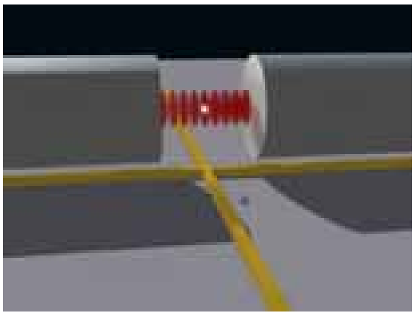
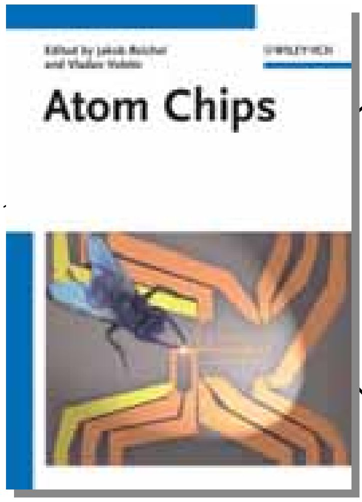


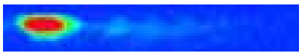
Creation and tomography of entangled states with up to 40 atoms in a cavity

Jakob Reichel
Laboratoire Kastler Brossel
E.N.S. / CNRS / Université Pierre et Marie Curie
Paris

Atom Chips



Complex manipulation



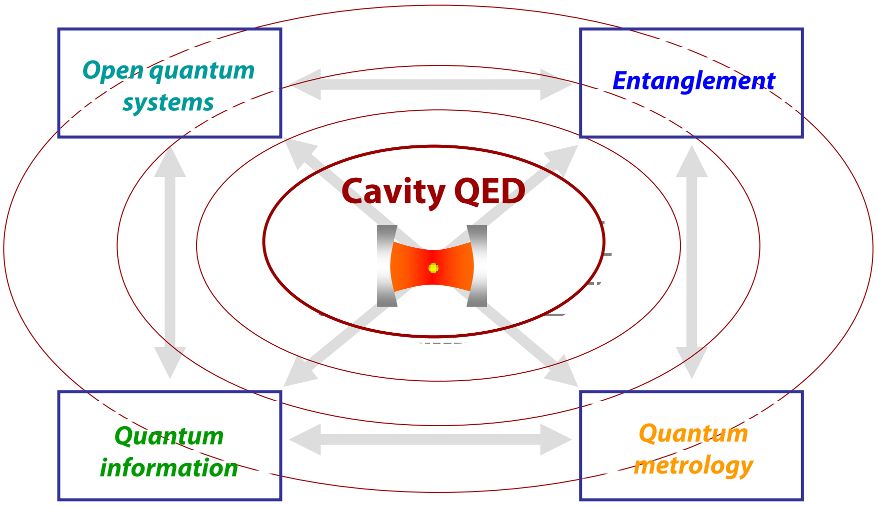
Compact setup, fast BEC

ColdQuanta.com

Interaction with surface

Long coherence time

C. Deutsch et al., PRL **105**, 020401 (2010)



Cavity QED

Open quantum systems

Entanglement

Quantum information

Quantum metrology

2012 Nobel prize

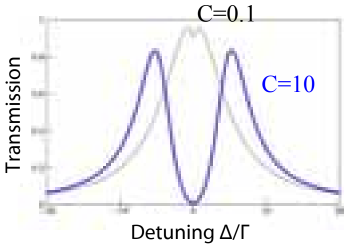
Purcell effect, Normal mode splitting, and Cooperativity

Purcell effect

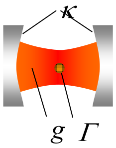
Probability for emission into resonant cavity mode (rather than into the continuum of free-space modes):

$$\frac{C}{C+1}$$

Normal mode splitting



Almost everything scales with



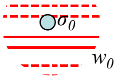
$$C = \frac{g^2}{2\kappa\gamma}$$

Cooperativity parameter -

the CQED generalization of optical density.

For a single small emitter:

$$C = \frac{\sigma_0}{\pi w_0^2}\mathcal{F}$$



Good reading: Tanji-Suzuki et al., arXiv:1104.3594 (Vuletic group)

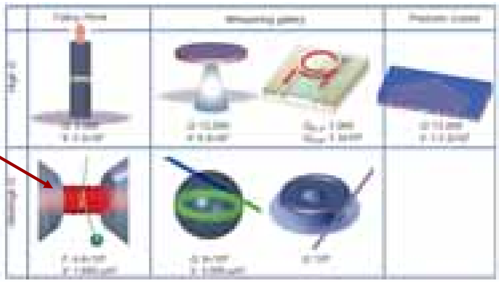
High-finesse optical cavities: An enabling tool

...especially powerful when miniaturized!

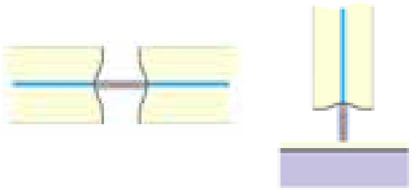
- *tunable*
- *highest finesse*
- *open*

but

D ~ several mm and
w_0~20µm



Wouldn't it be nice...



All advantages of macroscopic FP, plus

- *Sub-mm size*
- *Small waist => strong coupling*
- *Automatically fiber-coupled*

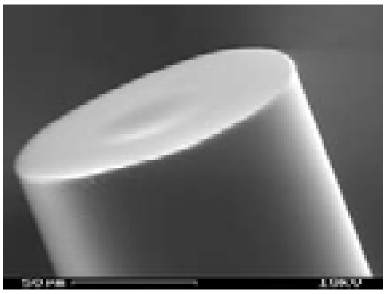
Outline

- **Stable Fiber Fabry-Pérot cavities (FFPs)**
- Atomic CQED: Collective interaction with BEC, qubit detection, W state generation and tomography
- Solid-state CQED: Tunable strong coupling with a semiconductor quantum well

Fiber cavity with CO_2 laser-shaped mirrors

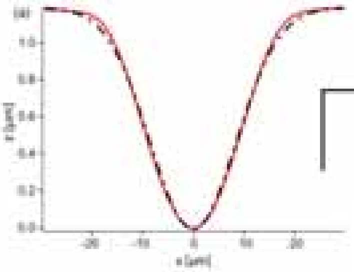
CO2 laser-machined fiber tip:

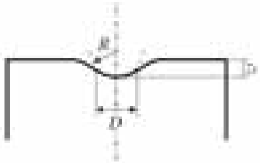
- Single, ~ms pulse of focussed CO2 light.
- Radius of curvature: ~ 1mm ... 10μm enables **very small waist** $w_0 < 1.3\mu m$

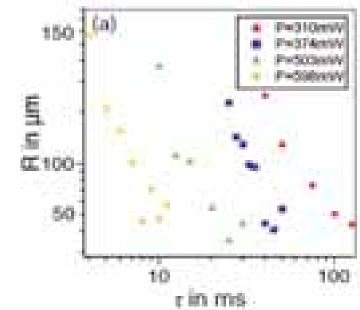


- Y. Colombe et al., Nature **450**, 272 (2007)
- D. Hunger et al., AIP Advances 2, 012119 (2012)
  Also see
- R. J. Barbour et al., J. App. Phys. **110**, 053107 (2011)

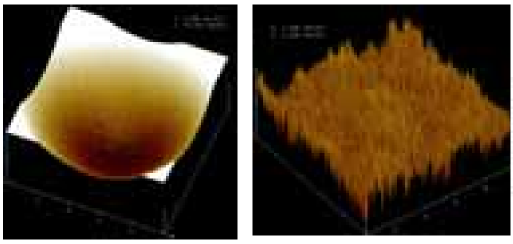
Measured profile and gaussian fit

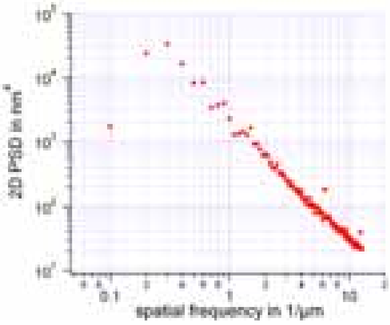






Surface quality and mirror coating



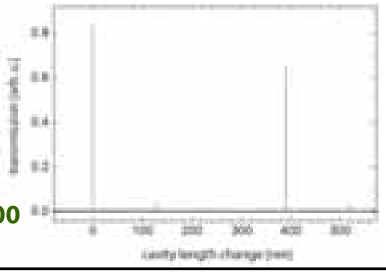


- Measure surface profile with AFM: rms roughness $\sigma_{sc} \sim 0.2$ nm
- Rule-of-thumb formula relating σ_{sc} to scatter loss:

$$S \approx \left(\frac{4\pi\sigma_{sc}}{\lambda}\right)^2 \sim 10 \text{ ppm}$$

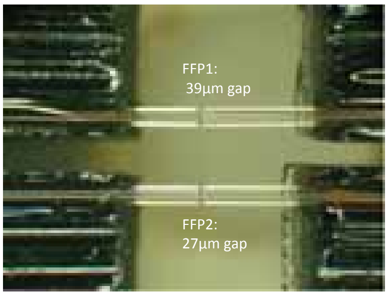
- *From cavity measurement:*

$$L = S + A \sim 15 \text{ ppm!}$$



Measured finesse $F > 140000$

CQED lab-on-a-chip



Mode waist: $w_0 = 3.4\ \mu\mathrm{m}$

Finesse: $F = 38000$

Coupling: $g_0 = 2\pi \times 240\,\mathrm{MHz}$

Cavity decay: $\kappa = 2\pi \times 53\ \mathrm{MHz}$

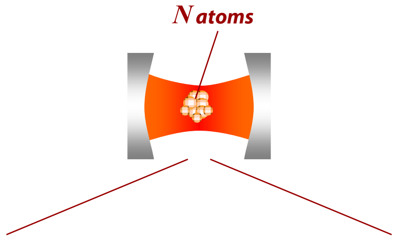
Atomic decay: $\gamma = 2\pi \times 3\ \mathrm{MHz}$

Cooperativity: $C = 181$

Outline

- Stable Fiber Fabry-Pérot cavities (FFPs)
- **Atomic CQED: Collective interaction with BEC, qubit detection, W state generation and tomography**
- Solid-state CQED: Tunable strong coupling with a semiconductor quantum well

CQED with ensembles of emitters

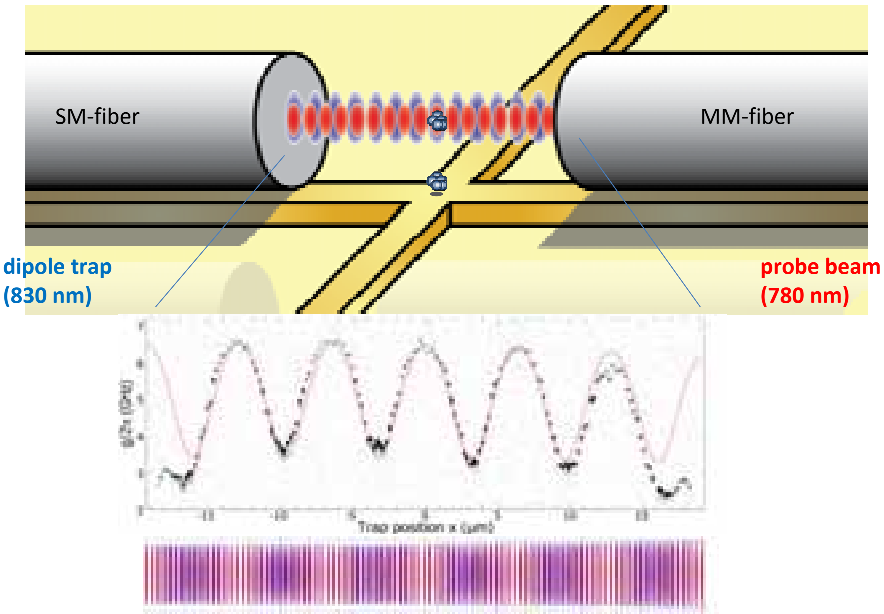


- *$\sqrt{N}$-increased dipole, "superatom"*
- *Strongest light-matter interaction (high OD + single mode!)*
- *Effective interaction between atoms ("quantum bus")*

- *Multiparticle entanglement*
- *Spin squeezing*
- *Quantum interfaces, quantum memories*
- *…*

Particularly interesting when emitters are identically coupled to the field.

Loading a BEC into the Cavity



Collective atom-light interaction

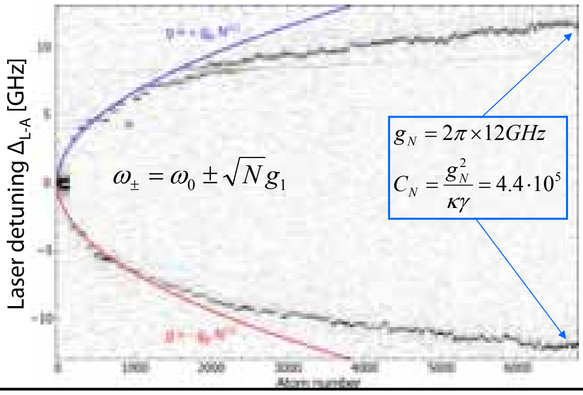
Interaction does not distinguish between particles.

The field couples $|\Psi_0\rangle = |g\dots g\rangle$ to the ***1st Dicke state*** ("W state")

$$|\Psi_1\rangle = \frac{1}{\sqrt{N}}\left(|e,g\dots g\rangle + |g,e,g\dots g\rangle + \dots + |g\dots g,e\rangle\right)$$

with matrix element $\langle 0| \otimes \langle \Psi_1|\hat{V}|\Psi_0\rangle \otimes |1\rangle = \sqrt{N} g_1$

⇒ ***Dipole matrix element scales*** $\boxed{\mu_c \propto \sqrt{N}\mu_1}$ ***"Superatom"***



$$\omega_{\pm} = \omega_0 \pm \sqrt{N} g_1$$

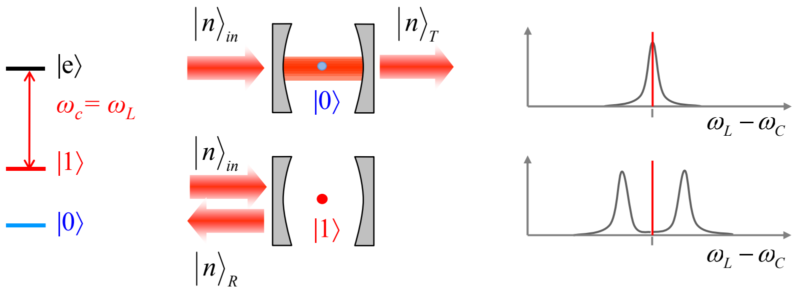
$$g_N = 2\pi \times 12GHz$$

$$C_N = \frac{g_N^2}{\kappa\gamma} = 4.4 \cdot 10^5$$

Y. Colombe et al.,
Nature **450**, 272 (2007)

Nondestructive detection of a single atomic excitation

Detection without spontaneous emission



Detection error in this scheme: $\varepsilon = \exp(-2n_{\mathrm{in}}) = 0.5 \exp(-2\, C\, m_{\mathrm{scatt}})$

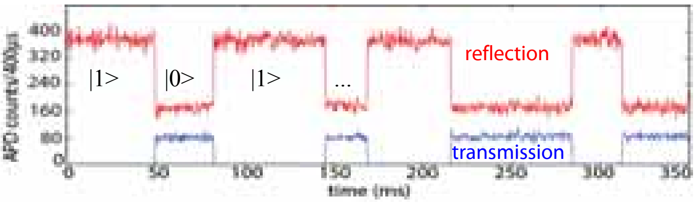
Free-space limit: $\varepsilon = 0.5 \exp(-2\, m_{\mathrm{scatt}})$

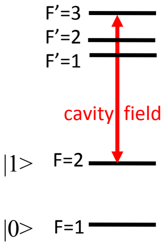
(Hope & Close, PRL 2004)

Signal enhanced by C → Detection without spontaneous emission

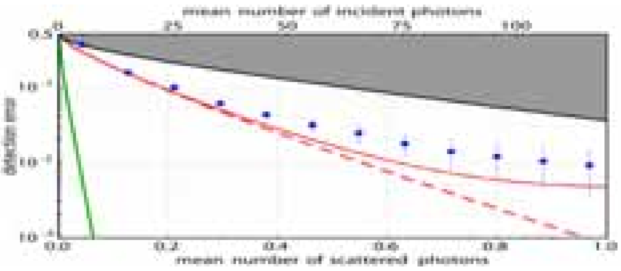
Volz, Gehr, Dubois, Estève & Reichel, Nature **475**, 210 (2011).

Qubit state detection





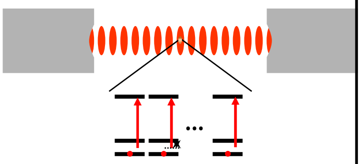
- ***Detection error*** **< 8·10-4** R. Gehr et al., PRL **104**, 203602 (2010)
  Also see J. Bochmann et al., PRL **104**, 203601 (2010)
  On par with best ion trap experiments.
- **... and without energy exchange** J. Volz et al., Nature **475**, 210, (2011).



> 99% detection efficiency with <1 spontaneous emission!

Mesoscopic entangled states : Creation and tomography

Multiparticle entanglement



- N atoms identically coupled to the probe field
- ⇒ ***Generation of entanglement***
- ⇒ ***Remain in symmetric subspace as long as no spontaneous emission***

Example:

- W-state: $|\Psi\rangle = \frac{1}{\sqrt{N}}(|1000...\rangle + |0100...\rangle + |0010...\rangle + ...)$
  - robust against particle loss
  - For 3 qubits, W and GHz represent the two fundamental forms of entanglement (Dür et al., PRA 2000)
- Previous realizations:
  - 14 Ions (Hume et al., PRA(2009), Monz et al., PRL(2011))
  - 6 photons (Wieczorek et al. PRL (2009))
  - 2 neutral atoms (Grangier et al. Nature Physics (2009))

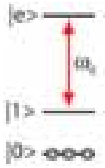
Fidelity drops rapidly with particle number !

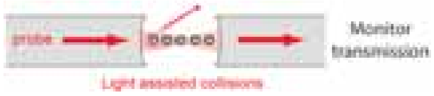
N-atom entangled state production and measurement

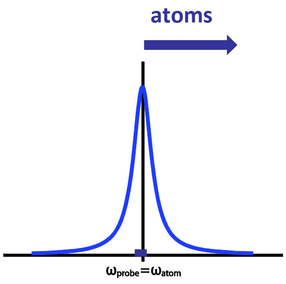
- ***Need to solve three problems:***
  1. ***Prepare mesoscopic ensemble (N atoms)***
  2. ***Create entanglement***
  3. ***Analyze the state (tomography)***

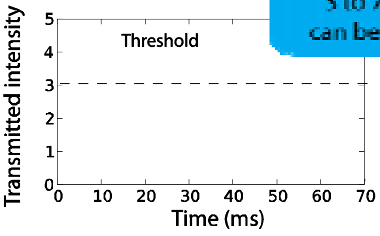
Preparing the mesoscopic ensemble from a BEC

Preparation of an atomic ensemble with a fixed atom number:

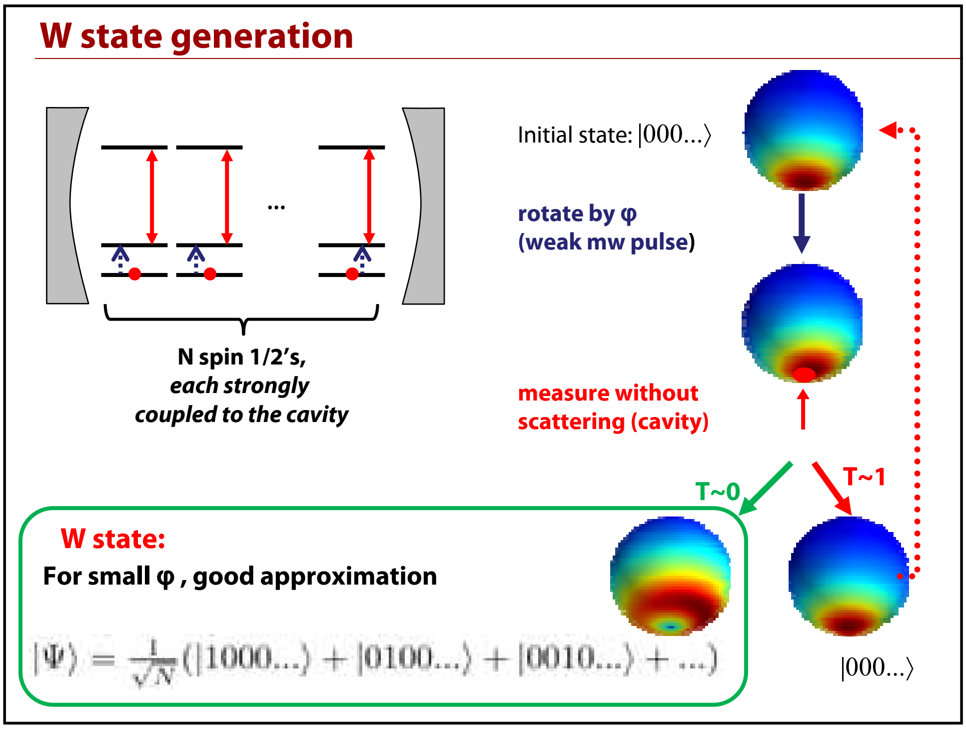








Small ensembles of 3 to 70 atoms can be prepared



W state generation

N spin 1/2's,
each strongly
coupled to the cavity

Initial state: $|000...\rangle$

rotate by φ
(weak mw pulse)

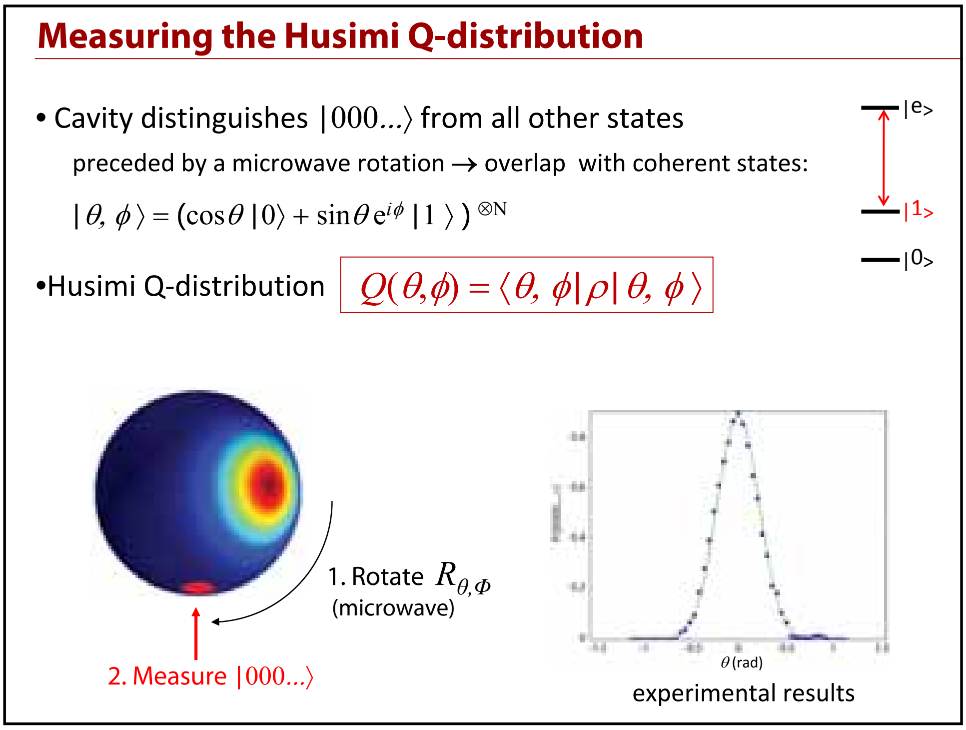
measure without
scattering (cavity)

W state:

For small φ , good approximation

$$|\Psi\rangle = \frac{1}{\sqrt{N}}(|1000...\rangle + |0100...\rangle + |0010...\rangle + ...)$$

$|000...\rangle$



Measuring the Husimi Q-distribution

- Cavity distinguishes $|000...\rangle$ from all other states

  preceded by a microwave rotation → overlap with coherent states:

  $|\,\theta,\,\phi\,\rangle = (\cos\theta\,|0\rangle + \sin\theta\, e^{i\phi}\,|1\,\rangle\,)^{\otimes N}$

- Husimi Q-distribution $\boxed{Q(\theta,\phi) = \langle\theta,\,\phi|\,\rho\,|\,\theta,\,\phi\,\rangle}$

1. Rotate $R_{\theta,\Phi}$
(microwave)

2. Measure $|000...\rangle$

experimental results

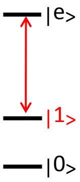
Measuring the Husimi Q-distribution

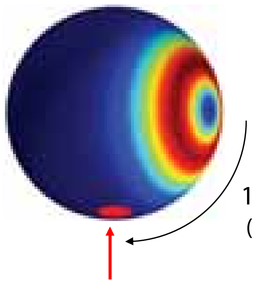
- Cavity distinguishes $|000...\rangle$ from all other states

  preceded by a microwave rotation → overlap with coherent states:

  $|\theta, \phi\rangle = (\cos\theta\,|0\rangle + \sin\theta\, e^{i\phi}\,|1\rangle)^{\otimes N}$

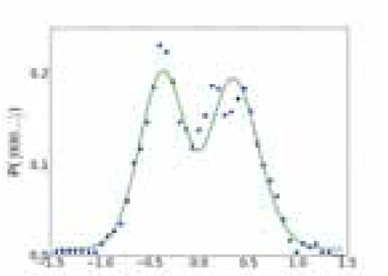
- Husimi Q-distribution $\boxed{Q(\theta,\phi) = \langle\theta, \phi|\rho|\theta, \phi\rangle}$





1. Rotate $R_{\theta,\Phi}$ (microwave)

2. Measure $|000...\rangle$



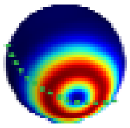
experimental results

Experimental results

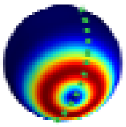
42 atoms

25 atoms

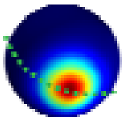
1st tomography axis:

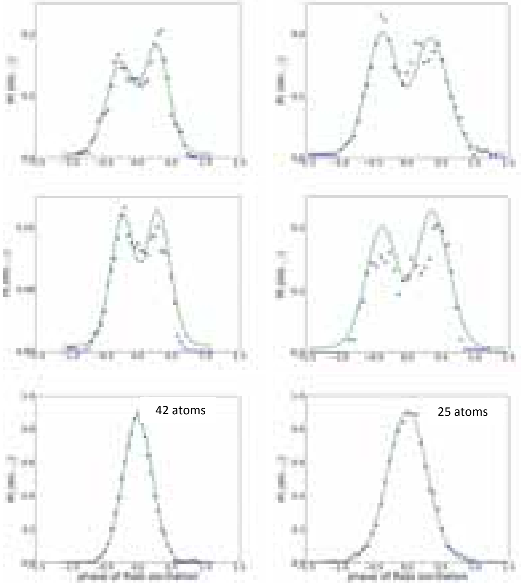


2nd tomography axis:



Atom number measurement: Coherent State





Outlook

- *Cavity-induced interaction + projective measurement: Powerful tools for quantum information*
- *Other entangled states*
  E.g., twin Fock states
- *Quantum Zeno dynamics:*
  Coherent evolution in a measurement-induced subspace
- *Spin squeezing in a "true" atomic clock:*
  TACC - Trapped-Atom Clock on a Chip
  (collaboration with SYRTE)

Outline

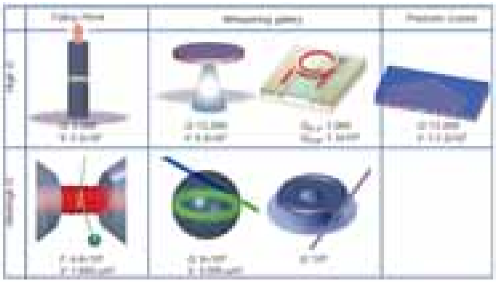
- Stable Fiber Fabry-Pérot cavities (FFPs)
- Atomic CQED: Collective interaction with BEC, qubit detection, W state generation and tomography
- **Solid-state CQED: Tunable strong coupling with a semiconductor quantum well**

Collaboration with
T. Volz, J. M. Sanchez, A. Reinhard, A. Imamoglu
Quantum Photonics Group, ETH Zurich

Solid-state CQED

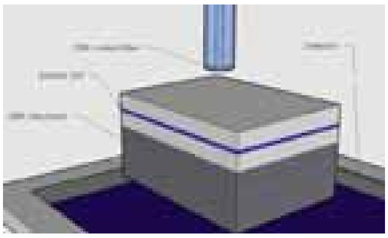
- **Active research area:**
  - Single-photon sources, energy-efficient light, quantum information, fundamental CQED
  - Semiconductor quantum dots, diamond color centers, ...
- Some **popular atomic wavelengths available** in semiconductor dots and color centers – but much larger linewidth
- Entanglement of dissimilar quantum systems?
- **Reproducibility issues, difficult fabrication**

FFP cavity for solid-state emitters



Established cavity types:
Complicated, multistep fabrication
Very limited tuning

Need to match emitter + cavity during fabrication

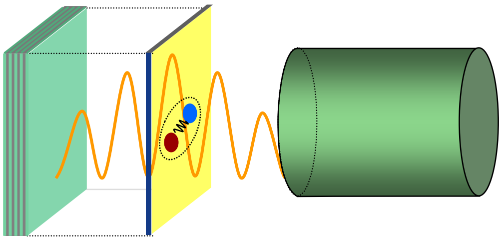


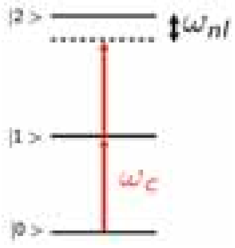
Fiber Fabry-Perot:

- ***Tunable***
- ***Fiber-coupled***
- ***High finesse***
- ***"Scanning cavity microscope"***

Microcavity Exciton-Polaritons in FFP cavity

Collaboration with T. Volz, J. M. Sanchez, A. Reinhard, A. Imamoglu
Quantum Photonics Group, ETH Zurich

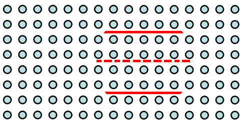




- Cavity can be tuned and scanned
  => Reduced fabrication effort, "scanning cavity microscope"
- Transverse confinement
  => increase polariton interactions
- *Blockade regime (interaction shift > cavity linewidth)?*

  A. Verger, C. Ciuti, I. Carusotto, PRB **73**, 193306 (2006).
  I. Carusotto, T. Volz, A. Imamoglu, EPL **90**, 37001 (2010)

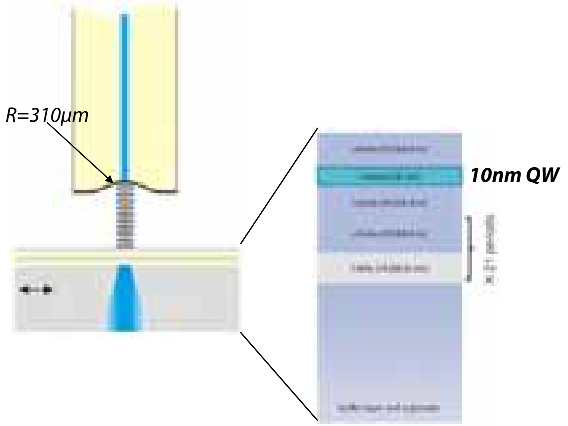
Collective interaction in a 2D system



- ***Photon illuminates millions of lattice sites***
  => creates collective excitation (Dicke state)
- Collective dipole scales $\mu_c \propto \sqrt{N}\mu_1$
- $g = \mu\sqrt{\frac{\omega}{2\hbar\varepsilon_M V_m}}$ with $V_m \propto w_0^2 L$ and $N \propto w_0^2$
- **=> g does not depend on w_0,** $\boxed{g \propto \frac{1}{\sqrt{L}}}$
- Cooperativity: ***$C=g^2/\kappa\gamma$ does not depend on w_0 and L!***

Cf. atoms: $C \propto \frac{1}{w_0^2}$ (for sample size < waist)

FFP + Quantum well




QW @ 900 nm

10 nm thickness
11% Indium content

Barrier

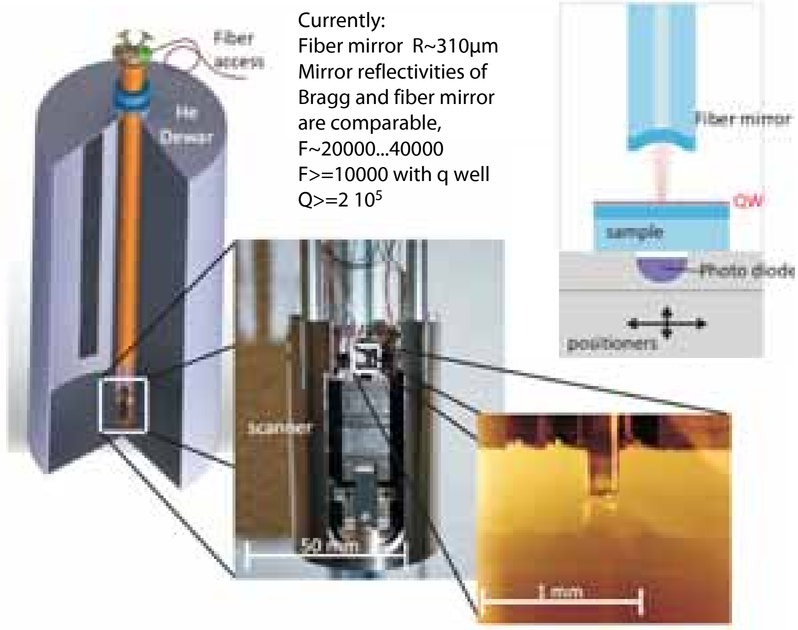
$\frac{\lambda}{2}$ GaAs thickness layers

Measured properties of
the exciton resonance @ 4K:
λ = 892 nm
linewidth ~ 1 meV (240 GHz)

Far from resonance ("empty cavity"):
Measured Q > 70000

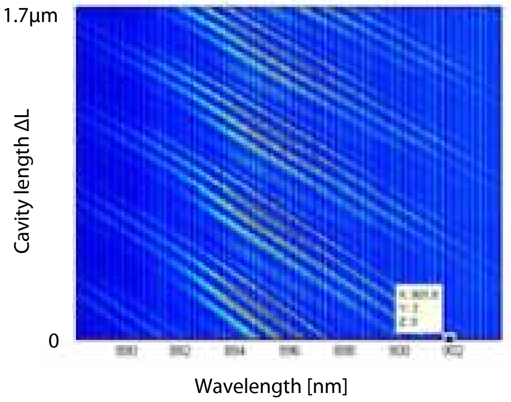
Cavity $\kappa \sim 20\ \mu eV$
QW $\gamma \sim 1\ meV$

Scanning Fabry-Perot microscope



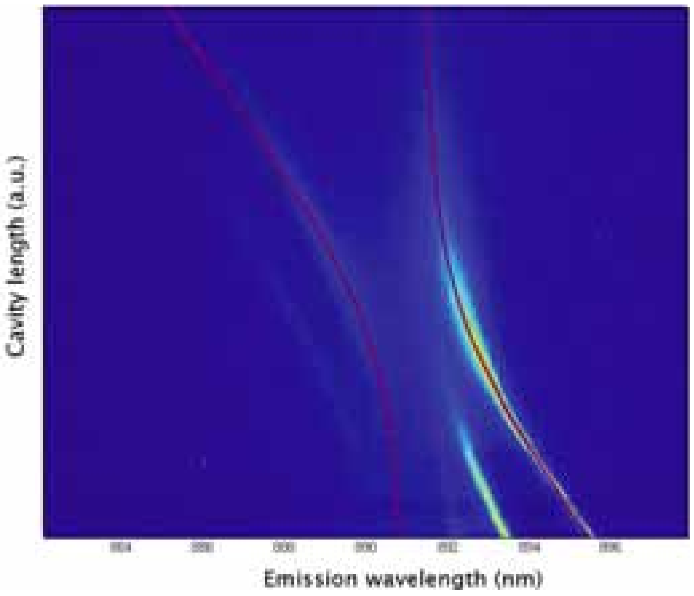
Currently:
Fiber mirror R~310µm
Mirror reflectivities of
Bragg and fiber mirror
are comparable,
F~20000...40000
F>=10000 with q well
Q>=2 10^5

Long cavity: Weak coupling, cavity modes



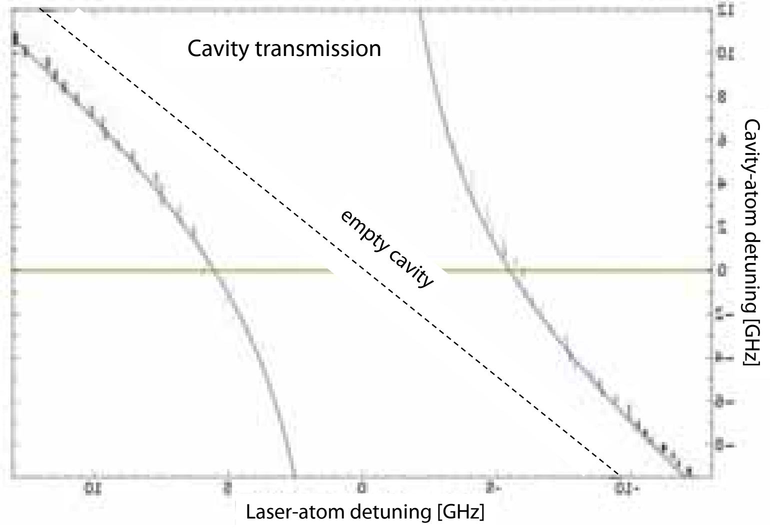
- Nonresonant excitation (“photoluminescence”)
- Cavity signal observed on spectrograph
- Here: Long cavity, weak coupling.

Strong coupling between QW and fiber cavity



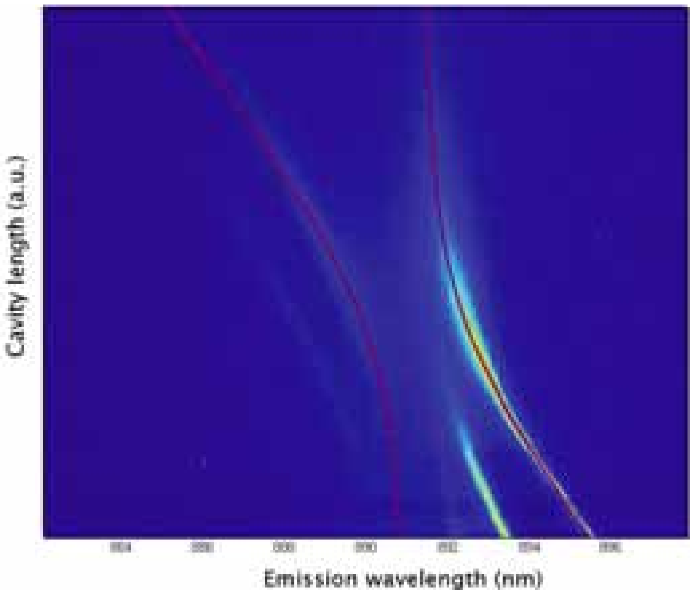
BEC: Eigenfrequencies of the coupled system

$$\omega_{\pm} = \omega_0 + \frac{1}{2}\left(\Delta_c \pm \sqrt{\Delta_c^{\,2} + 4Ng_1^{\,2}}\right)$$



BEC, *N*~750 atoms

Strong coupling between QW and fiber cavity



Single quantum well

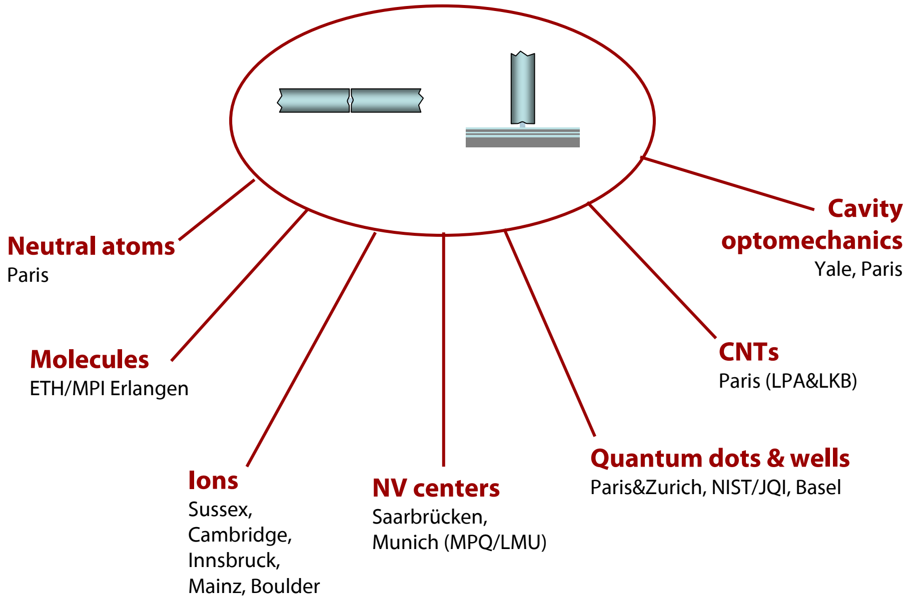
Cavity length (from FSR): ~7 µm

Normal mode splitting: 2g ~ 3.6 meV (870 GHz)!

Not far from Bragg mirror "lambda cavities".

- *Dielectric mirror has higher index contrast.*
- *Coupling scales only with 1/sqrt(L).*

Outlook: FFP Cavities as a Universal Tool



Neutral atoms
Paris

Molecules
ETH/MPI Erlangen

Ions
Sussex,
Cambridge,
Innsbruck,
Mainz, Boulder

NV centers
Saarbrücken,
Munich (MPQ/LMU)

Quantum dots & wells
Paris&Zurich, NIST/JQI, Basel

CNTs
Paris (LPA&LKB)

Cavity optomechanics
Yale, Paris

Former members:
Yves Colombe (NIST Boulder)
Christian Deutsch (MPQ Munich)
Guilhem Dubois (Astron OLED)
Vincent Dugrain (Zemax)
Roger Gehr (Swiss Re)
Clément Lacroûte (CalTech)
Felix Linke (BMW)
Kenneth Maussang (LPA ENS)
Friedemann Reinhard (U Stuttgart)
Tilo Steinmetz (Menlo Systems)
Jürgen Volz (TU Vienna)

Postdoc position available!

Alice Sinatra
Jérôme Estève
Romain Long
JR

Giovanni Barontini
Benjamin Besga
Sébastien Garcia
Florian Haas
Leander Hausmann
Claire Lebouteiller
Konstantin Ott
Cyril Vaneph

SYRTE:
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