Quantum feedback experiments stabilizing Fock states of light in a cavity

Collaborations and fundings

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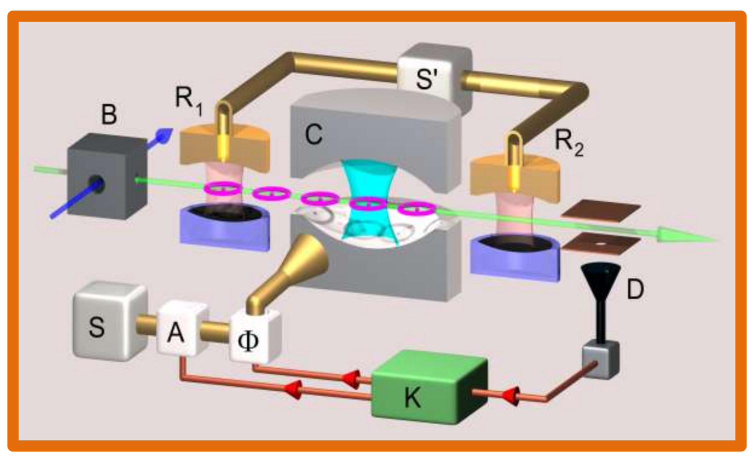
Aim of the experiments

Preparation of photon number (Fock) states of a cavity field and correction of quantum jumps due to decoherence using two quantum feedback schemes

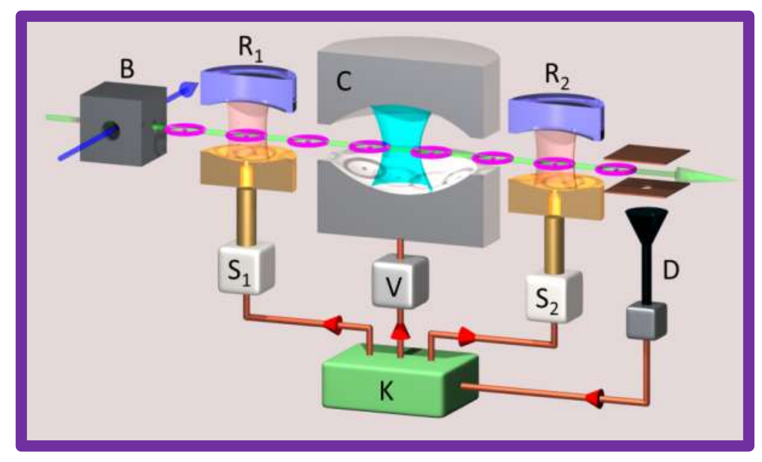
Feedback loop components

System: Microwave cavity field
Target: Fock state $|n_{target}\rangle$
Sensor (quantum): Off-resonant atoms performing a QND measurement of the field.
Controller (classical): State ρ estimation at each atomic detection and choice of the feedback action
(real time ADwin computer system)
Actuator: Injection of a small coherent field **(classical) OR** resonant atoms emitting or absorbing photons **(quantum)**

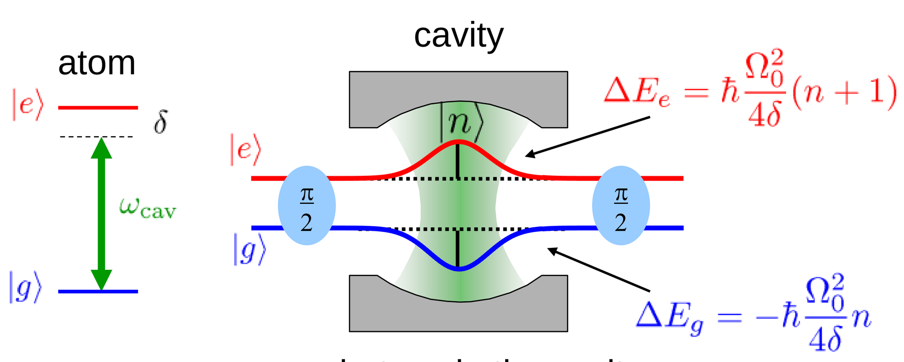


Two different feedback actions

- Controller *K* calculates the optimal classical field to inject in *C* (amplitude A and phase ϕ)
- *K* chooses the actuator atom type: $|e\rangle$ (emitter) or $|g\rangle$ (absorber)



Quantum Non-Demolition (QND) measurement of the photon number

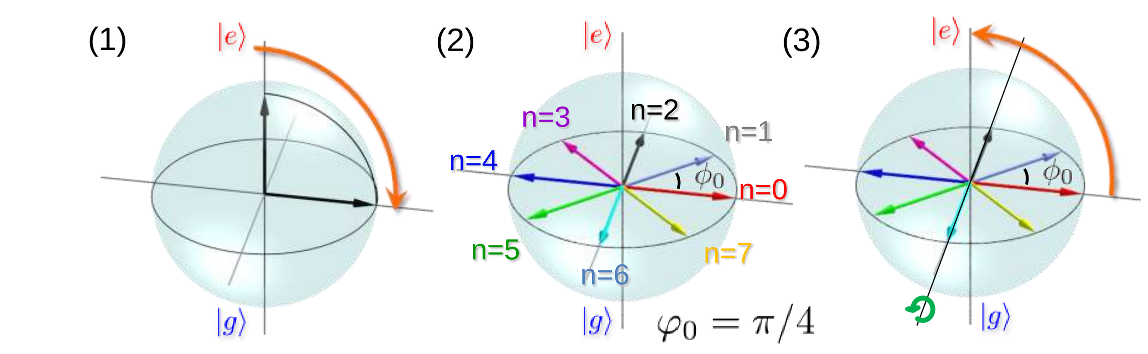


n photons in the cavity
Vacuum Rabi frequency : $\Omega_0 \sim 50\text{kHz}$

- Phase shift of atomic coherence:

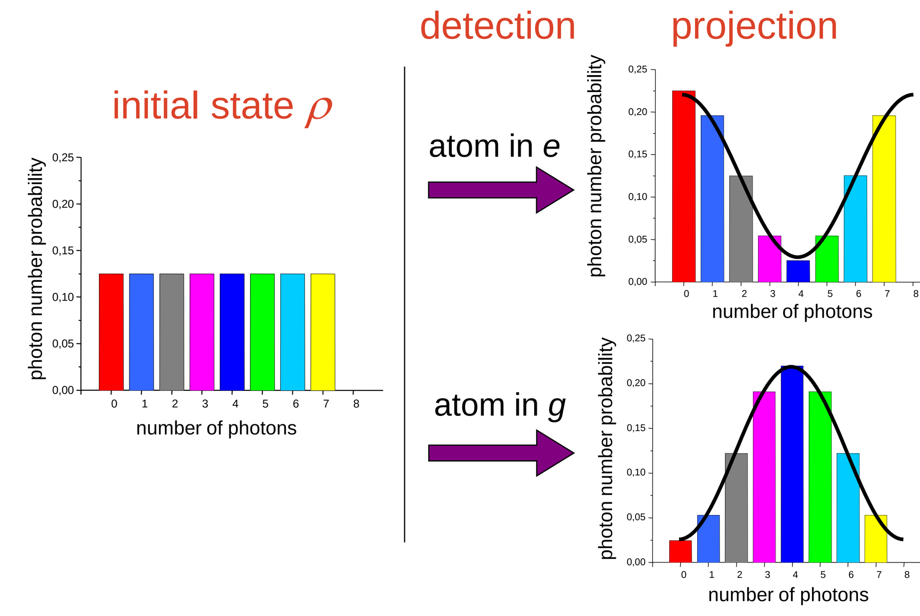
$$\phi(n) = (n+1/2)\phi_0 \qquad \phi_0 = \frac{\Omega_0^2}{2\delta}t_{int}$$

phase shift per photon — interaction time



- Atom prepared in state $|g\rangle$
- *1st Ramsey zone:* a $\pi/2$ pulse (1) brings the atom into $|e\rangle+|g\rangle$
- *Cavity:* phase shift (2) $\phi(n)$
- *2nd Ramsey zone:* $\pi/2$ pulse with a tunable phase φ_R (3) combined with atomic state detection

Ideal state estimation based on an atom detection



$$\rho_{proj} = \frac{M_j^{e+g}\rho M_j^{e+g\dagger}}{\mathrm{Tr}(M_j^{e+g}\rho M_j^{e+g\dagger})}$$

$$M_e^{e+g} = \cos\left(\frac{\varphi_R + \varphi(\hat N)}{2}\right)$$

Kraus operators — tunable phase

$$M_g^{e+g} = \sin\left(\frac{\varphi_R + \varphi(\hat N)}{2}\right)$$

Quantum state estimator

State estimation:

- Each detection projects ρ.
- Trace over unread atoms
- Cavity field relaxation (using a Liouville superoperator obtained from solving master equation)

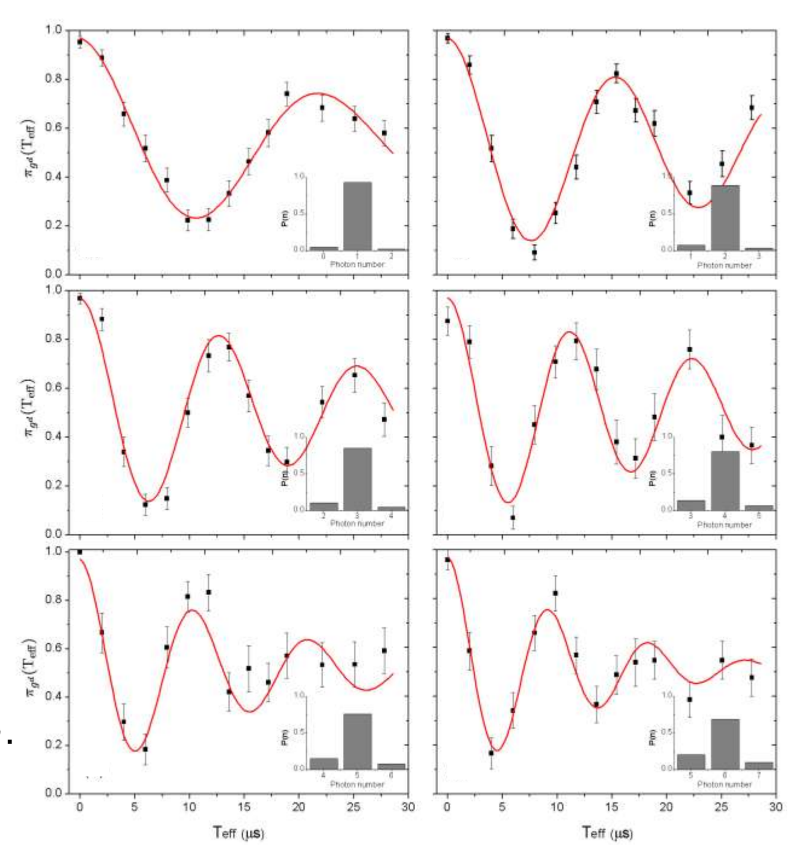
Experimental imperfections:

- Samples with Poisson atom number distribution: $\bar n = 0.5 - 1.3$ atom/sample
- Time between samples: T_a = 82 µs
- Atom preparation errors (~1%)
- Erroneous state detection (~5%)
- Detection efficiency: 25%
- Black-body thermal field: n_{th} = 0.05
- Cavity lifetime: T_{cav} = 65 ms

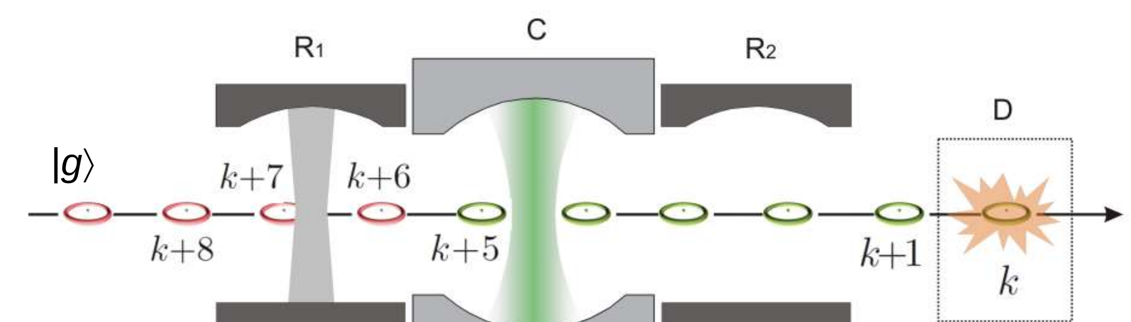
ρ updated as a mixing of all possible evolutions due to these limitations

Resonant interactions

- Atoms are tuned in resonance by a DC Stark field applied across the cavity.
- No coherences: considering photon number distribution p(n) is enough.
- After each detection p(n) updates using Bayes' law from previous p(n) and transition probabilities (Rabi oscillations in the cavity containing n photons).
- For all n, calibration of Rabi oscillations
- Interaction times t_e, t_g for $|e\rangle$ and $|g\rangle$ atoms set close to 2π-pulse in $|n_{target}\rangle$.
- Two-atom events also considered



Feedback controller
with resonant atoms



- Atomic samples sent in groups of 12 sensors and 4 actuators.
- Detection of atom k in *D*
- Controller chooses actuator atom k+8 preparation in *R1*:

QND sensor	$|e\rangle + |g\rangle$	: $\pi/2$ pulse
Absorber	$|g\rangle$	: do nothing
Emitter	$|e\rangle$	: π pulse

- Choice made minimizes the distance d to the target:

$$d = (\bar n - n_{target})^2 + \Delta n^2$$

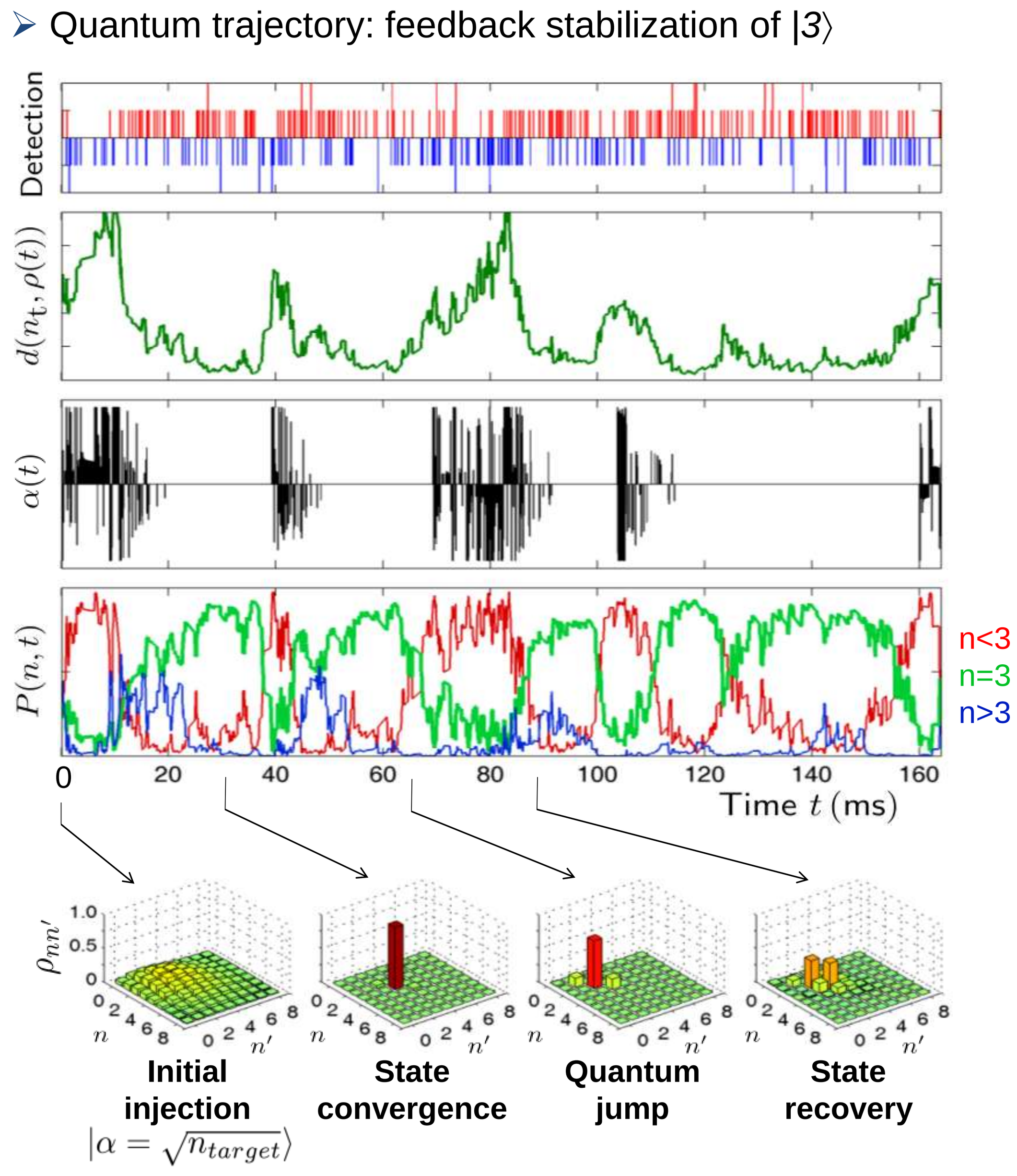
$\bar n$: mean photon number
Δn^2 : photon number variance

Feedback with coherent field injection

- Injection of a small coherent field (*classical*) as actuator to correct for *quantum* jumps of the cavity field state.
- State estimation needs to take into account the phase of the field and the full density operator.
- The injection of this small field displaces ρ :

$$\rho \to D(\alpha)\rho D(-\alpha) \quad \text{with} \quad D(\alpha) = \exp(\alpha a^\dagger - \alpha^* a)$$

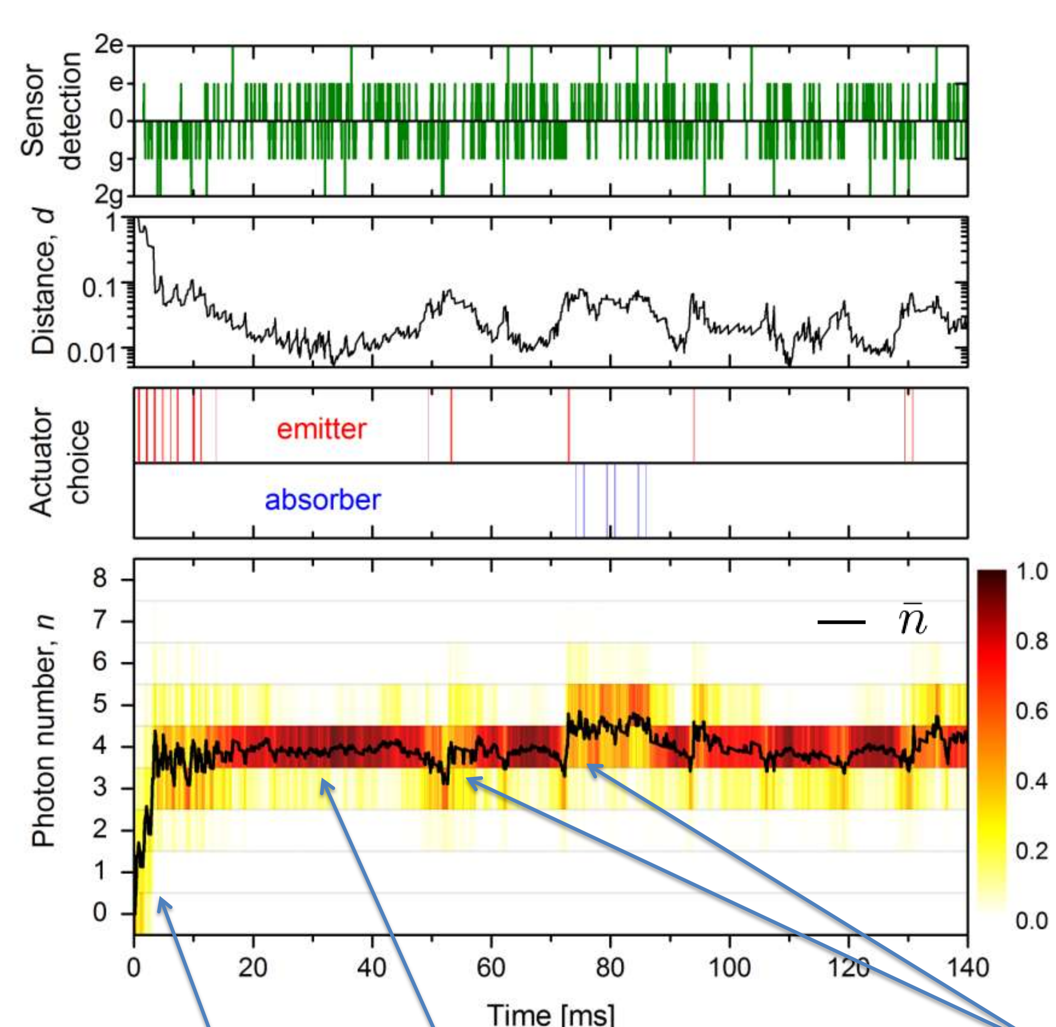
- Quantum trajectory: feedback stabilization of $|3\rangle$



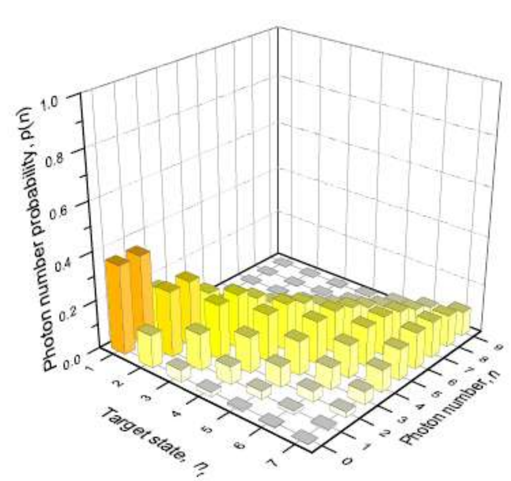
C. Sayrin *et al.*, Nature **477**, 73-77 (2011)

Results for feedback with atomic actuators

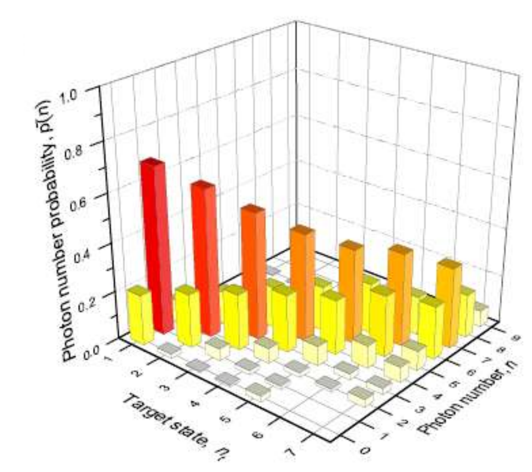
- Quantum trajectory: feedback stabilization of $|4\rangle$



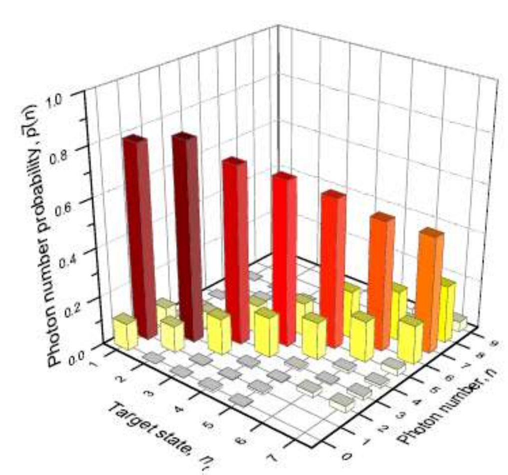
- Initial preparation : $|0\rangle$ (~5ms)
- Field state is $|4\rangle$
- Detection of quantum jumps down (up) and correction with an emitter (absorber)



- Photon populations of coherent states $|\alpha = \sqrt{n_{target}}\rangle$



- **Stabilization efficiency**: average populations for 4000 trajectories stopped at an arbitrary time



- **Preparation efficiency**: trajectory stopped when $P(n_{target}) \geq 0.8$

X. Zhou *et al.*, Phys. Rev. Lett. **108**, 243602 (2012)

Perspectives

- Adaptative QND measurement of photon numbers
  - S. Haroche *et al.*, J. Phys. II **2**, 659 (1992)
- Quantum feedback: stabilization of photon number cat states
  - M. Fortunato *et al.*, Phys. Rev. A **60**, 1687 (1999)
  - S. Zippilli *et al.*, Phys. Rev. A **67**, 052101 (2003)