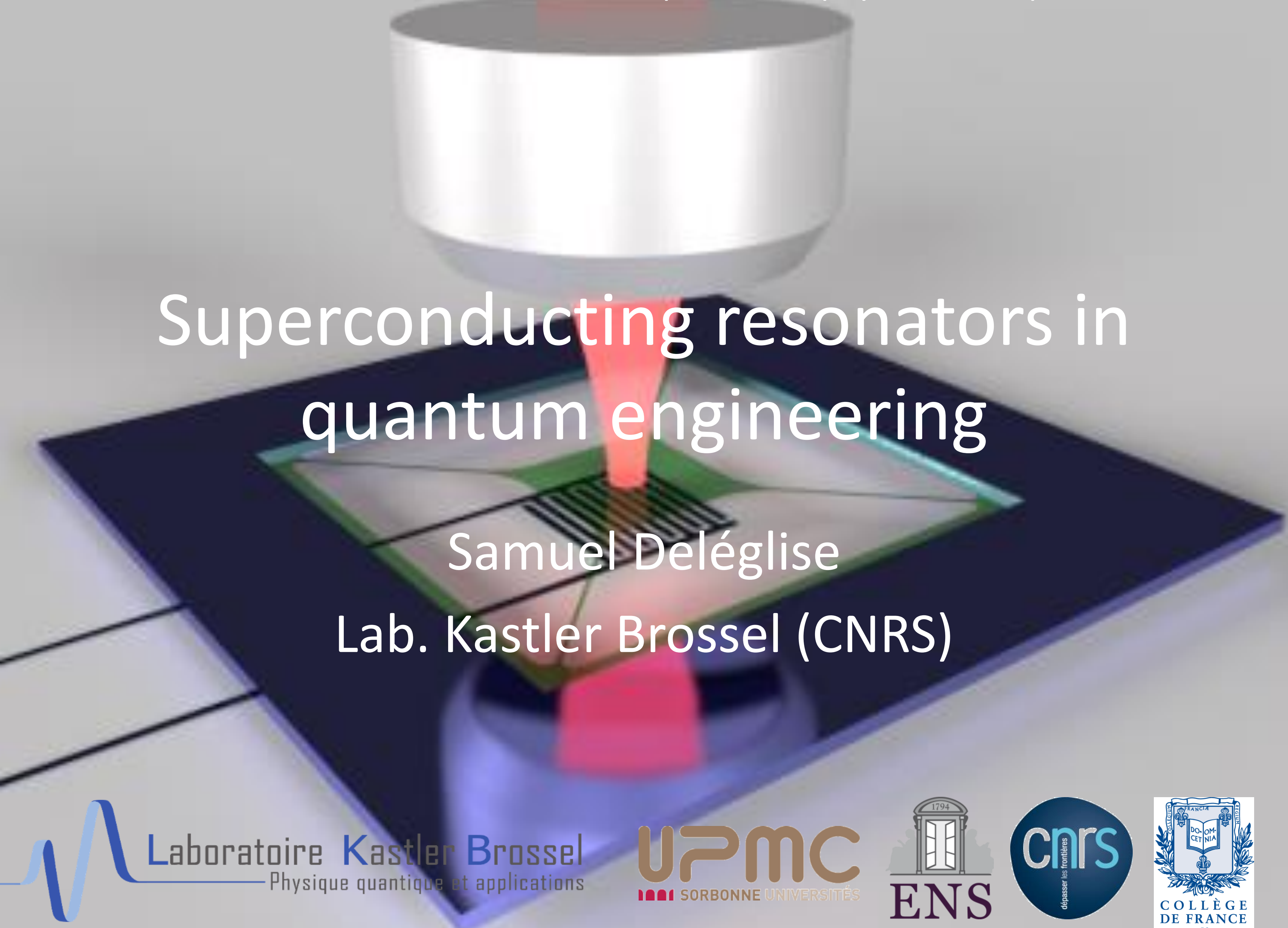

Superconducting resonators in quantum engineering

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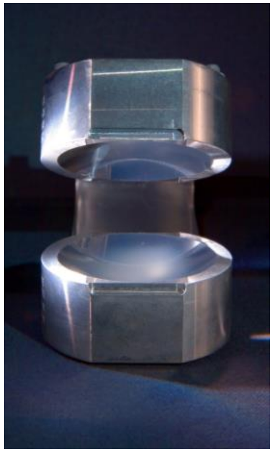
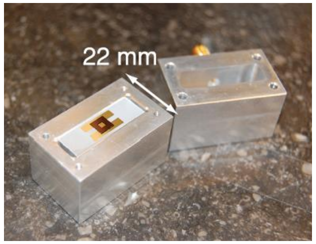
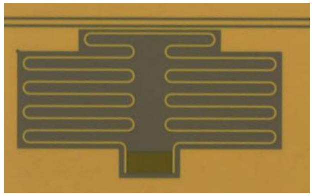
Superconducting resonators in quantum engineering

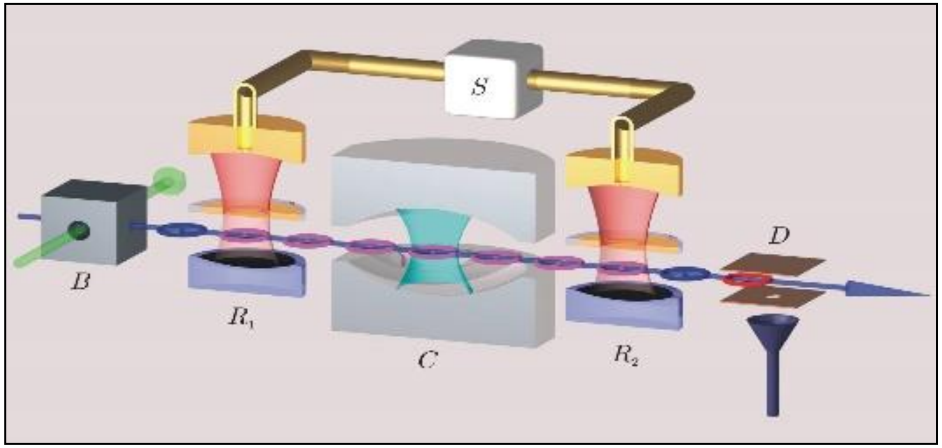
Superconducting microwave cavities



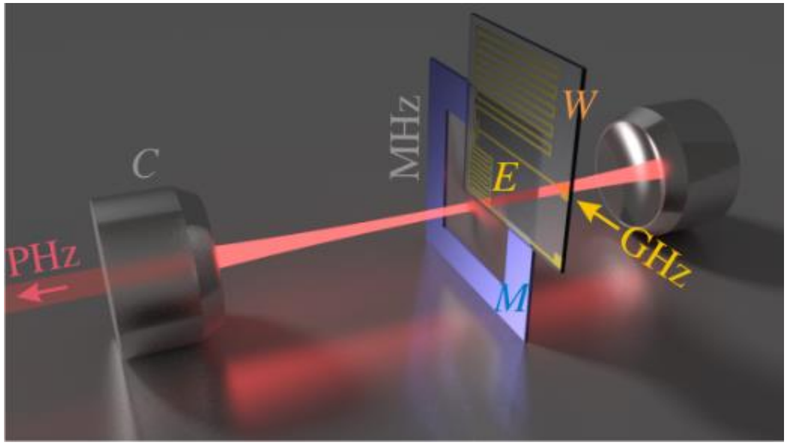




Manipulating the microwave field with Rydberg atoms



Quantum transducers: using radiation pressure to convert quantum signals from microwave to optical photons



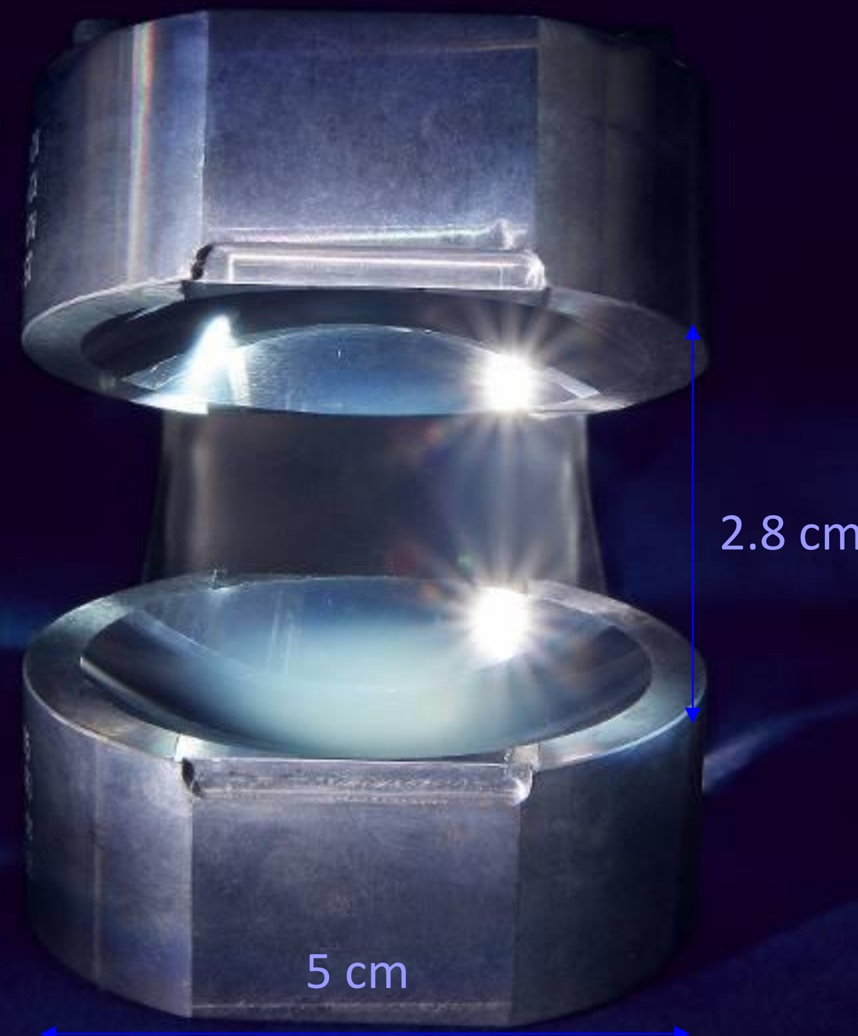
Microwave superconducting cavity: Storage box for photons

- Reson... $1\,\mathrm{GHz}$
- Q fac... $2 \cdot 10^{10}$
- Finess...

- Lifetime of a photon:

$$T_{\mathrm{cav}} = 130\,\mathrm{ms}$$

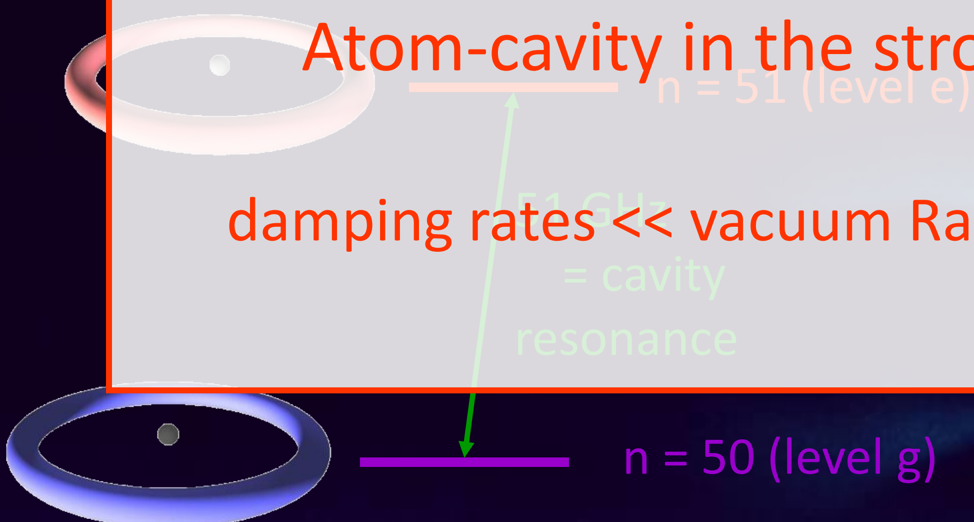
- best Fabry-Pérot resonator so far
- 1.4 billion bounces on the mirrors
- a light travel distance of 39 000 km
  (one full turn around the Earth)

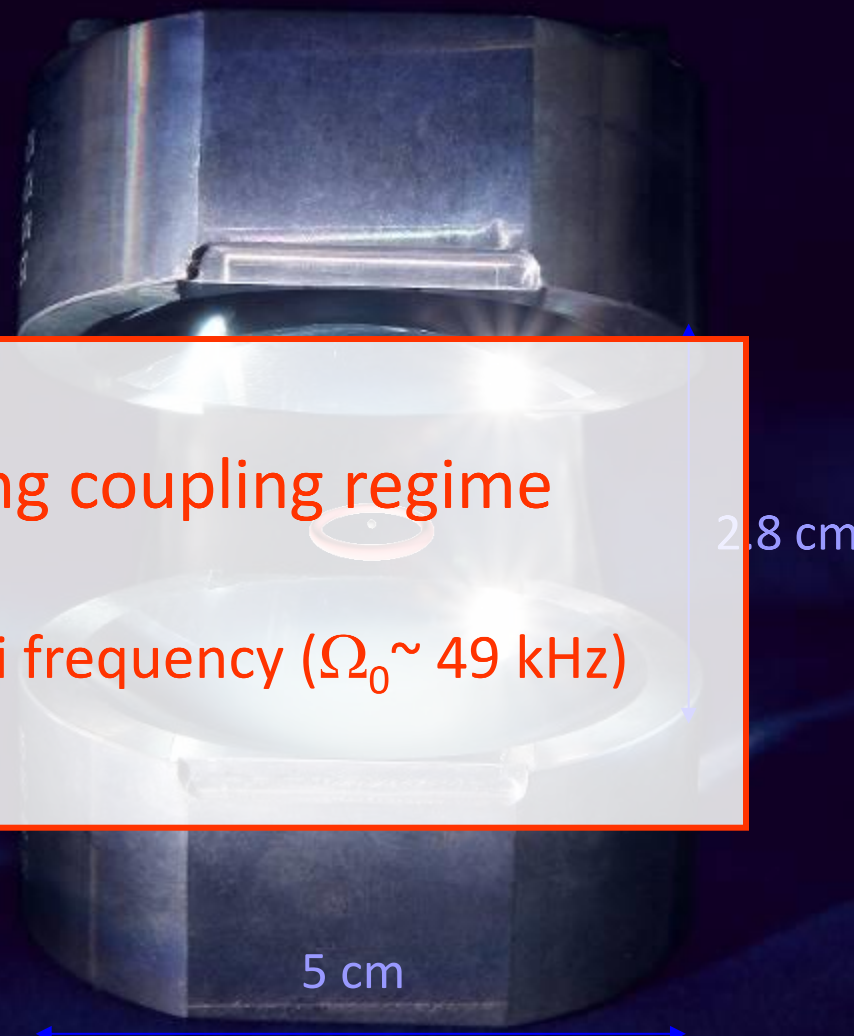


Microwave superconducting cavity: Storage box for photons

Circular Rydberg atoms

- ideal two-level atoms
- large dipole moment (~ $400\, d_{D_2}^{^{87}\mathrm{Rb}}$)
- long lifetime ~ 30ms

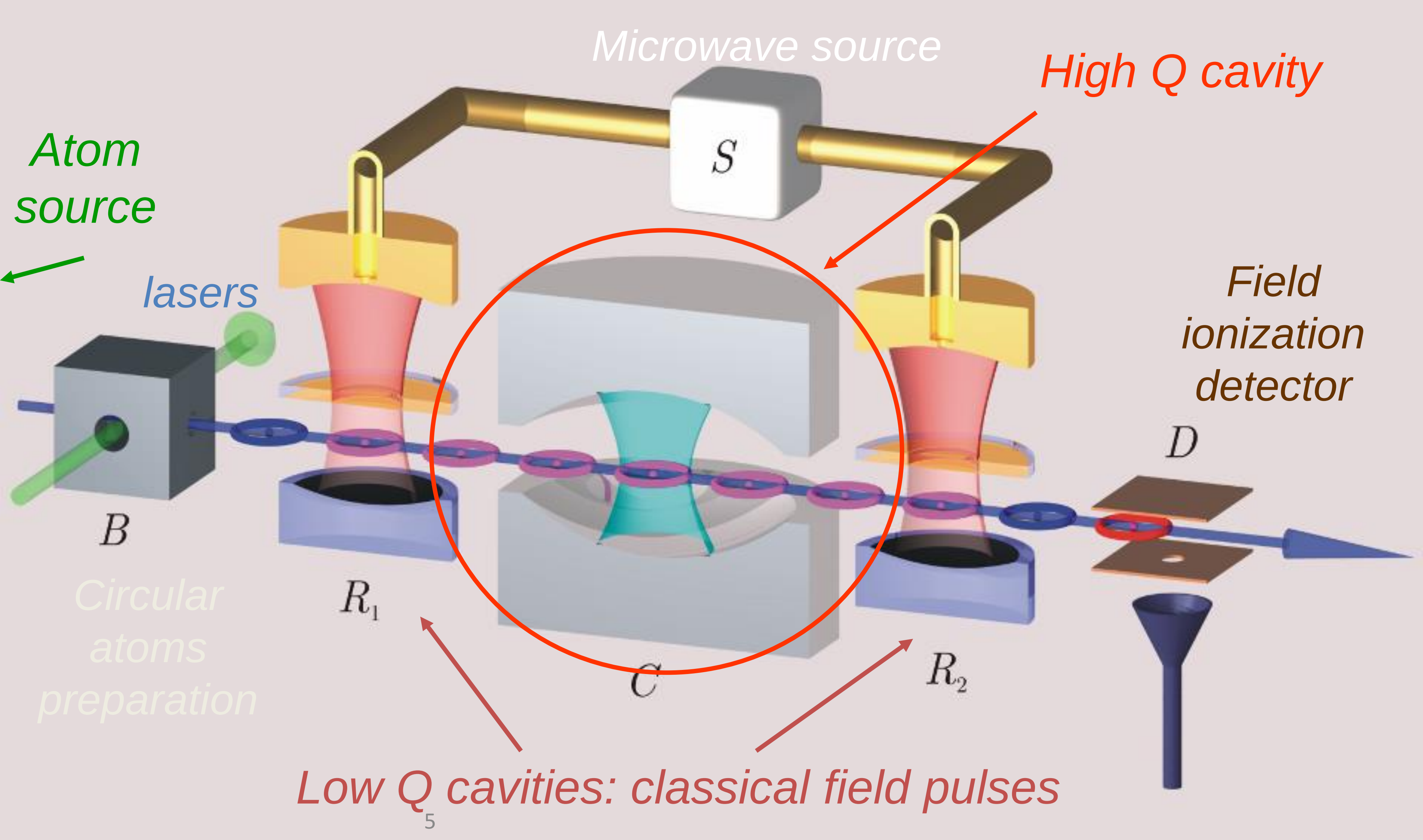




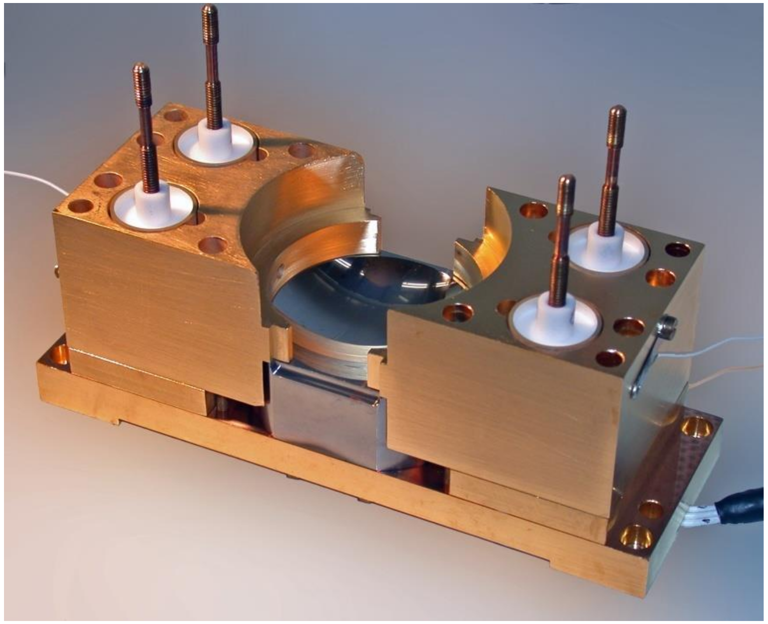
Atom-cavity in the strong coupling regime

damping rates << vacuum Rabi frequency (Ω_0~ 49 kHz)

Experimental setup

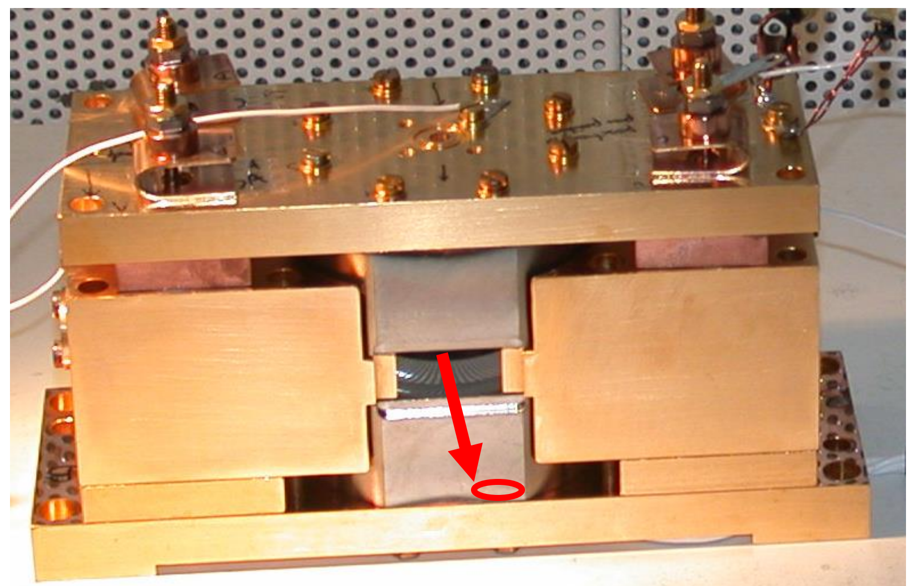


The microwave cavity



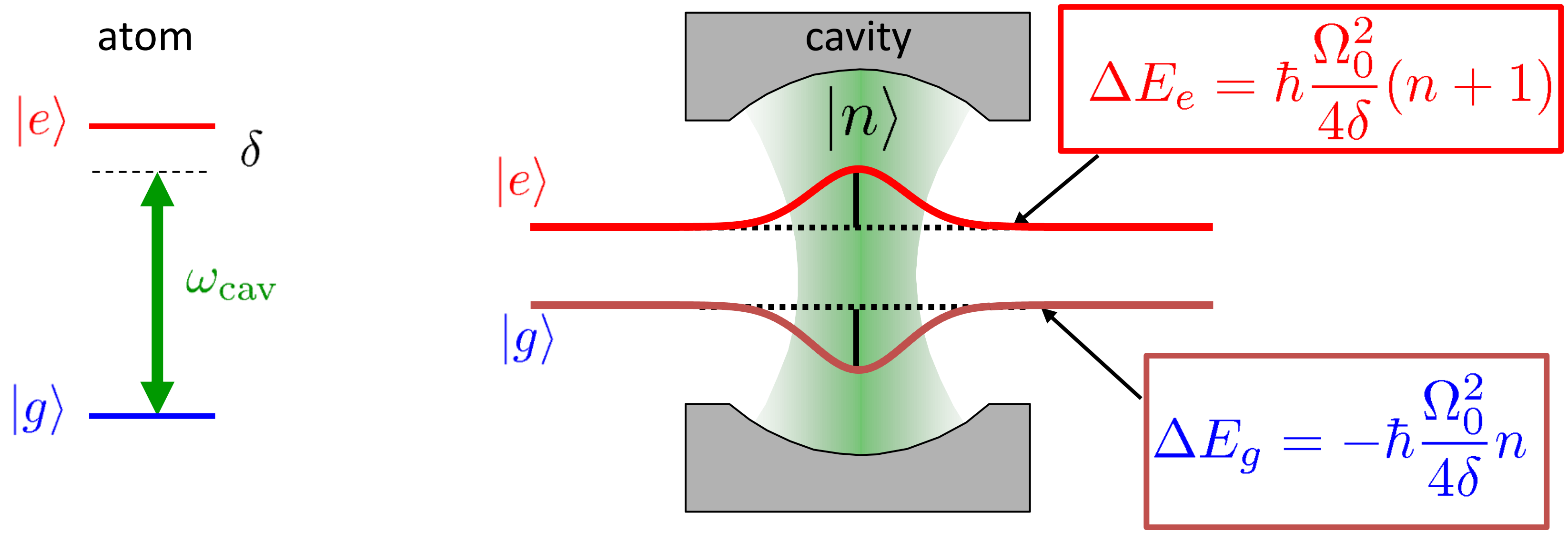
The bottom mirror in its mount…

…and the fully mounted cavity



S.Kuhr et al, Appl.Phys.Lett. *90, 164101 (2007)*

Dispersive interaction



- ➔ Energy conservation + adiabatic coupling : the field is preserved
- ➔ phase shift of atomic coherence (light shift)

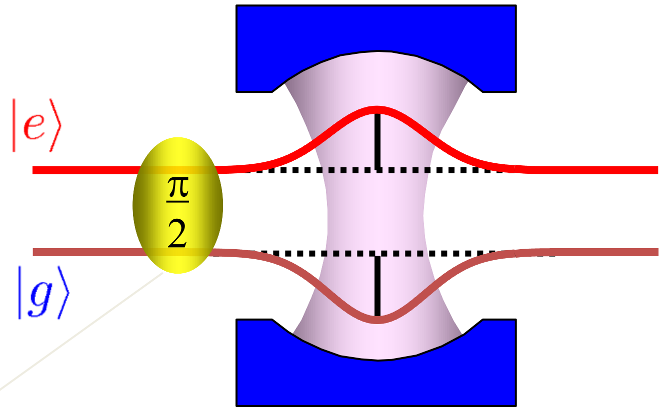
$$\varphi(n) = (n + 1/2)\varphi_0$$

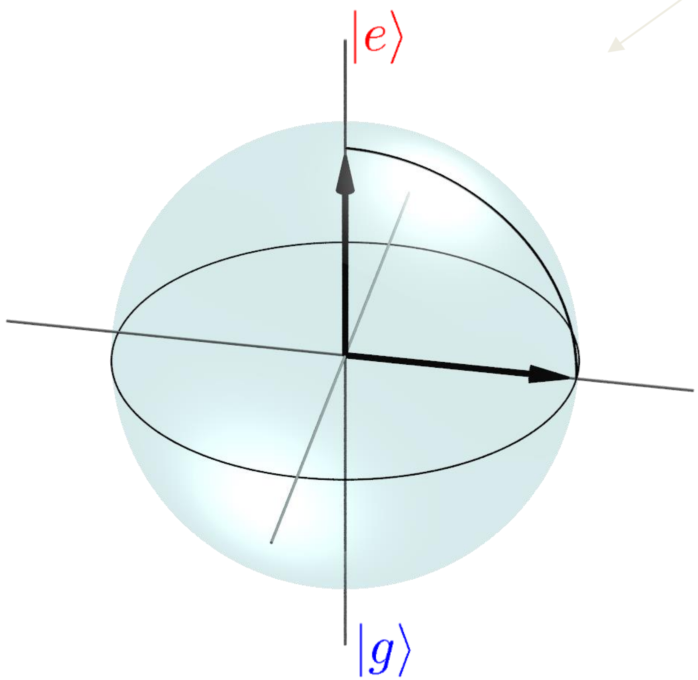
$$\varphi_0 = \frac{\Omega_0^2}{2\delta} t_{\mathrm{int}}$$

← Phase shift per photon

QND measurement of parity

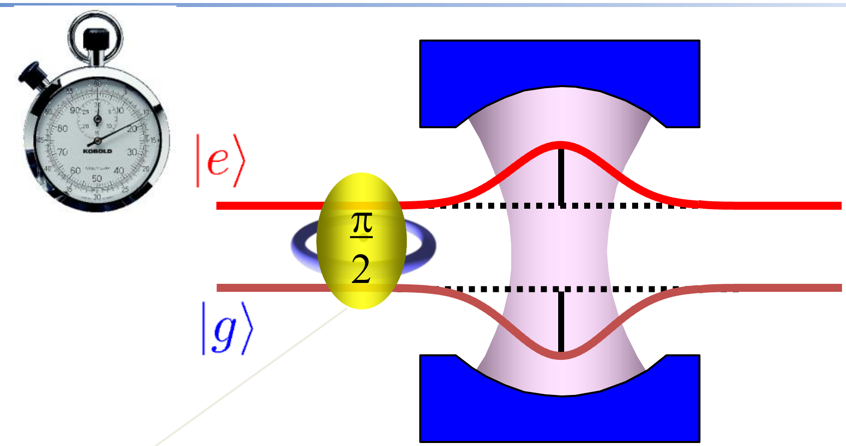
1. Trigger of the atom clock: resonant π/2 pulse

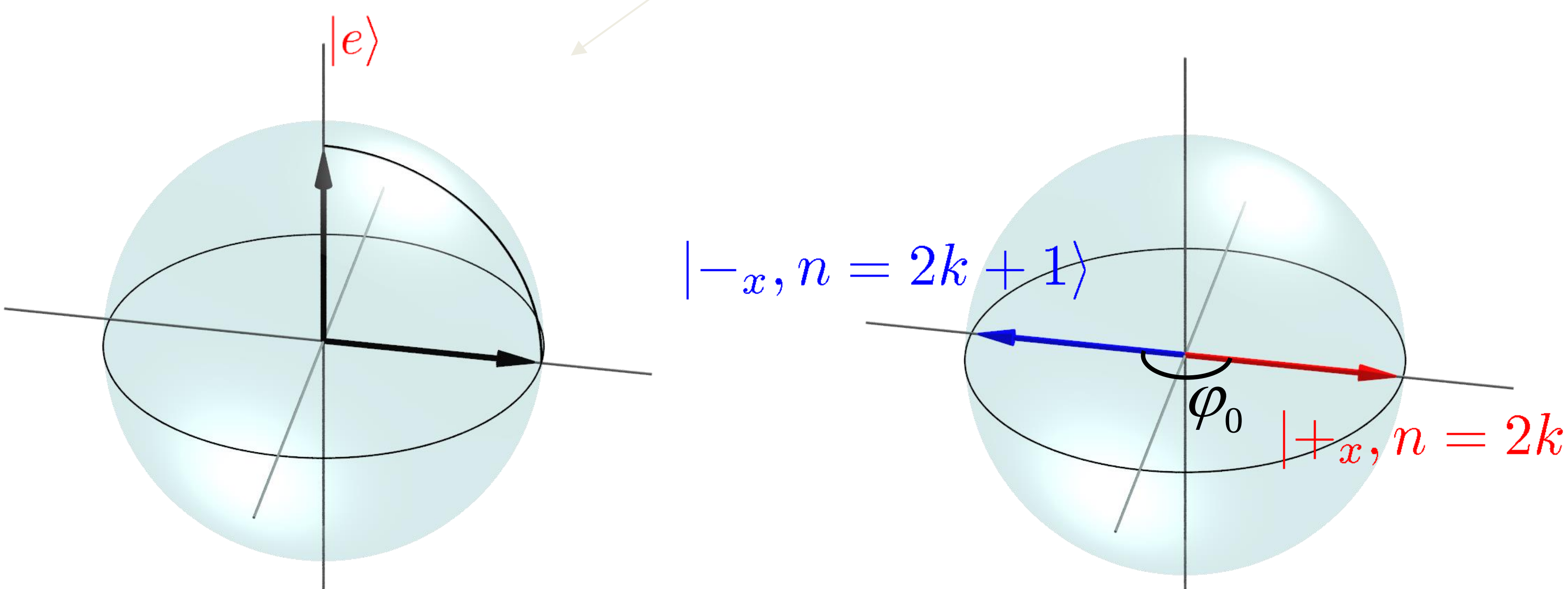




QND measurement of parity

1. Trigger of the atom clock:
Resonant $\pi/2$ pulse
2. Dephasing of the clock:
interaction with the cavity field





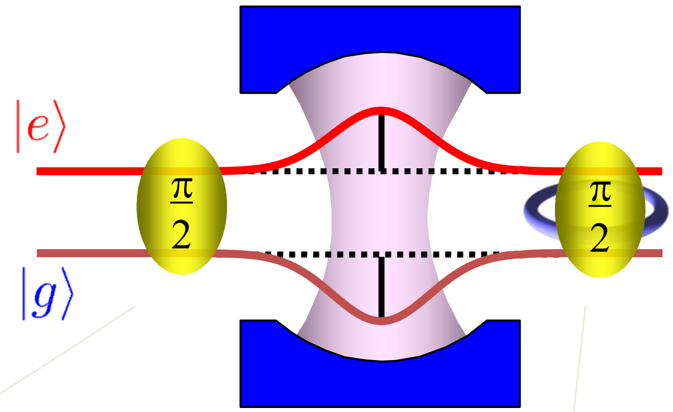
Phase shift per photon adjusted to $\varphi_0 = \pi$
➔ atom "spin" correlated to photon number parity

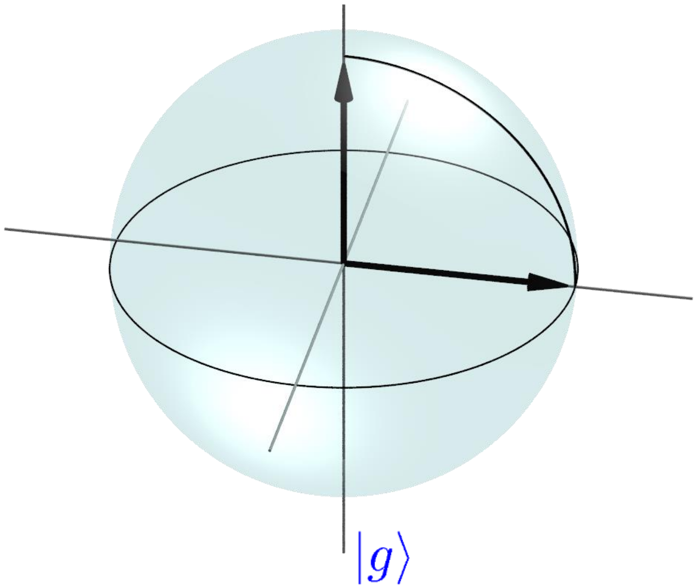
QND measurement of parity

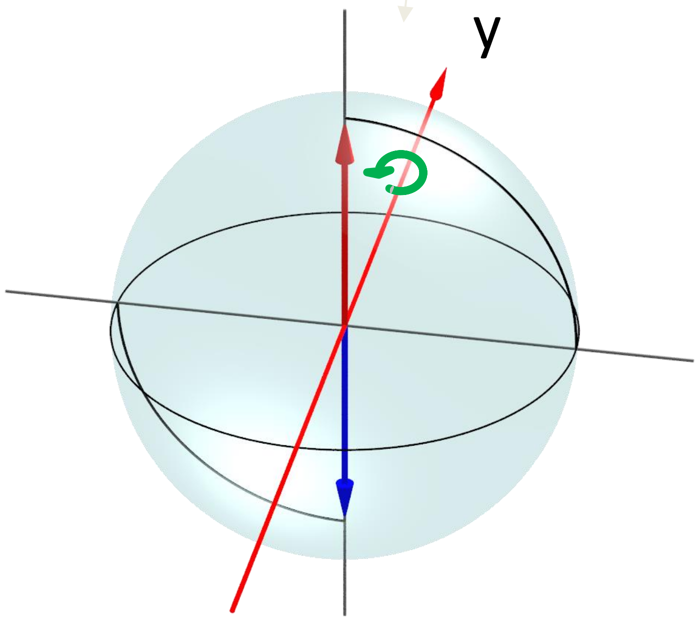
1. Trigger of the atom clock:
Resonant π/2 pulse

2. Dephasing of the clock:
interaction with the cavity field

3. Measurement of the clock:
2^{nd} π/2 pulse & atomic state detection





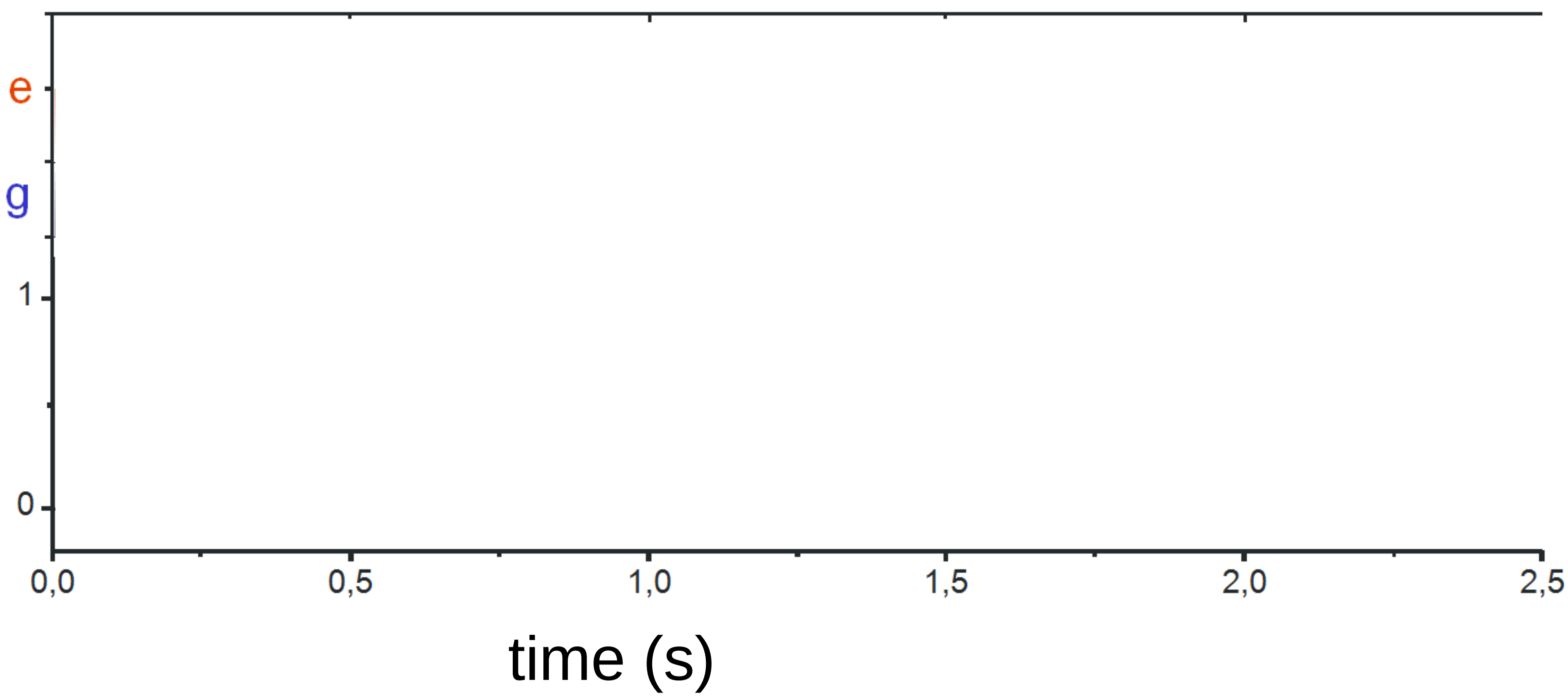


Measurement of atomic populations: $P_e - P_g = \left\langle \cos \pi \hat{N} \right\rangle$

Detection of a thermal photon

$$T = 0.8\,\mathrm{K}$$
$$\bar{n}_{\mathrm{th}} = 0.05\,\mathrm{ph}$$

3800 atoms detected:
200 atoms/Tcav



Gleyzes *et al*. *Nature* **446**, 297-300 (2007).

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More details about the cavity

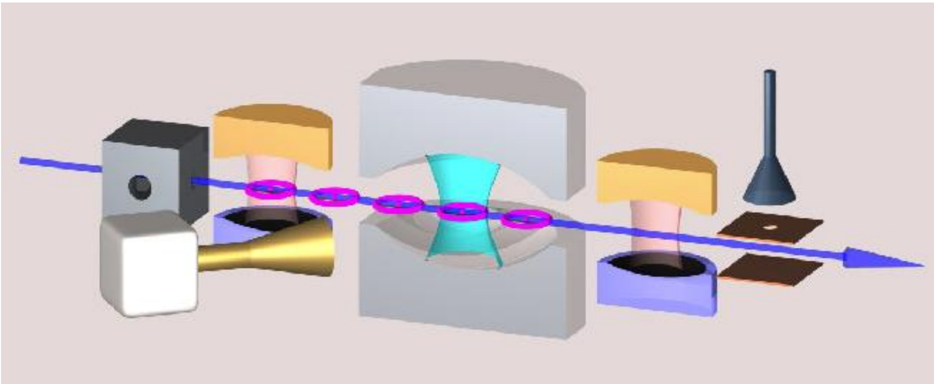
- Experimental constraints:
  - Well defined $\neq 0$ electric field → Fabry-Perot geometry required
  - Toroidal mirror shape to lift the degeneracy between orthogonal polarizations
  - In-situ tuning via Piezo-electric spacers

- Cavity Fabrication:
  1. High-precision machining of a 30-mm thick copper substrate (<10 nm rms roughness), long-range precision better than 300 nm.
  2. A 12 μm Nb layer is deposited by dc cathode sputtering in a magnetron discharge (technic developed for acceleration cavities of particle colliders).
  3. No coupling waveguides (to avoid surface defects on the mirrors)

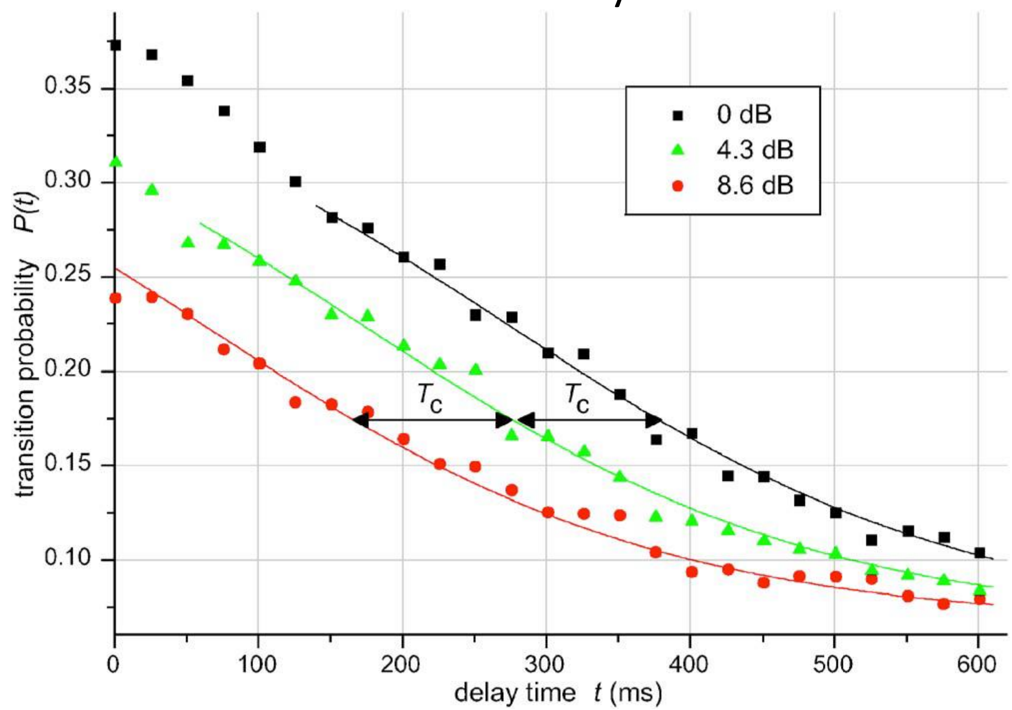
→ No transmission/reflection measurements possible

For more details, see: S.Kuhr et al, Appl. Phys. Lett. *90, 164101 (2007)*

Cavity lifetime measurement



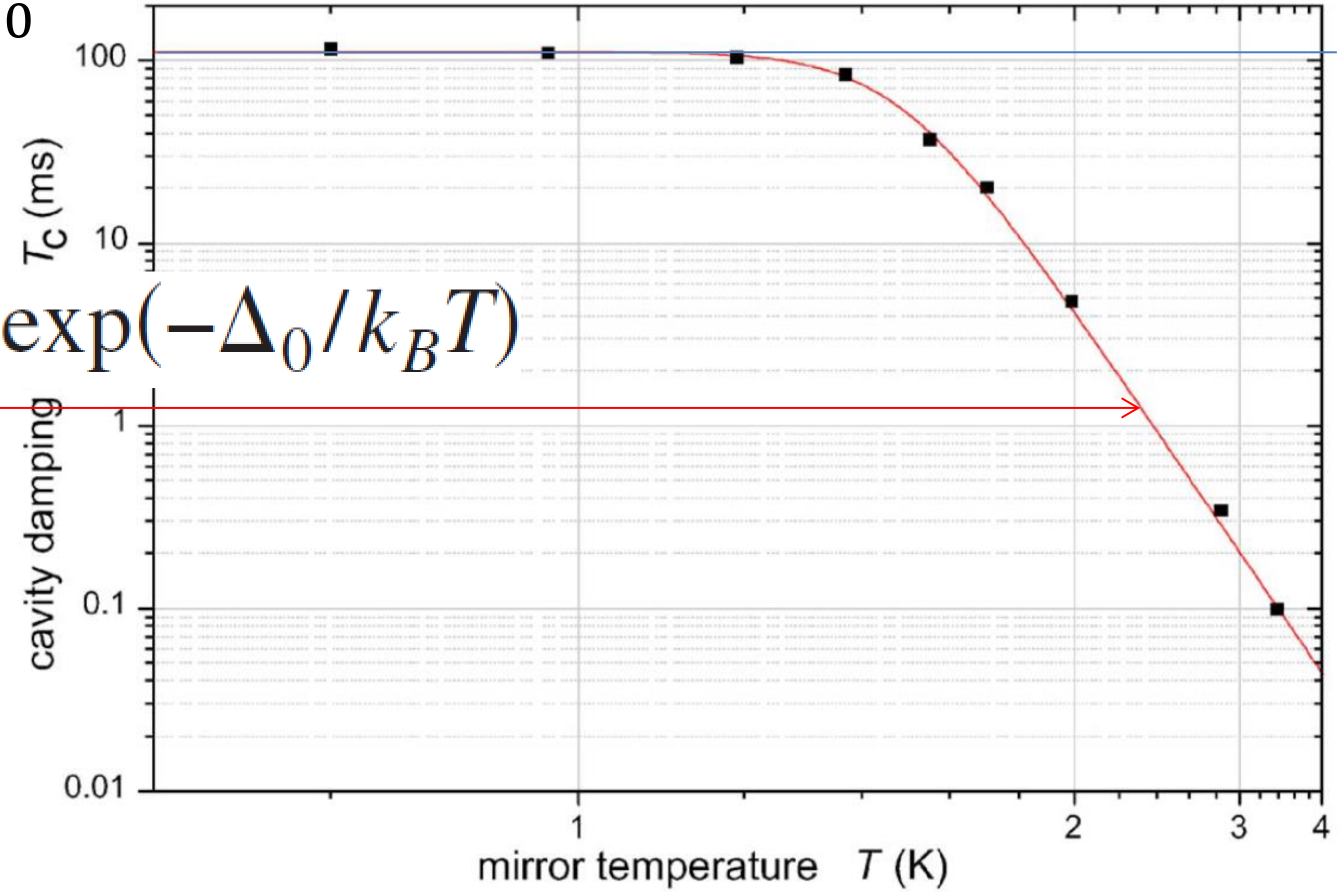
1. Inject a mesoscopic field in the cavity via an external antenna
2. Let the field decay everywhere except for the cavity mode
3. Send atoms initialy in the ground states after a given delay time
4. Repeat the experiment for different delays and initial field strength



Temperature dependance of T_c

$Q = 4.2\ 10^{10}$

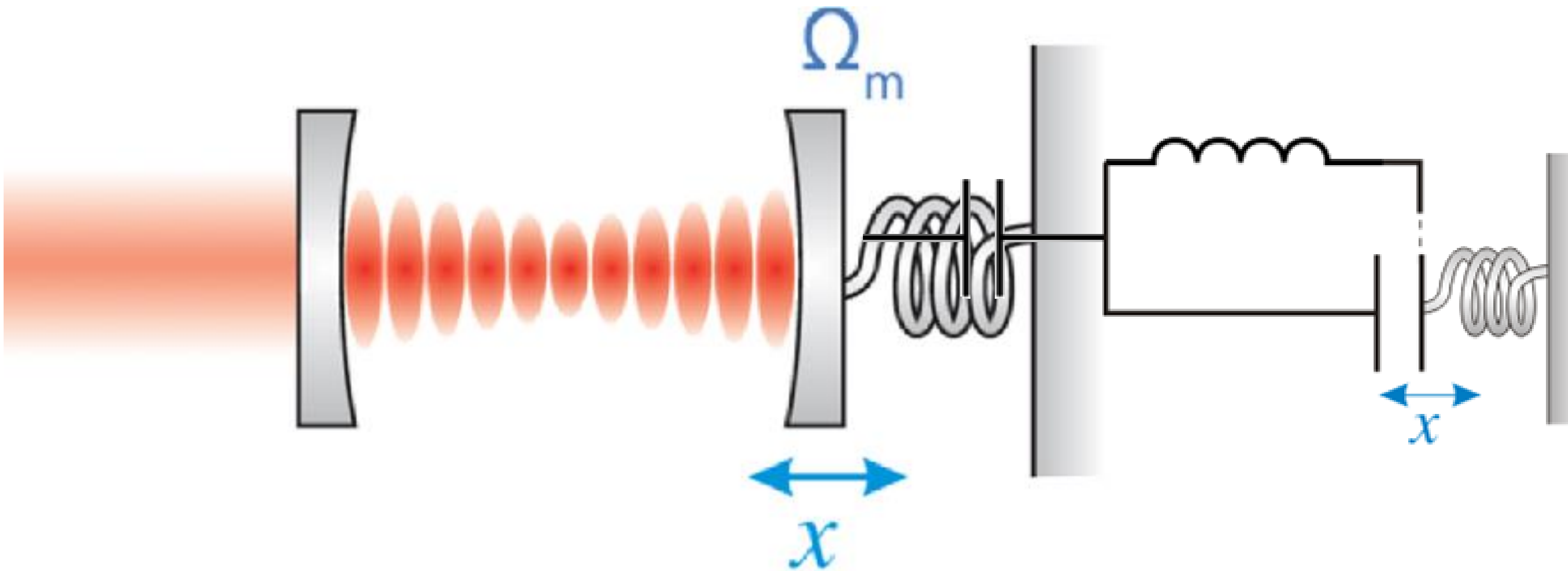
$$R_{\mathrm{BCS}} = (A/T)\exp(-\Delta_0/k_B T)$$

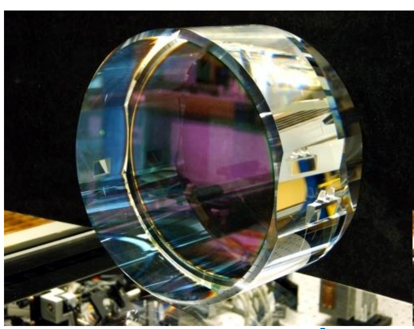


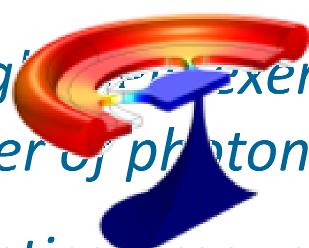
- Down to 1.6 K, the Q factor is limited by the finite resistivity predicted by BCS theory at $\neq 0$ frequency
- Below 1.4 K, Q-factor is limited by surface scattering and clipping.

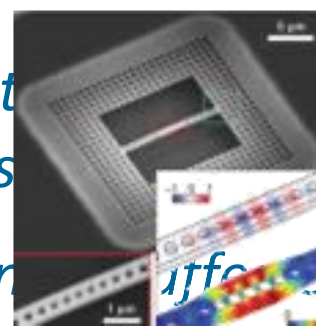
→ Comparable to the Q-factors obtained with closed cylindrical cavities.

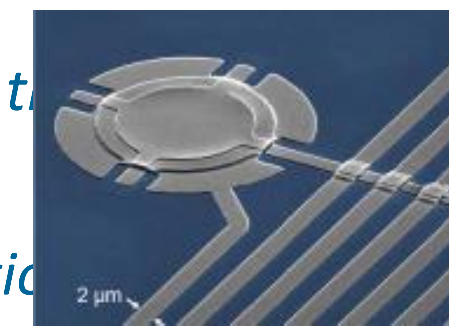
Optomechanics











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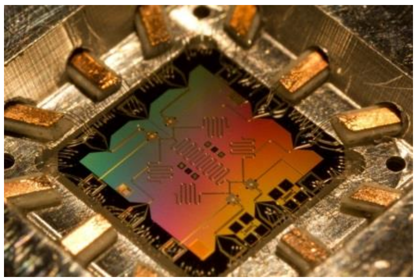
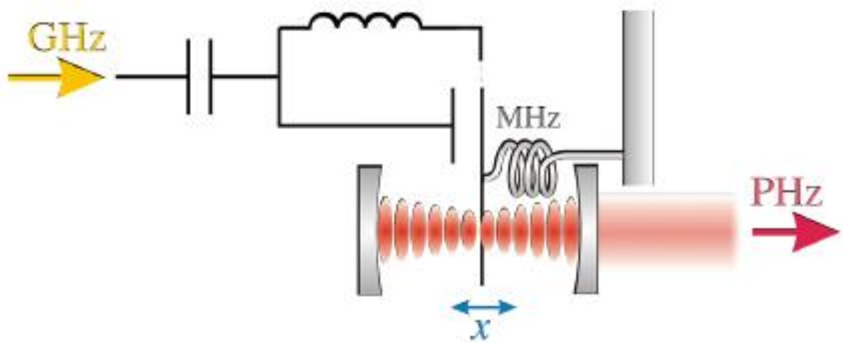
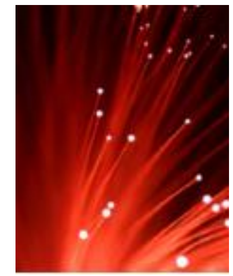
Quantum optomechanical transducer

Microwave Photons ⟷ Phonons ⟷ Optical Photons



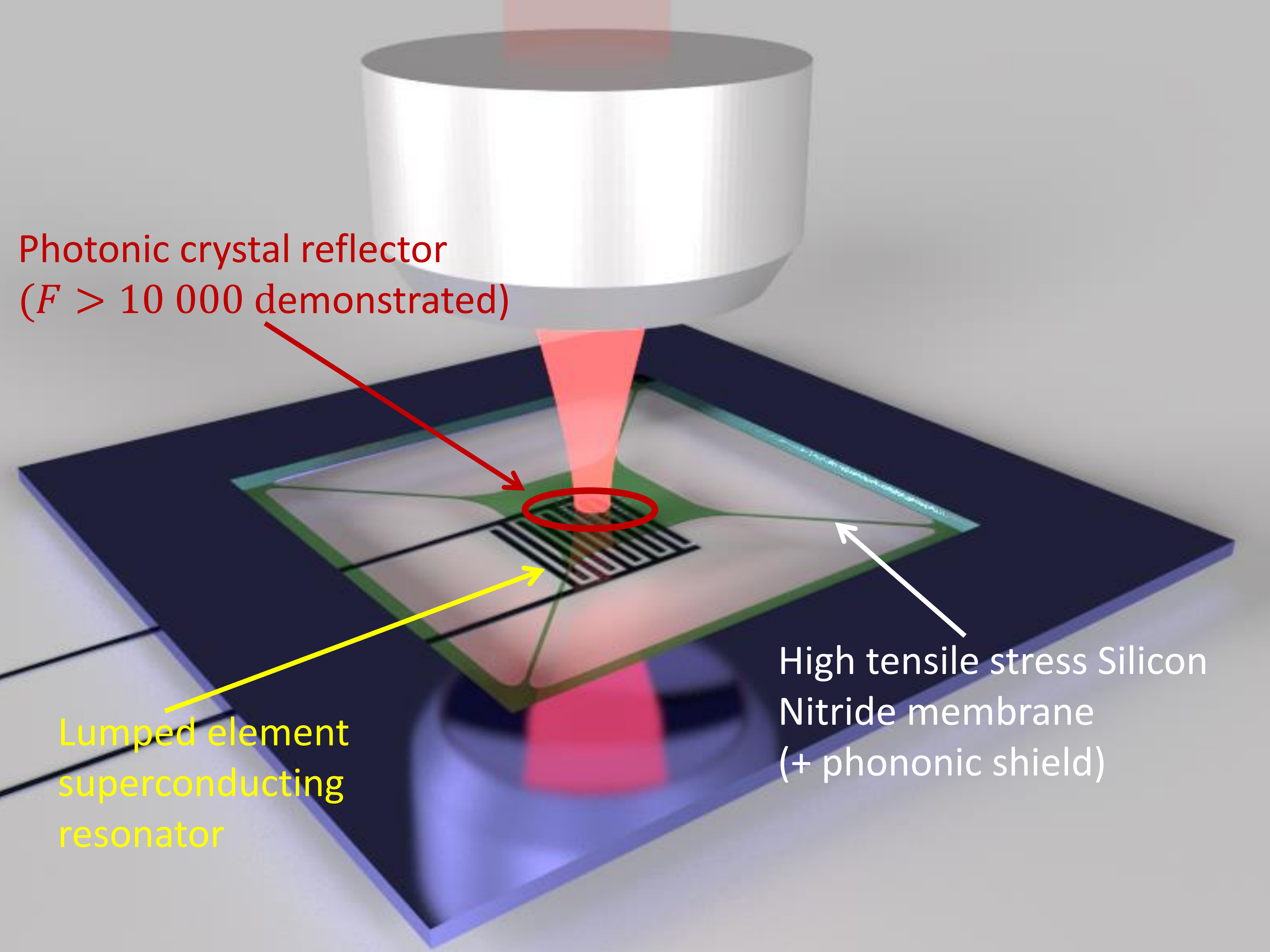




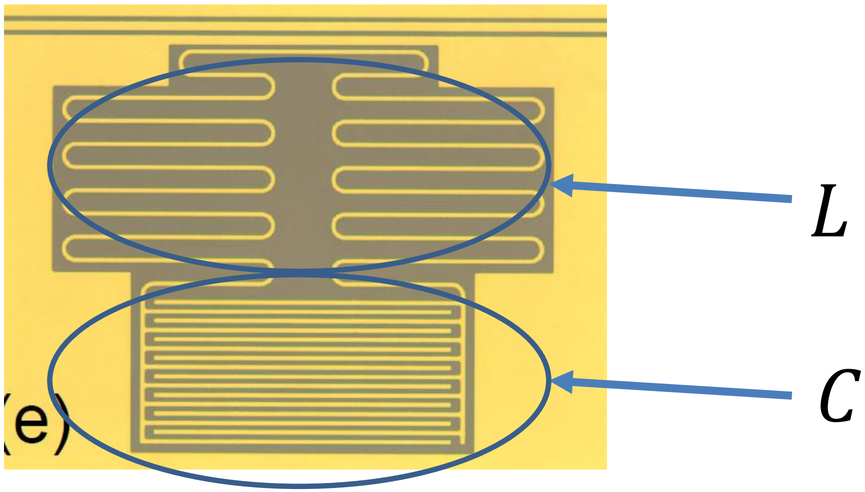
- Fast and efficient quantum gates
- Microwave photons are very sensitive to thermal decoherence

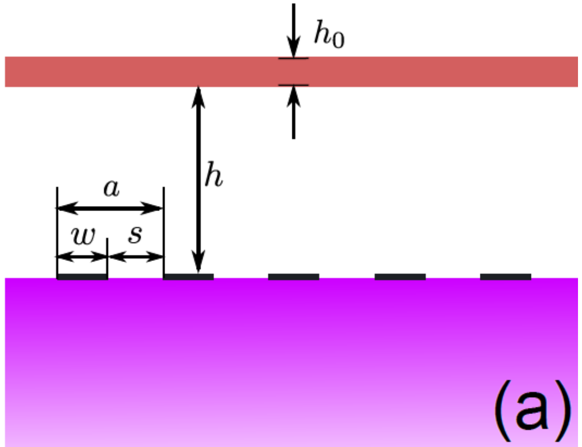
- High efficiency photodetectors
- Long distance-room temperature transmission via optical fibers
- Difficult to store and manipulate

See Schliesser Nature **517** 2014 « Optical detection of microwave through a nanomechanical transducer»


Photonic crystal reflector
($F > 10\,000$ demonstrated)
High tensile stress Silicon
Nitride membrane
(+ phononic shield)
Lumped element
superconducting
resonator

Lumped-elements superconducting resonators





- Lumped element resonator

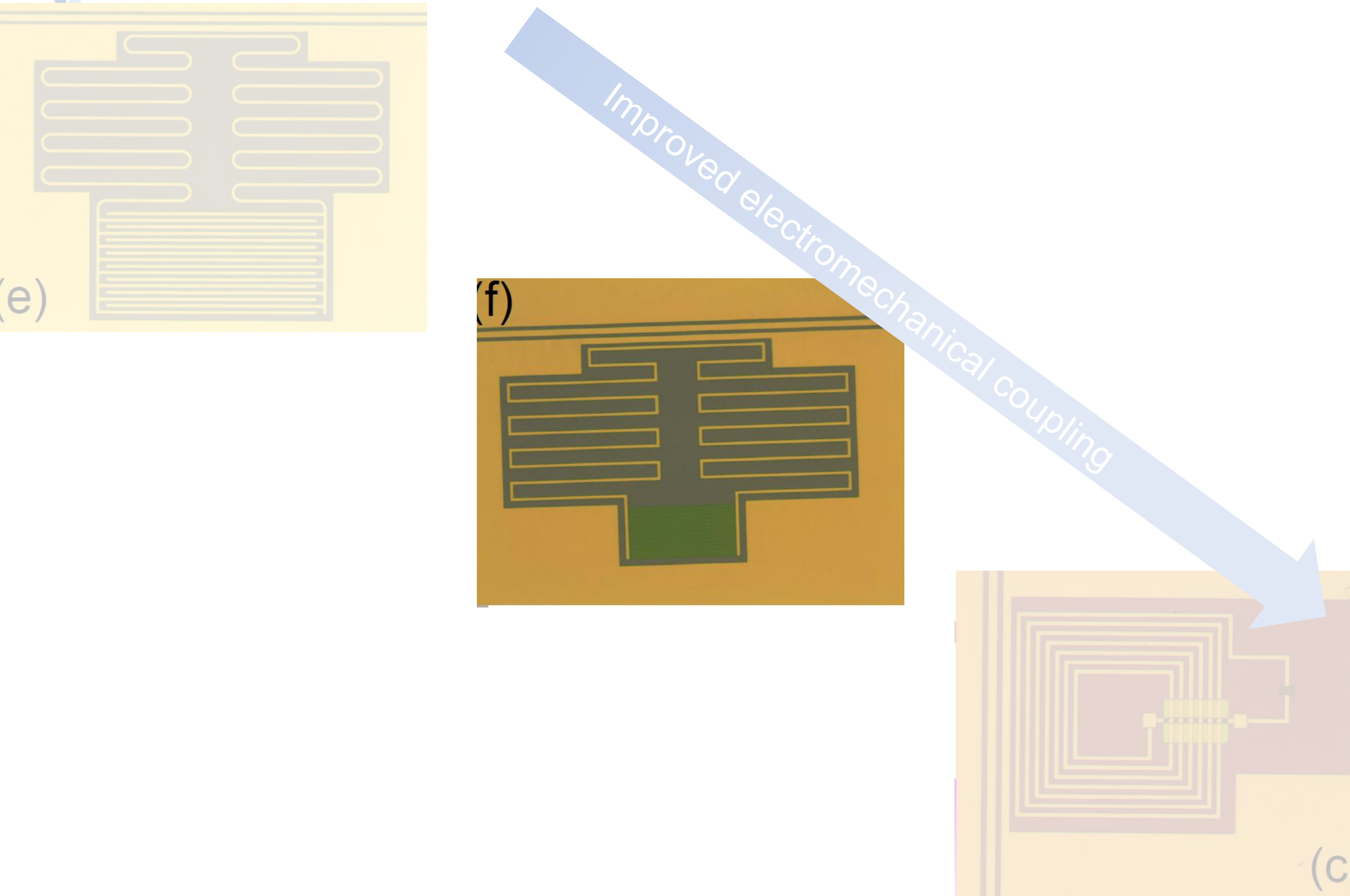
→ Maximizes the electrostatic energy stored in the membrane vicinity

- Coupling to the membrane via dielectric gradient forces
- Microfabrication by e-beam lythography in the ENS cleanroom
- Analytical model for the coupling strength

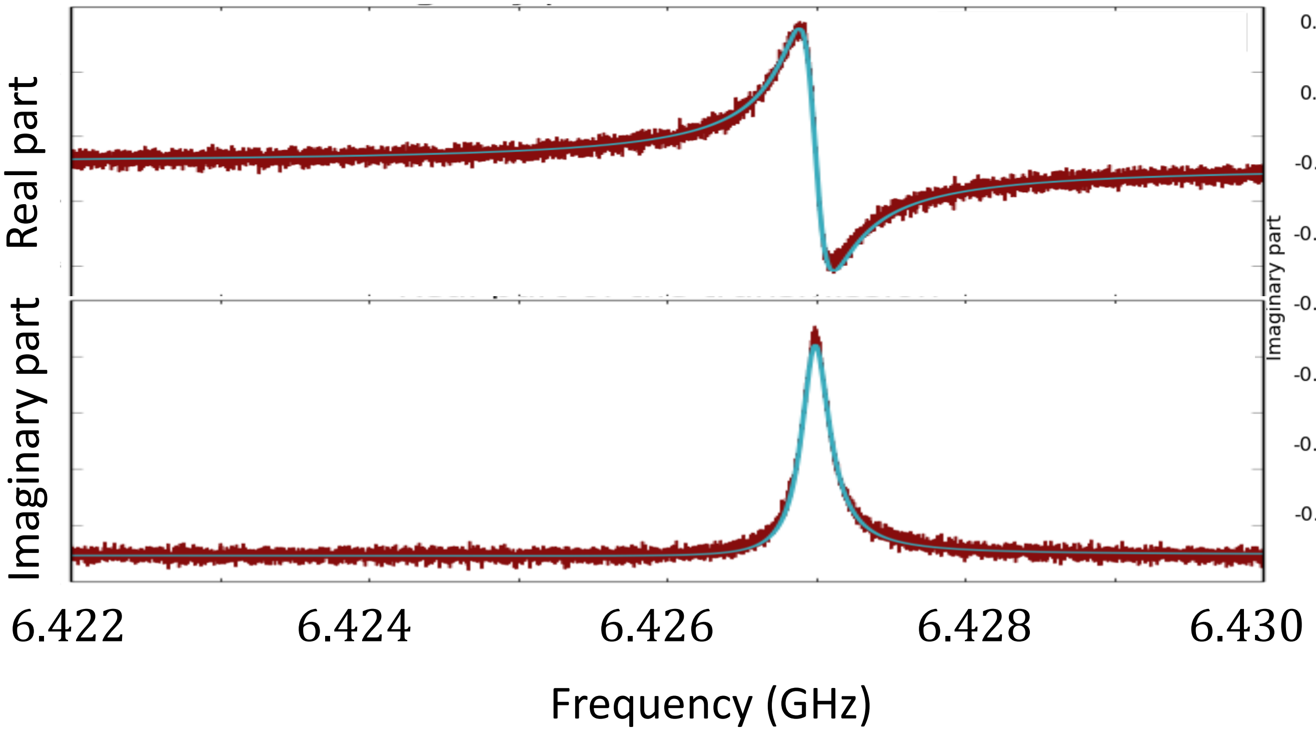
  → Reduce tooth spacing ($a \approx h$)

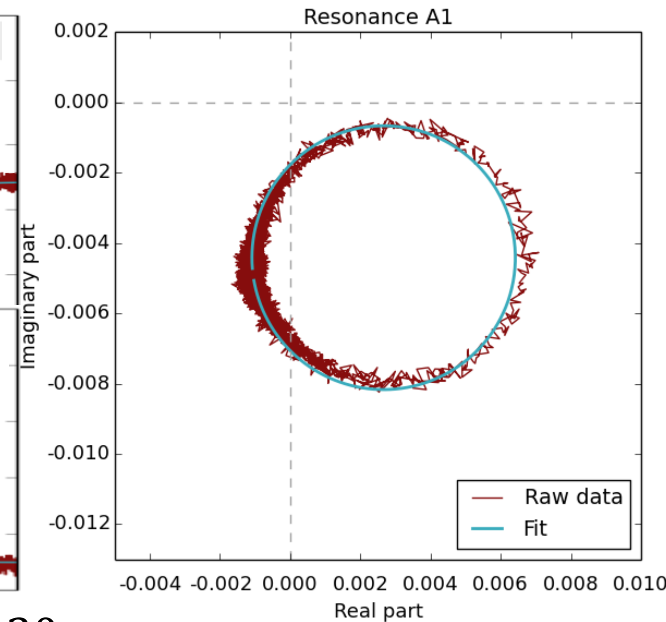
  → Use low ϵ substrate (SiO_2)

Resonator optimized for electromechanical coupling



Transmission measurements in the complex plane





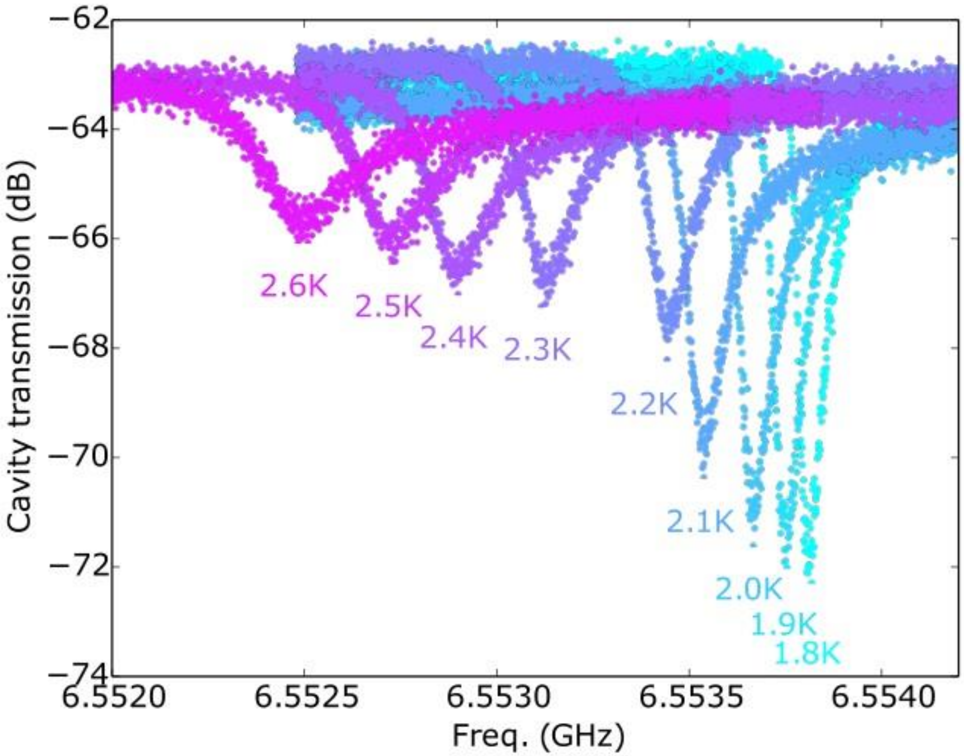
- Asymetric Fano-lineshape due to standing-waves in the transmission lines
- The effect can be properly taken into account by using the following formula instead of a Lorentzian:

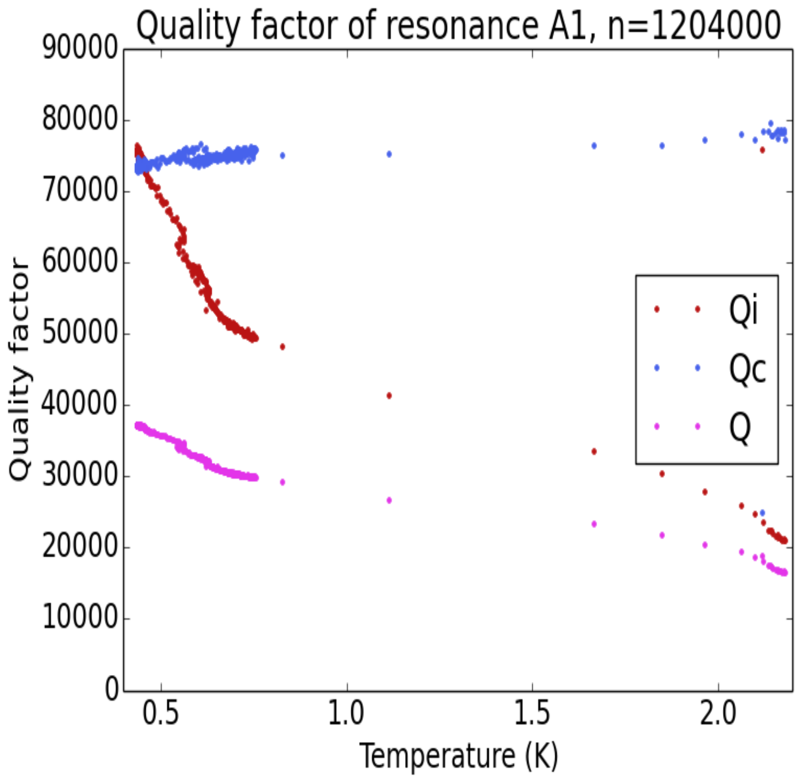
$$S_{21} = 1 - \frac{\frac{Q_0}{Q_c} - 2iQ_0\frac{\delta\omega}{\omega_0}}{1 + 2iQ_0\frac{\omega-\omega_0}{\omega_0}}$$

Geerlings et al. APL (2012)

Temperature dependance…

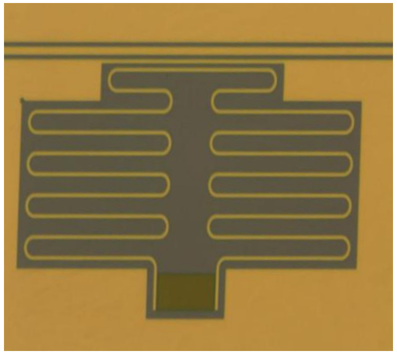
- Measurements down to 376 mK
- Internal Q factors up to 7.5×10^4

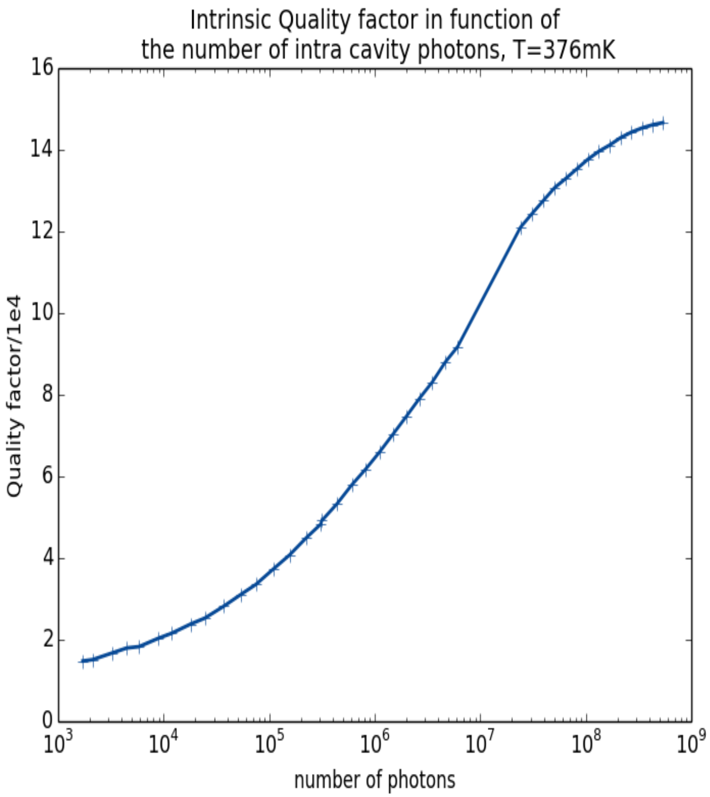




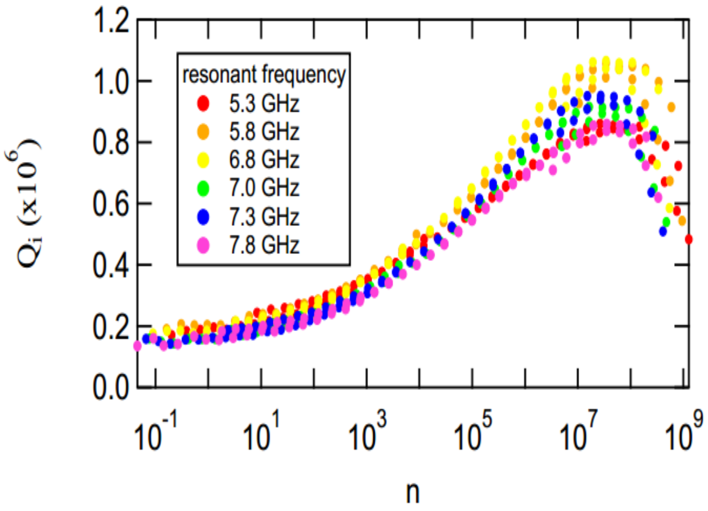
…Power dependence

- For large surface/volume ratio resonators, surface losses dominates.
- The Two-Level-Systems responsible for microwave damping can be saturated by large intracavity fields

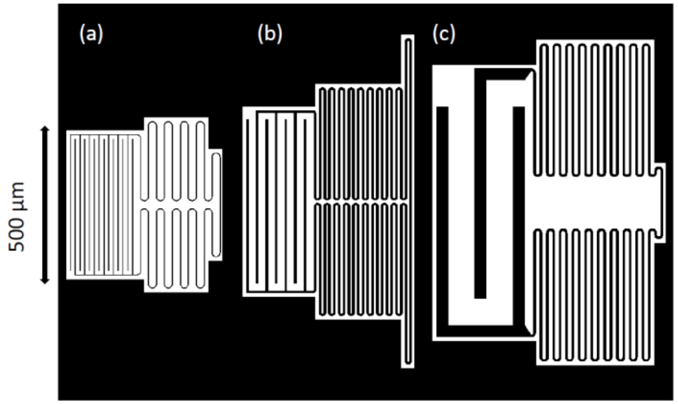




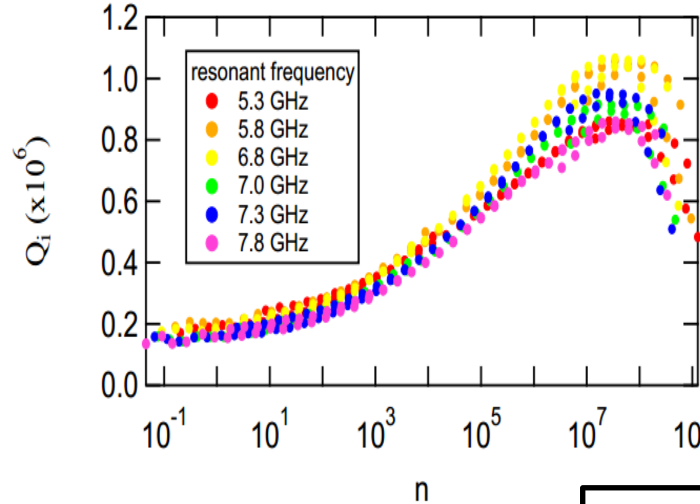
Also observed with larger interdigitated capacitors
See Geerlings et al. APL (2012)

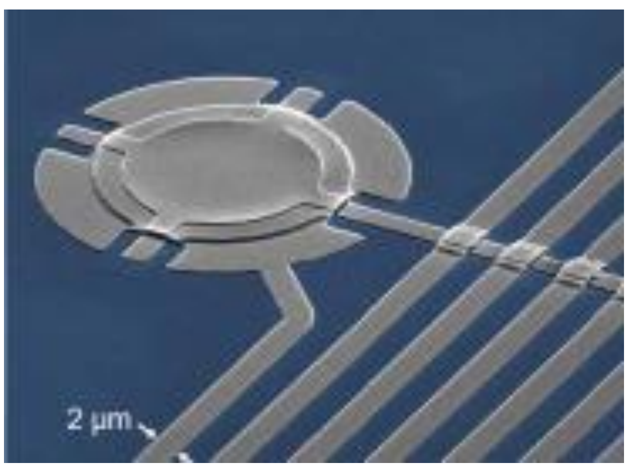


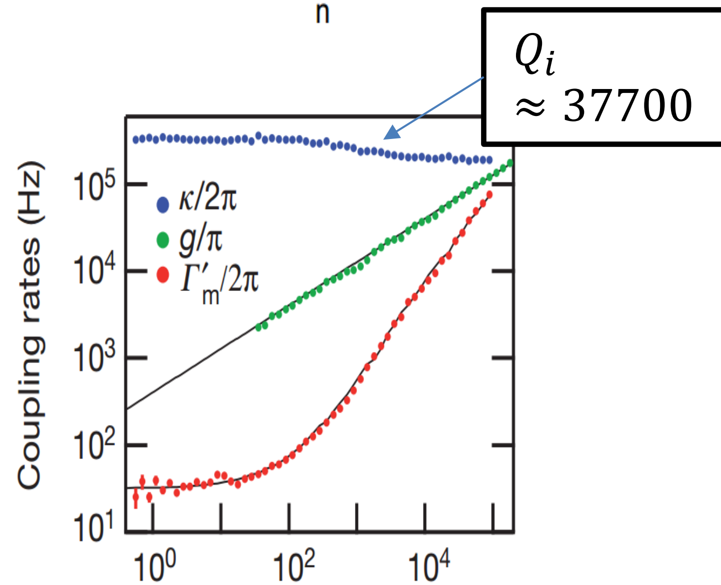
Lumped-element resonators: state-of-the-art



Geerlings et al. APL (2012) + Geerlings PhD thesis (2013)







Teufel et al. Nature 2011

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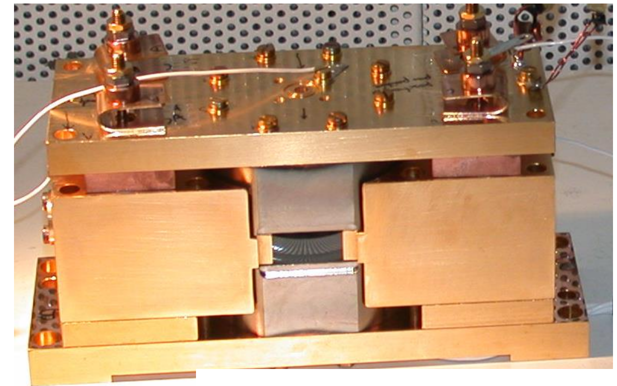
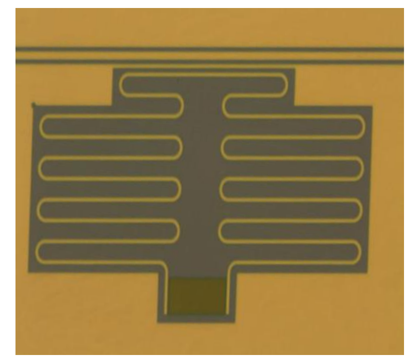
Conclusion/Perspectives



- Fabry-Perot/3D cavities
  - Q-factors $>10^{10}$
  - Large mode volume



- Lumped-element cavities
  - Q-factors $\approx 10^5$, limited by TLS
  - On-chip
  - Strong confinement of the electrostatic energy
- Towards 3d transmons coupled to a nanomechanical resonator

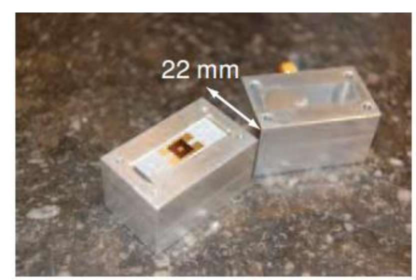
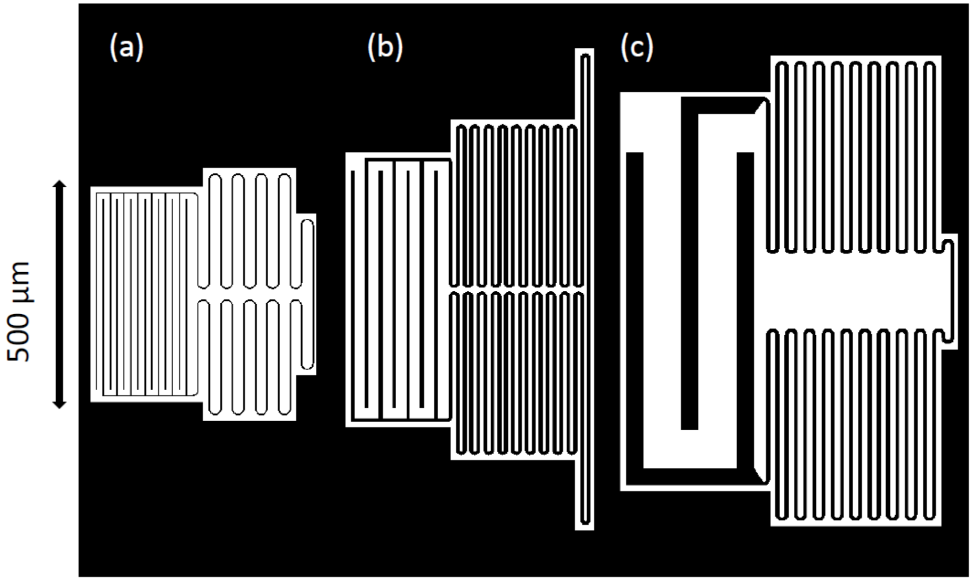
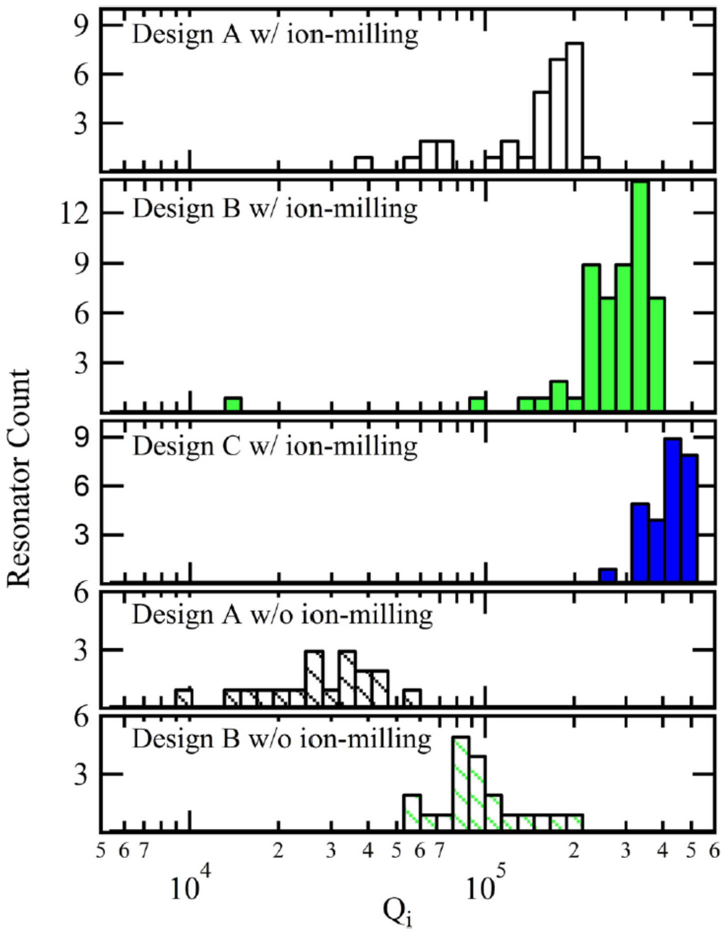


Image: Gary Steele

Lumped-element resonators





Detailled optimization of the geometry: Geerlings et al. APL (2012) + Geerlings PhD thesis