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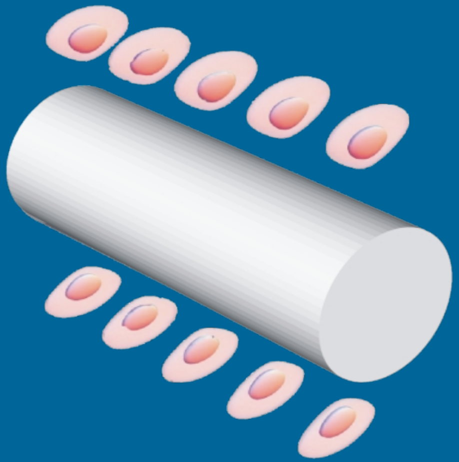
ATOMINSTITUT

Ground-state cooling of atoms close to a nanofiber

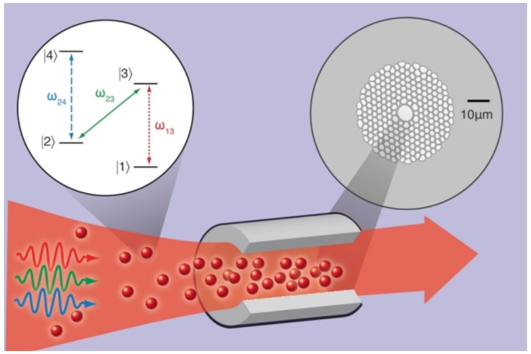


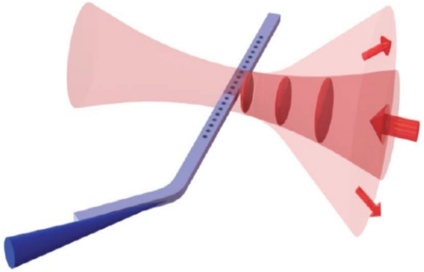
Alexandre Dareau, Y. Meng, B. Albrecht,
C. Clausen, P. Schneeweiss & A. Rauschenbeutel

Vienna Center for Quantum Science and Technology
TU Wien – Atominstitut

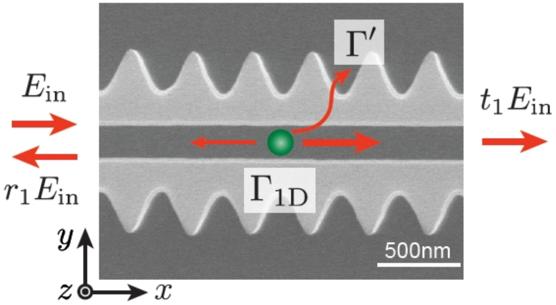
Introduction – nanophotonic atom-light interfaces

Systems overview





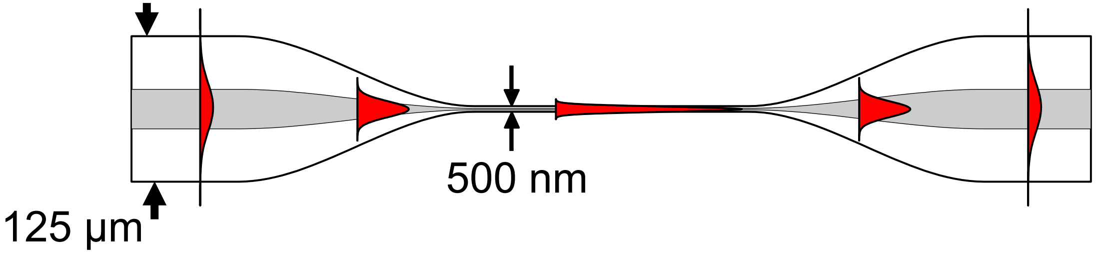
Thompson *et al.*,
Science **340**, 1202 (2013)



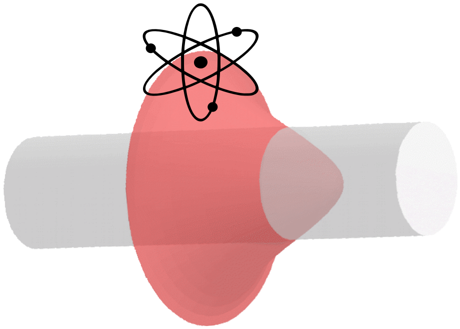
Christensen *et al.*, *PRA* **78**, 033429 (2008)
Bajcsy *et al.*, *PRL* **102**, 203902 (2009)

Goban *et al.*,
Nat. Comm. **5**, 3808 (2014)

Tapered optical nanofibers



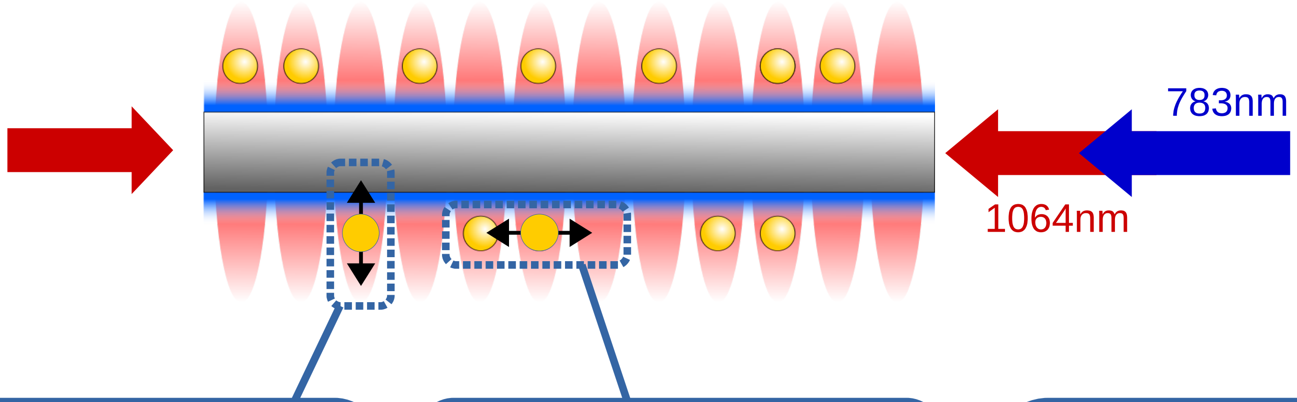
E. Vetsch *et al.*, *PRL* **104**, 203603 (2010)



- atoms trapped evanescent field
- strong atom-light interaction

Introduction – nanofiber-based optical trap

Two-color optical trap



radial confinement

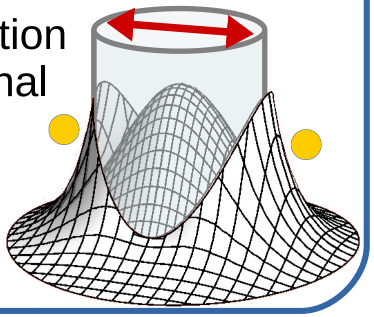
different decay length for blue-detuned (repulsive) & red-detuned (attractive) light fields

axial confinement

red-detuned standing wave at 1064 nm

azimuthal confinement

linear polarization breaks rotational symmetry

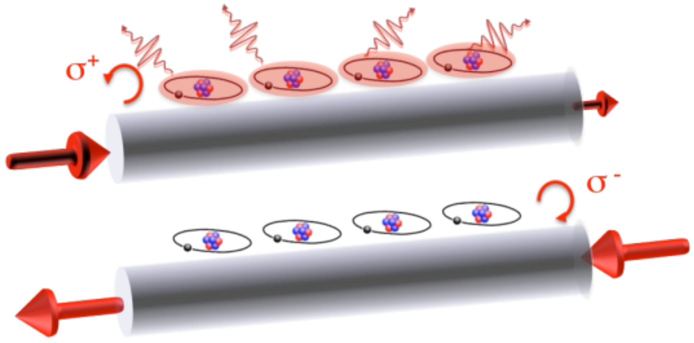


- typical trap frequencies : 90kHz to 250kHz
- atoms are in the Lamb-Dicke regime

Introduction – nanofiber-based optical trap

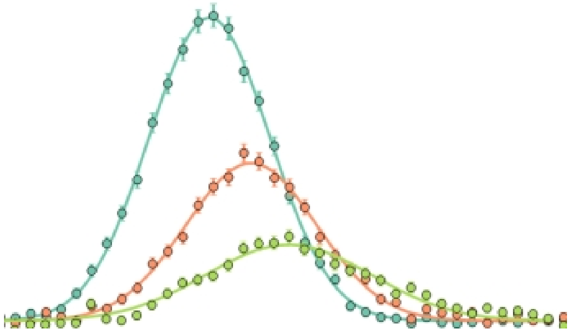
Application examples

optical diode



C. Sayrin *et al.*, *PRX* **5**, 041036 (2015)

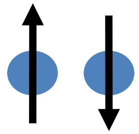
slow light



C. Sayrin *et al.*, *OPTICA* **2**, 000353 (2015)
B. Gouraud *et al.*, *PRL* **114**, 180503 (2015)

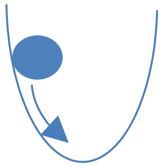
Motivation : control over atomic state at the quantum level

☑ **internal** degrees of freedom



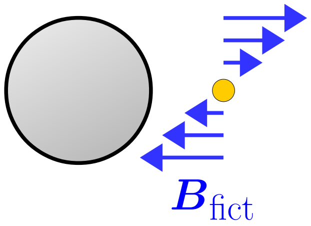
Prepare Hyperfine
and Zeeman state

☐ **external** degrees of freedom

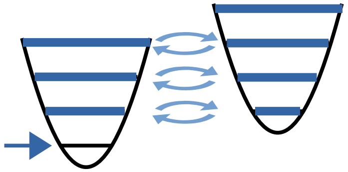


Ground state
cooling

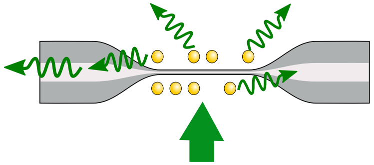
Outline



Fictitious magnetic fields in nanofiber-based traps



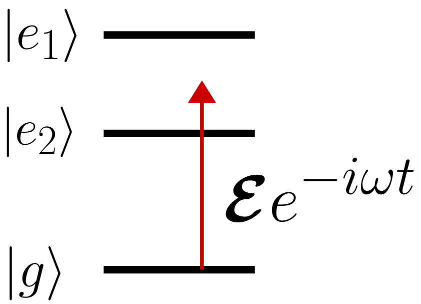
Degenerate Raman cooling of trapped atoms



Temperature measurement via fluorescence spectroscopy

Fictitious magnetic fields – general concept

Atom-light interaction



Light-shift operator for an Alkali atom in the ground state

$$\hat{V}_{A-L} = \underbrace{-\frac{1}{4}\alpha_s(\omega)|\boldsymbol{\mathcal{E}}|^2}_{\text{scalar}} + \underbrace{i\frac{1}{8F}\alpha_v(\omega)\left(\boldsymbol{\mathcal{E}}^* \times \boldsymbol{\mathcal{E}}\right)\cdot\hat{\boldsymbol{F}}}_{\text{vector}}$$

Fictitious magnetic field

vector light-shift ⟺ (Zeeman) interaction with a fictitious magnetic field

$$\hat{V}_{\text{vec}} = g_F\mu_B\,\boldsymbol{B}_{\text{fict}}\cdot\hat{\boldsymbol{F}}$$

$$\boxed{\boldsymbol{B}_{\text{fict}} = \frac{i\alpha_v}{8g_F\mu_B F}\left(\boldsymbol{\mathcal{E}}^* \times \boldsymbol{\mathcal{E}}\right)}$$

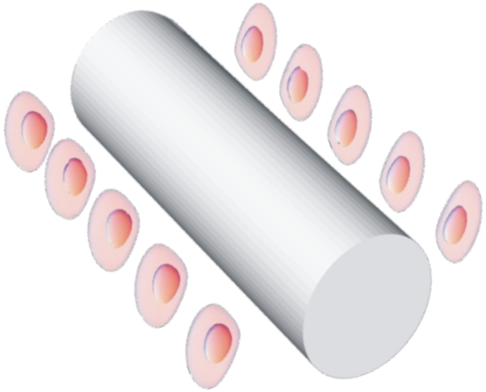
Depends on polarization :

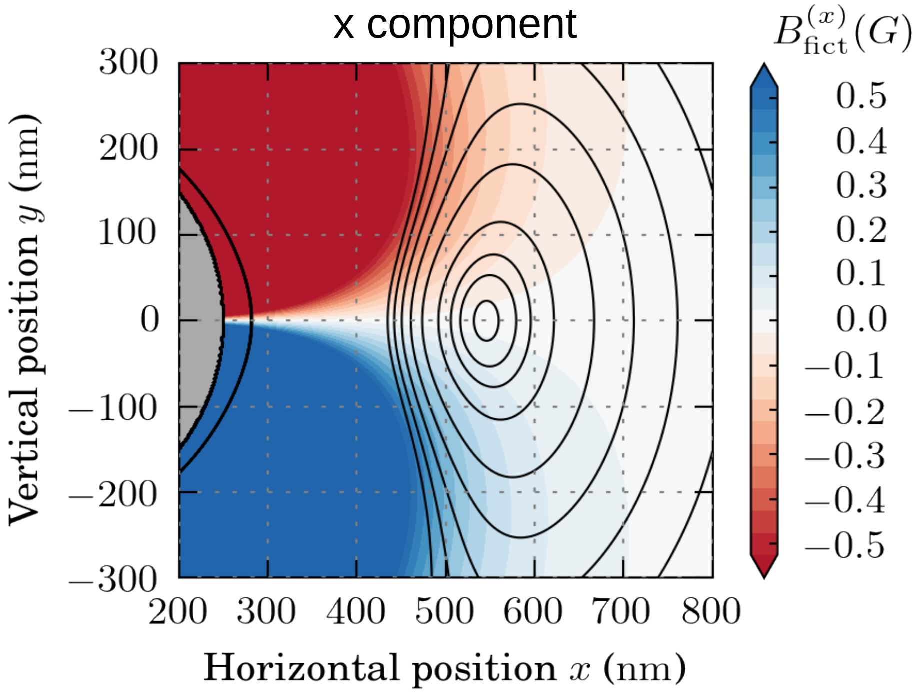
- linear → vanishes
- circular → maximal

C. Cohen-Tannoudji and J. Dupont-Roc, *PRA* **5**, 968 (1972)

Fictitious magnetic fields – in nanofiber traps

Fictitious magnetic field profile





Simple modelling

- points mainly along x
- near atoms' position:
  amplitude ~ linear gradient along y

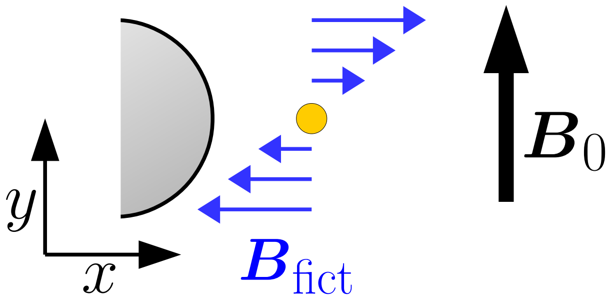
$$\boxed{\boldsymbol{B}_{\text{fict}} \approx b_y \times y\, \boldsymbol{e}_x}$$

Typ. value: $b_y = 1.3\,\mathrm{G}.\mu\mathrm{m}^{-1}$

B. Albrecht *et al.*, *PRA* **94**, 061401(R) (2016)

Cooling scheme – «spin-motion» coupling

- External offset magnetic field **orthogonal** to fictitious field



$$\begin{cases} \boldsymbol{B}_0 = B_0\, \boldsymbol{e}_y \\ \boldsymbol{B}_\text{fict} = b_y\, y\, \boldsymbol{e}_x \end{cases}$$

« natural »
quantization axis

- Ham. : $\hat{H} = \hbar\omega \hat{a}^\dagger \hat{a} + g_F \mu_B \left(B_0 \hat{F}_y + b_y\, \hat{y} \otimes \hat{F}_x \right)$

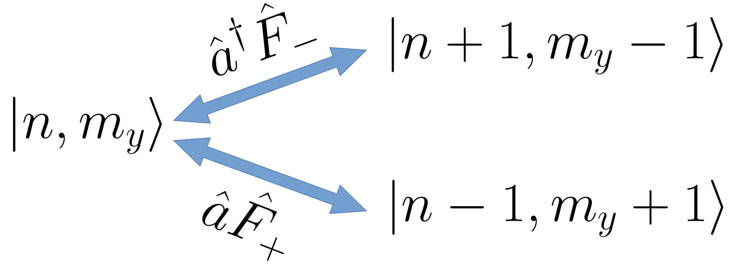
$$\begin{cases} \hat{y} = y_0 \left(\hat{a} + \hat{a}^\dagger \right) \\ \hat{F}_x = \frac{1}{2} \left(\hat{F}_+ + \hat{F}_- \right) \\ \hat{F}_\pm |m_y\rangle \propto |m_y \pm 1\rangle \end{cases}$$

$$\Rightarrow \quad \hat{H} = \hbar\omega \hat{a}^\dagger \hat{a} + \hbar \alpha_F B_0 \hat{F}_y + \hbar\gamma \left(\hat{a} + \hat{a}^\dagger \right) \left(\hat{F}_+ + \hat{F}_- \right)$$

harmonic oscillator

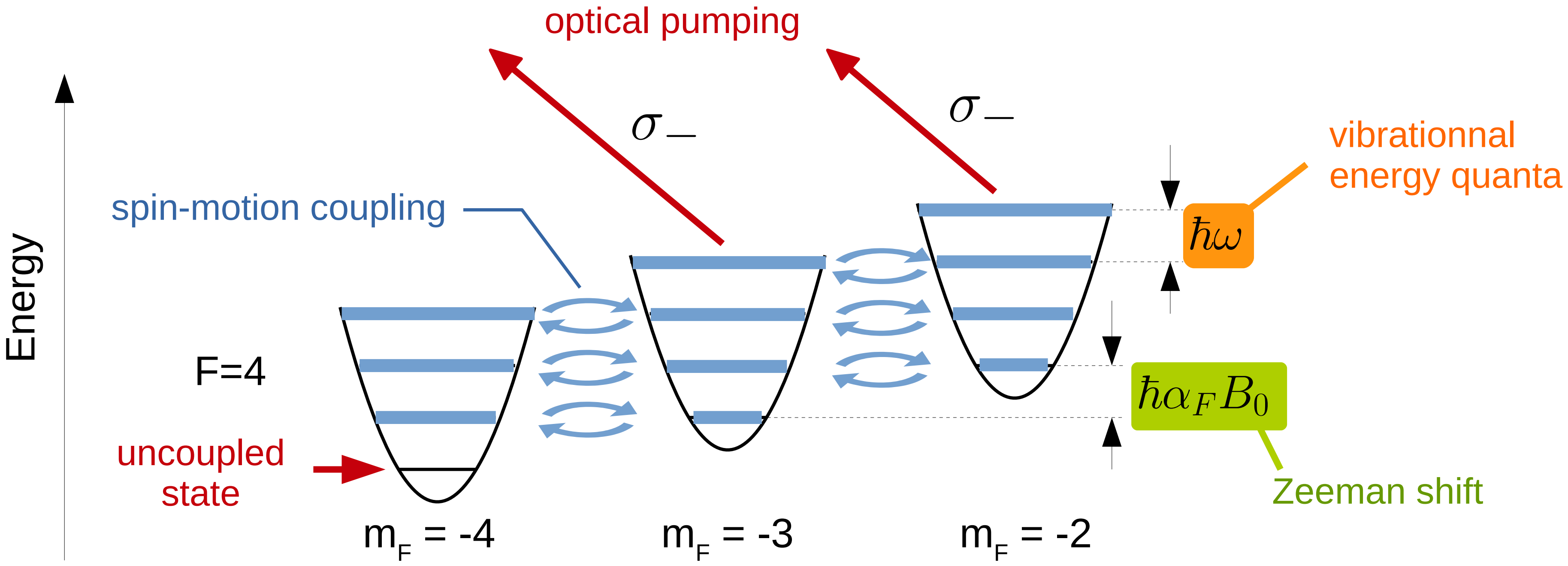
Zeeman shift

« spin-motion » coupling



Cooling scheme – degenerate Raman cooling

Degenerate Raman cooling principle



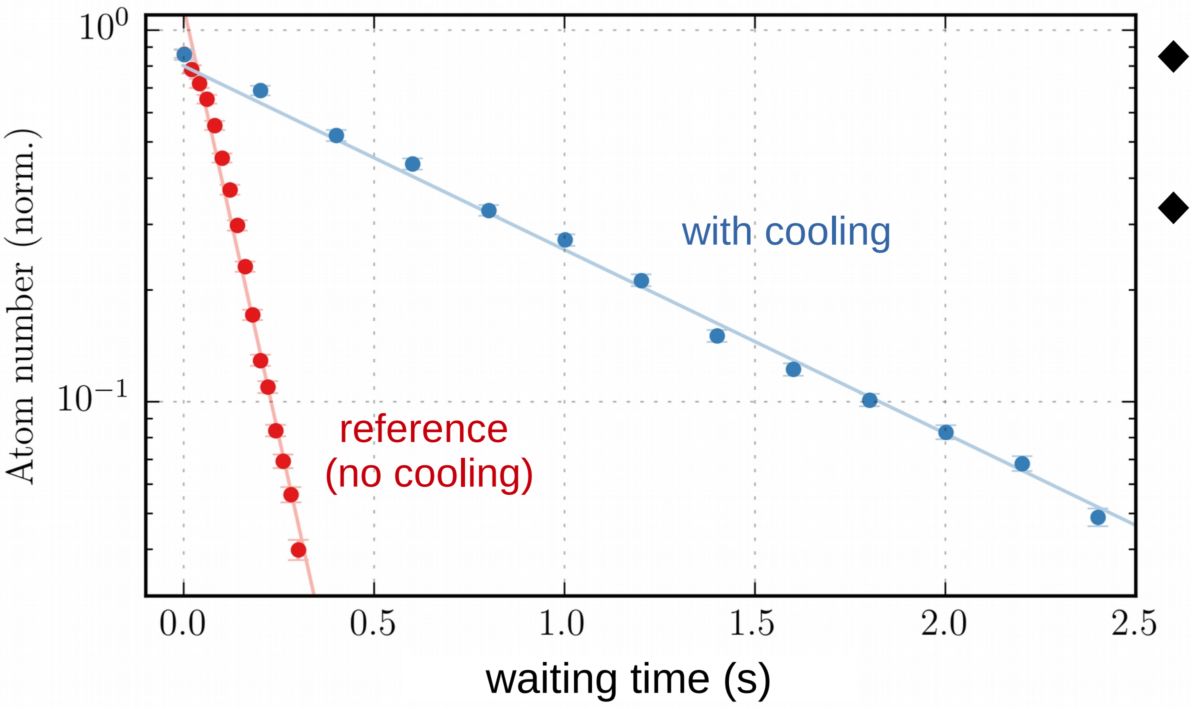
- uncoupled state : $|n = 0, m_F = -4\rangle$
- Lamb-Dicke regime : optical pumping preserves motional state

➡ atoms cooled to n=0

S. E. Hamman *et al.*, *PRL* **80**, 19 (1998) / A. J. Kerman *et al.*, *PRL* **84**, 3 (2000)

Cooling – experimental results

- Lifetime in presence of degenerate Raman cooling



◆ Reference lifetime (no cooling)	~ 90 ms
◆ With cooling	~ 900 ms

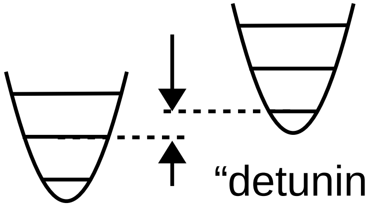
Background pressure limited lifetime

indication for cooling of all spatial degrees of freedom

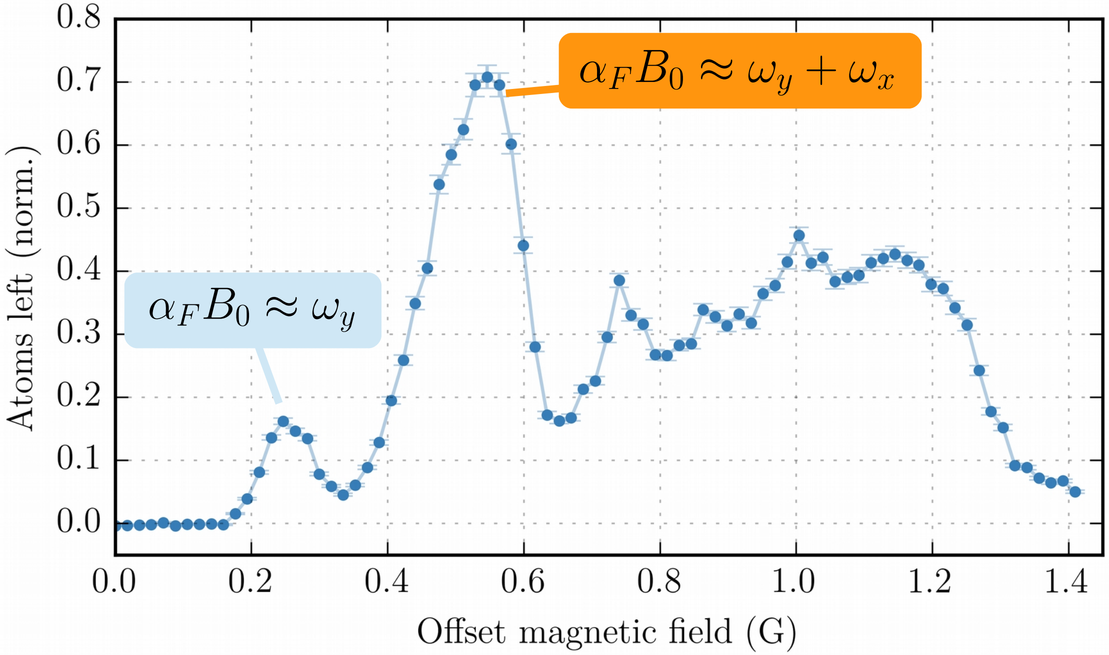
Cooling – experimental results

Observing the spin-motion resonances

- Vary external offset magnetic field
- Measure atoms left after 500ms cooling

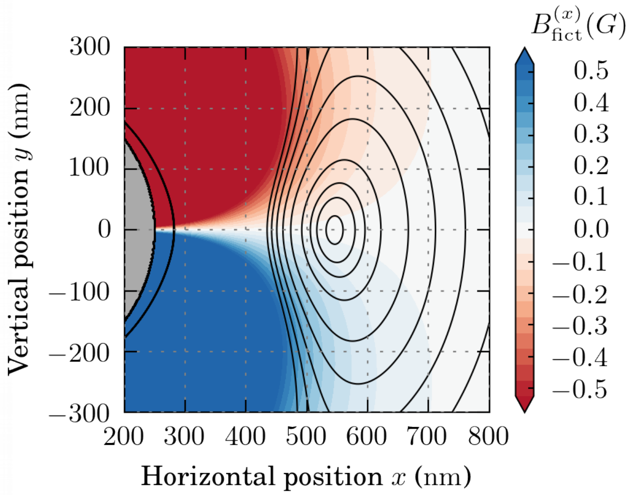


“detuning” depends on offset field



$\alpha_F B_0 \approx \omega_y + \omega_x$

$\alpha_F B_0 \approx \omega_y$



$$\boldsymbol{B}_{\text{fict}} \sim \boxed{b_x \hat{y}\, \boldsymbol{e}_x} + \boxed{b_{xy} \hat{x}\hat{y}\, \boldsymbol{e}_x} + \cdots$$

yields terms in $\hat{a}_x \otimes \hat{a}_y \otimes \hat{F}_+$

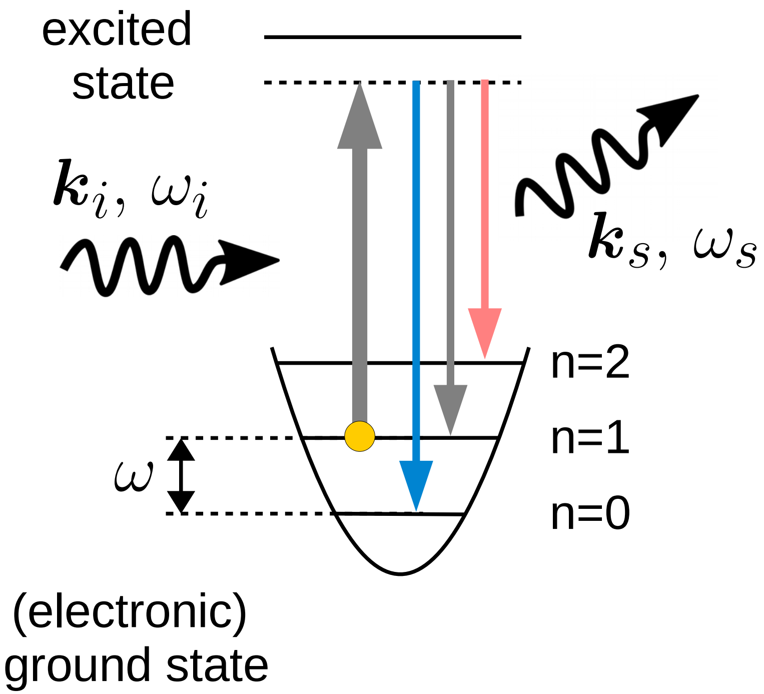
➡ multiple spin-motion resonances

Fluorescence Spectroscopy – temperature ?

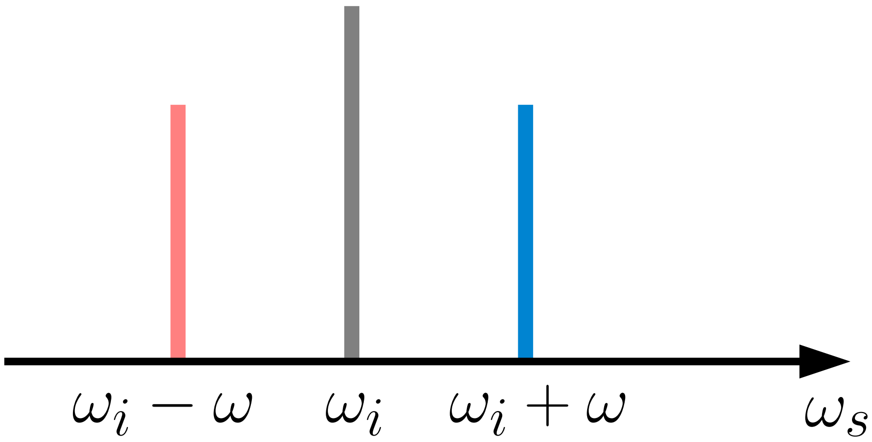
How to infer the atom’s temperature ?

- Increased lifetime → indication for cooling
- More quantitative measurement: fluorescence spectroscopy

Fluorescence sideband spectroscopy



Fluorescence spectrum



- Sidebands appear at trap frequency
- Sidebands’ amplitude ratio yields temperature

Fluorescence Spectroscopy – temperature ?

How to infer the atom’s temperature ?

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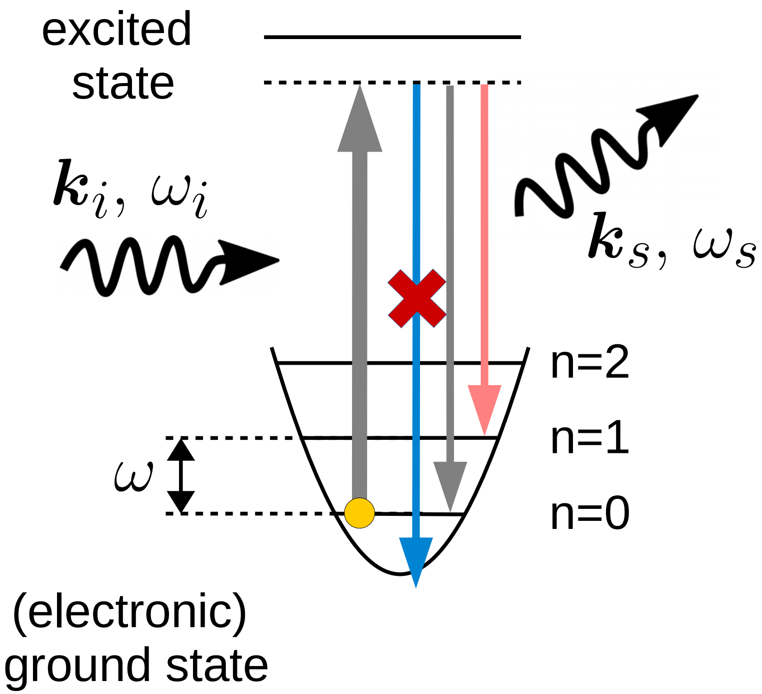
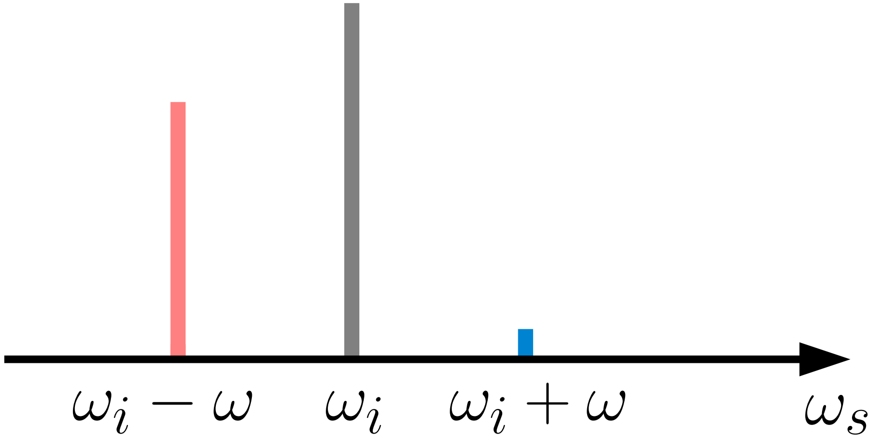
Fluorescence sideband spectroscopy



Fluorescence spectrum

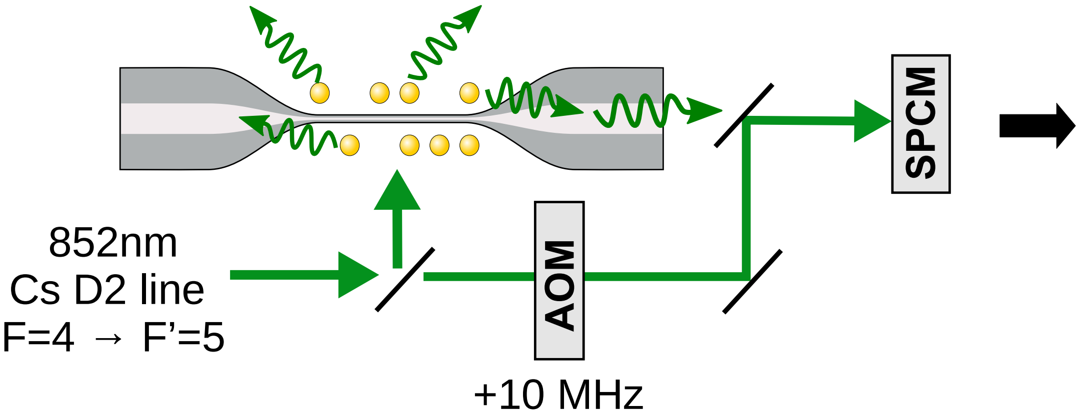


- Sidebands appear at trap frequency
- Sidebands’ amplitude ratio yields temperature

Fluorescence Spectroscopy – results

- heterodyne fluorescence spectroscopy

P. S. Jessen *et al.*, *PRL* **69**, 49 (1992)

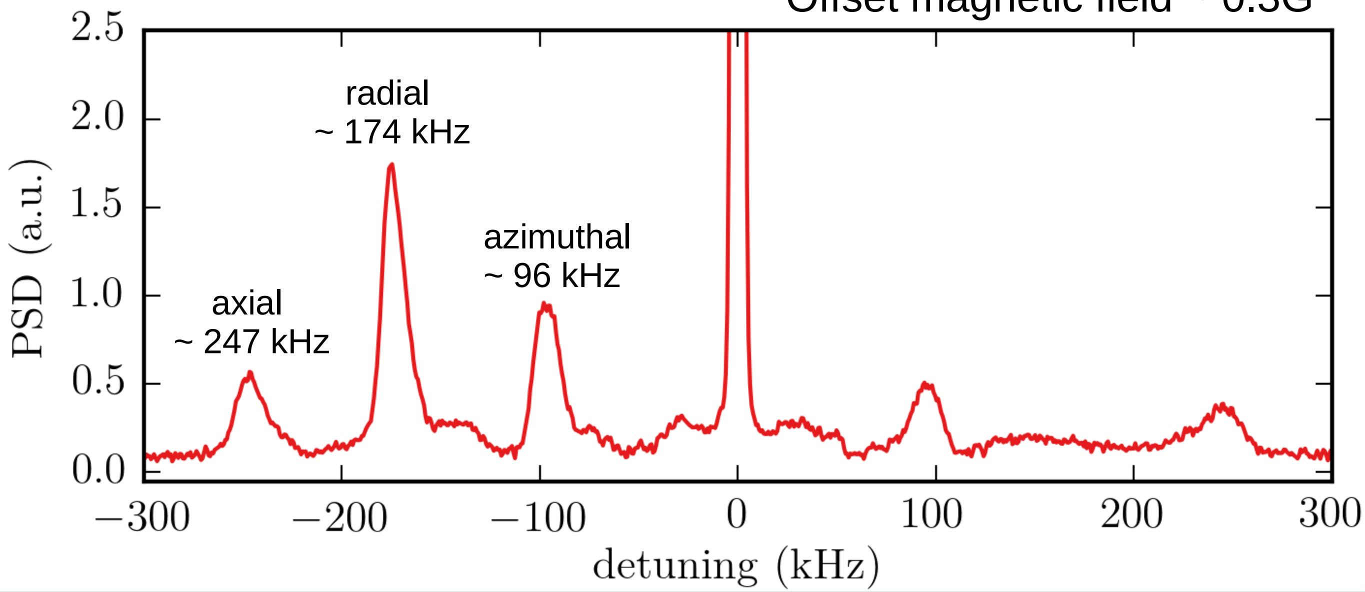


852nm
Cs D2 line
F=4 → F'=5

+10 MHz

Compute Power Spectral Density (PSD)

Offset magnetic field ~ 0.3G

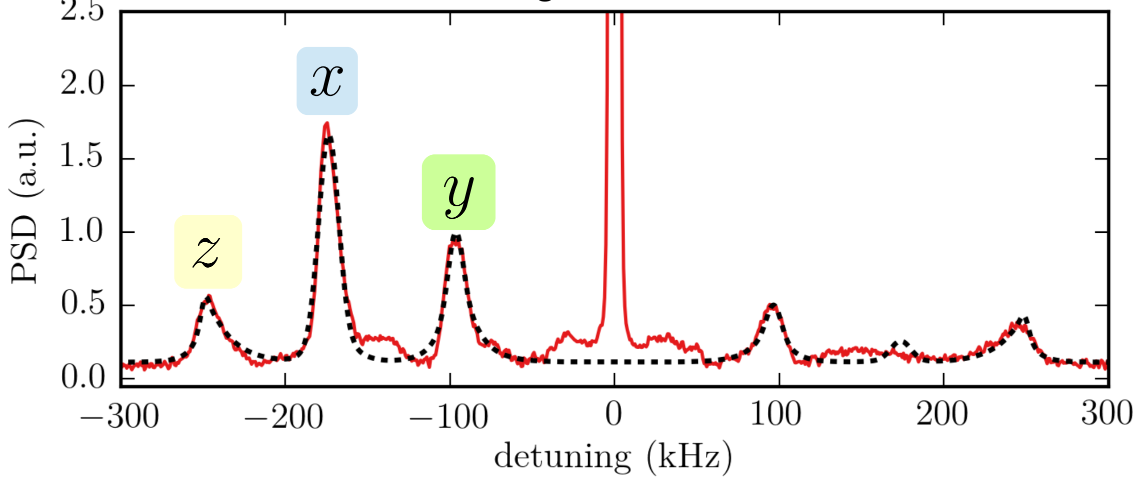


- Precise measurement of trap frequencies
- Sidebands amplitude ratio → temperature

Fluorescence Spectroscopy – results

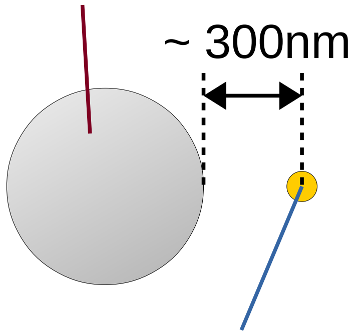
- Temperature from spectrum

Offset magnetic field ~ 0.3G



Fit results

mean number of excitation	ground state population	temperature
$\langle n_x \rangle = 0.1 \pm 0.01$	$\pi_{0,x} \approx 91\%$	$T_x \approx 3\,\mu\mathrm{K}$
$\langle n_y \rangle = 0.78 \pm 0.05$	$\pi_{0,y} \approx 56\%$	$T_y \approx 6\,\mu\mathrm{K}$
$\langle n_z \rangle = 2.5 \pm 0.3$	$\pi_{0,z} \approx 28\%$	$T_z \approx 36\,\mu\mathrm{K}$



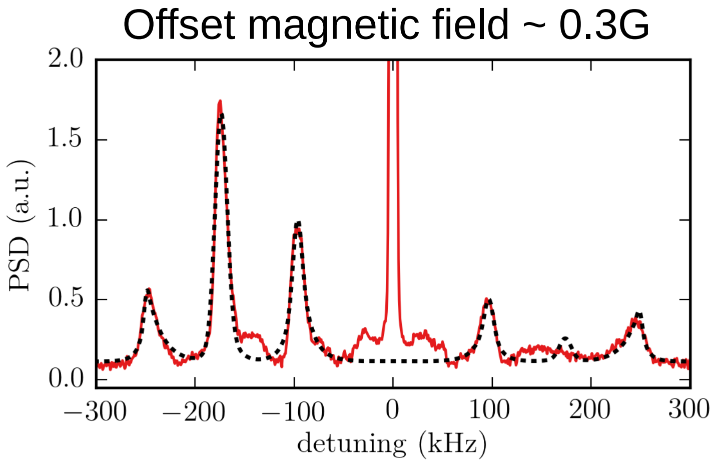
T ~ 10^2 K

~ 300nm

T ~ 10^{-6} K

Fluorescence Spectroscopy – results

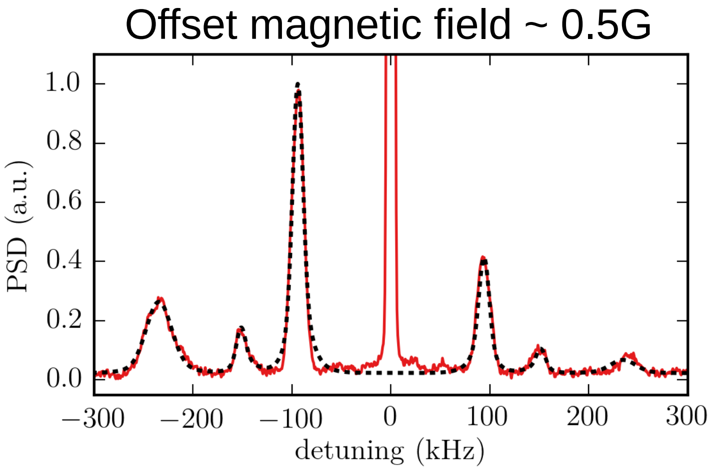
- Changing offset magnetic field : cooling different degrees of freedom



$$\langle n_x \rangle = 0.1 \pm 0.01$$

$$\langle n_y \rangle = 0.78 \pm 0.05$$

$$\langle n_z \rangle = 2.5 \pm 0.3$$

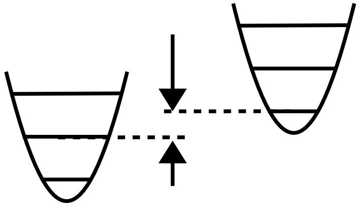


$$\langle n_x \rangle = 1.2 \pm 0.2$$

$$\langle n_y \rangle = 0.67 \pm 0.01$$

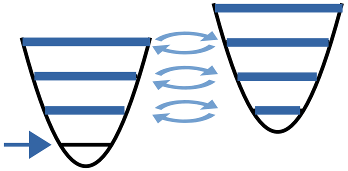
$$\langle n_z \rangle = 0.23 \pm 0.02$$

Changing the offset fields selects different spin-motion resonances → cools different degrees of freedom



Summary & Outlook

Summary

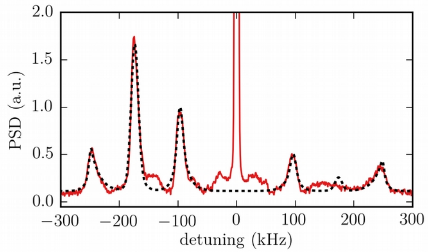


- Fictitious magnetic fields enable efficient cooling

  Degenerate Raman cooling : only requires **one** optical field (can be **fiberguided**)

- Fluorescence Spectroscopy as a powerful probe

  Precise measurement of trap **frequencies** and **temperatures** (3D)
  Provides evidence for ground-state cooling



Outlook

- Maximize 3D ground state population

  Optimize cooling scheme
  Good starting point to study new effects (e.g. surface forces)

- Ultra-strong coupling with cold atoms

  P. Schneeweiss *et al.*, arXiv:1706.07781

$$\hbar\gamma\left(\hat{a}+\hat{a}^{\dagger}\right)\left(\hat{F}_{+}+\hat{F}_{-}\right)$$

Aknowledgements

Arno Rauschenbeutel's group – « cold-atom » experiment

PhD position available !

Y. Meng, A. Rauschenbeutel, P. Schneeweiss & A. Dareau

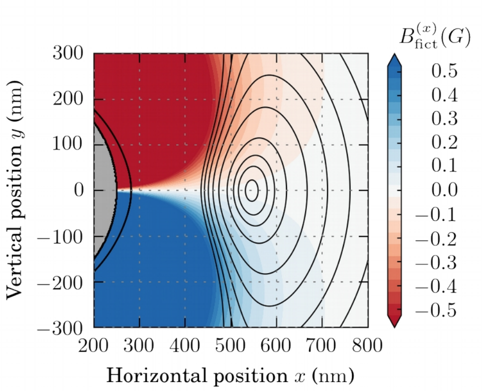
Former members: B. Albrecht, C. Clausen

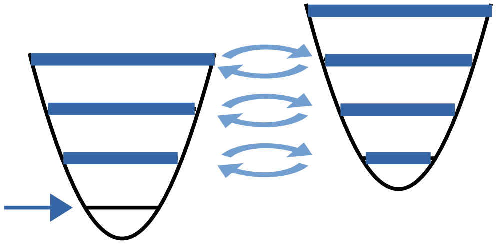
NEXT lite

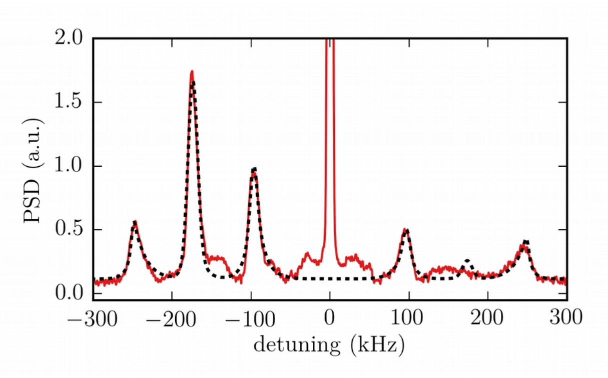
CoQuS
ComplexQuantumSystems

FWF
Der Wissenschaftsfonds.

erc







Thank you for your attention

See also : Ultra-strong coupling with cold atoms

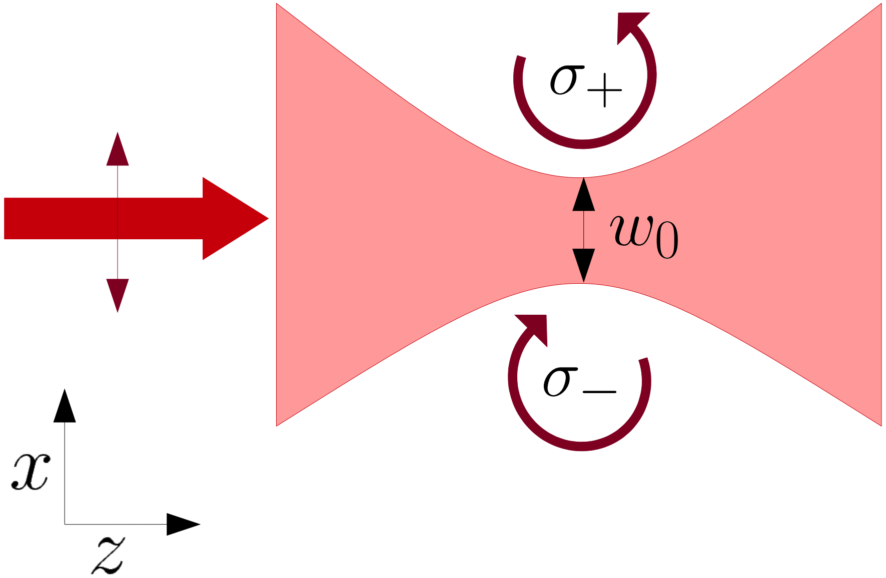
P. Schneeweiss *et al.*, arXiv:1706.07781

$$\hbar\gamma\left(\hat{a}+\hat{a}^{\dagger}\right)\left(\hat{F}_{+}+\hat{F}_{-}\right)$$

Appendix

Introduction – polarization in optical microtraps

- Strongly focused field (e.g. Gaussian)



$$\boldsymbol{\mathcal{E}} = \overbrace{\mathcal{E}_0(x,y,z)}^{\text{Gaussian profile}}\, e^{ikz}\,\mathbf{e}_x + \overbrace{\mathcal{E}_1\, e^{ikz}\,\mathbf{e}_z}^{\text{longitudinal polarization}}$$

Gauss' law

$$\boxed{\boldsymbol{\nabla}\cdot\boldsymbol{\mathcal{E}} = 0}$$

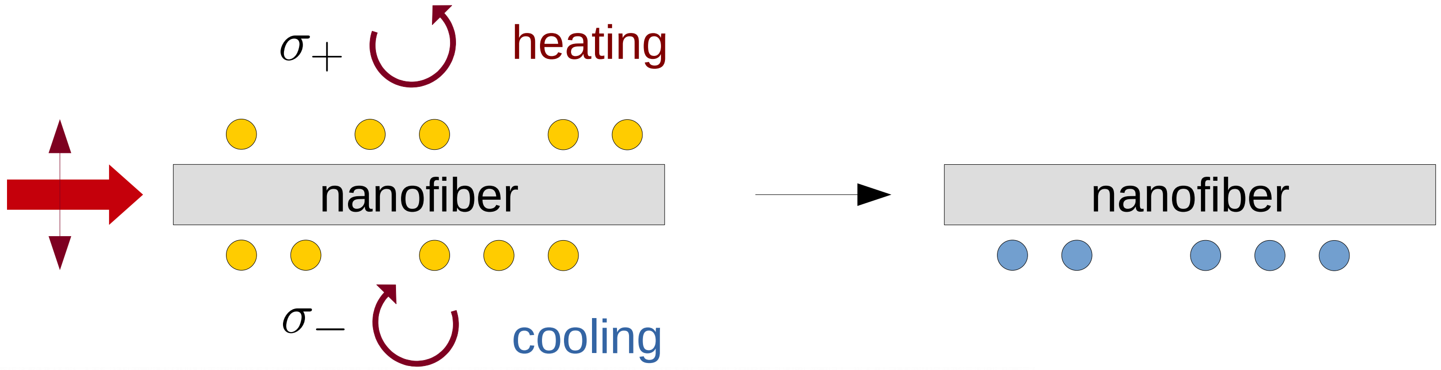
$$\mathcal{E}_1 \approx i\,\frac{\lambda}{2\pi}\,\partial_x\mathcal{E}_0$$

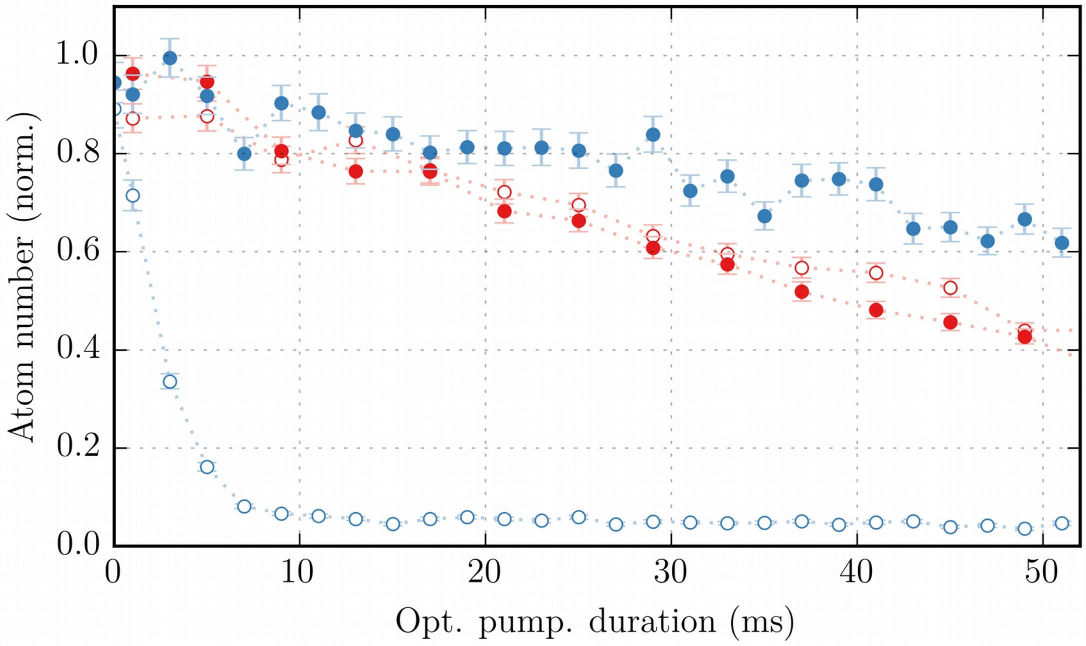
oscillates in quadrature

non-negligible if waist ~ λ

Transverse coupling – « spin motion » coupling

- In a nanofiber-based optical trap : side selective cooling/heating





○ atoms on σ+ side
● atoms on σ- side

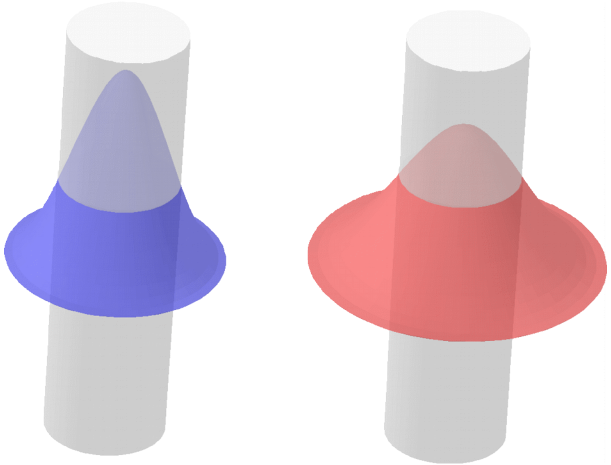
with opt. pump.

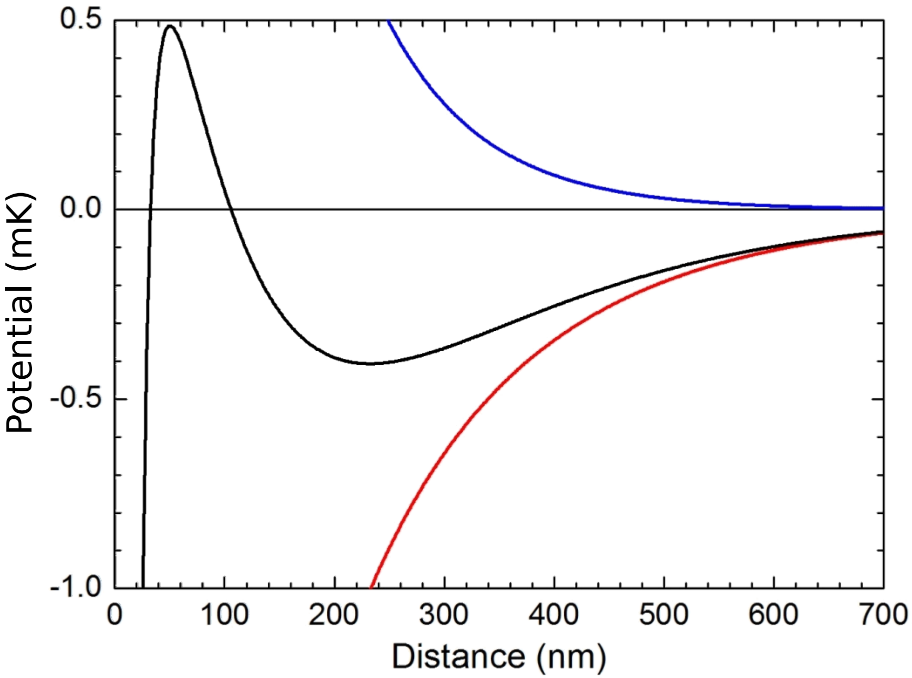
reference
(no opt. pump.)

Nanofiber based optical trap

Radial confinement

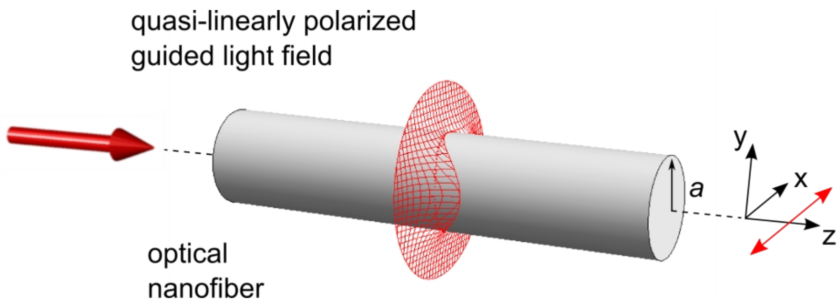
- Evanescent field exerts a dipole force on the atoms
- “Blue light” is more tightly bound to the nanofiber than “red light”

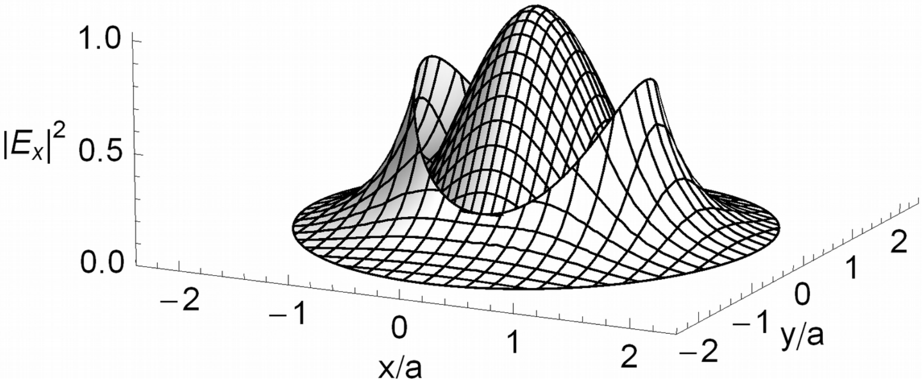




Nanofiber based optical trap

◆ azimuthal confinement





◆ axial confinement