Single-Photon Distillation via a Photonic Parity Measurement Using Cavity QED

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Author

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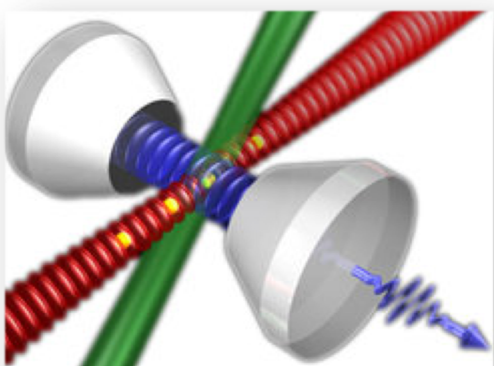
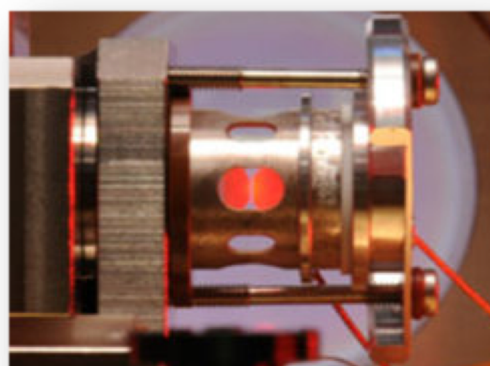
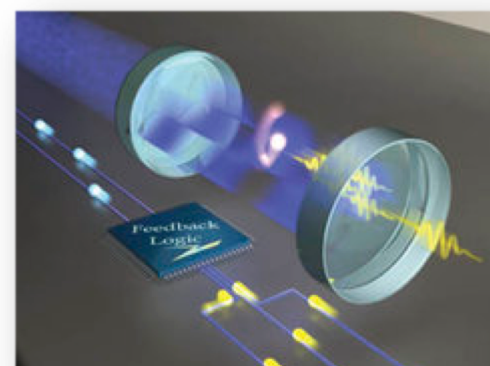
- Honorary Professor at the ***Technical University of Munich***
- Performed pioneering experiments in atomic and molecular physics, quantum optics, and quantum information processing
- PhD degree at the Ludwig-Maximilians-University of Munich in the group of Herbert Walther "investigation of the interaction of Rydberg atoms with radiation"



Quantum information processing



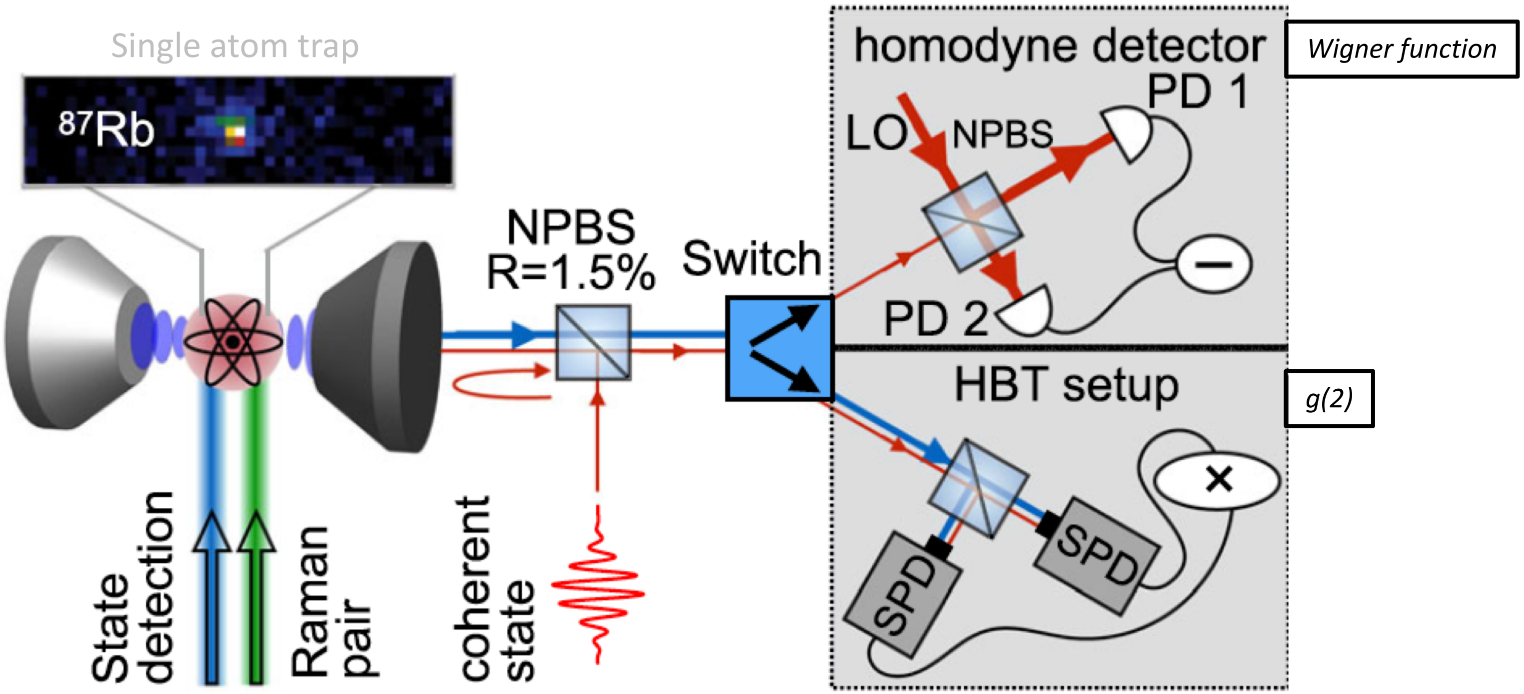
Cavity QED

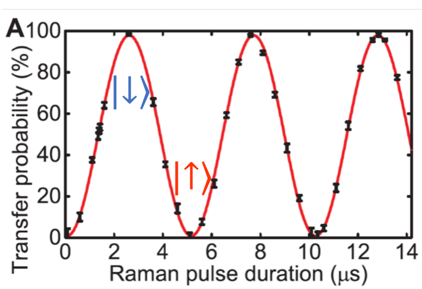


Feedback cooling of single atom

Experimental Setup

* Single-sided optical Fabry-Pérot cavity
$\mathcal{F} = 6\times10^5$





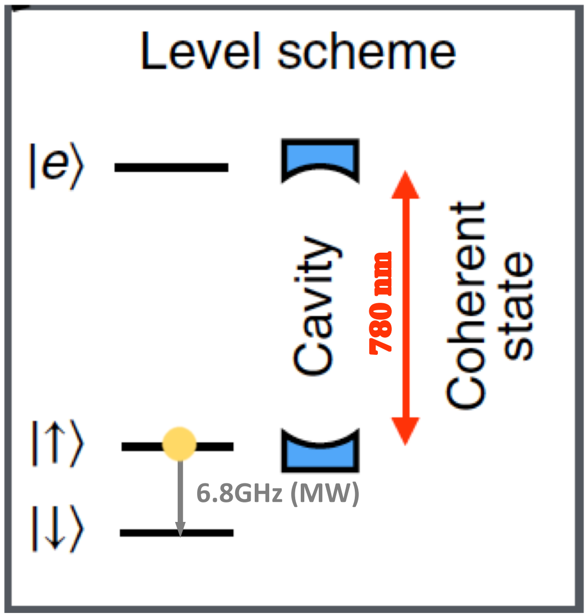
* Raman laser pair
➔ Coherent ground state control

Input coherent source (photon pulse)

$|\alpha\rangle = e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}(\alpha^n/\sqrt{n!}\,)|n\rangle$ $\quad \overline{n} = \alpha^2$ (avg. photon number)

Gaussian envelope (FWHM : $t = 2.3\mu s$) with 500 Hz repetition rate

Level structure (effectively 3-level system)



$|e\rangle = |5^2P_{3/2}, F = 3, m_F = 3\rangle$

$|\uparrow\rangle = |5^2S_{1/2}, F = 2, m_F = 2\rangle$

$|\downarrow\rangle = |5^2S_{1/2}, F = 1, m_F = 1\rangle$

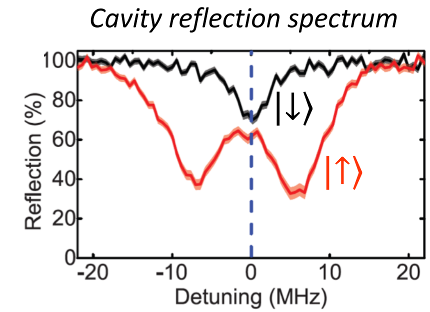
* Parameter for $|\uparrow\rangle$

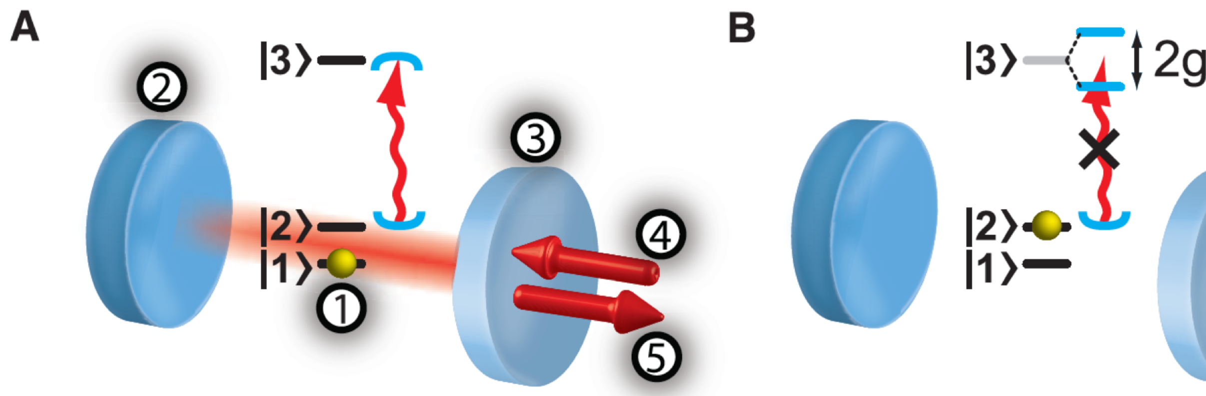
$$(g, \kappa, \kappa_r, \gamma) = 2\pi(7.8, 2.5, \underline{2.3}, 3)\ \mathrm{MHz}$$

Mostly decay through in-coupling mirror of cavity

G. Rempe, *Nature Photonics* **13**, 110–115 (2019)

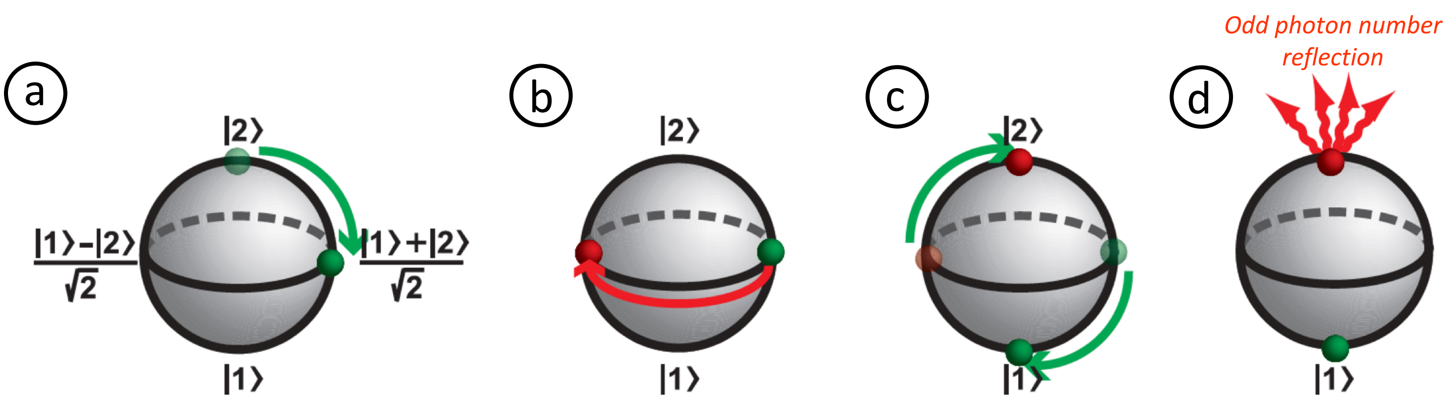
Nondestructive detection (photon)





$|n=1\rangle$: $\boldsymbol{\pi}$-phase shift ($|\downarrow\rangle$ or $|1\rangle$), **no**-phase shift ($|\uparrow\rangle$ or $|2\rangle$) *of atom-light state*

$|n\rangle$: $\mathbf{n}\boldsymbol{\pi}$-phase shift ($|\downarrow\rangle$ or $|1\rangle$), **no**-phase shift ($|\uparrow\rangle$ or $|2\rangle$) *of atom-light state*



$\frac{|2\rangle+|1\rangle}{\sqrt{2}}$: **odd** photon number Fock state → $\frac{|2\rangle-|1\rangle}{\sqrt{2}}$, **even** photon number Fock state → $\frac{|2\rangle+|1\rangle}{\sqrt{2}}$

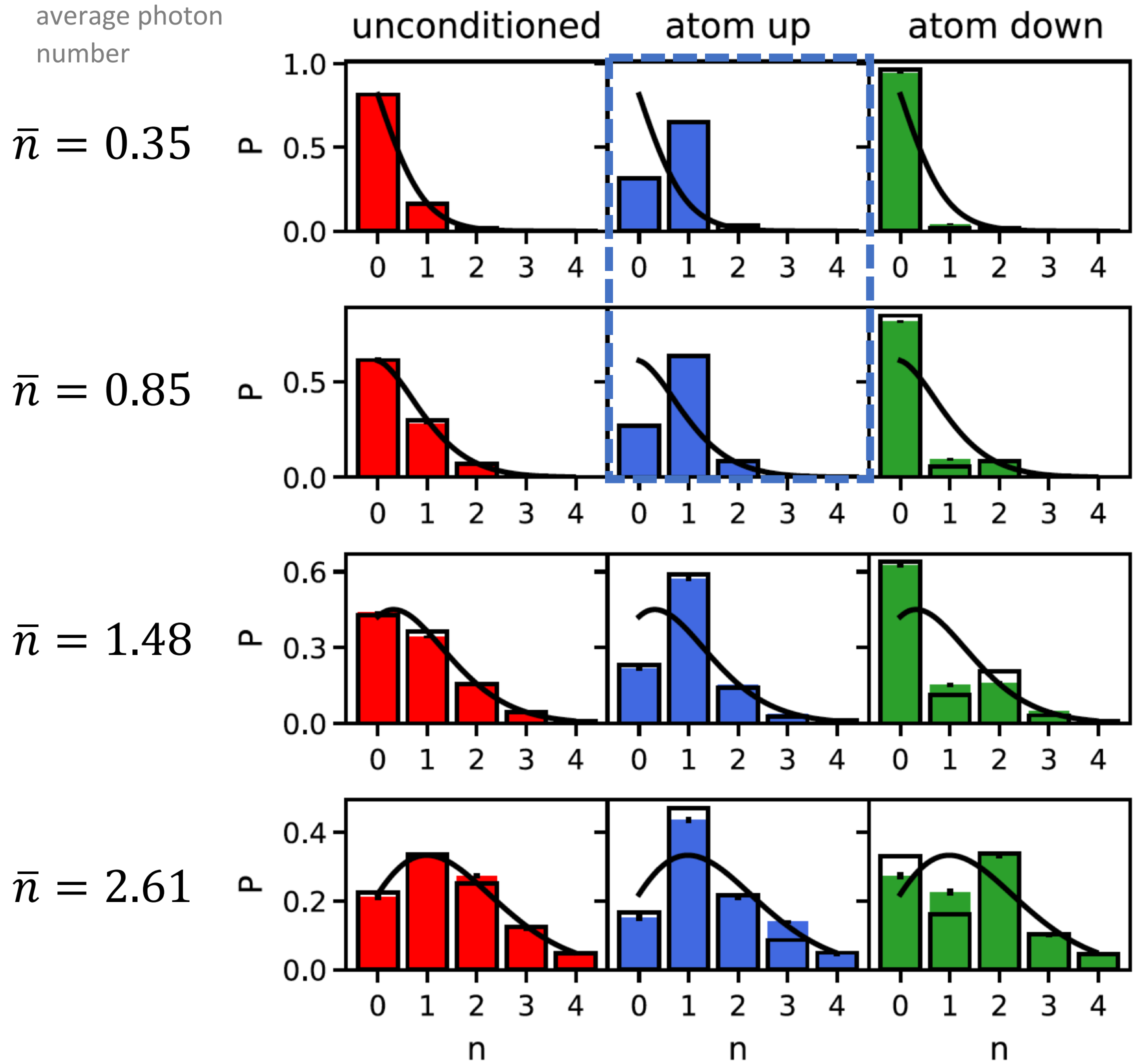
G. Rempe, *Science* 342, 1349 (2013)

Postselecting Fock state measurement

$\bar{n}$: input pulse average photon number

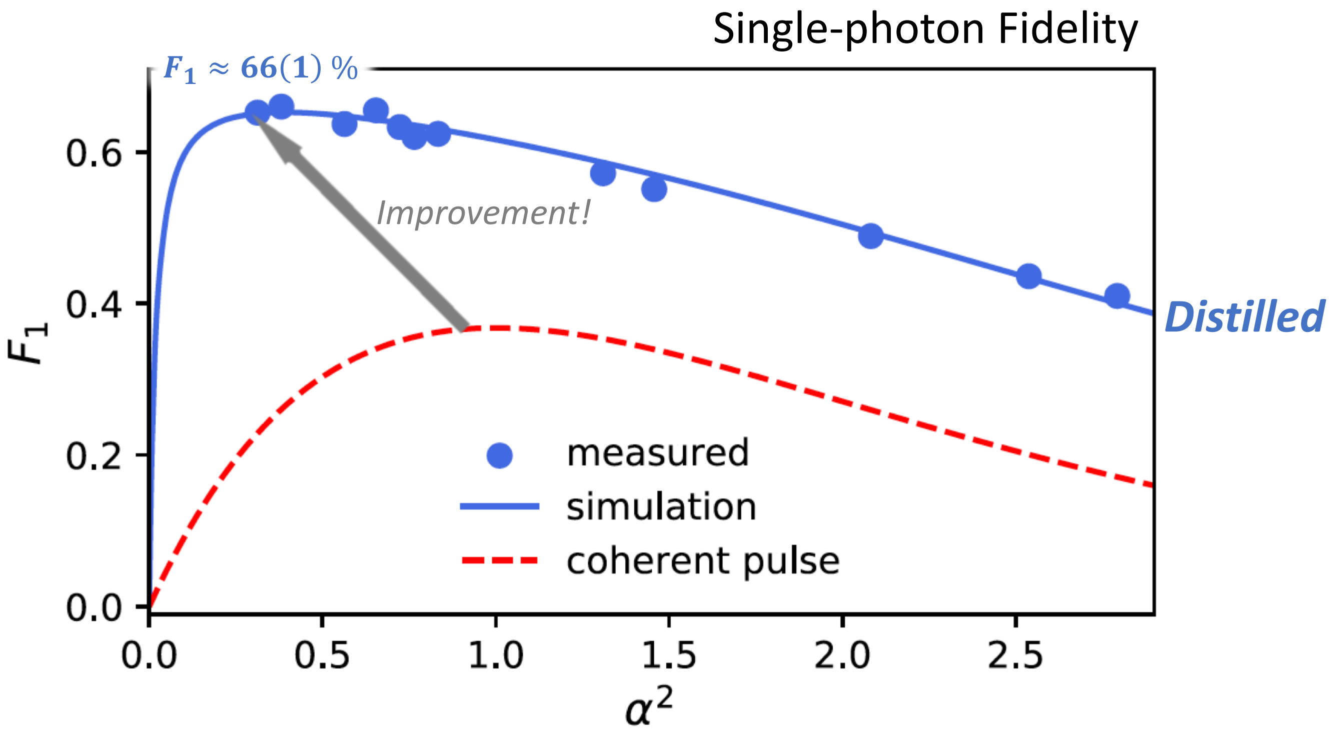
Coherent Poisson distribution

For $\alpha^2 \lesssim 1$, the dominant contribution of distilled pulse is single-photon component within odd photon number state



“Classical coherent state” → “single photon state”

Single-photon light state

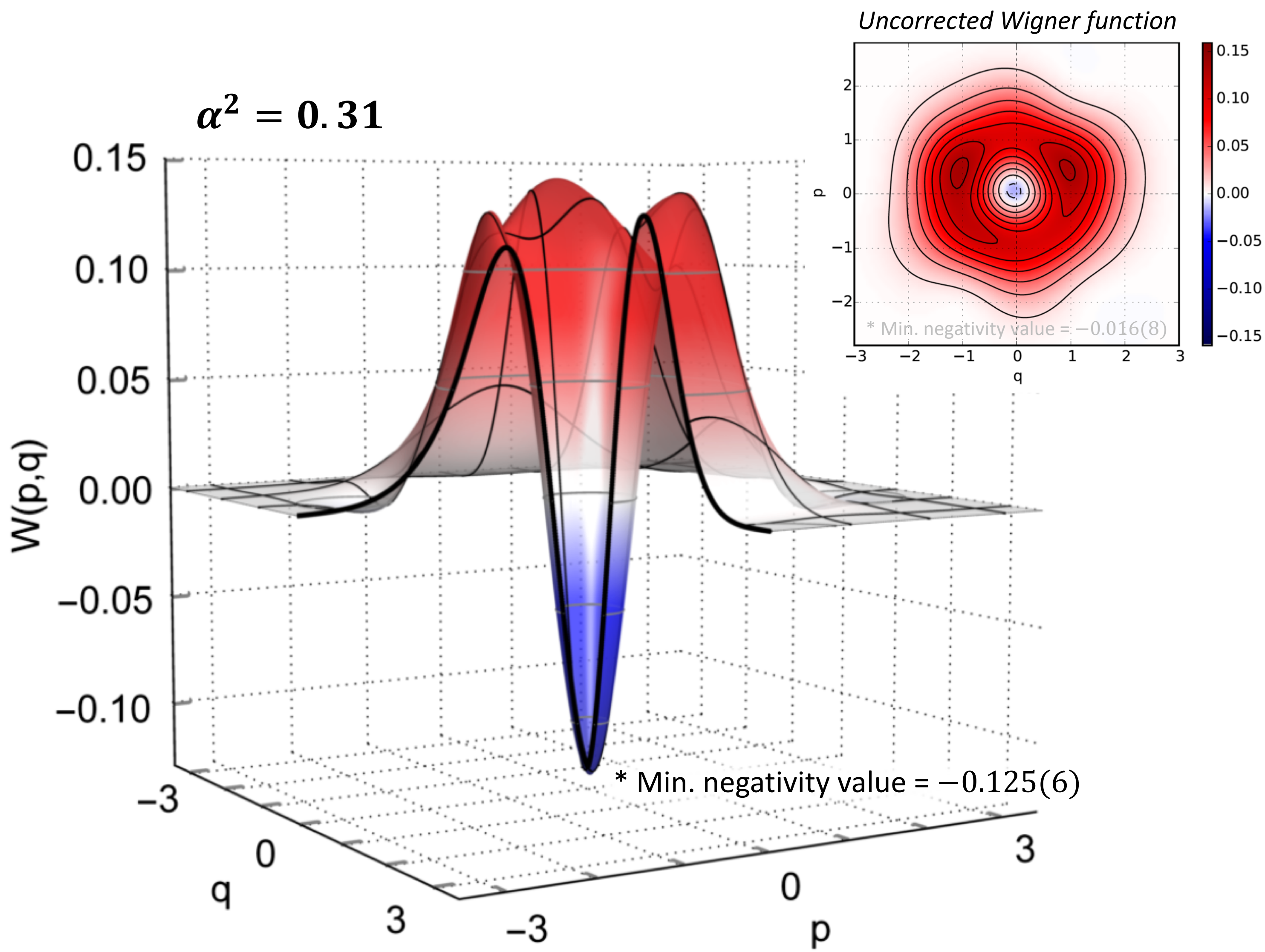


$$F_{1,max} = \frac{\kappa_r}{\kappa}\frac{2C}{2C+1}$$

$C = \frac{g^2}{2\kappa\gamma}$: cooperativity

For $C = 4.1$, $F_{1,max} = 0.819$ (theoretically)
equivalent to losses of $L_{cav} = 18.1\%$

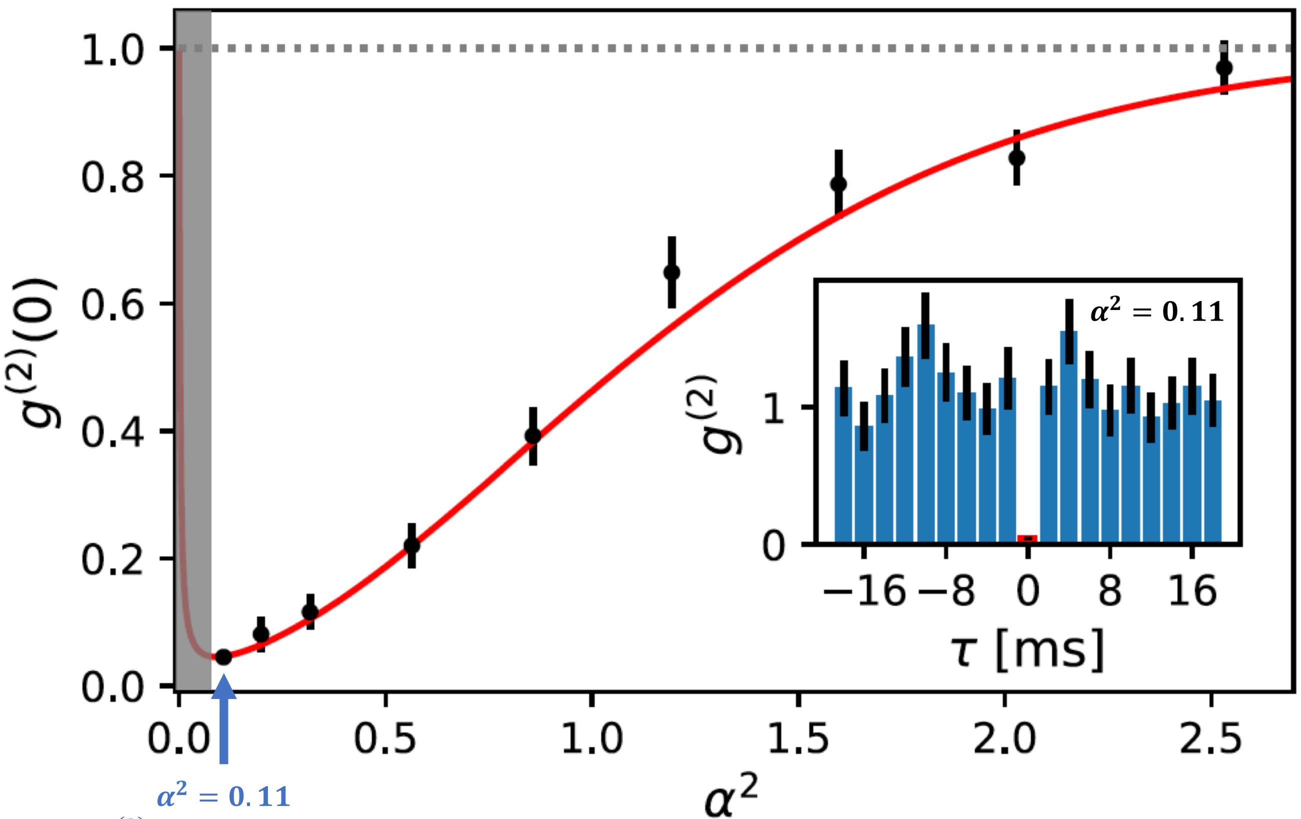
Wigner function of final light state



Wigner function of photon state reconstructed by Homodyne detection

Second-order correlation function

- For $\alpha^2 \to 0$, $g^{(2)}(0) \to 0$: anticipated
- However the dark-counts rate of the SPDs result in an uncorrelated signal that ultimately limits the lowest value obtained for $g^{(2)}(0)$ - *Shaded Area*

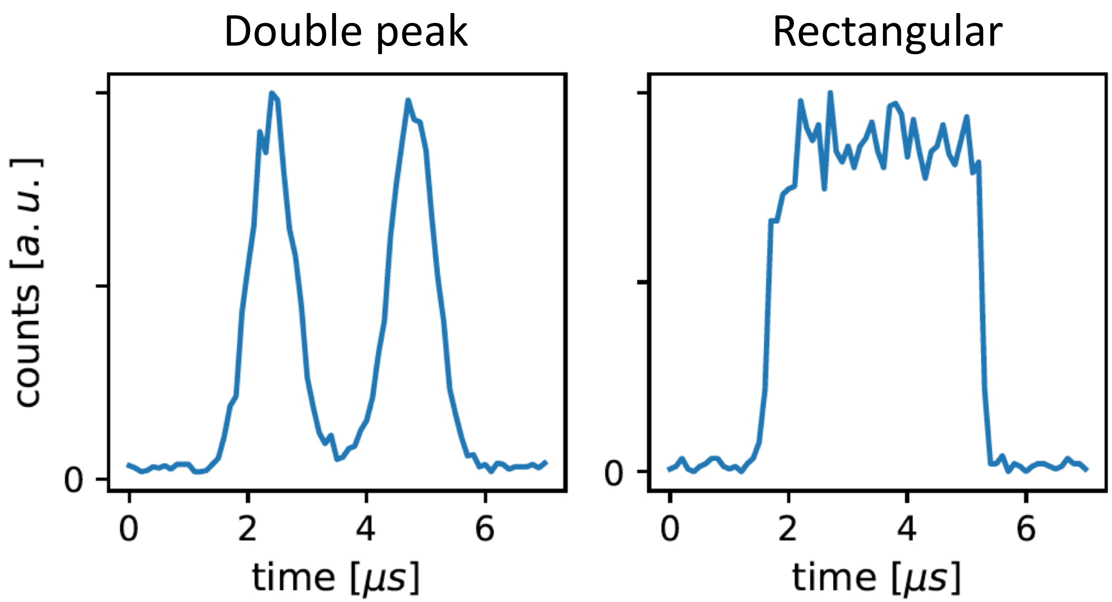


$\alpha^2 = 0.11$
$g^{(2)}(0) = 0.045(6)$

Photon pulse shape dependency

For different photon shape $\boldsymbol{\alpha^2 = 0.11}$

Photon shape	$g^{(2)}(0)$
Gaussian	0.045(6)
Double peak	0.06(3)
Rectangular	0.06(3)



The protocol is robust as long as the ***spectral width*** *of the photon is smaller than the* ***cavity linewidth κ***

* Photonic loss

TABLE SI. Loss budget listing the loss channels in propagation and detection that are not part of the production process. Unless otherwise specified, the uncertainties on the given values are on the order of 10%. Individually listed losses i are summed according to $1 - L_{\mathrm{sum}} = \prod_i (1 - L_i)$.

Source of loss	(effective) Loss L_i
Other optics: waveplates, mirrors and NPBS	7.6%
Mode matching with local oscillator (both paths)	6.0%
Limited isolator transmission	3.0%
Switch acousto-optical deflector	2.5%
Detector dark noise	2.5%
Laser classical noise	1.8%
NPBS reflectivity	1.5%
Limited quantum efficiency of homodyne detector	1.5(15)%
Electronic high pass 0.7 kHz signal reduction	1.1%
Vacuum viewport reflection	0.6%
Electronic high pass background noise	0.2%
Total losses L_{sum}	25.1%