Non-Gaussian atomic states for repeaters, etc

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NBI

COMPAS meeting
November 30, 2009

An incomplete list of cv protocols which require memory

•continuous variable entanglement distillation:
D.E. Browne, J. Eisert, S. Scheel, and M.B. Plenio, PRA 67, 062320, (2003).

•continuous variable cluster state quantum computation
PRA 79, 062318 (2009);
N. C. Menicucci, P. van Loock, M. Gu, C. Weedbrook, T. C. Ralph,
and M. A. Nielsen, PRL 97, 110501 2006

•communication/cryptography protocols involving several rounds:
PRL 94, 050503 (2005)

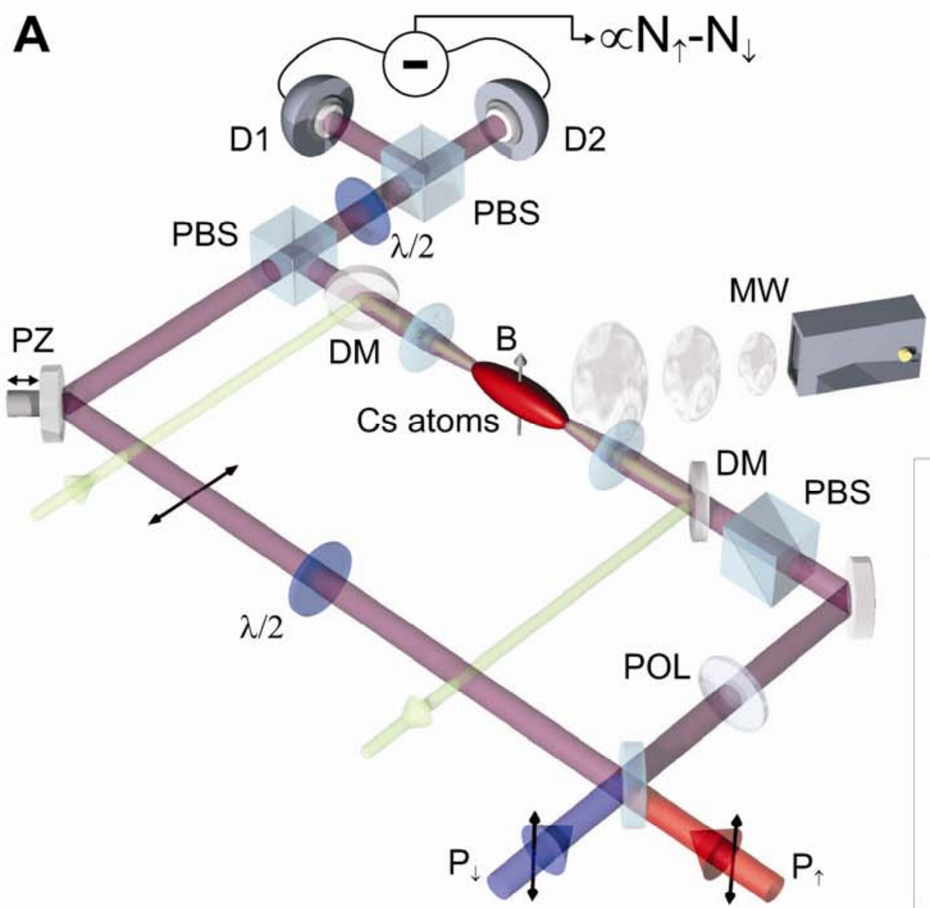
•quantum illumination:
S. Lloyd, Science 321, 1463 (2008)
S.H. Tan, B. I. Erkmen, V. Giovannetti, S. Guha, S. Lloyd, L. Maccone,
S. Pirandola, and J. H. Shapiro. PRL, 101, 253601 (2008)

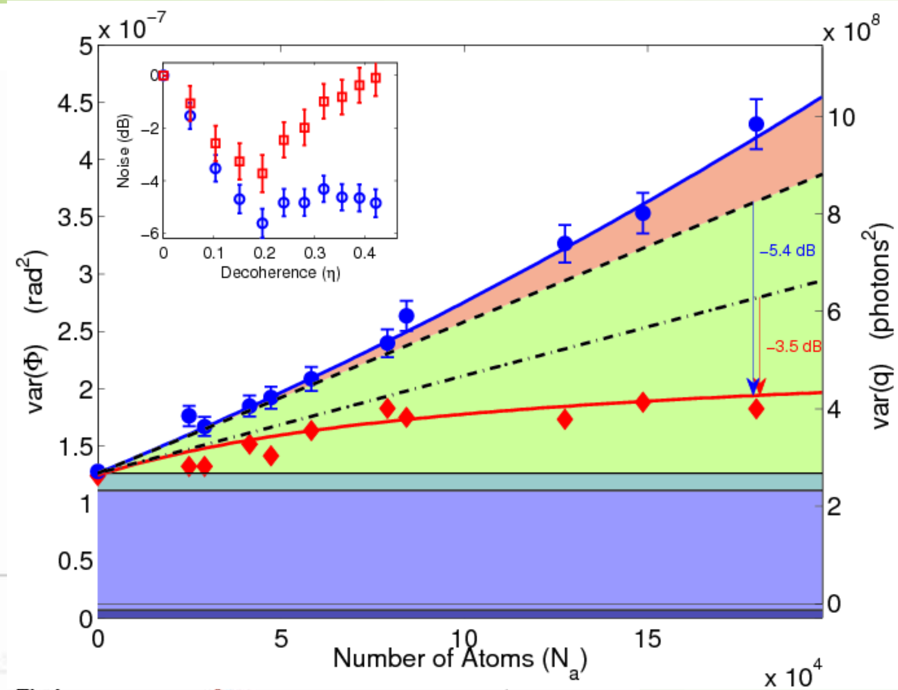
Ensemble-based memories

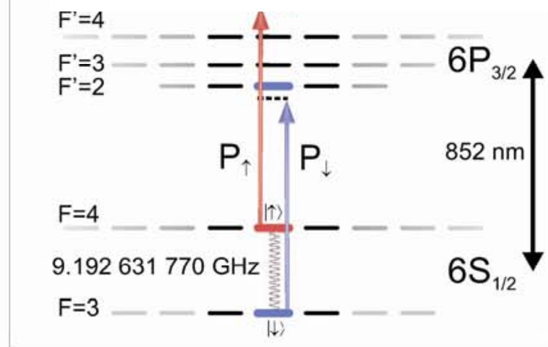
Room temperature gases
☺ high fidelity and efficiency, millisec storage time
BUT
difficult to combine this with non-Gaussian operations
like single photon detection

Cold trapped gases
Non-Gaussian protocols demonstrated
BUT
only low efficiency protocols so-far

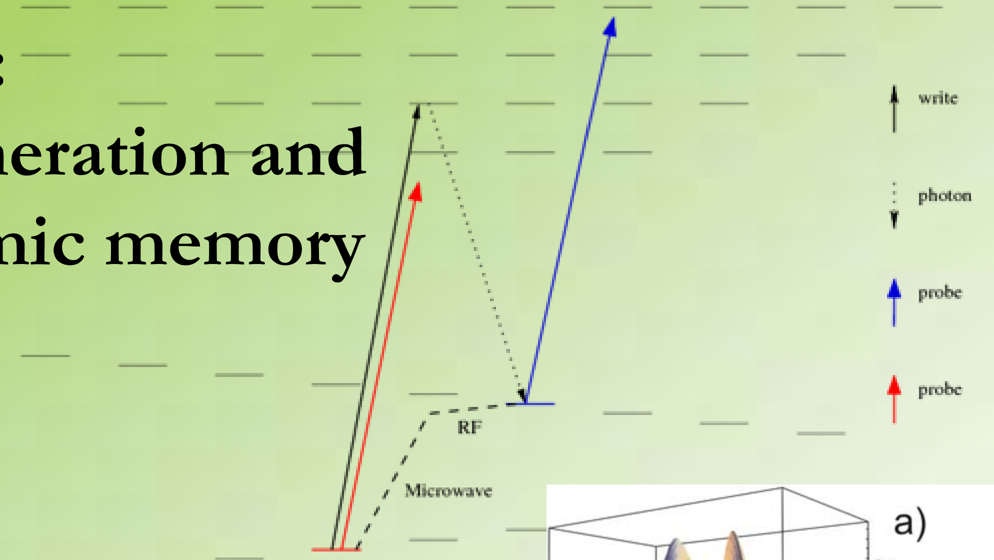
Starting point:
generation and homodyne tomography of Gaussian entangled state of memory
J. Appel et al, **PNAS** 2009, 106: 10960-10965

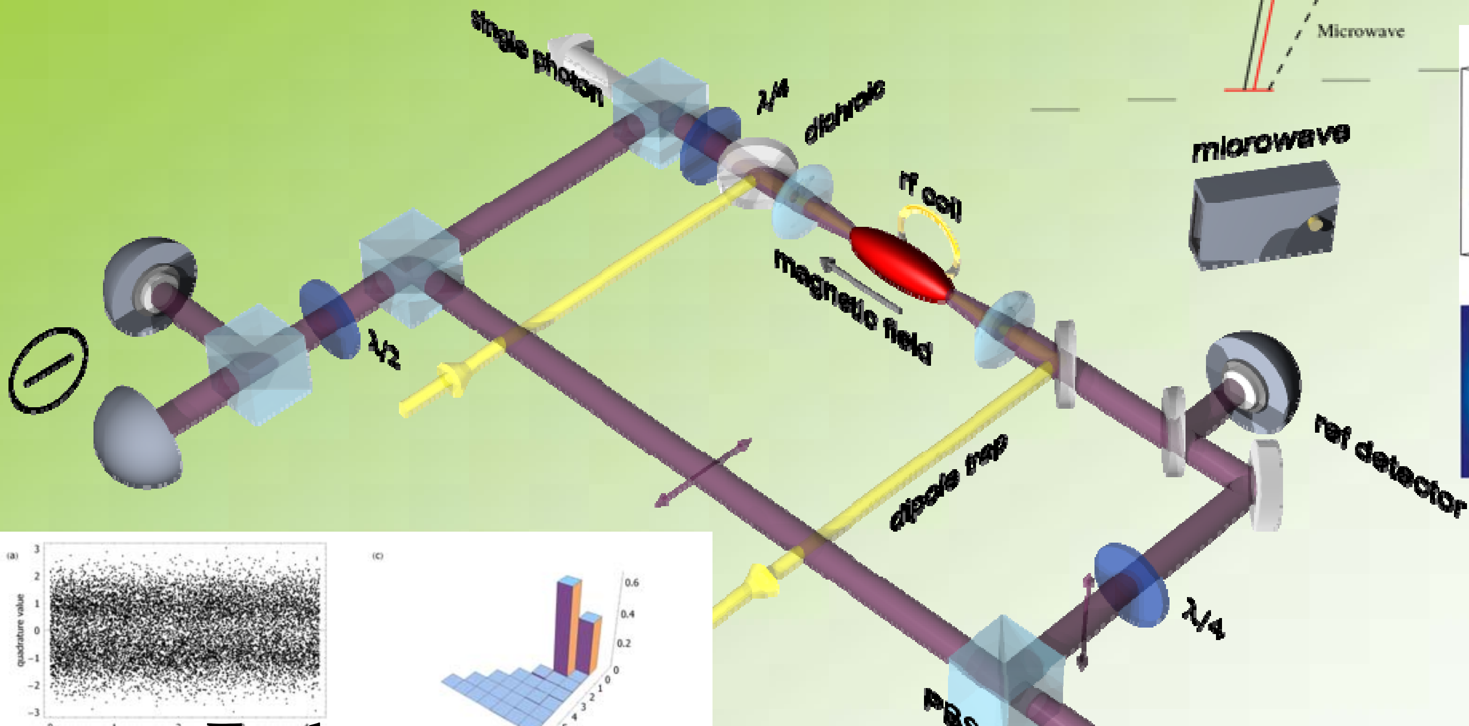


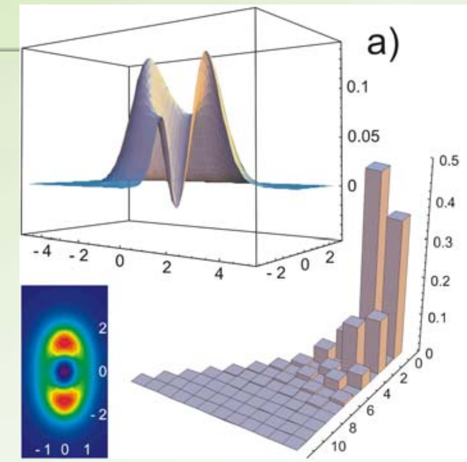




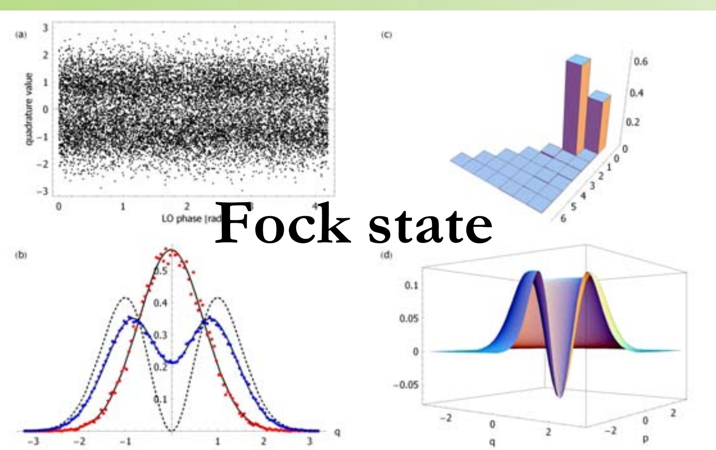
Near term goals:
Fock and/or kitten state generation and homodyne detection in atomic memory







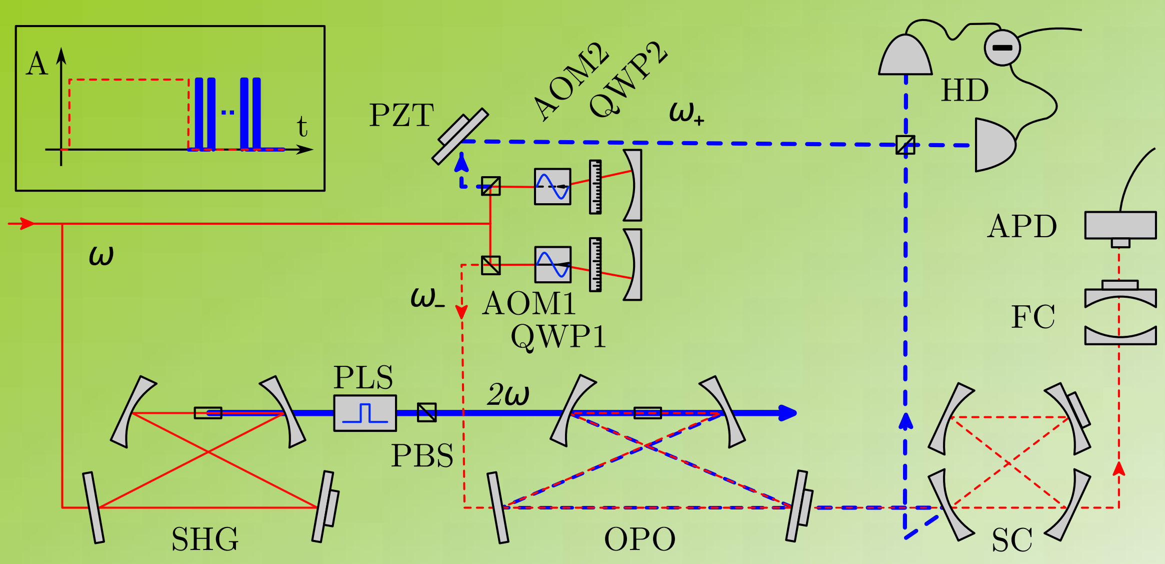
Squeezed Fock state = KITTEN

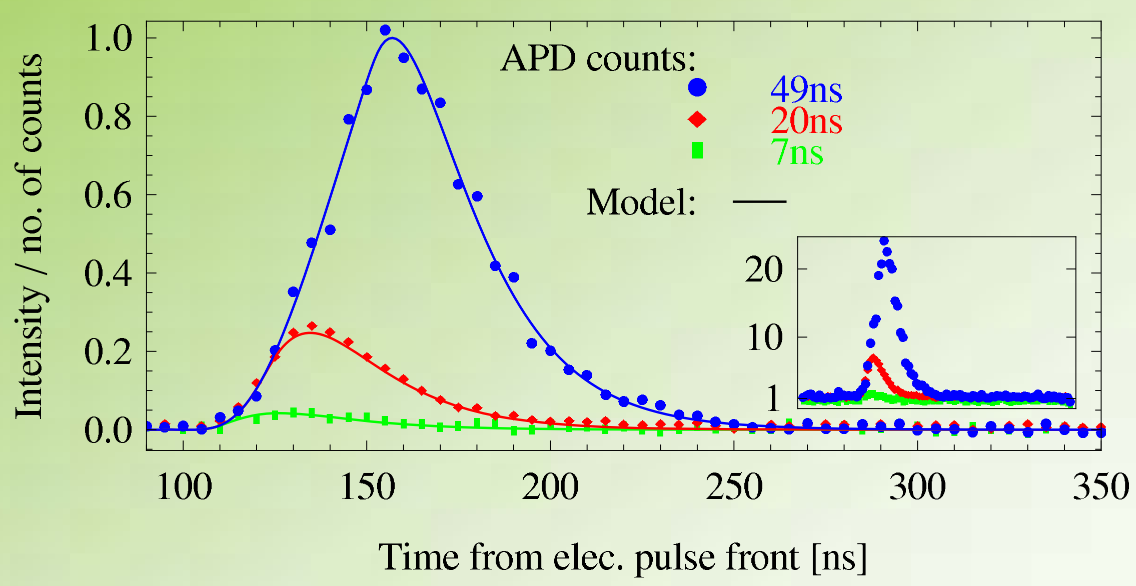


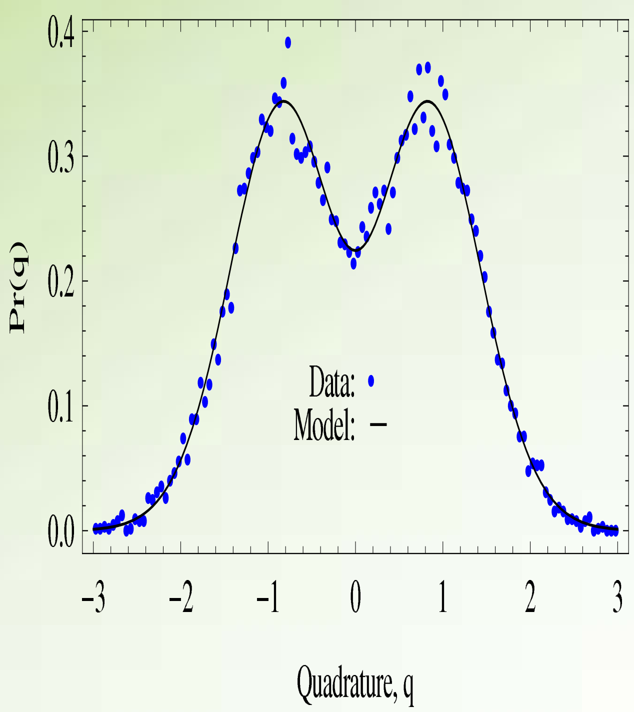
Fock state

Time gated single photon compatible with Cs memory

W. Wasilewski et al
Optics Lett. 17, 14444-14457 (2009)







Generation and Distribution of Schrödinger Cat States

Jonatan B. Brask[1], Ioannes Rigas[2], Ulrik L. Andersen[3], Anders S. Sørensen[1], Eugene S. Polzik[1]

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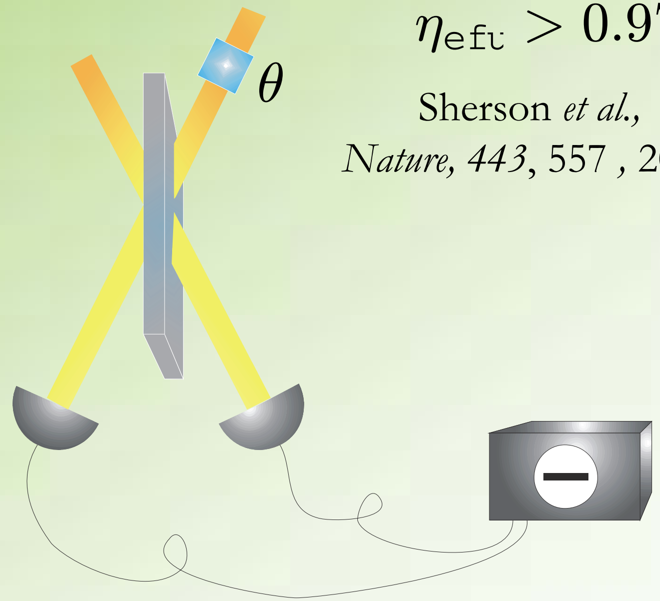
Homodyne detection and continuous variables

• Measuring quadratures of light rather than photon no. can yield high efficiencies.

$$X = \frac{1}{\sqrt{2}}(\hat{a}^\dagger + \hat{a}) \qquad P = \frac{i}{\sqrt{2}}(\hat{a}^\dagger - \hat{a})$$



$\eta_{eff} > 0.97$

Sherson *et al.*, *Nature*, *443*, 557 , 2006

• Use continuous variable entanglement, e.g. superpositions of coherent states.

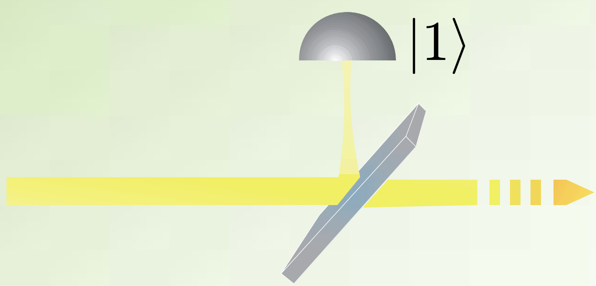
$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle, \quad \langle \frac{X}{\sqrt{2}} \rangle = \mathrm{Re}\ \alpha, \langle \frac{P}{\sqrt{2}} \rangle = \mathrm{Im}\ \alpha$$

$$|\xi\rangle = |-\alpha\rangle + |\alpha\rangle$$

$$|\gamma\rangle = |-\alpha, -\alpha\rangle + |\alpha, \alpha\rangle$$

• Caveat: propagating cats are difficult to make. In most experiments so far, only 'kittens' can be produced, using photon subtraction from squeezed states.

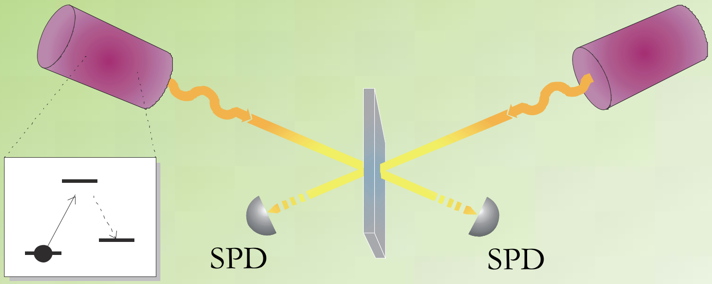
$|\psi_{\mathtt{trvff\{fe}}}\rangle$



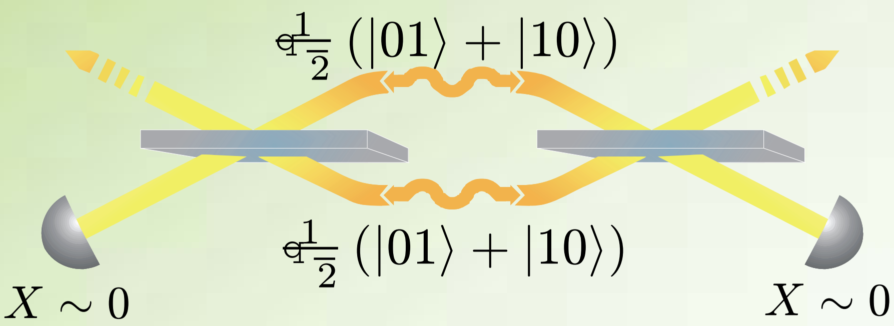
$|\alpha|^2 \ / \ 1$

A feline repeater based on single photon detection and homodyning

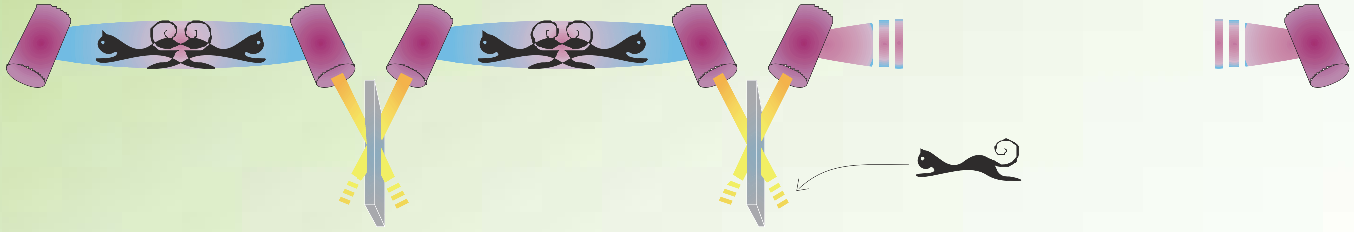
• Single-excitation entanglement can be generated in atomic ensembles, conditioning on SPD clicks.



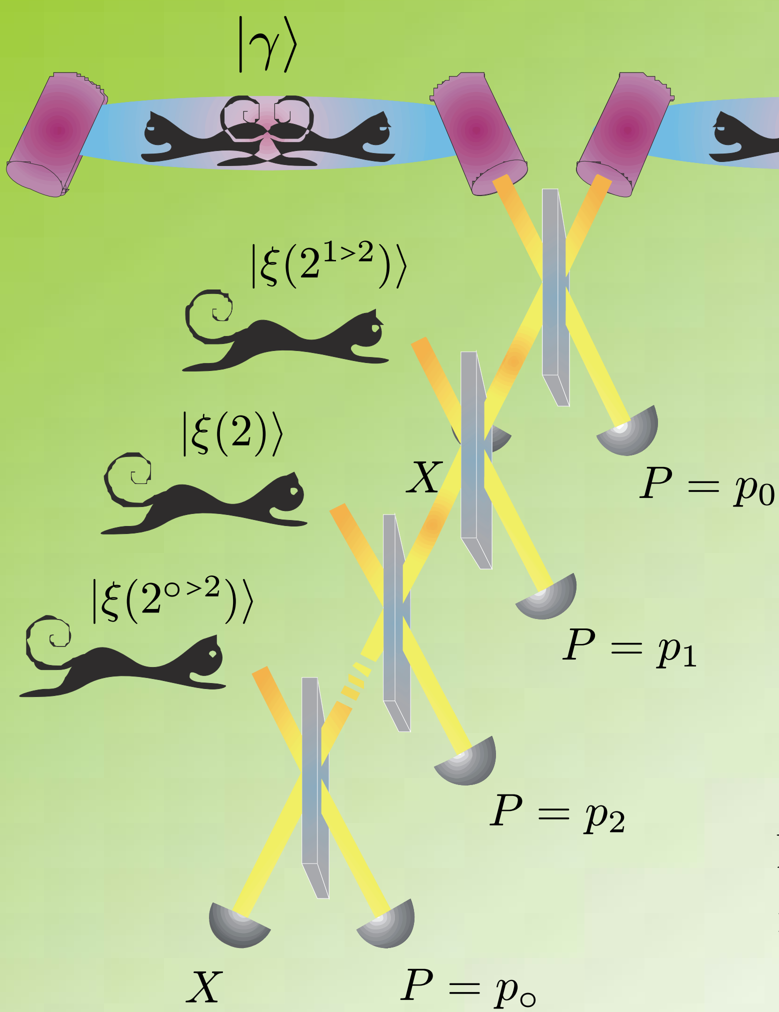
• The cat-growing protocol works in any number of dimensions.



• In principle, all ingredients necessary for a quantum repeater are there (assuming that storage and retrieval are possible).



Entanglement swapping with cats

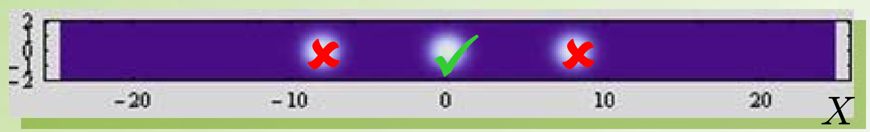


$$|\xi(k)\rangle = |-k\alpha\rangle + |k\alpha\rangle$$

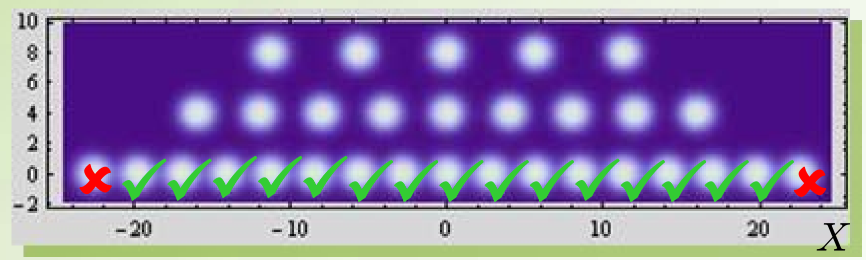
$$|\gamma\rangle = |-\alpha, -\alpha\rangle + |\alpha, \alpha\rangle$$

$$\alpha \in \mathsf{S}$$

$$p_{\mathtt{tvd}} \approx \frac{1}{2}$$



distr. of measurement outcomes



By mixing in single-mode cats, the probability for successful swapping can be increased

$$p_{\mathtt{tvd}}(n) = 1 - 2^{\circ ¢ 1} \qquad \alpha \sim 2^{\circ>2}$$

$$p_{\mathtt{n\ by}} \sim 1 - \frac{1}{2«^{3}_{\mathtt{n\ by}}}$$

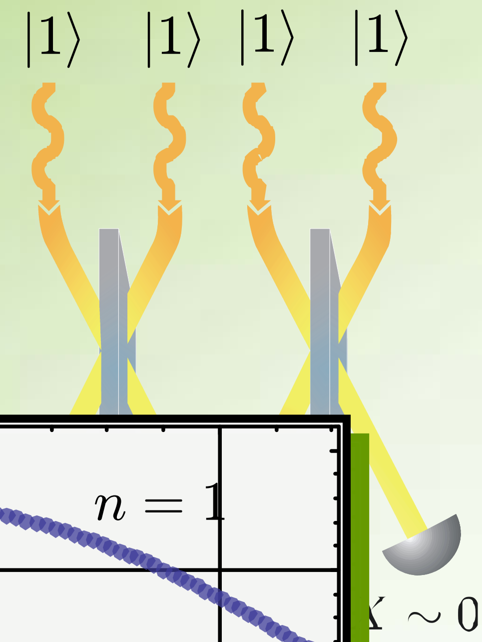
Growing cats from single excitations

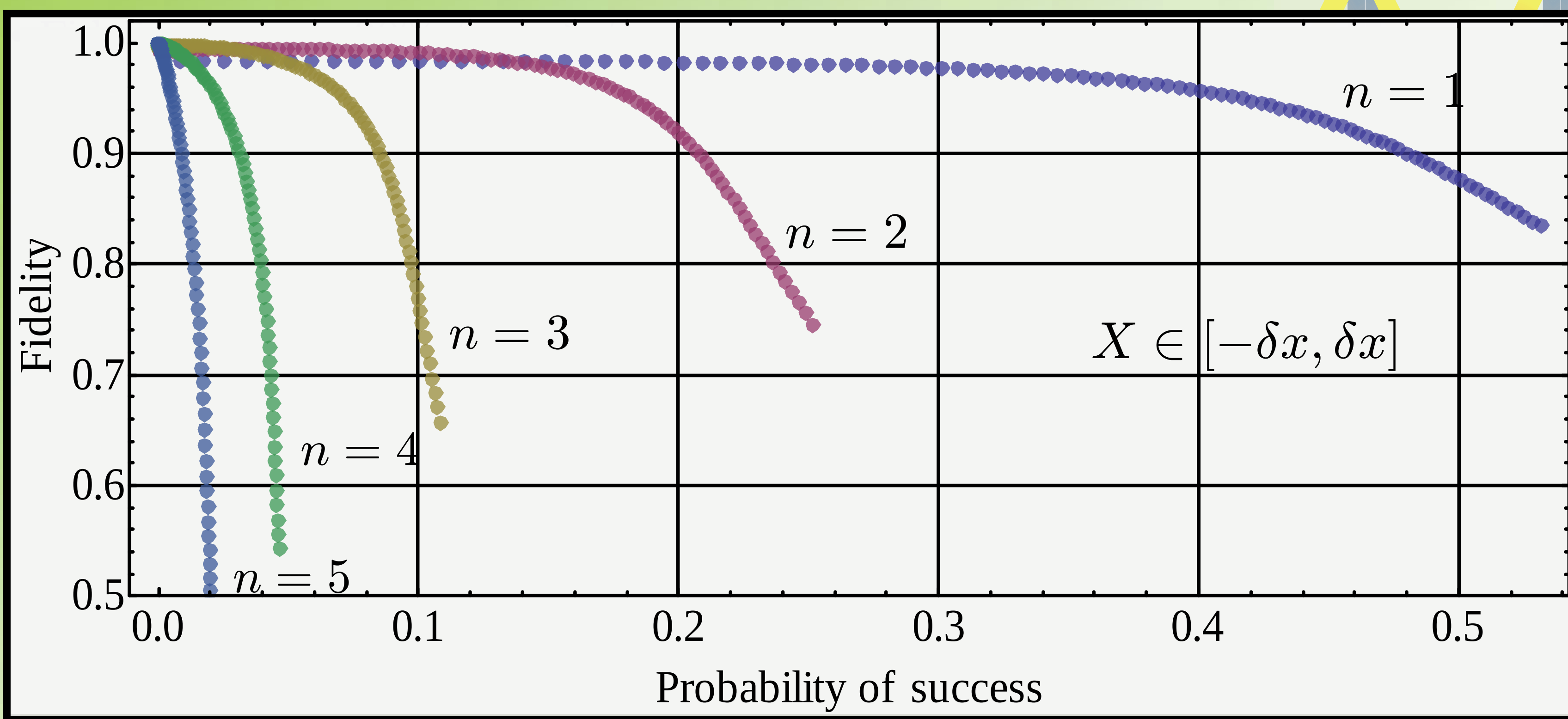
- Approximate squeezed cats can be grown from single photons.

$$\psi_{\circ}(x) = \Gamma(2^{\circ} + \tfrac{1}{2})^{¢\ 1>2} e^{¢\ y^{3}>2} x^{2^{\circ}}$$

$$|\psi_{\circ}\rangle \approx S(r)\left[|e^{s}\alpha\rangle + |-e^{s}\alpha\rangle\right]|vac\rangle$$

$$\alpha = \sqrt{2^{\circ\ ¢\ 1} + 1/4}, \qquad e^{2s} = 2$$





Related experiment: Ourjoumtsev *et al.*, *Nature*, 2007, *448*, 784-786

Preliminary simulation results for the feline repeater

• The feline repeater is a hybrid system, combining discrete variable entanglement generation with continuous variable state preparation and entanglement swapping.

• Shown here: preliminary results for entanglement vs. distance and corresponding swapping success probabilities (i.e. "rate"), when the discrete entanglement generation is perfect.