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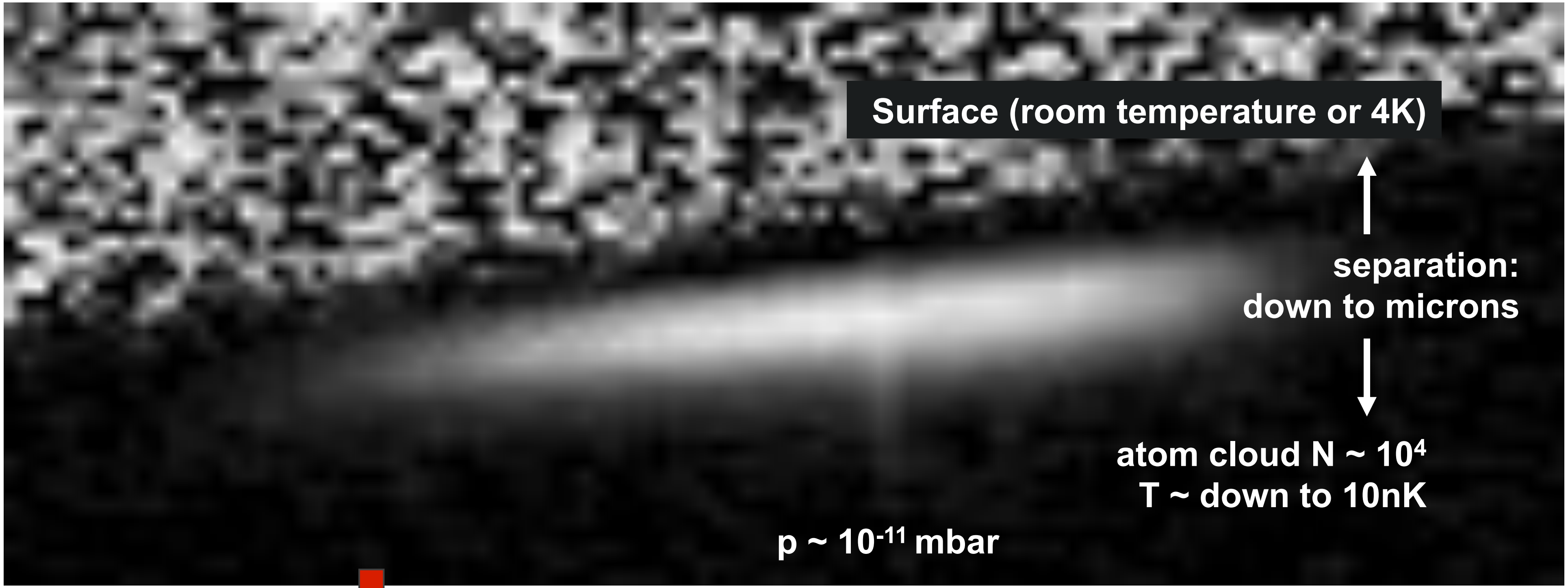
FACULTY OF
SCIENCE
Department of Physics

CQ Center for Quantum Science

Interfacing cold atoms and superconductors

József Fortágh

Cold atom – solid state interface



Surface (room temperature or 4K)

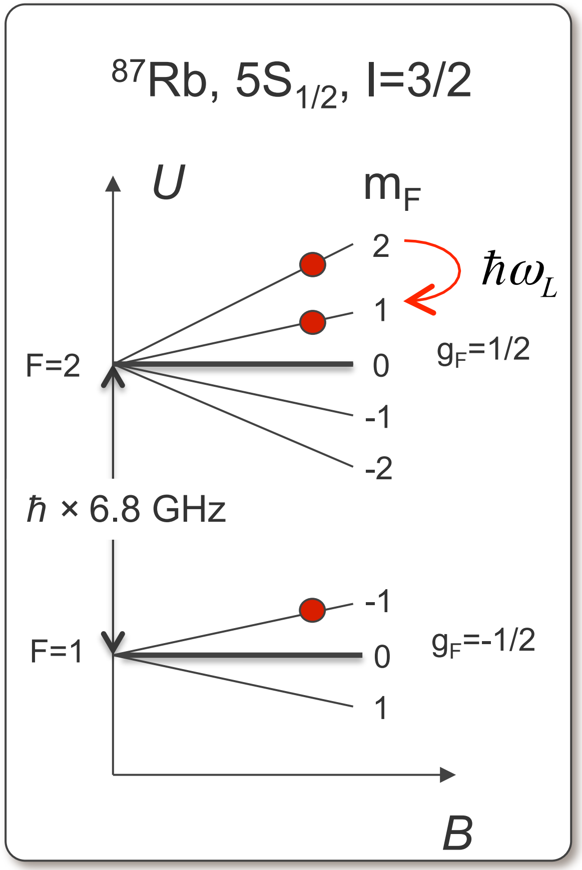
separation:
down to microns

atom cloud $N \sim 10^4$
$T \sim$ down to 10nK

$p \sim 10^{-11}$ mbar

Measure and control interactions → Coherent coupling between atoms and solid state devices ?

Rubidium ground state Zeeman splitting



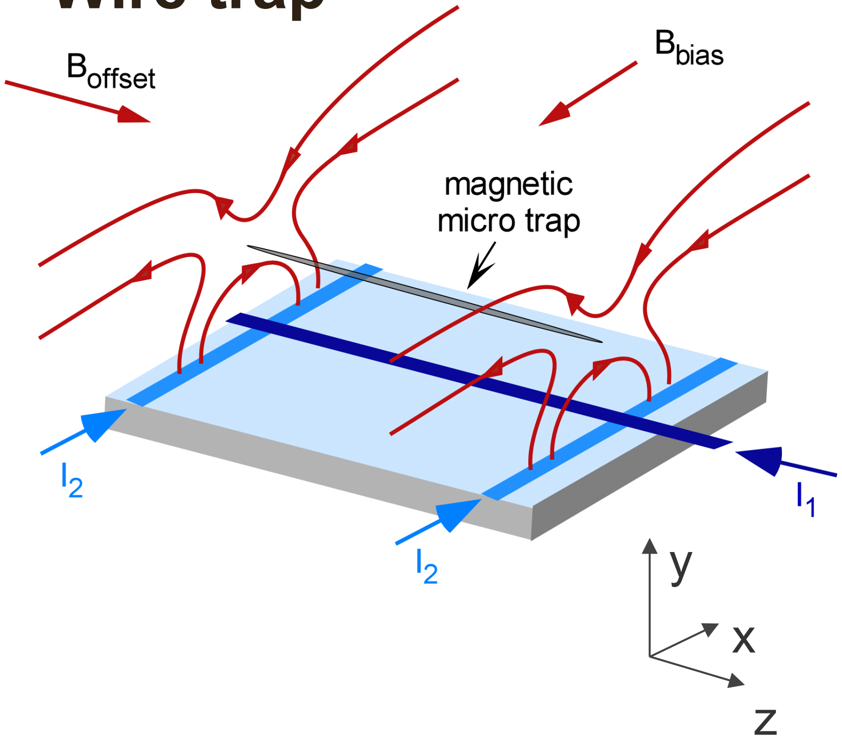
$$H_Z = -\overline{\mu}\cdot\overline{B}$$

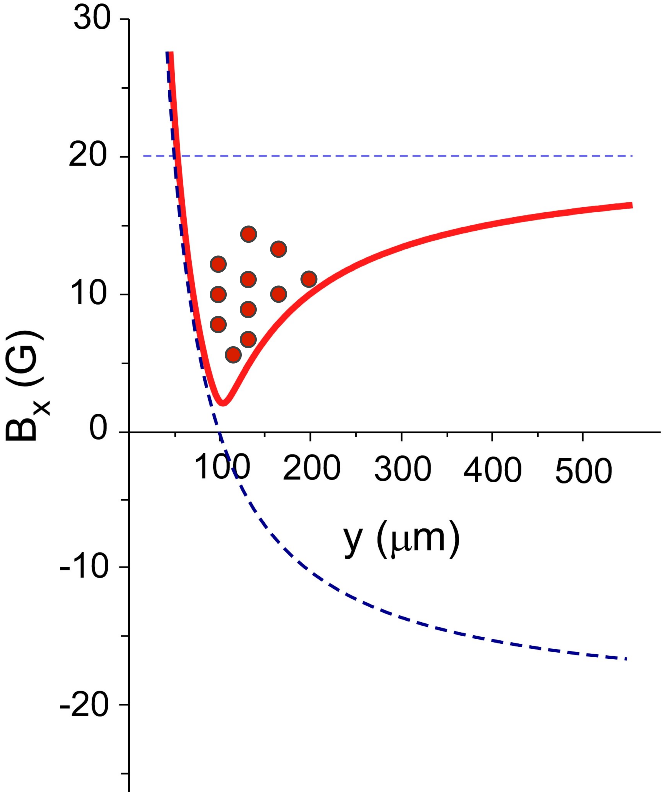
Magnetic moment: $\overline{\mu} = -g_F\mu_B\frac{\overline{F}}{\hbar} = -g_F\mu_B m_F$

Larmor frequency: $\omega_L = \frac{g_F\mu_B|B|}{\hbar}$

Magnetic trap: $U_{trap} = \mu\cdot|B|$

Wire trap





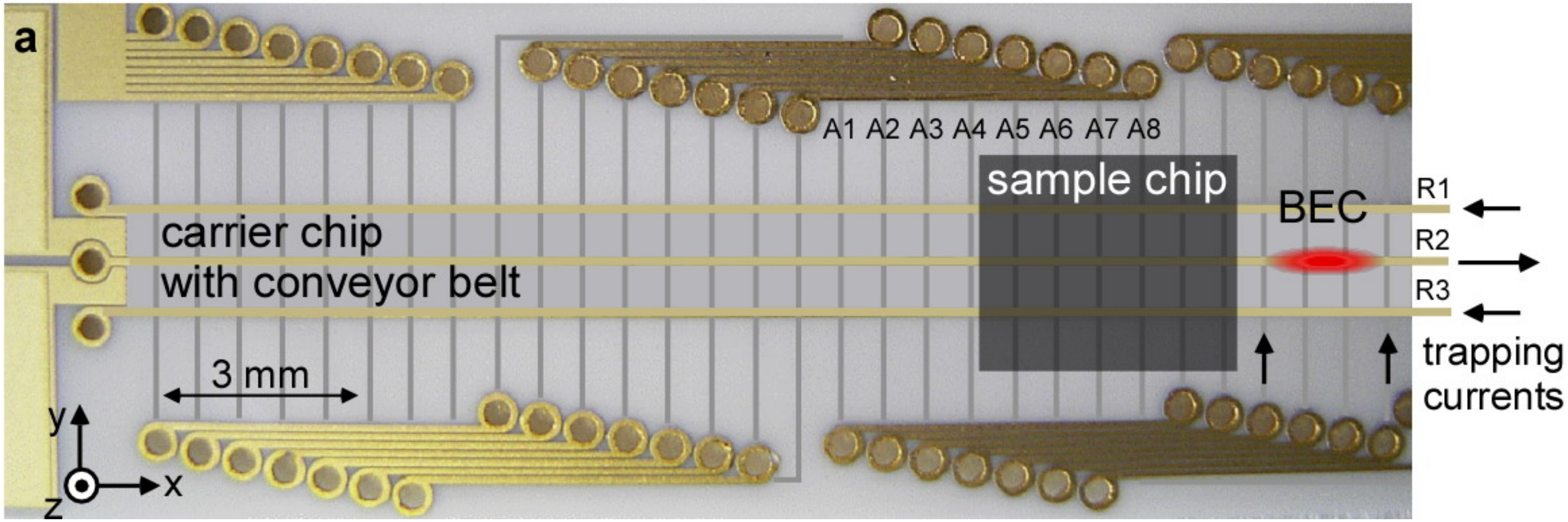
Harmonic potential *(Ioffe-Pritchard trap)*

Strong suppression of
Majorana spin-flip transitions:

Sukumar and Brink, *PRA* 56, 2451 (1997)

Review: “Magnetic microtraps for ultracold atoms”, Fortagh & Zimmermann, *Rev. Mod. Phys.* ***79****, 235 (2007)*

Nanopositioning atomic clouds

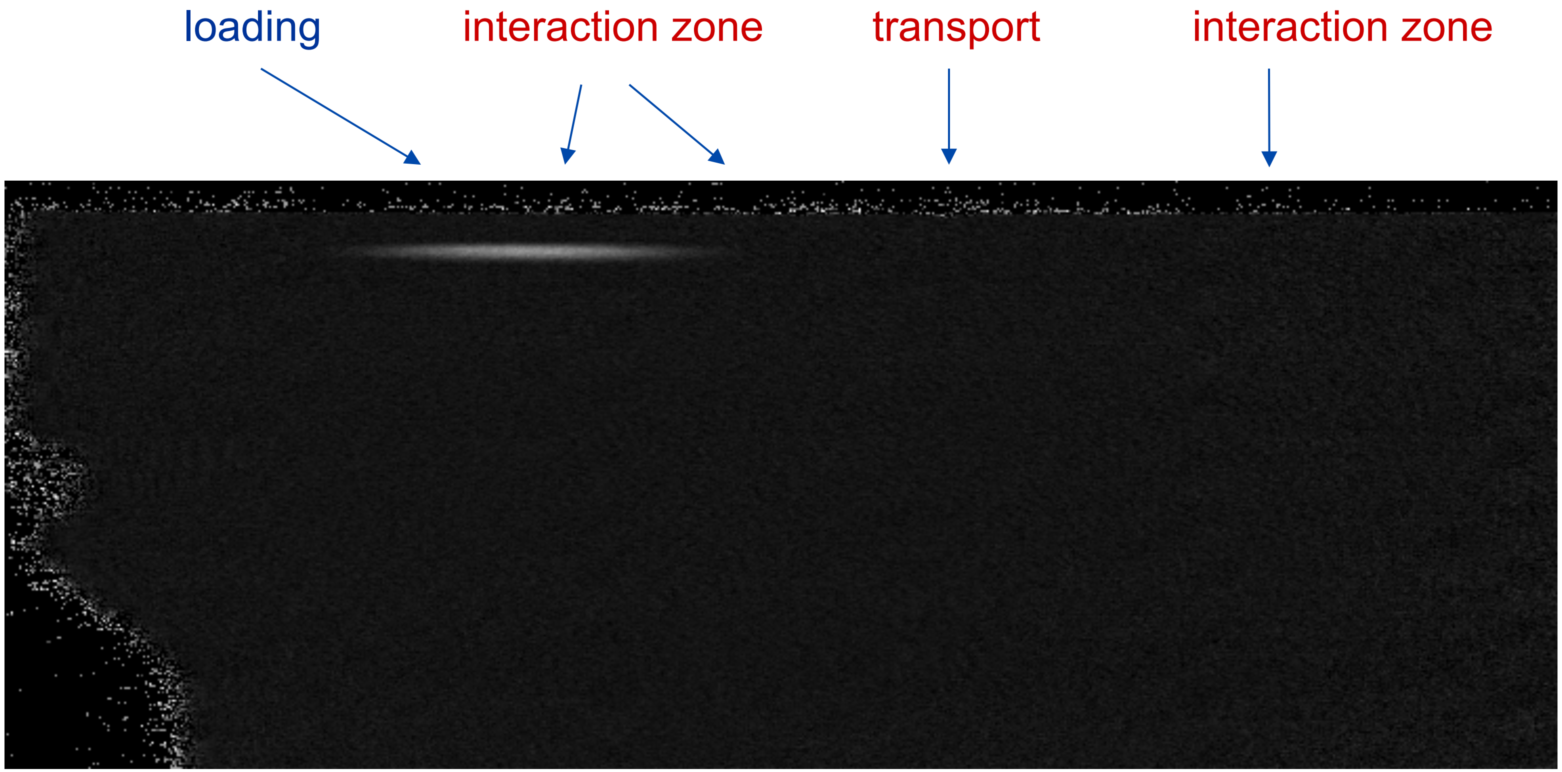


3D nanopositioning

positioning accuracy < ±250 nm velocity uncertainty Δv < ±25 μm/s

Gierling et al., Nat. Nanotechnol. **6**, 445-451 (2011)

Nano-positioning of atomic clouds on a chip

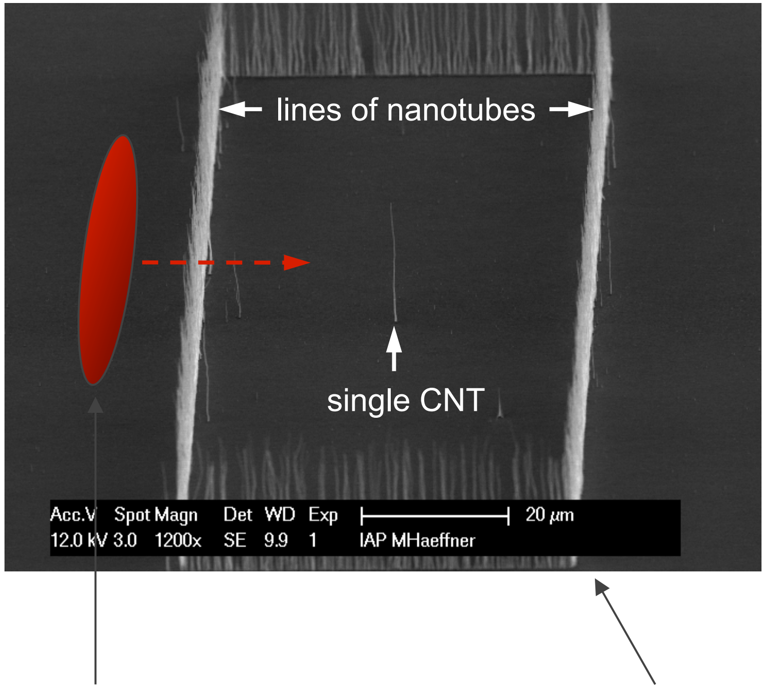


positioning accuracy < ±250 nm velocity uncertainty $\Delta v < \pm 25\ \mu m/s$

Gierling et al., Nat. Nanotechnol. **6**, 445-451 (2011)

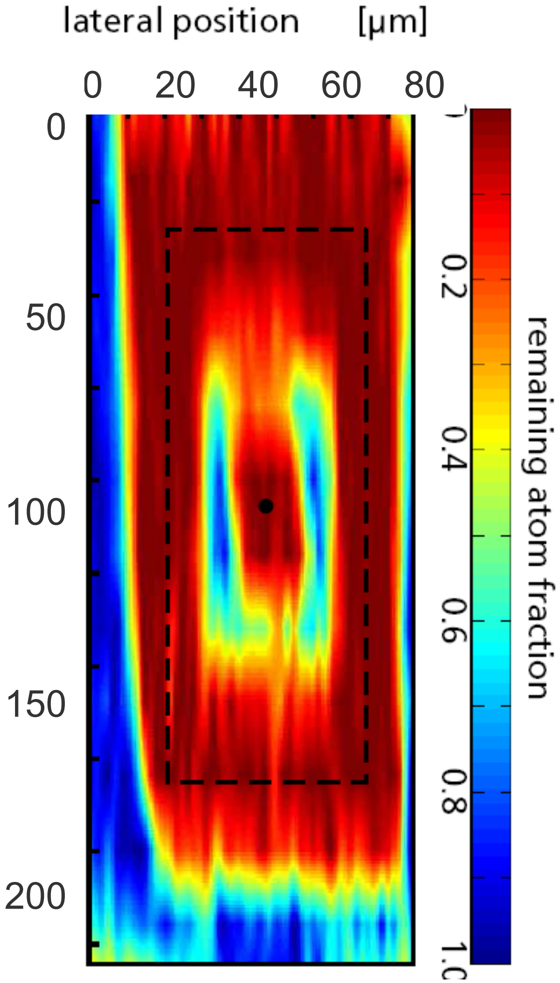
Scanning a BEC above the surface

Trap frequencies $(\omega_r, \omega_a) = 2\pi \times (81, 17)$ 1/s



Atomic cloud & scan direction

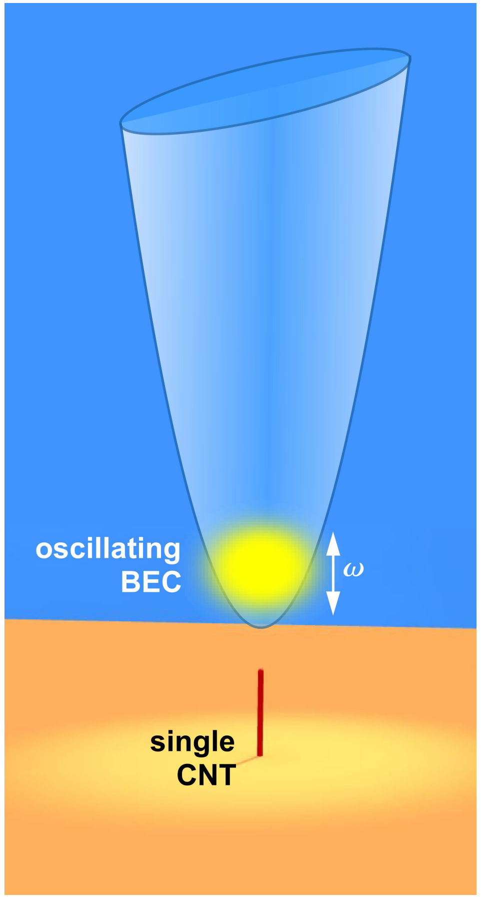
SEM image

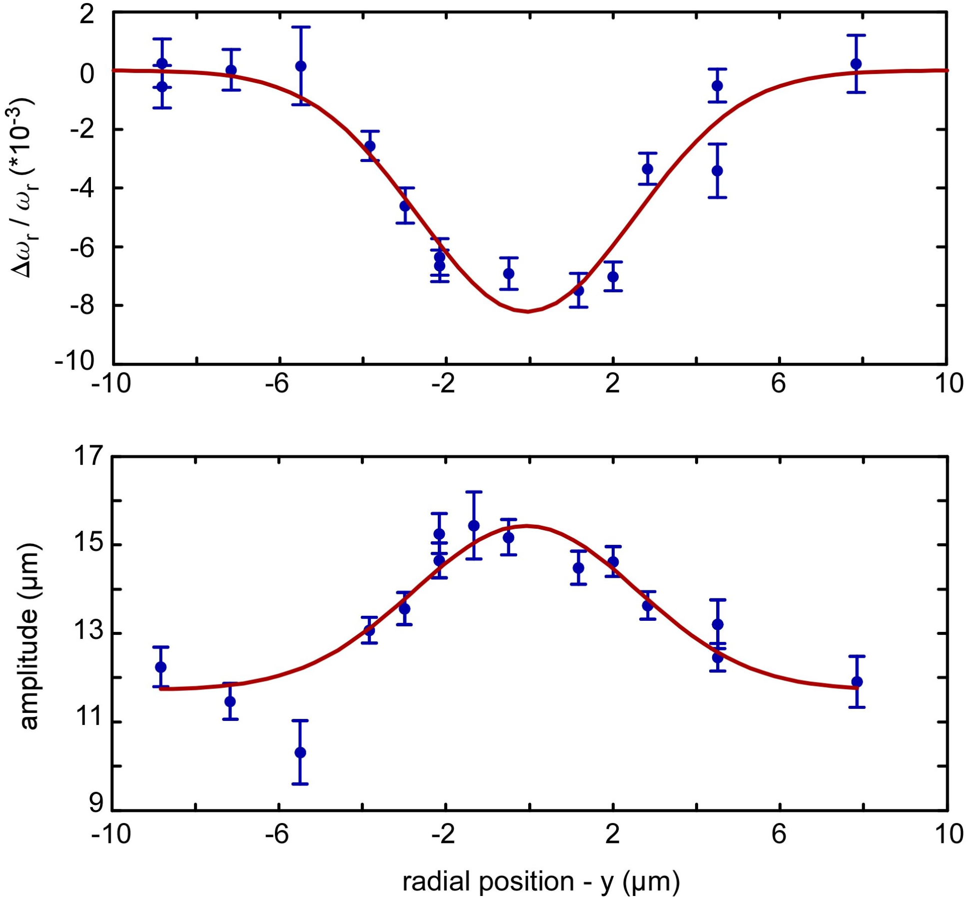


Gierling et al., Nat. Nano. 6, 445-451 (2011)

Schneeweiss et al., *Nat. Nano* ***7**, 515-519 (2012)*

BEC oscillating above the surface





Measured force between nanotube tip and an atom in the trap: $2\times10^{-25}\ N \cong 0.2\ yN$

Harber et al., PRA 72, 033610 (2005)

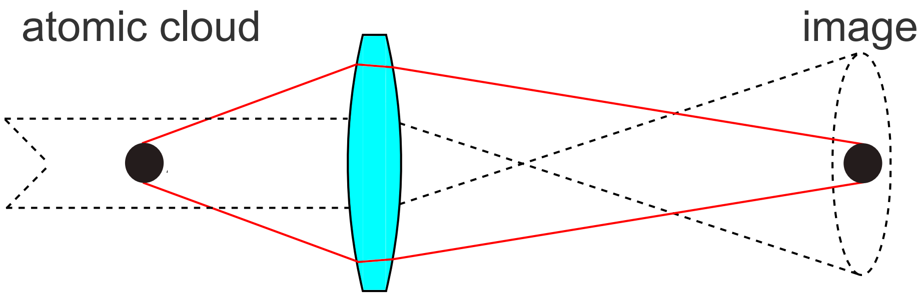
Obrecht *et al.*, *PRL* **98**, 063201 (2007)

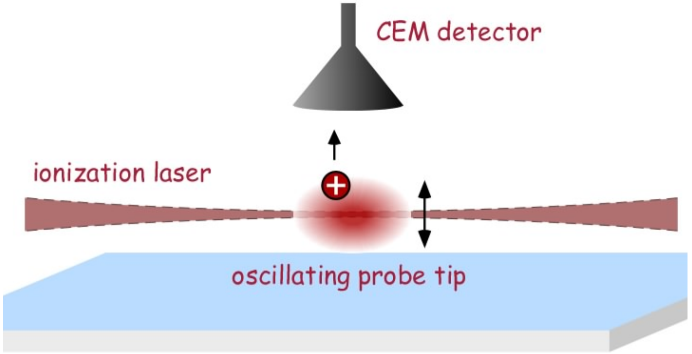
Gierling et al., Nat. Nano. 6, 445-451 (2011)

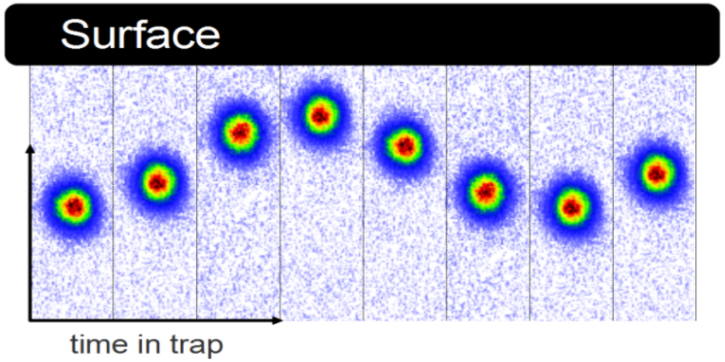
Schneeweiss et al., *Nat. Nano* ***7**, 515-519 (2012)*

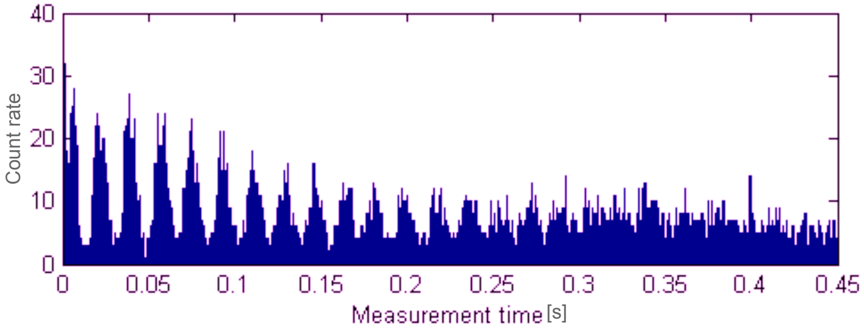
Absorption imaging

Single atom detection









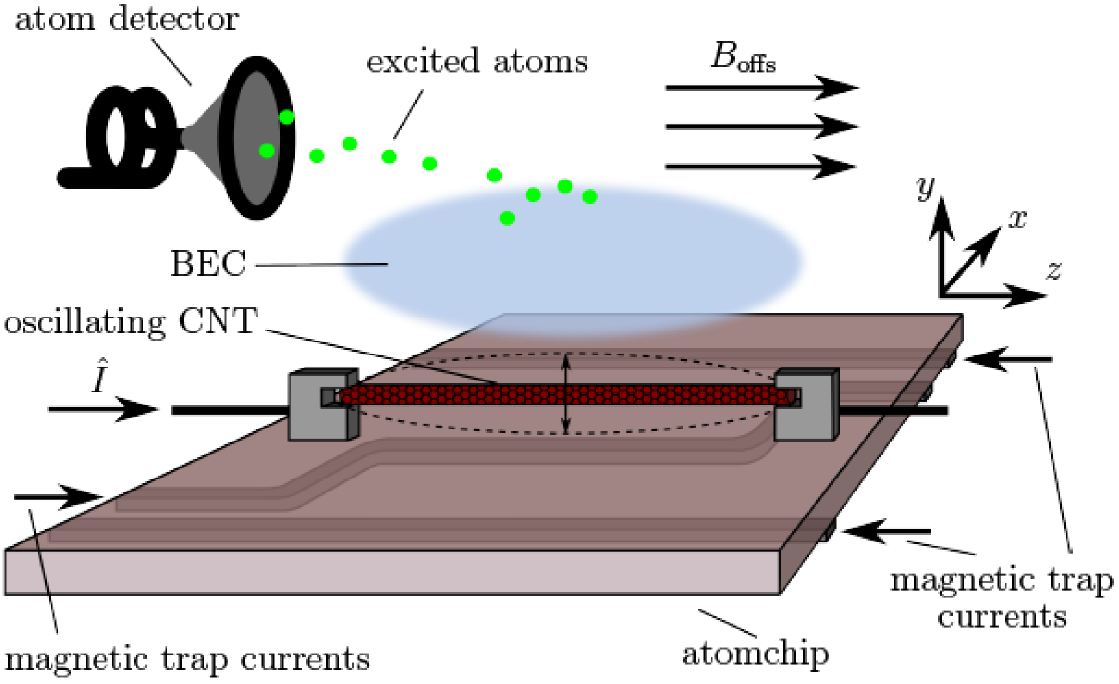
One meaurement point: few seconds

One point in <1 ms, full curve: few seconds

Stibor et al., New J. Phys. 12, 065034 (2010)

Quantum galvanometer / spectrum analyzer

Magneto-mechanical interface between atoms and a vibrating nanowire.



Quantum noise of electric currents?

Quantum drive of mechanical vibrations?

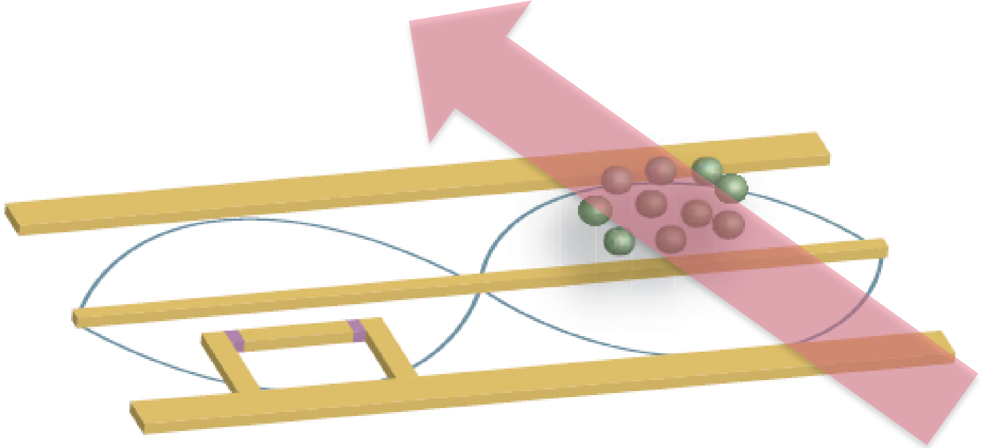
Quantum galvanometer:
Kálmán et al., Nano Letters 12, 435-439 (2013)

Parametric drive of mechanic oscillations by the BEC:
Darázs et al., Phys. Rev. Lett. 112, 133603 (2014)

Single atom detector:
Stibor et al., New J. Phys. 12, 065034 (2010)

Coupling superconducting devices and atomic gases

via superconducting-coplanar-waveguide resonators operating in the microwave regime



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

- Henschel et al., PRA **82**, 033810 (2010)
- Verdú et al., PRL 103, 043603 (2009)
- Petrosyan and Fleischhauer, PRL 100, 170501 (2008)
- Petrosyan et al., Phys. Rev. A 79, 040304 (2009)
- Rabl et al., PRL 97, 033003 (2006)
- Sorensen et al., PRL 92, 063601 (2004)

The list is growing…

Proposals for quantum information processing

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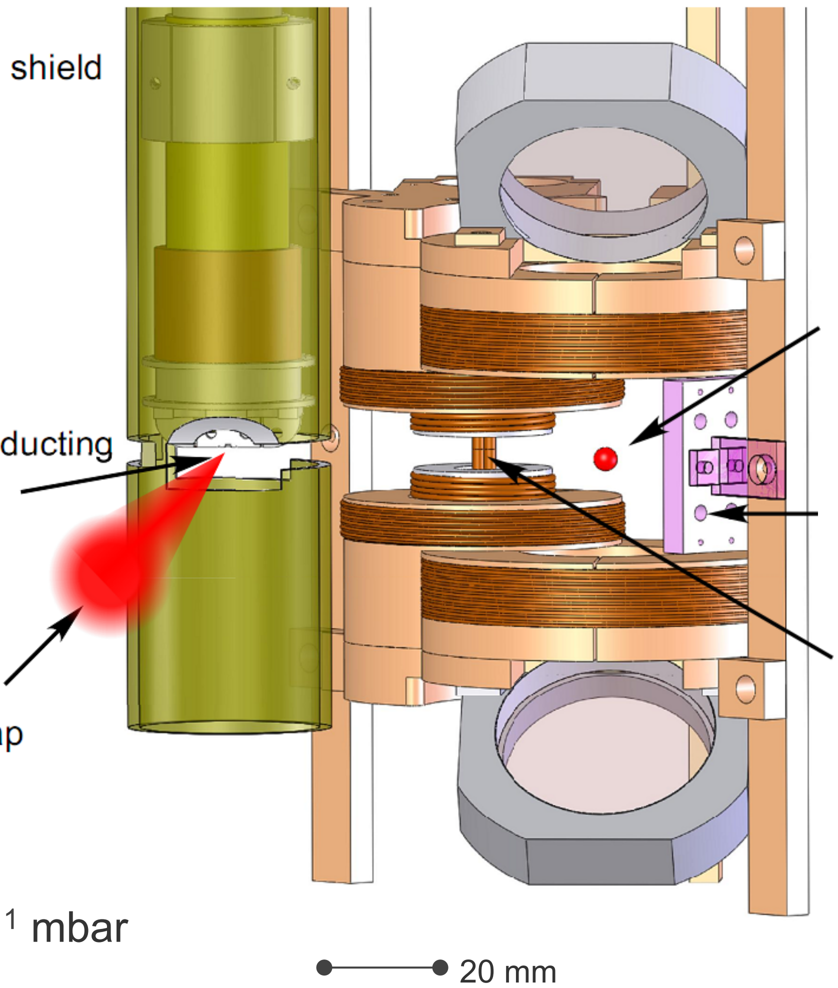
Cold atoms & superconductors



Cryostat **Cold atom set-up**

Radiation shield

Superconducting microtrap

Optical dipole trap

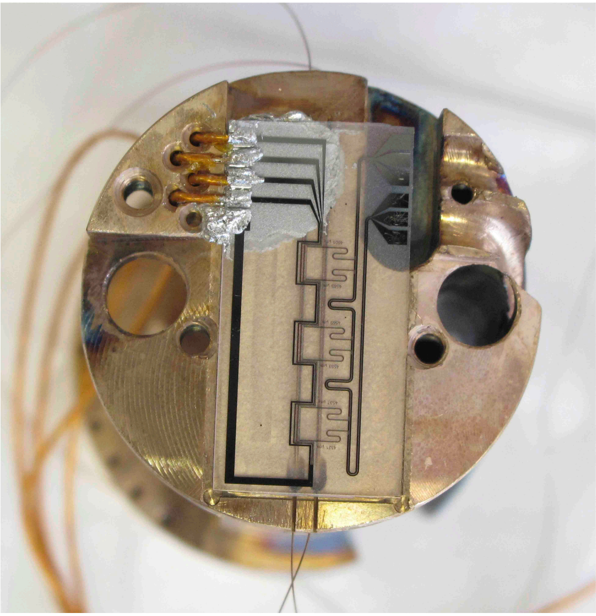
MOT / magnetic traps

2D-MOT

Two wire Ioffe trap

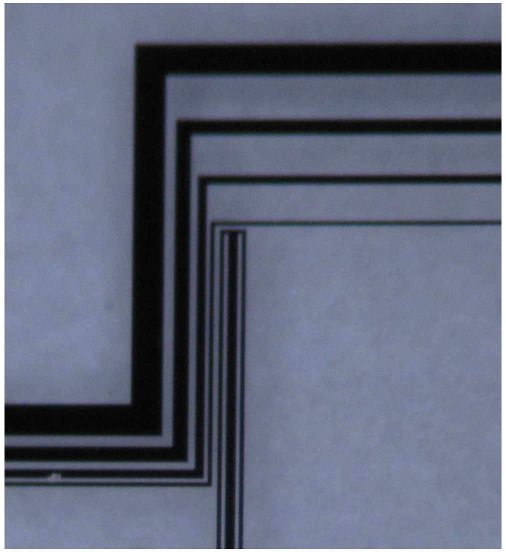
20 mm

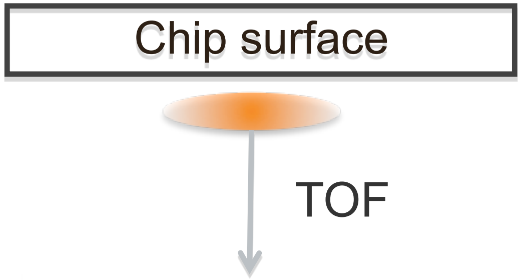
$P \sim 10^{-11}$ mbar



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

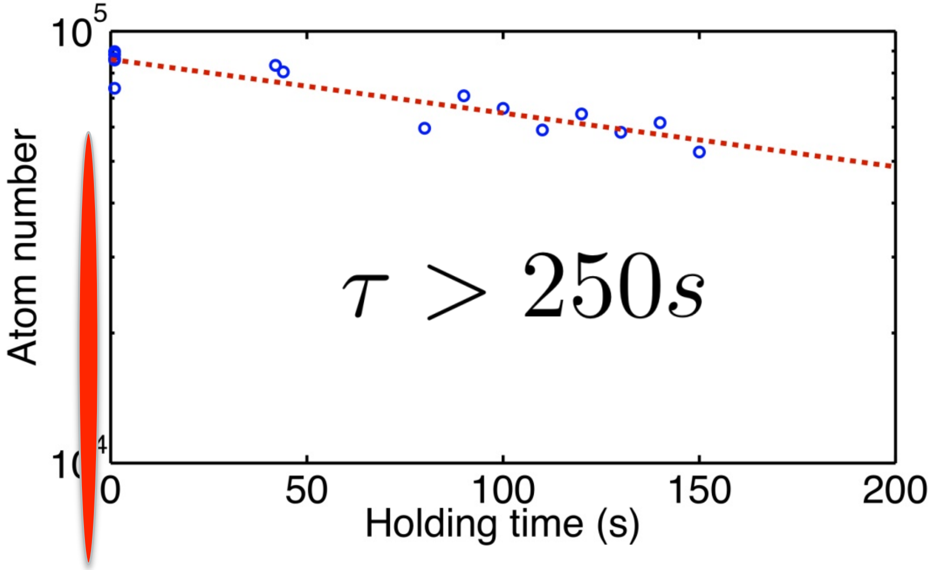
Cold atoms on the SC chip





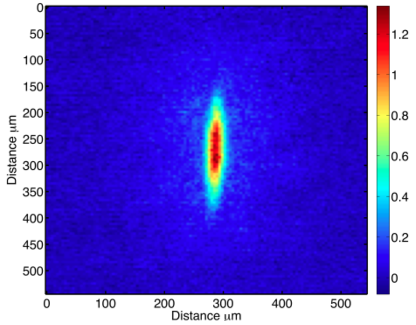
Chip surface

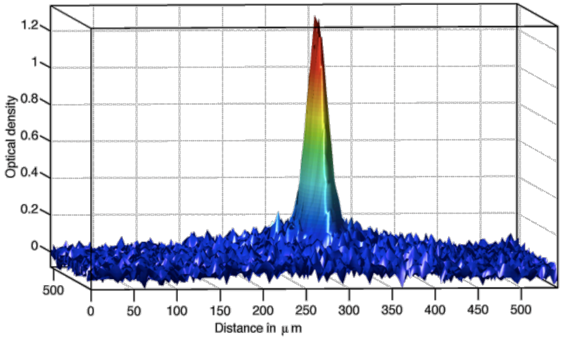
TOF

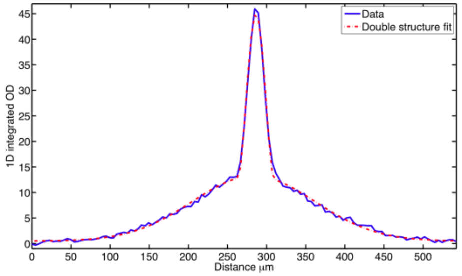


$\tau > 250s$

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

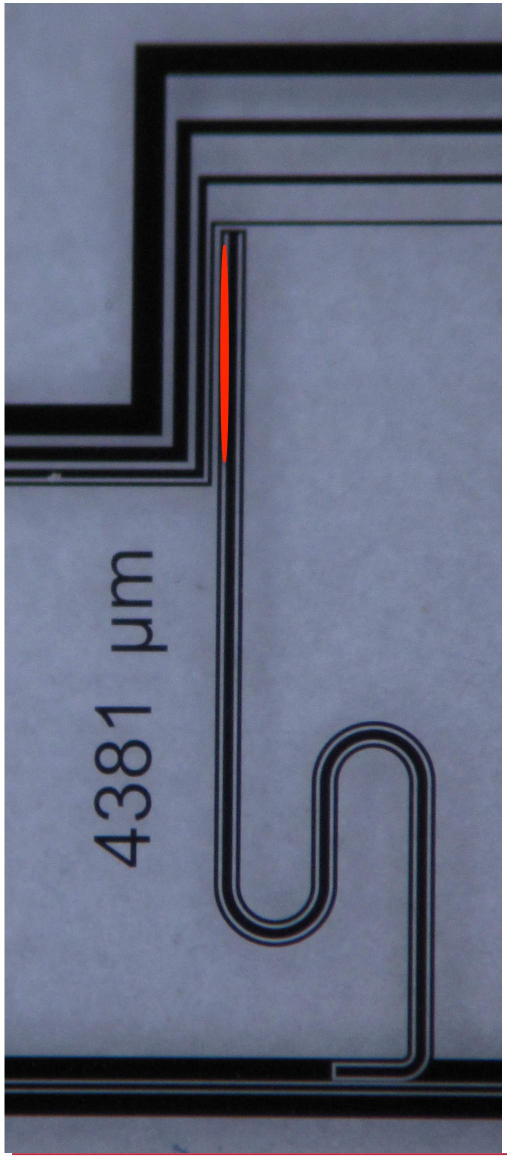




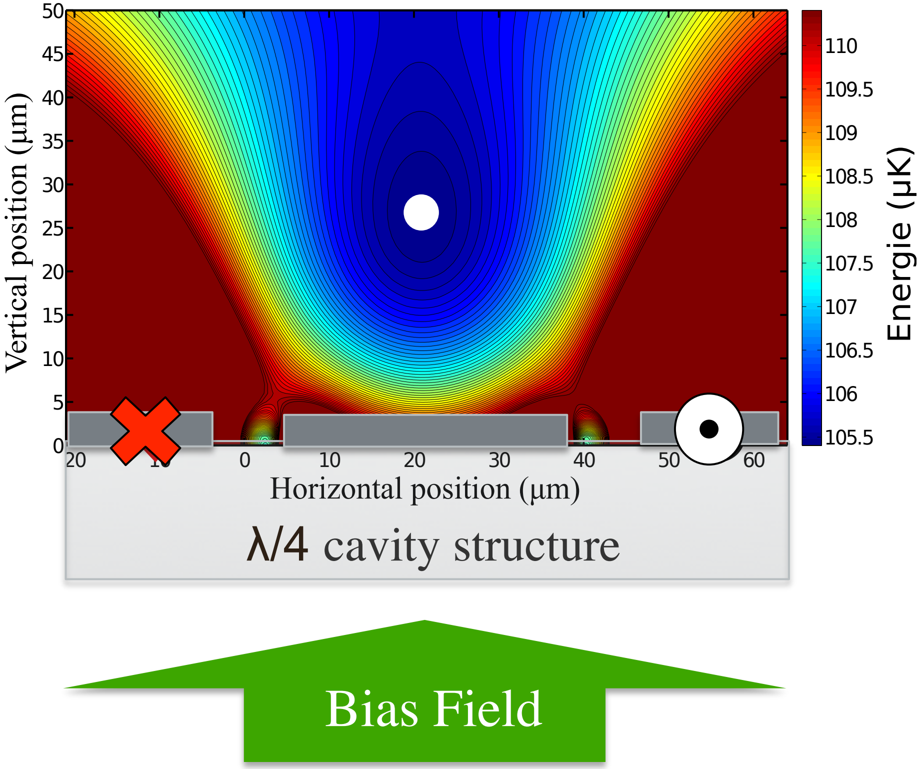


Bernon et al., Nat. Commun. **4**, 2380 (2013)

Trapping atoms at the superconducting microwave cavity

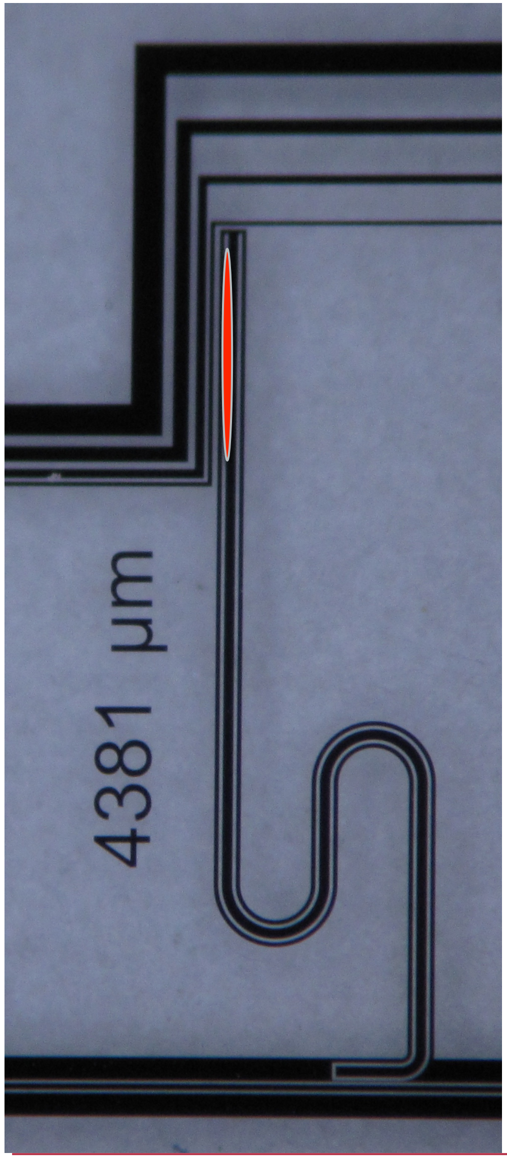


Persistent current trap



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

Atomic coherence at the superconducting coplanar cavity structure



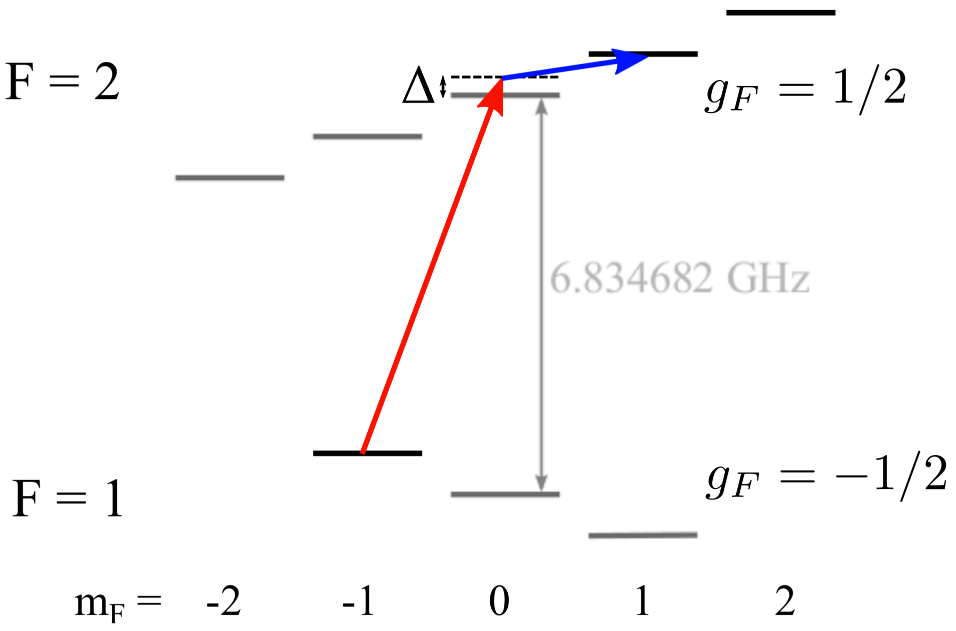
$$|0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$

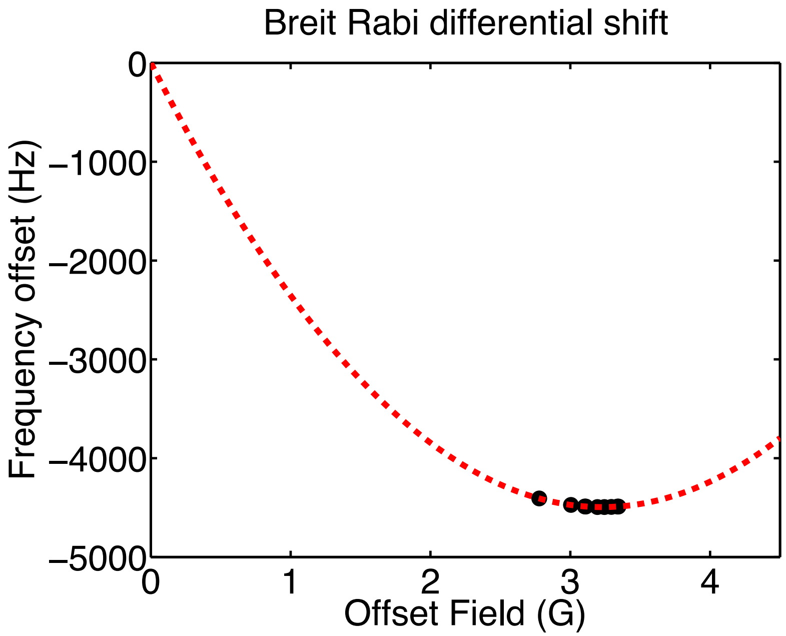
Time evolution

↓

Coherence ?

Atomic coherence on a SC chip



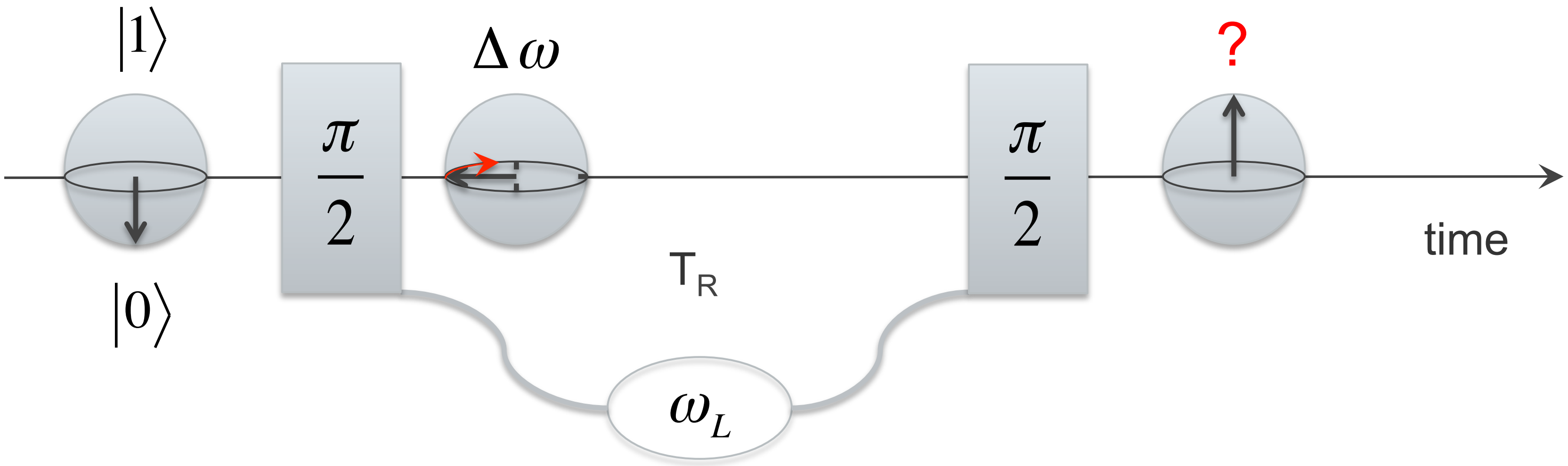


At 500 nK: differential shift < 1 Hz

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

Atomic coherence on a SC chip

Ramsey interferometry



$$|0\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \longrightarrow \text{Coherence ?}$$

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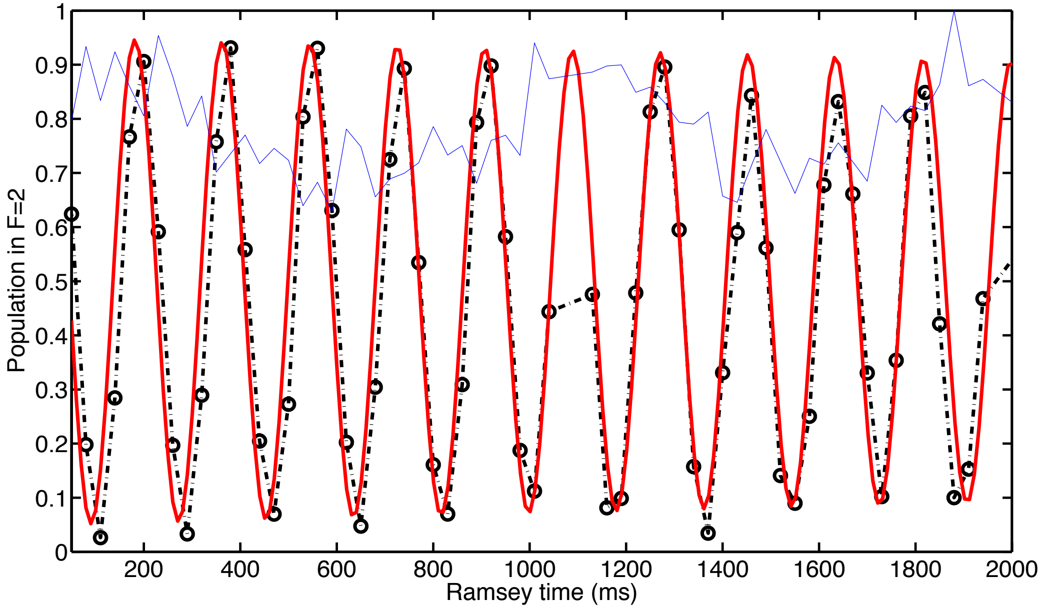
Atomic coherence on a SC chip

Ramsey interferometer $\frac{\pi}{2}\, T_R\, \frac{\pi}{2}$



Long coherence time > 2 s !!

Parameters:

Atomic cloud

$\omega_l/2\pi \approx 20\ \mathrm{Hz}$

$\omega_r/2\pi \approx 180\ \mathrm{Hz}$

$z_0 \approx 60\ \mu\mathrm{m}$

$N_{\mathrm{at}} \approx 3 \times 10^4$

$\overline{n} \approx 10^{13}\ \mathrm{at.cm}^{-3}$

Interefometer

Rabi frequency

$\Omega_R/2\pi = 400\ \mathrm{Hz}$

Single photon detuning

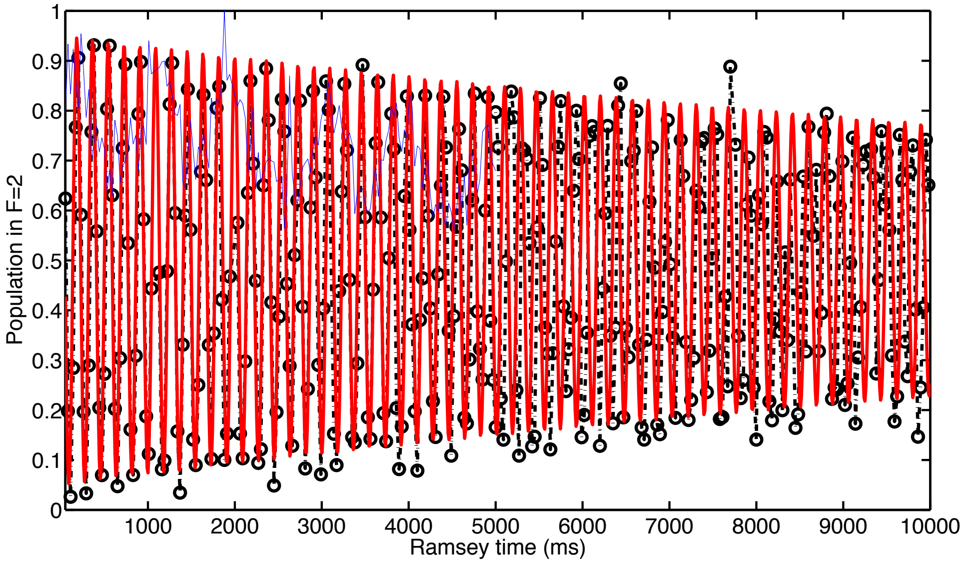
$\Delta/2\pi = 900\ \mathrm{kHz}$

Two photons detuning

$\delta/2\pi = 5.5 Hz$

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

Coherence and stability of operation

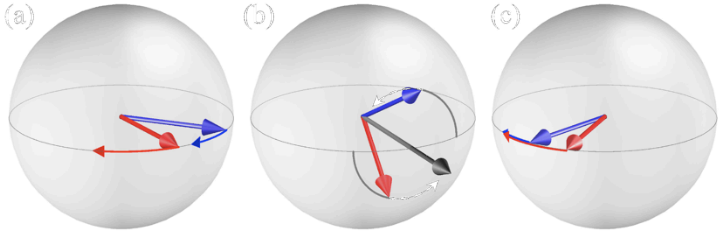


Coherence time $T_2 \approx 20\ s$

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

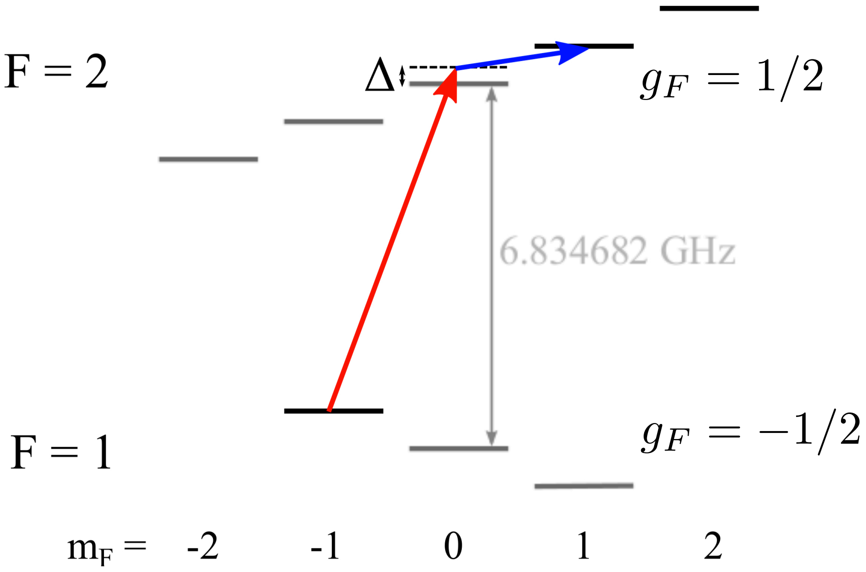
Identical spin rotation effect synchronizes the clock

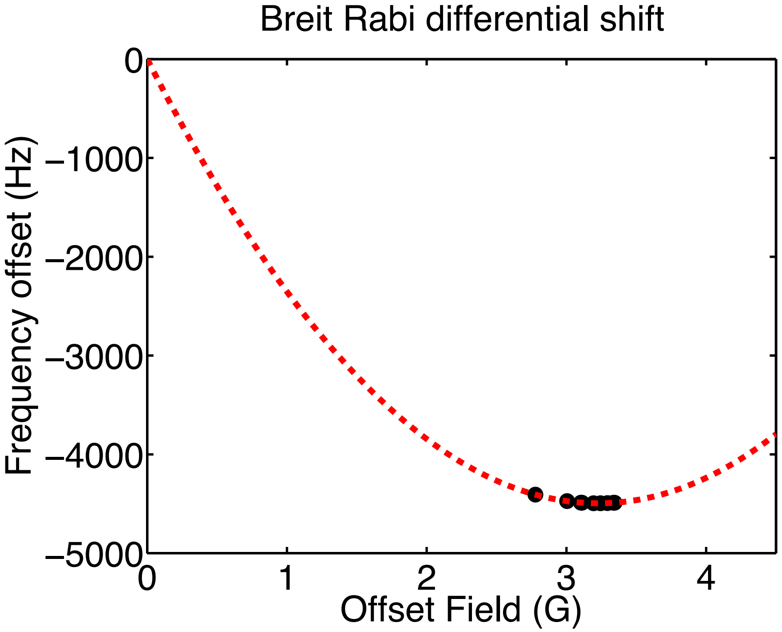
C. Deutsch *et al* Phys. Rev. Lett. **105**, 020401 (2010)



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

The differential Zeeman shift and magnetic field fluctuations limit the clock coherence





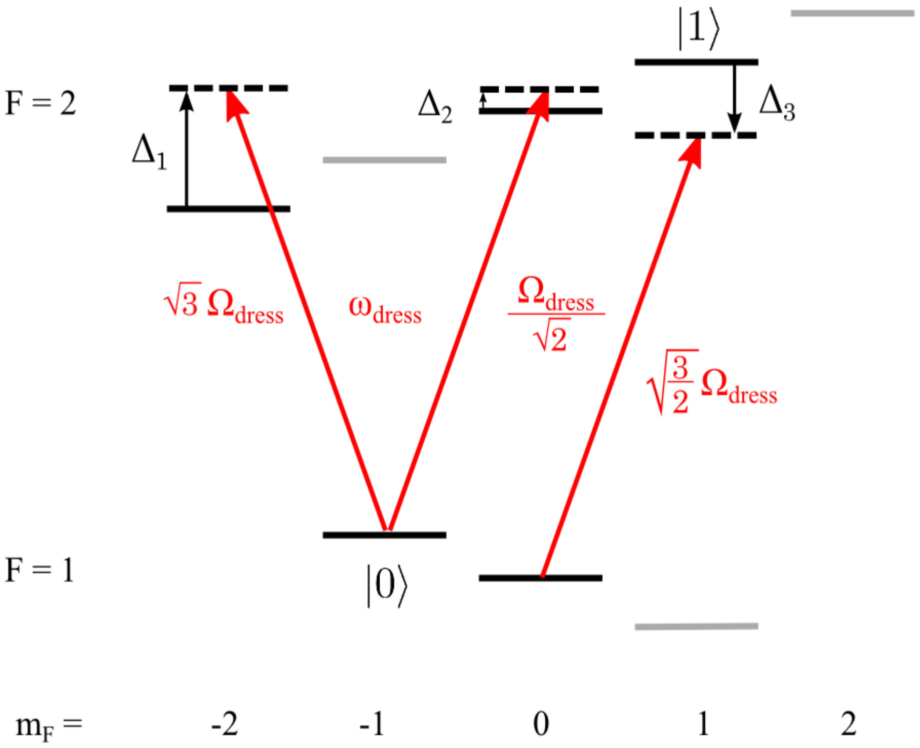
$$\Delta\omega(B) \cong \omega_f + \beta \cdot (B - B_0)^2$$

O. Zobay and B. M. Garraway
Phys. Rev. Lett. **86**, 1195 (2001)

L. A. Jones, J. D. Carter, and J. D. D. Martin
Phys. Rev. A 87, 023423 (2013)

Zanon-Willette, de Clercq, Arimondo
Phys. Rev. Lett. 109, 223003 (2012)

Dressing the clock transition



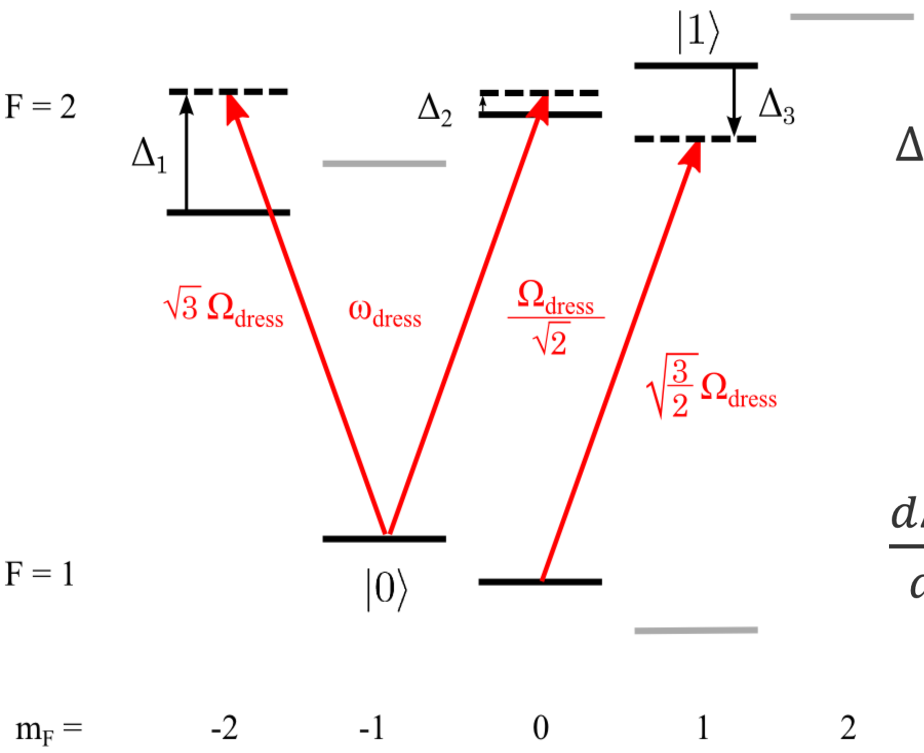
Dressing field with perpendicular polarisation to the magnetic field at the trap centre (quantisation axis).

$$H_0 = \hbar \begin{bmatrix} 0 & \sqrt{3}\Omega_{\mathrm{dress}} & \frac{1}{\sqrt{2}}\Omega_{\mathrm{dress}} \\ \sqrt{3}\Omega_{\mathrm{dress}} & -\Delta_1 & 0 \\ \frac{1}{\sqrt{2}}\Omega_{\mathrm{dress}} & 0 & -\Delta_2 \end{bmatrix}$$

$$H_1 = \hbar \begin{bmatrix} 0 & \sqrt{\frac{3}{2}}\Omega_{\mathrm{dress}} \\ \sqrt{\frac{3}{2}}\Omega_{\mathrm{dress}} & -\Delta_3 \end{bmatrix},$$

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

Dressing the clock transition



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

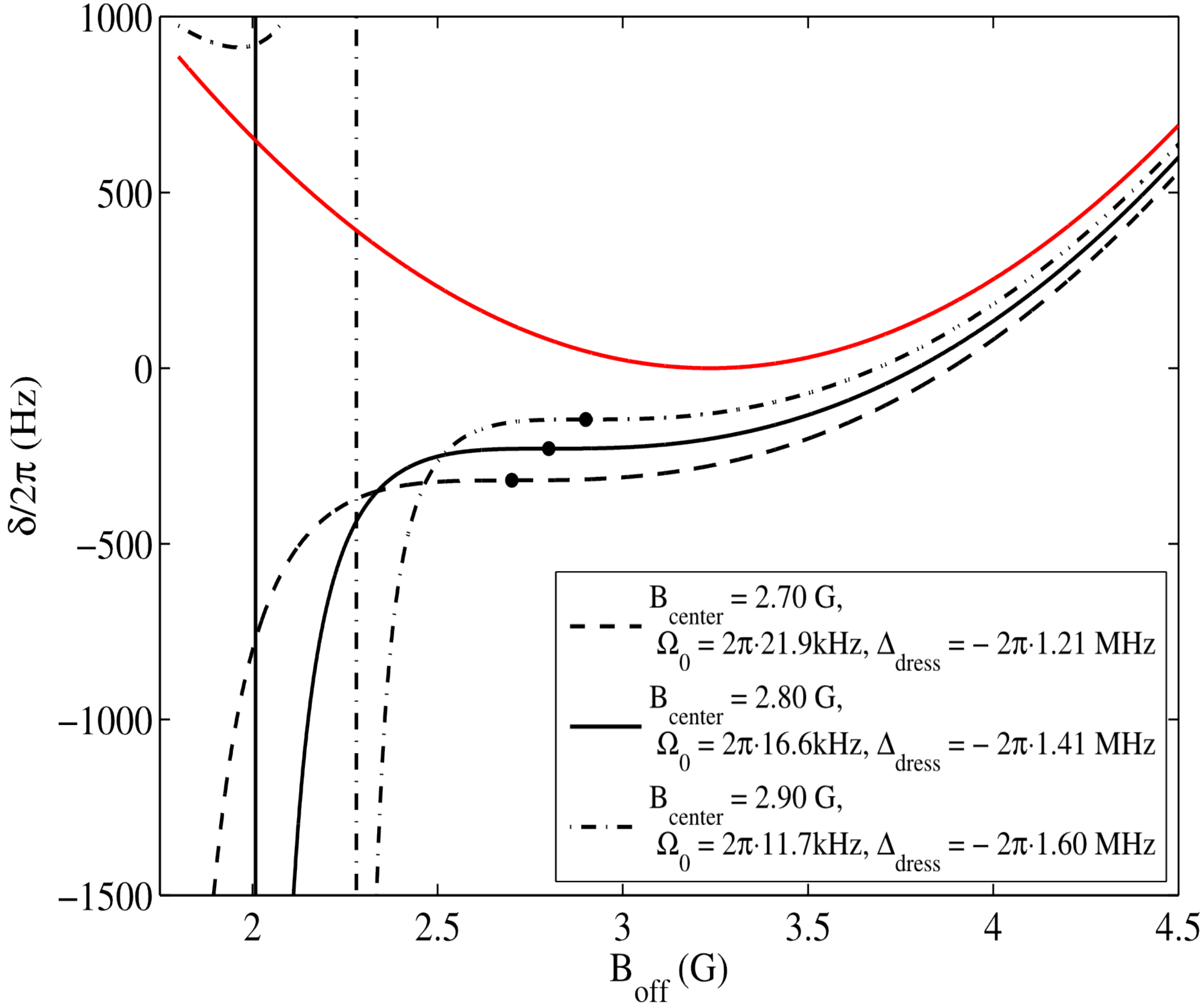
$$\frac{d\Delta\omega}{dB},\frac{d^2\Delta\omega}{dB^2}=0 \implies \Omega_{dress},\omega_{dress}$$

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

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

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

Dressed clock

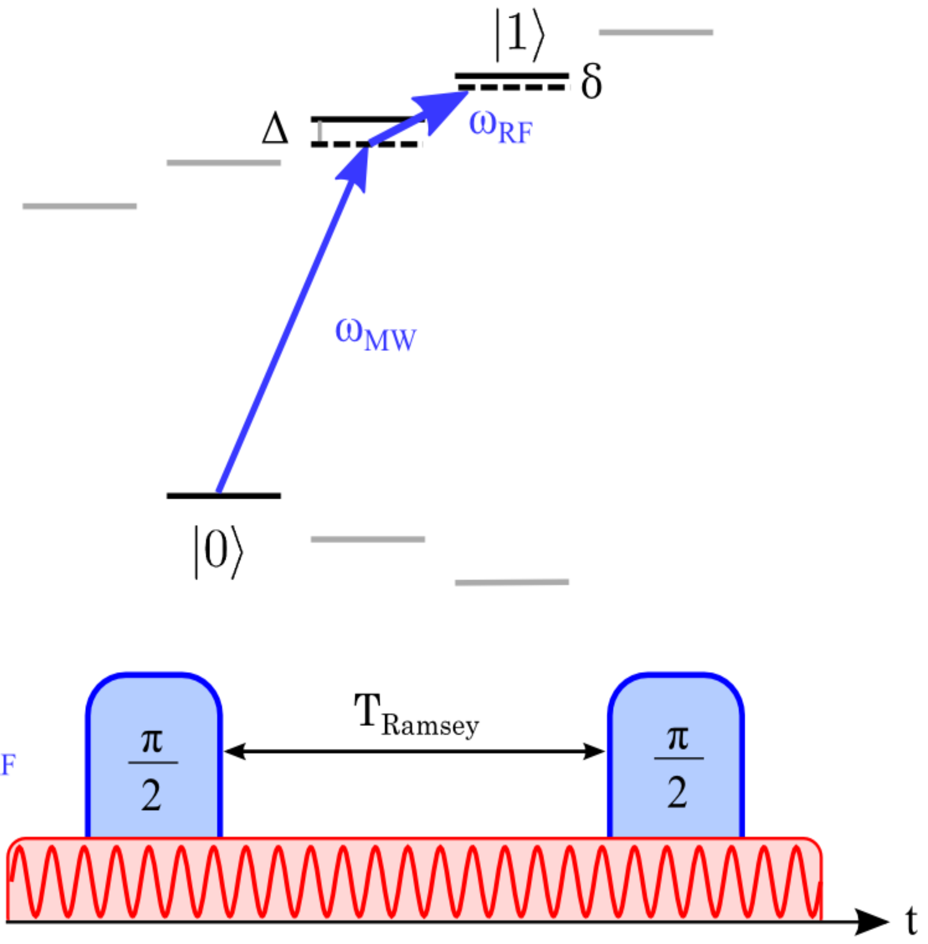


For any offset field the differential shift can be modified:

- suppressed
- enhanced
- structurred.

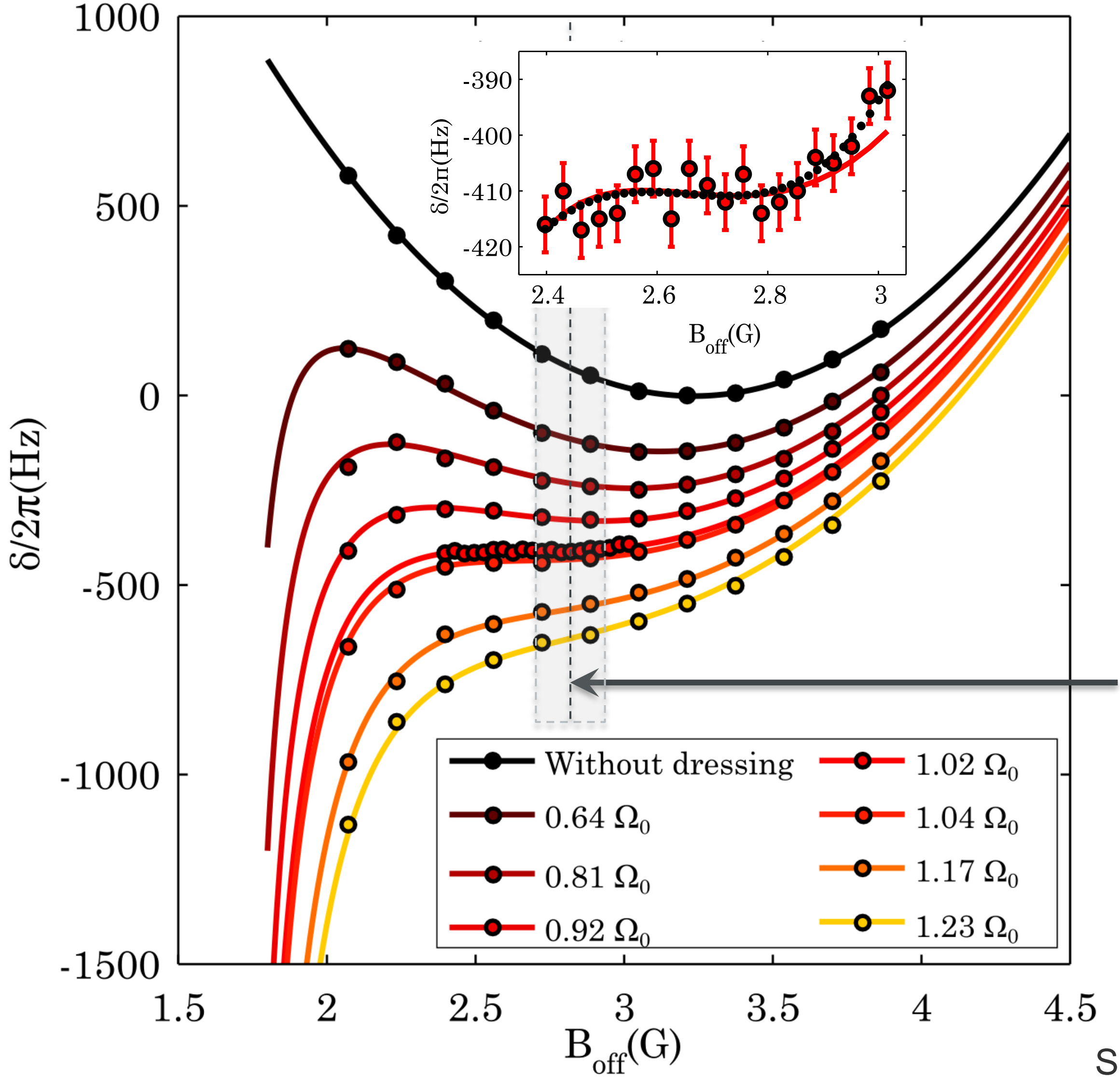
Sárkány et al., PRA **90**, 053416 (2014)

Ramsey interferometry with MW dressing



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

MW-control of the differential shift



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

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

$B_{\text{center}} = 2.65$ G

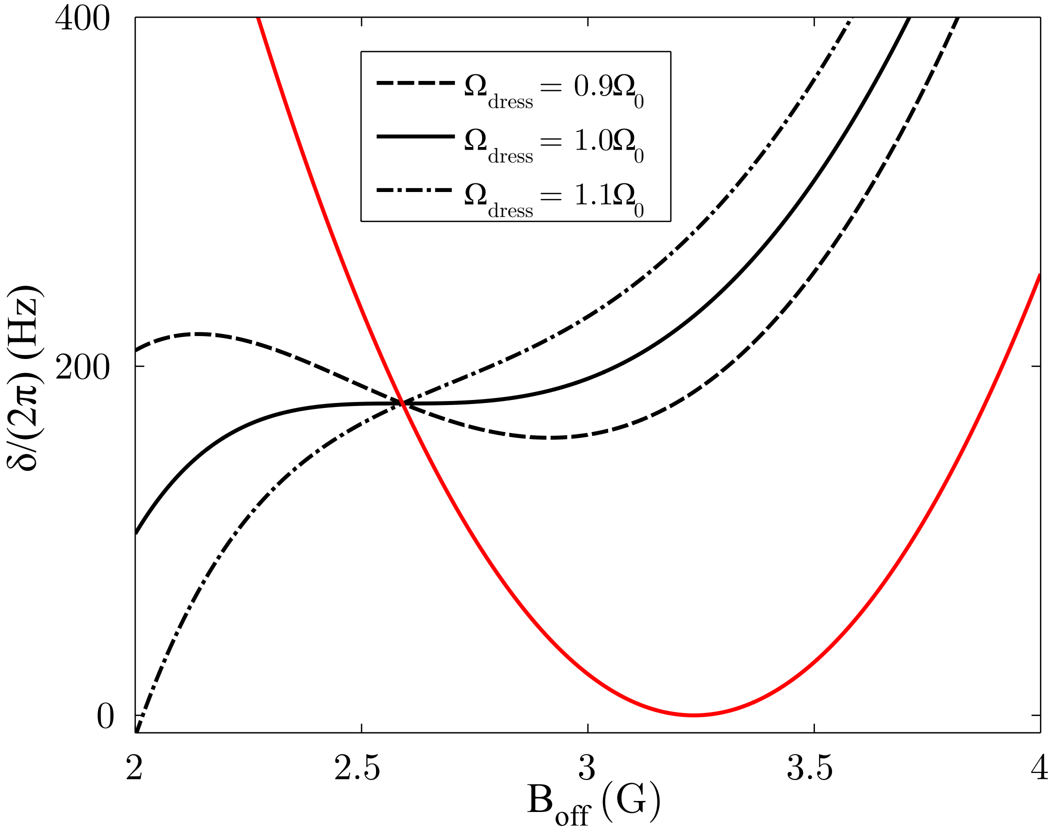
width (0.1 Hz): ~100 mG

The the first and second order differential Zeeman-shifts are suppressed.

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

Doubly protected clock states

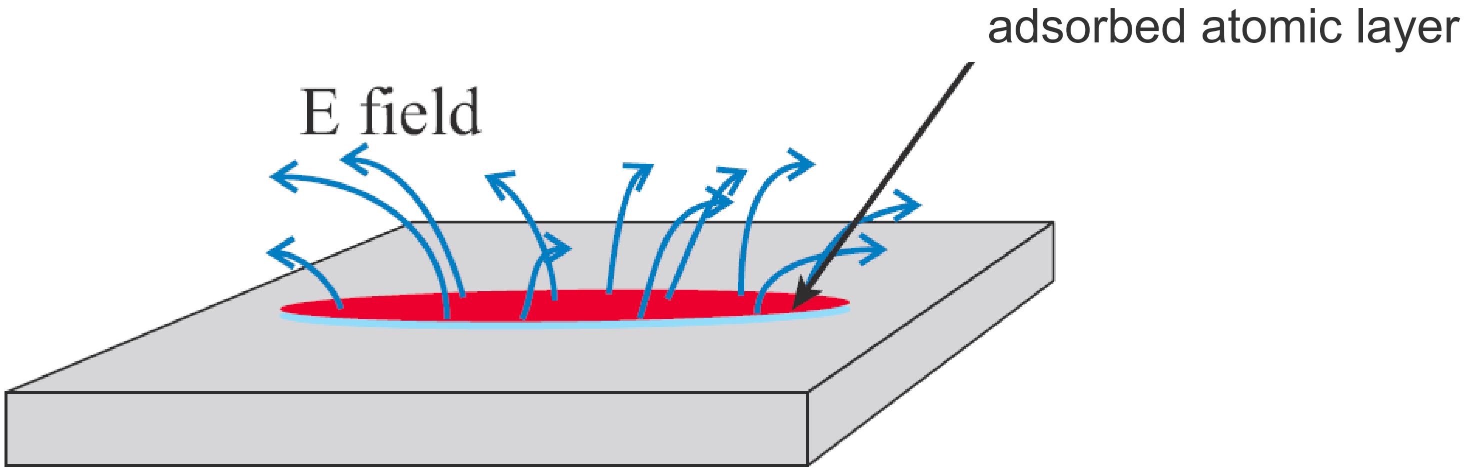
For certain offset fields the differential shift becomes independent also from the microwave power.



These **“double magic points”** are the preferable working points of trapped atomic clocks and quantum memories.

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

Polarized adatoms at the surface



McGuirk et al., PRA A **69**, 62905 (2004)

Tauschinsky PRA **81**, 063411 (2010)

Hattermann et al, PRA **86**, 022511 (2012)

Carter, Cherry, Martin, PRA **86**, 053401 (2012)

Chan et al., PRL **112** 026101 (2014)

Hermann-Avigliano et al., PRAA 90, 040502(R) (2014)

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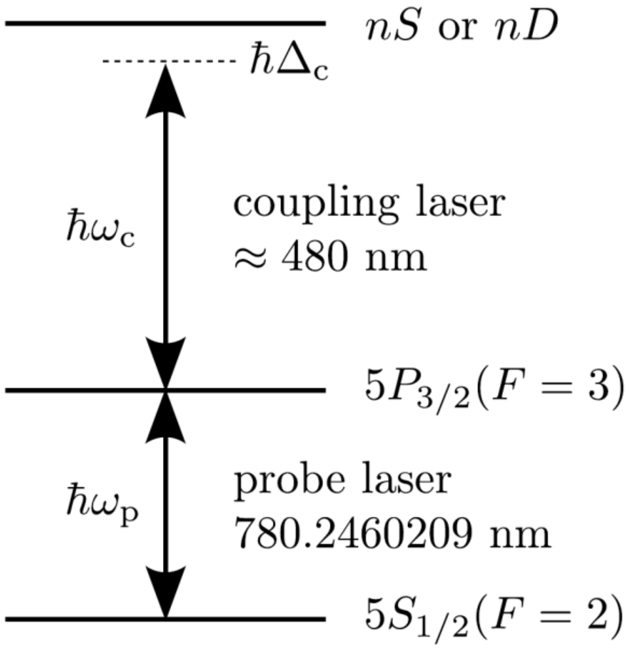
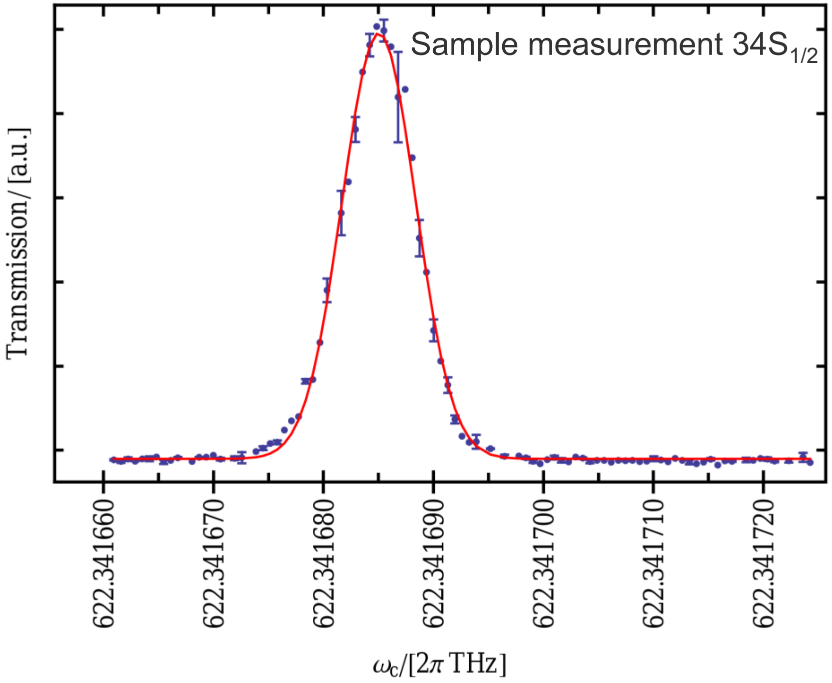
Spectroscopy of ^{87}Rb Rydberg states

Electromagnetically induced transparency (EIT)

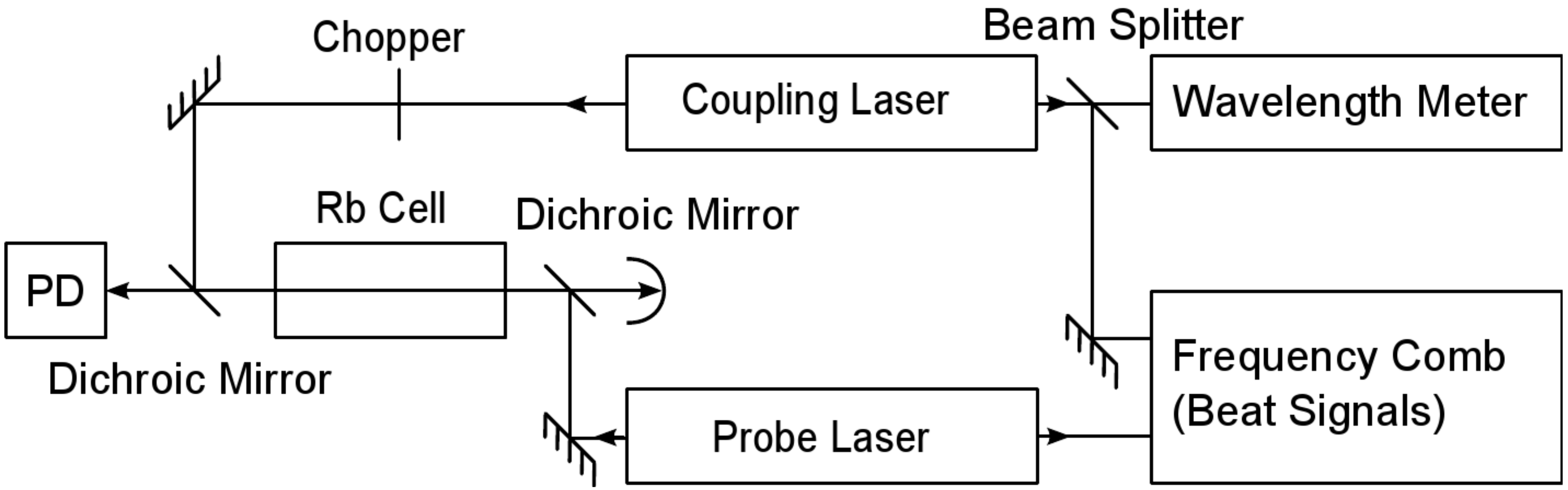




Mohapatra et al., PRL 98, 113003 (2002)

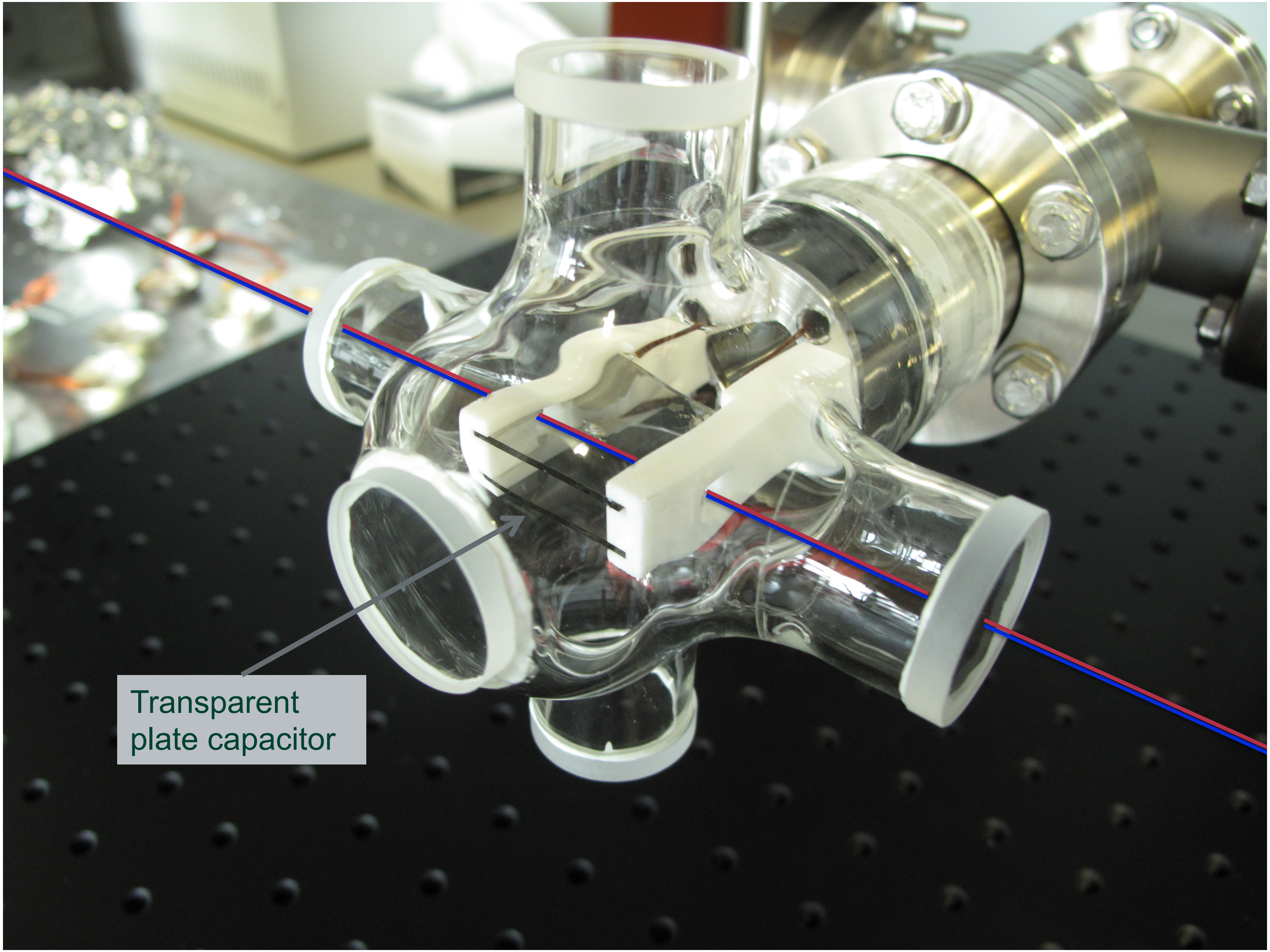
Karlewski et al., PRA 91, 043422 (2015)

EIT setup



Precise 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)

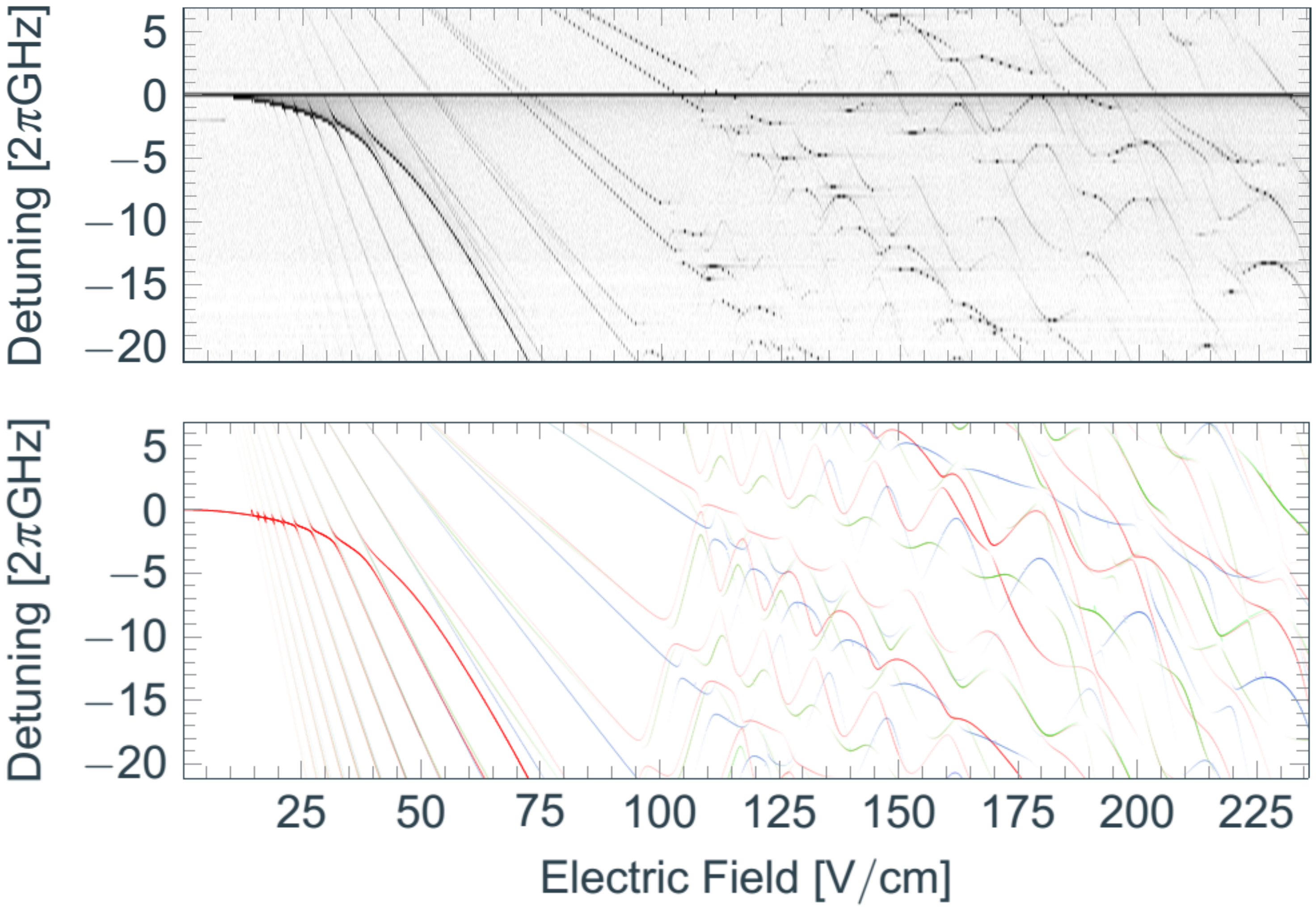
Quasi-classical quantum defect theory for describing the fine splitting of Rydberg states
Sanayei et al., PRA 91, 032509 (2015)



Transparent plate capacitor

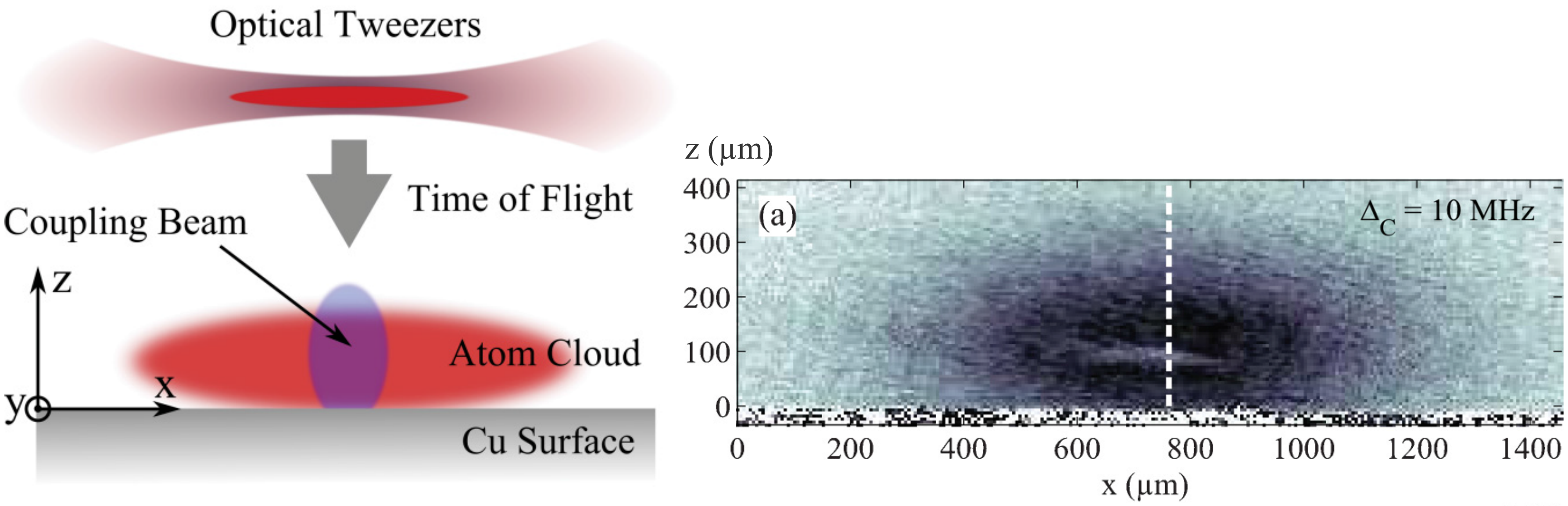
Stark-map in a cell

^{87}Rb 35S



Grimmel *et al., New J. Phys.* **17** 053005 (2015)

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

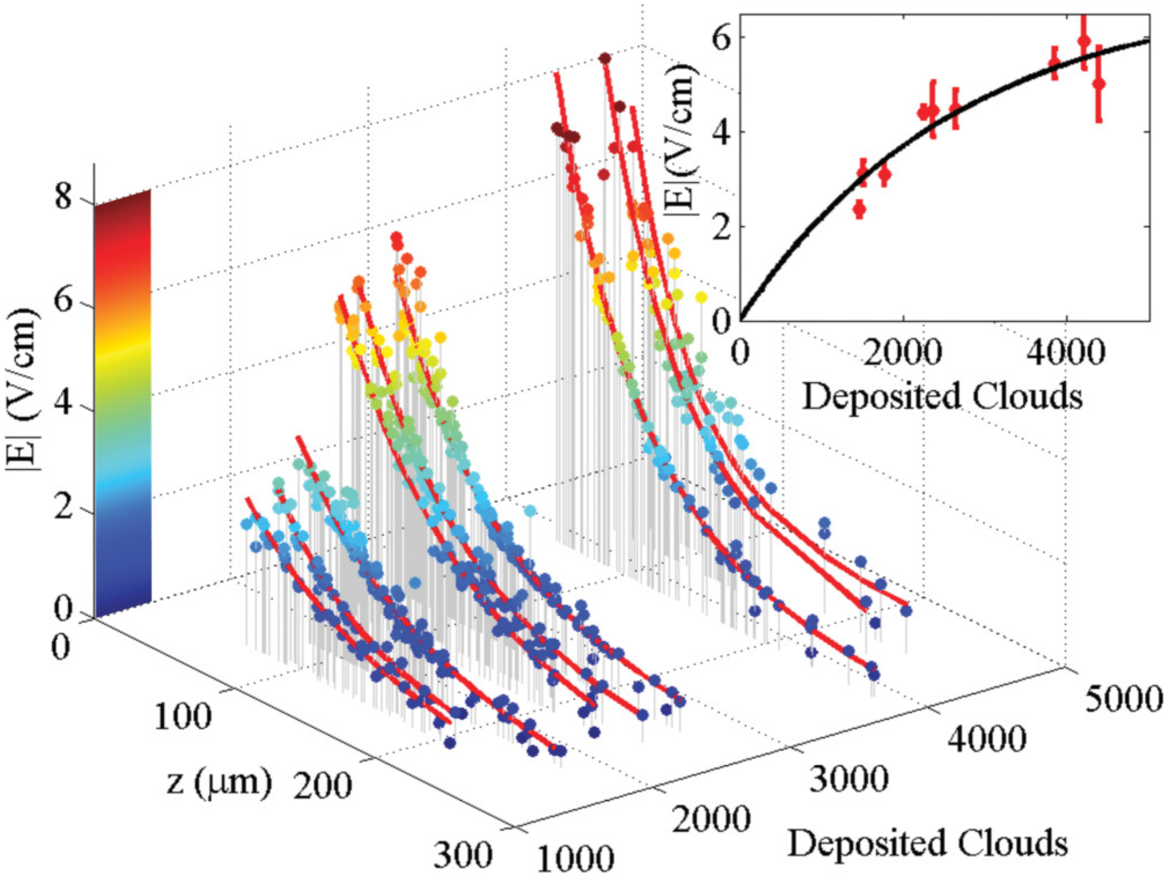


Energy shift measured with electromagnetically induced transparency (EIT)

Amsterdam: Tauschinsky Phys. Rev. A **81**, 063411 (2010)

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

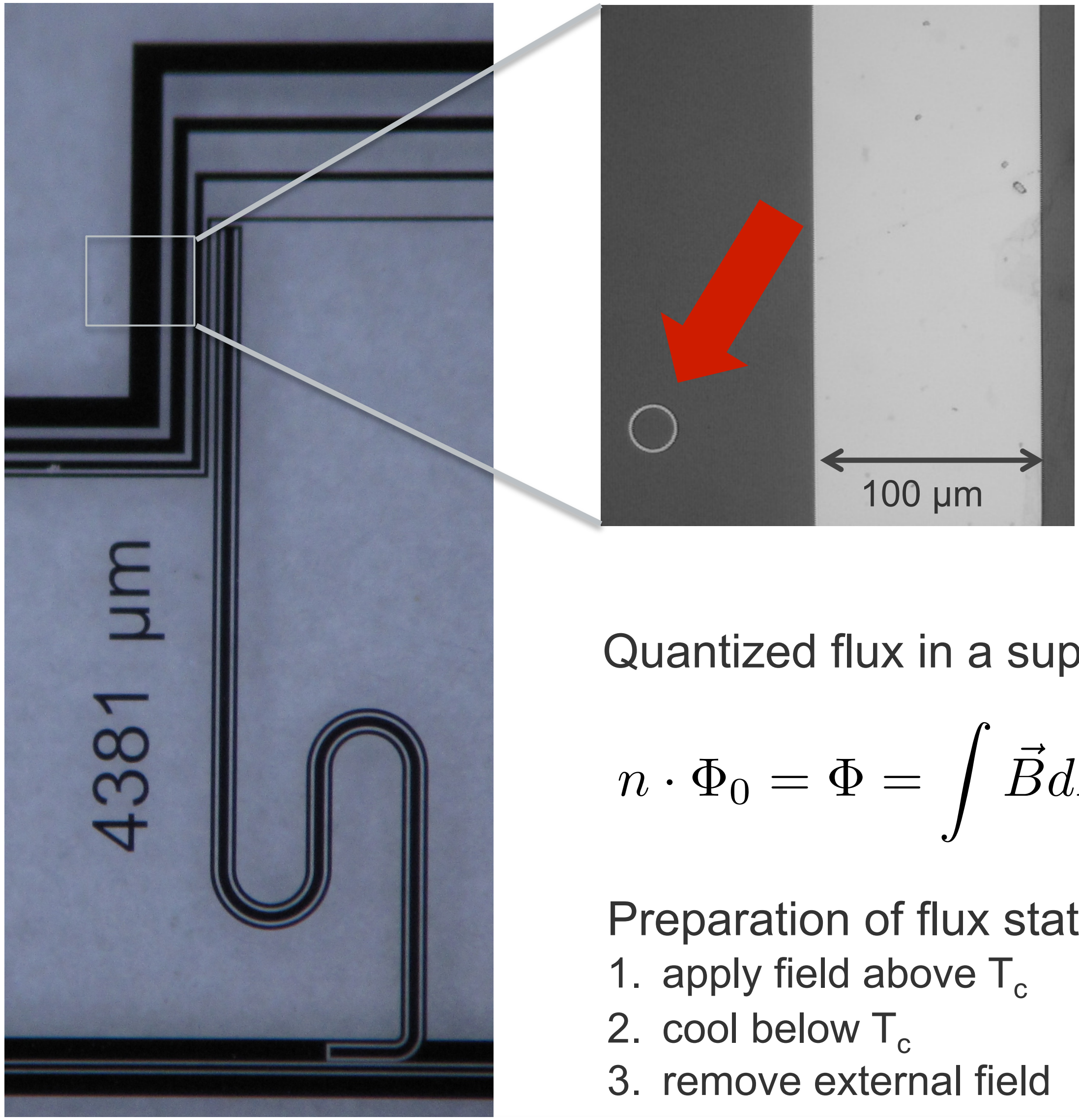
Build up of electric fields due to adsorbates

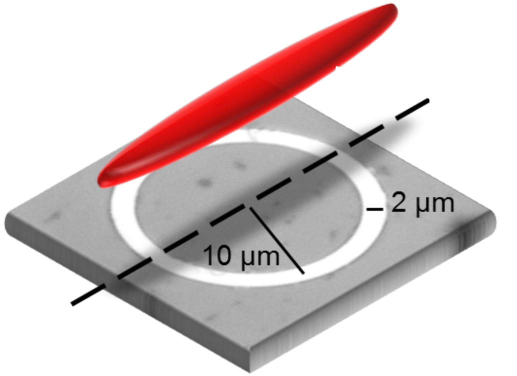


Hattermann et al,
Phys. Rev. A **86**, 022511 (2012)

Inversion of the electric field when cooling the chip to cryogenic temperatures:
Chan, Siercke, Hufnagel, Dumke, PRL **112**, 026101 (2014)

Superconducting ring





Quantized flux in a superconducting ring

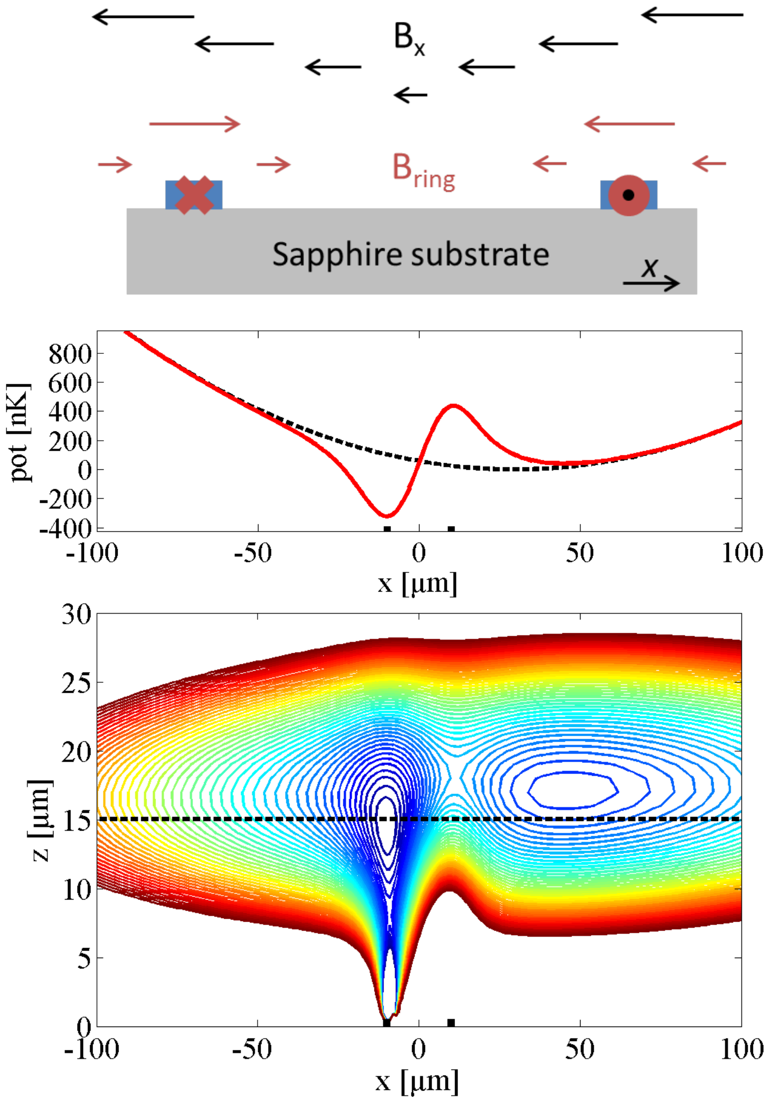
$$n \cdot \Phi_0 = \Phi = \int \vec{B} d\vec{A} \quad \text{with} \quad \Phi_0 = h/2e$$

Preparation of flux state:

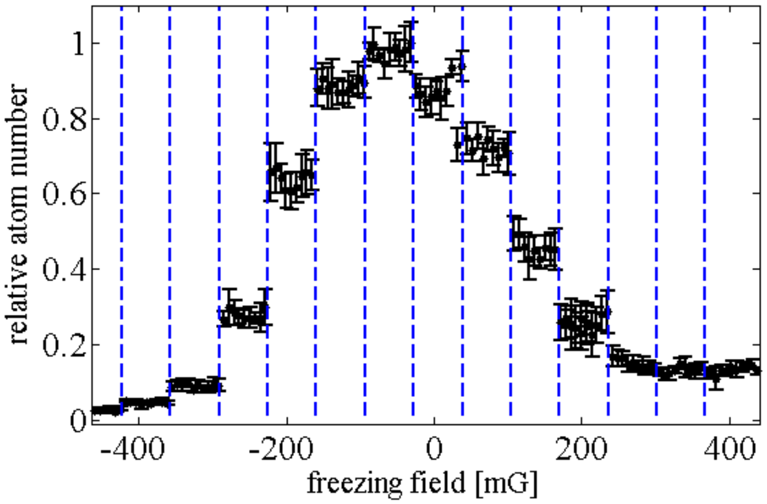
1. apply field above T_c
2. cool below T_c
3. remove external field

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

Mapping the flux state of the ring to atomic clouds

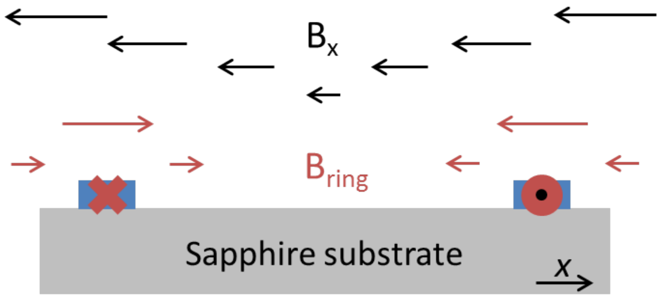


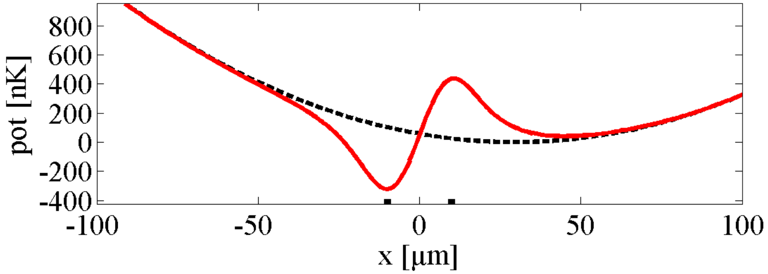
Total atom number after
1s holding time

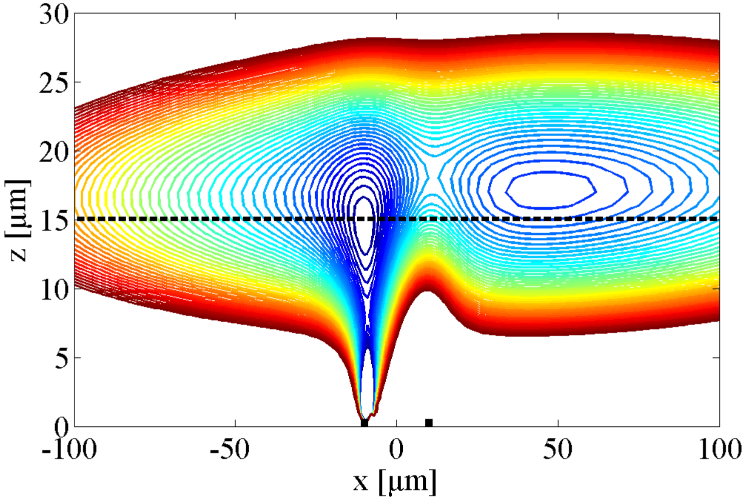


Weiss et al., PRL 114, 113003 (2015)

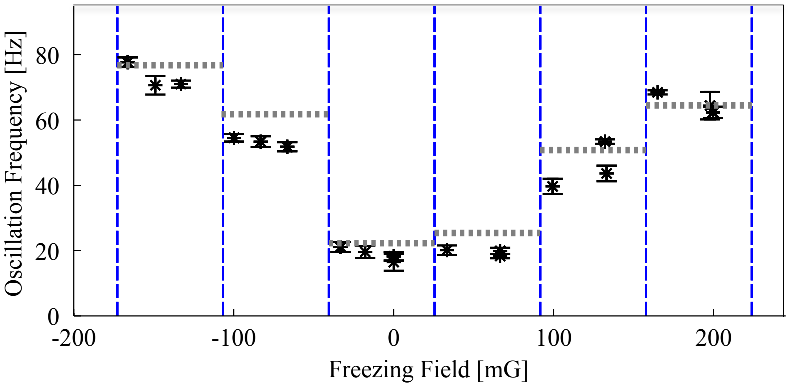
Mapping the flux state of the ring to atomic clouds

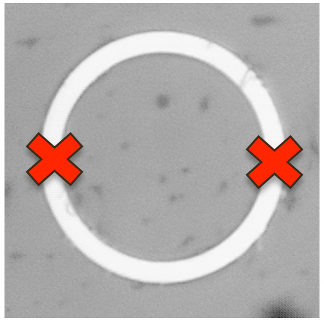






Dipole oscillation frequency in the left well





SQUID

Cold-atoms & superconductors

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Single atom detection

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