

# Multimode strong coupling of atoms close to a nanofibre-based ring resonator

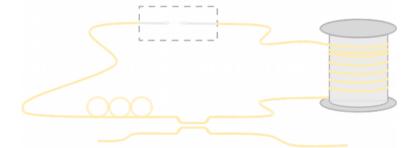
Aisling Johnson, Martin Blaha, Alexander Ulanov, Jürgen Volz,  
Philipp Schneeweiss, Arno Rauschenbeutel

# Outline

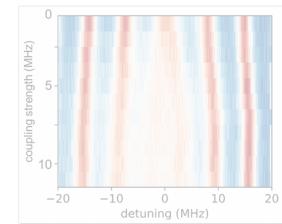
Nanofibers for multimode cavity QED



Experimental setup



Multimode strong coupling

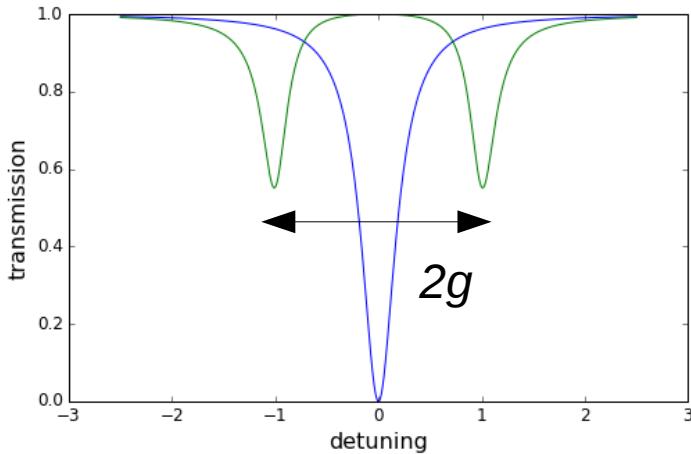


# Multimode cavity QED

## “Conventional” CQED

- Strong coupling criterion

$$C = \frac{g^2}{2\kappa\gamma} > 1$$

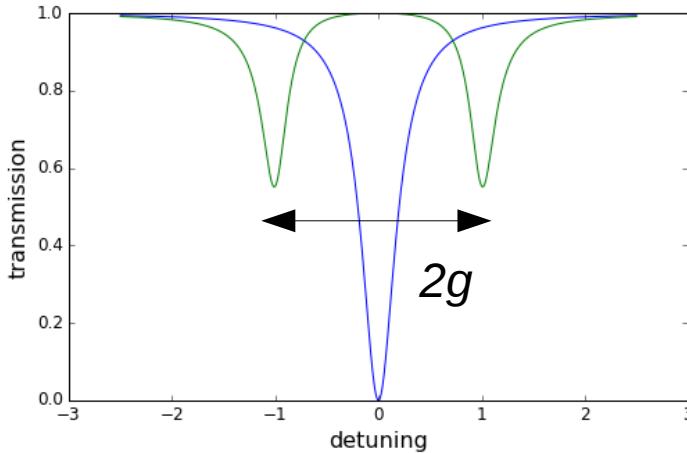


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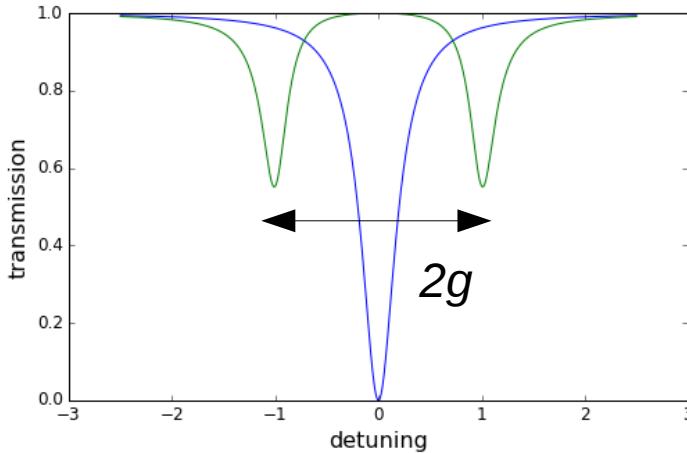
- Collective coupling:  $g_{coll} = \sqrt{N}g$ ,  $C_{coll} = NC_1$   
→ Interaction enhancement and new perspectives

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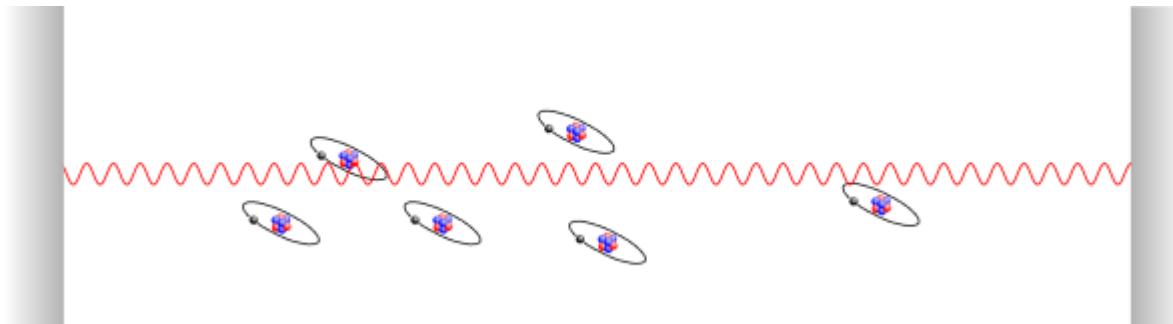
- Collective coupling:  $g_{coll} = \sqrt{N}g$ ,  $C_{coll} = NC_1$   
→ Interaction enhancement and new perspectives
- Complexify: add more modes

*What if  $g$  exceeds the separation between the cavity modes?*

# Multimode cavity QED

Strong coupling to many resonator modes

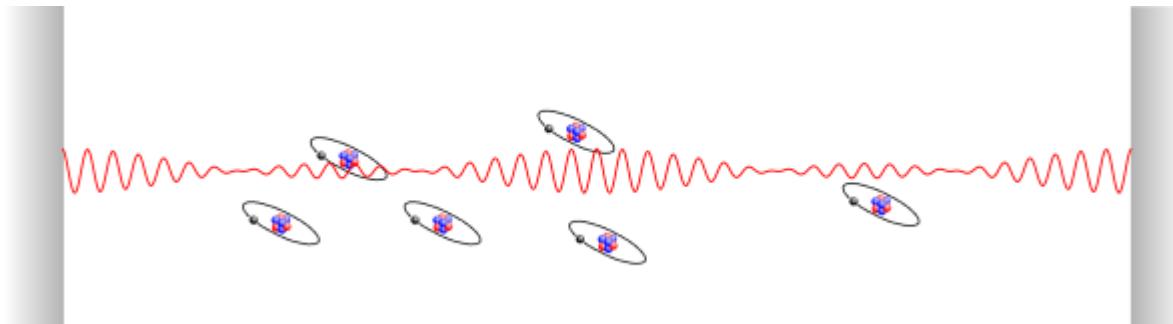
- $g > \text{FSR}$ , atoms emit into different cavity modes



# Multimode cavity QED

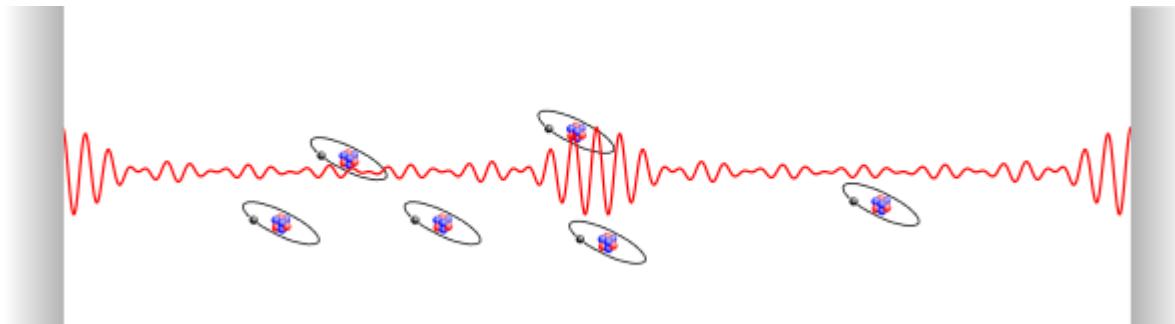
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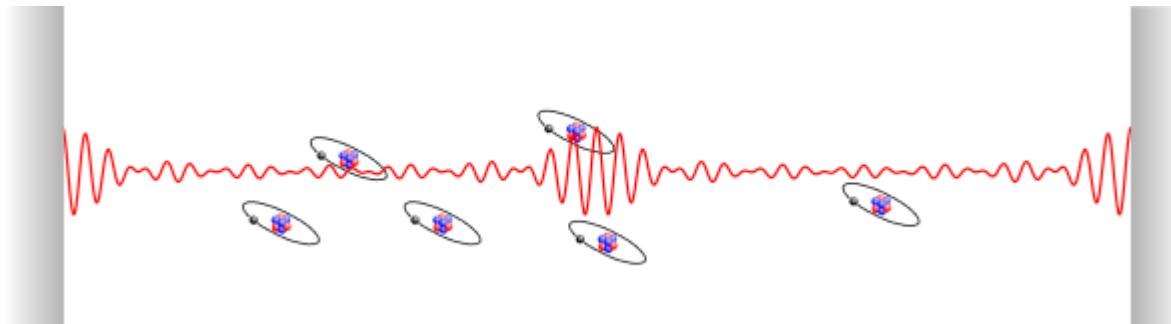


- Strongly coupled in a single round-trip: “Superstrong coupling”

*D.Meiser, P. Meystre, PRA (2006)*

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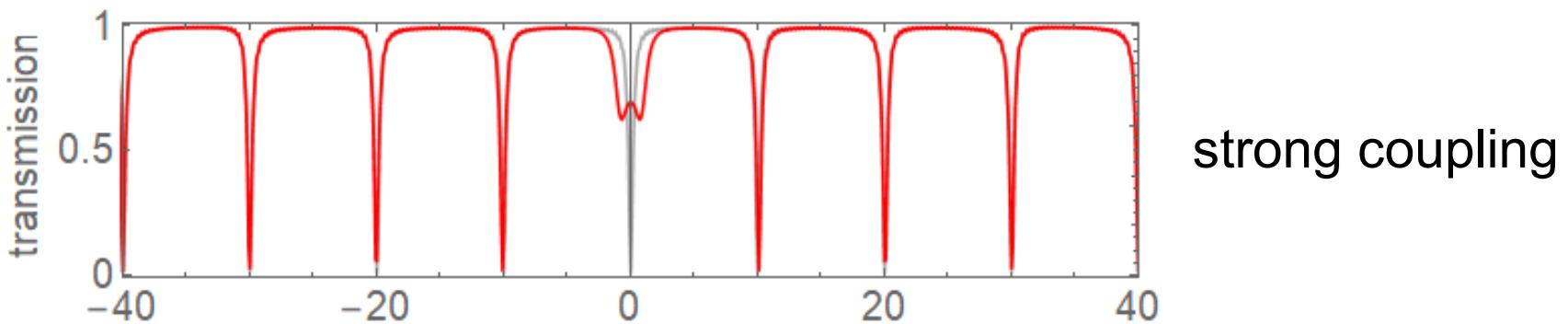
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→ Photon modes interact via the atoms

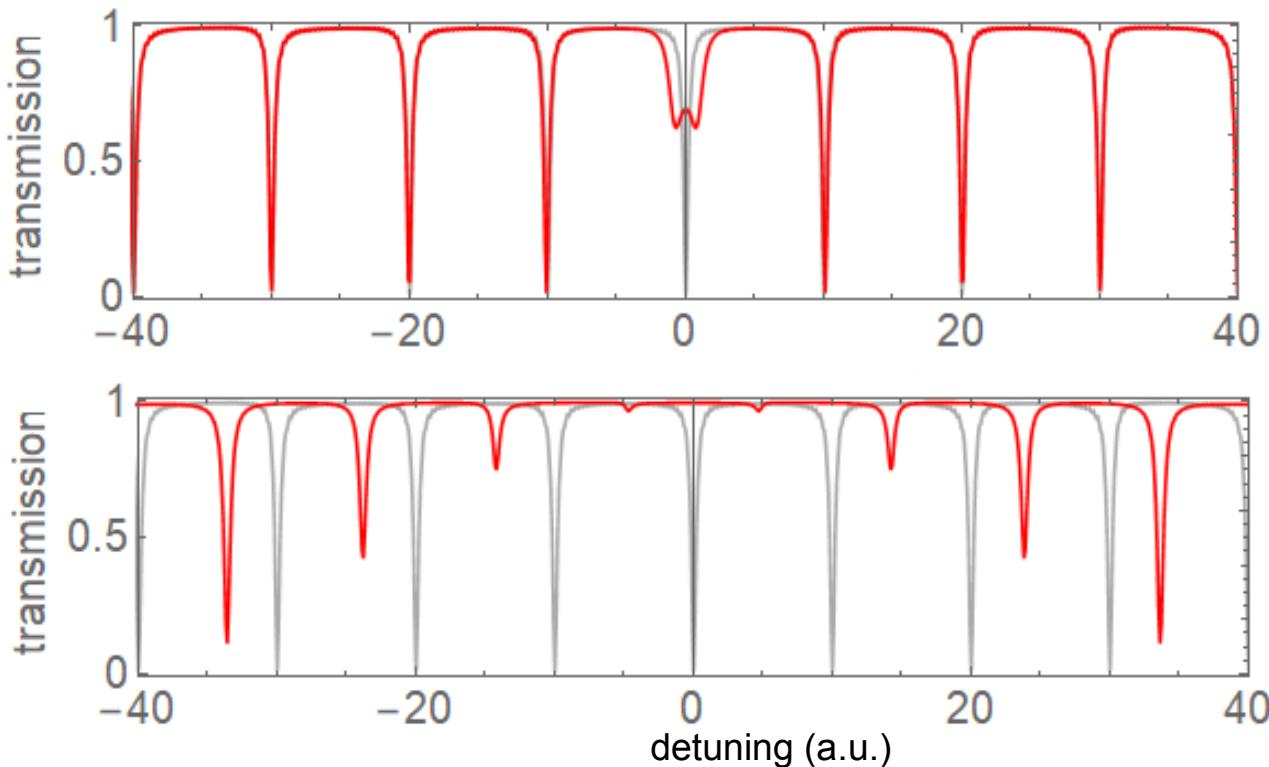
→ Atoms and field don't interact instantaneously, new dynamics

Overcome some limits of cavity QED with one mode

# Signature of multimode strong coupling?



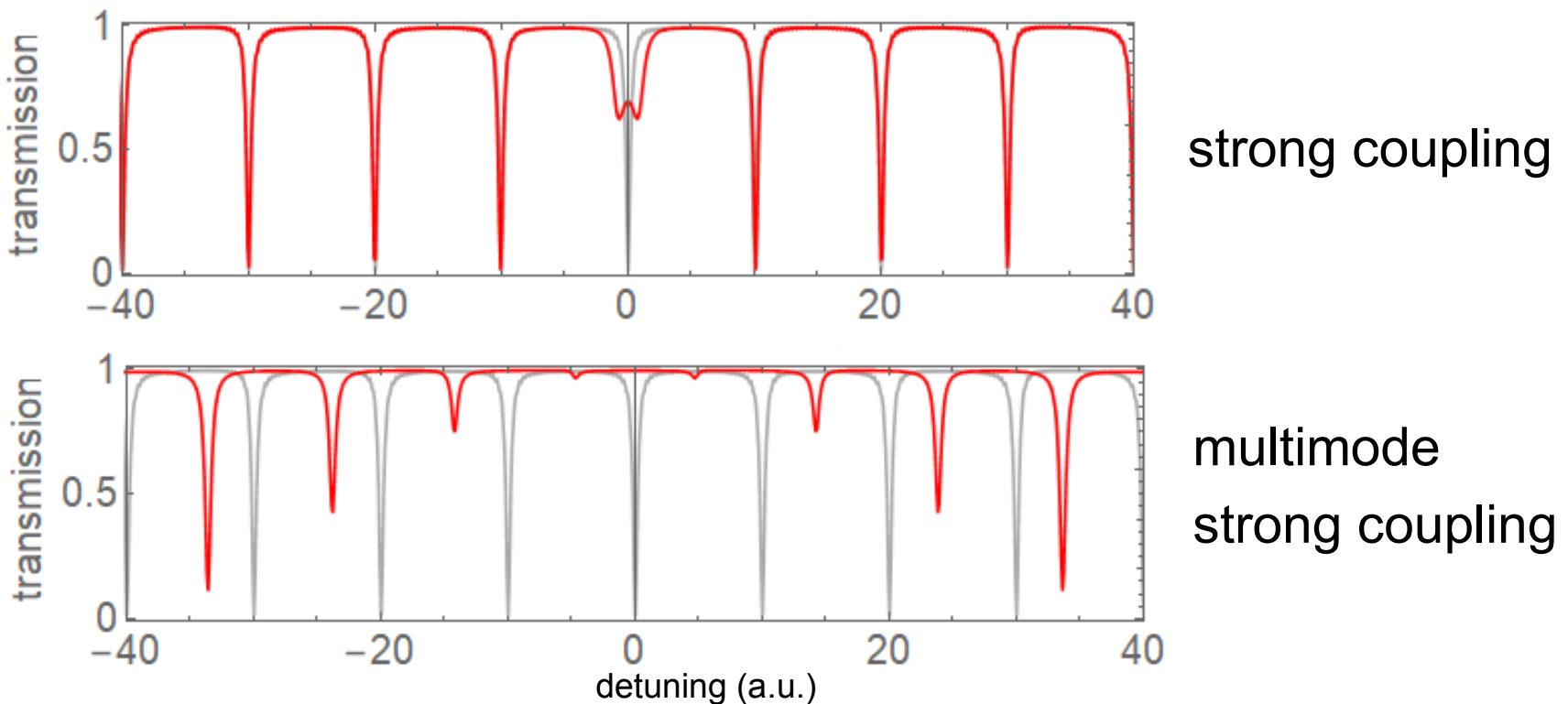
# Signature of multimode strong coupling?



strong coupling

multimode  
strong coupling

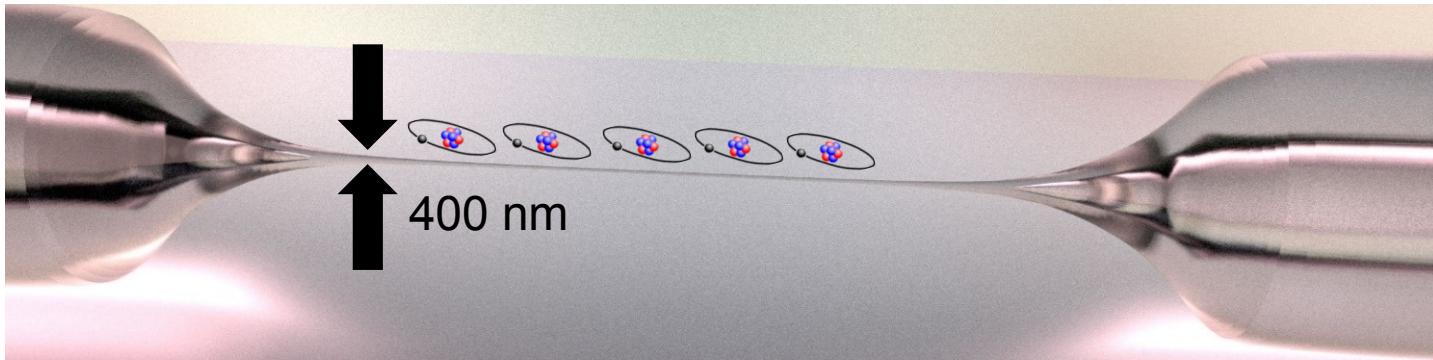
# Signature of multimode strong coupling?



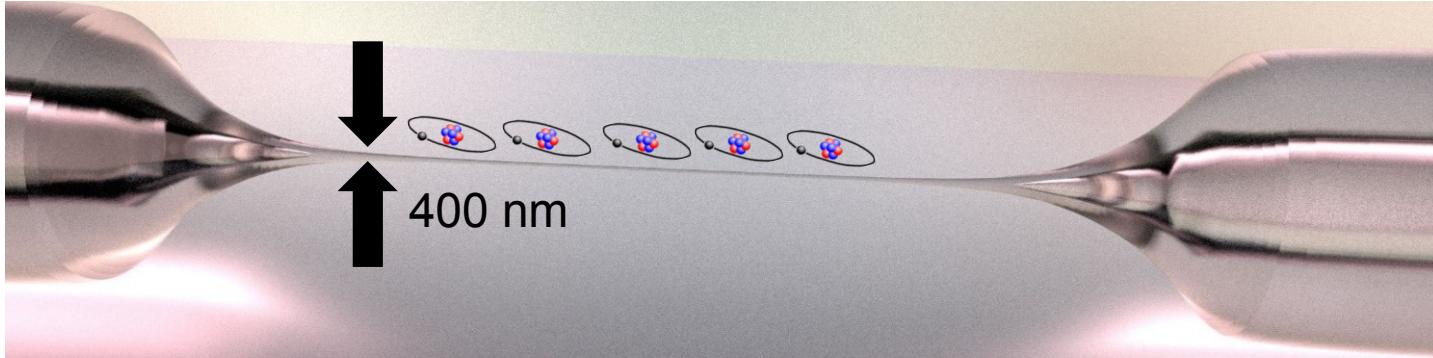
- atoms interact strongly with many resonator modes
- experimentally accessible spectrum

See Sundaresan et al., PRX 5, 021035 (2015)

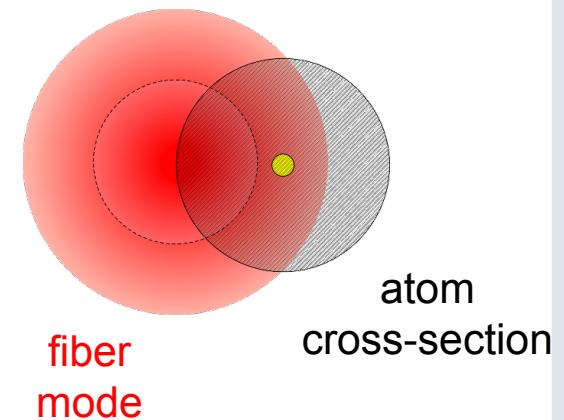
# Nanofibres for quantum photonics



# Nanofibres for quantum photonics



- Small mode volume
- High light-atom interaction strength
- Compatible with resonator
- Compatible with optical fibres



→ include into fibre resonator of desired length

# How to reach $g > \text{FSR}$

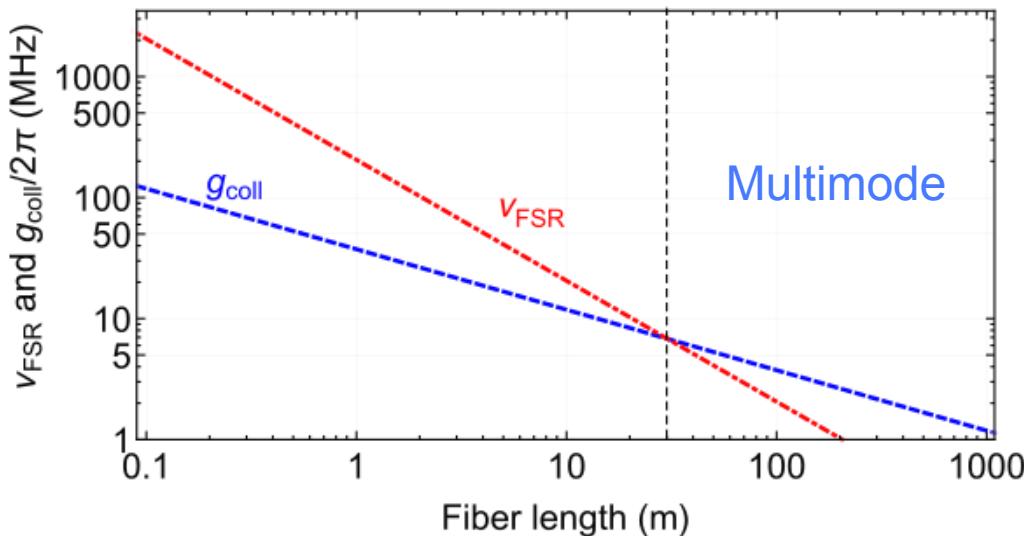
## Length dependence of resonator parameters

- Single atom cooperativity  $C = \frac{g^2}{2\kappa\gamma}$
- $\kappa \propto l^{-1}, g \propto V_{\text{mode}}^{-1/2} \propto l^{-1/2}$   
→ Increase / (decrease FSR) at will (almost)

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→ Increase  $l$  (decrease FSR) at will (almost)



$$\text{FSR} = \frac{c}{nL}$$

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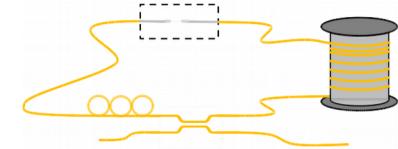
- $l \sim 30 \text{ m}$
- $N \sim 300 \text{ atoms}$

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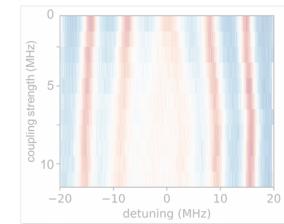
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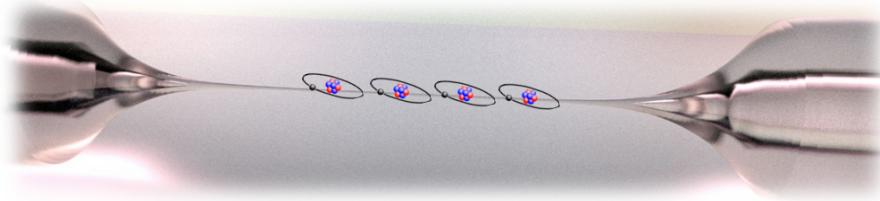
Experimental setup



Multimode strong coupling



# Nanofibre Ring Resonator



Nanofibre

+



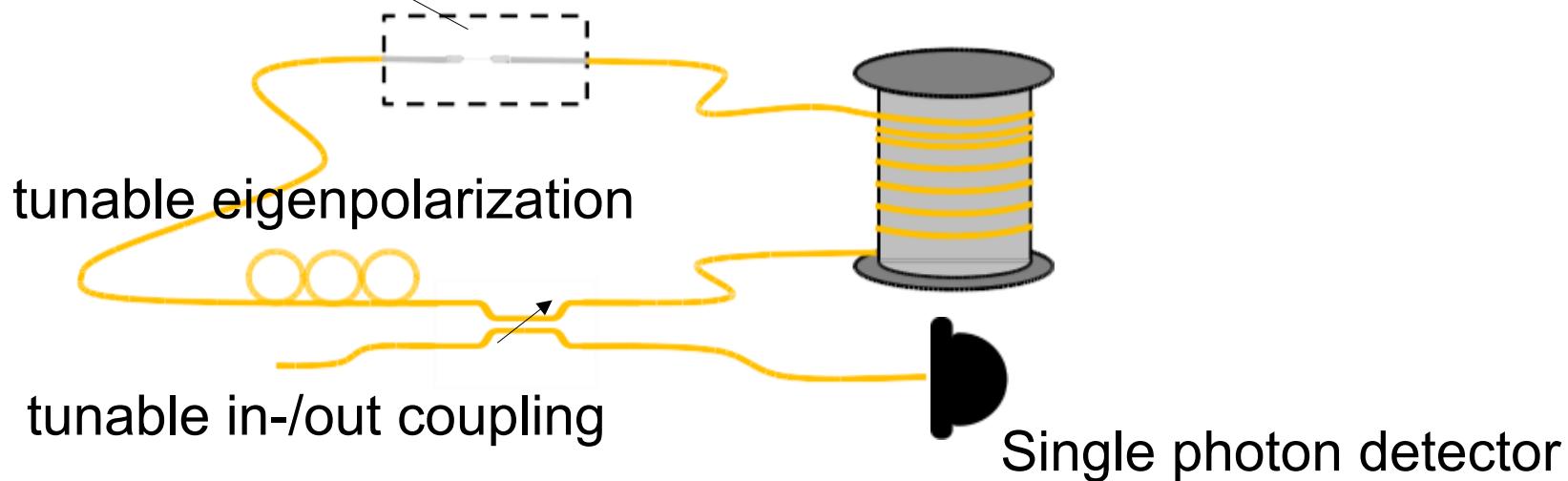
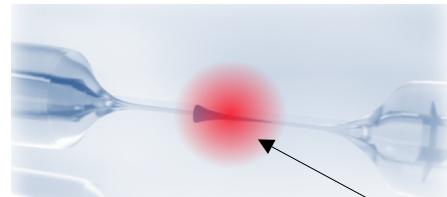
Optical fibre

+

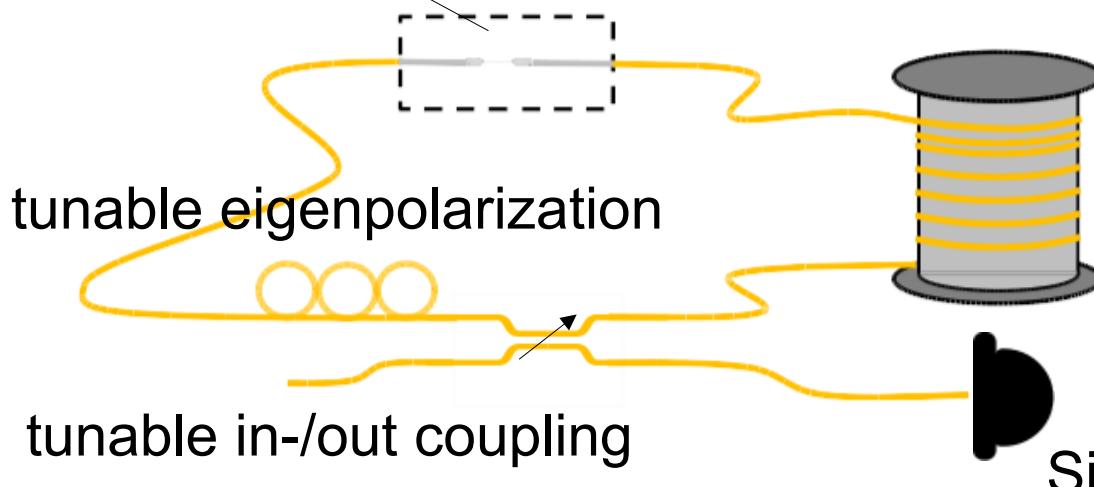
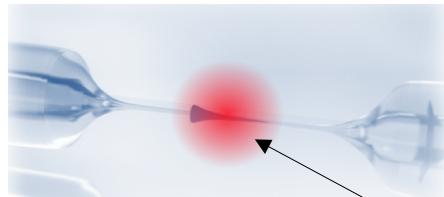


Adjustable fibre  
beam-splitter

# Nanofibre Ring Resonator



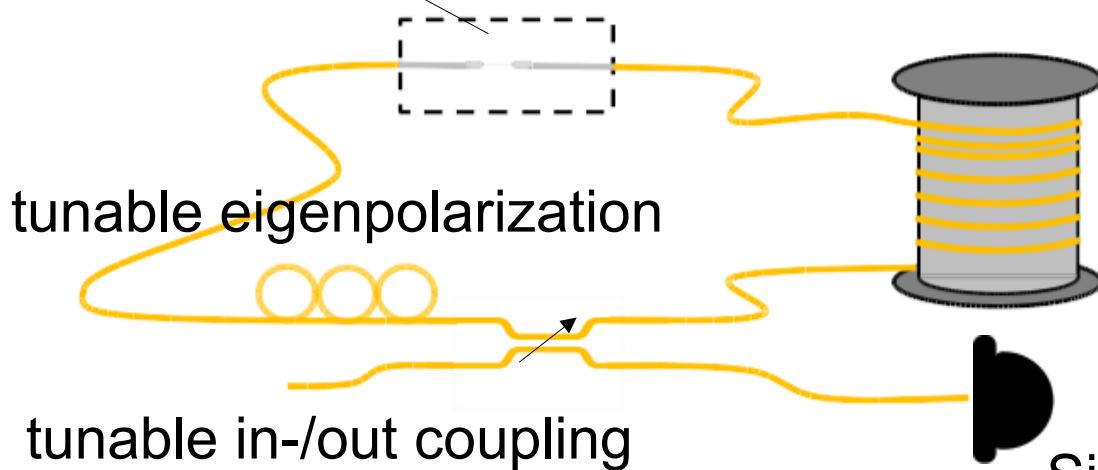
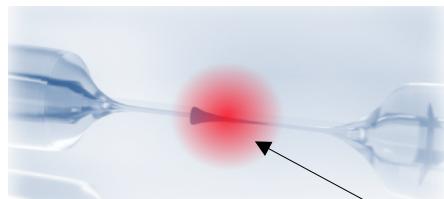
# Nanofibre Ring Resonator



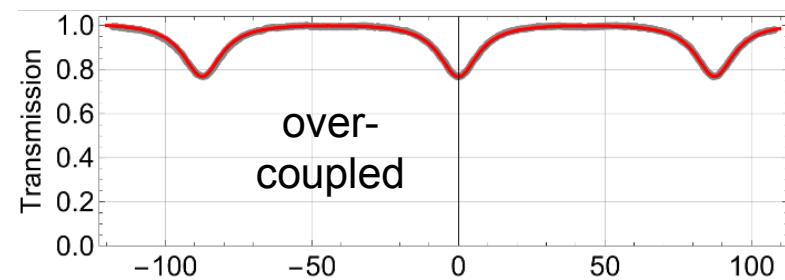
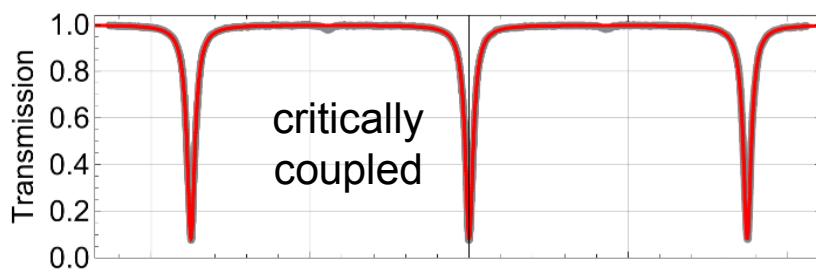
- Piezo for locking
- Passively insulated
- FSR 7.1 MHz
- Linewidth  $\sim 0.8$  MHz

Single photon detector

# Nanofibre Ring Resonator



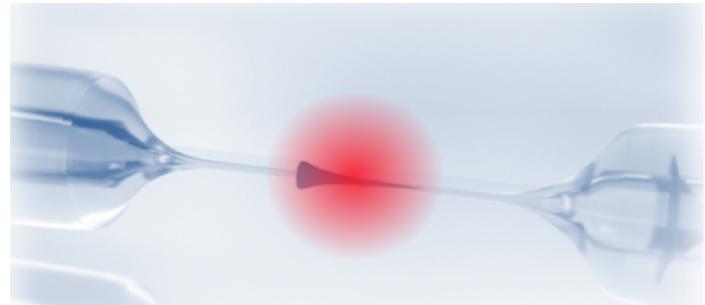
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# Interfacing the nanofibre with atoms

Magneto optical trap

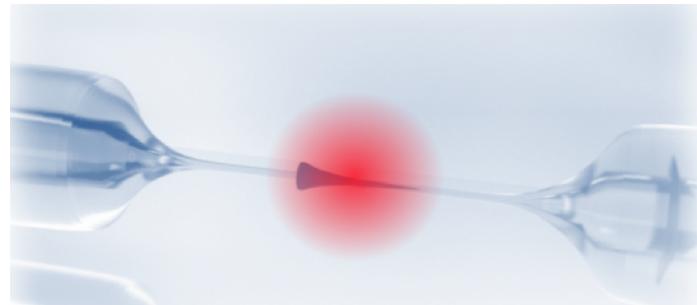
→ reservoir of cold Cs atoms



# Interfacing the nanofibre with atoms

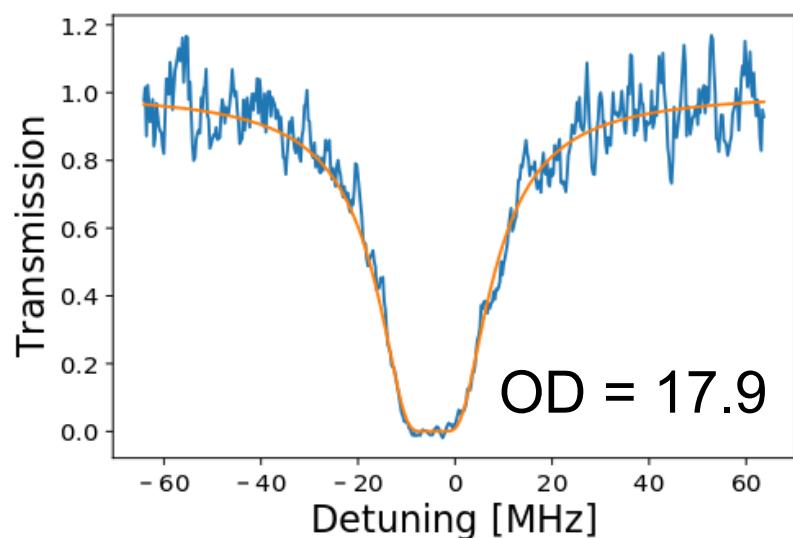
## Magneto optical trap

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## Transmission spectroscopy → collective coupling

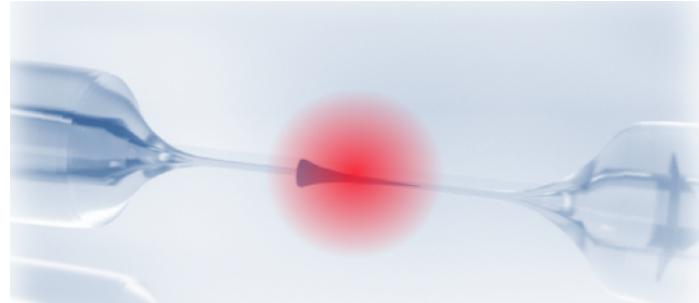
- Set resonator to fully overcoupled  
→ single round-trip of light



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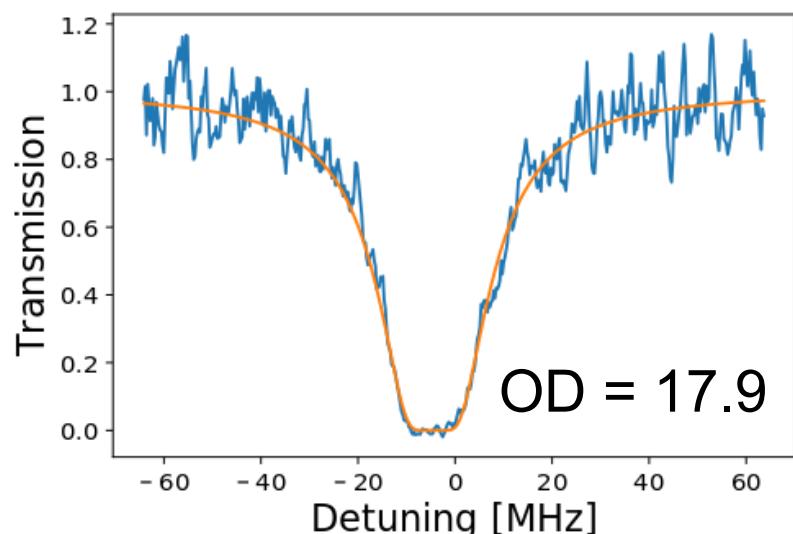
## Magneto optical trap

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## Transmission spectroscopy → collective coupling

- Set resonator to fully overcoupled  
→ single round-trip of light
- From  $C_{coll} = \frac{F}{\pi} OD$ :  
→  $g_{coll} = 12 \text{ MHz}$
- OD per atom  $\sim 0.05$
- “effective” atom number  $\sim 400$

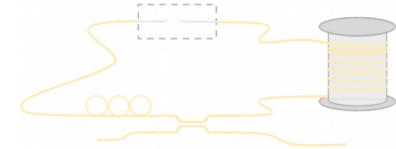


# Outline

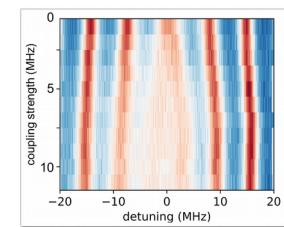
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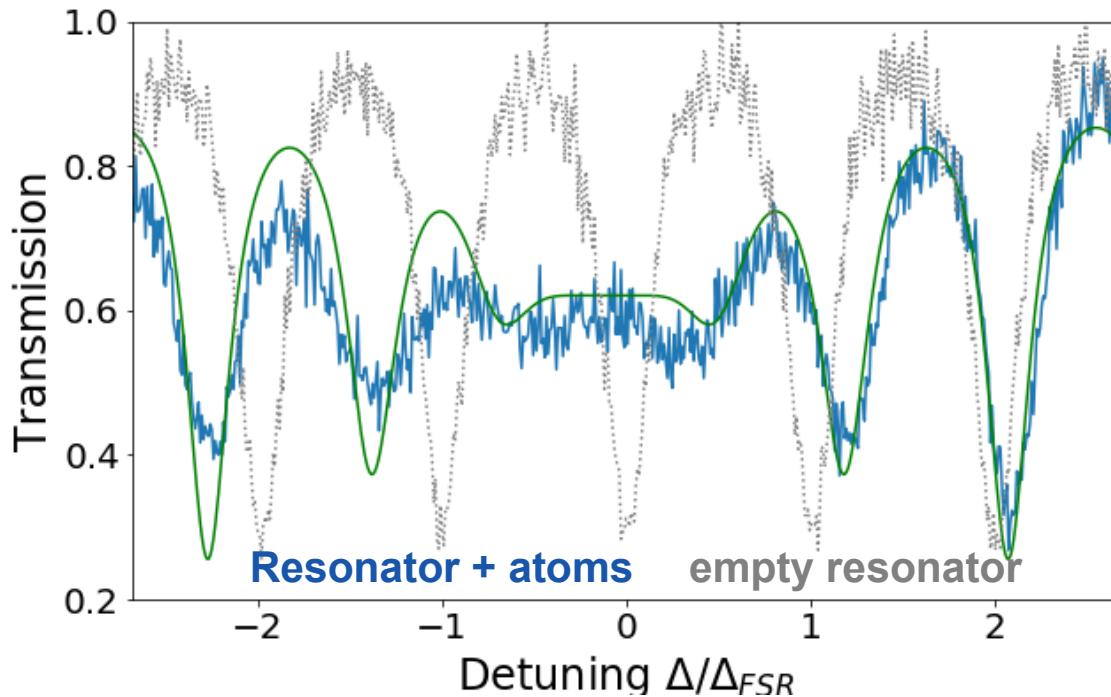


Multimode strong coupling



# Multimode strong coupling

## Measurement (for critical coupling)



- 1 ms probing pulse with frequency scanned
- Approx 100 shots

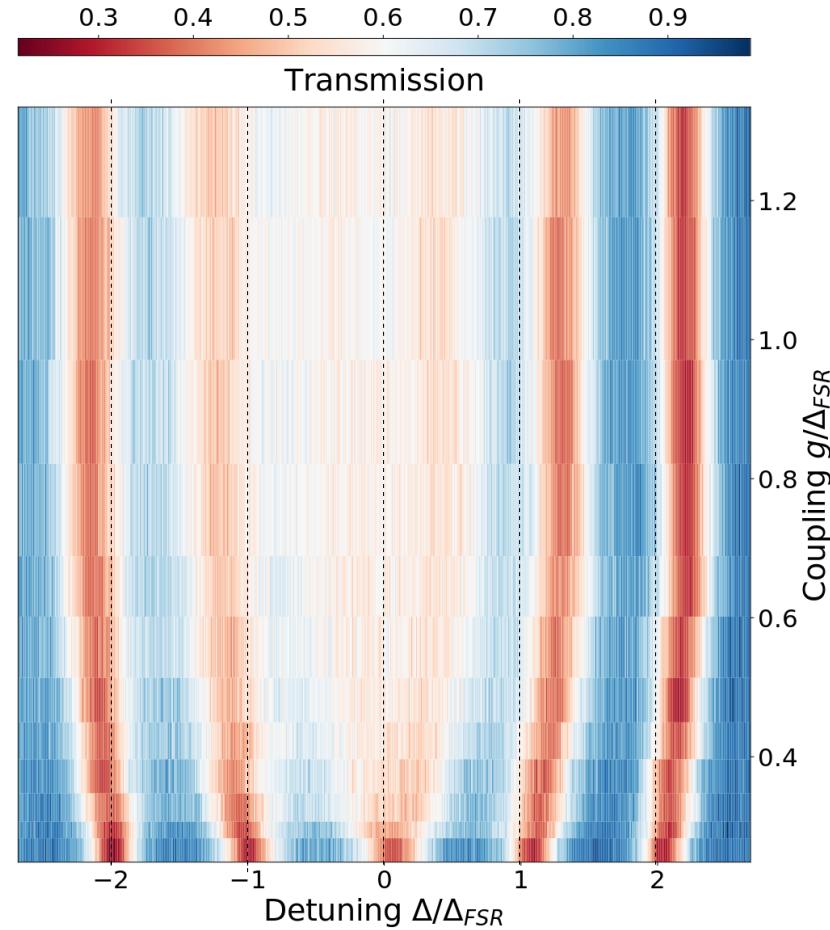
# Transition to multimode strong coupling

- Tune overlap of MOT with nanofibre, increase  $g$

multimode  
strong coupling

„conventional“  
strong coupling

Increase OD

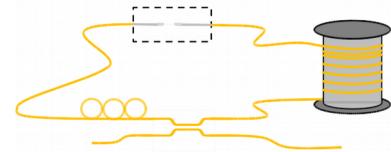


→ Central splitting up to FSR

# Summary

## Nanofibre ring resonator

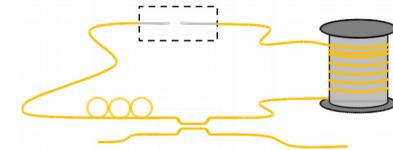
- Combining nanofibre quantum interface and fiber ring resonator
  - entering a new regime of CQED
- Versatile setup



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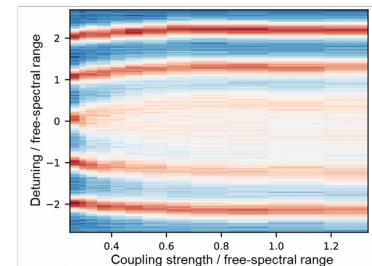
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## Study of multimode strong coupling

- Coupling strength exceeds free-spectral range
- Observation of the transition:  
“standard” → multimode strong coupling



## Next experimental steps

- Investigate nonlinear properties ( $g^{(2)}$ )
- Trapping atoms in evanescent field of the nanofibre
- Optimizing resonator finesse (reduce linewidth to 100 kHz)

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## And then?

- “non-Markovian”
  - new type of photon-resonator dynamics
- New types of entangled states, photonic info processing...
- Taylor interaction range between atoms
  - Self-organisation

# Thank you for your attention

