Deterministic Free-Propagating Photonic Qubits with Negative Wigner Functions

Valentin Magro, Julien Vaneecloo, Sebastien Garcia and Alexei Ourjoumtsev

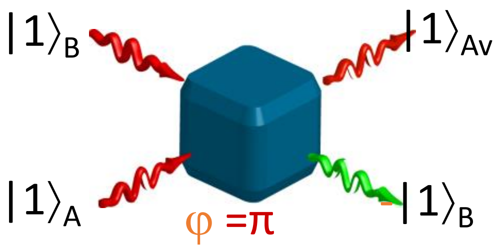
Young Physics Teams of Collège de France

A new experimental platform

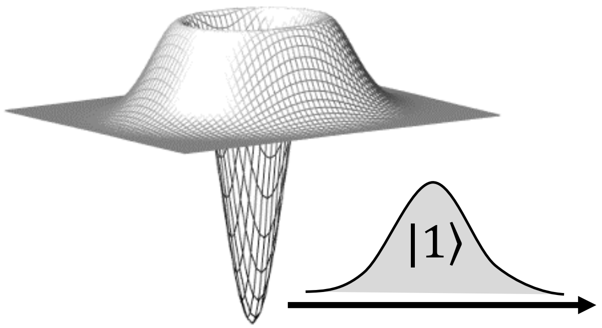
Why making photons interact ? And How ?

- Photons can carry information as qubits without dephasing
- Need highly nonlinear medium

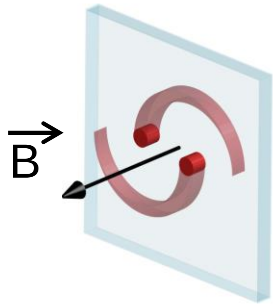
Quantum gates



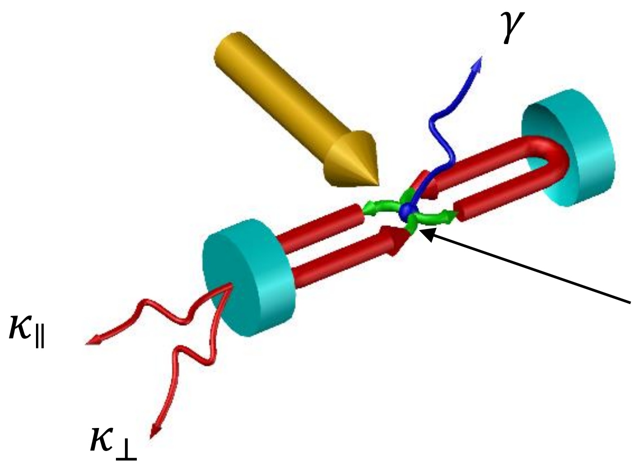
Non-classical states of light



Optical quantum simulations



Making photons interact

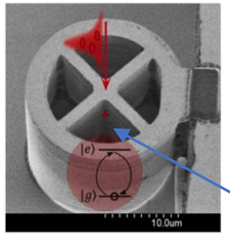


Rempe@MPQ

Single atom

Single emitters:

- Photon extraction η_{cav} and cooperativity C:
  - $\eta_{cav} = \frac{\kappa_{\parallel}}{\kappa_{\parallel}+\kappa_{\perp}} = \frac{Transmission}{Transmission + Losses}$
  - $C = \frac{g^2}{2\,\kappa\,\gamma} = \frac{Scattering\ cross\ section}{Beam\ cross\ section} \times \frac{1}{Transmission+Losses}$
  - $\eta_C = \frac{2C}{1+2C}$, mapping efficiency
- Technical limitations :
  - high reflectivity with low losses mirror
  - small volume cavity ➔less control on atom cavity coupling



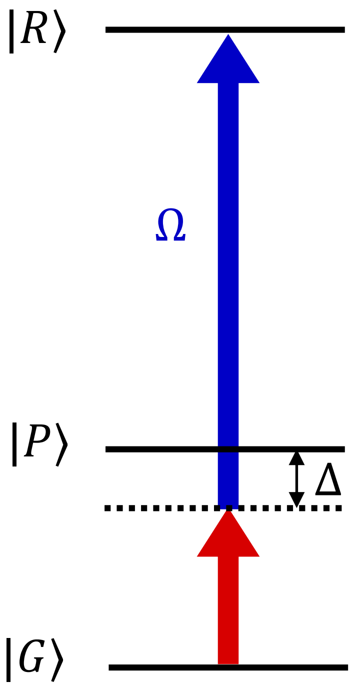
Senellart@C2N

Quantum dot

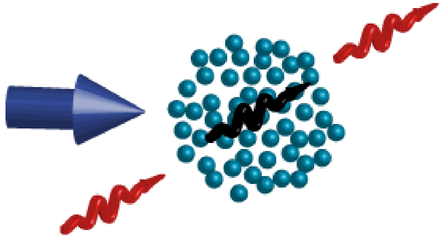
Quasi-deterministic cat states: Hacker & al, Nature Photonics **13**, 110 (2019)

Making photons interact

- Rydberg atoms in free space



EIT, Electromagnetically induced transparency



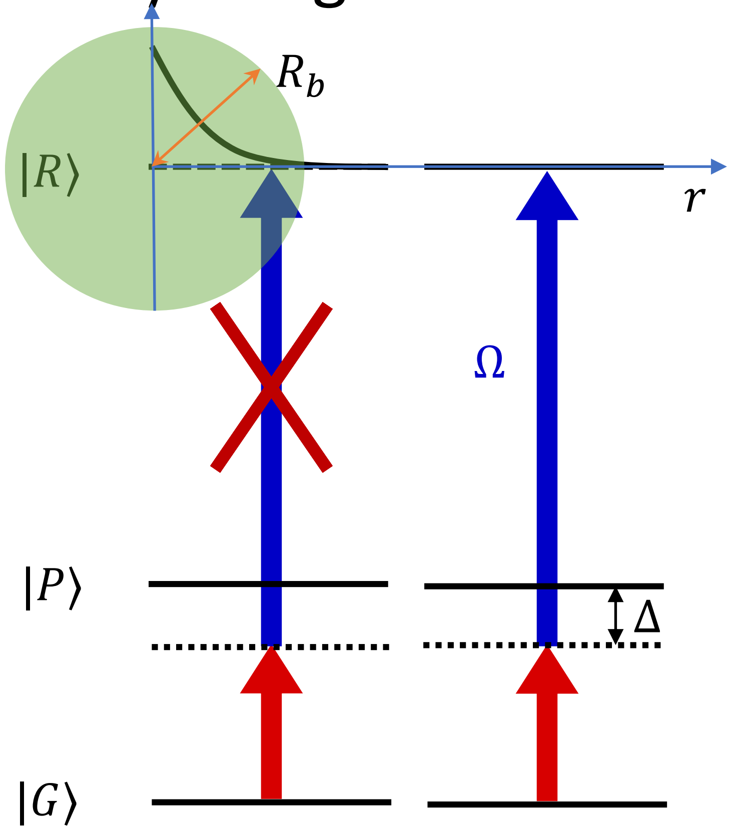
$|1_{\mathrm{A}}\rangle \rightarrow |\mathrm{D}_{\mathrm{A}}\rangle$

$|D\rangle = \cos(\beta)\,|G,1\rangle - \sin(\beta)\,|R,0\rangle$

$\tan(\beta) = \frac{2g}{\Omega}, \; g \propto \sqrt{N}$

Making photons interact

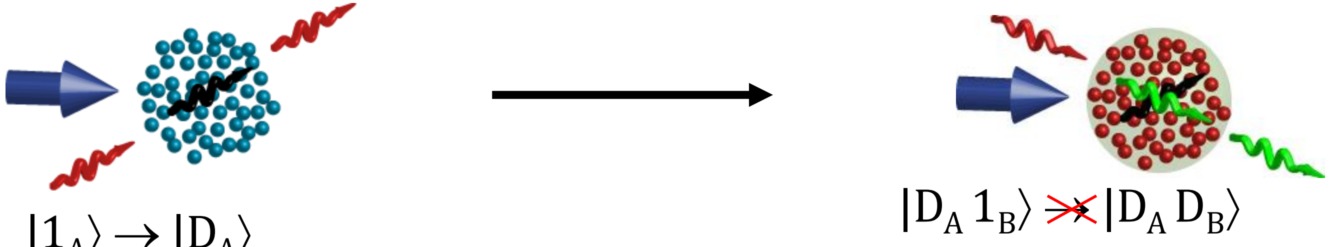
- Rydberg atoms in free space



Van der Walls interactions, $V_{vdW}(r) = \frac{C_6}{r^6}$ and $C_6 \propto n^{11}$

For $n \sim 100 \rightarrow V_{vdW}(r = 10\ \mu m) \sim 100\ MHz$

Blockade sphere, for $n \sim 100 \rightarrow R_b \sim 30\ \mu m$



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Making photons interact

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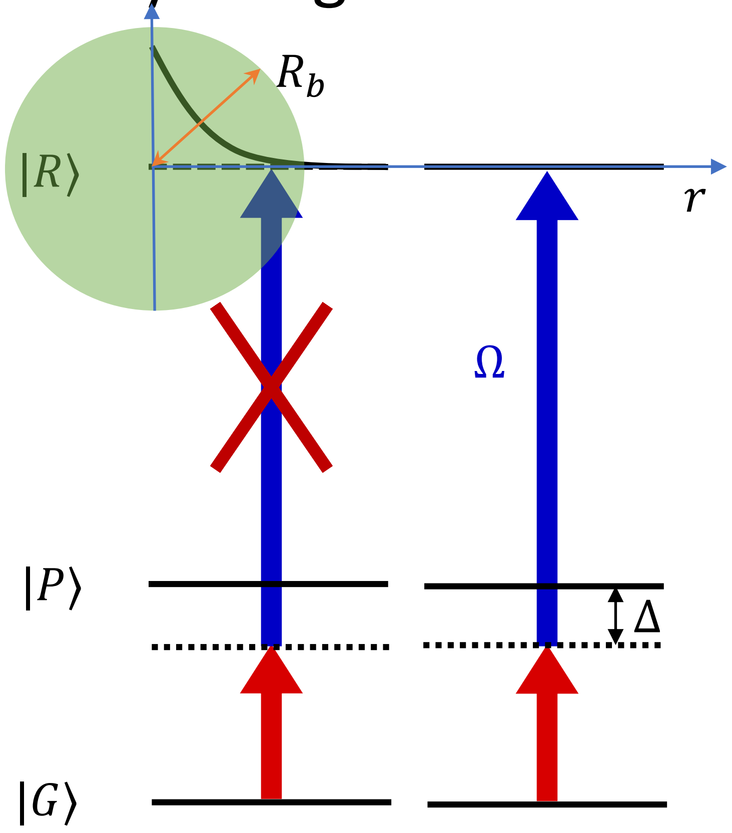
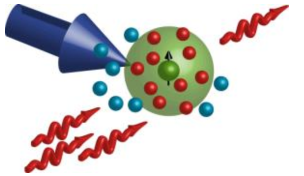
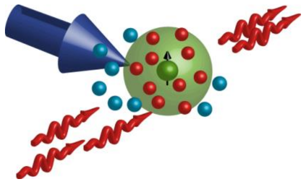


- At resonance $\Delta = 0$, absorption
  - Photon Transistor
  - Photon sources

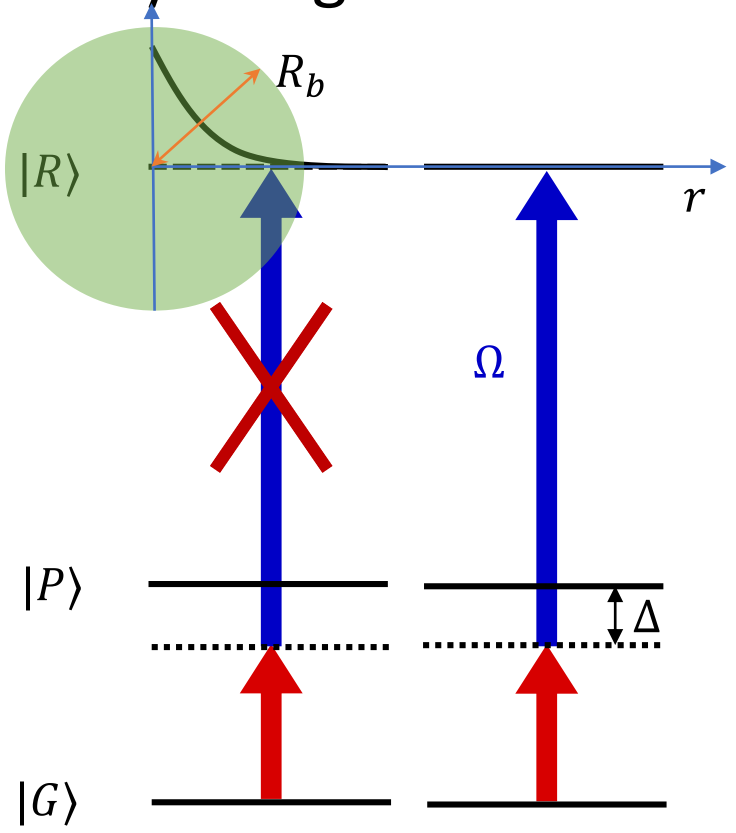


- Out of resonance $\Delta \neq 0$, dispersion
  - Photonic molecules
  - 2 photon gates



Making photons interact

- Rydberg atoms in free space



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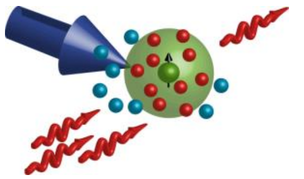

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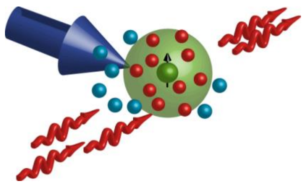
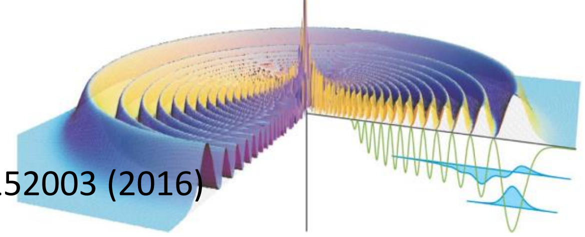


- Physical limitations:
  - Strong nonlinearity ➔ Needs high optical density
  ➔ high atomic density ➔ losses

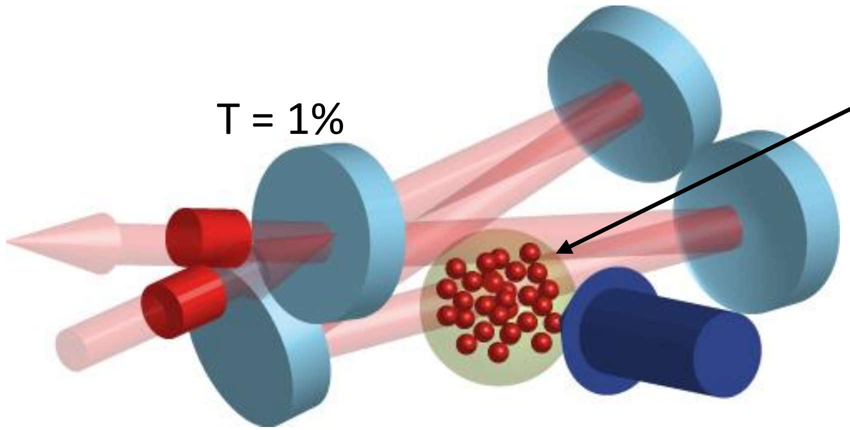
$\langle r \rangle \propto a_0 n^{*2}$ ~1 µm!



Reviews:

Murray & Pohl, AAMOP **65**, 321 (2016)
Firstenberg, Adams & Hofferberth, J. Phys. B **49,** 152003 (2016)
Wu &al, Chin. Phys. B **30**, 020305 (2021)

Experimental platform



- Medium finesse cavity F = 600, $\kappa = 3$ MHz
  - ➔easier to fabricate
  - ➔extraction efficiency $\eta_{cav} = 90\ \%$
  - ➔cooperativity $C \gg 1$
- With a large volume ➔ optical access for atom trapping/cooling
- Easier and reproductible collective atom cavity coupling of g = 10 MHz
- Cloud size $\sigma = 5\ \mu m < R_b$
- Moderate density

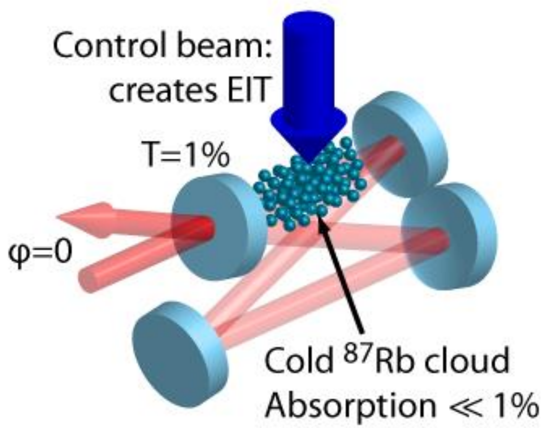
Experimental platform

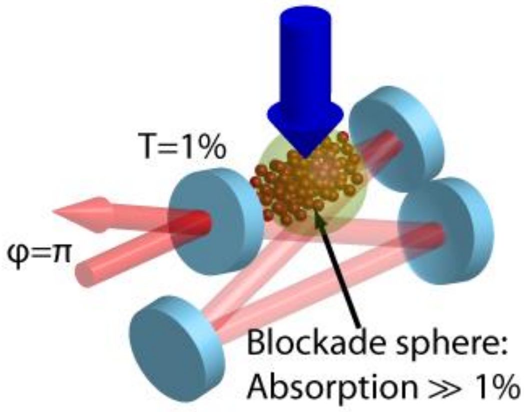
- Conditional π phase shift:

$$E_r = \frac{T - L}{T + L} E_i$$

$E_r \sim E_i$

$T \gg L$





$E_r \sim -E_i$

$T \ll L$

Julien Vaneecloo, Sébastien Garcia, and Alexei Ourjoumtsev
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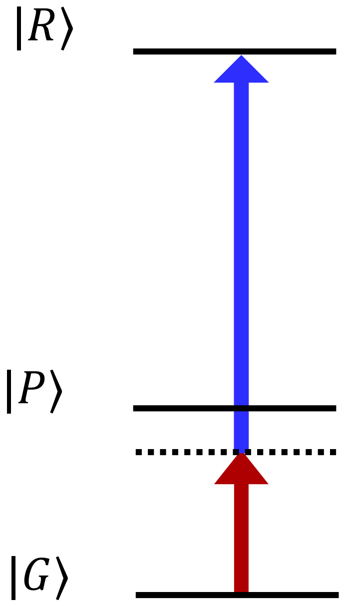
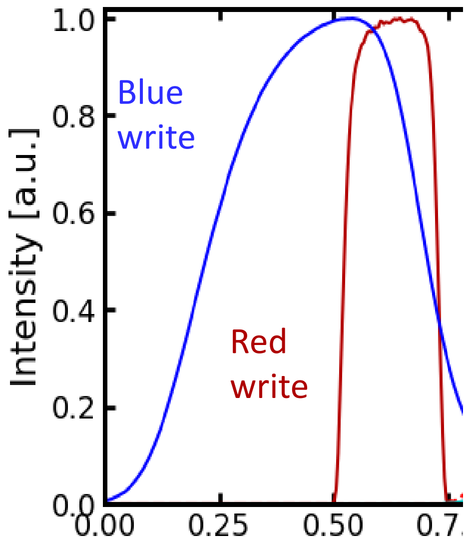
Deterministic generation of single photon

Superatom state $\cos\left(\frac{\theta}{2}\right)|G\rangle - \sin\left(\frac{\theta}{2}\right)|R\rangle$





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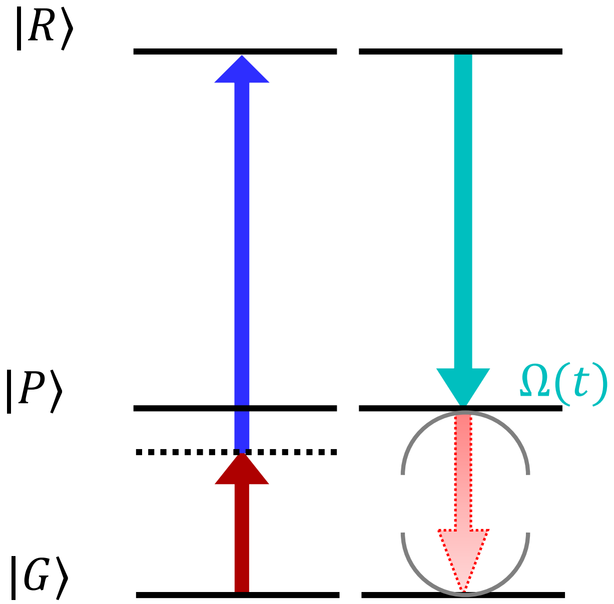
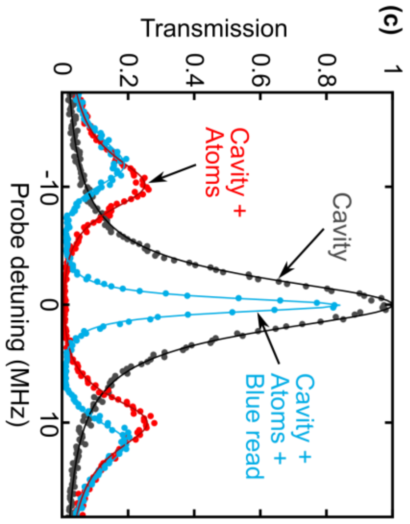
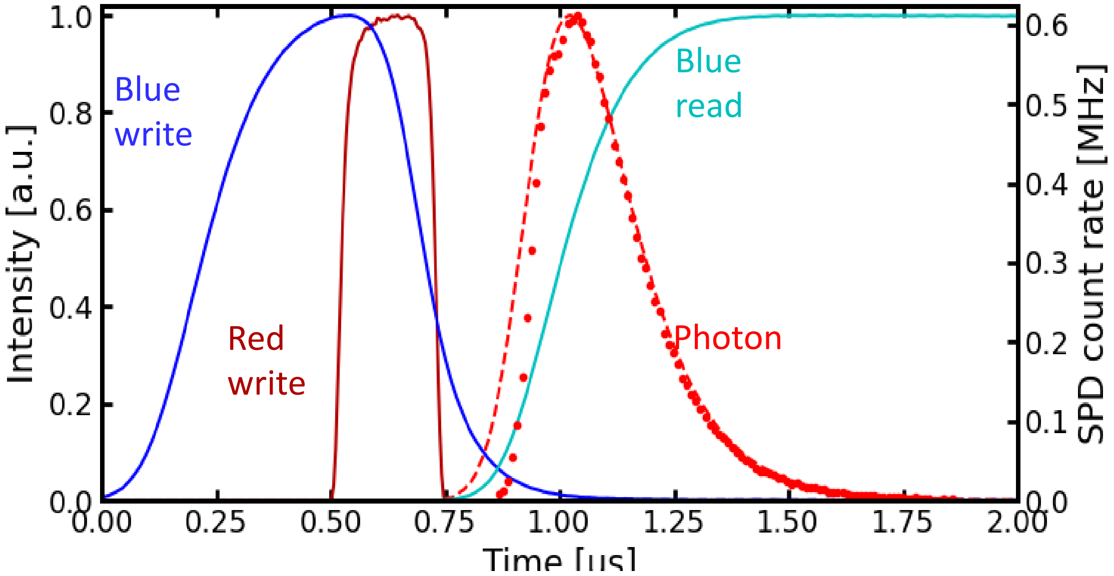
Deterministic generation of single photon

Superatom state $\cos\left(\frac{\theta}{2}\right)|G\rangle - \sin\left(\frac{\theta}{2}\right)|R\rangle$ ➔ Photonic state $\cos\left(\frac{\theta}{2}\right)|0\rangle + \sin\left(\frac{\theta}{2}\right)|1\rangle$

$|D\rangle = \cos(\beta)\,|G,1\rangle - \sin(\beta)\,|R,0\rangle$ $\tan(\beta) = \frac{2g}{\Omega(\mathrm{t})}$







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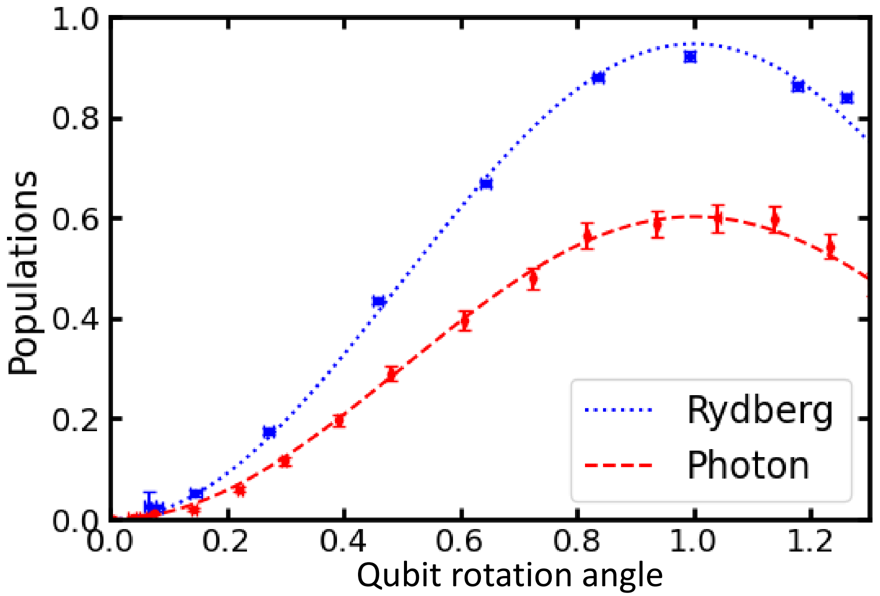
High efficiency generation of single photon

Map superatom state $\cos\left(\frac{\theta}{2}\right)|G\rangle - \sin\left(\frac{\theta}{2}\right)|R\rangle$ to photonic state $\cos\left(\frac{\theta}{2}\right)|0\rangle + \sin\left(\frac{\theta}{2}\right)|1\rangle$



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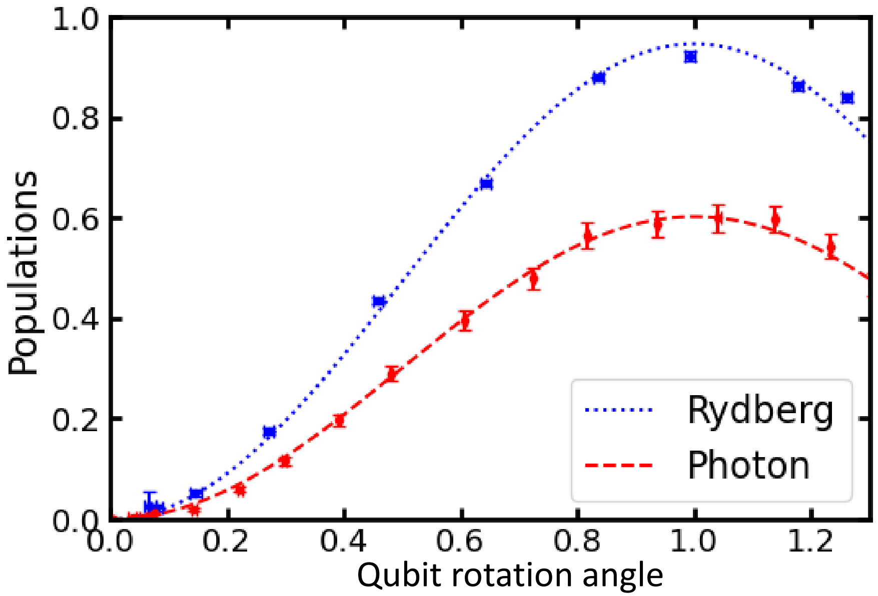
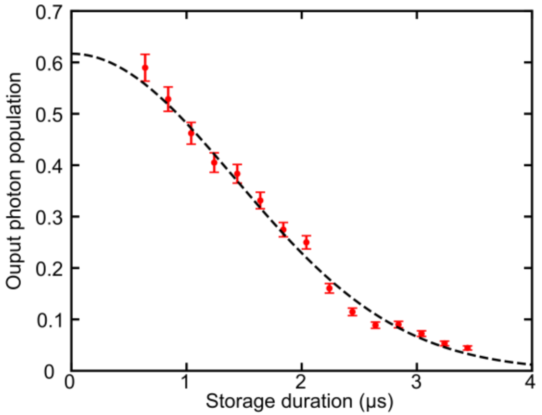
High efficiency generation of single photon

- Detail of efficiencies contributions:
  - $p_1 = 60 \pm 3$ % at $\theta = \pi$
  - $\eta = \eta_C \eta_{cav} \eta_{exc} \eta_s = 62$ % at $\theta = \pi$
    - $\eta_C = \frac{2C}{1+2C} = 93\%$, mapping efficiency
    - $\eta_{cav} = 90$ %, extraction efficiency
    - $\eta_{exc} = 77$ % , excitation efficiency
    - $\eta_s = e^{-(t_s/\tau_s)^2} = 95$ %,
    with $\tau_s = 2\ \mu s$, $t_s = 0{,}48\ \mu s$





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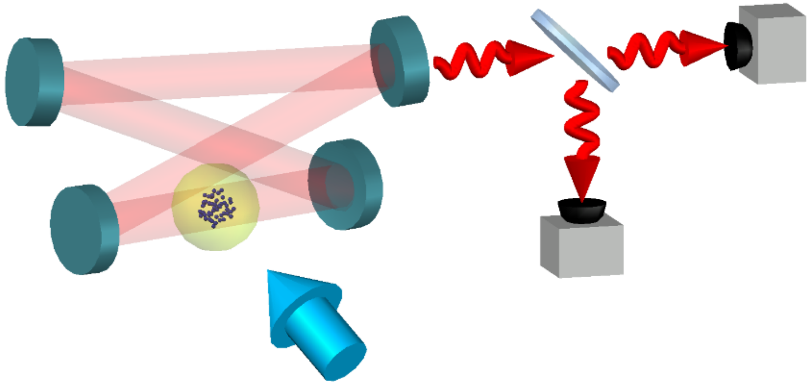
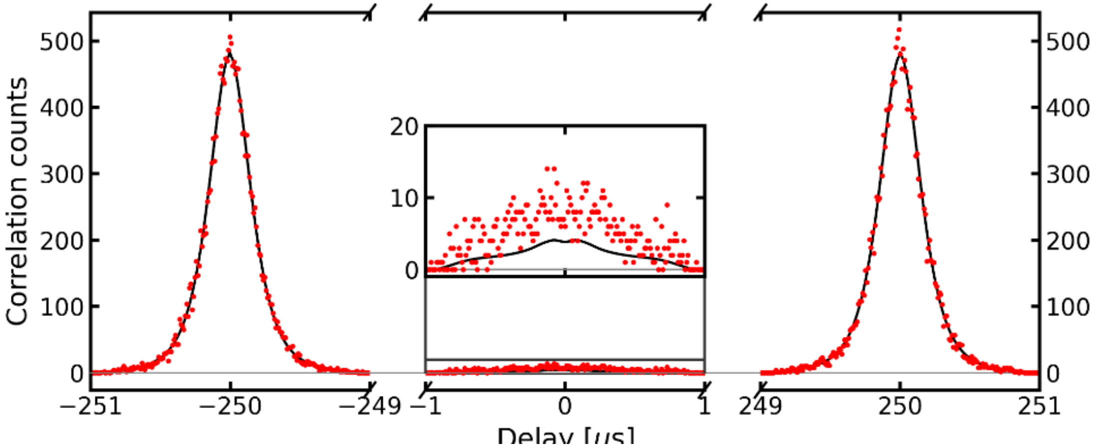
High efficiency generation of single photon

- Intensity autocorrelation measurement:
  - $g_2(0) = 0.027 \pm 0.002$
  - $p_2 = 0.49 \pm 0.05\ \%$





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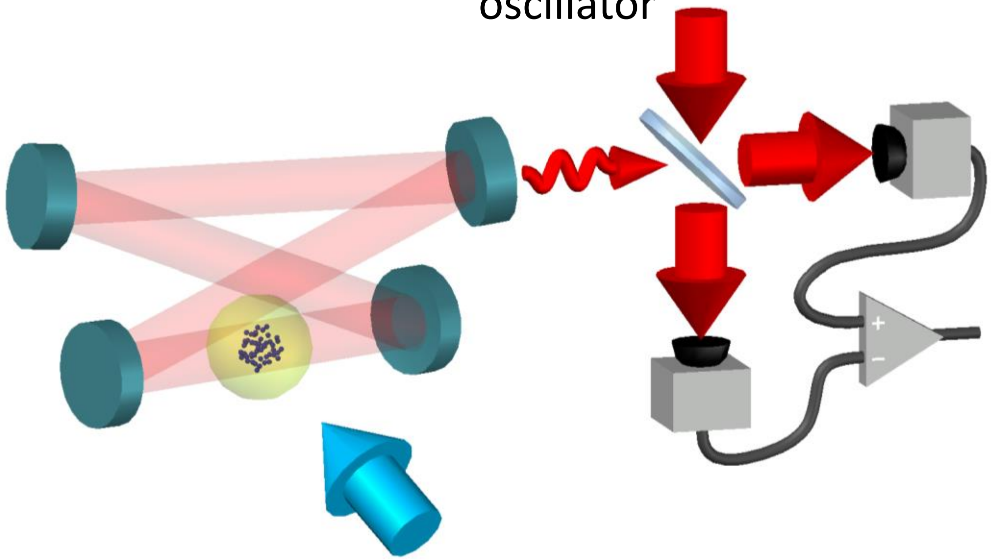
Homodyne tomography



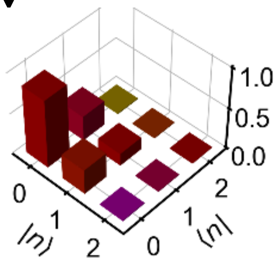
$$\hat{a} = \int \sqrt{\frac{I(t)}{\int I(t')dt'}}\, a_{out}(t)\, dt$$

Quadrature distribution:

$$P\left(\hat{X}(\phi)\right) = \mathrm{P}\left(\frac{\hat{a}\, e^{i\phi} + \hat{a}^{\dagger} e^{-i\phi}}{\sqrt{2}}\right)$$

Maximum likelihood algorithm

Density matrix



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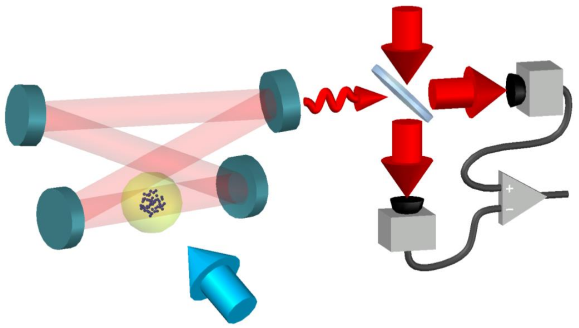

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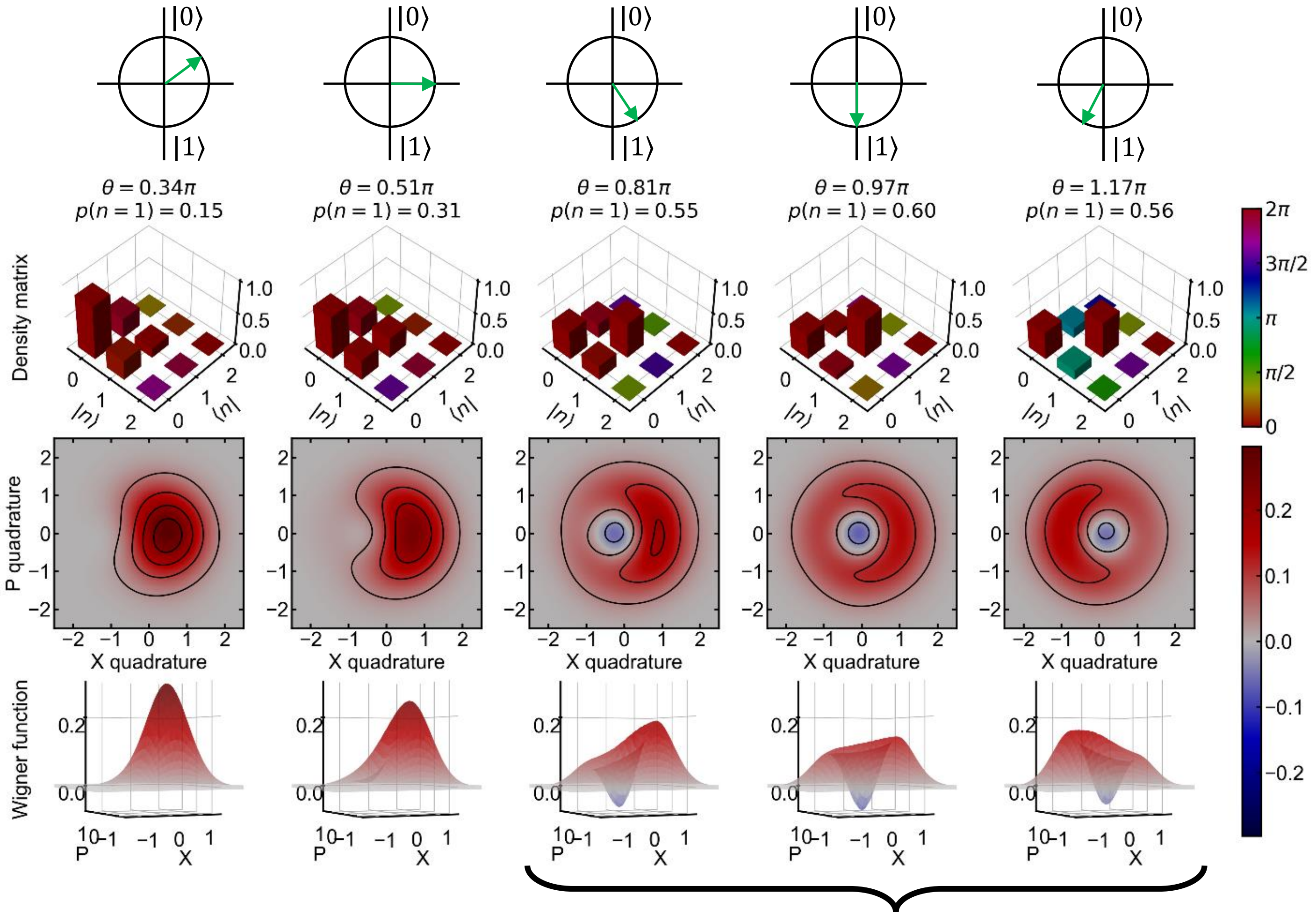

Wigner negative ! ➔ non gaussian states

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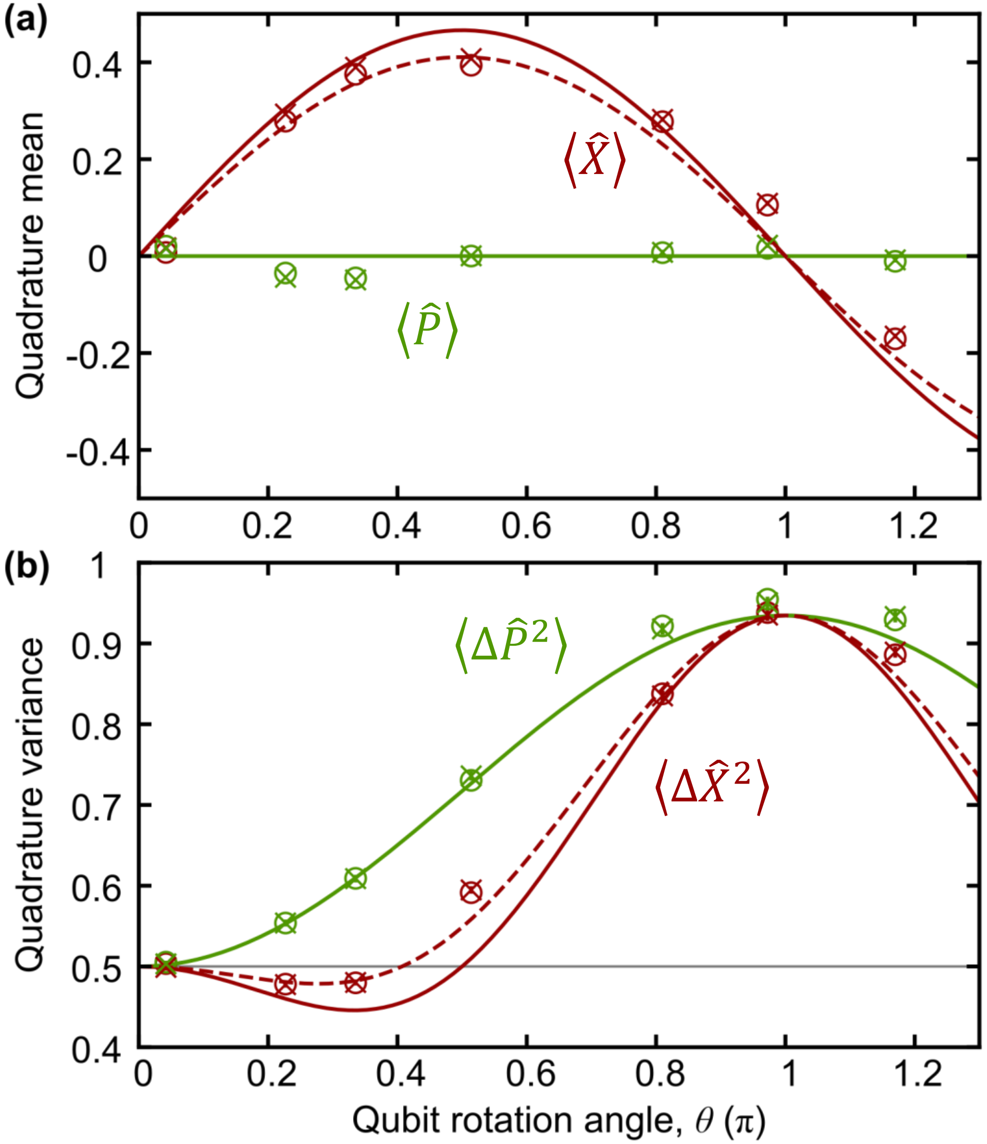
Field quadratures

Maximum squeezing of 4.4%

Pure dephasing $\gamma_\perp = 40\ kHz$

An alternative way for Ramsey spectroscopy



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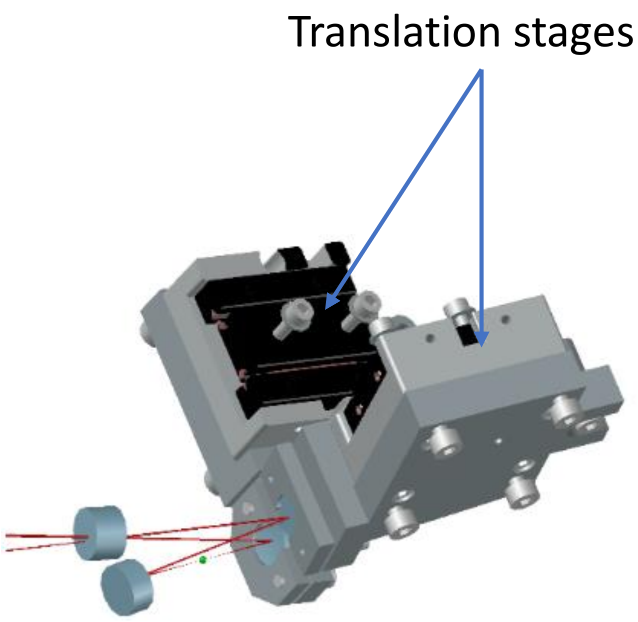
Perspectives

- Excite superatom more efficiently

- Two superatoms inside the cavity
  - CC-phase gate
  - Multi photons state

- Spatial cavity multimodes experiments
  - Quantum fluids of light (J.Simon, Chicago)



Photonic team

COLLÈGE DE FRANCE 1530

jeipcdf.cnrs.fr/
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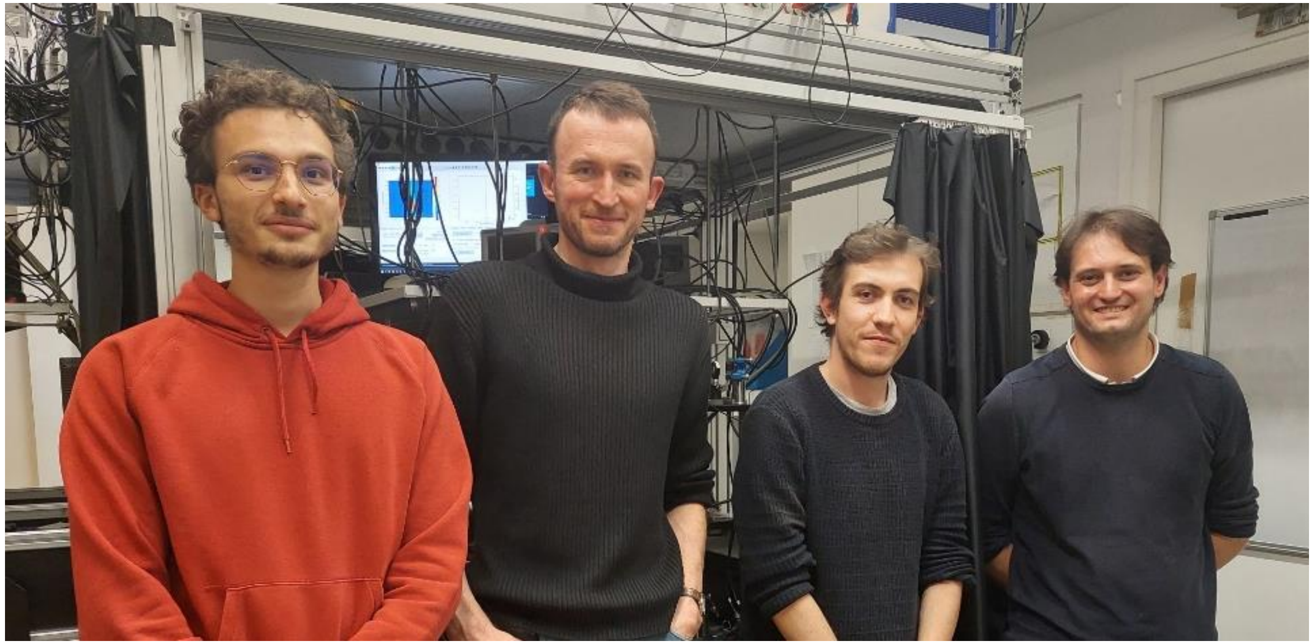

Alexei Ourjoumtsev, PI

Julien Vaneecloo, Pasqual

Sébastien Garcia, CNRS

Thanks for your attention !

High efficiency generation of single photon

- Rydberg population measurement