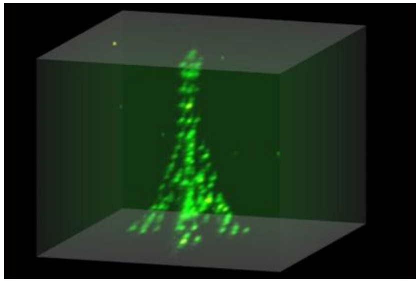
An all-optical quantum processor for iterative generation of quantum states

Lucas Caron, Hector Simon, Hugo Basset, Romaric Journet and Rosa Tualle-Brouri

Laboratoire Charles Fabry de l'Institut d'Optique, 91127 Palaiseau, France

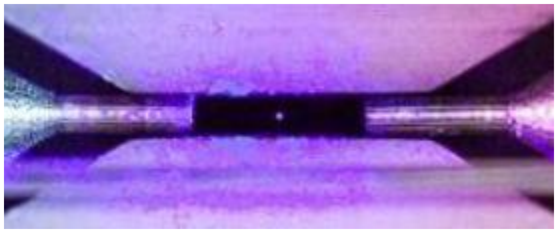
Congrès QuiDiQua 3, 5 - 7 Novembre 2025, Paris

Motivation of this work



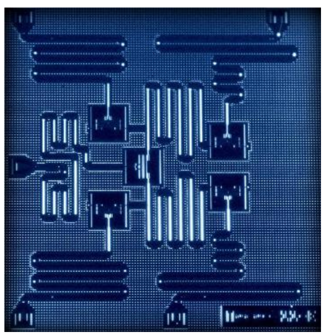
Electronic state of atomic/molecular systems

LCF, Université Paris-Saclay



Trapped ions

Department of Physics University of Oxford



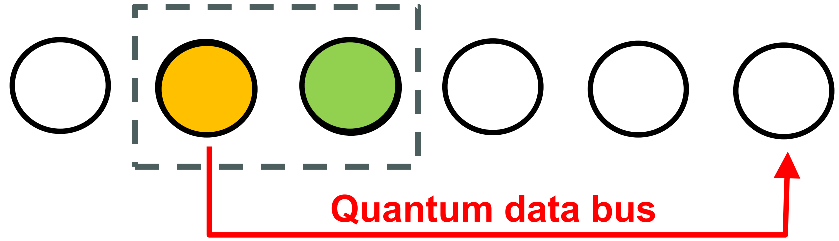
IBM 5 qubits processor

Superconducting structures

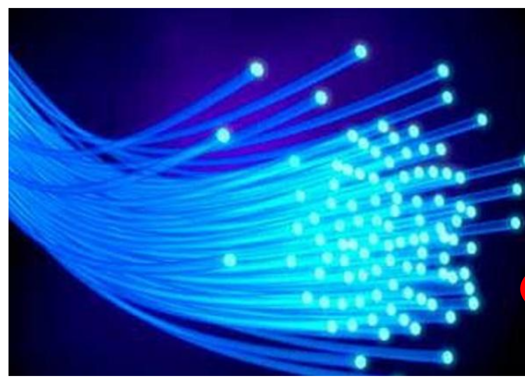
QED cavities

Departments of Physics and Applied Physics Yale University

There are many promising physical platforms for encoding qubits:



Light as a carrier for quantum information



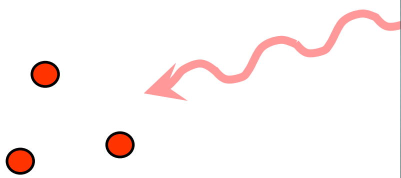
- Transfer of quantum information through light/matter interaction
- All-optical architectures

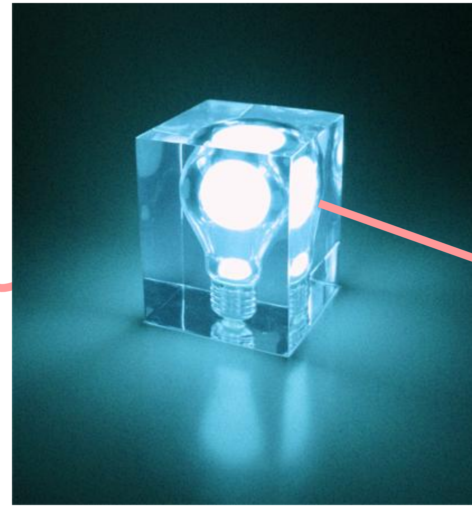
How can we encode quantum information on a light pulse ?

Discrete variables

Light is constituted of photons:

Photon number N



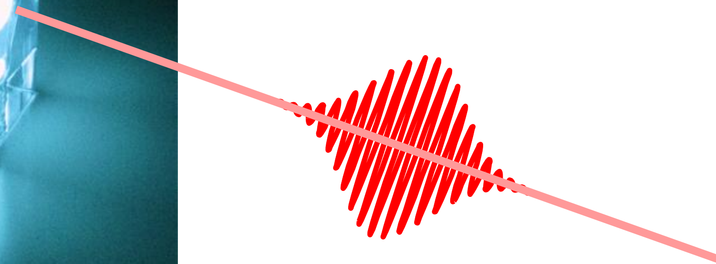


- Photon counting

(ex: avalanche photodiode)

Continuous variables

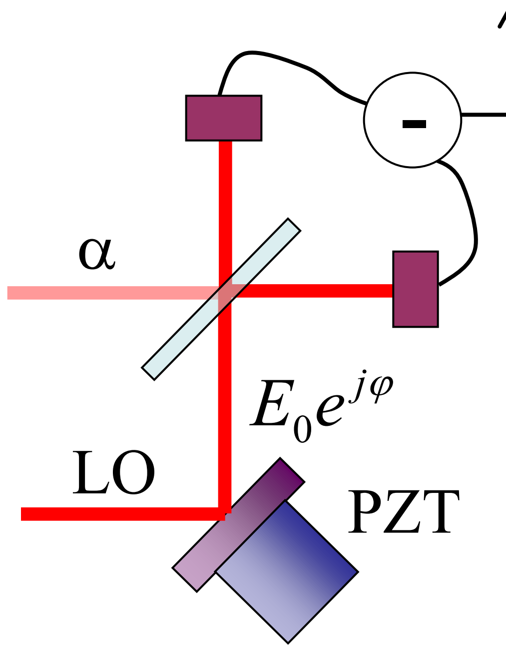
Light is also a wave:



- Complex amplitude α

(values in a continuum)

$$\propto X(\varphi) = \sqrt{2}\,\Re_e\left\{\alpha\, e^{-j\varphi}\right\}$$



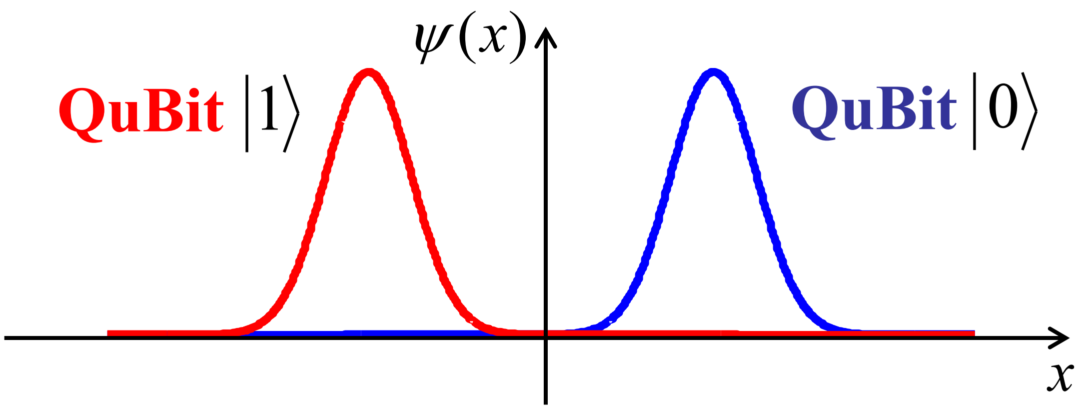
- Homodyne detection

(quadrature measurement)

→ Efficient detection at room temperature

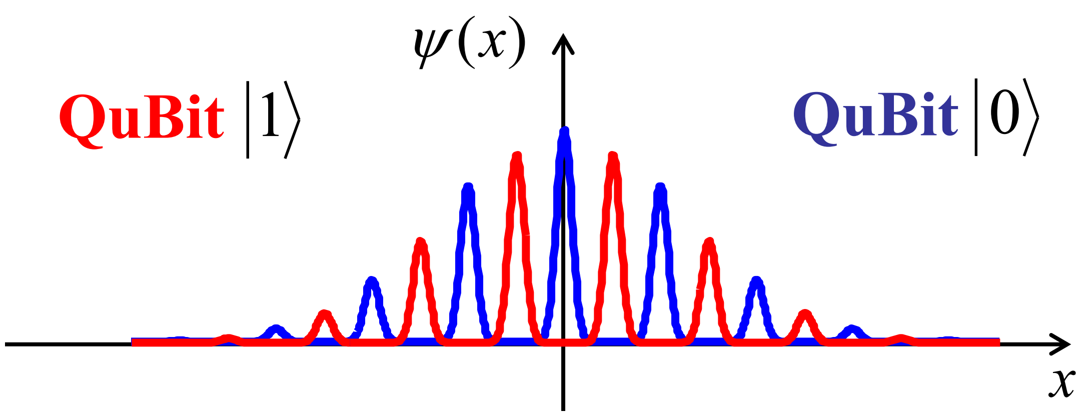
« Continues Variables »: Encoding quantum information

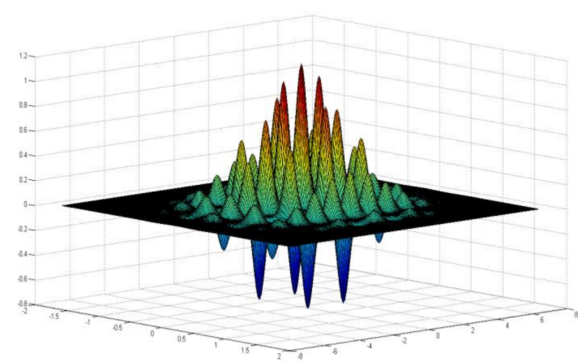
COHERENT STATES ENCODING



ENCODING ON QUADRATURE COMB STATES (GKP STATES)

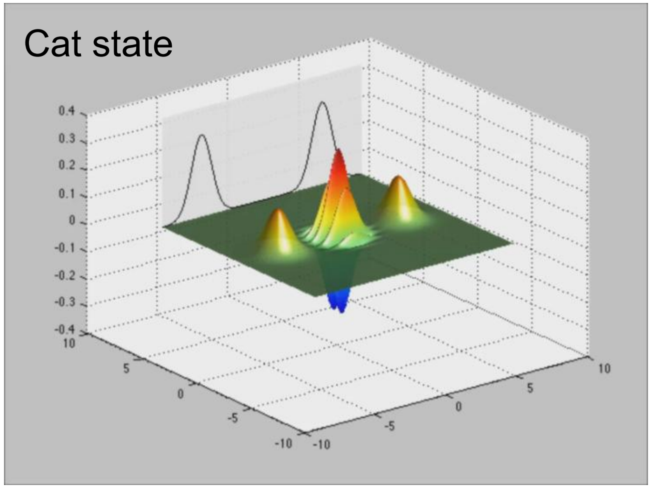
D. Gottesman, A. Kitaev, and J. Preskill, *Encoding a qubit in an oscillator*, Phys. Rev. A **64**, 012310 (2001).





Those encodings allow the **implementation of all basic quantum gates for quantum computing**

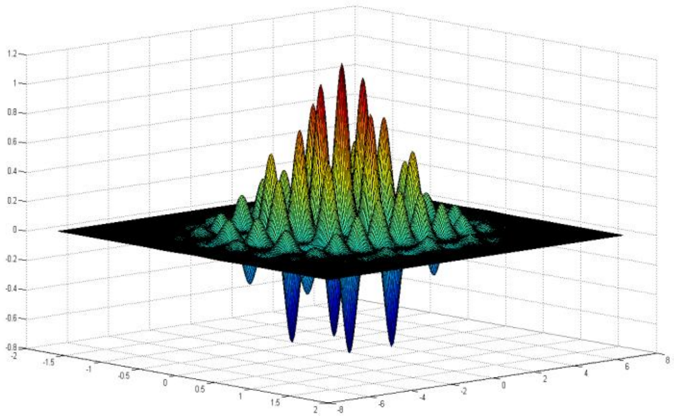
COHERENT STATES ENCODING



- T.C. Ralph, A. Gilchrist, G.J. Milburn, W.J. Munro and S. Glancy, *Quantum computation with optical coherent states*, Phys. Rev. A **68**, 042319 (2003).
- A. Lund, T. C. Ralph, and H. L. Haselgrove, *Fault-Tolerant Linear Optical Quantum Computing with Small-Amplitude Coherent States,* Phys. Rev. Lett. **100**, 030503 (2008).

➢ Protocols based on **photon counting** and **quadrature measurements**

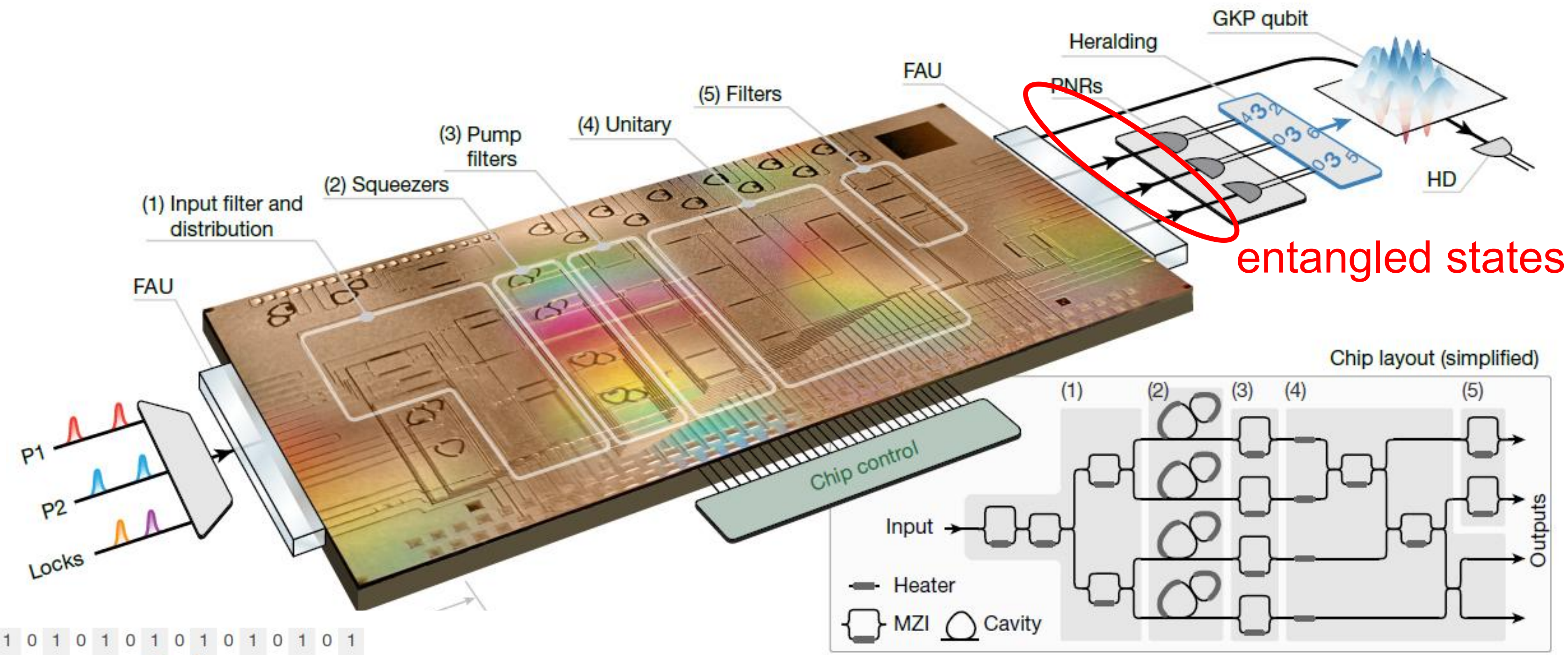
GKP STATES ENCODING

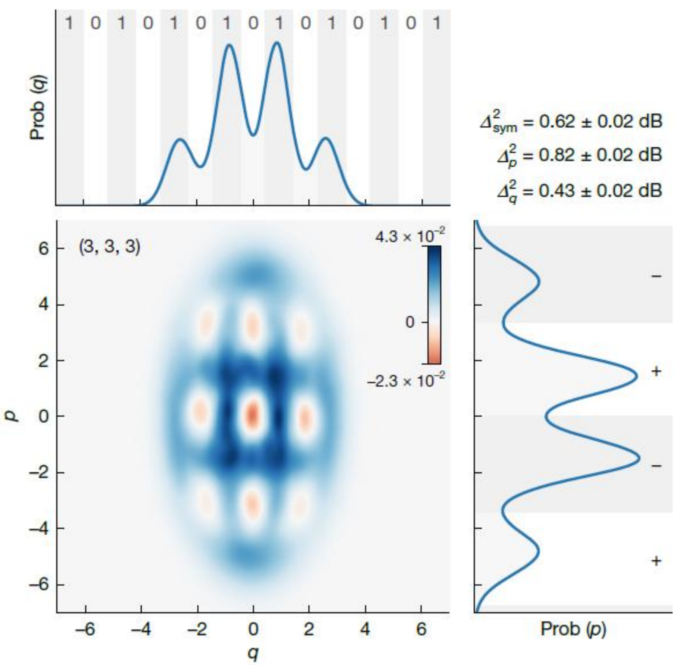


- D. Gottesman, A. Kitaev, and J. Preskill, *Encoding a qubit in an oscillator*, Phys. Rev. A **64**, 012310 (2001).
- B.Q. Baragiola, G. Pantaleoni, R.N. Alexander, A. Karanjai, and N.C. Menicucci, *All-Gaussian Universality and Fault Tolerance with the Gottesman-Kitaev-Preskill Code* Phys. Rev. Lett. **123**, 200502 – Published 13 November 2019

➢ Protocols based on **quadrature measurements only !!!**

First generation of free-propagating optical GKP states





M. V. Larsen, J. E. Bourassa, S. Kocsis, J. F. Tasker, R. S. Chadwick, C. González-Arciniegas, J. Hastrup, C. E. Lopetegui-González, F. M. Miatto, A. Motamedi, R. Noro, G. Roeland, R. Baby, H. Chen, P. Contu, I. Di Luch, C. Drago, M. Giesbrecht, T. Grainge, I. Krasnokutska, M. Menotti, B. Morrison, C. Puviraj, K. Rezaei Shad, B. Hussain, J. McMahon, J. E. Ortmann, M. J. Collins, C. Ma, D. S. Phillips, M. Seymour, Q. Y. Tang, B. Yang, Z. Vernon, R. N. Alexander & D. H. Mahler

Integrated photonic source of Gottesman-Kitaev-Preskill qubits

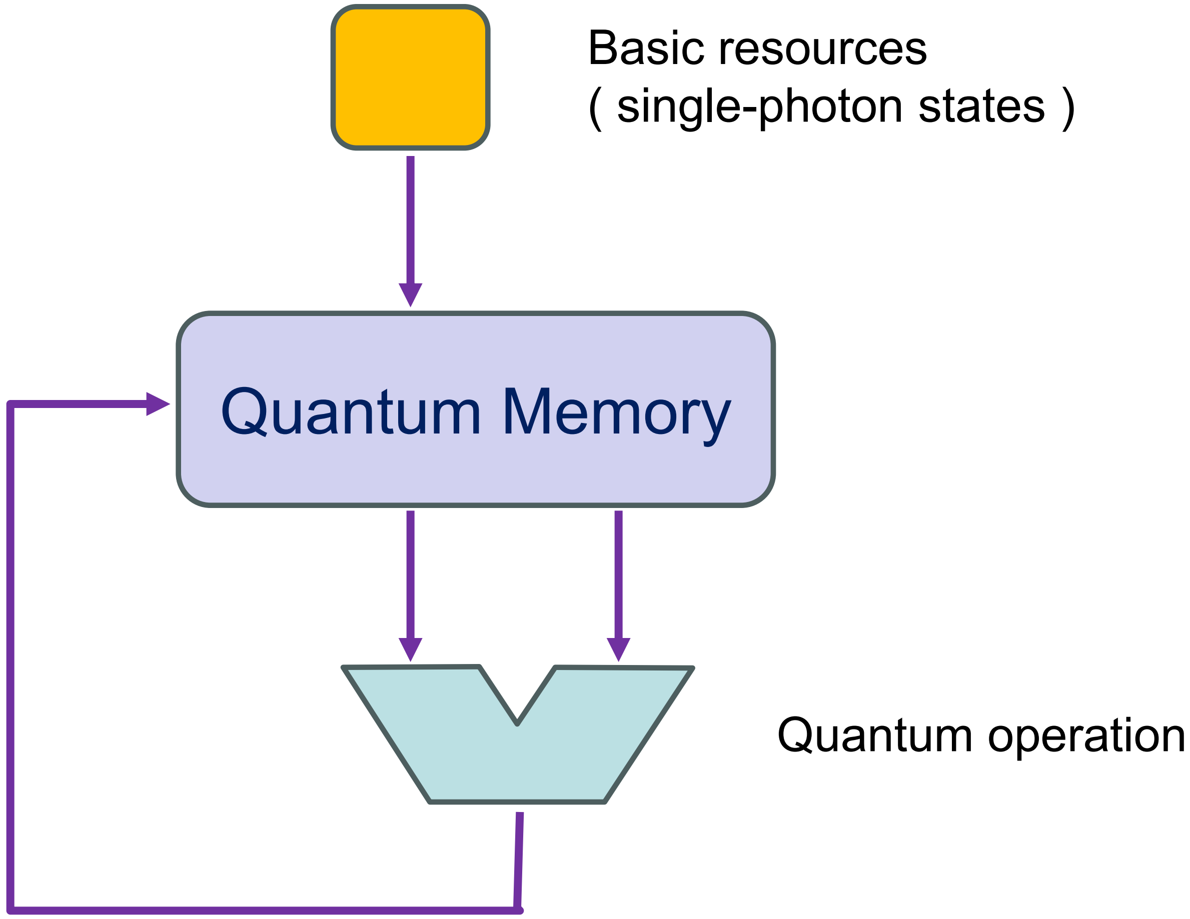
Nature (june 4, 2025) https://doi.org/10.1038/s41586-025-09044-5

30 Hz success rate

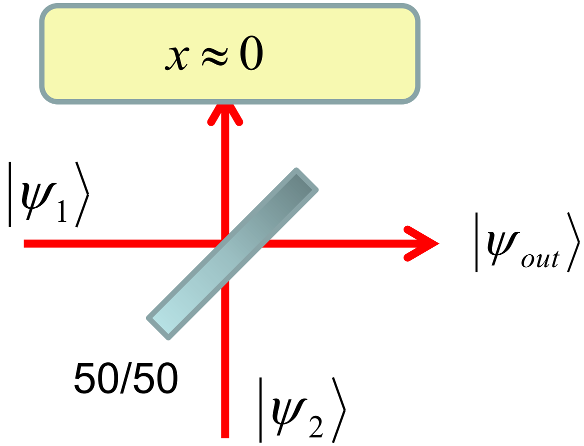
$$|\langle \hat{S}_x \rangle| = 0.241 \pm 0.002$$

$$|\langle \hat{S}_p \rangle| = 0.273 \pm 0.0012$$

Iterative generation of complex mesoscopic states: An all-optical quantum processor



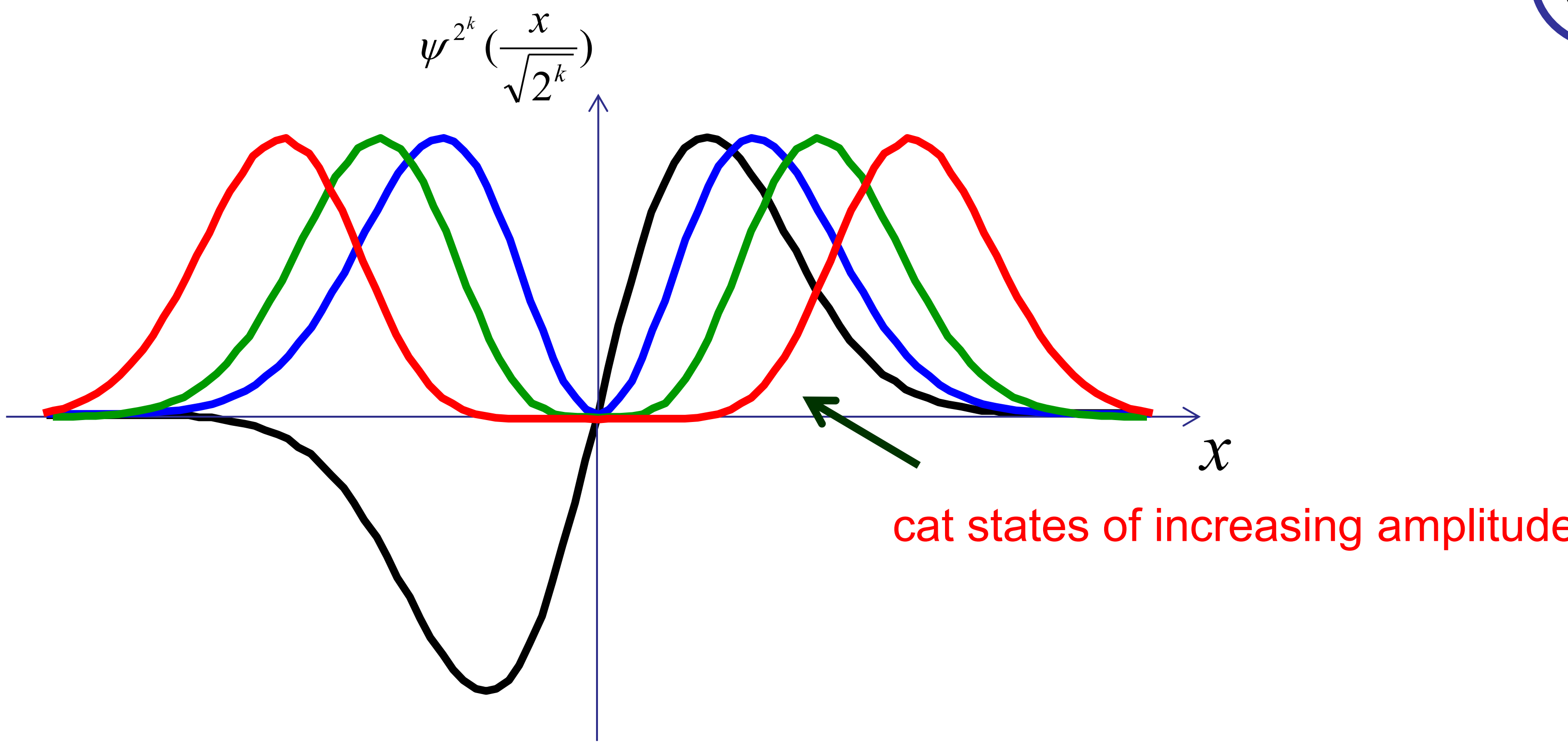
Iterative generation of complex mesoscopic states: the breeding operation



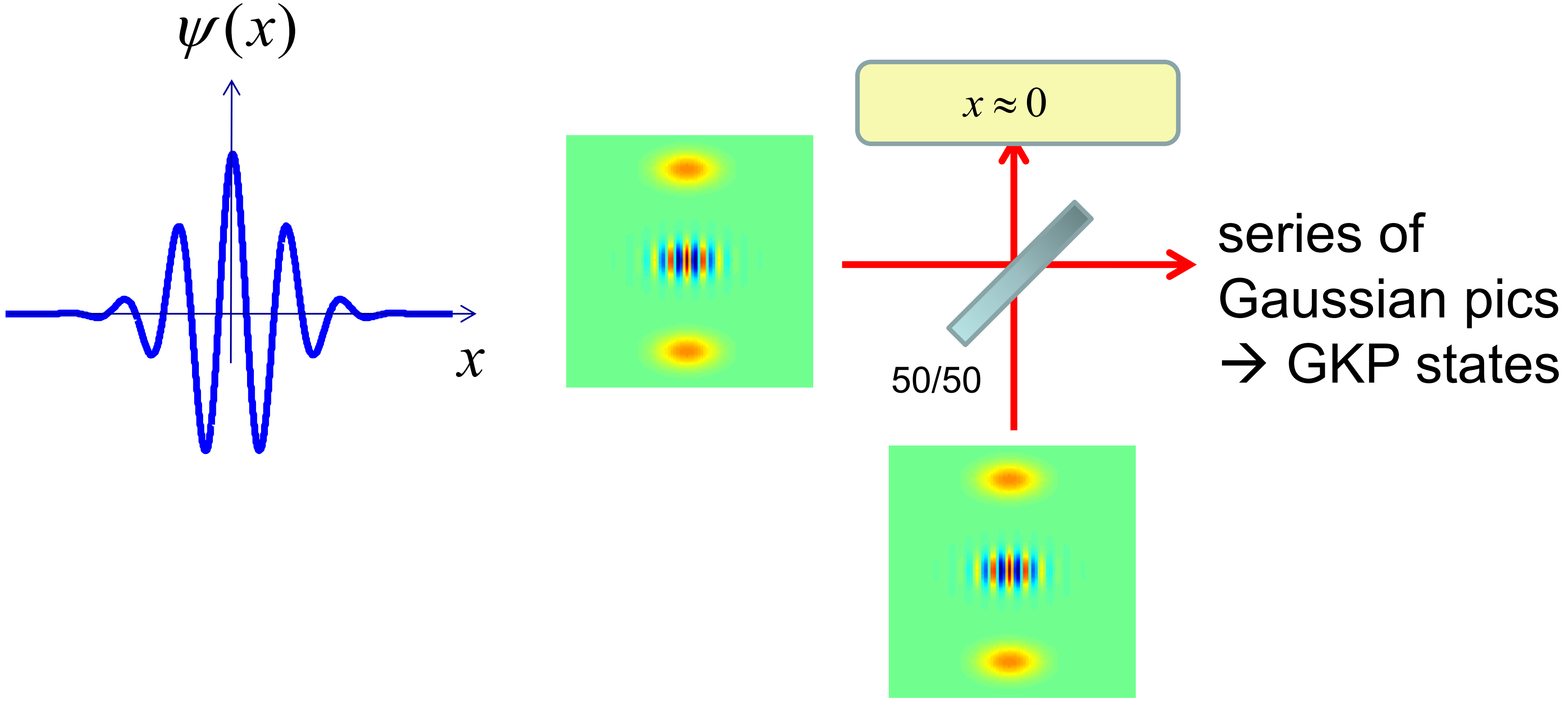
→ Probability amplitude $\psi(x) \equiv \langle x|\psi\rangle$

$$\psi_{out}(x) = \psi_1\left(\frac{x}{\sqrt{2}}\right)\psi_2\left(\frac{x}{\sqrt{2}}\right) = \psi^2\left(\frac{x}{\sqrt{2}}\right)$$

→ after *k* iterations: $\psi_{out}(x) = \psi^{2^k}\left(\frac{x}{\sqrt{2^k}}\right)$

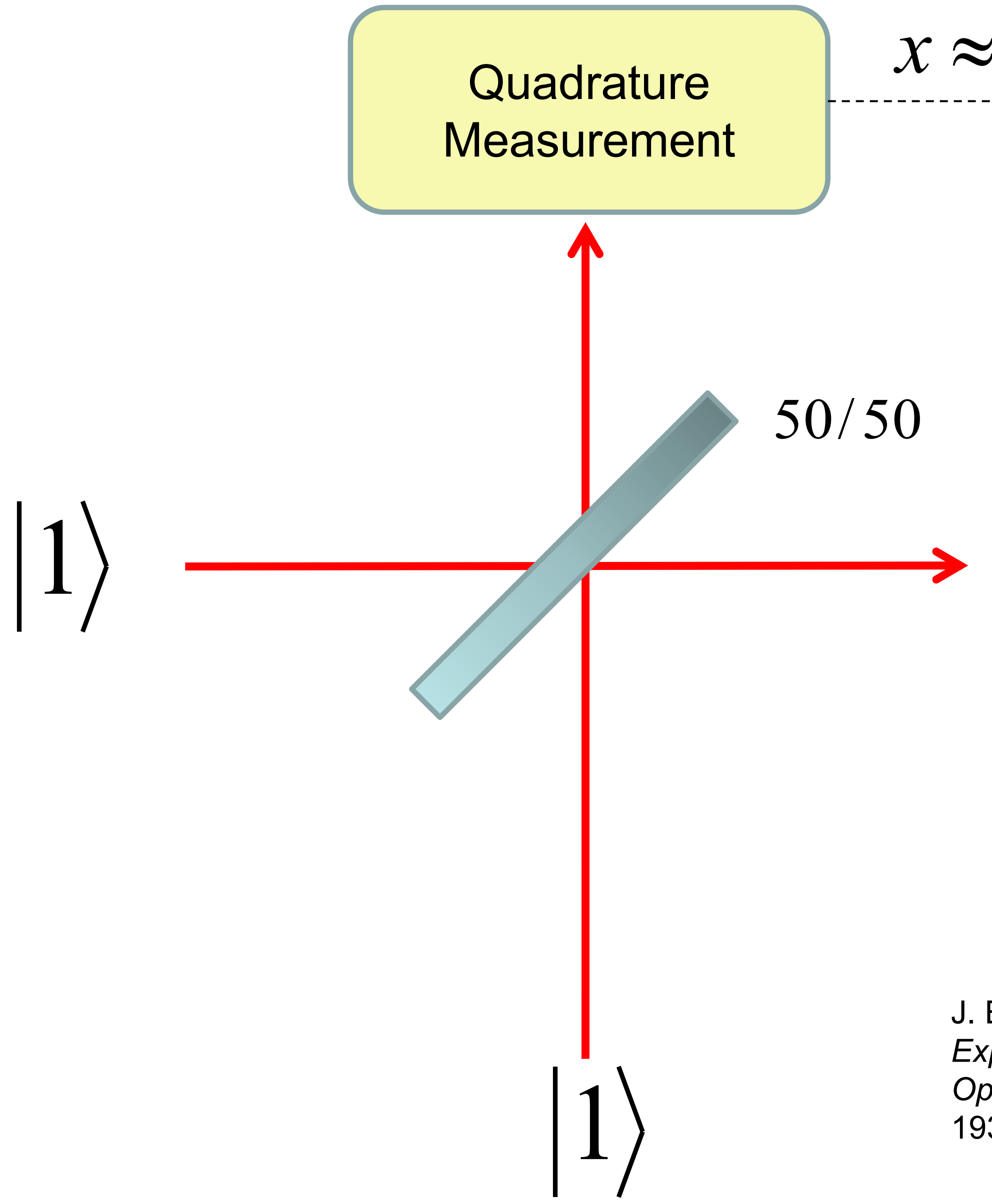


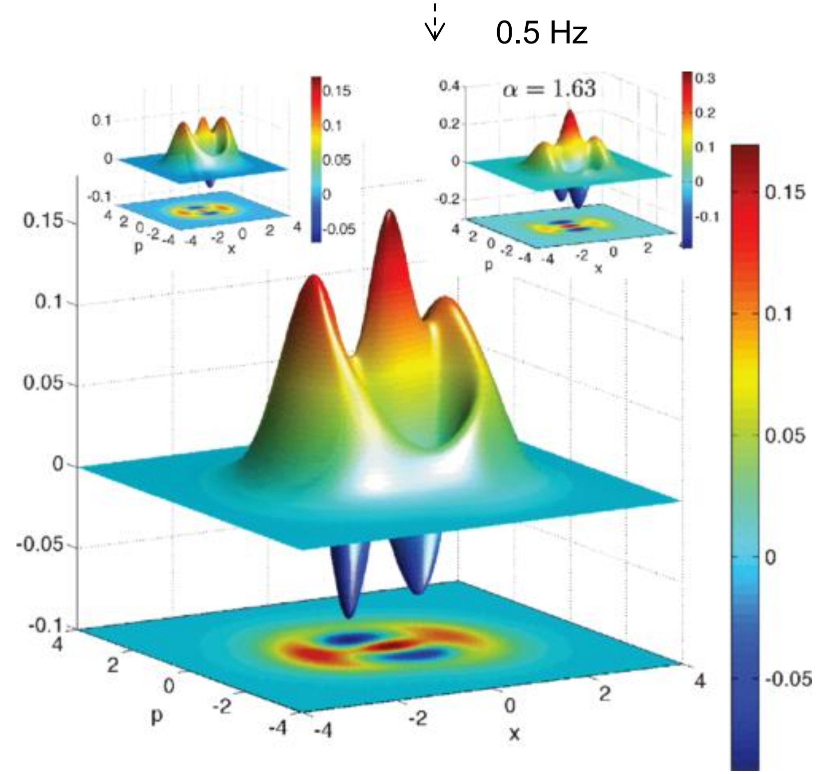
→ Principle of "cat breeding":



→ Possibility to iteratively generate complex mesoscopic states

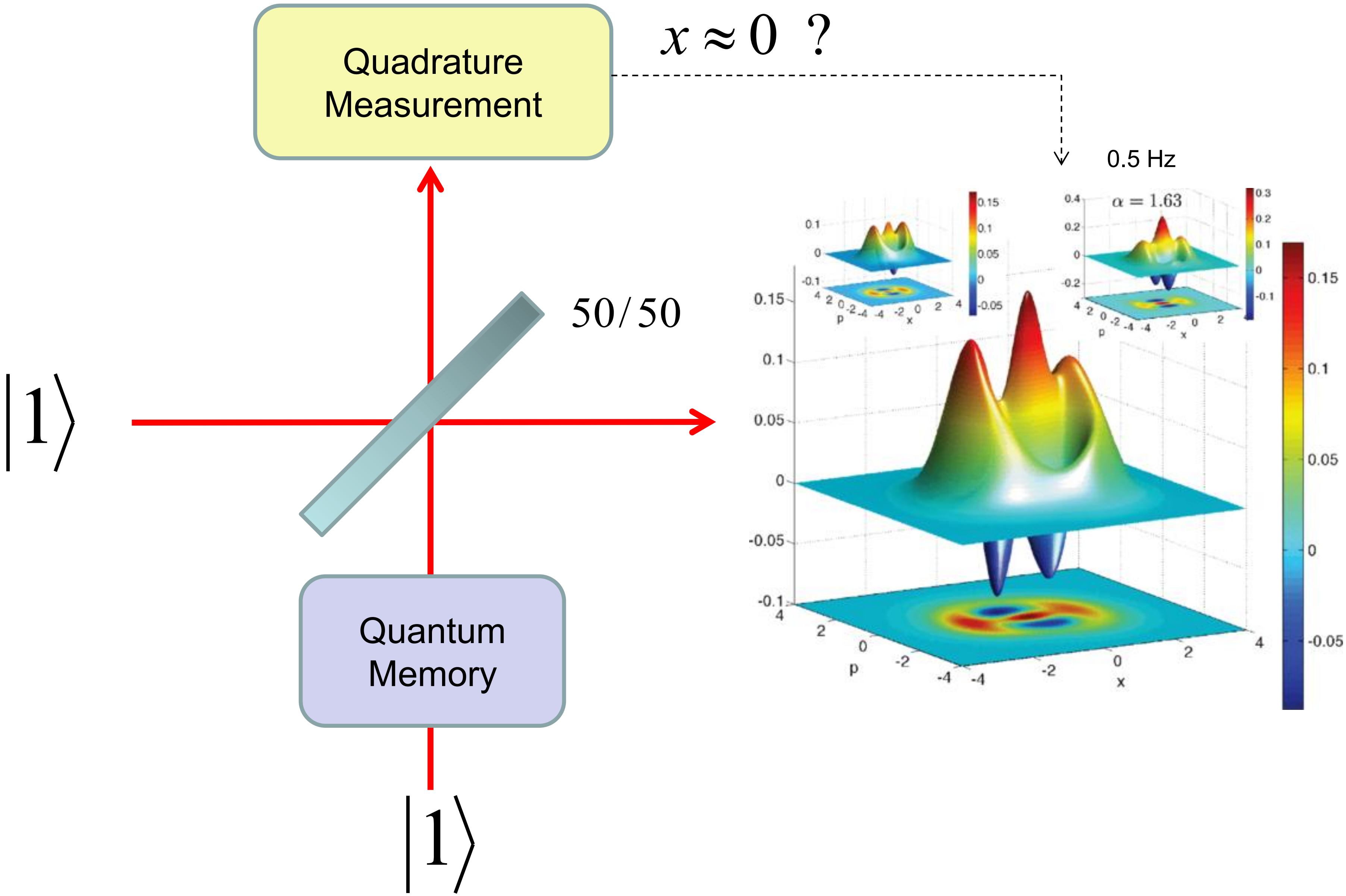
Iterative generation of complex mesoscopic states: the breeding operation



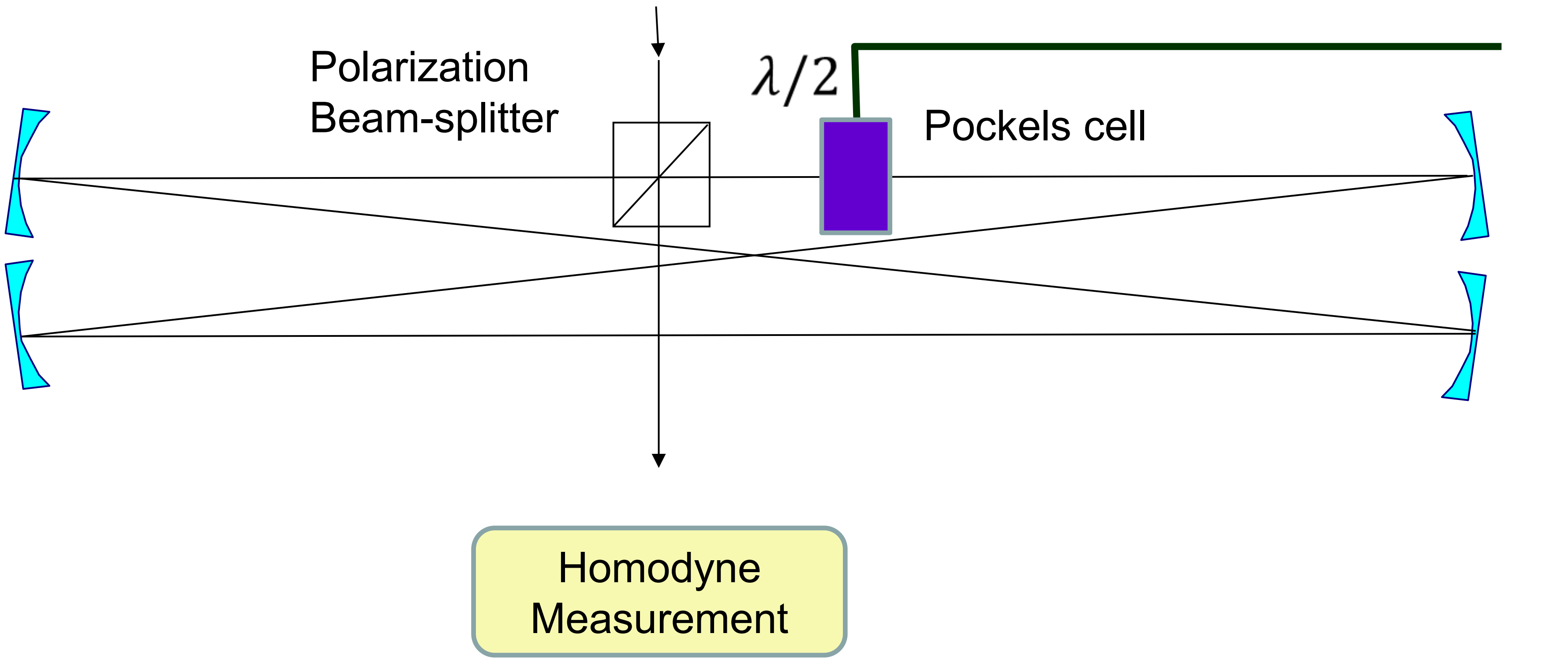


J. Etesse, M. Bouillard, B. Kanseri, and R. Tualle-Brouri *Experimental Generation of Squeezed Cat States with an Operation Allowing Iterative Growth,* Phys. Rev. Lett. **114**, 193602 (2015)

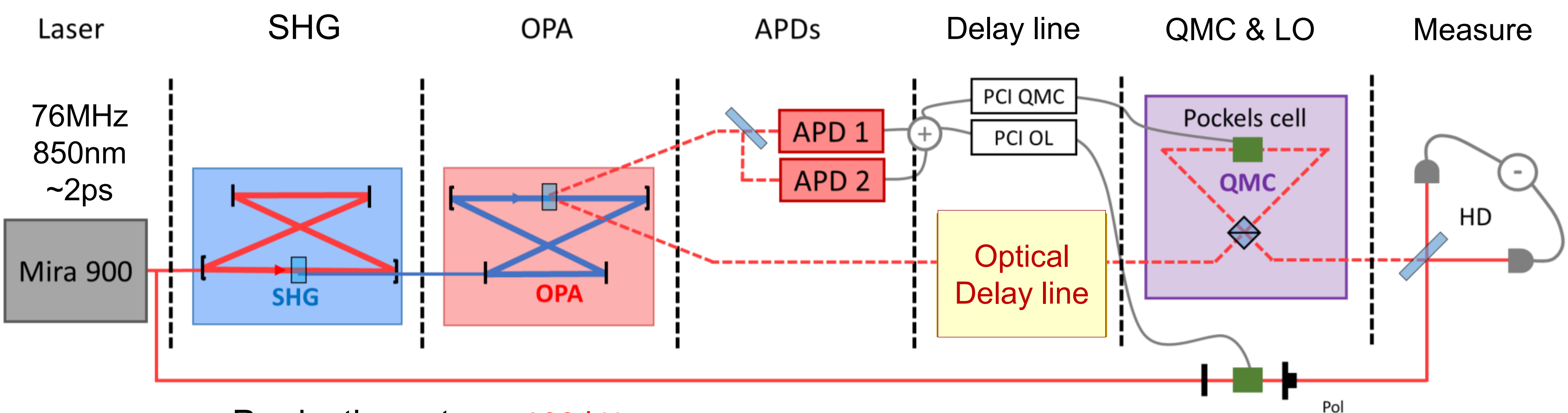
Iterative generation of complex mesoscopic states: the breeding operation



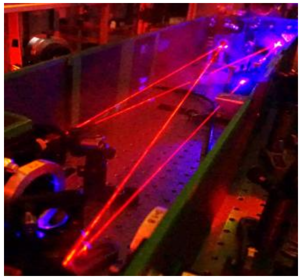
At the heart of iterative schemes: Quantum Memories

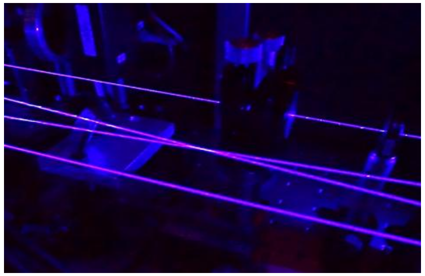


Generation of a cat state with a quantum memory cavity (QMC): experimental scheme

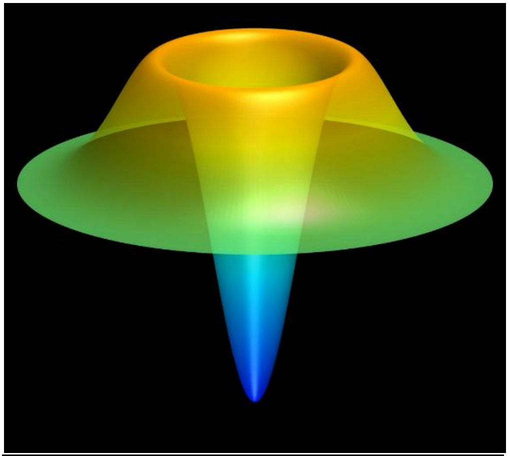


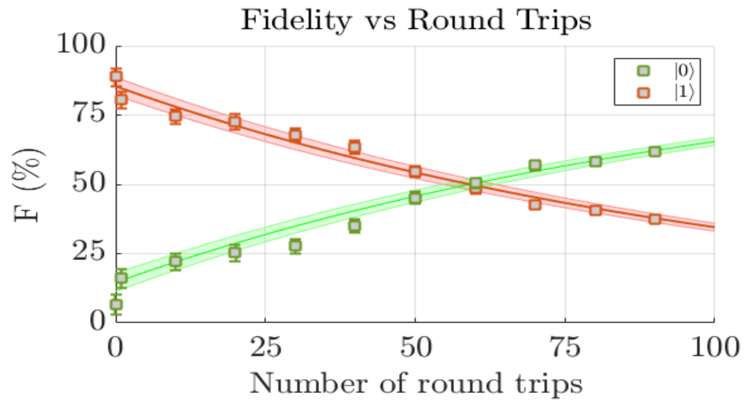
Production rate > 100 kHz

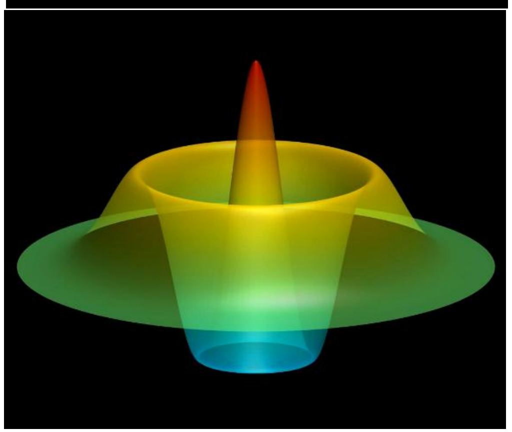


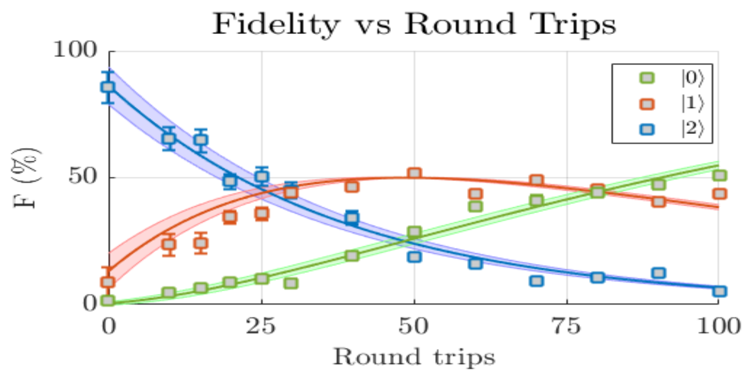


Storage of single-photons and two-photons Fock states









Lifetime

$|1\rangle \longrightarrow$ **110 turns** (1450ns)

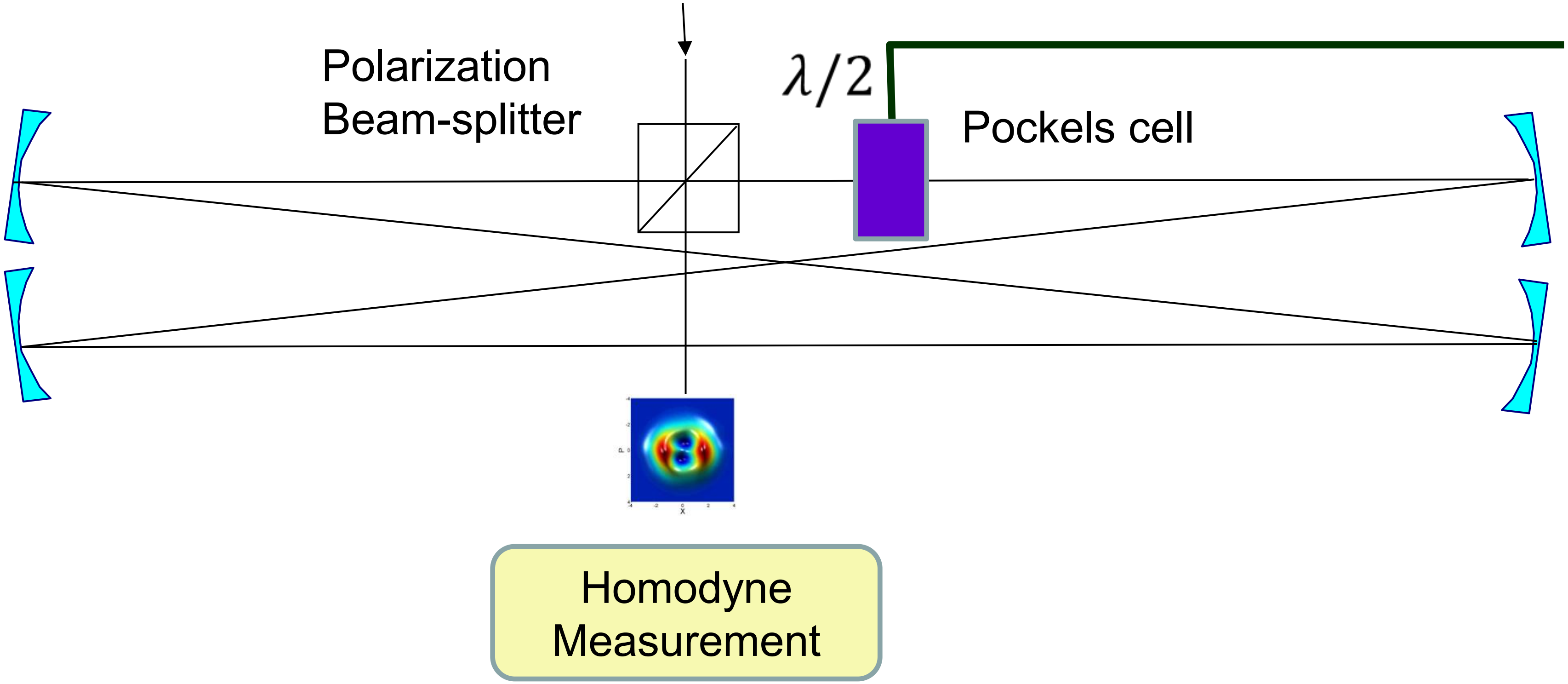
~1% loss per turn

$|2\rangle \longrightarrow$ **39 turns** (510ns)

Fock states are phase independent (Rotational symmetry of the Wigner functions) but things are more complex with cat states…

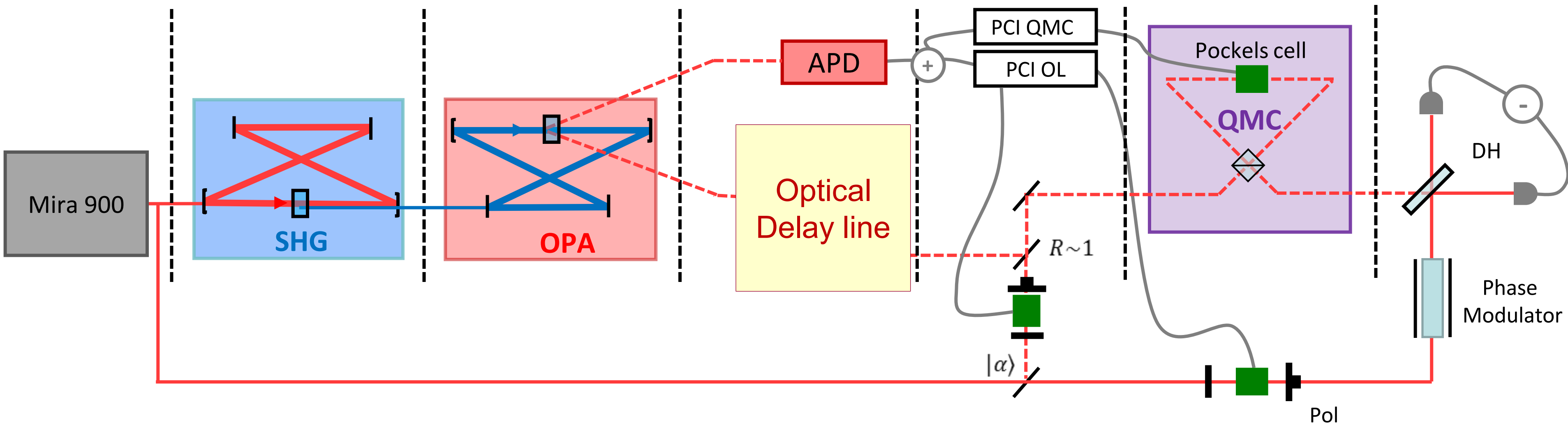
M. Bouillard, G. Boucher, J. Ferrer Ortas, B. Pointard, and R. Tualle-Brouri
Quantum Storage of Single-Photon and Two-Photon Fock States with an All-Optical Quantum Memory,
Phys. Rev. Lett. **122**, 210501 (2019)

At the heart of iterative schemes: Quantum Memories



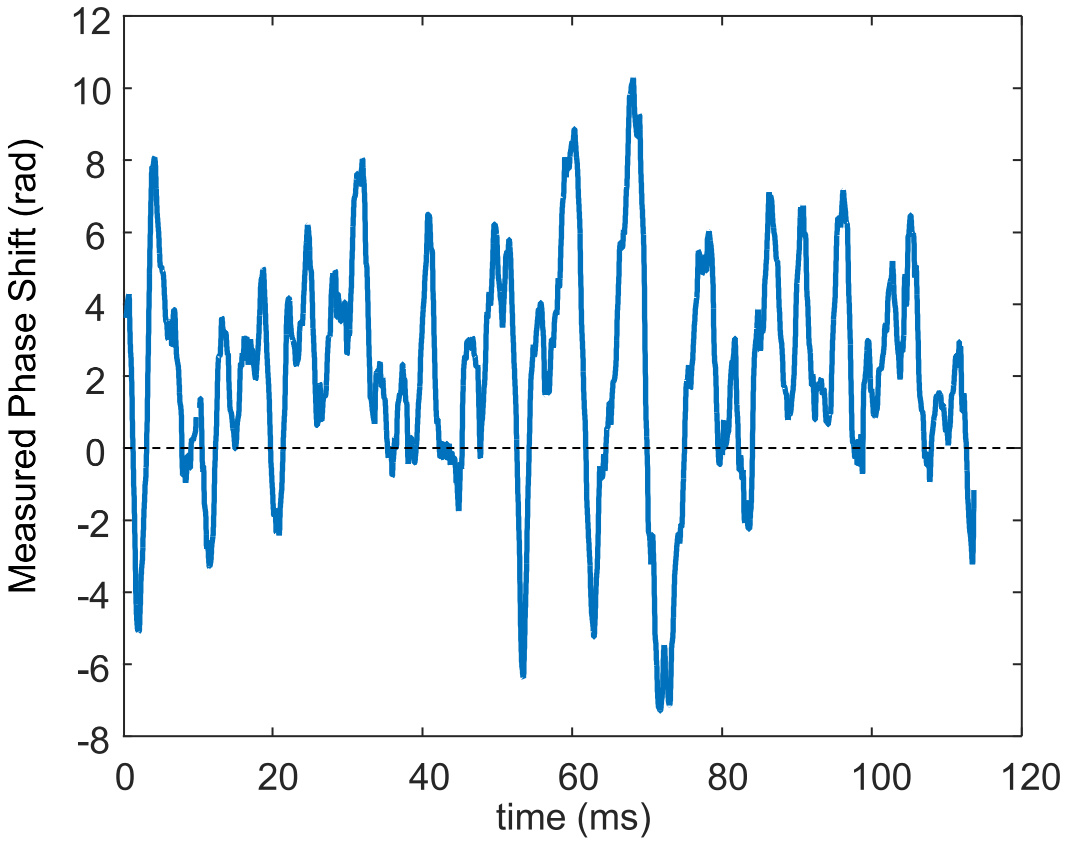
⇨ Need of a knowledge **of the phase shift** induced by the storage of the cat state in the QMC

Measurement of the phase shift induced by the QMC



Measurement of the phase shift induced by the QMC

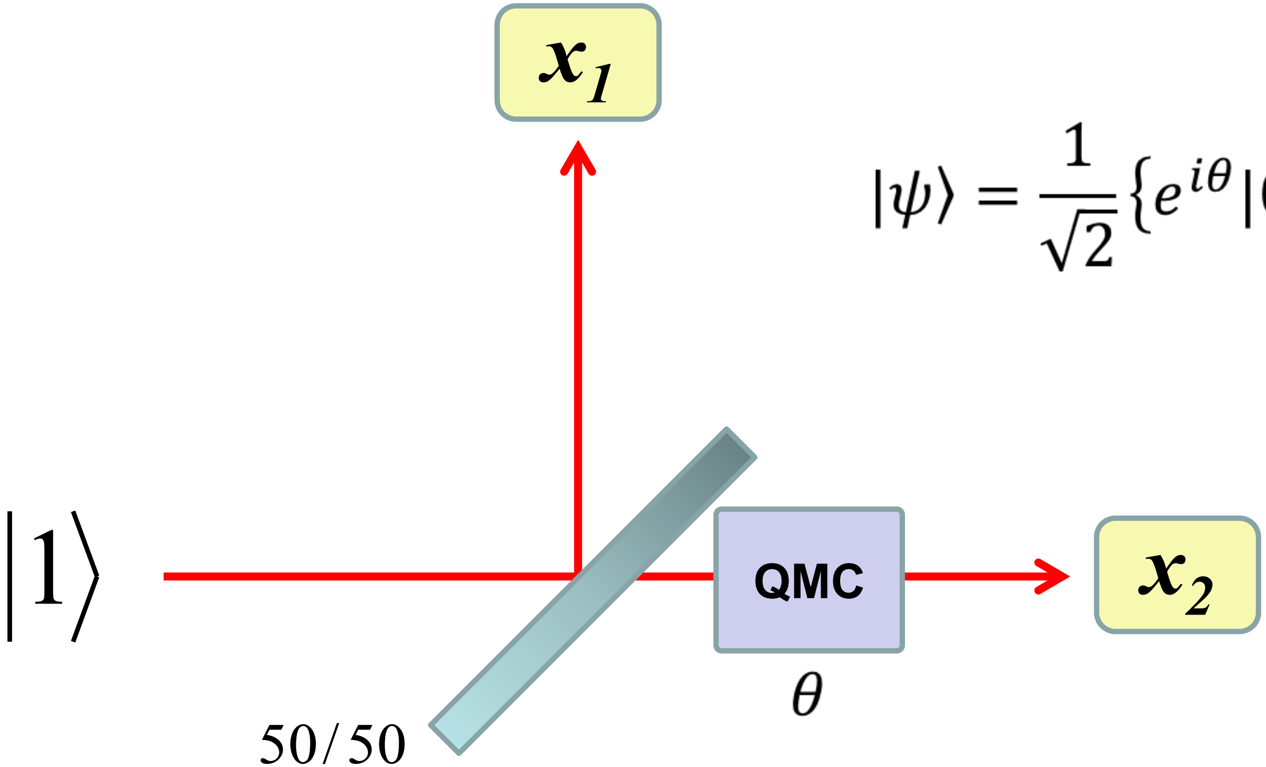
(storage time of 14 round trips / 180ns)



⇨ Assessment of this measurement using **NOON states**

Measurement of the phase shift induced by the QMC

⇨ Assessment of the measurement using **NOON states**



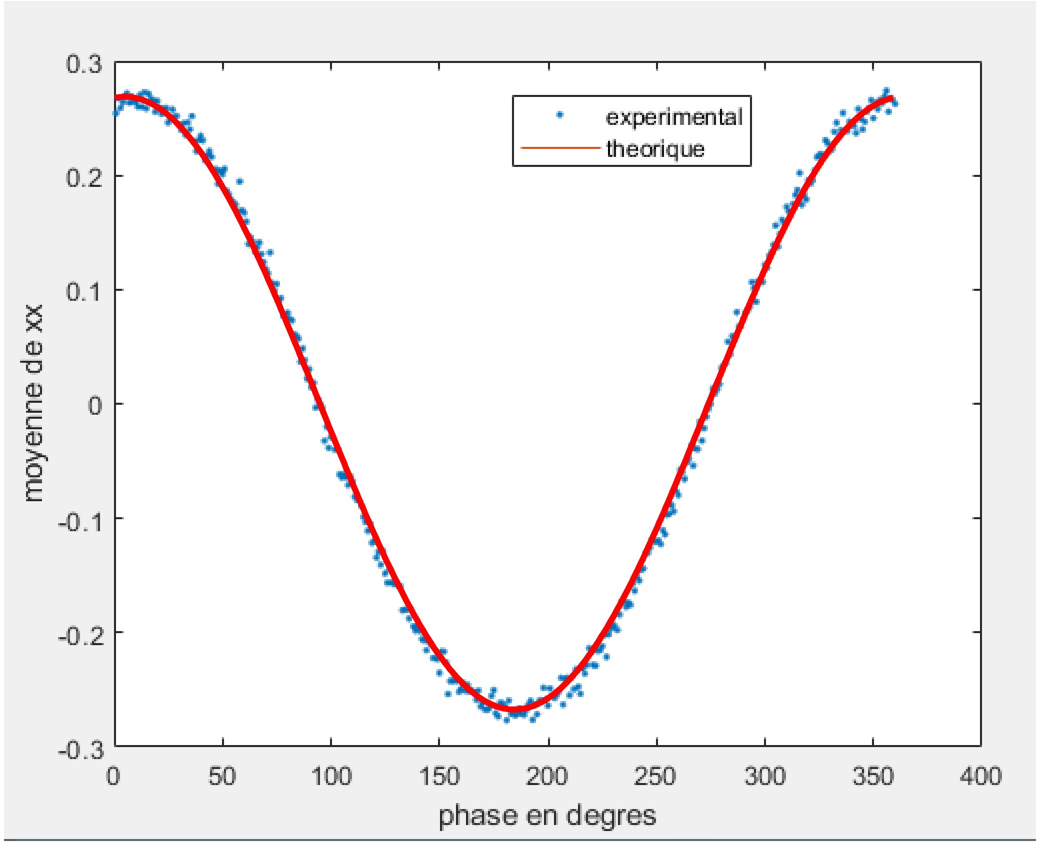
$$|\psi\rangle = \frac{1}{\sqrt{2}}\{e^{i\theta}|01\rangle + |10\rangle\}$$

⇨ $$\langle x_1 x_2 \rangle = A\cos\theta$$

Measurement of the phase shift induced by the QMC

→ Assessment of the measurement using **NOON states**

$\langle x_1 x_2 \rangle$



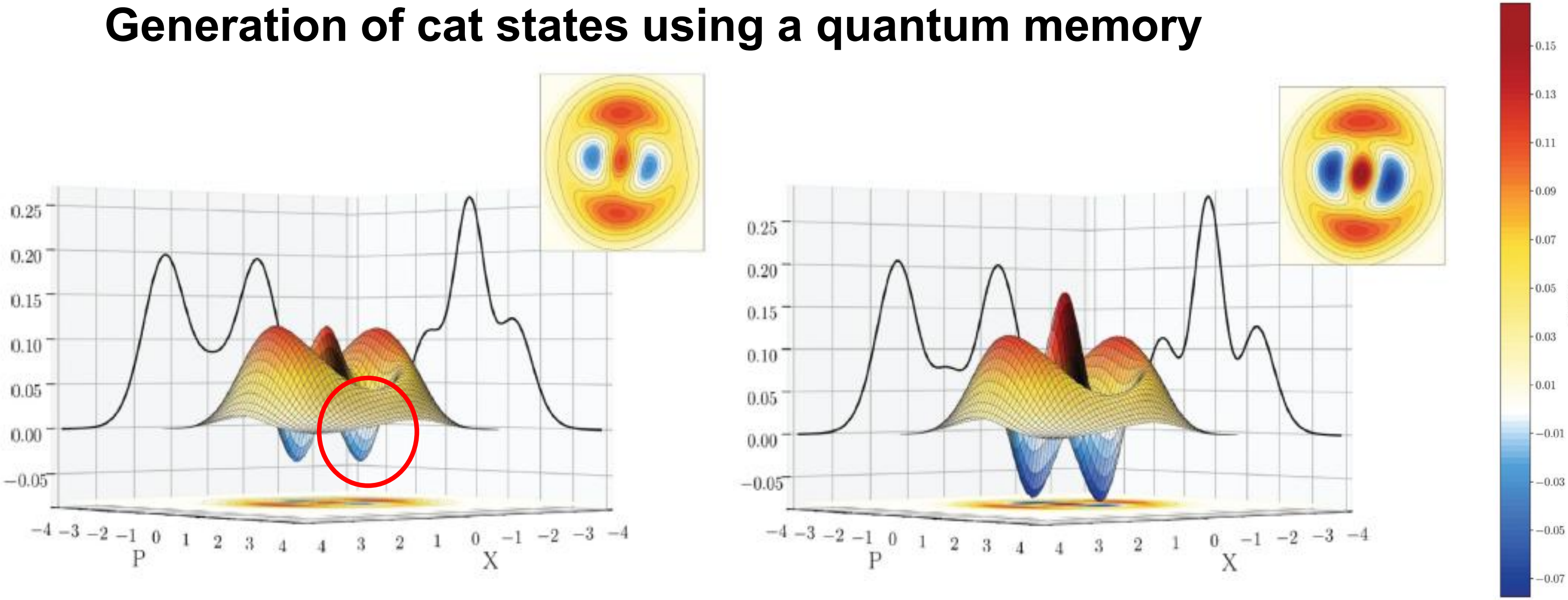
Estimated QMC Phase shift (in degrees)

Generation of cat states using a quantum memory

- Implementation of a programmable wave plate ($\lambda/2$, $\lambda/4$) ✓
- Measurement of the phase shift induced by the QMC ✓
- Real-time implementation of the protocol ✓

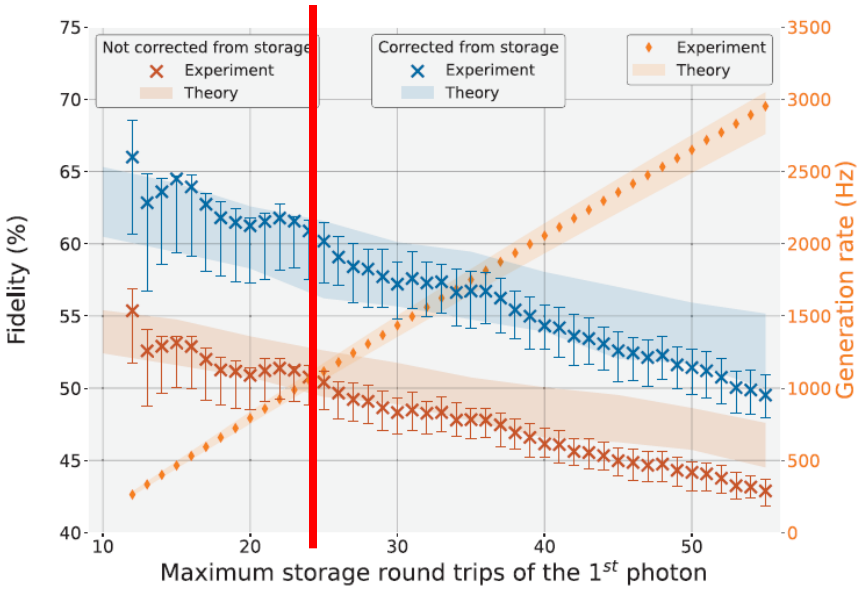
Experimental implementation of a breeding operation: Generation of cat states

Generation of cat states using a quantum memory



First results:

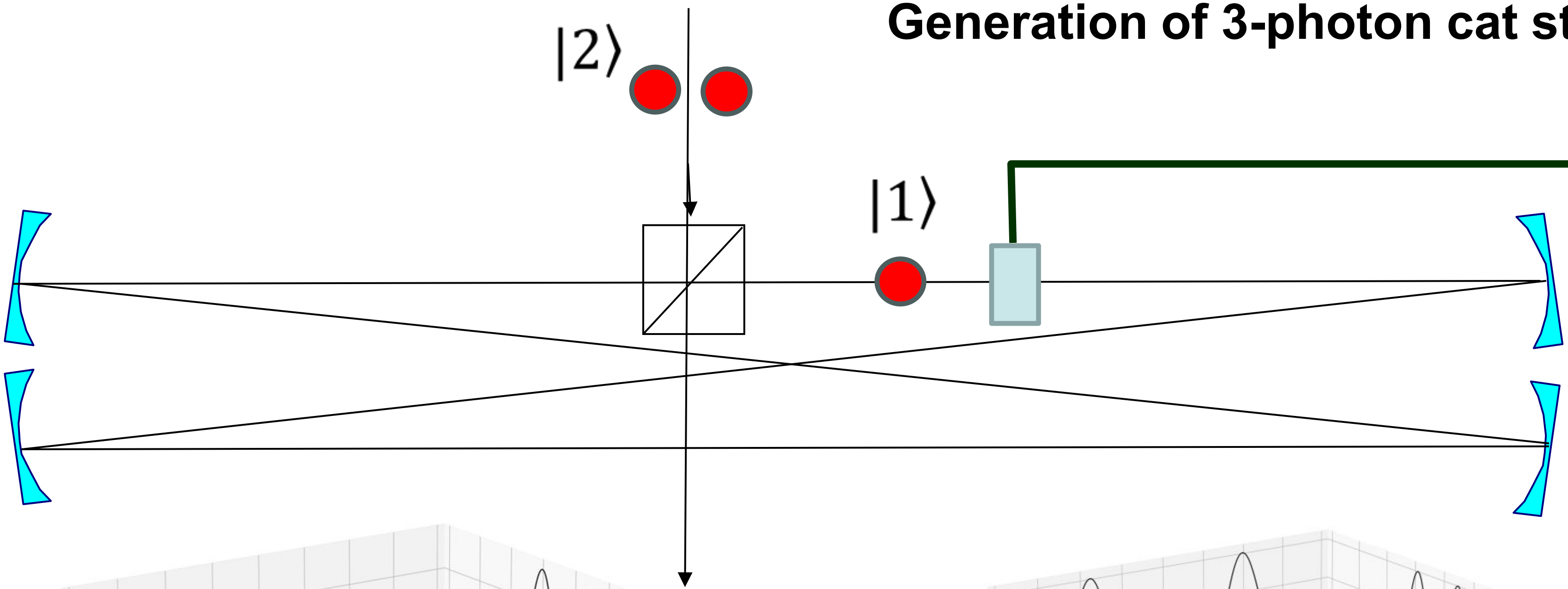
- → Generation rate ~1kHz (x15)
- → Fidelity ~50% with ideal state
- → Fidelity ~60% after storage correction
- → Storage of a cat state (200ns)
- → Wigner function with < 0 values

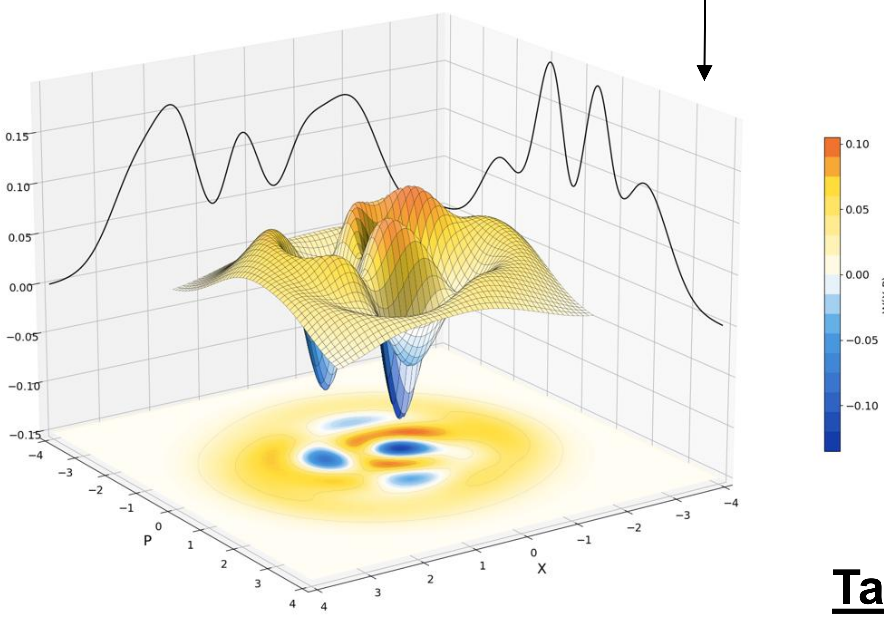


H. Simon, L. Caron, R. Journet, V. Cotte, and R. Tualle-Brouri,
Experimental Demonstration of a Versatile and Scalable Scheme for Iterative Generation of Non-Gaussian States of Light,
Phys. Rev. Lett. **133**, 173603 (2024)

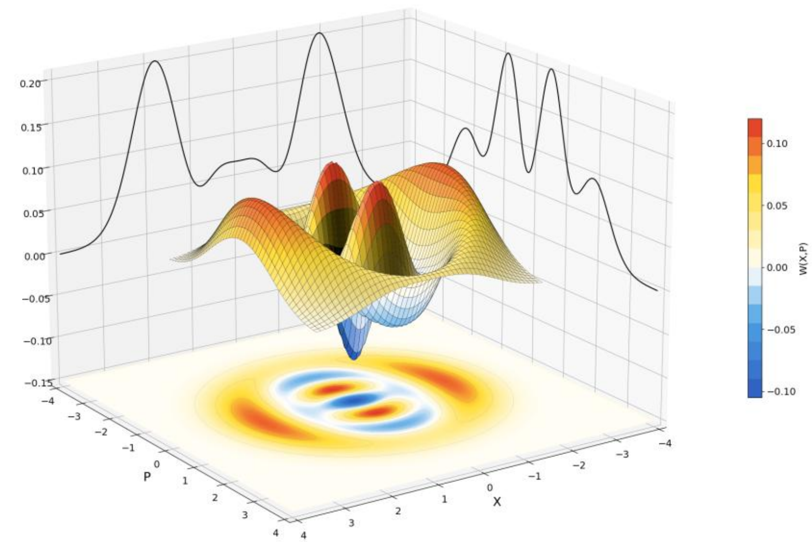
Experimental implementation of a breeding operation: Generation of cat states

Generation of 3-photon cat states





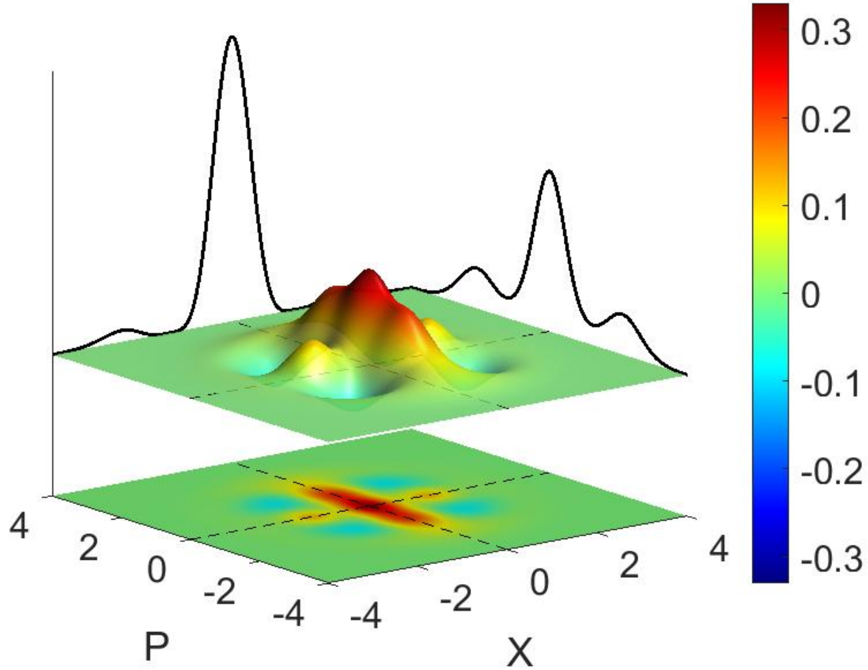
First Results



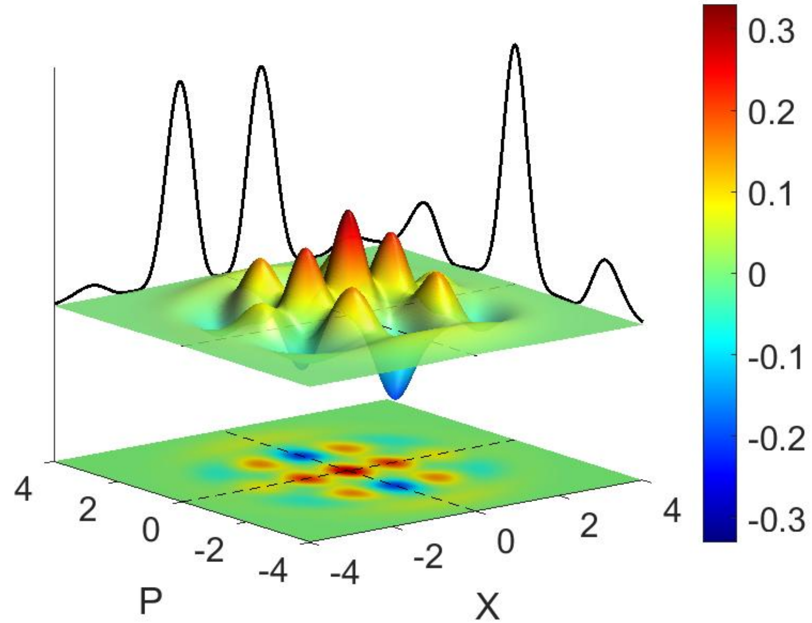
Targeted experimental state

55.3% fidelity with an odd cat state with:
$\alpha = 2.46$, $4.79\ dB$ squeezing

Generation of GKP states ?



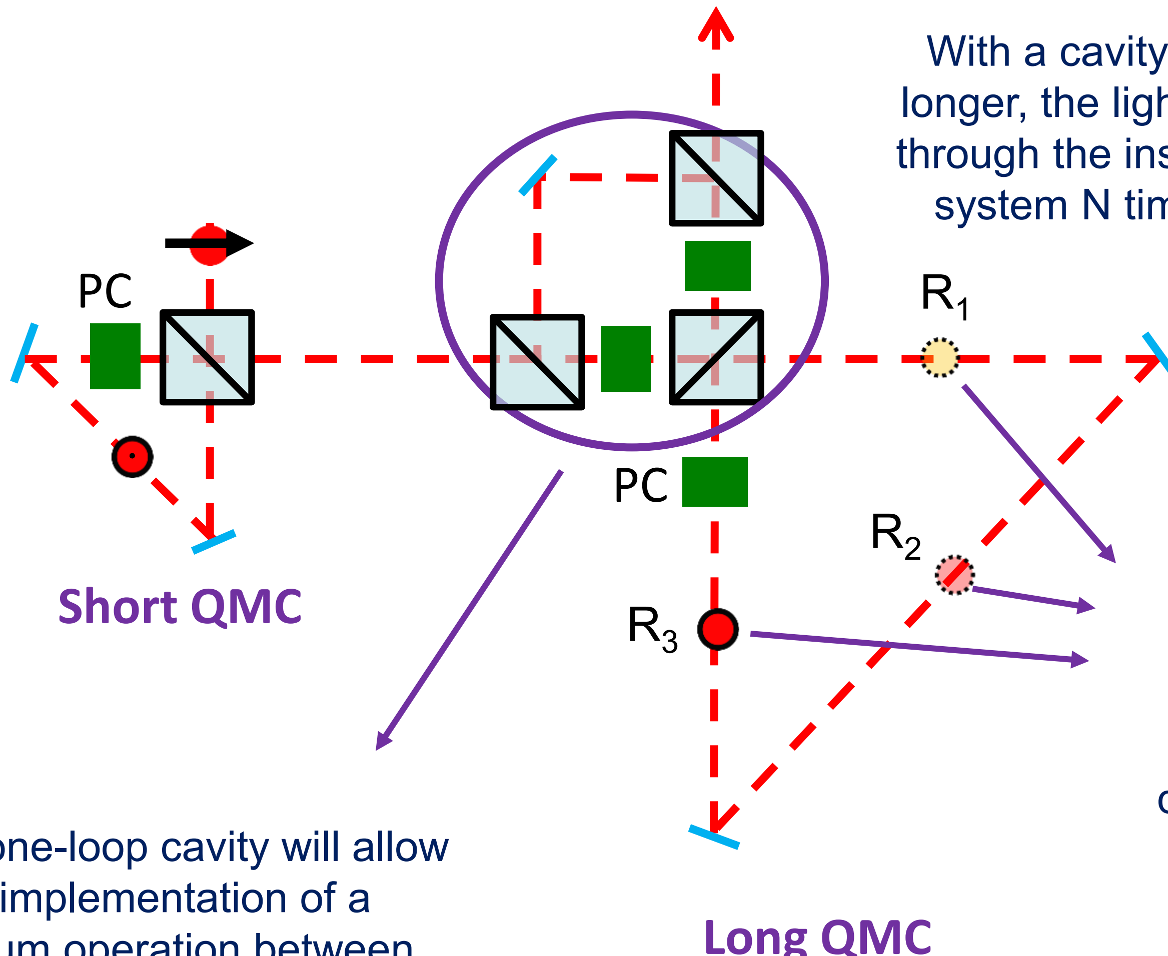
From two 2-photons cat states



From two 3-photons cat states

Limitations due to cavity losses (~1% / rt)

A quantum processor with a multi-register quantum memory

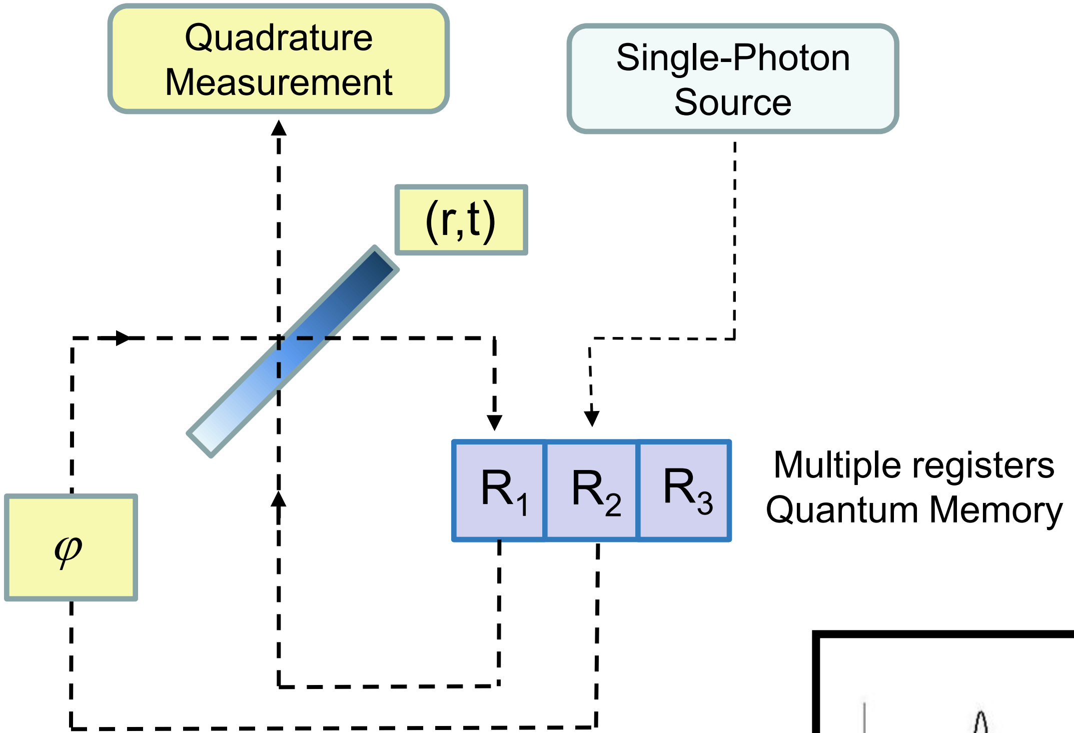


With a cavity that is N times longer, the light pulse will pass through the insertion/extraction system N times less often !

A cavity N times longer will correspond to a N-register quantum memory

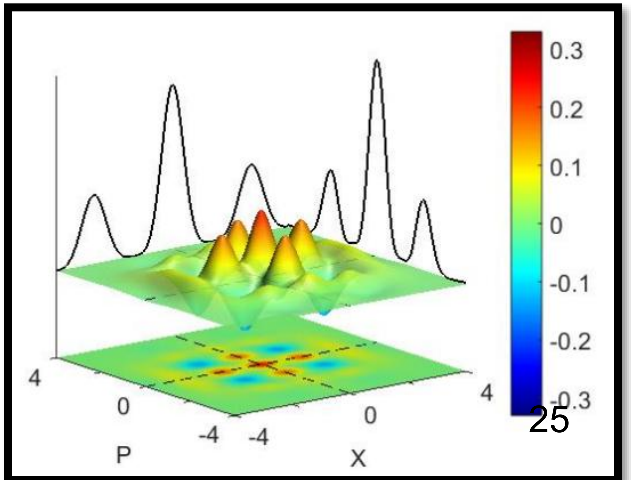
A third one-loop cavity will allow the implementation of a quantum operation between two successive registers

A quantum processor with a multi-register quantum memory



➡ Possibility to implement complex protocols

Theoretical GKP state obtained from
3-photons cat states (mid-term target)



Iterative generation of quantum states: Conclusion

- Iterative protocols could allow efficient generation of complex states

- They can be implemented using all-optical schemes

  → Multiple optical cavities / Multi-registers quantum memories
  → All-optical quantum processor

- Mainly technical bottlenecks

  → Cavity losses
  → Phase lock
  → Quality of the single-photon sources
  → Real-time management of data and light pulses

⇒ Promising tools for all-optical quantum computing

Thanks …

Jean Etesse
Bhaskar Kanseri
Martin Bouillard
Guillaume Boucher
Benjamin Pointard
Viviane Cotte
Hector Simon
Lucas Caron
Hugo Basset
Romaric Journet

SPOQC
IGNITION

PROGRAMME DE RECHERCHE
OQULUS
NISQ2LSQ