News on continuous variables

Contributions from Potsdam node to the goals of COMPAS

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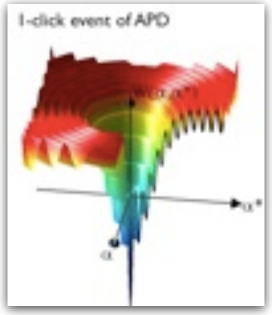
Partly joint work with Konrad Kieling and Andrea Mari
Brussels, December 2009

- **Overview:**



- **Systems identification and detector tomography**

  - "Learn much from little": Ideas of *systems identification* with error bars
  - *Detector tomography*
  - Measures of *non-classicality* (negative Wigner functions) and how to measure them
  - Entanglement in *multi-mode states*
  - Applications to CV *entanglement distillation*

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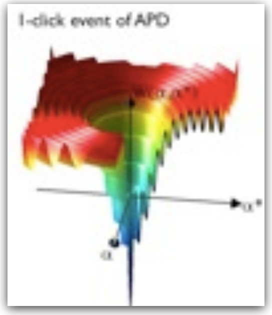

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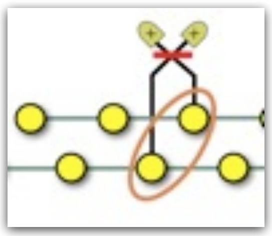

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  - *No-go statements* on Gaussian approaches to measurement-based quantum computing
  - Full potential of *non-Gaussian states for computing*

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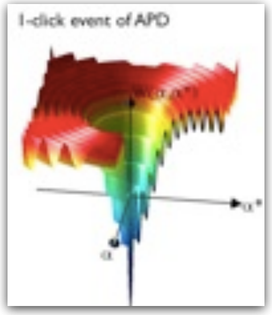

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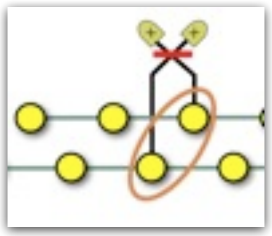

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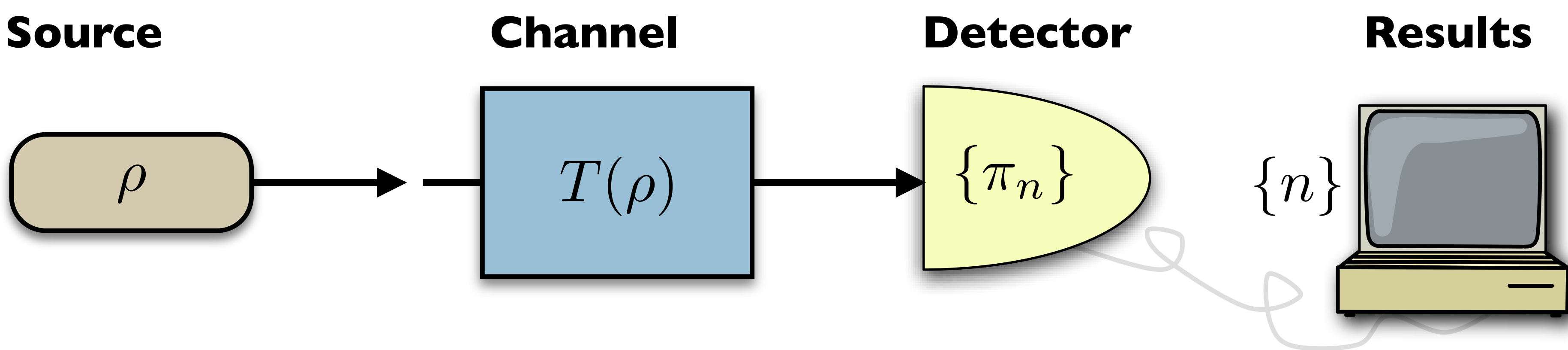
- **Some perspectives**

- Detector tomography and certifiable bounds for CV entanglement and non-classicality

- **A typical quantum experiment**

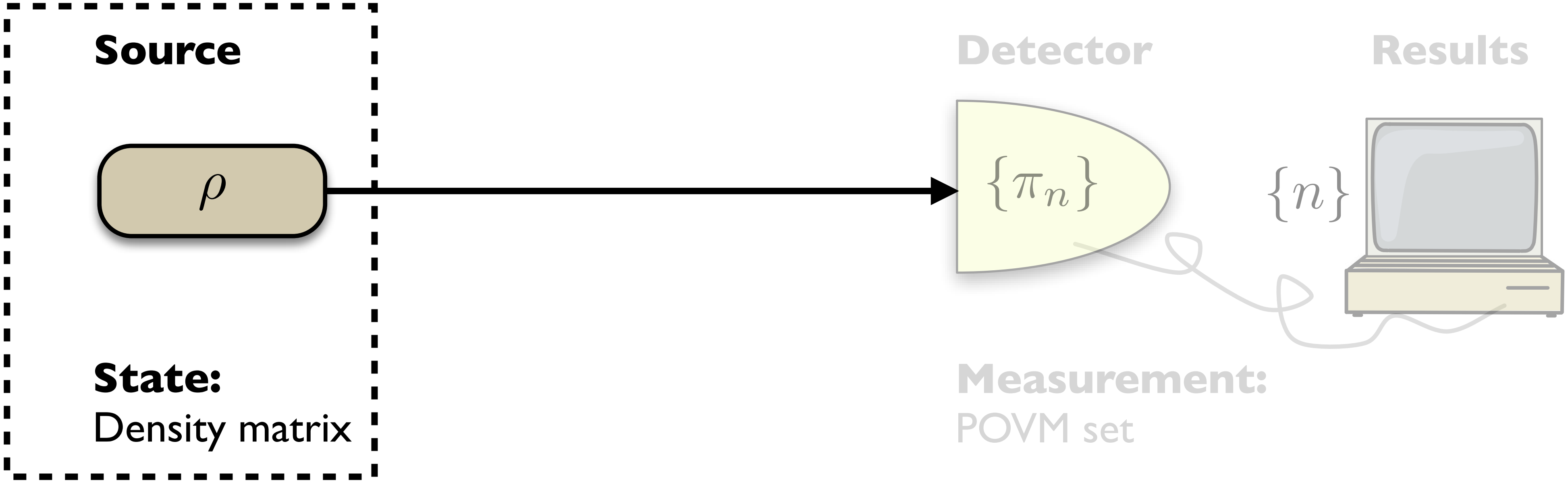


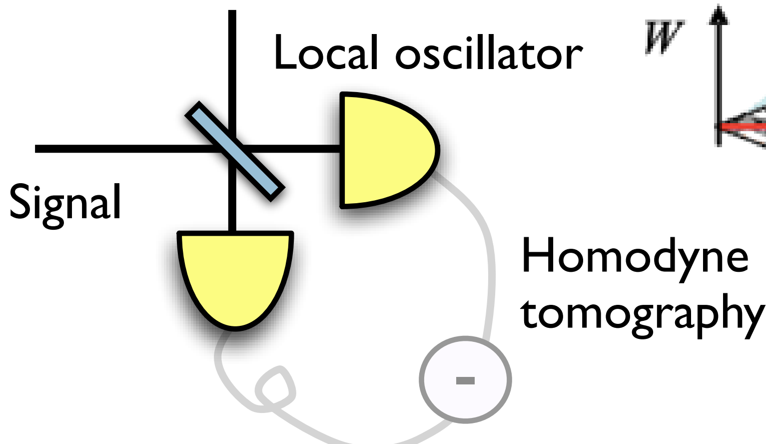
State:
Density matrix

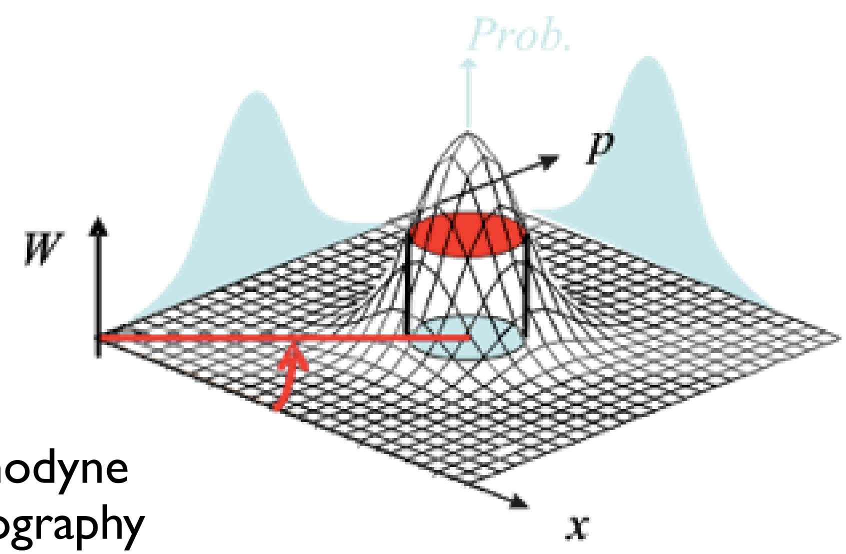
Process:
Kraus operators

Measurement:
POVM set

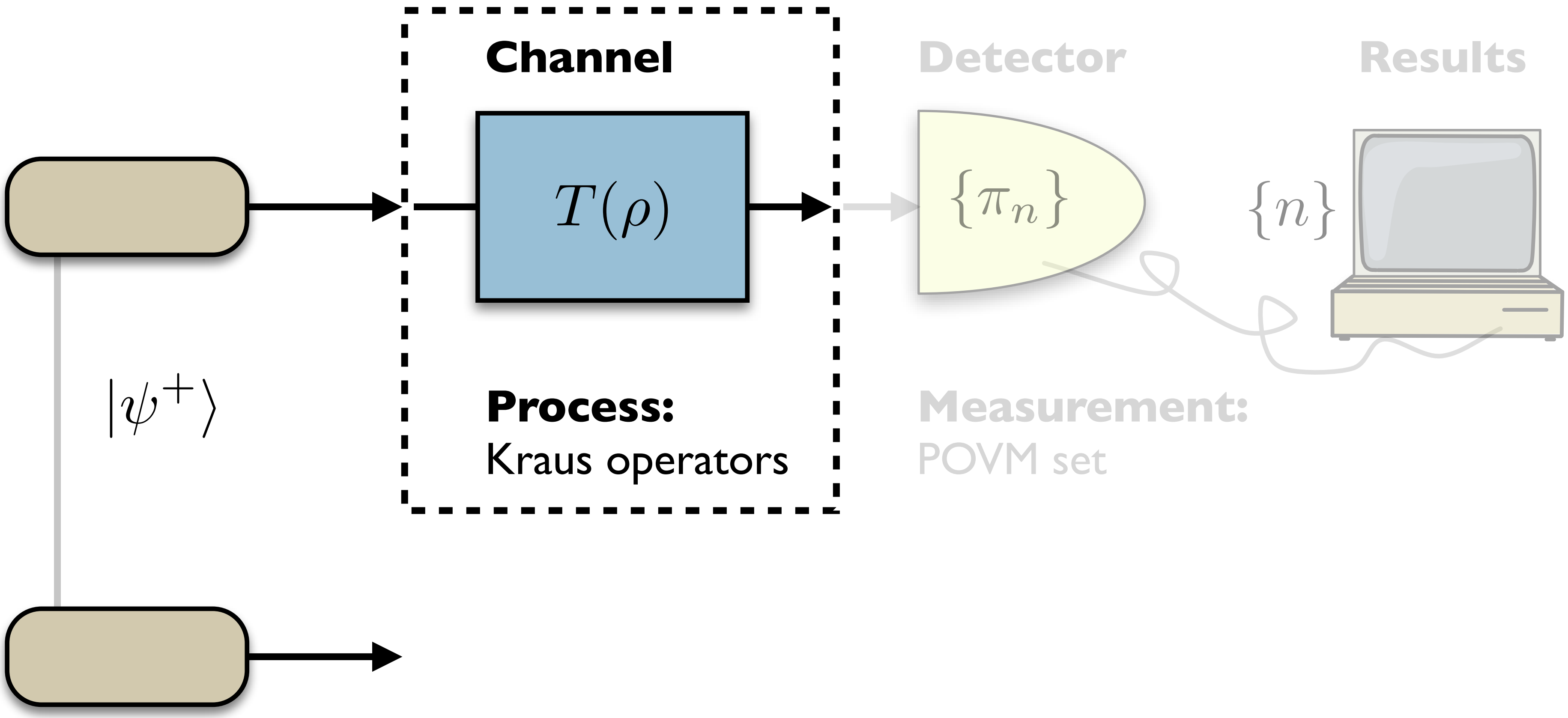
- **State tomography**





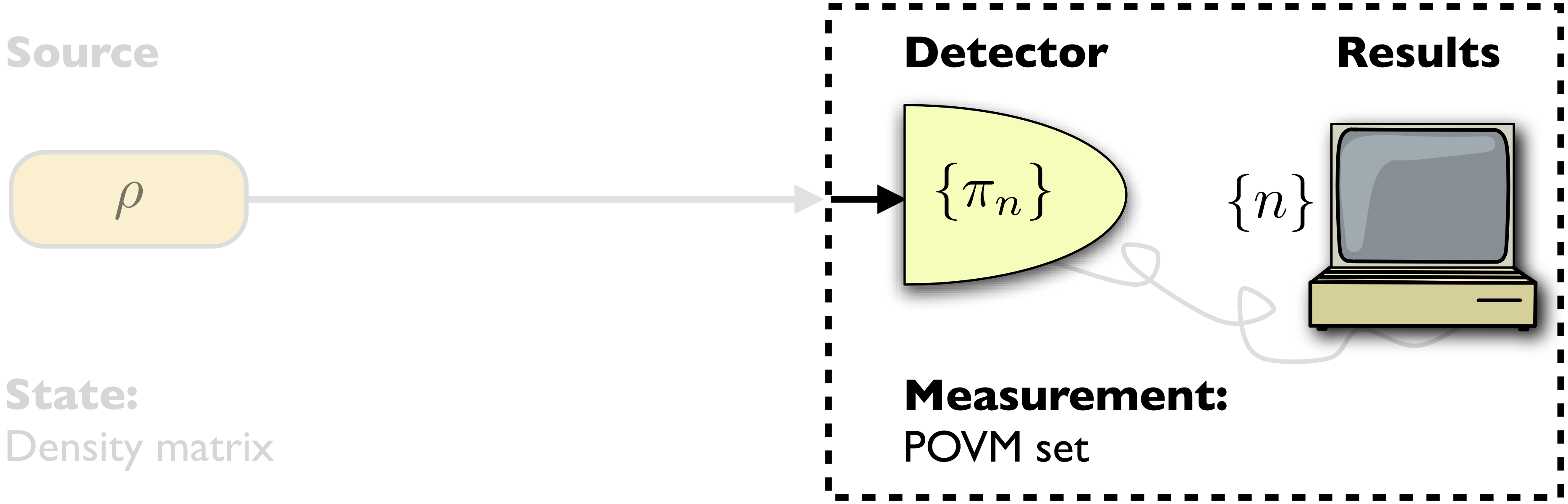


- **Process tomography**



- State tomography on channel acting on entangled input

•Completing the triangle: Detector tomography



•Positive operator valued measure (**POVM**) of detector

$$\pi_n \geq 0 \quad \text{(One POVM element per outcome)}$$

$$\sum_{j=1}^{K} \pi_j = \mathbb{I} \quad \text{(Completeness)}$$

•Reconstruction:

$$p_n(\rho) = \mathrm{tr}(\rho \pi_n)$$

Need to know **results** and **states** to get **POVM** elements (tomographically complete probe set)

- **Completing the triangle: Detector tomography**
- Calibration of detectors difficult, therefore employ „Black Box Approach“
- Sending coherent states to the detector measures Q-Function

$$Q(\alpha, \alpha^*) = \langle \alpha | \rho | \alpha \rangle$$

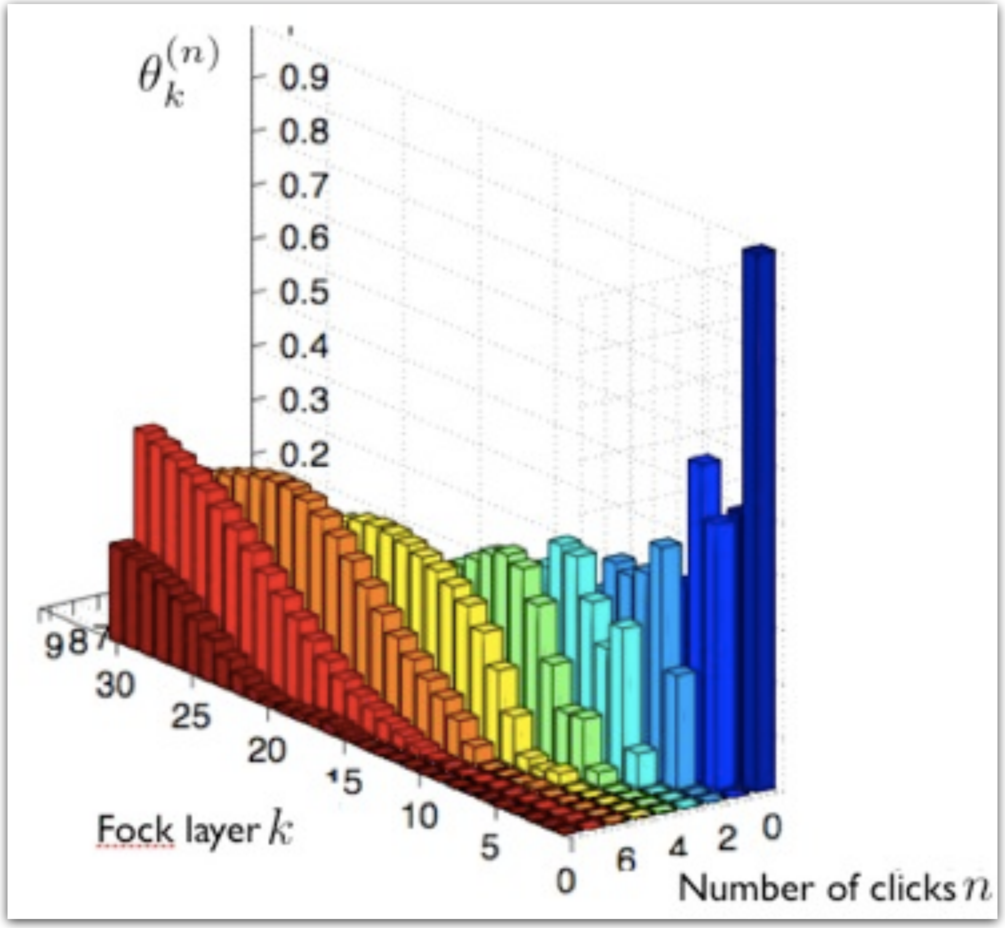
- Due to noise, Q-Function can correspond to non-physical POVM-element
- When no phase dependence observed: $\pi_n = \sum_{k=0}^{\infty} \theta_n^k |k\rangle\langle k|$
- Find physical POVM closed to the one corresponding to the measured statistics

$$P = F\Pi \qquad F_{i,k} = \frac{|\alpha|_i^{2k} \exp(-i|\alpha_i|^2)}{k!}$$

$$\min\{||P - F\Pi||_2 + g(\Pi)\}$$

subject to $\sum_{n=1}^{N} \pi_n = 1 \quad \pi_n \geq 0$

- **Completing the triangle: Detector tomography**



•Detecting negative Wigner functions

- Negative Wigner function is a sign of non-classicality.

- Pure state: Wigner function positive if and only if the state is Gaussian

- Mixed states: State with positive Wigner function can be „a little“ non-Gaussians e.g. mixtures of Gaussian states.

- Quantitative Measure:

$$N = \int |W(\xi)| d\xi - 1$$

Bound from „few“ measurements

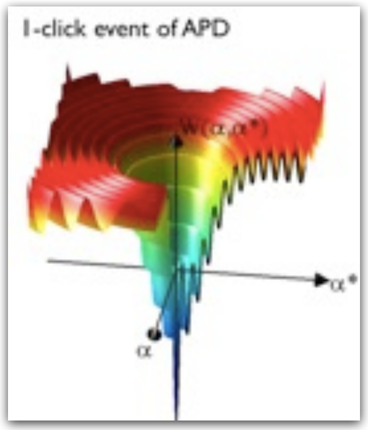
- Find the state with the *lowest* Wigner-functions-negativity consistens with given measurement statistics

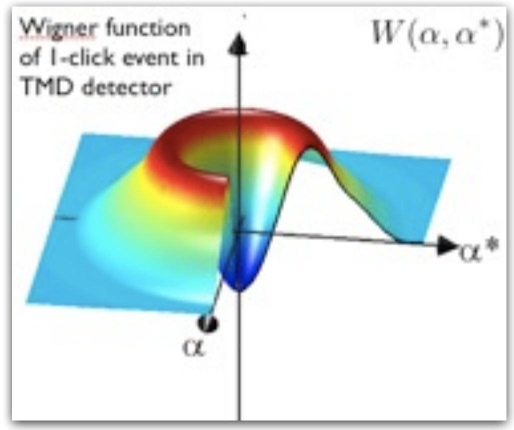
- **Projects in last period:**

1. Experimental implementation/theoretical analysis of detector tomography

D1.6

- Including techniques of filtering in ill-conditioned settings
- Applications to weak homodyning: Photon counting with a weak phase reference as a "*hybrid*" *between a CV and a discrete variable approach*

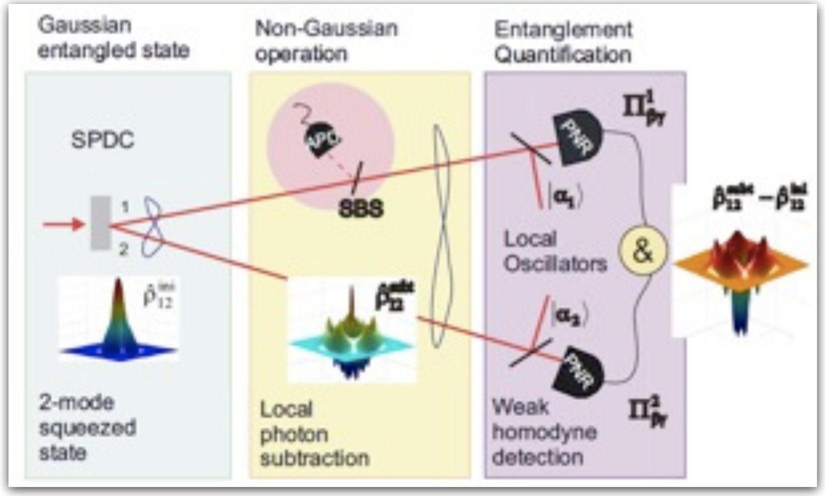




- *Measuring measurement: theory and practice,* A. Feito, J. Lundeen, H. Coldenstrodt-Runge, J. Eisert, M.B. Plenio, and I.A. Walmsley, New Journal of Physics **11**, 093038 (2009)
- *A proposed testbed for detector tomography*, H.B. Coldenstrodt-Ronge, J.S. Lundeen, K.L. Pregnell, A. Feito, B.J. Smith, W. Mauerer, C. Silberhorn, J. Eisert, M.B. Plenio, I.A. Walmsley, Journal of Modern Optics **56**, 432 (2009)
- *Tomography of quantum detectors*, J. Lundeen, A. Feito, H. Coldenstrodt-Runge, T.C. Ralph, C. Silberhorn, J. Eisert, M.B. Plenio, and I.A. Walmsley, Nature Physics **5**, 27 (2009)

- **Projects in last period:**

2. Good direct bounds to entanglement



- Bounds from few measurements of a weak homodyning measurement:
- "Minimal degree of entanglement consistent with measurements", based on much less than tomographic knowledge
- *Tool to certify success of CV entanglement distillation*

- *Entanglement quantification from incomplete measurements: Applications using photon-number-resolving weak homodyne detectors*, G. Puentes, A. Feito, A. Datta, J. Eisert, M.B. Plenio, I.A. Walmsley, arxiv.org:0911.2482

3. Directly detecting negative Wigner functions

- *Direct bounds* with error bars from mere two slices in phase space
- Including certified bounds to a *non-classicality measure* based on the negativity of the Wigner function
- Tight practical bounds for photon subtraction
- Connection to non-Gaussianity measures

D1.1

- *Directly detecting negative Wigner functions*, A. Mari, K. Kieling, J. Eisert, in preparation (2009)

4. Characterization of spatially entangled photon pairs

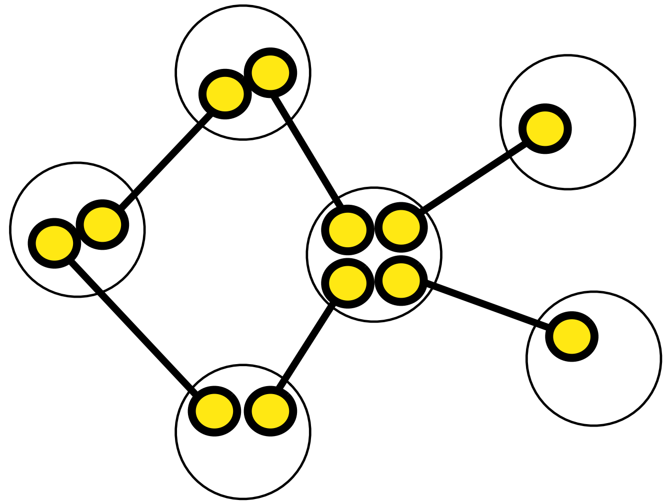
- *Two-dimensional characterization of spatially entangled photon pairs*, M. Ostermeyer, D. Korn, P. Pihlmann, C. Henkel, and J. Eisert., Journal of Modern Optics, iFirst November (2009).

- Measurement based quantum computing with CV-quantum states

- **Realistic Gaussian Cluster states:**

  - Start every mode in finitely squeezed vacuum state and employ Gaussian operation between „neighboring“ pairs

  - Generalization to Gaussian Projected Entangled Pair States (GPEPS)



- **Resource for Measurement Based Quantum Computing ?**

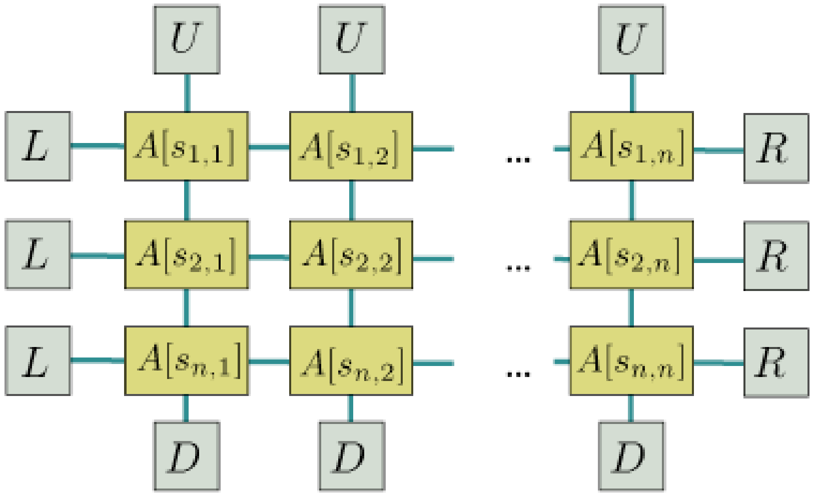
  - For Gaussian measuremens, no entanglement between distant points:

$$E_{\mathrm{G}}(A,B) \leq C e^{-d(A,B)/\xi}.$$

  - Strong connection to Gaussian repeater networks for entanglement distribution

•Non-Gaussian CV-resource states for MBQC:

- CV computational tensor network states with *finite-dimensional* correlation system



- Efficiently describable but not efficiently simulatable

- Restricted set of measurements based on physical feasibility, e.g. homodyning, single-photon detection

- Allow for computing with homodyning only (on the expense of difficult resource state)

- **Non-Gaussian CV-resource states:**

Sequential interaction with two-dimensional ancilla system with particular class of Hamiltonians

-Schoen, Hammerer, Wolf, et. al, *Phys Rev A* **75** (2007)

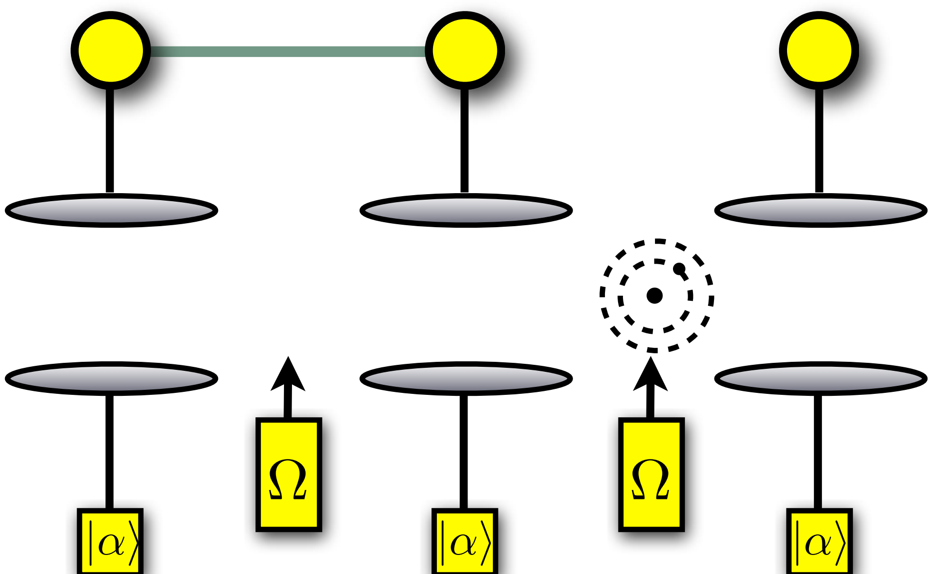
$$H = \sum_{s=0}^{\infty} H_2(s) \otimes |s\rangle\langle s|$$

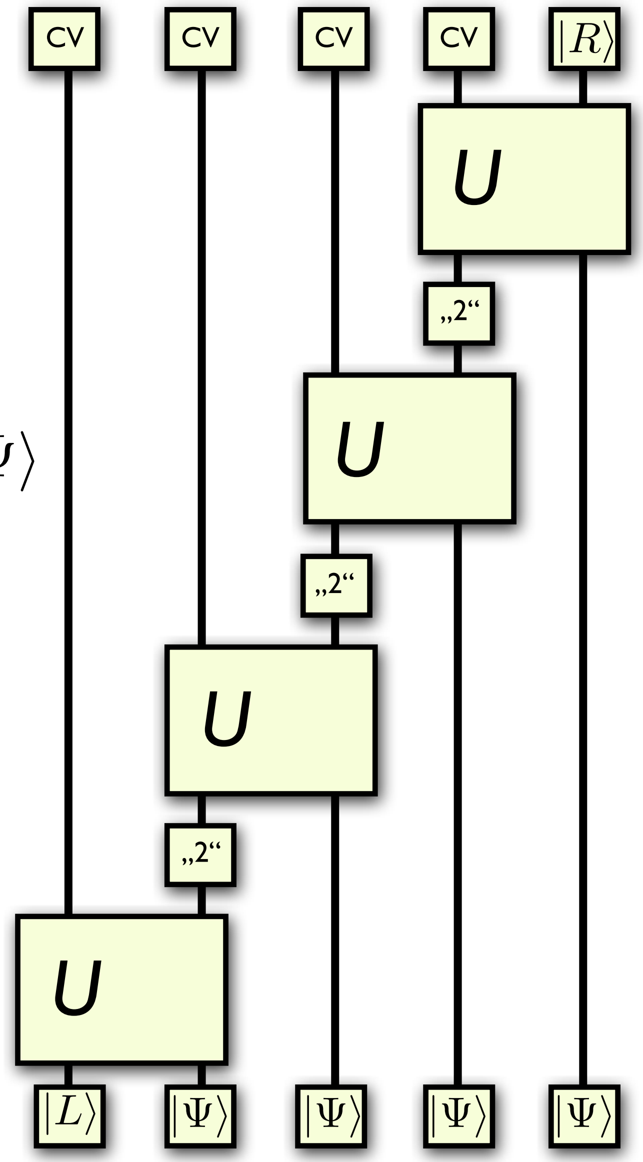
Hamiltonian on qubit subspace

Fock basis of light mode

$$U(s) = e^{-iH_2(s)t}$$

$$A[\phi] = \sum_{s=0}^{\infty} U(s)\langle\phi|s\rangle\langle s|\Psi\rangle$$

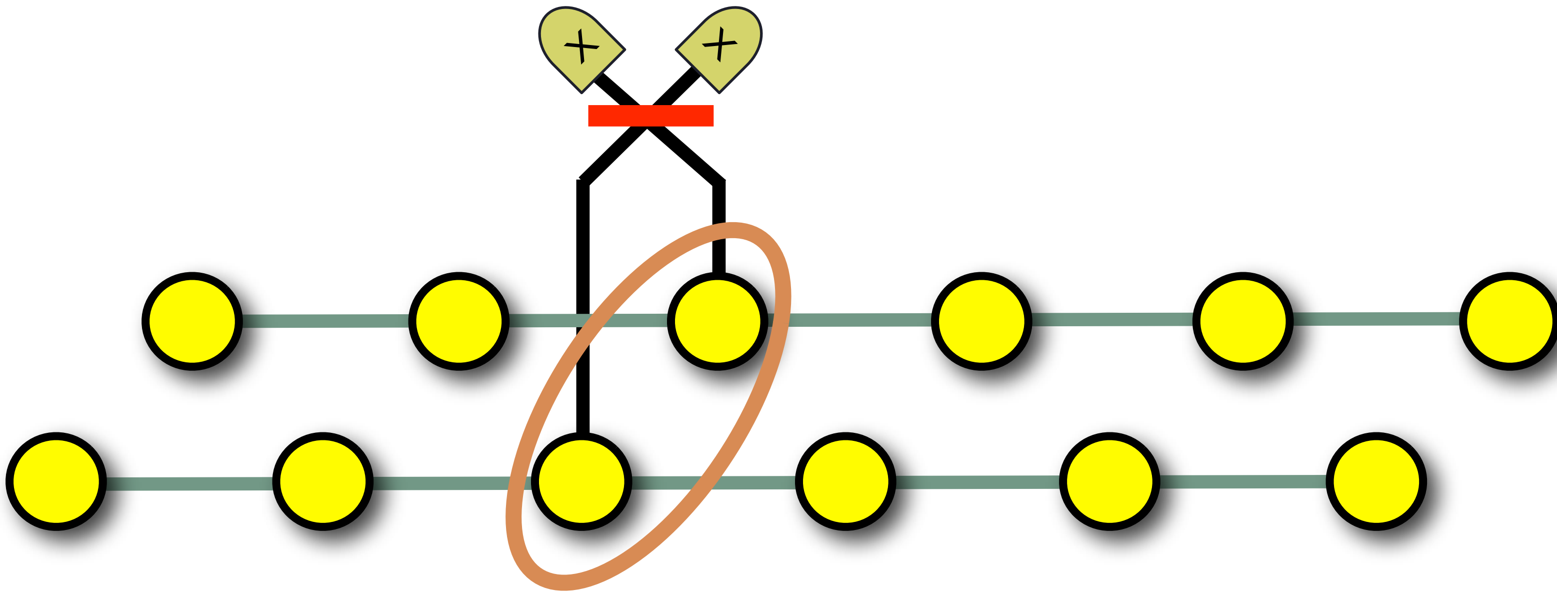




$$U = e^{-iHt}$$

•Non-Gaussian CV-resource states:

- Coupling of two logical wires by “simple” joined measurements



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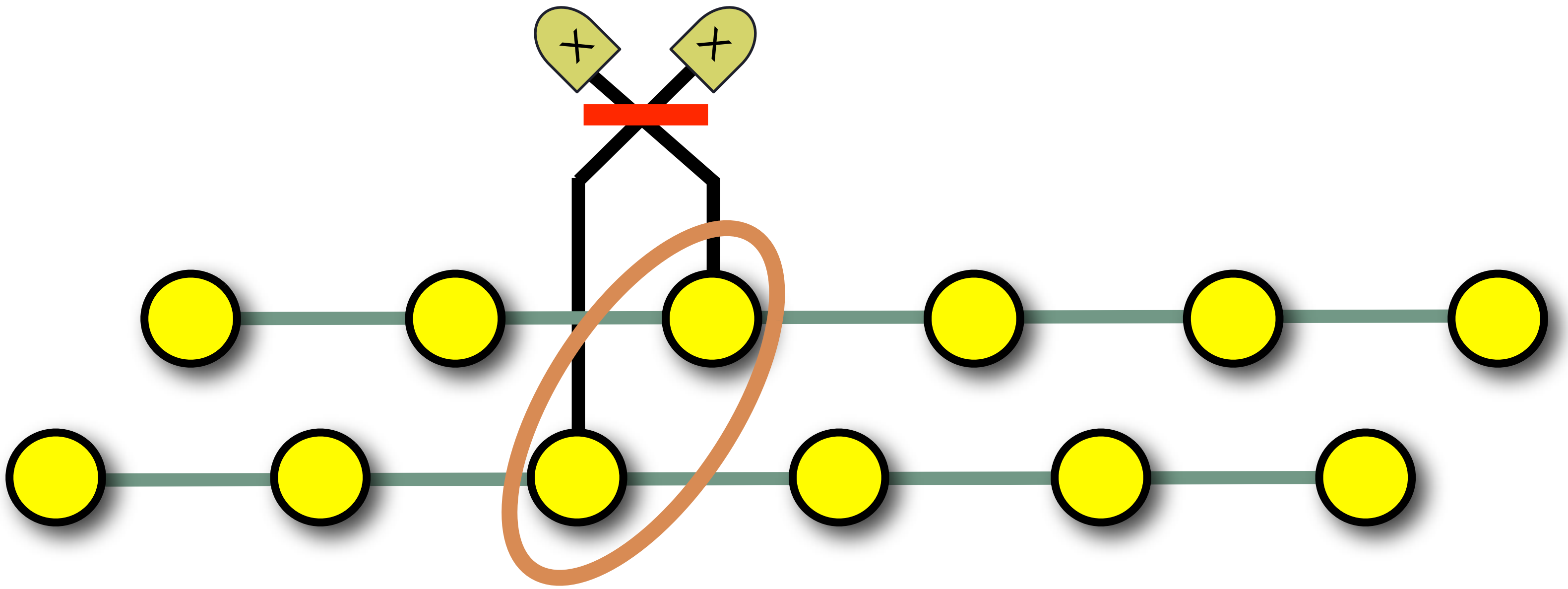


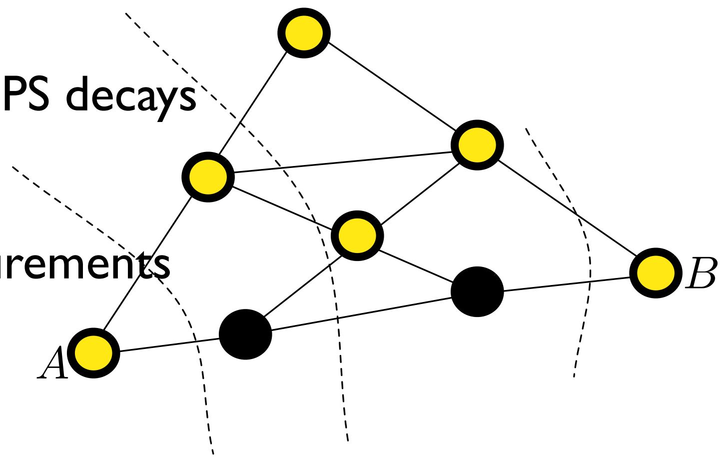
• Important questions:

  - How to handle inherent randomness?
  - How to perform error correction?

- **Projects in last period:**

5. Limitations of Gaussian cluster state computing

- Gaussian *localizable entanglement* between two points in a GEPS decays exponentially with the distance between them
- For one-dimensional GPEPS even true under arbitrary measurements
- Percolation strategies on general graphs



- *Limitations of quantum computing with Gaussian cluster states,* M. Ohliger, K. Kieling, J. Eisert, to be published

D1.2/D2.5

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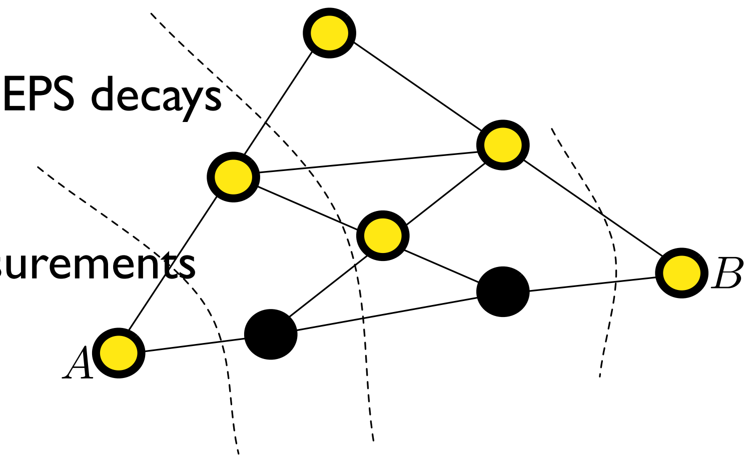

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D1.2/D2.5

6. MBQC with non-Gaussian resources

- General classification of one-dimensional CV-resources
  (Extension of *Quantum computational webs,* D. Gross, J. Eisert, arXiv: 0810.2542)
- Efficient measurement scheme by homodyne detection only
- Resource preparation by Jaynes-Cummings type interaction

- M. Ohliger, K. Kieling, J. Eisert, to be published

D1.2

- Some perspectives

- **Think more in terms of CV-discrete hybrid approaches:**
  - Photon counting with weak phase reference (weak homodyning), quantum dot sources ...
  - … aiming at exploiting advantages of "both worlds"
- **More on computing:**
  - Explore full potential of non-Gaussian states for QC
  - Small-scale computing, say, in quantum repeaters
- **More on physical hybrids:**
  - Link results of last years on CV quantum information more to hybrid architectures, combining CV light with cold atoms
- **Combining CV-light with optomechanics:**
  - Transferring non-classicality between CV light and optomechanical systems
- **More on entanglement purification and distillation:**
  - Realize fully-fledged entanglement distillation

- **Systems identification:**
  - Compressed sensing paradigm to measuring quantum objects
  - Emphasize paradigm of having error bars

- **Metrology:**
  - Explore full potential of non-Gaussian states for metrology applications

- Thanks!