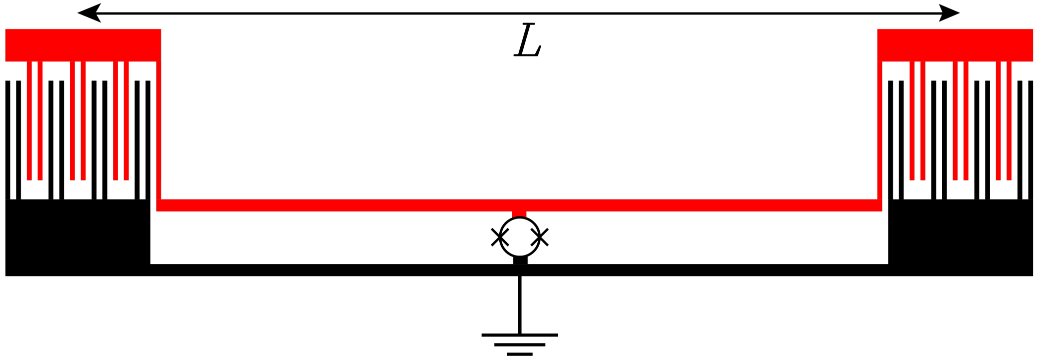
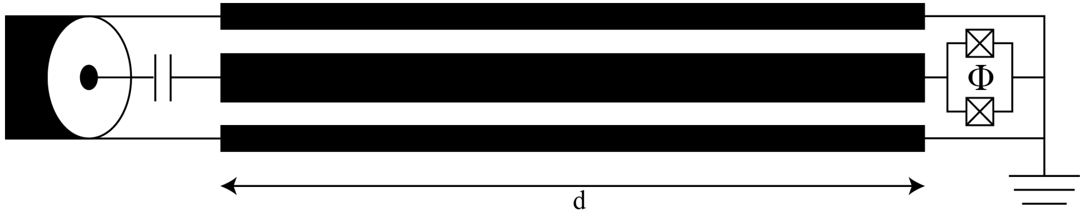
A giant artificial atom: Nonexponential decay

A driven resonator in the quantum regime: Period multiplication





G. Andersson *et al*., Nature Physics **15**, 1123 (2019)

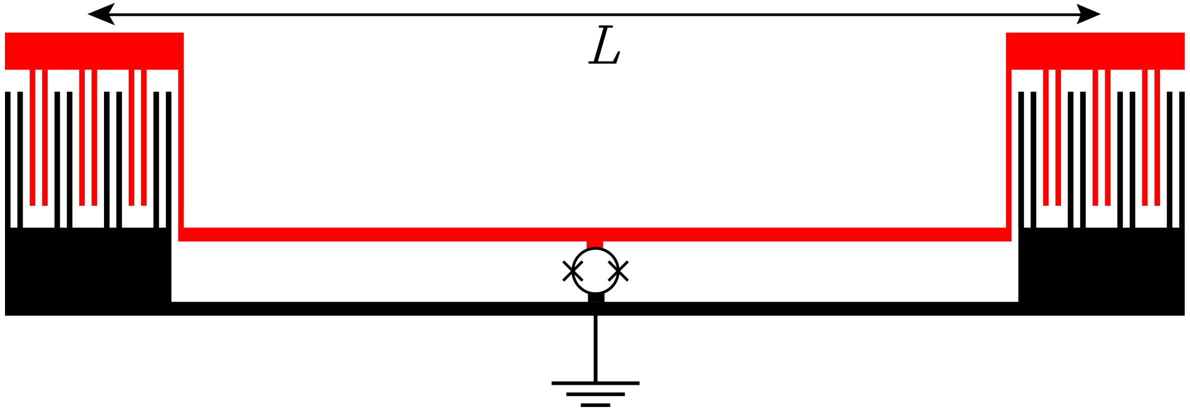
I.-M. Svensson *et al*. Phys. Rev. B **96**, 174503 (2017)
I.-M. Svensson *et al*. Appl. Phys. Lett. **113**, 022602 (2018)

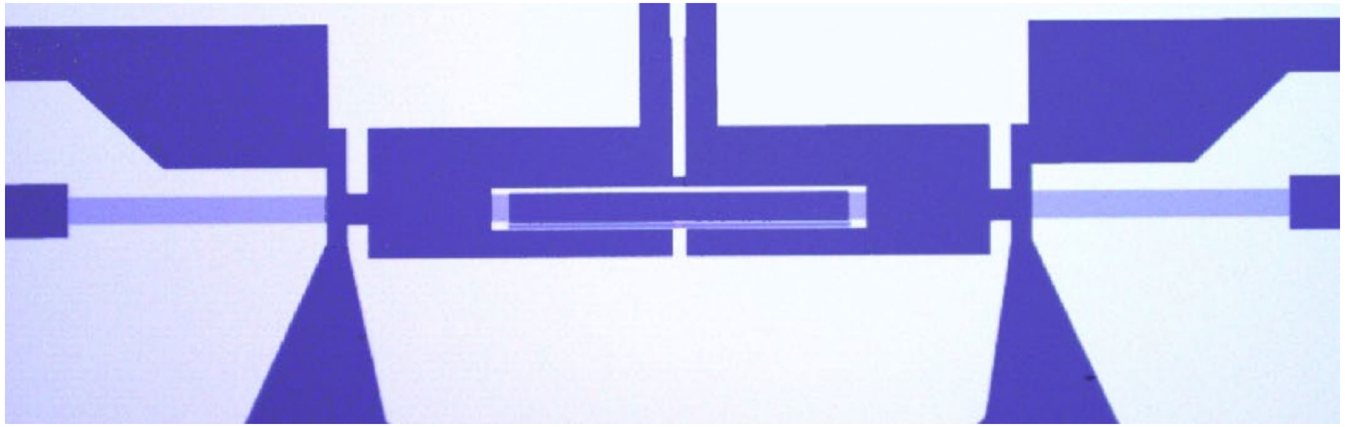
Knut and Alice Wallenberg Foundation
Vetenskapsrådet
SAWtrain network

A giant artificial atom: Nonexponential decay

Outline

- Atoms coupling to sound
- The size of an atom
  - Small, Large, or Giant atoms
- Experiments on a giant atom
  - Atom emission
  - Nonexponential decay
- Conclusions





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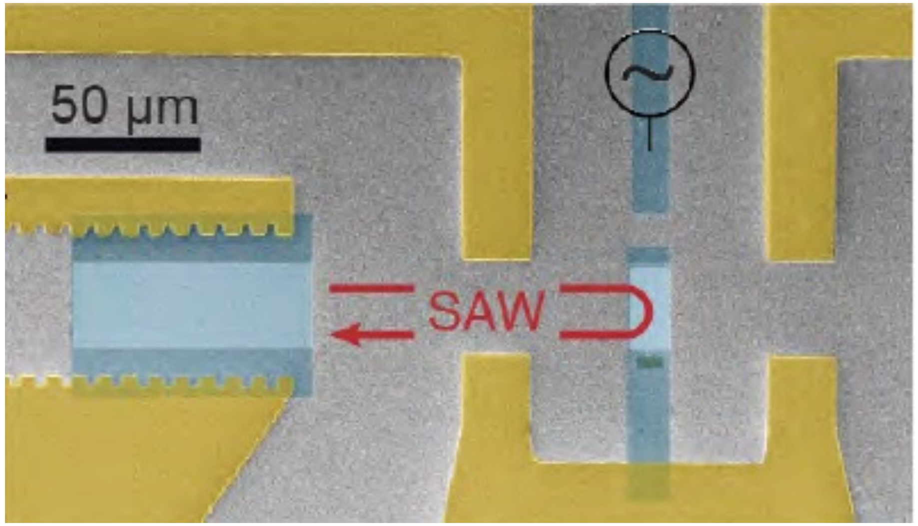
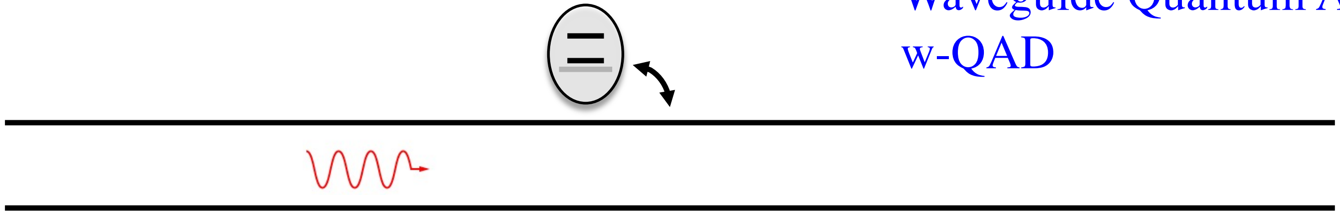
SAWtrain network

G. Andersson *et al.*, Nature Physics **15**, 1123 (2019)

Qubit coupling to propagating surface acoustic waves



Nonlinear reflection
Qubit decay by emitting phonons

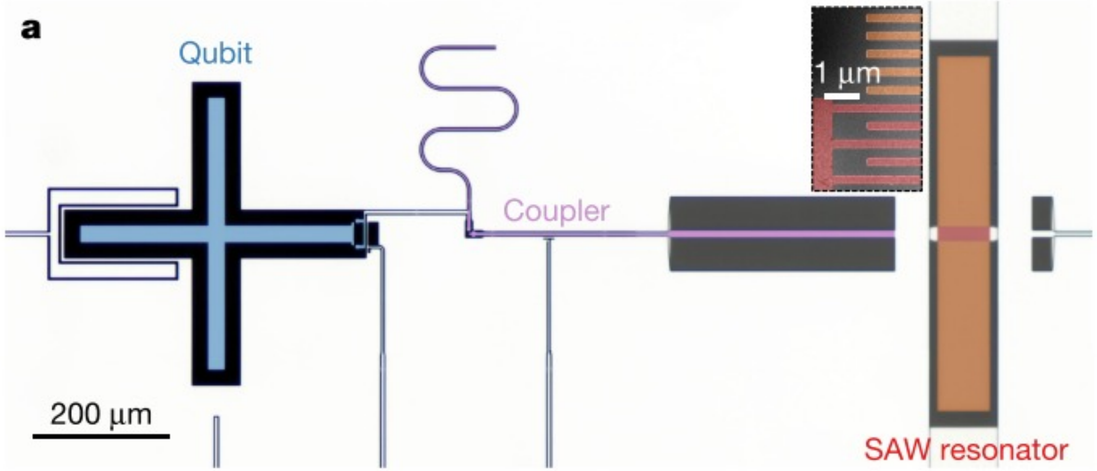


Waveguide Quantum AcoustoDynamics
w-QAD

M. V. Gustafsson et al. Nature Physics **8**, 338 (2012)
M. V. Gustafsson et al. *Science* **346**, 207 (2014)

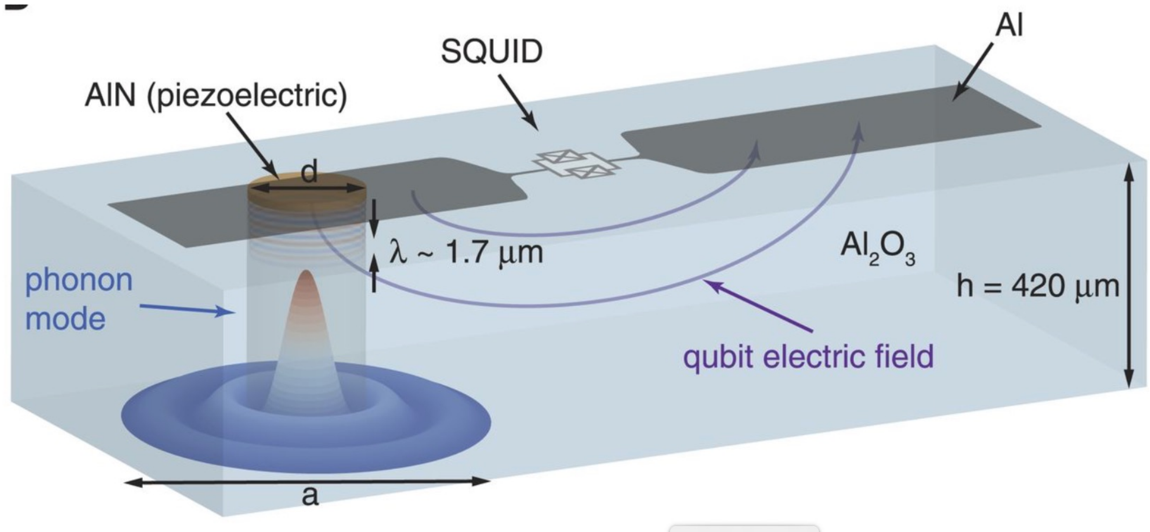
Coupling qubits to mechanical resonators

UChicago Qubit+SAW resonator



K. Satzinger et al. *Nature* 563 (2018)

Yale: Qubit+Bulk acoustic wave resonator



Y. Chu *et al*. Science **358**, 199–202 (2017)
Y. Chu *et al*. Nature **563**, 666-670 (2018)

Phonon Fock states

Surface Acoustic Waves (SAW)

SAW exist at different length scales, from earthquakes to filters in cell phones

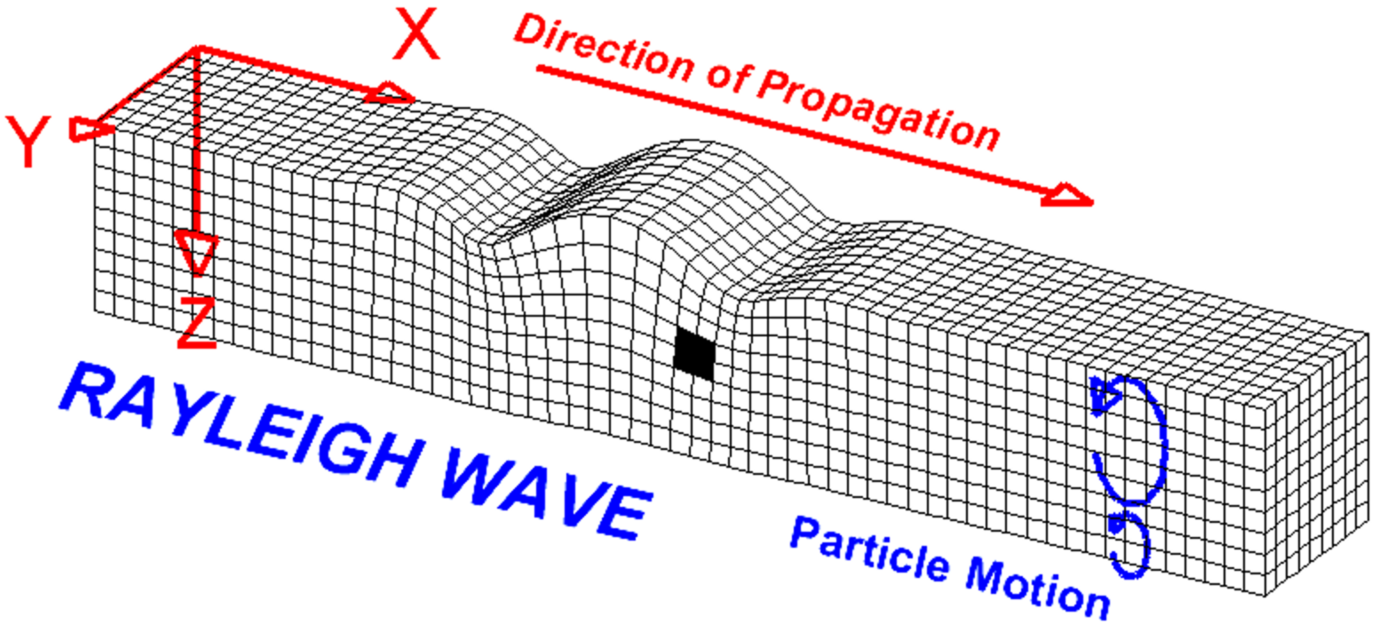
Exited either mechanically or electrically using the piezoelectric effect

Confined to the surface within approximately λ

GHz frequencies
mK temperatures

$$\hbar\omega >> k_B T$$

Very low powers
~ -130 dBm



Rayleigh, Proc. London Math. Soc., 1885
Animation by L. Braile

Generating and detecting SAW with an IDT

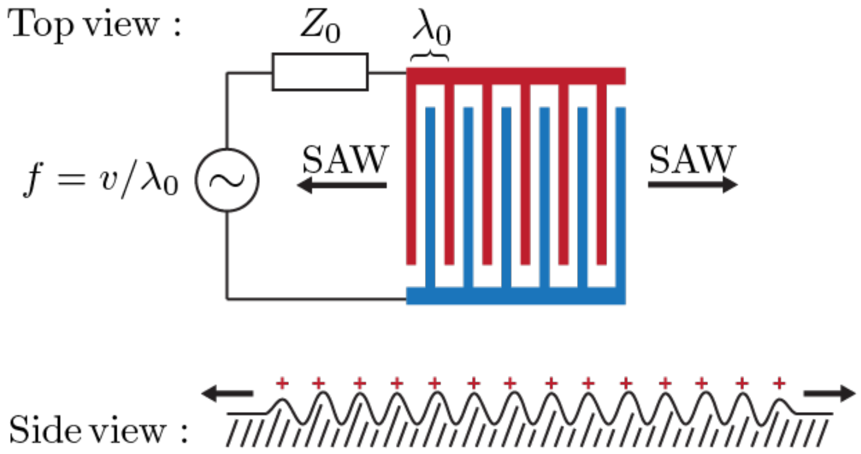
- Piezoelectric substrate (**GaAs**, quartz, $LiNbO_3$…)
- Propagation speed: v ≈ 2900 m/s
- $f \approx 2.3$ GHz, $\lambda \approx 1.25\ \mu$m
- Generator and receiver:

  The Interdigital Transducer (IDT)

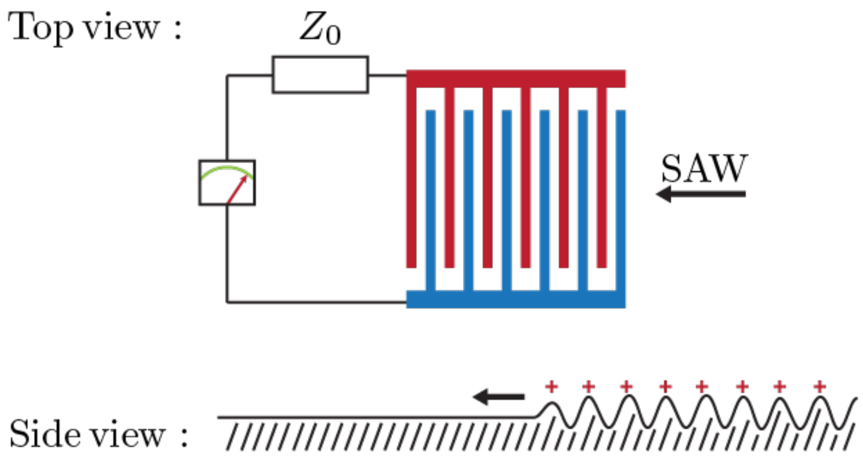
Photon to phonon converter

$b^{\dagger}a$	anihilates a photon and creates a phonon
$a^{\dagger}b$	anihilates a phonon and creates a photon

Finger distance, p=λ



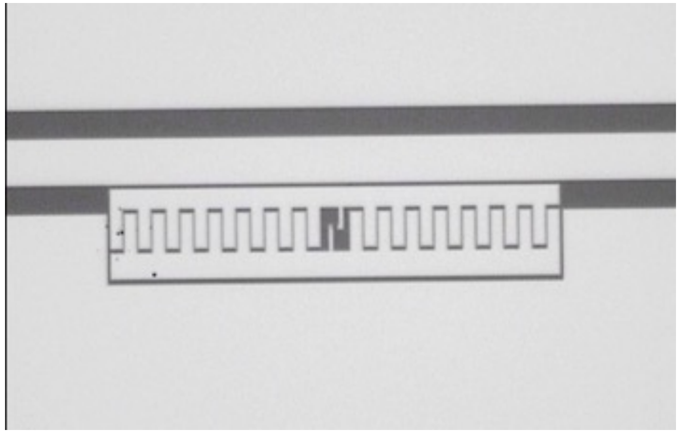
Datta, *Surface Acoustic Wave devices*, 1986

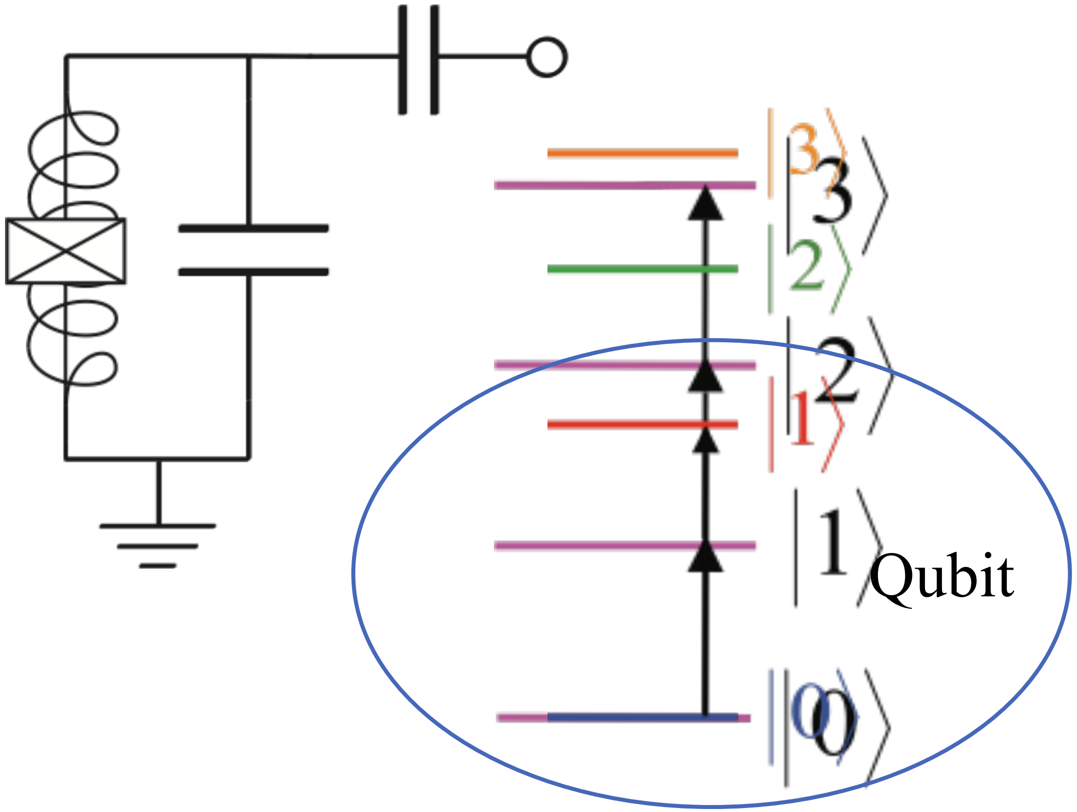


Morgan, *Surface acoustic wave filters*, 2007

Superconducting qubits

- Quantized electrical circuit
- Harmonic oscillator is not an atom
- Nonlinearity makes the circuit anharmonic and addressable
- Small JJ is a good nonlinear inductor

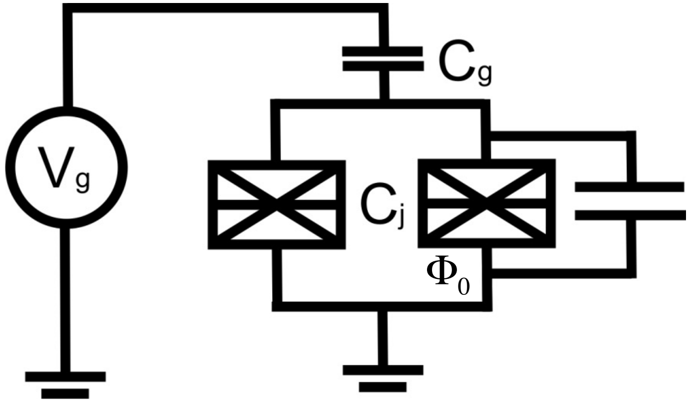




Koch *et al*. PRA (2007)

The transmon qubit as an artificial atom

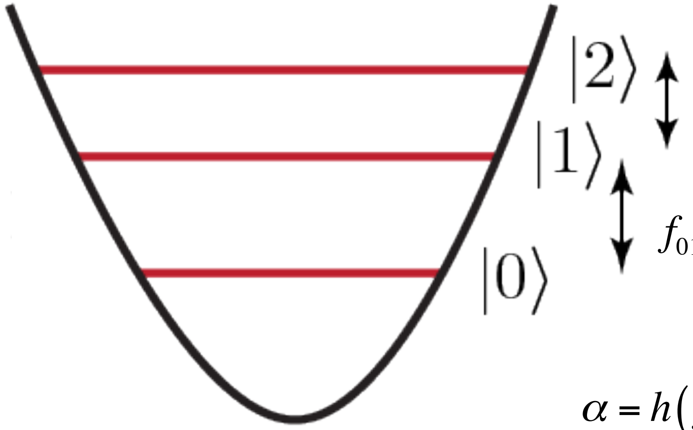
A capacitively shunted Cooper-pair box



Atom frequency is flux tunable

$f_{01} \approx$ 4-8 GHz

Anharmonicity $\approx E_C \approx$ 0.1-0.5 GHz



$$f_{12} = \frac{\sqrt{8E_J E_C} - 2E_C}{h}$$

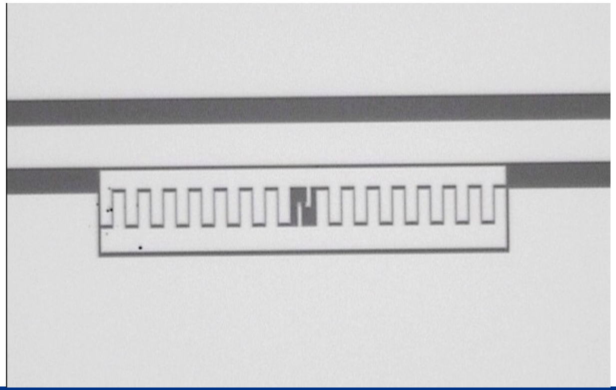
$$f_{01} = \frac{\sqrt{8E_J E_C} - E_C}{h}$$

$$\alpha = h\left(f_{12} - f_{01}\right) \approx E_C$$

$$H = 4E_C(n - n_g)^2 - E_J\left|\cos\left(\pi\tfrac{\Phi}{\Phi_0}\right)\right|\cos\theta$$

$$E_C = \frac{e^2}{2C}, n = \frac{Q}{2e}, n_g = \frac{C_g V_g}{2e}$$

Jens Koch *et al.* PRA (2007)

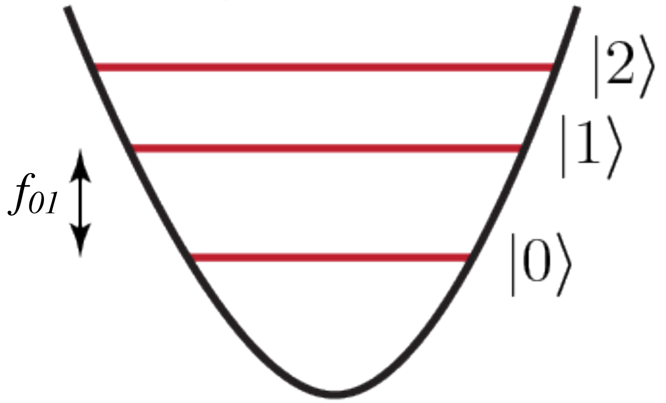


A large SAW-coupled transmon qubit

The qubit has two important frequencies

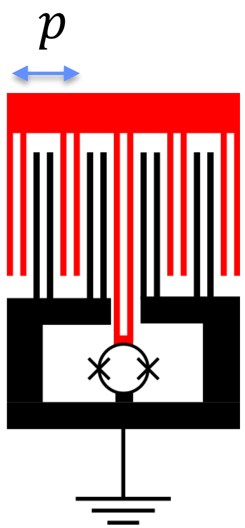
- f_{01} where it stores its energy
- f_{QDT} where it couples to SAW

Qubit levels



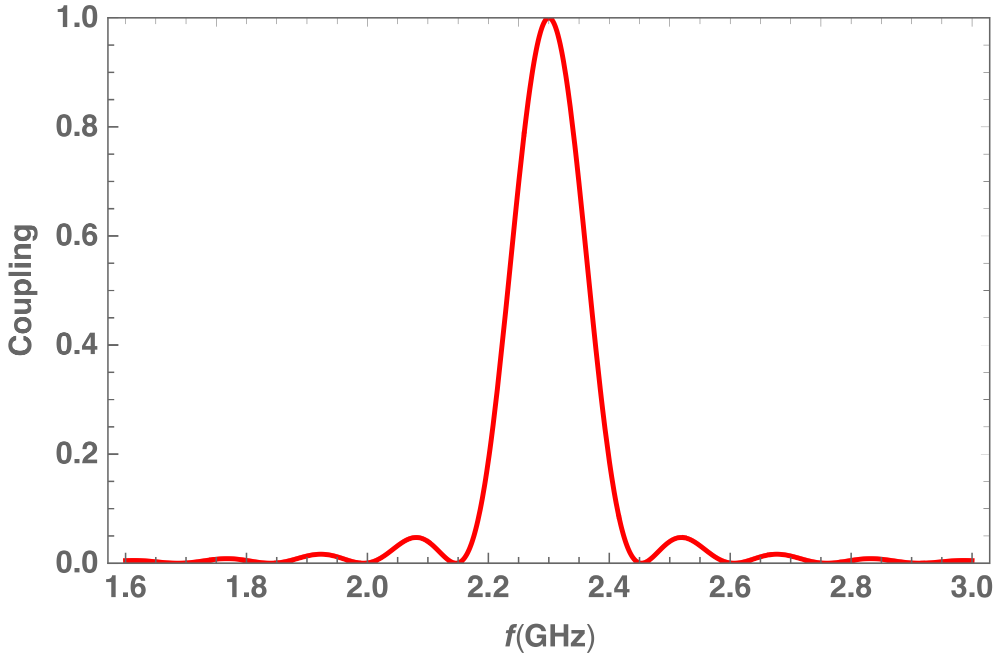
$$f_{01}(\Phi) = \sqrt{E_J(\Phi) E_C} - E_C$$

Capacitance forms an IDT
Qubit coupled IDT = QDT



$$f_{QDT} = \frac{v}{p}$$

Frequency dependent coupling

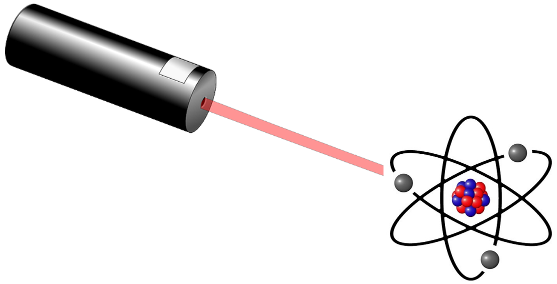


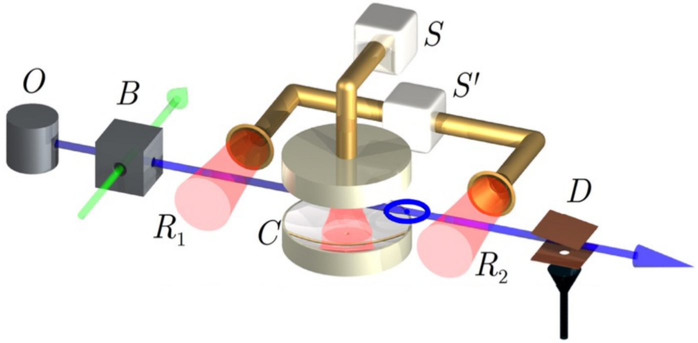
$$\frac{\Gamma}{2\pi} = 0.5\, K^2\, N_p f_{01}\, \mathrm{sinc}^2\left(\pi N_p \frac{f_{01}(\Phi) - f_{QDT}}{f_{QDT}}\right)$$

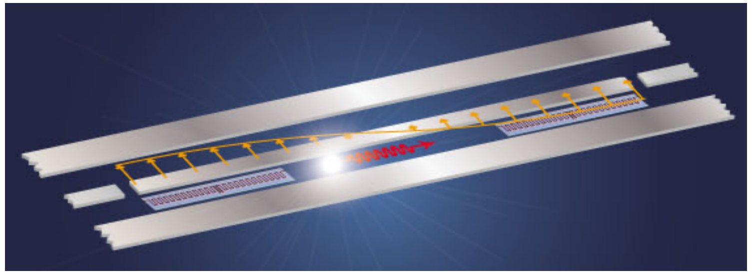
N_p = Number of finger pairs
K^2 = 0.07%, the electromechanical coupling constant for GaAs

The size of an atom

Atoms are normally small compared to the wavelength, d<<λ







Atomic physics

$\lambda \sim 10^{-6}$ m

$d \sim 10^{-10}$ m

Cavity QED

$\lambda \sim 10^{-3}$ m

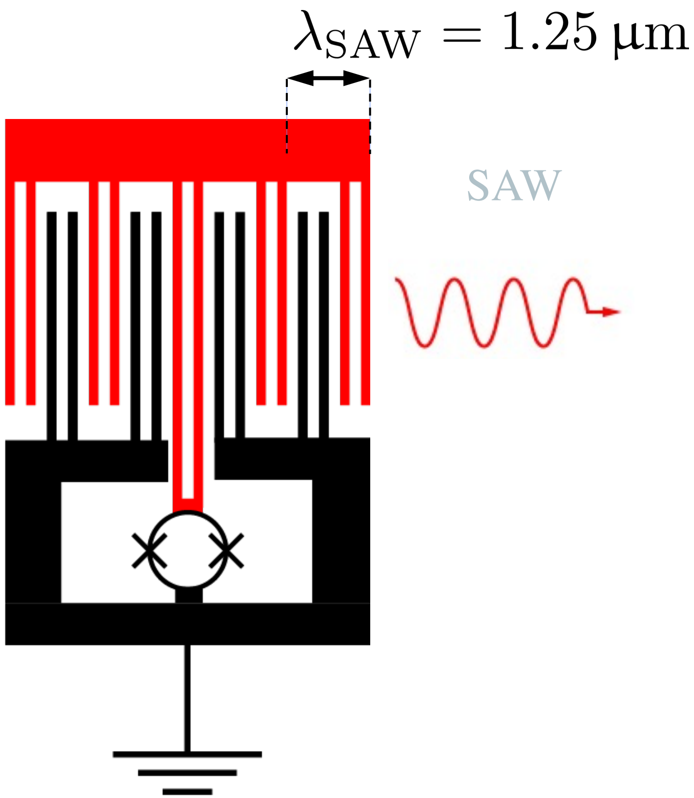
$d \sim 10^{-7}$ m

Circuit QED

$\lambda \sim 10^{-2}$ m

$d \sim 10^{-4}$ m

SAW coupled atoms are larger than the wavelength of SAWs



Atoms coupled to sound are big

Normally, the size of an atom is much smaller than the wavelength of the bosonic field that the atom interacts with. $d<<\lambda$

Large atoms

Atom larger than the wavelength

$$d = N_p \lambda > \lambda$$

$$N_p > 1$$

Dipolar approximation breaks down

This allows to put an "antenna" on the atom

Coupling can be tailored both in space and frequency

Giant atoms

Atom is long compared to the distance that the wave propagates during one lifetime

$$d = N_p \lambda > v\,\tau$$

$$N_p > \frac{1}{\sqrt{\pi K^2}}$$

a stronger requirement than $N_p > 1$ since K^2 is small

Emitted phonons can be reabsorbed.
Non-Markovian behavior, nonexponential decay

Different regimes

Small

Large

Giant

$d = \lambda$

$d = v\,\tau$

Dipolar approximation holds

Tailor emission in Frequency and space

Non-Markovian dynamics

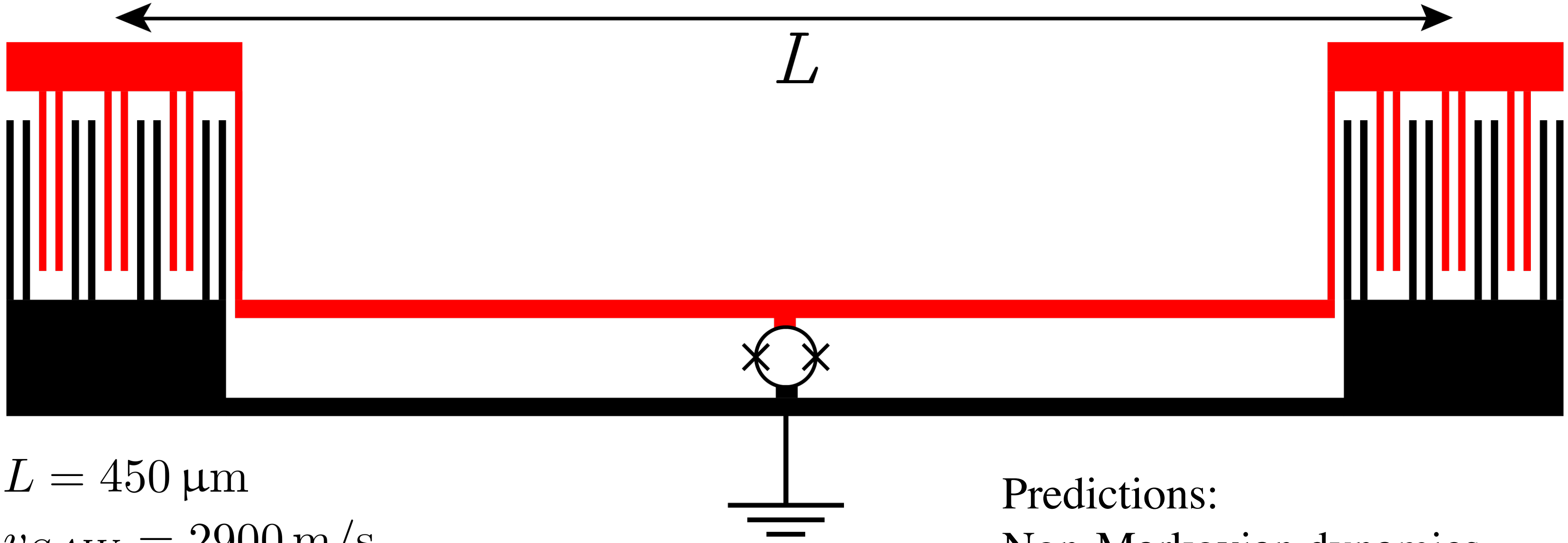
d = atom size
λ = wavelength of interacting field
v = velocity of field
τ = relaxation time of atom

L. Guo, et al., Physical Review A **95**, 053821 (2017)
A.F. Kockum, Proceedings of MQC 2019, pp.125 (2017)
P. Delsing and A. Cleland, J. Phys. D: Appl. Phys. **52** 353001 (2019)

Large atom in circuit QED setting without sound:
B. Kannan et al, Nature **583**, 775 (2020)

The giant artificial atom

Aluminium in GaAs



$L = 450\,\mu\text{m}$

$v_{SAW} = 2900\,\text{m/s}$

$T = L/v_{SAW} \approx 170\text{ ns} > 1/2\gamma$

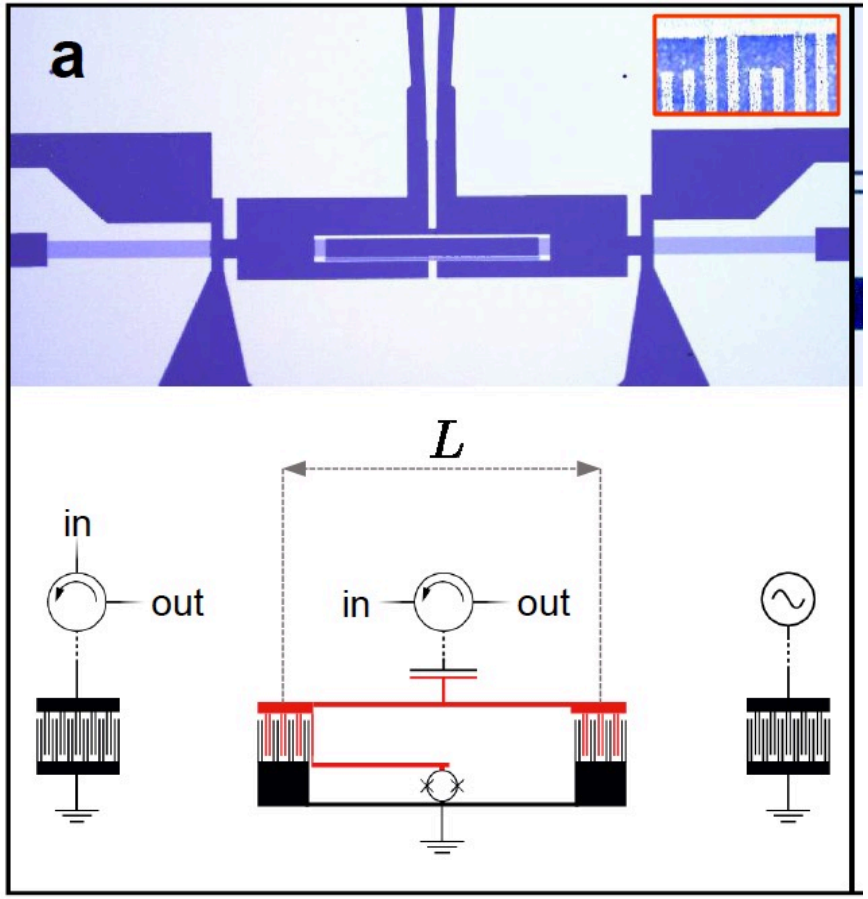
Predictions:
Non-Markovian dynamics
Nonexponential decay

L Guo, et al., Physical Review A **95**, 053821 (2017)

Measured samples

Qubit, IDT and resonators made from Aluminum on GaAs

Type A samples



Sample parameters

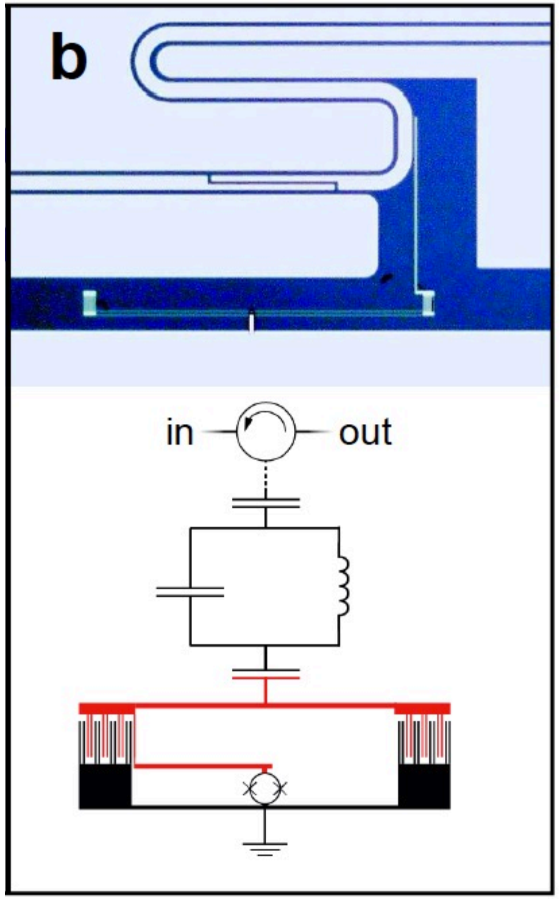
sample	N_p	$\gamma/2\pi$	T	γT	L	$\gamma_{gate}/2\pi$	$2\gamma/\gamma_{ext}$
A1	14	6.1 MHz	19 ns	0.8	55 µm	1.25 MHz	4.4
A2	14	4.4 MHz	46 ns	1.4	125 µm	1.5 MHz	1.8
A3	18	5.8 MHz	190 ns	7.0	550 µm	2.2 MHz	1.9
A4	18	5.3 MHz	190 ns	6.3	550 µm	-	-
B1	14	4.8 MHz	160 ns	4.8	450 µm	-	1.4

Giant atom if $\gamma T > 1$
Total coupling $\Gamma = 2\gamma$

Qubits designed with f_{01} higher than f_{QDT} and then tuned down by flux

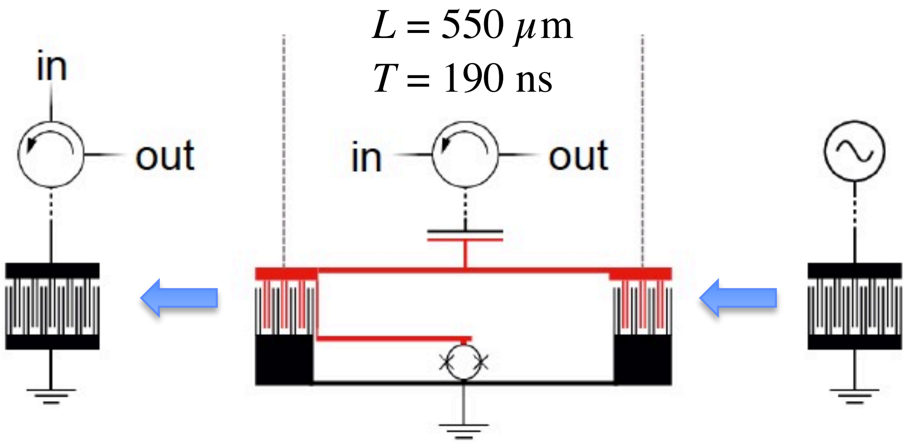
$f_{IDT} = f_{QDT} = 2.29$ GHz
$Bw_{IDT} = 14$ MHz
$N_{p,IDT} = 150$

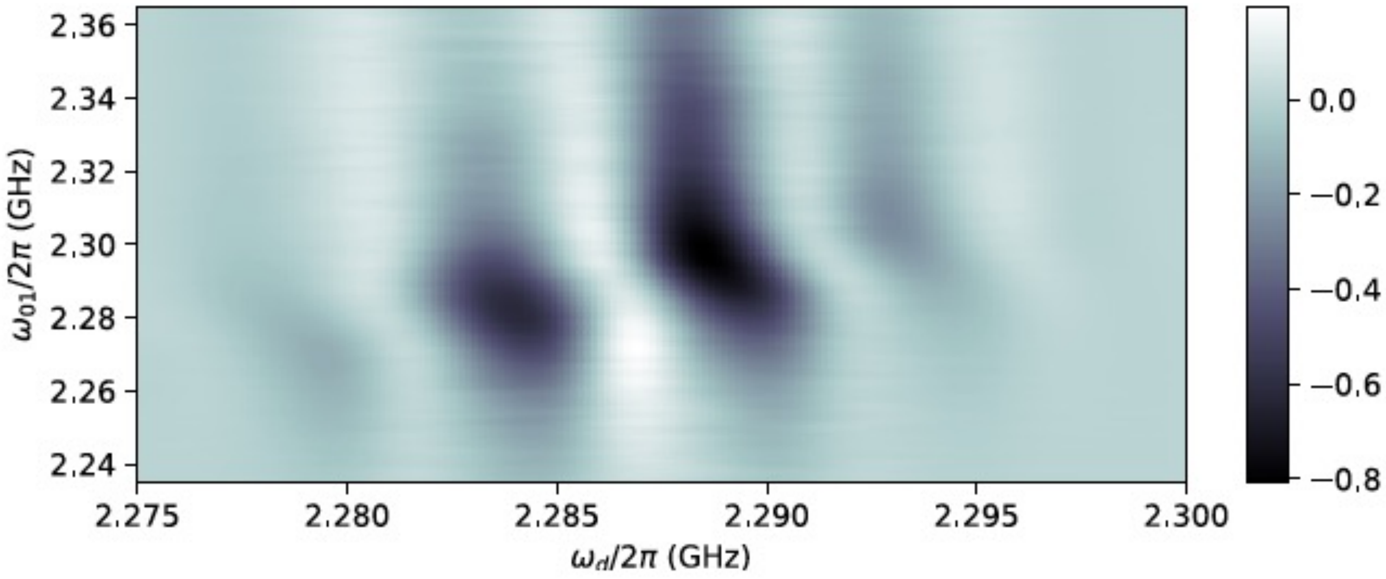
Type B samples



$f_{cavity} = 2.77$ GHz
$\Delta = 480$ MHz
g = 15 MHz

Acoustic transmission





Acoustic transmission is probed at low power

$$P < \hbar\,\omega\,\Gamma$$

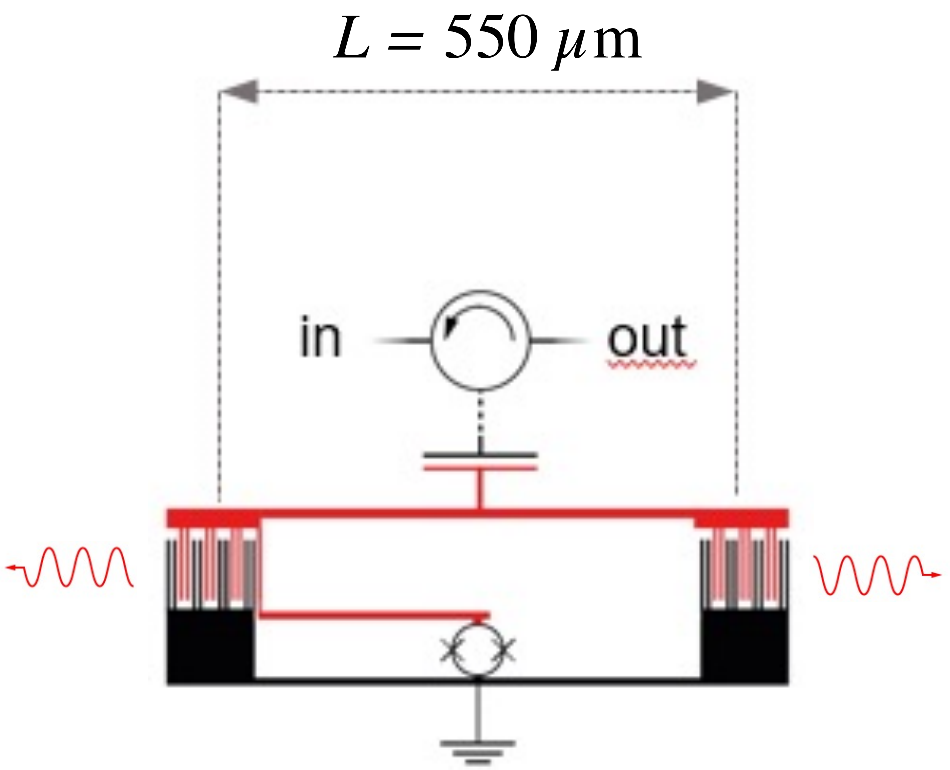
A small atom would reflect on resonance, resulting in a Lorentzian line shape

We observe interference fringes in the acoustic transmission with a period of ~5MHz agreeing well with 1/190 ns.

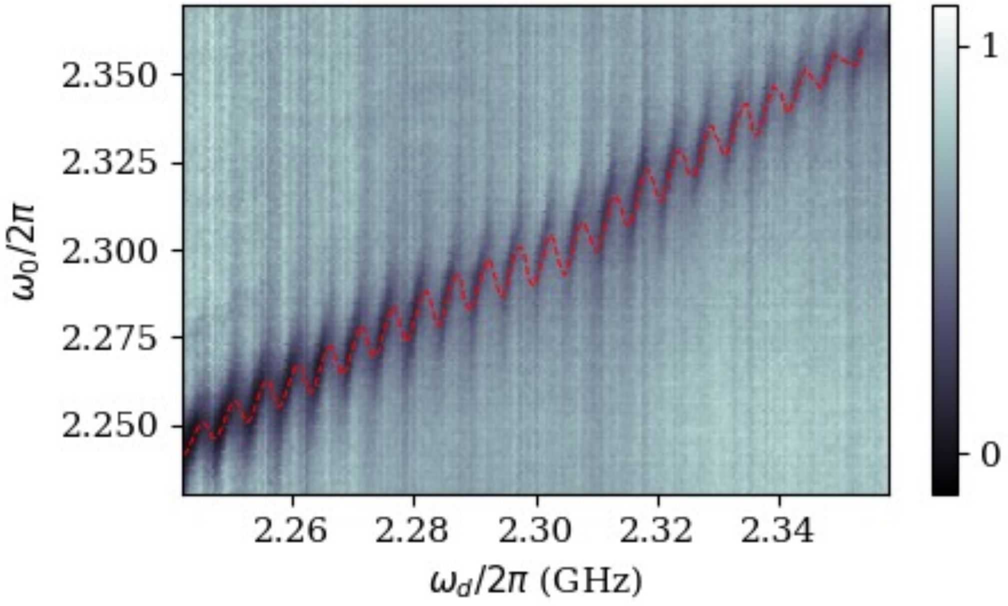
Limited bandwidth due to IDTs, 14 MHz

SAW emission from the giant atom

SAW emission probed by measuring the reflection from the gate (larger bandwidth)



Reflectance from sample A3

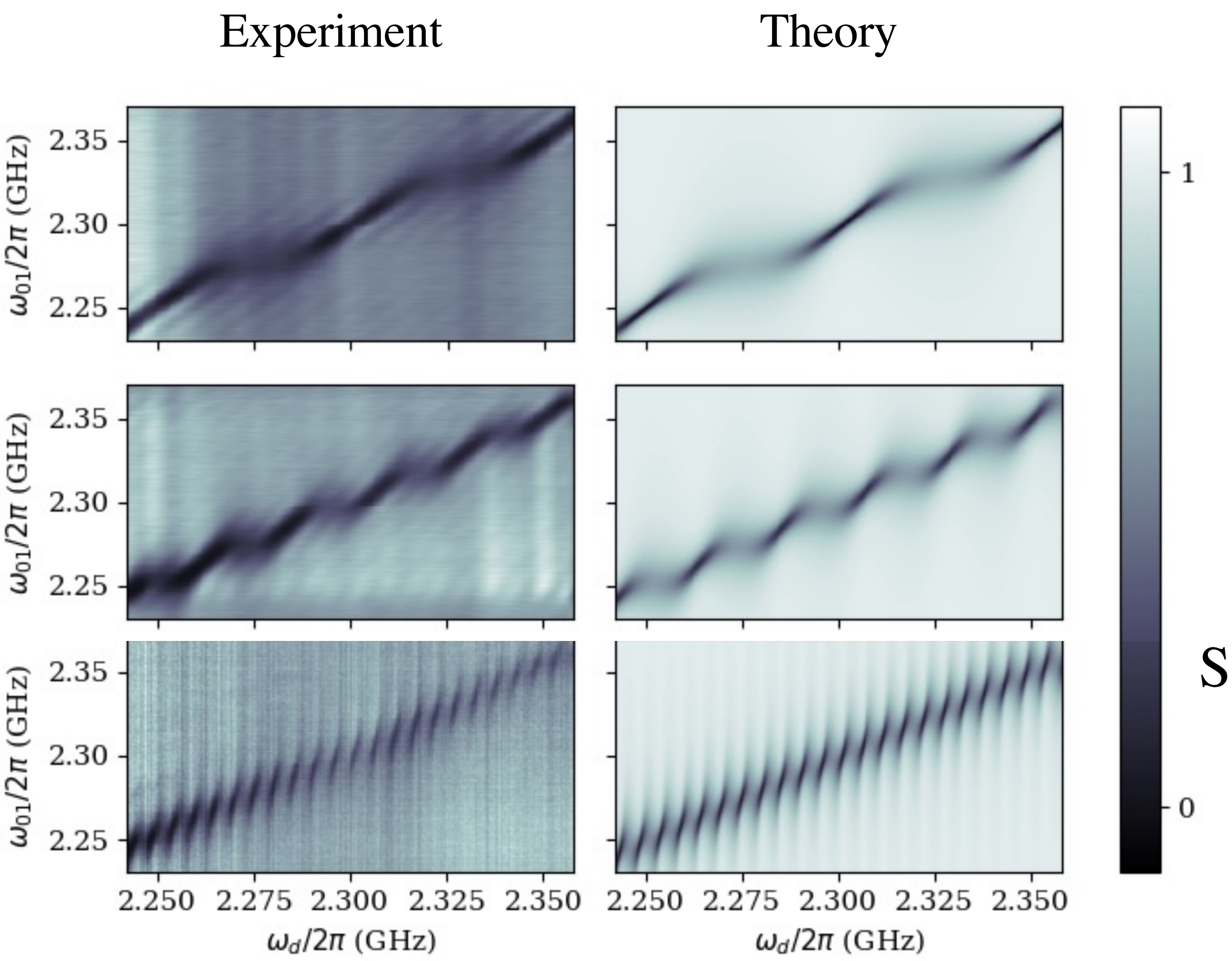


Maximal emission (minimal reflection) when

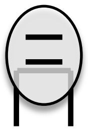
$$\omega_0 = \omega_d - \gamma \sin \omega_d T$$

$$T = L/v_{\mathrm{SAW}} \approx 190\,\mathrm{ns}$$

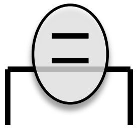
Reflectance depending on atom size



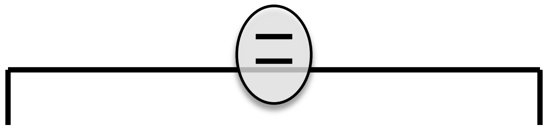
Sample A1, L = 55 μm, T = 19 ns



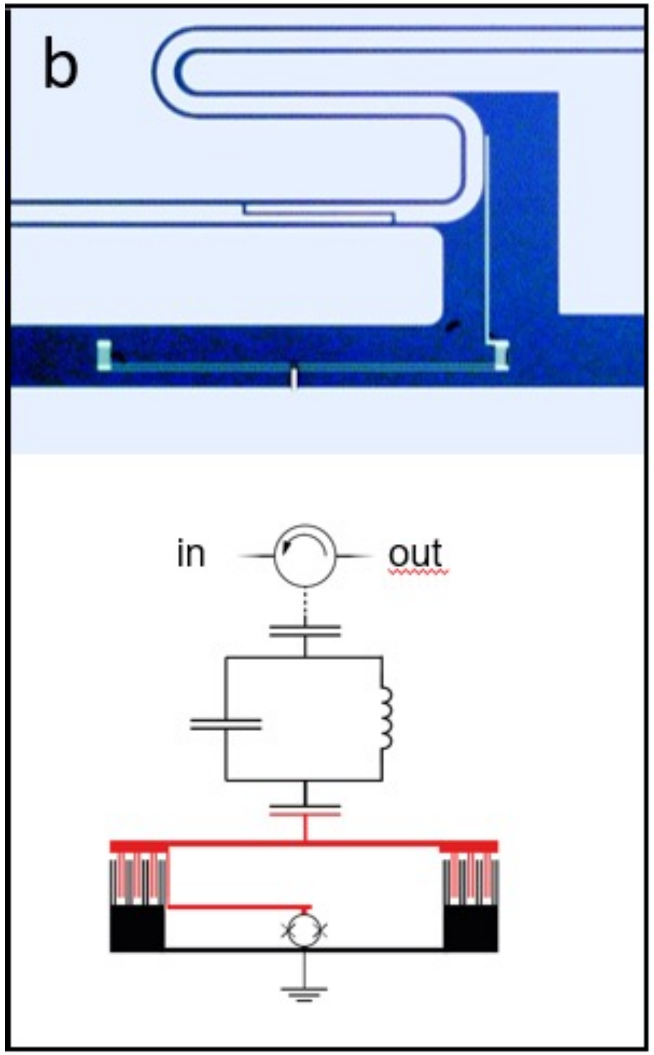
ample A2, L = 125 μm, T = 46 ns



Sample A3, L = 550 μm, T = 190 ns



Measuring the giant atom via the mw-resonator



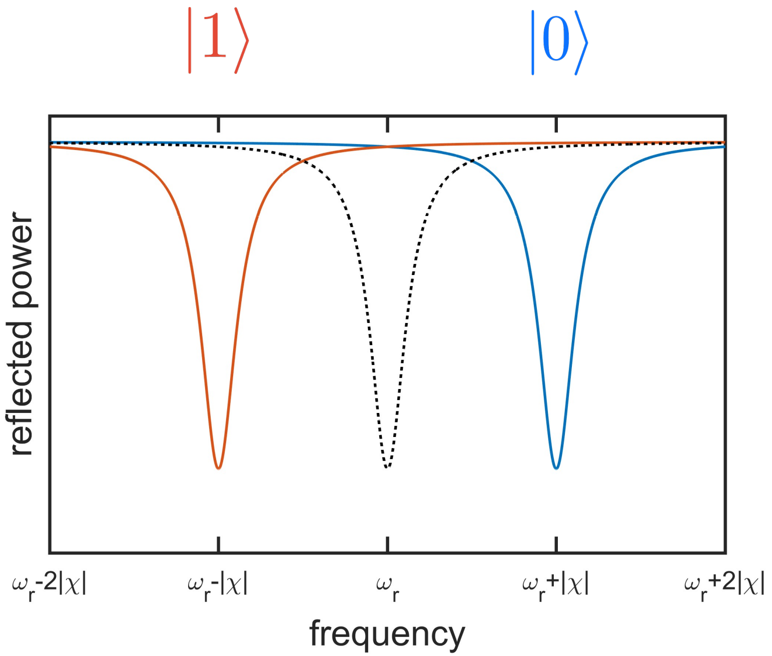
A superconducting cavity is dispersively coupled to the atom

f_{01} =2.29 GHz
f_{cavity} =2.77 GHz
Δ = 480 MHz
g = 15 MHz

Dispersive regime

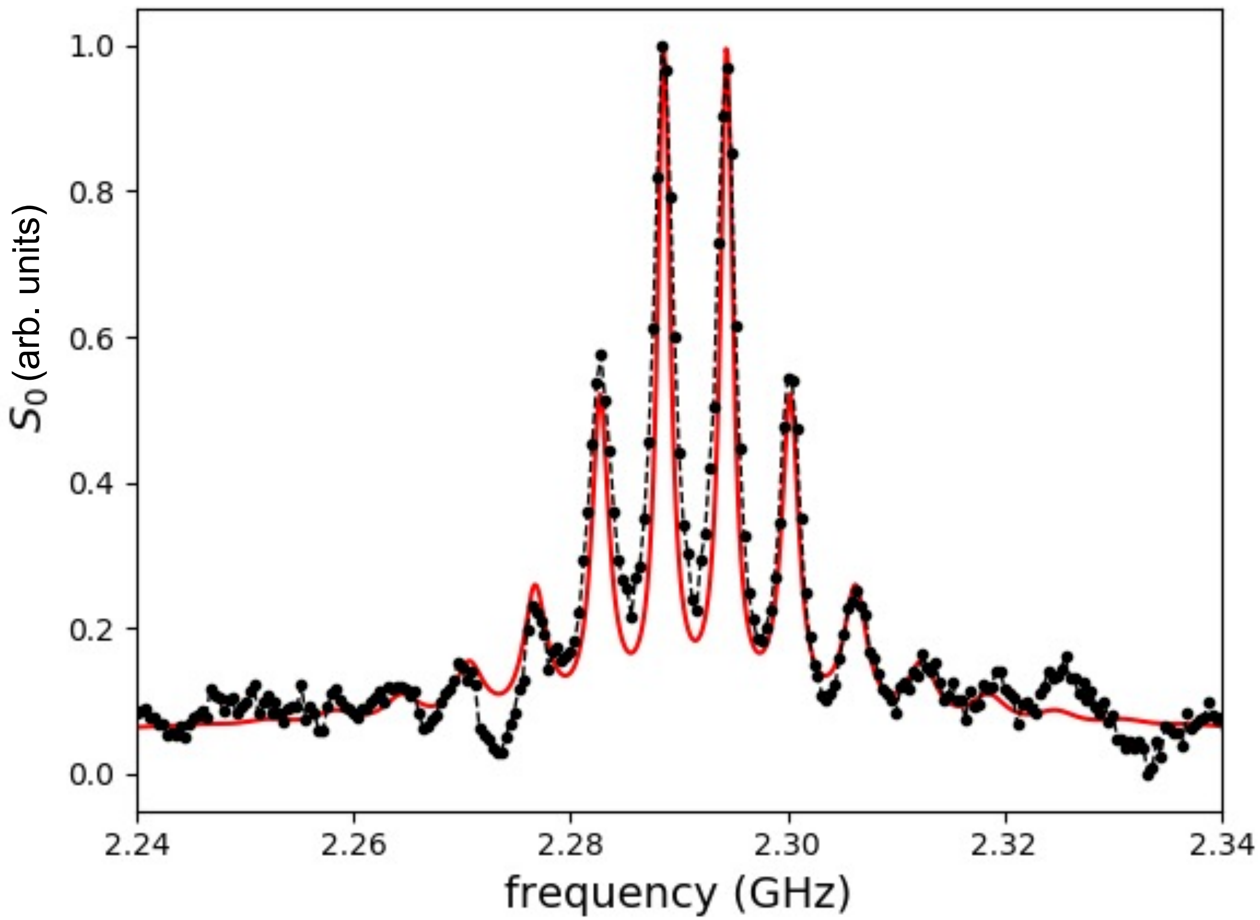
$$|\Delta| = |\omega_{01} - \omega_r| \gg g$$

$$\omega_r' = \omega_r + \frac{g^2}{\Delta}\sigma_z$$



Spectroscopy of the giant atom

Spectrum of sample B1



Two tone spectroscopy

- Fixed readout at f_{cavity}
- Sweep drive frequency close to f_{01}

Small atom gives Lorentzian

Giant atom gives multi peaked structure with Lorentzian envelope

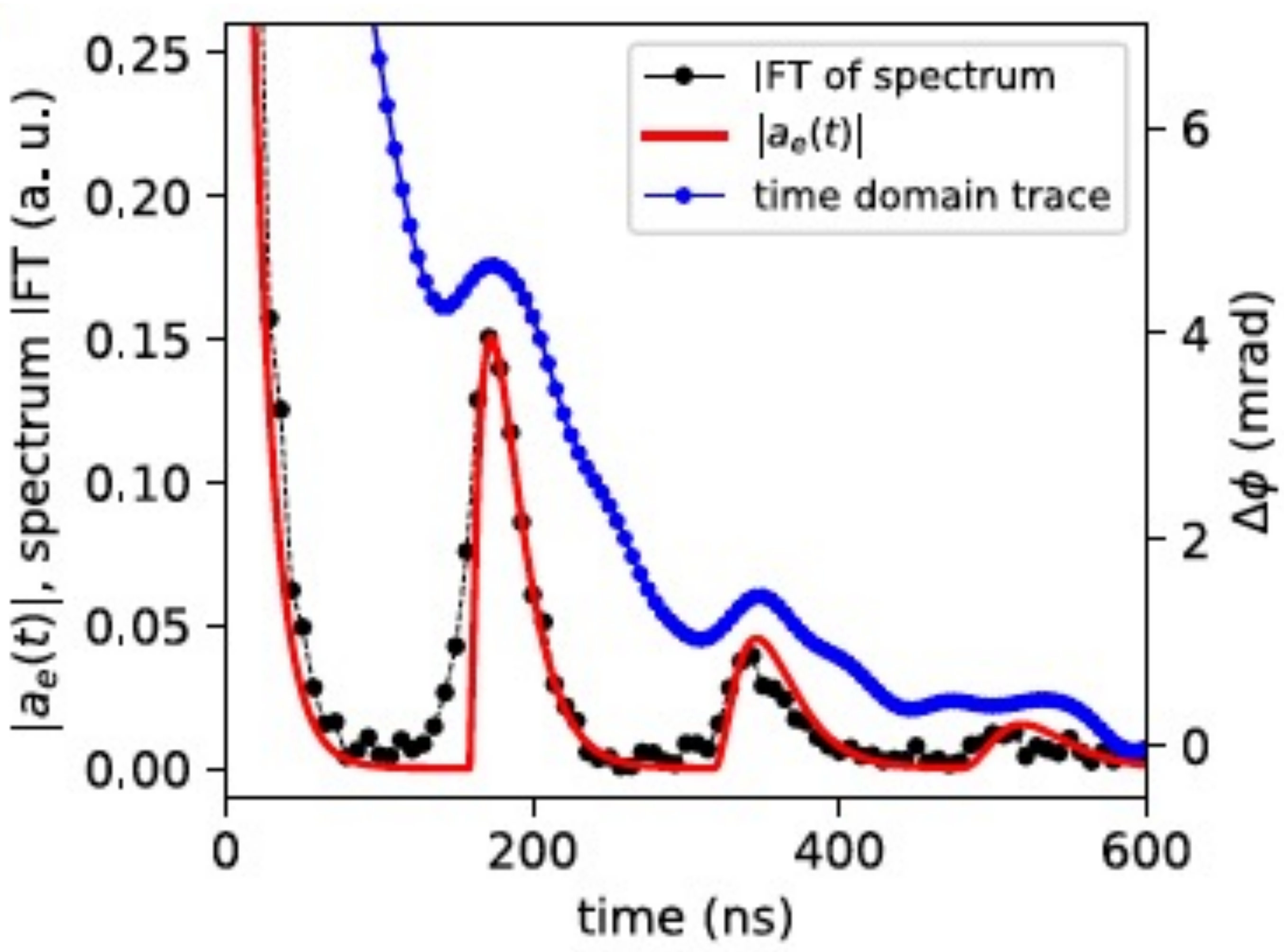
Peak distance depends on 1/T
Lorentzian width depends on γ
# of peeks $\approx \gamma$ T

Red curve is theory
L. Guo et al. PRA 95, 053821 (2017)

Pupulation during decay

We apply a π-pulse and do a weak continuous measurement of the population in the qubit.

Averaging a large number (10^7) of weak measurements, we observe revivals in the population at times that agree well with the distance between the coupling points.
$T = 160$ ns



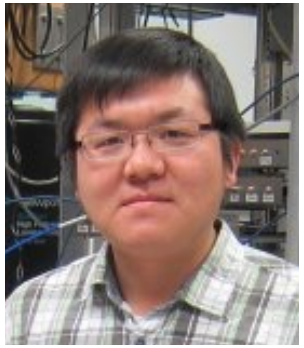
G. Andersson *et al.*, Nature Physics **15**, 1123 (2019)

Summary I: Giant atoms

- Artificial atoms in a new regime: Large atoms and Giant atoms
- Non-Markovian dynamics
- Nonexponential decay with revivals

Gustav Andersson

Baladitya Suri

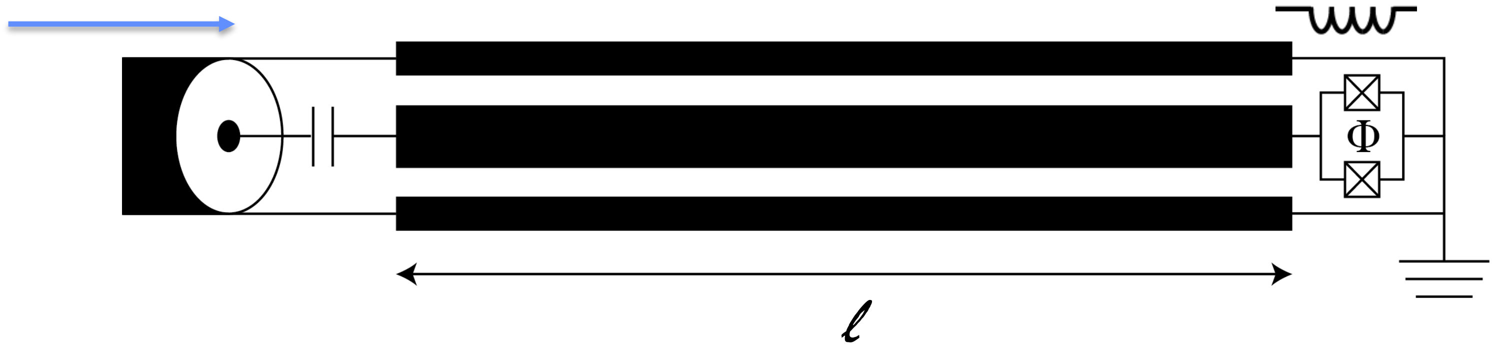


Lingzhen Guo

Thomas Aref

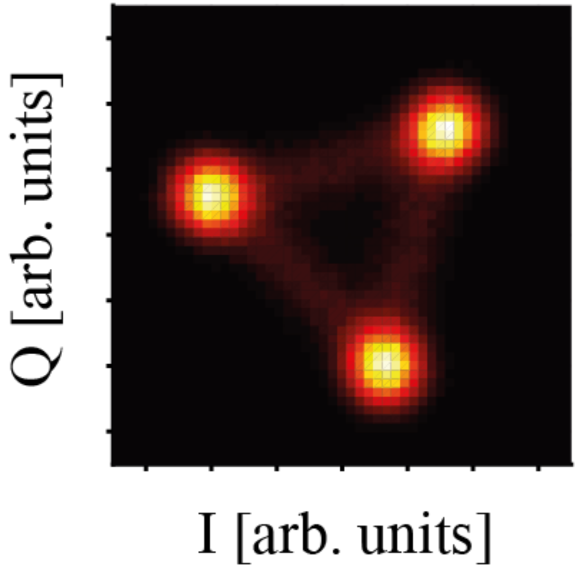
G. Andersson *et al.*, Nature Physics **15**, 1123 (2019)

Period-tripling in a superconducting resonator



- **Nonlinear resonators**
  - Parametric pumping
  - Subharmonic oscillations, period tripling
  - Further multiples

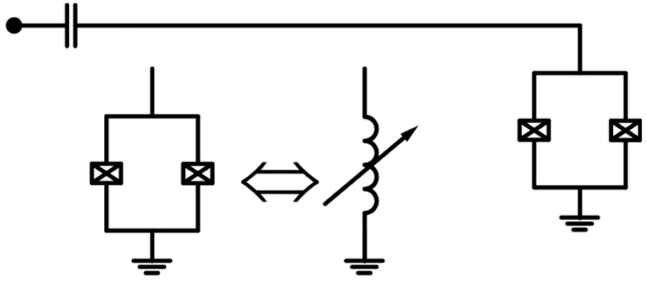
Generating three photons from one, $a_1^{\dagger 3} a_2$

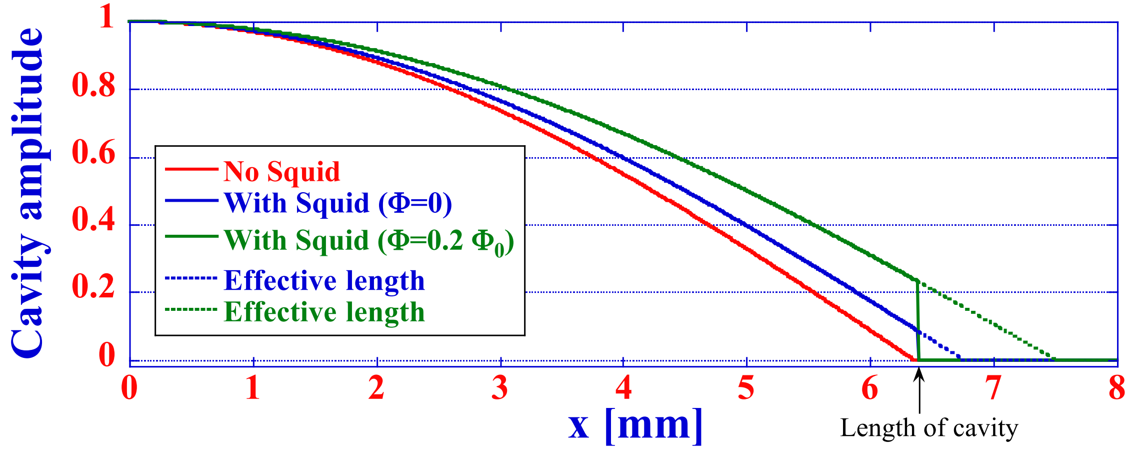


I.-M- Svensson *et al*., Phys. Rev. B **96**, 174503 (2017)
I.-M- Svensson et al., Appl. Phys. Lett. **113**, 022602 (2018)

A flux tunable resonator

λ/4 Coplanar Waveguide
terminated by a Josephson inductance of a SQUID





Resonance frequency, *f*

$$f(\Phi) = \frac{f_0}{1 + \frac{L_{SQ}(\Phi)}{L_{cav}}}$$

$$L_{SQ}(\Phi) = \frac{\hbar}{2e\, I_C \cos(\pi \frac{\Phi}{\Phi_0})}$$

$$\Phi = \Phi_{dc} + \Phi_A \sin(2\pi f_D t)$$

Time varying flux gives time varying resonance frequency
Resonance frequency can be varied faster than the oscillation period

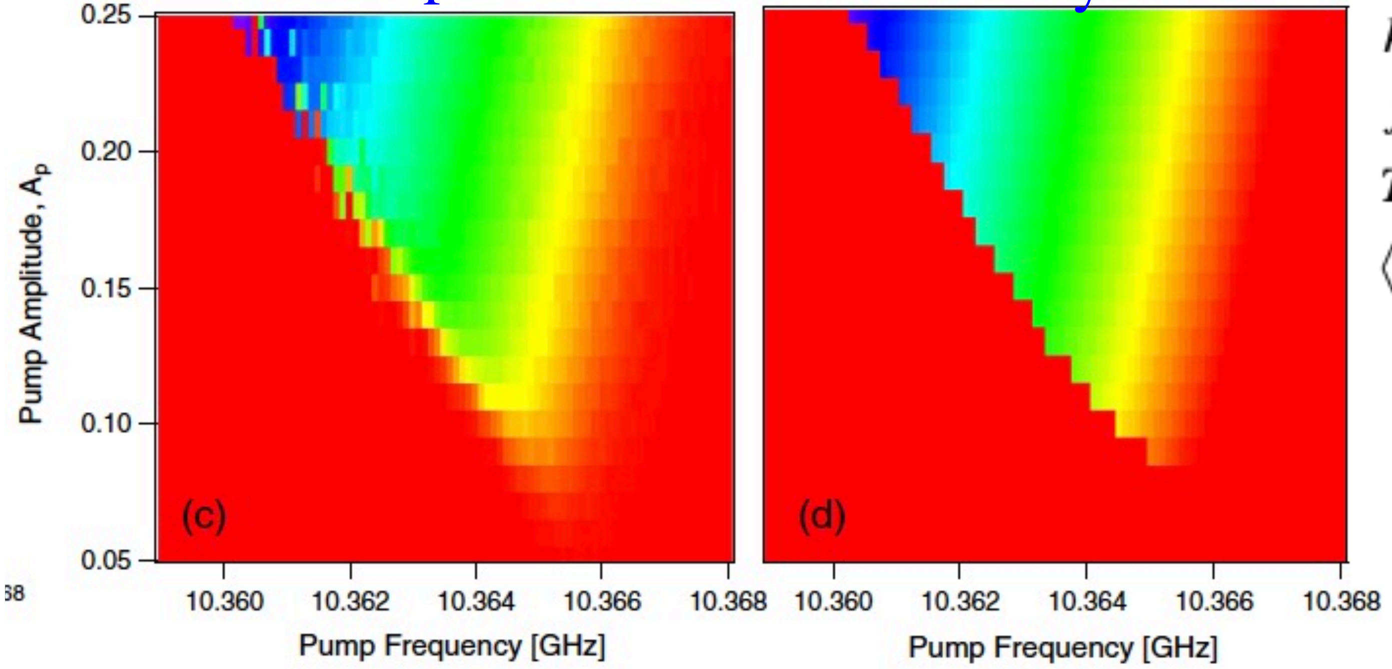
M. Sandberg et al. APL **92**, 203501 2008

Parametric oscillations: Flux pumping at twice the resonance frequency

Pumping at $f_D \approx 2f_0$, vary amplitude and frequency we observe photons coming out at f_0
Note λ/4: no mode at $2\,f_0$

Experiment

Theory



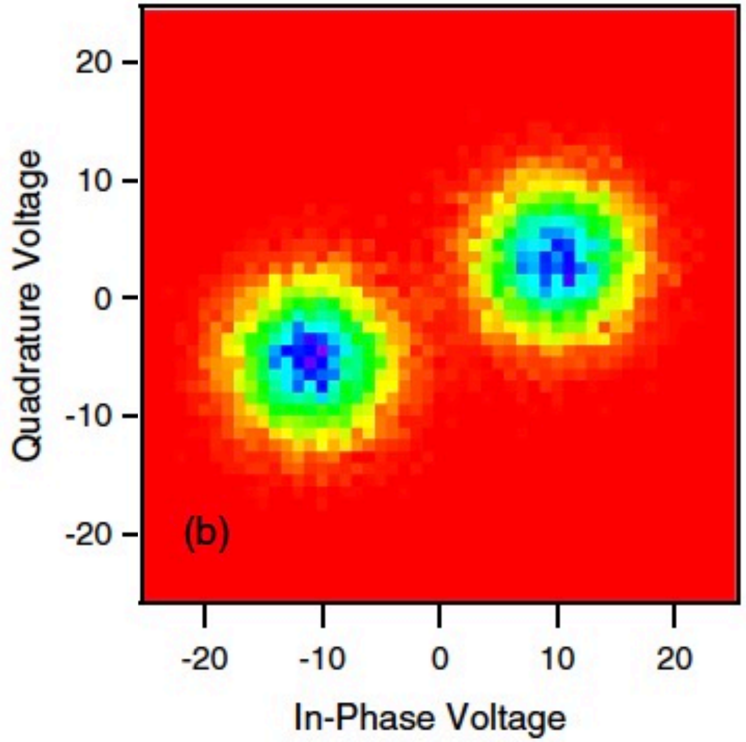
$hf_0 >> k_B T$

$f_0 = 5$ GHz

$T = 50$ mK

$\langle n_T \rangle = 0.008$

Quadrature histogram

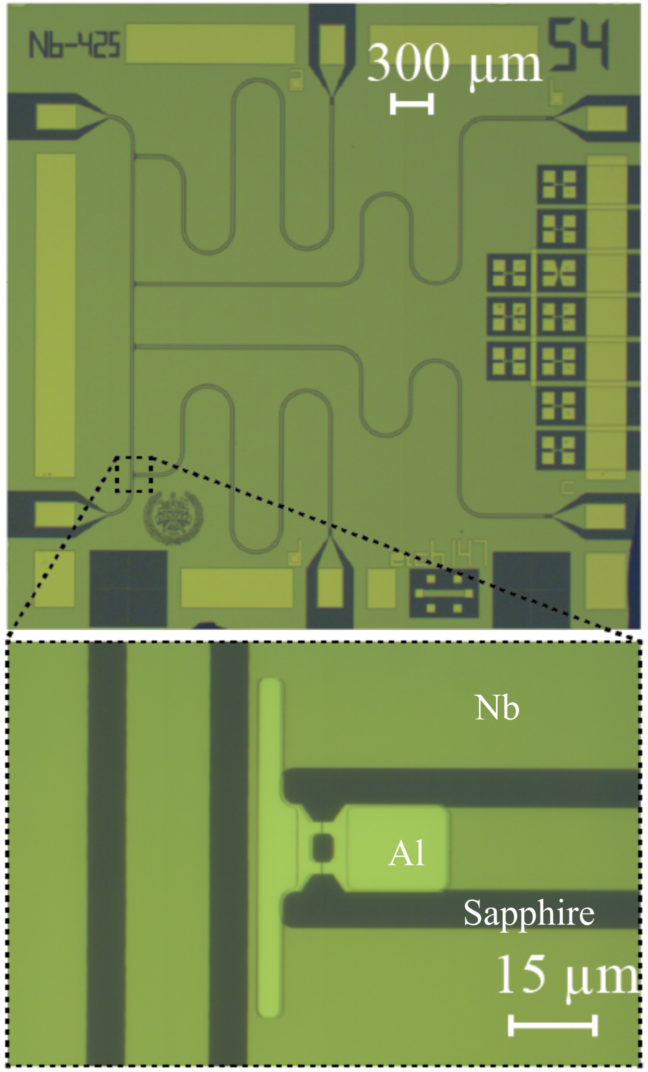


Flux pumping at $3f_0$, nothing should happen

Theory:
M. I. Dykman, et al. Phys. Rev. E **57**, 5202 (1998)
M. Faraday, Phil. Trans. Roy. Soc. (London), **121**, 299 (1831)

Experiement:
C.M. Wilson et al. Phys. Rev. Lett **105**, 233907 (2010)

Sample and Measurement configuration

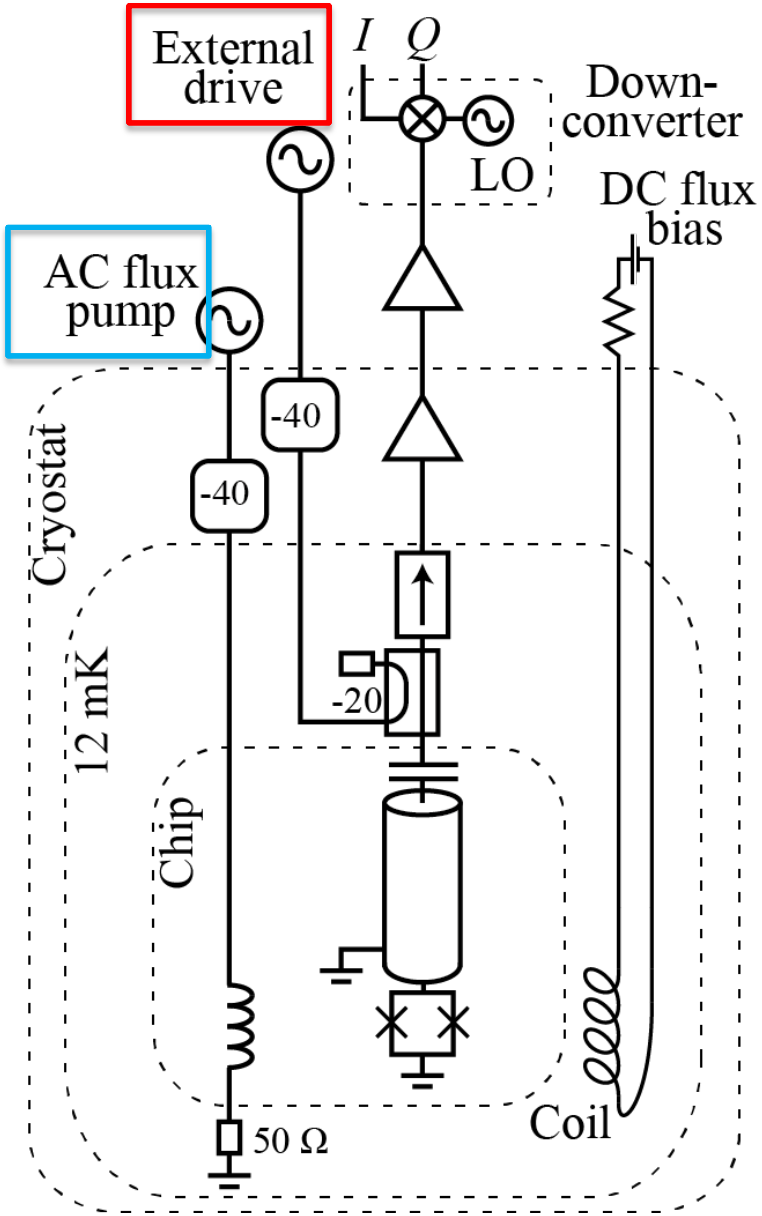


$$L_{SQ}(t) = \frac{L_{SQ,0}}{\cos\left(\pi \frac{\Phi(t)}{\Phi_0}\right)\sqrt{1 - \frac{I(t)^2}{I_C^2}}}$$

Flux pump

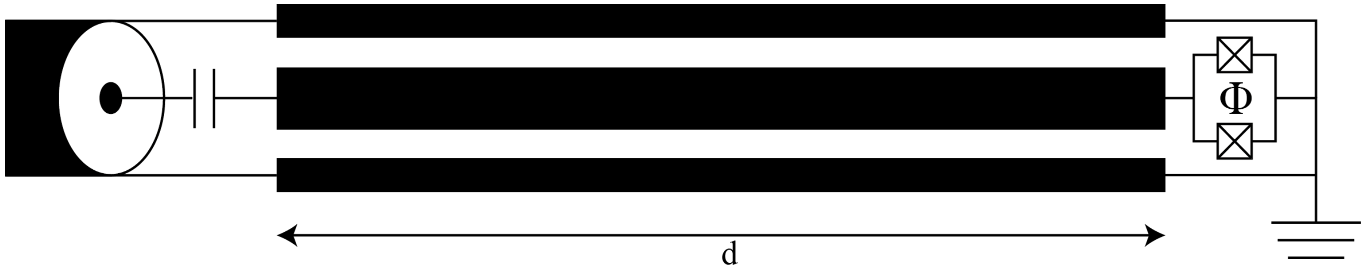
Current drive

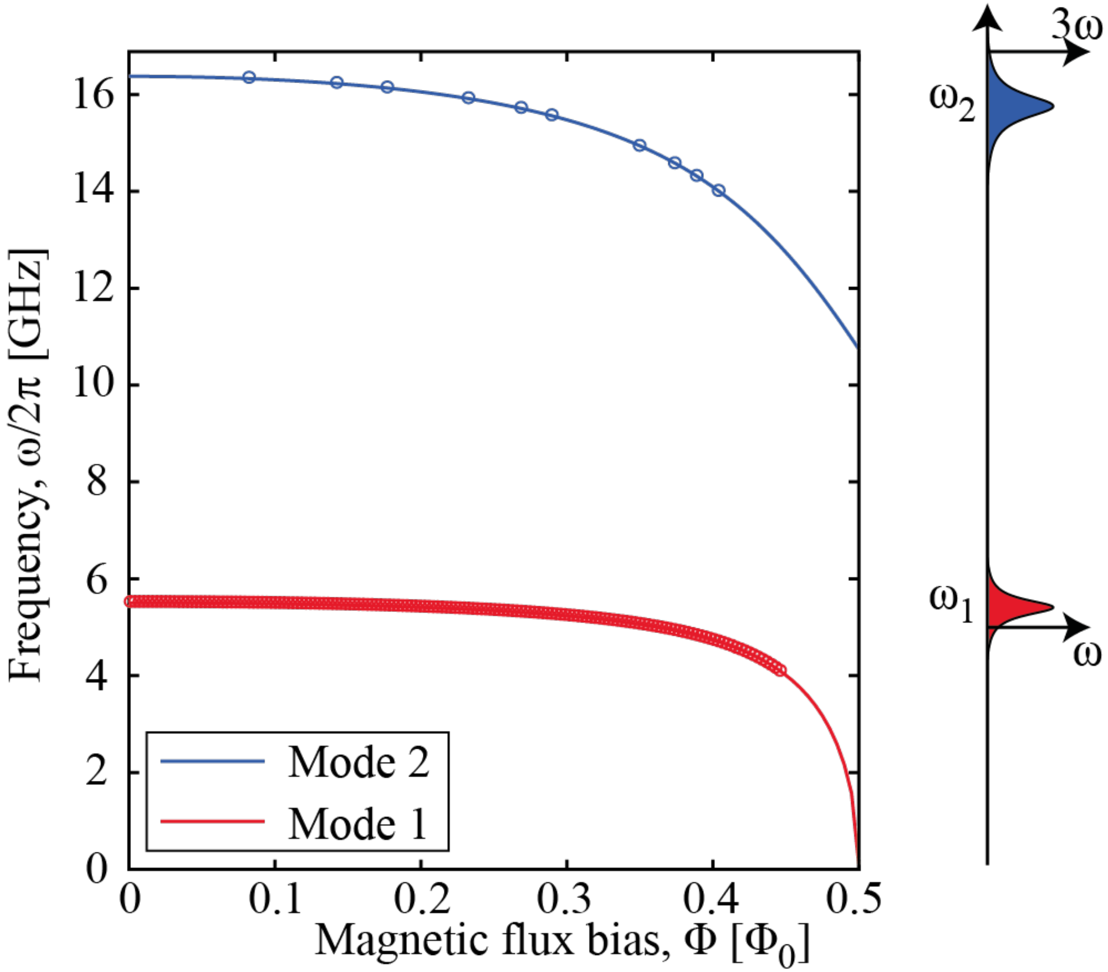
Aluminum SQUID
Niobium resonator
Sapphire substrate



The current pumped resonator

λ/4-cavity with a SQUID at the end

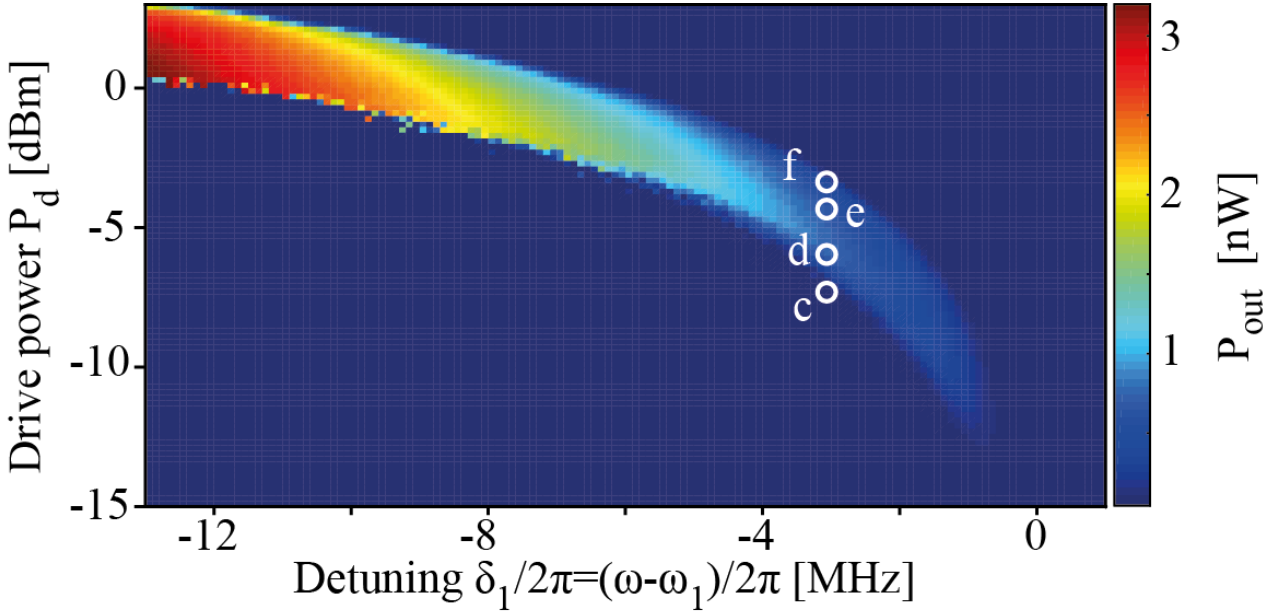


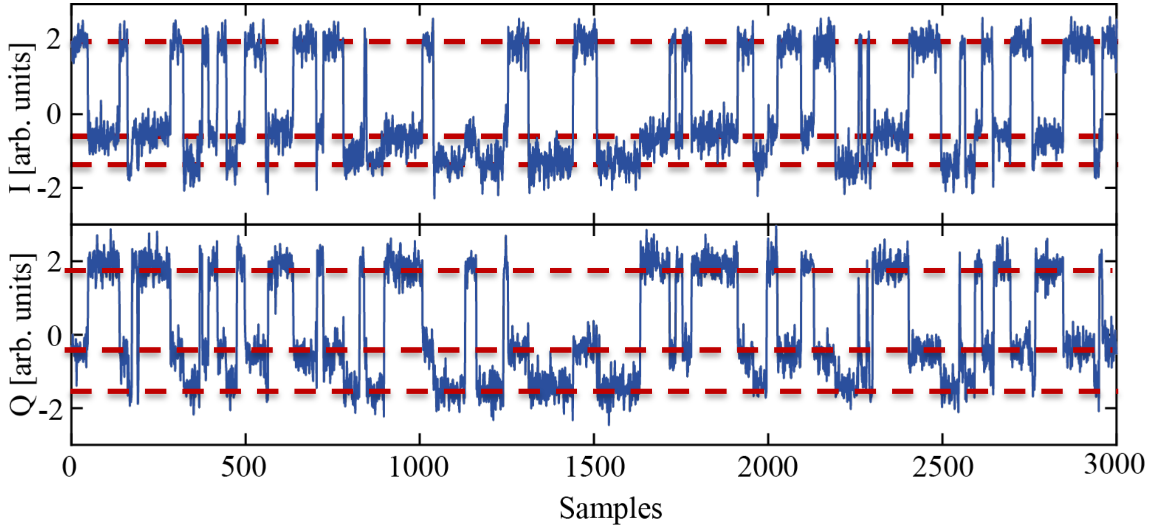


Resonator properties at zero flux

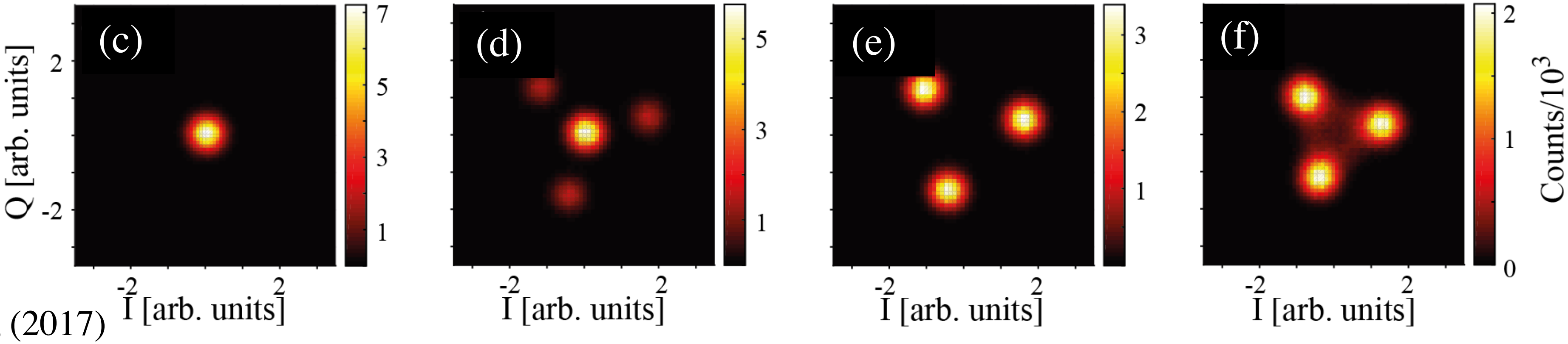
- Resonance frequency, $\omega_1/2\pi = 5.504$ GHz
- Mode linewidth first mode, $2\Gamma_1/2\pi = 0.38$ MHz
- First mode quality factors, $Q_{int} = 61000, Q_c = 19000$
- Spectrum anharmonicity, $(3\omega_1 - \omega_2)/2\pi = 136$ MHz

Current driving at Φ=0 : Observation of period-tripling





Quadrature histograms



Svensson *et al*. Phys. Rev. B **96** 174503, (2017)

Current driving: Theory comparison

Model with two coupled modes, Vitaly Shumeiko

$\delta_1 = \omega - \omega_1$

$\delta_2 = 3\omega - \omega_2$

The second mode acts as a parametric pump of the first mode

Kerr effect

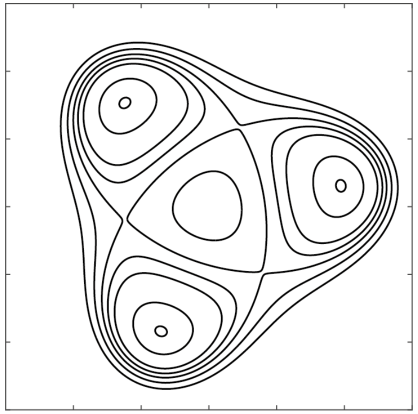
Cross Kerr effect

External drive signal

$$i\dot{a}_1 + (\delta_1 + i\Gamma_1 + \alpha_1|a_1|^2 + 2\alpha|a_2|^2)a_1 + \tilde{\alpha}{a_1^*}^2 a_2 = 0$$

$$i\dot{a}_2 + (\delta_2 + i\Gamma_2 + \alpha_2|a_2|^2 + 2\alpha|a_1|^2)a_2 + \frac{\tilde{\alpha}}{3}a_1^3 = \sqrt{2\Gamma_{2,ext}}B_2$$

Pseudo potential



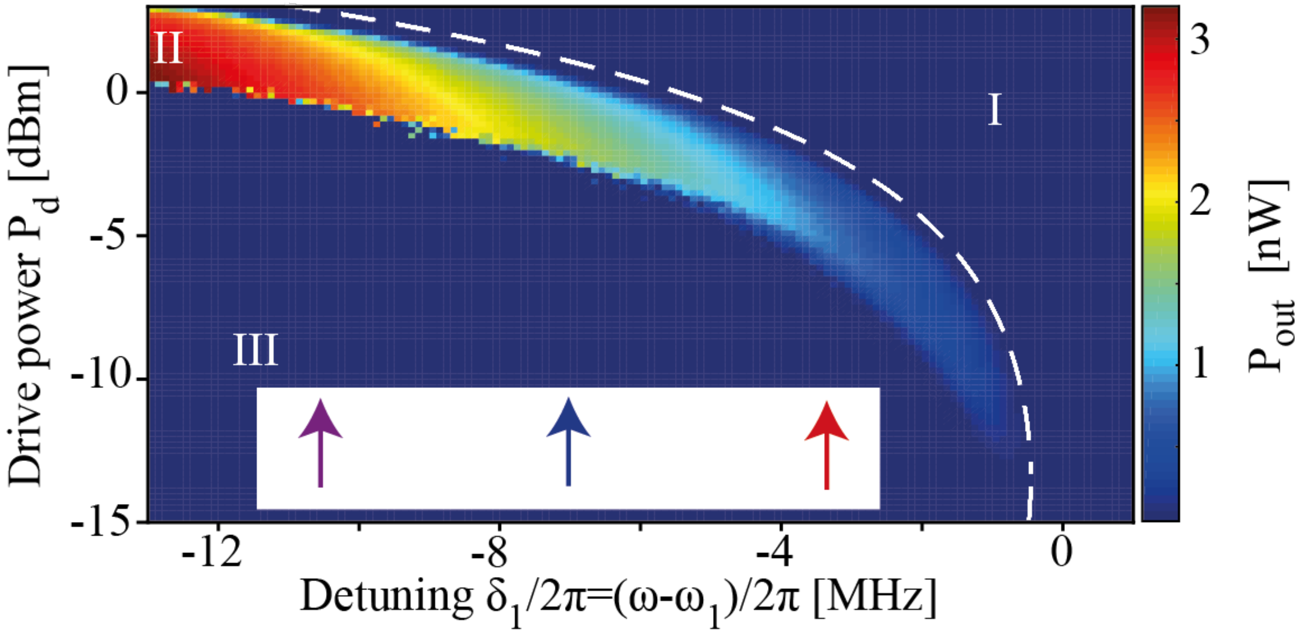
Quantum description
Y. Zhang et al. *Physical Review A* **96**, 052124 (2017)

Experiment and theory:
Svensson et al. *Physical Review B* **96**(17):174503, 2017

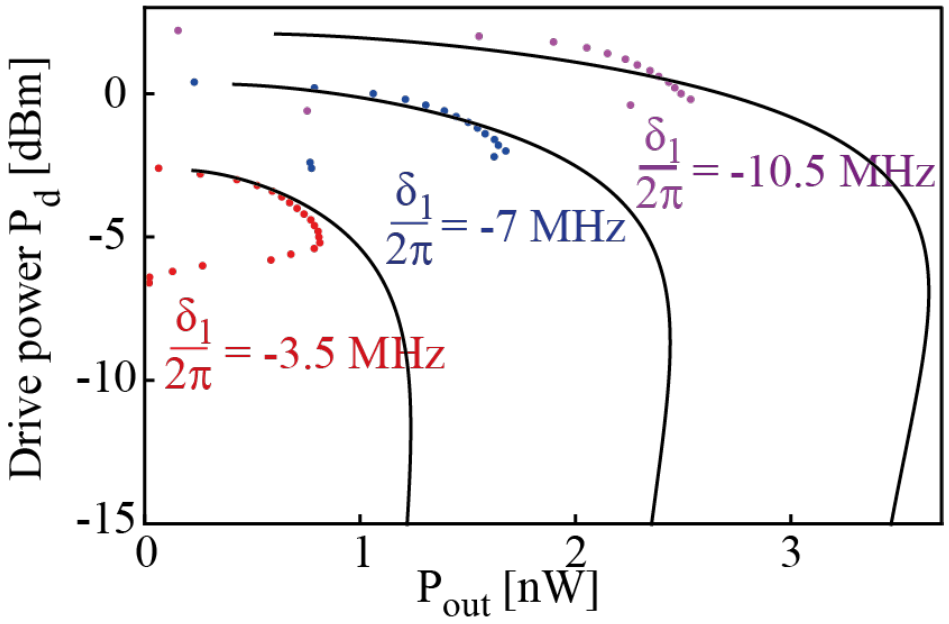
Current driving: Theory comparison

$\Phi = 0\ \Phi_0$

Subharmonic oscillation region



Line cut fit



Regions: I Silent state
II Oscillating state
III Oscilating state exists but not energetically favorable

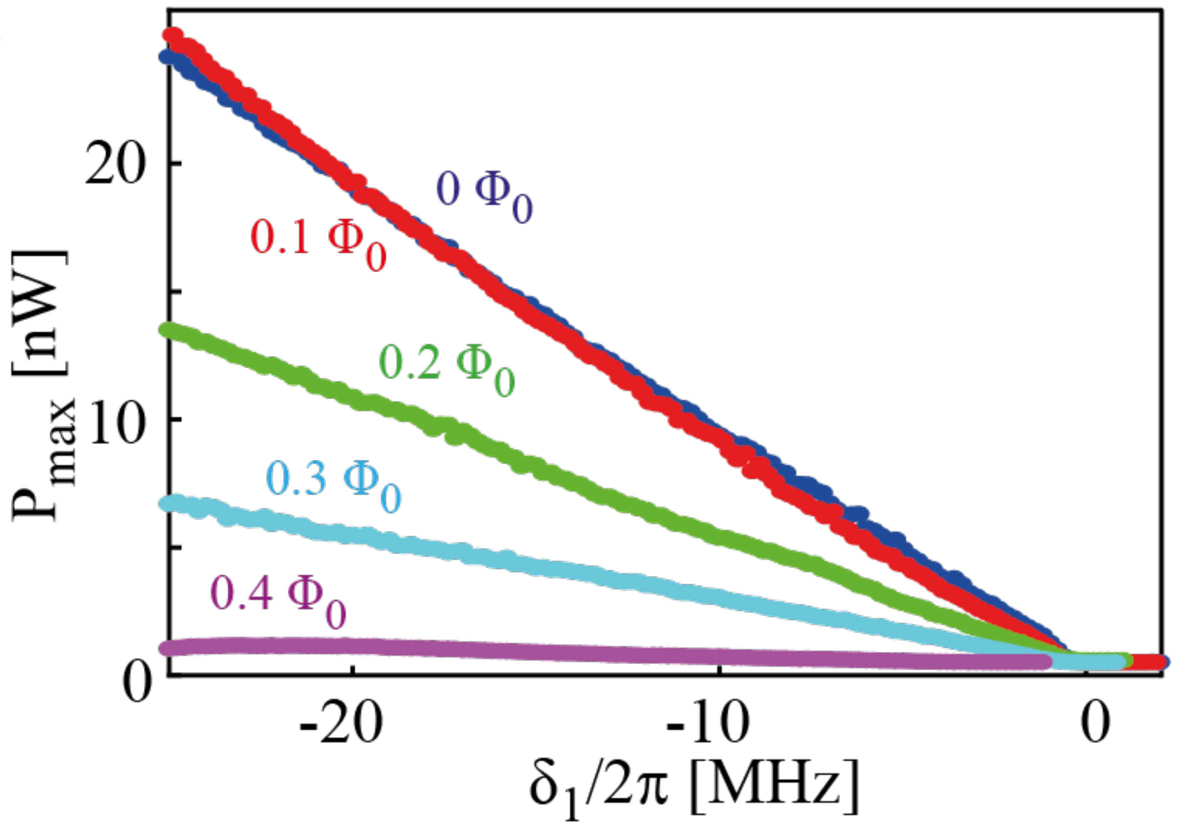
Svensson et al. *Physical Review B* **96** 174503, 2017

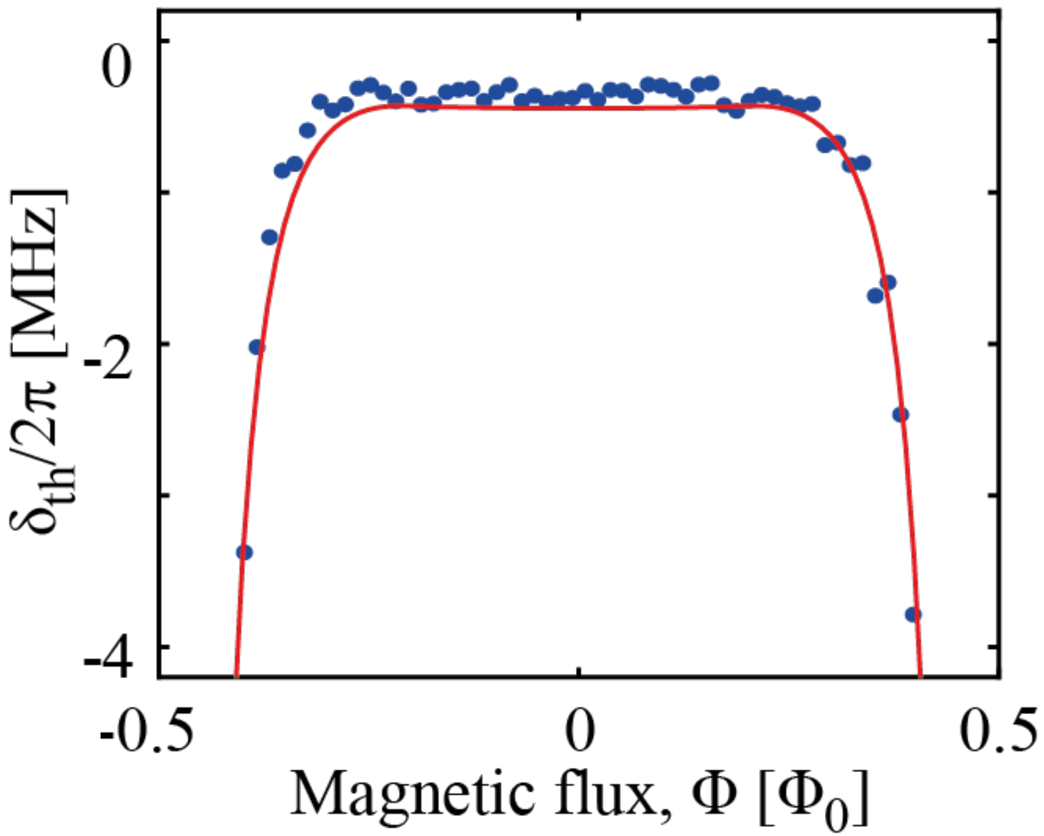
More properties of period-tripling subharmonic oscillations

Increasing intensity with δ_1
Decreasing intensity with flux

$\delta_1 = \omega - \omega_1$
Γ_1, damping rate

Threshold frequency
$\delta_1 \leq -\sqrt{7}\Gamma_1 = \delta_{th}$



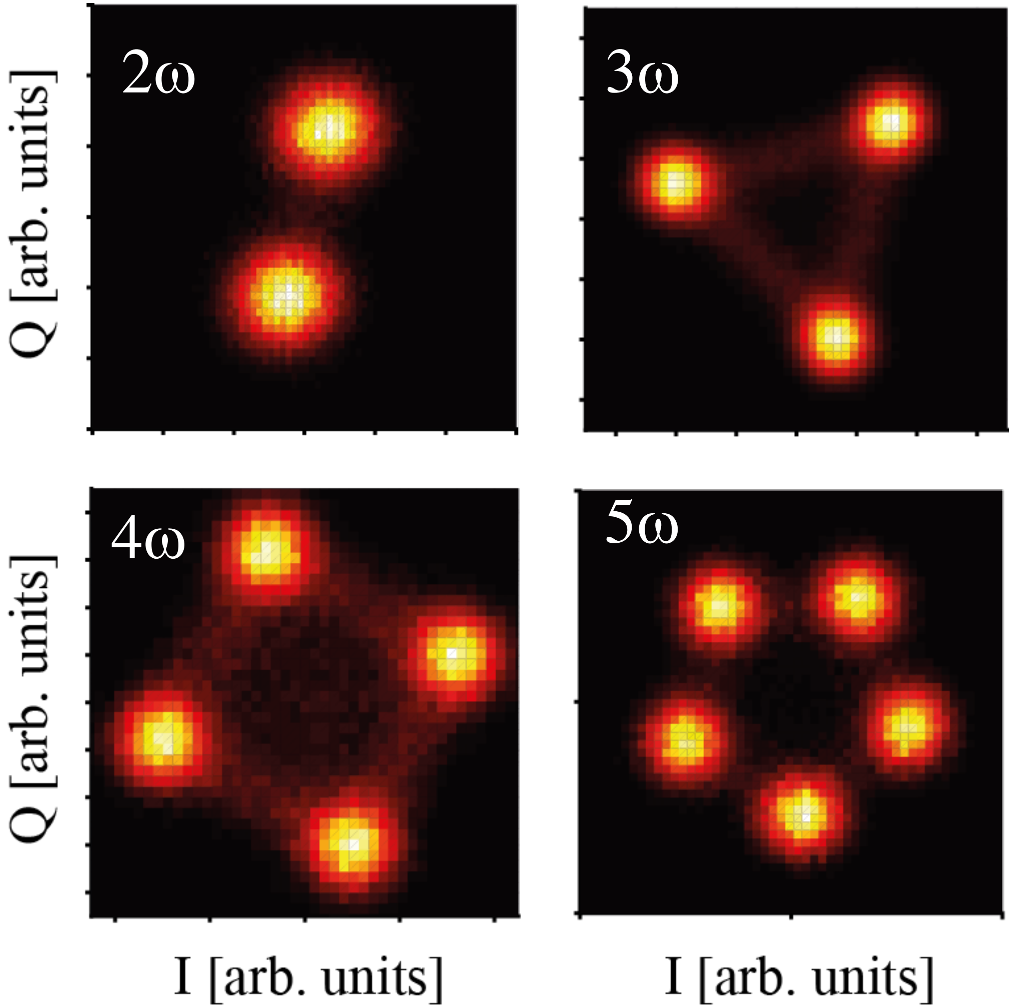


What about higher order pumping

- $f_{pump} = n f_0$,
- n=2 flux pumping, n=3 Current pumping
- Good agreement with theory

- Pumping at higher order multiples can also generate subharmonic states
- n = 4 and 5 also observed (no theory yet)

- Phase space crystals
  - Gou et al. Phys. Rev. Lett. **111**, 205303 (2013)
- Similar to time crystals
  - F. Wilczek, Phys. Rev. Lett. 109, 160401 (2012)



I.-M- Svensson et al., Appl. Phys. Lett. **113**, 022602 (2018)

Summary II: Period tripling

- Current pumping a multimode nonlinear oscillator close to a higher mode can generate oscillations at the fundamental mode which have an n-fold phase symmetry.
- The oscillations in the higher mode act as a parametric pump for the fundamental mode.
- Observation of period tripling, n=3, good agreement with theory. n = 4, 5 also observed.
- Hamiltonians of the type $a_1^{\dagger n} a_2$ implemented.


Ida-Maria Svensson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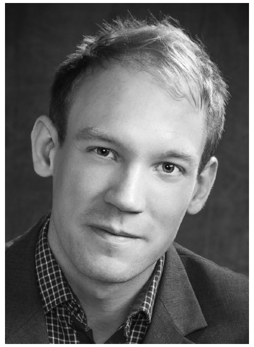
Philip Krantz


Jonas Bylander


Vitaly Shumeiko

I.-M- Svensson *et al*. Phys. Rev. B **96**, 174503 (2017) I.-M- Svensson et al. Appl. Phys. Lett. **113**, 022602 (2018)