Center for
Quantum Science

# Cold atoms meet flux quanta & microwave cavities

József Fortágh

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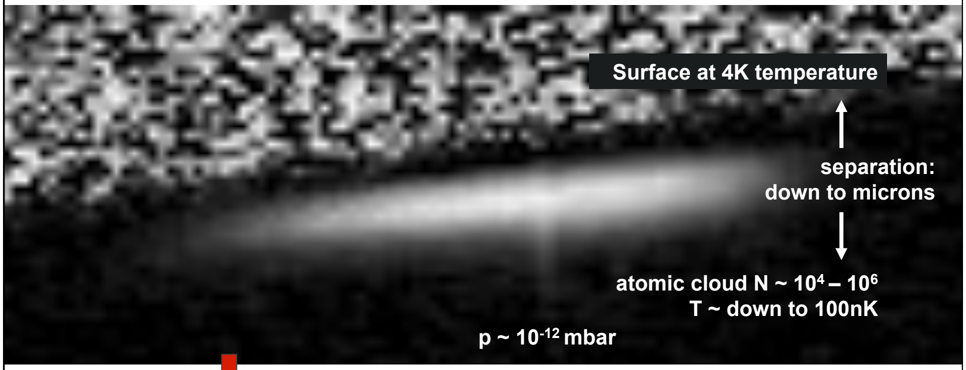
## Cold atoms on the superconducting chip


Surface at 4K temperature

separation:
down to microns

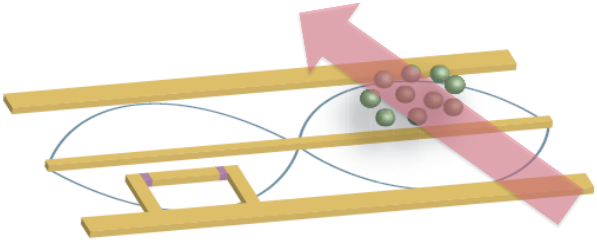
atomic cloud N ~ $10^4 – 10^6$
T ~ down to 100nK

$p \sim 10^{-12}$ mbar

**Measure and control interactions** → **Couple atoms to quantum electronic circuits**

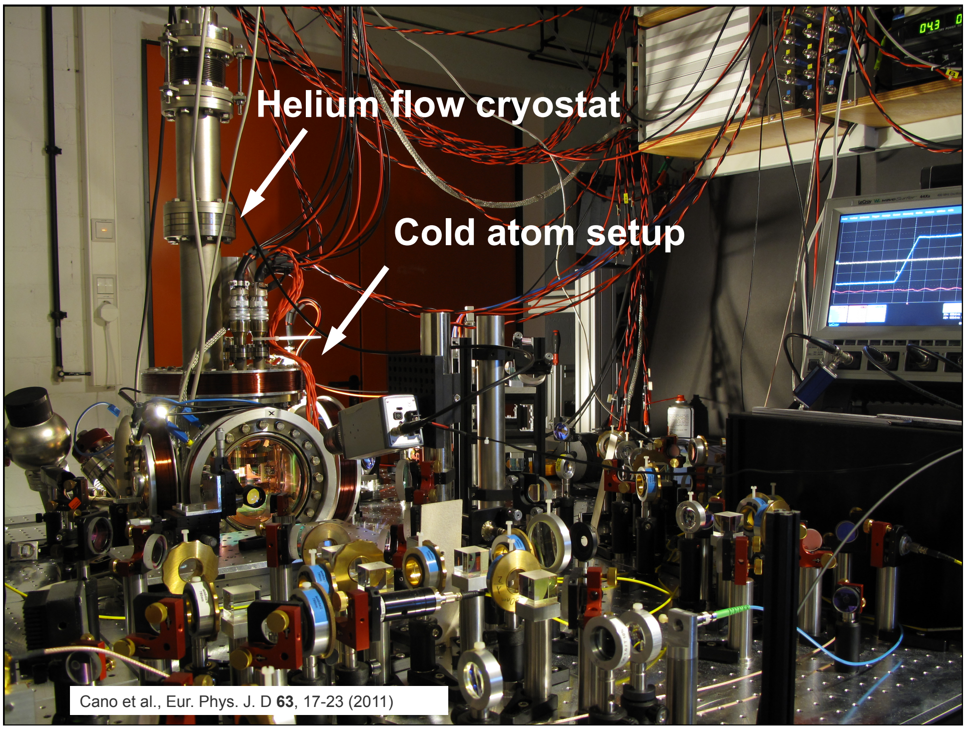
# Vision: Quantum processor on a chip

Possible architecture:  superconductors – microwaves – atoms – light



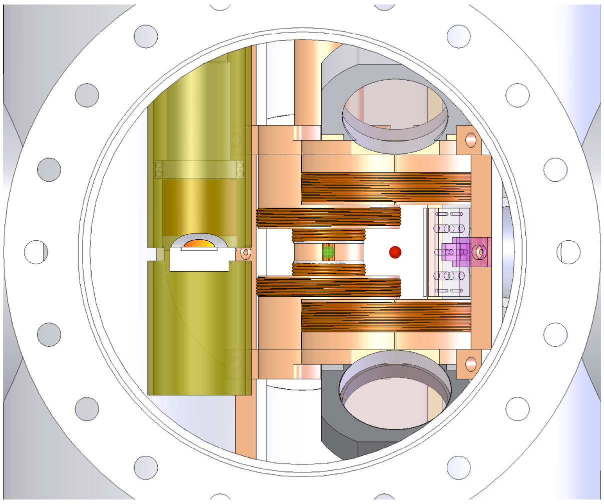
$$\frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$

Image: K. Tordrup and K. Molmer, PRA  77, 020301(R) (2008)



Cano et al., Eur. Phys. J. D **63**, 17-23 (2011)

## Mangneto-optical trap, magnetic trap, optical tweezers



Cano et al., Eur. Phys. J. D **63**, 17-23 (2011)

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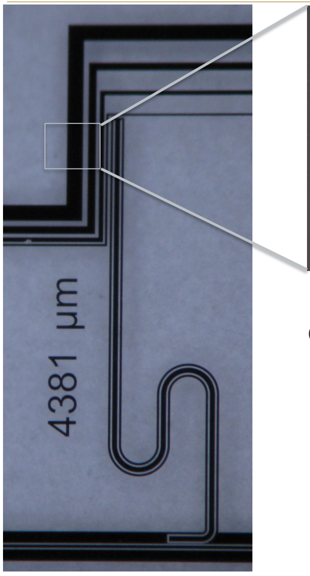
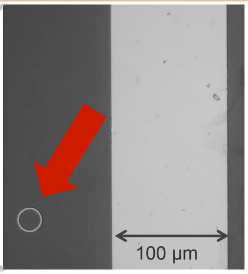
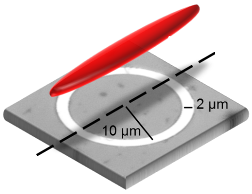
## Superconducting ring







Quantized flux in a superconducting ring

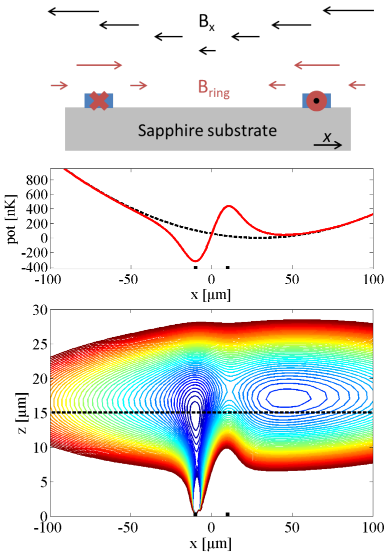
$$n \cdot \Phi_0 = \Phi = \int \vec{B} d\vec{A} \quad \text{with} \quad \Phi_0 = h/2e$$

Preparation of flux state:

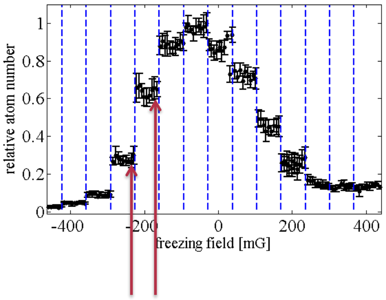
1. apply field above $T_c$
2. cool below $T_c$
3. remove external field

Weiss et al., PRL 114, 113003 (2015)

# Mapping the flux state of the ring to atomic clouds



Total atom number after 1s storage



Trap depth varies in steps with the number of flux quanta

Weiss et al., PRL 114, 113003 (2015)

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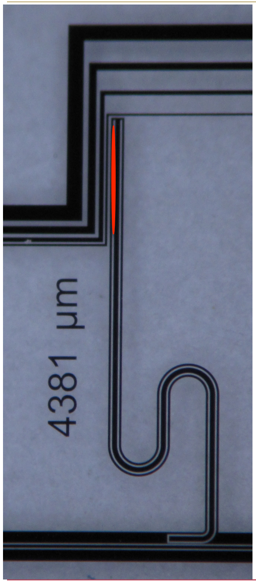
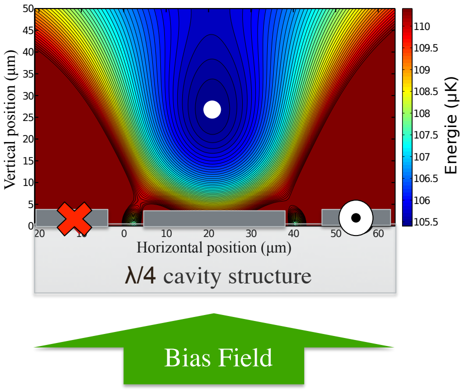
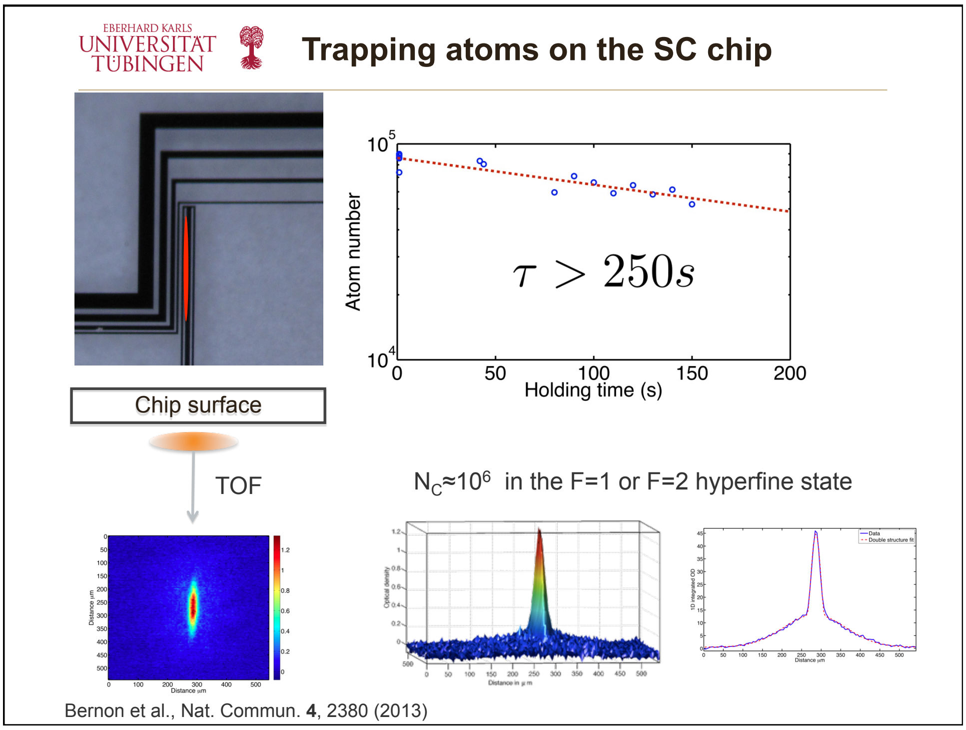
# Trapping atoms on the SC chip



Persistent current trap



Bernon et al., Nat. Commun. **4**, 2380 (2013)

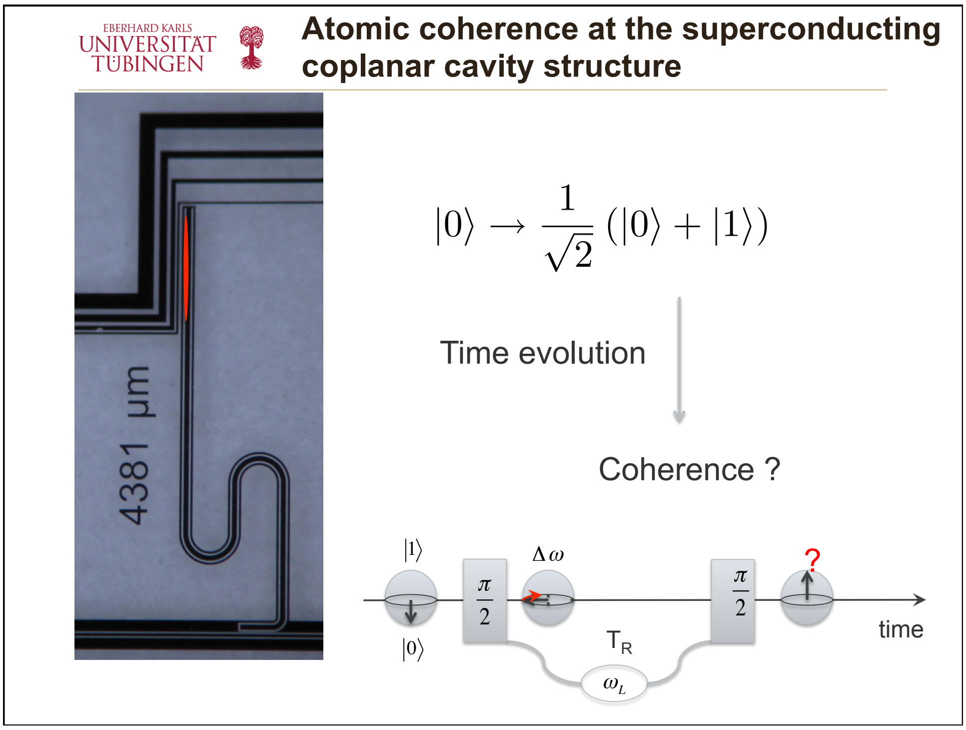


## Trapping atoms on the SC chip

$$\tau > 250s$$

$N_C \approx 10^6$ in the F=1 or F=2 hyperfine state

Bernon et al., Nat. Commun. **4**, 2380 (2013)



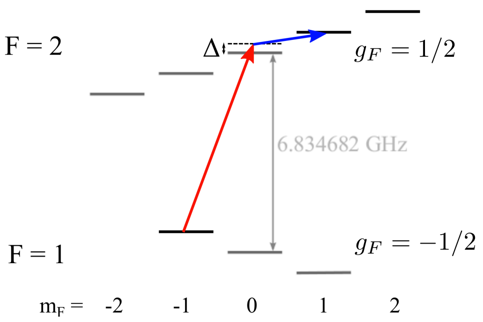
## Atomic coherence at the superconducting coplanar cavity structure

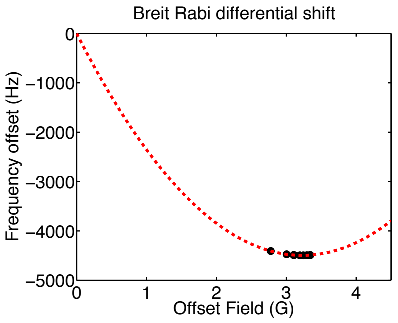
$$|0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$

Time evolution

Coherence ?

# Atomic coherence on a SC chip





$$\Delta\omega(B) \cong \omega_f + \beta\cdot(B-B_0)^2$$

D.M. Harber *et al* Phys. Rev. A **66**, 053616 (2002)
P. Treutlein *et al* Phys. Rev. Lett. **92**, 203005 (2004)

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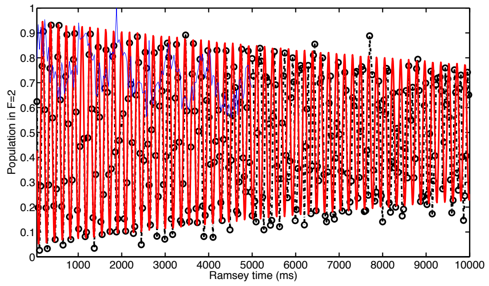
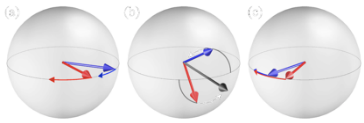
# Coherence and stability of operation



Coherence time $T_2 > 10\ s$

Expected due to residual frequency inhomogenity in the trap $T_2 \approx 6.5\ s$

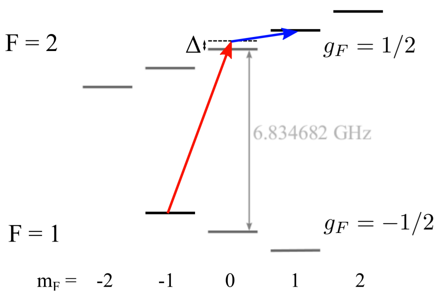
Identical spin rotation effect synchronizes the clock

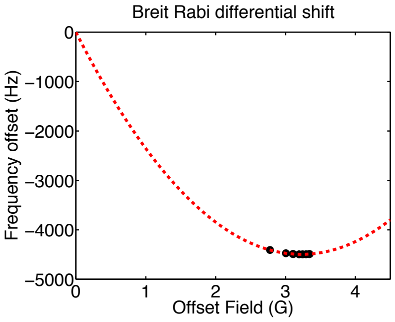


C. Deutsch *et al* Phys. Rev. Lett. **105**, 020401 (2010)

Bernon et al., Nat. Commun. **4**, 2380 (2013)

## Differential Zeeman shift: dephasing and phase shift





$$\Delta\omega(B) \cong \omega_f + \beta\cdot(B-B_0)^2$$

Suppression of the differential shift?

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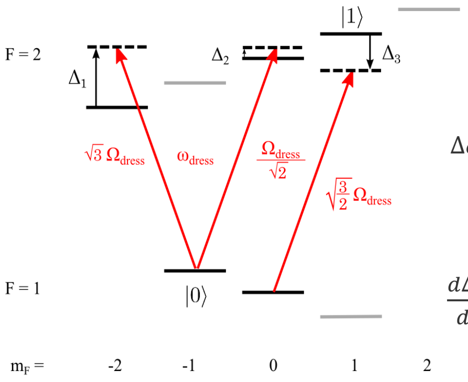
## Dressing the clock transition



Dressing field with perpendicular polarisation to the magnetic field at the trap centre (quantisation axis).

$$\Delta\omega(B) \cong \omega_f + \beta\cdot(B-B_0)^2 + \Omega_{dress}^2\cdot\left(\frac{3}{\Delta_1(B)}+\frac{1/2}{\Delta_2(B)}-\frac{3/2}{\Delta_3(B)}\right)$$

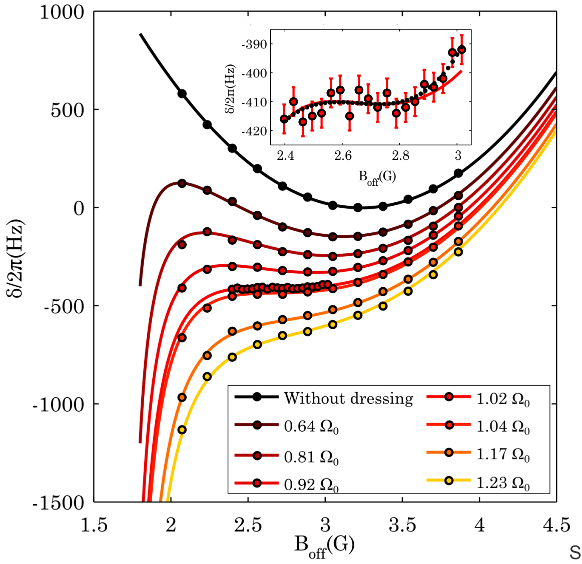
$$\frac{d\Delta\omega}{dB}, \frac{d^2\Delta\omega}{dB^2} = 0 \implies \Omega_{dress}, \omega_{dress}$$

$$\Omega_{dress} = \Omega_{dress}(B_{center})\ !$$

$$\omega_{dress} = \omega_{dress}(B_{center})\ !$$

For any offset field the **differential Zeeman shift can be suppressed** up to 2nd order.

## MW-control of the differential shift



$\Delta_{\text{dress}} = -2\pi \times 1.19$ MHz

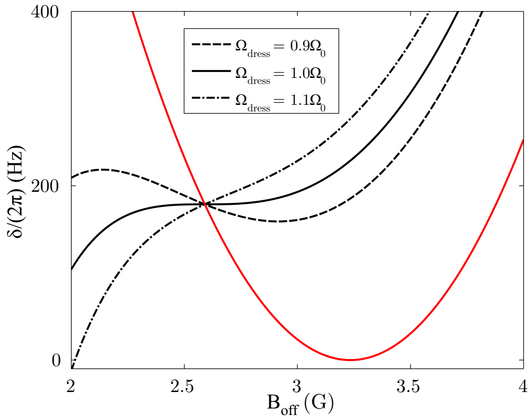
$\Omega_0 = 2\pi \times 20.1$ kHz

For any offset field the differential shift can be suppressed **up to 2$^{\text{nd}}$ order**.

Sárkány et al., PRA **90**, 053416 (2014)

## Doubly protected clock states

For certain offset fields the differential shift becomes independent also from the microwave power.

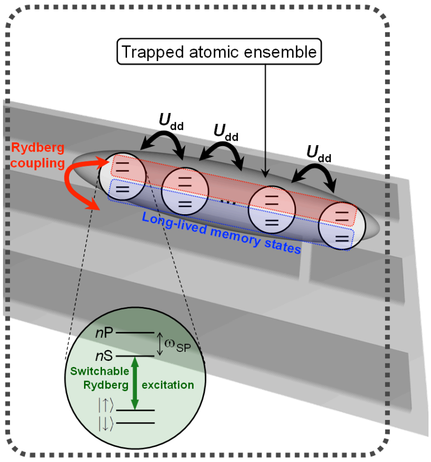


These **"double magic points"** are the preferable working points.

Sárkány et al., PRA **90**, 053416 (2014)

# Intermediate status

- Rubidium atomic clouds (BEC) at a superconducting chip
- Coherence of hyperfine superposition states: seconds
- Noise-protected memory states
- Atom-cavity coupling?



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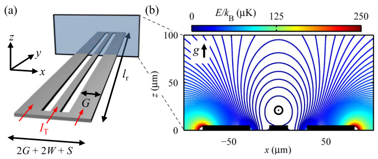
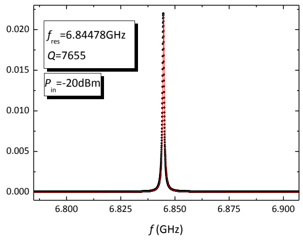
# Fabricated superconducting cavity





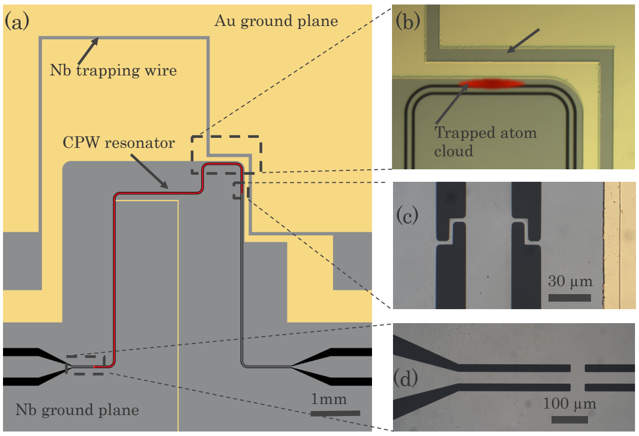
**Inductively coupled co-planar superconducting cavitiy** [1]

- Niobium on sapphire
- Fundamental frequency 6.8 GHz
- Measured Q ~ $10^4$ for the fundamental mode at 4K
- Higher modes Q ~ $10^3$

**With integrated traps**

[1] Bothner et al., New J. Phys. 15, 093024 (2013)
In-house collaboration with the group of Reinhold Kleiner & Dieter Koelle.

## Fabricated atom chip



Trapping

MW output port

MW input port

Ground planes are partially made of gold in oder to avoid the Meissner effect

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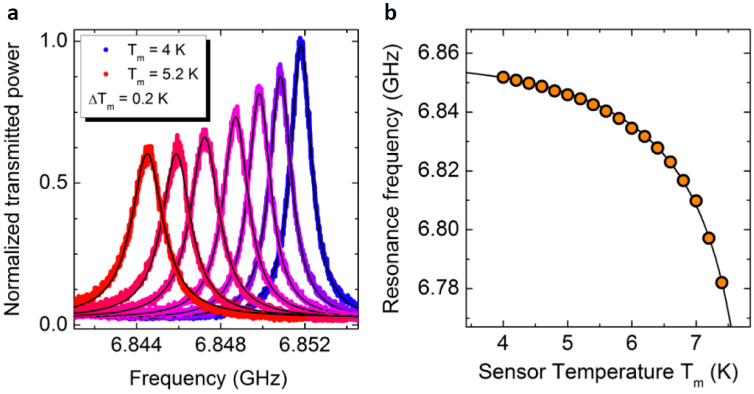
## Resonance frequenc vs. temperature



- Fundamental frequency tunable with temperature over 30 MHz
- Quality factor Q ~ $10^4$
- Cavity resonance matches HF-Splitting at T ~ 6K

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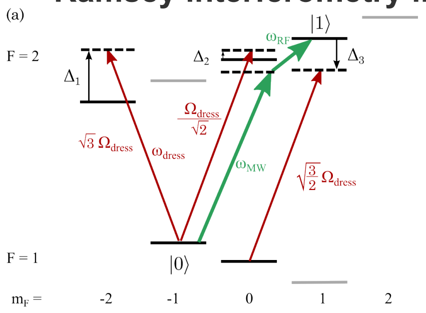
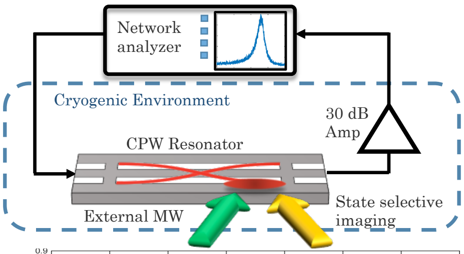
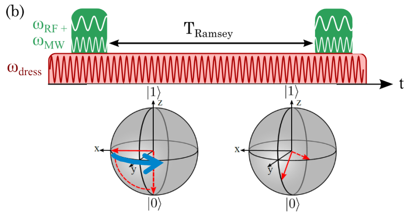
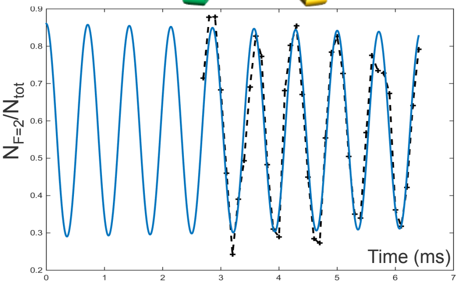
UNIVERSITÄT
TÜBINGEN

# Ramsey interferometry in the resonator









The Ramsey frequency varies with the dressing power and frequency.

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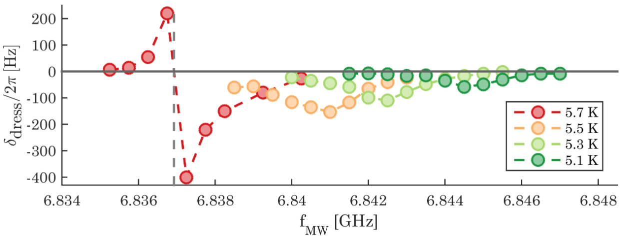
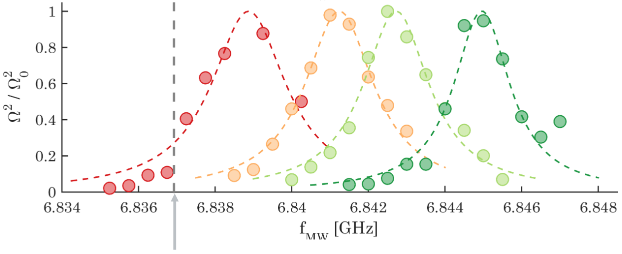
# Off-resonant dressing by the cavity field



**Dressing shift**

$$\delta \propto \frac{\Omega^2_{resonator}}{\Delta}$$

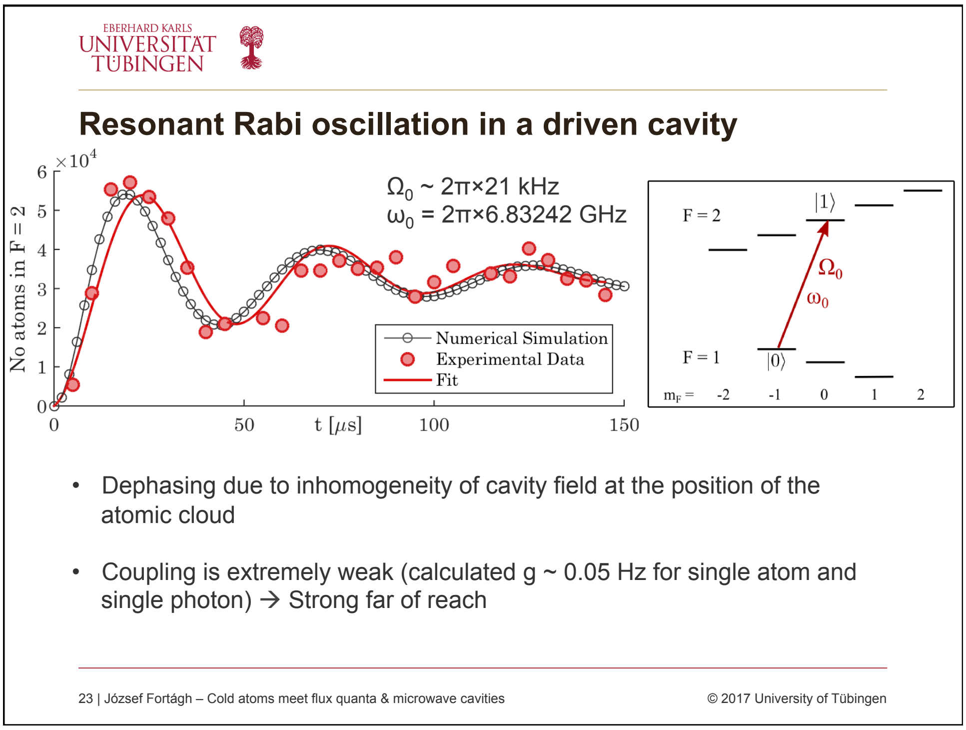


F = 1, $m_F$ = 0 → F = 2, $m_F$ = 1 resonance

**Rabi frequency** reconstructed from dressing shift

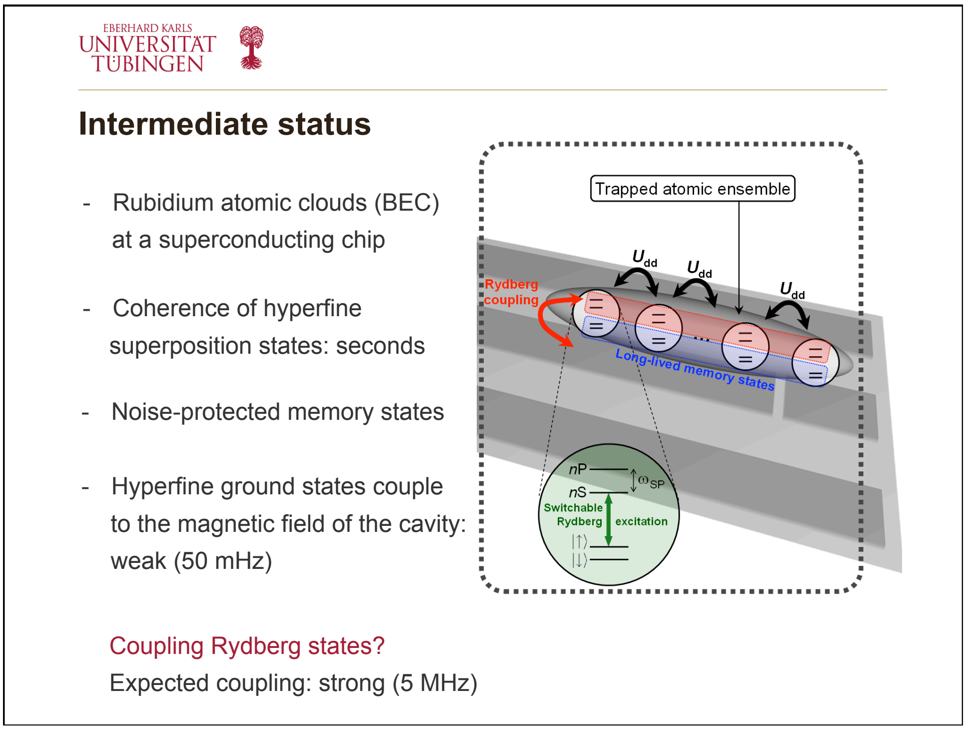
**Direct proof of magnetic coupling between atoms & driven cavity:** ~ 50 mHz

→ weak magnetic coupling



## Resonant Rabi oscillation in a driven cavity

- Dephasing due to inhomogeneity of cavity field at the position of the atomic cloud
- Coupling is extremely weak (calculated g ~ 0.05 Hz for single atom and single photon) → Strong far of reach



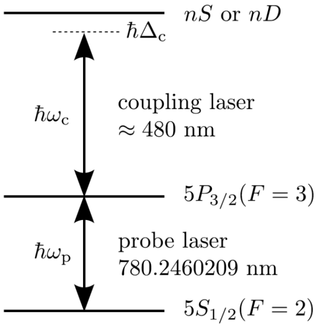
## Intermediate status

- Rubidium atomic clouds (BEC) at a superconducting chip
- Coherence of hyperfine superposition states: seconds
- Noise-protected memory states
- Hyperfine ground states couple to the magnetic field of the cavity: weak (50 mHz)

Coupling Rydberg states?
Expected coupling: strong (5 MHz)

# Spectroscopy of $^{87}$Rb Rydberg states

Electromagnetically induced transparency (EIT)



$nS$ or $nD$

$\hbar\Delta_c$

$\hbar\omega_c$

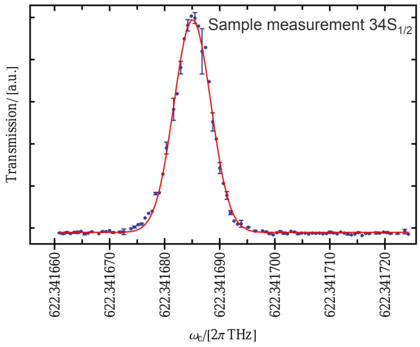
coupling laser
$\approx$ 480 nm

$5P_{3/2}(F=3)$

$\hbar\omega_p$

probe laser
780.2460209 nm

$5S_{1/2}(F=2)$



Lasers locked to frequency comb & wavemeter.

**Measurement of quantum defects and ground state ionization energy of $^{87}$Rb**
( ≤1 MHz abs. accuracy)
Mack et al., Phys. Rev. A **83**, 052515 (2011)

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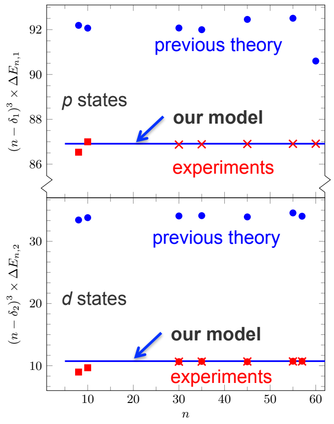
# Core potential



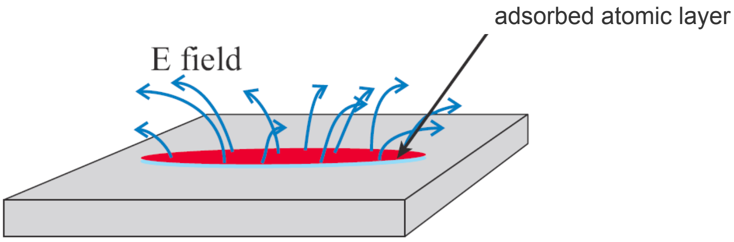
Fine splitting of $^{87}$Rb Rydberg
p- and d-states

Previous models:
Marinescu et al., PRA 49, 982 (1994)
Pawlak et al., PRA 89, 042506 (2014)

**Our model:**
**Sanayei et al., PRA 91, 032509 (2015)**

## State of research

Polarized adatoms at the surface produce inhomogeneous electric fields



McGuirk et al., Phys. Rev. A **69**, 62905 (2004)
Tauschinsky Phys. Rev. A **81**, 063411 (2010)
Hattermann et al, Phys. Rev. A **86**, 022511 (2012)
Carter et al., Phys. Rev. A **86**, 053401 (2012)
Chan et al., Phys. Rev. Lett. **112**, 026101 (2014)
Sedlacek et al., Phys. Rev. Lett. **116**, 133201 (2016)
...

**Solution:**

Selection of Rydberg state pairs
- to match the cavity resonance
- to suppress differential shift

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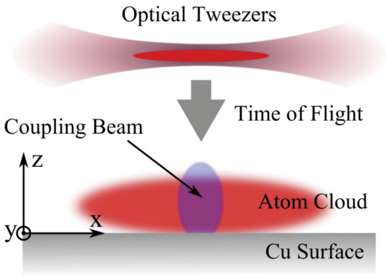
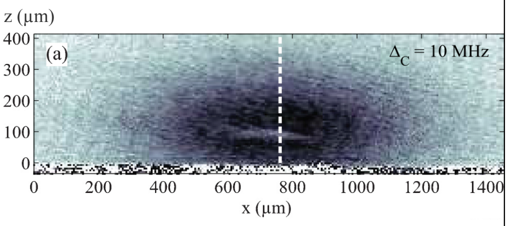
## Stark shift near a dipole layer (copper surface with Rb adsorbates)

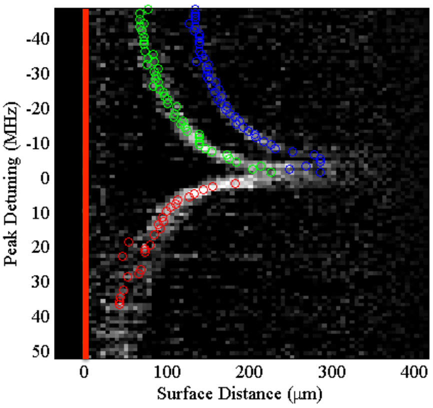


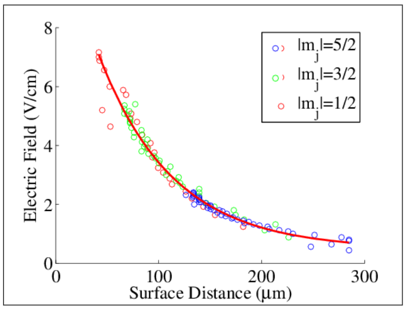


Energy shift measured with electromagnetically induced transparency (EIT)

**Amsterdam:** Tauschinsky Phys. Rev. A **81**, 063411 (2010)
**Tübingen:** Hattermann et al, Phys. Rev. A **86**, 022511 (2012)

## Rubidium Rydberg level shifts near a copper surface





Coupling laser detuning to the $5P_{3/2} \rightarrow 35D_{5/2}$ transition of $^{87}$Rb
We observe the stark shift of the $|m_j|$= 1/2, $|m_j|$= 3/2, and $|m_j|$ =5/2 states

Hattermann et al, Phys. Rev. A **86**, 022511 (2012)

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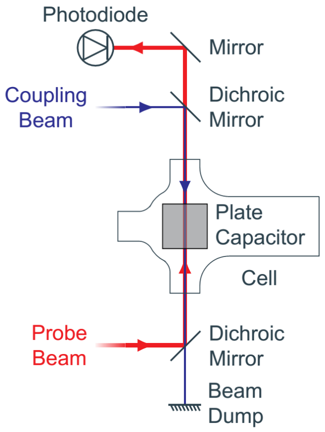
## Stark-map in a cell



**Setup**

- Room-temp. vapor cell with electrodes
- EIT spectroscopy on $^{87}$Rb, n=35 to 70
- Lasers locked to frequency comb & wavemeter

**Measured Stark maps**

- E = 0-500 V/cm, 3mV/cm field steps
- 2 MHz optical resolution

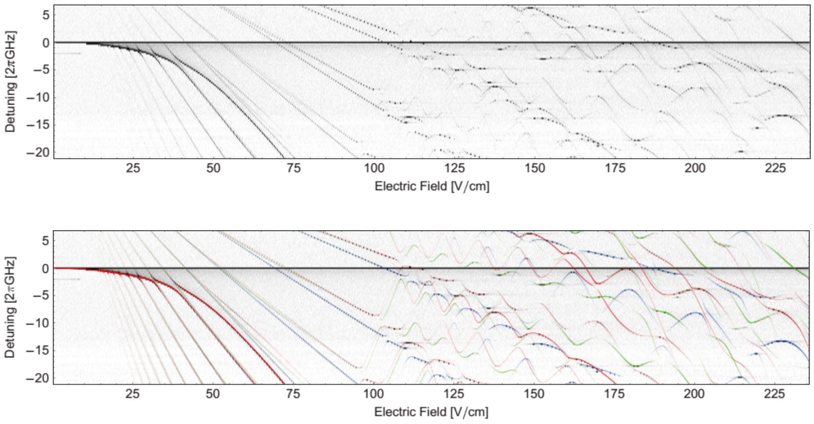
**Improved numerical calculation**

based on Zimmerman PRA 20, 2251 (1979)

**incl. transition strengths:**

- Grimmel et al., NJP 17, 053005 (2015)

## $35S_{1/2}$ Stark Map – EIT measurement (greyscale) and results from numerical calculations (colors)



Grimmel et al., NJP 17, 053005 (2015)

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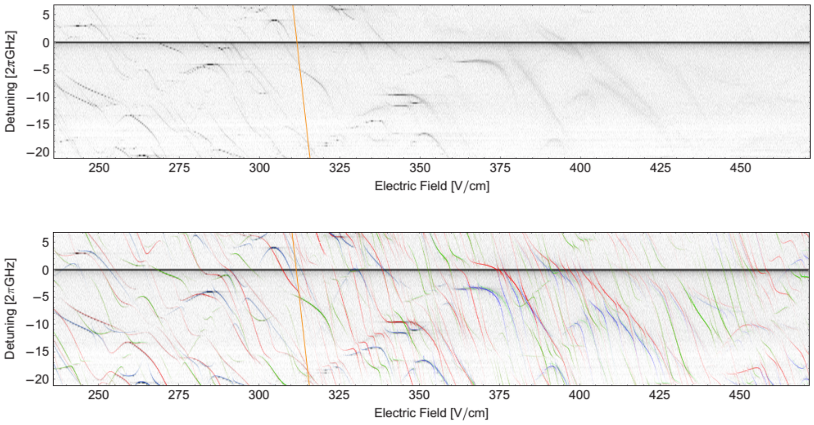
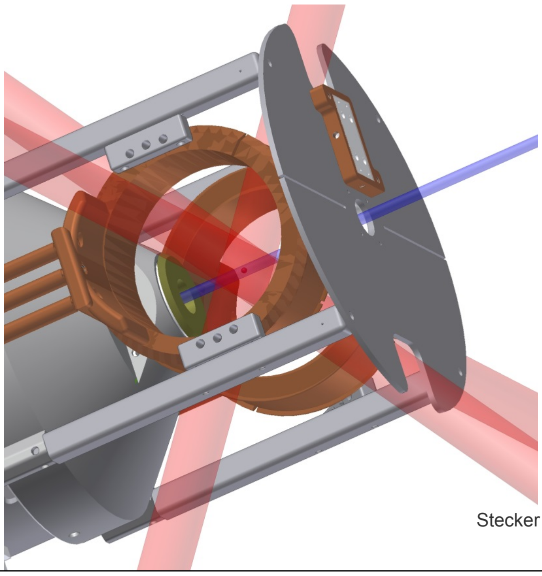
## $35S_{1/2}$ Stark Map – EIT measurement (greyscale) and results from numerical calculations (colors)



Grimmel et al., NJP 17, 053005 (2015)

# Ionization Stark spectra from a MOT



Stecker et al., NJP 19, 043020 (2017)

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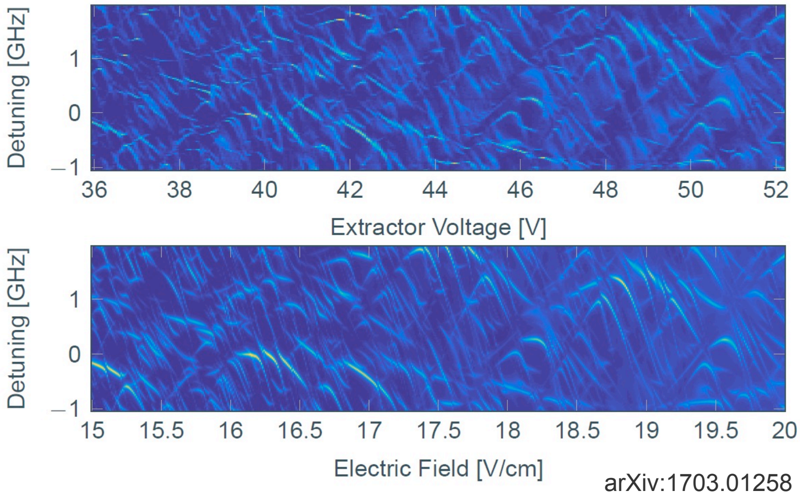
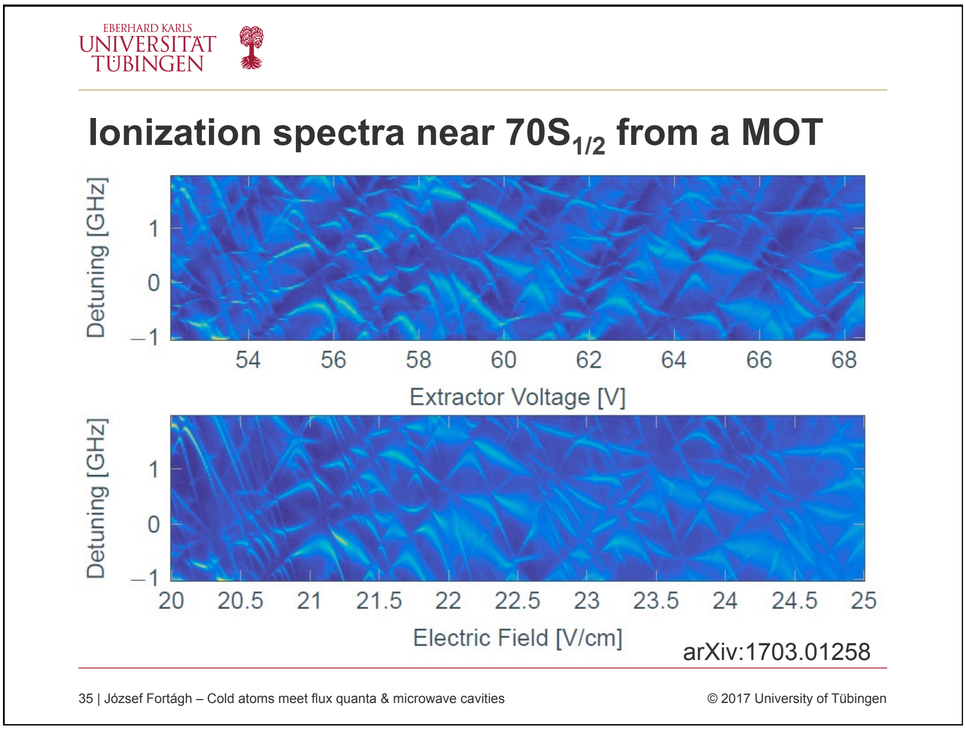
# Ionization spectra near $70S_{1/2}$ from a MOT



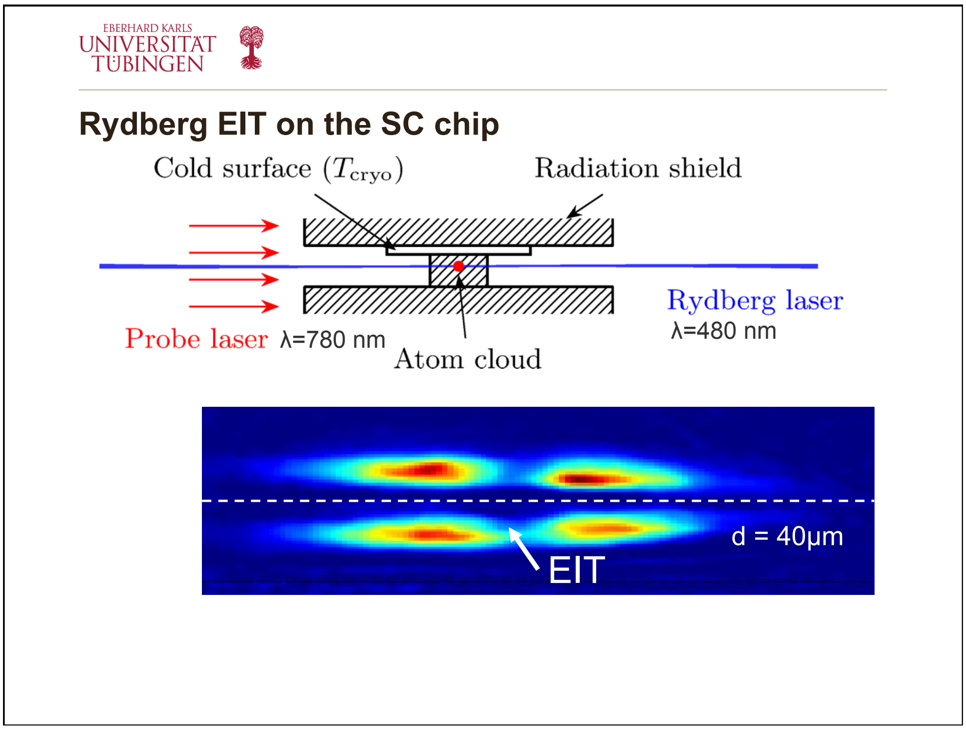
arXiv:1703.01258



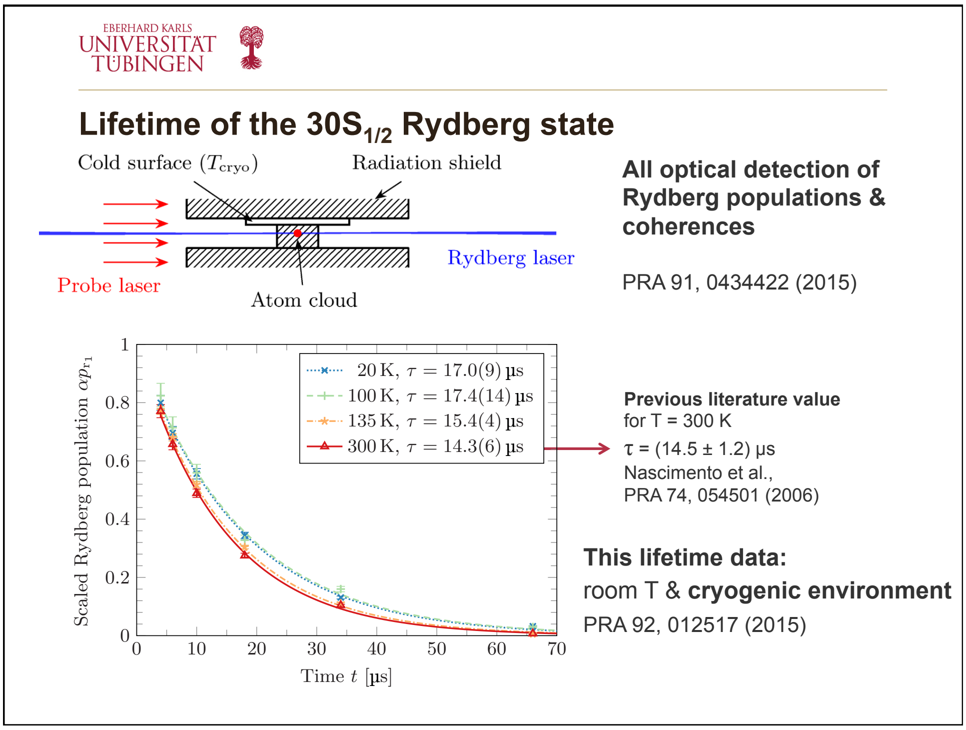
## Ionization spectra near $70S_{1/2}$ from a MOT

arXiv:1703.01258

35 | József Fortágh – Cold atoms meet flux quanta & microwave cavities



## Rydberg EIT on the SC chip



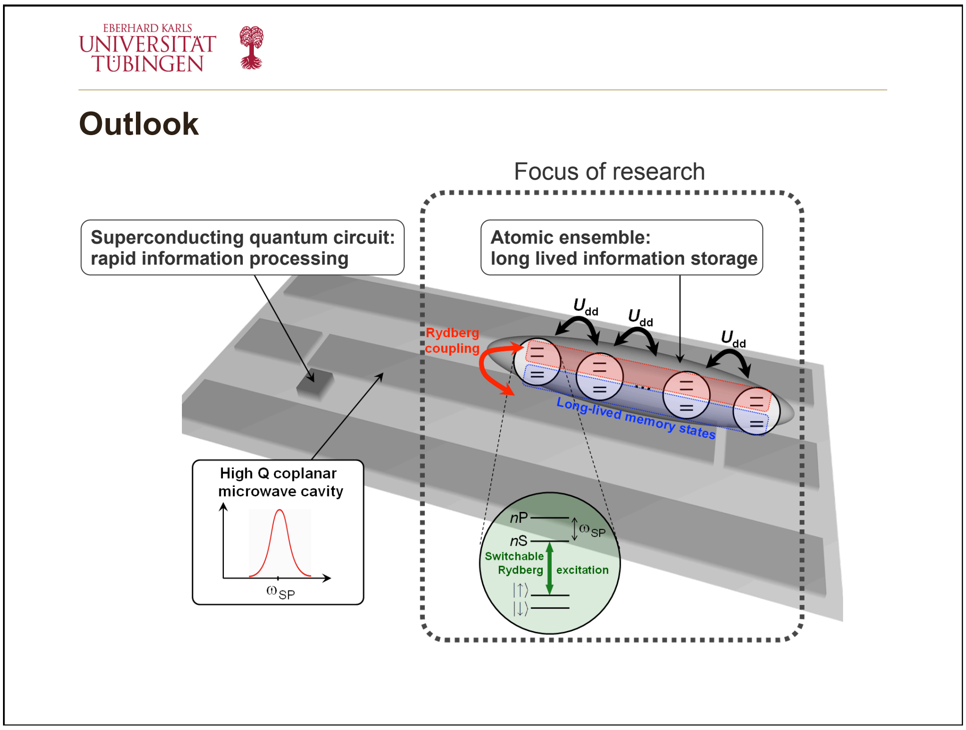
## Lifetime of the $30S_{1/2}$ Rydberg state

**All optical detection of Rydberg populations & coherences**

PRA 91, 0434422 (2015)

**Previous literature value**
for T = 300 K
τ = (14.5 ± 1.2) µs
Nascimento et al.,
PRA 74, 054501 (2006)

**This lifetime data:**
room T & **cryogenic environment**
PRA 92, 012517 (2015)



## Outlook

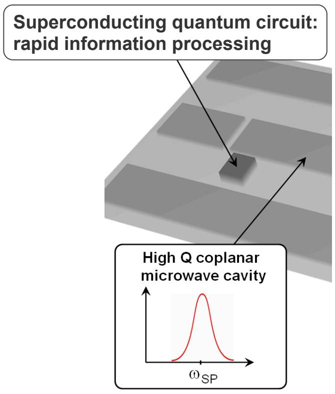
Focus of research

**Superconducting quantum circuit: rapid information processing**

**Atomic ensemble: long lived information storage**

**High Q coplanar microwave cavity**

# Outlook



**Coherence of solid-state-qubits is short at 4K** (<1µs)

➔ **50mK cryostat** (~100µs)
MOT & magnetic traps achieved
in the 4K stage of the cryostat

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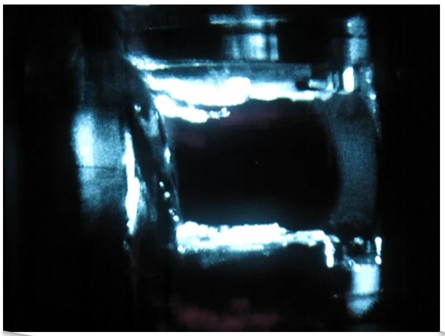
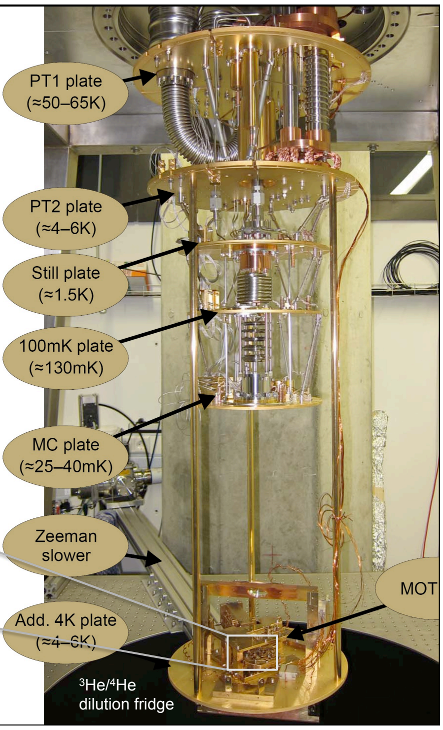
## MOT & magnetic traps achieved in the 4K stage of dilution fridge



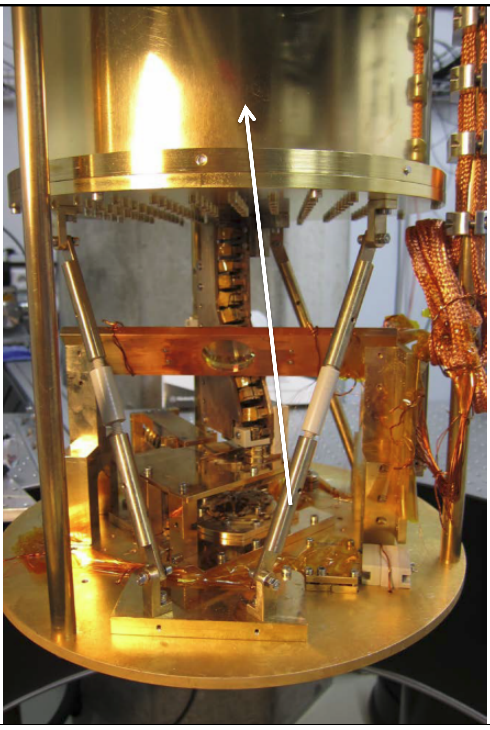


Jessen et al., Appl. Phys. B **116**, 665-671 (2014)

**25 mK stage**

**magnetic transport**

**4K stage**



Jessen et al., Appl. Phys. B **116**, 665-671 (2014)

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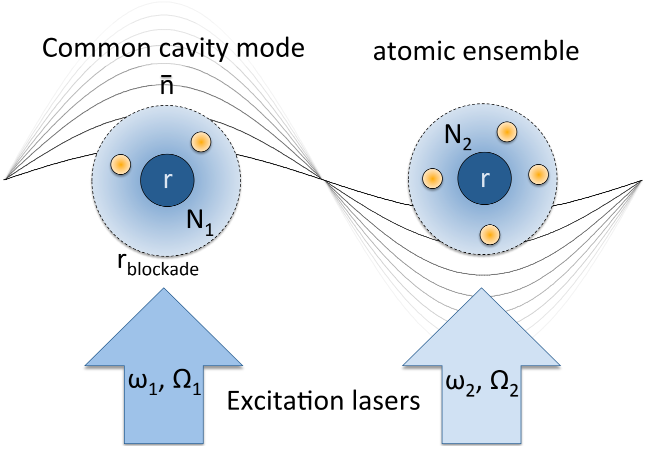
## Long distance quantum gate in a thermal cavity ?



Common cavity mode

$\bar{n}$

atomic ensemble

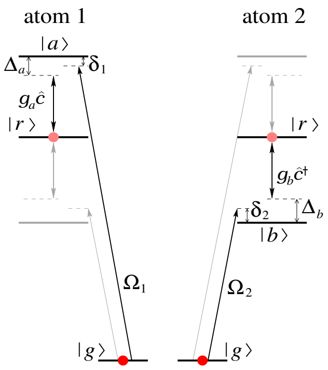
$N_1$ $N_2$ $r$ $r$

$r_{blockade}$

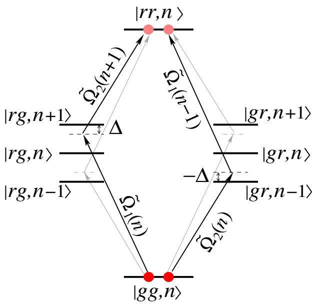
$\omega_1, \Omega_1$ Excitation lasers $\omega_2, \Omega_2$

Sárkány, Fortágh, Petrosyan, PRA **90 (R)**, 030303 (2015)

## Sørensen-Mølmer scheme: Conditional excitation of a pair of Rydberg atoms in a cavity with *n* photons



Two optical photon excitation paths + virtual microwave cavity photon exchange



Resonant 4th order process is independent of *n* due to interference of the two paths

Sárkány, Fortágh, Petrosyan, PRA **90 (R)**, 030303 (2015)

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## Contributors to this work

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