Coupling, controlling, and processing non-transversal photons with a single atom

8th International Summer School of the SFB/TRR21
"Control of Quantum Correlations in Tailored Matter"
Heinrich-Fabri-Haus, Blaubeuren, Germany
July 27–29, 2015

Arno Rauschenbeutel
Vienna Center for Quantum Science and Technology,
Atominstitut, TU Wien, Austria

Photonic Quantum Applications

Photons

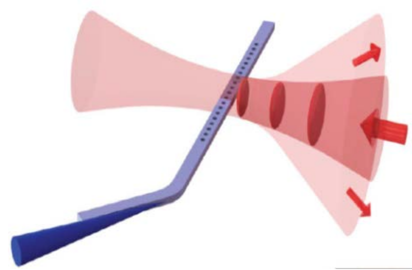
- Easy state manipulation and detection.
- Weakly coupled to environment.

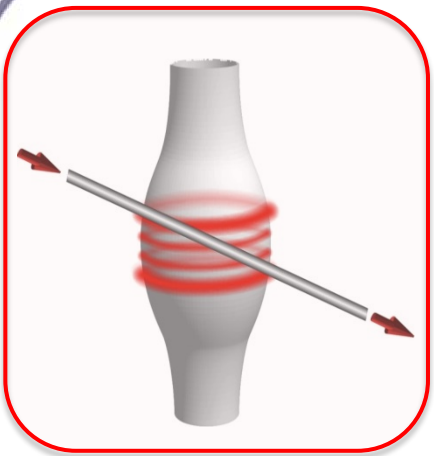
  → Ideal for (quantum) communication and information processing.

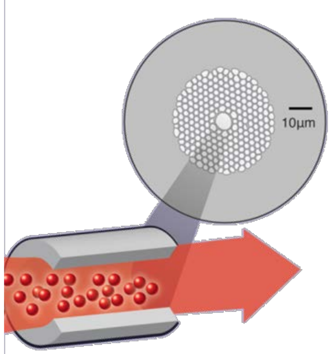
But: Photons do not interact with each other → no quantum gates !

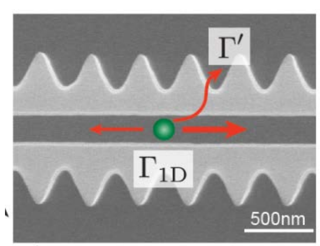
Solution: Atom-Photon Quantum Interfaces

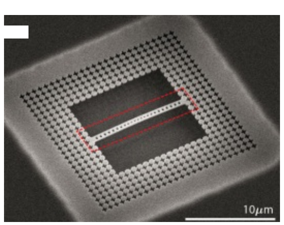
- Photons coupled to atoms → provide photon-photon interaction











Optical Microresonators

An optical microresonator can be characterized by its mode volume V_{mode} and its quality factor Q:

$$V_{\mathrm{mode}} = \iiint |f(\vec{r})|^2 \, d^3 r$$

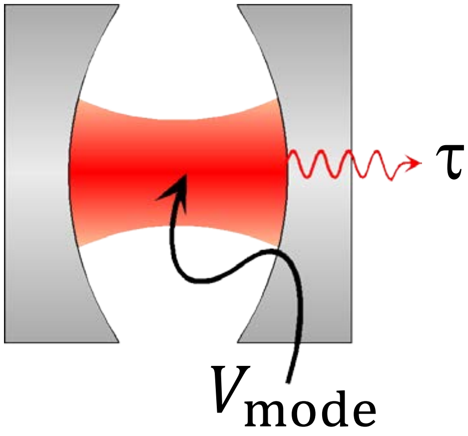
$f(\vec{r})$: spatial mode function

$$|f_{\mathrm{max}}(\vec{r})|^2 = 1$$

$$Q = \omega_{\mathrm{opt}} \tau$$

ω_{opt}: optical frequency

τ: photon lifetime

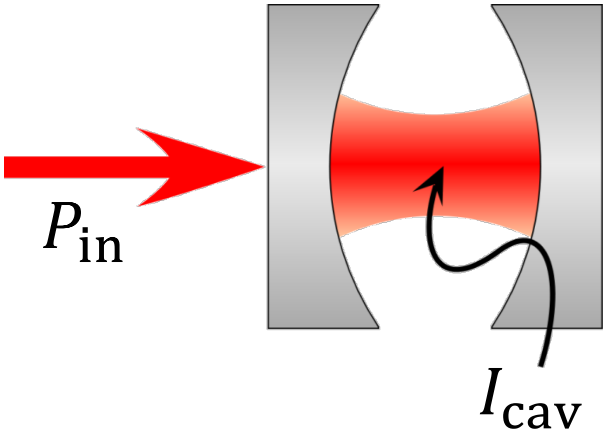


Optical Microresonators

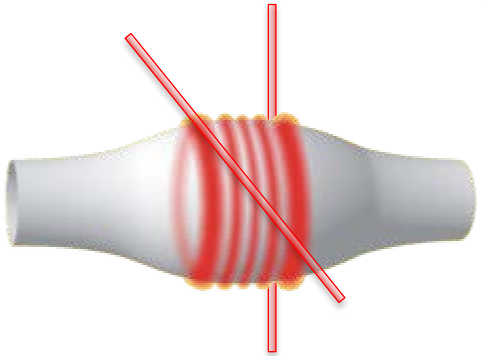
For a given input power P_{in}, the intracavity intensity scales as

$$I_{\text{cav}} \propto P_{\text{in}} \times \frac{Q}{V_{\text{mode}}}$$

⇒ make Q/V_{mode} as large as possible in order to enhance coupling of light and matter.

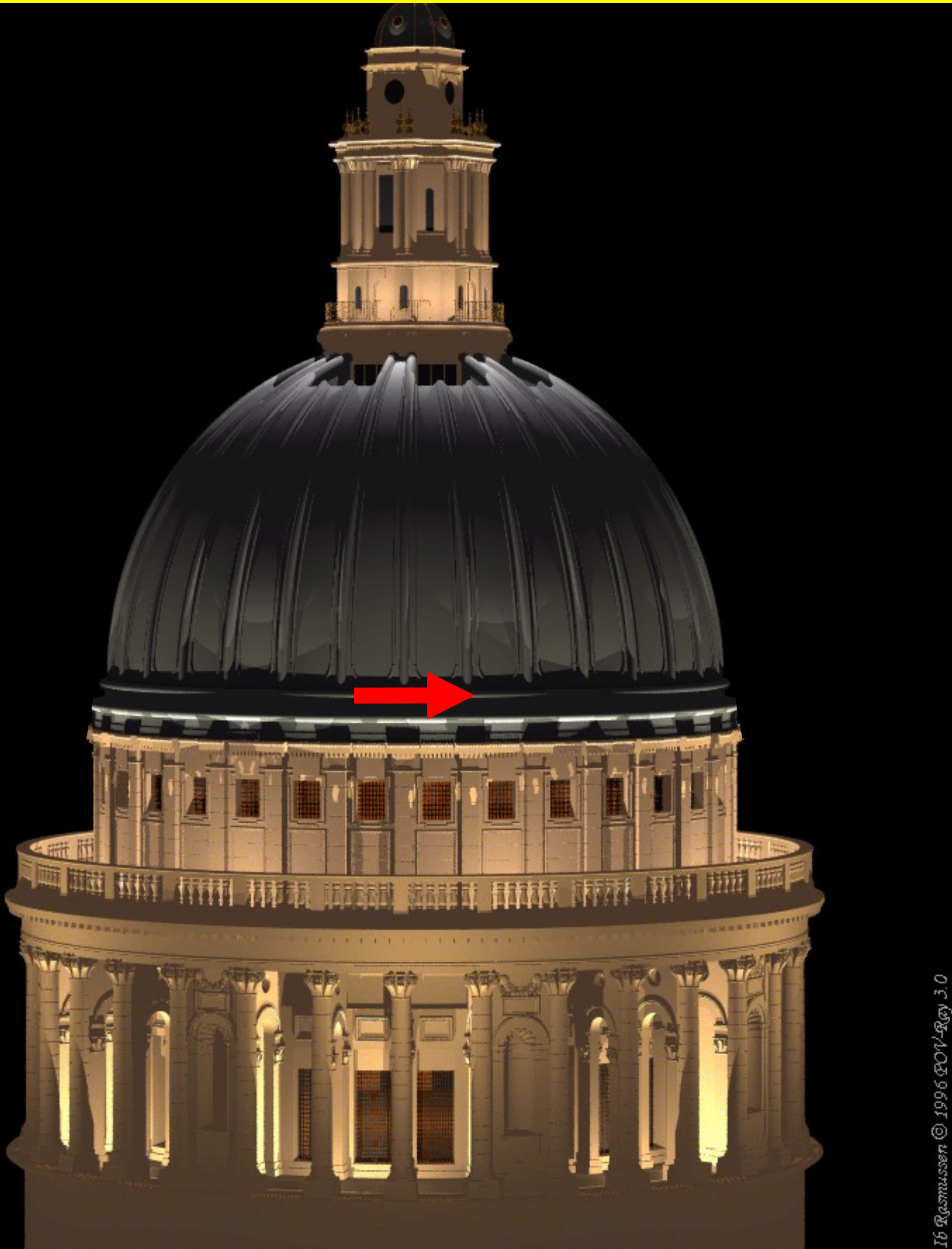


Overview



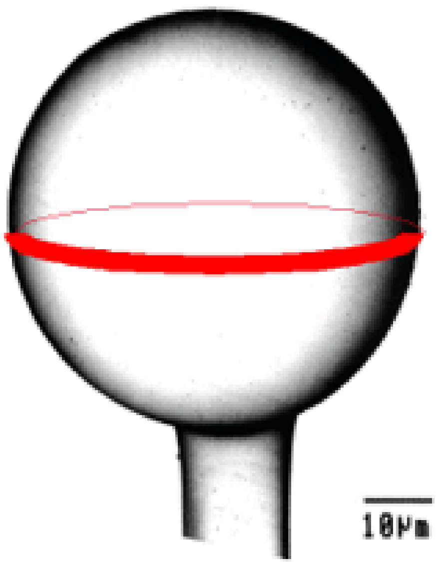
- Light-matter coupling in whispering-gallery-mode resonators
- The role of non-transversal polarization
- Switching light with a single atom
- Nonlinear π phase shift for single fiber-guided photons

Whispering Gallery Modes

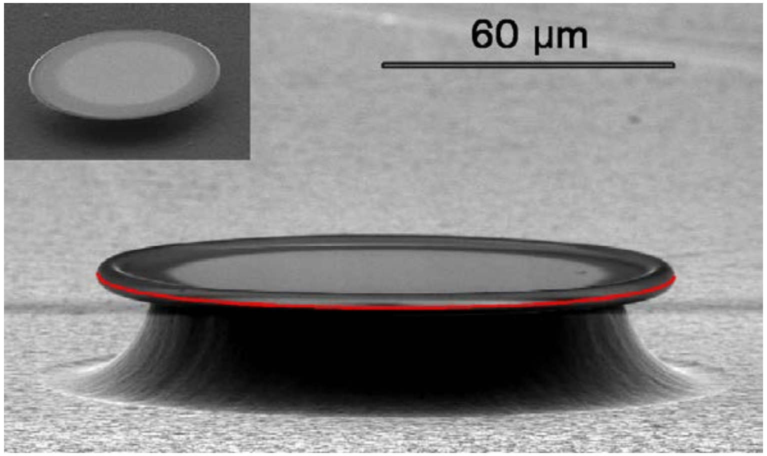


Whispering Gallery Mode Microresonators

"Equatorial" whispering gallery modes (WGMs) in fused silica microresonators:



V. Lefèvre, private commun.



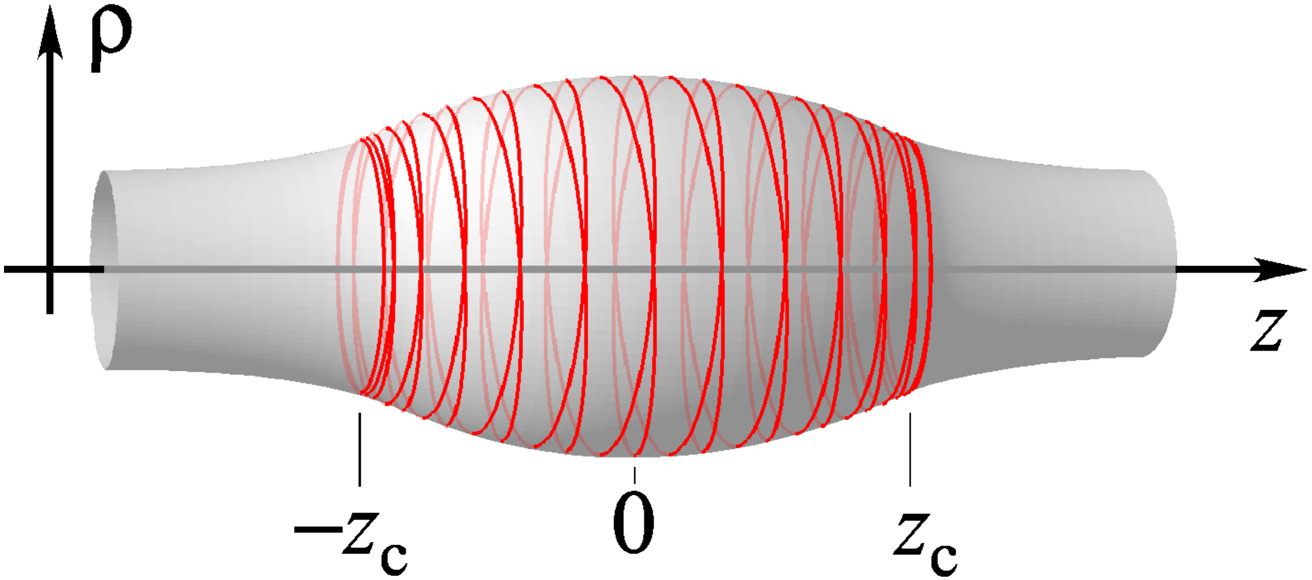
D. K. Armani et al., Nature 421, 925 (2003)

✓ ultra-high Q factor, small mode volume

✗ limited tunability, restricted access to light field

The "Bottle Microresonator"

Alternative approach: WGMs in a bulge on an optical fiber:



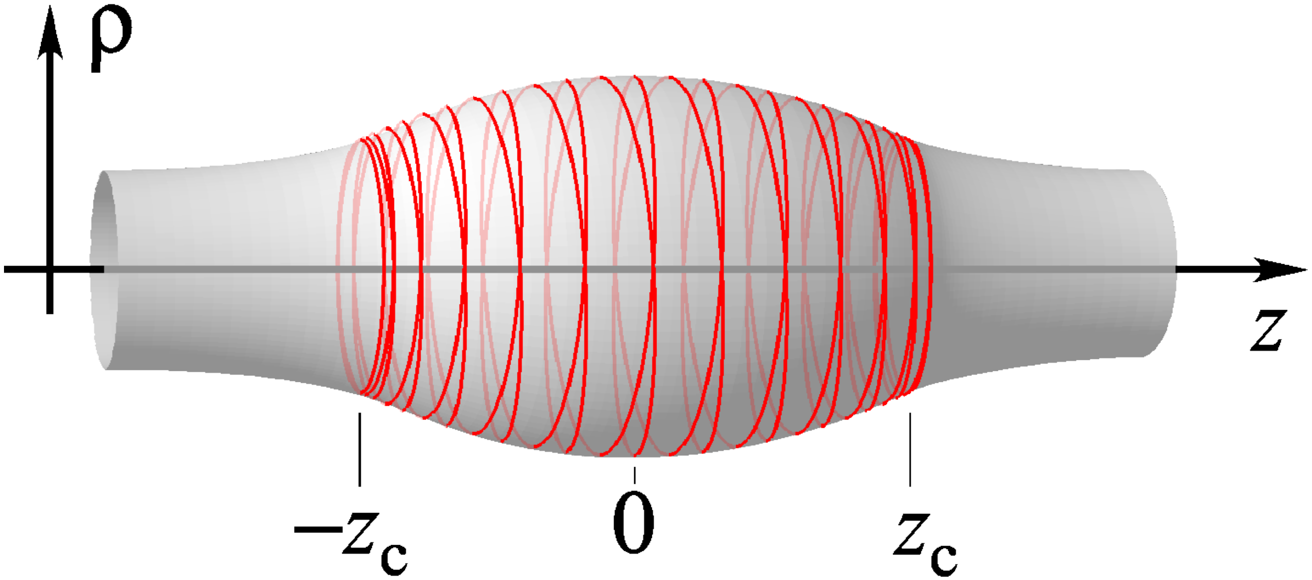
Our prediction in 2005:

- ultra-high Q factor, small mode volume
- strain tunable, advantageous mode geometry

Thanks to Peter Würtz

The "Bottle Microresonator"

Alternative approach: WGMs in a bulge on an optical fiber:

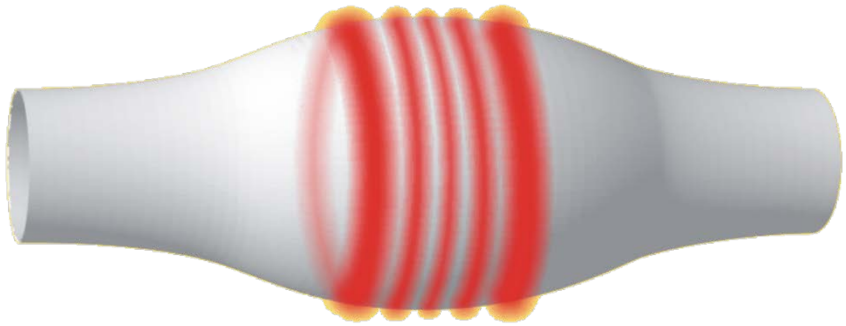


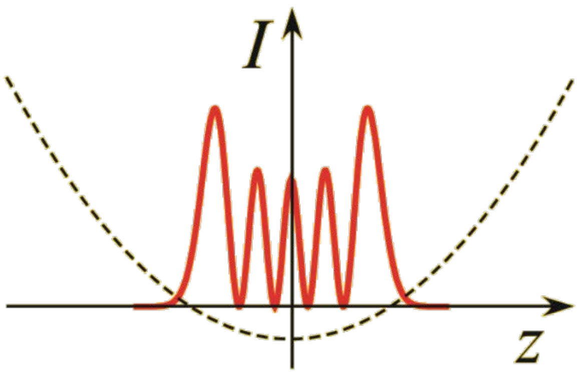
Our prediction in 2005:

- ultra-high Q factor, small mode volume
- strain tunable, advantageous mode geometry

WGMs in a Bottle Microresonator

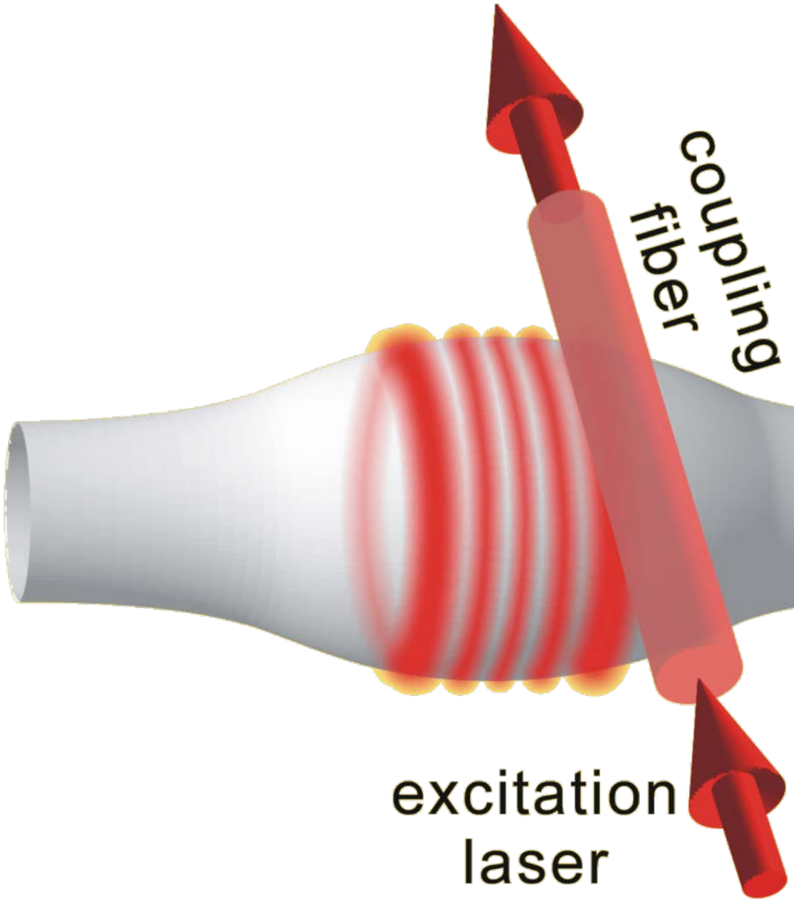
Axial confinement due to effective harmonic potential.





Resulting intensity distribution ↔ eigenfunctions of 1d-h.o.

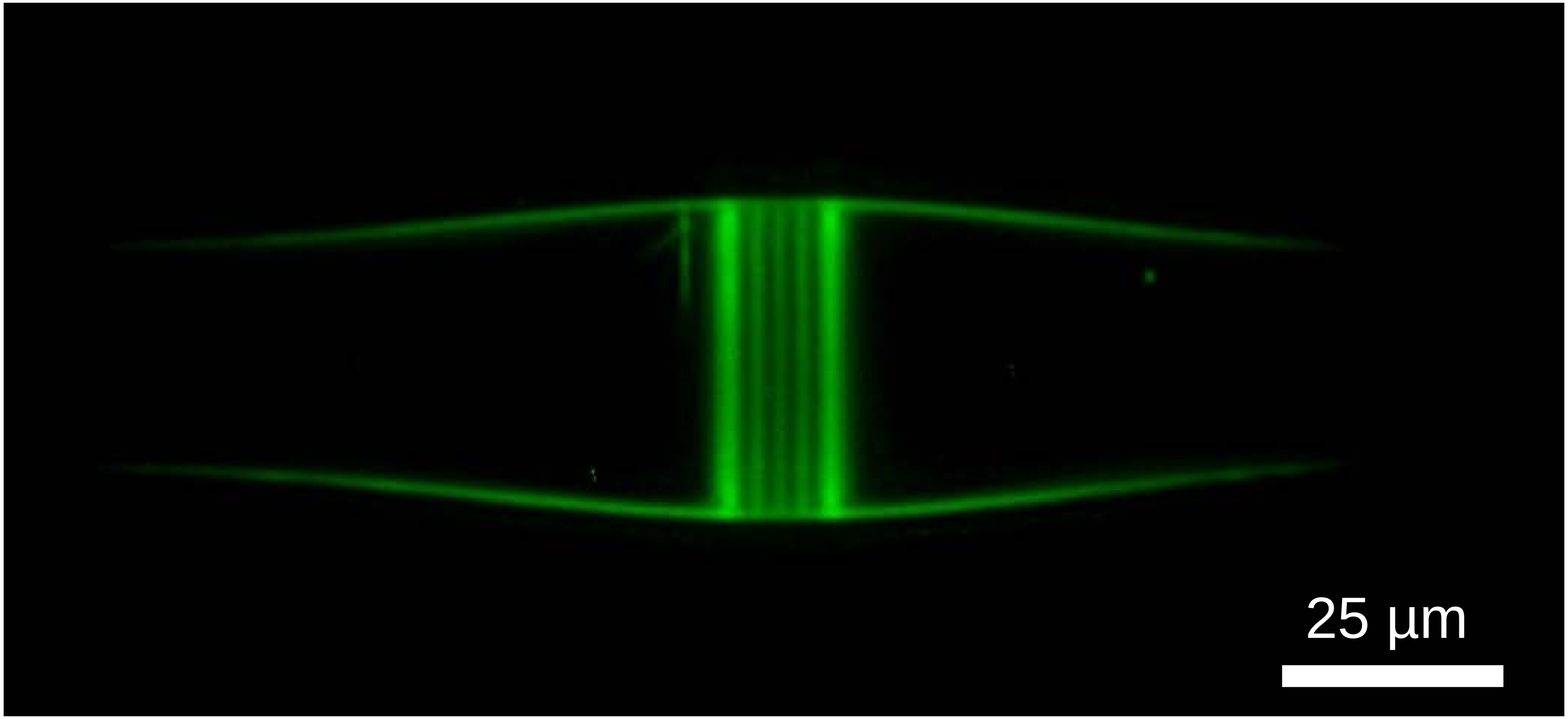
Observing “Bottle Modes”



Direct observation not possible ⇒ dope resonator with Er-ions.

Observing "Bottle Modes"

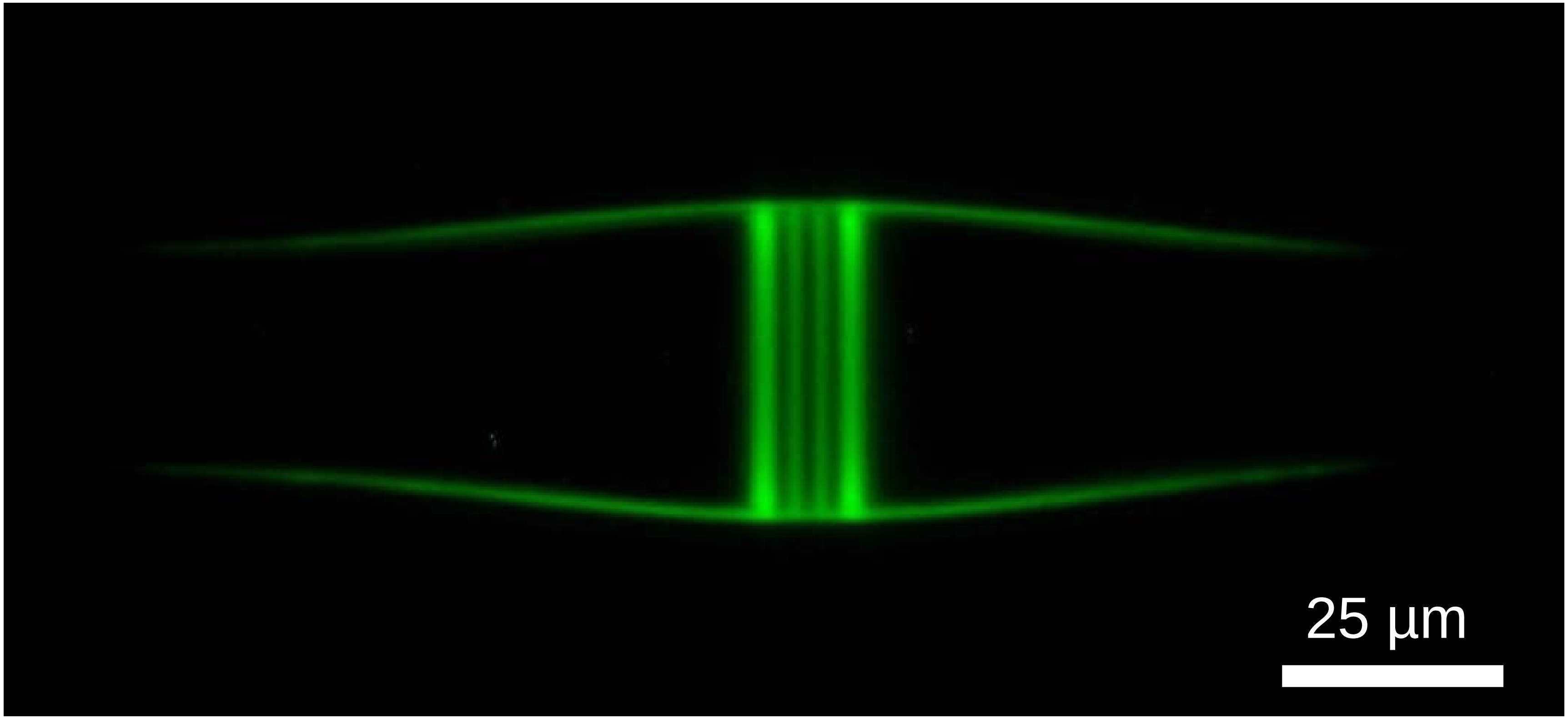
PRL **103**, 053901 (2009)



Green fluorescence through 2 photon up-conversion process.

Observing “Bottle Modes”

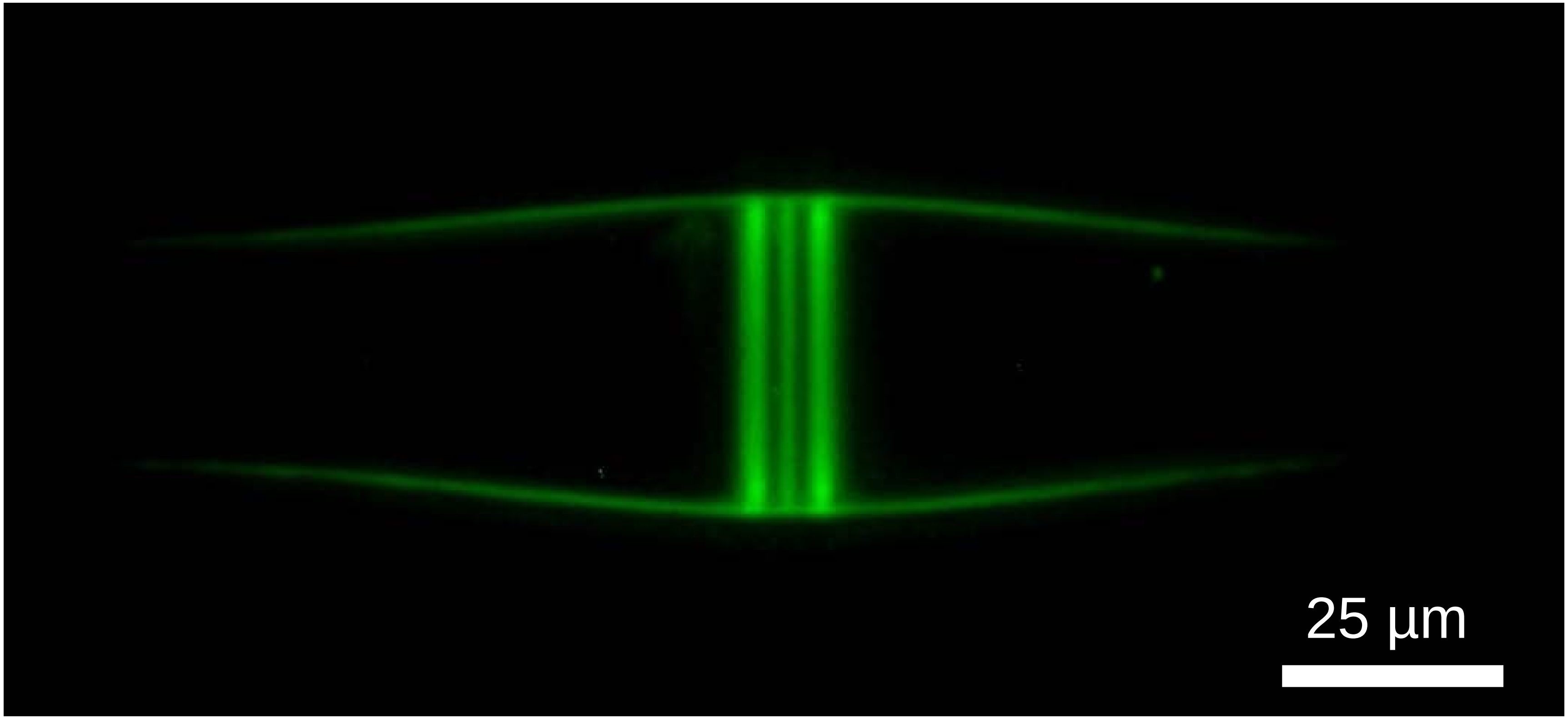
PRL **103**, 053901 (2009)



Green fluorescence through 2 photon up-conversion process.

Observing "Bottle Modes"

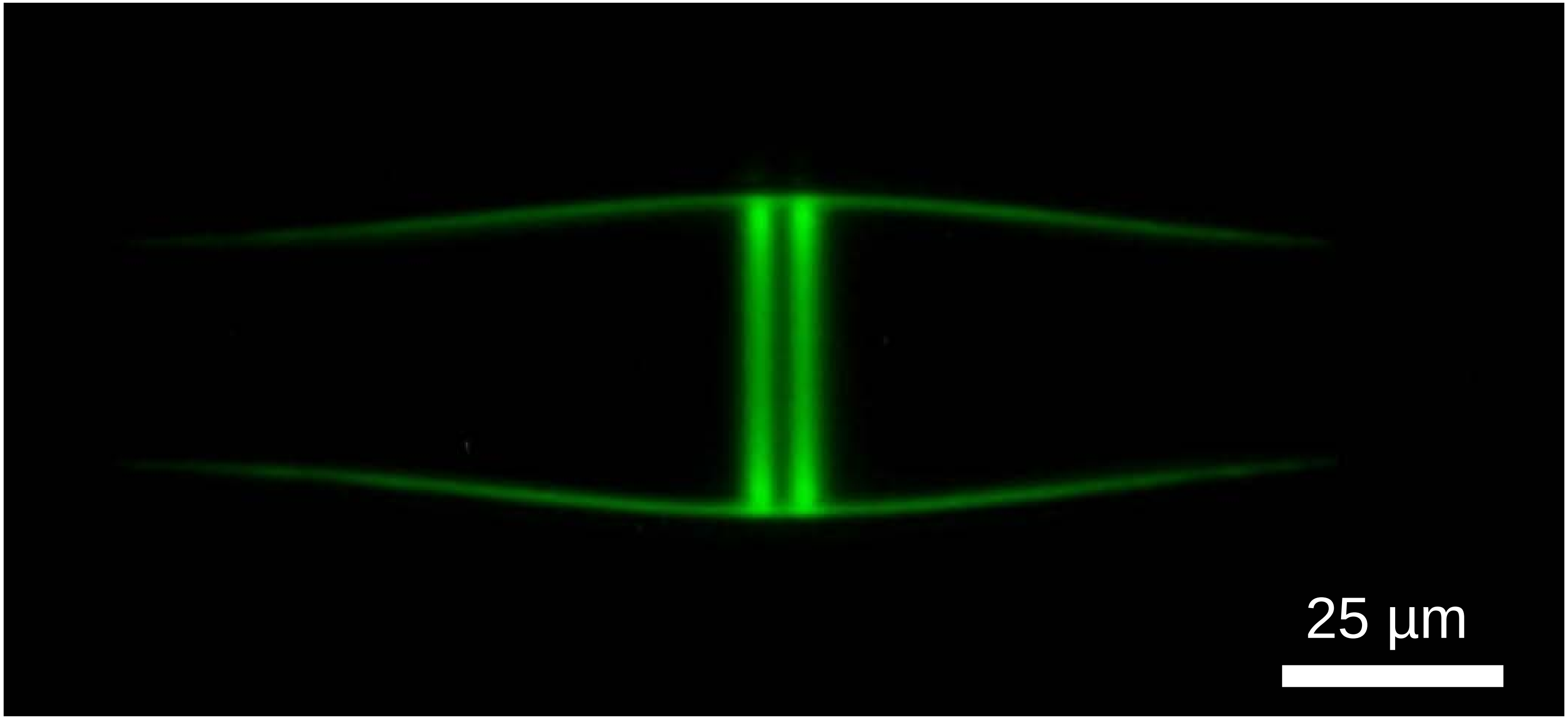
PRL **103**, 053901 (2009)



Green fluorescence through 2 photon up-conversion process.

Observing “Bottle Modes”

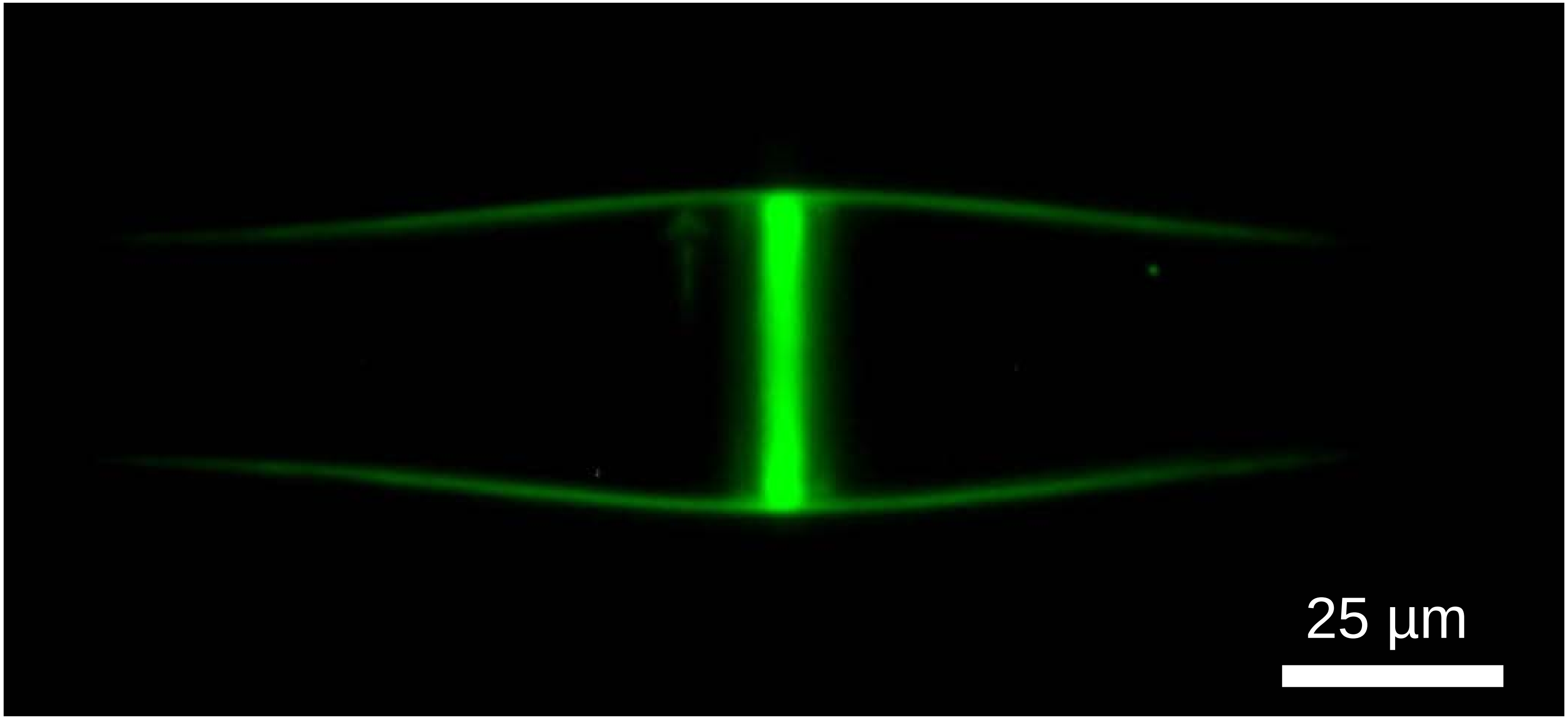
PRL **103**, 053901 (2009)



Green fluorescence through 2 photon up-conversion process.

Observing “Bottle Modes”

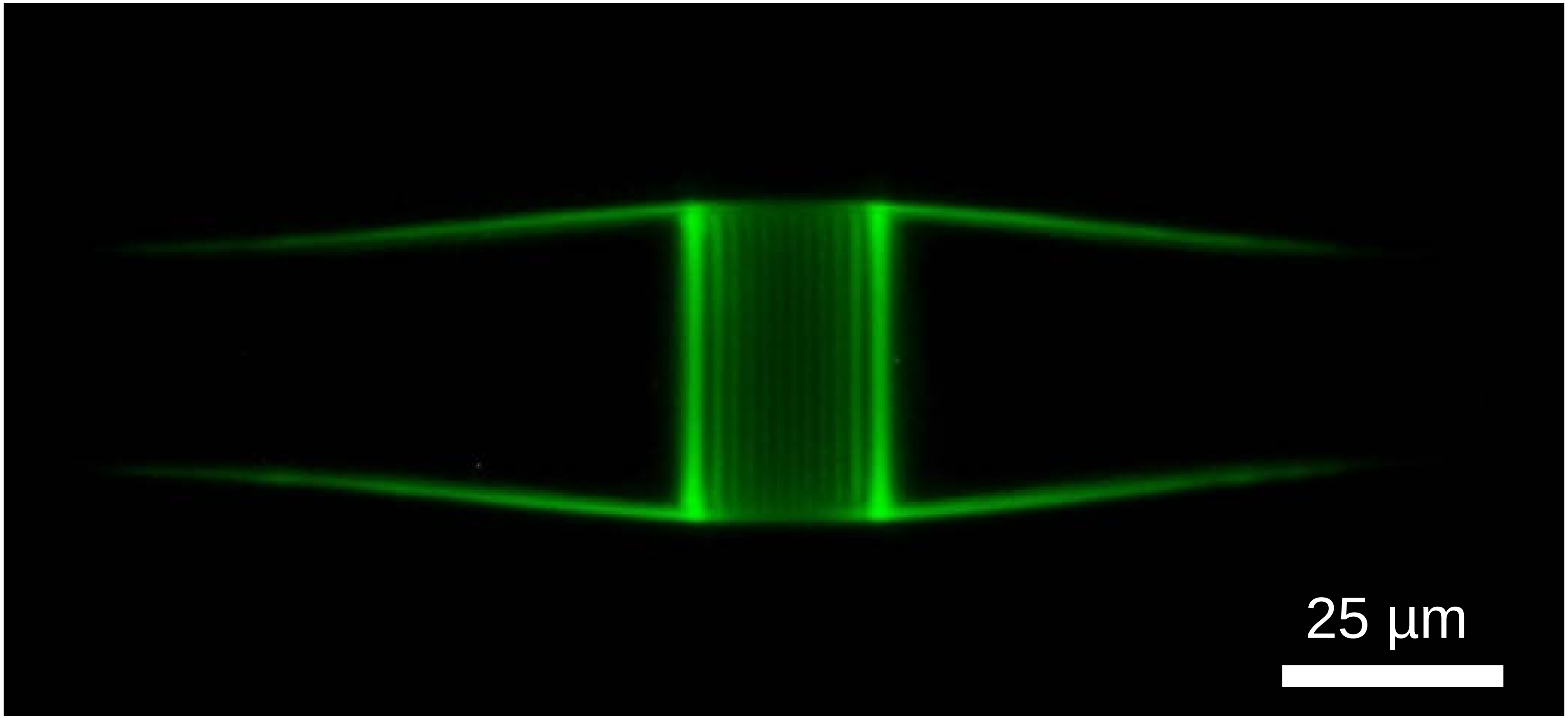
PRL **103**, 053901 (2009)



Green fluorescence through 2 photon up-conversion process.

Observing "Bottle Modes"

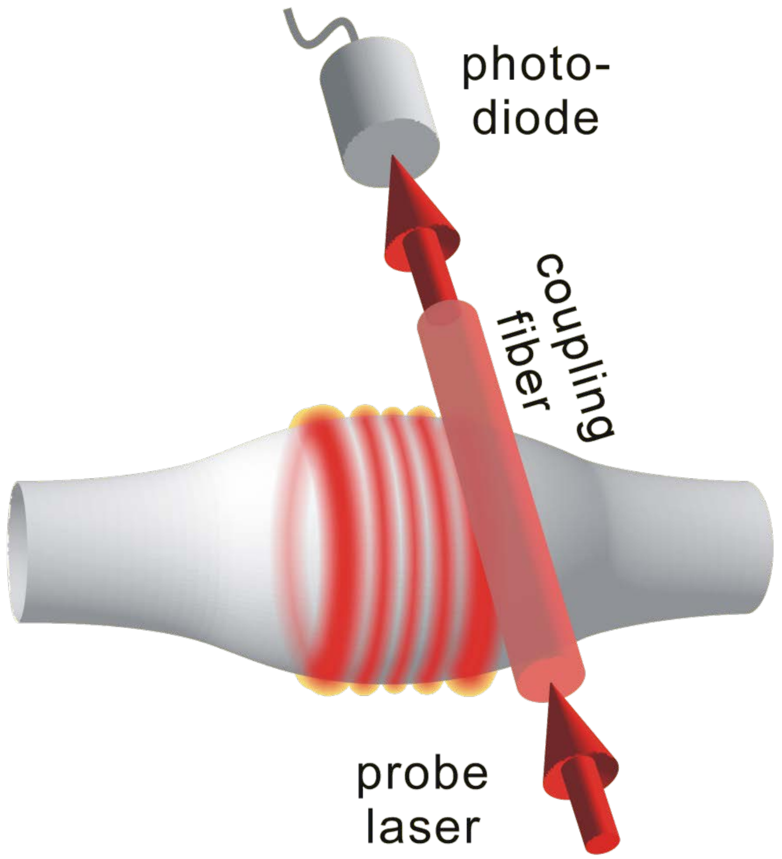
PRL **103**, 053901 (2009)



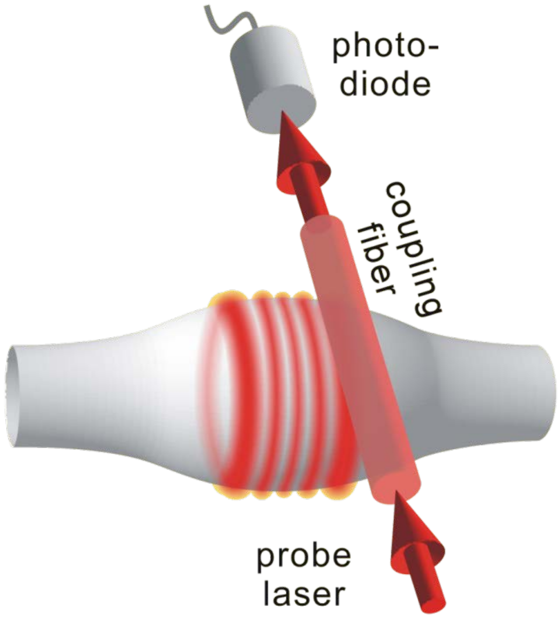
Green fluorescence through 2 photon up-conversion process.

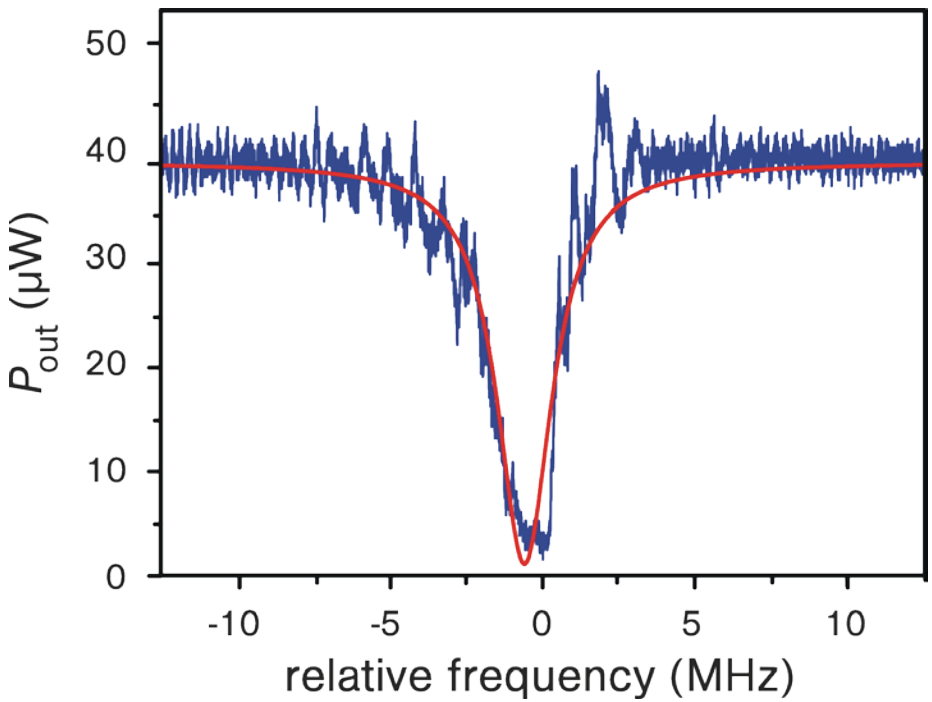
Characterizing Bottle Modes

Resonances show up as dips in transmitted power.



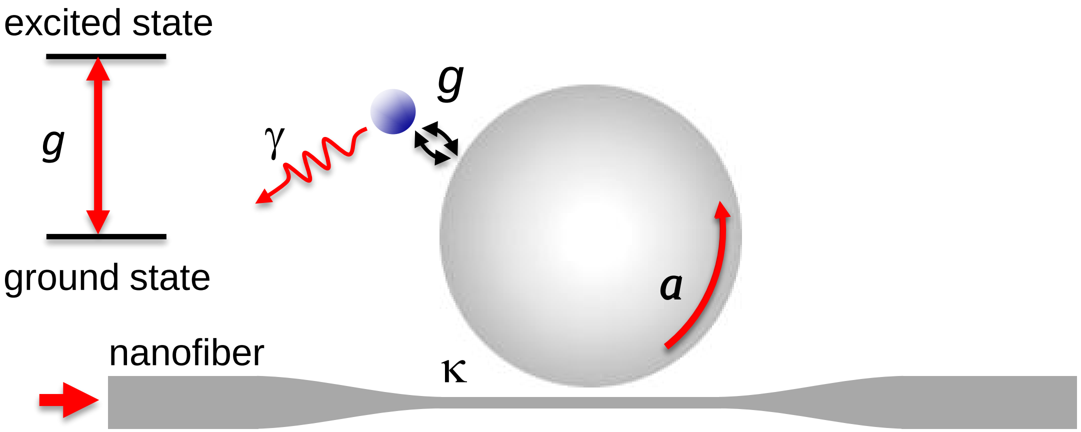
Characterizing Bottle Modes

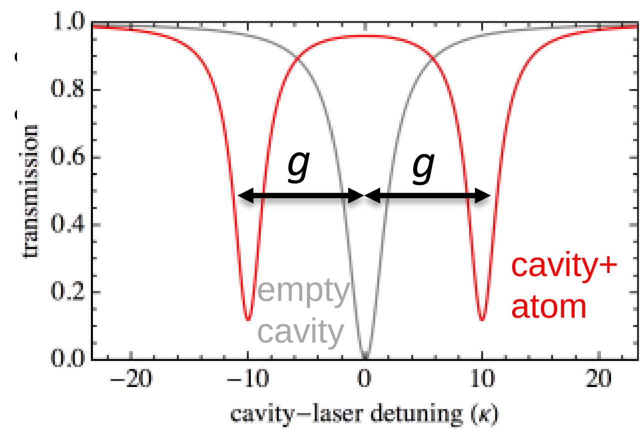




- Linewidth: 2.1 ± 0.1 MHz @ λ=850 nm
- $\Rightarrow Q_0 \approx 3.3 \times 10^8$
- $\Rightarrow Q_0 / V_{mode} \approx 6 \times 10^4 (\lambda/n)^{-3} \Rightarrow$ strong coupling regime

CQED – The Jaynes-Cummings Model





Atom-resonator interaction:

$$H_{JC} = g\,(\,a^{\dagger}\sigma^{-} + a\sigma^{+}\,)$$

$a^{\dagger}$ ... photon creation operator
σ^{+} ... atom excitation operator

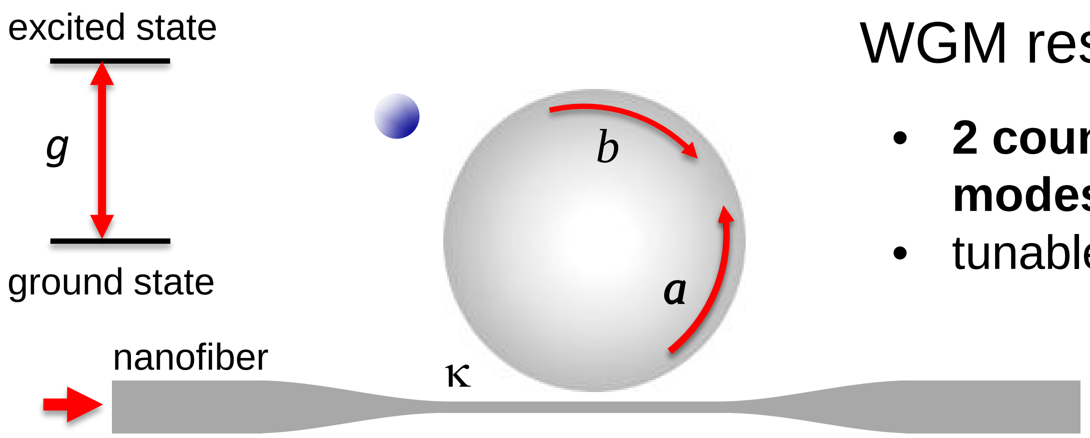
g ... atom-cavity coupling
κ ... cavity decay rate
γ ... atomic decay rate

Strong coupling regime

$g > \kappa, \gamma$

Vacuum-Rabi splitting indicates strong coupling

CQED with WGM resonators



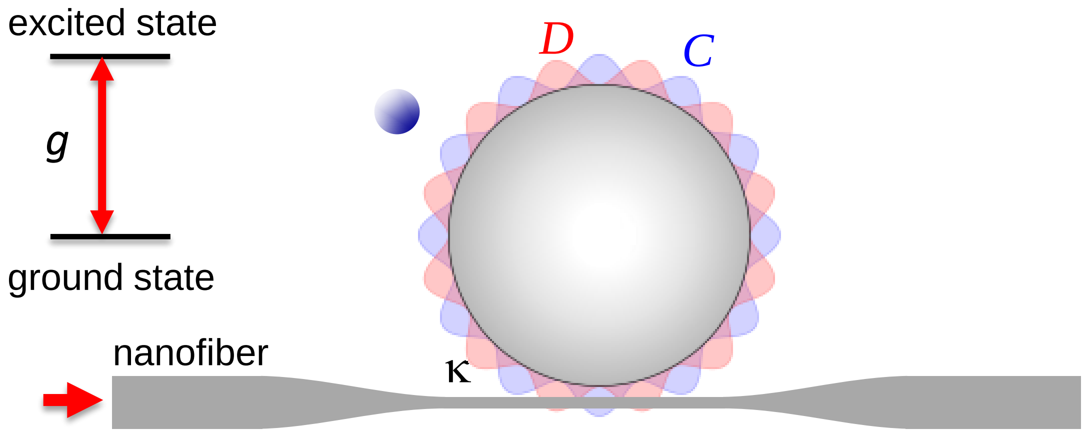
WGM resonators as ring resonators

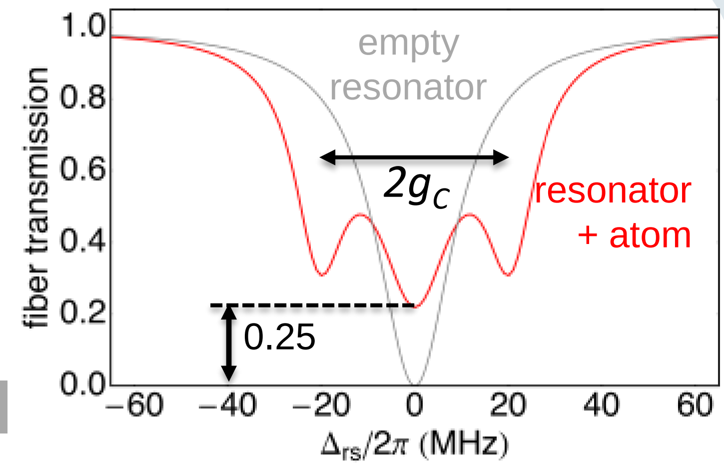
- **2 counter-propagating optical modes: *a, b***
- tunable fiber-resonator coupling: κ

Atom-resonator interaction:

$$H_{JC} = g\,(a^{\dagger}\sigma^{-} + a\sigma^{+}) + g\,(b^{\dagger}\sigma^{-} + b\sigma^{+})$$

CQED with WGM resonators





Atom-resonator interaction:

$$H_{JC} = g\,(a^\dagger\sigma^- + a\sigma^+) + g\,(b^\dagger\sigma^- + b\sigma^+)$$

Standing wave description: $C = (a+b)/\sqrt{2}$

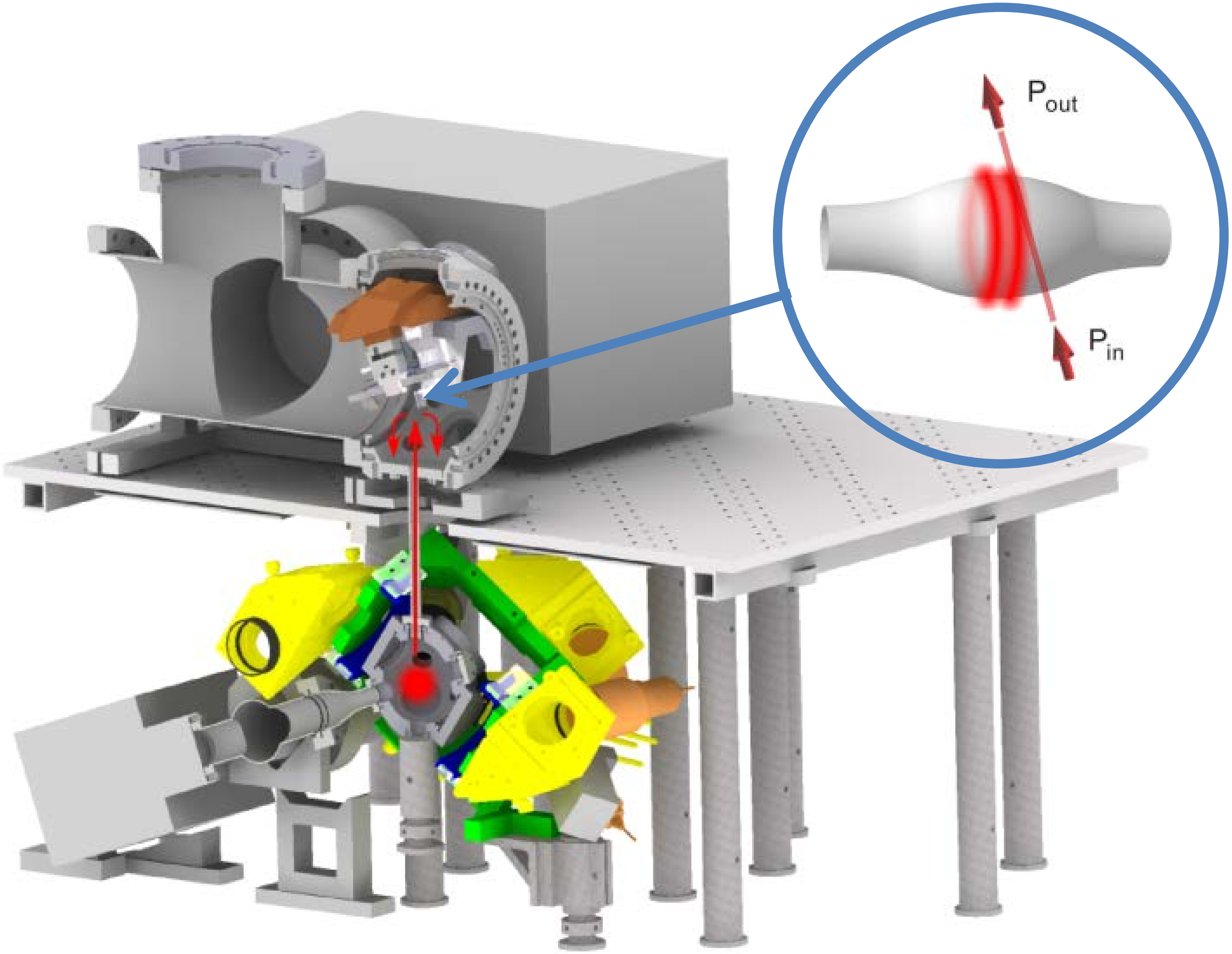
$$D = (a-b)/\sqrt{2}$$

equivalent description

$$H_{JC} = g_C\,(C^\dagger\sigma^- + C\sigma^+) + g_D\,(D^\dagger\sigma^- + D\sigma^+)$$

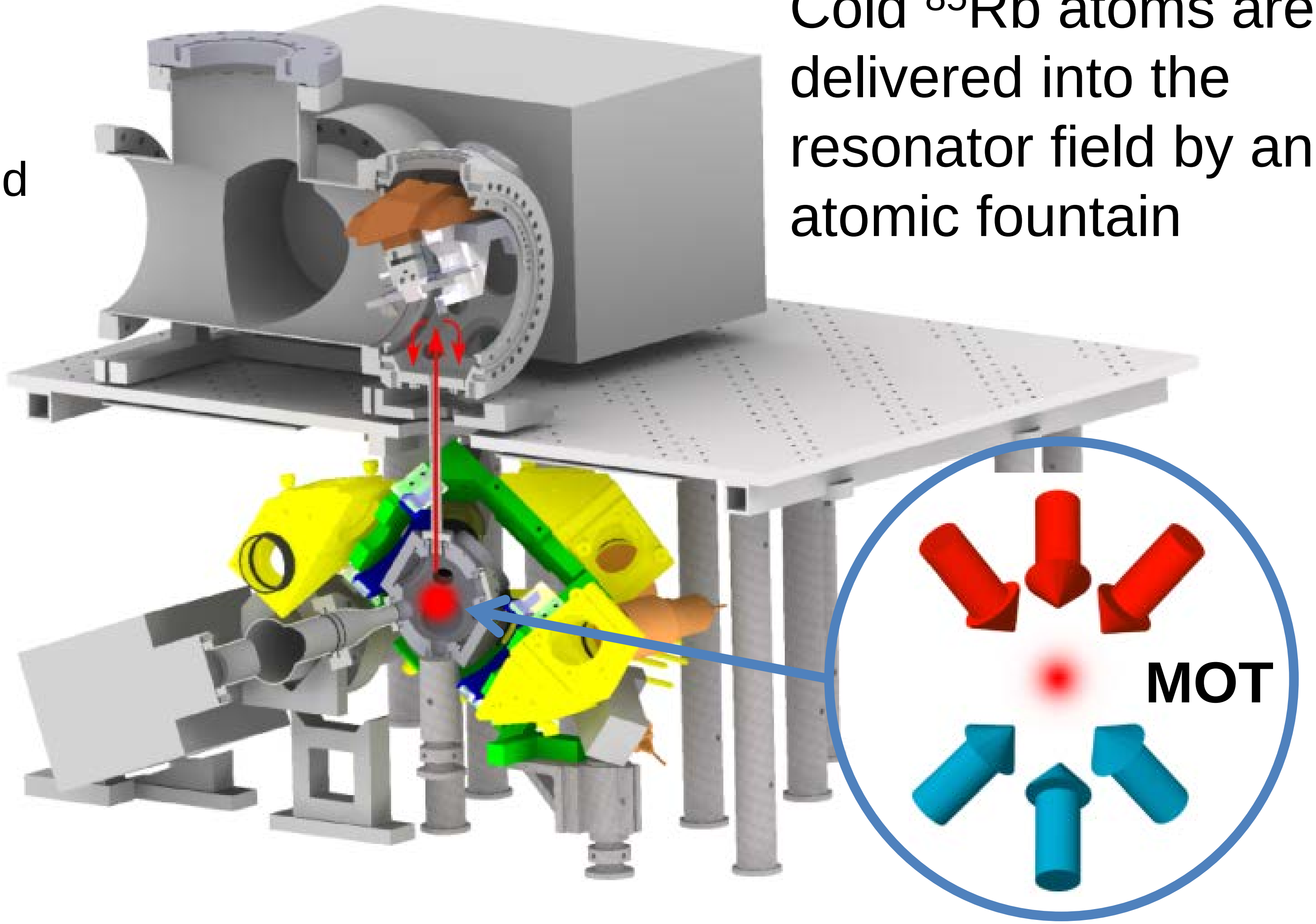
- Always possible to choose, e.g., g_D=0: uncoupled standing wave
- Only 50% of the light interacts with the atom

The CQED Experiment



The CQED Experiment

Atomic cloud
T = 5 µK
10^7 atoms

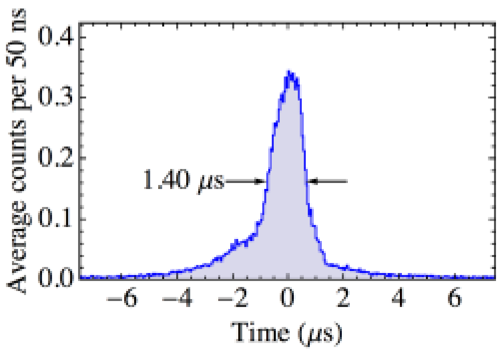


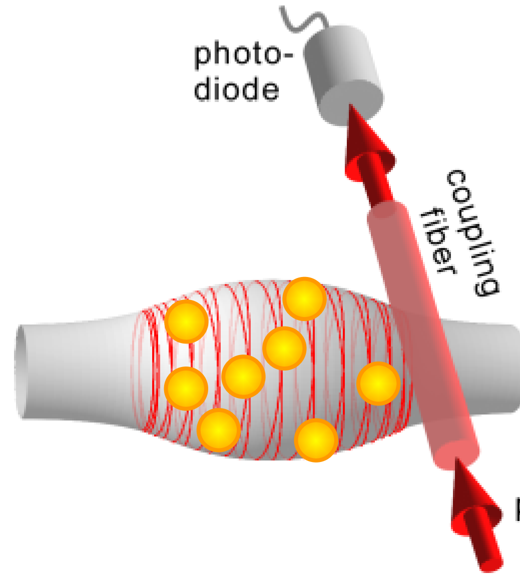
Cold ^{85}Rb atoms are delivered into the resonator field by an atomic fountain

Coupling single atoms to the bottle resonator

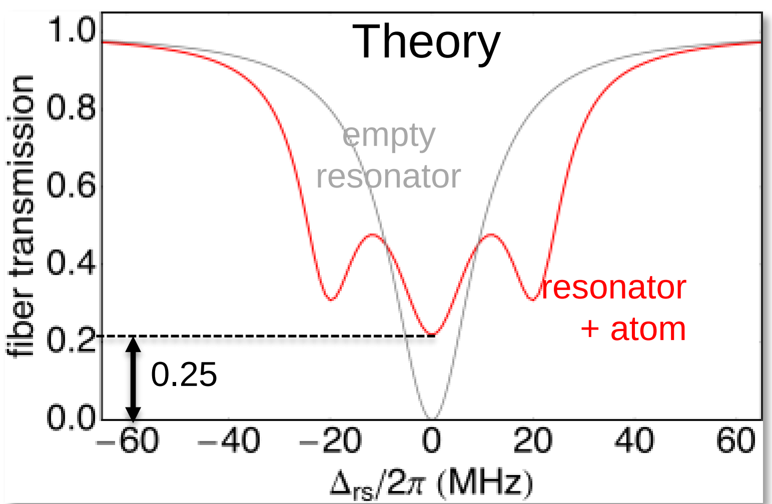
- Detecting ^{85}Rb atoms from atomic fountain

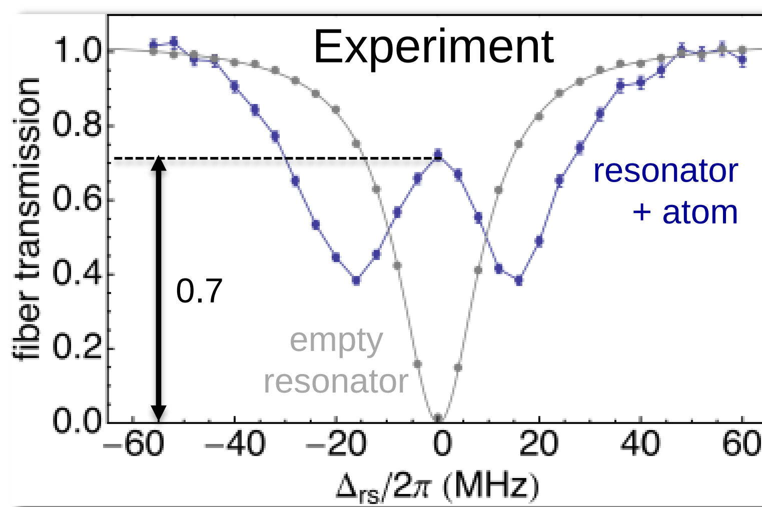
  Transmission increase heralds atom transit





- Spectroscopy of atom-resonator system



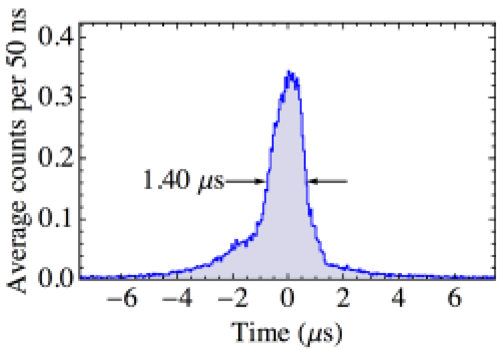


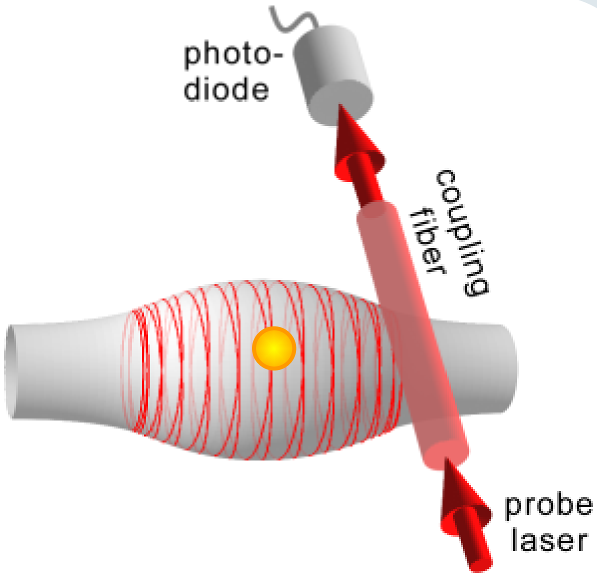
➡ Theory and experiment disagree qualitatively

Coupling single atoms to the bottle resonator

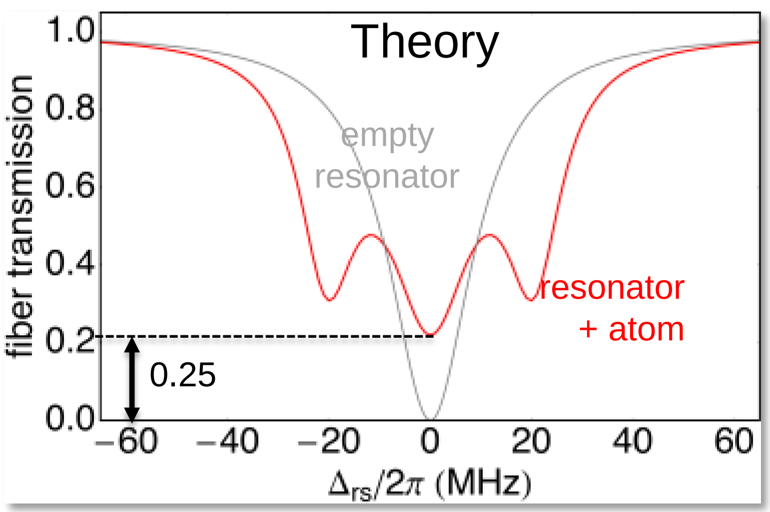
- Detecting ^{85}Rb atoms from atomic fountain

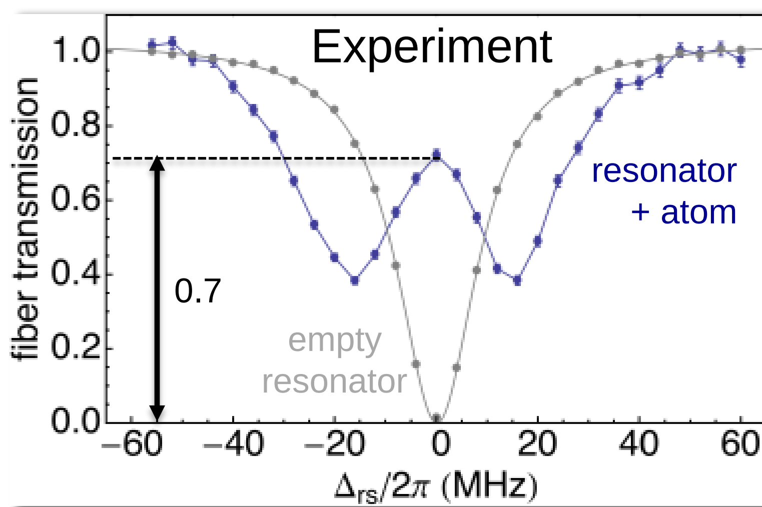
  Transmission increase heralds atom transit





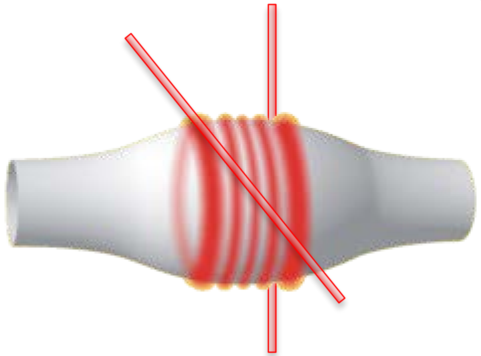
- Spectroscopy of atom-resonator system





➡ Theory and experiment disagree qualitatively

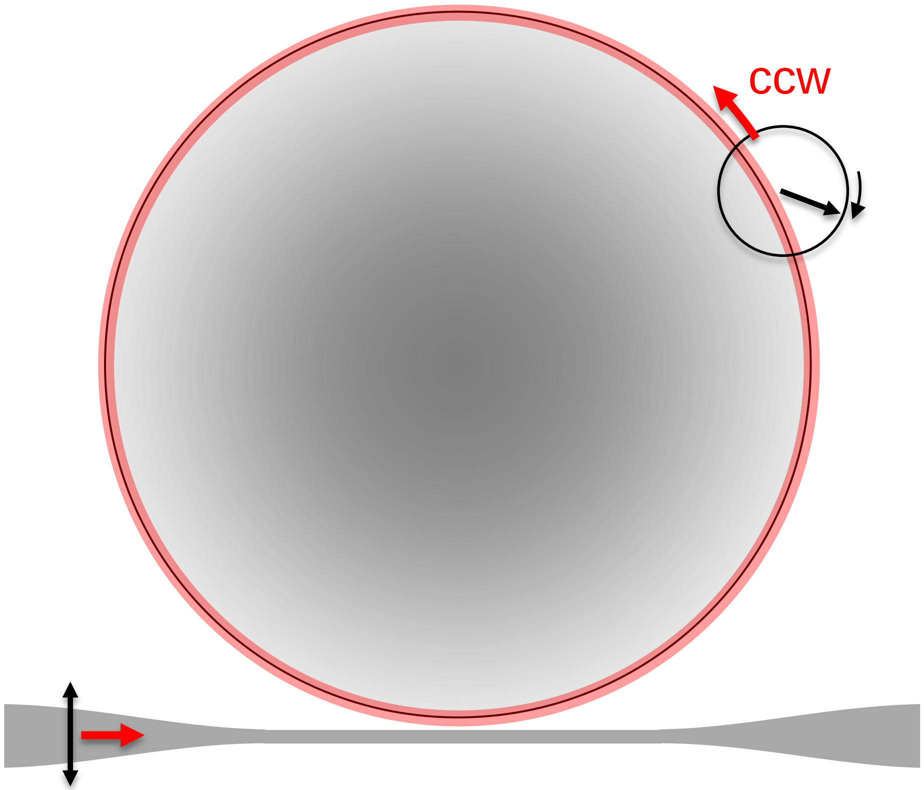
Overview



- Light-matter coupling in whispering-gallery-mode resonators
- The role of non-transversal polarization
- Switching light with a single atom
- Nonlinear π phase shift for single fiber-guided photons

TM polarization in the resonator

- Effect of longitudinal polarization:



➔ Strong longitudinal field component:

$$E_{\text{long}} = i\underbrace{\sqrt{1-n^{-2}}}_{=0.7\text{ (for glass)}}E_{\text{trans}}$$

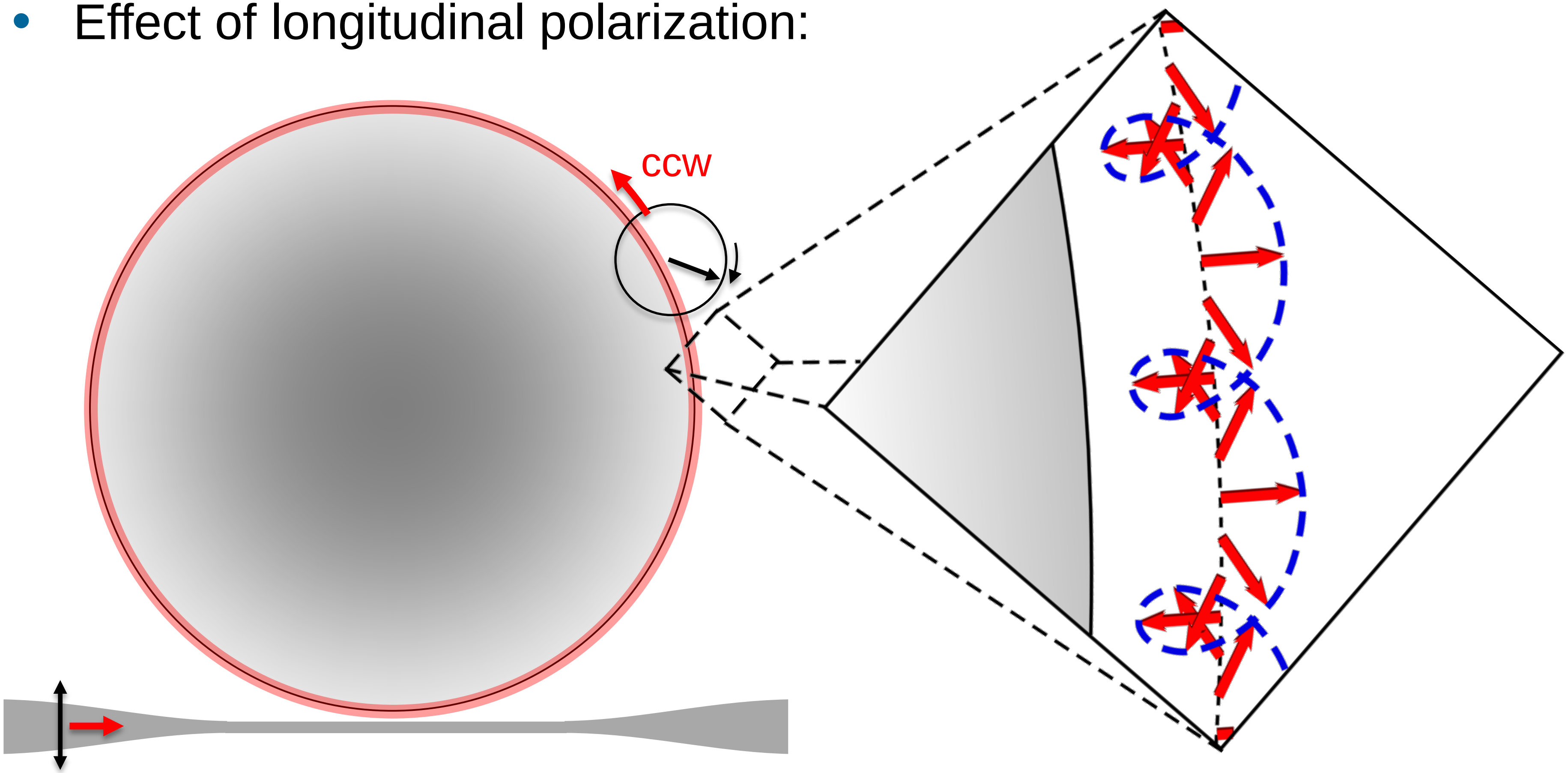
- 90° out of phase

➔ **almost pefectly circularly polarized (overlap ~ 97%)**

PRL 110, 213604 (2013)

TM polarization in the resonator

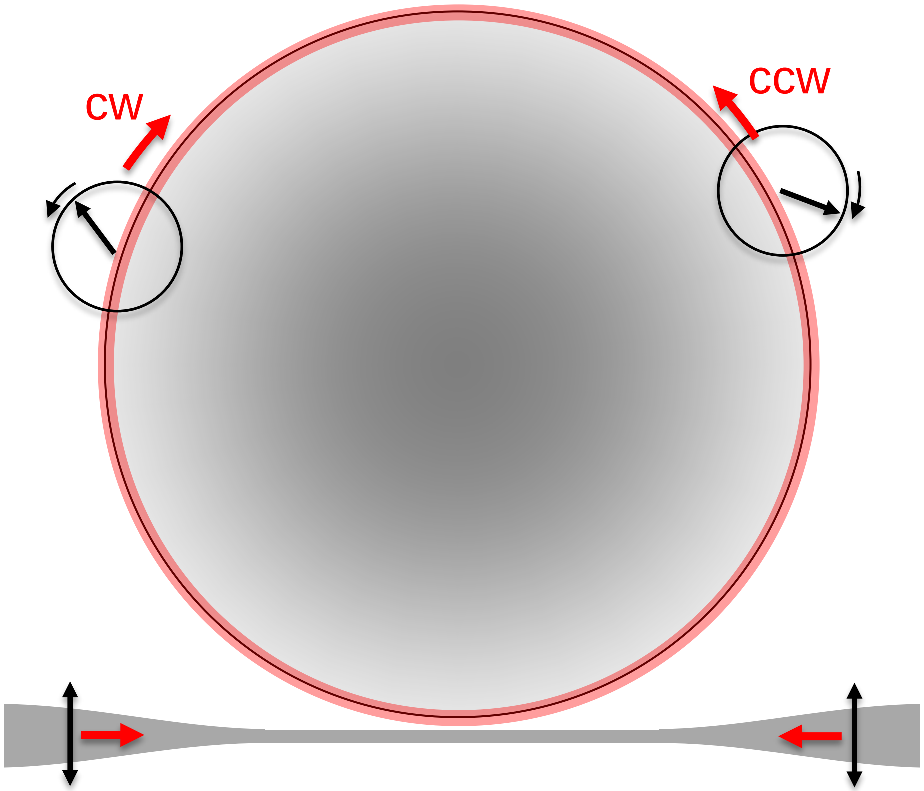
- Effect of longitudinal polarization:



PRL 110, 213604 (2013)

TM polarization in the resonator

- Effect of longitudinal polarization:

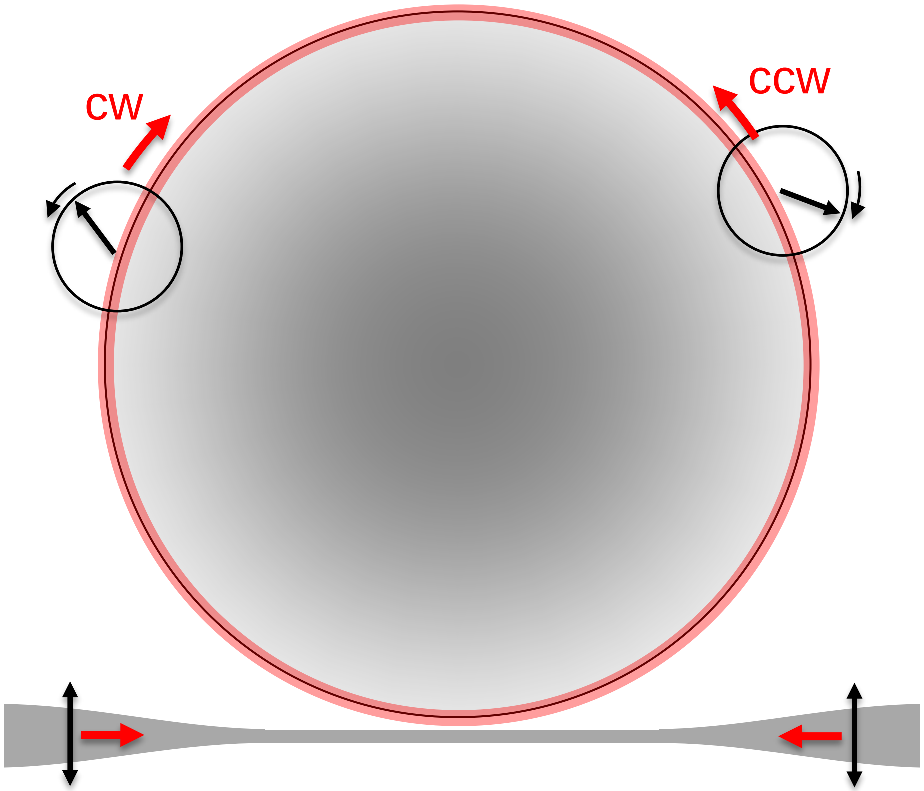


- Counterporpagating modes nearly orthogonally polarized
  - WGM resonator ≠ ring resonator
  - No destructive interference
  - No uncoupled standing wave

PRL 110, 213604 (2013)

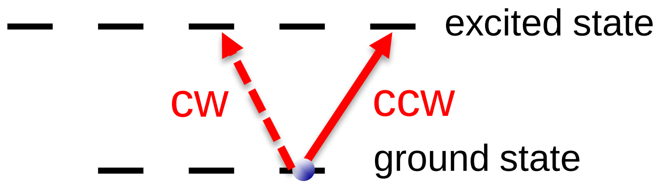
TM polarization in the resonator

- Effect of longitudinal polarization:



- Counterporpagating modes nearly orthogonally polarized
  - WGM resonator ≠ ring resonator
  - No destructive interference
  - No uncoupled standing wave

- Atom-resonator coupling:



Upon detection, atom is pumped into extremal m_F state
→ effective two-level system

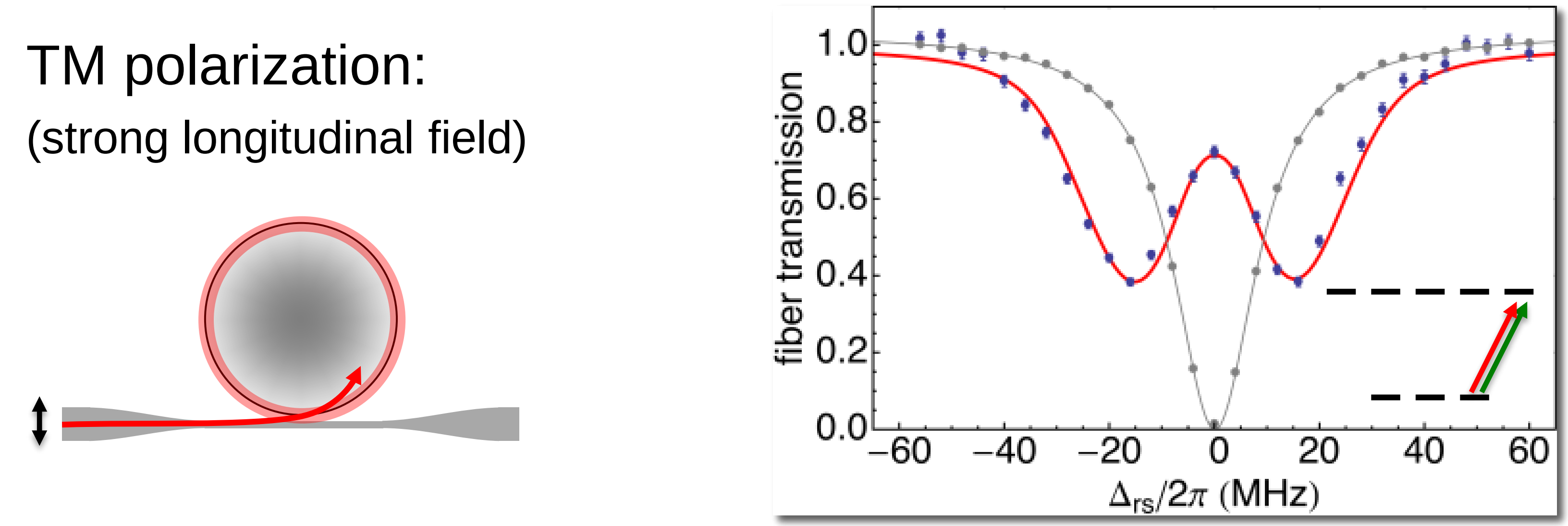
➡ Ideal CQED system: 2-level atom + single resonator mode

PRL 110, 213604 (2013)

Experimental verification

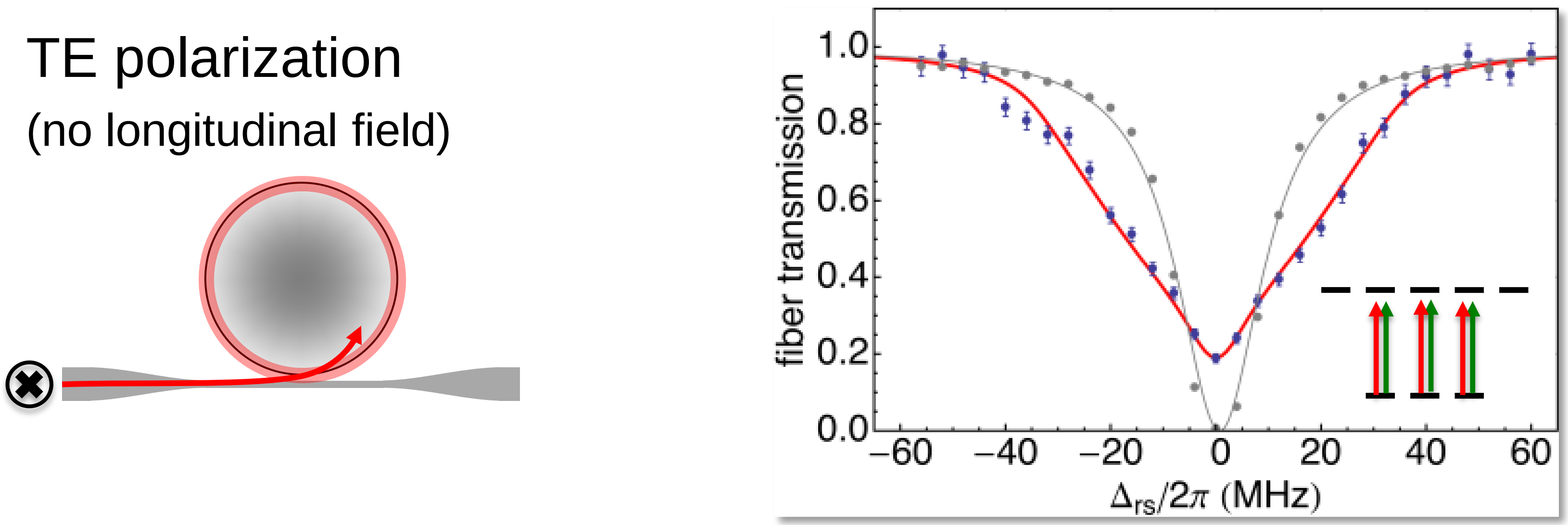
TM polarization:

(strong longitudinal field)



TE polarization:

(no longitudinal field)

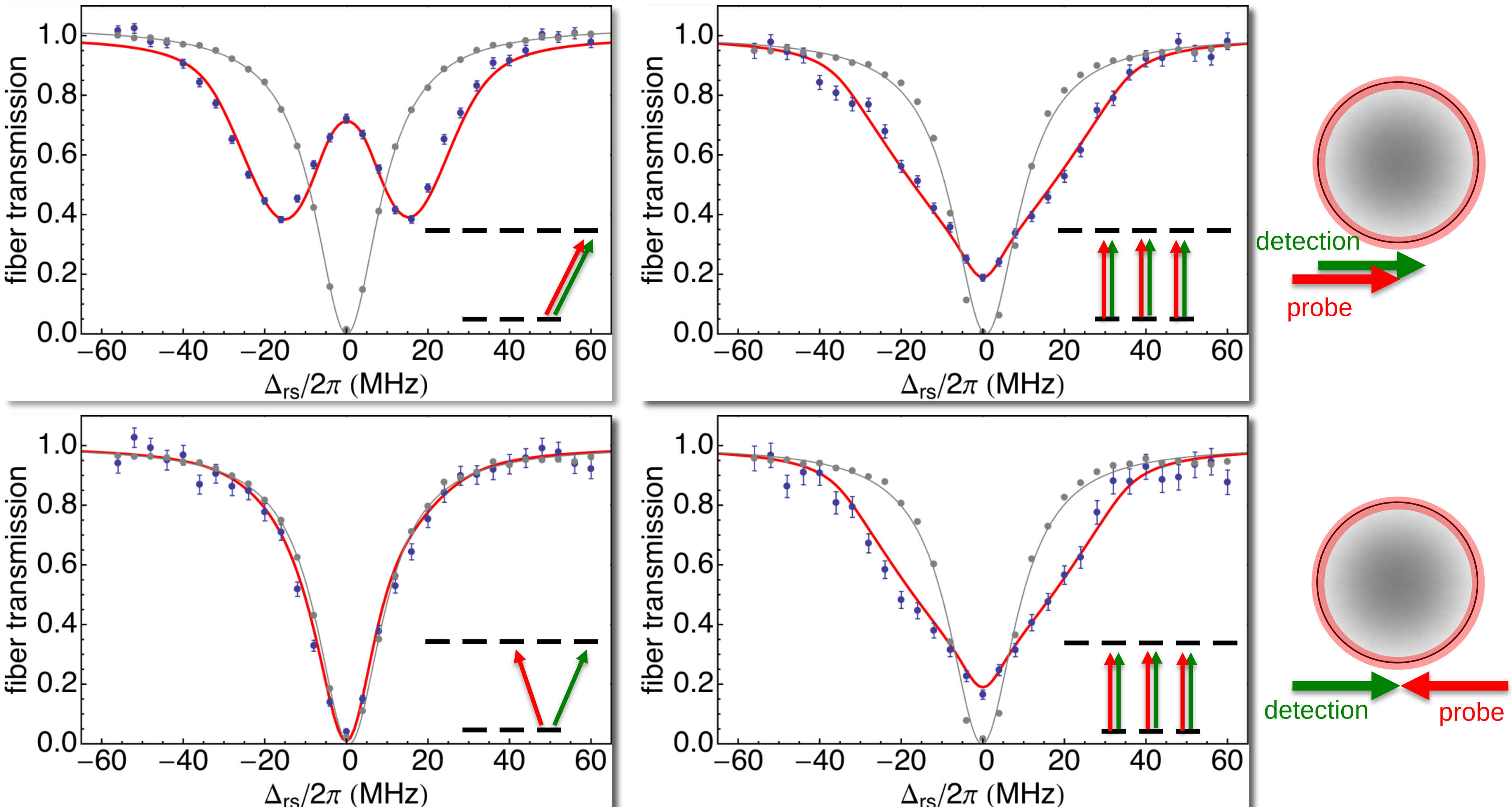


- probe polarization qualitatively changes atom-light interaction
- 3 orthogonal polarizations (TM: σ^+, σ^-, TE: π)

PRL 110, 213604 (2013)

Experimental verification

TM polarization | TE polarization

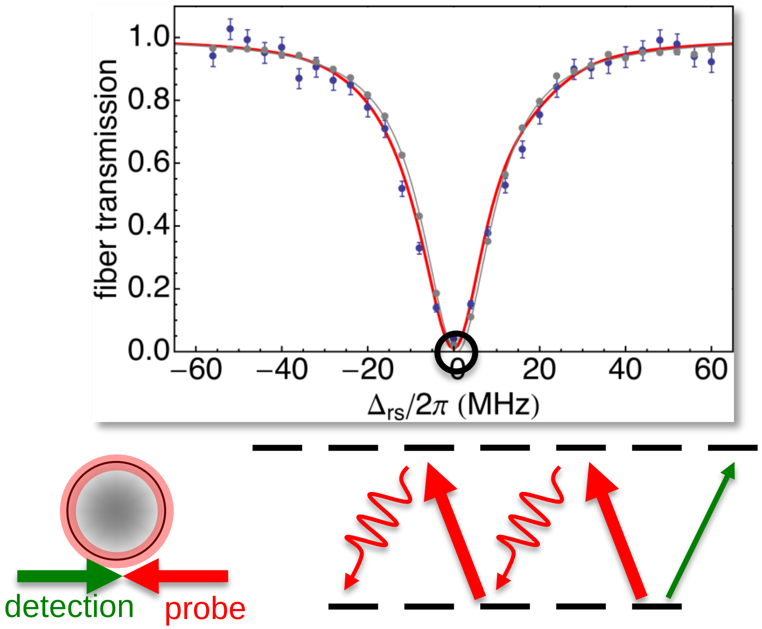


➡ Good agreement between theory and experiment

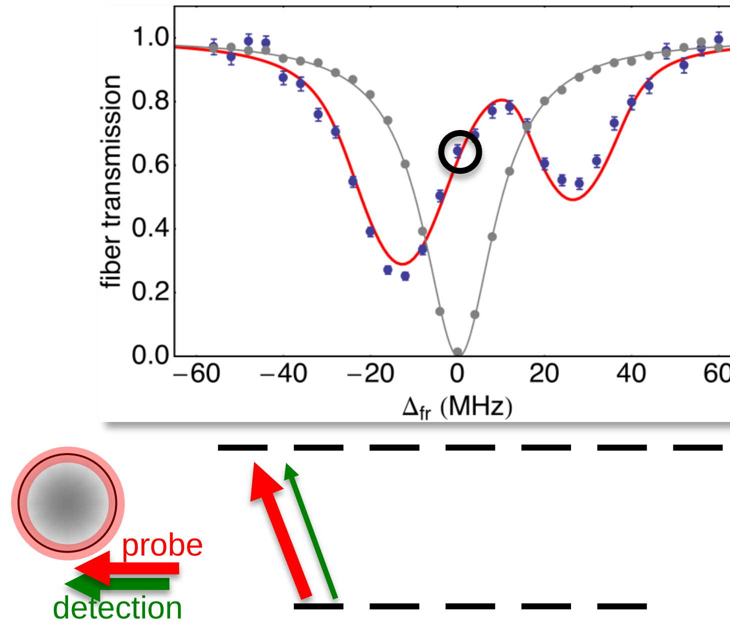
PRL **110**, 213604 (2013)

Time evolution

Spectrum at $t = 0$

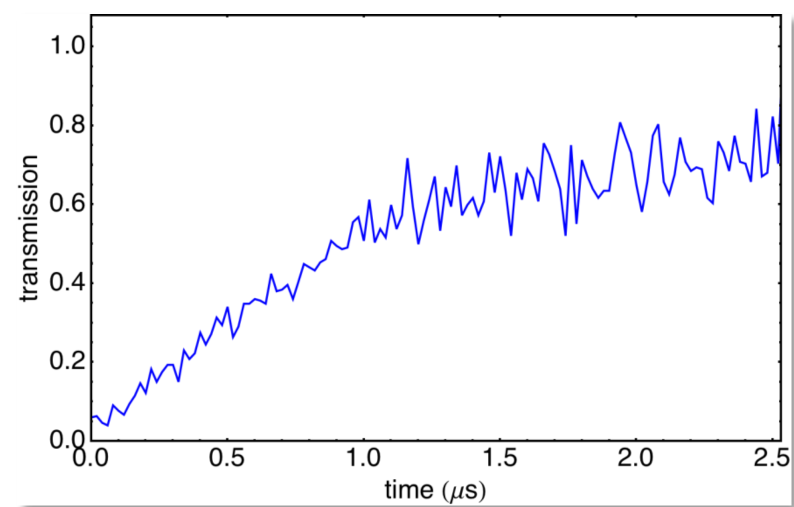


Spectrum at large *t*

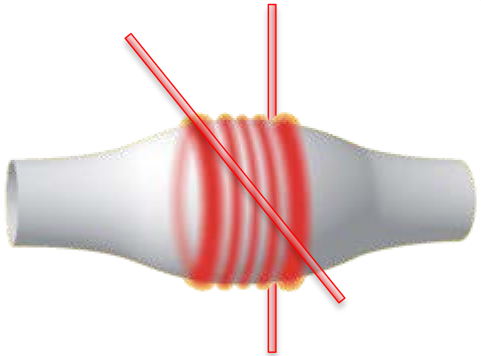


On resonance transmission (with atom)

- pumping with cavity field
- polarization correlated with propagation direction

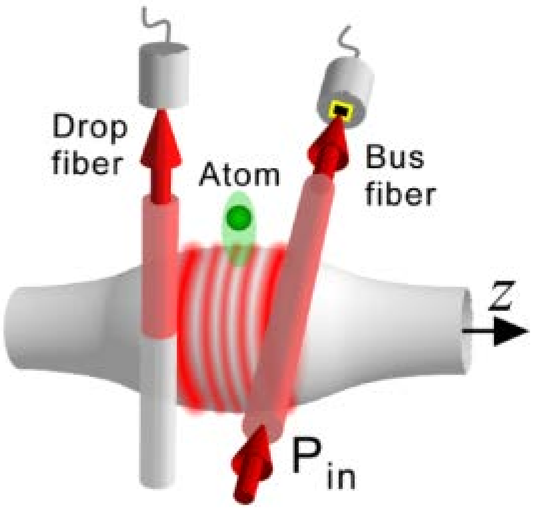


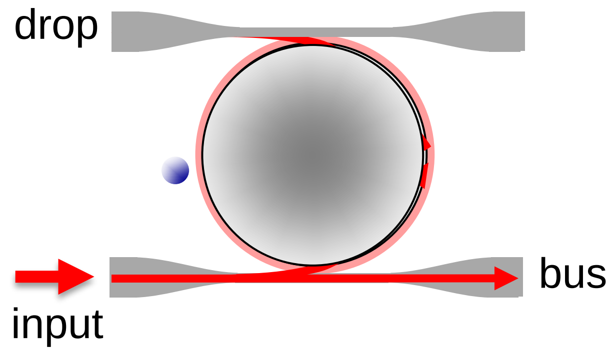
Overview



- Light-matter coupling in whispering-gallery-mode resonators
- The role of non-transversal polarization
- Switching light with a single atom
- Nonlinear π phase shift for single fiber-guided photons

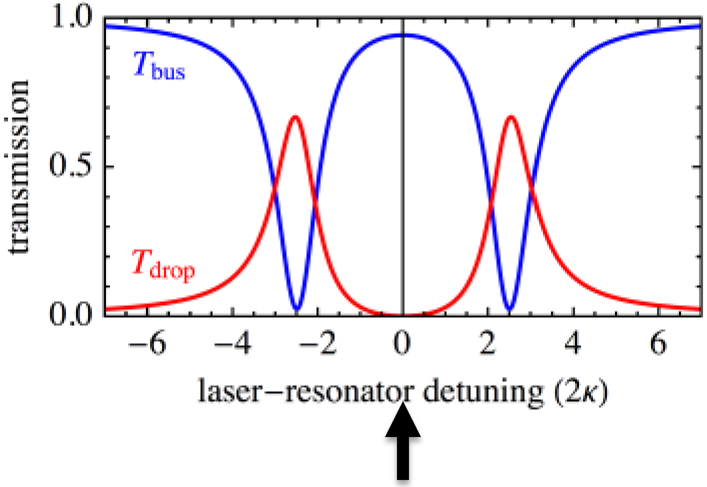
Switching light with a single atom





Add-drop configuration

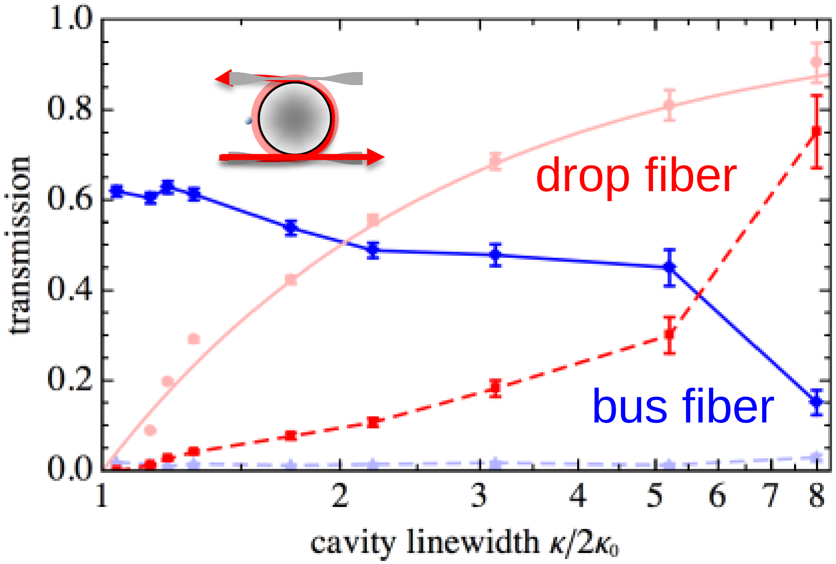
- Efficient transfer of light
- Resonator frequency controls light path
- Idea: Presence of atom switches light
- Uses effect of non-transversal polarization



Characterization of the switch

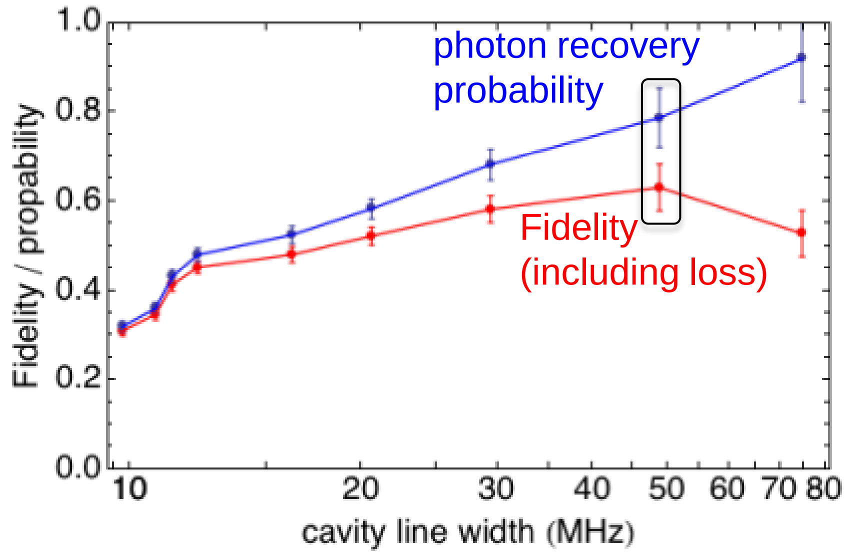
Efficiency vs. fiber distance from resonator

- 90% efficiency without atom
- Stable atom-light coupling



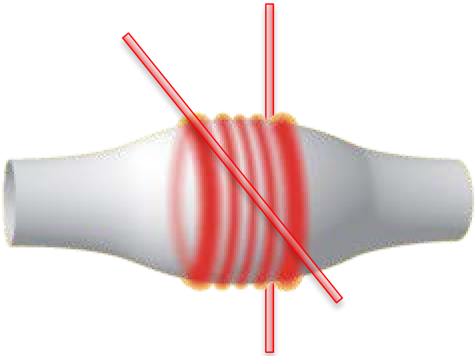
Optimal working point

- High raw fidelity
- 80% probability to recover incoming photons
- Fast cavity regime κ > g^2/κ > γ
- Prospects: Fidelity > 90 % within reach



PRL 111, 193601(2013)

Overview

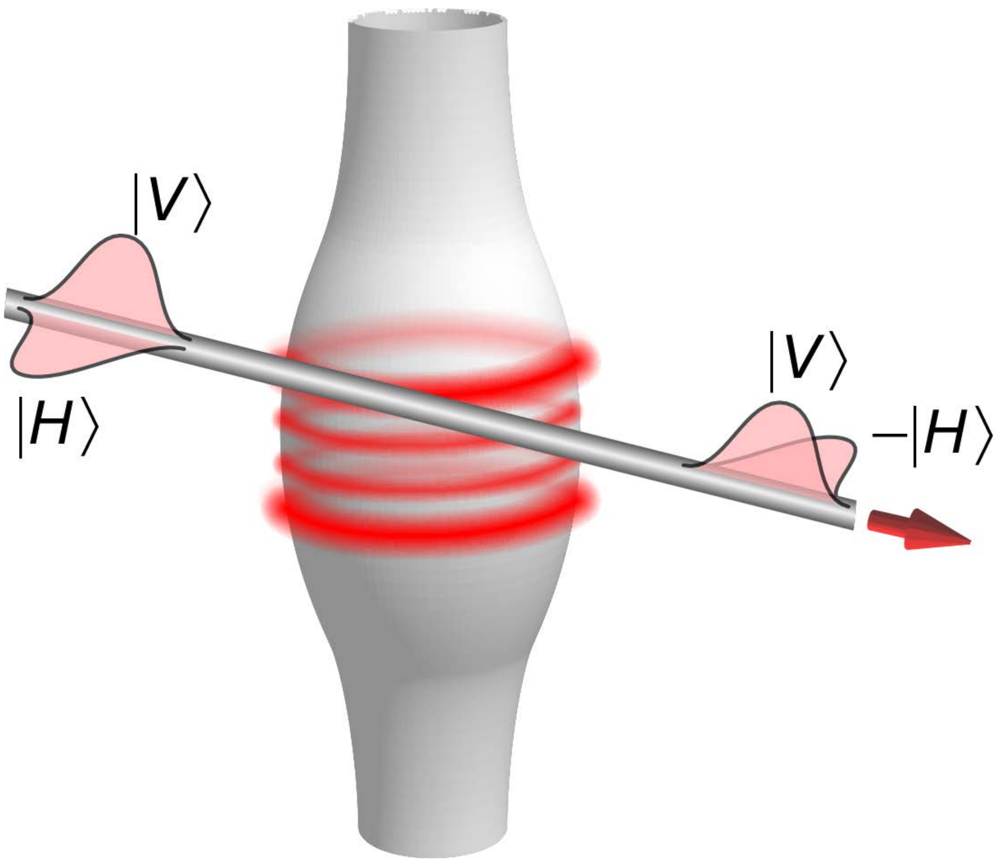


- Light-matter coupling in whispering-gallery-mode resonators
- The role of non-transversal polarization
- Switching light with a single atom
- Nonlinear π phase shift for single fiber-guided photons

Single atom polarization switch

Ingredients:

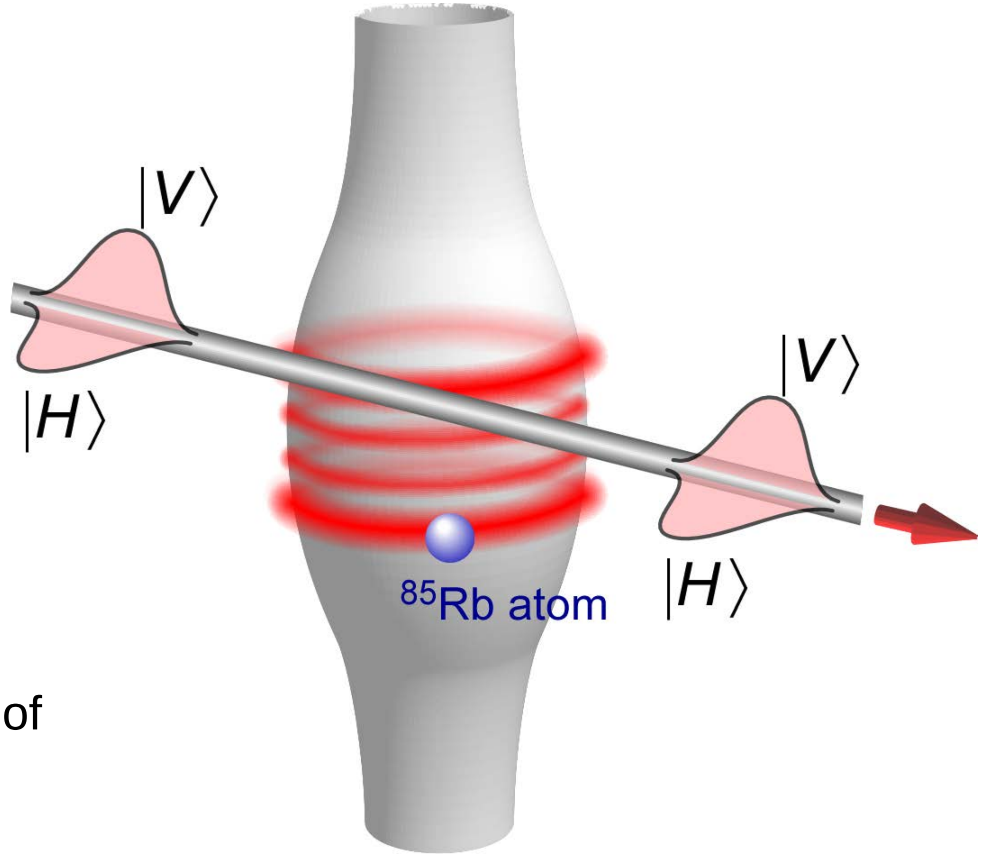
- **Birefringence**
  → only H-polarized light is resonant with bottle resonator
- **Overcoupled regime**
  → H-component is in- and out-coupled and acquires π phase



Single atom polarization switch

Ingredients:

- **Birefringence**
  → only H-polarized light is resonant with bottle resonator
- **Overcoupled regime**
  → H-component is in- and out-coupled and acquires π phase
- **Strong coupling**
  → single atom blocks incoupling of H-component



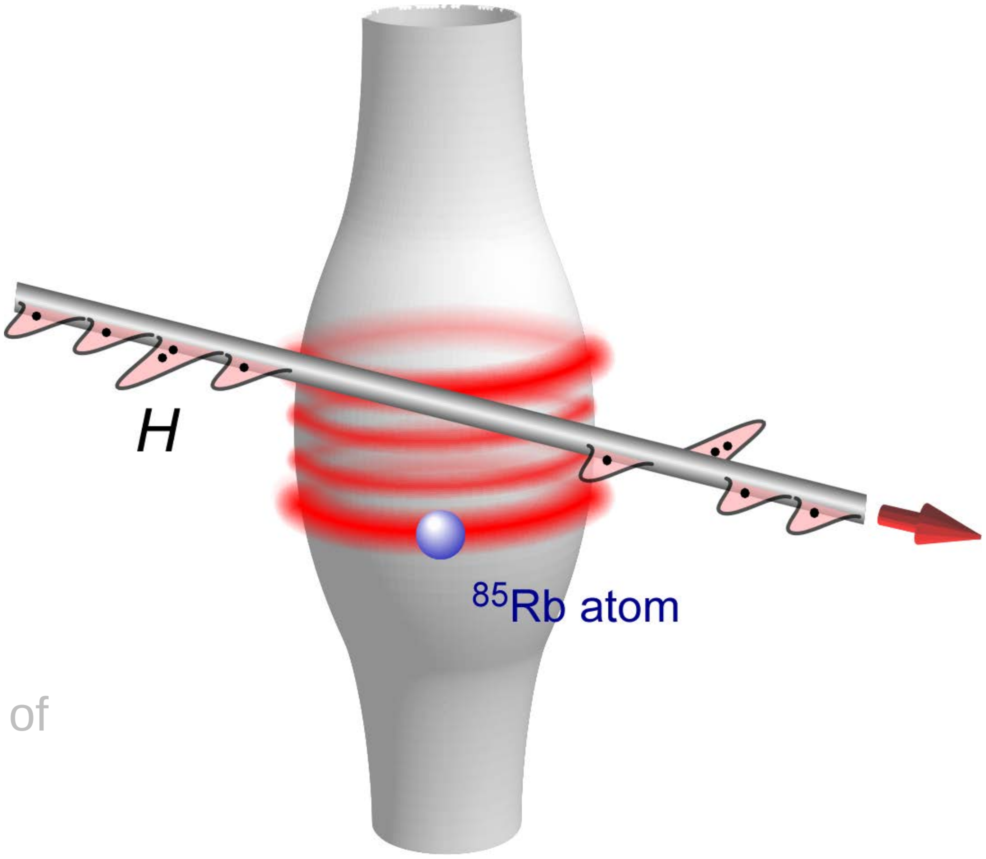
$$|H\rangle + |V\rangle \rightarrow \begin{cases} -|H\rangle + |V\rangle, & \text{without atom} \\ |H\rangle + |V\rangle, & \text{with atom} \end{cases}$$

related work by M. Lukin and G. Rempe

Single photon nonlinear phase shift

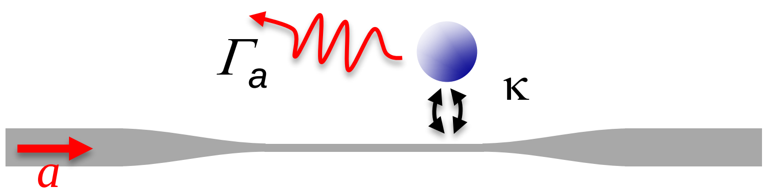
Ingredients:

- **Birefringence**
  → only H-polarized light is resonant with bottle resonator
- **Overcoupled regime**
  → H-component is in- and out-coupled and acquires π phase
- **Strong coupling**
  → single atom blocks incoupling of H-component
- **Nonlinearity of J.-C.-Hamiltonian**
  → photon number-dependent intra-cavity loss due to saturation of atom

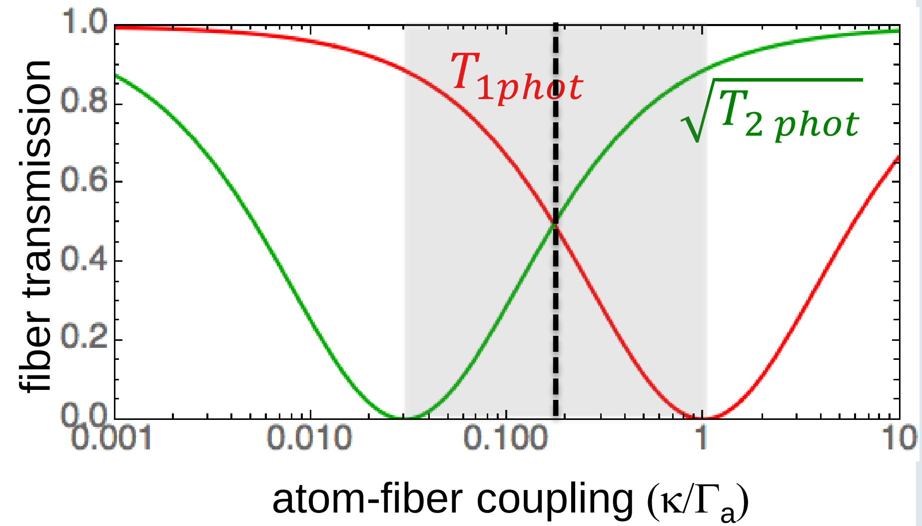


Single photon nonlinear phase shift

Photon number dependent phase shift



- 2 photons arrive simultaneously:
  → lower absorption per photon
  → photon-number dependent phase shift

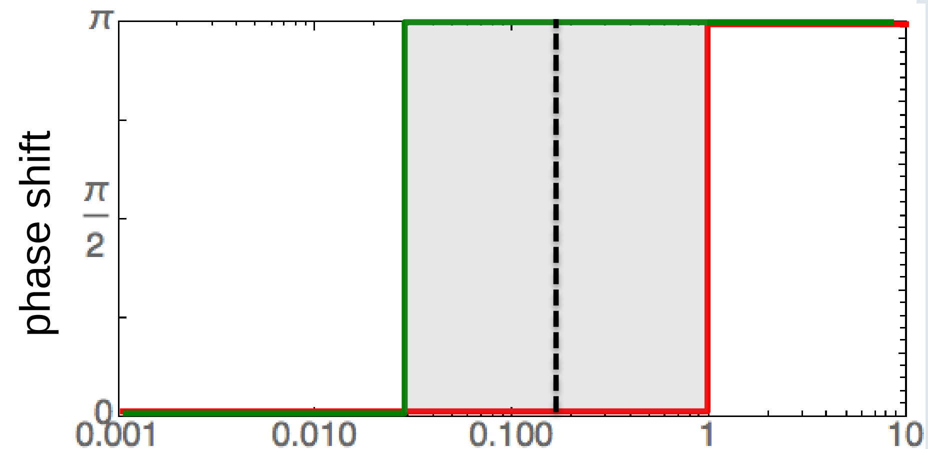


1 photon:

$$\hat{a}_H^\dagger |0\rangle \rightarrow \hat{a}_H^\dagger |0\rangle$$

2 photons:

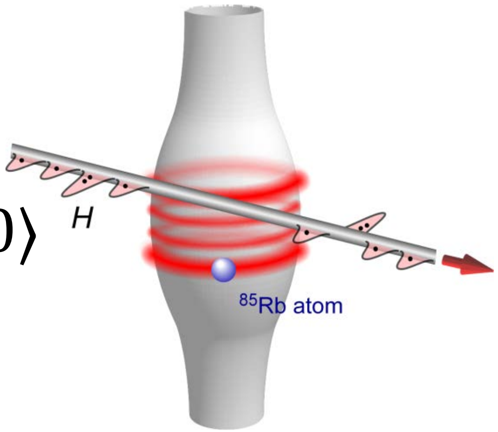
$$\hat{a}_H^\dagger \hat{a}_H^\dagger |0\rangle \rightarrow -\hat{a}_H^\dagger \hat{a}_H^\dagger |0\rangle$$



⇨ Effective photon – photon interaction („collisional“ phase shift)

Single photon nonlinear phase shift

- **Chose input polarization along H+V-direction:**



$$|\psi_{\text{initial}}\rangle = \frac{1}{2\sqrt{2}}(a_H^+ a_H^+ + 2a_H^+ a_V^+ + a_V^+ a_V^+)|0\rangle$$

$$|\psi_{\text{final}}\rangle = \frac{1}{2\sqrt{2}}(-a_H^+ a_H^+ + 2a_H^+ a_V^+ + a_V^+ a_V^+)|0\rangle$$

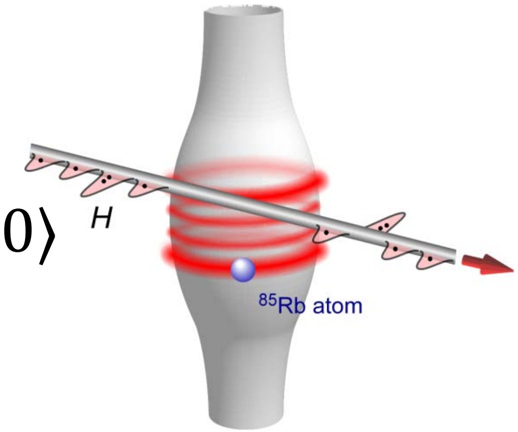
$$= \frac{1}{2\sqrt{2}}[a_V^+(a_H^+ + a_V^+) - a_H^+(a_H^+ - a_V^+)]|0\rangle$$

- **Final state $|\psi\rangle_{\text{final}}$ is maximally entangled.**

Single photon nonlinear phase shift

- **Chose input polarization along H+V-direction:**

$$|\psi_{\text{initial}}\rangle = \frac{1}{2\sqrt{2}}(a_H^+ a_H^+ + 2a_H^+ a_V^+ + a_V^+ a_V^+)|0\rangle$$



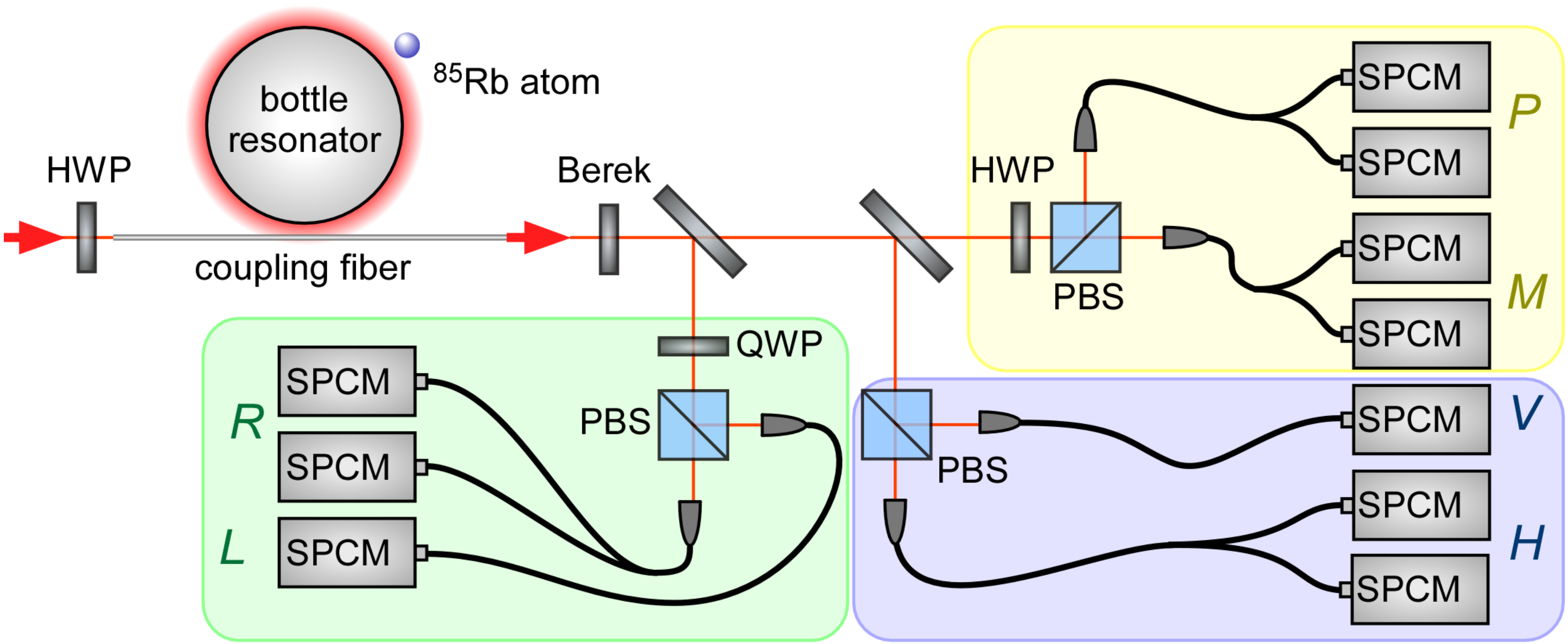
$$|\psi_{\text{final}}\rangle = \frac{1}{2\sqrt{2}}(-a_H^+ a_H^+ + 2a_H^+ a_V^+ + a_V^+ a_V^+)|0\rangle$$

$$= \frac{1}{2\sqrt{2}}[a_V^+(a_H^+ + a_V^+) - a_H^+(a_H^+ - a_V^+)]|0\rangle$$

- **Final state $|\psi\rangle_{\text{final}}$ is maximally entangled.**

State reconstruction

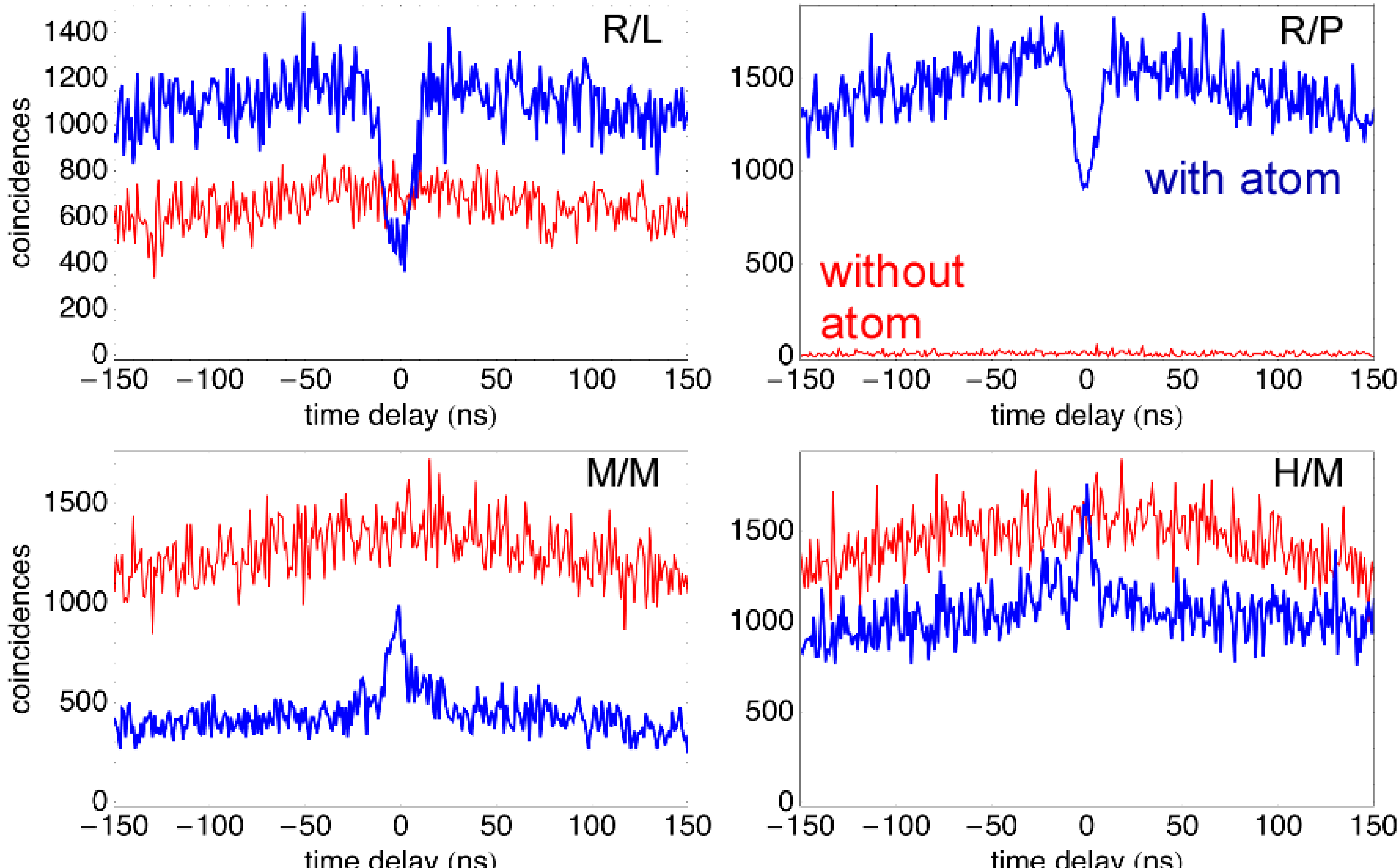
- **Record coincidences for all possible combinations of three polarization bases (H, V, +45°, -45°, R, L).**



Nat. Photon. 8, 965 (2014)

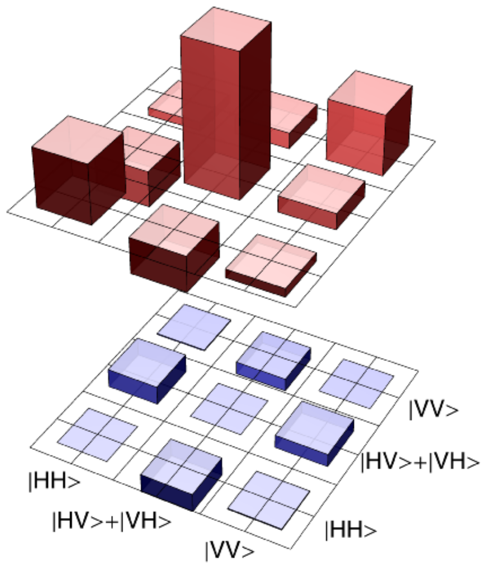
State reconstruction

- **Record coincidences for all possible combinations of three polarization bases (H, V, +45°, -45°, R, L).**

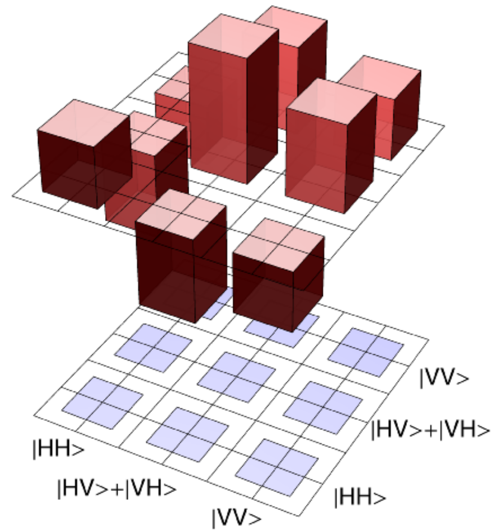


Experimental results

two photon density matrix:



measured

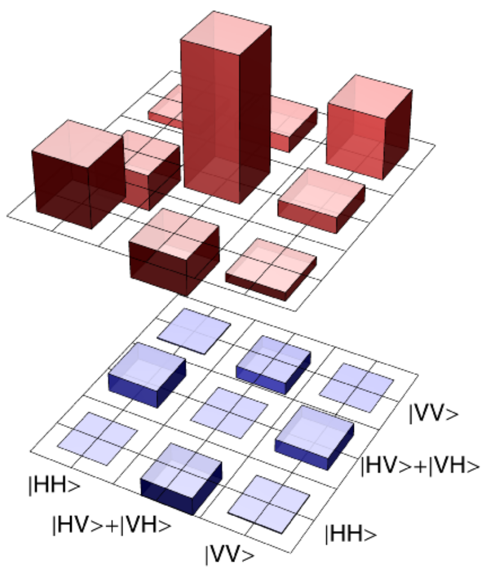


(simple) theory

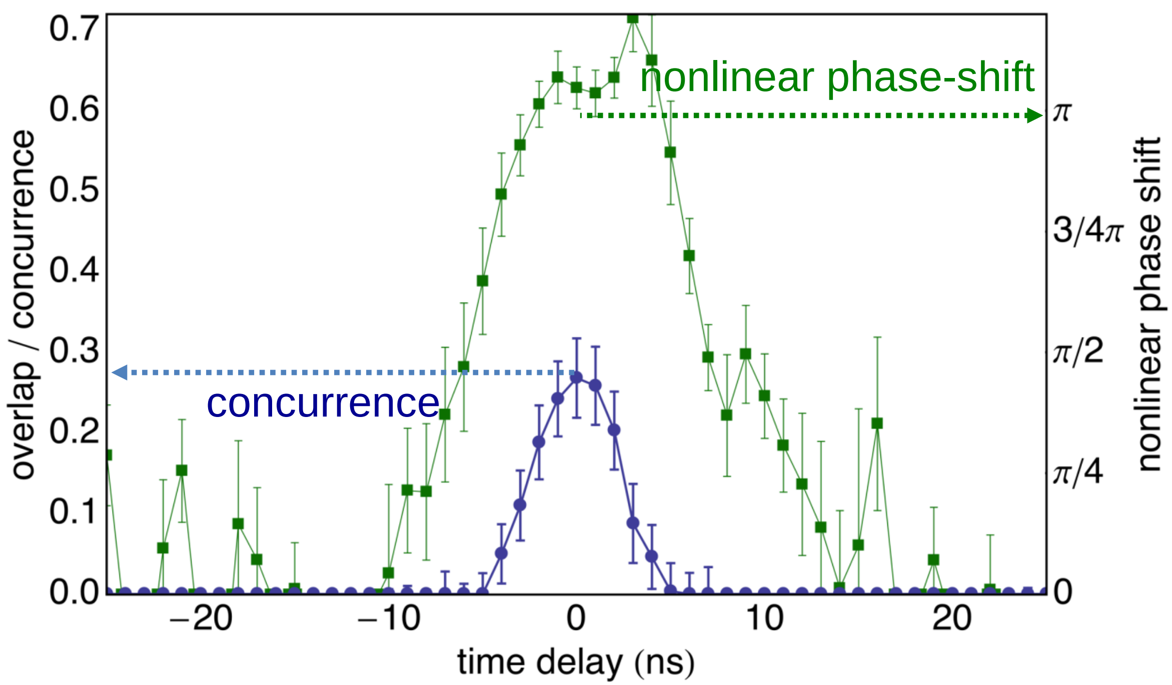
Nat. Photon. 8, 965 (2014)

Experimental results

two photon density matrix:



measured



- nonlinear phase shift of π
  → Entanglement of initially independent photons (C=0.28)
- maximally strong photon-photon interaction

Nat. Photon. 8, 965 (2014)

Summary

- Longitudinal polarization component fundamentally alters light–matter interaction.
- Effect makes WGM resonators ideally suited for CQED experiments.
- Strong coupling between single atoms and bottle microresonator demonstrated and understood.
- Fiber-optical switch operated by a single atom.
- Nonlinear π phase shift leads to entanglement of initially independent incident photons.

Thanks…

Students: Bernhard Albrecht, Benjamin Fränkel, Rudolf Mitsch, David Papencordt, Jan Petersen, Daniel Reitz, Michael Scheucher, Stefan Walser, Daniel Weiss, Elisa Will

Group Technician: Thomas Hoinkes

Postdocs & Senior Scientist: Christoph Clausen, Pham Le Kien, Sarah Skoff, Clément Sayrin, Philipp Schneeweiß, Jürgen Volz

Funding

FWF : SFB FoQuS

NEXT lite

CoQuS

: MARIE CURIE ACTIONS

siqs

VCQ
Vienna Center for Quantum Science and Technology

Studienstiftung des deutschen Volkes

Thank you for your attention!