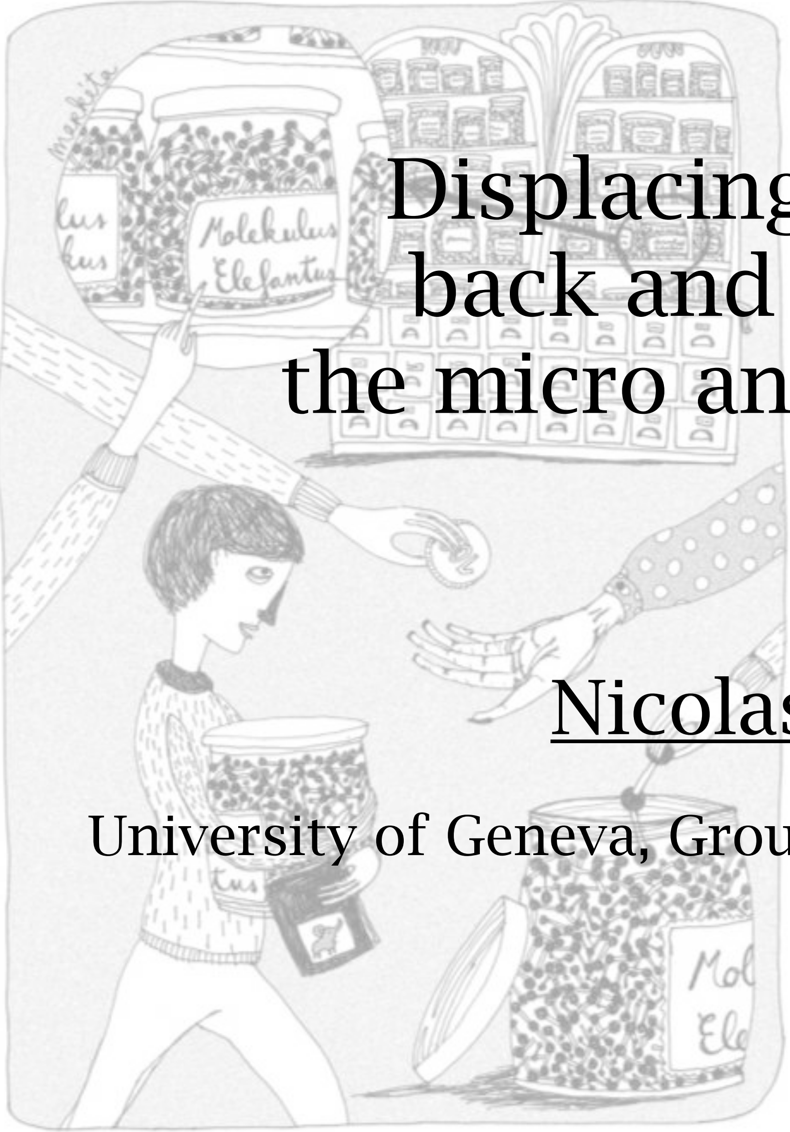
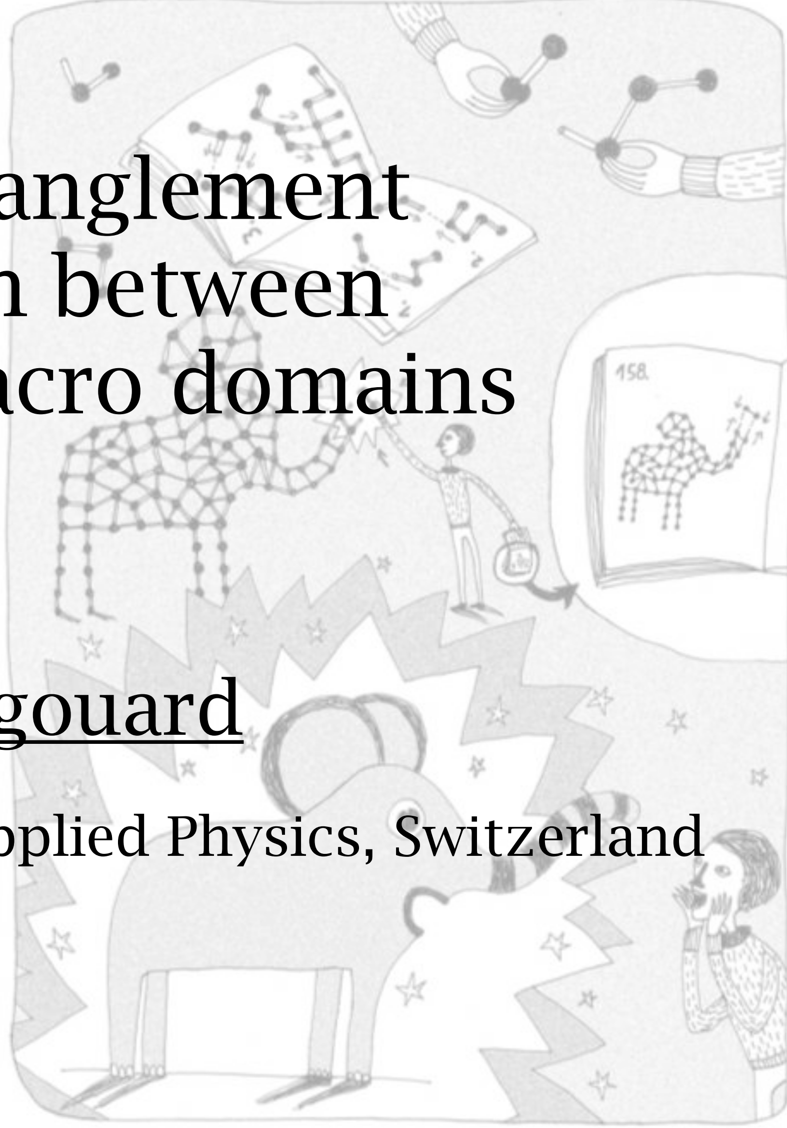




Displacing entanglement back and forth between the micro and macro domains

Nicolas Sangouard

University of Geneva, Group of Applied Physics, Switzerland

Why do we not observe macro quantum systems?

Existence of a quantum/classical border

Decoherence

Measurement precision

Lacking suited entanglement witness

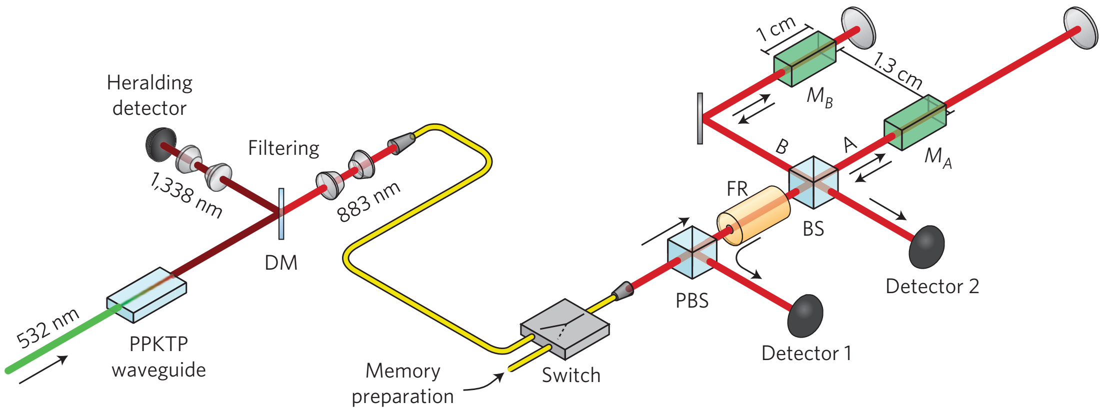
motivations ?

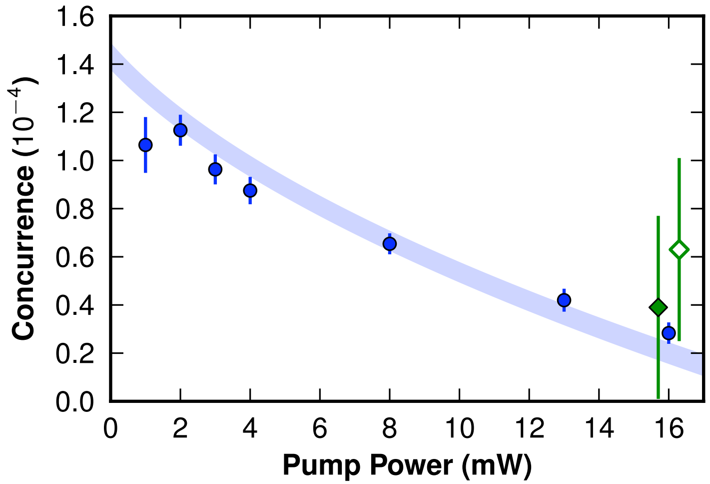
macro in nature?
macro in the lab?

What is a macroscopic quantum state?

The number of particles is not a sufficient criteria

Example: massive crystal entanglement



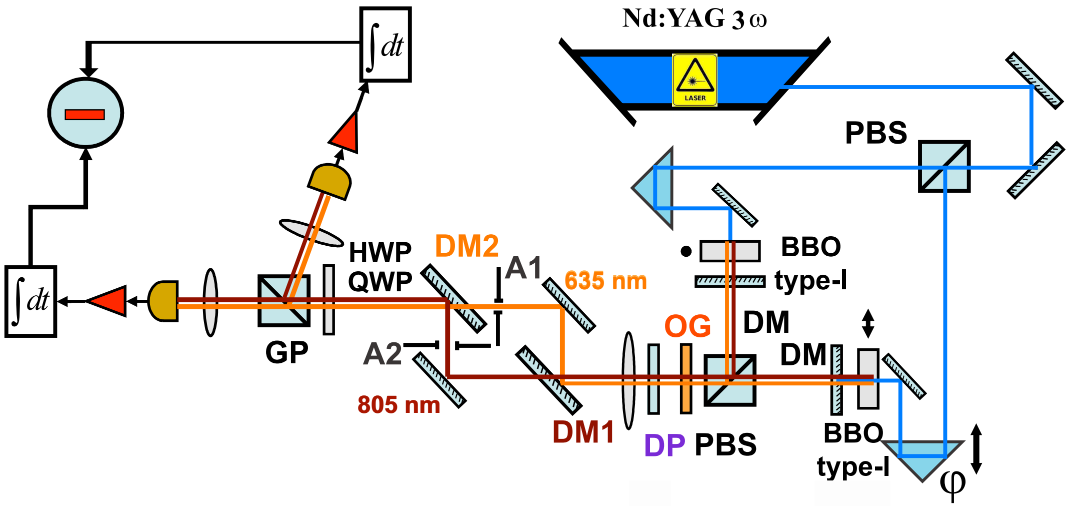


I. Usmani, C. Clausen, F. Bussieres, N. Sangouard, M. Afzelius, and N. Gisin, Nature Photonics. 6, 234 (2012)

What is a macroscopic quantum state?

The number of particles is not a sufficient criteria

Example: entanglement involving 100 000 photons



$$\left[\frac{1}{\sqrt{2}}(|0_A 1_B\rangle - |1_A 0_B\rangle)\right]^{\otimes 100000}$$

T.S. Iskhakov, I.N. Agafonov, M.V. Chekhova, and G. Leuchs, PRL 109, 150502 (2012)

The Schroedinger cat provides an example

From $|1\rangle_{\rm atom}|0\rangle_{\rm photon} + |0\rangle_{\rm atom}|1\rangle_{\rm photon}$

to $|1\rangle_{\rm atom}|{\rm Alive}\rangle_{\rm cat} + |0\rangle_{\rm atom}|{\rm Dead}\rangle_{\rm cat}$

Macroscopicity vs entanglement

Macroscopicity is not invariant through local unitary!

$$\Big(|\uparrow\rangle_a|\downarrow\rangle_b - |\downarrow\rangle_a|\uparrow\rangle_b\Big)\otimes|\uparrow\rangle_b^{\otimes N-1} \xrightarrow{\text{C-NOT gates}} |\uparrow\rangle_a|\downarrow\rangle_b^{\otimes N} - |\downarrow\rangle_a|\uparrow\rangle_b^{\otimes N}$$

micro-micro

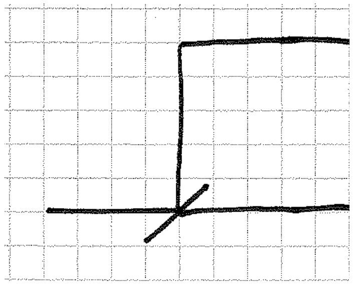
C-NOT gates

micro-macro

photonic entanglement + displacement in the phase space

$$\mathcal{D}(\alpha) = e^{\alpha\hat{a}^\dagger - \alpha^\star \hat{a}}$$

Creating Entanglement at a beamsplitter



Consider a separable state

$$\rho = \sum_i p_i \; \rho_a^i \otimes \rho_b^i = \sum_k \bar{p}_k |\psi_a^k\rangle\langle\psi_a^k| \otimes |\,\psi_b^k\rangle\langle\psi_b^k|$$

for each component

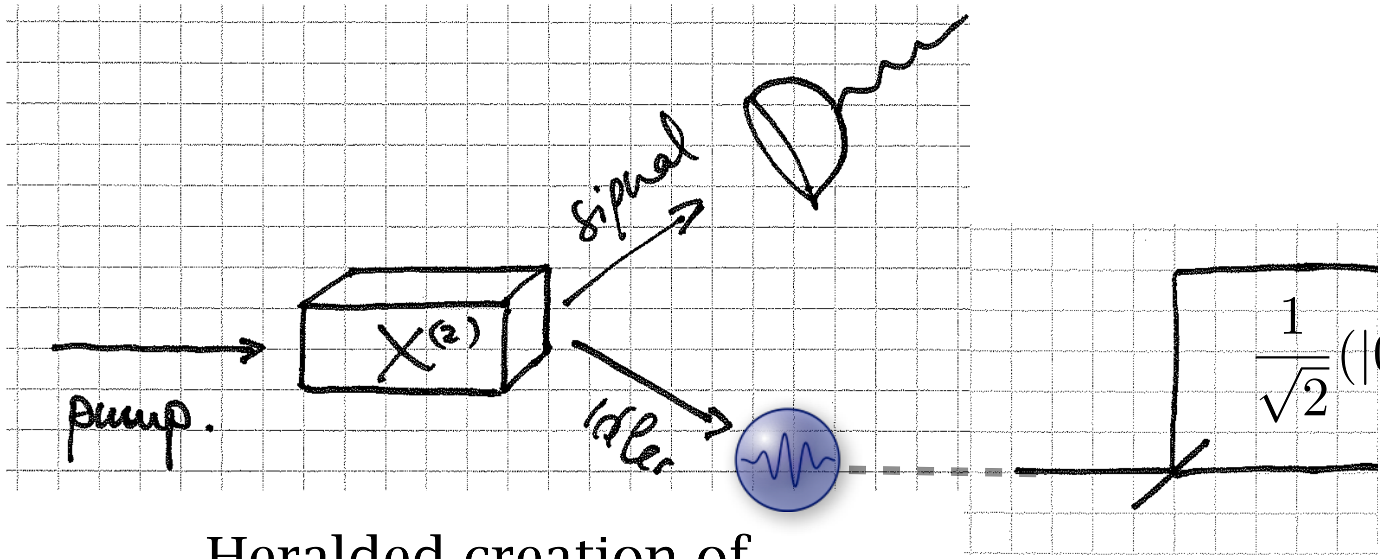
$$U_{\rm bs}^{-1}|\psi_a^k\rangle|\psi_b^k\rangle = |\Psi_i\rangle|0\rangle$$

Since the only pure state leading to a product state after a beamsplitter is the coherent state

All non-classical states lead to entanglement

$$\int d^2\alpha \; P(\alpha)|\alpha\rangle\langle\alpha| \otimes |\,0\rangle\langle 0|, \;\; P(\alpha) \geq 0$$

Heralded creation of micro-micro entanglement

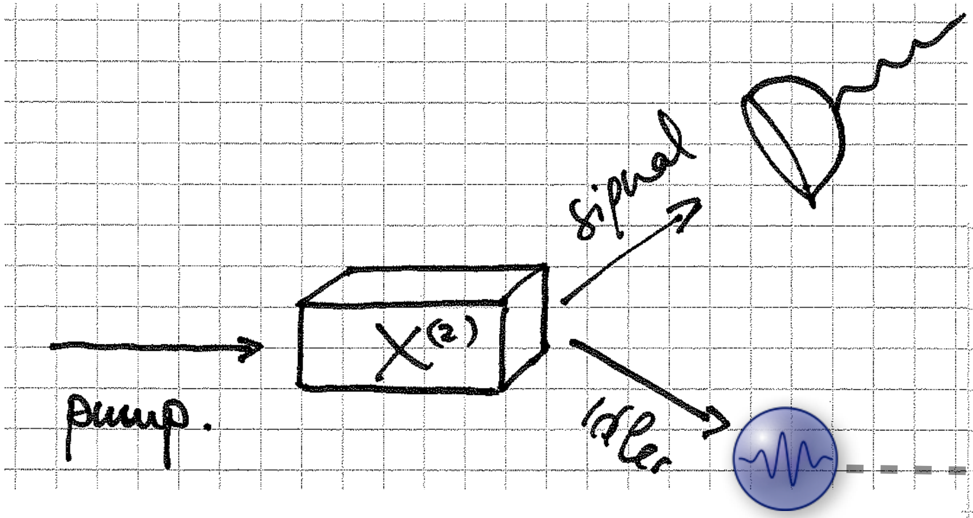


$$\frac{1}{\sqrt{2}}(|0_A 1_B\rangle - |1_A 0_B\rangle)$$

Heralded creation of
non-classical state
by means of SPDC

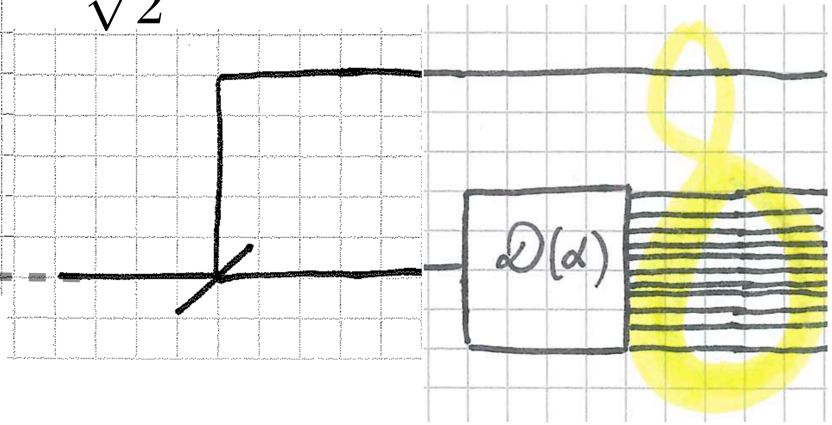
Heralded creation of
single-photon entanglement

Heralded creation of micro-macro entanglement?



Heralded creation of
non-classical state
by means of SPDC

$$\frac{1}{\sqrt{2}}\left(\mathcal{D}_a(\alpha)|1\rangle_A|0\rangle_B + |\alpha\rangle_A|1\rangle_B\right)$$



Diplaced single-photon
entanglement

Definitions of a macroscopic quantum state

$\Phi_0 + \Phi_1$ involving N particles

1_ Sensitive to decoherence mechanisms

W. Dur, C. Simon, and J.I. Cirac, Phys. Rev. Lett. 89, 210402 (2002)

2_ Local distinguishability between Φ_0 and Φ_1

NaN

J.I. Korbakken et al., Phys. Rev. A 75, 042106 (2007)

3_ Large number of one particle operators to go from Φ_0 to Φ_1

NaN

F. Marquardt et al., Phys. Rev. A 78, 012109 (2008)

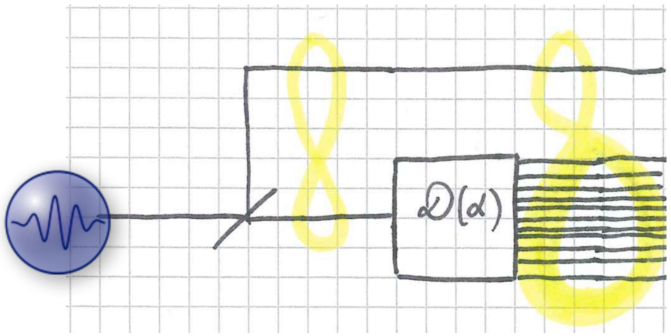
4_ $\Phi_0 + \Phi_1$ significant advantage for interferometric applications over Φ_0 and Φ_1

G. Bjork and P. Mana, J. of Opt. B 6, 429 (2004)

Displaced single-photon entanglement

Micro-macro entanglement ?

_ large number of photons



$$\frac{1}{\sqrt{2}}\left(\mathcal{D}_a(\alpha)|1\rangle_A|0\rangle_B + |\alpha\rangle_A|1\rangle_B\right)$$

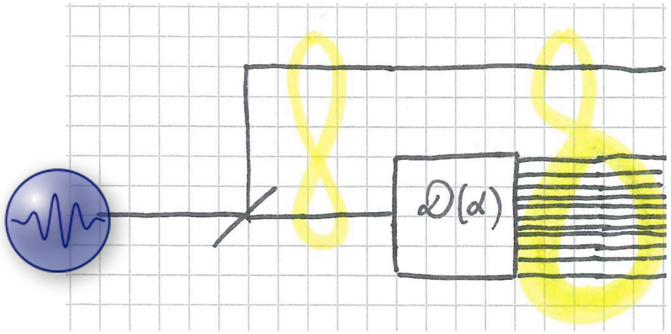
P. Sekatski, N. Sangouard, F. Bussieres, M. Afzelius, and N. Gisin, Phys. Rev. A 86, 060301 (2012)

Displaced single-photon entanglement

Micro-macro entanglement ?

_ large number of photons

_ local unitary



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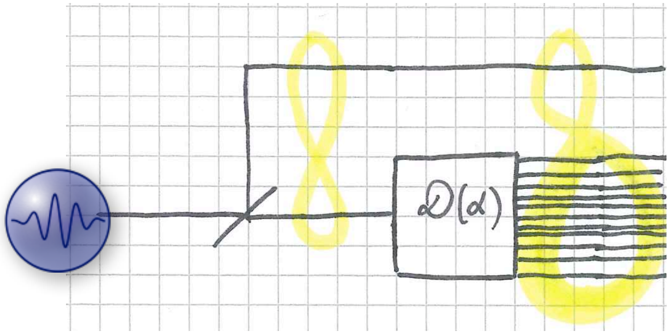

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P. Sekatski, N. Sangouard, F. Bussieres, M. Afzelius, and N. Gisin, Phys. Rev. A 86, 060301 (2012)

Displaced single-photon entanglement

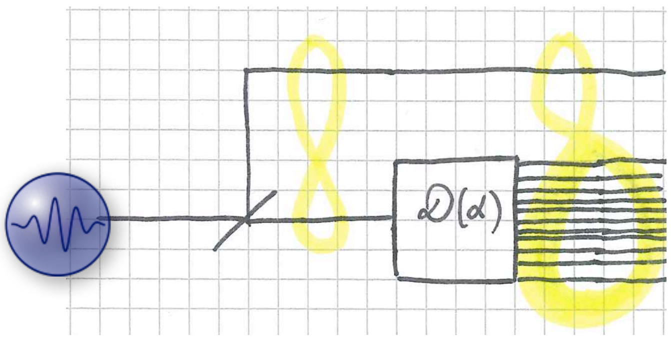
Micro-macro entanglement ?

_ large number of photons

_ local unitary

_ 1ebit

_ entanglement decreases fast under dephasing process



$$\frac{1}{\sqrt{2}}\left(\mathcal{D}_a(\alpha)|1\rangle_A|0\rangle_B + |\alpha\rangle_A|1\rangle_B\right)$$

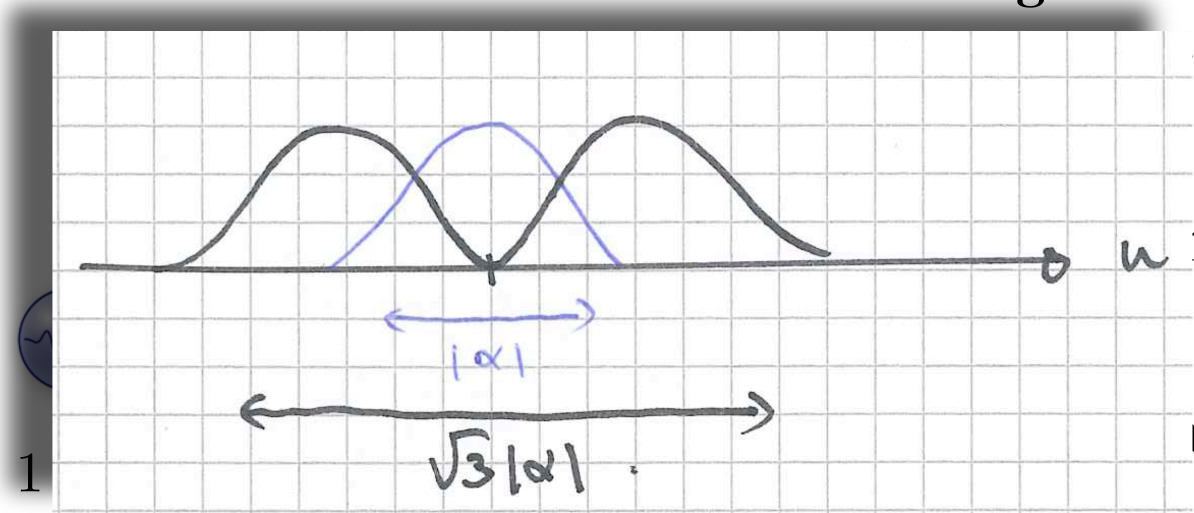
$$\mathcal{N} = (1 - 3|\alpha|^2\delta\phi)/2$$

P. Sekatski, N. Sangouard, F. Bussieres, M. Afzelius, and N. Gisin, Phys. Rev. A 86, 060301 (2012)

Displaced single-photon entanglement

Micro-macro entanglement ?

_ large number of photons



ary

ment decreases fast under
process

l components have larger
han the superposition

$$\frac{1}{\sqrt{2}}\left(D_a(\alpha)|1\rangle_A|0\rangle_B + |\alpha\rangle_A|1\rangle_B\right)$$

P. Sekatski, N. Sangouard, F. Bussieres, M. Afzelius, and N. Gisin, Phys. Rev. A 86, 060301 (2012)

Displaced single-photon entanglement

Micro-macro entanglement ?

_ large number of photons

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the photon number space

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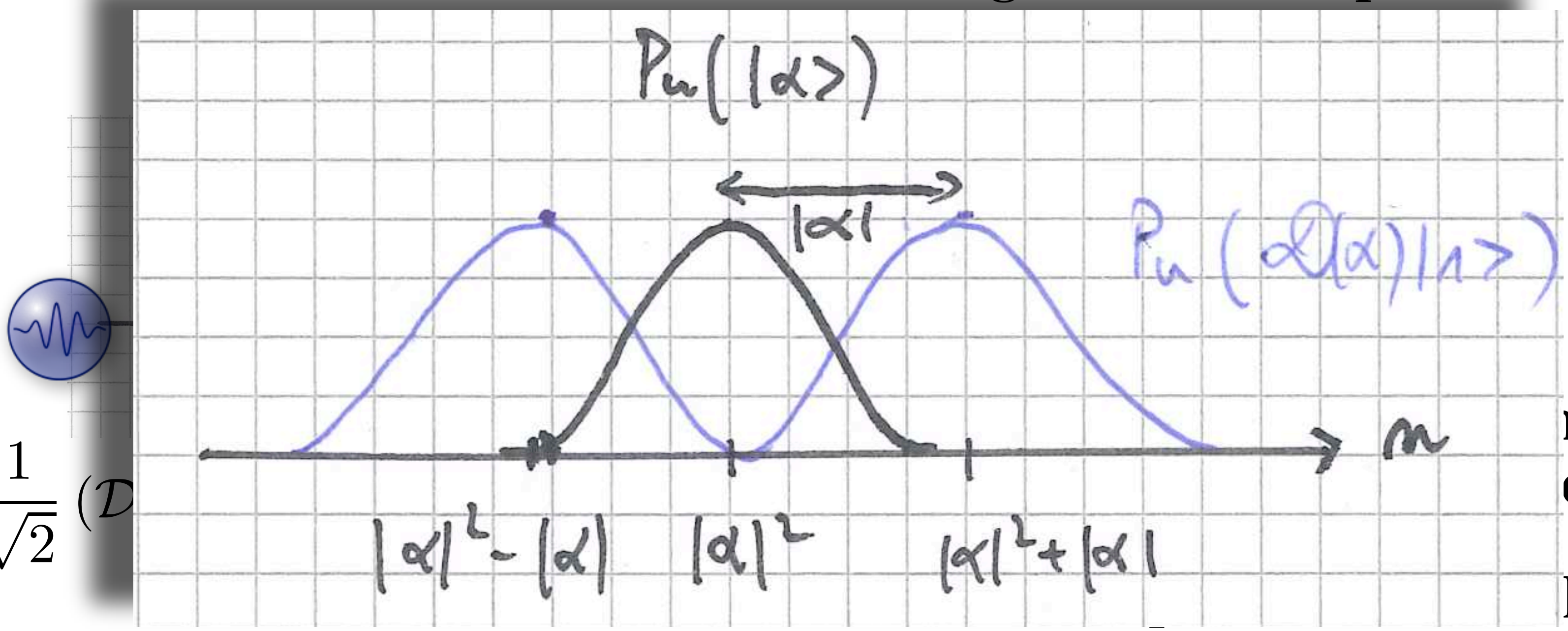


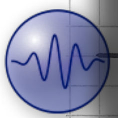
P. Sekatski, N. Sangouard, F. Bussieres, M. Afzelius, and N. Gisin, Phys. Rev. A 86, 060301 (2012)

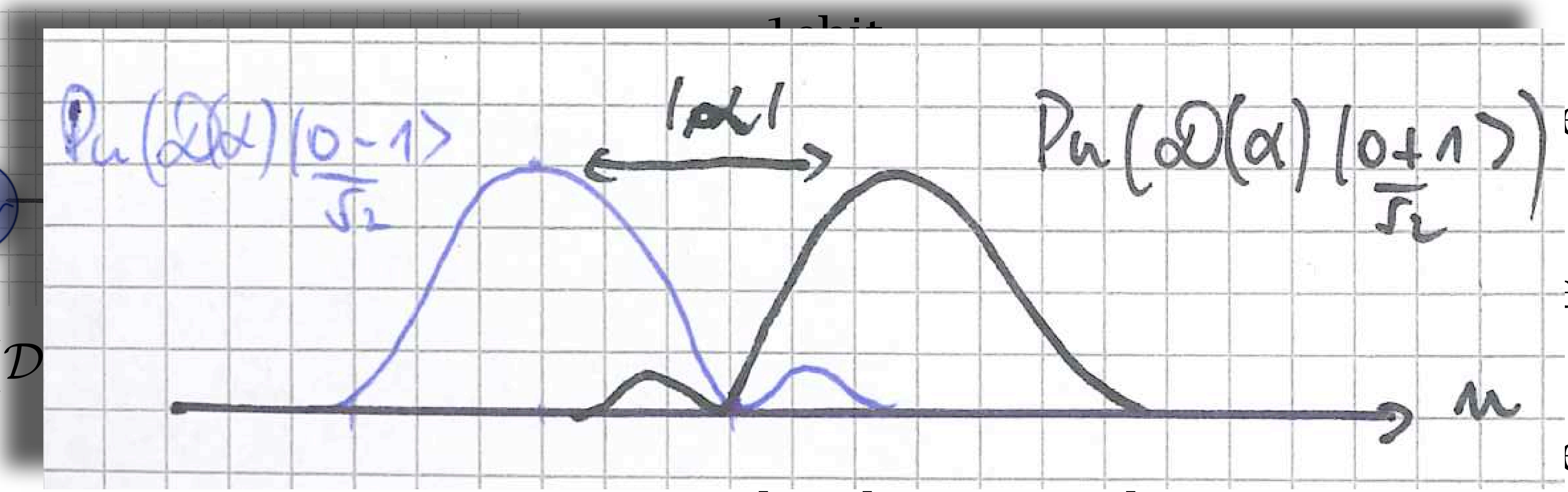
Displaced single-photon entanglement

Micro-macro entanglement ?

_ large number of photons

_ local unitary





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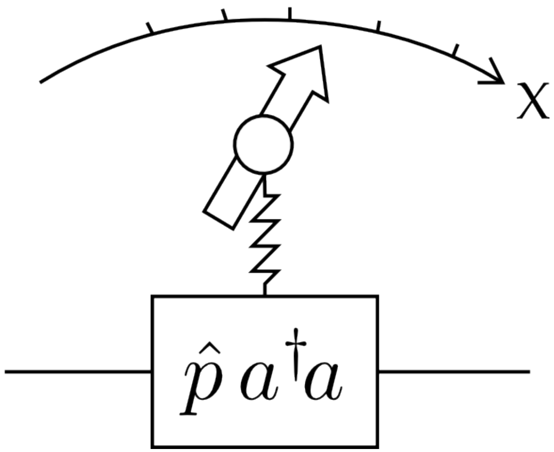
the photon number space

P. Sekatski, N. Sangouard, F. Bussieres, M. Afzelius, and N. Gisin, Phys. Rev. A 86, 060301 (2012)

Proposal of a macro measure

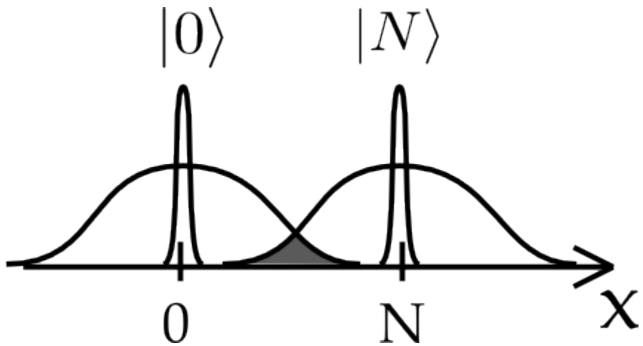
based on the distinguishability with a «classical» detector

No need for a microscopic resolution to distinguish $|\mathrm{Alive}\rangle_{\mathrm{cat}}$ and $|\mathrm{Dead}\rangle_{\mathrm{cat}}$



Pointer state $\rho_{\hat{x}} = \int dx\ G(x)\ |x\rangle\langle x|$

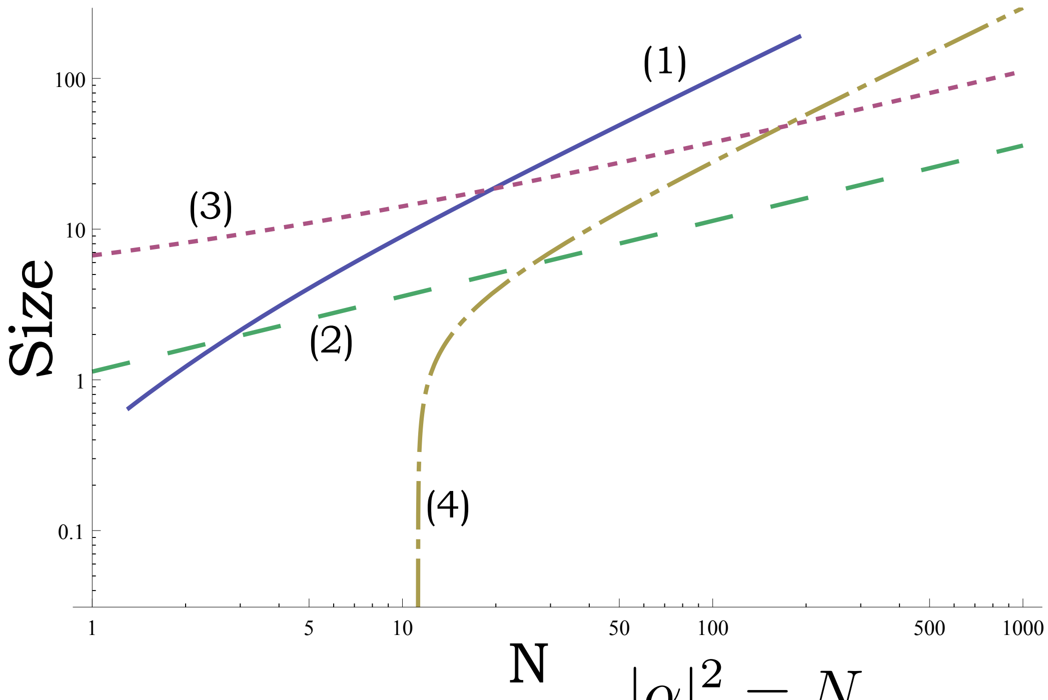
$G(x)$ Gaussian with spread σ



P. Sekatski, N. Sangouard, and N. Gisin, in preparation

Proposal of a macro measure

based on the distinguishability with a «classical» detector



$|\alpha|^2 = N$

Examples

Pguess=0.85

(1) $|0\rangle, |\alpha\rangle$

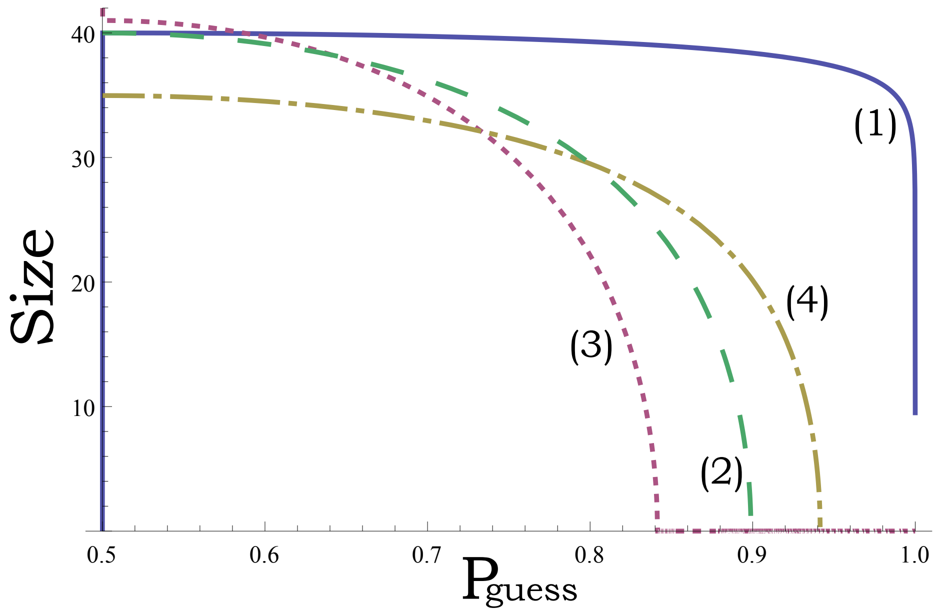
$|\alpha|^2 = N$

(2) $\mathcal{D}(\alpha)|+\rangle,\ \mathcal{D}(\alpha)|-\rangle$

P. Sekatski, N. Sangouard, and N. Gisin, in preparation

Proposal of a macro measure

based on the distinguishability with a «classical» detector



Macroscopicity as a function of Pguess

(1) $|0\rangle, |\alpha\rangle$

$$|\alpha|^2 = N$$

(2) $\mathcal{D}(\alpha)|+\rangle,\ \mathcal{D}(\alpha)|-\rangle$

P. Sekatski, N. Sangouard, and N. Gisin, in preparation

Proposal of a macro measure

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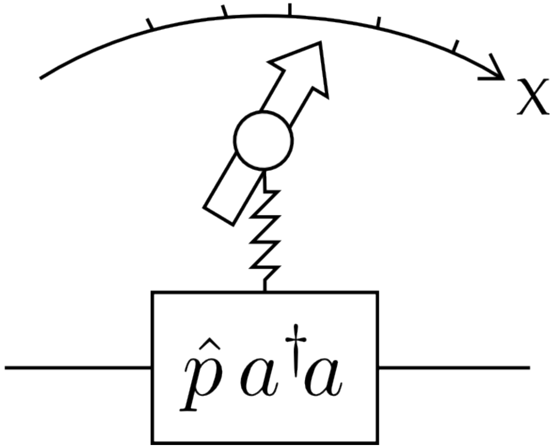


Any phase fluctuation can be seen as a weak measurement of the photon number

→ States that are macro with respect our criteria are inevitably very sensitive to phase decoherence

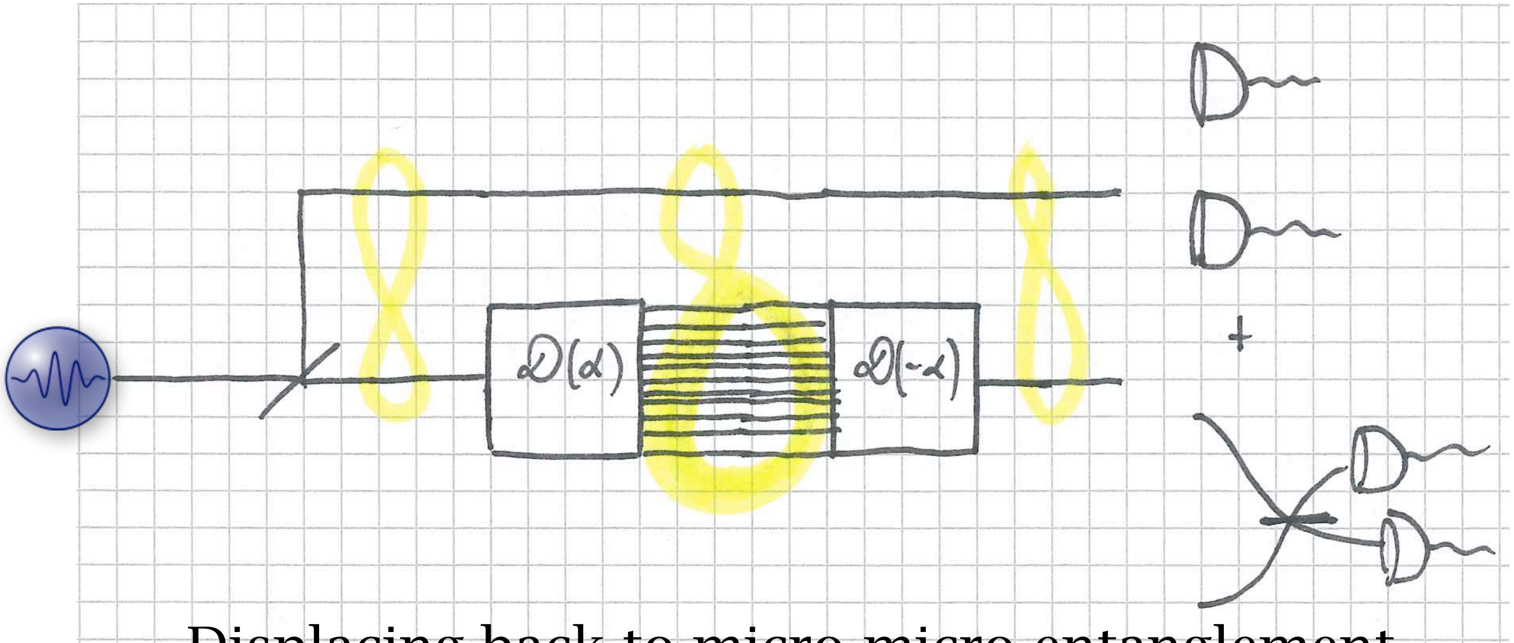
P. Sekatski, N. Sangouard, and N. Gisin, in preparation

Detecting displaced single-photon entanglement

Detecting macro entanglement is a difficult task

_ decoherence inevitably increases the Hilbert space dimension

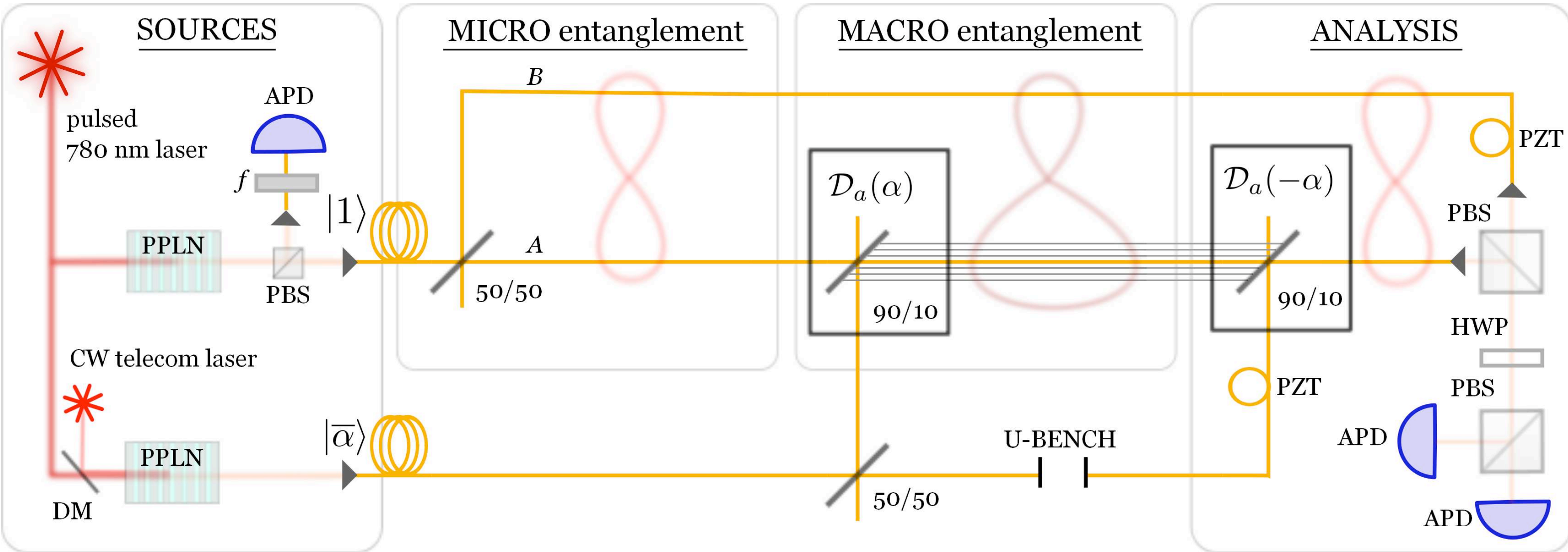
_ requires high resolution detection



Displacing back to micro-micro entanglement before using a well established entanglement measure

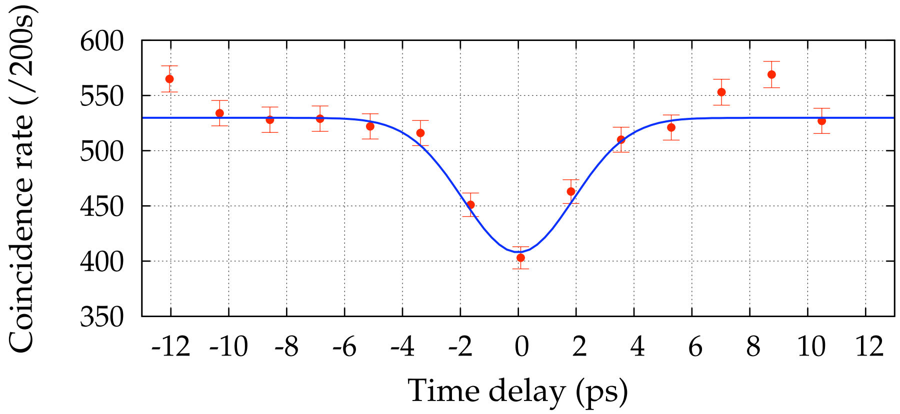
P. Sekatski, N. Sangouard et al., Phys. Rev. A 86, 060301 (2012)

Displaced single-photon entanglement: experiment



N. Bruno, A. Martin, P. Sekatski, N. Sangouard, R. Thew, and N. Gisin, arXiv:1212.3701

Displaced single-photon entanglement: experiment



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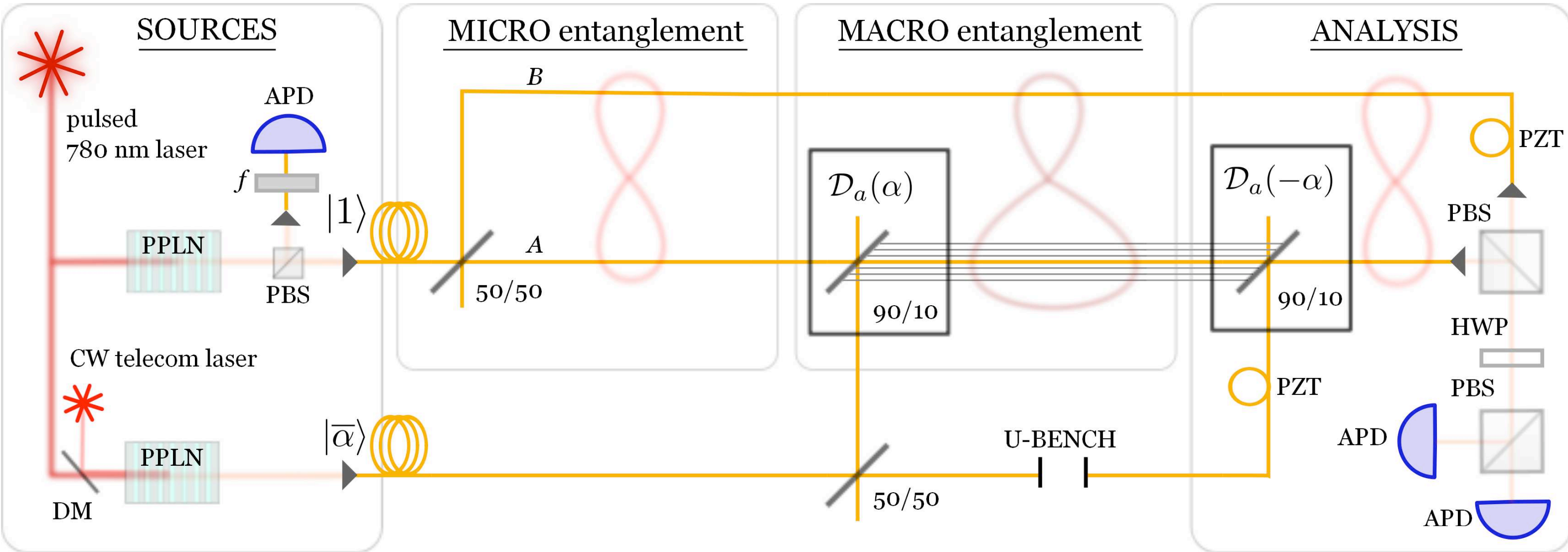

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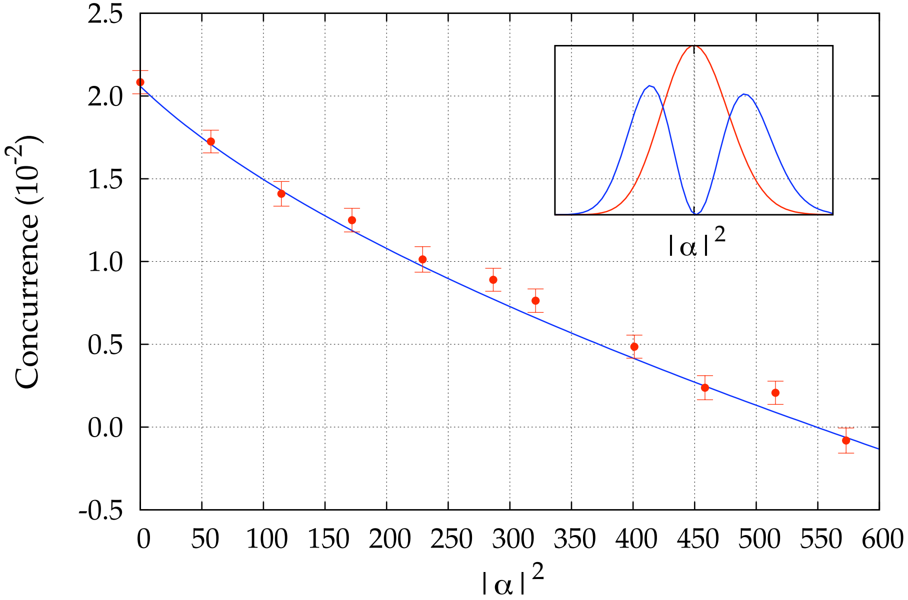

N. Bruno, A. Martin, P. Sekatski, N. Sangouard, R. Thew, and N. Gisin, arXiv:1212.3701

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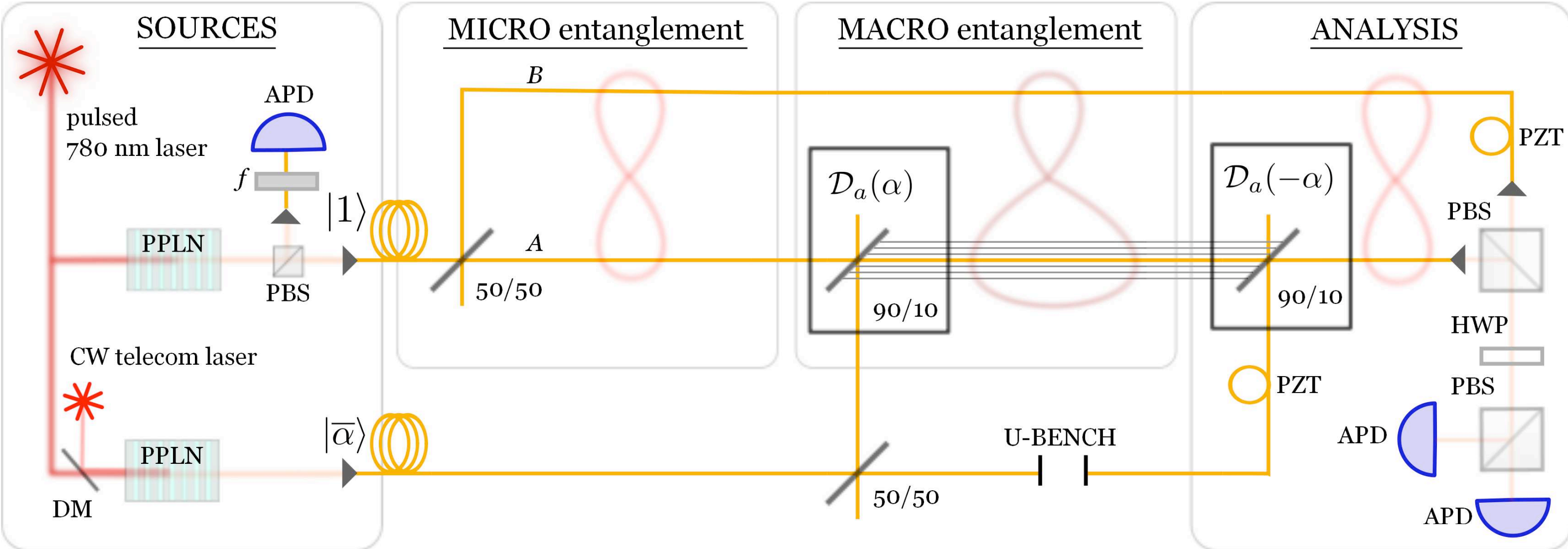

The decoherence problem and the requirement on the precision of the measurement are two facets of the same problem

N. Bruno, A. Martin, P. Sekatski, N. Sangouard, R. Thew, and N. Gisin, arXiv:1212.3701

Conclusion

Proposal for a macro measure based on the distinguishability of superposition components with a «classical» measurement

Displaced single-photon entanglement as an example

Use of a well established entanglement measure

measurements precision <------> decoherence

Useful for opto-mechanics? phase estimation in interferometric measurement?