Macroscopic Entanglement

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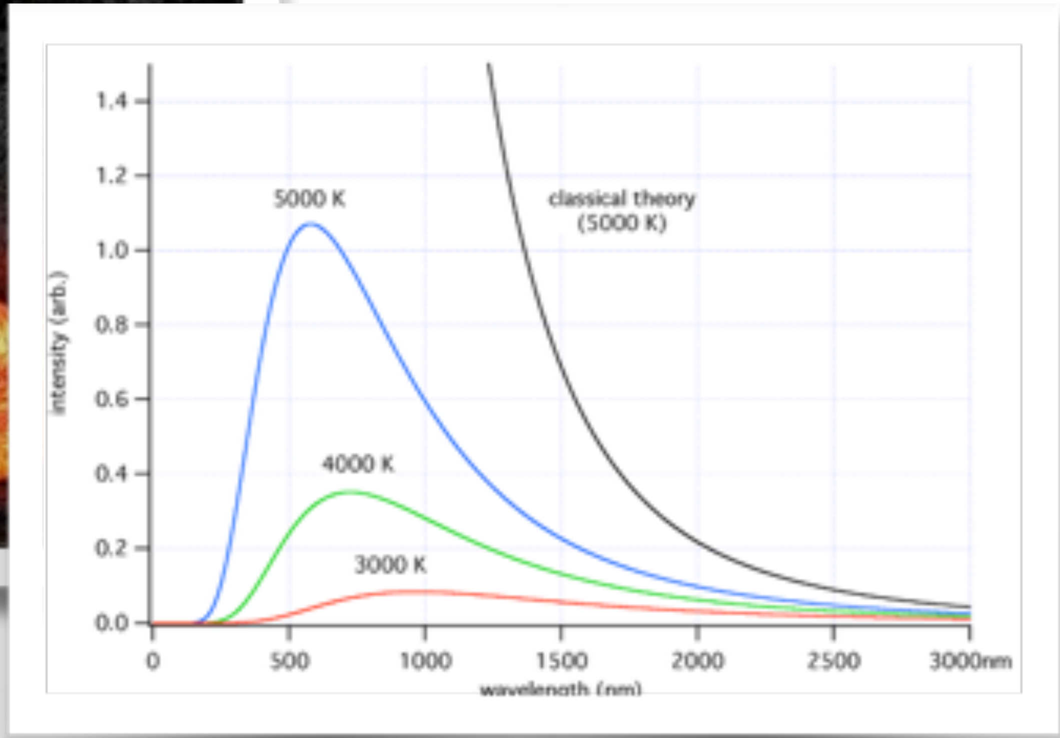
Olomouc , March 2015

The quantum world is weird...

Do quantum properties hold at any scale?

Macroscopic quantum effects ?



Microscopic quantum effect only!

A.J. Leggett Prog. Theor. Phys. Supplement 69, 80 (1980)

Why don’t we observe quantum effects at macro scales ?

Decoherence

Nothing else?

What is a macroscopic quantum state ?

Quantum : e.g. Entanglement

Macro : e.g. mass ?

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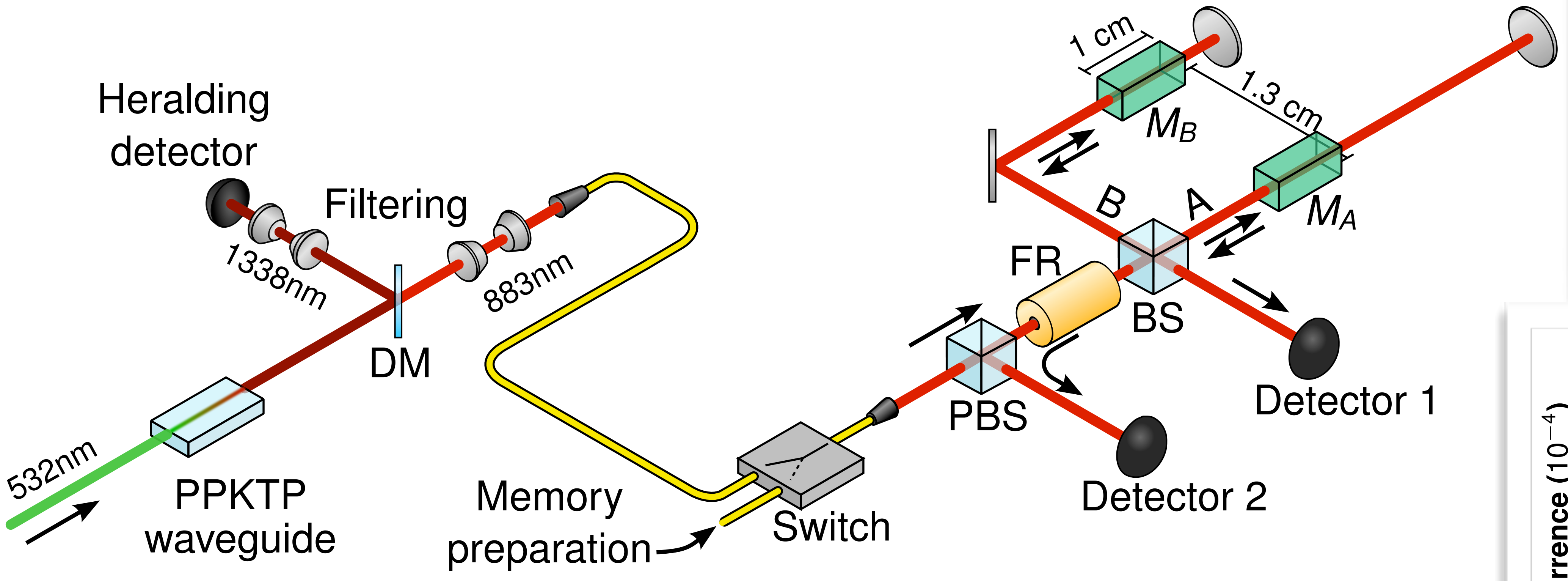
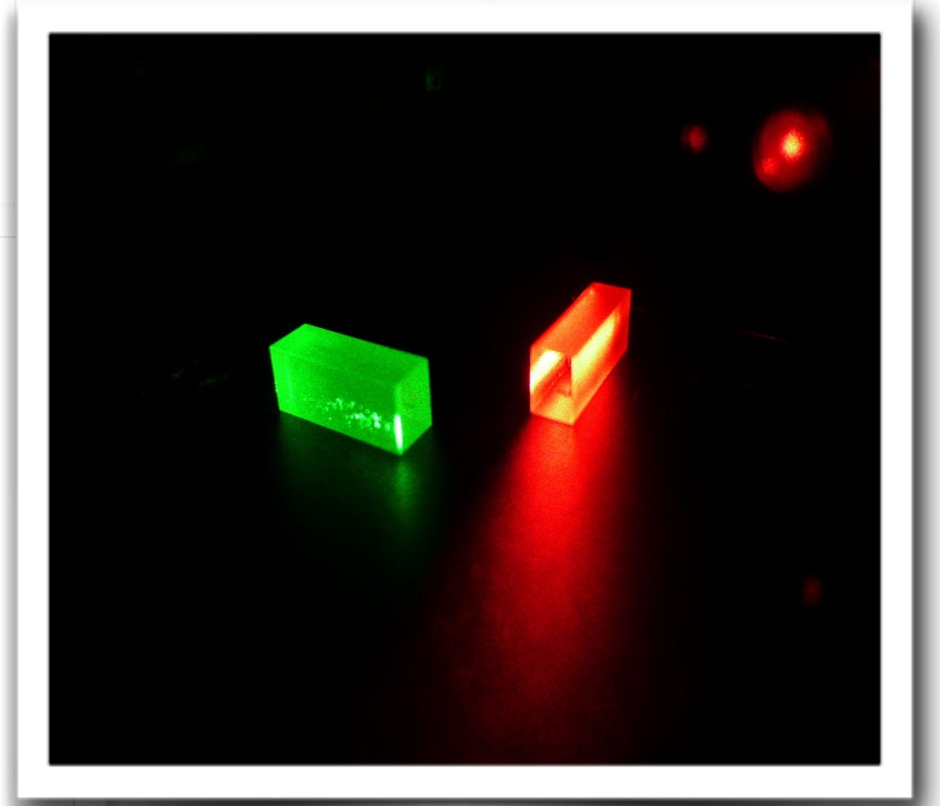
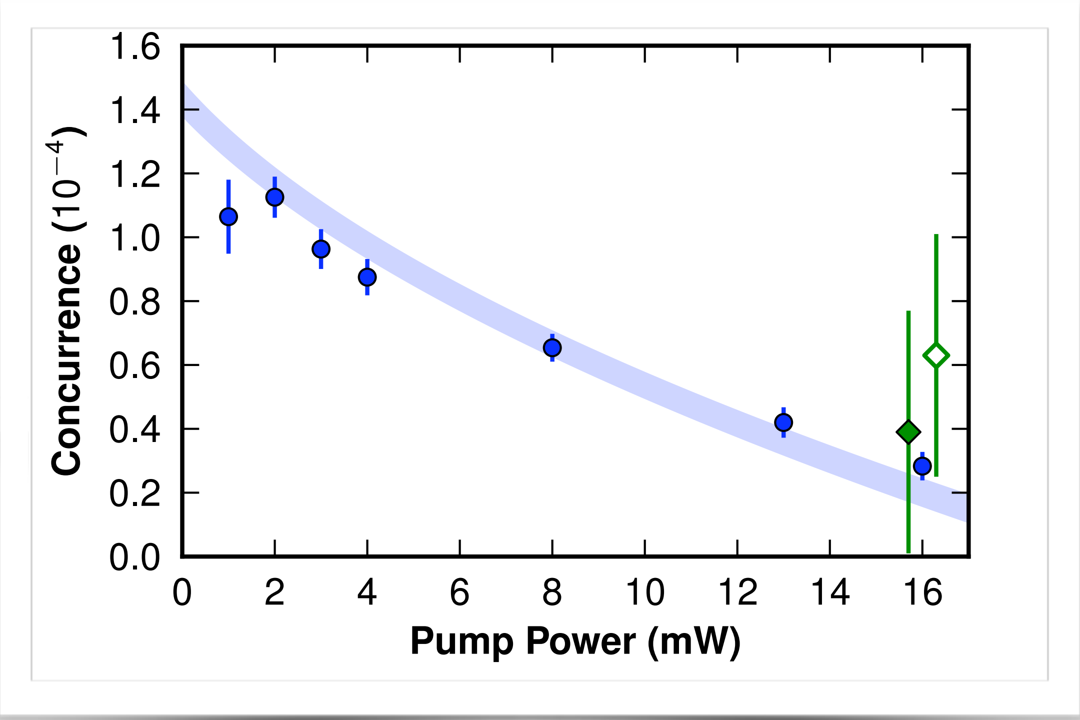




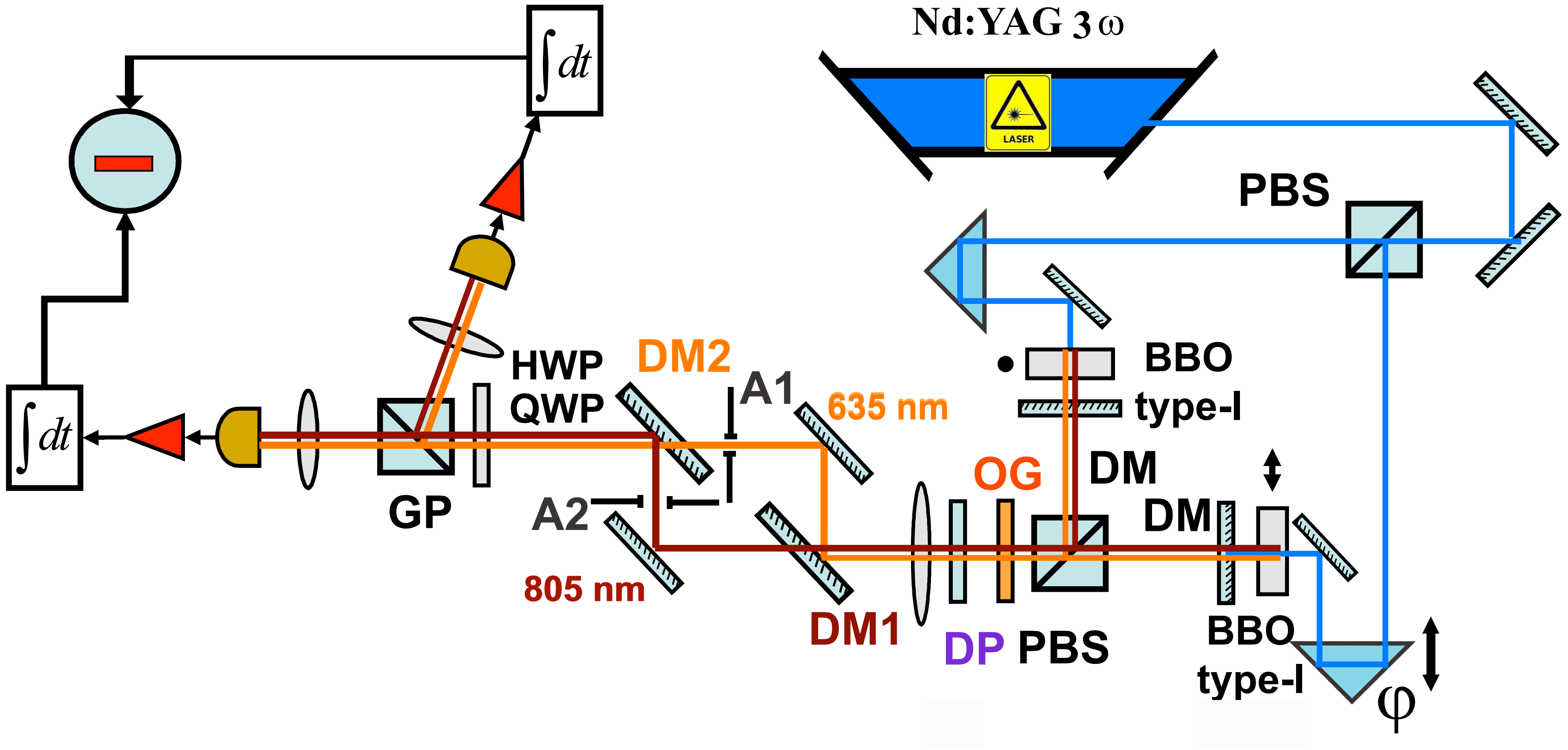


I. Usmani et al. Nature Photonics 6, 234 (2012) (Collaboration with the N. Gisin group)

What is a macroscopic quantum state?

Quantum : e.g. Entanglement

Macro : e.g. Number of particles ?



Example: entanglement involving 100 000 photons

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

Many copies of a micro state

T.S. Iskhakov et al. PRL 109, 150502 (2012)

Review of available definitions

$$\boxed{\Phi_0 + \Phi_1 \text{ macro ?}}$$

1_ Sensitive to decoherence mechanisms

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

For a review, see F. Frowis, N. Sangouard and N. Gisin, Opt. Comm. 337, 2 (2015)

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

4_ Large number of one particle operators to go from Φ_0 to Φ_1

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

For a review, see F. Frowis, N. Sangouard and N. Gisin, Opt. Comm. 337, 2 (2015)

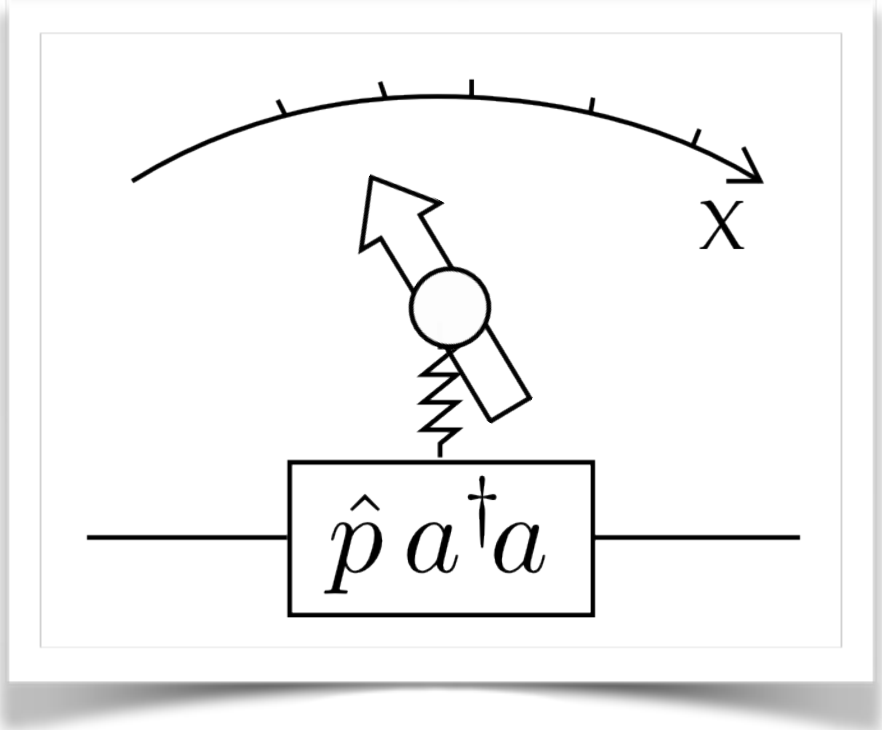
Proposal for a macro measure

based on the distinguishability with a coarse-grained detector

$$\boxed{\Phi_0 + \Phi_1 \text{ macro ?}}$$

Intuition : Φ_0 and Φ_1 can be distinguished with a detector having no microscopic resolution

Consider a general detector model :
A pointer sifted by a value corresponding to the photon number



P. Sekatski, N. Sangouard and N. Gisin Phys. Rev.A 89, 012116 (2014)

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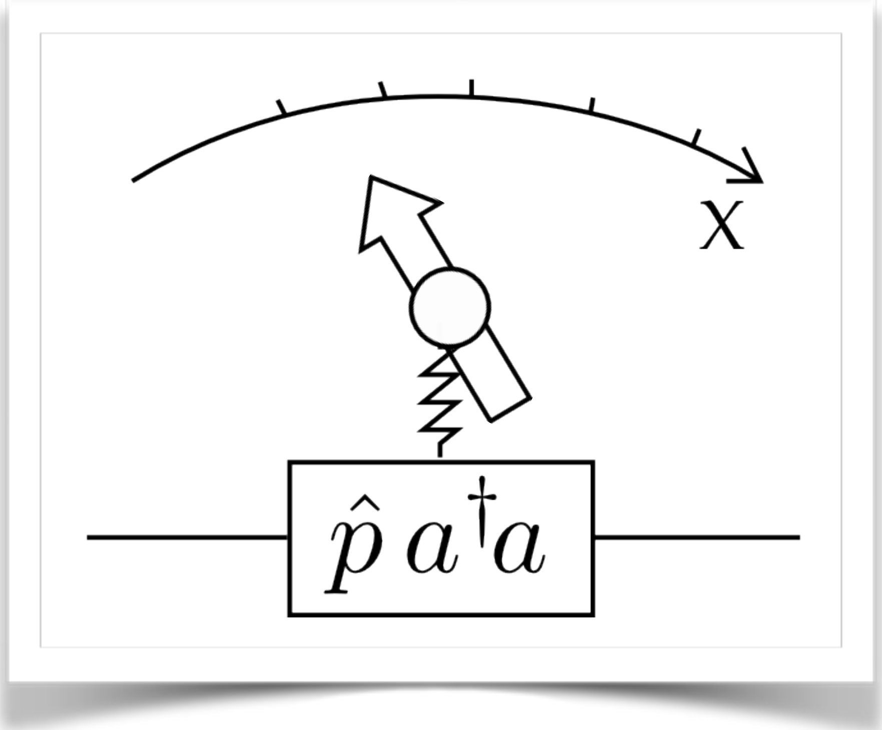

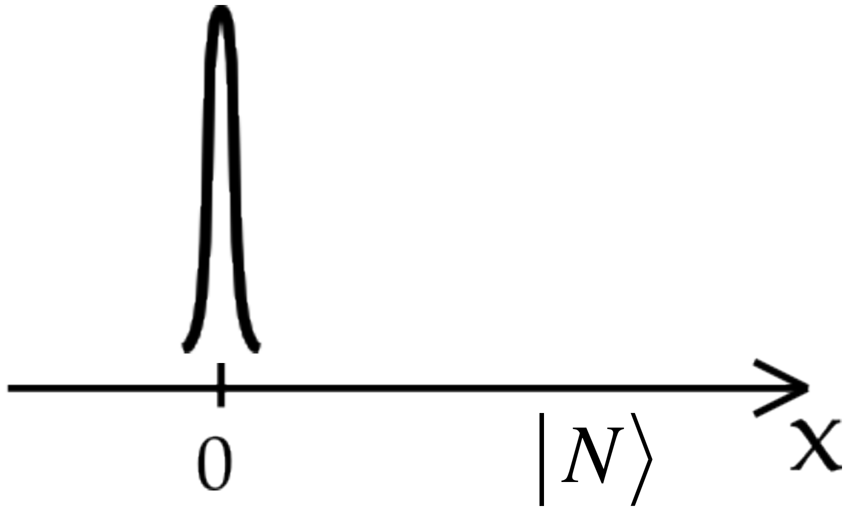

Pointer position is δ-peaked

$\longrightarrow$ Projective measurement

P. Sekatski, N. Sangouard and N. Gisin Phys. Rev. A 89, 012116 (2014)

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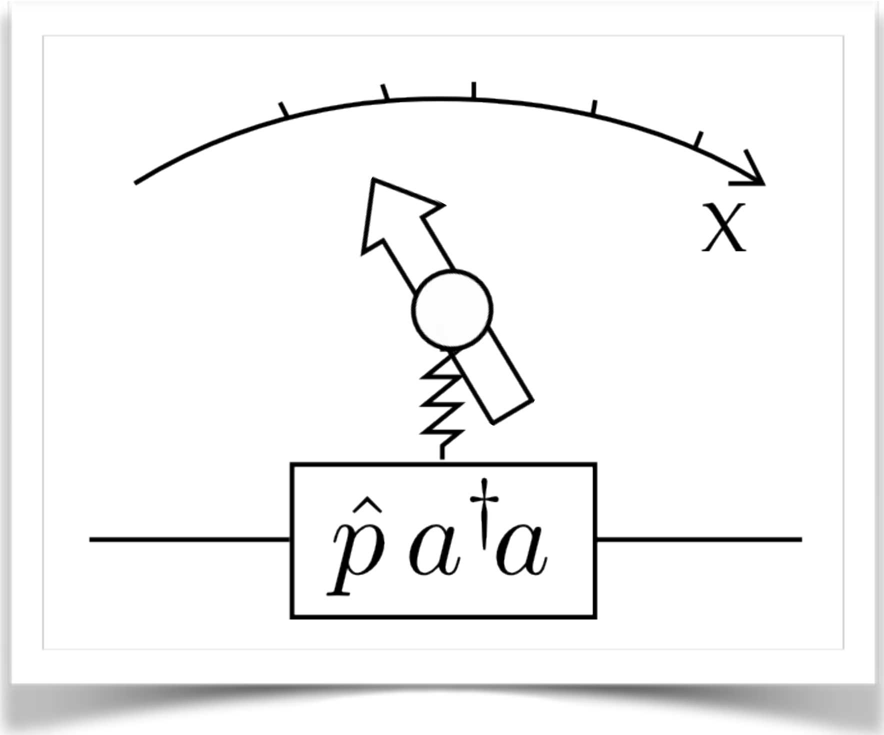

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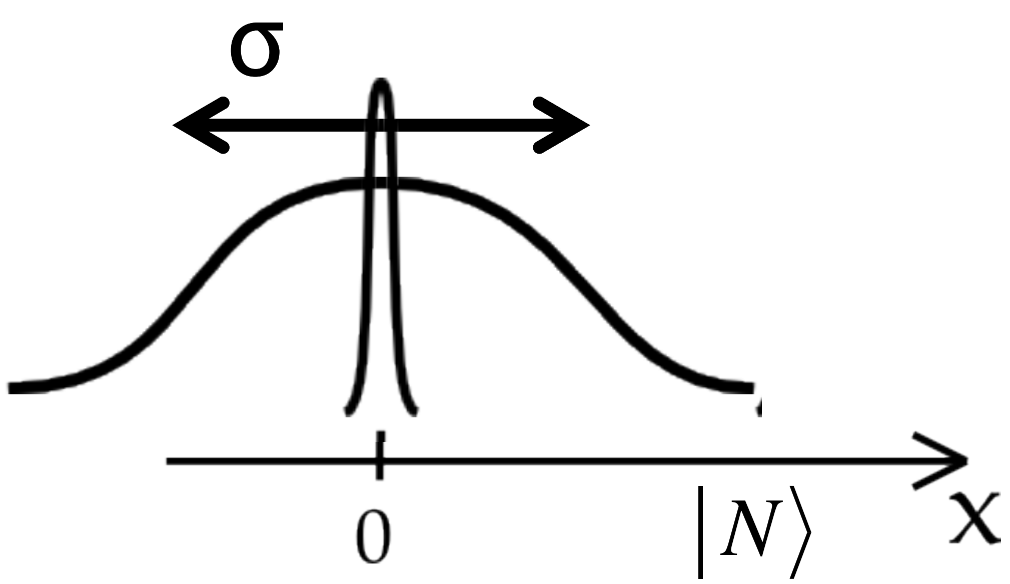

Pointer has a no-zero σ spread

$\longrightarrow$ Coarse-grained measurement

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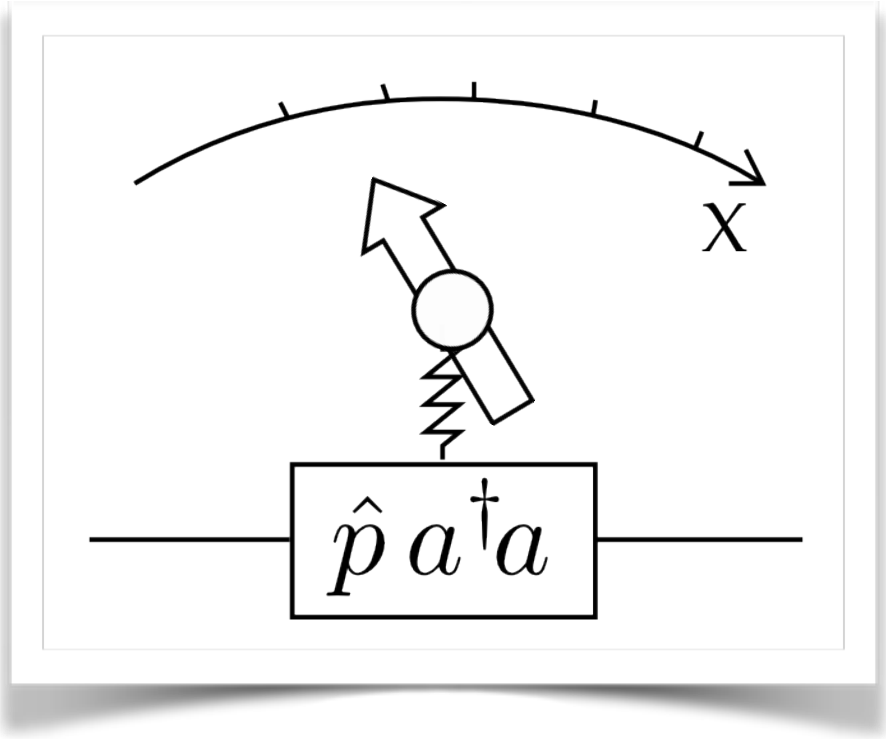

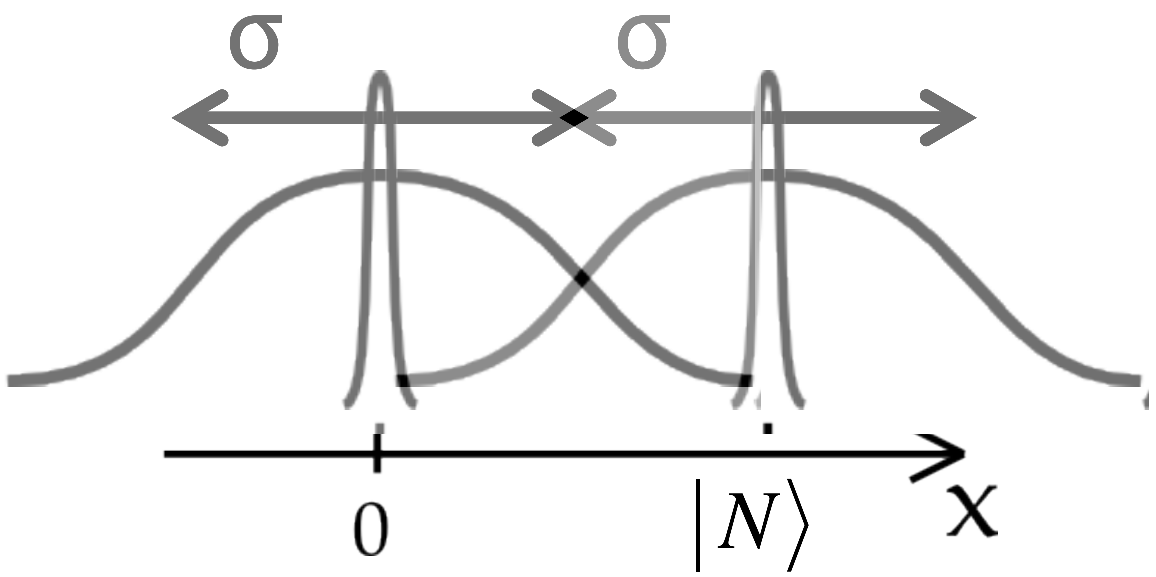

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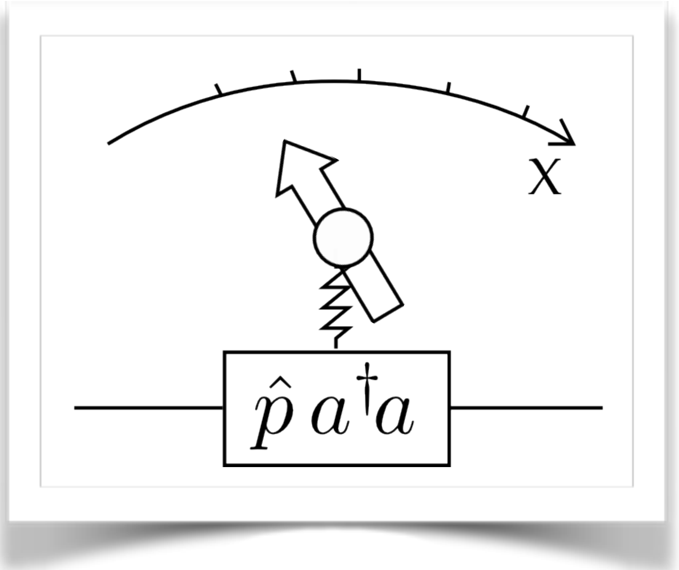
$\boxed{\Phi_0 + \Phi_1 \text{ macro ?}}$

Alice Φ_0 Φ_1 $\longrightarrow$ Bob



The guessing probability is given $P_{\text{guess}} = \frac{1}{2} + \frac{1}{4}\int dx |P_0^\sigma(x) - P_1^\sigma(x)|$

Fixing $P_{\text{guess}} \longrightarrow \sigma_{\max}[\Phi_0, \Phi_1]$

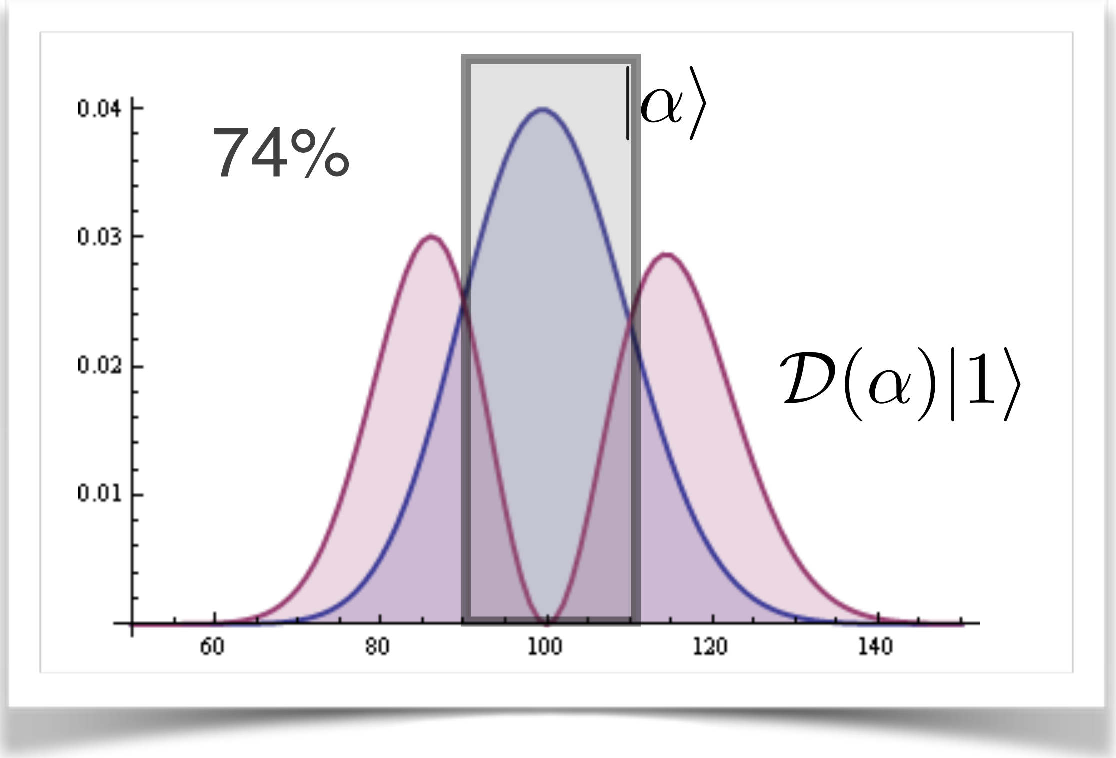
Take a reference state $|0\rangle + |N\rangle \longrightarrow$ The size of $\Phi_0 + \Phi_1$ is the value of N s.t. we can distinguish $|0\rangle$ and $|N\rangle$ with P_{guess} with a coarse grained detectors $\sigma_{\max}[\Phi_0, \Phi_1]$

P. Sekatski, N. Sangouard and N. Gisin Phys. Rev. A 89, 012116 (2014)

Example a macroscopic quantum state

with respect to the macro measure based on coarse-graining

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



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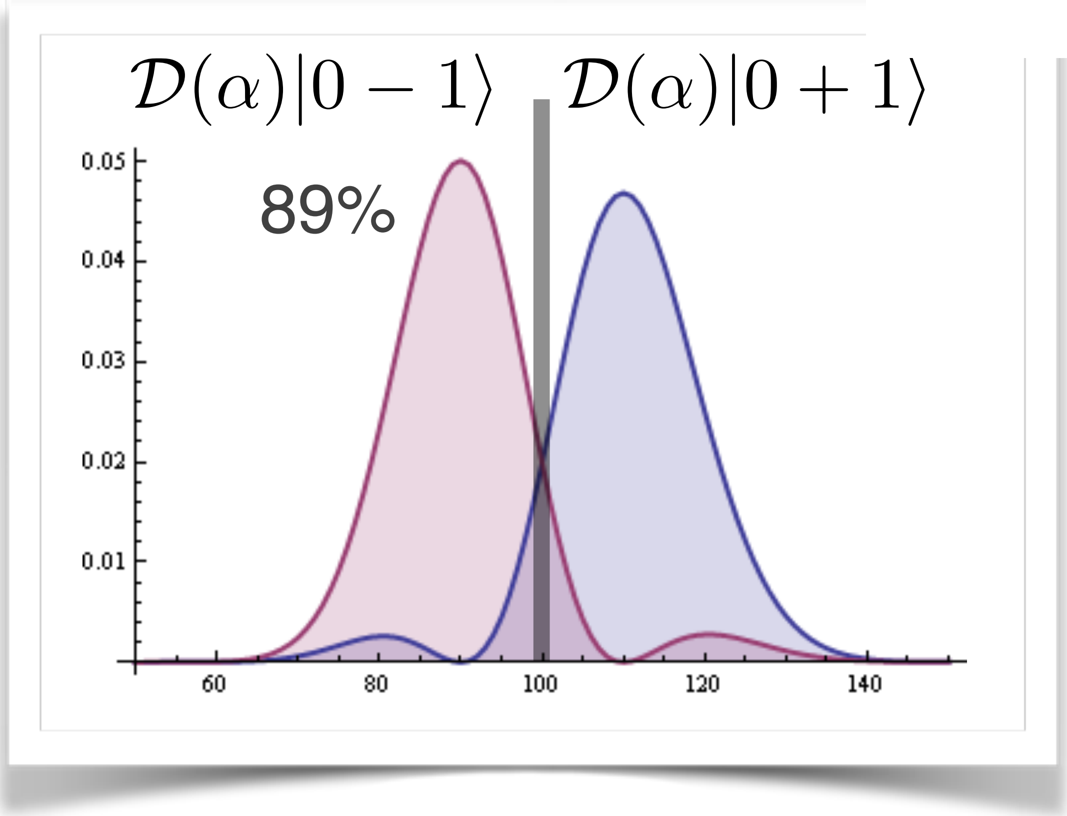
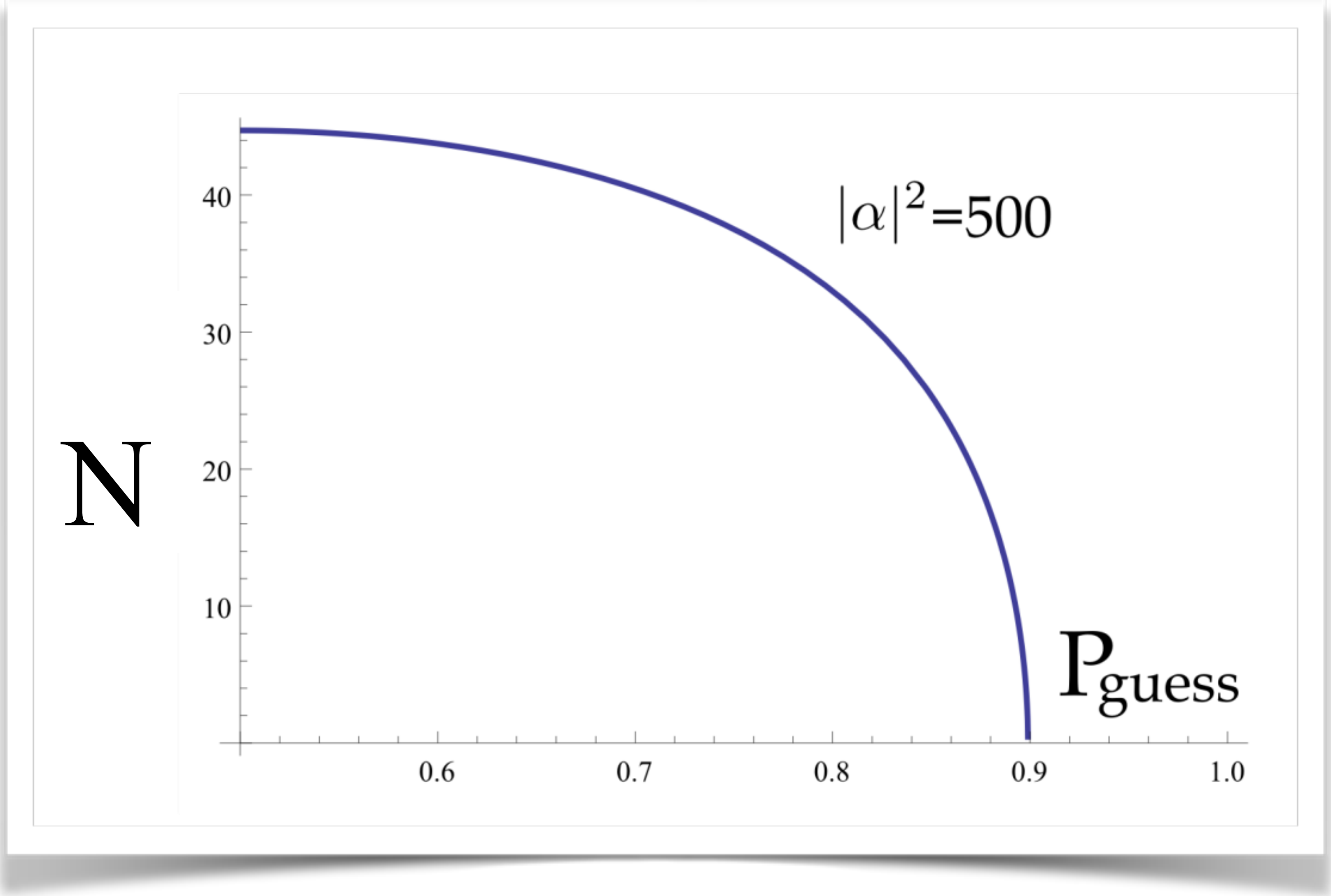


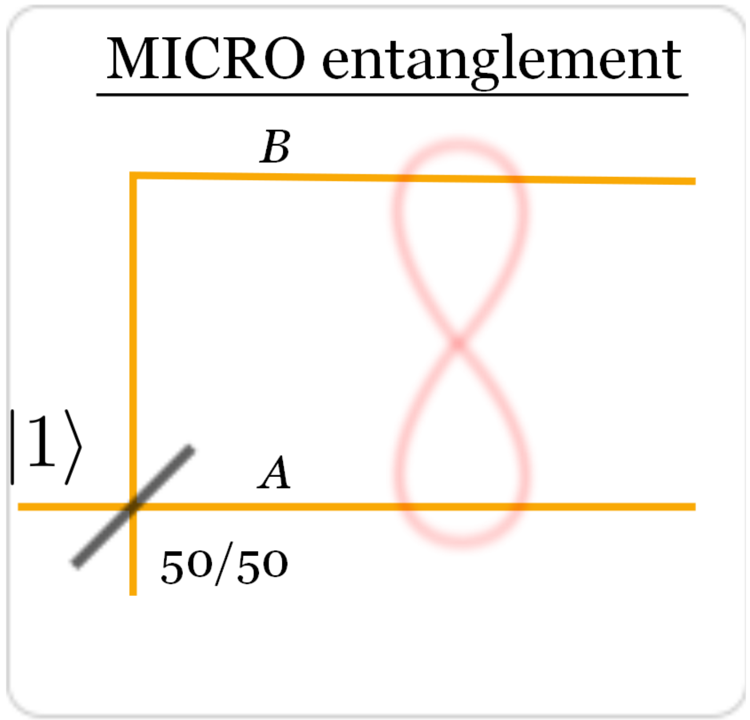


For $P_{\text{guess}} = 2/3$ the size of a displaced single-photon entanglement with 500 photons is the same than

$$|0\rangle_A|\uparrow\rangle_B + |N \approx 38\rangle_A|\downarrow\rangle_B$$

Example a macroscopic quantum state

with respect to the macro measure based on coarse-graining

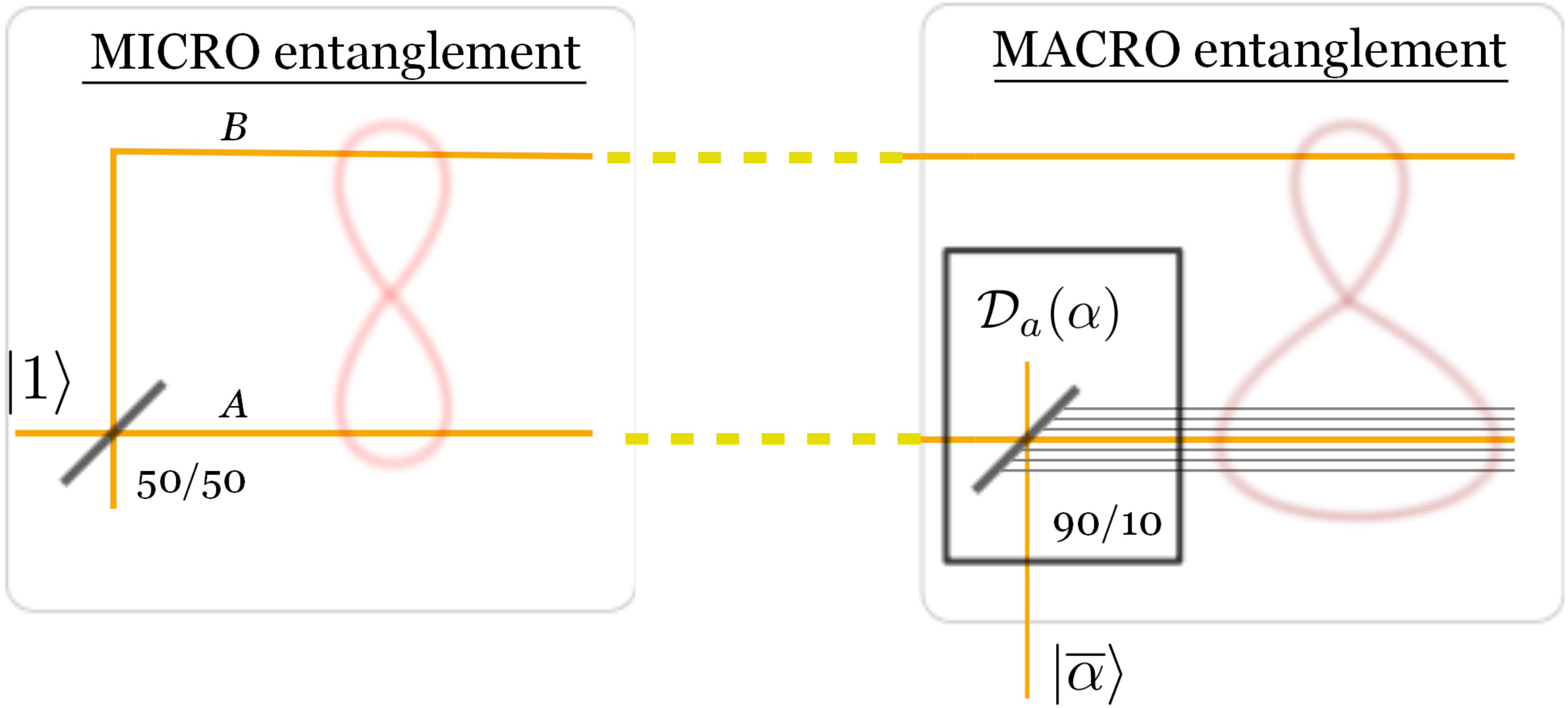


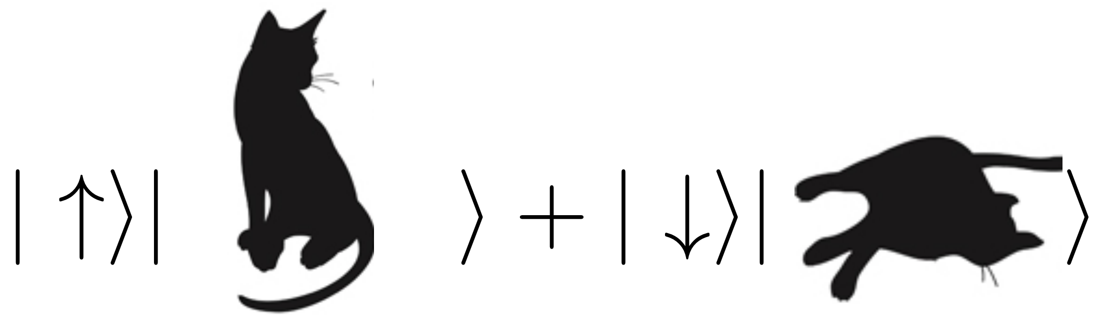
Entanglement between two spatial modes

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

Example a macroscopic quantum state

with respect to the macro measure based on coarse-graining





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Micro-Macro entanglement

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

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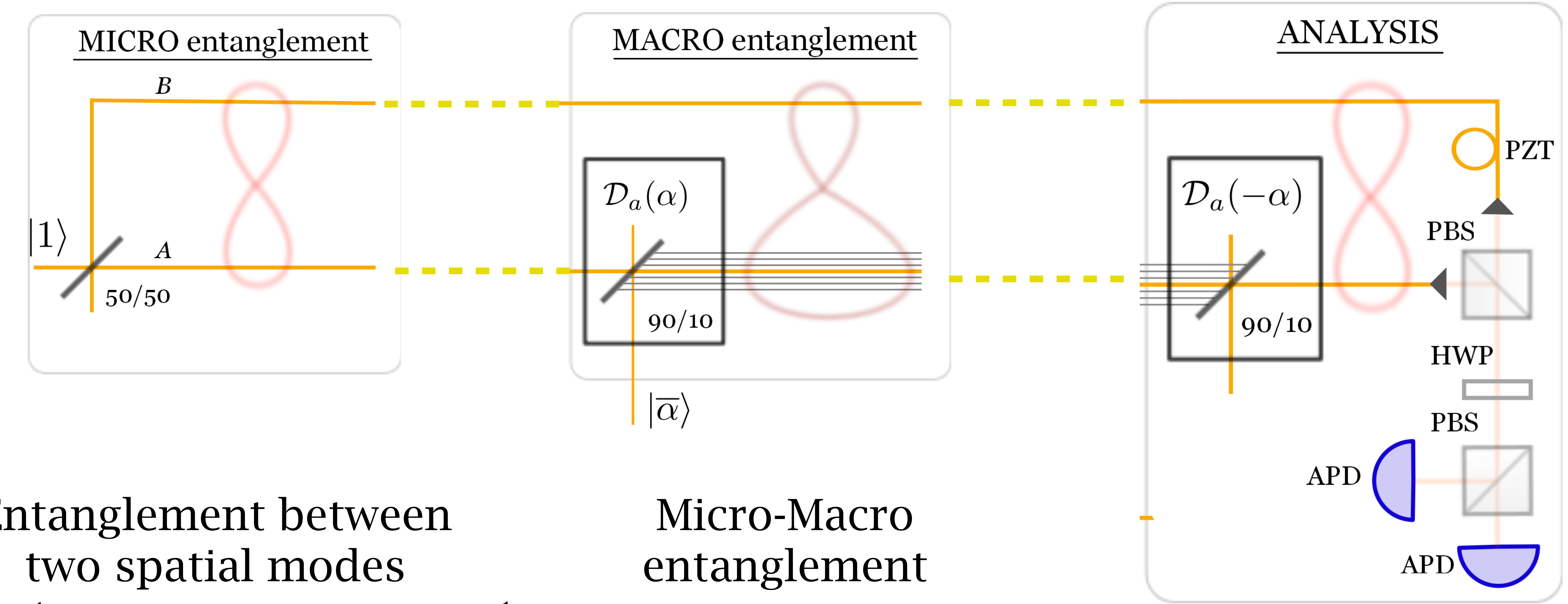

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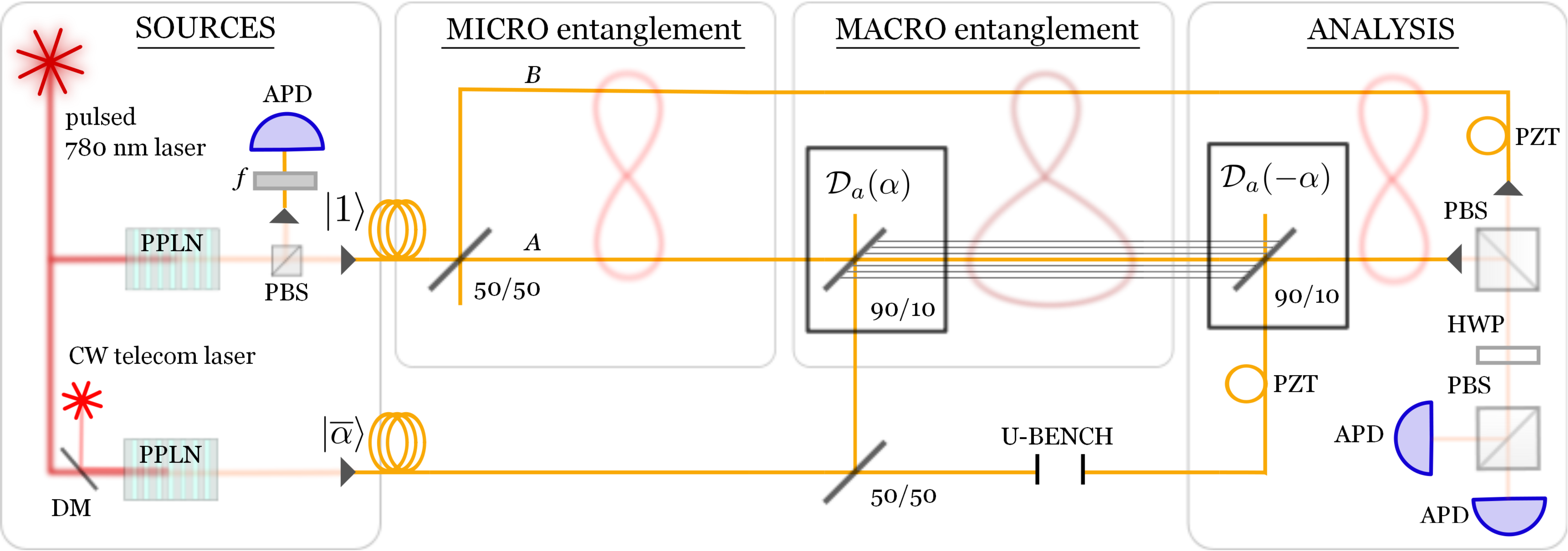
Displacement back to Micro-Micro entanglement before detection

Experimental setup

for creating & detecting a displaced-single photon entangled state



N. Bruno, A. Martin, P. Sekatski, N. Sangouard, R. Thew, and N. Gisin, Nature Physics 9, 545 (2013)

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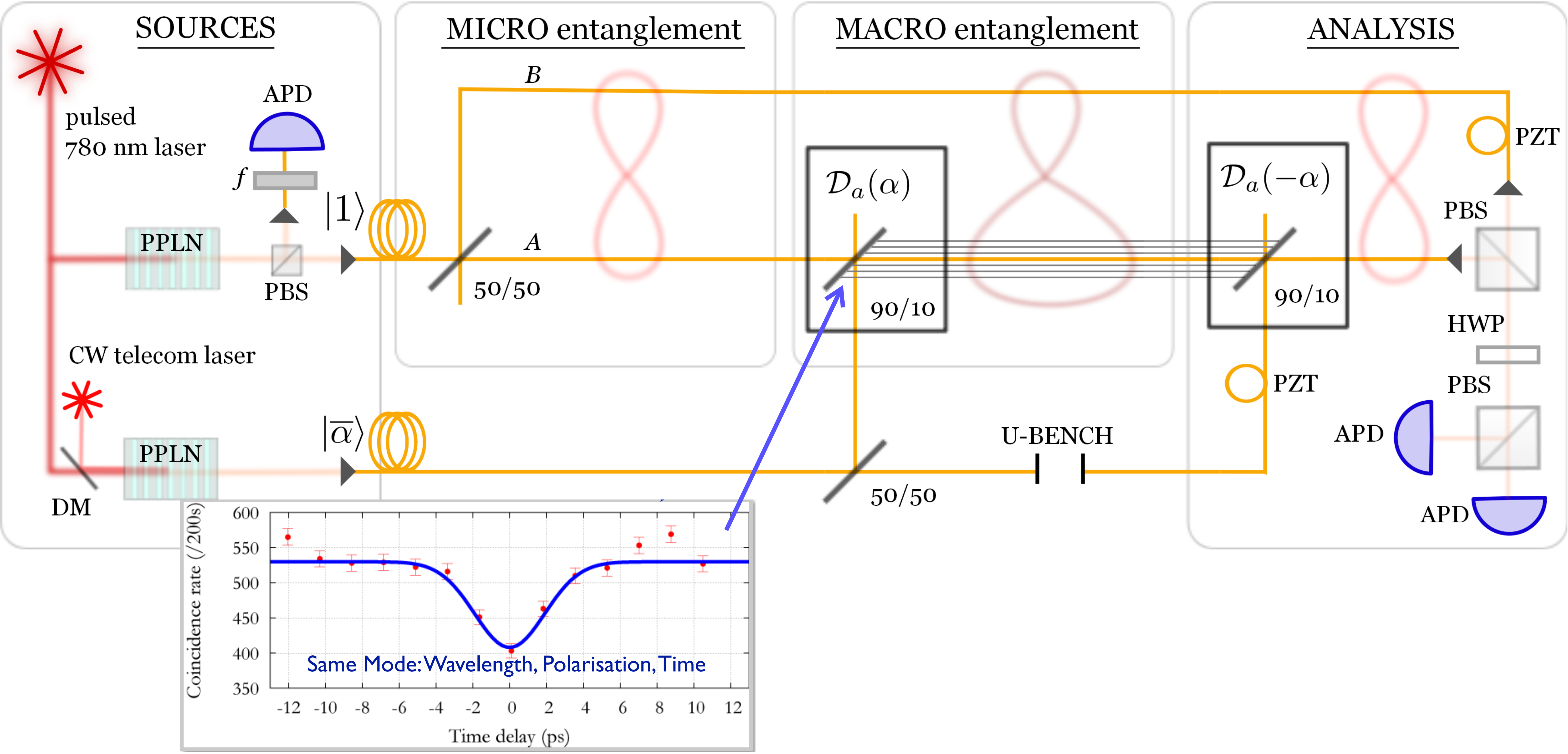

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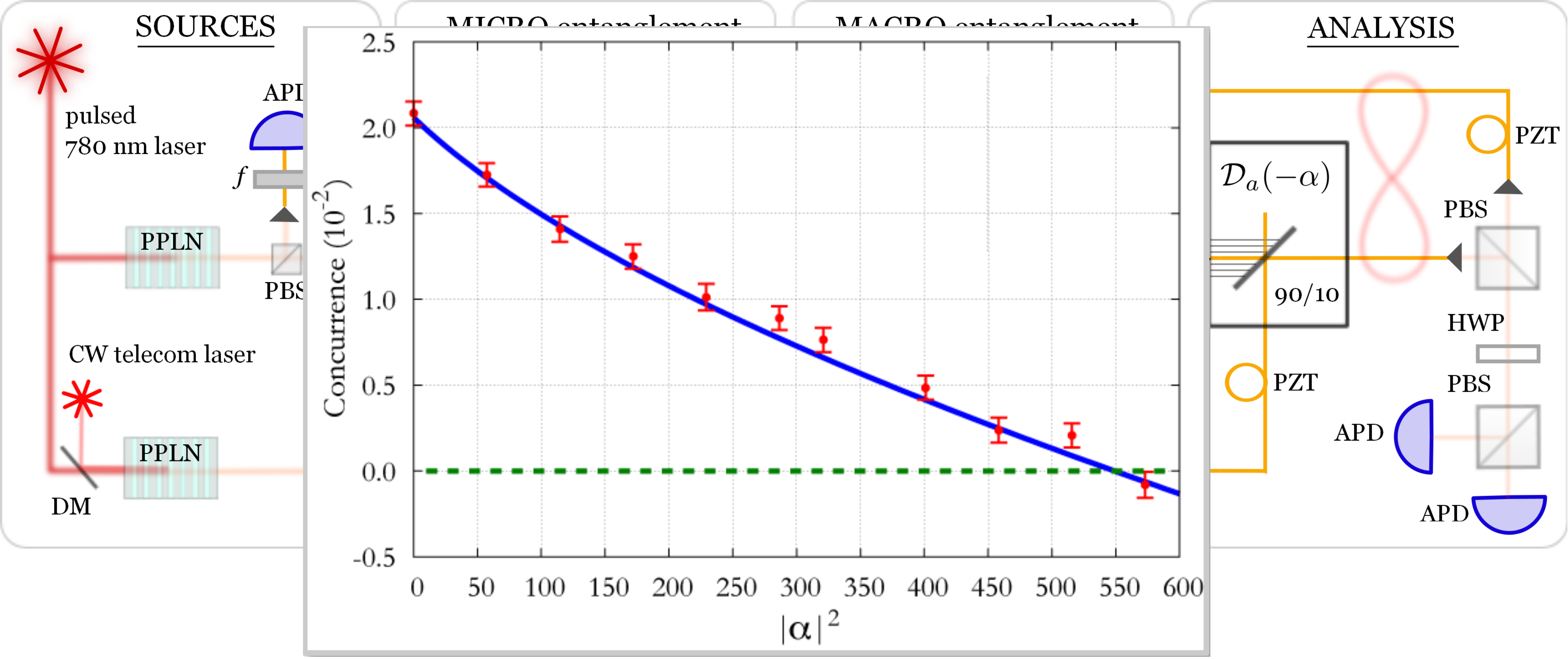

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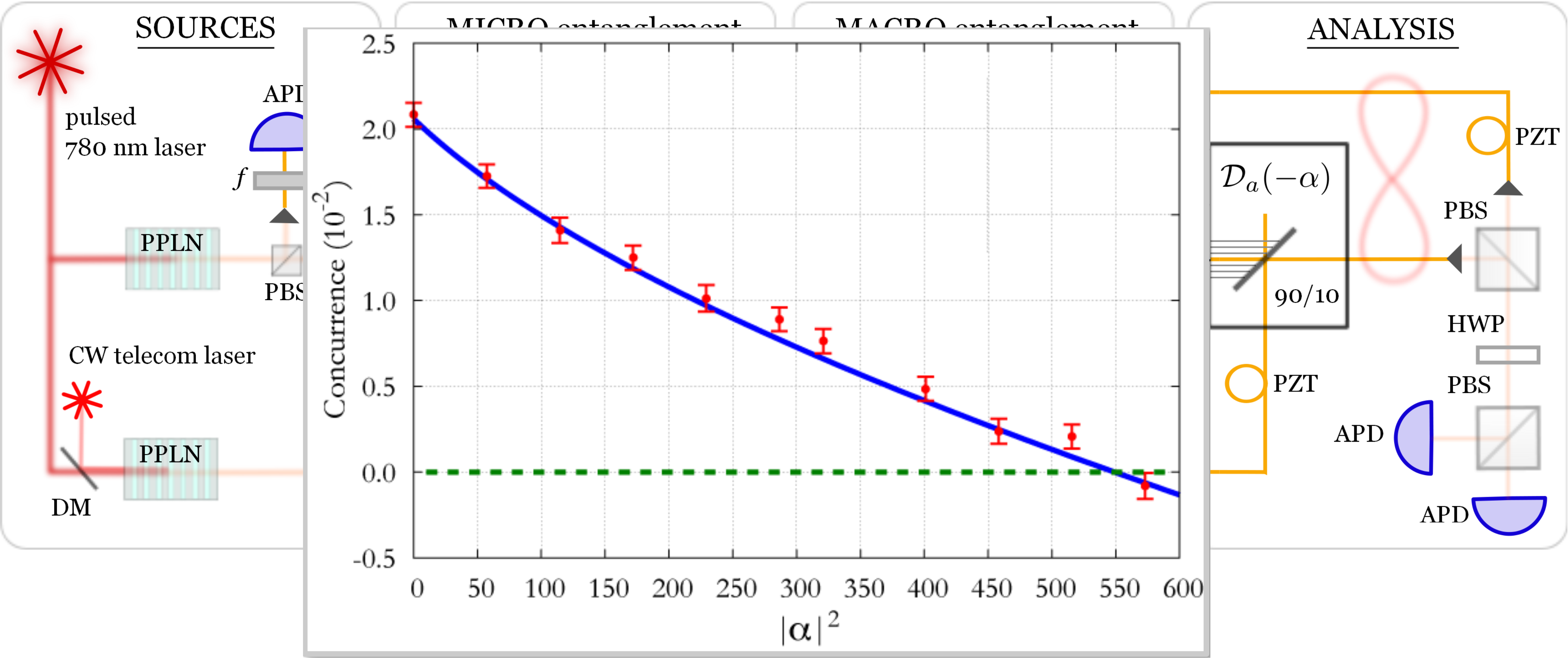

See also A. Lvovsky et al. Nature Physics 9, 543 (2013)

N. Bruno, A. Martin, P. Sekatski, N. Sangouard, R. Thew, and N. Gisin, Nature Physics 9, 545 (2013)

How hard is it to observe the quantumness of macro states?

Consider a phase noise channel $\zeta_\Delta(\rho) = \int d\varphi\, \bar{p}_\Delta(\varphi) e^{-i\varphi a^\dagger a} \rho e^{i\varphi a^\dagger a}$

with a Gaussian distribution of phase noise $\bar{p}_\Delta(\varphi)$ (standard deviation Δ)

It can be seen as a weak measurement of the photon number

Pointer state $|E_0\rangle$ with a Gaussian shape $|\langle x|E_0\rangle|^2$ and spread Δ^{-1}

Interaction $U = e^{i\hat{p}a^\dagger a}$ $\quad$ $\mathrm{tr}_E U\rho|E_0\rangle\langle E_0|U^\dagger = \zeta_\Delta(\rho)$

The entangled states that are macro with respect to the coarse-grained measure are inevitably very sensitive to phase noise!

P. Sekatski, N. Gisin and N. Sangouard, Phys. Rev. Lett. 113, 090403 (2014)

How hard is it to observe the quantumness of macro states?

Consider a micro-macro entangled state

$$|\psi\rangle_{mM} = \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_m |\phi_0\rangle_M - |\downarrow\rangle_m |\phi_1\rangle_M \right)$$

i.e. for which the components can be distinguished with a very coarse-grained detector

$$P_{\frac{1}{\Delta}}[\phi_0, \phi_1] \sim 1 \quad \text{even for} \quad \frac{1}{\Delta} \to +\infty$$

the entanglement remaining in $|\psi\rangle_{mM}$ after a tiny phase noise $\Delta \to 0$

$$\mathcal{N}\left(\zeta_\Delta\left(|\psi\rangle_{mM}\right)\right) \leq \sqrt{P_{\frac{1}{\Delta}}[\phi_0, \phi_1]\left(1 - P_{\frac{1}{\Delta}}[\phi_0, \phi_1]\right)}$$

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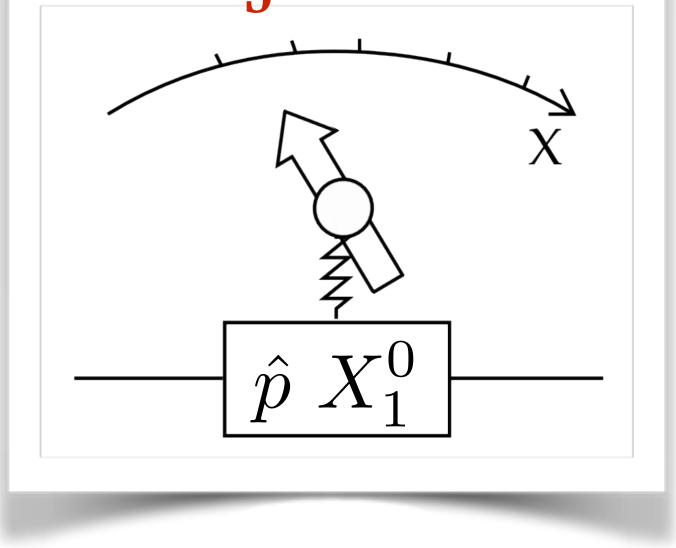
Two mode squeezed states as macro states?

based on the distinguishability with a coarse-grained detector

Alice

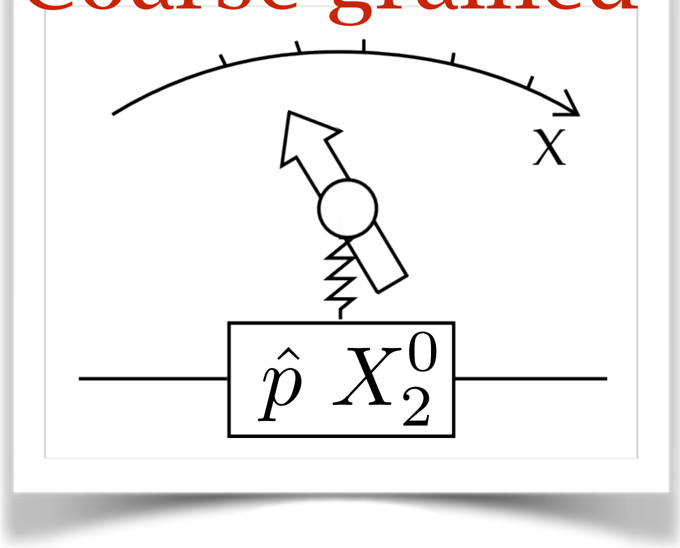
+/-

Projective



Two-mode squeezed state

Coarse grained



Bob

?

The guessing probability is given $P_\sigma^{\text{guess}} = \int_0^{+\infty} |p(x_1, x_2, \sigma)|^2 \mathrm{d}x_1 \mathrm{d}x_2 + \int_{-\infty}^{0} |p(x_1, x_2, \sigma)|^2 \mathrm{d}x_1 \mathrm{d}x_2$

Fixing $P_{\text{guess}} \longrightarrow \sigma_{\max}[\Phi_0, \Phi_1]$

$$(1 - \tanh^2 g)^{\frac{1}{2}}\ e^{\tanh g\ a_1^\dagger a_2^\dagger}|00\rangle \overset{\text{size}}{\longleftrightarrow} |\uparrow\rangle|\alpha\rangle - |\downarrow\rangle|-\alpha\rangle$$

Lagahaout et al. Opt. Comm. 96, 337 (2015)
E. Oudot et al. arXiv:1410.8421

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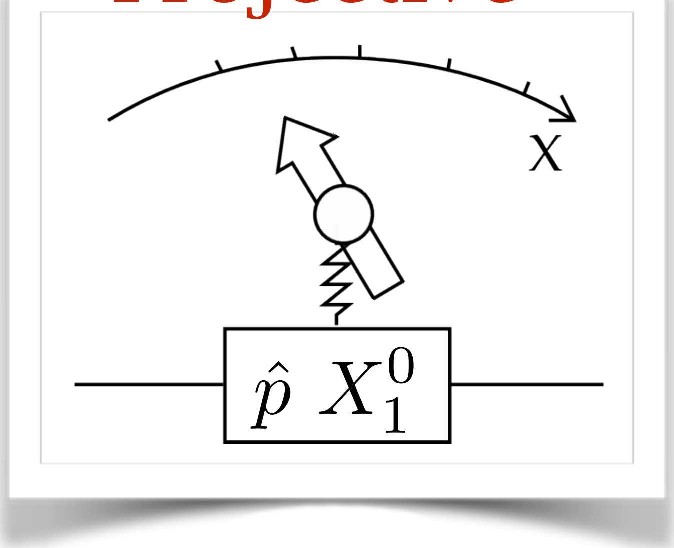

Two-mode squeezed state

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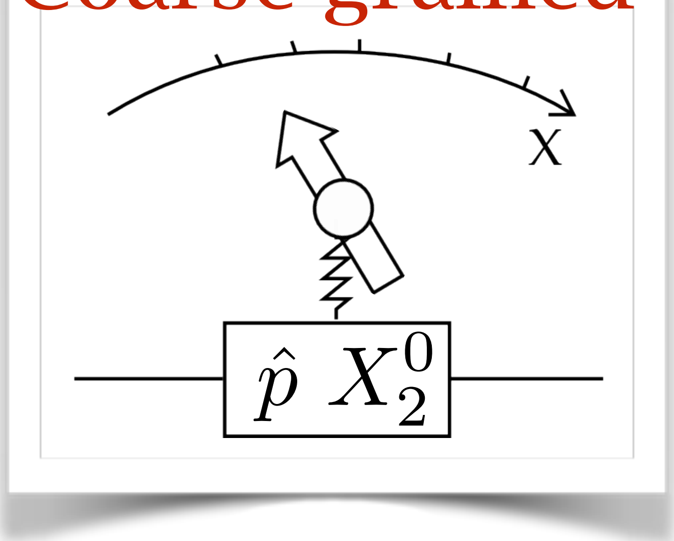

Bob

?

For any state, its size is bounded by $x_C = \frac{1}{\sqrt{V_{\psi_{\mathrm{tms}}}(\bar{X}_1^{\frac{\pi}{2}} + \bar{X}_2^{\frac{\pi}{2}})}}.$

Hard to observe quantum features of macro states

loss $\quad V(\bar{X}_1^{\pi/2}+\bar{X}_2^{\pi/2}) \mapsto \eta V(\bar{X}_1^{\pi/2}+\bar{X}_2^{\pi/2}) + 1 - \eta \quad N_{\mathrm{eff}} \leq \frac{1}{\sqrt{1-\eta}}$

E. Oudot, P. Sekatski, F. Frowis, N. Gisin and N. Sangouard arXiv:1410.8421

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based on the distinguishability with a coarse-grained detector

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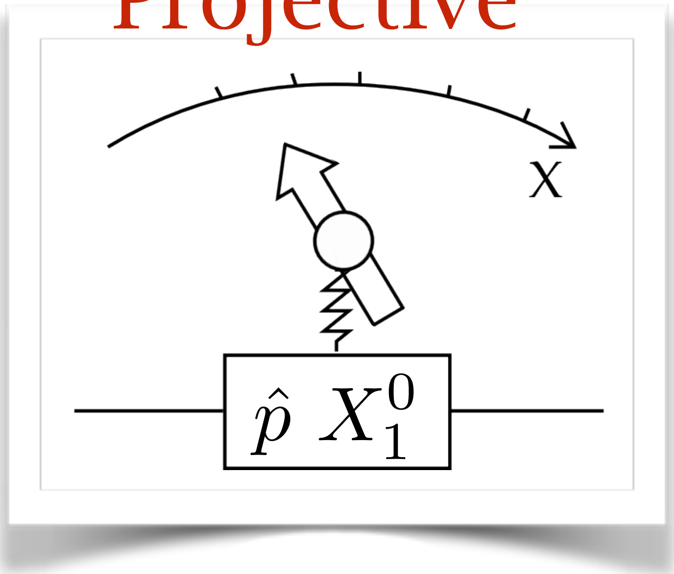
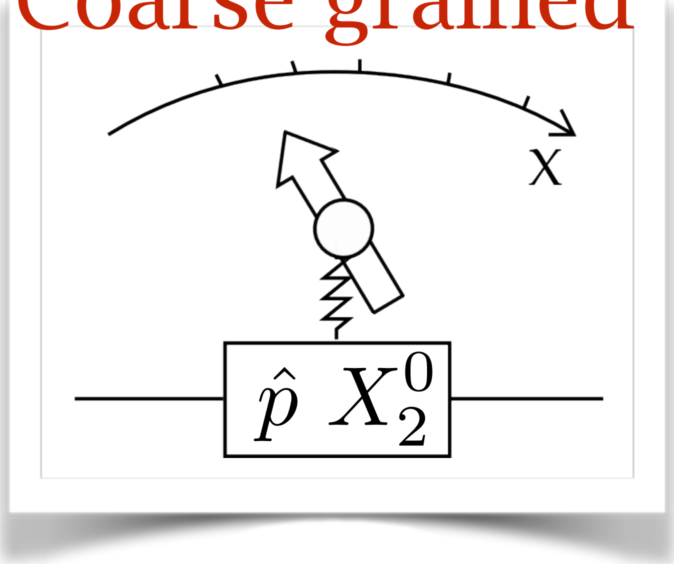


Two-mode squeezed state



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Hard to observe quantum features of macro states

noise $\quad \rho \mapsto \int d\lambda\, h(\lambda) e^{i\hat{X}_0\lambda} \rho e^{-i\hat{X}_0\lambda}$

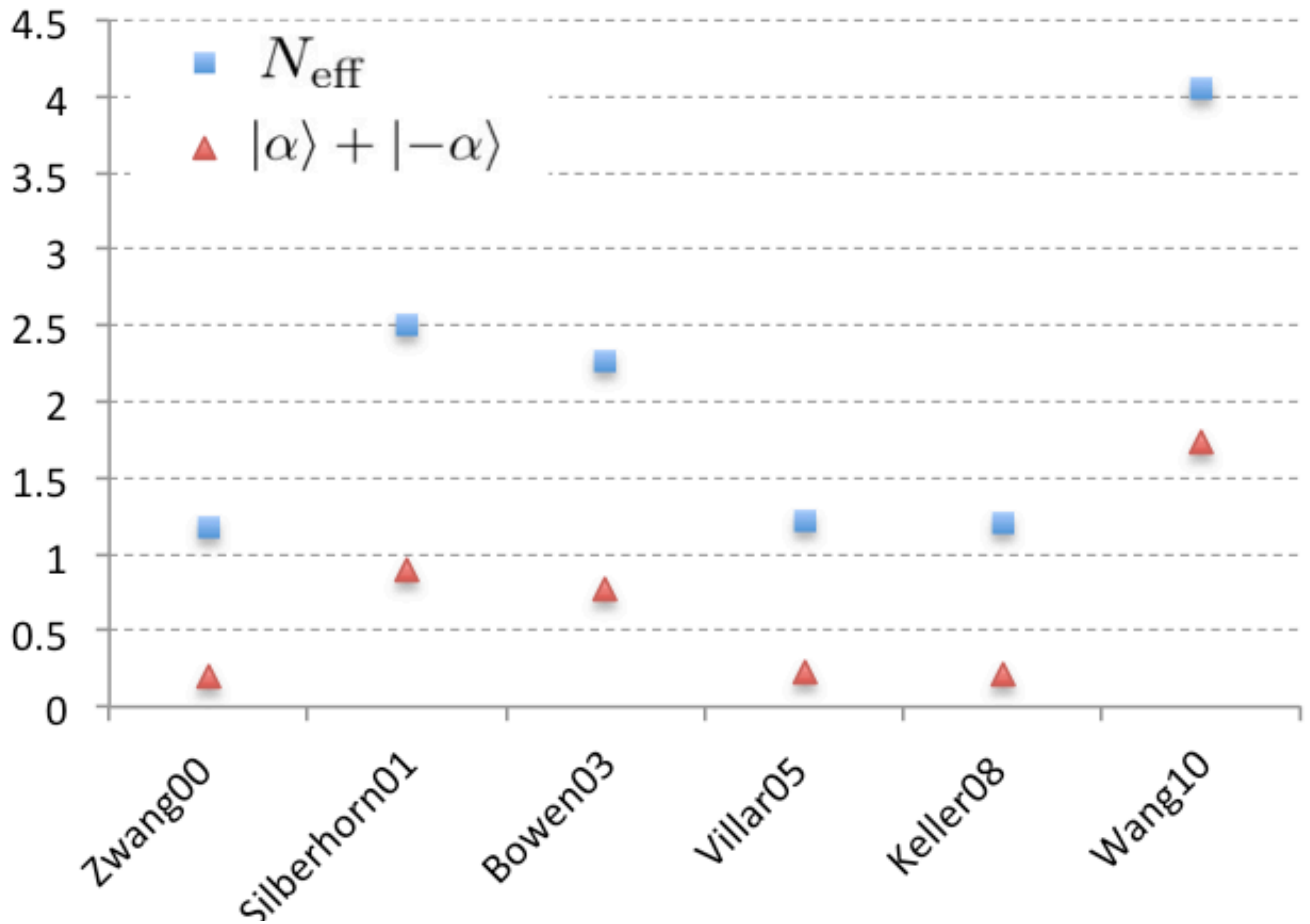
$$V(\bar{X}_1^{\pi/2} + \bar{X}_2^{\pi/2}) \mapsto V(\bar{X}_1^{\pi/2} + \bar{X}_2^{\pi/2}) + \Delta^2 h_1 + \Delta^2 h_2 \qquad N_{\mathrm{eff}} \leq \frac{1}{\sqrt{\Delta^2 h_1 + \Delta^2 h_2}}$$

E. Oudot, P. Sekatski, F. Frowis, N. Gisin and N. Sangouard arXiv:1410.8421

Two mode squeezed states as macro states?

based on the distinguishability with a coarse-grained detector

Interestingly, the proposed bound allows one to compare the size of states obtained in various experiments



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Testing explicit collapse models with macro states

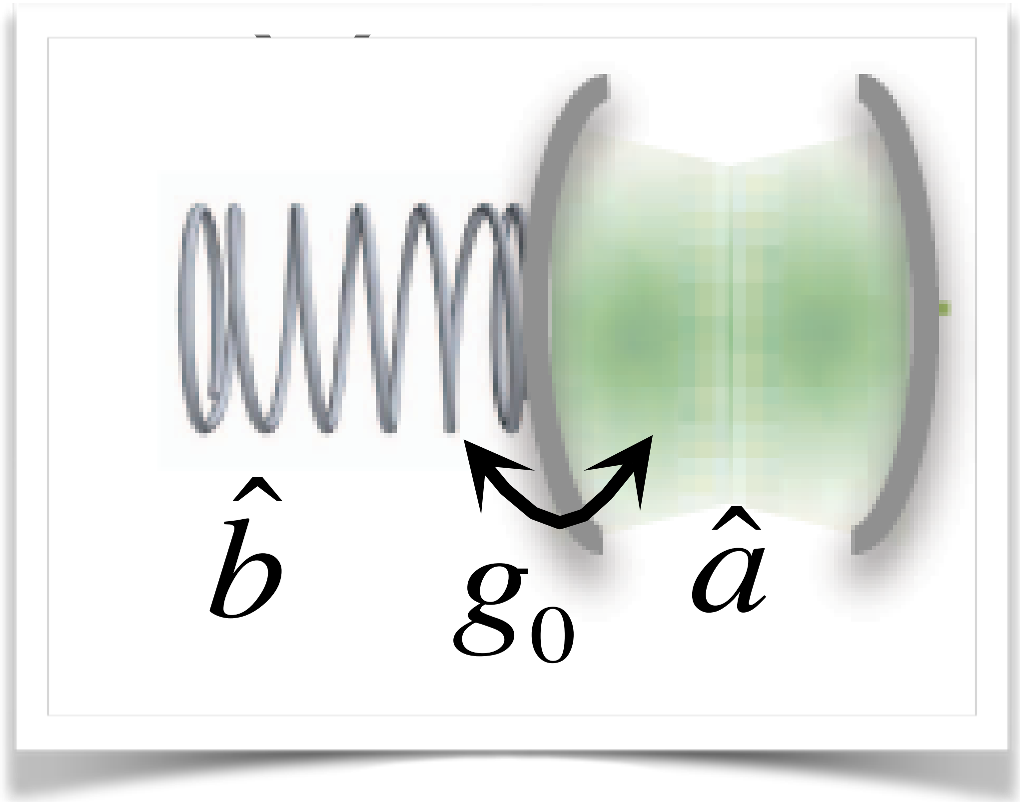
Does a massive object in a superposition of two well distinct positions undergo intrinsic decoherence ? GRW model Diosi & Penrose model...

Tool : Optically controlled mechanical device

Movable mirror with a large mass

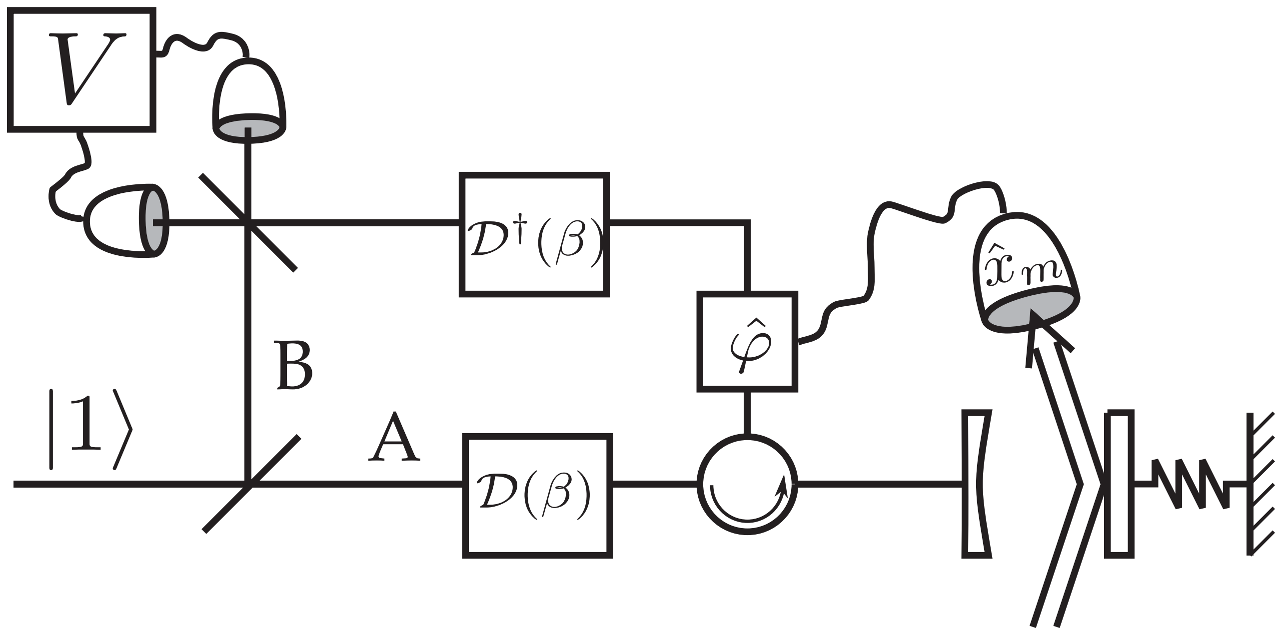
$$g_0 a^\dagger a \left(b + b^\dagger\right)$$

Interaction with an optical field in a superposition of well distinct states in photon number



P. Sekatski, M. Aspelmeyer and N. Sangouard, Phys. Rev. Lett. 112, 143602 (2014)

Proposal of a test bench for unconventional decoherence



$$\longrightarrow \frac{1}{\sqrt{2}}\left(\mathcal{D}(\beta)|+\rangle_A|-\rangle_B - \mathcal{D}(\beta)|-\rangle_A|+\rangle_B\right)$$

$$\longrightarrow \frac{1}{\sqrt{2}}\left(|+\rangle_A|-\rangle_B - |-\rangle_A|+\rangle_B\right)$$

$\longrightarrow$ The interference pattern allows one to «see» the mirror decoherence

test bench for post-quantum theories
+ even in the weak optomechanical coupling regime
+ even if the mechanical device is NOT prepared in its motional ground state

P. Sekatski, M. Aspelmeyer and N. Sangouard, Phys. Rev. Lett. 112, 143602 (2014)

Conclusion

Macro measure based on the distinguishability
with a coarse-grained detector

Realization of a micro-macro entangled state

The quantum features of such states are very hard to observe
decoherence + measurement precision

Potential useful to test post-quantum theories with an explicit collapse
model

Extension to CV states