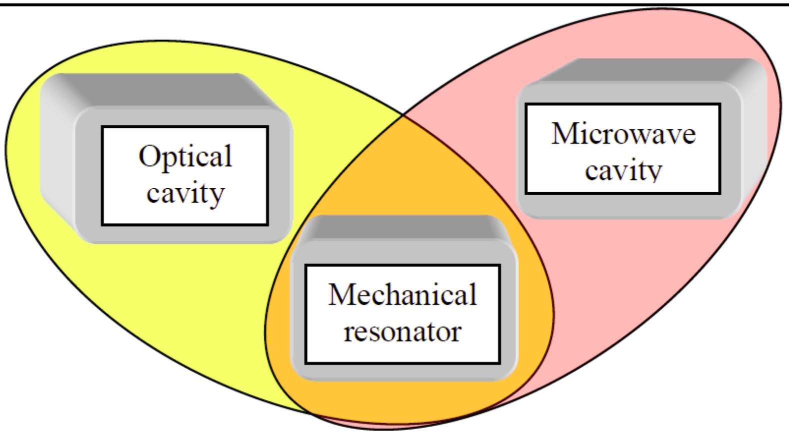
WP2 PHOTON-PHONON-INTERFACES

WP2: Photon-phonon interfaces

Main objective: implementation of coherent interconversion between microwave/optical photons and MHz/GHz phonons



Deliverables:

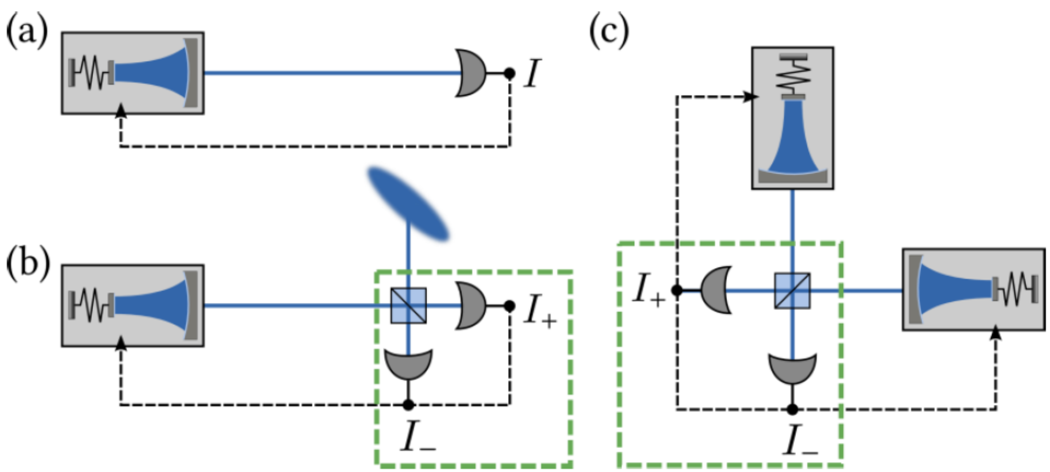
D2.3 Detection of optomechanical correlations by means of quantum filtering techniques (Month 24)
D2.4 Coherent photon-phonon conversion in an optomechanical system (Month 24)
D2.5 Demonstration of large single-photon optomechanical coupling rates (one order of magnitude improvement in g_0/κ) at cryogenic temperatures (Month 36)

iquoems universität wien VCQ Vienna Center for Quantum Science and Technology

D2.3 Detection of optomechanical correlations by means of quantum filtering techniques (Month 24)

LUH + UNIVIE:
design and analysis of novel quantum protocols to control the mechanical system

- employ **optomechanical entanglement as a resource** for measurement-based feedback protocols:
  - preparation of a low-entropy mechanical state by feedback cooling
  - creation of bipartite mechanical entanglement by time-continuous entanglement swapping
  - preparation of a squeezed mechanical state by time-continuous teleportation.



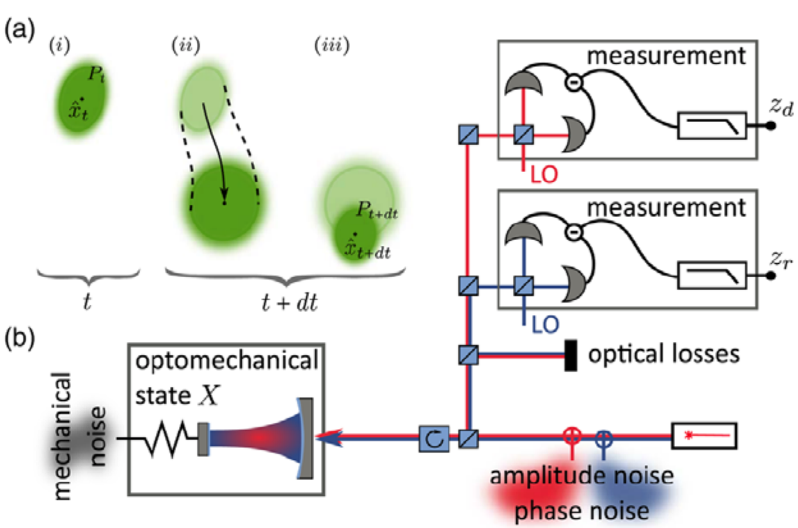
Physical Review A 91, 033822 (2015)

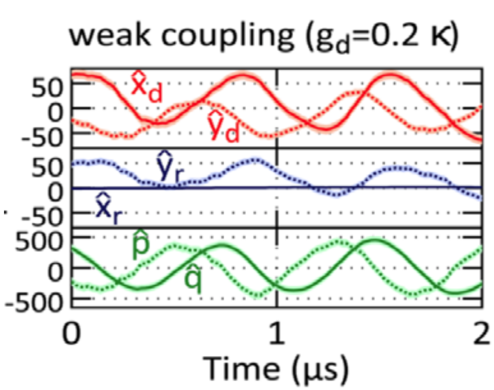
extensive toolbox for time-continuous control of optomechanical systems

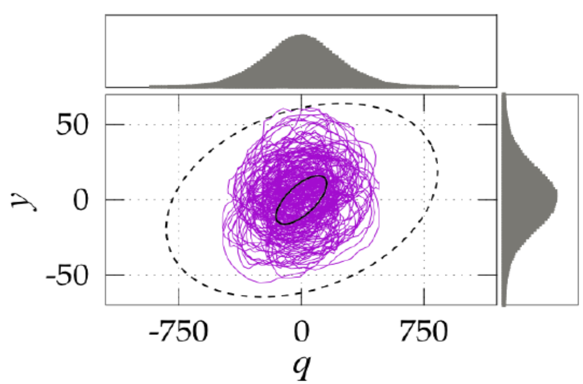
D2.3 Detection of optomechanical correlations by means of quantum filtering techniques (Month 24)

UNIVIE + LUH:
observe optomechanical correlations using Kalman filtering

- based on accurate model of experimental setup (including colored laser amplitude and phase noise, photon losses, multiple mechanical modes)
- produces the least-square-error estimates of optomechanical dynamical variables
- trajectories allow monitoring of optomechanical correlations in real time





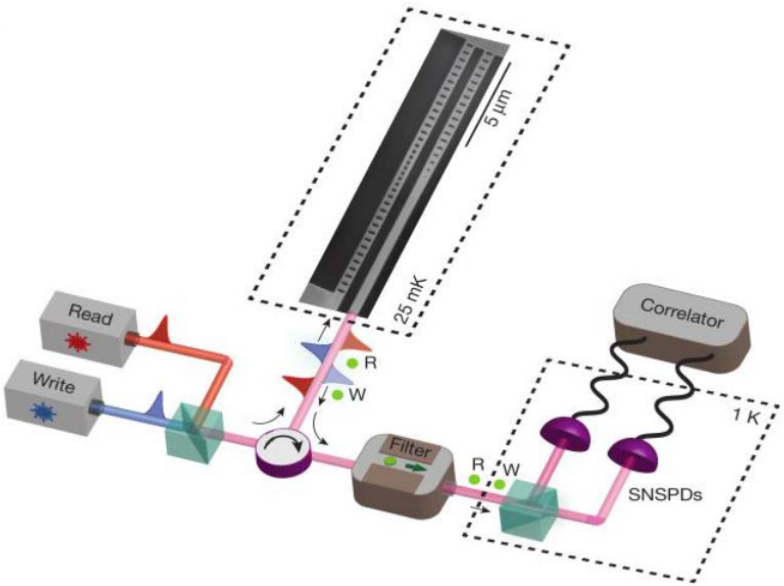


towards real-time optimal (classical and quantum) control of cavity optomechanical systems

Physical Review Letters 114, 223601 (2015)

D2.4 Coherent photon-phonon conversion in an optomechanical system (Month 24)

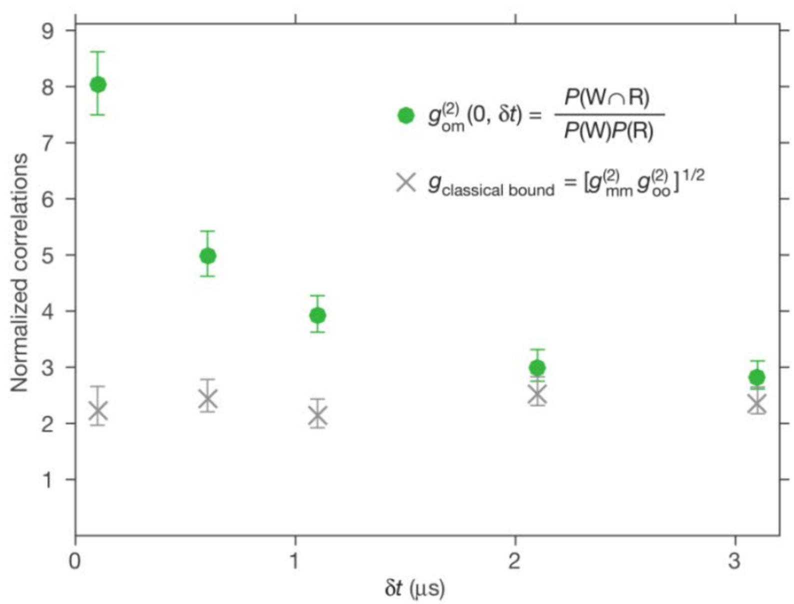
UNIVIE + TU Delft:
coherent **photon—phonon—photon conversion** on the level of single quanta



on-chip solid-state mechanical resonators as light–matter quantum interface

fully quantum protocol:

- initialization of the resonator in its quantum ground state of motion
- subsequent generation and read-out of *correlated photon–phonon pairs*
- violation of Cauchy-Schwarz inequality:
- unambiguous evidence for non-classical mechanical state



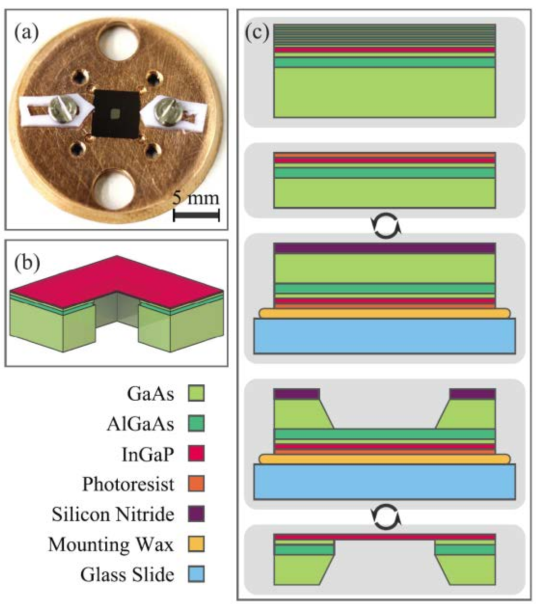
Nature 530, 313 (2016)

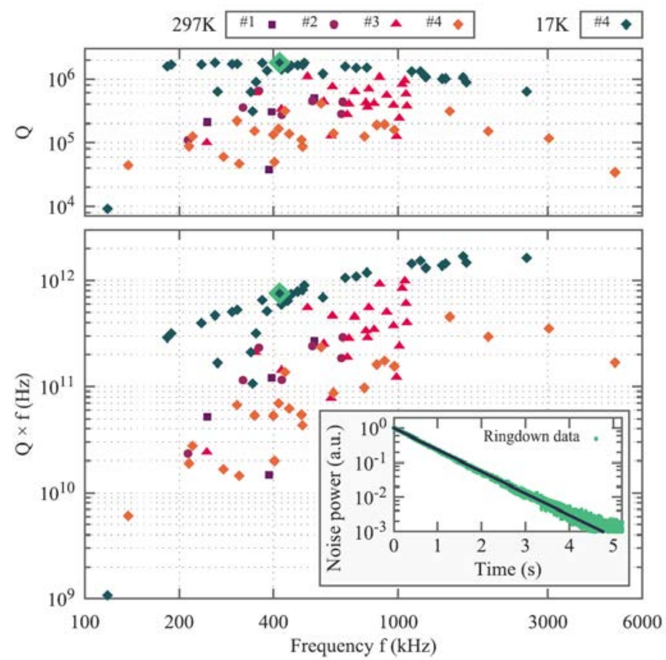
D2.5 Demonstration of large single-photon optomechanical coupling rates (one order of magnitude improvement in g_0/κ) at cryogenic temperatures (Month 36)

UNIVIE + JILA:
optomechanical properties of tensile-strained $In_xGa_{1-x}P$ nanomembranes on GaAs

intrinsic tensile strain to a monocrystalline thin film of $In_xGa_{1-x}P$

- mechanical quality factors of $>10^6$
- Q-f products of $>10^{12}$
- optical loss <40 ppm@1064nm





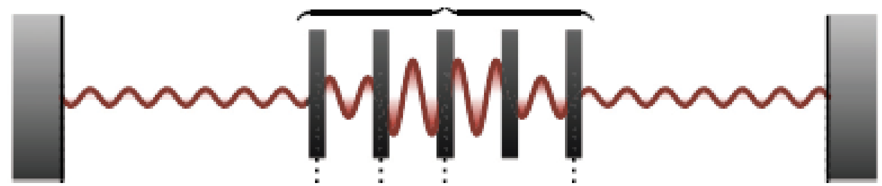
novel experimental architecture for realizing **stacks of membranes** for enhanced optomechanical coupling

Applied Physics Letters 104, 201908 (2014)

LARGE SINGLE-PHOTON COUPLING WITH TWO MEMBRANES-IN-THE-MIDDLE

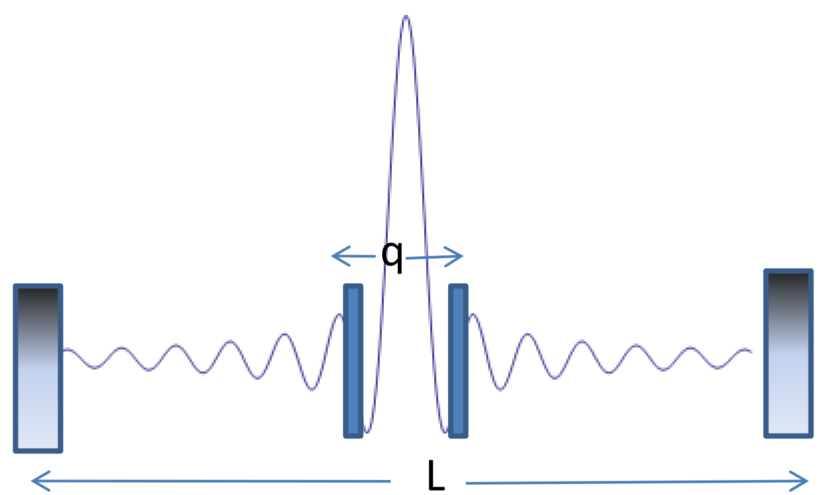
Strong optomechanical coupling can be achieved with a stack on N equidistant membranes in a Bragg reflector configuration

Strong coupling is obtained when light is mostly confined within the membranes

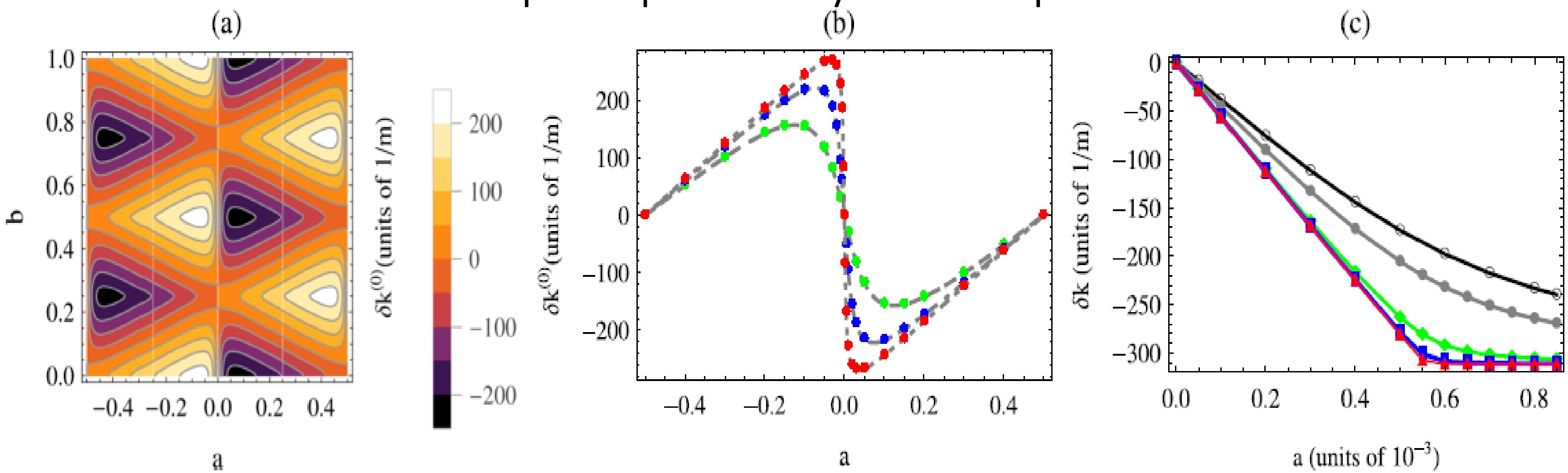


We have shown (J. LI et al, J. Opt. 2016) that the strong coupling condition can be achieved already with TWO membranes only

$$\boxed{\frac{g}{\kappa} \approx 1}$$



From the explicit optical cavity mode frequencies



(a) Frequency shift of a cavity mode as a function of membrane distance q = (10.5+a) λ and their center of mass Q=bλ, for R_m = 0.8. (b) Frequency shift versus q = (10.5+a) λ (Q = 0), for various values of the reflectivity: R_m = 0.5 (dashed curve; green dots), R_m = 0.8 (dotted–dashed; blue dots) and R_m = 0.95 (dotted; red dots). (c) The same as (b), very close to the limit R_m = 1. In practice we take $T_m = 1-R_m = 2 \times 10^{-3}$, (black); 10^{-3} (gray); 10^{-4} (green); 10^{-5} (blue); 10^{-6} (red).

We find for the relative motion optomechanical coupling

$$g_q = -\frac{\cos(2k^{(0)}Q) + \sqrt{R_m}}{T_m} g_{sing},$$

which saturates for R_m -> 1, to

$$\boxed{\frac{\omega_0}{q} x_{zpm} = g_q^{max},}$$

Strong coupling is achieved for membrane reflectivities R_m -> 1 and when the inner cavity is close to resonance

•The ratio g/k is significantly improved because the the coupling tends to that of the inner cavity, while the finesse remains that of the external, longer cavity.

$$\boxed{\left|\frac{(g/\kappa)_{\mathrm{double}}}{(g/\kappa)_{\mathrm{sing}}}\right| = \left|\frac{g_q^{\max}}{g_{\mathrm{sing}}}\right| = \frac{L}{2q},}$$

The price to pay is that the membrane separation and alignment has to be controlled at the level of λ (1-R_m)

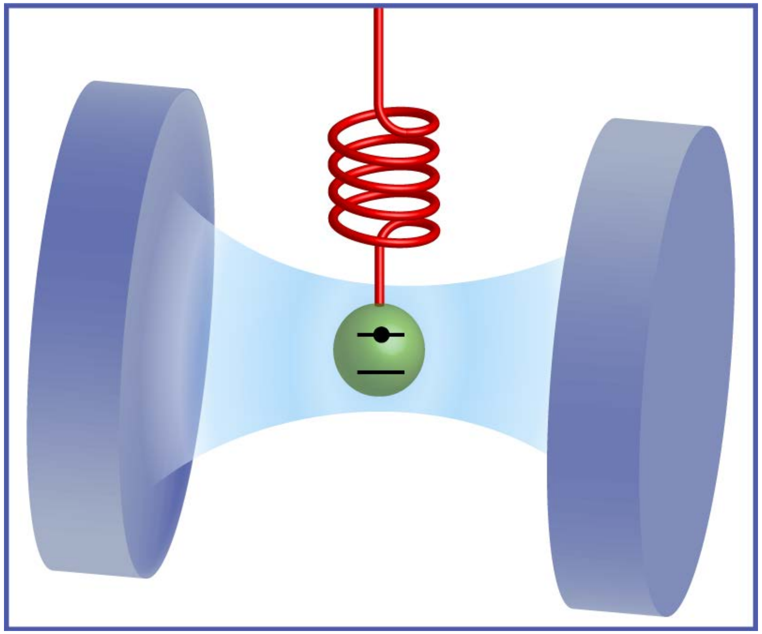
Qubit coupled to resonator

- **Qubit**
- **photonic cavity**

$$H_c = \omega_c\left(\hat{a}^+\hat{a}+\frac{1}{2}\right)$$

- **phononic cavity**

$$H_m = \omega_m\left(\hat{b}^+\hat{b}+\frac{1}{2}\right)$$



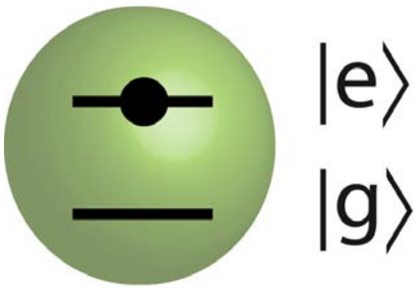
$$H = H_{QB} + H_c + H_m + H_{QB\text{-}c} + H_{QB\text{-}m}$$

$$H_{QB\text{-}c} = g_c\left(\hat{a}^+ + \hat{a}\right)\hat{\sigma}_x \qquad g_m \approx 100\ \mathrm{MHz} \approx f_m$$

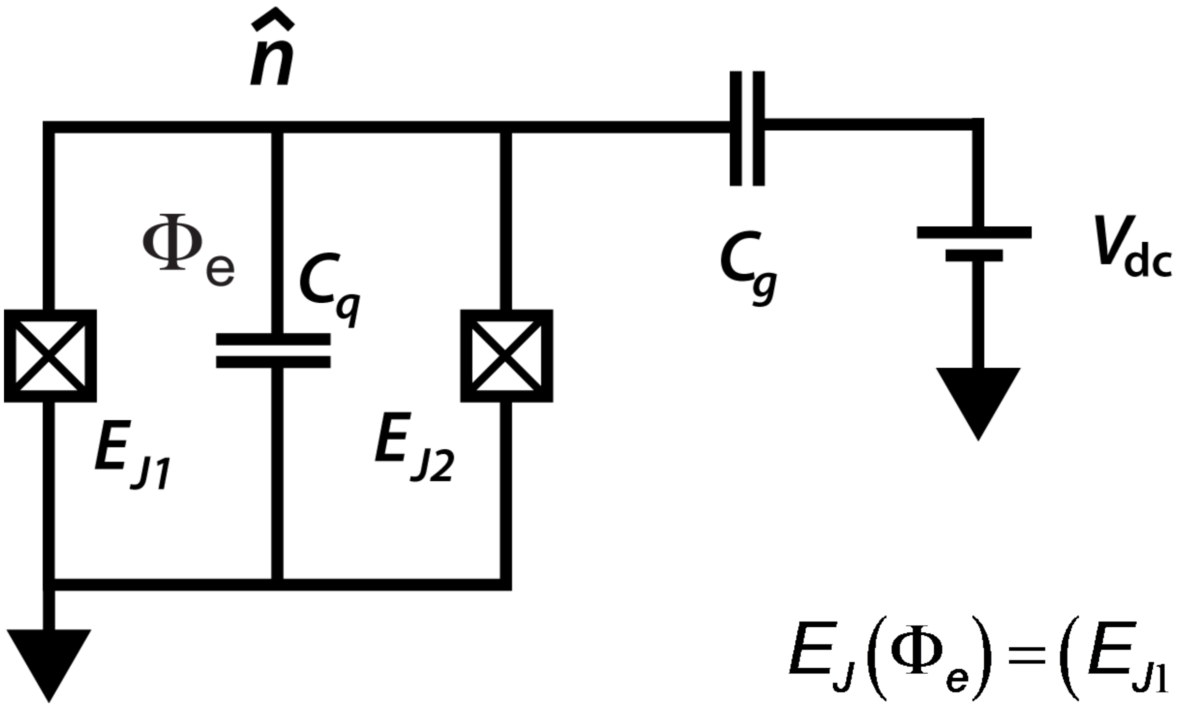
$$H_{QB\text{-}m} = g_m\left(\hat{b}^+ + \hat{b}\right)\hat{\sigma}_z \qquad g_c \approx \sqrt{Z_0/R_Q}\,E_J \approx 1\ \mathrm{GHz}$$

Cooper-pair box = charge qubit

- Small capacitance $E_J / E_c < 1$



$$H_{QB} = -2E_C\left(1-2n_g\right)\hat{\sigma}_z - \frac{1}{2}E_J\hat{\sigma}_x$$



$$n_g = \frac{C_g V_{dc}}{2e}$$

$$E_C = \frac{e^2}{2C_\Sigma}$$

$$E_J(\Phi_e) = \left(E_{J1} + E_{J2}\right)\cos\left(\pi\frac{\Phi_e}{\Phi_0}\right)$$

Cooper-pair box coupled to a phonon

$$H_{QB} = -2E_C\left(1-2n_g\right)\hat{\sigma}_z - \frac{1}{2}E_J\hat{\sigma}_x$$

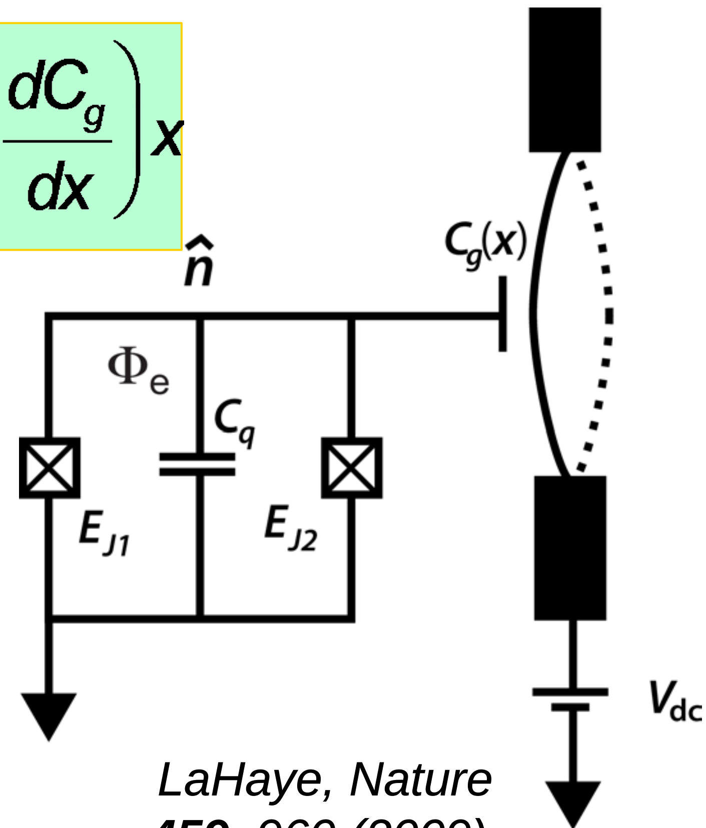
$$C_g(x) = C_{g0} + \frac{dC_g}{dx}x$$

Motion affects gate charge (scaled by 2e)

$$n_g(x) = \frac{V_{dc}}{2e}C_{g0} + \frac{V_{dc}}{2e}\left(\frac{dC_g}{dx}\right)x$$

$$\hat{H} = \hat{H}_{QB} + \omega_m\left(\hat{b}^+\hat{b} + \frac{1}{2}\right) - g_m\left(\hat{b}^+ + \hat{b}\right)\hat{\sigma}_z$$

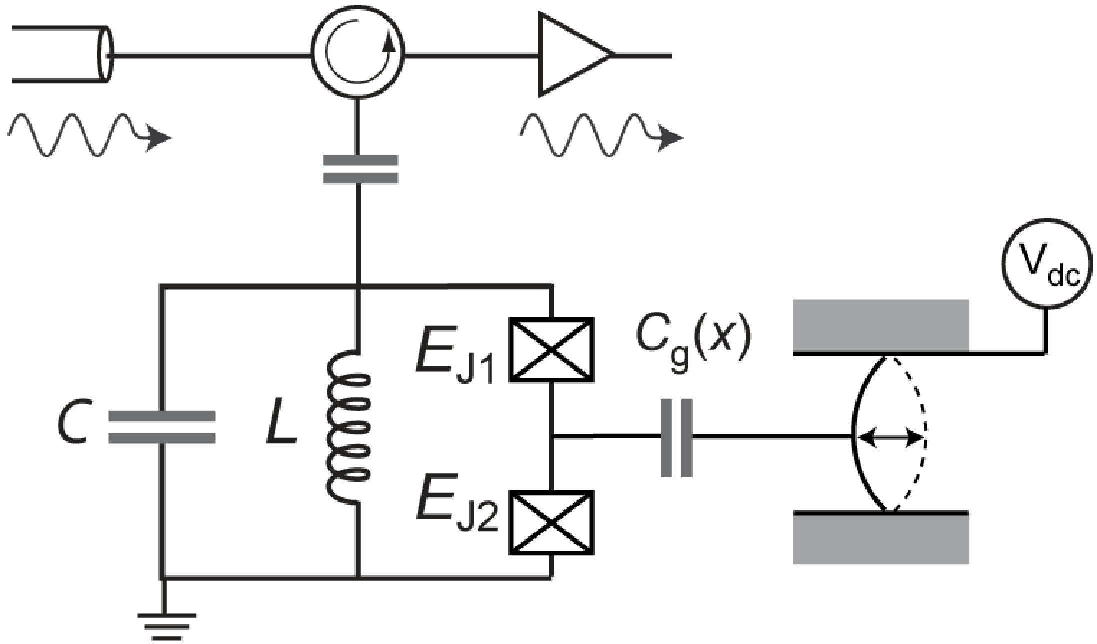
$$g_m = \frac{2E_C}{e}x_{ZP}V_{\mathrm{dc}}\left(\frac{\partial C_g}{\partial x}\right) \approx 1\ldots100\ \mathrm{MHz}$$



LaHaye, Nature ***459****, 960 (2009).*

Effective optomechanical system

- Qubit-cavity coupling very large



$$H_{QB\text{-c}} = g_{\mathrm{c}}\left(\hat{a}^{+} + \hat{a}\right)\hat{\sigma}_x \qquad g_m \approx 100\ \mathrm{MHz} \approx f_m$$

$$H_{QB\text{-m}} = g_m\left(\hat{b}^{+} + \hat{b}\right)\hat{\sigma}_z \qquad g_{\mathrm{c}} \approx \sqrt{Z_0/R_Q}\,E_J \approx 1\,\mathrm{GHz}$$

Effective optomechanical system

- ***Qubit tweaks a linear coupling into σ_z coupling***
- Trace out the qubit with Schrieffer-Wolff
- ***Effective cavity*** couples to ***effective*** mechanics via ***radiation-pressure***

$$H_{eff} = \omega_c^{eff} a^+ a + \omega_m^{eff} b^+ b + \boxed{g a^+ a x} + g_{xx} x_c x + g_4 a^+ a b^+ b$$

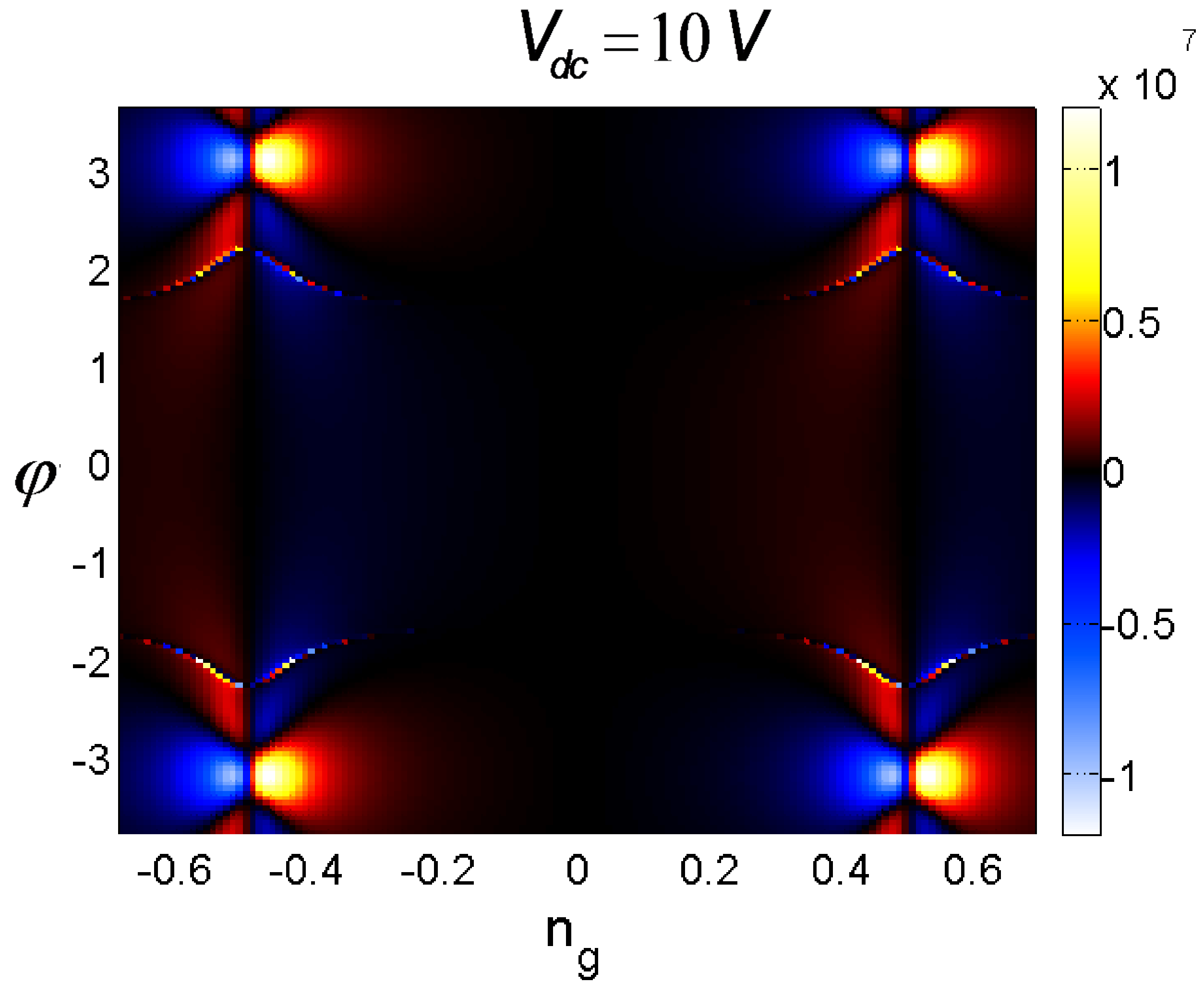
$$\boxed{\frac{g}{g_0} = \frac{C_g V_{dc} L_{tot}}{2e} \frac{\partial L_J^{-1}}{\partial n_g} \approx \frac{C_g V_{dc}}{2e} \left(\frac{E_C}{E_J} \right)}$$

$$g_{xx} \approx g << g_m$$

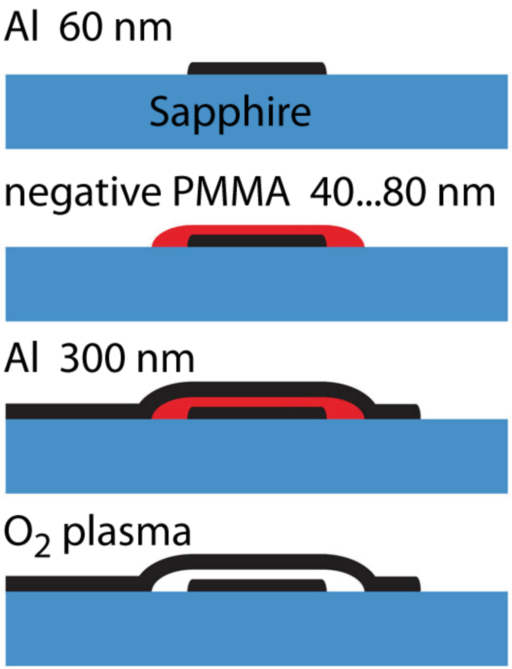
$$\frac{g_4}{g} \approx \frac{g}{E_J} \frac{R_Q}{Z_0} < 1$$

$$\boxed{\begin{array}{l} V_{dc} = 10\,\mathrm{V} \\ E_J / E_C = 0.1 \\ g / g_0 \sim 10^6 \end{array}}$$

Radiation-pressure coupling



Bridge type micromechanical resonator

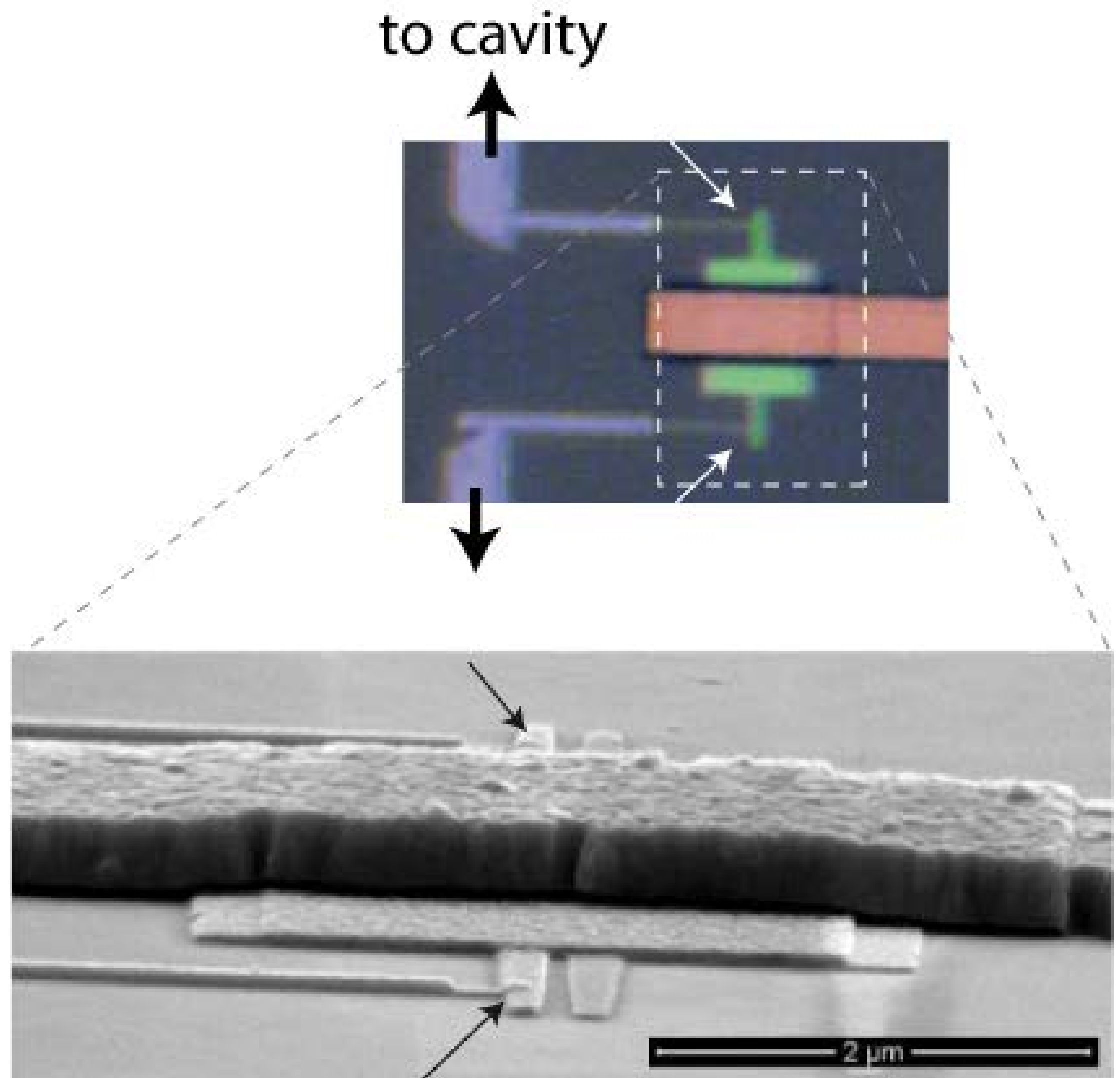


$$L = 5\mu m$$

$$W = 2\mu m$$

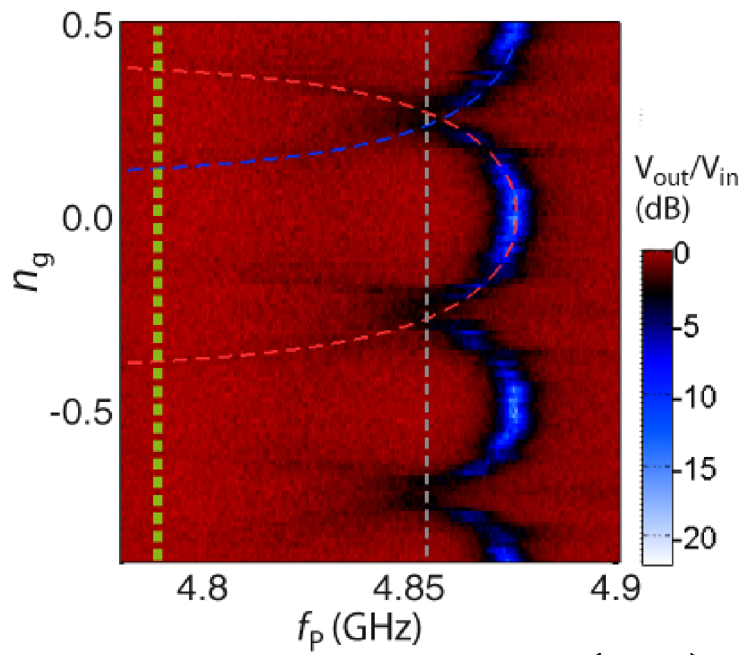
$$d = 40\,\mathrm{nm}$$

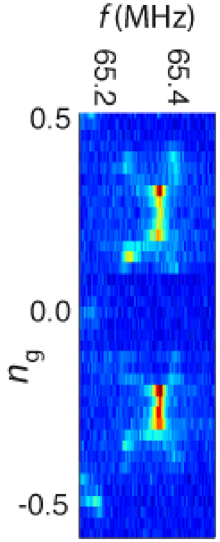
$$x_{ZP} = 6.2\,\mathrm{fm}$$



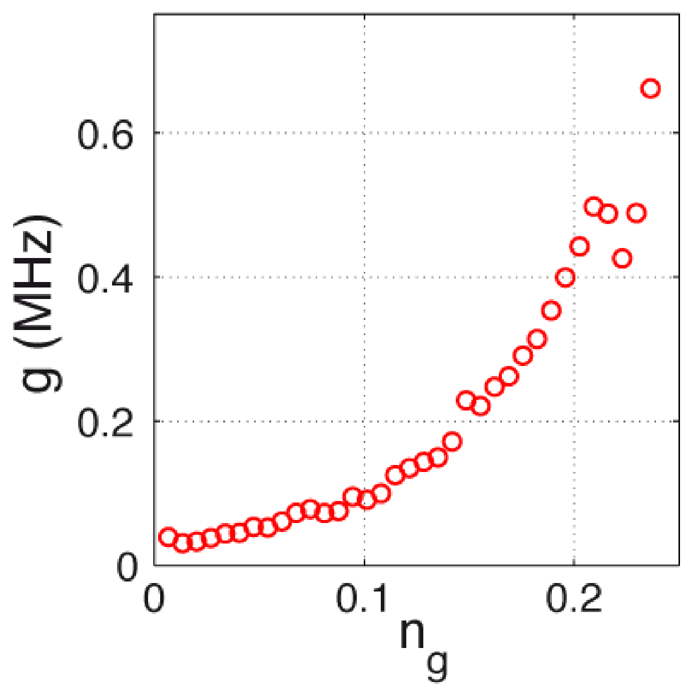
Cavity charge modulation

- Tune down effective $E_J/E_C \rightarrow 0.6$ by flux bias $\Phi_e \approx 0.4\Phi_0$
- Cavity frequency is sensitive to charge





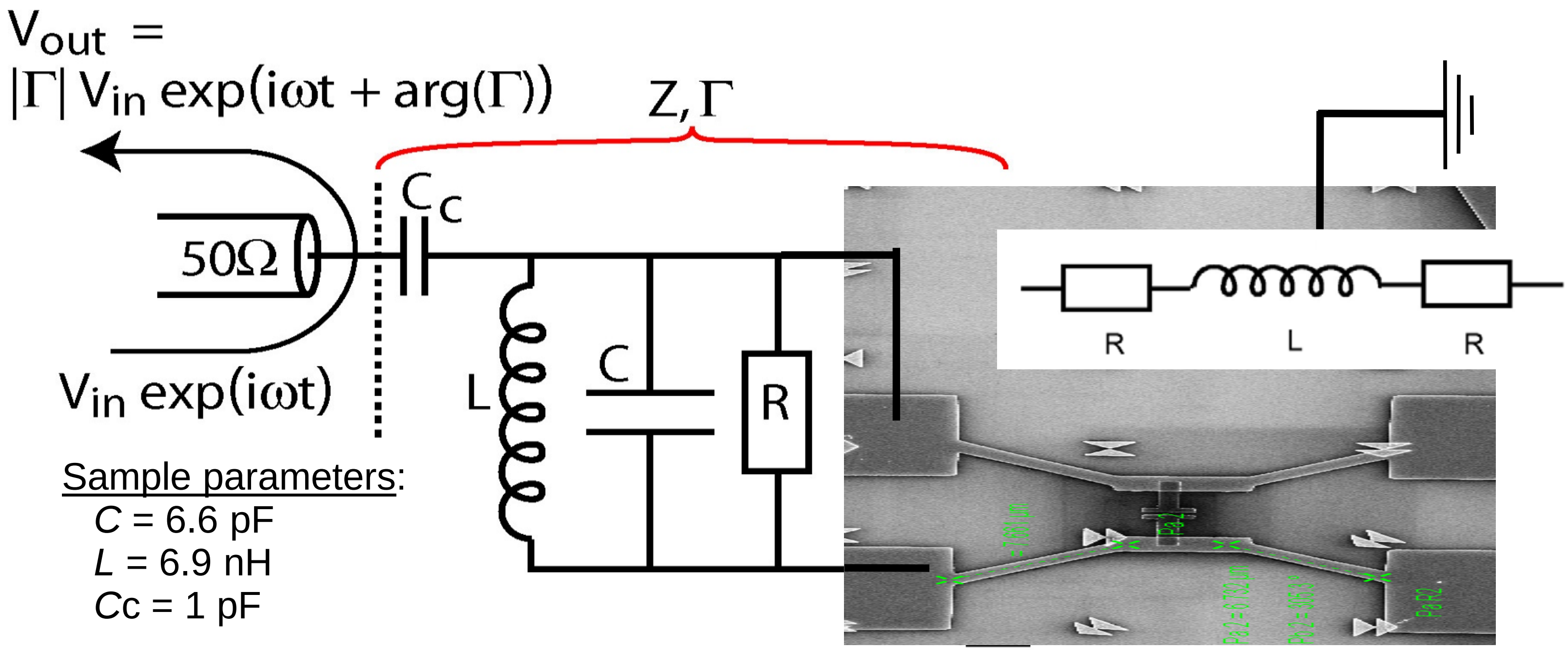
$$V_{dc} = 4.6\,V$$



$$g \equiv x_{ZP}\frac{\partial f_c}{\partial x} = x_{ZP}\frac{V_{dc}}{2e}\left(\frac{\partial f_c}{\partial n_g}\right)\left(\frac{\partial C_g}{\partial x}\right)$$

$\boxed{1\,\mathrm{Hz} \Rightarrow 0.5\,\mathrm{MHz}}$

Superconducting CNT transistor



<u>Sample parameters</u>:
- C = 6.6 pF
- L = 6.9 nH
- Cc = 1 pF

Microwave reflection

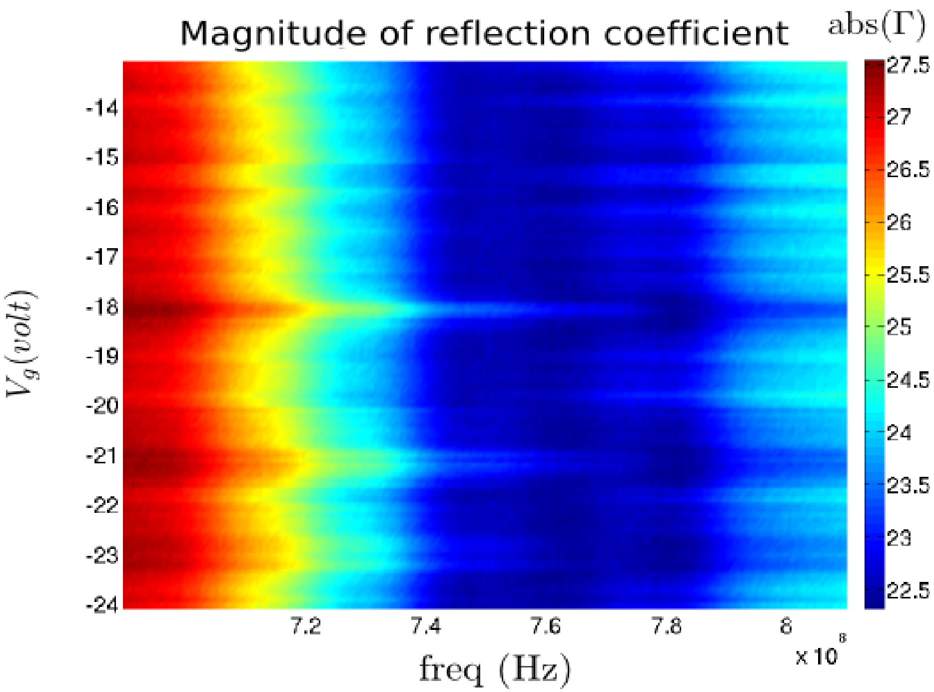
$$\Gamma = \frac{Z - Z_0}{Z + Z_0}$$

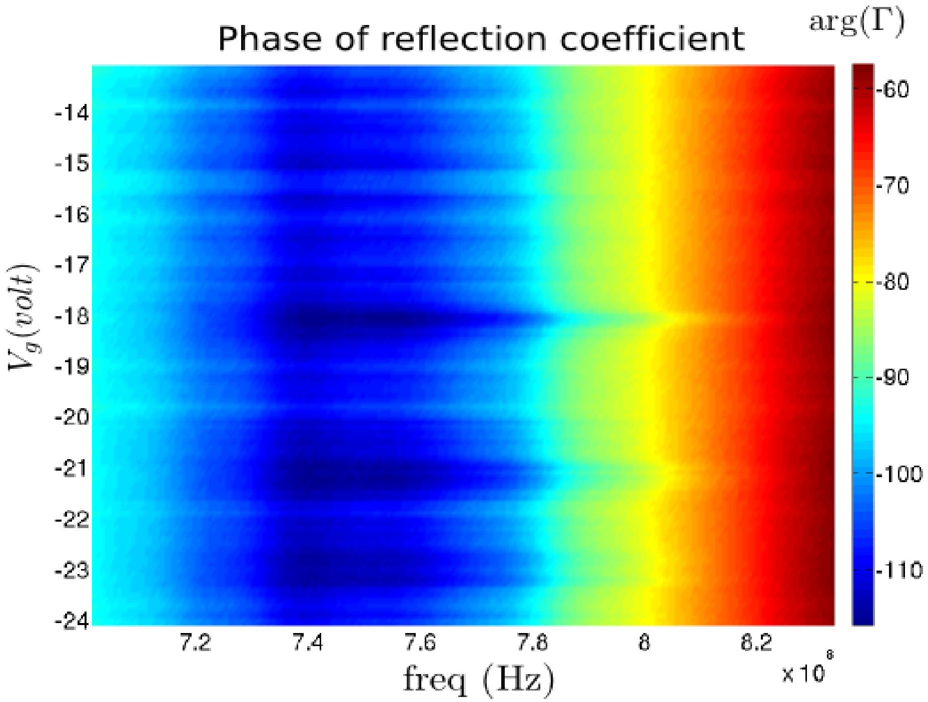
$$Z = \frac{1}{i\omega C_C} + \left(i\omega C + \frac{1}{i\omega L} + \frac{1}{i\omega L_J^*} + \frac{1}{R} \right)^{-1}$$

$$\frac{1}{L} = \left(\frac{2e}{\hbar} \right)^2 \frac{\partial^2 E}{\partial \varphi^2}$$

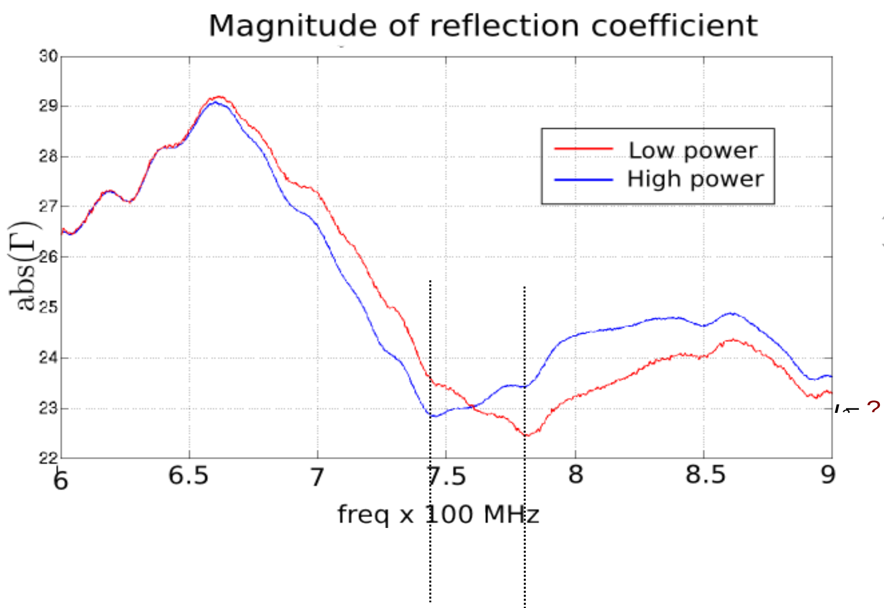
$$L_J = \frac{\hbar}{2eI_C}$$

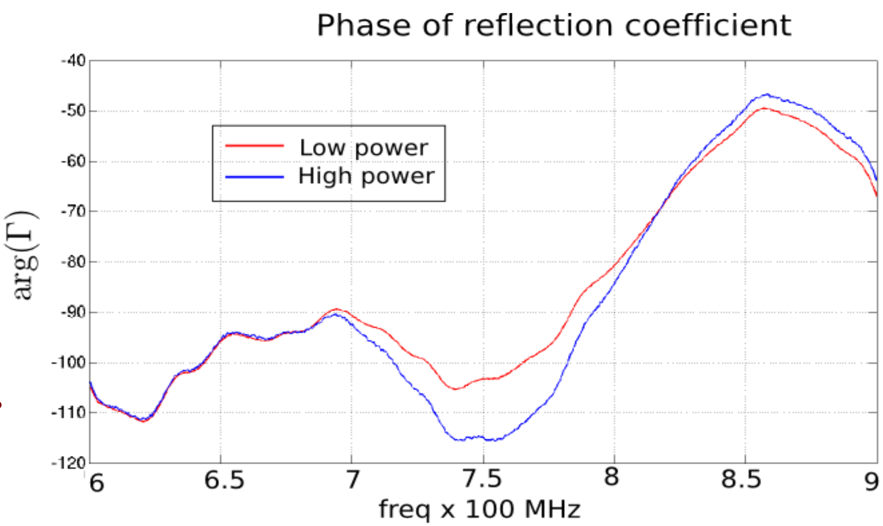
Gate dependent supercurrent





Josephson inductance and supercurrent





Δf = 37 MHz

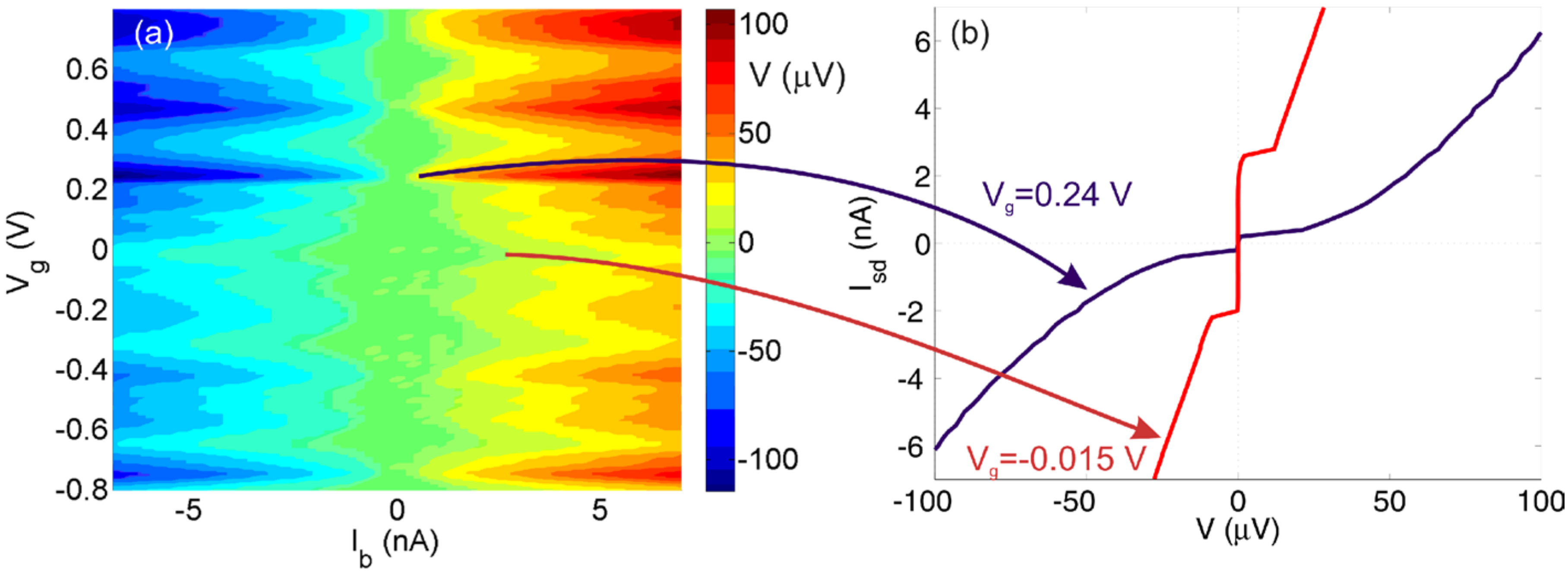
$$\boxed{\frac{1}{L_j} = C(2\pi f)^2 - \frac{1}{L}}$$

$$\boxed{I_c = \frac{\hbar}{2eL_J}}$$

L_J = 68 nH

I_C = 4.8 nA

I_c modulation and microwaves



P. Häkkinen, A. Fay, P. Lähteenmäki, D. Golubev, and P. Hakonen, APL 2015

Classical phase diffusion

Zero bias resistance:

$$R_0 = \frac{Z_{env}}{I_0(E_J/k_BT)^2 - 1} \qquad R_0 = 2Z(0)\left(\frac{k_BT}{E_J}\right)^2$$

Maximum current:

$E_J << k_BT$

$$I_{cm} = \frac{E_J}{4k_BT} I_{c0} \qquad I = \frac{I_{c0}^{\ 2}}{2} \frac{Z(0)V}{V^2 + \left(\frac{2eZ(0)k_BT}{\hbar}\right)^2}$$

$$\boxed{I_{cm} \propto \frac{1}{R_n^2}} \qquad \frac{eV}{k_BT} << 1, \quad Z(0)\,\text{small}$$

$$\boxed{I_{cm} \propto I_C^2}$$

$$I(V_B) = I_0 \,\mathrm{Im}\left[\frac{I_{1-2i\beta eV_B/\hbar R_B}(\beta E_J)}{I_{-2i\beta eV_B/\hbar R_B}(\beta E_J)}\right]$$

Yu. Ivanchenko and L. Zil'berman, Sov. Phys. JETP **28**, 1272 (1969).

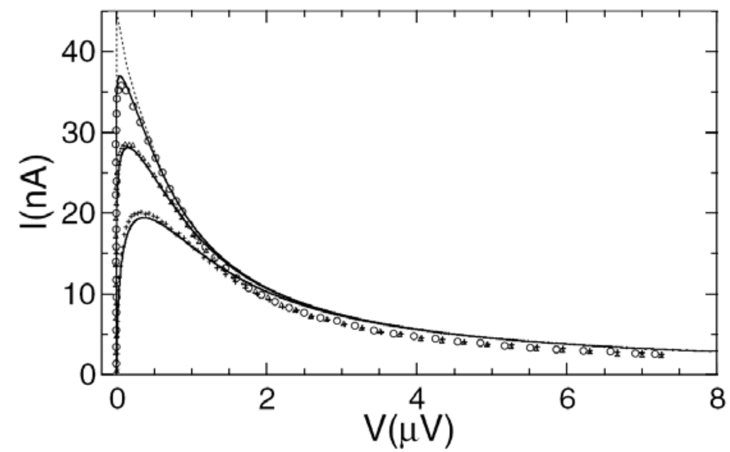


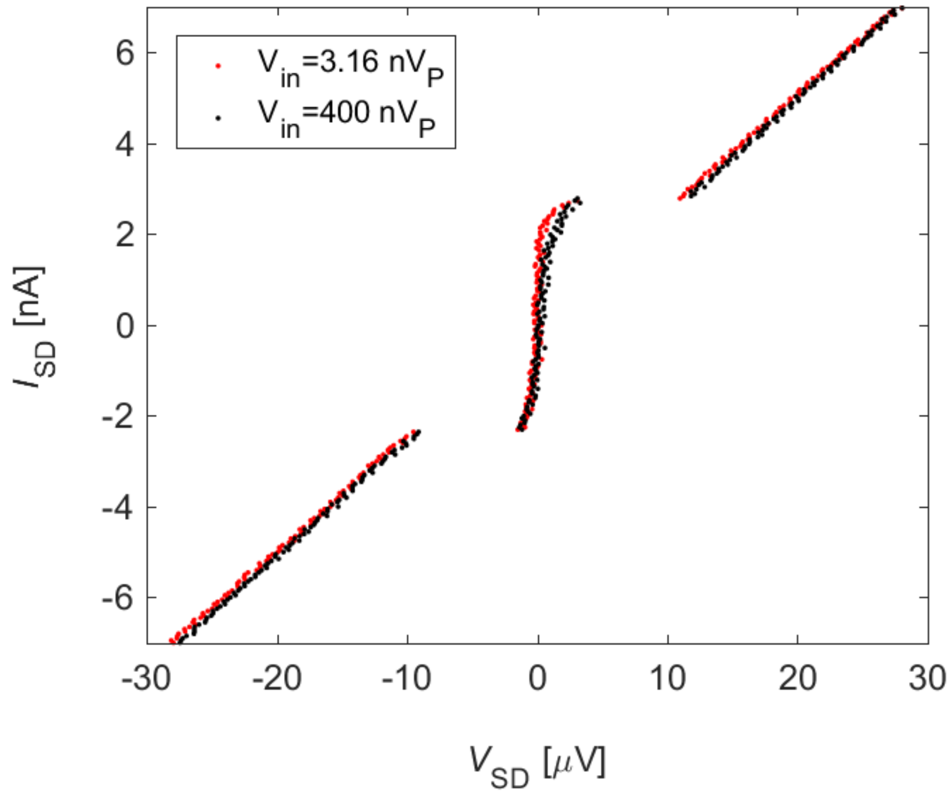
FIG. 3. Comparison between the $I(V)$ characteristics measured at different temperatures (symbols) and the calculated ones (full lines) using Eq. (1) and $I_0 = 44.9$ nA and $R = 24\ \Omega$. From top to bottom: $T = 34$, 157, and 400 mK, respectively. Dashed line represents the $I(V)$ predicted at $T = 0$.

A. Steinbach, et al., Phys. Rev. Lett. **87**, 137003 (2001).

Maximum of drive amplitude

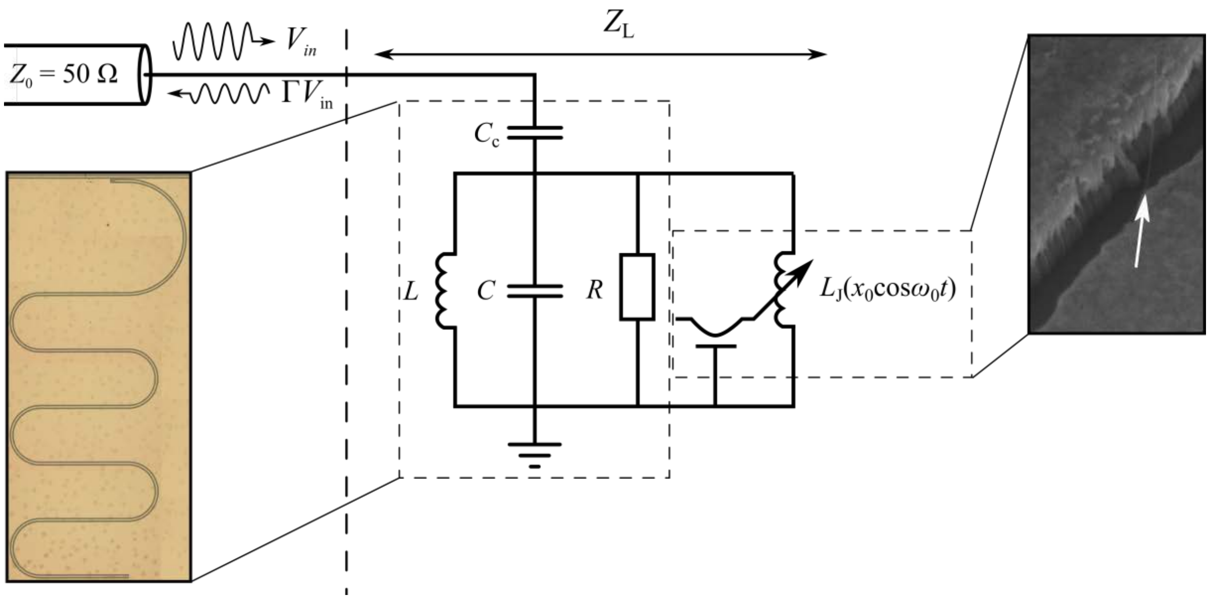
How high voltage can be applied?

P. Häkkinen, A. Fay, P. Lähteenmäki, D. Golubev, and P. Hakonen, APL 2015



- Experiments with MWNTs suggest that $V_{in} \approx 0.4\,\mu\mathrm{V_P}$ (-118 dBm) can be applied on source of a $I_{SW} \approx 2.6\,\mathrm{nA}$ junction before the zero voltage branch starts to become resistive.

Coupling to LC-circuit: principle



$$\omega_{\lambda/4} = 2\pi \cdot 5\ \text{GHz}$$

$$L = 2.1\ \text{nH}$$

$$C = 0.49\ \text{pF}$$

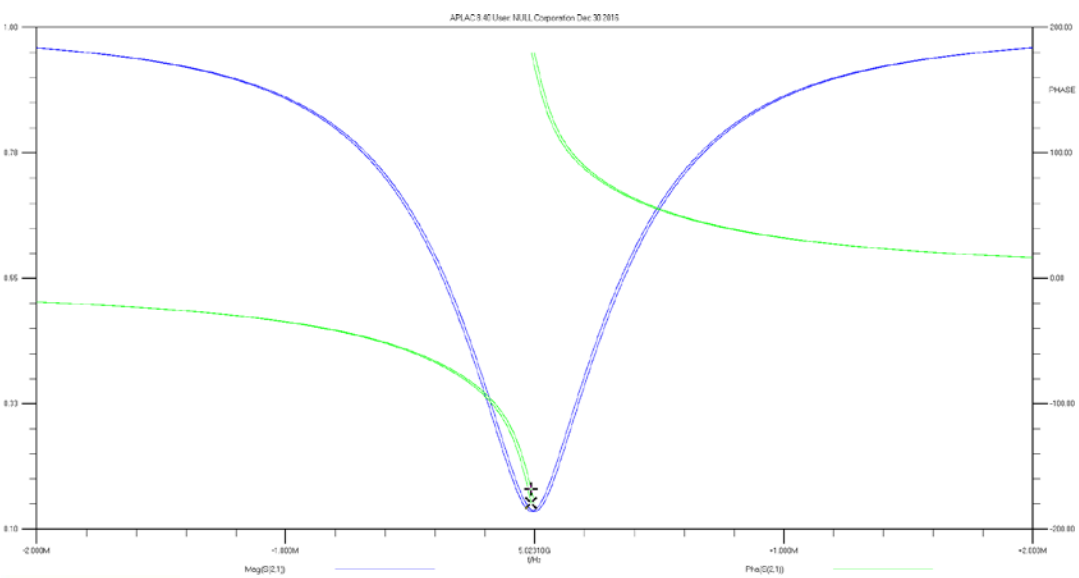
$$L_{\text{J}} = 55\ \text{nH}$$

$$\delta L_{\text{J,zpm}} = 5\ \text{pH},$$

$$\text{when } \delta Q_{\text{G,zpm}} = 200\ \mu\text{e}$$

$$Q_{\text{int}} = 10000$$

$$Q_{\text{ext}} = 17000$$



We would like to know:

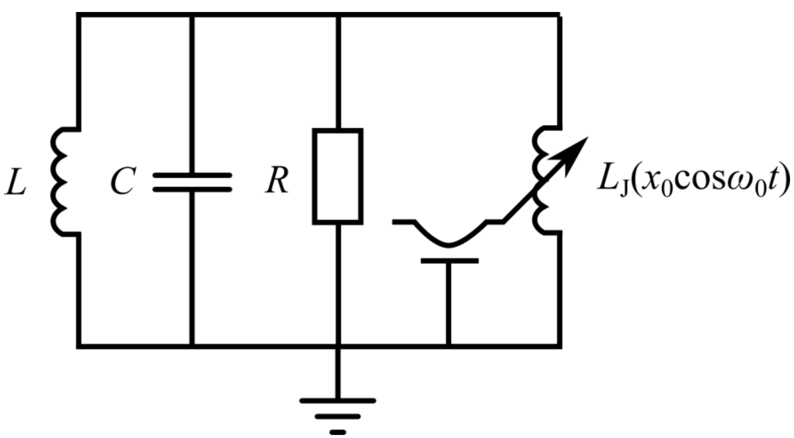
1. Coupling strength
2. Sideband signal to noise ratio

Coupling strength

$$g_0 = \frac{\partial \omega_{0,\text{loaded}}}{\partial x} x_{\text{zpm}} = \frac{\partial \omega_{0,\text{loaded}}}{\partial L_\text{J}} \delta L_{\text{J,zpm}}$$

$$\approx \left(1 - \sqrt{\frac{2}{\pi Q_\text{C}}}\right) \frac{\partial \omega_0}{\partial L_\text{J}} \delta L_{\text{J,zpm}} \approx \frac{\partial \omega_0}{\partial L_\text{J}} \delta L_{\text{J,zpm}}$$

→ OK to neglect couping capacitor

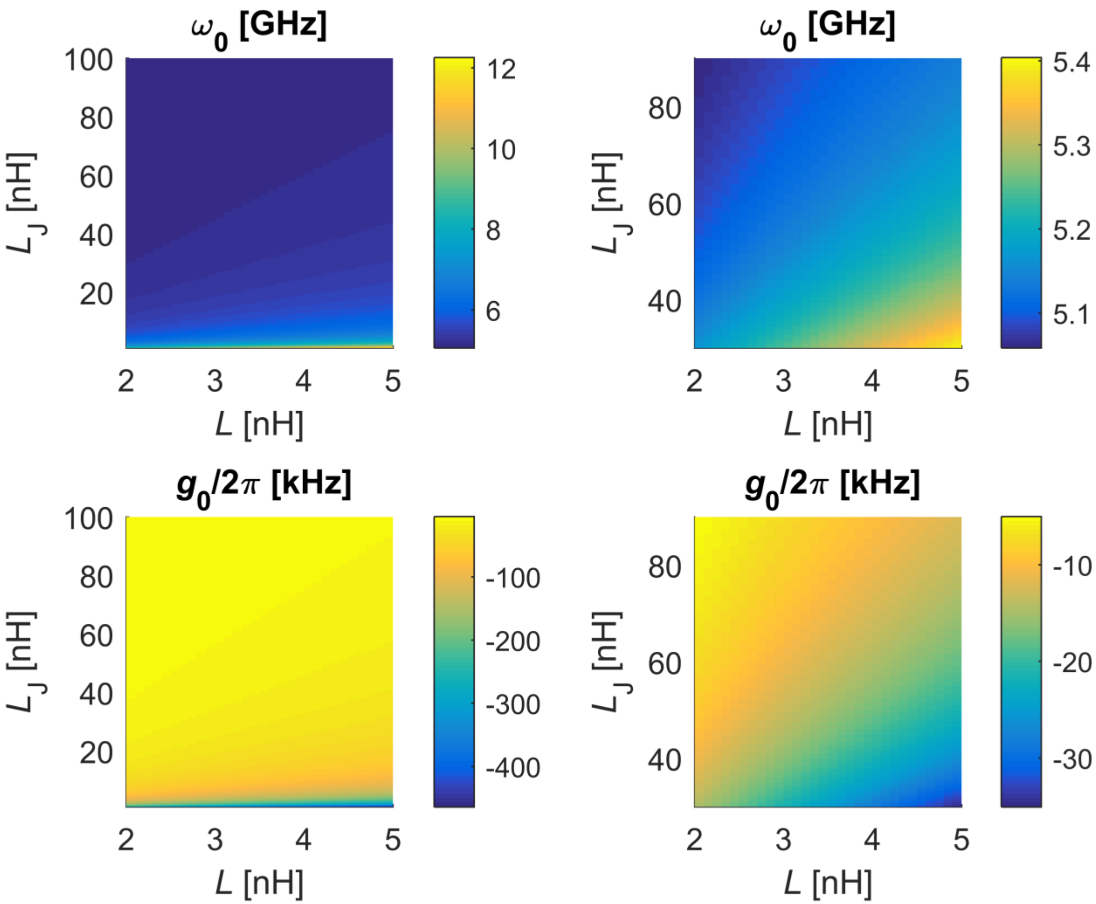


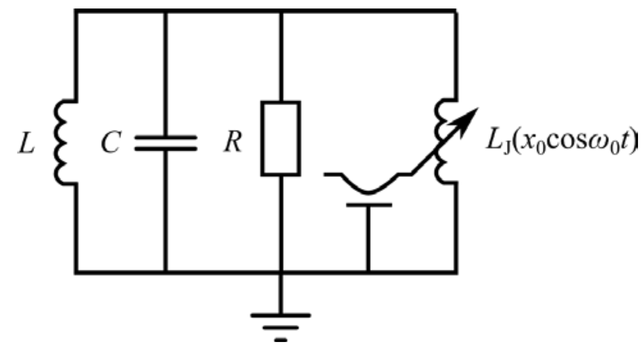
$$\omega_0 = \sqrt{\frac{1}{(L \parallel L_\text{J})C}}, \quad Q_\text{i} = \omega_0 RC$$

$$g_0 \approx \frac{\partial \omega_0}{\partial L_\text{J}} \delta L_{\text{J,zpm}} = -\frac{\omega_0}{2} \frac{L / L_\text{J}}{(L + L_\text{J})} \delta L_{\text{J,zpm}}$$

J. Pirkkalainen, …, P. Hakonen, M. Sillanpää, *Single-photon cavity optomechanics mediated by a quantum two-level system*, Nature Communications **6**, 6981 (2015).

Coupling strength



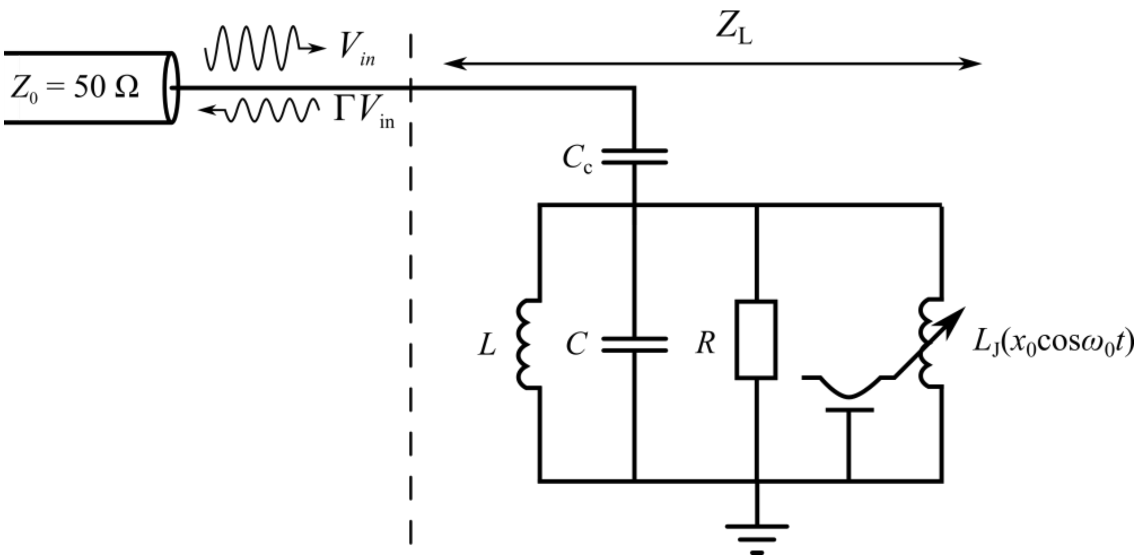


$$\frac{\delta L_{\mathrm{J,zpm}}}{L_{\mathrm{J}}} = \frac{5\cdot 10^{-12}}{55\cdot 10^{-9}}\ \forall\ L_{\mathrm{J}}$$

$$\omega_{\lambda/4} = 2\pi \cdot 5\,\mathrm{GHz}.$$

$$g_0 = 2\pi \cdot (-8.5\,\mathrm{kHz})\text{ at } L = 2.1\,\mathrm{nH} \wedge L_{\mathrm{J}} = 55\,\mathrm{nH}$$

Reflection coefficient



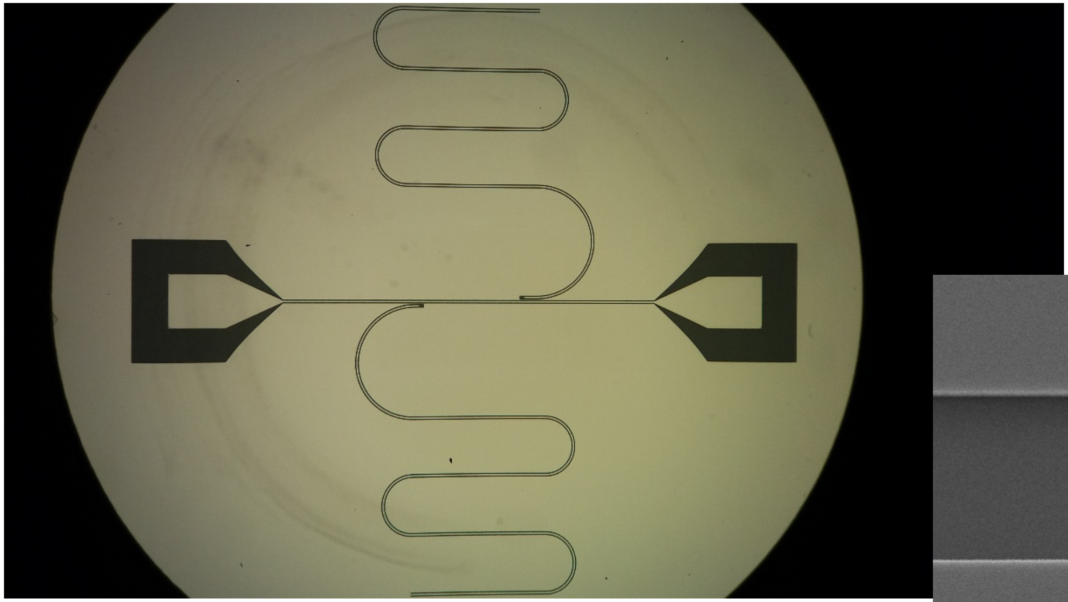
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

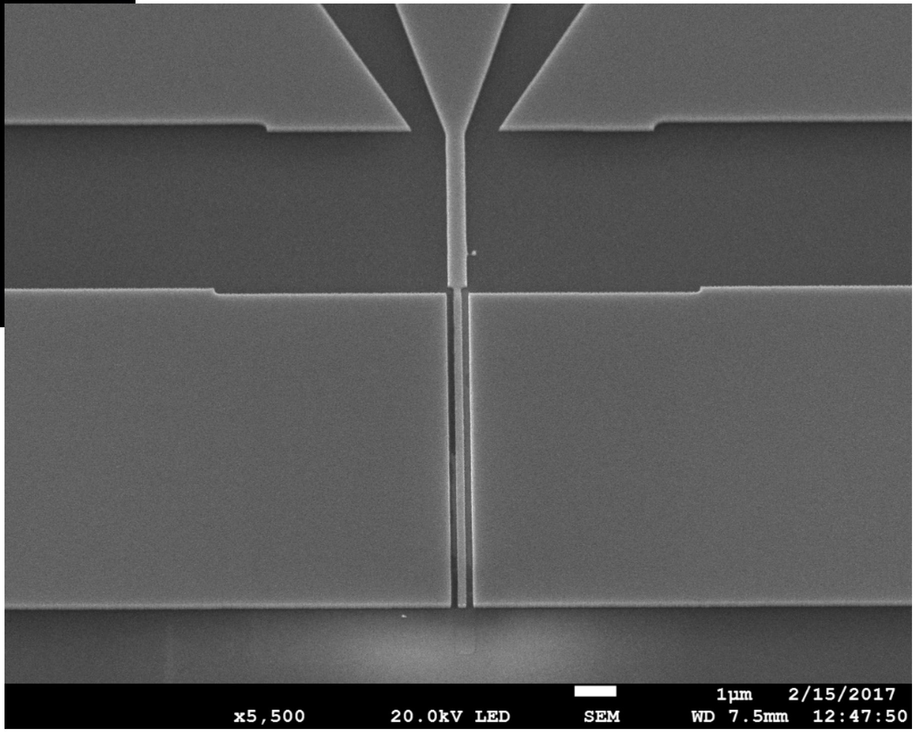
$$\Gamma V_{in} = V_{in}\,\Gamma\big|_{\omega_{in}} \cos\left(\omega_{in} t\right) + V_{in}\,\delta\Gamma\big|_{\omega_{in}} \tfrac{1}{2}\left\{\cos\left[\left(\omega_{in} + \omega_0\right)t\right] + \cos\left[\left(\omega_{in} - \omega_0\right)t\right]\right\}$$

$$\text{Signal}: \left|V_\pm\right| = \frac{V_{in}}{2}\left|\frac{\partial\Gamma}{\partial x}\bigg|_{\omega_{in}}\right| x_0 \quad \text{Noise}: \delta V_N = \sqrt{4k_B T_N Z_0 B} \quad SNR = \frac{\left|V_\pm\right|^2}{\delta V_N^2}$$

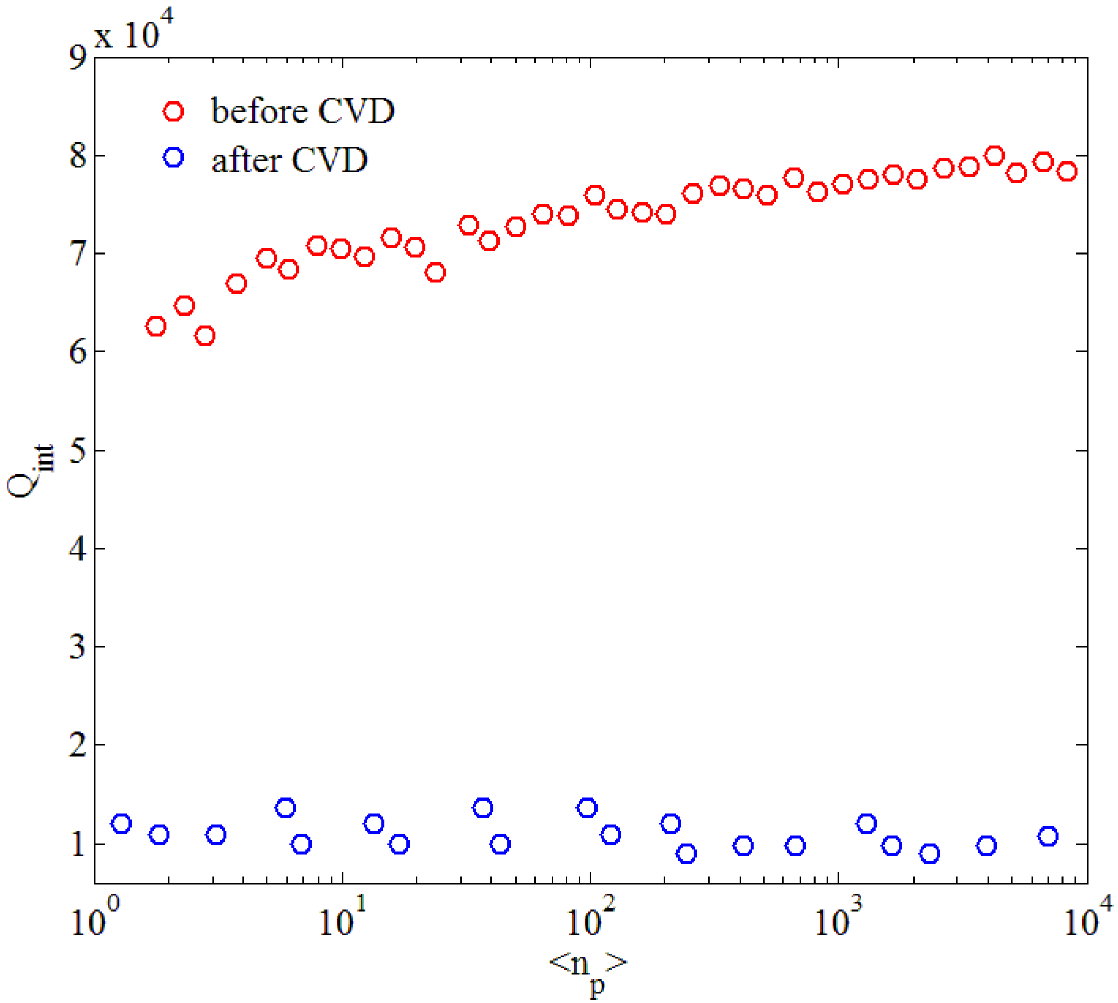
$|\delta\Gamma|$ from numerical calculation

MoRe microwave cavity

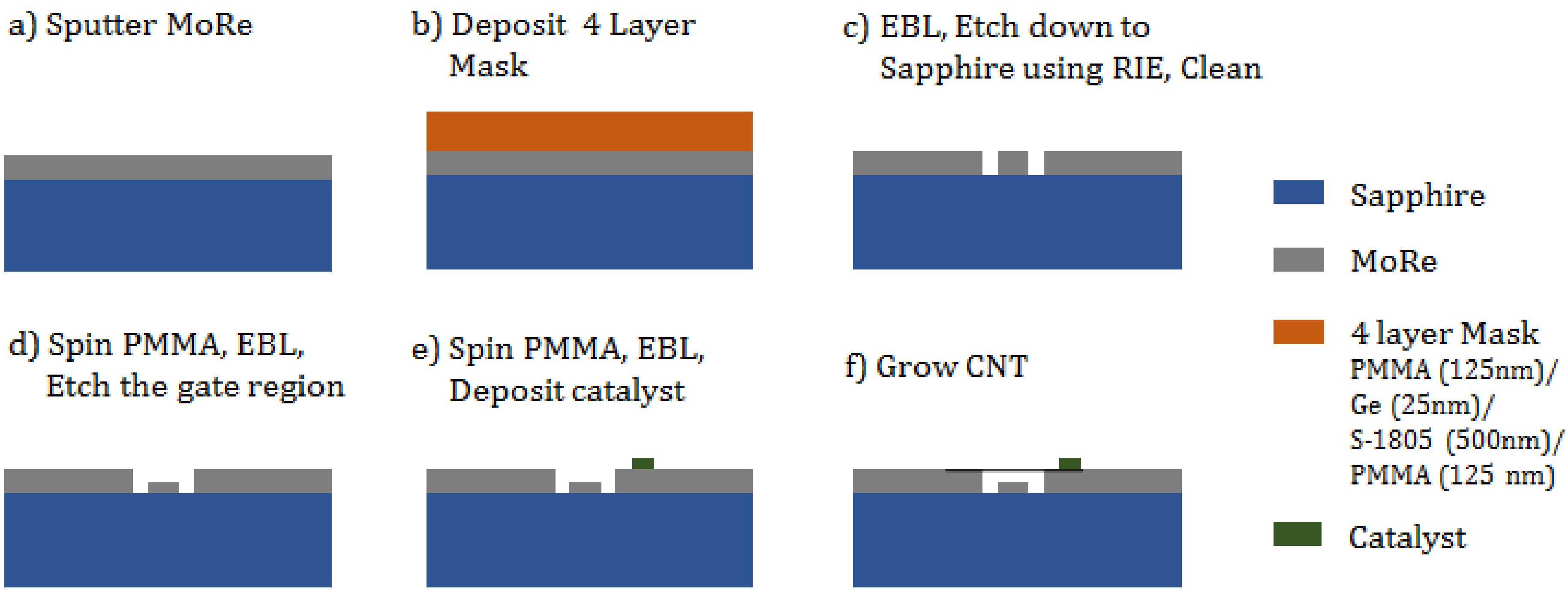




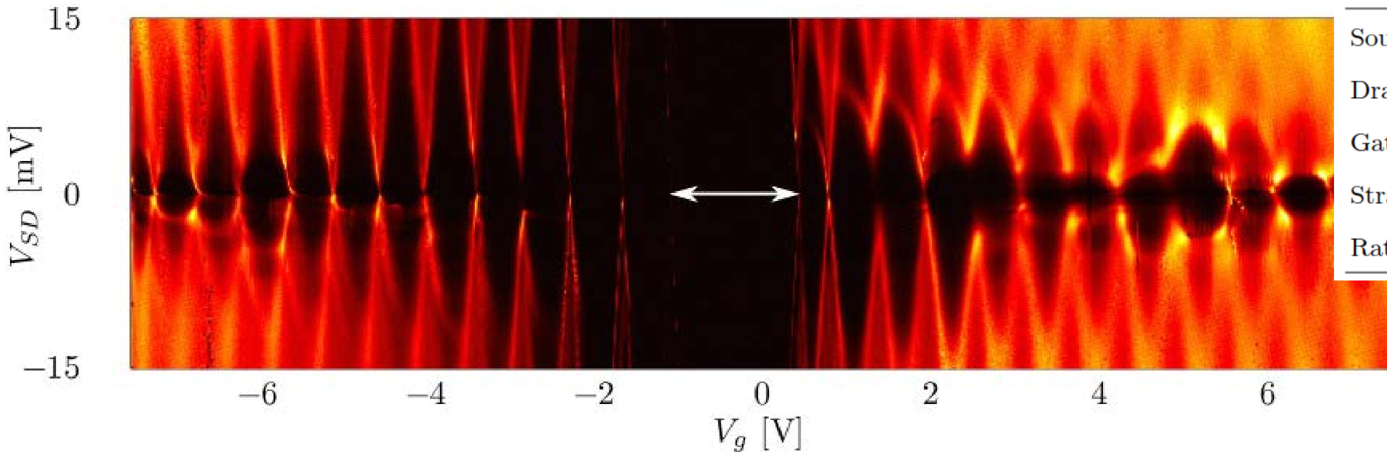
Losses in microwave cavity



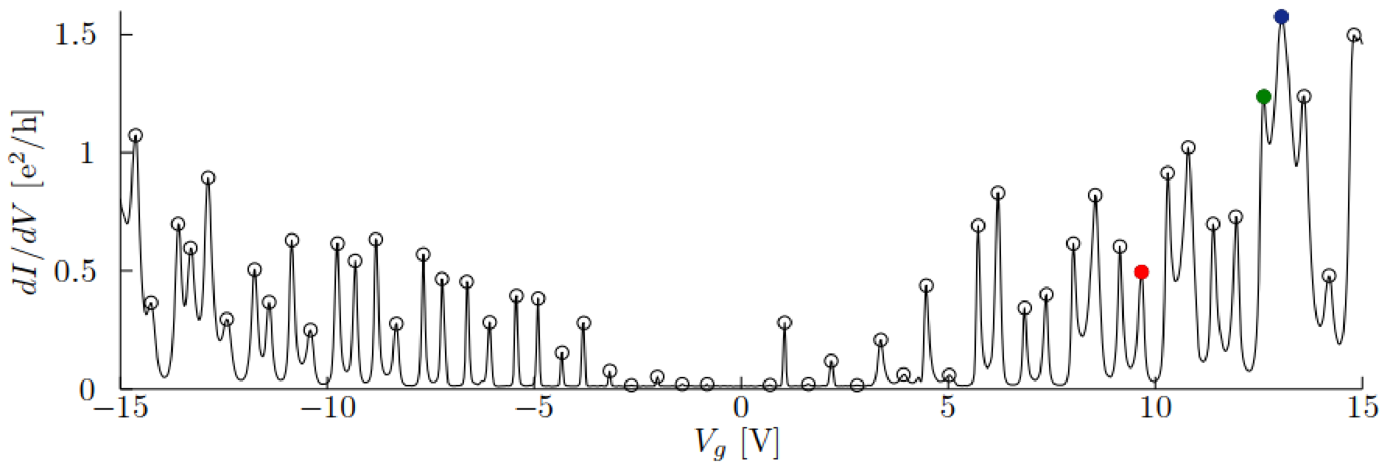
CVD growth of carbon nanotubes



Quality of CNTs



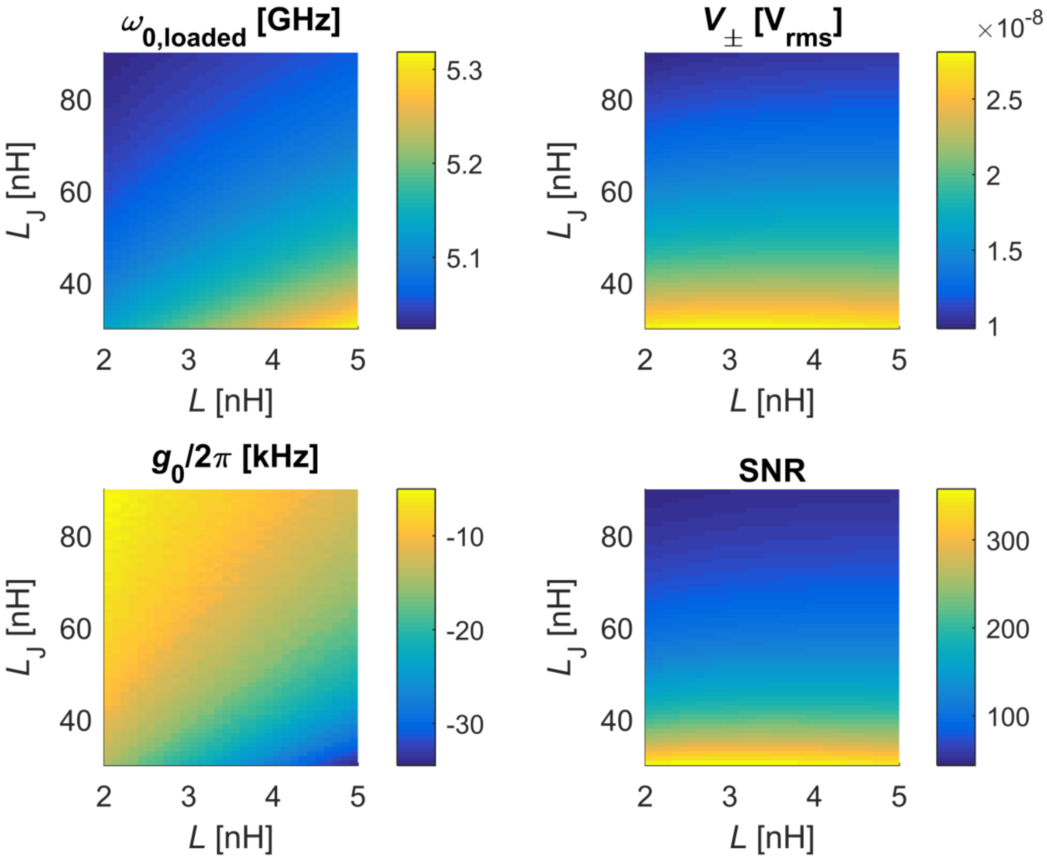
Quantity	Value
Source capacitance, C_S	3.4 aF
Drain capacitance, C_D	7.2 aF
Gate capacitance, C_G	0.34 aF
Stray capacitance, C_0	1.0 aF
Rate constant, $\Gamma_{L,R}/\Delta_D$	0.25×10^{34} s^{-1}J^{-1}



- supercurrents too small

Reflected signal

$$V_{in} = 1\,\mu\mathrm{V_P} \quad T_\mathrm{N} = 4\,\mathrm{K} \quad \mathrm{RBW} = 200\,\mathrm{Hz} \quad Q_\mathrm{int} = 10^4 \quad Q_\mathrm{ext} = 1.7\times10^4$$



$$@\ L = 2.1\,\mathrm{nH} \wedge L_\mathrm{J} = 55\,\mathrm{nH}$$

$$\omega_0 = 2\pi\cdot 5.085\,\mathrm{GHz}$$

$$g_0 = 2\pi\cdot(-8.5)\,\mathrm{kHz}$$

$$V_\pm = 15.8\,\mathrm{nV_{rms}}$$

$$\mathrm{SNR}\approx 113$$