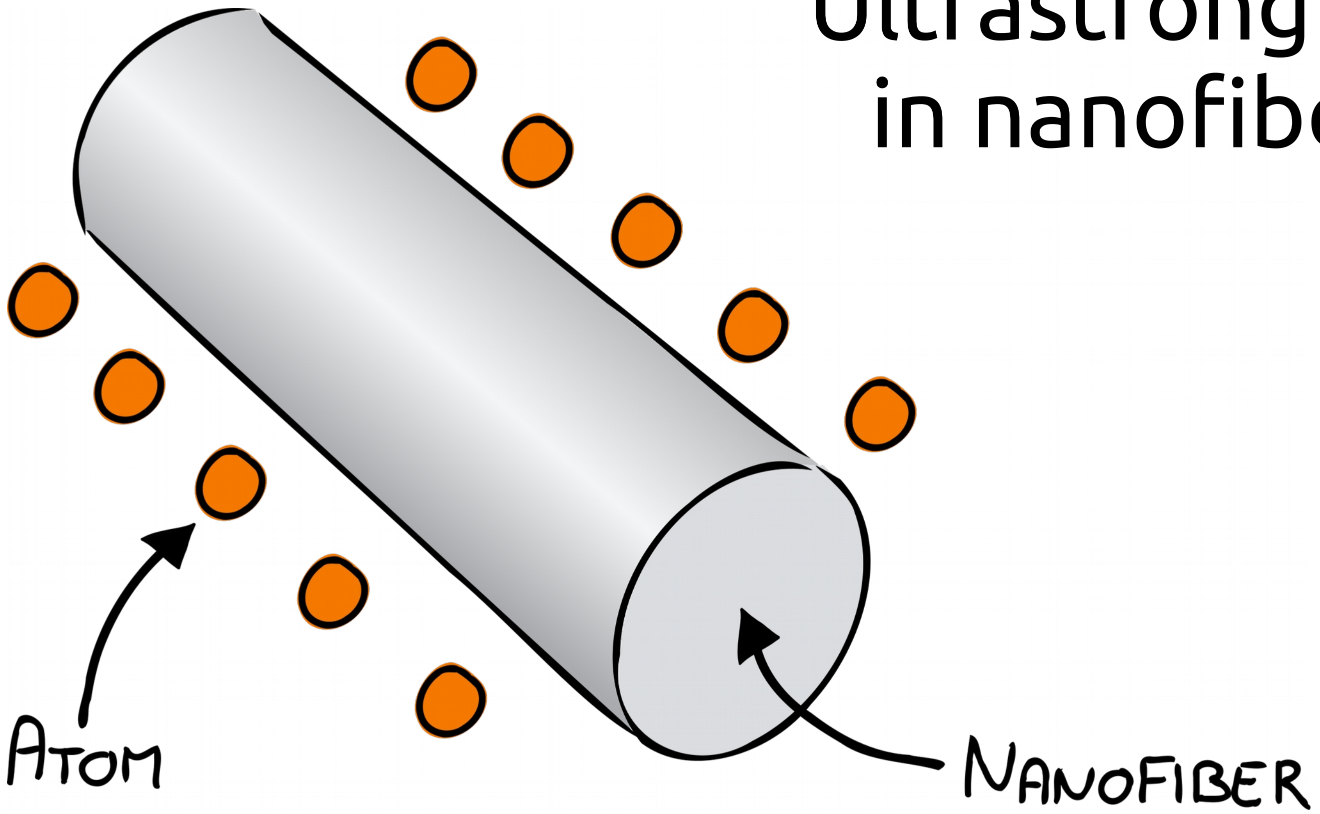
Ultrastrong spin-motion coupling in nanofiber-based optical traps



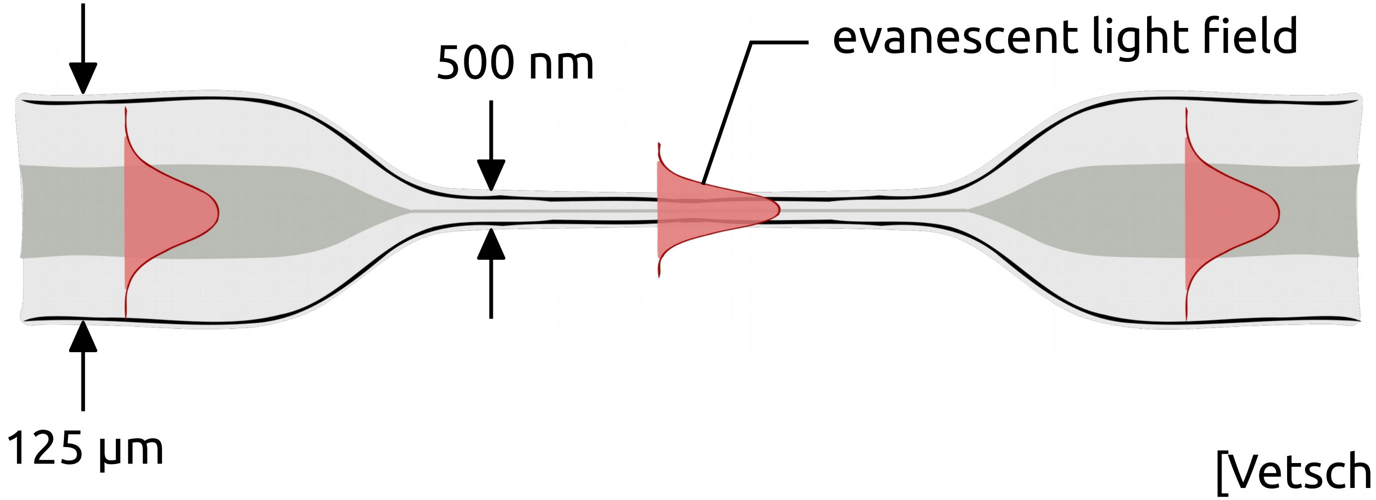
Alexandre Dareau*, Y. Meng,
P. Schneeweiss & A. Rauschenbeutel

VCQ – TU Wien – Atominstitut
(Vienna, Austria)

* now at Laboratoire Charles Fabry, IOGS (Palaiseau, France)

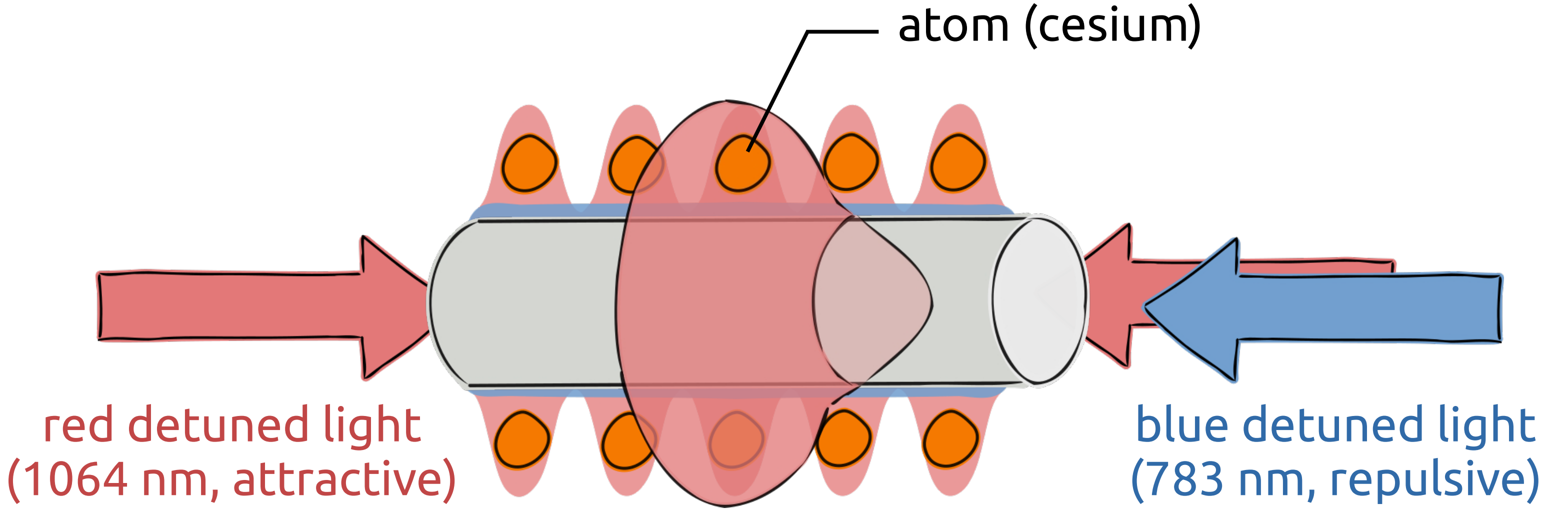
Nanofiber-based optical traps

Optical nanofiber



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

Trapping atoms



- light-assisted collisions during loading
  → max. 1 atom / site
- typically : $N = 10^2 - 10^3$ atoms
  OD = 1 – 10

Trapping atoms in evanescent light fields

Fictitious magnetic field ! [Cohen-Tannoudji & Dupont-Roc, *PRA* **5**, 968 (1972)]

evanescent light field (size ~ λ) → polarization gradient → gradient of vector ac Stark shift

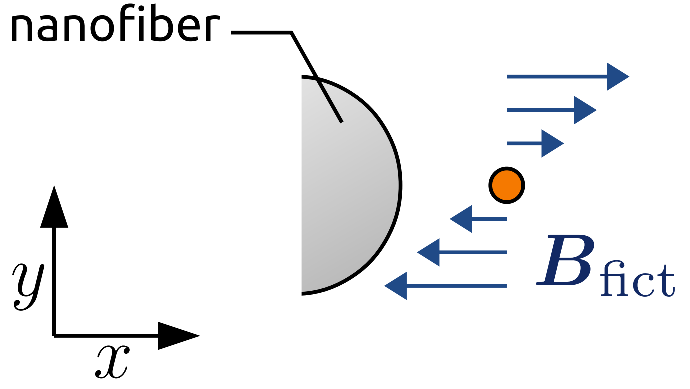
depends on the atom's spin state

$$\hat{V}_{\text{vec}} \propto \alpha_v(\omega)\, (\boldsymbol{\mathcal{E}}^* \times \boldsymbol{\mathcal{E}}) \cdot \hat{\boldsymbol{F}}$$

← analogous to a Zeeman interaction with a **gradient** of **fictitious magnetic field**

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

With our trap configuration, to first order : linear gradient

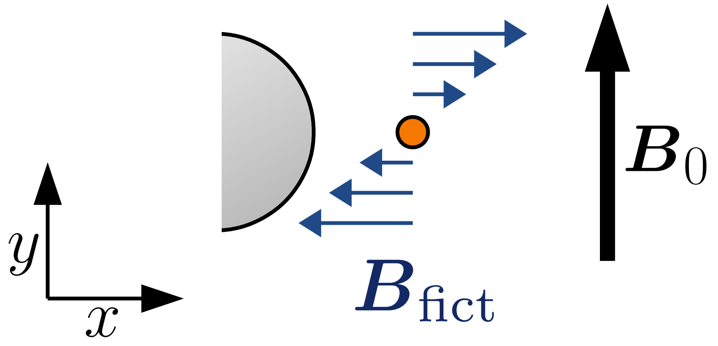


$$\boldsymbol{B}_{\text{fict}} \approx b_y \times y\, \boldsymbol{e}_x$$

b_y: $1.3\,\text{G}.\mu\text{m}^{-1}$

What is the effect on the atoms ?

Spin-motion coupling



« natural » quantization axis

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

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

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

(Cesium, F=4)

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

harmonic oscillator	Zeeman shift	« spin-motion » coupling
↕	↕	↕
quantized light field (in cavity)	N-level system (atom[s])	Atom-light coupling

atoms in nanofiber based optical trap

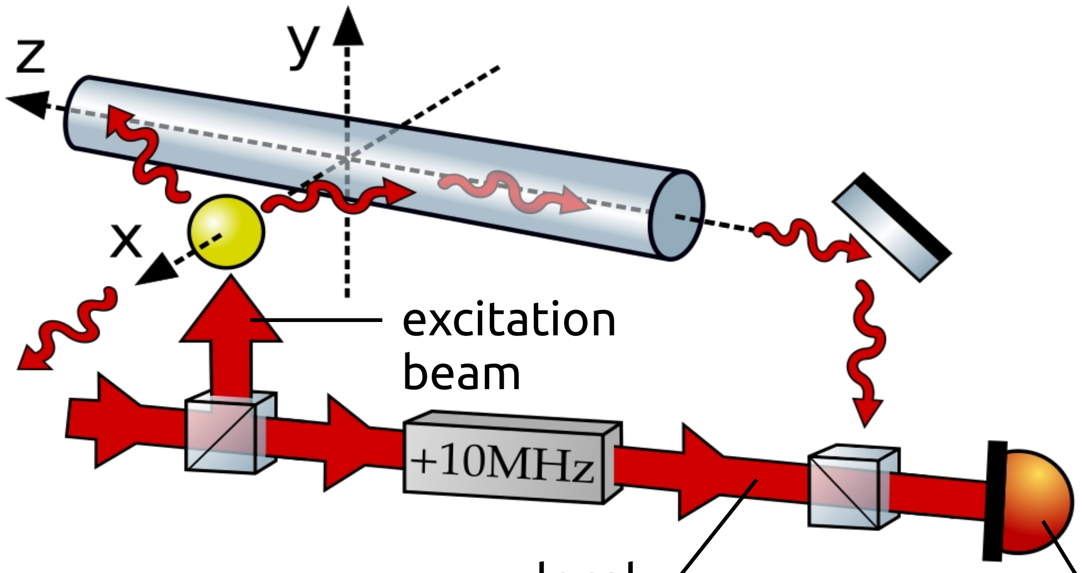
↕

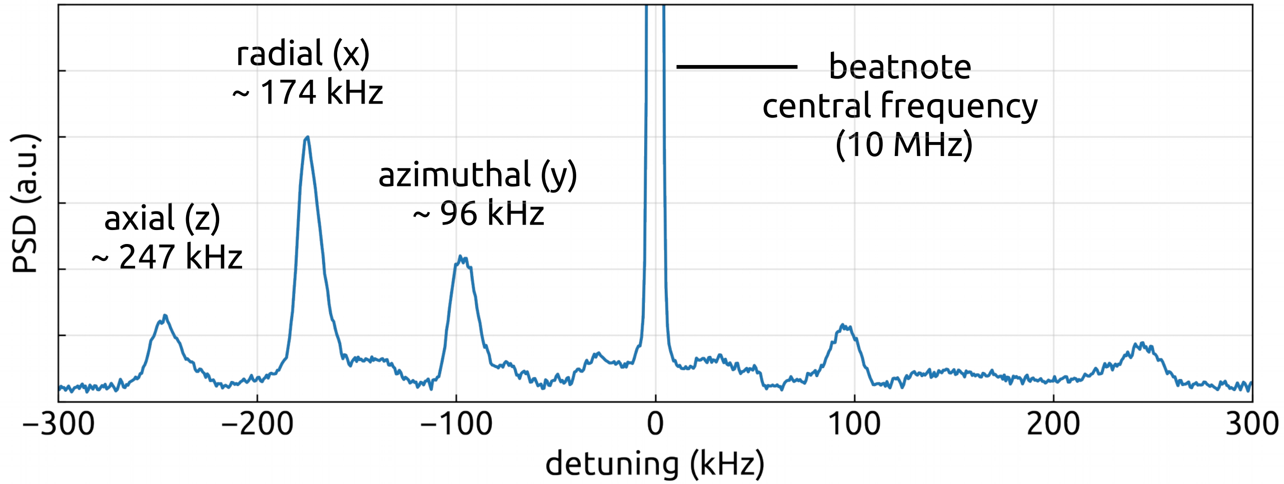
CQED model(s) (Jaynes-Cummings/Dicke)

[Schneeweiss, Dareau & Sayrin, *PRA* **98**, 021801(R) (2018)]

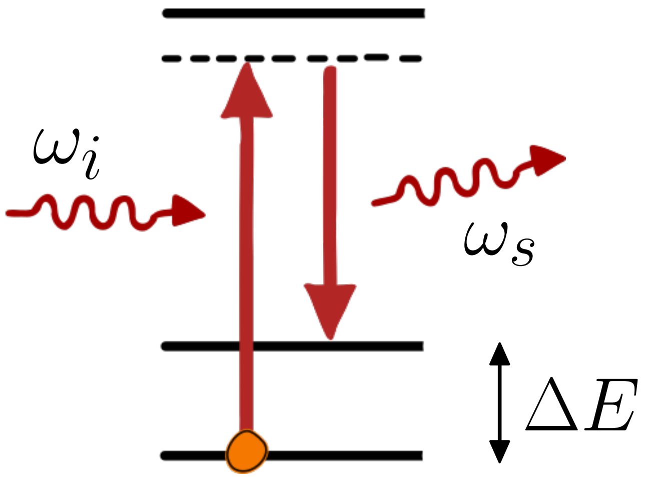
Looking for an experimental signature...

Our probe : fluorescence spectroscopy





- heterodyne detection
- power spectral density (PSD) yields energy spectrum



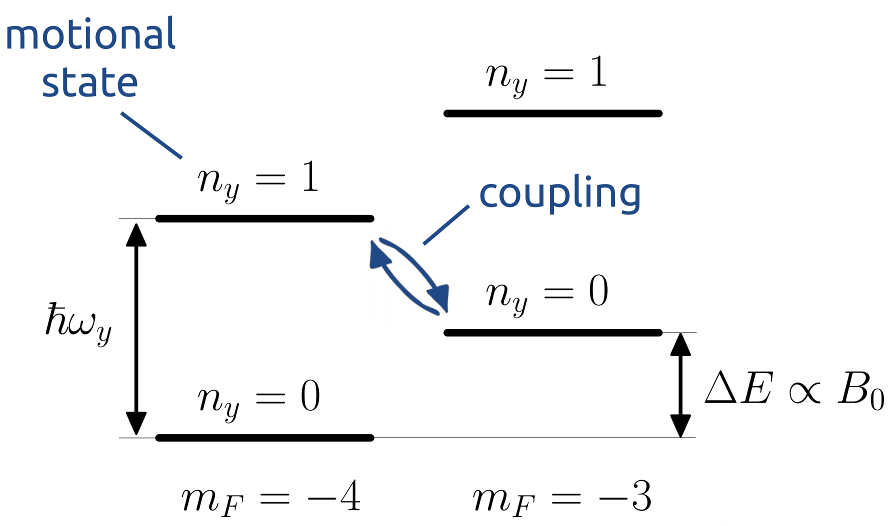
$$\hbar\omega_s = \hbar\omega_i - \Delta E$$

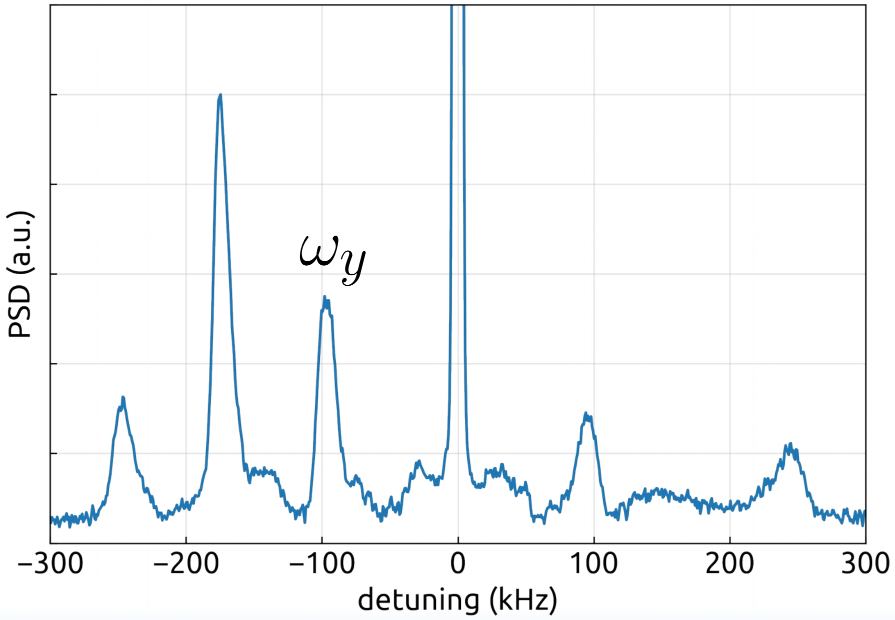
for off-resonant spin-motion coupling
→ yields trap frequencies

(transitions from ground state to first excited motional states)

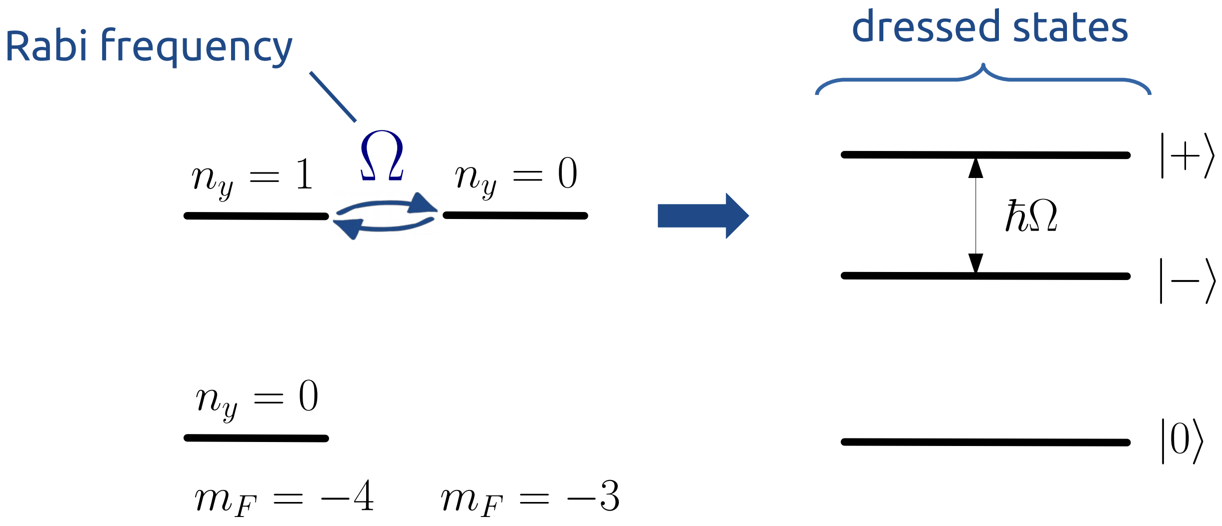
Experimental signature of the spin-motion coupling !

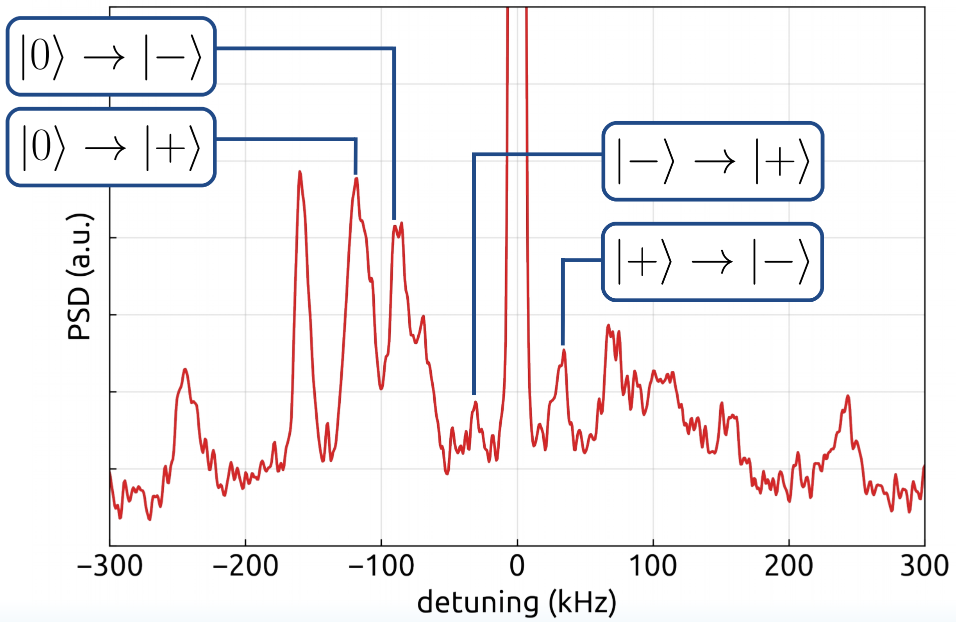
off-resonant coupling





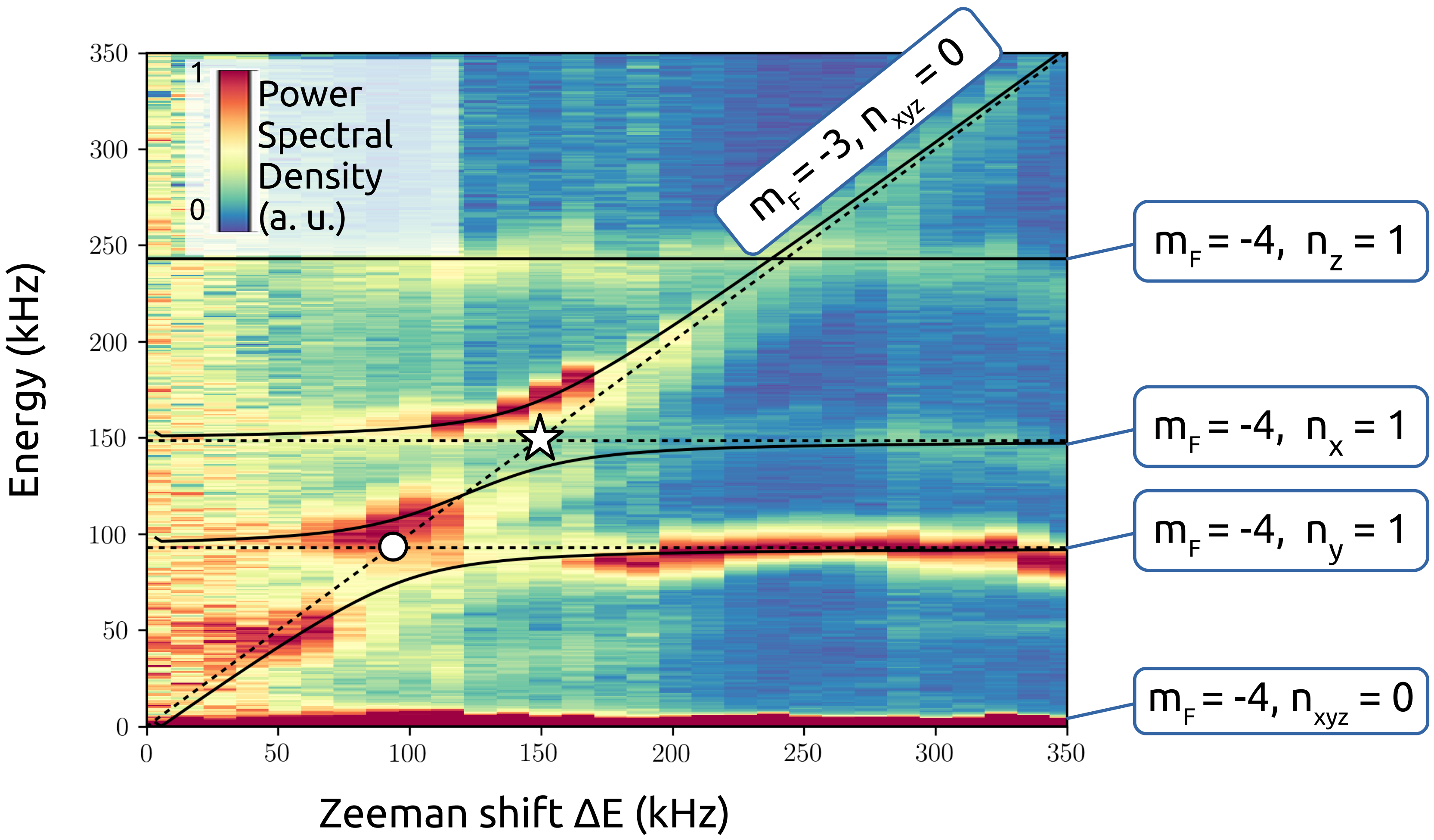
resonant coupling → vacuum Rabi splitting





Experimental signature of the spin-motion coupling !

Scanning across resonance [Dareau *et al.*, PRL **121**, 253603 (2018)]



Trap frequencies

f_x = 149(2) kHz
f_y = 93(2) kHz
f_z = 243(5) kHz

Rabi frequency (for n=1)

☆ $\Omega_x = 2\pi \times 35(1)$ kHz
○ $\Omega_y = 2\pi \times 36(1)$ kHz

$\Omega_x / \omega_x = 0.24(2)$
$\Omega_y / \omega_y = 0.38(2)$

ultra-strong coupling !

+ possible to increase coupling strength even further (e.g. in optical lattices) [Schneeweiss *et al.*, *PRA* **98**, 021801(R) (2018)]

Tuning the coupling strength

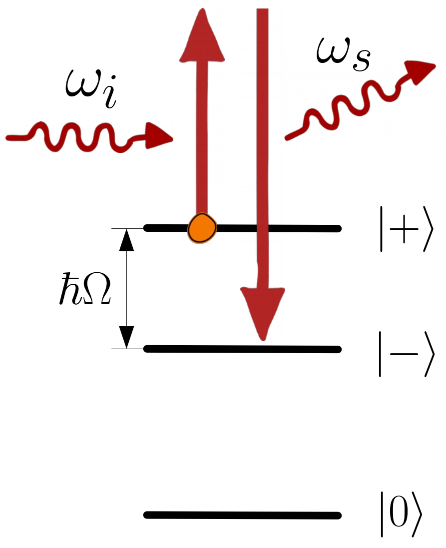
- **Idea :** **compensate** the vector ac Stark shift using **fiber-guided laser** at the **"tune-out"** wavelength (λ=880 nm)

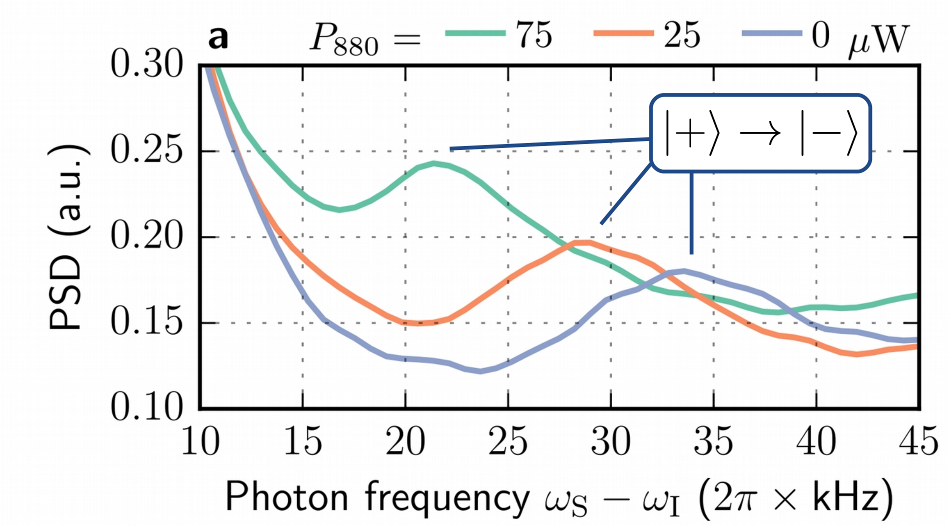
  scalar polarizability vanishes
  → do not affect scalar trapping potential
  → "pure" fictitious magnetic field

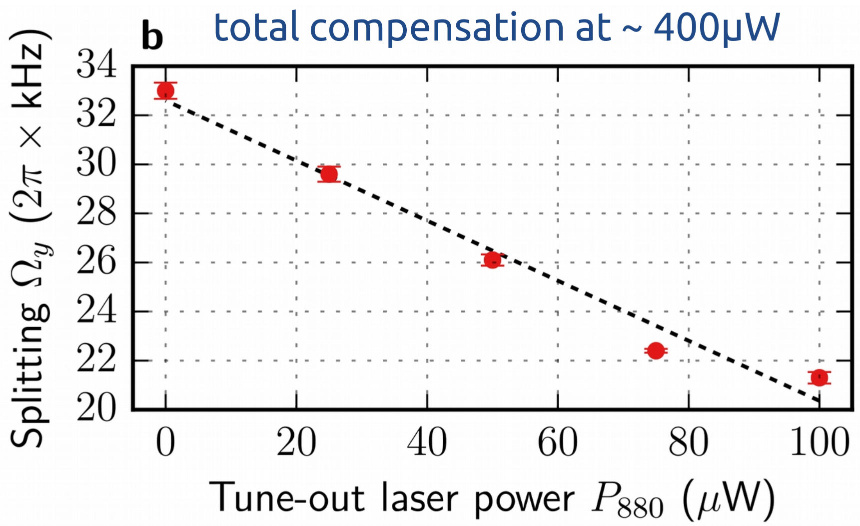
- **Experiment :** reduction of vacuum Rabi splitting

  looking at direct transitions between excited dressed states yields Rabi splitting

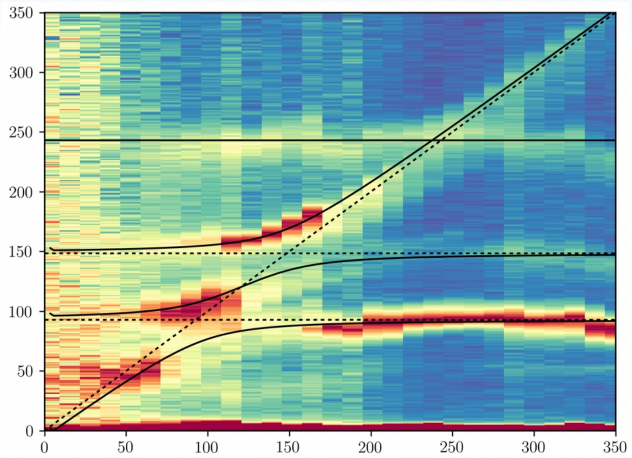
  Rabi splitting **decreases** when tune-out laser power **increases**







Conclusion & outlook



Ultra-strong spin-motion coupling

- **naturally** present in nanofiber-based optical traps (& in optical microtraps)
- possible to **tune** with additional light field
- analogy with **CQED** (Jaynes-Cummings / Dicke)

Outlook : tunability

- ▶ increase coupling strength

  "deep-strong coupling regime" (coupling > trap frequency)

- ▶ dynamical tuning / quenches

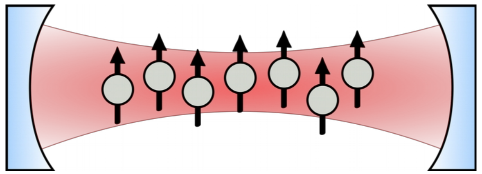
  $\Omega(t)$ with variation faster than trap oscillation period.

  Dynamical Casimir effect ?

Outlook : CQED

- ▶ increase coupling strength

  Dicke model (F=4 → N=8 atoms)

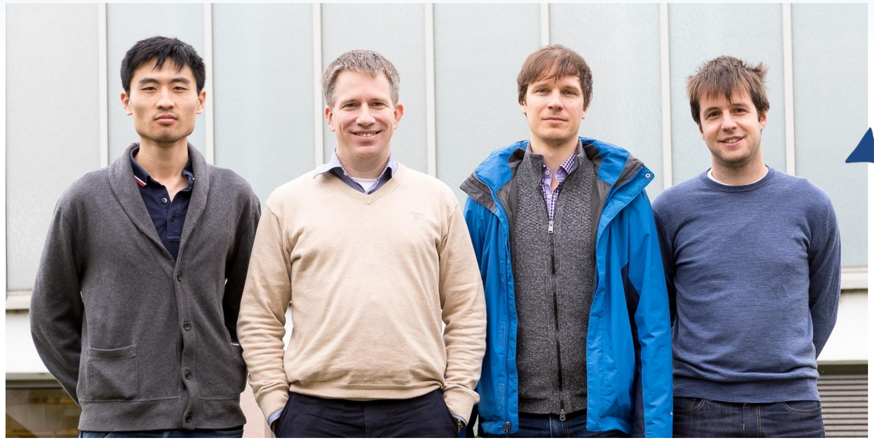


Phase transition in the "mesoscopic" regime ($N < \infty$) ?

Note : also in optical lattices >> Schneeweiss et al., PRA 98, 021801(R) (2018)

Thank you for your attention !

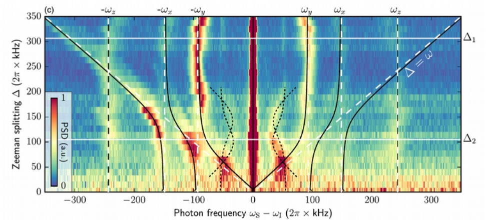
Slides available on www.adphys.eu



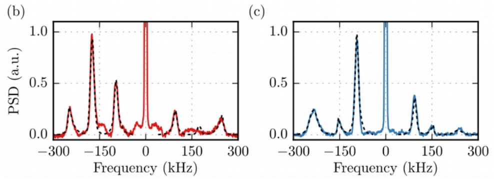
The ~~Vienna~~ Berlin Team

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

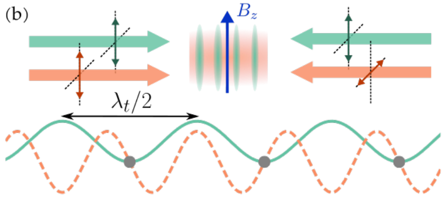
References :



Observation of Ultrastrong Spin-Motion Coupling for Cold Atoms in Optical Microtraps,
A. Dareau, Y. Meng, P. Schneeweiss, and A. Rauschenbeutel
PRL **121**, 253603 (2018) [arXiv:1809.02488]



Near-ground-state cooling of atoms optically trapped 300nm away from a hot surface,
Y. Meng, A. Dareau, P. Schneeweiss, and A. Rauschenbeutel
PRX **8**, 031054 (2018) [arXiv:1712.05749]



Cold-atom based implementation of the quantum Rabi model (theory),
P. Schneeweiss, A. Dareau, and C. Sayrin
PRA **98**, 021801(R) (2018) [arXiv:1706.07781]

@adphys