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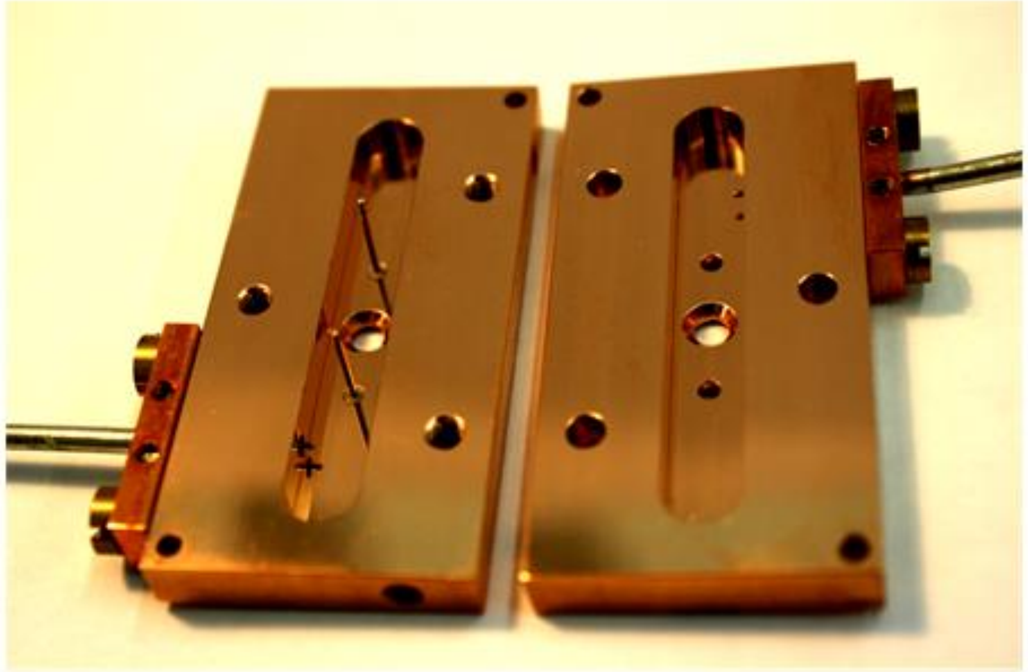
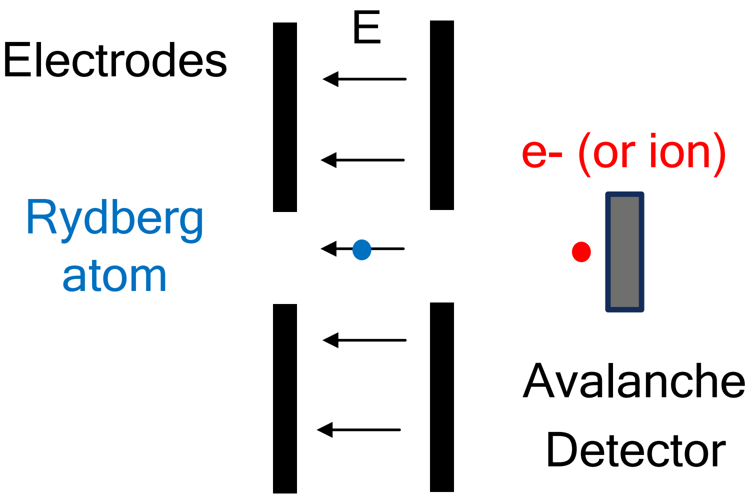


Non-destructive detection of ensembles of Rydberg atoms with microwave cavity transmission measurements

Detection of Rydberg atoms : standard techniques

Ionization



E

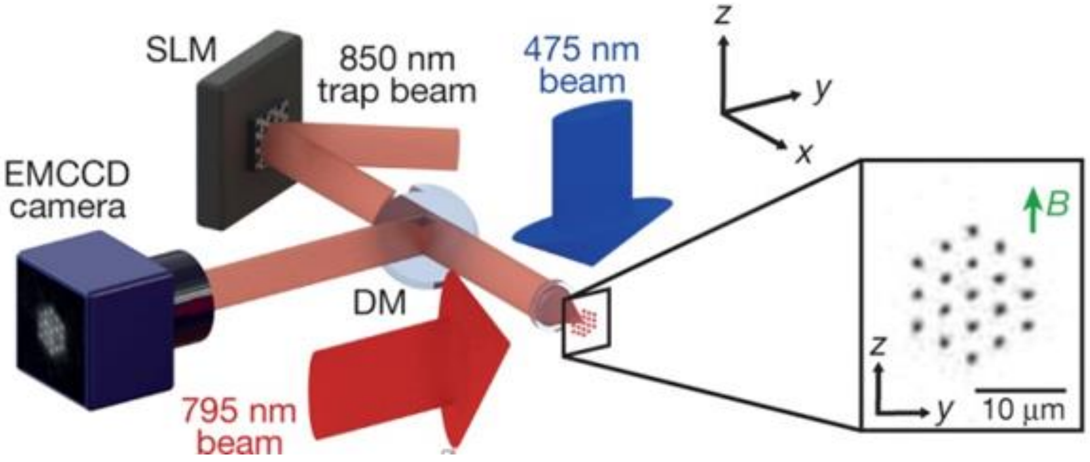
Electrodes

Rydberg atom

e- (or ion)

Avalanche Detector

Detection of missing atoms



(Labuhn, … ,Browaeys, Nature 534, 2016)

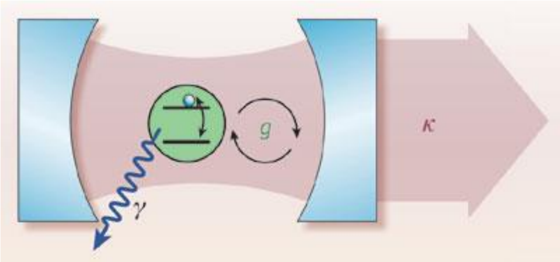
Both methods are very efficient
But they are destructive

Non destructive detection advantages :

- Multiple measurement with single preparation
- Preparation of quantum states by projection
- Quantum feedback

Cavity QED for non-destructive detection

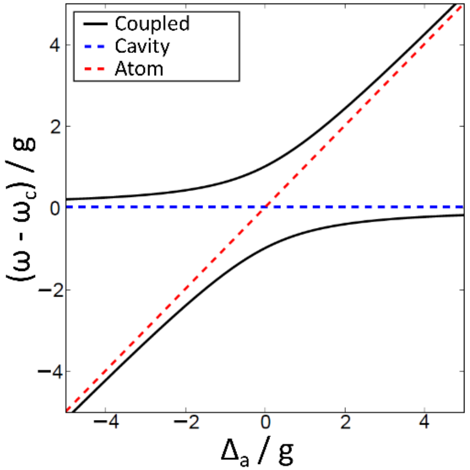
Cavity QED



(Schoelkopf & Girvin, Nature 451, 2008)

$$H_{JC} = \hbar\omega_c\left(a^\dagger a\right) + \hbar\frac{\omega_a}{2}\,\sigma_z + \hbar g\left(a\sigma_+ + a^\dagger\sigma_-\right)$$

dispersive limit: $\Delta_\mathrm{a} = \omega_a - \omega_c \gg g$



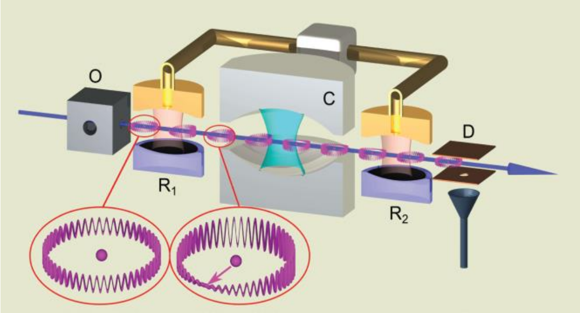
Dispersive Shift - Quantum Non-demolition Measurements

Atomic dispersive shift

$$\delta\omega_a = \frac{g^2}{\Delta_\mathrm{a}}\left(2a^\dagger a + 1\right)$$

Cavity dispersive shift

$$\chi = \frac{g^2}{\Delta_\mathrm{a}}\sigma_z$$

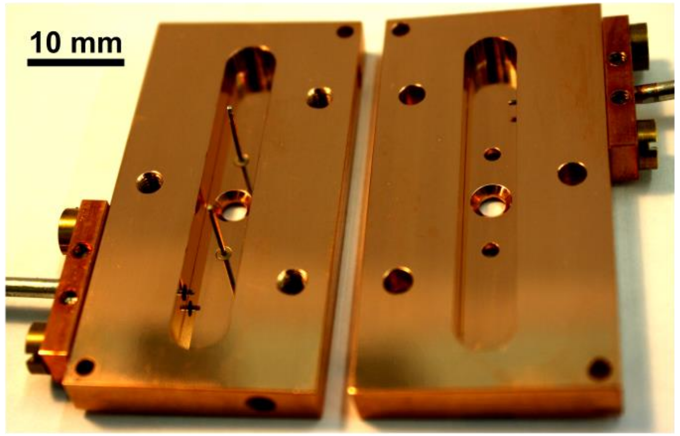


(Haroche, Nobel lecture, 2012)

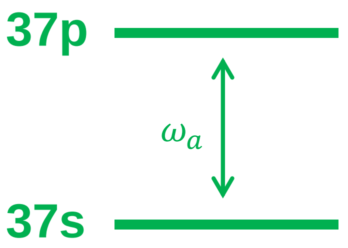
Cavity QND atomic state measurement:

- Neutral atoms in optical cavity: detection and preparation
- Circuit QED: standard readout
- Rydberg atoms with microwave: ? (Maioli et al., PRL 94, 2005)

Resonator & Atom



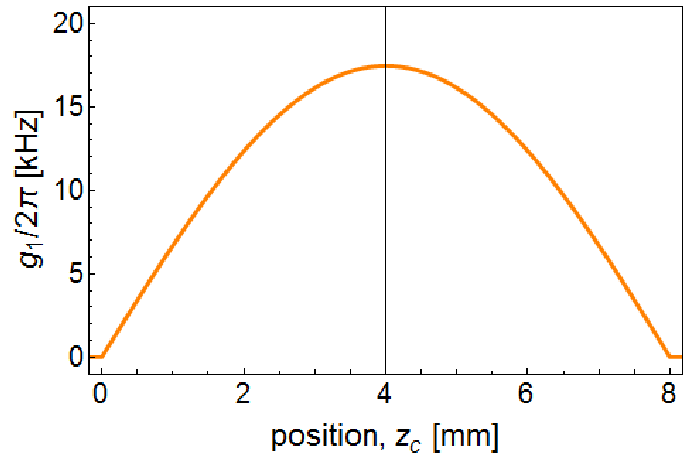
- Rectangular microwave cavity (circuit QED)
- TE_{301} mode: $\frac{\omega_c}{2\pi} = 21.532\ \mathrm{GHz}$ & $\frac{\kappa}{2\pi} = 4\ \mathrm{MHz}$



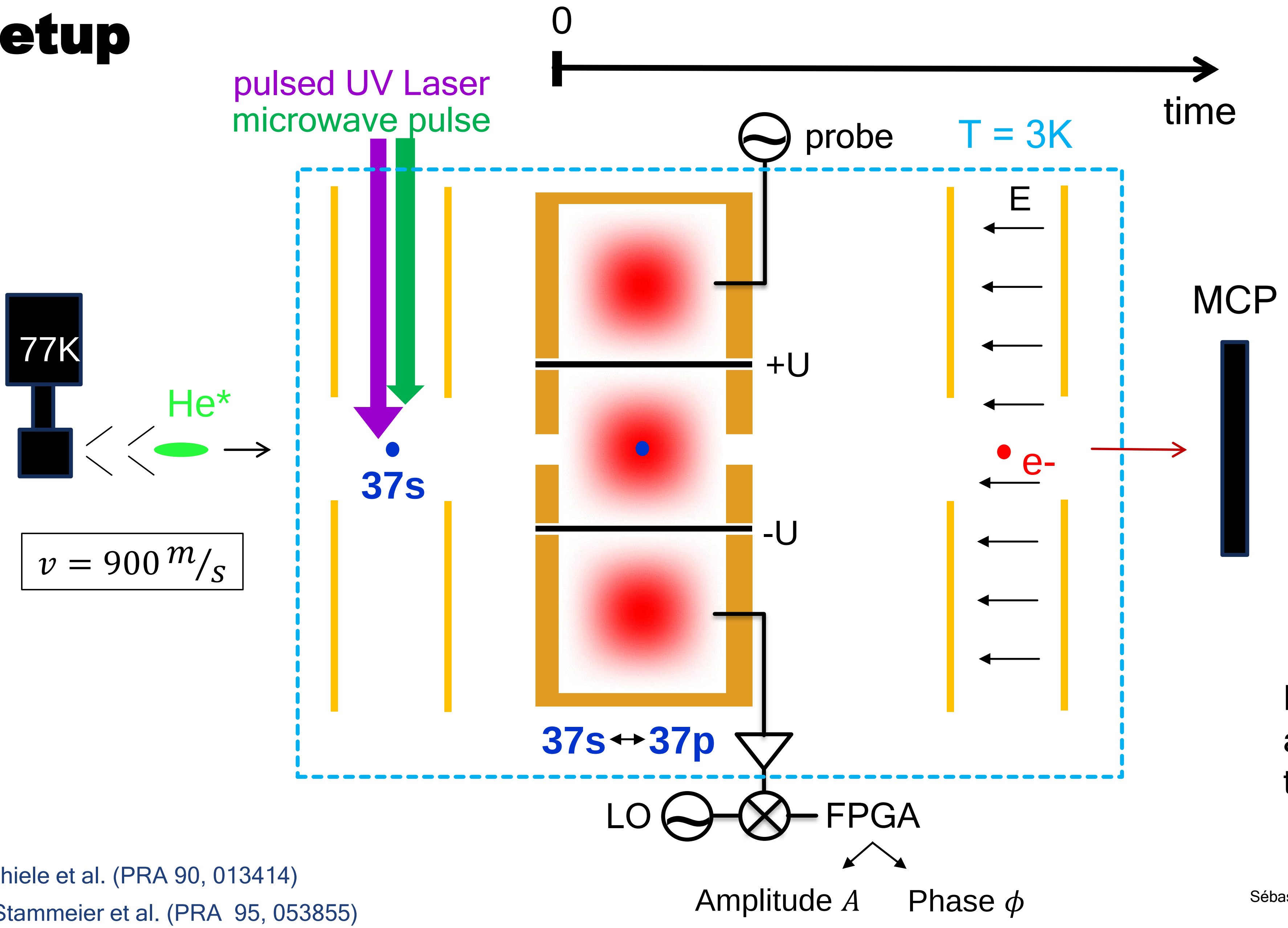
- Helium atoms
- $\frac{\omega_a}{2\pi} \cong \frac{\omega_c}{2\pi} + 20\ \mathrm{MHz}$
- (adjusted with DC quadratic Stark effect)

Coupling

- Coupling $g_1(z) = \frac{d \cdot E_0 \cdot f(z)}{\hbar}$ ≈ 17.5 kHz at maximum
- Dipole $\mathrm{d} = 1092\ \mathrm{e}a_0$
- Mode function $f(z)$ and $E_0 = 1.2\ \frac{\mathrm{mV}}{\mathrm{m}}$
- collective coupling $g_N = g_1\sqrt{N}$ (Tavis-Cummings)



Setup



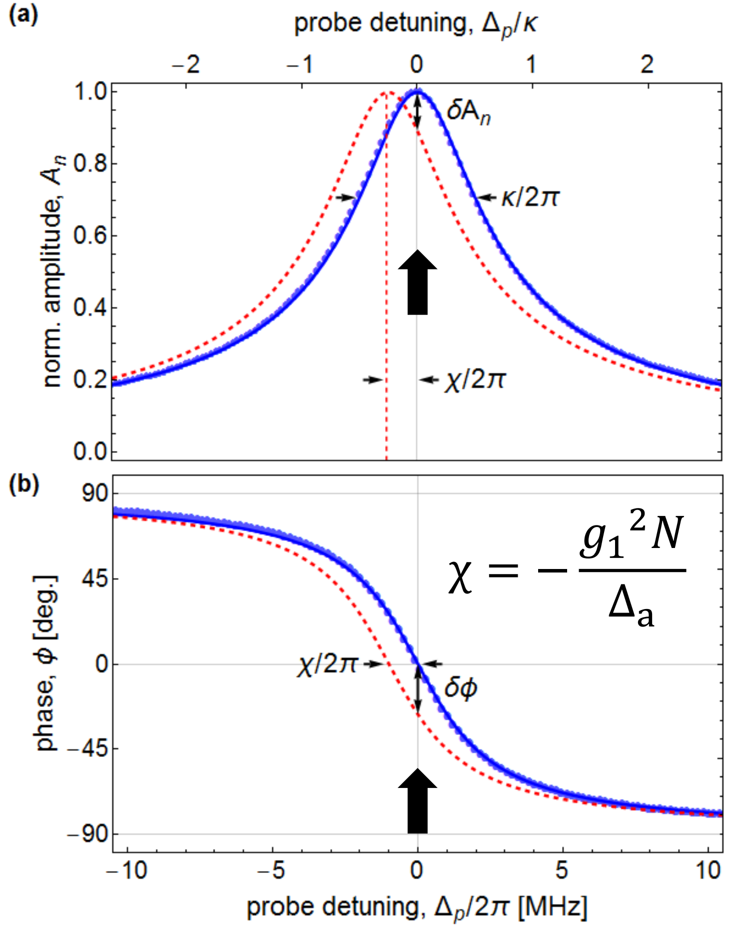
1) Excitation
2) Cavity transmission measurement
3) Ionization and standard detection

Repeat at 25 Hz and average over $\sim 5.10^4$ to reduce microwave noise

T. Thiele et al. (PRA 90, 013414)
M. Stammeier et al. (PRA 95, 053855)

Transmission at cavity resonance

Dispersive effect

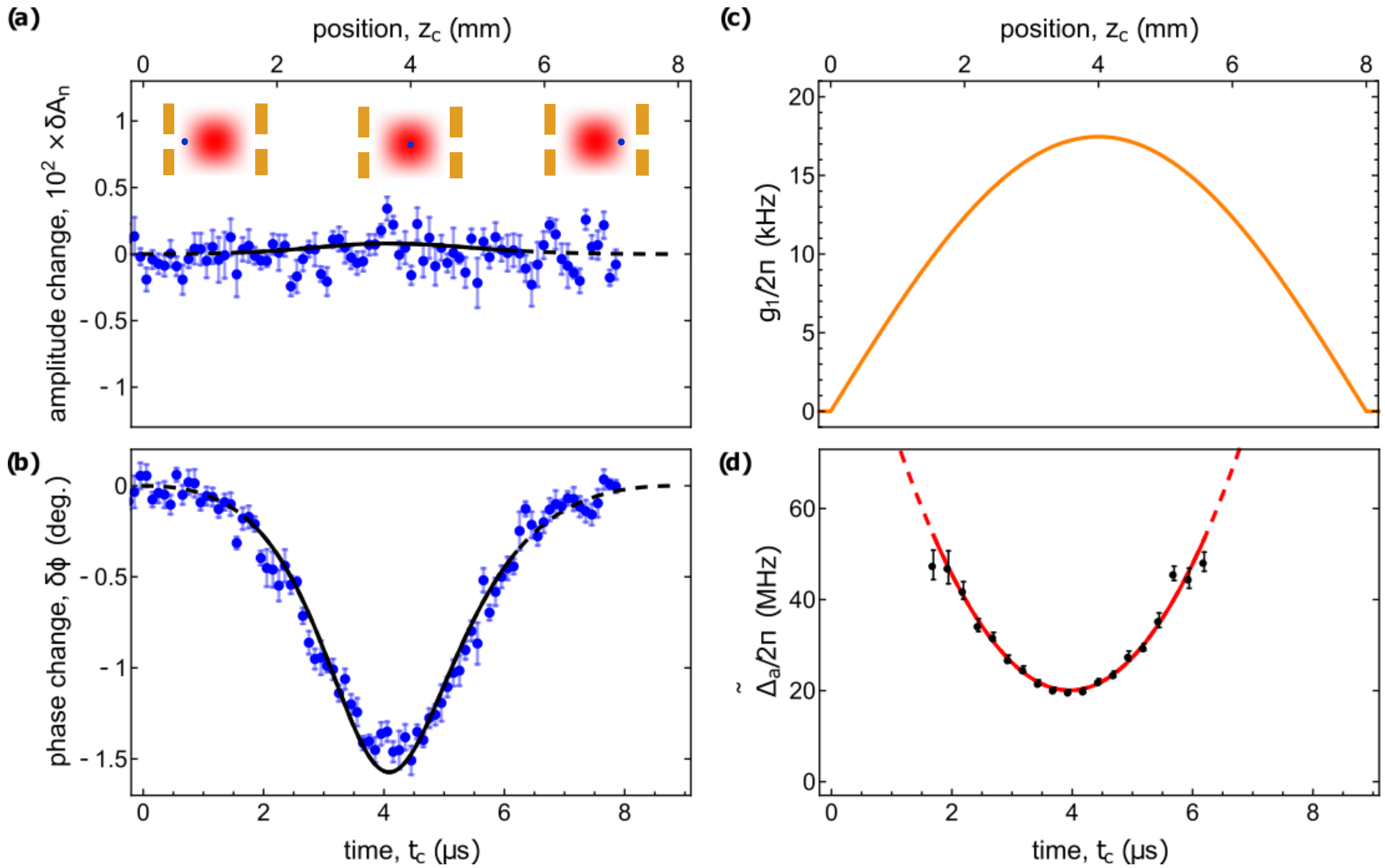


$$\chi = -\frac{g_1{}^2 N}{\Delta_a}$$

Probe detuning: $\Delta_p = \omega_p - \omega_c$

(plot with exaggerated dispersive shift)

Dispersive effect along atomic path

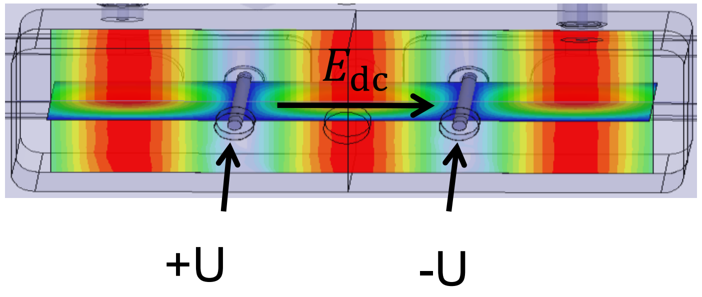


- Fit with coupling and detuning dependence:

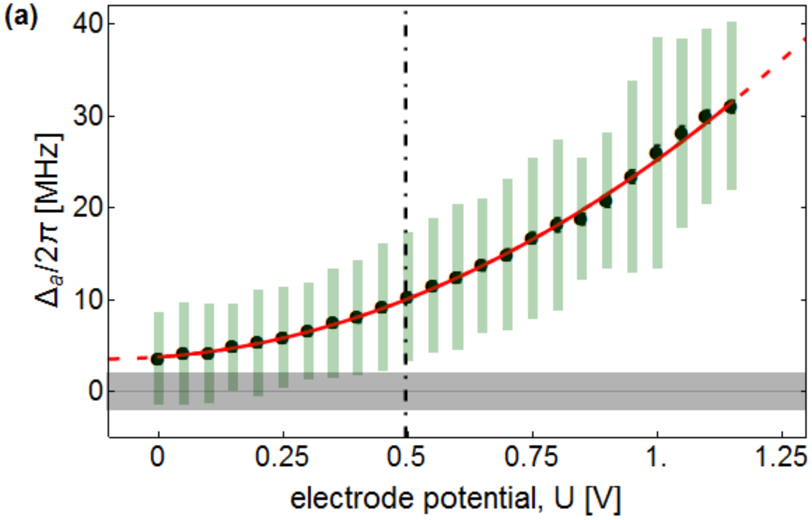
$N = 3.3(2) \cdot 10^3$ coupled Rydberg atoms

Variation of atom-cavity detuning

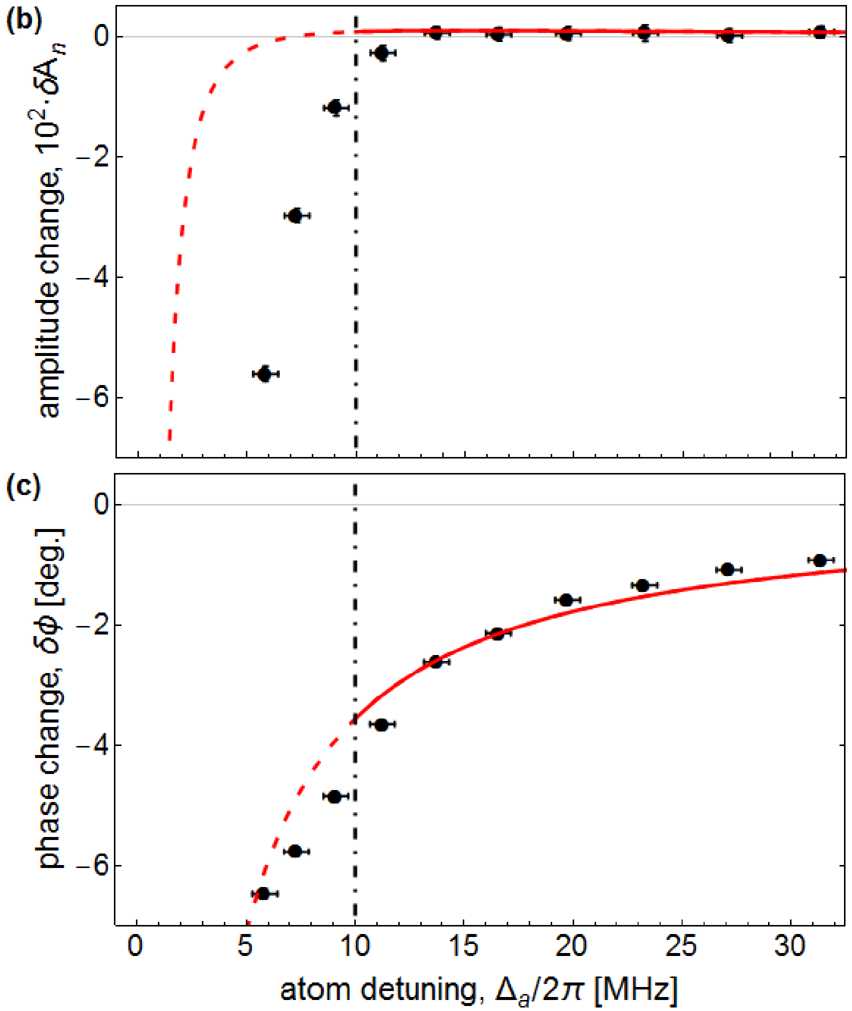
Simulated |E| of the TE301 mode



Quadratic Stark effect

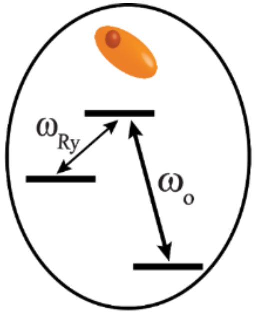


Cavity response :



Close to cavity resonance :

atom absorbs a microwave
photon and decays
to ground state
=> Microwave absorption



Dispersive shift :

$$\delta\phi \propto \chi = -\frac{g_1{}^2 N}{\Delta_a}$$

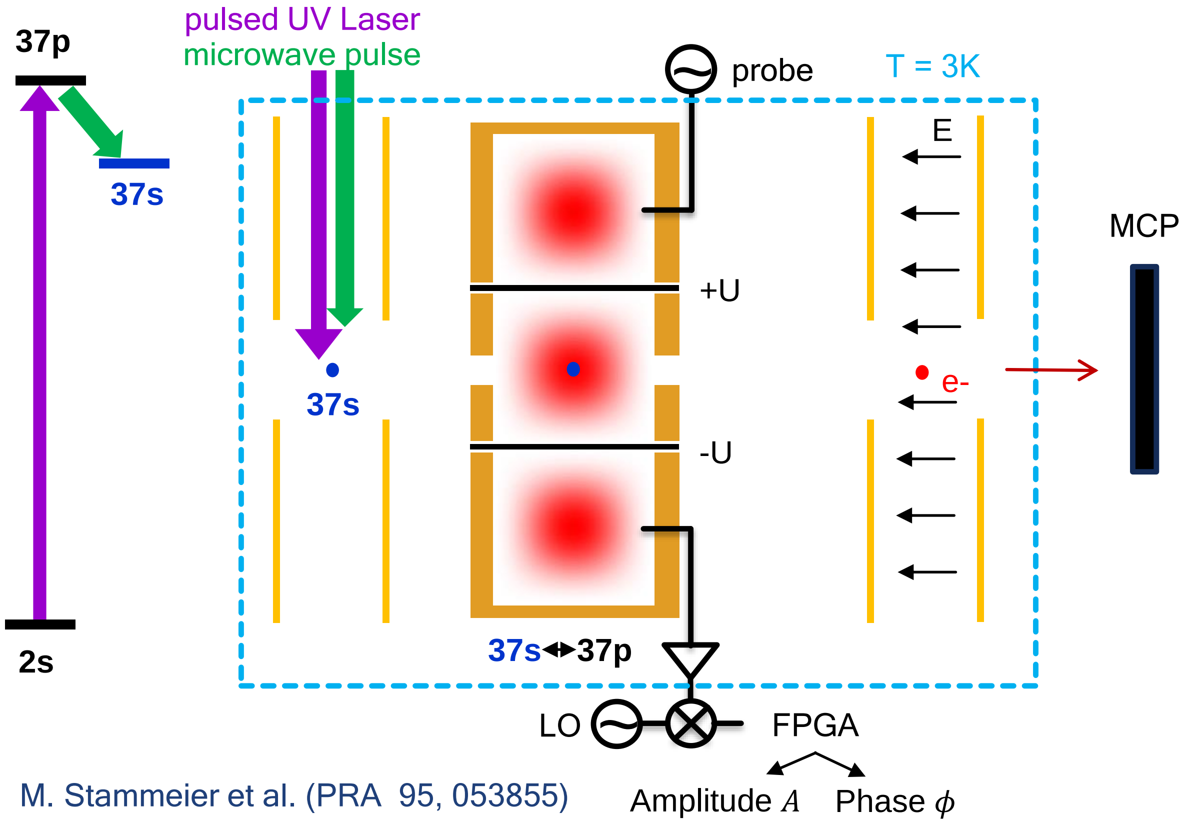
Variation of Rydberg atom number

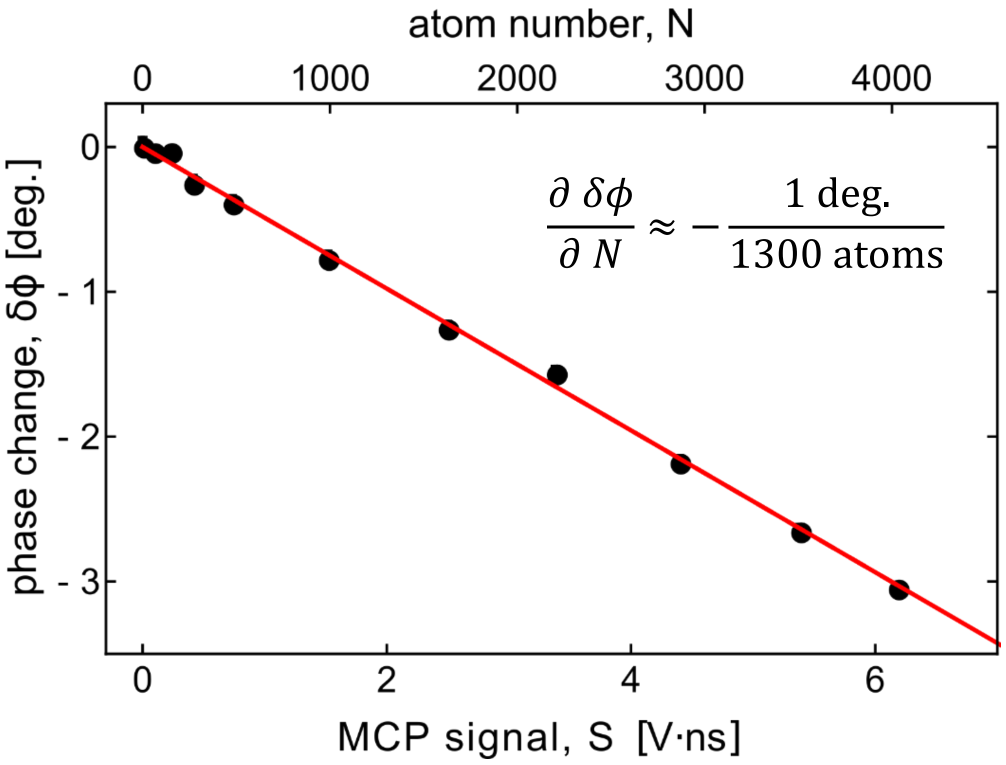
Measure:

- Phase change (at cavity center)
- Signal on Multi Channel Plate

And change efficiency of MW transition to 37s state

37p atoms decay to ground state before entering cavity





$$\frac{\partial\,\delta\phi}{\partial N} \approx -\frac{1\text{ deg.}}{1300\text{ atoms}}$$

dispersive shift measurement = non-destructive detection of the number of Rydberg atoms

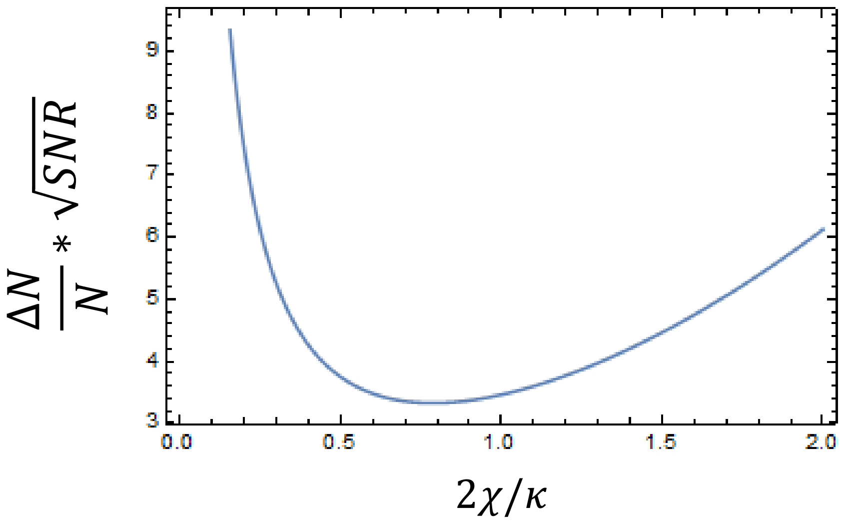
M. Stammeier et al. (PRA 95, 053855)

Detection efficiency

Precision of atom number measurement:

$$\frac{\Delta N}{N} = \left(\frac{2\chi}{\kappa} + \frac{\kappa}{2\chi}\right)\sqrt{2 + \left(\frac{2\chi}{\kappa}\right)^2}\,\frac{1}{\sqrt{SNR}}$$

Single shot power SNR : $SNR = \dfrac{n_c\,\kappa_{out}\,\tau}{n_{noise}}$



Small dispersive effect

Lower effect on phase
Lower transmission

M. Stammeier et al. (PRA 95, 053855)

Precision optimization :

1) Optimal response :
$\Rightarrow$ $g_N >> \kappa$: collective strong coupling
$\Rightarrow$ Reduce cavity linewidth κ

2) Increase interaction time τ :
$\Rightarrow$ Reduce atom velocity
/ Increase cavity lenght
$\Rightarrow$ Trap atoms

3) Optimize output coupling κ_{out} :
$\Rightarrow$ Asymmetric and overcoupled cavity

4) Reduce detection noise n_{noise} :
$\Rightarrow$ Quantum limited amplifiers

5) Increase number of photons n_c :
$\Rightarrow$ Limited by critical photon number

Critical photon number

- Dispersive shift tends towards 0 for large probe powers due to higher order terms neglected in the dispersive approximation

Single atom (circuit QED):

- Jaynes-Cummings hamiltonian eigenvalues

$$\omega_{\pm,n_c} = n_c\,\omega_c + \frac{1}{2}\left(\Delta_a \pm \sqrt{\Delta_a^{\,2} + 4\,n_c\,g_1^{\,2}}\right)$$

- Power dependent dispersive shift

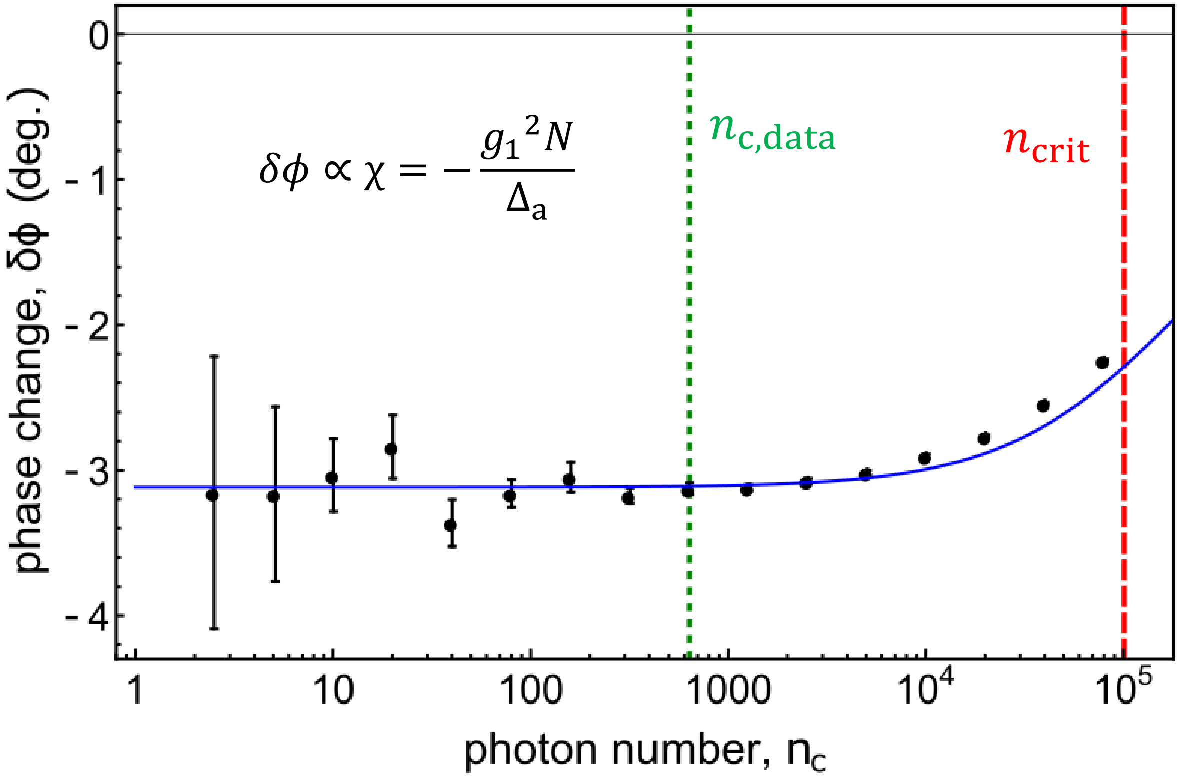
$$\chi(n_c) \simeq -\frac{g_1^{\,2}}{\Delta_a}\frac{1}{\sqrt{1+\frac{n_c}{n_{crit}}}}$$

with $n_{crit} = \frac{\Delta_a^{\,2}}{4\,g_1^{\,2}}$

N atoms:

- Tavis-Cummings hamiltonian approx. eigenvalues
- Power dependent dispersive shift

$$\chi(n_c) \simeq -\frac{g_1^{\,2}N}{\Delta_a}\frac{1}{\sqrt{1+\frac{n_c}{n_{crit}}}}$$



Limit of the detection

Precision of atom number measurement:

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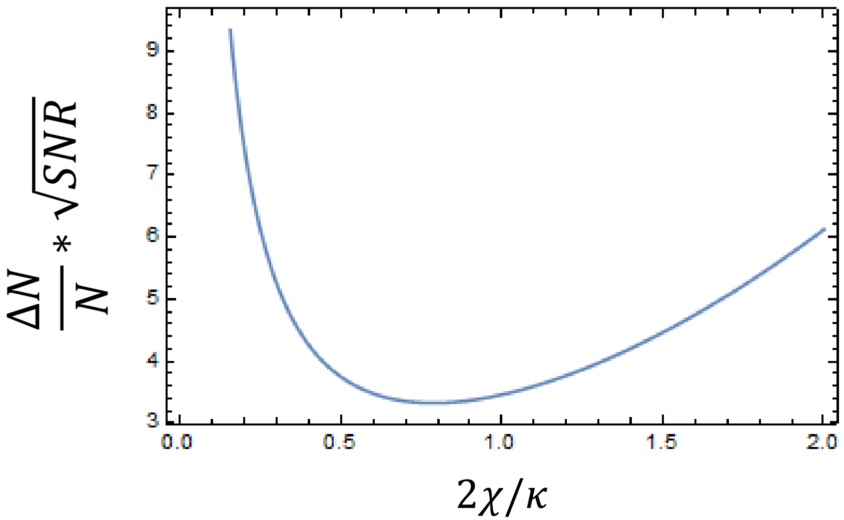
Single shot power SNR : $SNR = \frac{n_c\, \kappa_{\text{out}}\, \tau}{n_{\text{noise}}}$



Small dispersive effect

Lower effect on phase
Lower transmission

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With reasonable parameters :

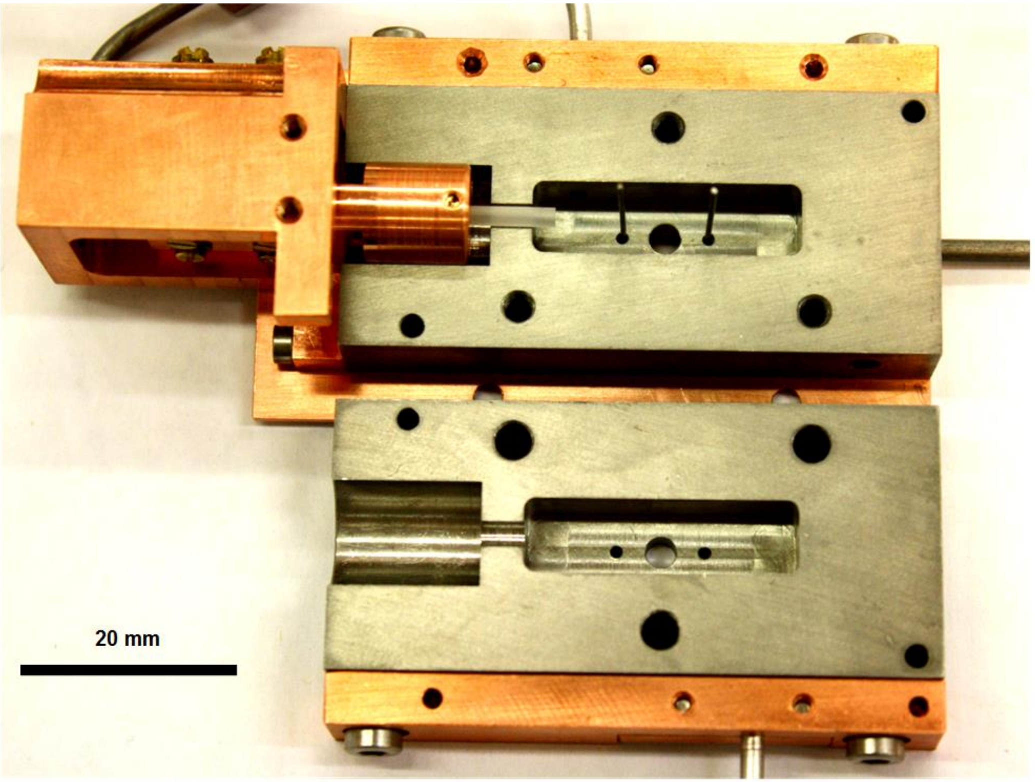
$N = 4000$
$\frac{g_N}{2\pi} = 1.1$ MHz
$\frac{\kappa_{\text{out}}}{2\pi} = 300$ kHz
$\frac{\Delta_{\text{a,opt}}}{2\pi} = 10$ MHz
$\tau = 50$ µs
$n_{\text{noise}} = 1$
$n_c = 880 = 10^{-2} n_{\text{crit}}$

$\frac{\Delta N}{N} = 1.2$ %
$\Delta N = 49$
(sub-poissonian)
In a single-shot measurement

M. Stammeier et al. (PRA 95, 053855)

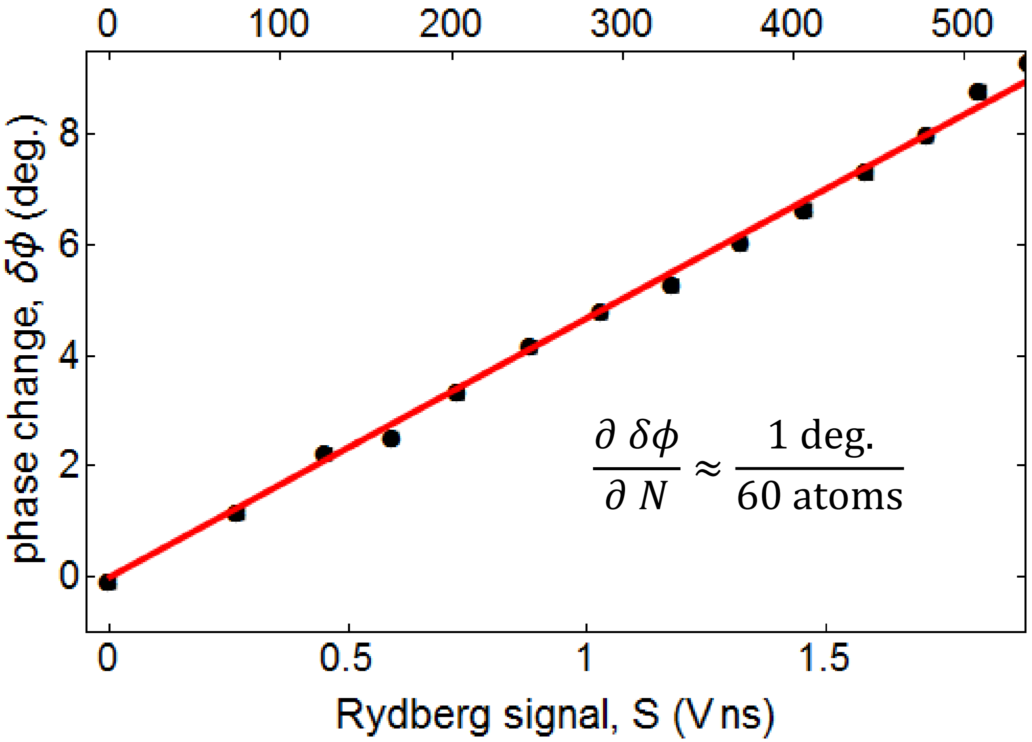
Improvement of the detection (1st step)

Superconducting cavity (Niobium):



$\frac{\kappa_{int}}{2\pi} = 12\ \mathrm{kHz}$ $\frac{\kappa}{2\pi} = 237\ \mathrm{kHz}$

Atom number measurement:



$$\frac{\partial\ \delta\phi}{\partial\ N} \approx \frac{1\ \mathrm{deg.}}{60\ \mathrm{atoms}}$$

Gain of a factor ≈20 in sensitivity

Conclusions

- Transmission measurement of dispersive shift induced by Rydberg atoms
- Non-destructive detection of atom numbers :

  Possible application : Merged beam experiments (P. Allmendinger et al.,ChemPhysChem 17, 3596 (2016))

Outlook

- Measurement of pseudo-spin $J_z = \frac{1}{2}\sum_j \sigma_{z,j}$ of the ensemble $\chi = \frac{{g_N}^2}{\Delta_\mathrm{a}} \frac{J_z}{N/2}$
- Increase the coupling by using photons confined in 2D waveguides
- Hybrid cavity QED

  with superconducting qubit