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Surface acoustic wave resonators in the quantum regime

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NQIT Networked Quantum Information Technologies

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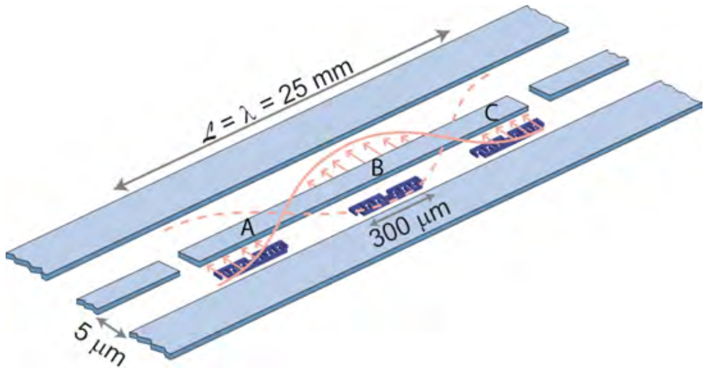
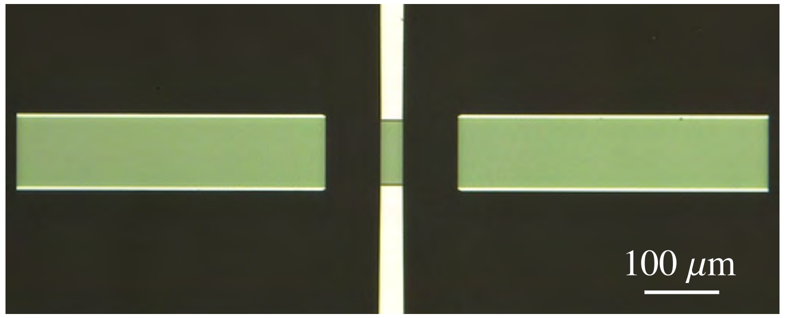
SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

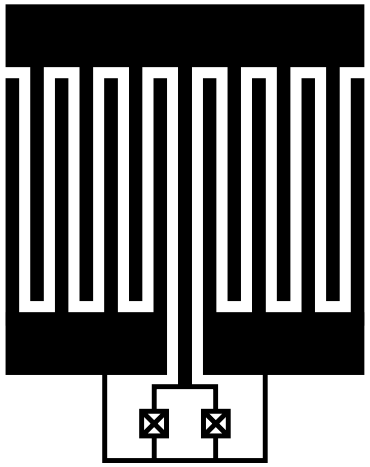
Outline



- Intro: Resonators in quantum devices

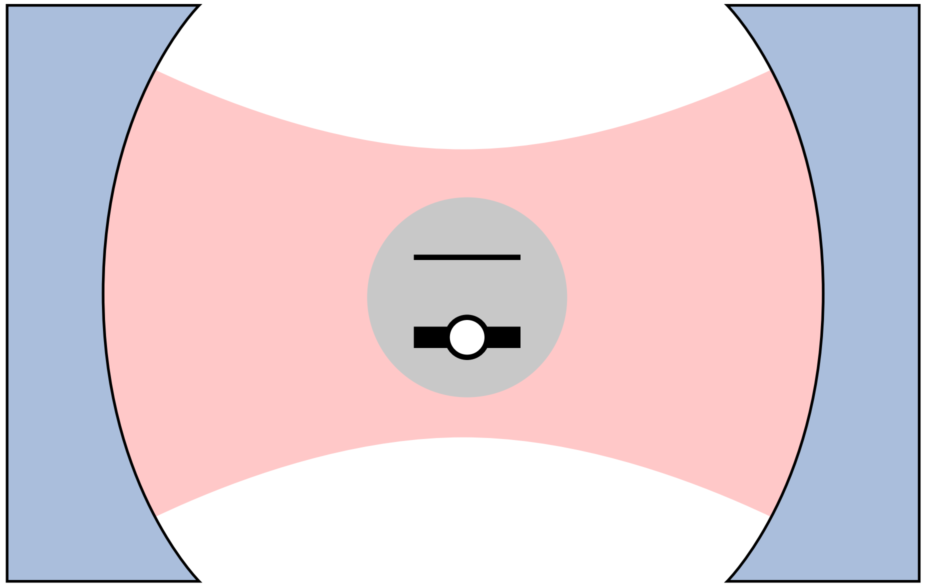


- SAW resonators in the quantum regime



- Steps towards SAW-cQED and SAW-SR

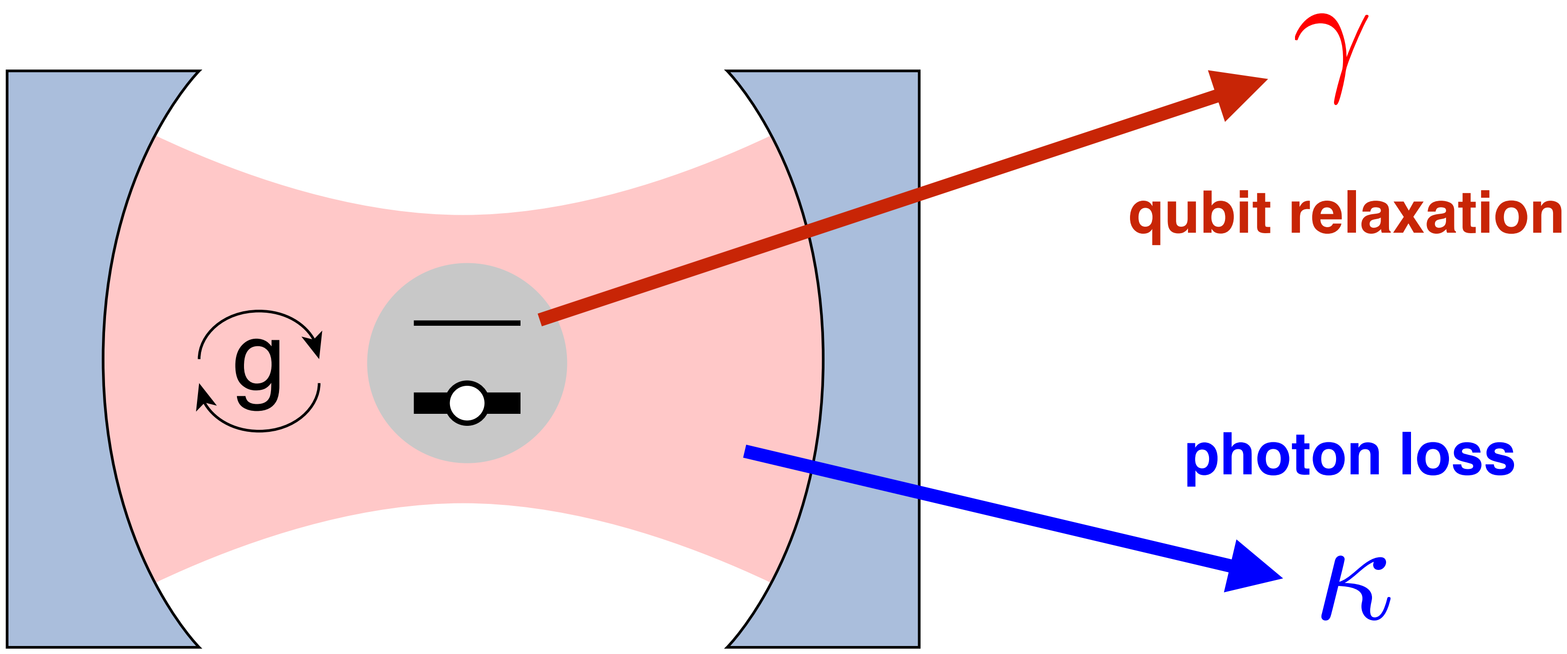
Cavity quantum electrodynamics



Enhance atom-light interactions by confining to a cavity

Enable coherent exchange of quantum information between static and 'flying' quantum systems

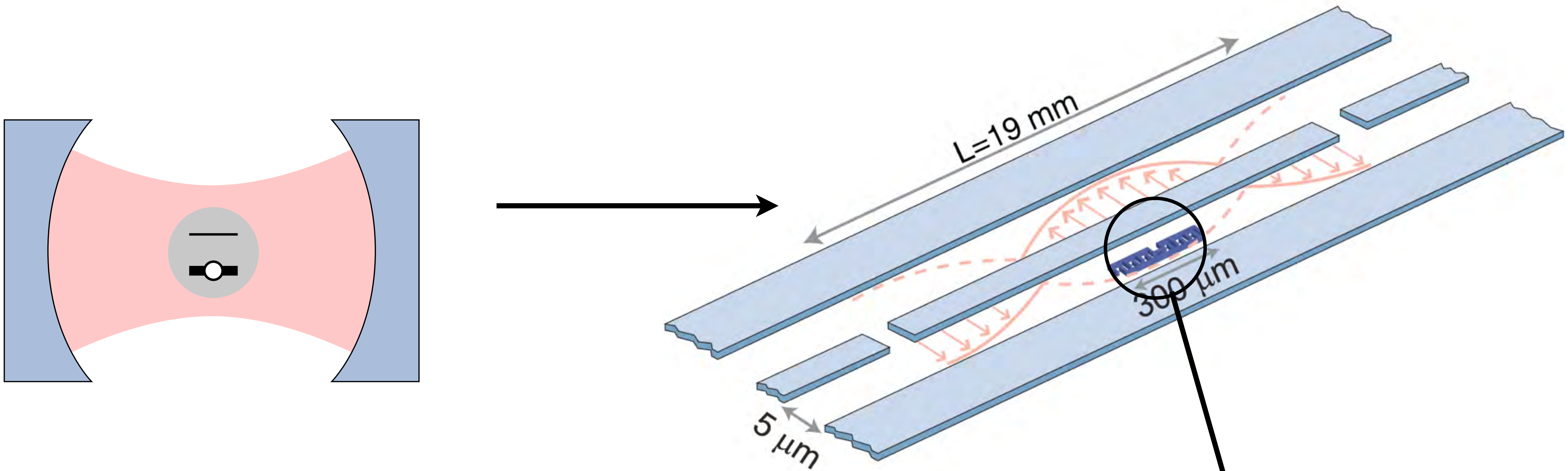
Cavity quantum electrodynamics



- Coupled system Hamiltonian (Jaynes-Cummings)

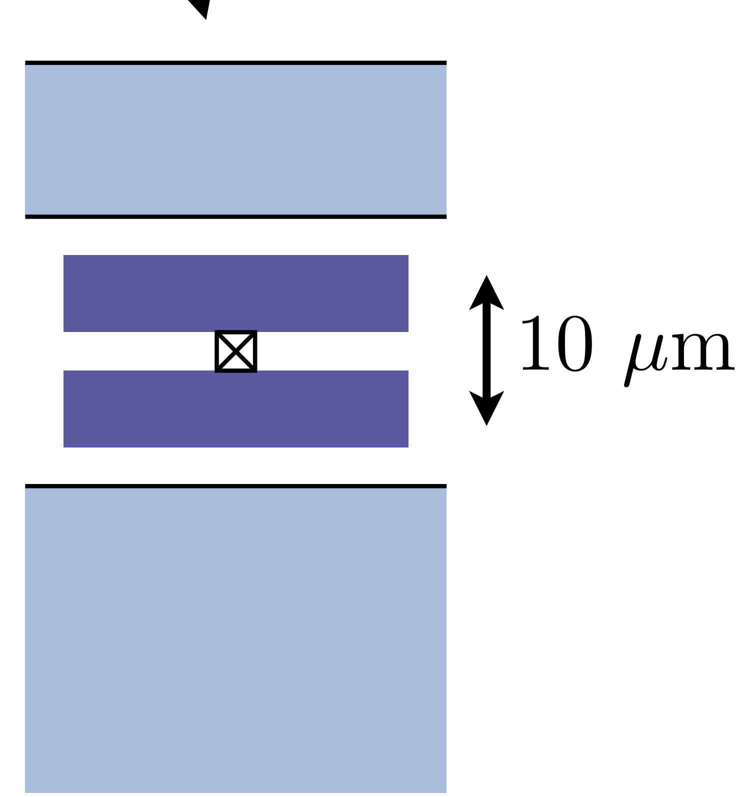
$$\hat{H}_{JC} = \hbar\omega_r(\hat{a}^\dagger\hat{a} + \frac{1}{2}) + \frac{\hbar\omega_a}{2}\hat{\sigma}_z + \hbar g(\hat{a}^\dagger\hat{\sigma}_- + \hat{a}\hat{\sigma}_+)$$

Field mode Qubit Interaction

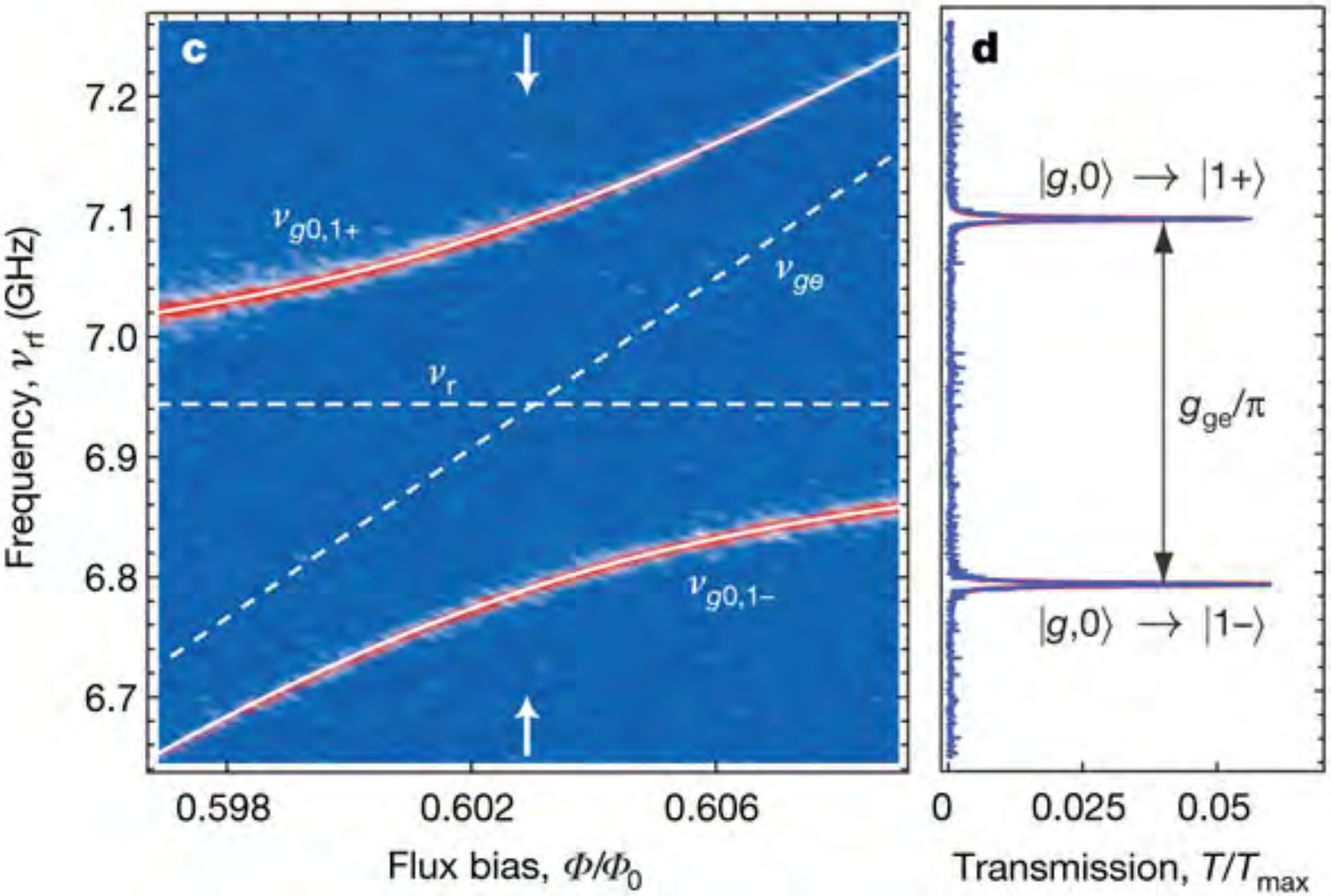


- Transmission line resonator as cavity
- Strong confinement of electromagnetic field
- Superconducting qubit as artificial atom

- Large electric dipole moment of qubit
- Very strong coupling achievable



- Wallraff *et al.* Nature **431,** 162 (2004)
- Blais *et al.* PRA, **69**, 062320 (2004)

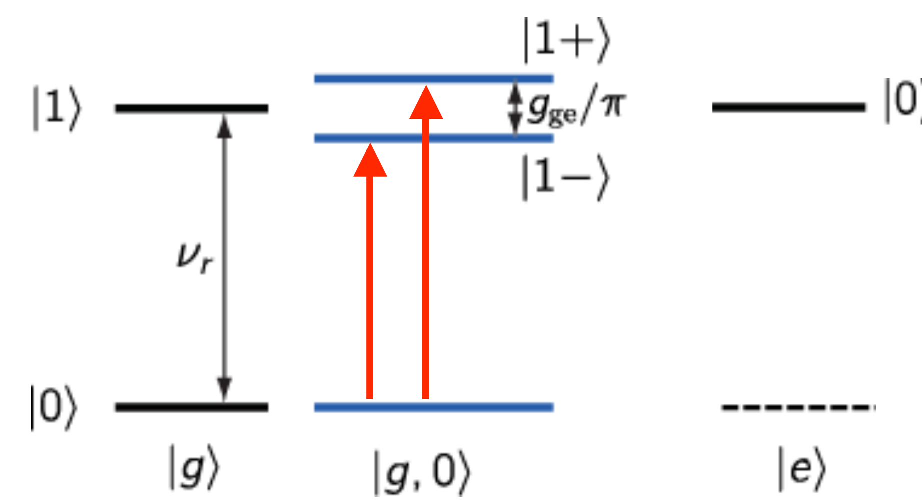


Very strong coupling:

$g/\pi = 308$ MHz

$\kappa, \gamma < 1$ MHz

$g_{ge} \gg \kappa, \gamma$



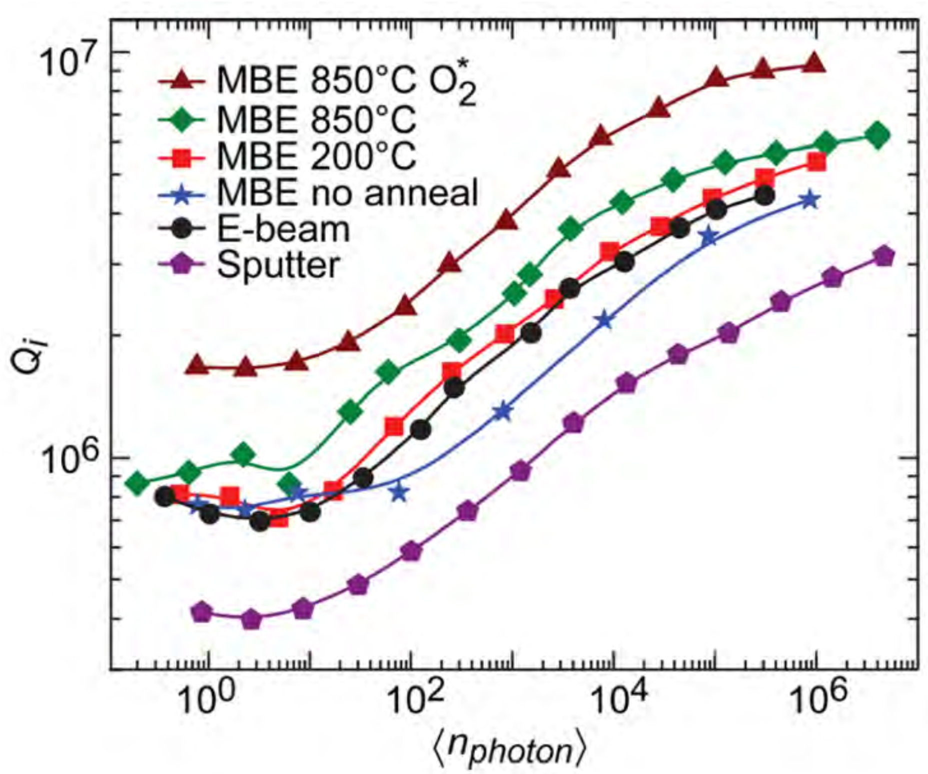
First observation: Wallraff *et al.* Nature **431**, 162 (2004)

This data: Fink *et al.* Nature **454**, 315 (2008)

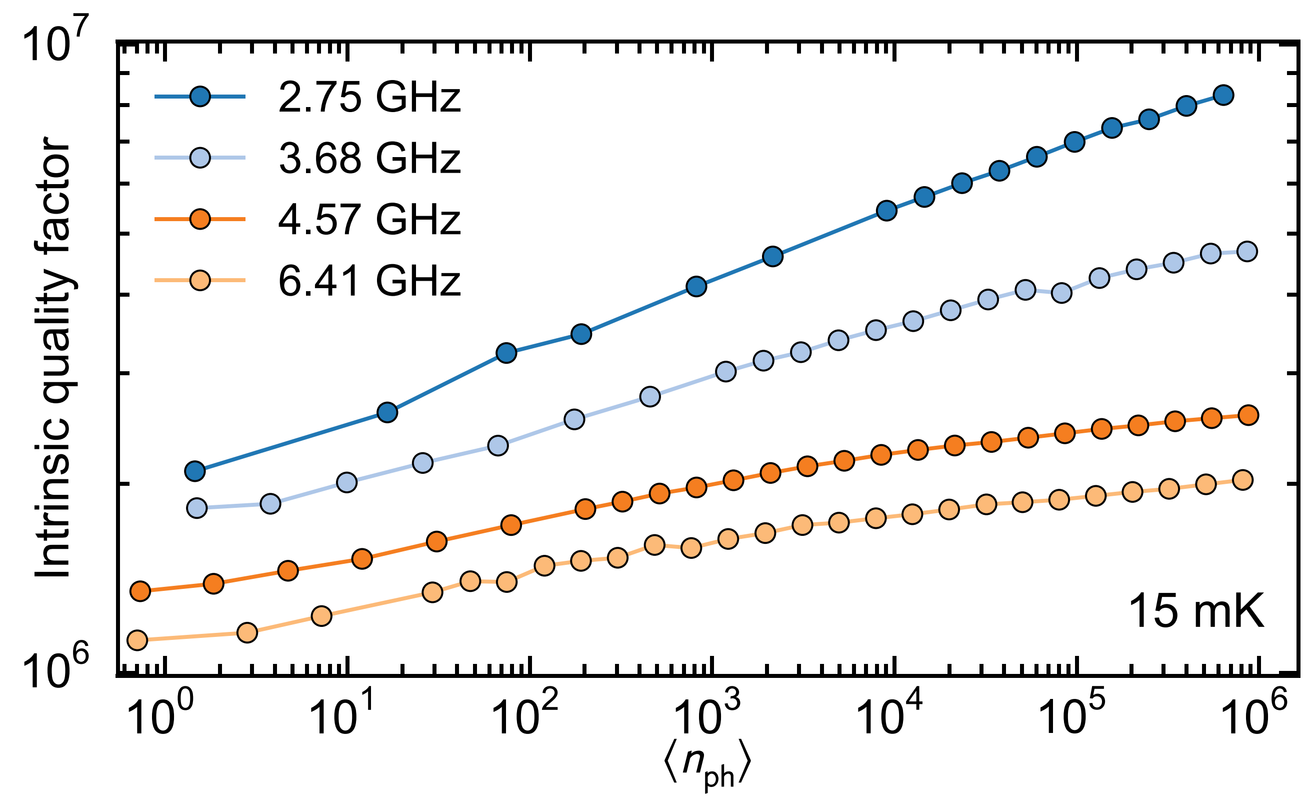
$$Q = \omega/\kappa$$

Resonators in cQED

- Superconducting CPW resonators typically reach Q > 100,000
- Evidence suggests limited by defects/‘TLS’s in environment @ low T
- Specialist fabrication techniques can give Q > 1M



Megrant *et al.*, APL (2012)
Surface treatments, annealing
Q > 1M



Bruno *et al.*, APL (2015)
Surface treatments, deep etching
Q > 1M

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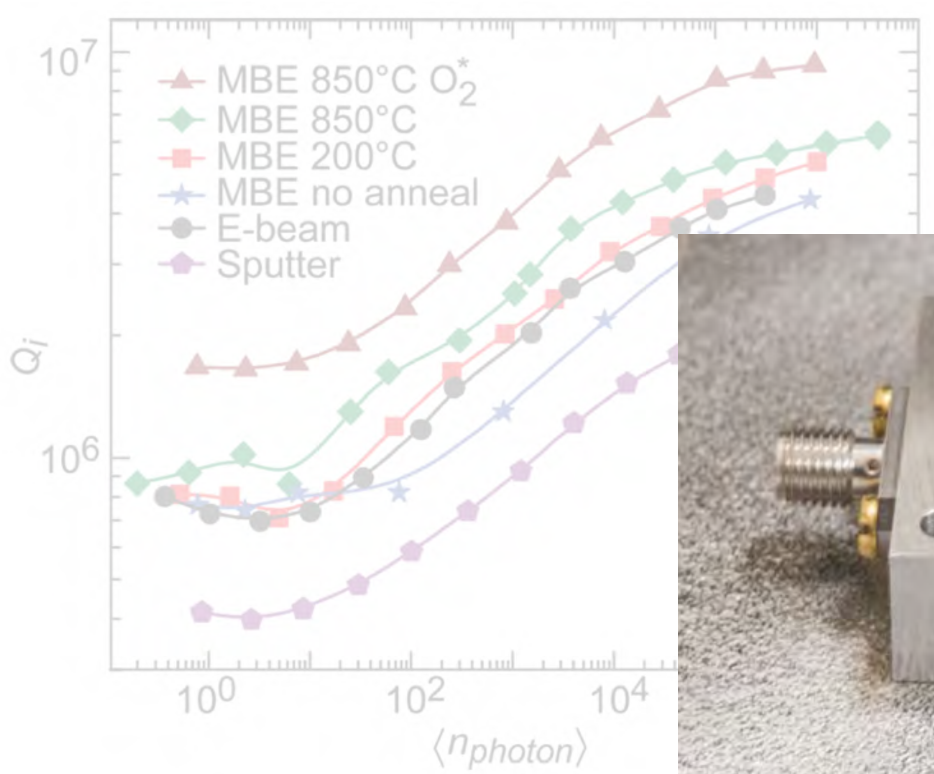
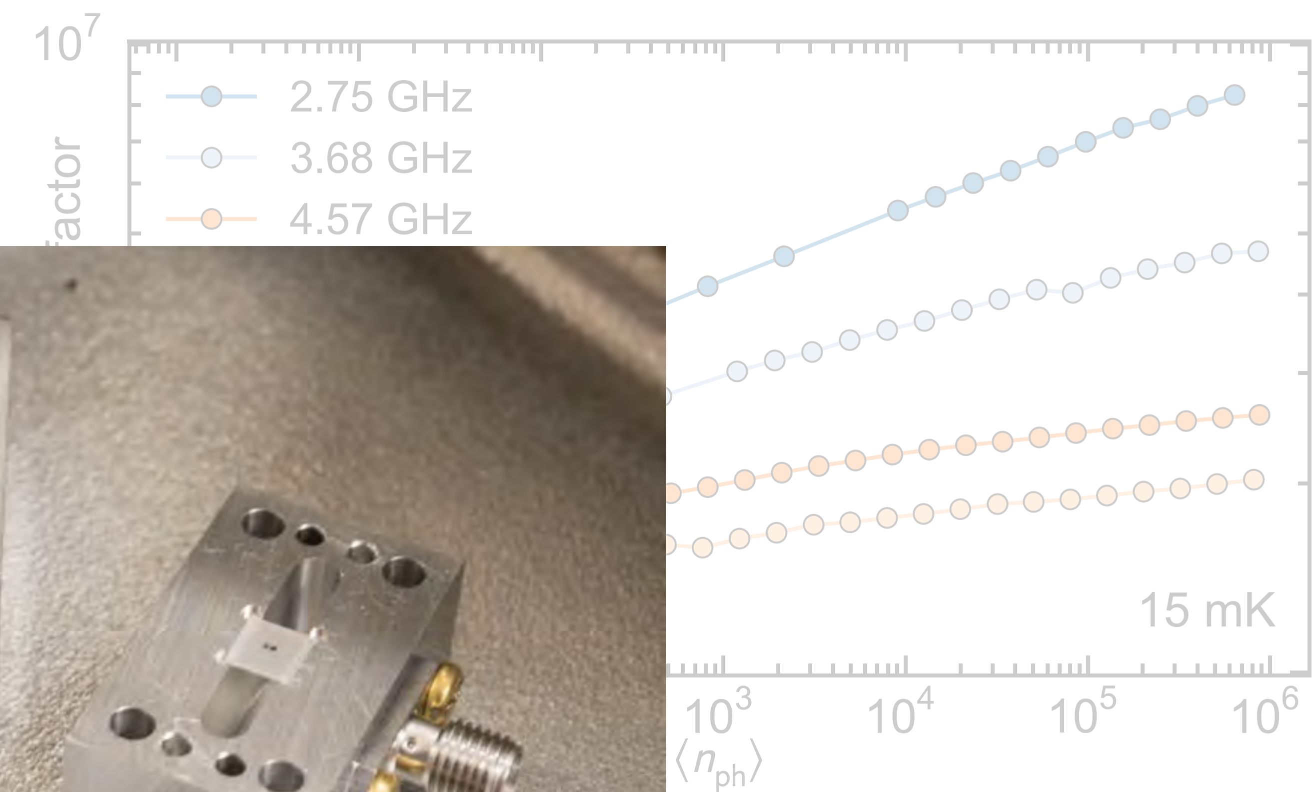
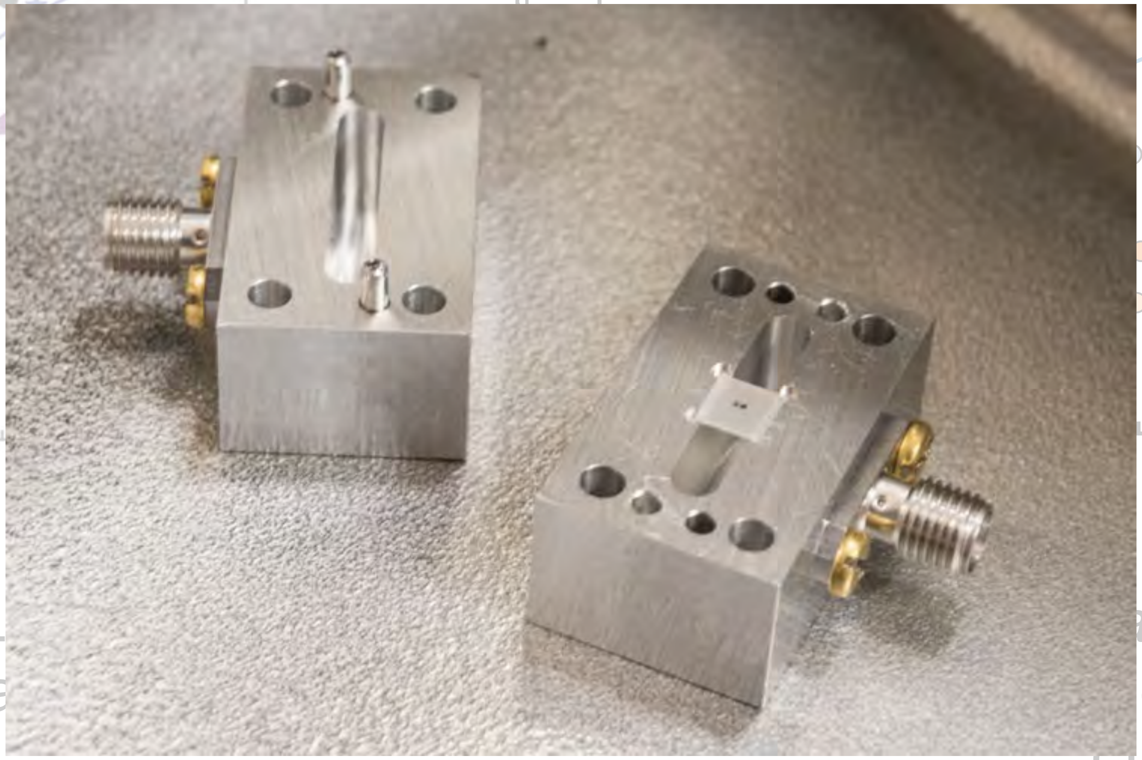


Megrant *et al.*, APL
Surface treatments, a
Q > 1M

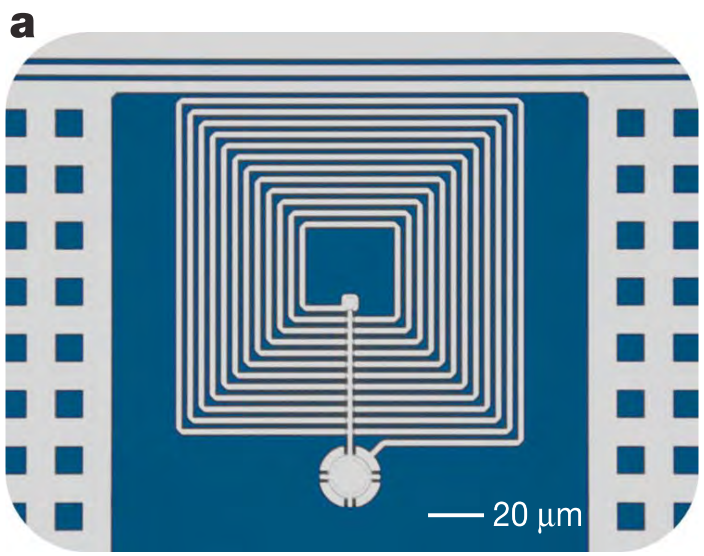


al., APL (2015)
ents, deep etching
Q > 1M

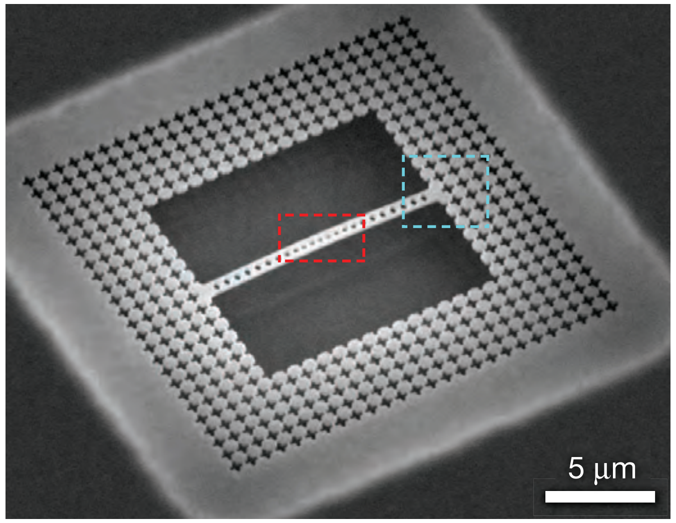


- Also 3D cavities, which can reach Q > 100M (Paik, PRL 2011, Reagor APL, 2012)

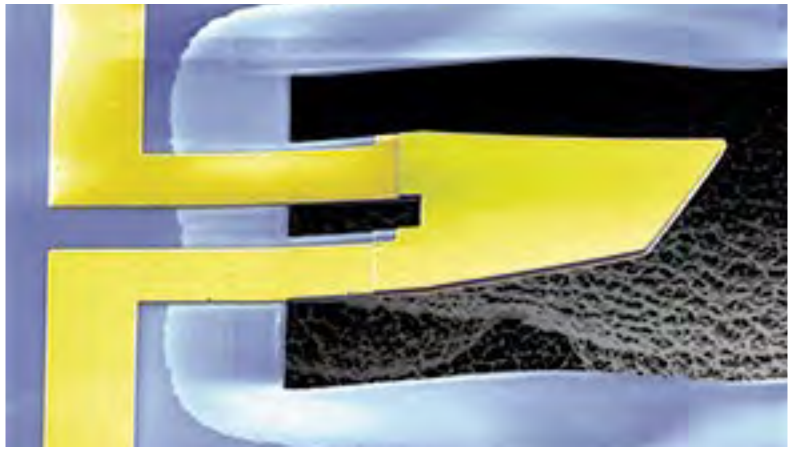
Mechanical systems in the quantum regime



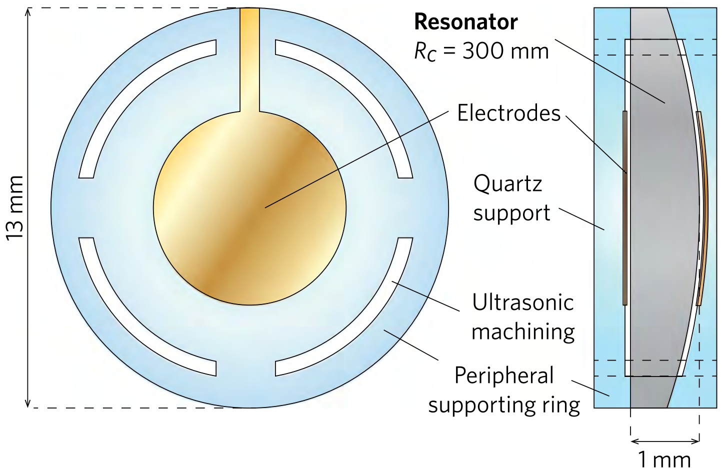
Teufel 2011



Chan, Painter 2011

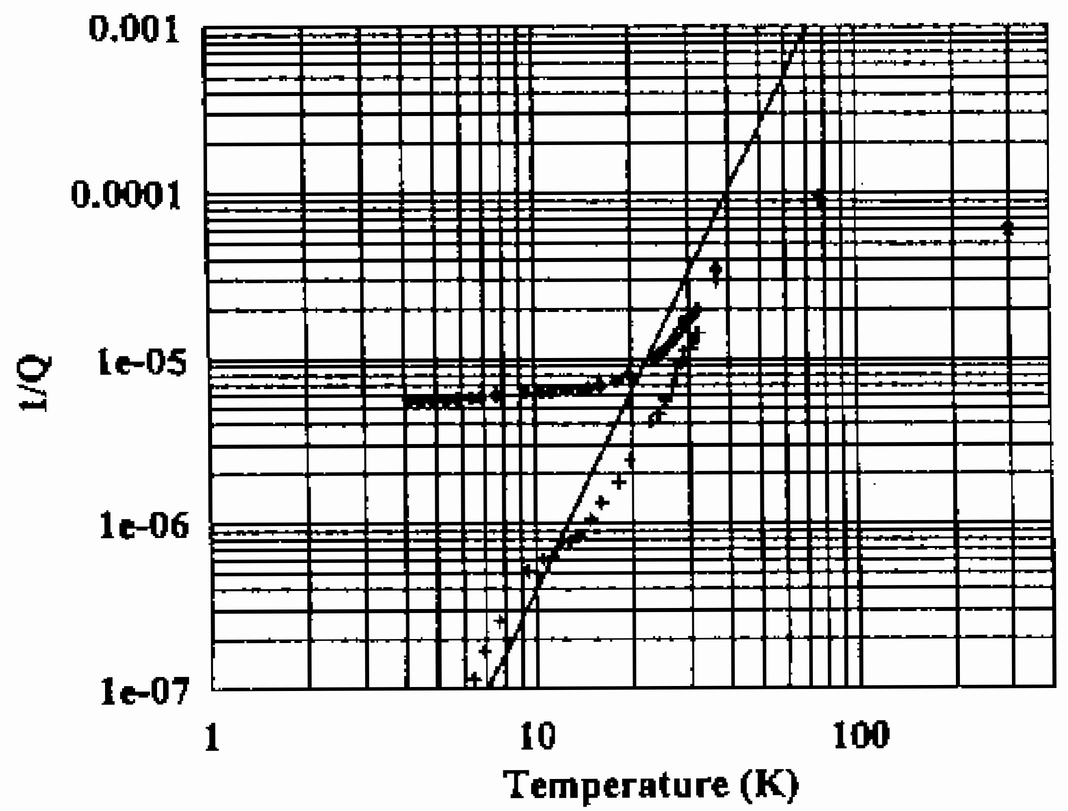


O'Connell, Cleland 2010

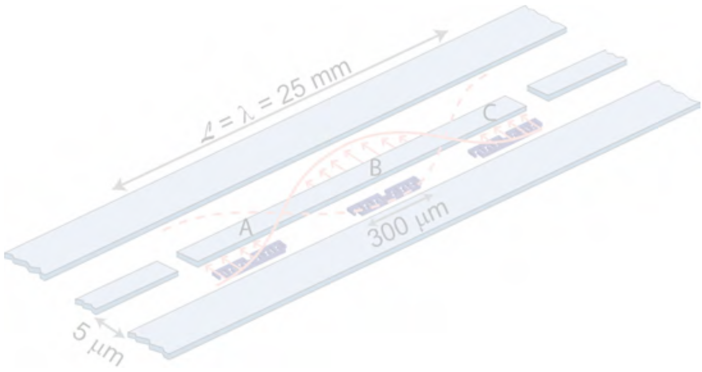


- Bulk MHz acoustic resonators reach Q > 1 billion at mK

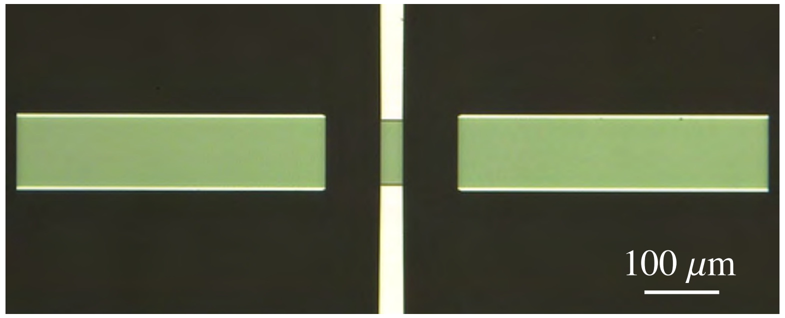
Goryachev *et al.*, APL **100**, 243504 (2012)



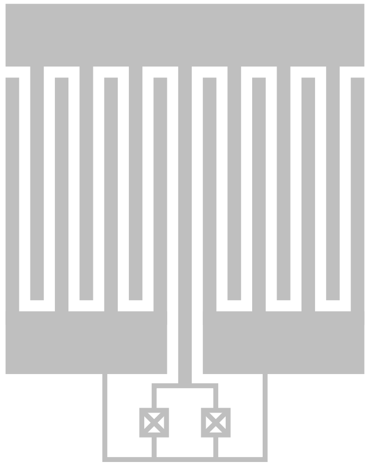
El Habti *et al.*, IEEE Ultrasonics (1995)



- Intro: Resonators in quantum devices

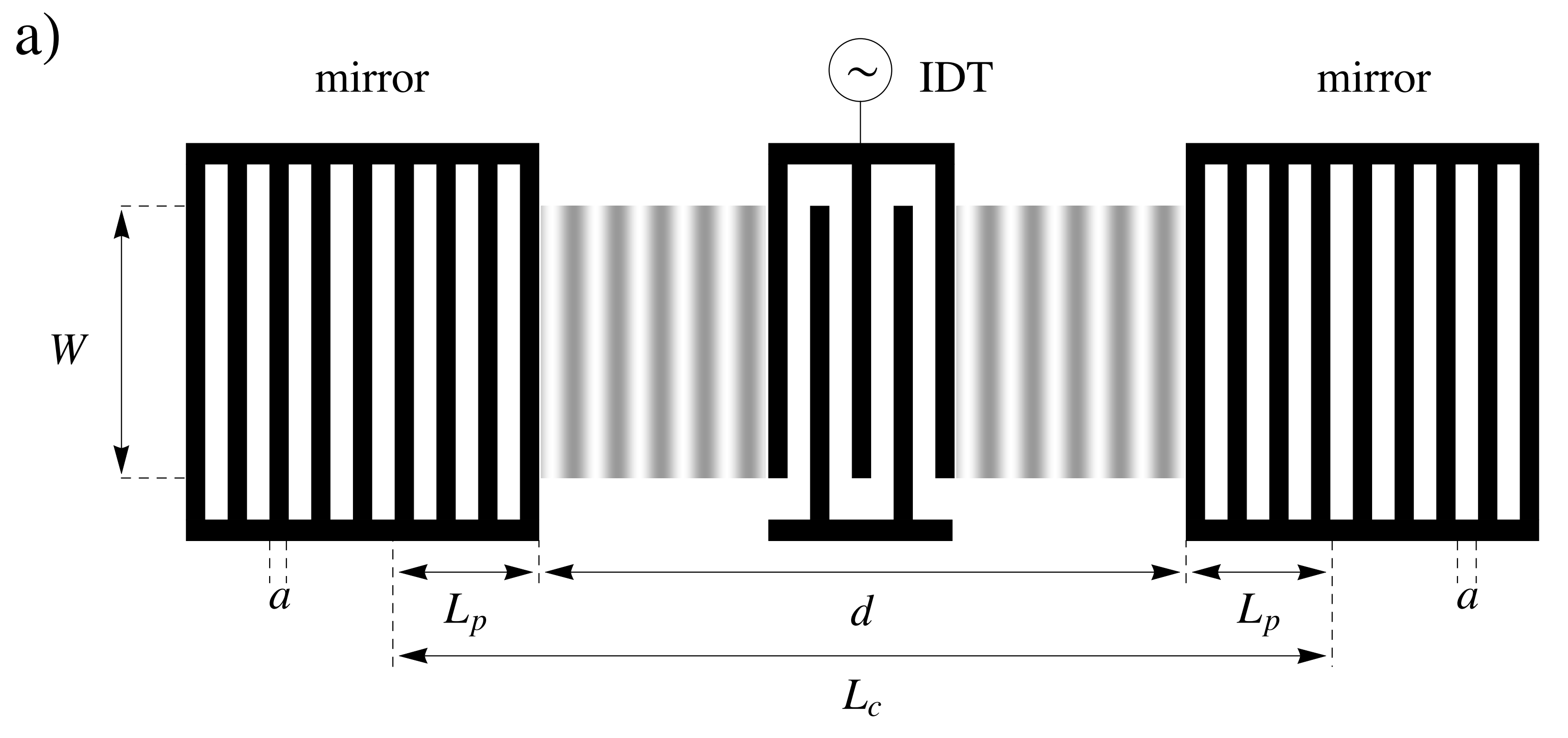


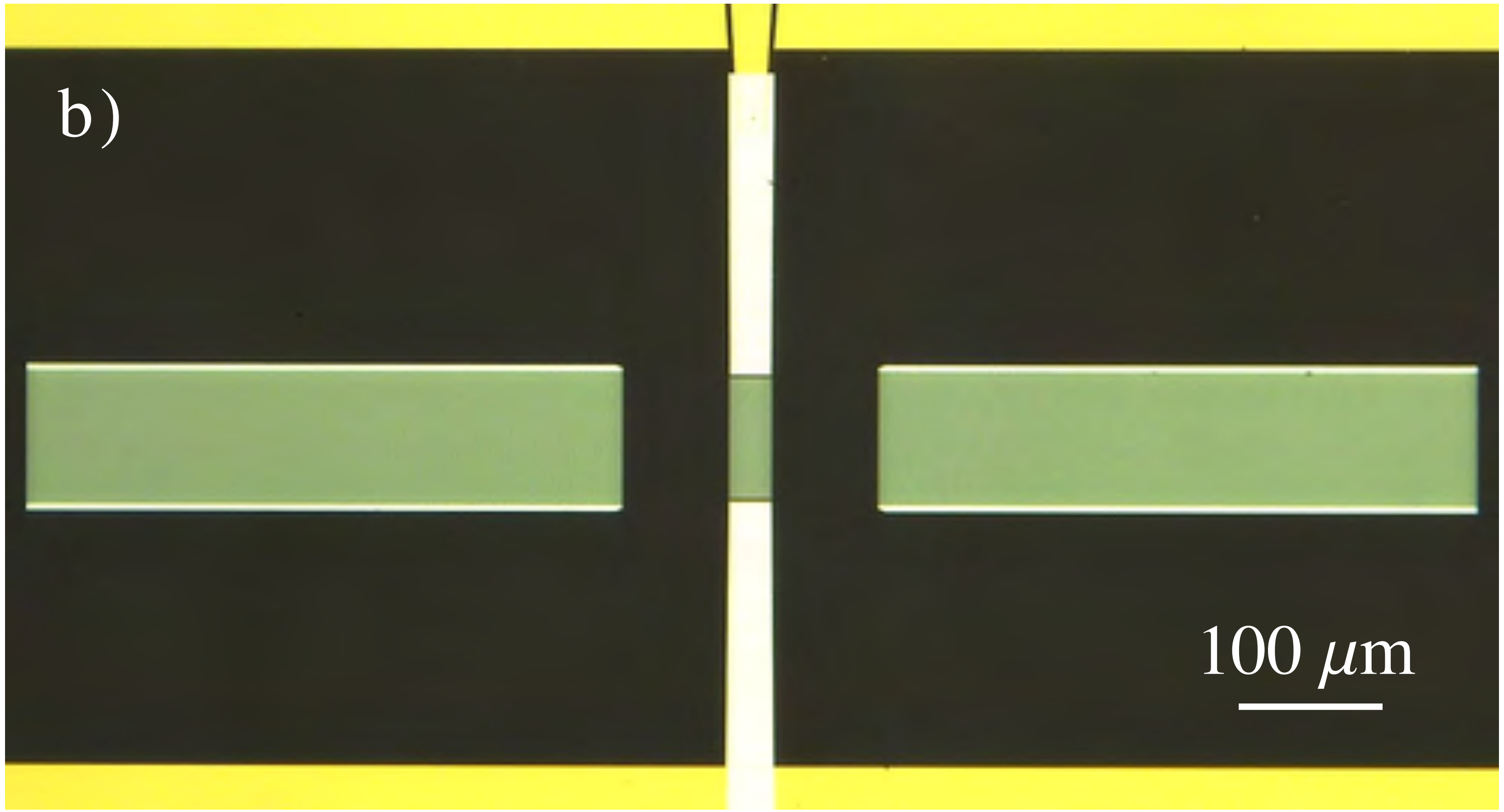
- SAW resonators in the quantum regime



- Steps towards SAW-cQED and SAW-SR

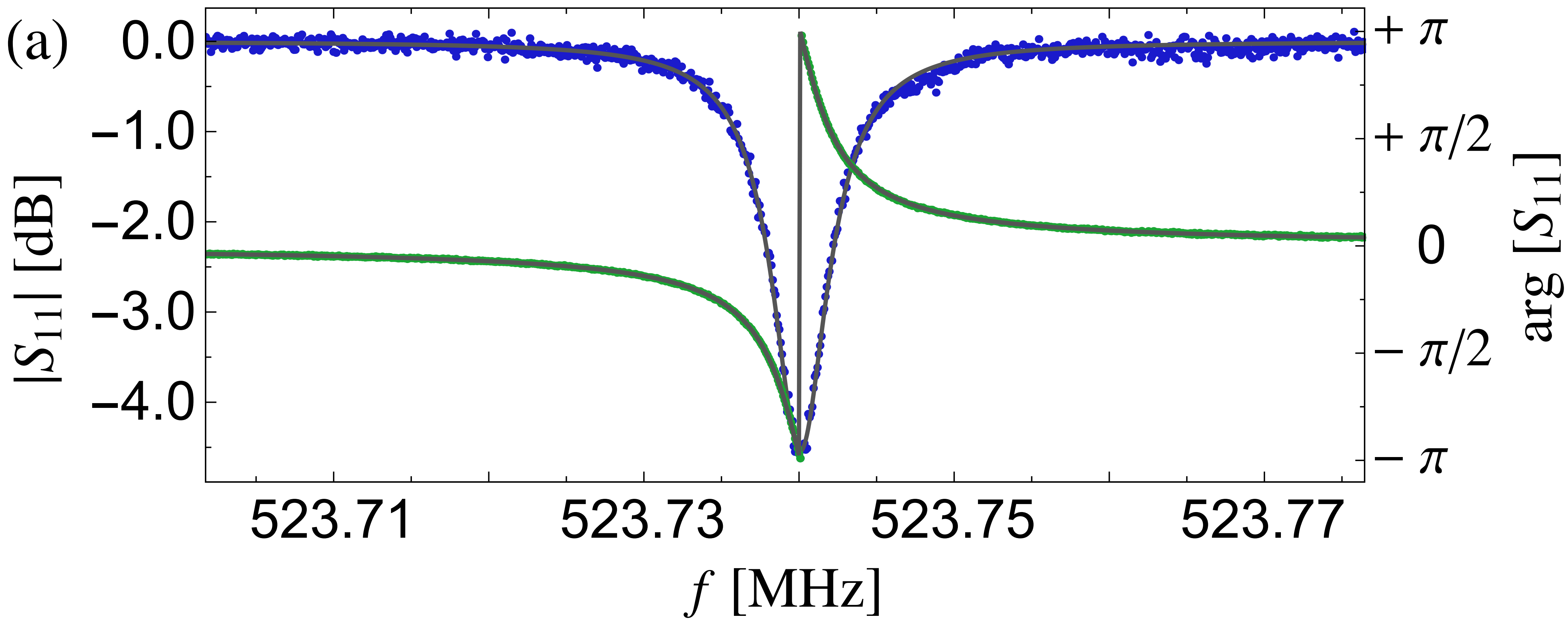
SAW resonator devices





- Quartz substrate (ST-cut)
  $K^2 \sim 0.15\%$
  $v_{SAW} \sim 3100$ m/s
- Weak piezoelectric — an almost entirely mechanical system
- Devices up to 500 MHz (wavelength 6 μm) fabricated using photolithography
- Higher frequencies fabricated using E-beam lithography
- All devices measured in dilution fridge at ~10 mK

Example measurement @ 500 MHz



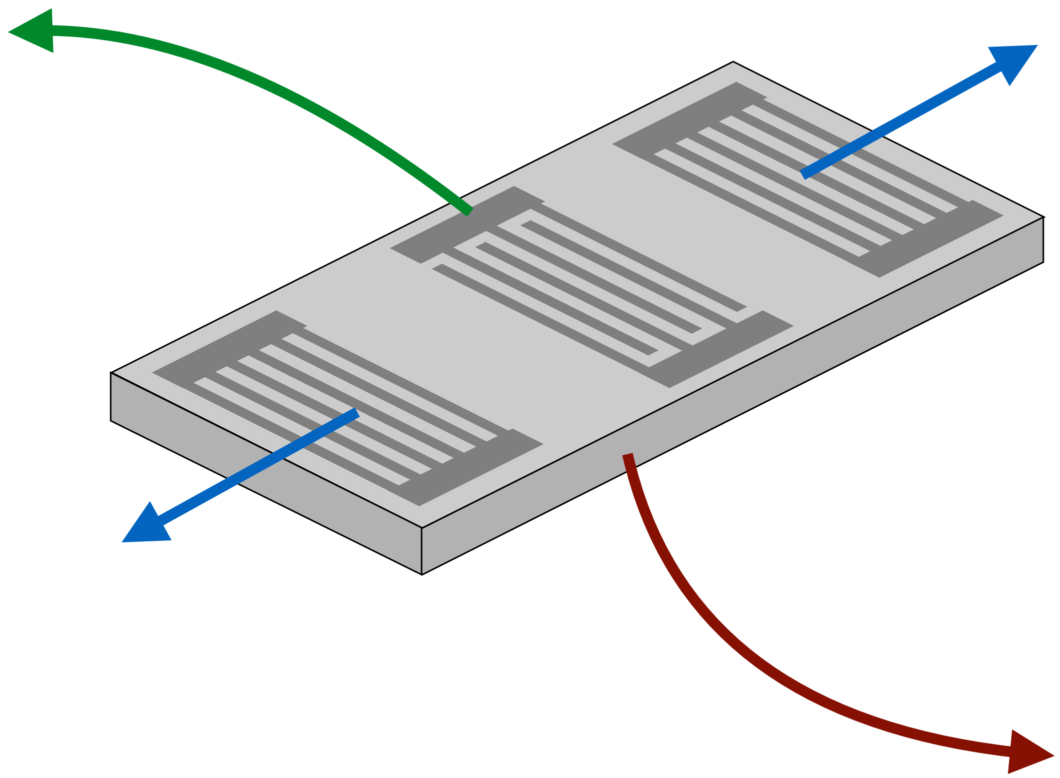
$$S_{11} = \frac{(Q_e - Q_i)/Q_e + i(2Q_i(f - f_0))/f_0}{(Q_e + Q_i)/Q_e + i(2Q_i(f - f_0))/f_0}$$

$Q_e = 1.16 \times 10^5$ $\qquad$ $Q_i = 4.53 \times 10^5$

What can contribute to SAW resonator loss?

External Q due to the IDT
A larger IDT will cause more effective transduction of the SAW to an electrical signal and hence a lower external Q.

Internal Q due to the Bragg gratings
The gratings have finite reflectivity - a longer grating or longer cavity will give a higher Q, similar to an optical Fabry-Perot cavity.

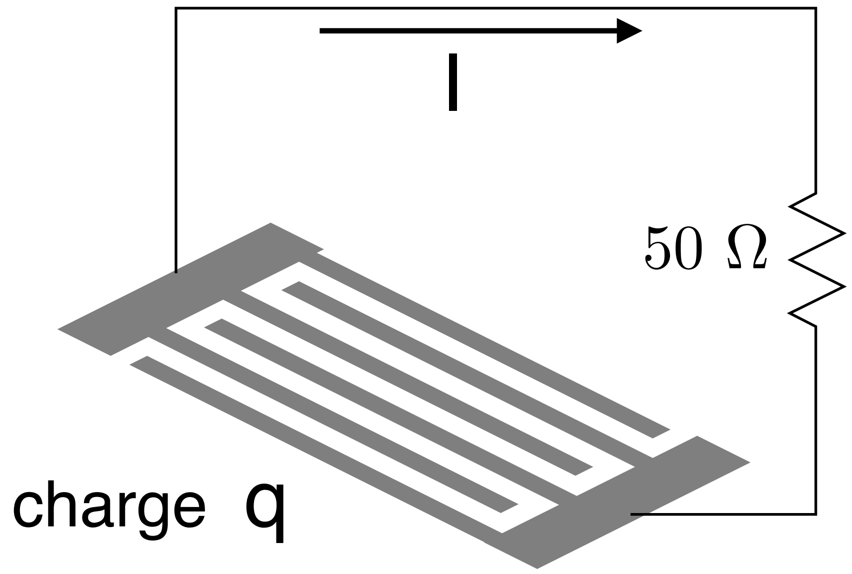


Other contributions
- phonon-phonon scattering
- diffraction
- finite electrode resistivity
- substrate misalignment
- …

Loss rate

$$\kappa = \frac{1}{Q} = \boxed{\frac{1}{Q_i}} + \boxed{\frac{1}{Q_e}}$$

External Q due to coupling IDT

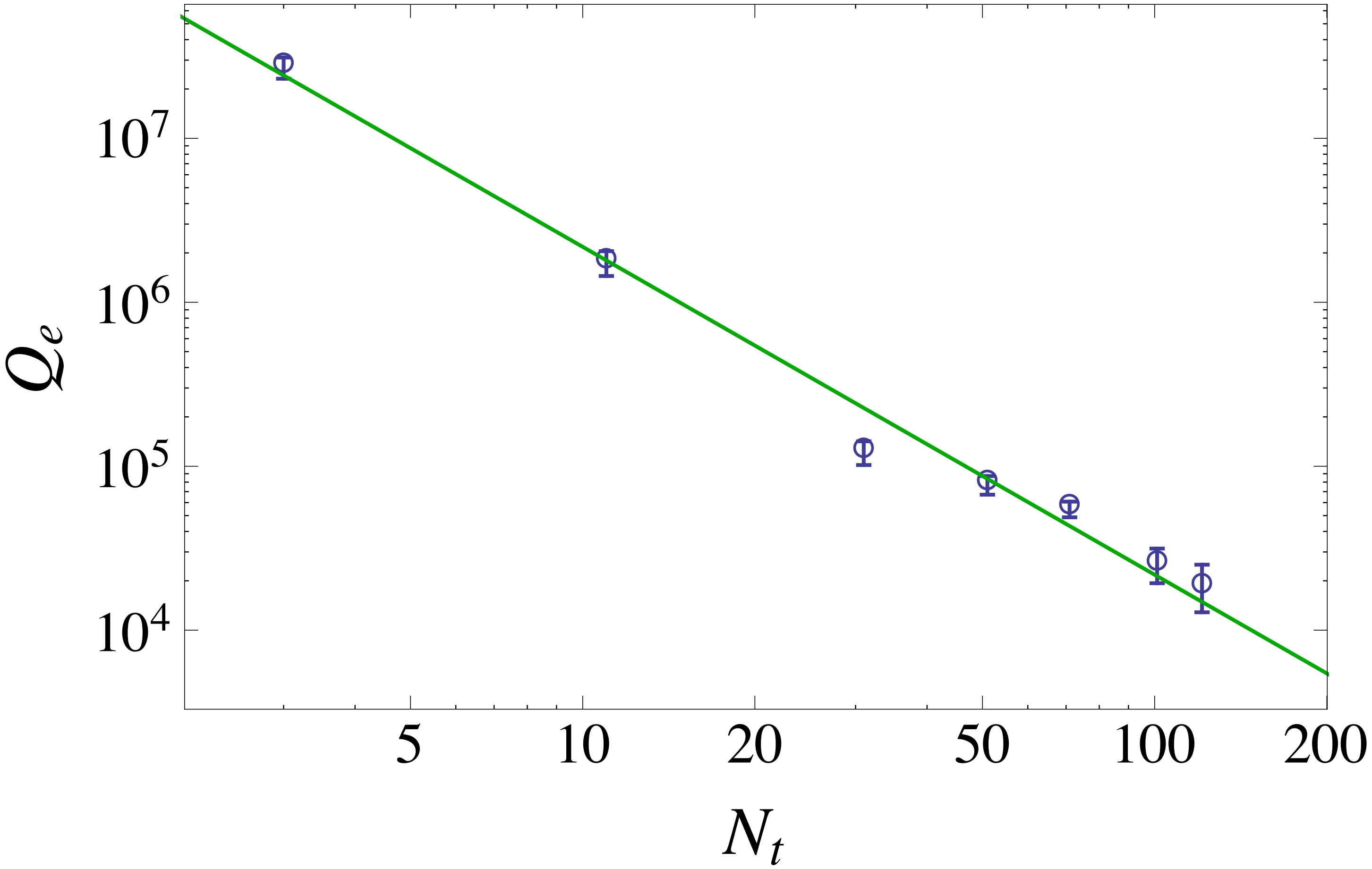


- Charge accumulates on transducer fingers to maintain charge neutrality
- AC current *I* flows through 50 ohm load and dissipates power *P*

$$P = I^2 R$$

$$I \propto q \propto N_t \implies P \propto N_t^2$$

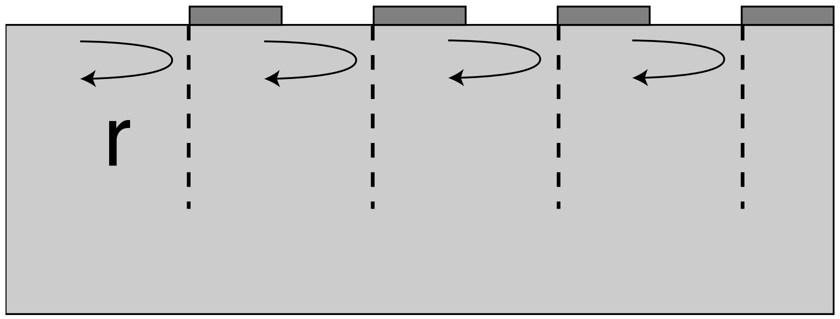
External quality factor $Q_e \propto 1/N_t^2$



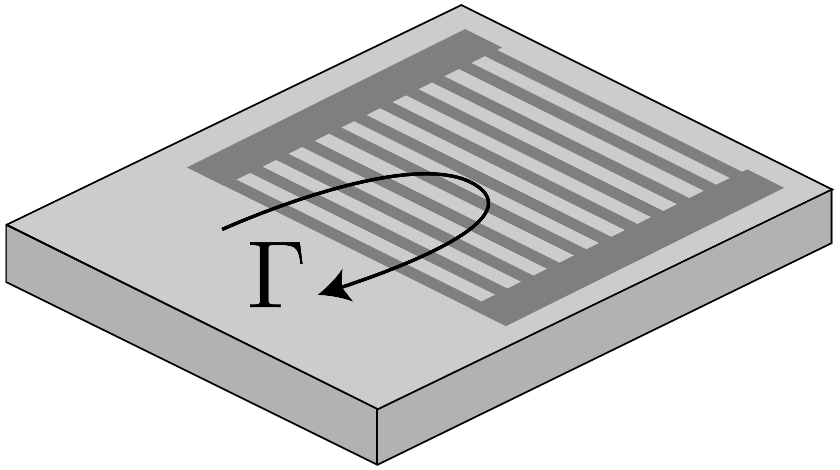
Q due to Bragg grating reflectivity

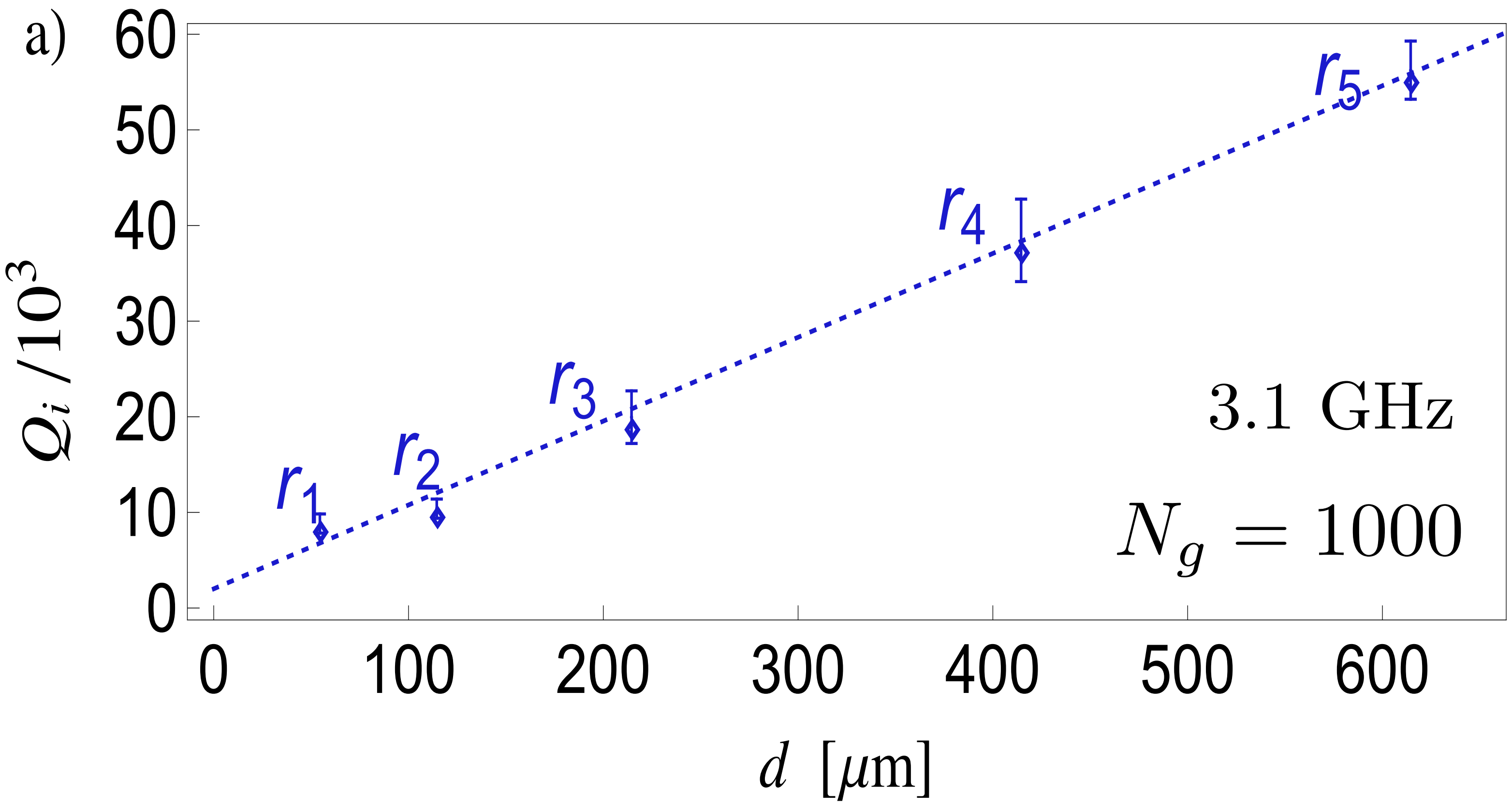
- Metallized surface changes the acoustic wave impedance and causes a reflection
- Constructive interference of reflections from large array of electrodes

$$Q_g = \omega/\kappa = \frac{\omega d}{2v_{\mathrm{SAW}}(1-\Gamma)}$$



$$\Gamma = \tanh(rN_g)$$





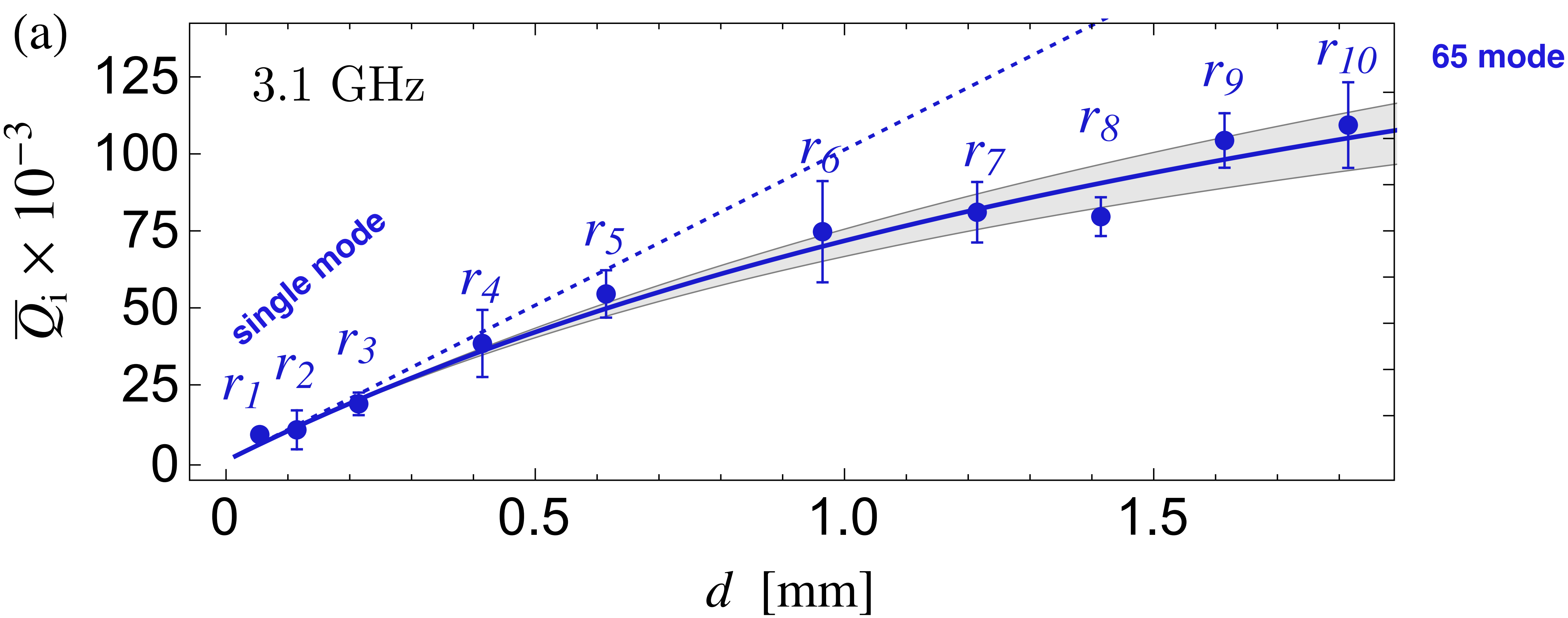
$$r \approx 0.2\%$$

$$N_g = 1000 \implies \Gamma = 0.96$$

$$N_g = 1500 \implies \Gamma = 0.995$$

Q due to propagation loss

- Longer devices reveal contribution from propagation loss:



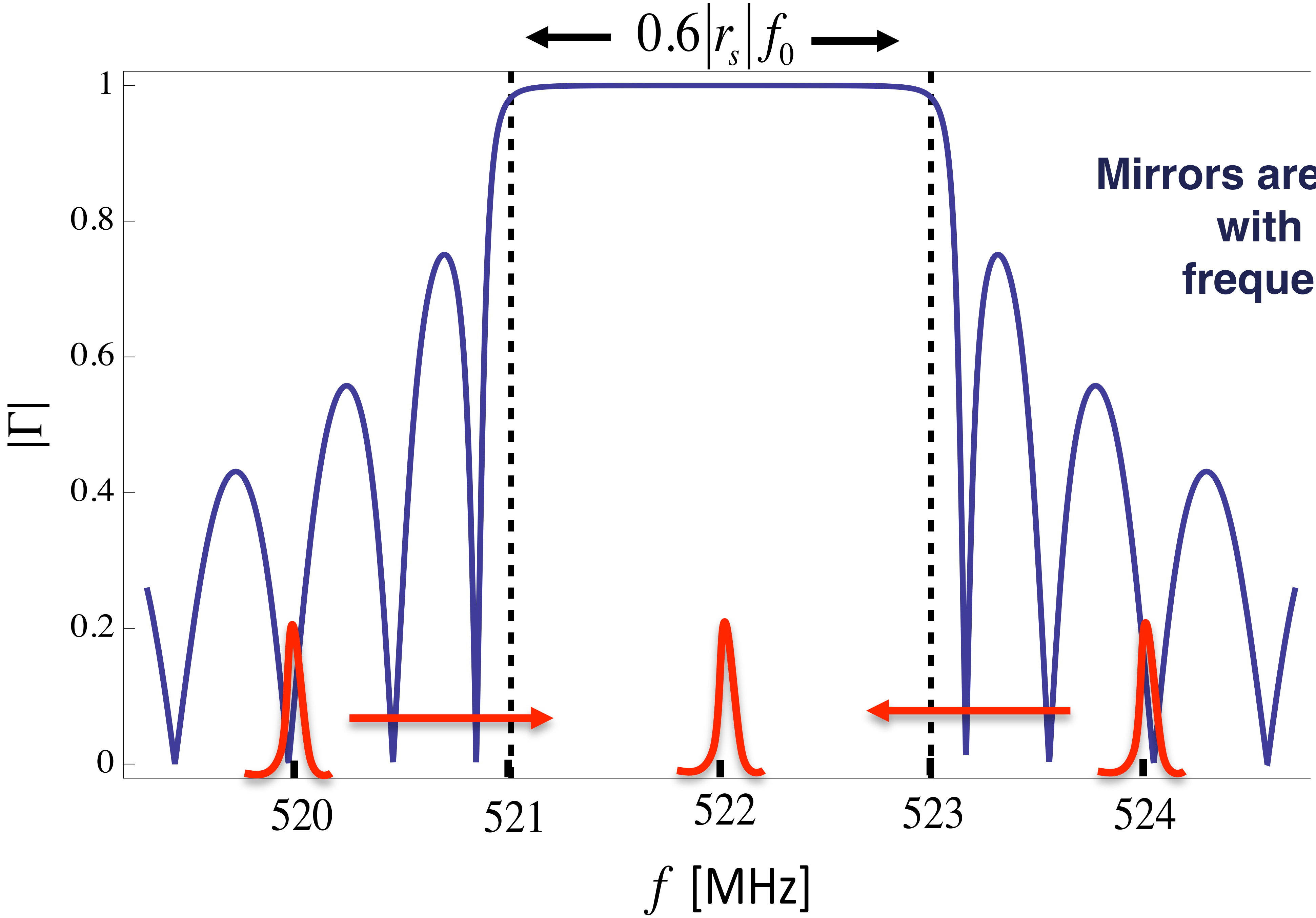
$$Q_\mathrm{i} = \left(\frac{1}{Q_\mathrm{g}} + \frac{v\alpha_\mathrm{p}}{\pi f_0} \right)^{-1}$$

- Phonon mean free path:

$$l = 1/\alpha_\mathrm{p} \approx 6\,\mathrm{cm}$$

Manenti *et al.*, PRB (2016)

Frequency response of a SAW resonator

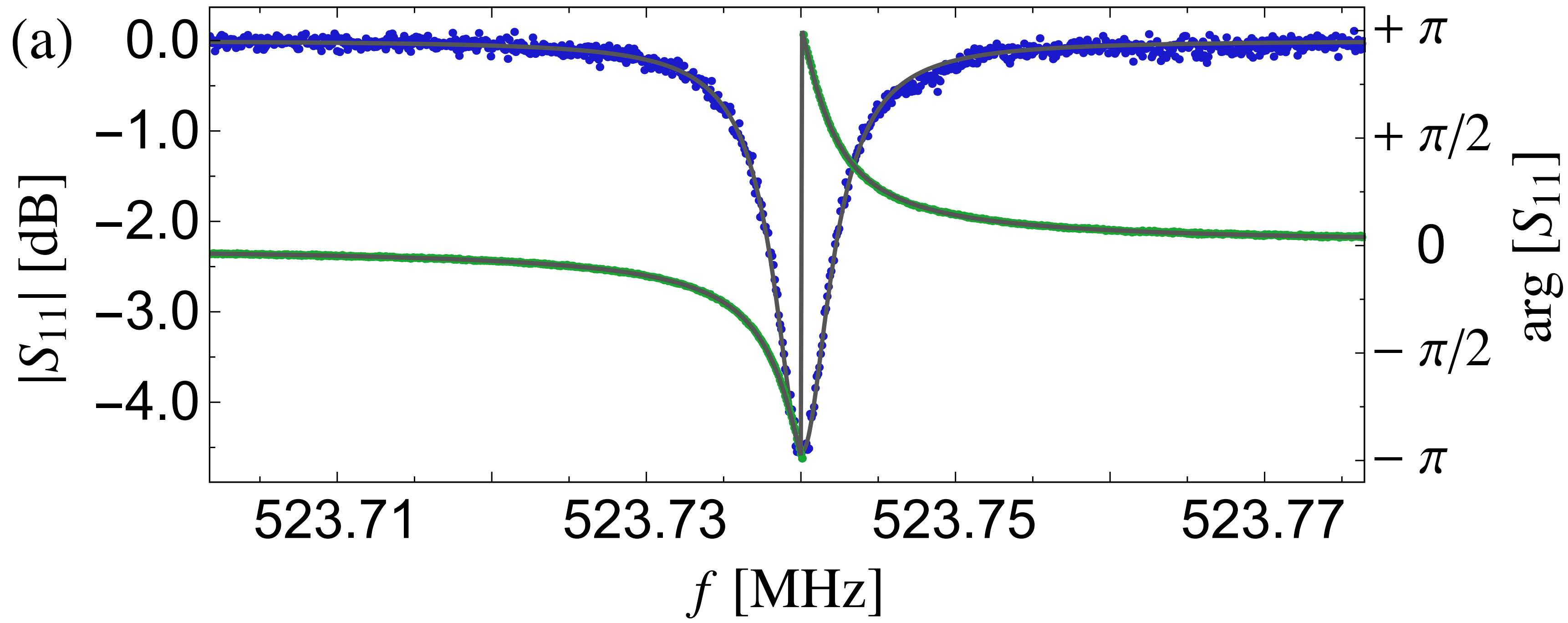


Mirrors are Bragg reflectors, with narrowband frequency response

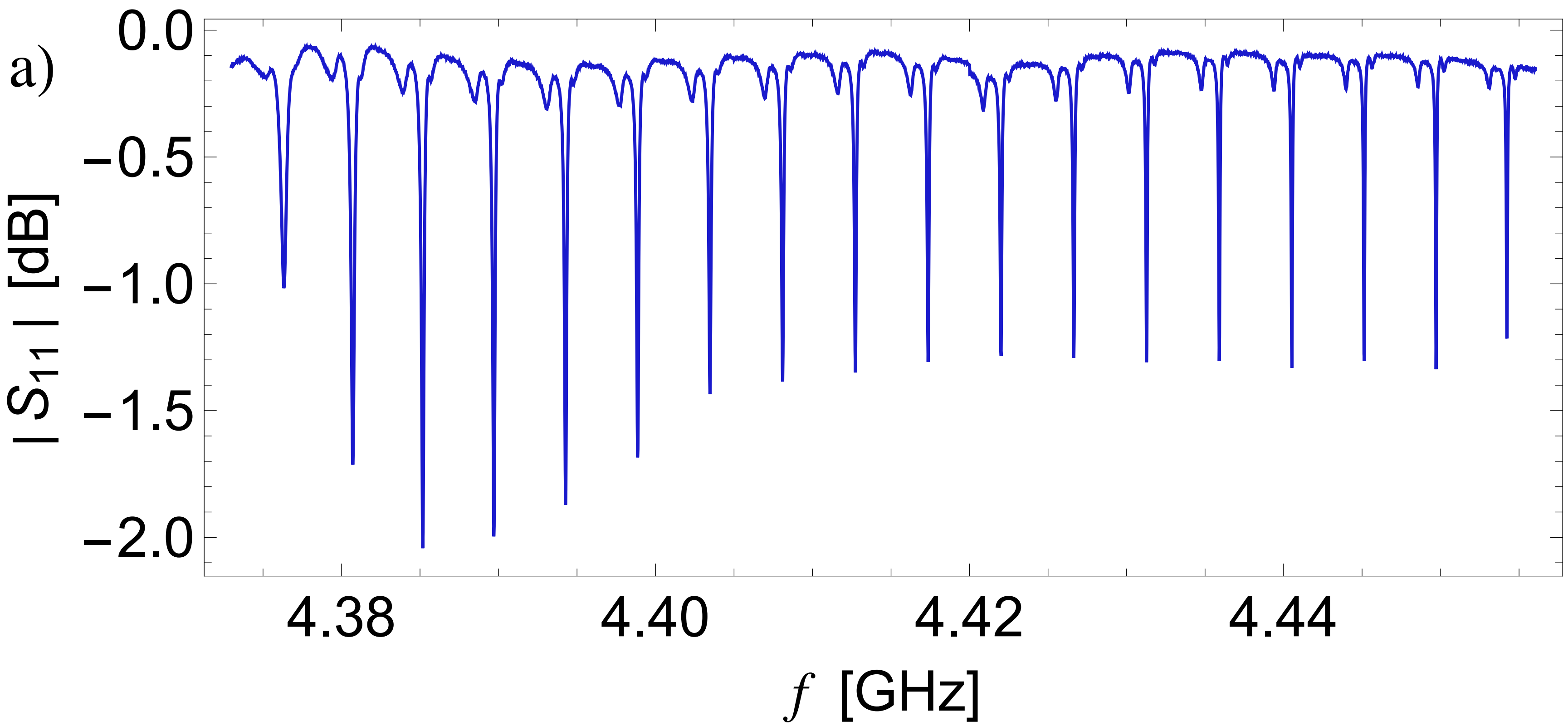
Long cavities have more closely spaced modes just like a Fabry-Perot cavity

$$\Delta f = v_{SAW}/L_c$$

Multimode SAW resonators

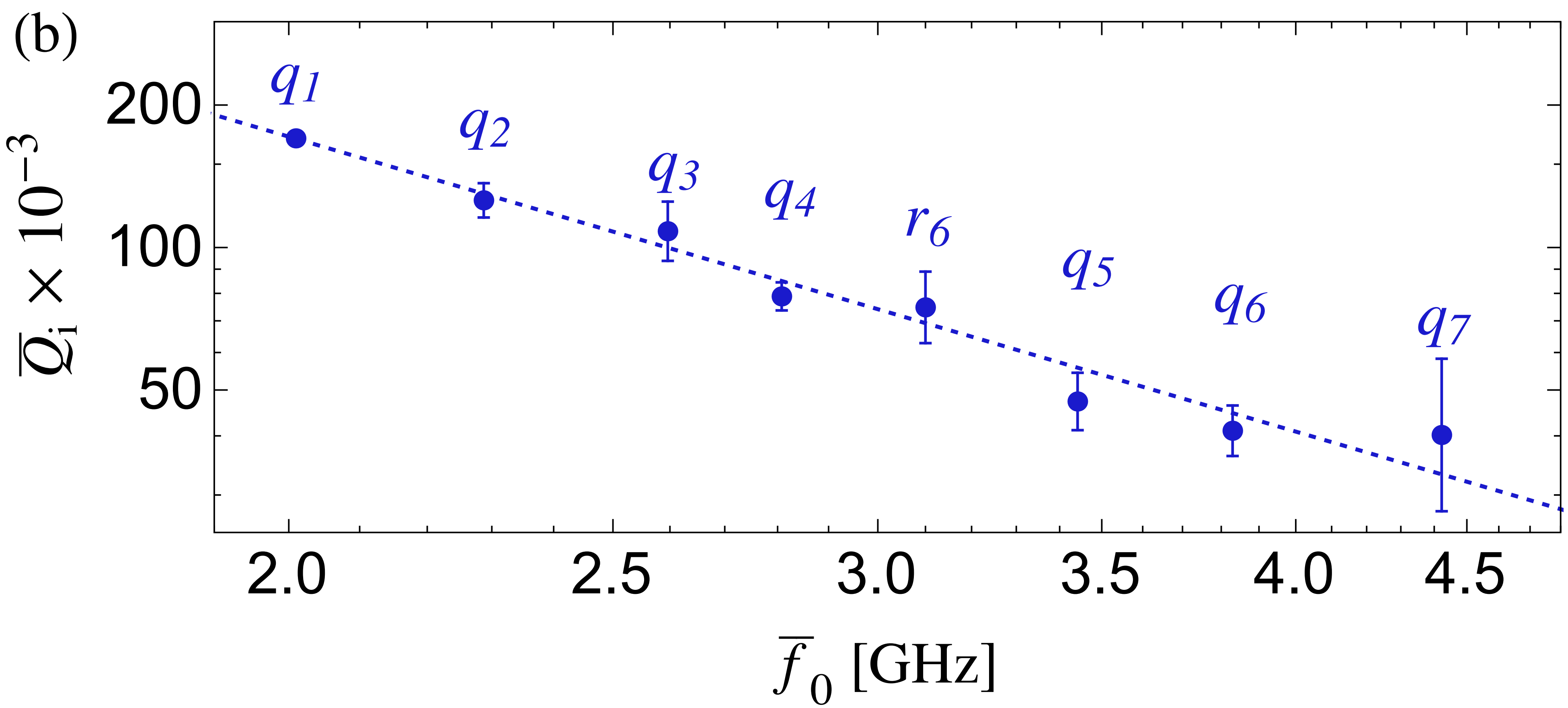


$$\lambda = 6\ \mu\text{m}$$
$$Q = 450,000$$
$$Q.f \sim 10^{14}$$



$$\lambda = 0.7\ \mu\text{m}$$
$$Q = 55,000$$
$$\Delta f = 500\ \text{kHz}$$
$$F \simeq 6$$

Manenti *et al.*, PRB (2016)



- Polynomial fit: $Q_i = c_1 f^{-c_2}$ $\quad c_2 = 2.07 \pm 0.13$
- Implies phonon scattering rate ~ f^3 as has been suggested in the hf > kT limit*

Manenti *et al.*, PRB (2016)

* Sakuma & Nakayama, APL **25**, 176 (1974)

Phonon scattering in hf>kT limit

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Attenuation of elastic surface waves by anharmonic interactions at low temperatures*

Tetsuro Sakuma and Tsuneyoshi Nakayama

Department of Engineering Science, Faculty of Engineering, Hokkaido University, Sapporo, Japan
(Received 19 April 1974)

Based on the theory of surfons, we present a formalism to calculate the attenuation rate of elastic surface waves at low temperatures in the high-frequency region. A general formula for the attenuation rate due to the cubic anharmonic terms in the elastic energy of an isotropic elastic continuum is given by means of a temperature-dependent Green's function. In a frequency region between 20 and 40 GHz at $T=1\,°\mathrm{K}$, our result shows quite different frequency and temperature dependence $\omega^{1+n}\ T^{4-n}$ $(1.9 \lesssim n \lesssim 2.2)$ from that obtained in the low-frequency region.

In the field of anharmonic attenuation of elastic surface waves at low temperatures, theoretical investigations in low-frequency regions have been done by Maradudin and Mills[1] and King and Sheard.[2] In both of their works, it is assumed that the absorption mechanism is the interaction between Rayleigh waves and the bulk thermal phonons and their results show that the attenuation rate is proportional to ωT^4. This assumption is valid in the low-frequency region. However, when the frequencies of ultrasonic Rayleigh waves become comparable to those of thermal phonons, the surface effect on the wave functions of thermal phonons should be taken into account.

$$\omega^{1+n}\ T^{4-n}\ (1.9 \lesssim n \lesssim 2.2)$$

Modification of standard result at low temperature

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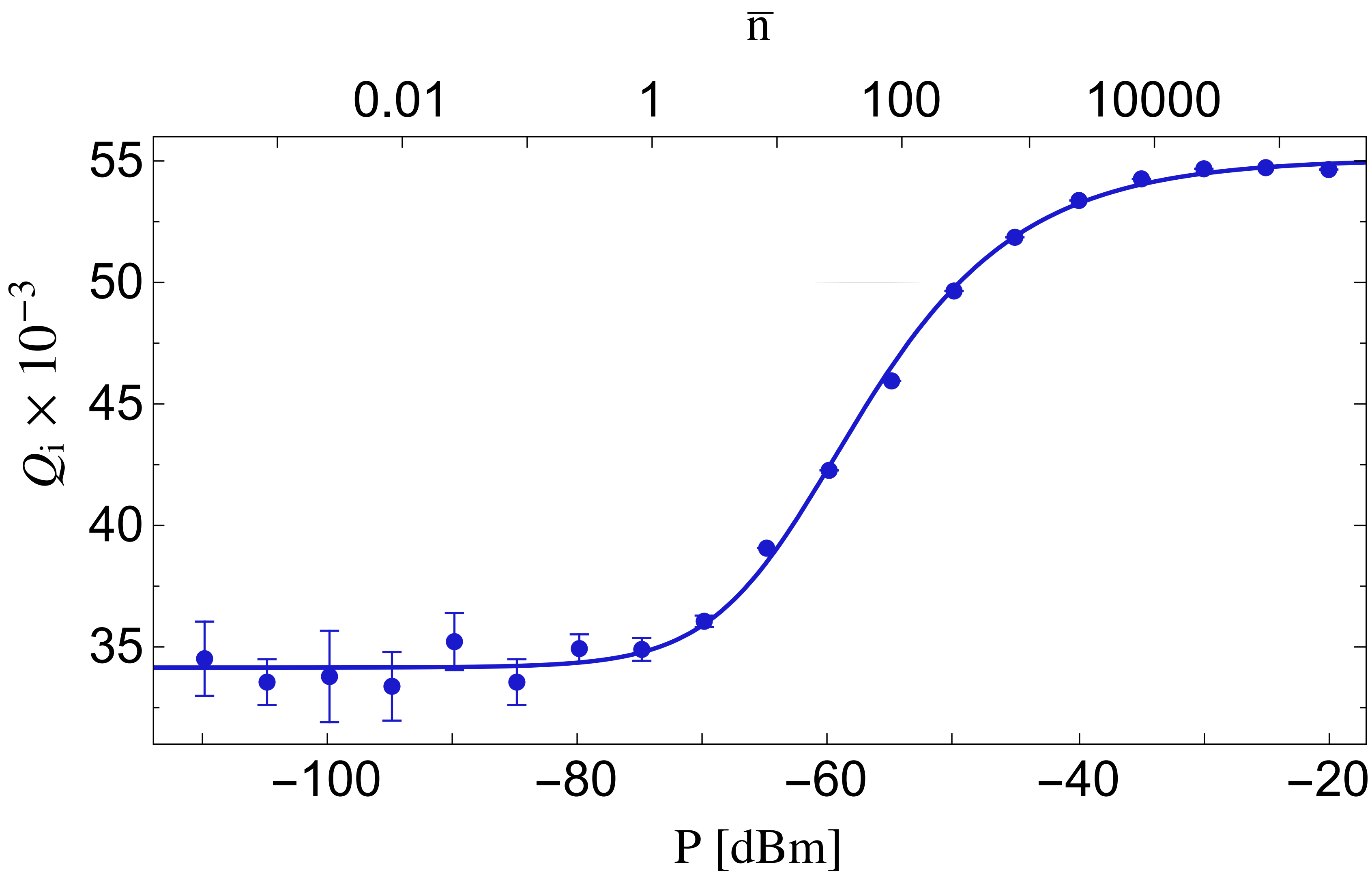
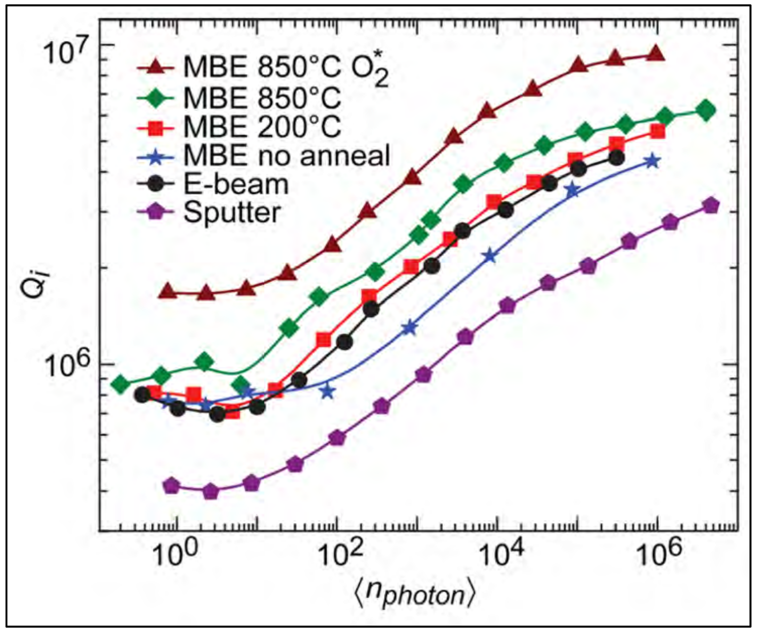
$$\omega^{1+n}\quad T^{4-n}\quad (1.9 \lesssim n \lesssim 2.2)$$

Modification of standard result at low temperature

The numerical calculations were performed using a FACOM 230-60 computer at the Computer Center of Hokkaido University.

Power dependence at single phonon level





Megrant *et al.*, APL (2012)

- Q reduces at low power, similar to CPW resonators
- May be explained as coupling to a TLS bath

$$\mathrm{Q_i} \sim \quad [v\,\alpha_{\mathrm{TLS}}/(\pi f_0) + 1/Q_{\mathrm{rl}}]^{-1}$$

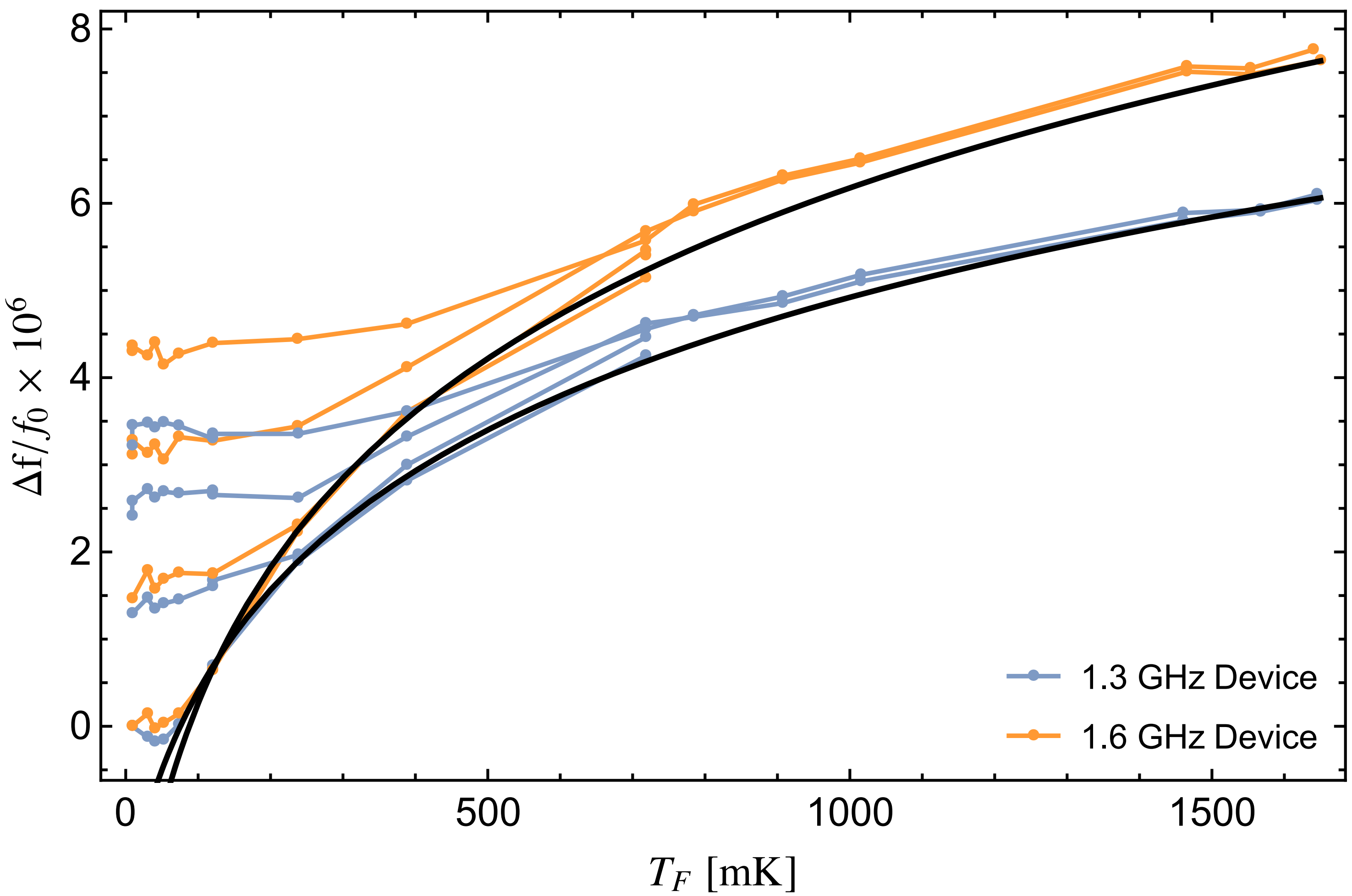
$$\alpha_{\mathrm{TLS}} = F\frac{2\pi^2 f_0 n_0 \gamma^2}{\rho v^2}\tanh\left(\frac{hf_0}{2k_{\mathrm{B}}T}\right)\left(1+\frac{P}{P_{\mathrm{c}}}\right)^{-0.5}$$

$$Fn_0\gamma^2 \approx 5\times 10^4 J/m^3$$

W. A. Phillips, Rep. Prog. Phys. **50**, 1657 (1987)

Manenti *et al.*, PRB (2016)

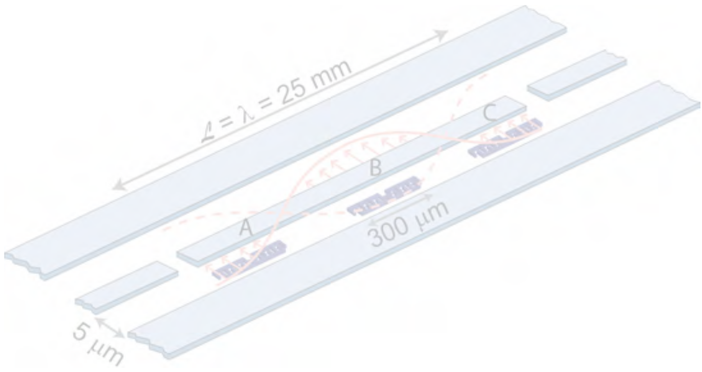
Further evidence for TLS environment



$$\frac{\Delta f}{f_0} = \left(\frac{n_0\gamma^2}{\rho v^2}\right) \ln \frac{T}{T_0}$$

$$n_0\gamma^2 = 7 - 8 \times 10^4 J/m^3$$

- Few ppm cavity frequency shifts observed over 0-1 K
- Not explained by crystal expansion (~1000x larger effect)
- Parameters from TLS model fit consistent with P-dependence, and with other reports of SAWs on quartz: Vanreyten, Solid State Comms. **60**, 63 (1986)



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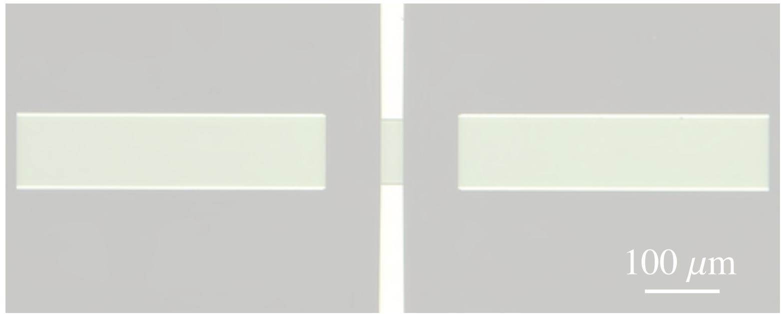

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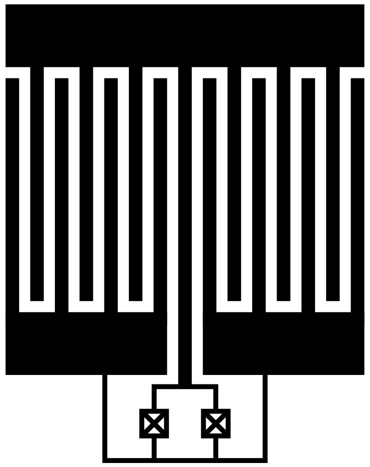
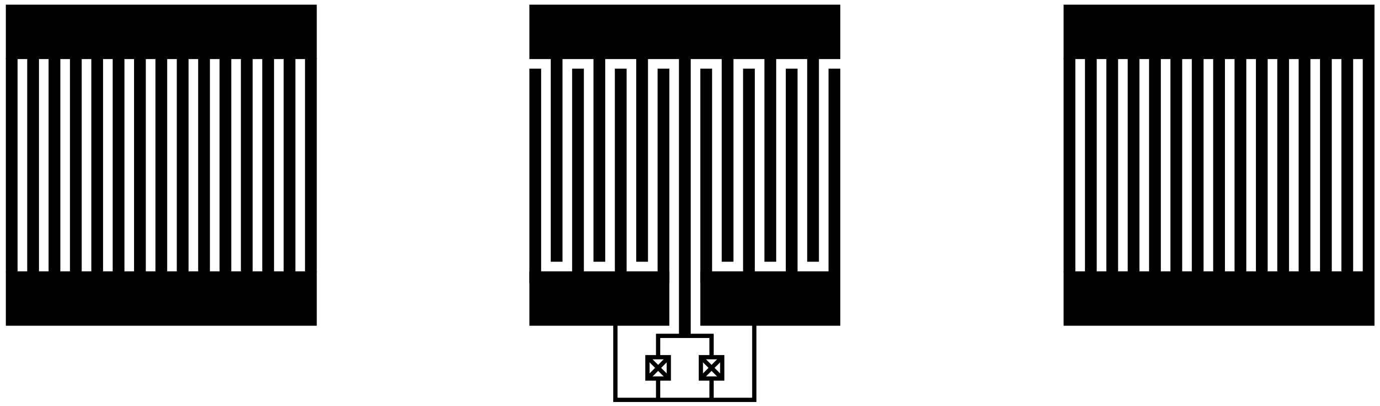


- Steps towards SAW-cQED and SAW-SR

Prospects for SAW circuit QED



Require $g > \kappa, \gamma$

- is this realistic?

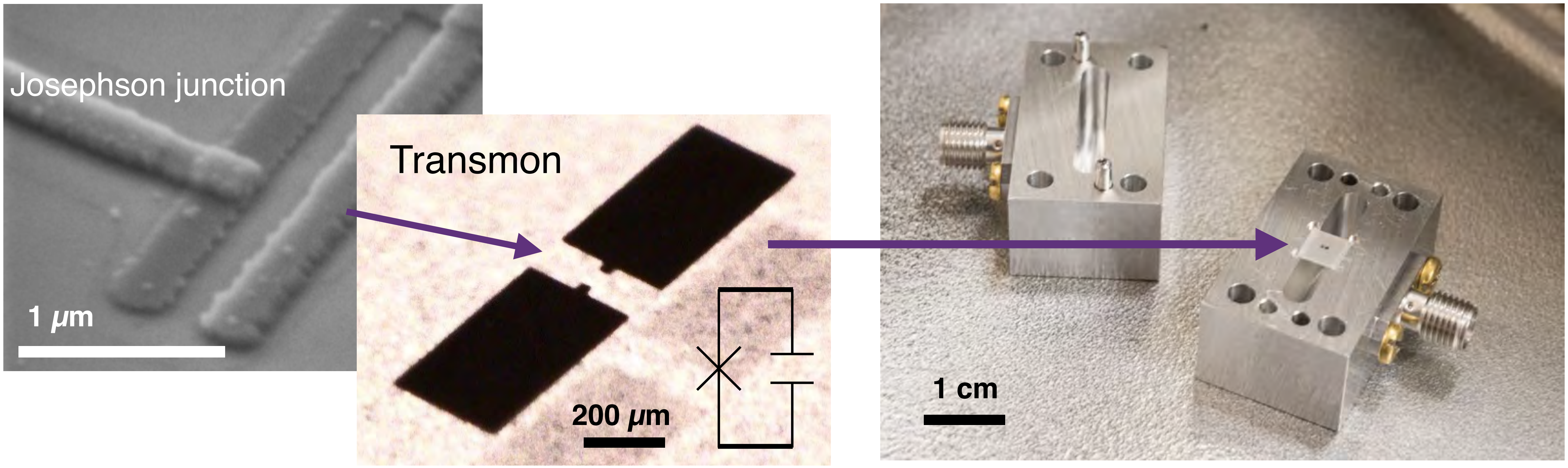
$$u_0 = \sqrt{\frac{\hbar}{\rho W L \pi v_{\mathrm{SAW}}}} \qquad \Phi_0 = \frac{e_{14}}{\epsilon} u_0 \qquad g \sim e\Phi_0$$

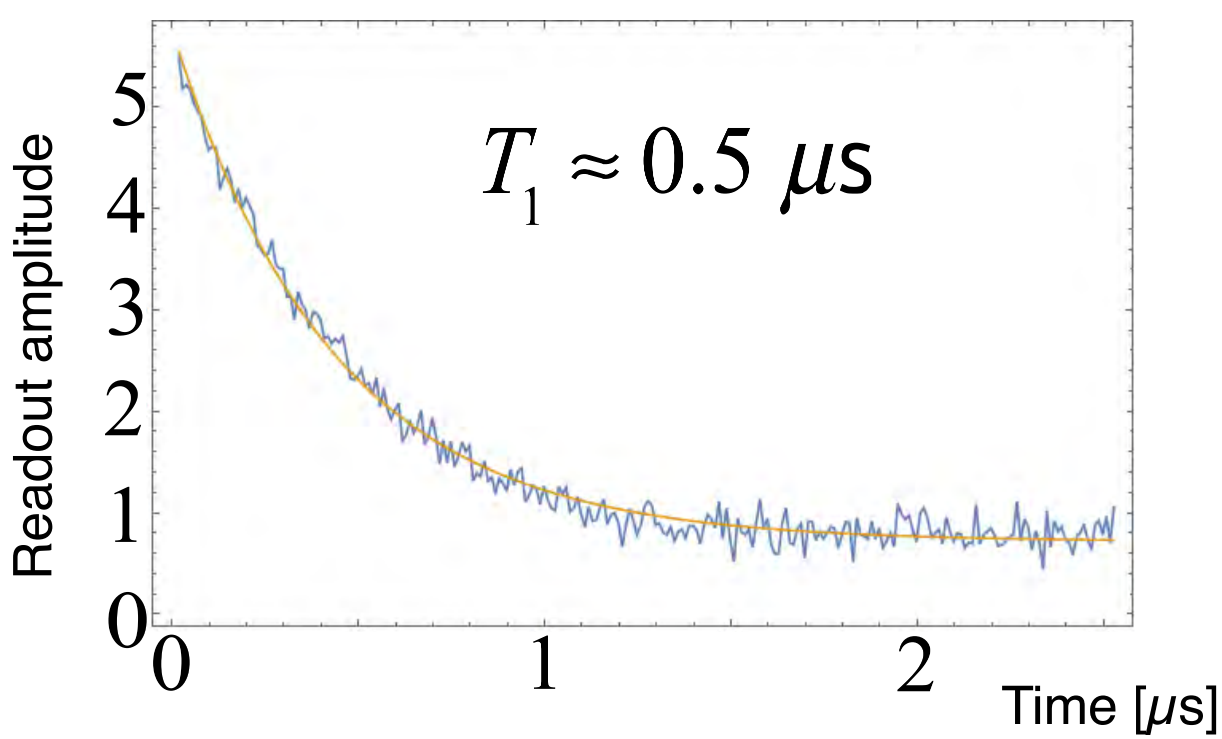
- Estimate for our current geometries on quartz: $g \approx 1 - 10\ \mathrm{MHz}$
- Cavity Q ~ 10,000 at 4.5 GHz in a single mode cavity: $\kappa \leq 1\ \mathrm{MHz}$
- Qubit linewidth on quartz?

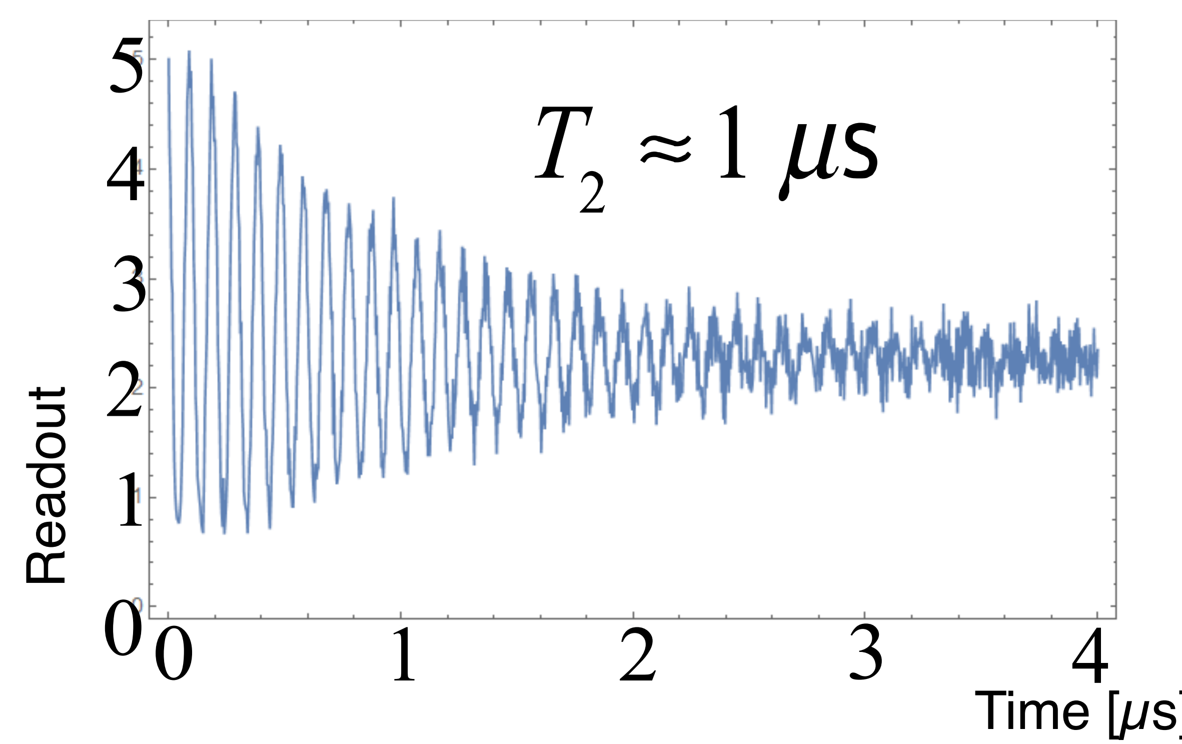
✳ Will suffer from bulk phonon emission

✳ Check with a clean 3D circuit QED experiment…

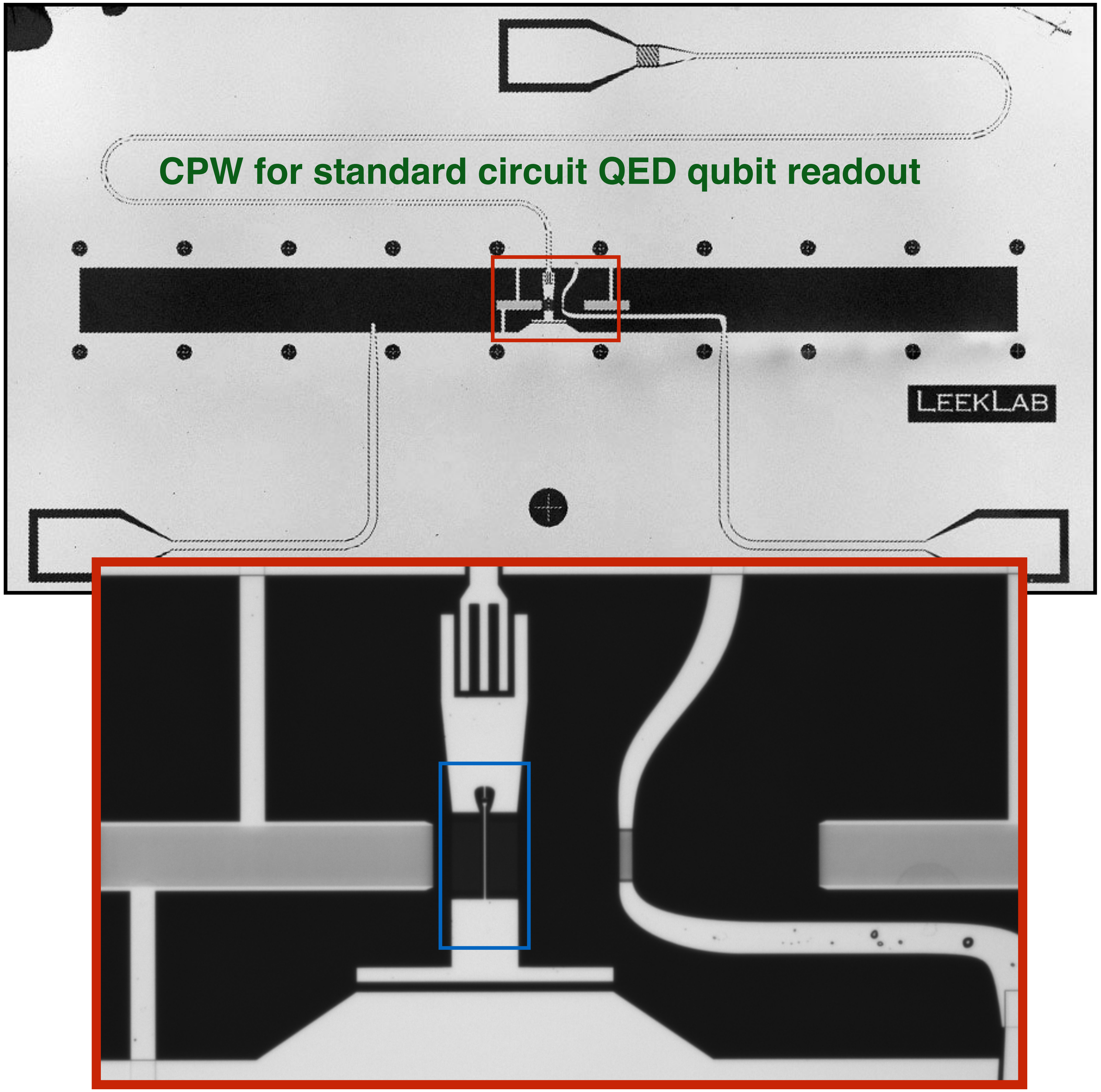
Qubit coherence on quartz in 3D



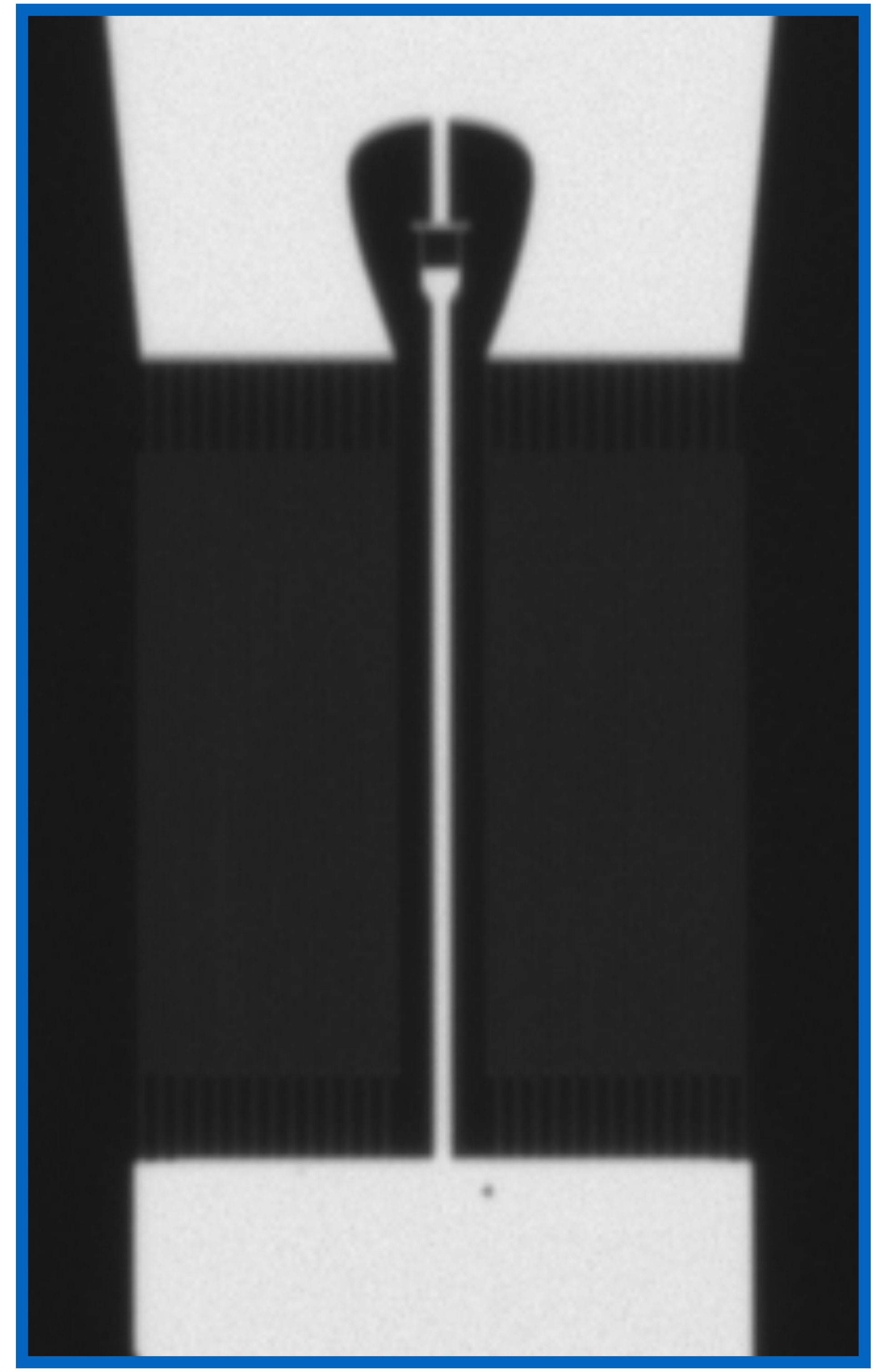




SAW Circuit QED device



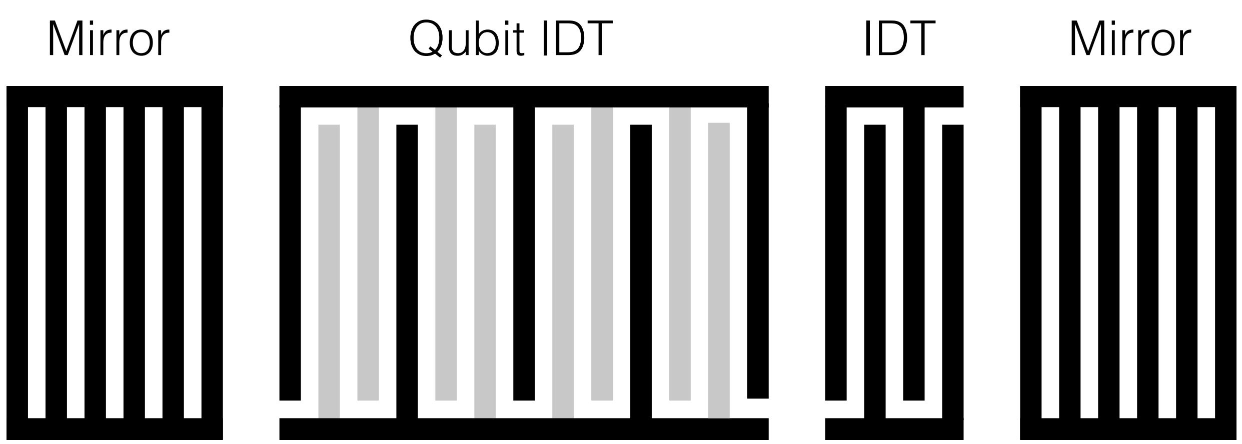
Transmon embedded in SAW resonator

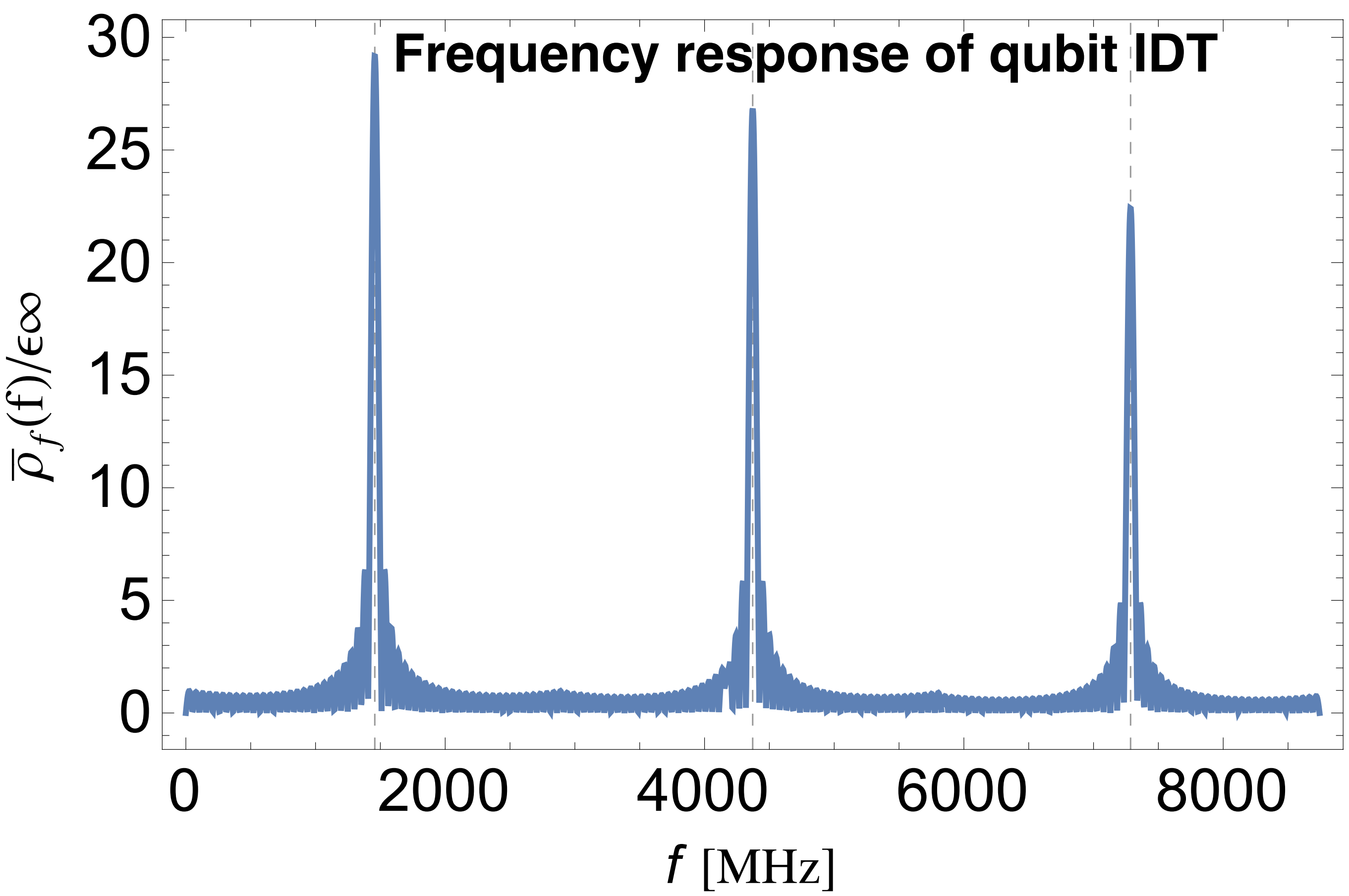


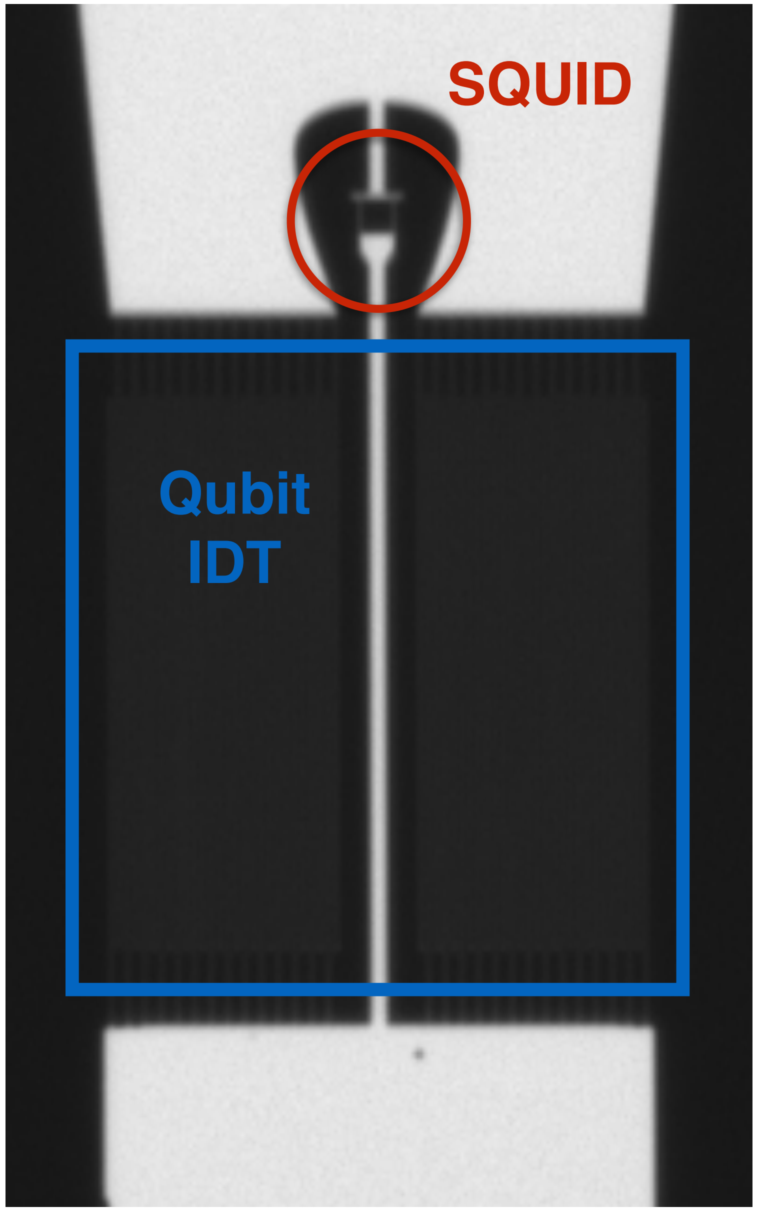
Transmon design

Device design for SAWR-qubit coupling

- 3x period transducer for qubit, to enable simultaneous fabrication with shadow evaporated Josephson junctions

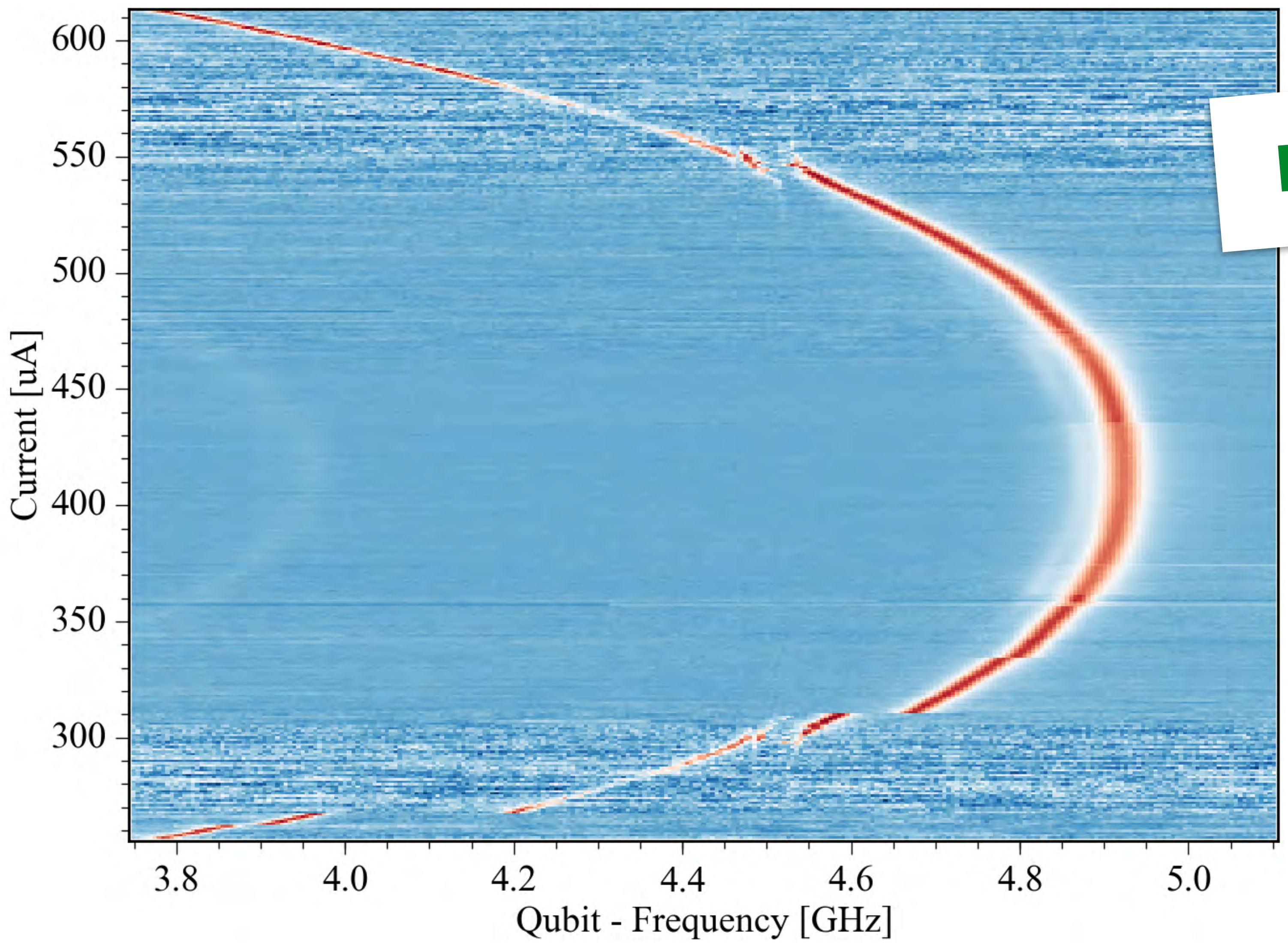


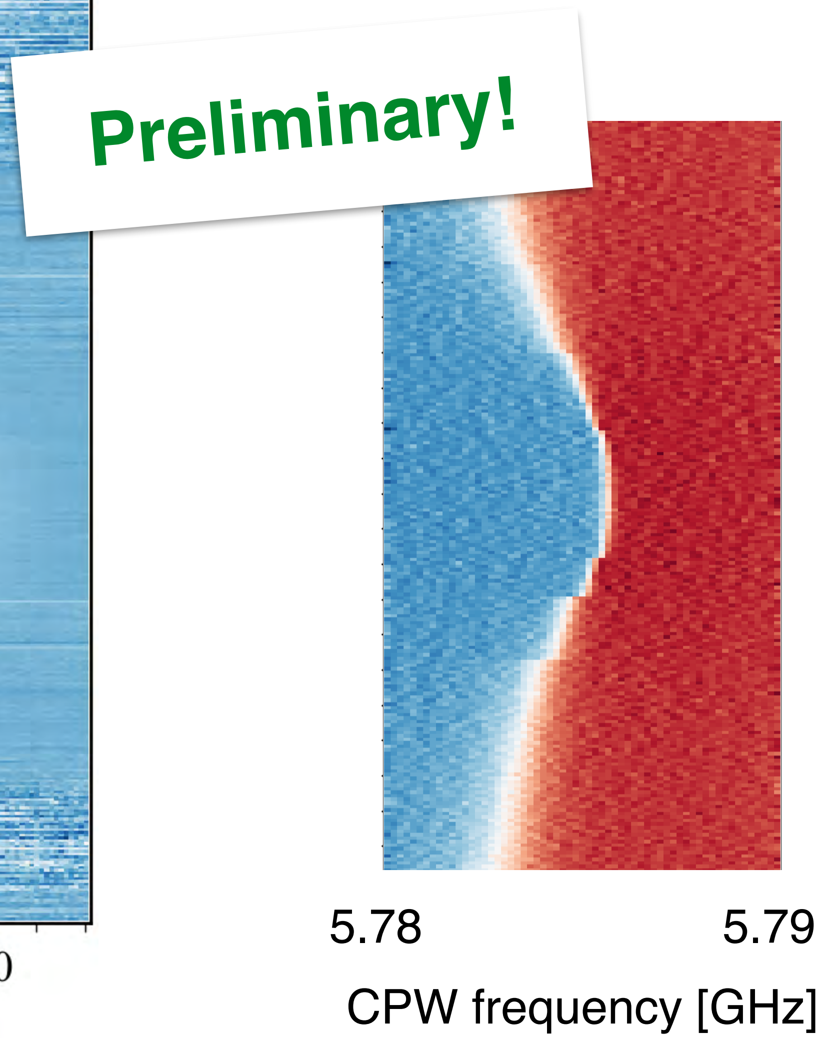




- Qubit IDT couples to SAW resonator (4.35 GHz) at its 3rd harmonic

First measurements of a SAWR/qubit device



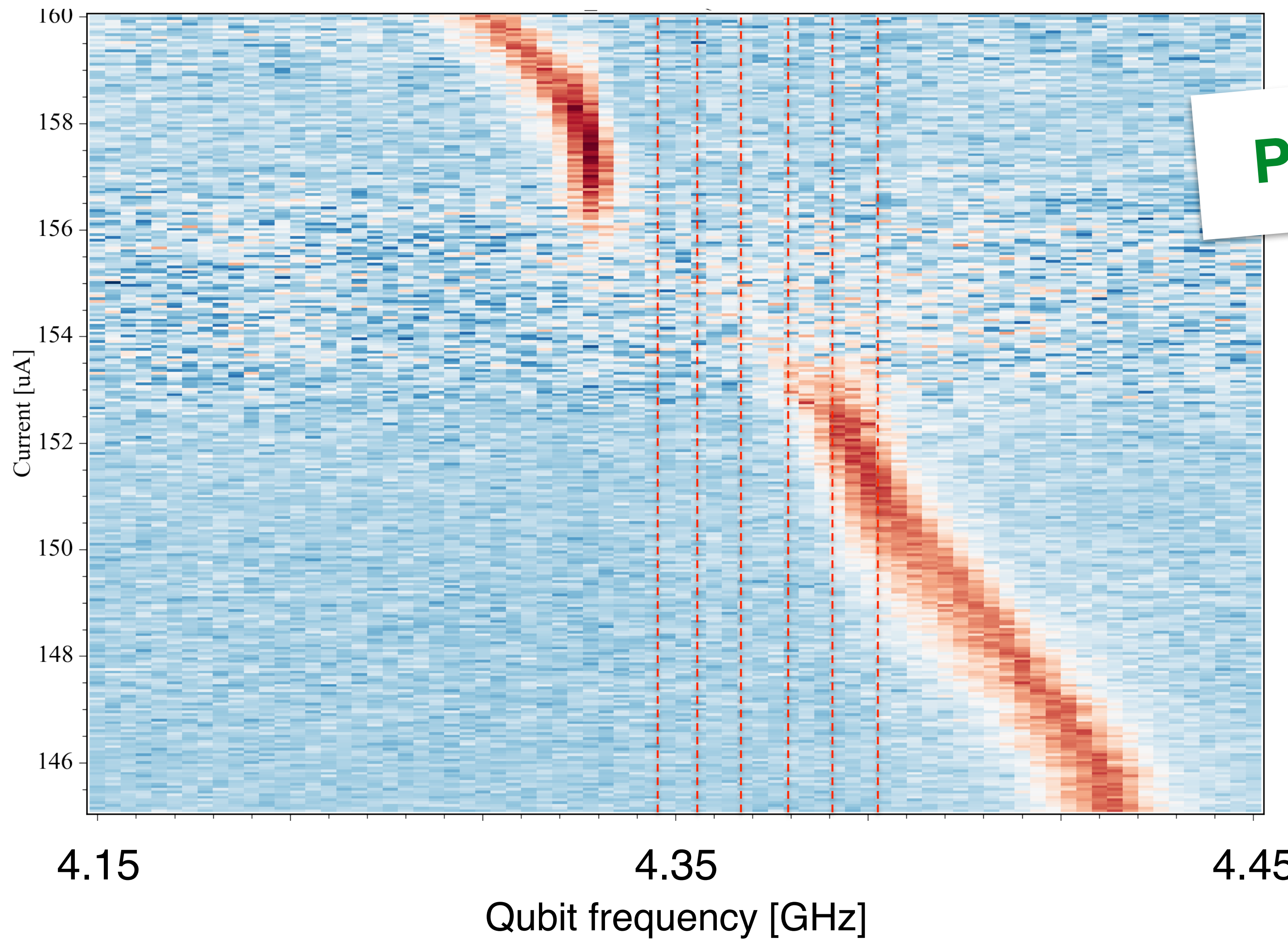


$f_{\mathrm{CPW}} = 5.8\ \mathrm{GHz}$ $\qquad$ $g_{\mathrm{CPW}} \sim 2\pi.100\ \mathrm{MHz}$

$f_{\mathrm{SAW}} = 4.3\ \mathrm{GHz}$

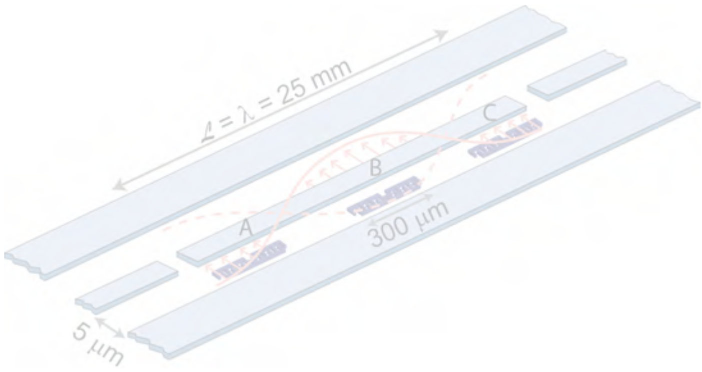
SAW modes at 4.35 GHz
(~10 modes, FSR ~ 10 MHz, Q ~ 10,000)

First measurements of a SAWR/qubit device

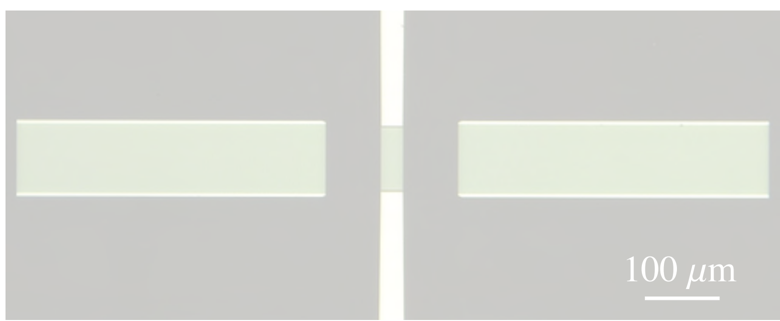


Preliminary!

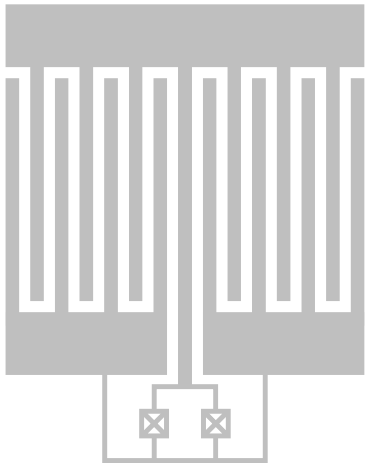
- Qubit spectral line disappearance — likely phonon emission due to qubit IDT, which has a bandwidth of around 100 MHz
- No clear sign of coupling to SAW resonator modes (probably $g < \mathrm{FSR} < \gamma$)
- Work underway to measure devices which should have higher coupling



- Intro: Resonators in quantum devices



- SAW resonators in the quantum regime



- Steps towards SAW-cQED …and SAW-SR

An electric field sensitive spin ensemble

UNIVERSITY OF OXFORD

PRL **110,** 027601 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2013

Coherent Spin Control by Electrical Manipulation of the Magnetic Anisotropy

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(Received 20 October 2012; published 7 January 2013)

High-spin paramagnetic manganese defects in polar piezoelectric zinc oxide exhibit a simple, almost axial anisotropy and phase coherence times of the order of a millisecond at low temperatures. The anisotropy energy is tunable using an externally applied electric field. This can be used to control electrically the phase of spin superpositions and to drive spin transitions with resonant microwave electric fields.

$$H = \mu_B \hat{\mathbf{S}} \cdot \mathbf{g} \cdot \mathbf{B} + g_N \mu_N \hat{\mathbf{I}} \cdot \mathbf{B} + \hat{\mathbf{S}} \cdot \mathbf{A} \cdot \hat{\mathbf{I}} + H_{\mathrm{ZFS}}, \qquad (1)$$

where the axial anisotropy, or zero-field splitting (ZFS), term

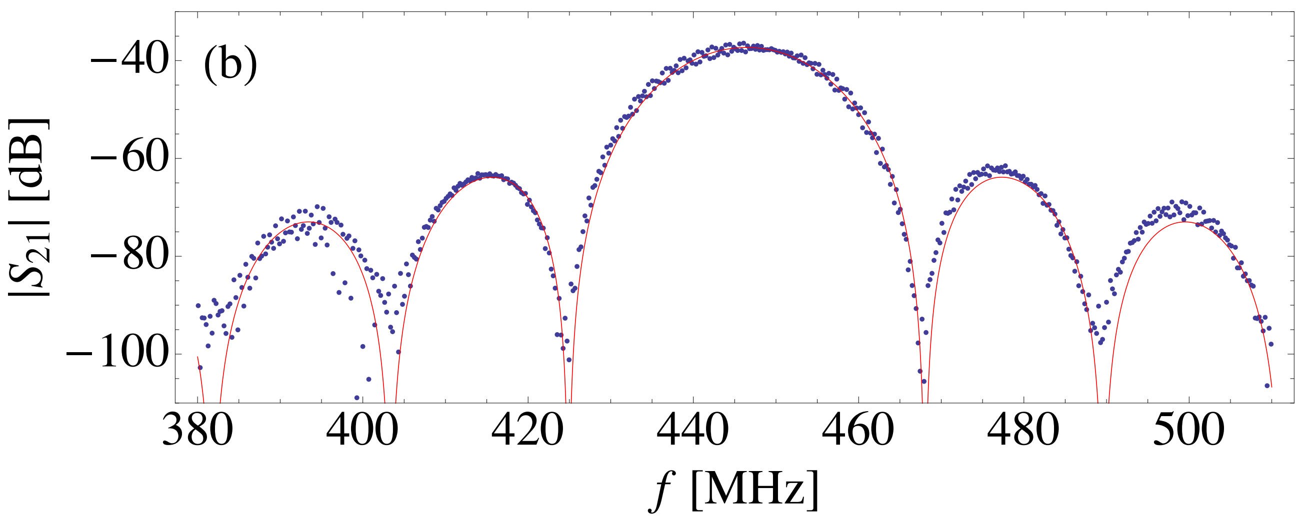
$$H_{\mathrm{ZFS}} = -D\hat{S}_z^2.$$

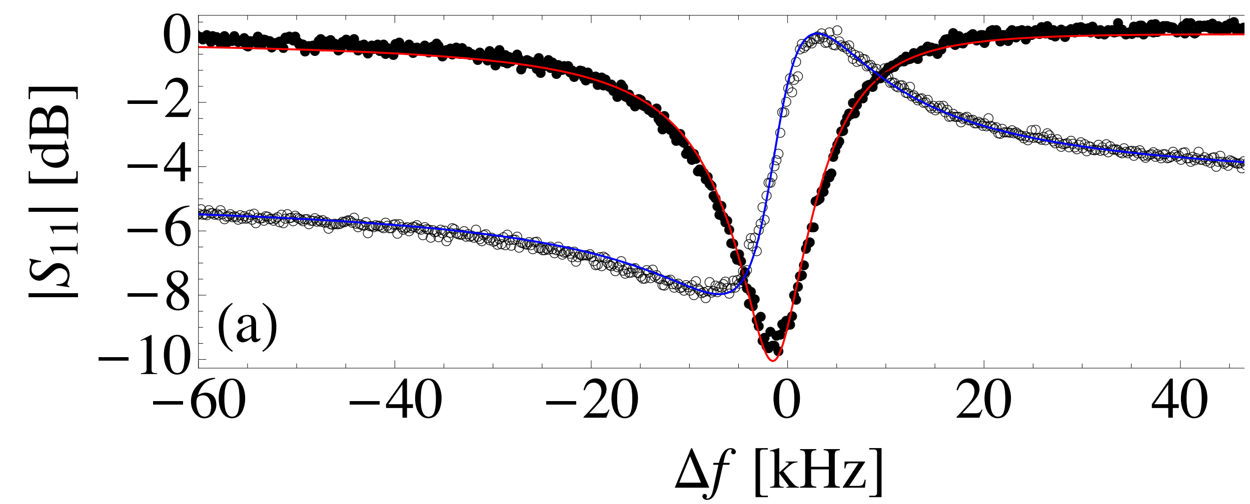
Anisotropy of crystal causes zero-field splitting and sensitivity of spins to strain / electric field.

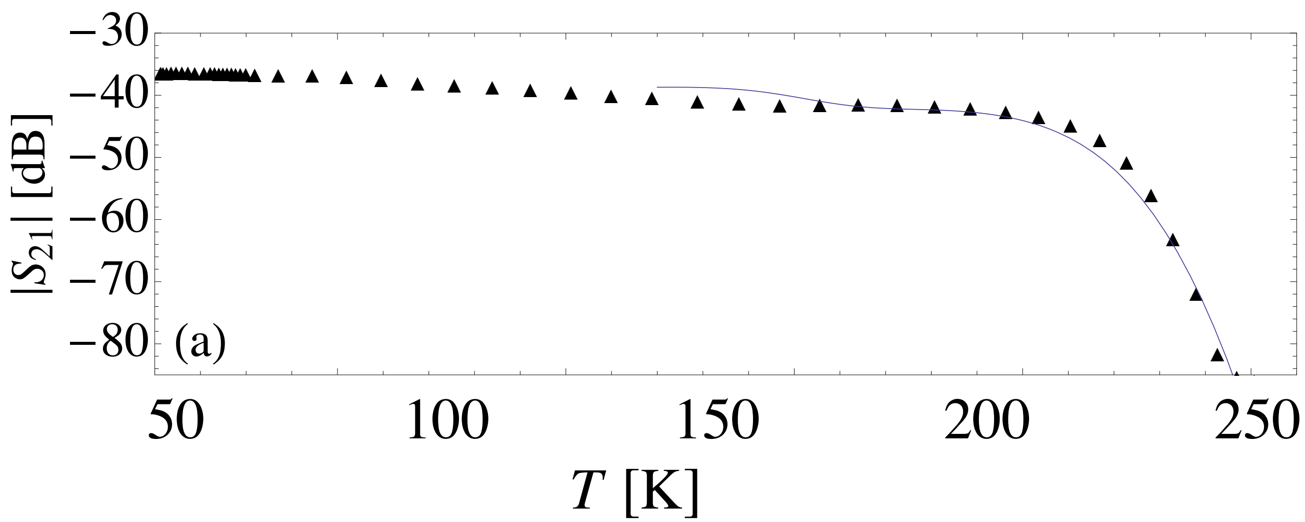
$D = 1.6$ GHz

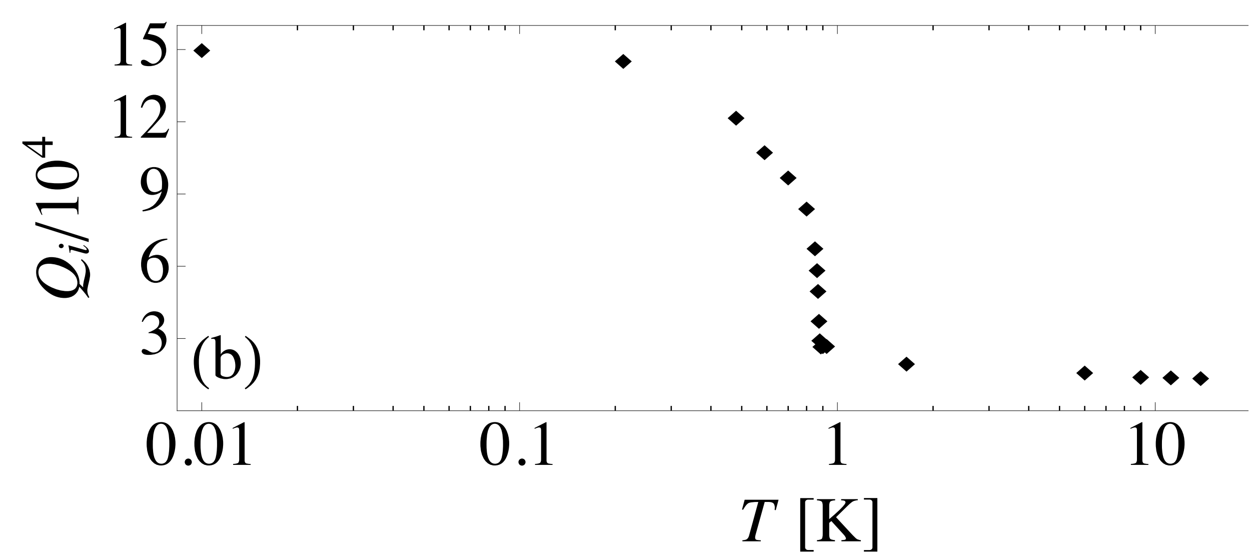
- Can we make high quality SAW devices on ZnO, and acoustically excite these spins?

SAW devices on bulk crystal ZnO









- Delay lines at ~500 MHz behave according to theory, and dissipation correlates with bulk crystal conductivity
- Resonator at ~1.7 GHz reaches internal Q of 150,000 at 10 mK

Magnusson et al., APL **106**, 063509 (2015)

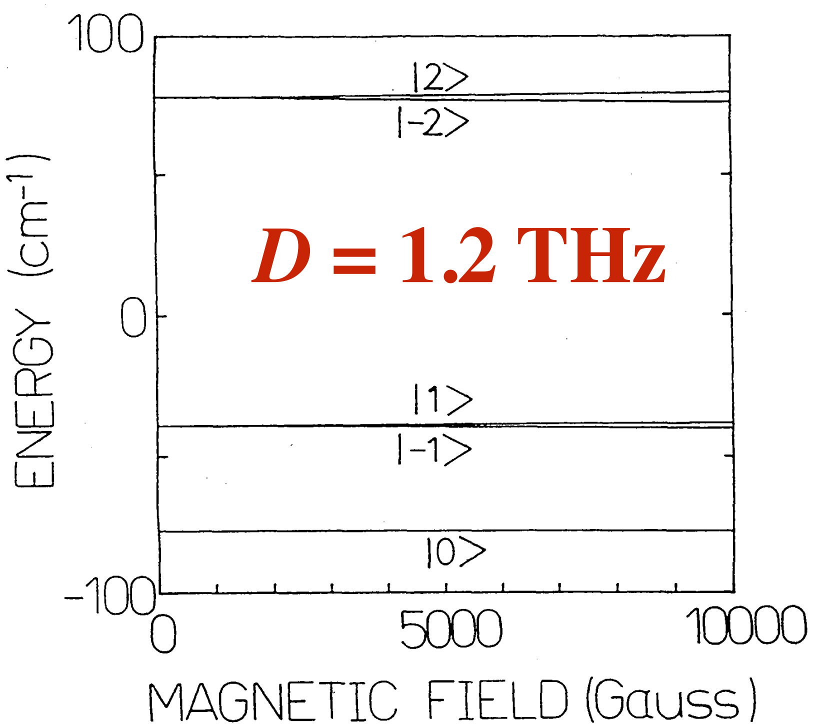


Fig. 3. Low-lying energy levels of Fe^{2+} in Li site.

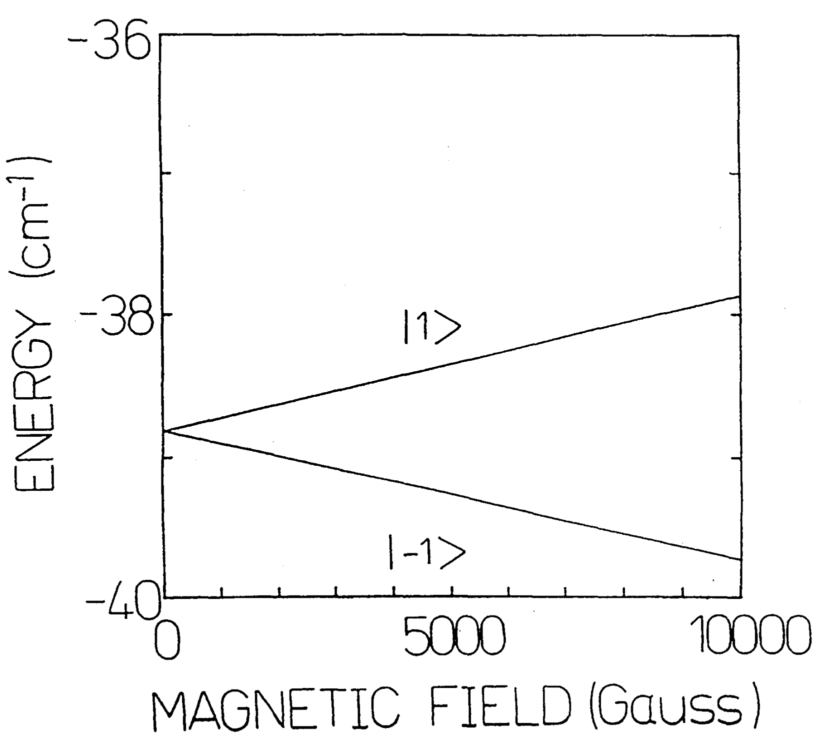


Fig. 4. Extension of Fig. 3.

Cho et al., JJAP **29**, 19 (1990)

$$H_{so} = \beta(g_{\perp}(H_x S_x + H_y S_y) + g_{/\!/} H_z S_z) + D(S_z^2 - S(S+1)/3)$$

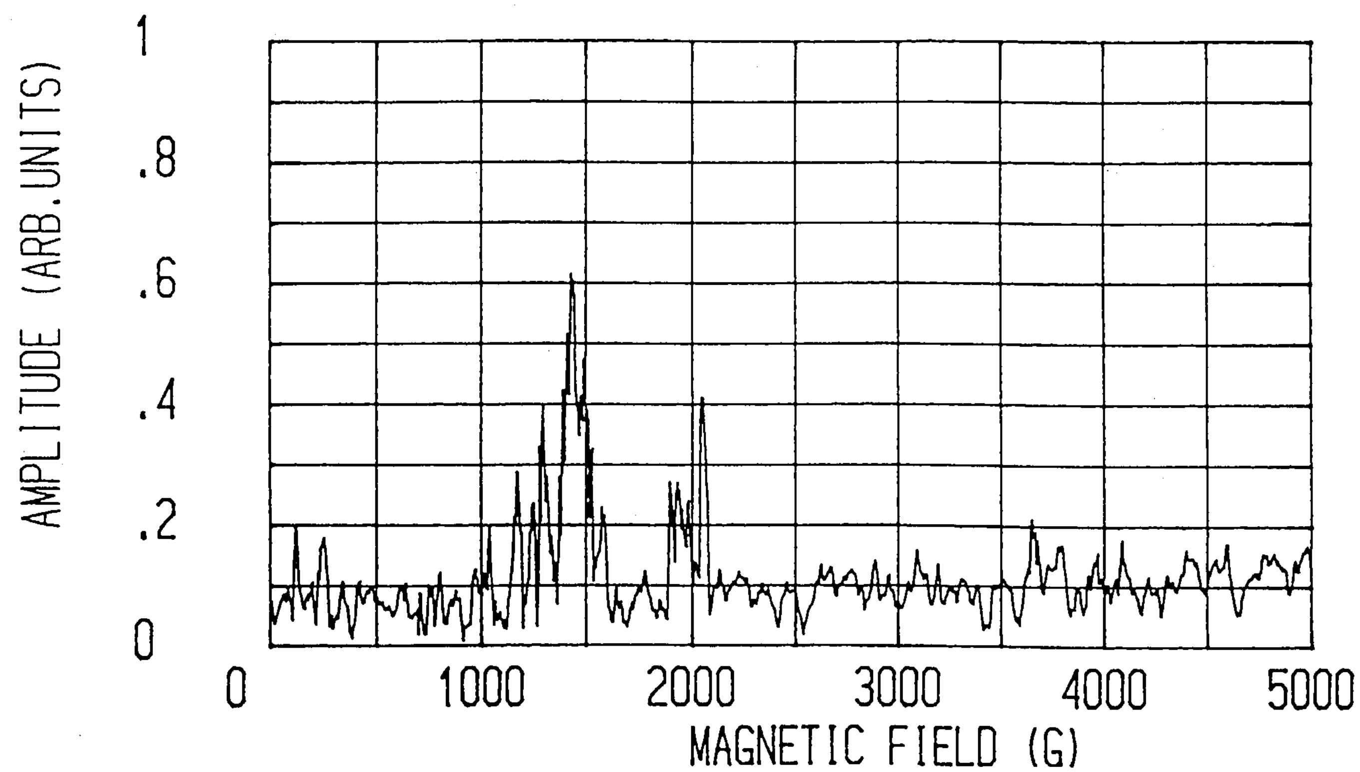
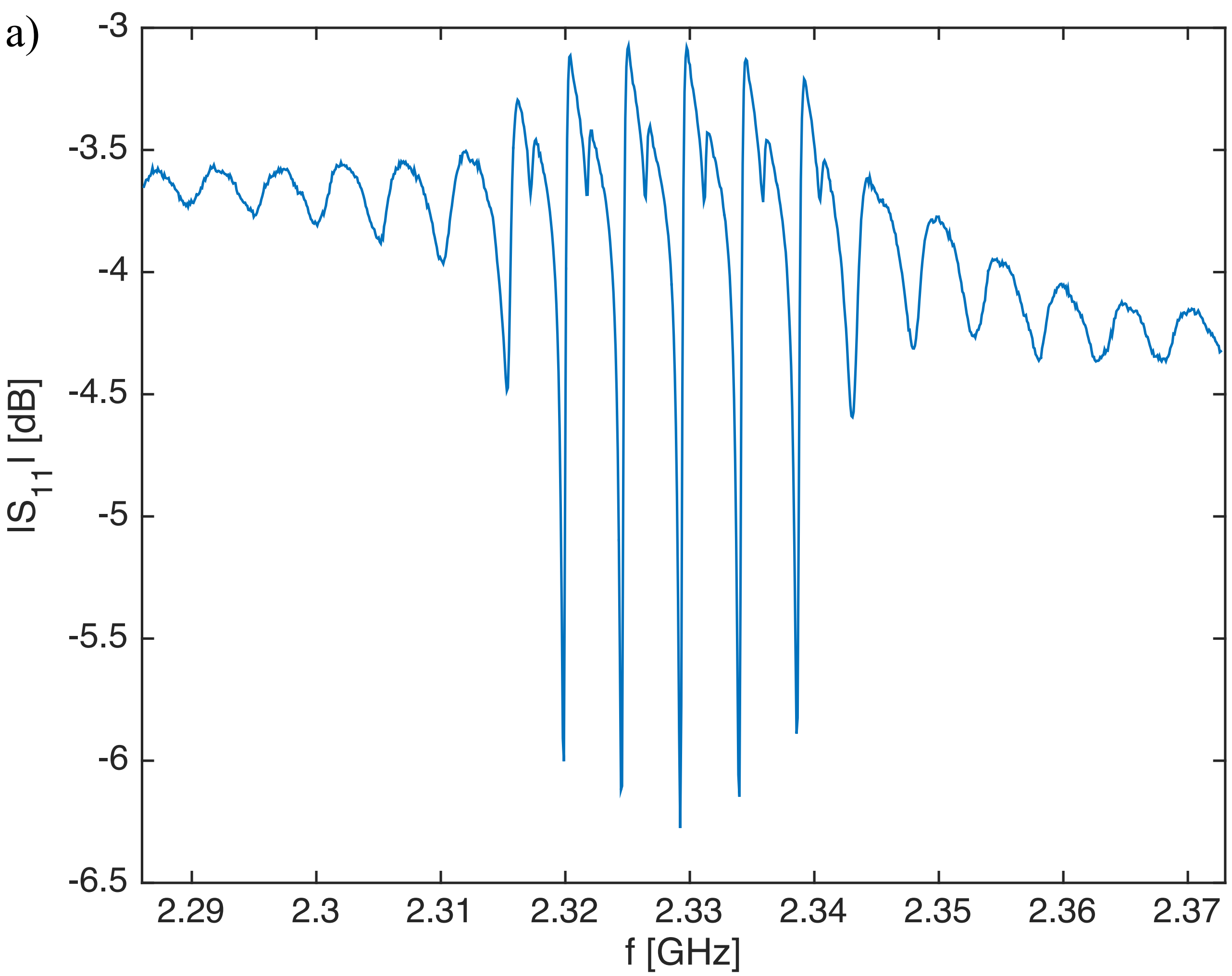


Fig. 5. SAW-APR absorption curve at about 20 K.

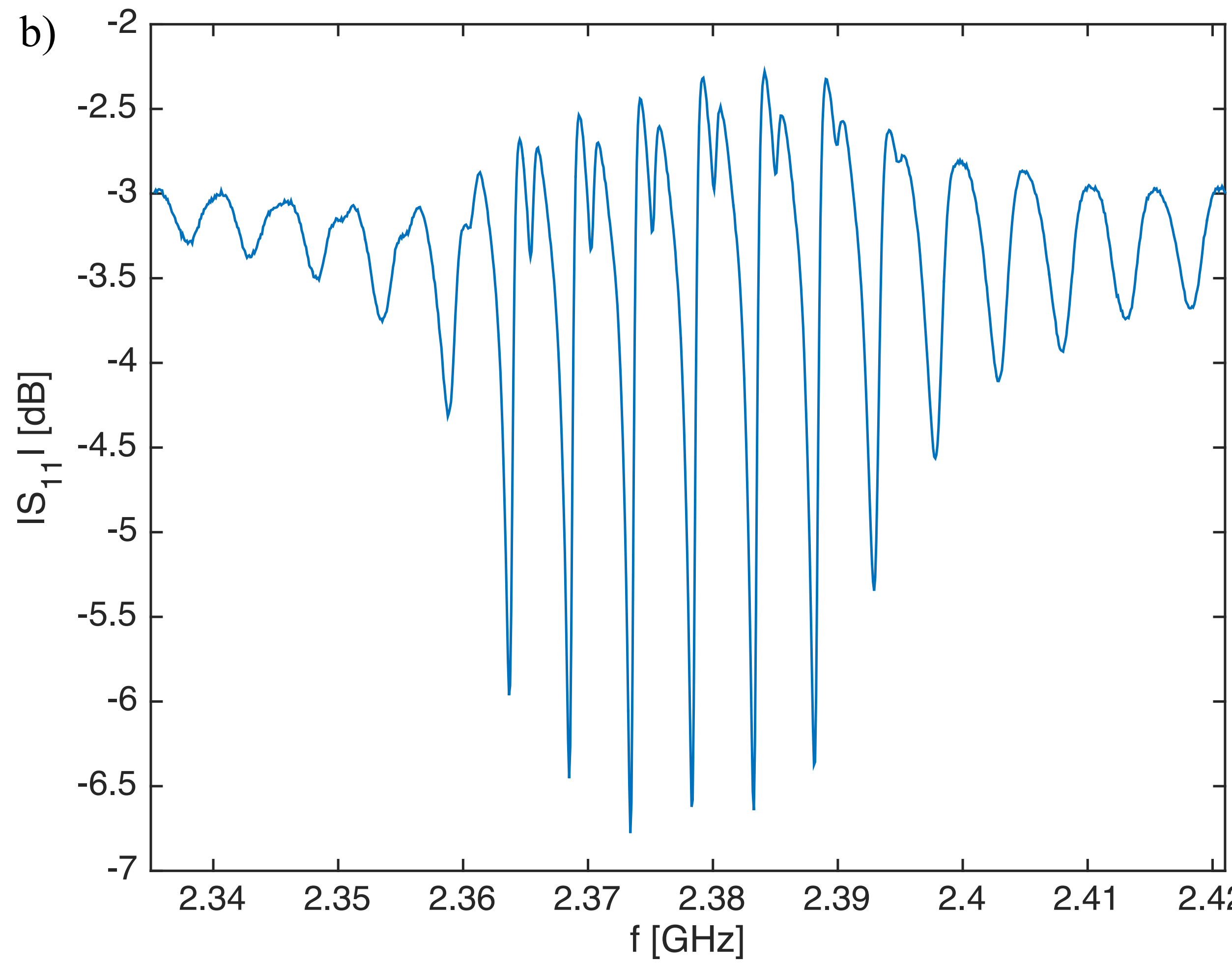
- Continuous wave 5.8 GHz SAW absorption, peaks predominantly in 100-150 mT range

- Z-cut $LiNbO_3$, 0.05% Fe-doped, reduced to Fe^{2+}
1000-finger gratings, 21-finger IDT, Q ~ 10,000

X propagation

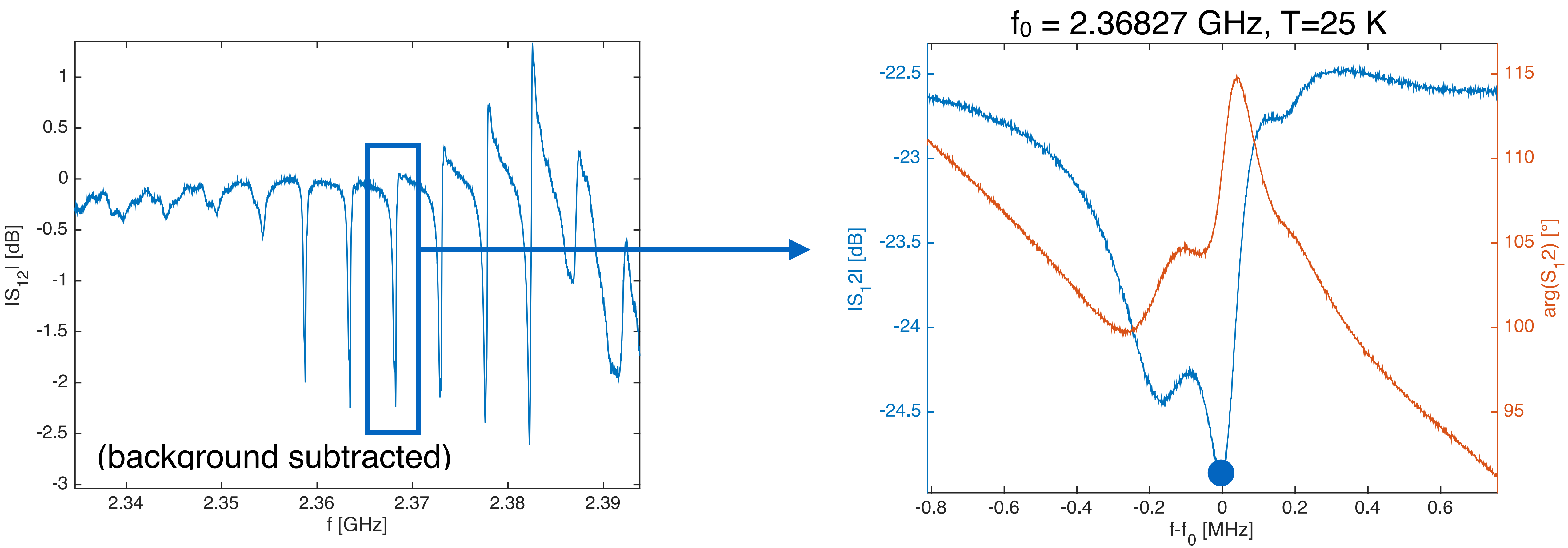


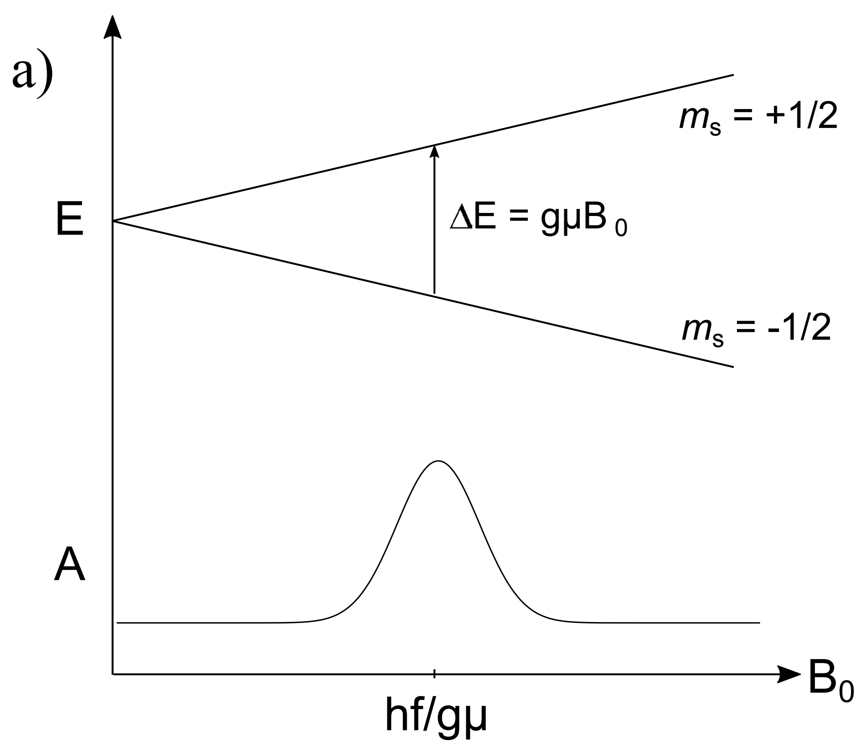
Y propagation

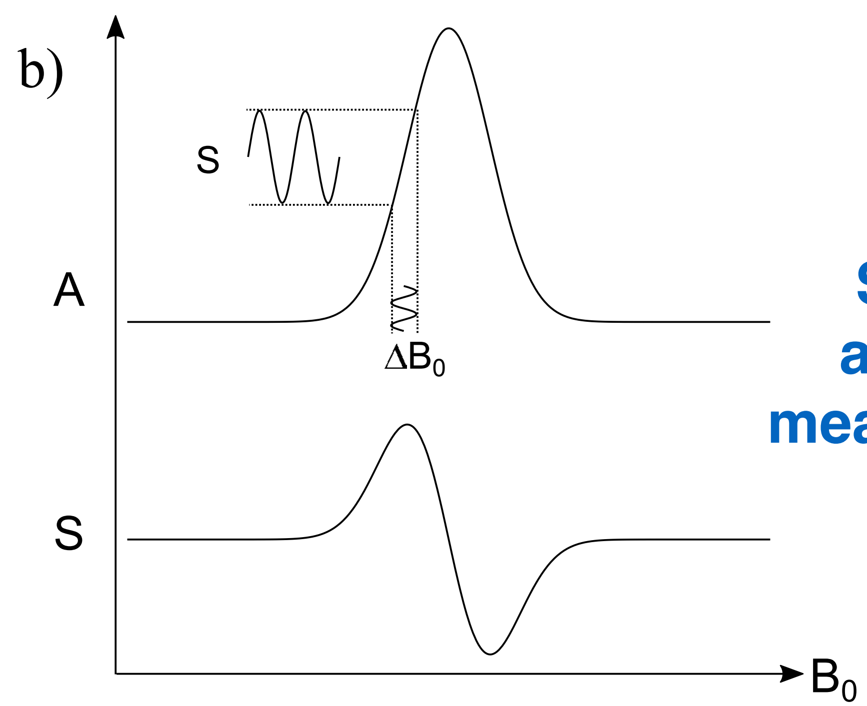


$v_X \approx 3730 \text{ m/s}$ $\lambda \approx 1.6\ \mu\text{m}$ $v_Y \approx 3810 \text{ m/s}$

SAW resonator on Fe^{2+} $LiNbO_3$ at low T

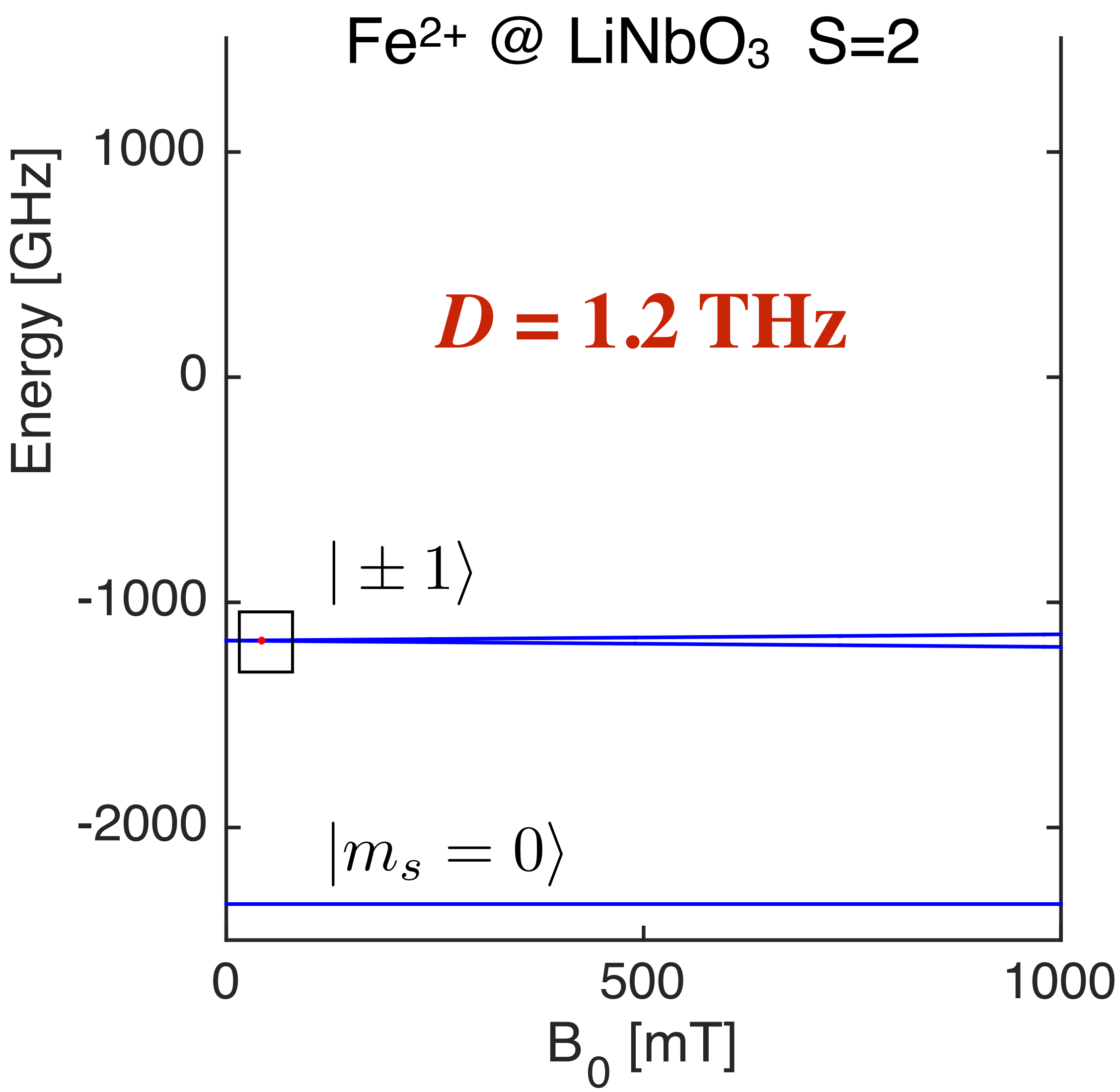


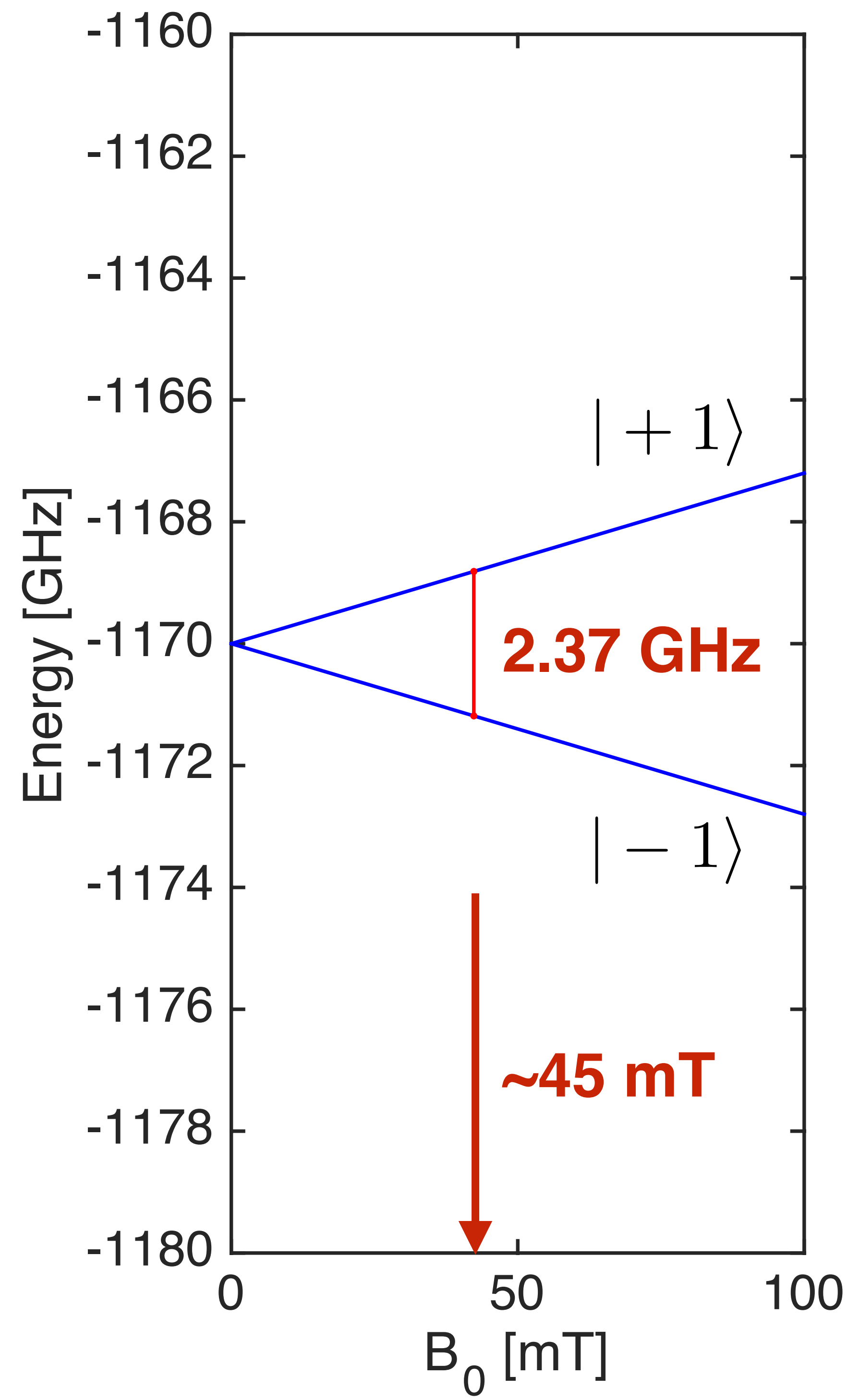




Sweep magnetic field and carry out ESR-like measurement of absorption

Energy levels of Fe^{2+} @ $LiNbO_3$

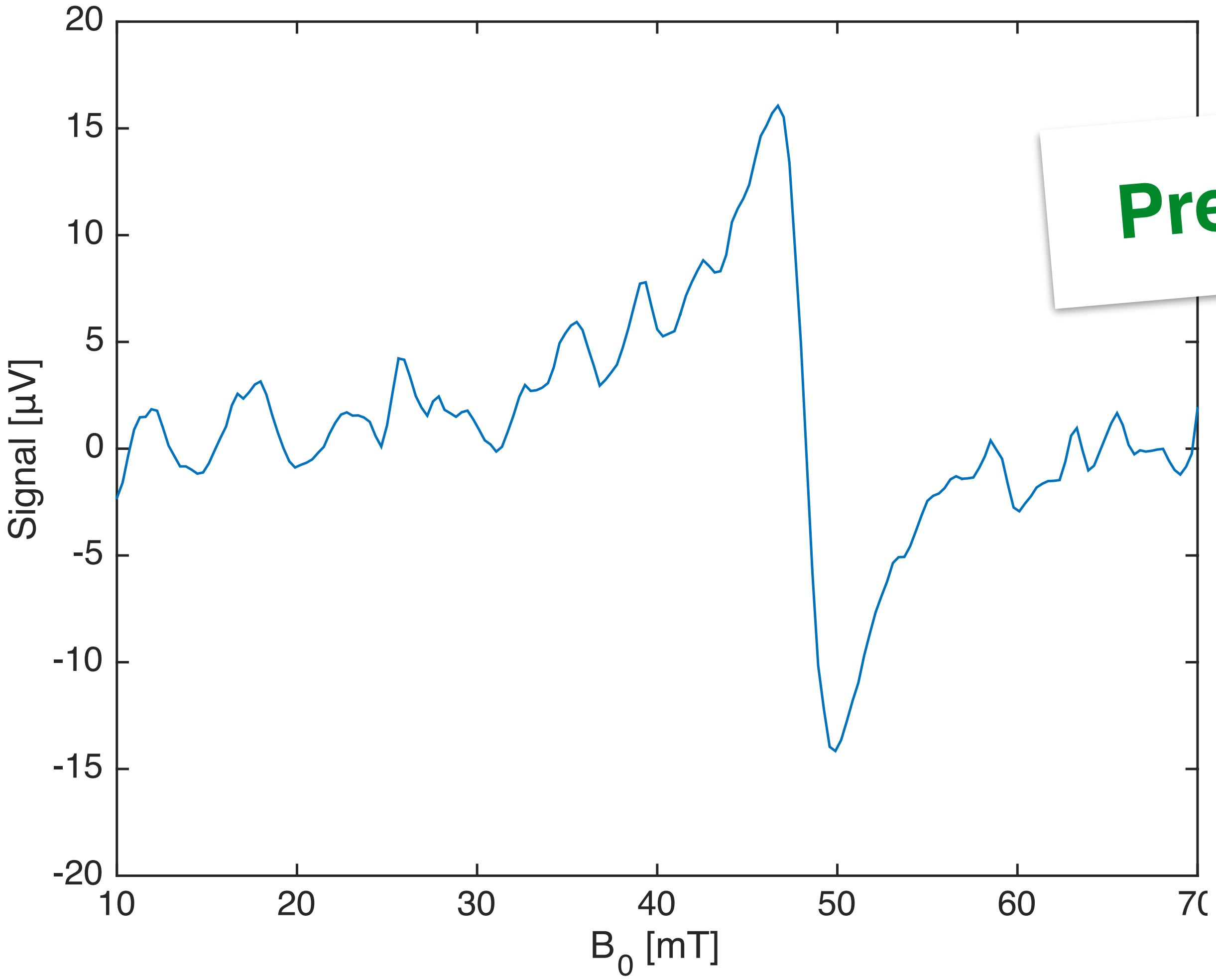


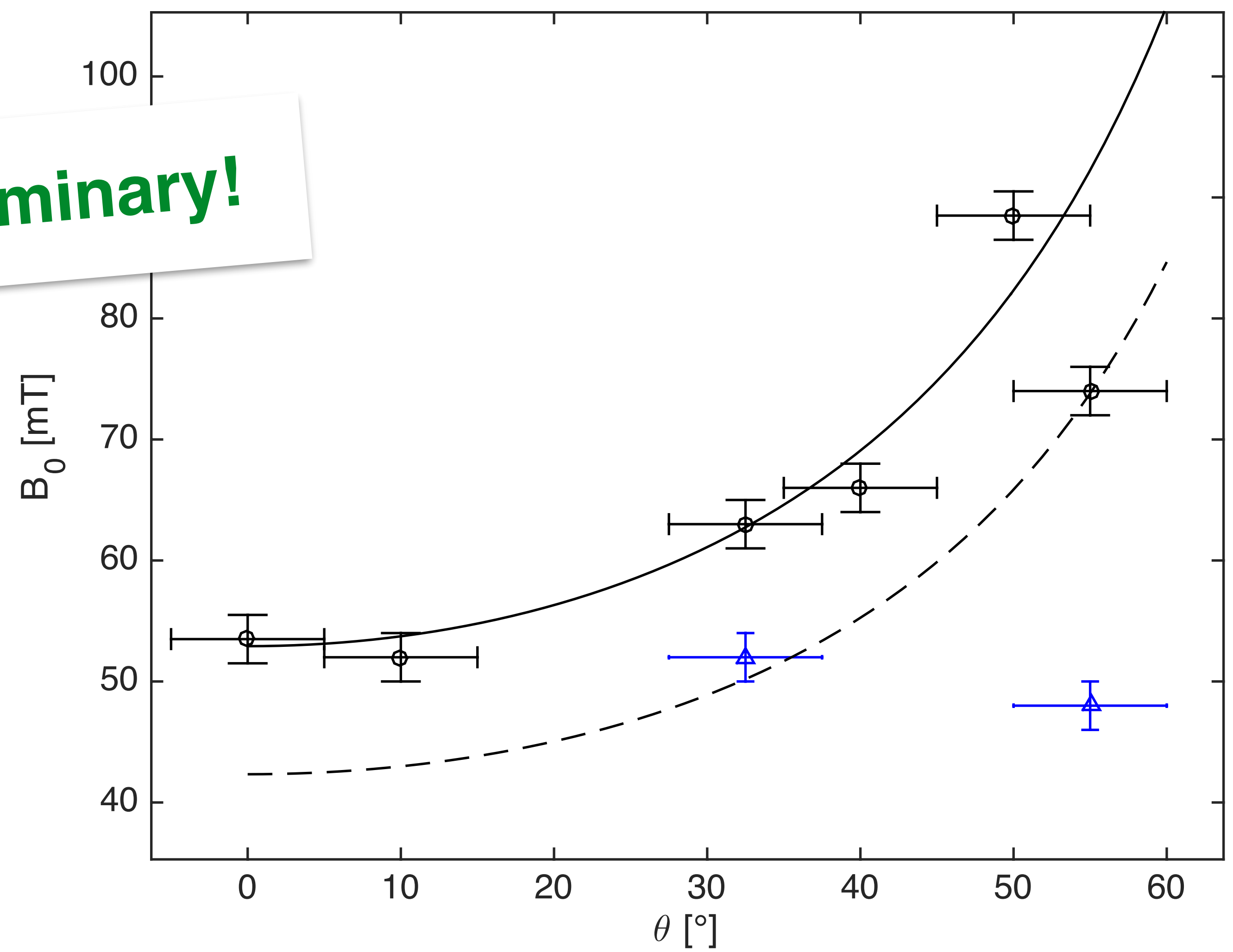


$$H = H_0 + D(S_z \cos(\theta) + S_x \sin(\theta))^2$$

$$= H_0 + D\left(S_z^2 \cos^2(\theta) + \frac{\sin(2\theta)}{2} S_z(S_+ + S_-) + \frac{1}{4}\sin^2(\theta)(S_+^2 + 2S_+S_- + S_-^2)\right)$$

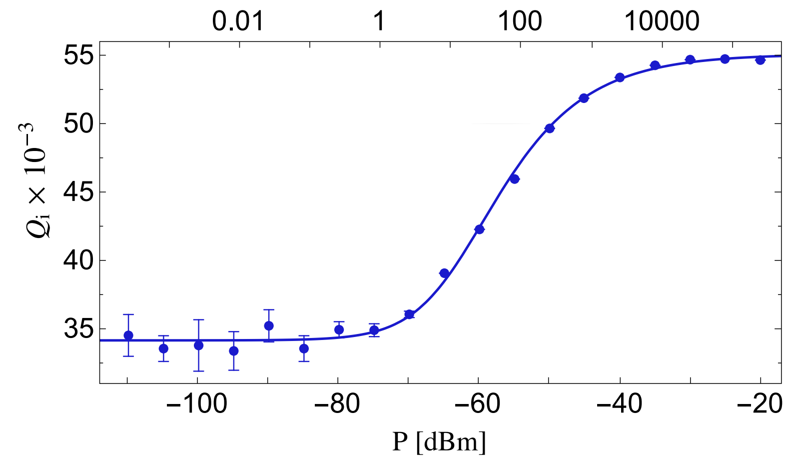
SAW resonator on Fe^{2+} $LiNbO_3$ at T = 25K



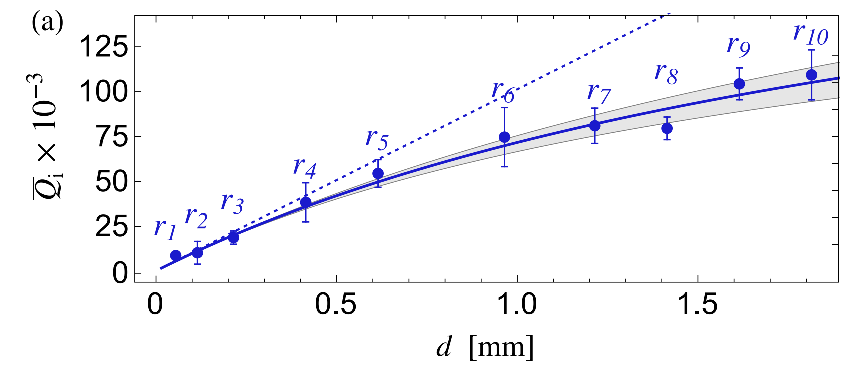


- SAW spin resonance signal observed at approximately calculated field
- Angular dependence appears to fit to $g = 1.6$ (unexplained)
- No signal observed on control (unreduced) Fe^{3+} sample
  => likely that this is Fe^{2+} resonance

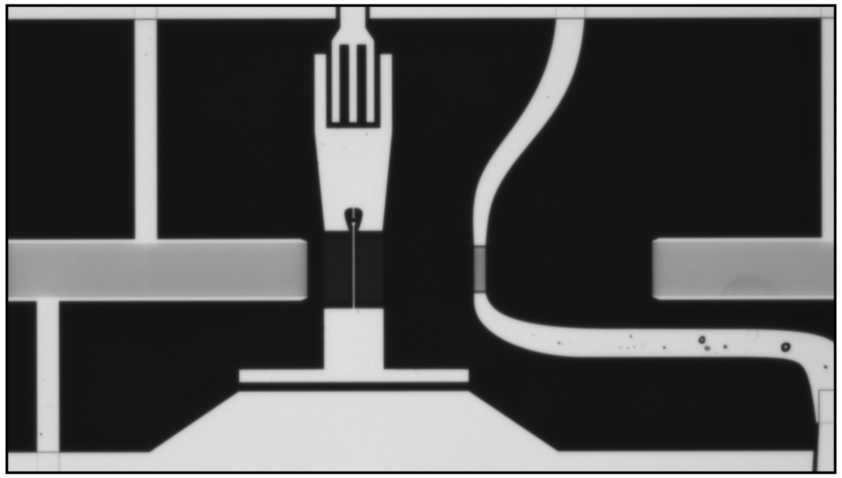
- Quartz SAW resonators at low temperature reach:
  Q ~ 450,000 at 500 MHz
  Q ~ 30,000 at 4 GHz in the single phonon regime



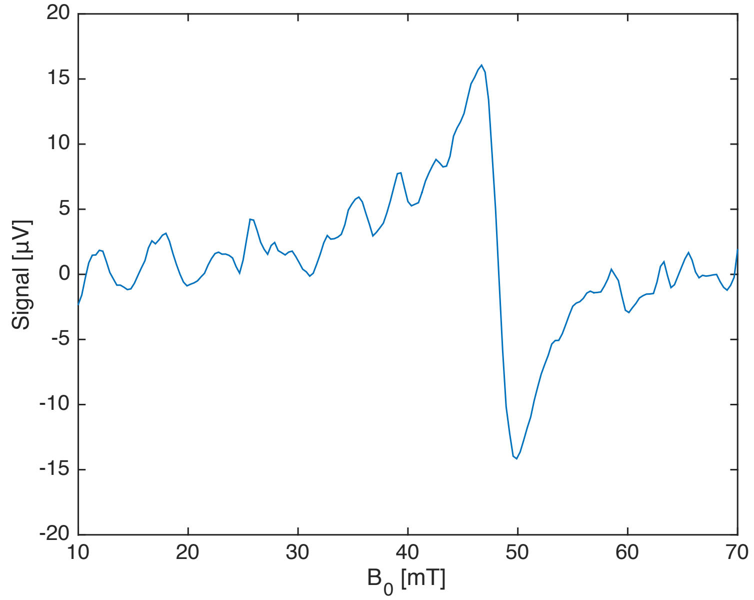
- Losses likely limited by phonon scattering, TLSs



- SAWR - qubit coupling experiments underway



- Indication of SAW spin resonance in Fe^{2+}@$LiNbO_3$



Manenti *et al.*, PRB **93**, 041411(R) (2016)
Magnusson *et al.*, APL **106**, 063509 (2015)
Aref *et al.*, arXiv:1506.01631

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SAWs

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