CONDITIONAL PREPARATION OF LOW-NOISE BRIGHT TWIN BEAMS

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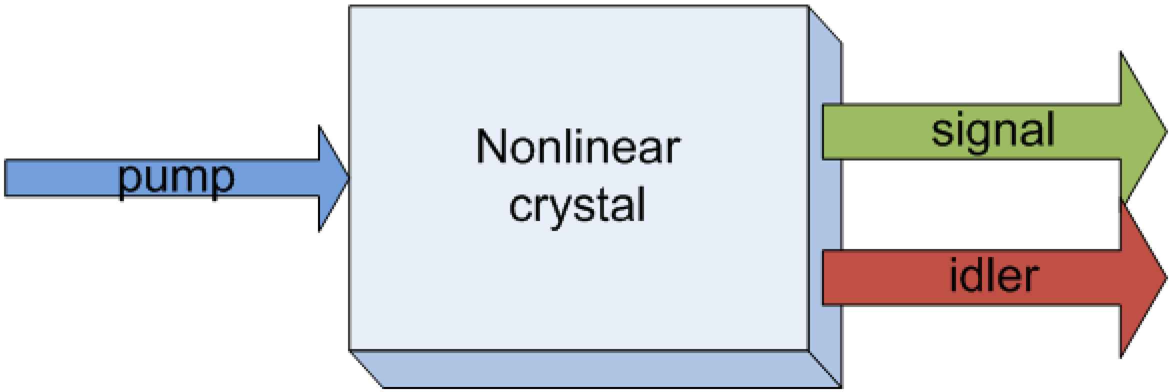
Outline

- Twin-beam states and their use in CV quantum communication
- Multimode structure
- Feed-forward technique
- **Increasing correlations between the beams**
- **Reducing photon-number fluctuations within the beams**
- Summary

Twin-beam states (TWB)

Output of an OPA with a vacuum input:



Pump photon is splitted to signal and idler photons.

They satisfy momentum and energy conservation.

The process can be described by the quadratic Hamiltonian.

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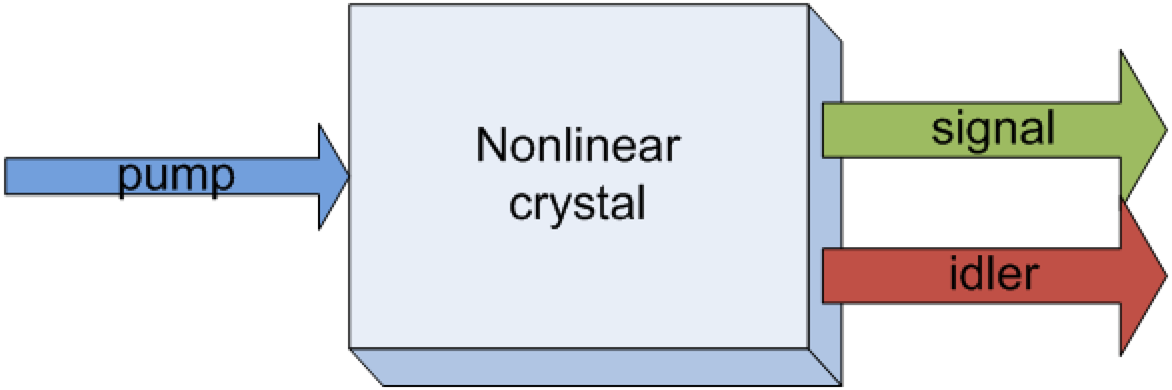

Use:

• Quantum metrology [G. Brida et al., J. Opt. Soc. Am. B 23, 2185 (2006)]

• Quantum imaging [G. Brida et al., Nature Photonics 4, 227 – 230 (2010)]

• Quantum key distribution [L. S. Madsen, VU et al., Nature Communications 3, 1083 (2012)]

Use of TWB / squeezed beams in CV quantum communication

- Squeezed states can partially substitute the inefficient classical error-correction in CV QKD [*VU, R. Filip, NJP 13, 113007, 2011*]
- Modulated TWB states can improve CV QKD [*L. S. Madsen, VU et al., Nature Communications 3, 1083 (2012)*]
- Multimode TWB can be used for CV QKD *[VU, L. Ruppert, R. Filip, PRA 90, 062326, 2014*]
- Optimally modulated squeezed states cancel information leakage in CV quantum channels [*C. S. Jacobsen, VU et al., arXiv:1408.4566*]

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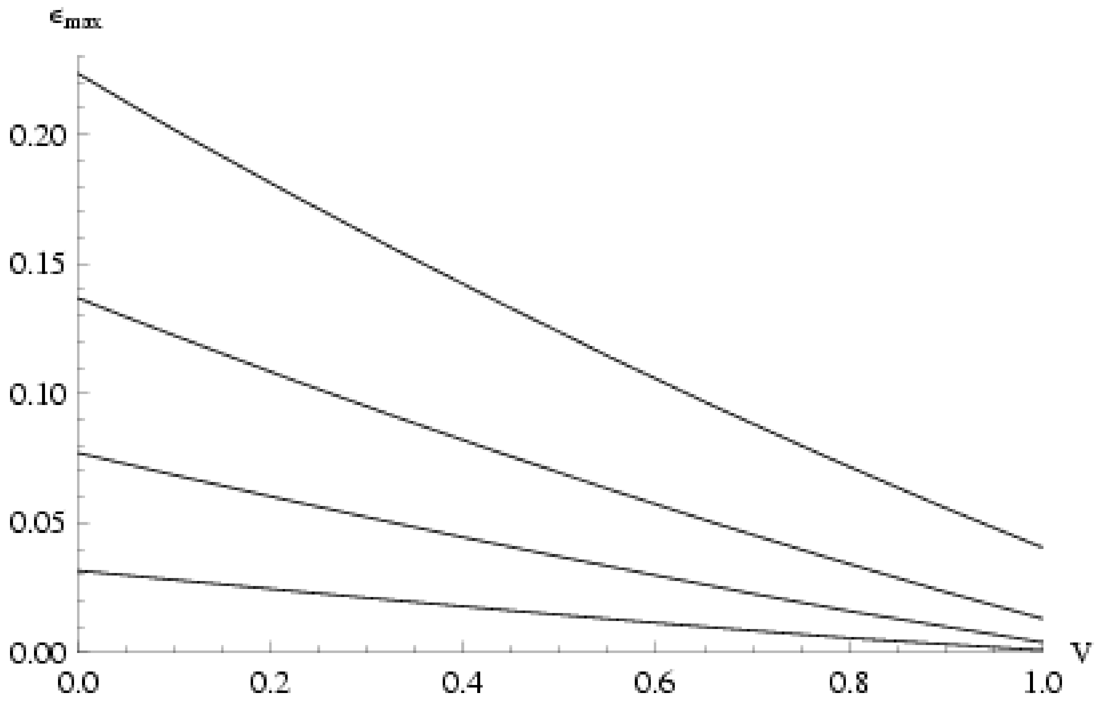

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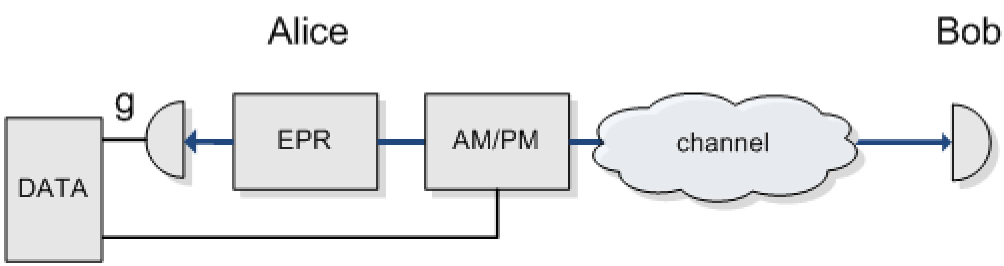

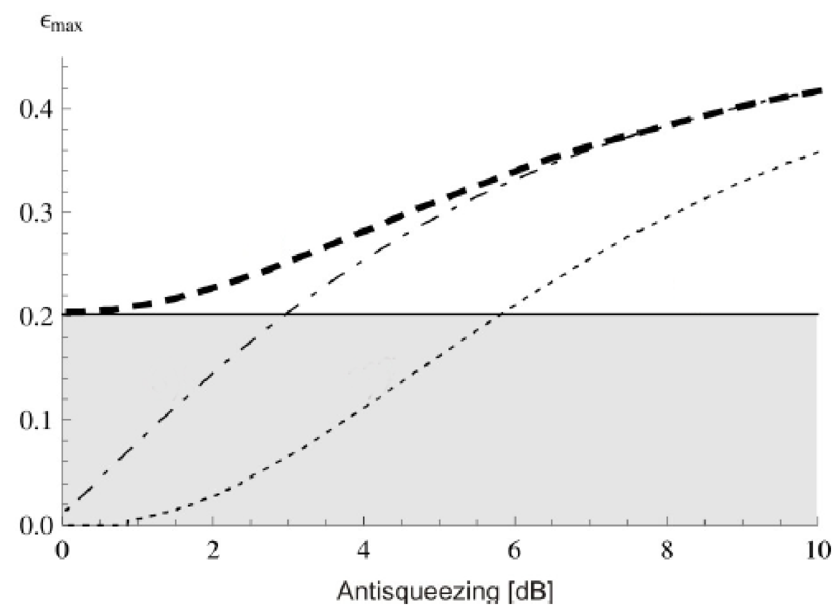

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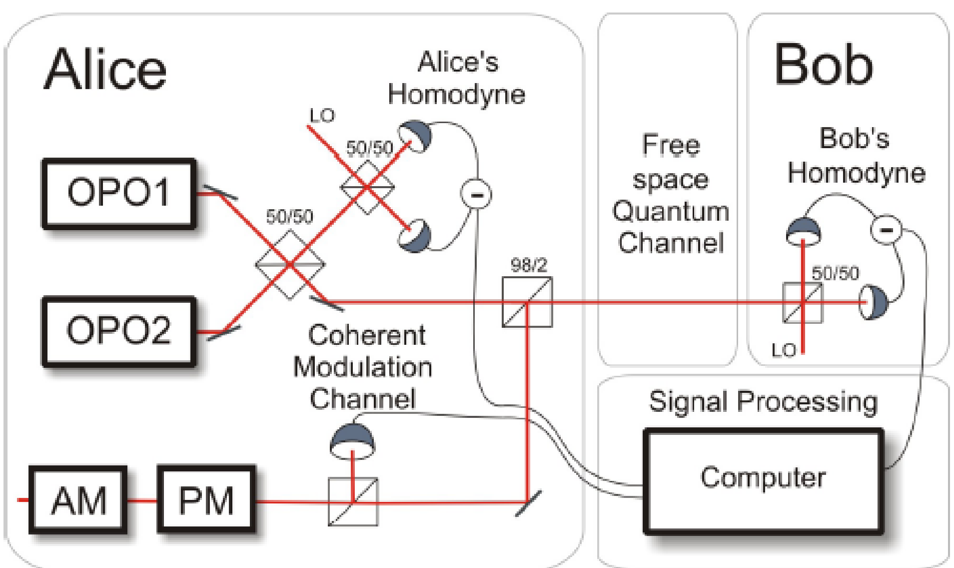

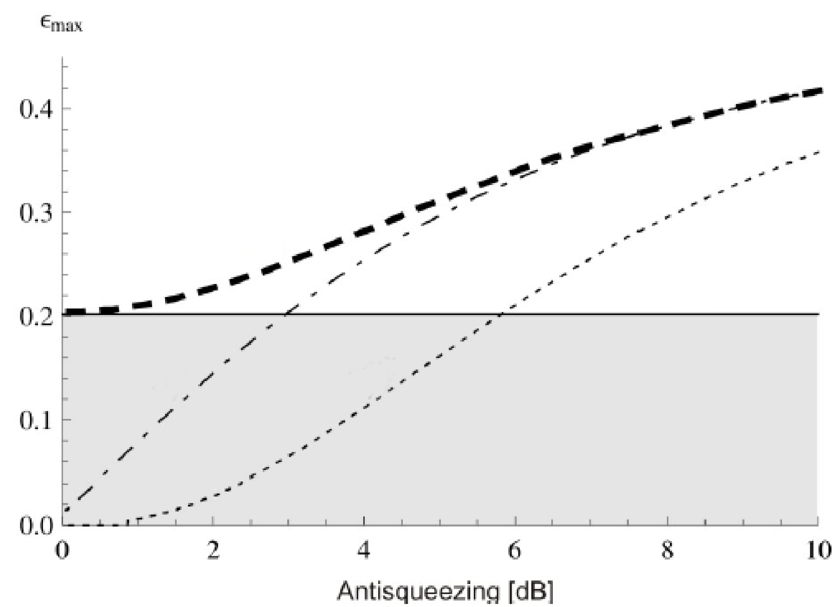

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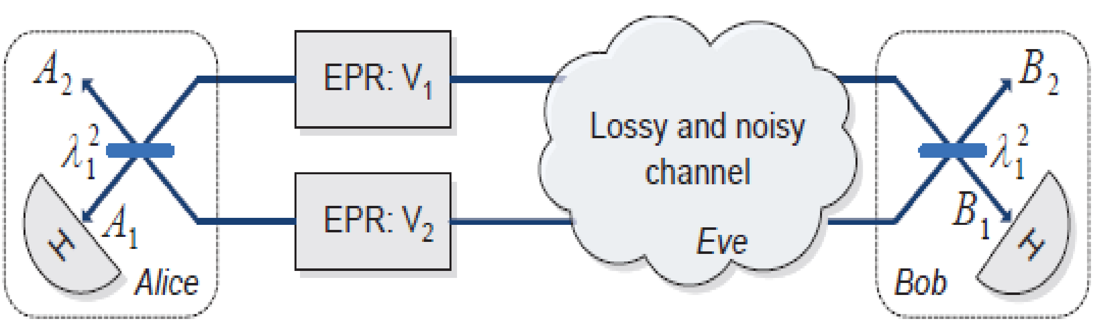

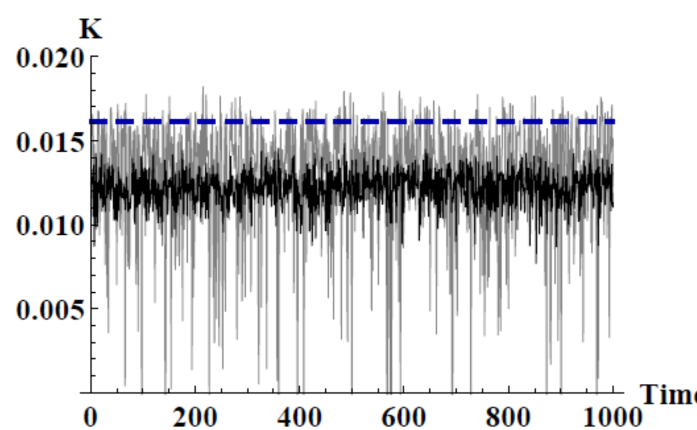

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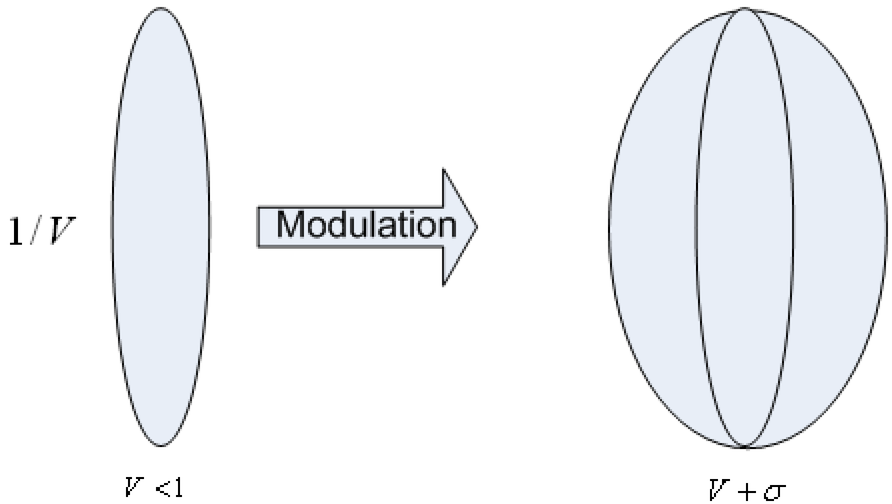

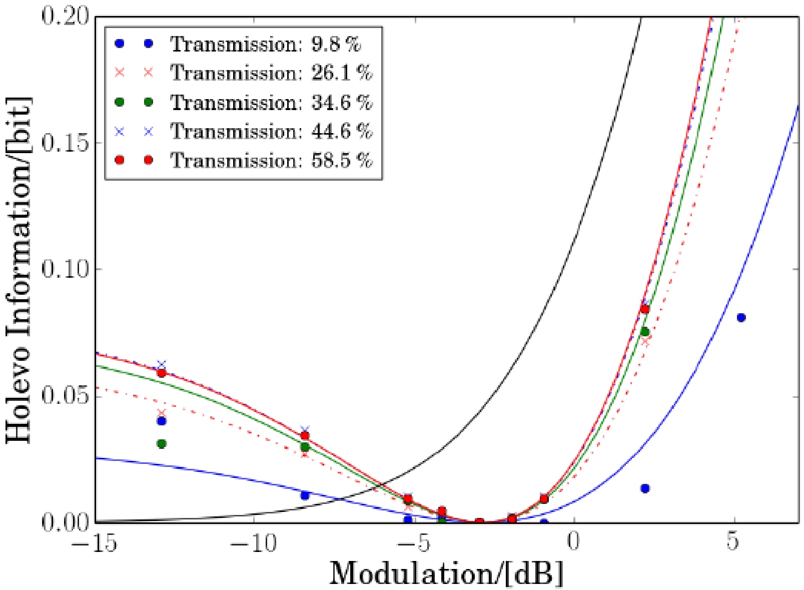

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It was about quadrature squeezing, now let's look at photon-number / intensity measurements.

TWB: photon-number description

Photon numbers ($a^{+}a$) can be measured in each beam.

Representation in the Fock (number) basis:

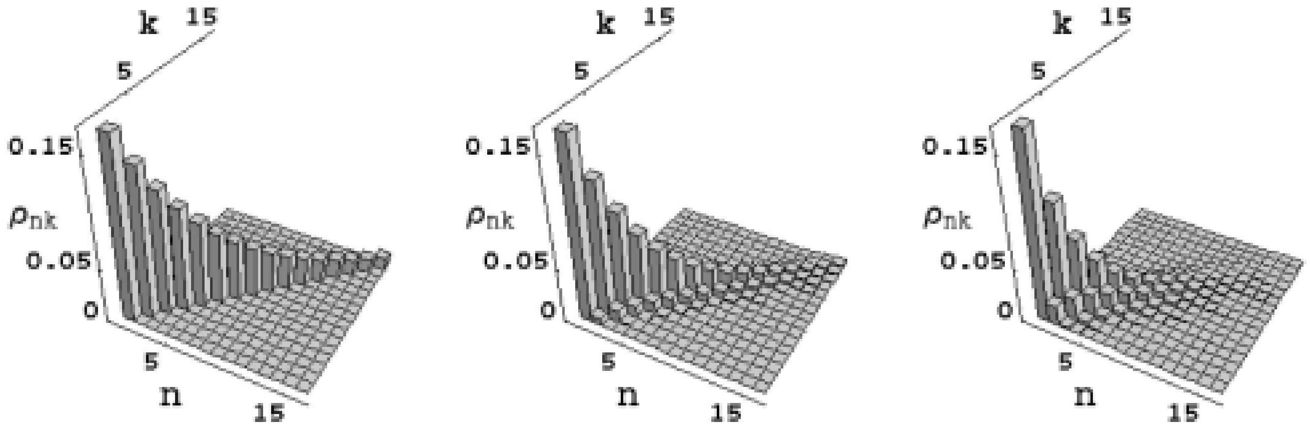
$$\boxed{|x\rangle\rangle = \sqrt{(1-x^2)}\sum_n x^n\,|n,n\rangle\rangle} \quad , \quad |n,n\rangle\rangle \equiv |n\rangle_s \otimes |n\rangle_i$$

$x \in \mathbb{C}$ and $0 \leq |x| \leq 1$

$x = \sqrt{N/(N+1)}$, where N – mean photon number

TWB: photon-number description

Photon-number statistics in each beam is thermal:



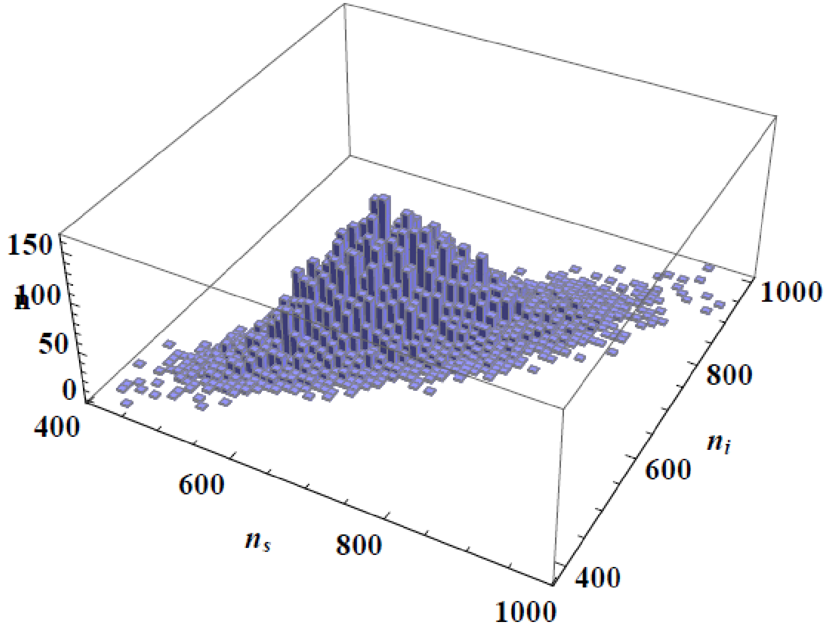
Correlation is (almost) perfect, thus **sub-shot-noise** photon-number difference correlation is observed.

Multimode twin-beams

Bright twin-beams are heavily multimode (spatial, frequency etc)

The state becomes the mixture of multiple twin-beam states.

Statistics becomes “bell-shaped”:



100 modes with N=10 photon each

Multimode twin-beams

Twin-beams can be multimode (spatial, frequency etc)

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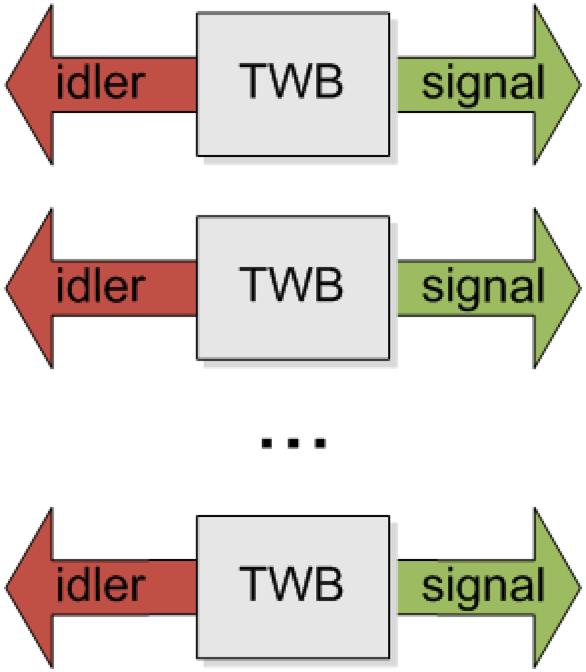

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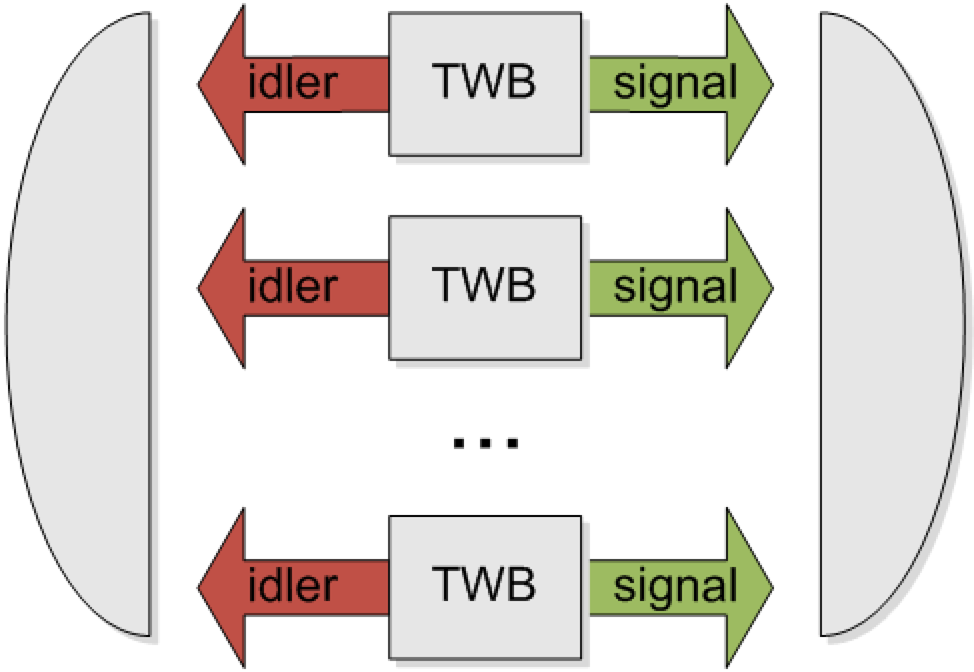
Mode-nondiscriminating photon-counting:



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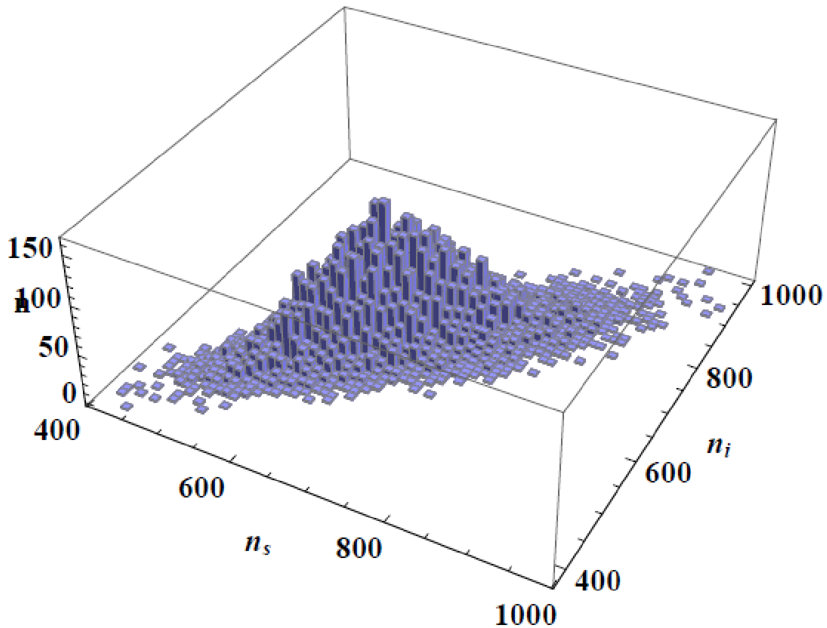

Correlations are degraded due to losses, inefficient detection and mode mismatch. Nonclassicality can be lost.

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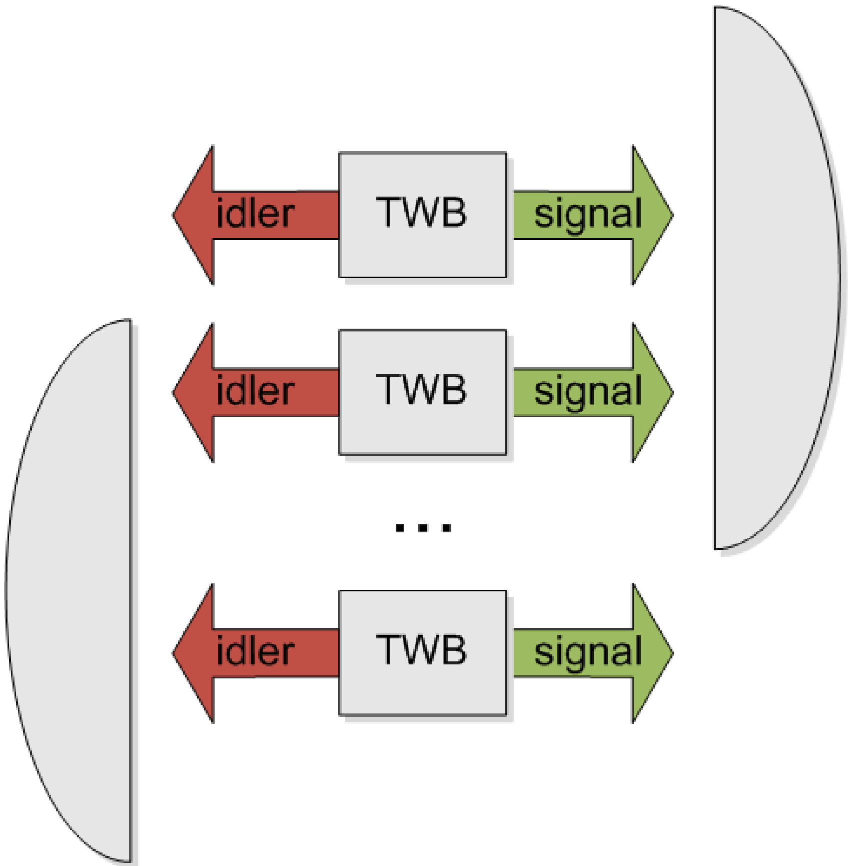
Mode mismatch:



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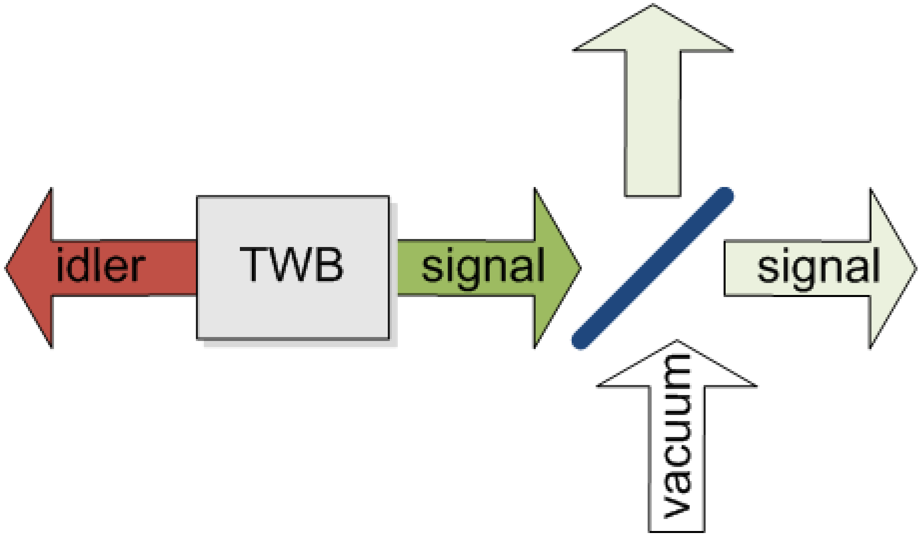
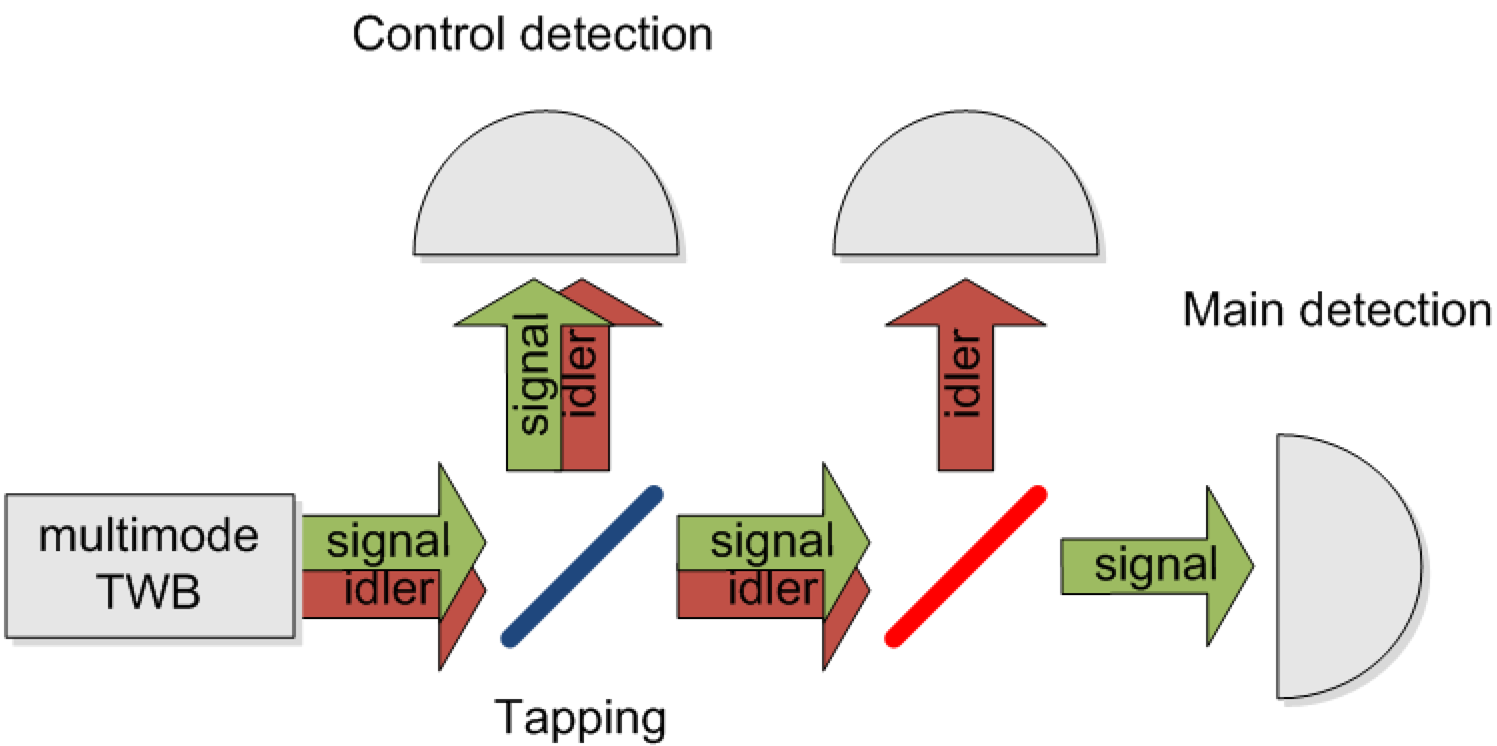
Loss:



Restoring nonclassical correlations

Feed-forward measurement:



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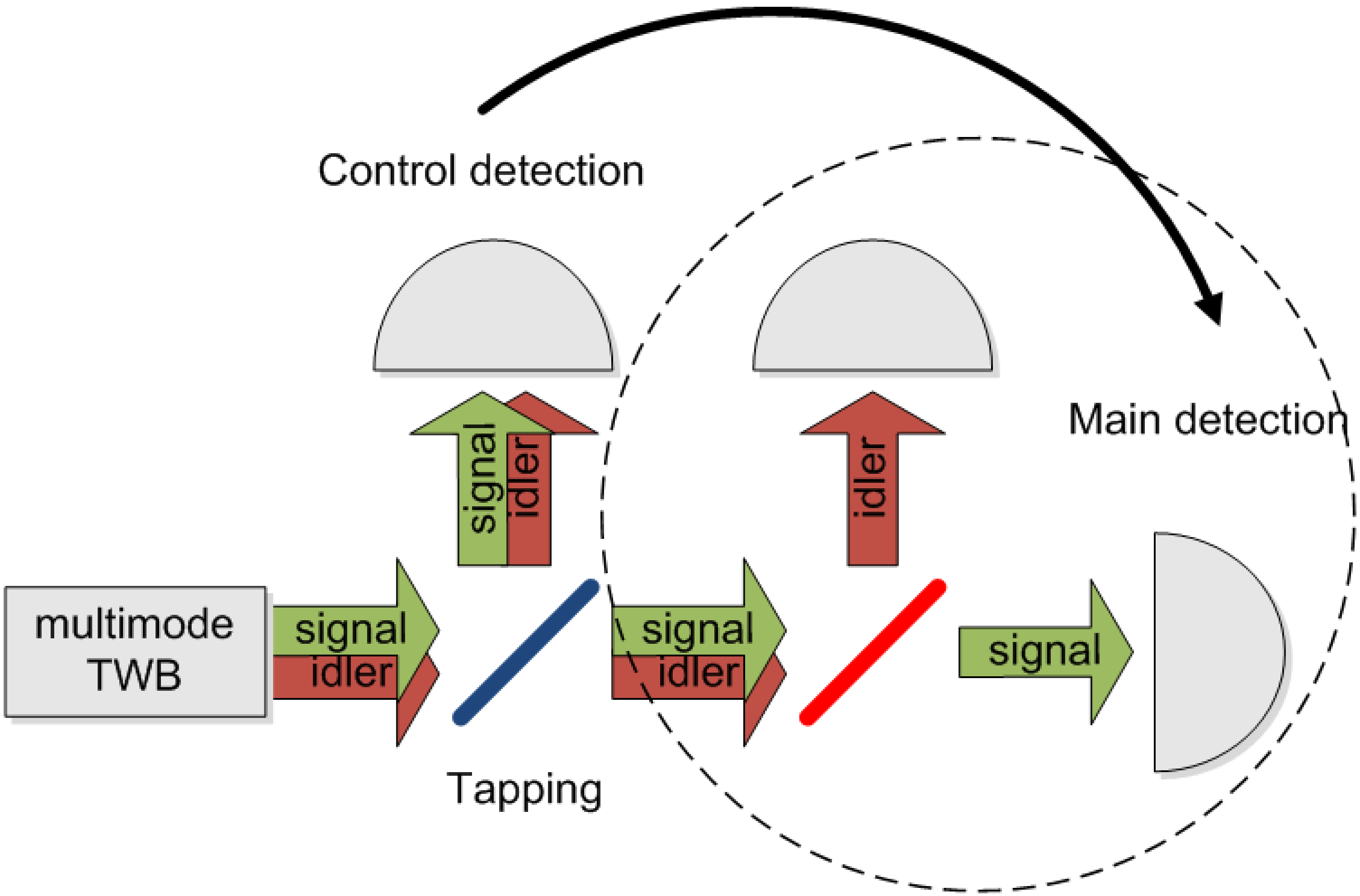

When measurement outcome on control detector satisfies a condition (defined by position and width), the main detection is performed.

Restoring nonclassical correlations

Correlation can be characterized by noise reduction factor (NRF):

$$NRF \equiv Var(N_i - N_s)/\langle N_i + N_s \rangle$$

In case of m matched and k mismatched modes:

$$NRF_{meas} = 1 - \frac{m}{m+k}\eta + \frac{k}{m+k}\eta N_{mode}.$$

Photon-number sum fluctuations can be characterized by normalized variance of photon-number sum:

$$F \equiv Var(N_i + N_s)/\langle N_i + N_s \rangle$$

which reads $F = 2\eta N_{mode} + 1.$

Multimode TWB: Numerical model

Conditional preparation was modeled as generation of multimode TWB states, coupling to vacuum modes, mode-nondiscriminating photon-counting measurements and conditioning.

Generated states: $p(n) = (1 - x^2)x^{2n}$

After coupling to vacuum: $p(k) = \dfrac{n!}{k!(n-k)!}T^{n-k}(1-T)^k$

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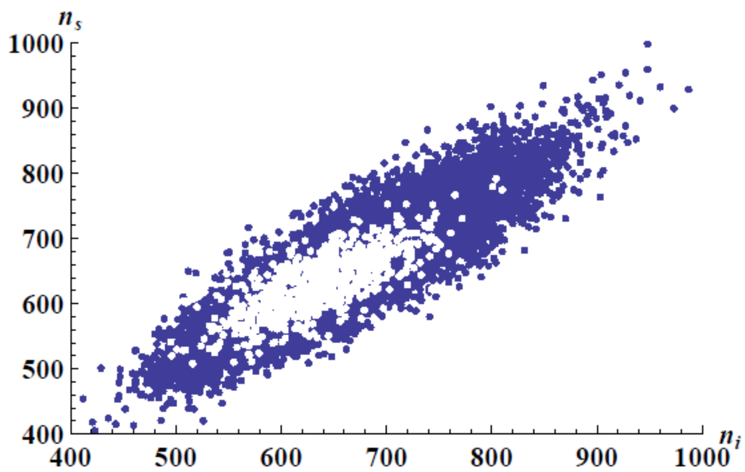

Photon-number distributions before and after optimal conditioning

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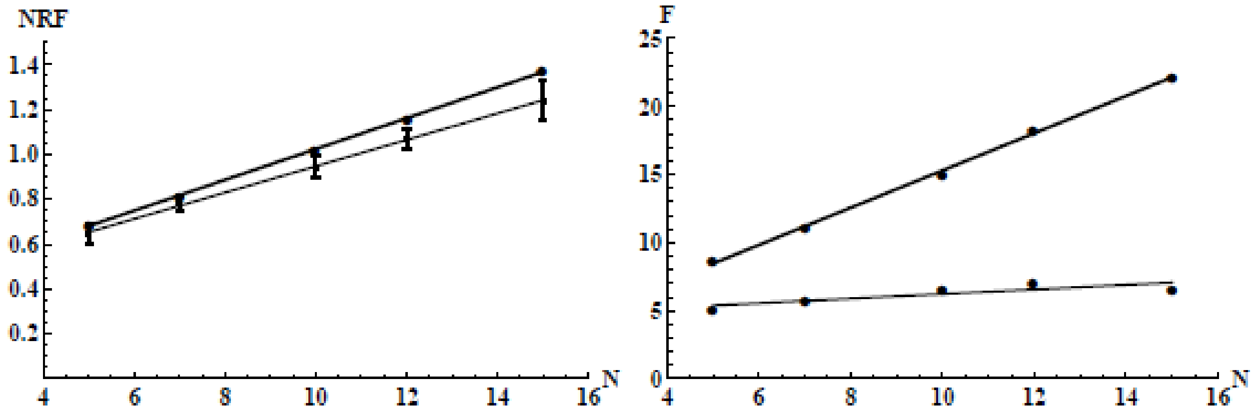
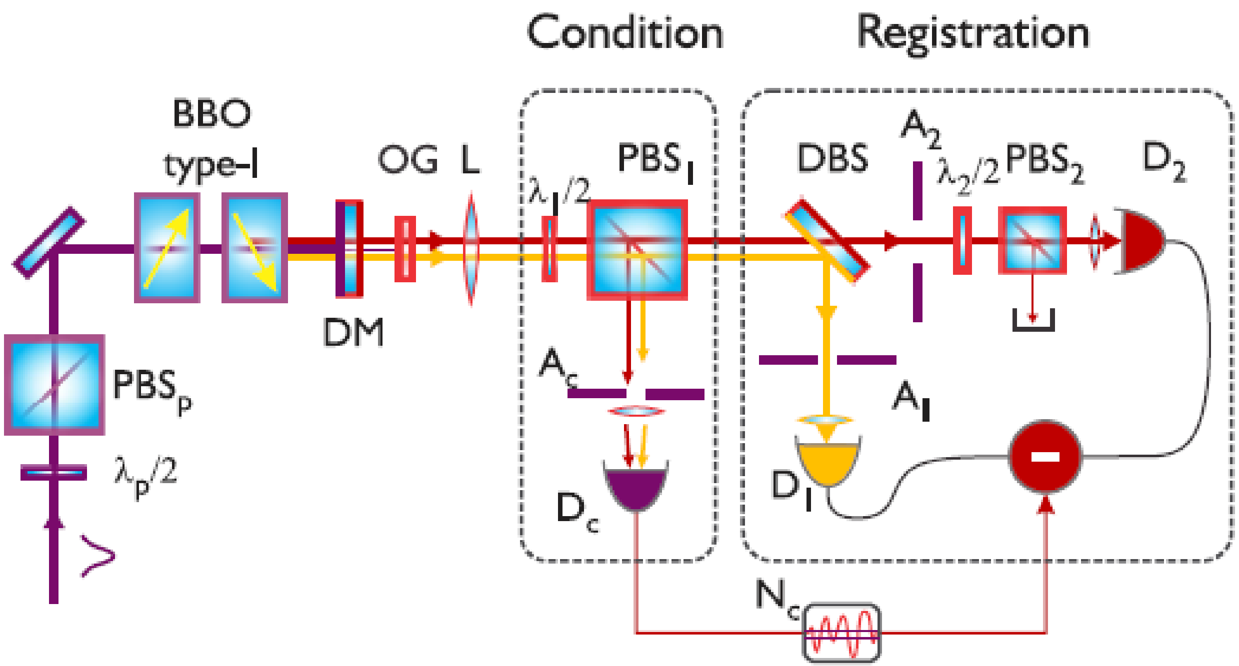


NRF and F-factors before and after optimal conditioning

Multimode TWB: NRF experiment

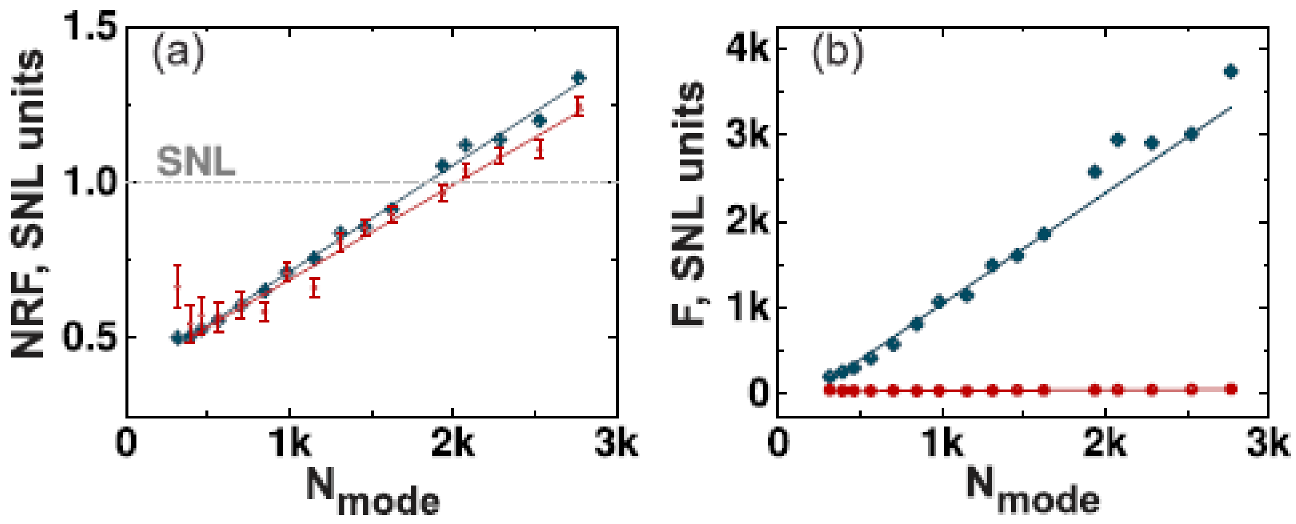
Correlation can be improved by feed-forward measurement:



Sketch of the experiment at MPI in Erlangen

Multimode TWB: NRF experiment

Experimental results:



Optimal conditioning leads to reduction of NRF and F factors.

Singe-mode case

Single-mode state: $$|\Psi\rangle = \frac{1}{\sqrt{1+N_{mode}}}\sum_{n=0}^{\infty}\lambda^{\frac{n}{2}}|n\rangle_S|n\rangle_I$$

with $\lambda = \frac{N_{mode}}{N_{mode}+1}$

After perfect subtraction of N photons:

$$(a_S a_I)^N|\Psi\rangle = \frac{1}{\sqrt{1+N_{mode}}}\sum_{n=0}^{\infty}\frac{(n+N)!}{N!}\lambda^{\frac{n+N}{2}}|n\rangle_S|n\rangle_I$$

After normalization:

$$|\Psi'\rangle = \frac{\sum_{n=0}^{\infty}\frac{(n+N)!}{n!N!}\lambda^{\frac{n}{2}}|n\rangle_S|n\rangle_I}{\sqrt{{}_2F_1\left[1+N,1+N,1,\lambda\right]}}$$

With increasing N the maximum moves away from the origin, brightness increases.

Statistics characterization

To characterize the statistics after conditioning, we suggest using mean-deviation-ratio (MDR):

$$\mathrm{MDR} = \frac{\langle n \rangle}{\sqrt{\langle (\Delta n)^2 \rangle}} \approx \begin{cases} \sqrt{2\lambda N - 1} & \lambda \ll 1 \text{ and large } N, \\ \sqrt{2\lambda N + 1} & \lambda \to 1 \text{ and large } N. \end{cases}$$

In the multimode regime MDR can grow with increasing number of modes. By conditional preparation we increase it without changing the mode structure.

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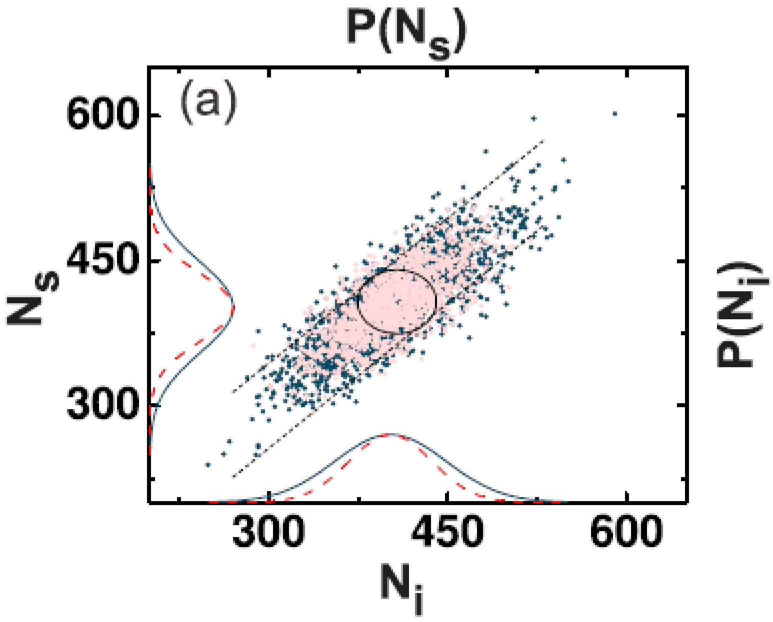
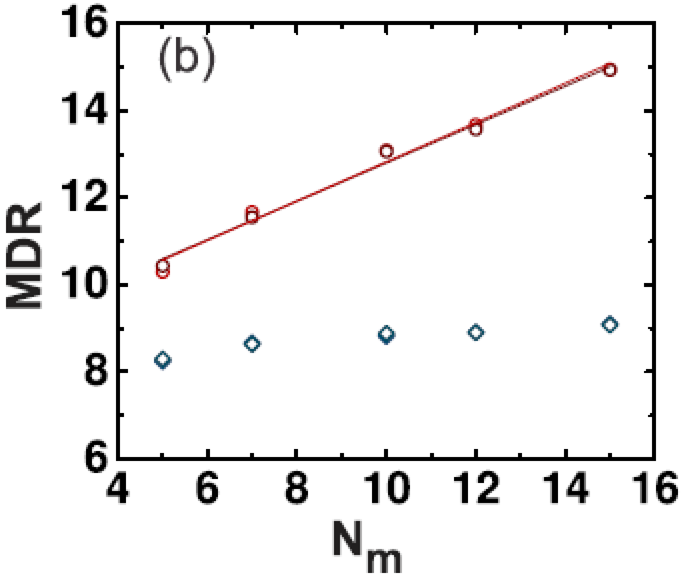
Why not $g^{(2)} \equiv (\langle n^2 \rangle - \langle n \rangle)/\langle n \rangle^2$?

It can be decreased by the number of modes $g^{(2)}(0) = 1 + \frac{1}{M}$

Why not Fano? It can be reduced by attenuation, it is weakly changed for intense beams.

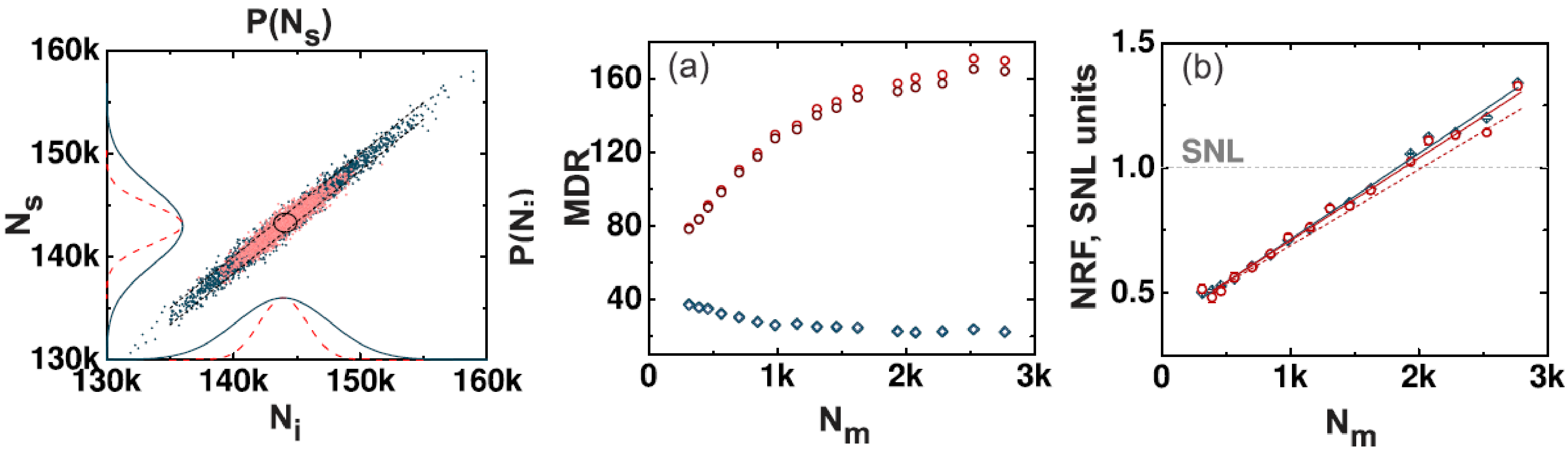
Suppressing the noise: numerics





Distributions and MDR before and after conditioning

Suppressing the noise: experiment



Distributions, MDR and NRF before and after conditioning

Summary

- We suggest the method of conditional preparation of special low-noise twin-beam states;

- Numerical model and experimental test confirm possibility to increase correlations of bright multimode twin-beams using feed-forward;

- MDR is suggested to characterize the statistical properties of multimode beams after feed-forward;

- It is shown theoretically and experimentally that photon-number fluctuations of multimode twin-beams can be reduced without reduction of correlations between the beams.

Acknowledgements

SEVENTH FRAMEWORK PROGRAMME

BRISQ2

Further plans and the follow-up

- Homodyning on the bright multimode squeezed states / twin beams
- Homodyning without local oscillator – Laszlo Ruppert

Thank you for attention!

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