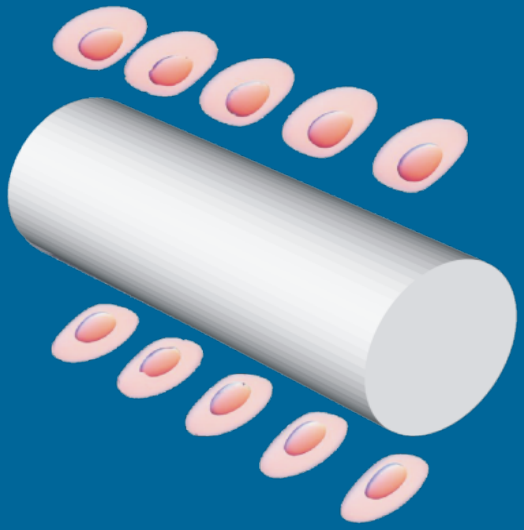
Quantum optics with nanofiber-trapped cold atoms: Coupling between internal and external degrees of freedom

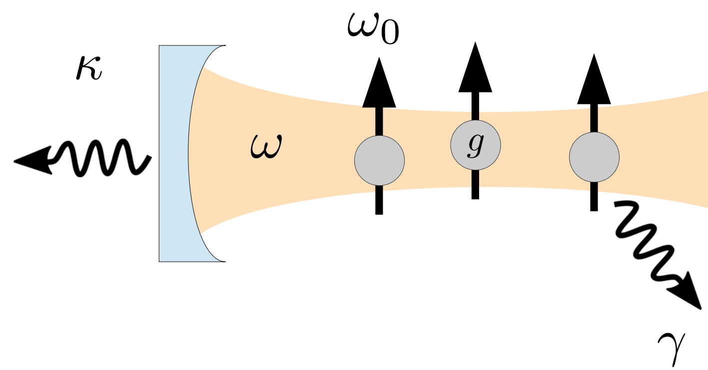


A. Dareau, Y. Meng,
P. Schneeweiss & A. Rauschenbeutel

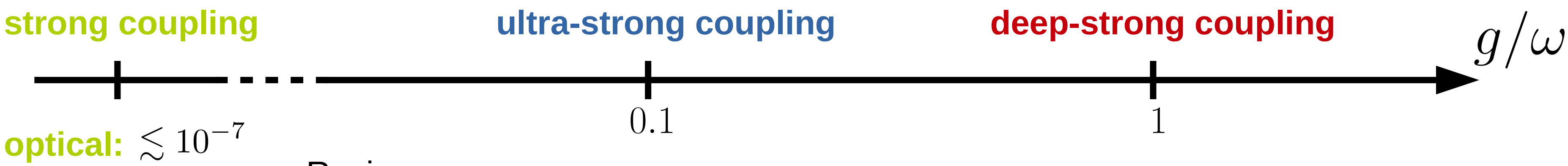
Humboldt-Universität zu Berlin, Germany
TU Wien, Vienna, Austria

Introduction: Light-Matter interaction

Coupling regimes



- coherent *strong coupling*: $g > (\kappa, \gamma)$
- *ultra-strong coupling* and beyond:



Reviews:
Forn-Diaz et al., Rev. Mod. Phys. **91**, 025005 (2019)
Kockum et al., Nature Reviews Physics **1**, 19 (2019)

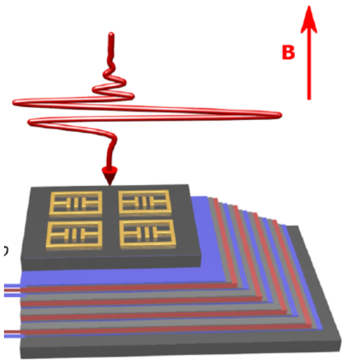
Microscopic description

$$\frac{\hat{H}}{\hbar} = \omega \hat{a}^\dagger \hat{a} + \omega_0 \hat{F}_z + \frac{g}{\sqrt{N}} (\hat{a} + \hat{a}^\dagger)(\hat{F}_+ + \hat{F}_-)$$

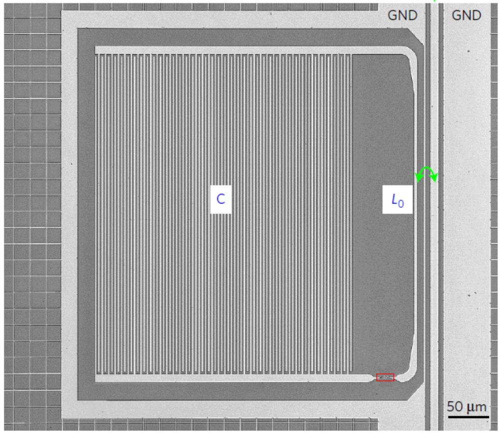
- F = 1/2: Quantum Rabi model (1 atom)
  F >= 1 : Dicke model, describing N = 2F atoms

Introduction – (some) experiments on USC & DSC

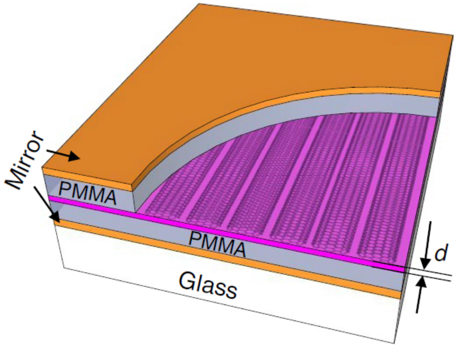
Systems overview



Bayer *et al.*,
Nano Lett. **17**, 6340 (2017)

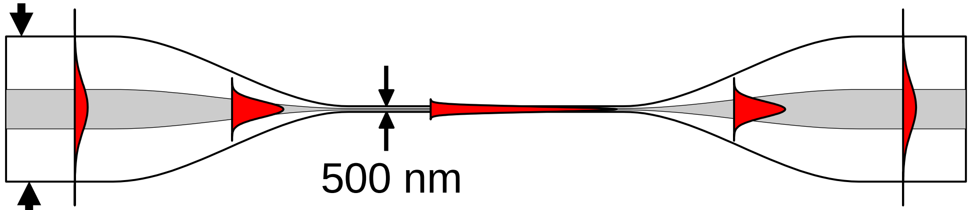


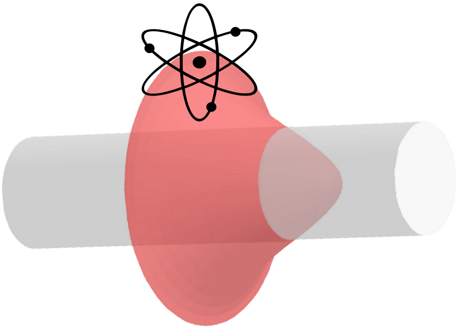
Yoshihara et al.,
Nat. Phys. **13**, 44 (2017)



Gao et al.,
Nat. Phot. **12**, 362 (2018)

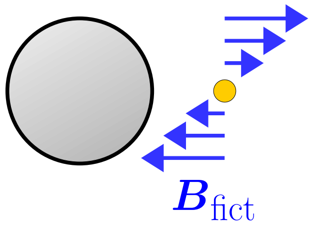
Optical nanofibers





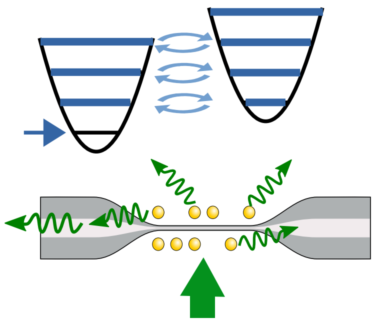
- atoms **trapped** in evanescent field
- (weak) atom-light interaction

Outline



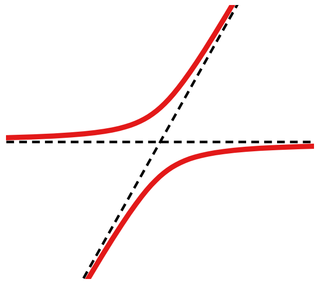
Trapping cold atoms around an optical nanofiber

- fictitious magnetic fields in optical micro-traps
- quantum Rabi model / Dicke model



Application: ground-state cooling

- Degenerate Raman Cooling
- Thermometry: fluorescence spectroscopy



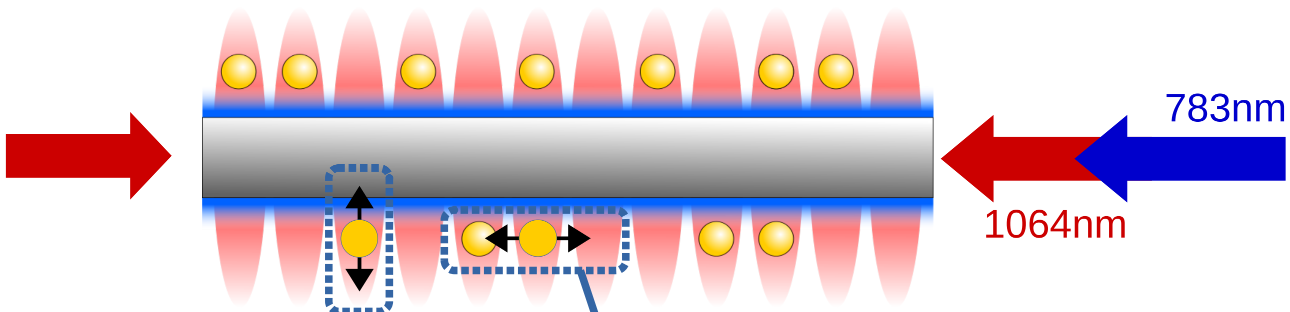
Signatures of ultra-strong coupling

Nanofiber-based optical trap for cold atoms

- Optical dipole trap (tweezer)

optical tweezer:
Nobel Prize 2018

- Two-color optical trap



radial confinement

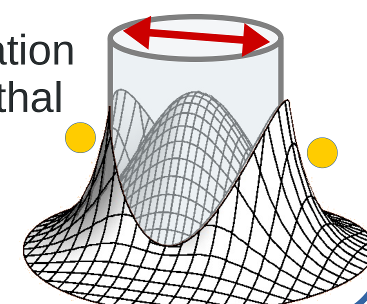
different decay length for blue-detuned (repulsive) & red-detuned (attractive) light fields

axial confinement

red-detuned standing wave

azimuthal confinement

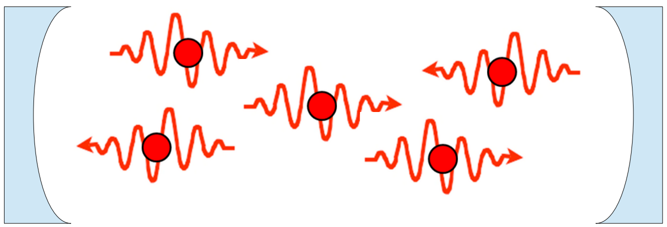
linear polarization breaks azimuthal symmetry

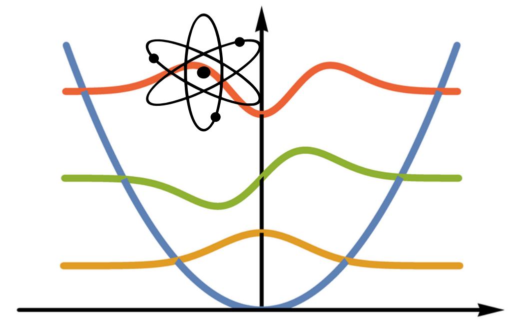


E. Vetsch et al., PRL **104**, 203603 (2010)

Mapping the in-trap motion to the Dicke model

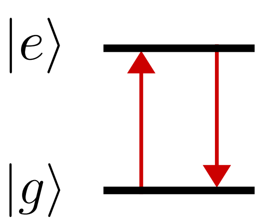
- "phonons are the new photons"



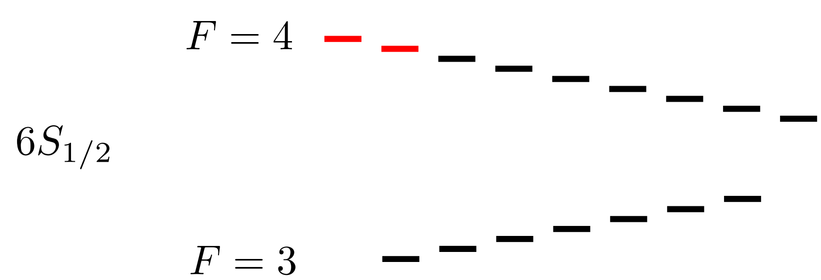


typical trap frequencies:
90 kHz to 250 kHz

- Zeeman states correspond to electronic levels of the atoms



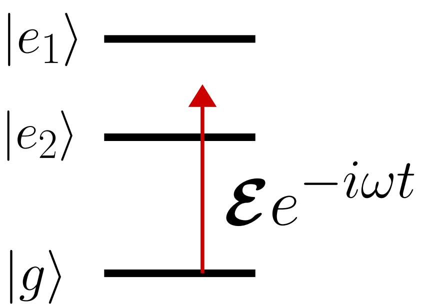
Cesium



P.S. et al.,
PRA **98**, 021801(R) (2018)

Fictitious magnetic fields – general concept

Atom-light interaction



Light-shift operator for an Alkali atom in the electronic 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

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

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

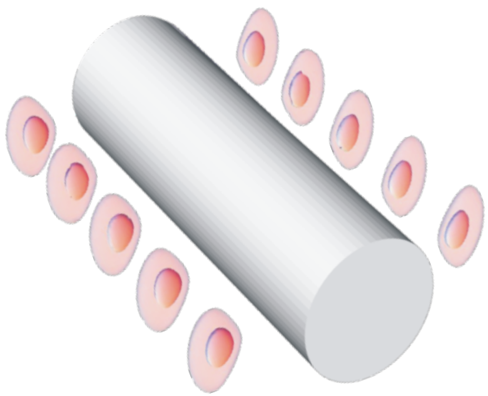
Depends on polarization :

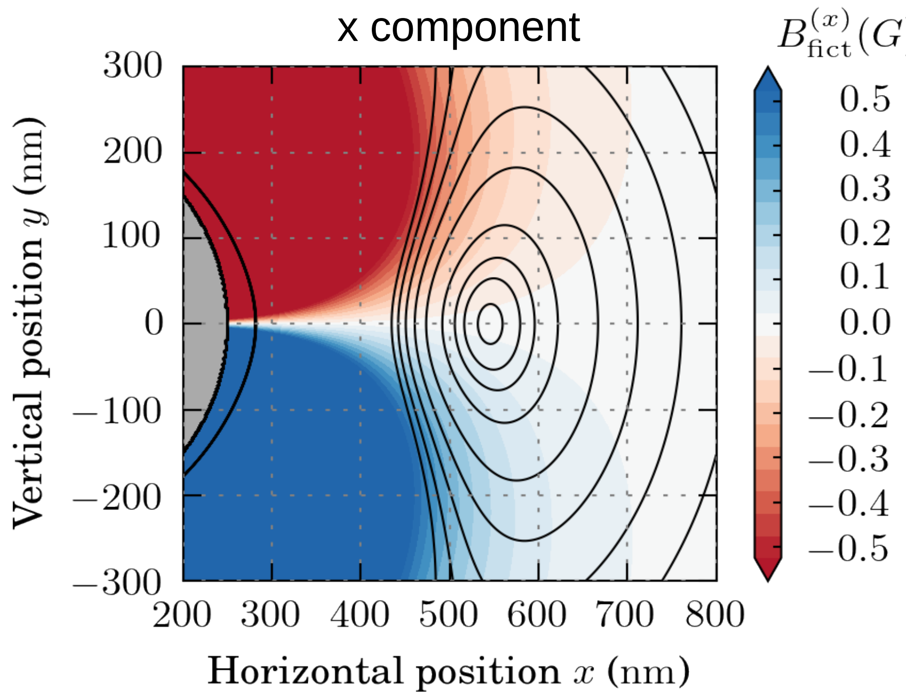
- linear → vanishes
- circular → maximal

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

Fictitious magnetic fields – in nanofiber traps

Fictitious magnetic field profile





Minimal model

- points mainly along x
- near trap minimum:
  amplitude ~ linear gradient along y

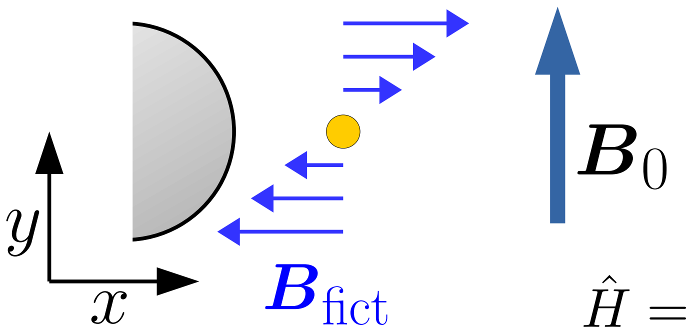
$$\boldsymbol{B}_{\text{fict}} \approx b_y \times y\, \boldsymbol{e}_x$$

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

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

Spin-motion coupling – theory

Hamiltonian of an atom in one trapping site



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

$$\hat{H} = \hbar\omega \hat{a}^\dagger \hat{a} - \hat{\vec{\mu}} \vec{B}$$

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

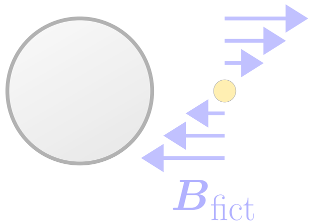
$$\Rightarrow \quad \hat{H} = \hbar\omega \hat{a}^\dagger \hat{a} + \underbrace{g_F \mu_B B_0}_{\hbar\omega_0} \hat{F}_y + \underbrace{g_F \mu_B b_y y_0}_{\hbar g'} (\hat{a} + \hat{a}^\dagger)(\hat{F}_+ + \hat{F}_-)$$

$$\frac{\hat{H}}{\hbar} = \omega \hat{a}^\dagger \hat{a} + \omega_0 \hat{F}_y + \frac{g}{\sqrt{N}} (\hat{a} + \hat{a}^\dagger)(\hat{F}_+ + \hat{F}_-)$$

quantized light field (in cavity) — **N-level system (atom)** — **Atom-light coupling**

P.S. et al.,
PRA **98**, 021801(R) (2018)

Outline



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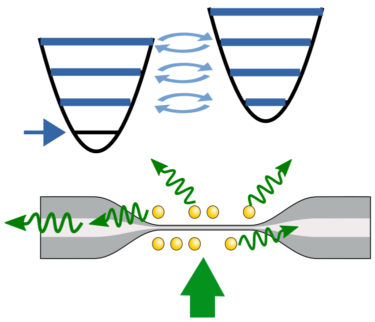
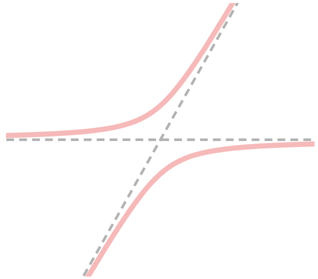
- quantum Rabi model / Dicke model



Application: ground-state cooling

- Degenerate Raman Cooling
- Thermometry: fluorescence spectroscopy

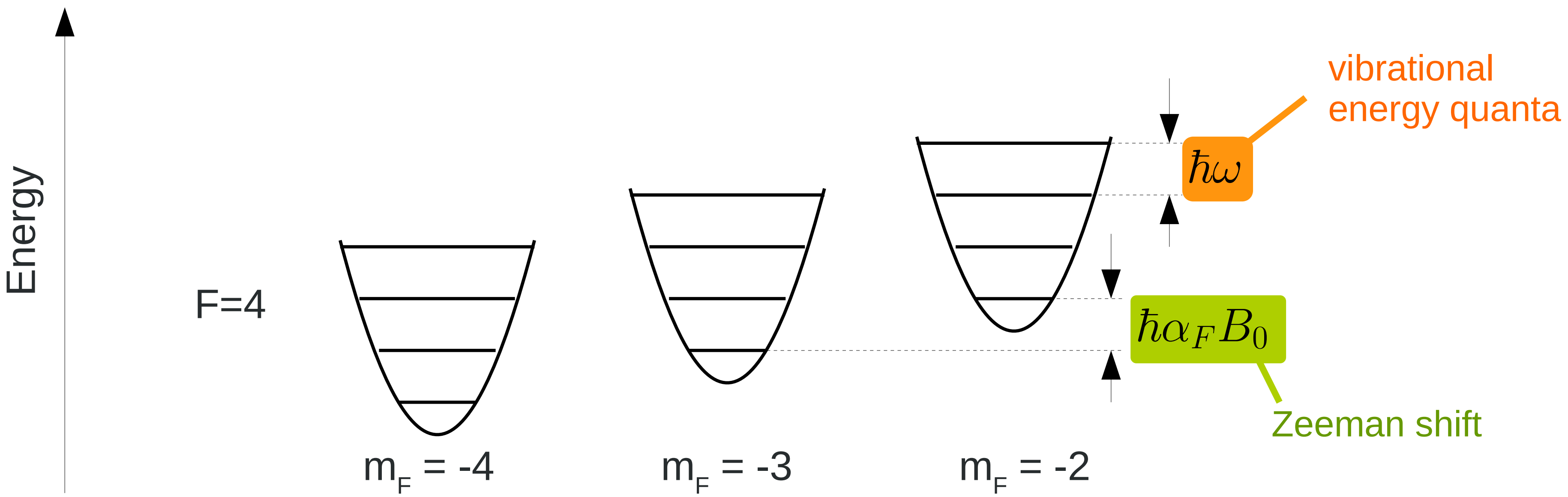


Signatures of ultra-strong coupling

Spin-motion coupling – application to cooling

Degenerate Raman cooling principle

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



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

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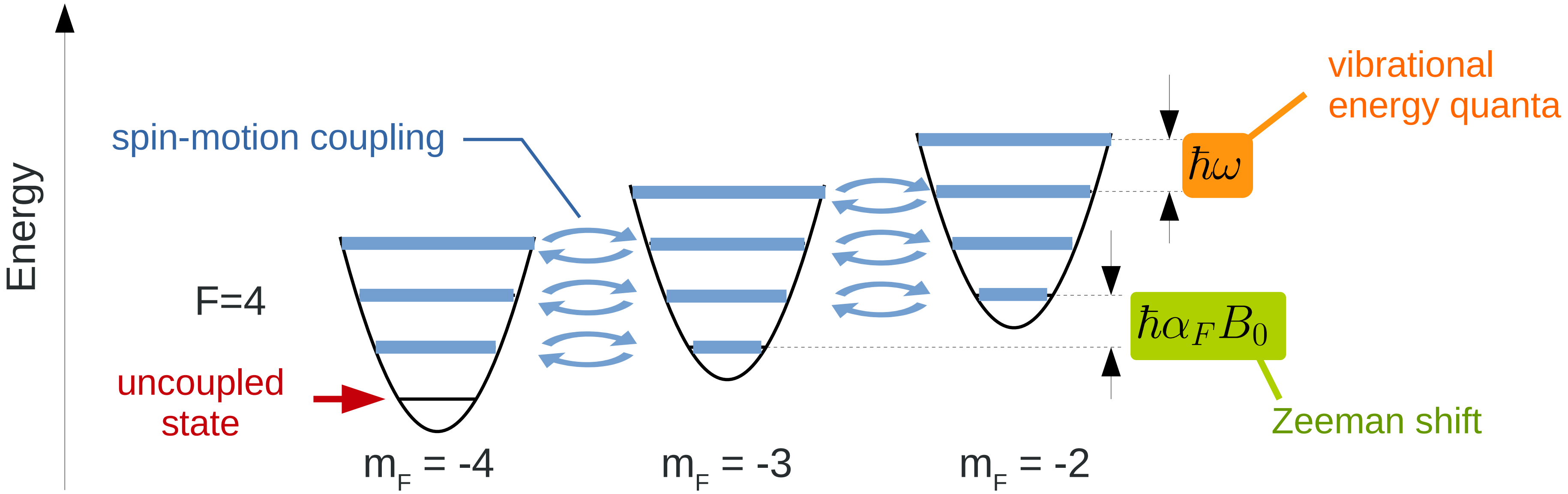

- uncoupled state: $|n=0, m_F=-4\rangle$

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

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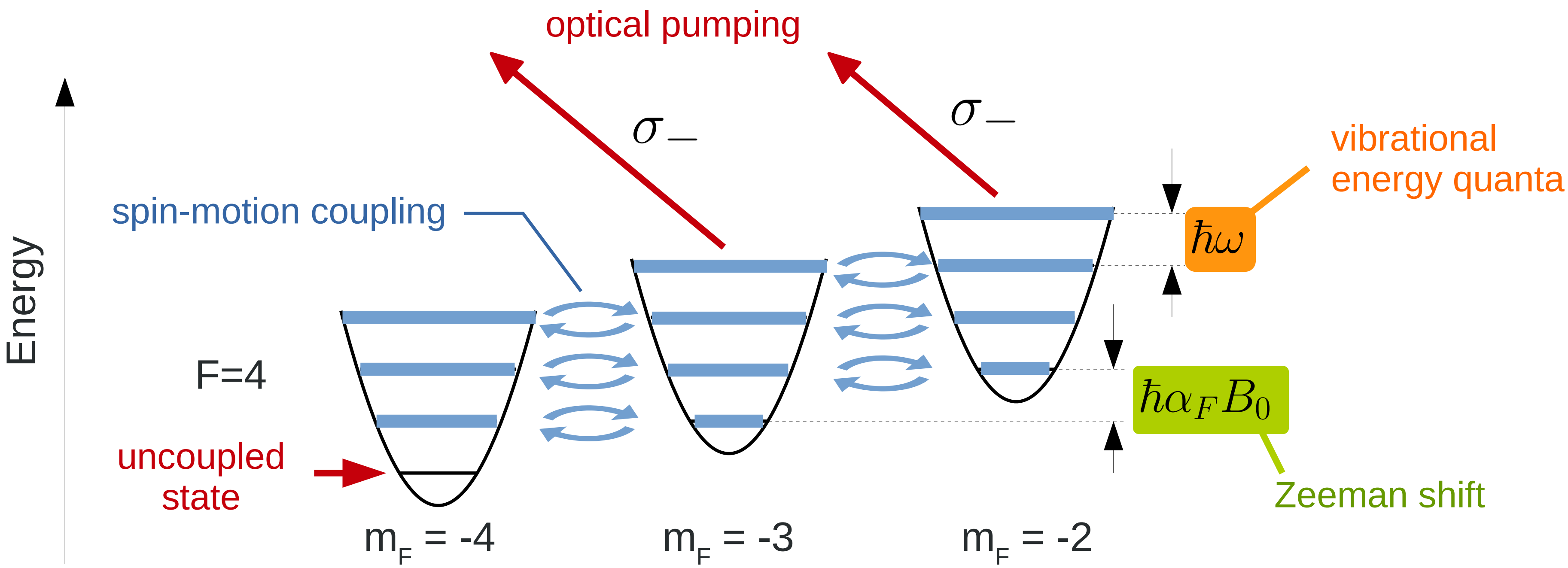


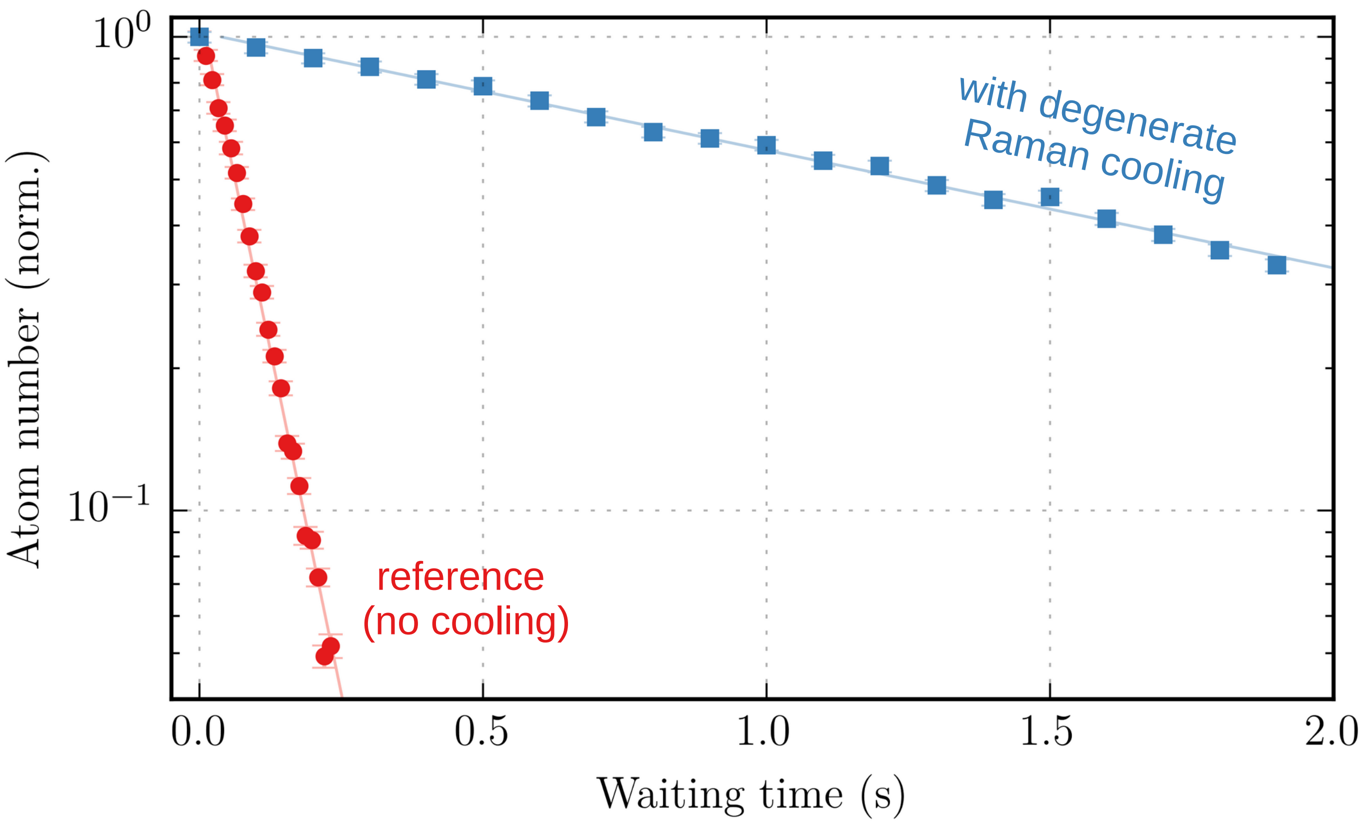
- uncoupled state: $|n=0, m_F=-4\rangle$
- Lamb-Dicke regime: optical pumping preserves motional state

➡ 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 (no cooling)

τ_{ref} = 75(1) ms

with deg. Ram. cooling

τ_{cool} = 1750(30) ms

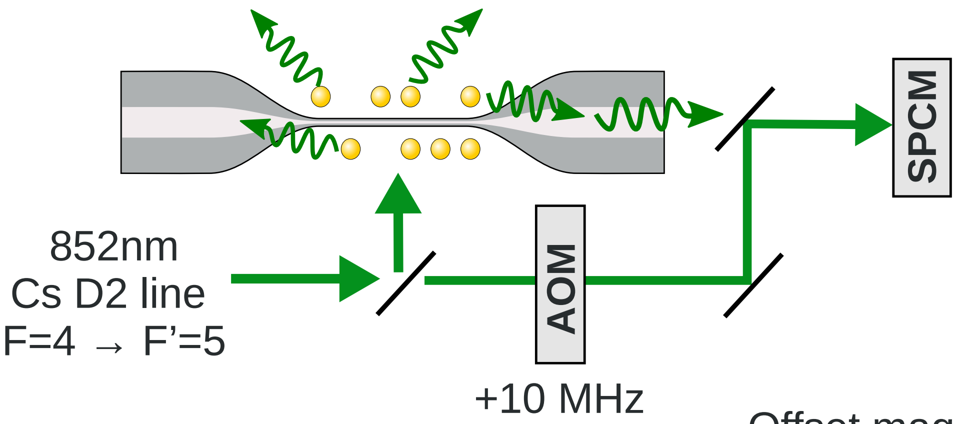
Background pressure limited lifetime → indication for cooling of all spatial degrees of freedom

Y. Meng et al., PRX **8**, 031054 (2018)

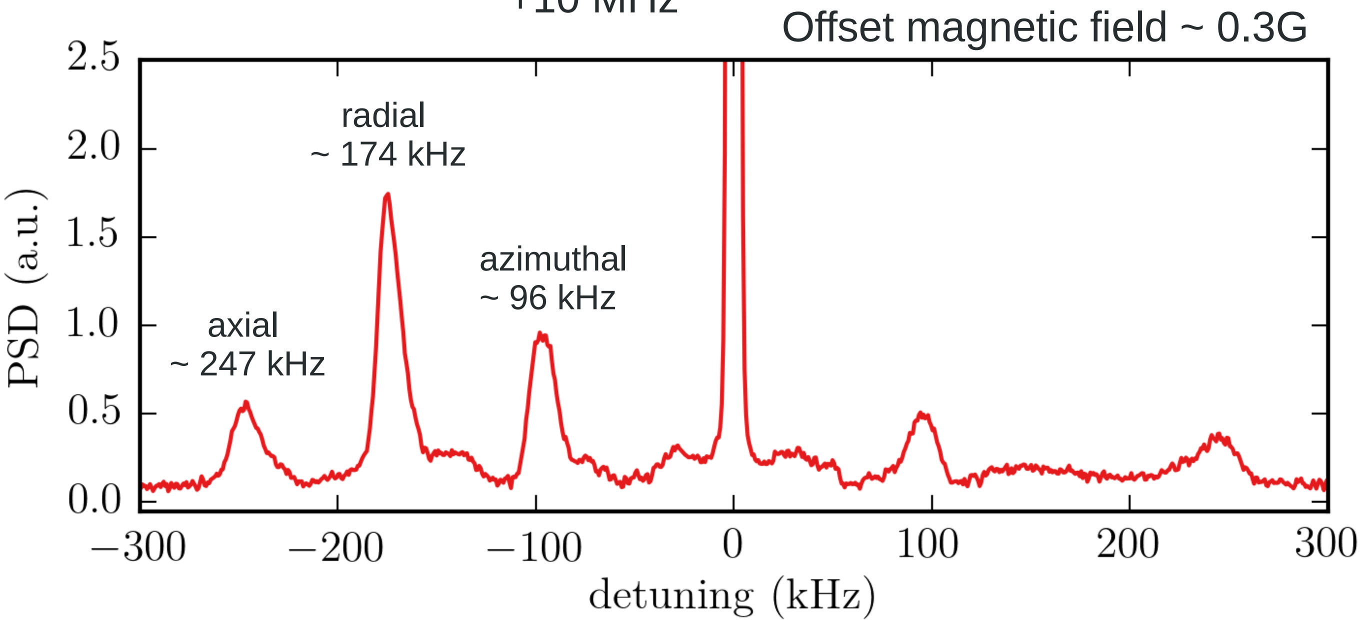
Fluorescence Spectroscopy – results

Heterodyne fluorescence spectroscopy

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



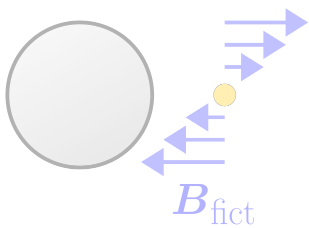
➡ Compute Power Spectral Density (PSD)



- Precise measurement of trap frequencies
- Sidebands amplitude ratio → temperature
- Close to the motional ground state => few-phonon regime

Y. Meng et al., PRX **8**, 031054 (2018)

Outline



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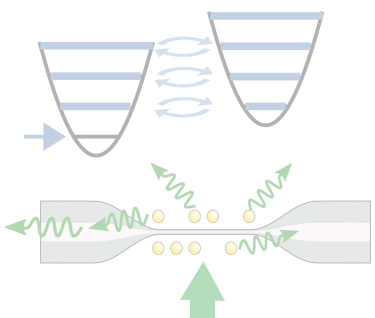

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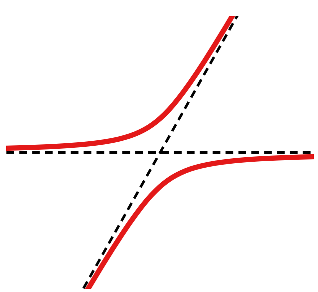
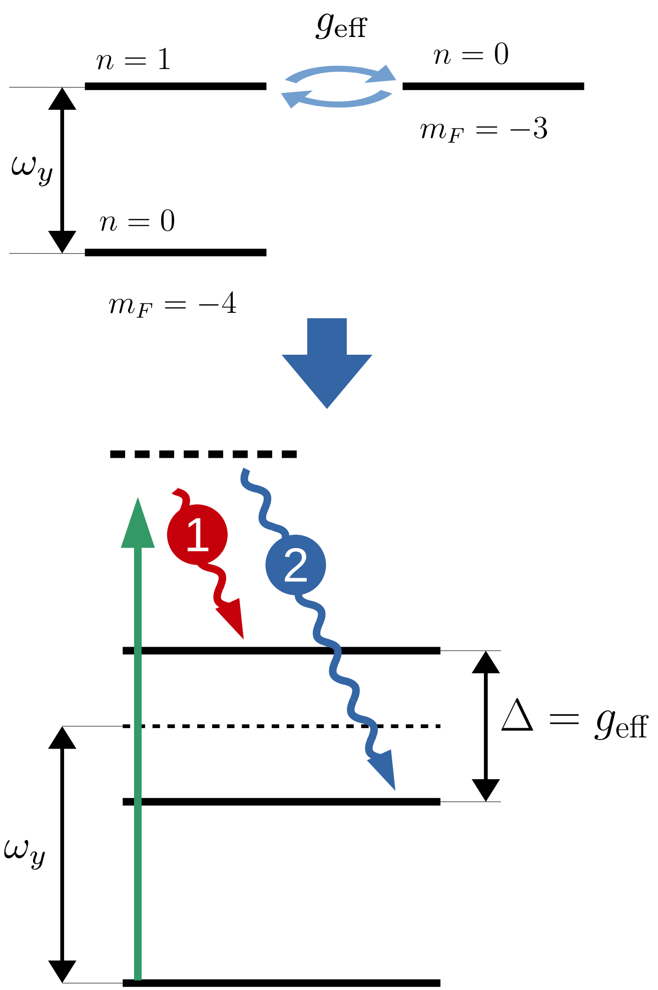
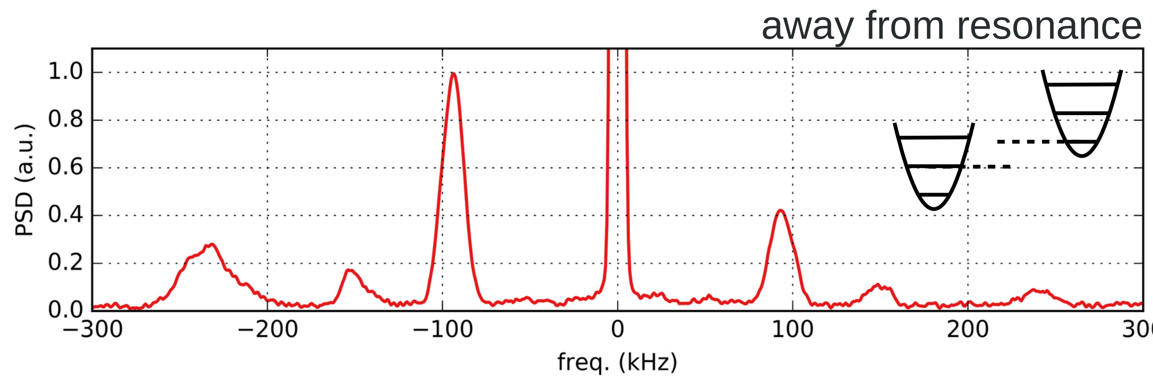


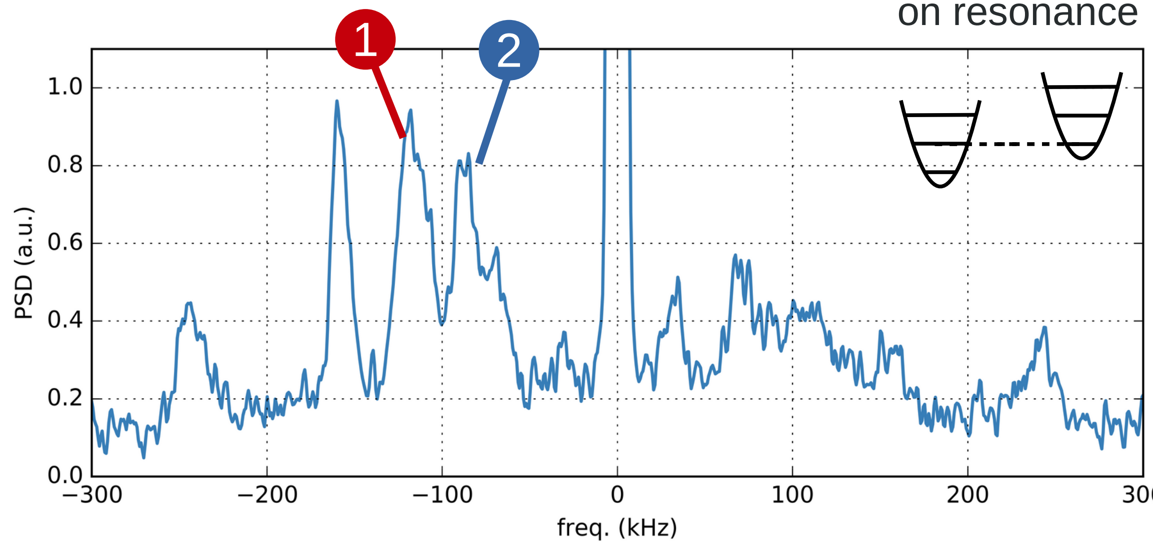
Signatures of ultra-strong coupling

Ultra-Strong Coupling – exp. signatures

On resonance: (vacuum Rabi) splitting







observed splitting: $\Delta \approx 2\pi \times 34\,\text{kHz} \approx 0.36\,\omega_y$

A. Dareau et al., PRL **121**, 253603 (2018)

Ultra-Strong Coupling – exp. signatures

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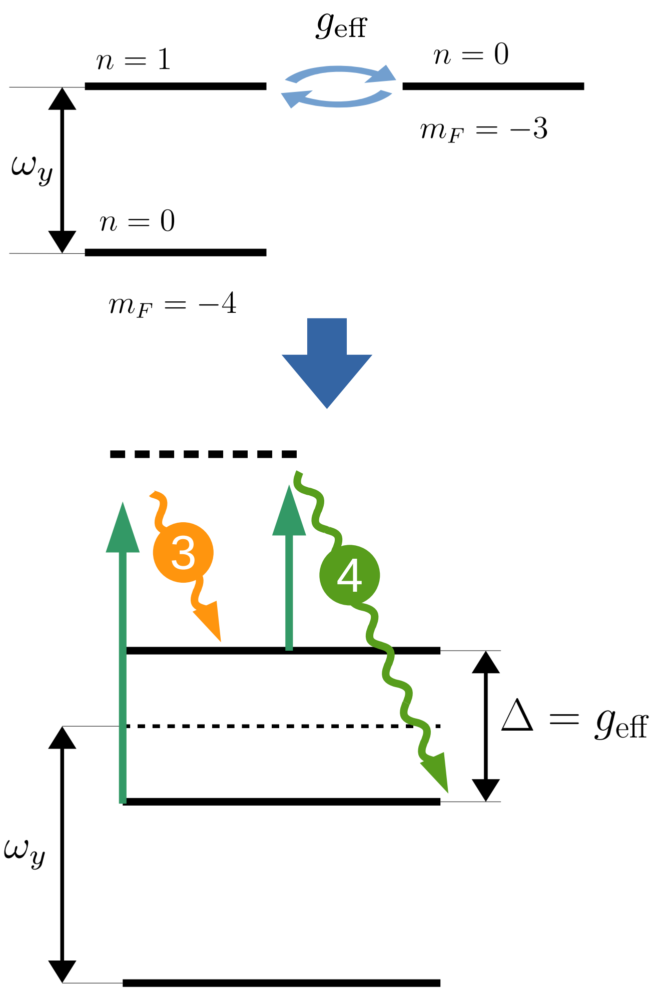

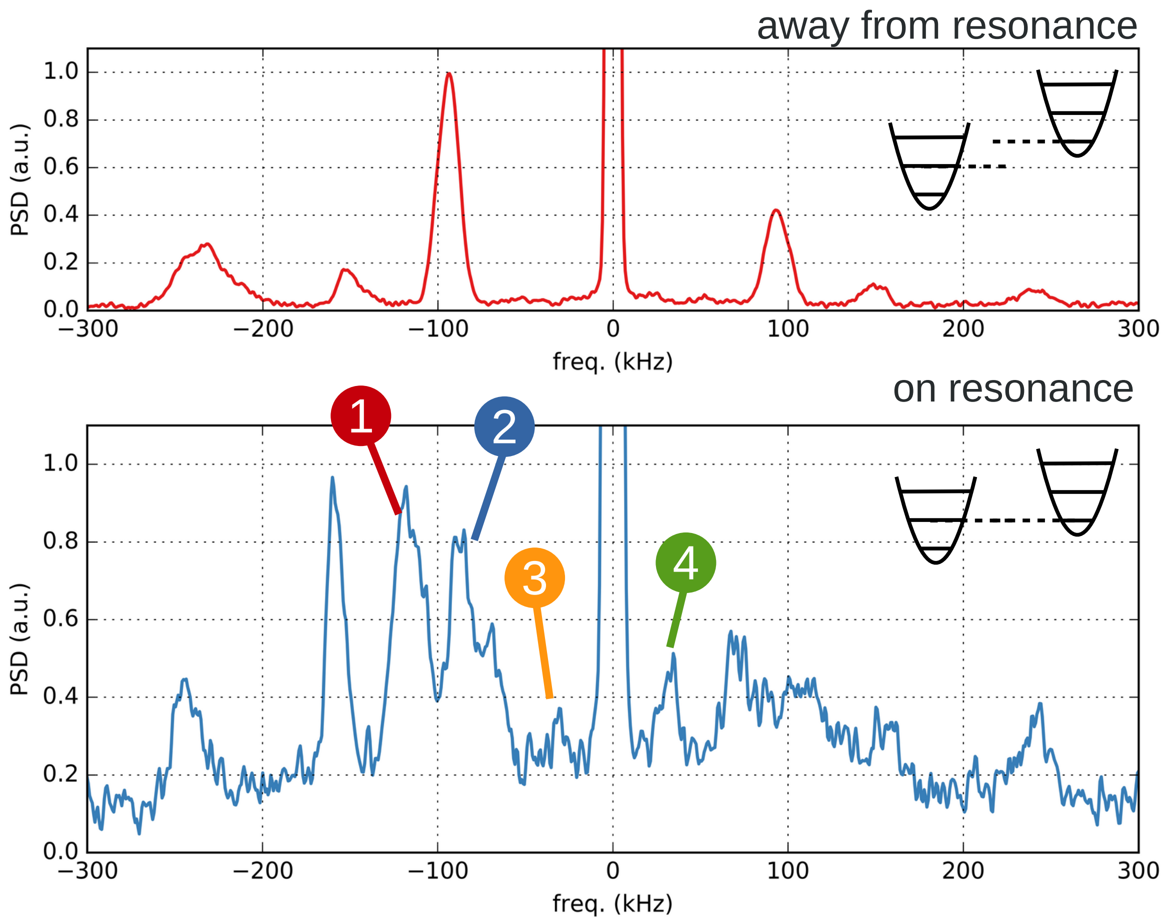

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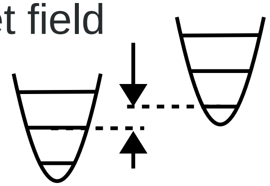
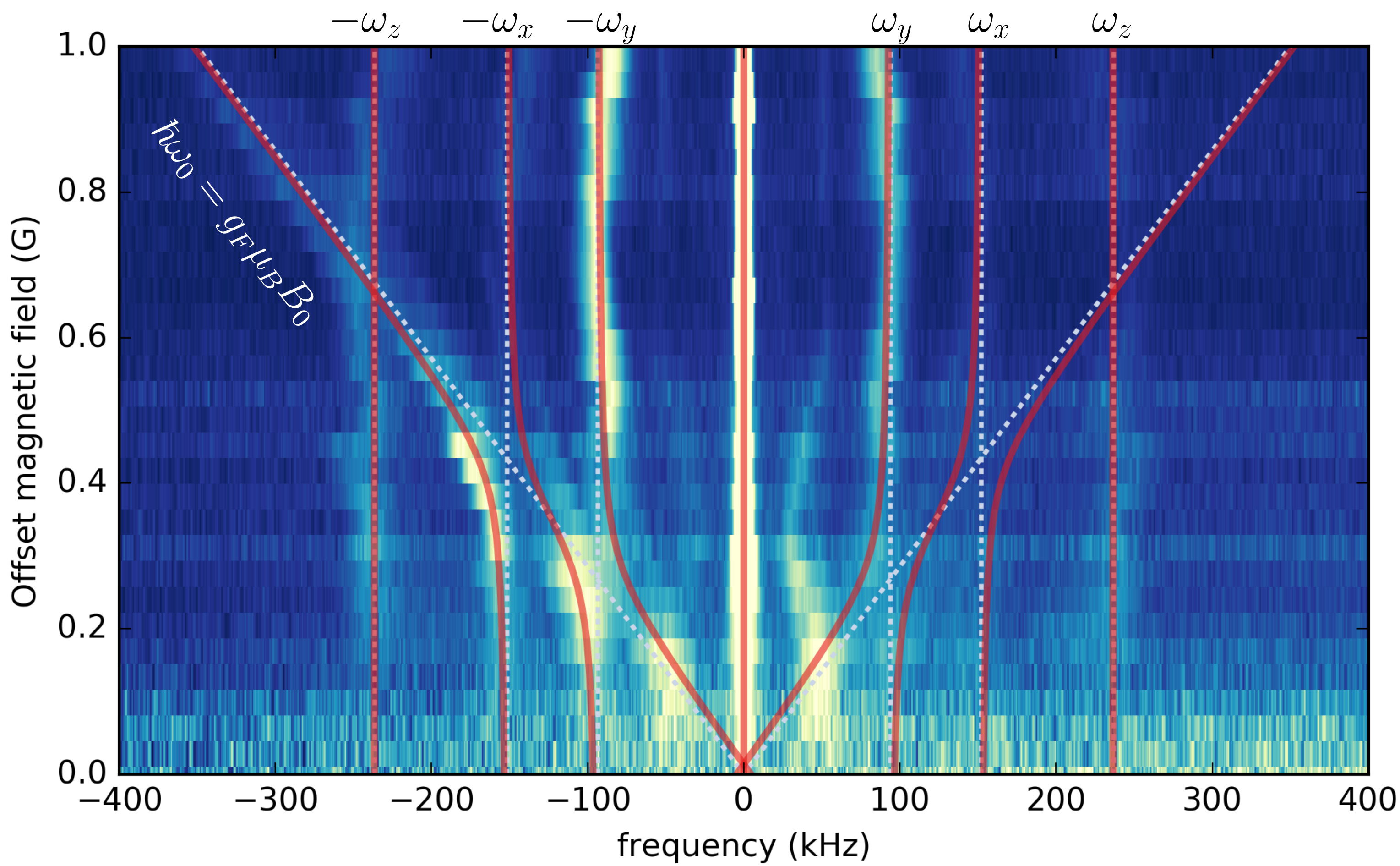
A. Dareau et al., PRL **121**, 253603 (2018)

Ultra-Strong Coupling – exp. signatures

- Scanning the offset magnetic field

detuning depends on offset field
$g_F \mu_B = h \times 350\,\mathrm{kHz/G}$





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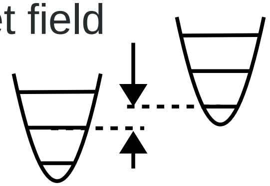
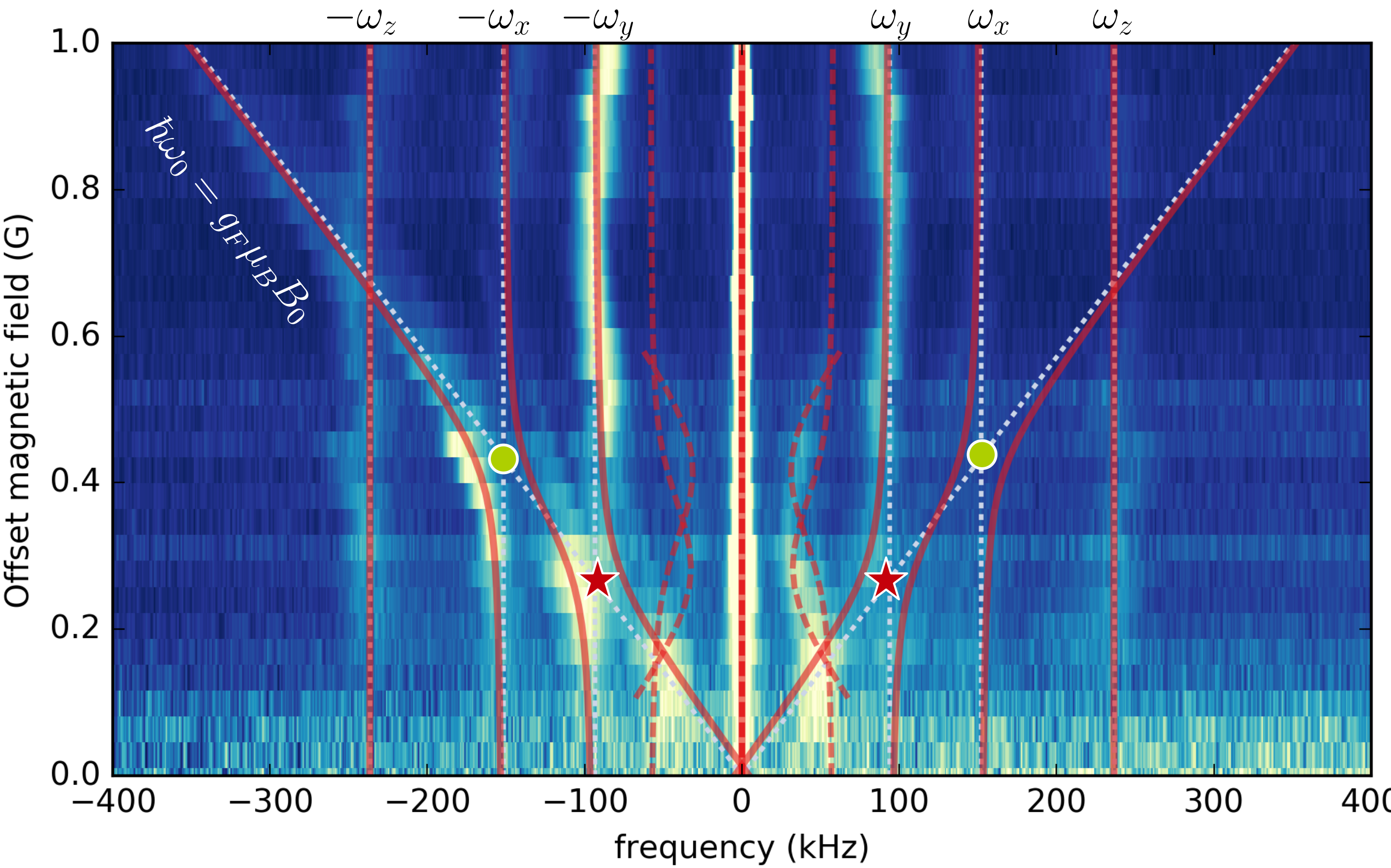




★ y-coupling (azimuthal)

$\omega_y \approx 94\,\mathrm{kHz}$
$g_y \approx 12\,\mathrm{kHz}$
$g_{y,\mathrm{eff}} \approx 34\,\mathrm{kHz}$

$g_{y,\mathrm{eff}}/\omega_y \approx 0.36$

● x-coupling (radial)

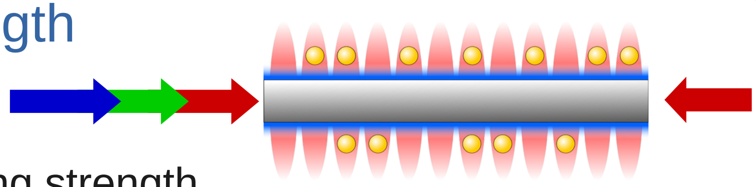
$\omega_x \approx 152\,\mathrm{kHz}$
$g_x \approx 11\,\mathrm{kHz}$
$g_{x,\mathrm{eff}} \approx 31\,\mathrm{kHz}$

$g_{x,\mathrm{eff}}/\omega_x \approx 0.20$

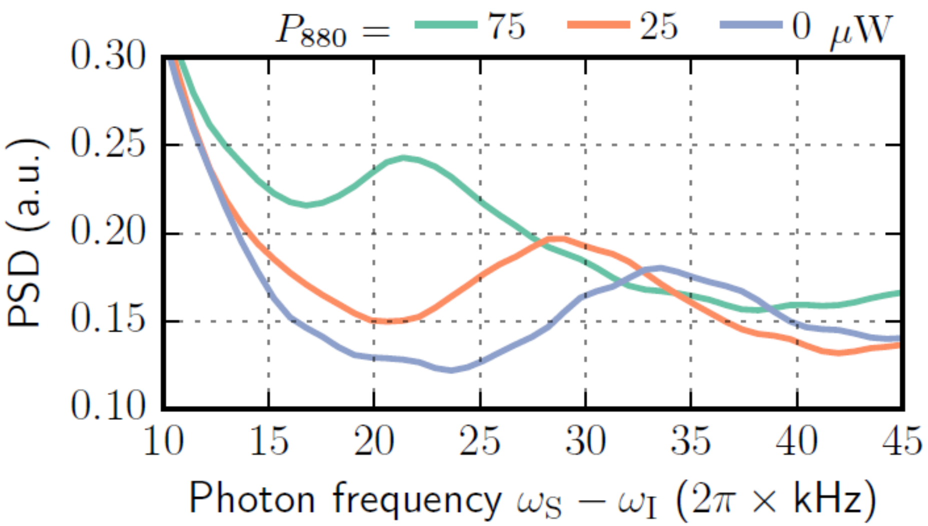
A. Dareau et al., PRL **121**, 253603 (2018)

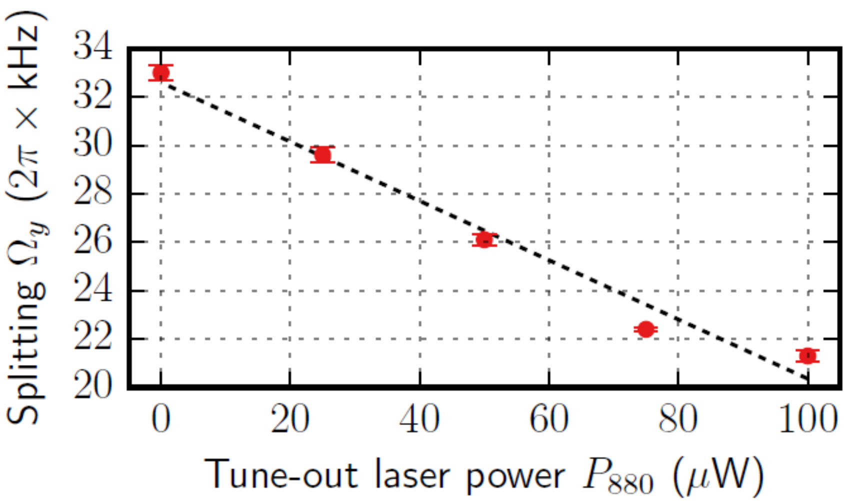
Ultra-strong Coupling – tuning **g**

- Additional laser field at "tune-out" wavelength
  - gives rise to an additional vector light shift
    - ➡ tune fictitious field gradient ➡ tune coupling strength



- Polariton spectra





Tuning of coupling strength observed

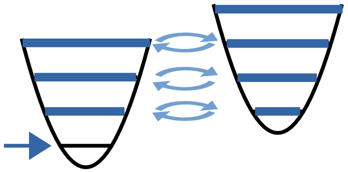
A. Dareau et al., PRL **121**, 253603 (2018)

Summary & Outlook

Summary

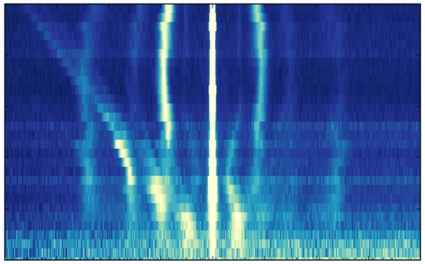
- **Implementation of the Quantum Rabi model**

  Principle is general:
  - Shaping the fictitious field allows realizing various effective light-matter interactions
  - e.g., two-photon Rabi model



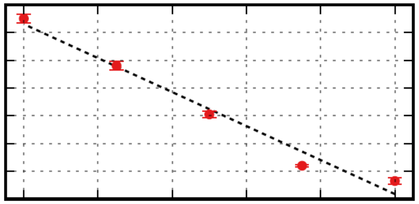
- **Experimental evidence of ultra-strong coupling**

  Coupling strength gets comparable to the **trap frequencies**
  Coupling observed for **two motional degrees of freedom**



- **Tuning demonstrated**

  Works also on **sub-cycle time scale**



Summary & Outlook

Outlook

- Increase coupling strength (DSC regime?)

$$g/\omega \gtrsim 1$$

- Expand state preparation and read-out schemes
  - Study Dicke Quantum phase transitions
    - ➡ e.g., phase transition to a nonstationary phase
      F. Reiter et al., Phys. Rev. Lett. **125**, 233602
  - Engineer dissipation

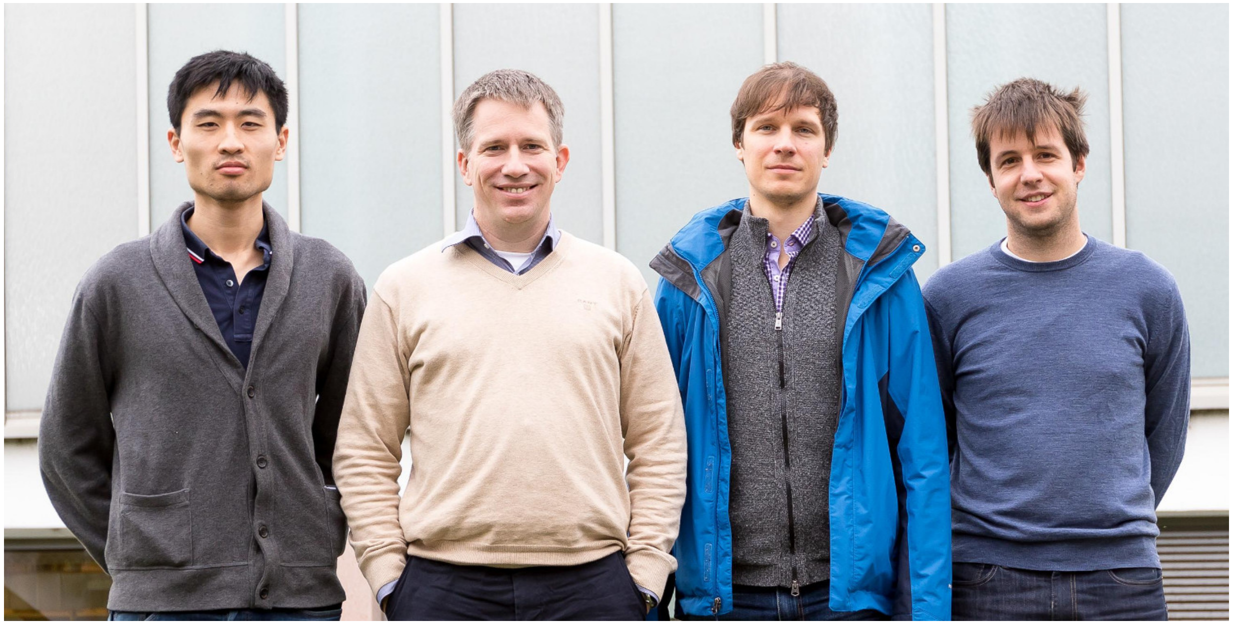
- Time-variation of the system parameters

$$g \to g(t)$$

  - dynamical Casimir effect, adiabatic ground-state preparation, ...

Acknowledgements

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



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

NEXT lite

CoQuS ComplexQuantumSystems

FWF Der Wissenschaftsfonds.

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

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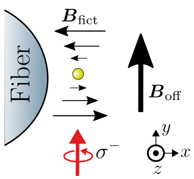
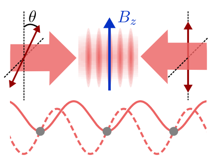
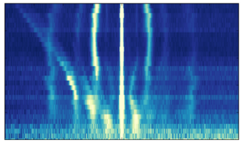
Thank you for your attention



Near-ground-state cooling of nanofiber-trapped atoms
Y. Meng, A. Dareau, P. Schneeweiss, and A. Rauschenbeutel
[PRX **8**, 031054 (2018)]



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



Observation of ultra-strong spin-motion coupling for cold atoms in optical microtraps (experiment)
A. Dareau, Y. Meng, P. Schneeweiss, and A. Rauschenbeutel
[PRL **121**, 253603 (2018)]

Imaging and localizing individual atoms interfaced with a nanophotonic waveguide (experiment)
Y. Meng, C. Liedl, S. Pucher, A. Rauschenbeutel, P. Schneeweiss
[PRL **125**, 053603 (2020)]