Physics of superconducting quantum systems

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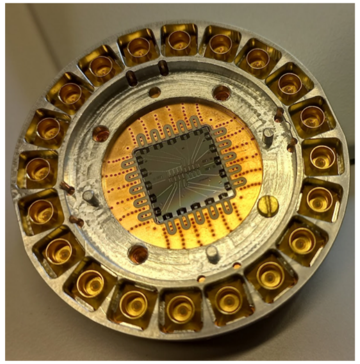
1. Лаборатория основана в 2015 г.
2. ~30 сотрудников
3. Большой опыт в области сверхпроводниковых квантовых технологий
4. Физика сверхпроводниковых квантовых систем
5. Квантовая оптика на чипе
6. Квантовая акустика
7. Сверхпроводниковые 5-ти, 8-ми, 12-ти, 16-ти кубитные процессоры



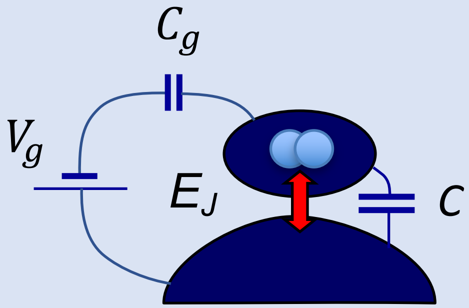
Сверхпроводниковый 8-ми кубитный квантовый процессор. Работает!

Superconducting Quantum Technologies

- Introduction into superconducting quantum systems
- Fabrication and measurement techniques
- Large quantum systems, quantum processors
- Quantum optics with artificial quantum systems
- Quantum acoustics
- Coherent Quantum Phase Slips (CQPS)

Superconducting quantum systems

Charge is quantized ($Q_0 = 2e$)

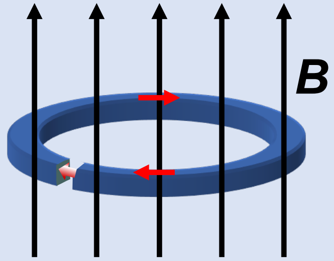


$$U = \frac{Q_0^2}{2C}(N - n)^2$$

$$Q_{ext} = C_g V_g = nQ_0$$

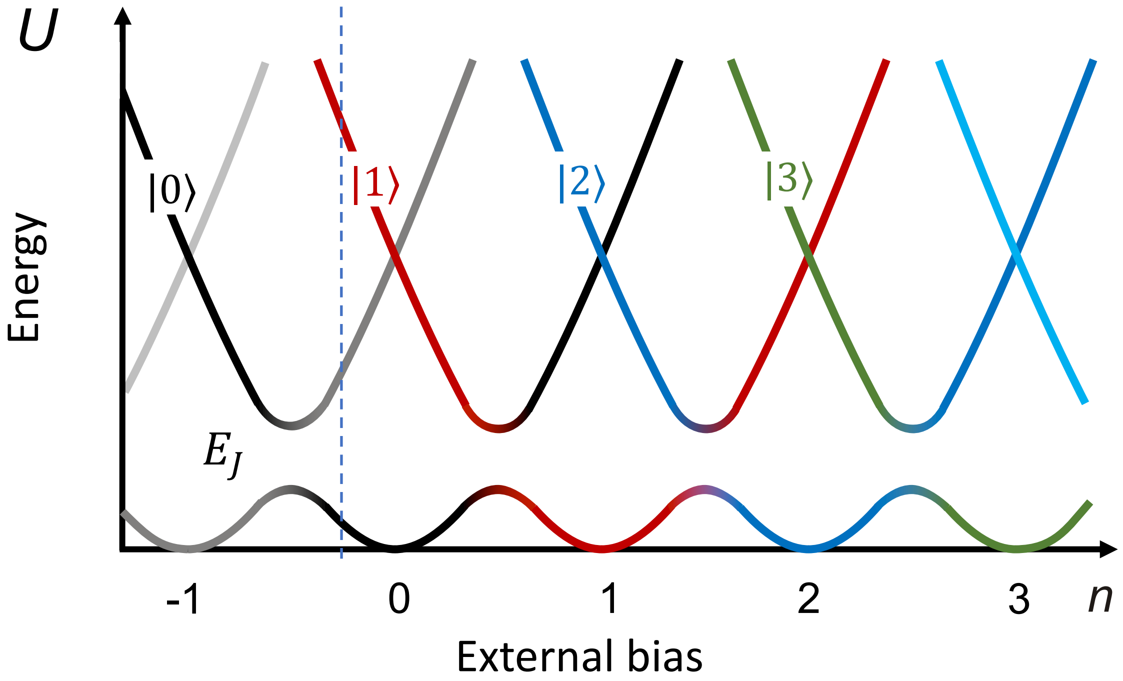
Continuous variable

Magnetic flux is quantized ($\Phi_0 = \frac{h}{2e}$)



$$U = \frac{(N\Phi_0 - \Phi_{ext})^2}{2L}$$

$$\Phi_{ext} = BS = n\Phi_0$$



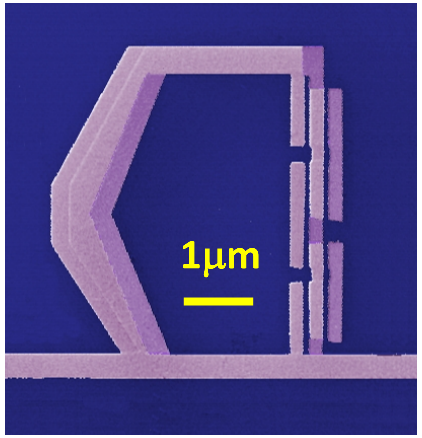
Energy levels

- Cooper pairs (charge 2*e*) are elementary charge in superconductors
- Josephson junction is a tunnel barrier for Cooper pairs
- Josephson junction is a key element in superconducting quantum systems
- Necessary condition: $E_C \ll k_B T$

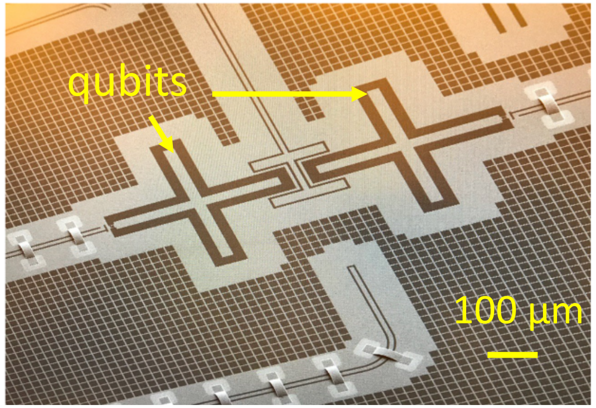
Superconducting Quantum Technologies

Quantum Optics in mcrowaves: 1 – 10 GHz (λ = 1 – 10 cm)

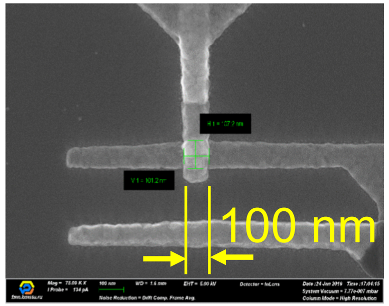
Flux qubits



Charge qubits



Josephson junction



Typical capacitance:
$C = 10^{-15} - 10^{-13}$ F

Charging energy:
$$\frac{E_C}{h} = \frac{(2e)^2}{Ch} = 10^9 - 10^{11}\ \text{Hz}$$

$$T = 1\ \text{K}: \frac{k_B T}{h} = 2\times 10^{11}\ \text{Hz}$$

Superconducting Quantum systems:

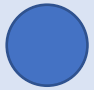
- Fully controllable
- Can be designed with known parameters
- On-chip
- Scalable (integrated circuits)
- Based on nanofabrication processes

Research directions:

- **Superconducting Quantum Systems**
  - *Quantum bits*
  - *Quantum Simulators*
- **Quantum Optics with Artificial Atoms**
- **Quantum metrology and sensing**
  - *Coherent Quantum Phase Slips*
  - *Quantum metrology*
- **Quantum Acoustics**

Quantum Mechanics of Electric circuit

Mass



m

Position: x

Velocity: $\dot{x}$

Momentum: *p*

$$p = m\dot{x}$$

Kinetic energy:

$$T = \frac{m\dot{x}^2}{2}$$

Mass: *m*

Momentum operator:

$$\hat{p} = -i\hbar\frac{\partial}{\partial x}$$

Commutation relations:

$$[\hat{x}, \hat{p}] = i\hbar$$

Inductance

L

Charge: *Q*

Current: $I = \dot{Q}$

Magnetic Flux: Φ

$$\Phi = LI = L\dot{Q}$$

Kinetic energy:

$$T = \frac{L\dot{Q}^2}{2}$$

Mass: *L*

Momentum operator:

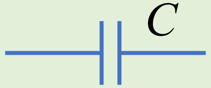
$$\hat{\Phi} = -i\hbar\frac{\partial}{\partial Q}$$

Commutation relations:

$$[\hat{Q}, \hat{\Phi}] = i\hbar$$

$Q \leftrightarrow x \quad \Phi \leftrightarrow p \quad L \leftrightarrow m$

Capacitance



C

Magnetic Flux: Φ

Voltage: $V = \dot{\Phi}$

Charge: Q

$$Q = CV = C\,\dot{\Phi}$$

Kinetic energy:

$$T = \frac{C\dot{\Phi}^2}{2}$$

Mass: *C*

Momentum operator:

$$\hat{Q} = -i\hbar\frac{\partial}{\partial \Phi}$$

Commutation relations:

$$[\hat{\Phi}, \hat{Q}] = i\hbar$$

$\Phi \leftrightarrow x \quad Q \leftrightarrow p \quad C \leftrightarrow m$

A key element is tunnel junction: Josephson junction is superconducting circuits

Superconducting Quantum Technologies

Cryogenic
He-free dilution fridge (~10 mK)

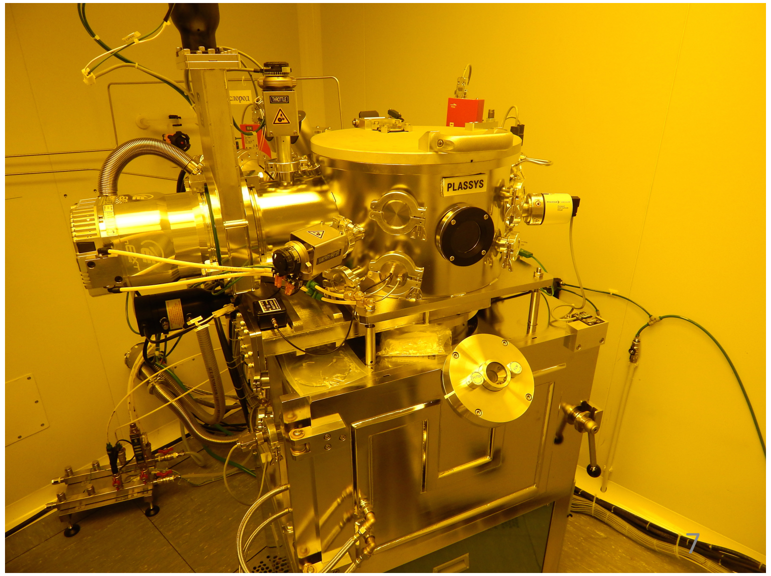
Measurements
- Signal generators
- NT analyzer up to 20 GHz
- Signal analyzers (20 GHz)
- Fast digital electronics

Fabrication
- EBL system (Crestec)
- Evaporator dedicated for Josephson junctions
- …

Experimental setup

Electron-beam Lithography

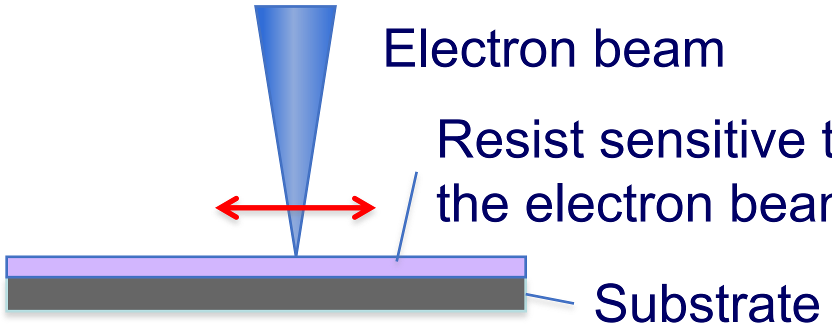
Josephson junction evaporator



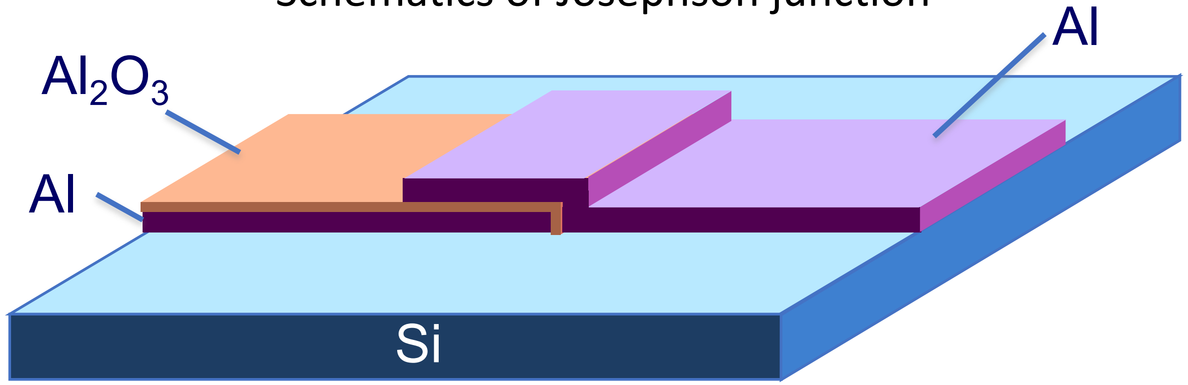
Nano-technology

Electron-beam lithography systems (EBL)

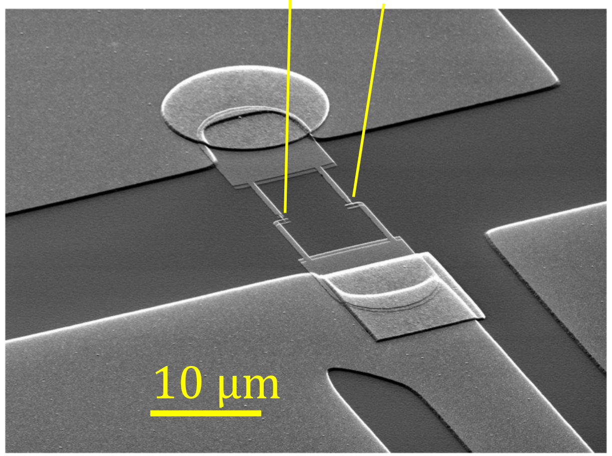
Resolution: ~2 nm



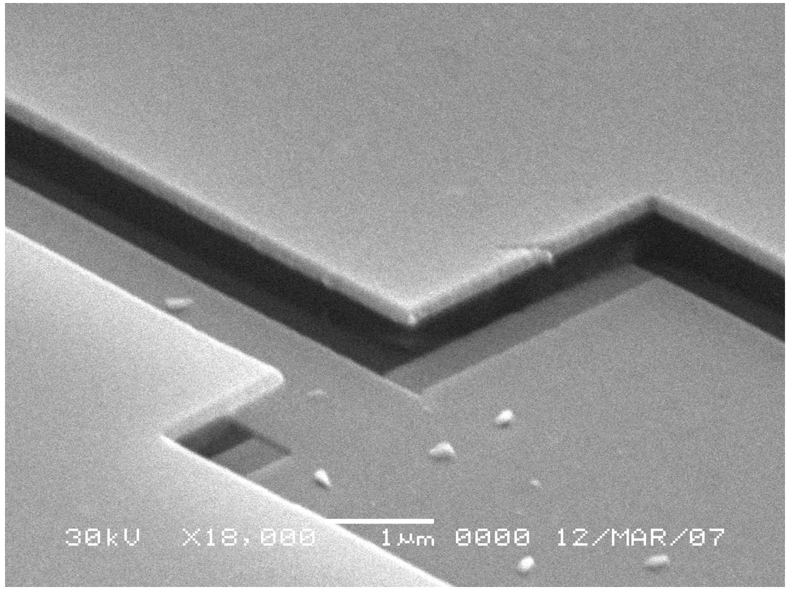
Schematics of Josephson junction

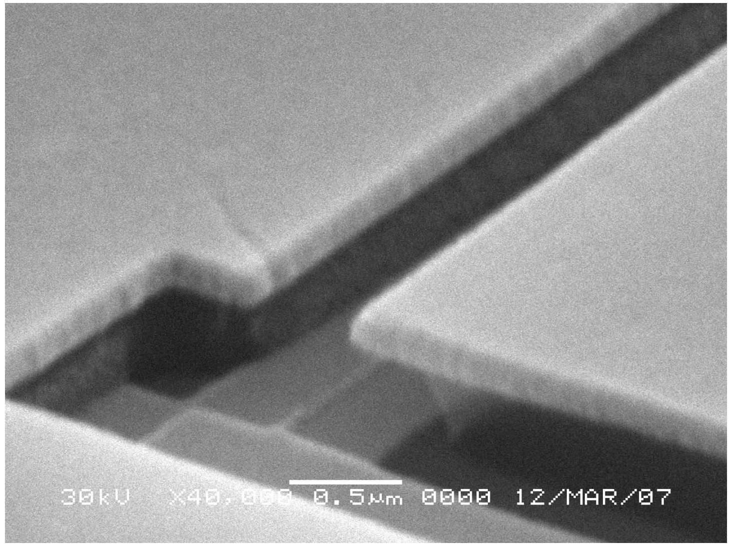


Josephson junctions ~ $100 \times 100\ nm^2$



Au film pictured after evaporation
on double layer resist





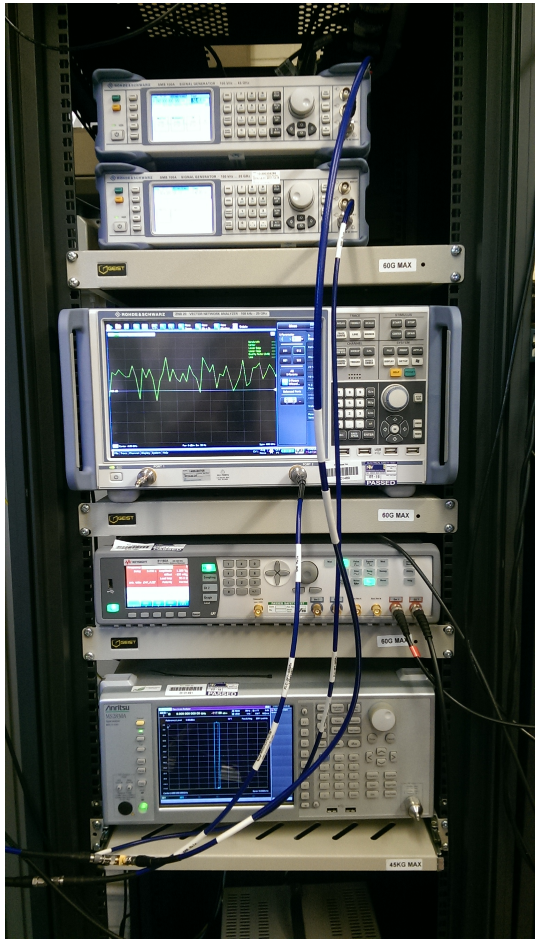
Experimental setup

Dilution refrigerator and measurement equipment

Dilution refrigerator

Internal view

Measurement MW equipment (f = 1 – 10 GHz)



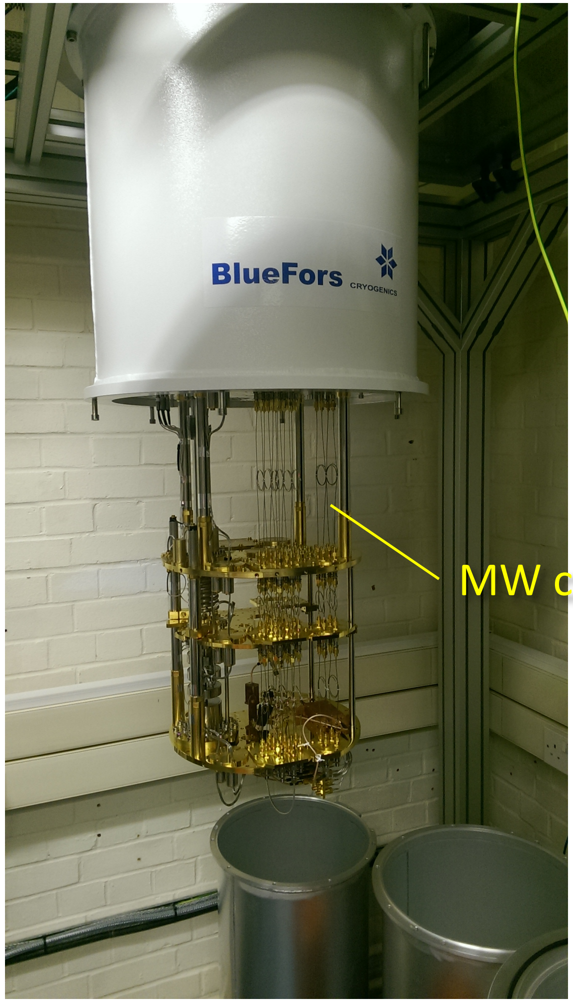
MW generators

NT analyser

Pulse generator

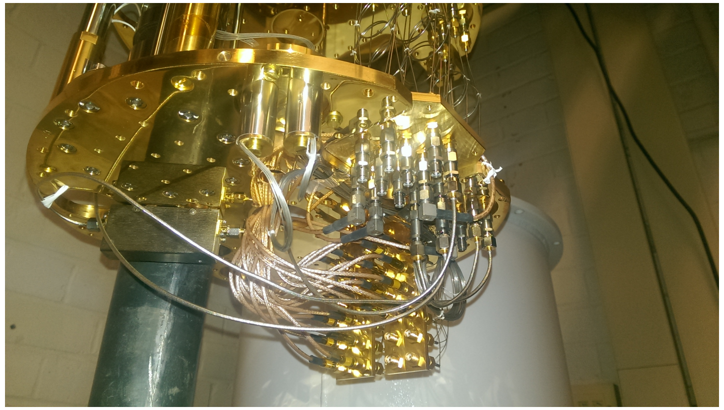
Spectrum analyser

The lowest temperature is 10 mK

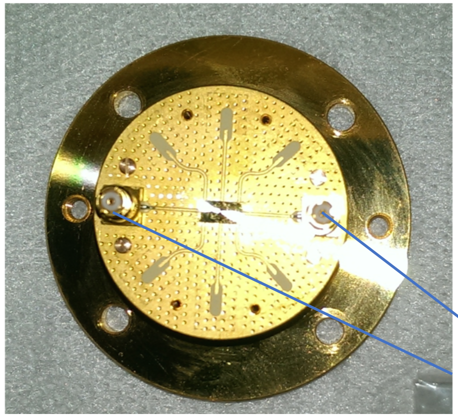


MW cables

Bottom view of a cold plate

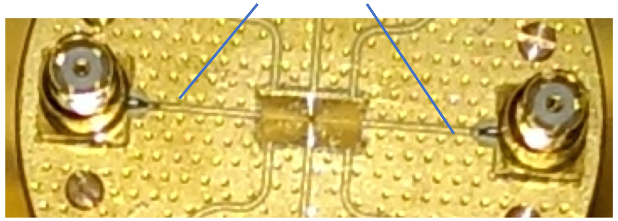


Sample holder

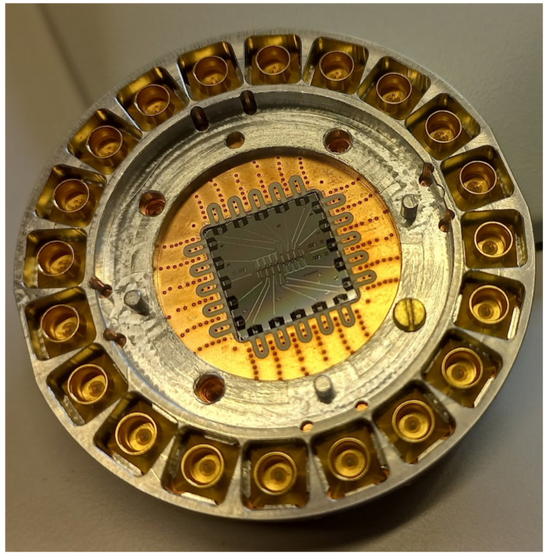


MW connectors

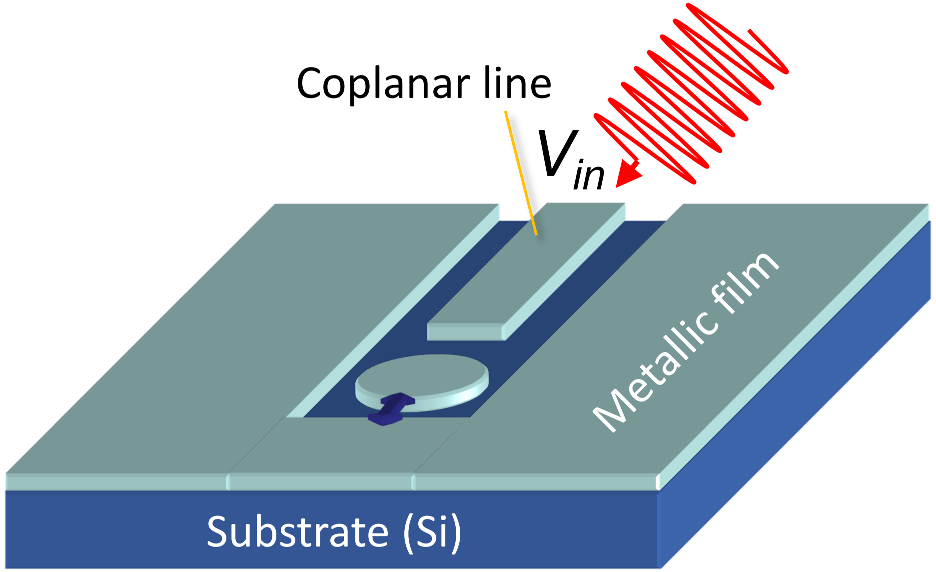
MW lines

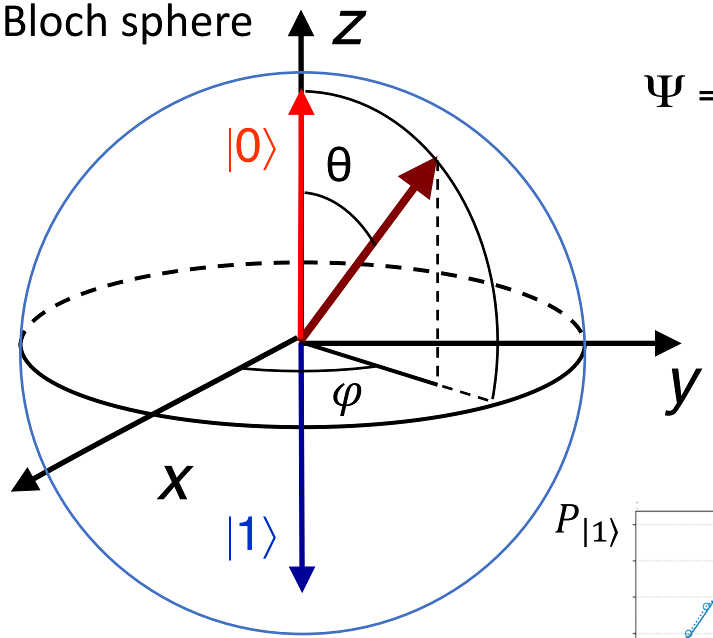


Wavefunction of a two-level system on the Bloch sphere

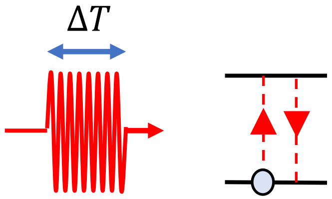


- Qubit is a two-level quantum system
- The qubit dynamics can be mapped to dynamics of spin ½
- Control of the qubit states by microwaves

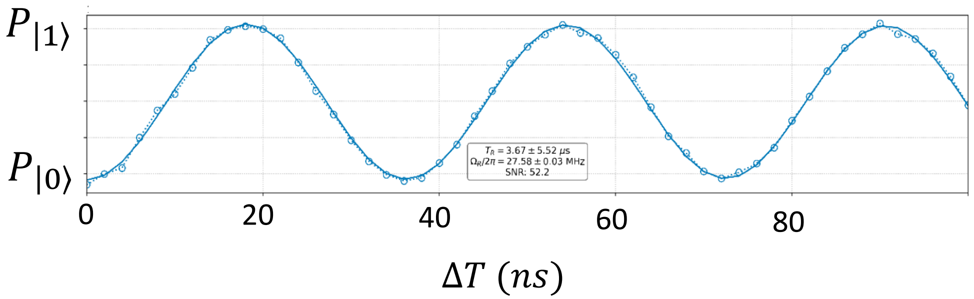




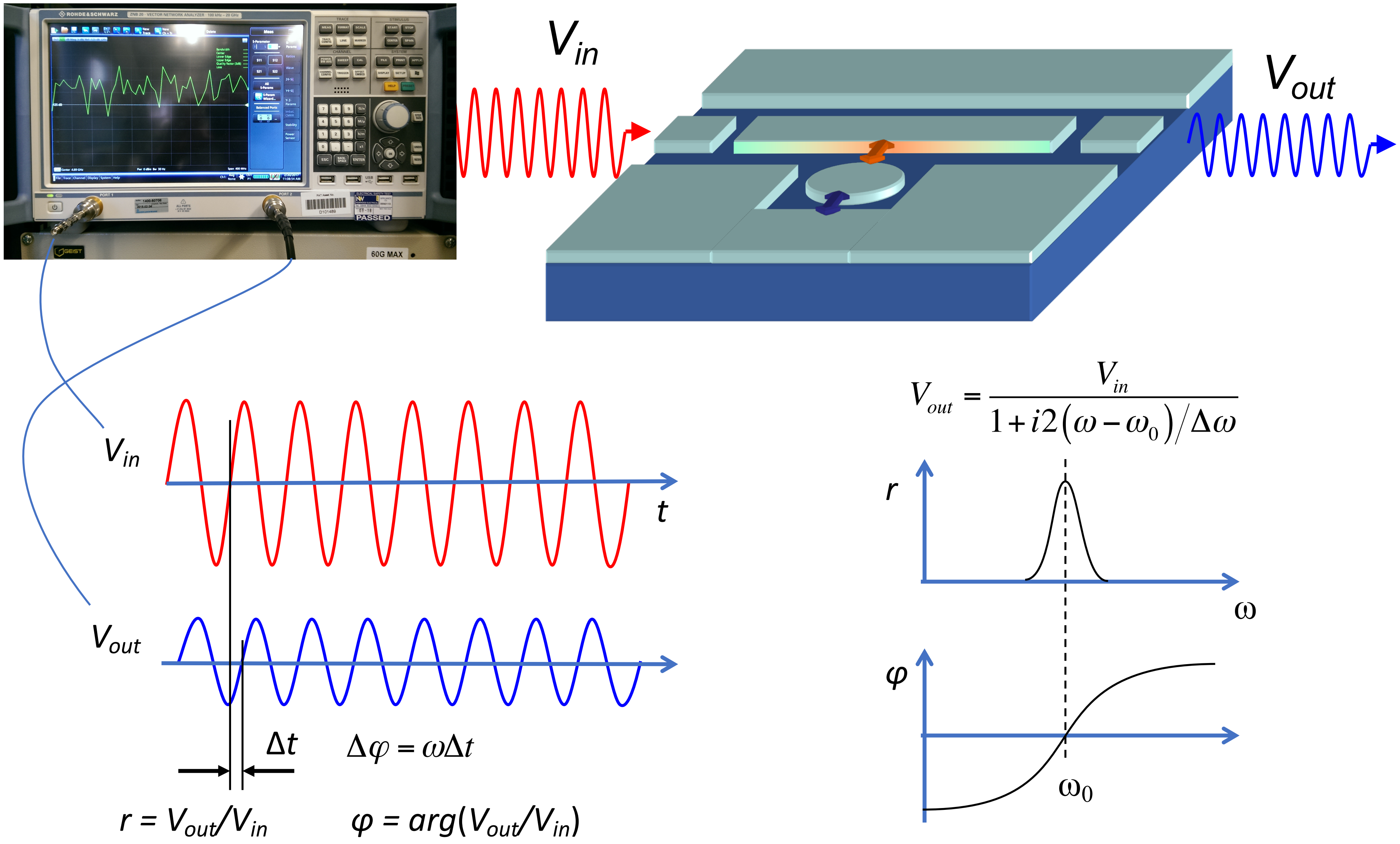
$$\Psi = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$



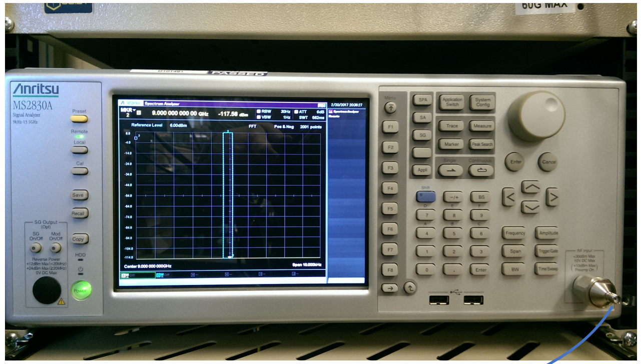
Oscillations of probability

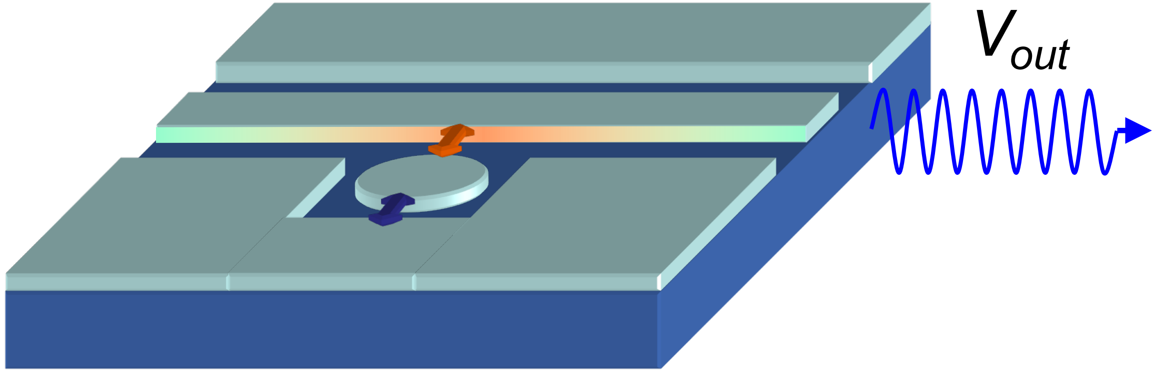


Phase-sensitive detection of transmitted signal by a network analyzer



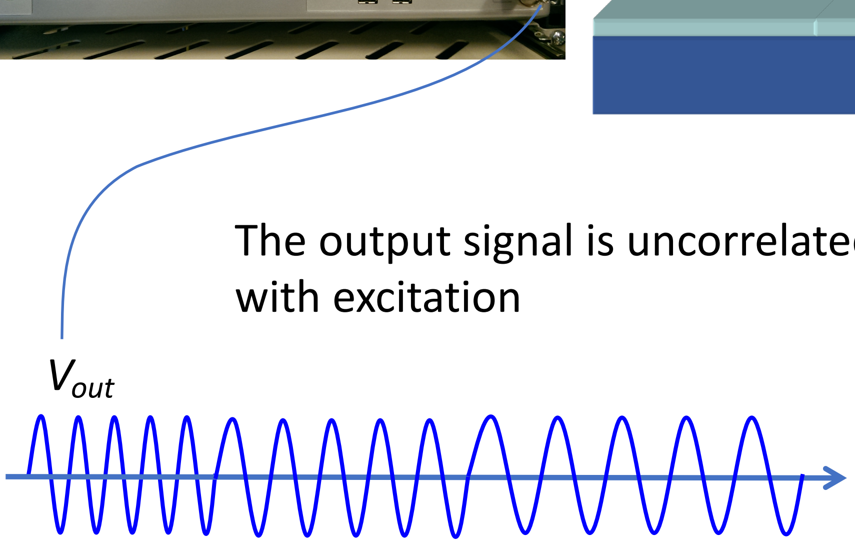
Spectrum detection of emission by a spectrum analyzer

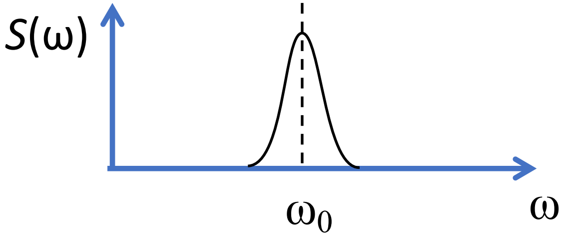




The output signal is uncorrelated in phase with excitation

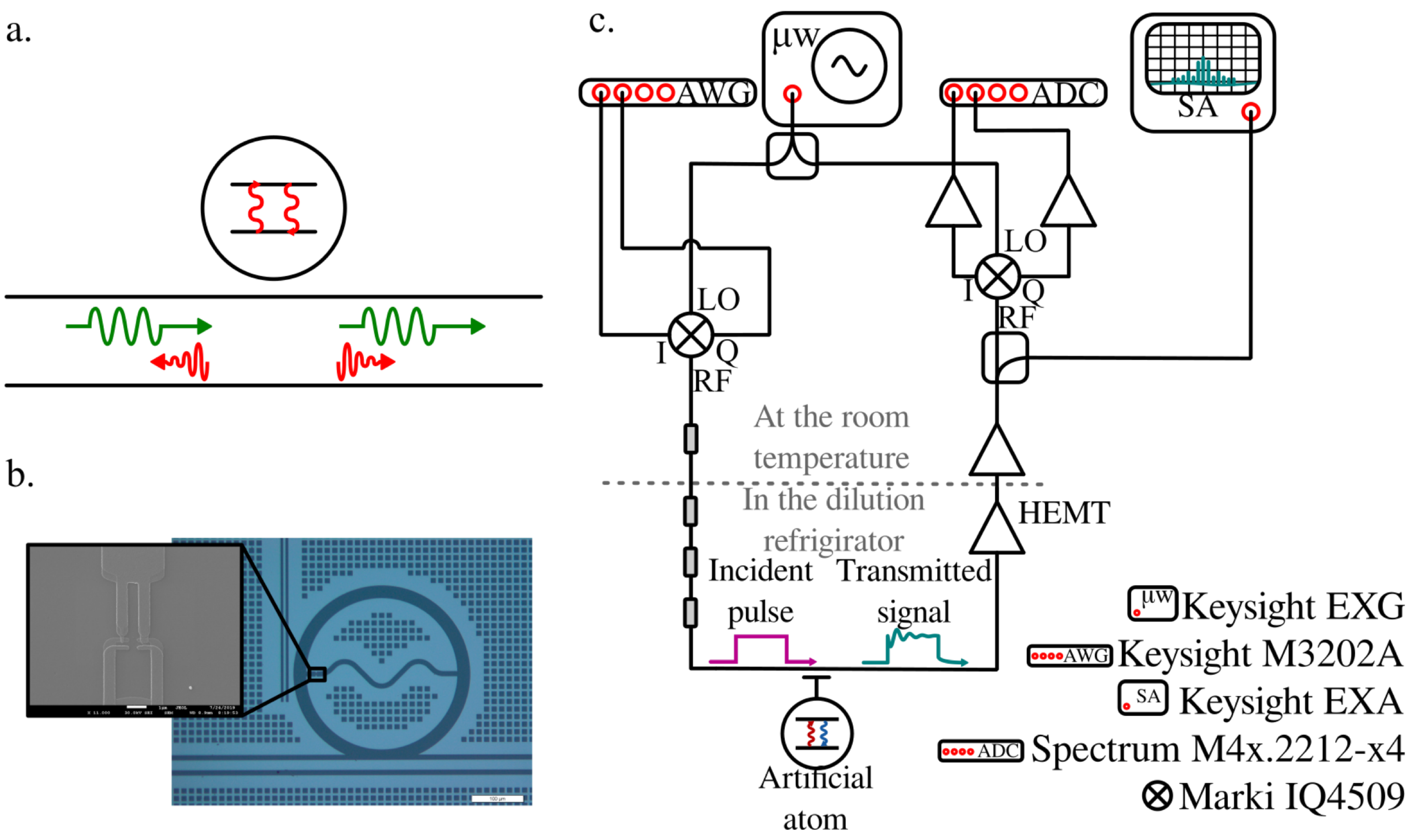
$$S_{out}(\omega) = \frac{S_0}{1 + \left[2(\omega - \omega_0)/\Delta\omega\right]^2}$$





Spectral power density: $S(\omega)$

Interaction of a two-level atom with a propagated field



Directions of research

Quantum bits (qubits)

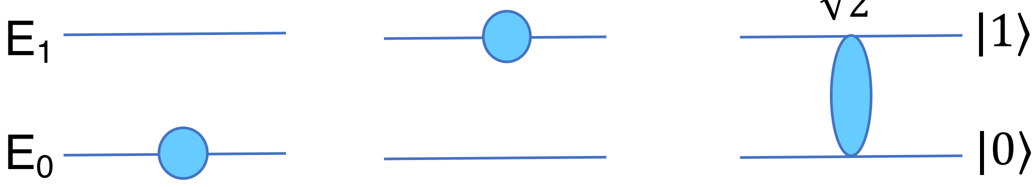
The information is encoded with quantum states

Ground state
0

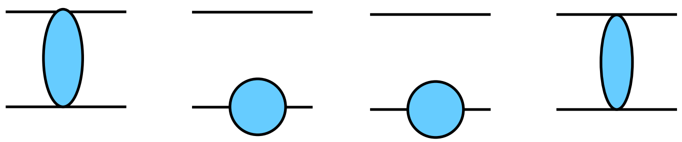
Excited state
1

Superposition

$$\frac{|0\rangle + |1\rangle}{\sqrt{2}}$$



Encoding numbers in quantum systems



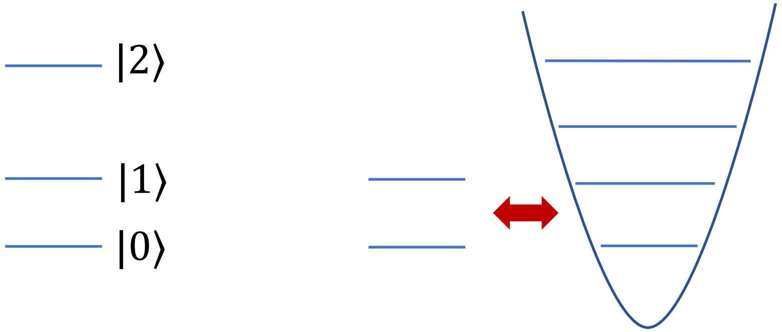
$$\left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\otimes|0\rangle\otimes|0\rangle\otimes\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right) = \frac{|0000\rangle + |1000\rangle + |0001\rangle + |1001\rangle}{\sqrt{4}}$$

Strong coupling: interaction strength is large then relaxation:
Easily achieved in superconducting quantum systems

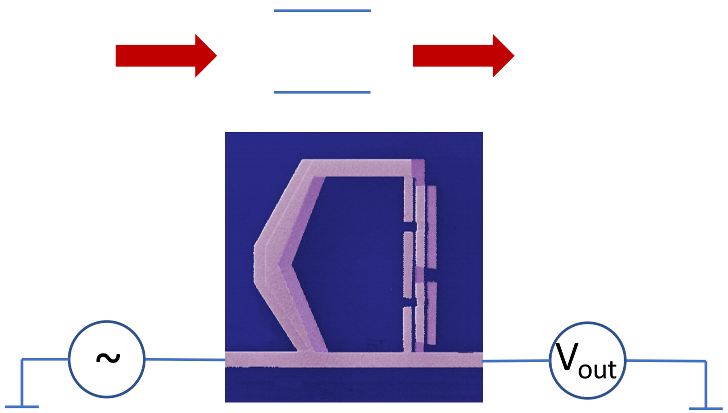
Artificial atoms (Quantum Optics)

Three-level atom

Cavity QED



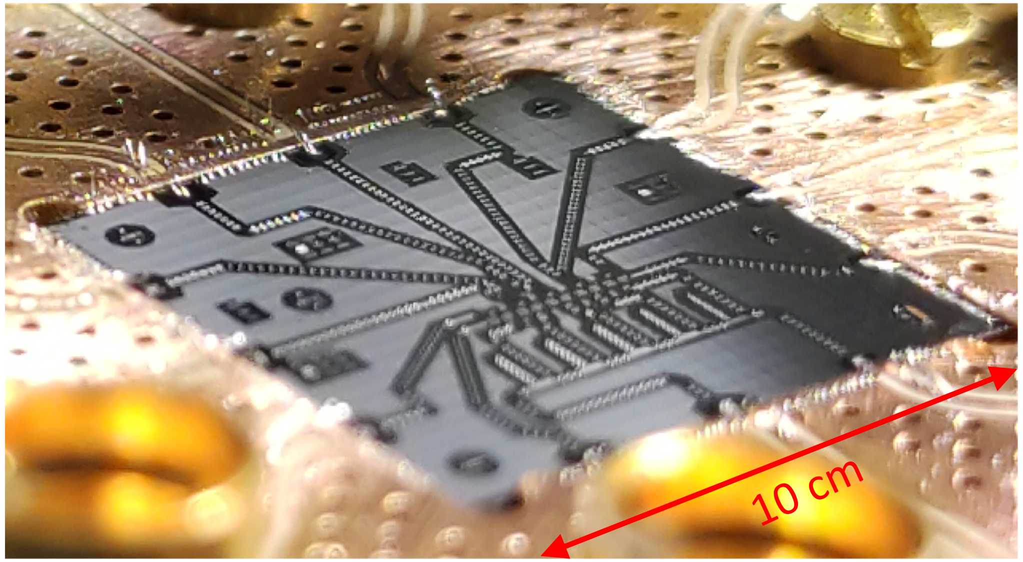
Artificial atom in the open space



$g \gg \Gamma$ Typical number of osillations $\frac{g}{\Gamma}$

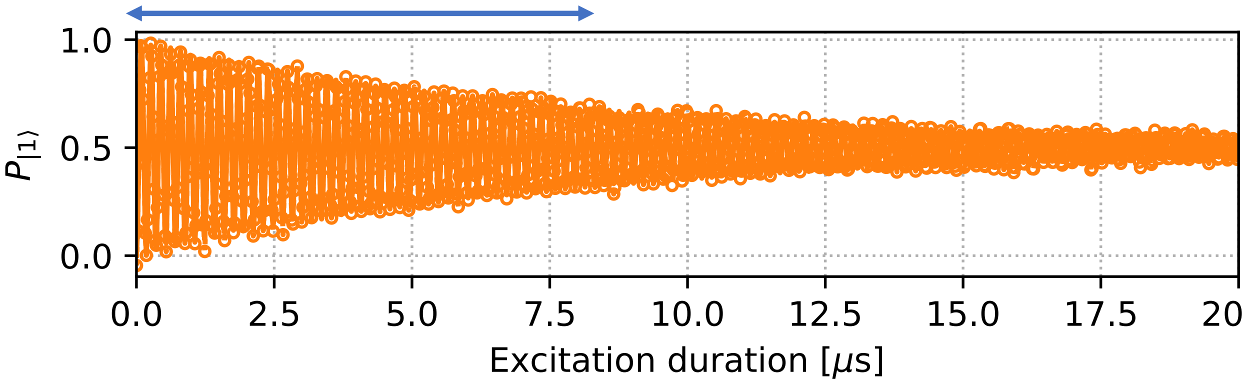
Quantum processors

5 qubit processor



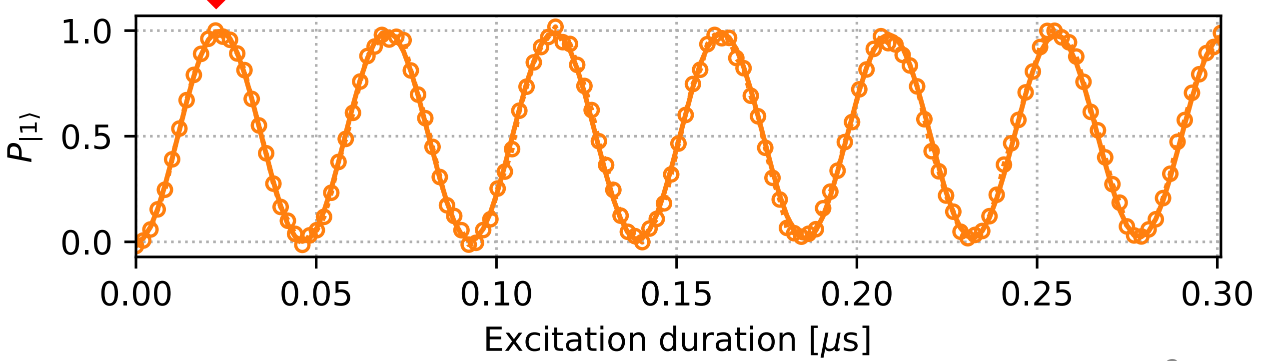
Universal processor We demonstrated solving problems of machine learning (Quantum simulator)

Typical coherence times in multi-qubit circuits are ***5 – 20 μs***



99.7% Efficiency of qubit manipulation in multiqubit circuit

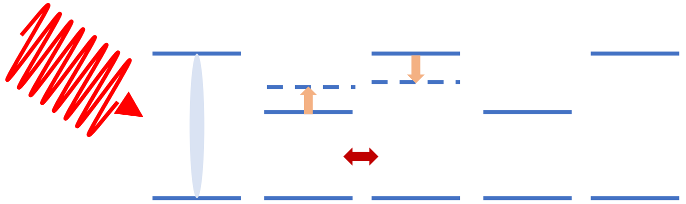
99.9% in single qubit

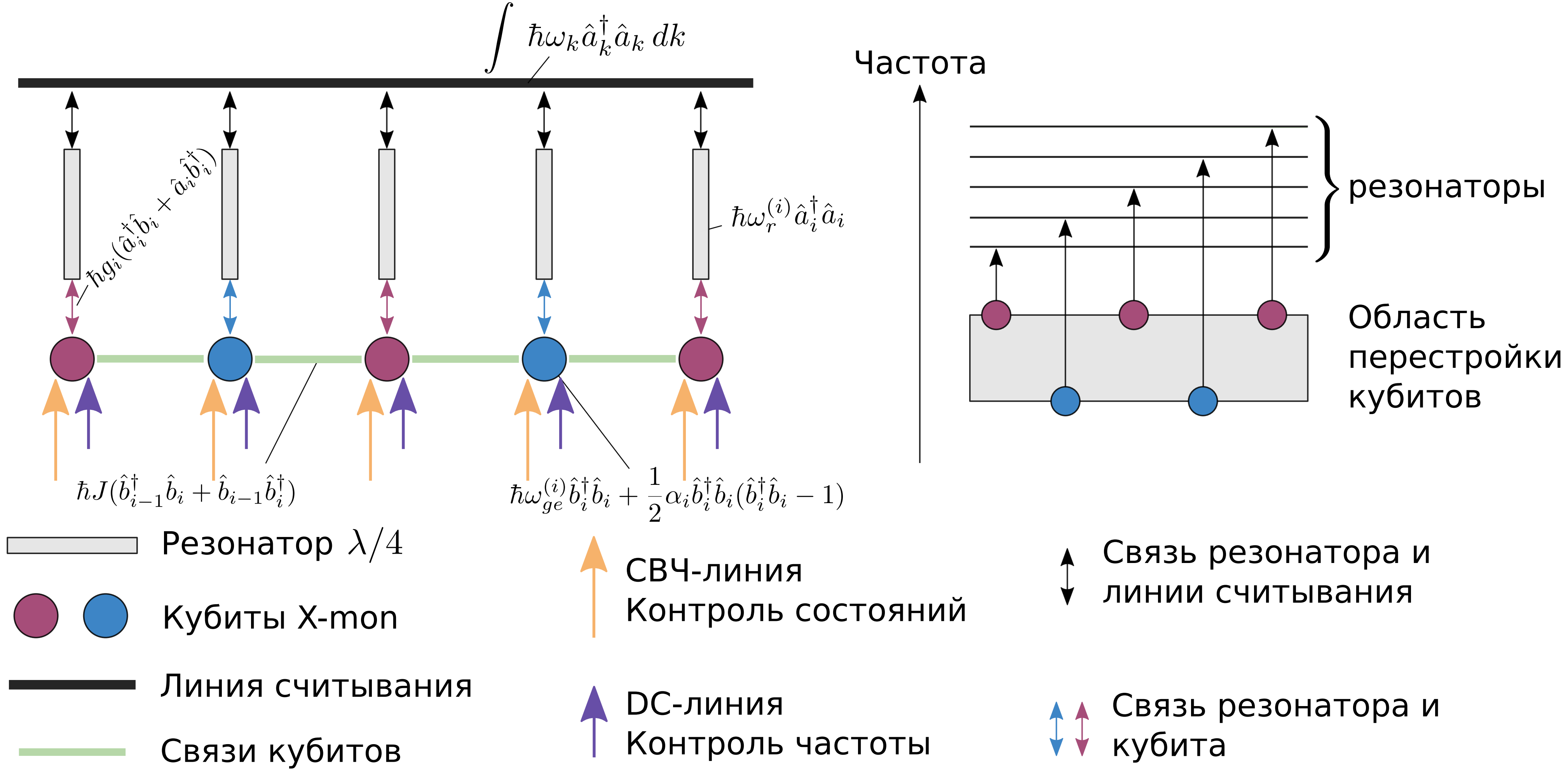


Transfer of states with high efficiency has been demonstrated

5-ти кубитный процессор: принцип работы

- State control by Microwave
- Each qubit Energy control
- 2-qubit interaction control

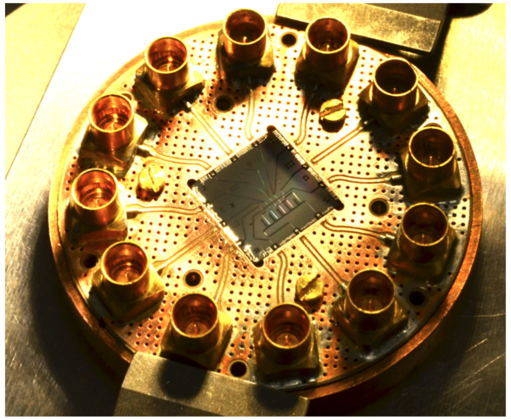


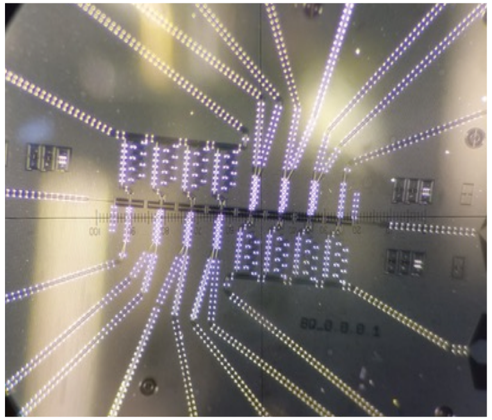


Квантовые процессоры

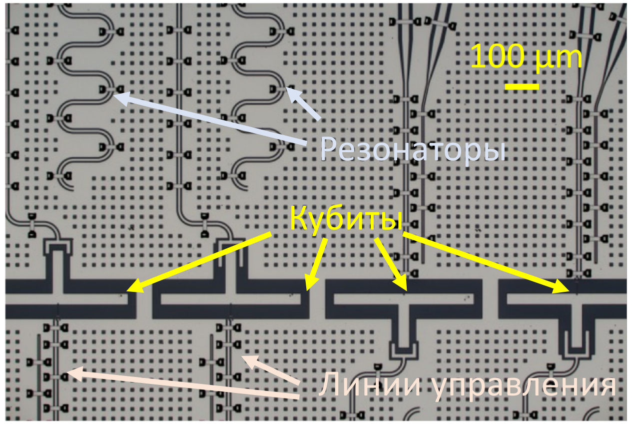
1. На базе ЦКП МФТИ ***отлажена технология изготовления*** высококачественных квантовых устройств (T = 10 – 60 μs).
2. Разрабатывается ***несколько геометрий процессоров*** различной сложности и функциональности.
3. Наиболее изученной является схема из 5-ти кубитов. Это полноценный квантовый процессор.
4. На 5-ти кубитной схеме продемонстрировано решение реальных ***задач машинного обучения***.
5. Продемонстрирована высокая эффективность одиночного гейта **99.7%** (в ***многокубитной*** *схеме* – не путать с эффективностью в одно- и двухкубитных схемах).
6. В настоящий момент изготовлен, полноценно работает и тестируется ***8-кубитный*** квантовый процессор.
7. Разрабатывается 12/16-ти кубитная геометрия

8-кубитный процессор

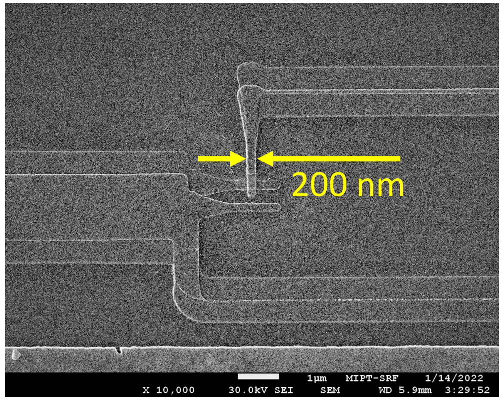




Элементы на чипе

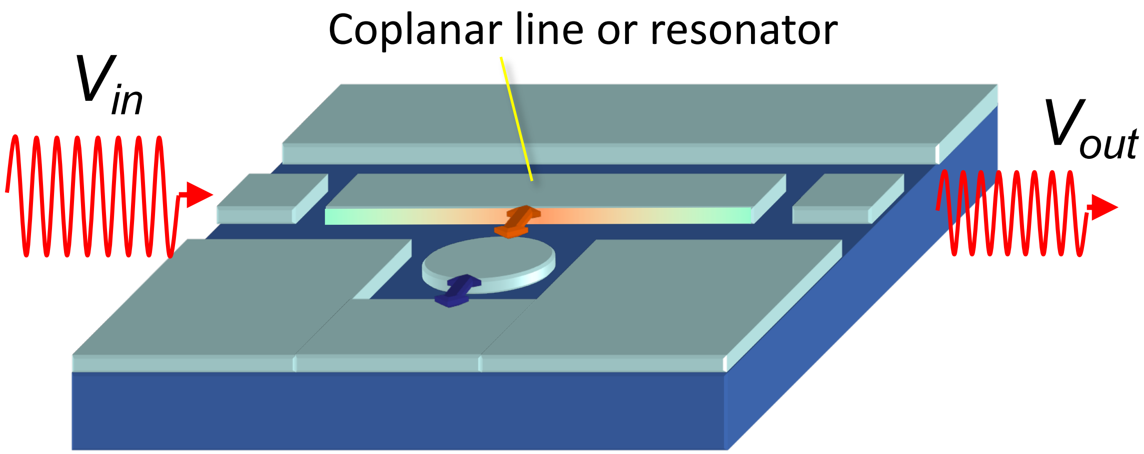


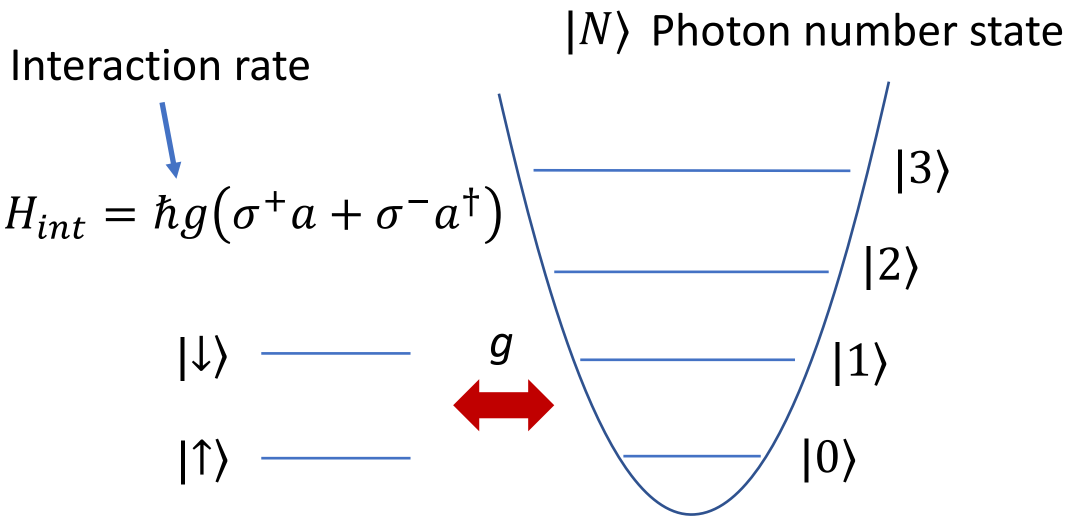
Джозефсоновский переход



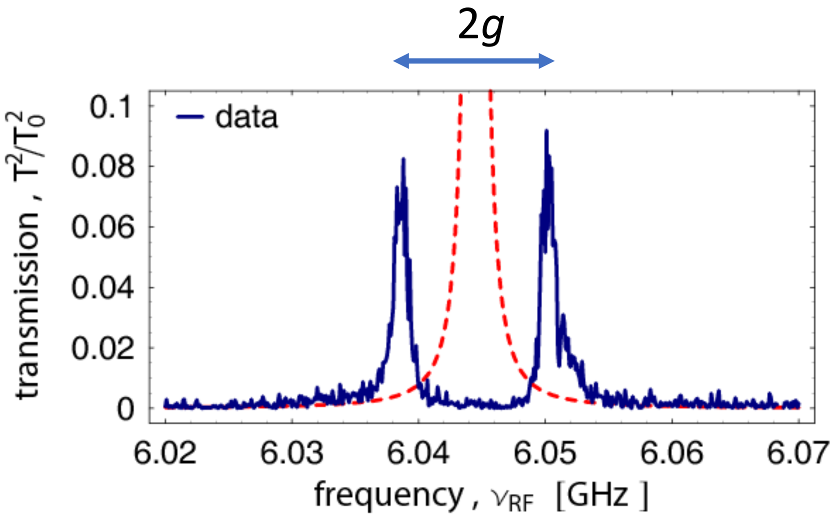
Quantum Optics
with superconducting quantum systems
(artificial atoms)
in the microwave range

Quantum optics in the microwave range

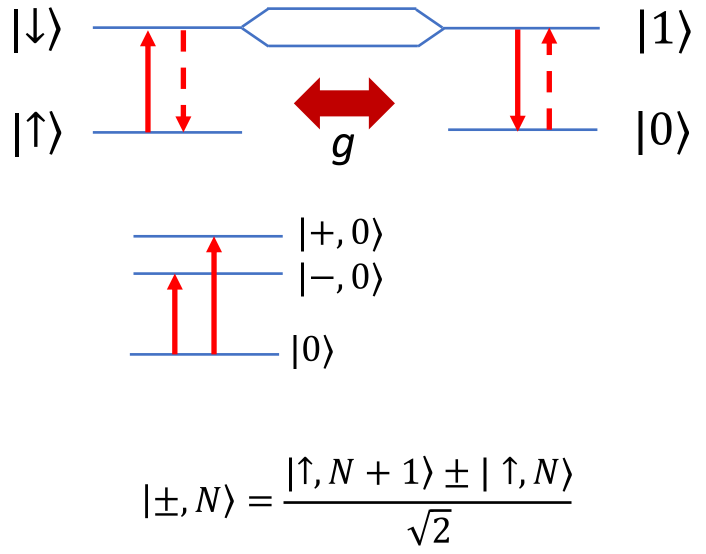




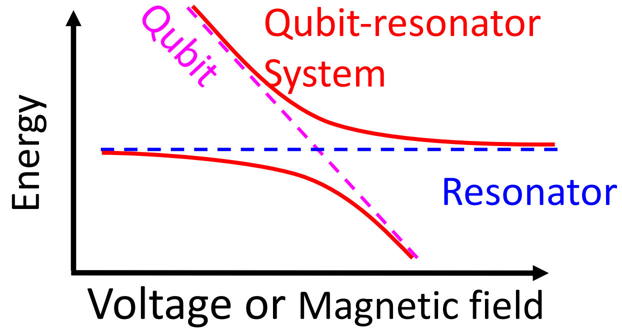
Experimental observation of atom-resonator interaction

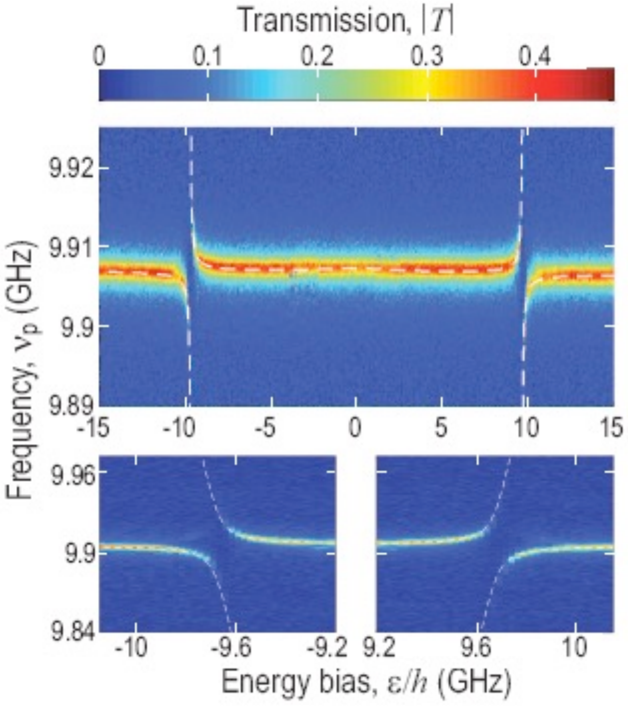


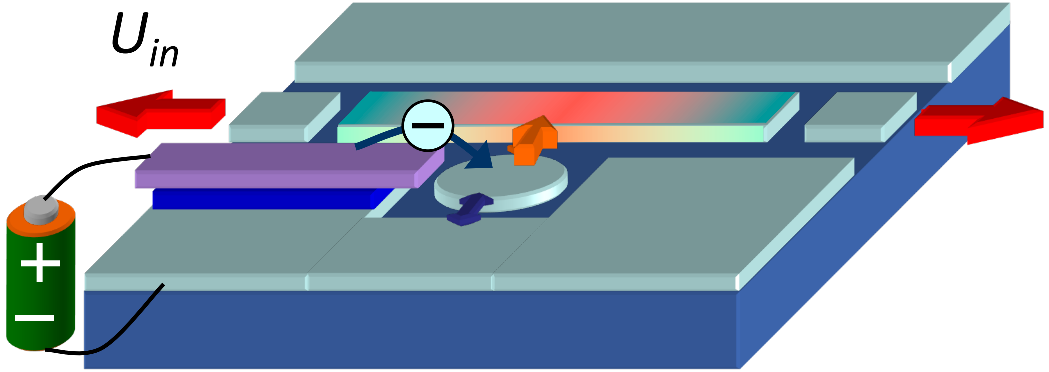
- Basic QO circuit
- Cavity Quantum Electrodynamics
- Lasing
- Fock ($|N\rangle$) state generation
- Quantum bath
- Stark shift

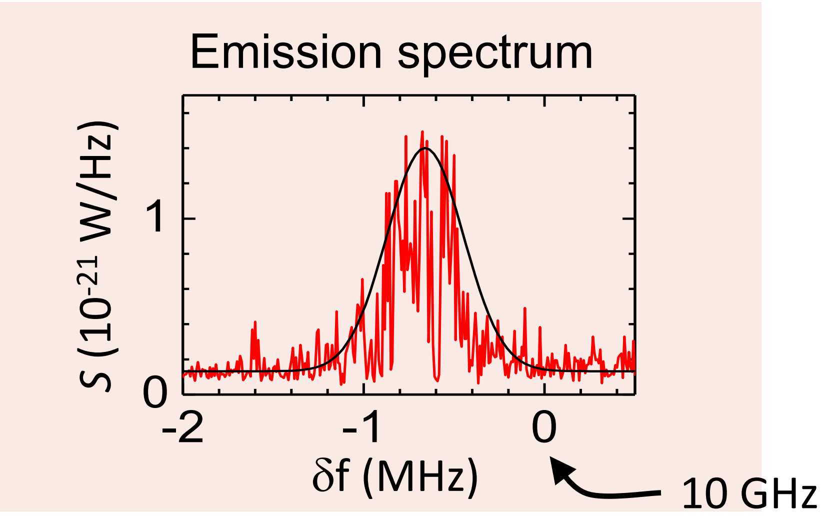


Cavity quantum elcetrodynamics: Single artificial-atom lasing







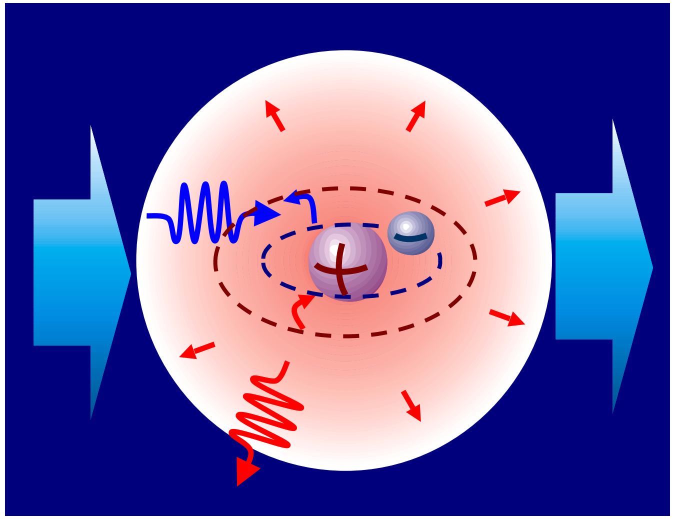


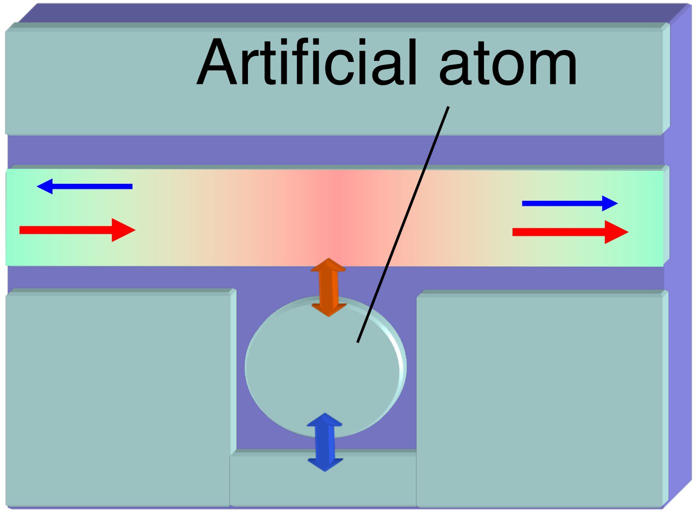
O. Astafiev, K. Inomata, A. O. Niskanen, T. Yamamoto, Yu. A. Pashkin, Y. Nakamura, J. S. Tsai. Single artificial-atom lasing , *Nature* **449**, 588 (2007)

Artificial atom in the open space

Atom in the open space

Light scattering by an atom





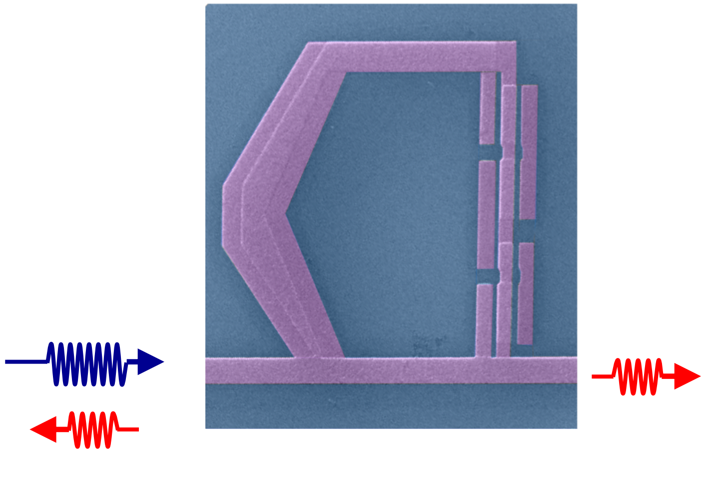
Artificial atoms are strongly coupled to electromagnetic waves
Natural atoms are weakly coupled to electromagnetic waves (weak scattering)

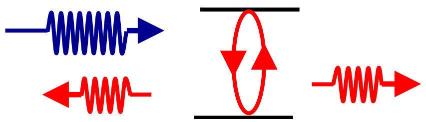
Strong scattering of propagating waves

A series of very promising applications

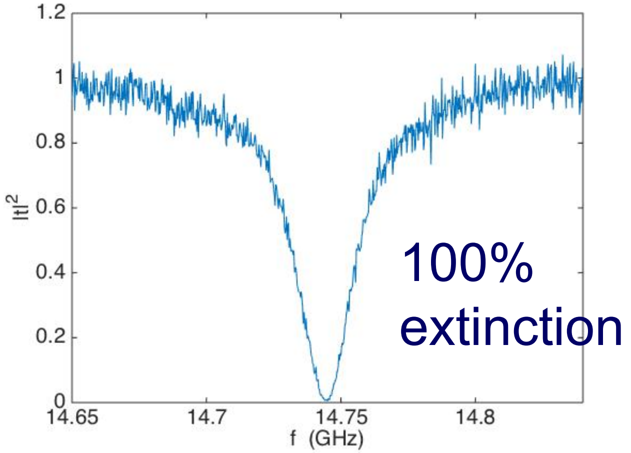
O. Astafiev, A. M. Zagoskin, A.A. Abdumalikov, Yu. A. Pashkin, T. Yamamoto, K. Inomata, Y. Nakamura, and J.S. Tsai. Resonance fluorescence of a single artificial atom. *Science* **327** (2010).

Resonance Fluorescence with a single atom: Elastic and inelastic scattering

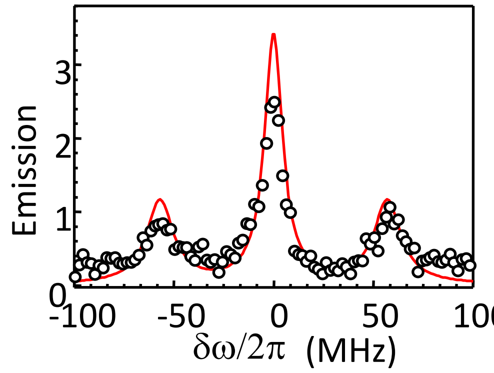


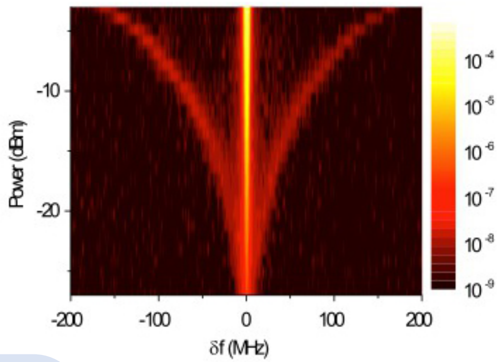


Normalized transmission power



Inelastic scattering





The artificial atom **strongly** interacts with modes of 1D open space

⇓

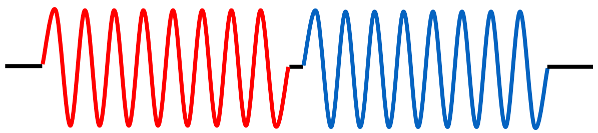
Promising candidate for quantum information processing with photons

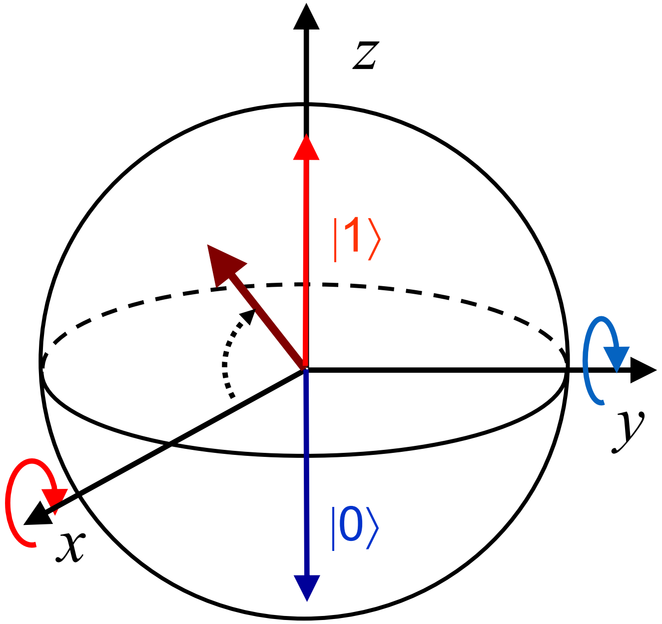
Time domain measurements. Quantum state tomography

$$H = -\hbar\Omega\left(\cos\varphi\sigma_x + \sin\varphi\sigma_y\right)$$

$$\frac{d}{dt}\begin{pmatrix}\langle\sigma_x\rangle\\ \langle\sigma_y\rangle\\ \langle\sigma_z\rangle\end{pmatrix} = \begin{pmatrix}-\gamma & 0 & -\Omega\sin\varphi\\ 0 & -\gamma & \Omega\cos\varphi\\ \Omega\sin\varphi & -\Omega\cos\varphi & -\Gamma\end{pmatrix}\begin{pmatrix}\langle\sigma_x\rangle\\ \langle\sigma_y\rangle\\ \langle\sigma_z\rangle\end{pmatrix} + \begin{pmatrix}0\\ 0\\ -\Gamma\end{pmatrix}$$

State manipulation





Coherent emission: $I_{emit}(t) = i\frac{\hbar\Gamma}{\phi_p}\langle\sigma^-\rangle e^{-i\omega t}$

$\langle\sigma^\pm\rangle = \langle\sigma_x\rangle \pm i\langle\sigma_y\rangle$

$$\mathrm{Re}[I_{emit}] = \frac{\hbar\Gamma}{\phi_p}\left(\langle\sigma_y\rangle\cos\omega t + \langle\sigma_x\rangle\sin\omega t\right)$$

Incoherent emission: $P = \frac{\hbar\omega}{T}\rho_{11} = \frac{\hbar\omega}{T}\frac{\langle\sigma_z\rangle + 1}{2}$

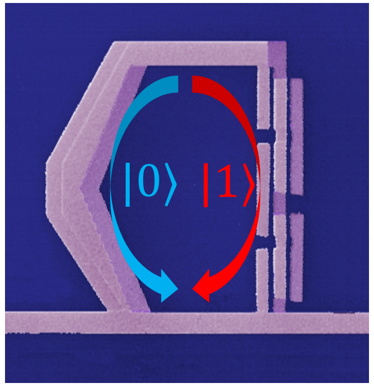
Max coherent emission

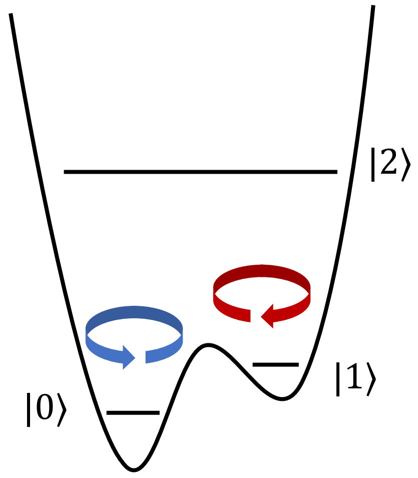
$$\sqrt{\langle\sigma_x\rangle^2 + \langle\sigma_y\rangle^2} = 1 \Rightarrow \frac{|0\rangle + e^{i\varphi}|1\rangle}{\sqrt{2}}$$

Max incoherent emission

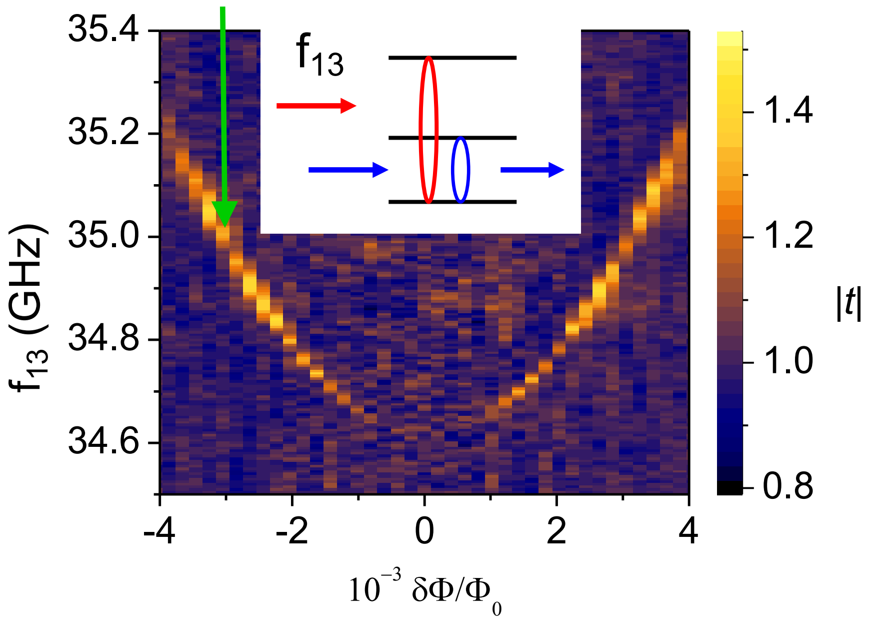
$$\langle\sigma_z\rangle = 1 \Rightarrow \rho_{11} = 1 \Rightarrow |1\rangle$$

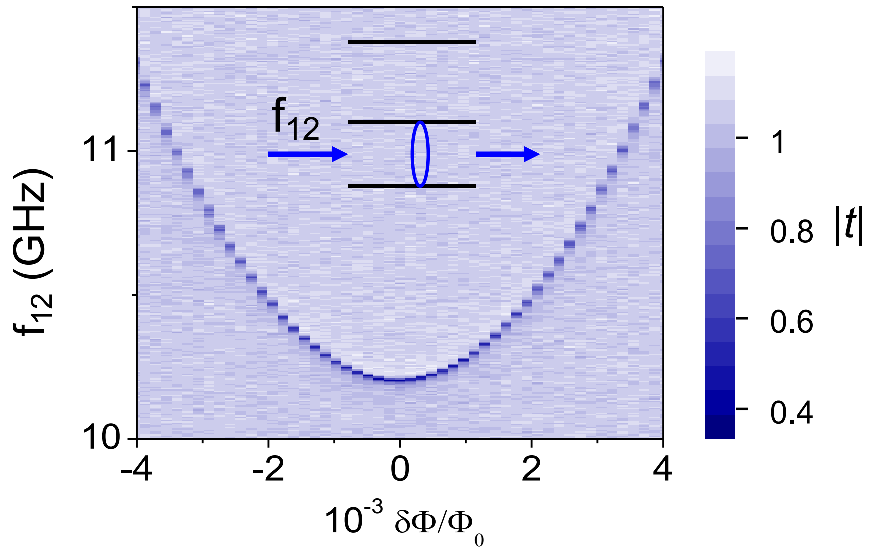
Two-frequency spectroscopy of three-level atom



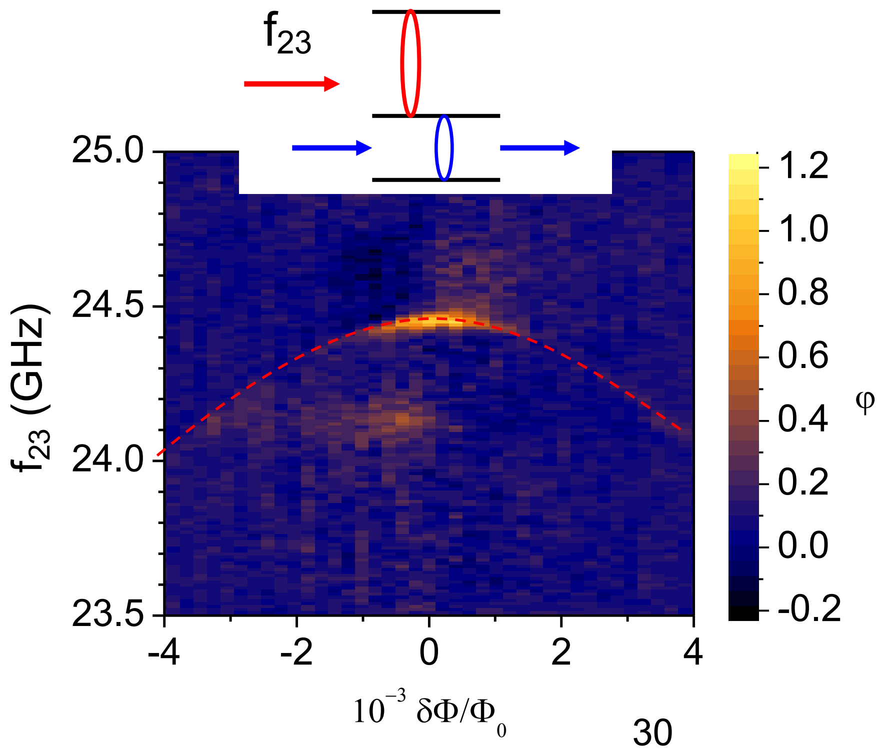


1 → 3 is allowed

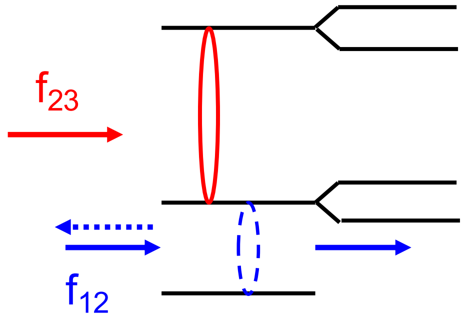


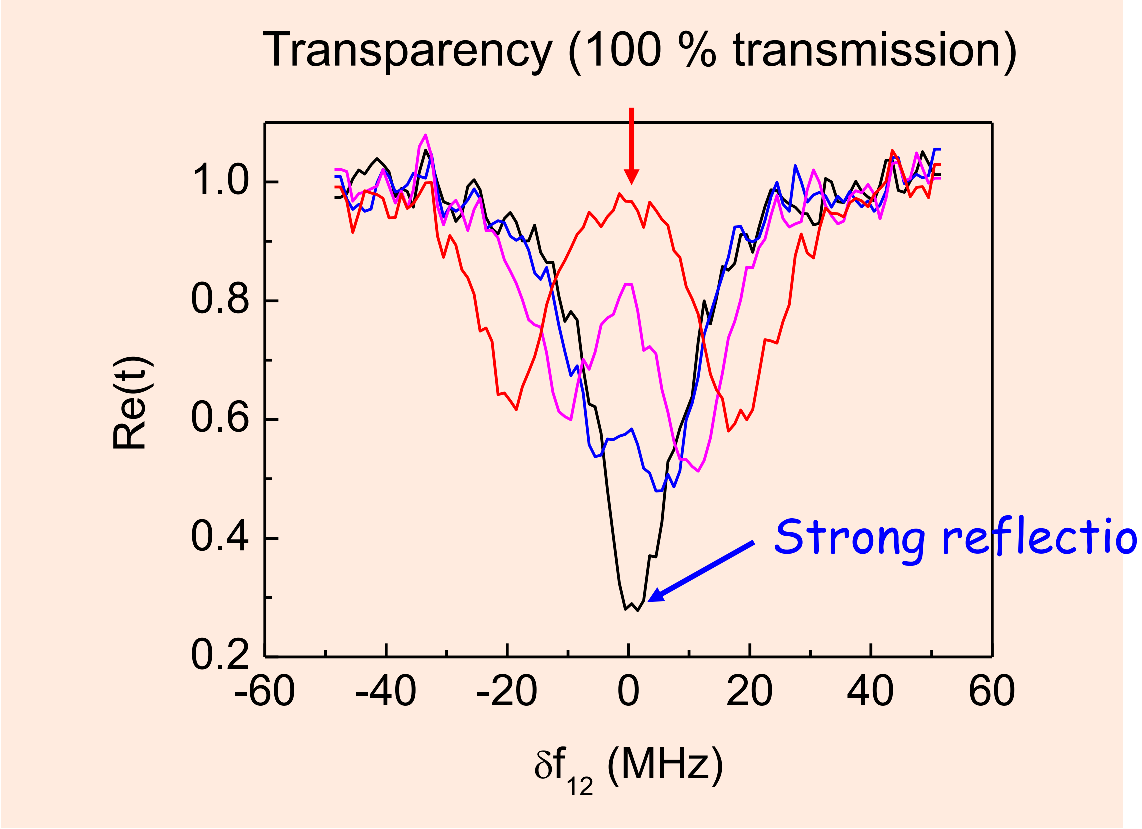


Transmission coefficient at different driving conditions

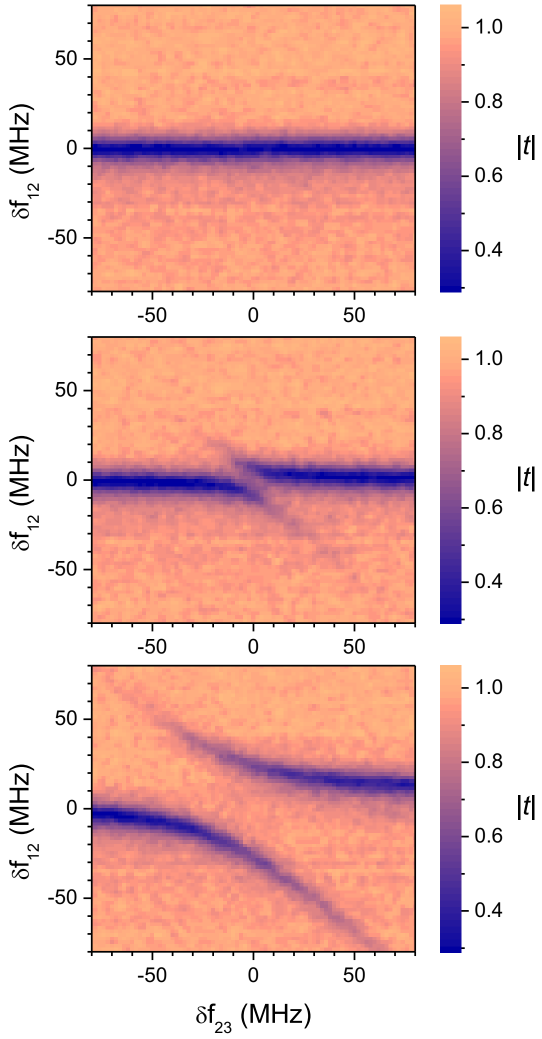


Electromagnetically induced transparency



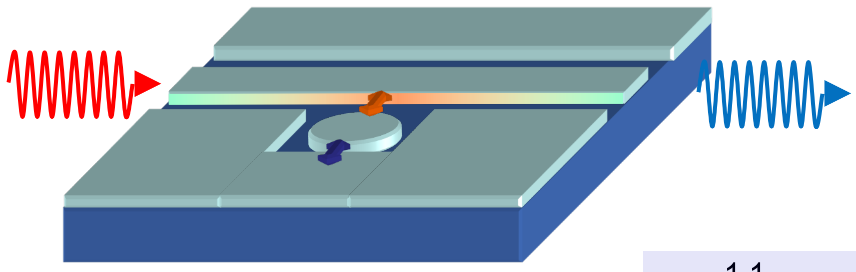


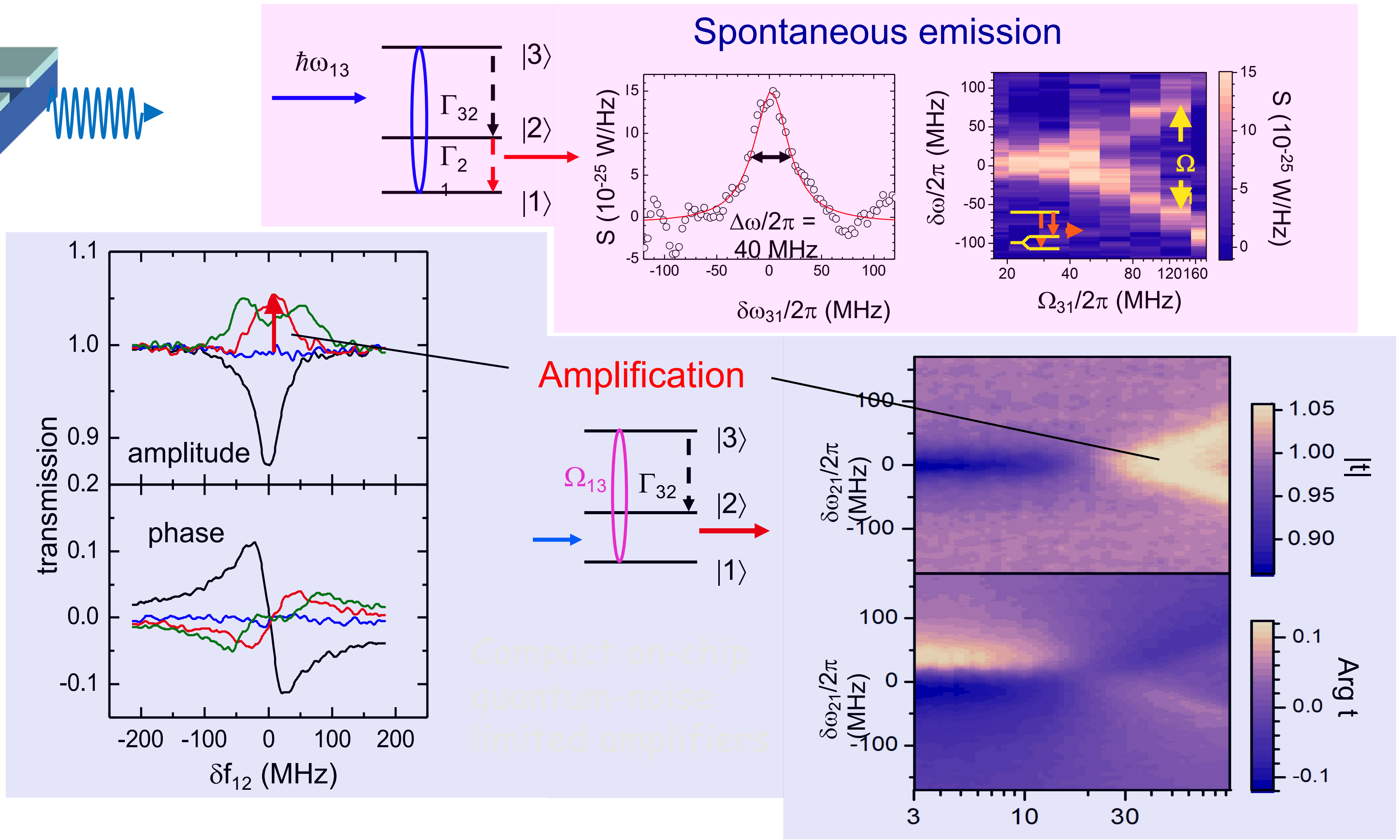
On-chip switchers, computation



*A. Abdumalikov, **O. V. Astafiev**, A. M. Zagoskin, Yu. A. Pashkin, T. Yamamoto, K. Inomata, Y. Nakamura, and J.S. Tsai. Electromagnetically Induced Transparency on a Single Artificial Atom. Phys. Rev. Lett 104, 193601 (2010).*

Ultimate (single atom) on-chip quantum amplifier

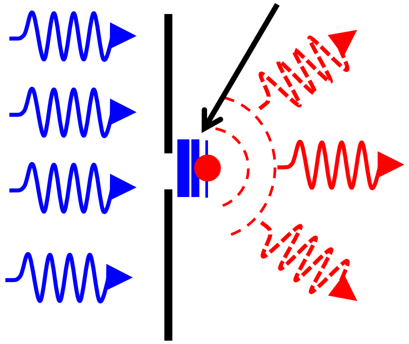


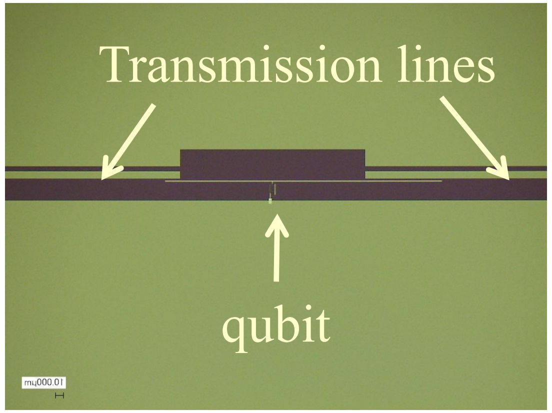


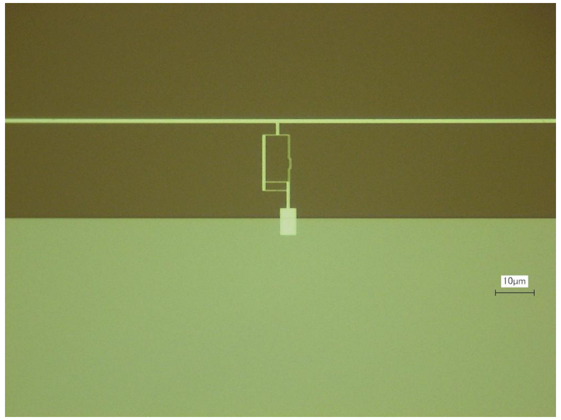
__O. Astafiev__, A. A. Abdumalikov, A. M. Zagoskin, Yu. A. Pashkin, T. Yamamoto, K. Inomata, Y. Nakamura, and J. S. Tsai. Ultimate on-chip quantum amplifier. [Phys. Rev. Lett](#) 104, 183603 (2010).

Tunable on-demand single-photon source

Photon can encode information ⇔ quantum simulators with photons => Boson sampling



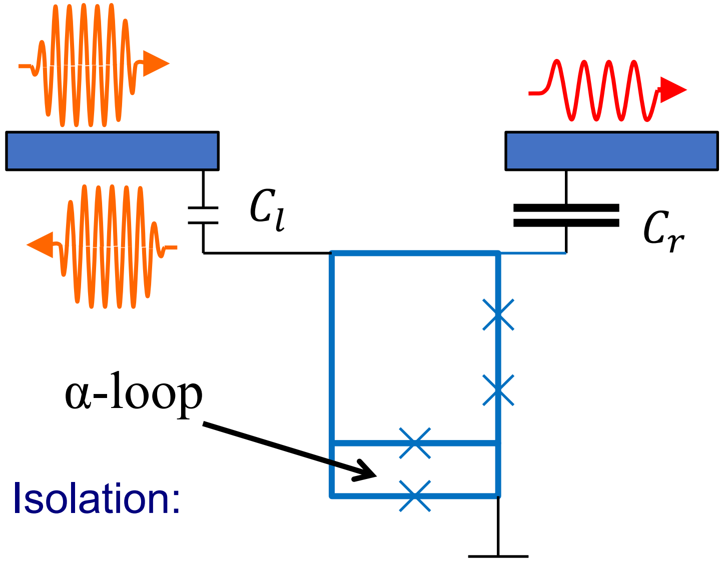




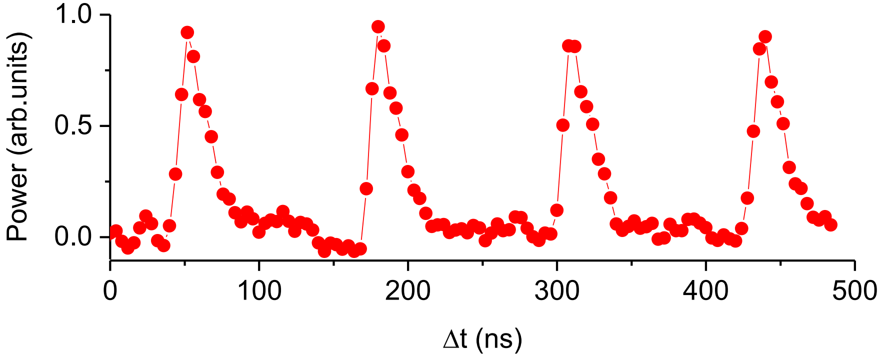
Recently demonstrated photon generation efficiency: > 98%

Photon mission to the right line is proportional to

$$1-\left(\frac{C_l}{C_r}\right)^2$$

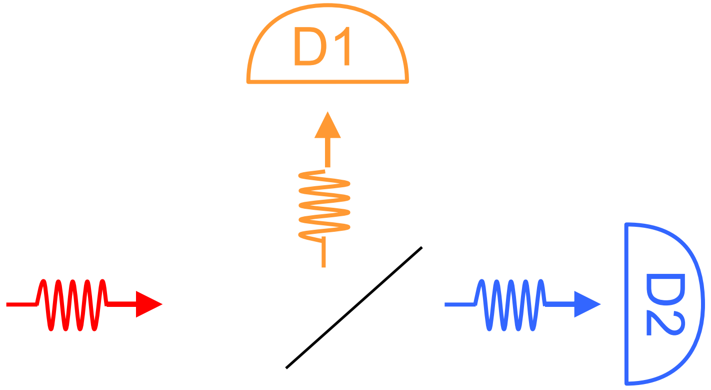


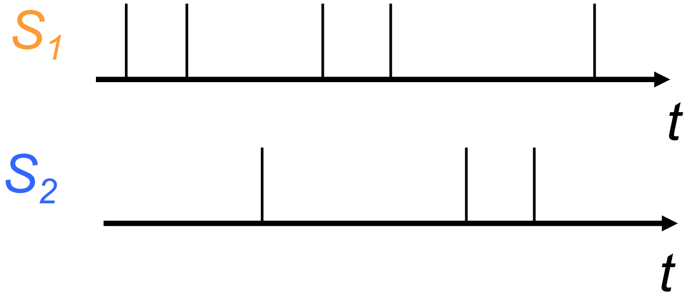
Averaged photons



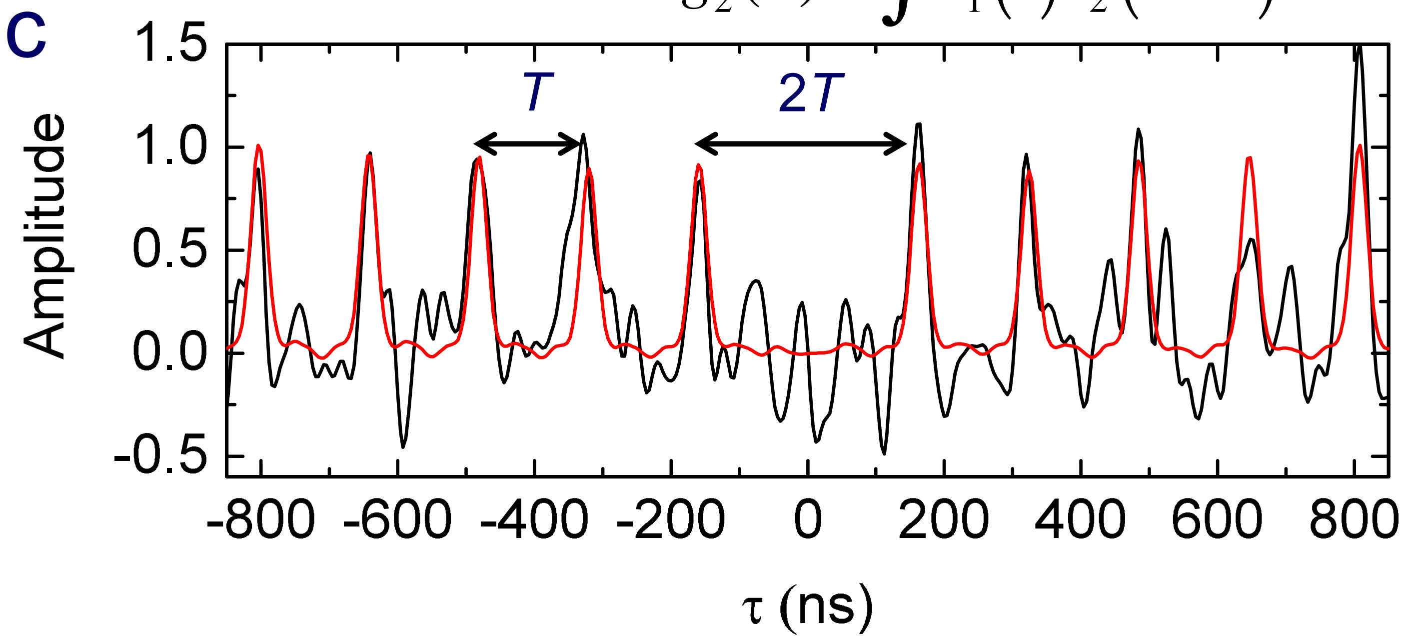
Nature Communications **7**, 12588 (2016).

Second order correlation function





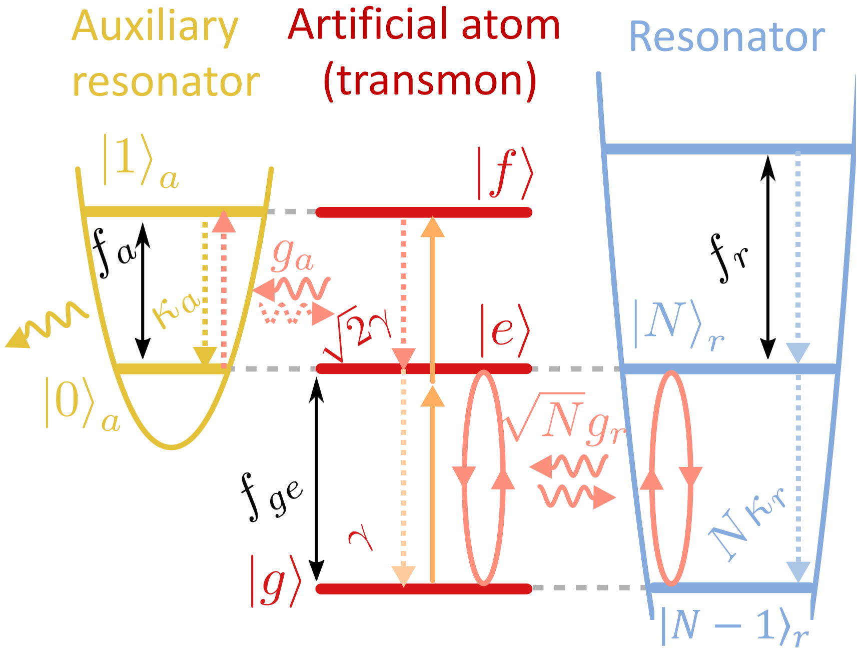
$$g_2(\tau) = \int S_1(t) S_2(t+\tau)\, dt$$



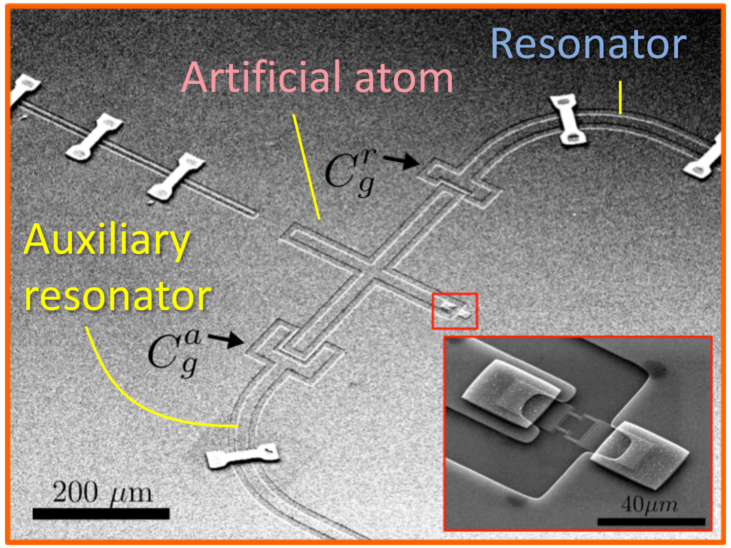
10^{10} traces: Took a month of averaging!

Quantum engineering: Lasing with an artificial atom

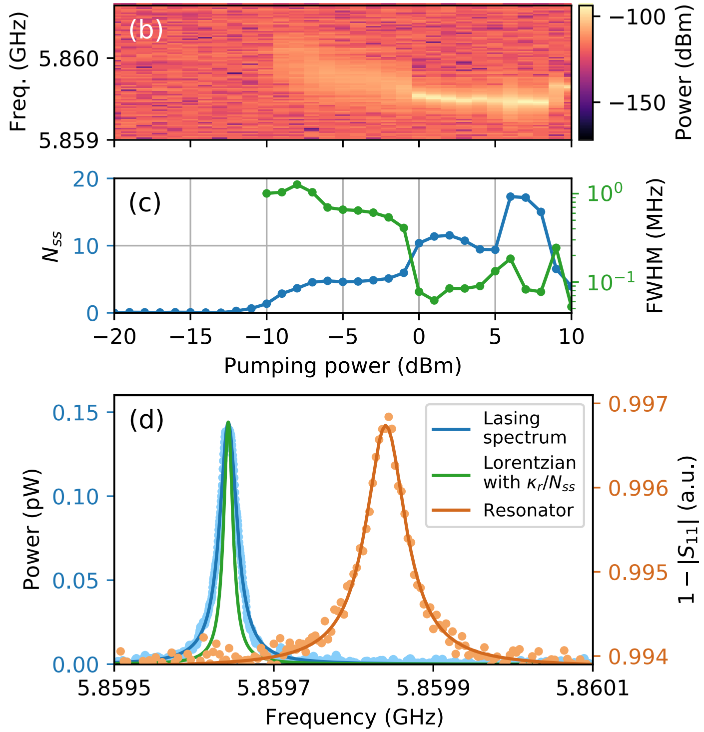
Atomic transition $|f\rangle \rightarrow |e\rangle$ is enhanced via an auxiliary resonator



Circuit



Experimental data



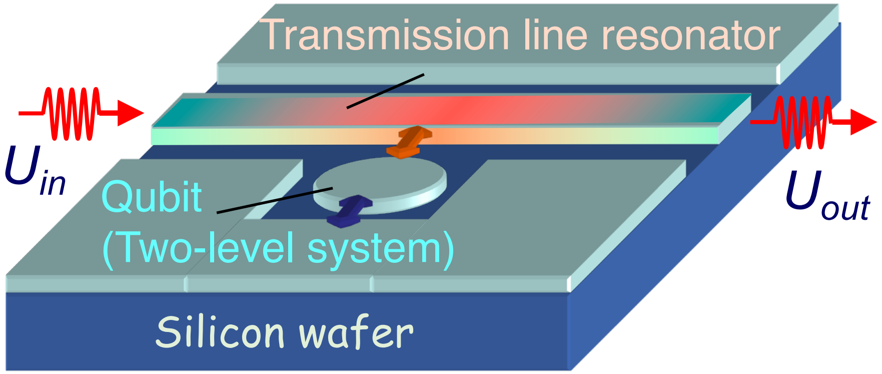
Sokolova, A. A., Fedorov, G. P., Il'ichev, E. V., & Astafiev, O. V. (2021). Single-atom maser with an engineered circuit for population inversion. *Physical Review A*, *103*(1), 013718

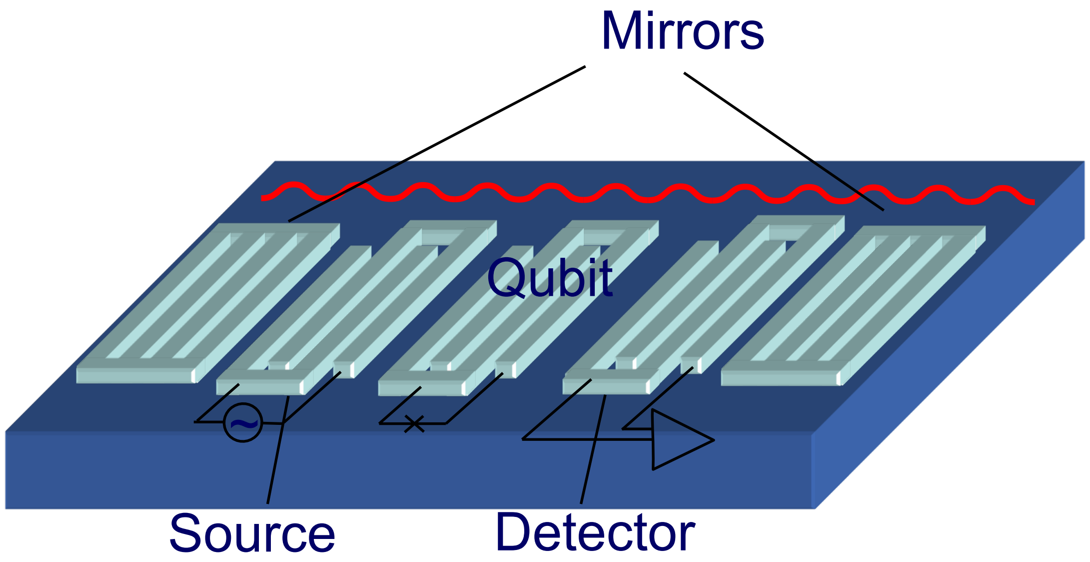
Quantum Acoustodynamics
Coupling of a superconducting two-level system to a quantized vacuum mode of a surface acoustic wave (SAW) resonator

A. N. Bolgar, J. I. Zotova, D. D. Kirichenko, I. S. Besedin, A. V. Semenov, R. S. Shaikhaidarov, and O. V. Astafiev. Quantum regime of a two-dimensional phonon cavity. *Phys. Rev. Lett.* 1**20**, 223603 (2018).

Why Acoustics?

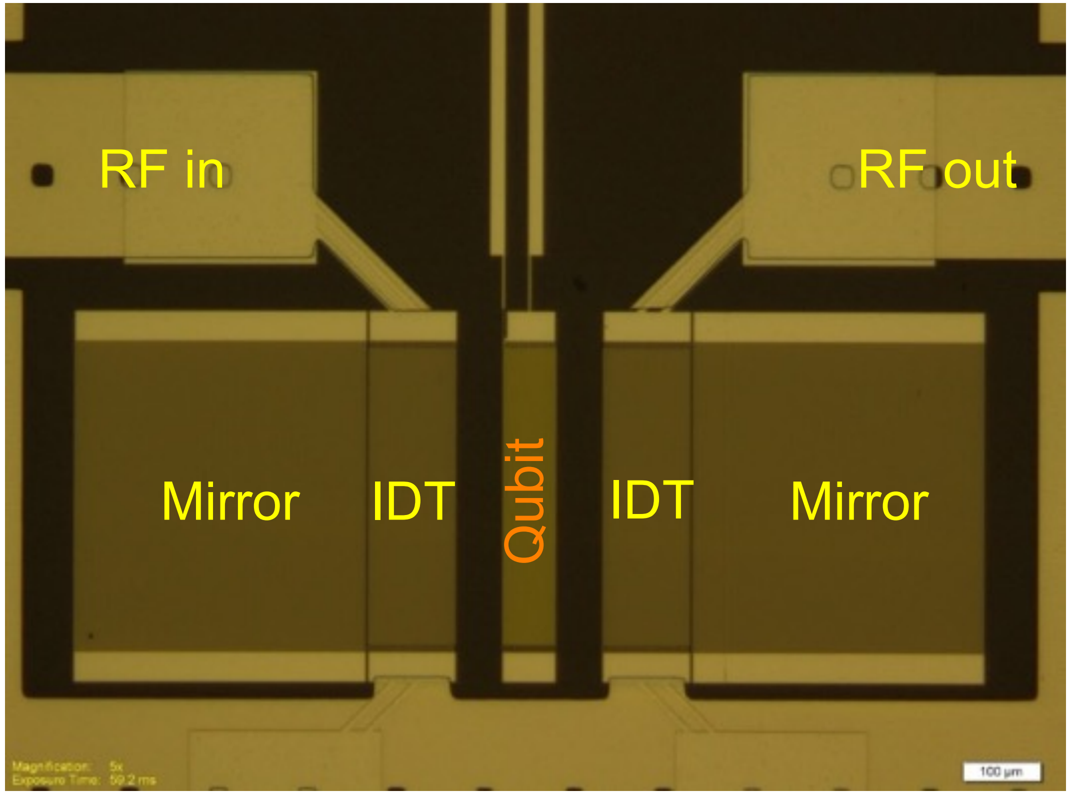
Cavity and Circuit QED



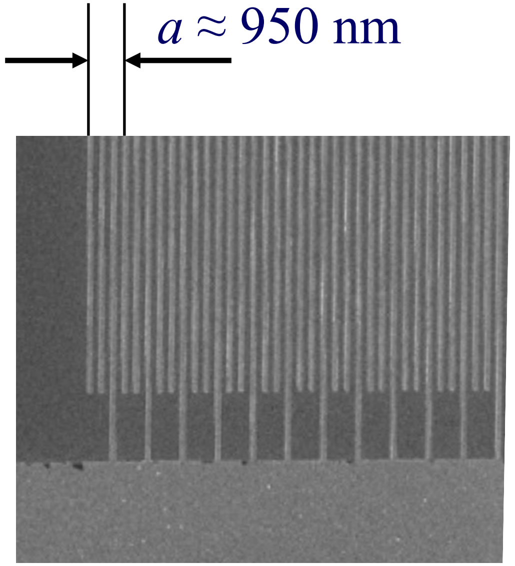


- Quantum mechanics becomes true quantum mechanics
- New physics
- Speed of sound 3000 m/s => compact elements
- 2D-geometry

Device geometry



Split gate geometry



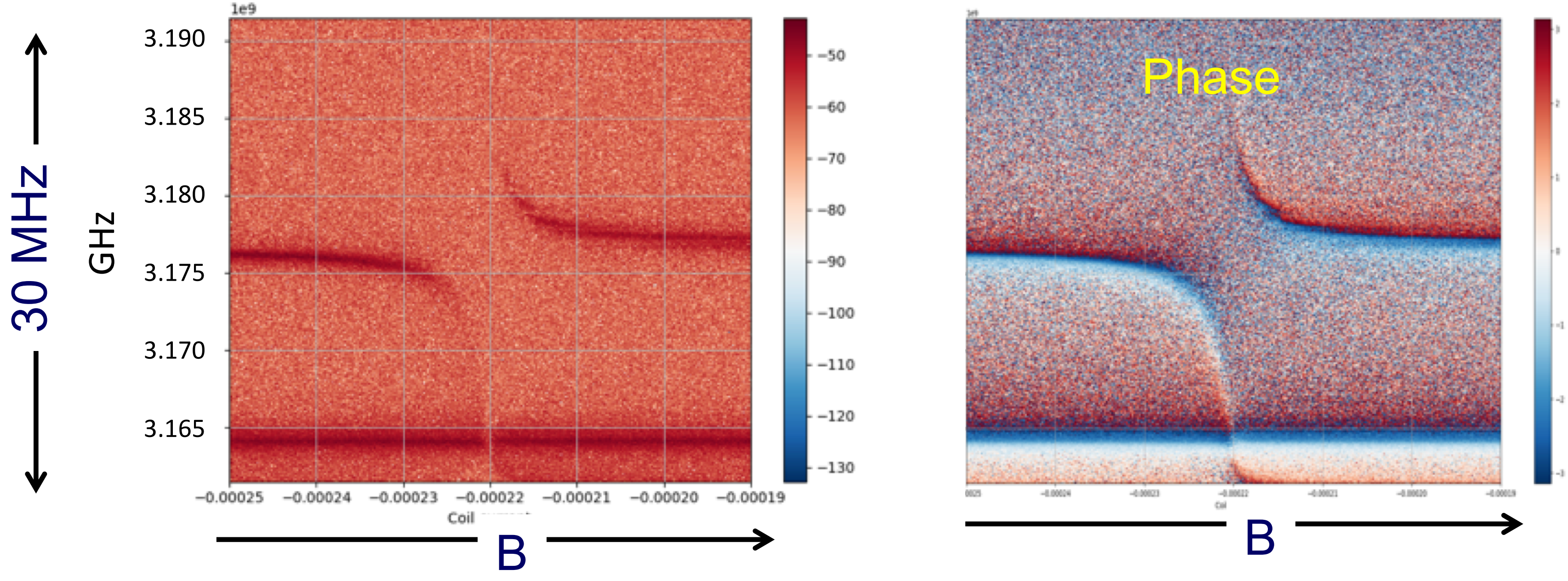
Technologically extremely challenging

Interaction between an artificial atom and a SAW resonator

Interaction of acoustic resonator with a superconducting artificial atom

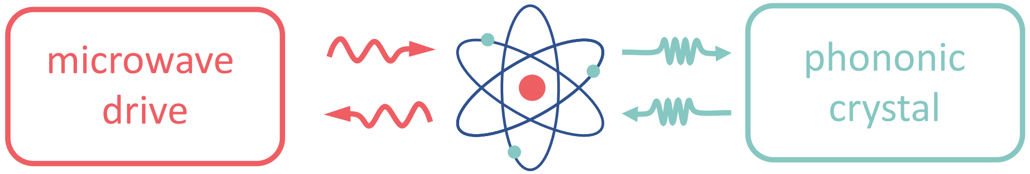
$$H_{JC} = -\frac{\Delta E}{2}\sigma_z + \hbar\omega_r b^\dagger b + g\left(b\sigma^+ + b^\dagger\sigma^-\right)$$

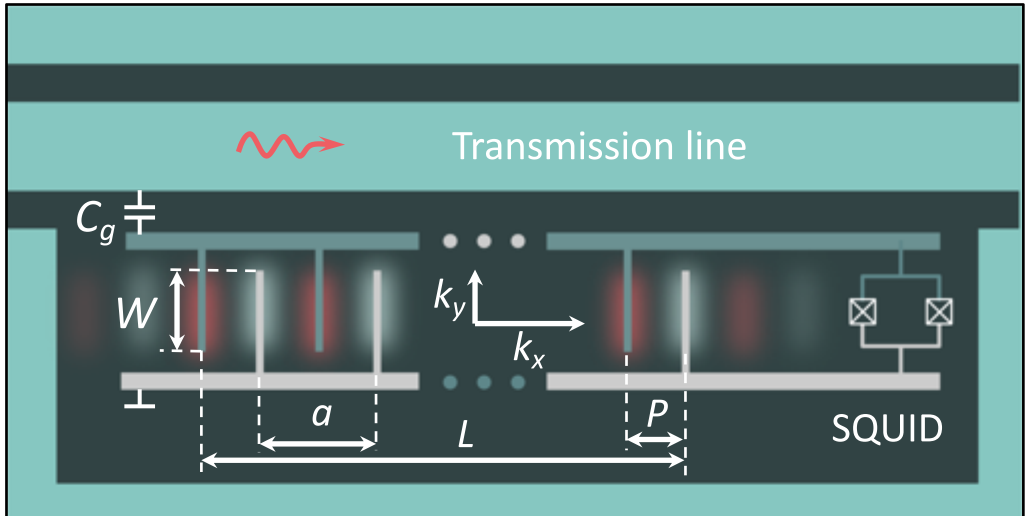
$b^\dagger$ (b) – phonon creation (annihilation) operators

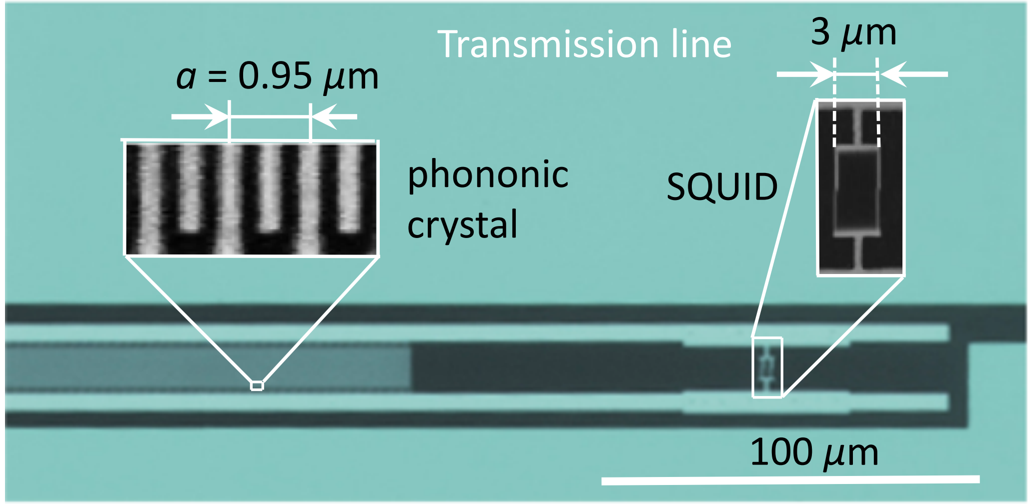


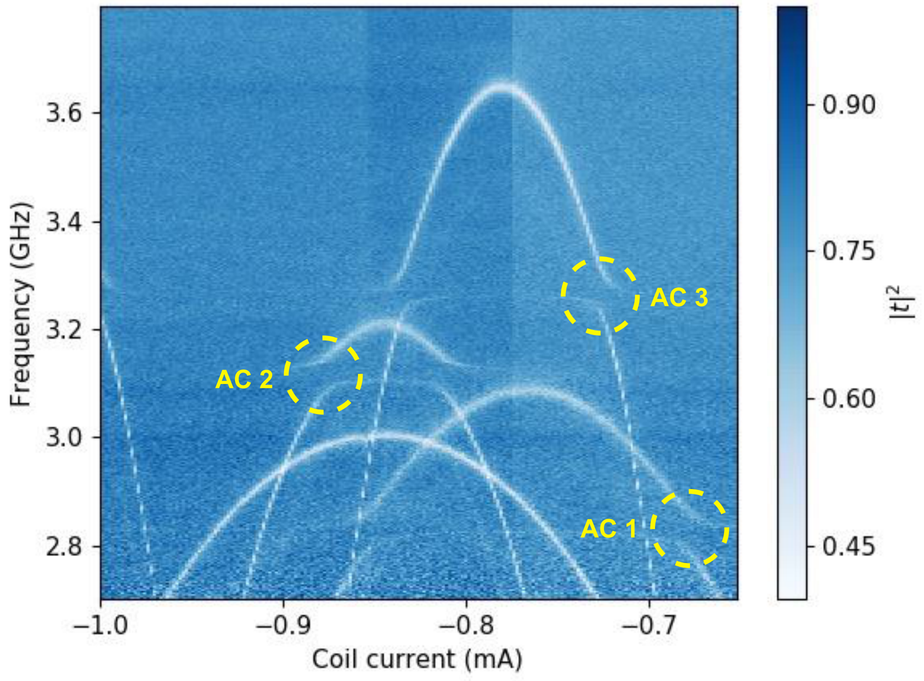
Coupling strength: $2g$ = 26 MHz

A. N. Bolgar, J. I. Zotova, D. D. Kirichenko, I. S. Besedin, A. V. Semenov, R. S. Shaikhaidarov, and O. V. Astafiev. Quantum regime of a two-dimensional phonon cavity. *Phys. Rev. Lett.* 1**20**, 223603 (2018).

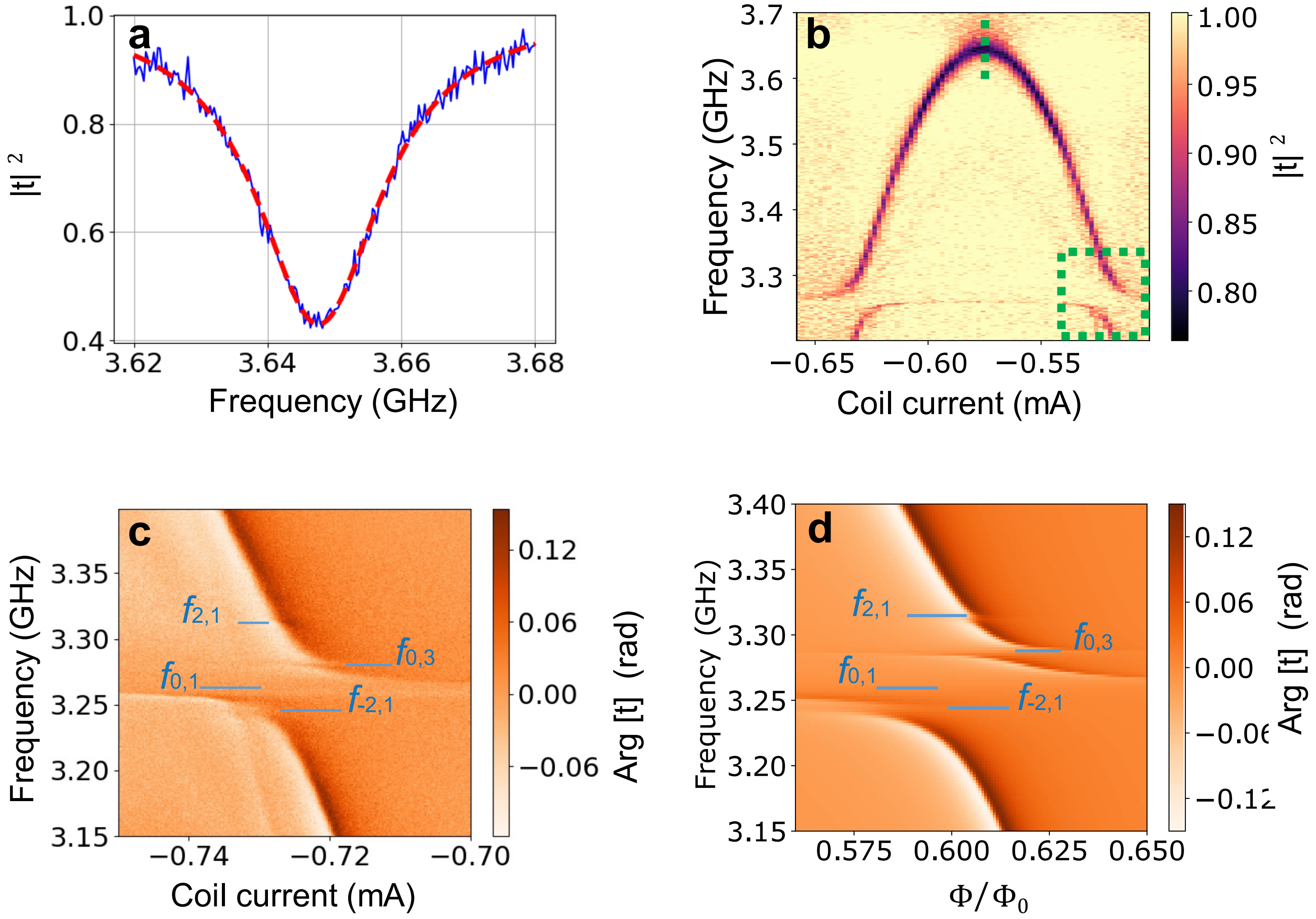

microwave drive
phonic crystal


Transmission line
C_g
W
k_y
k_x
a
L
P
SQUID

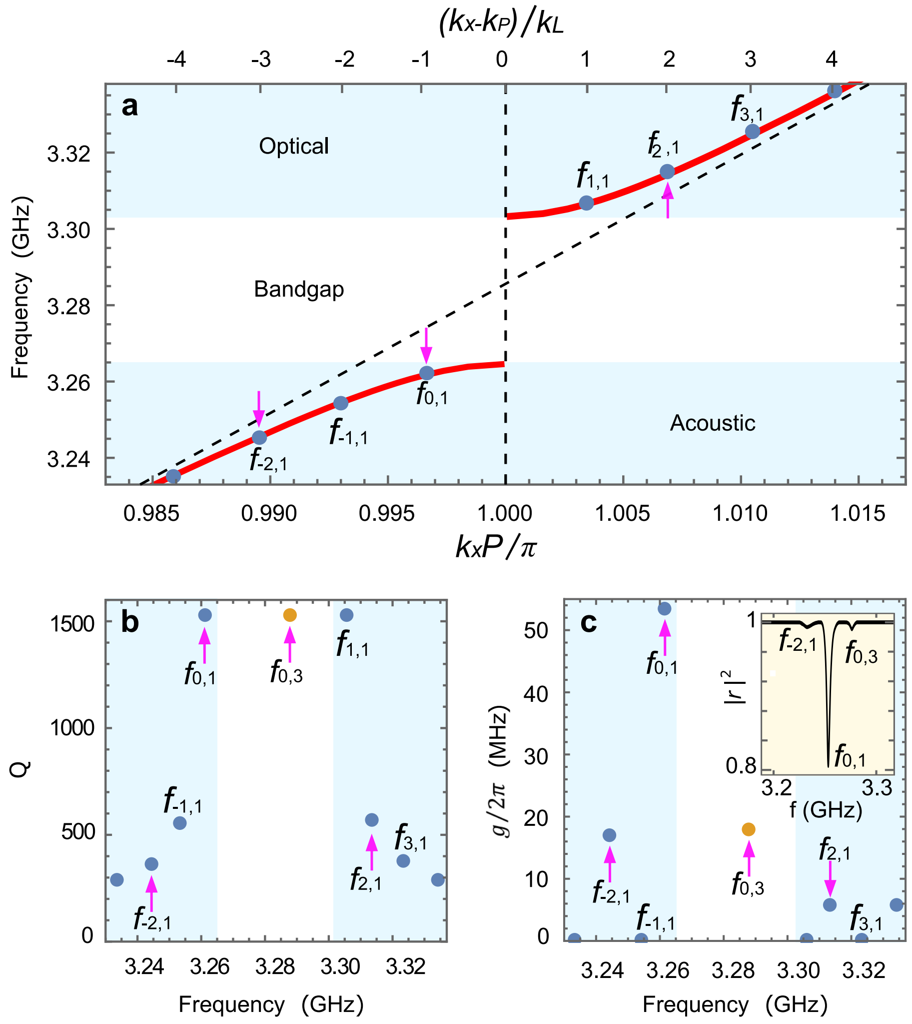

Transmission line
a = 0.95 μm
3 μm
phononic crystal
SQUID
100 μm

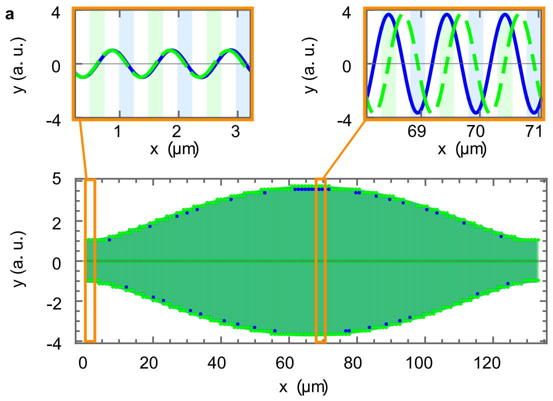

Frequency (GHz)
Coil current (mA)
$|t|^2$
AC 1
AC 2
AC 3

Spectra


a
|t| 2
Frequency (GHz)
b
Frequency (GHz)
Coil current (mA)
|t| 2
c
Frequency (GHz)
Coil current (mA)
Arg [t] (rad)
f2,1
f0,1
f0,3
f-2,1
d
Frequency (GHz)
Φ/Φ0
Arg [t] (rad)
f2,1
f0,1
f0,3
f-2,1

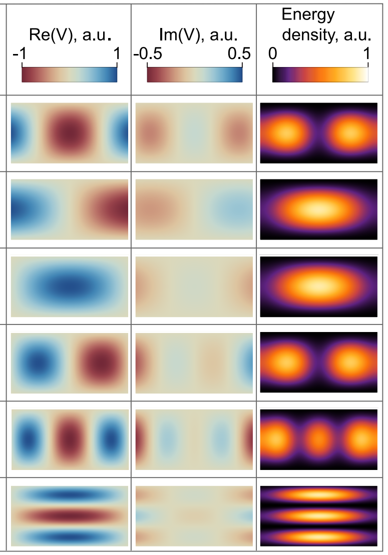
Phononic crystal modes





b

Mode	$k_x-\frac{\pi}{P}$	f (GHz)	$\frac{g}{2\pi}$ (MHz)
2,1	$2k_L$	3.313	6
1,1	k_L	3.306	0
0,1	$-k_L$	3.262	53
-1,1	$-2k_L$	3.253	0
-2,1	$-3k_L$	3.244	16
0,3	$-k_L$	3.287	18



Coherent Quantum Phase Slip (CQPS)
AC CQPS effect

- *Nature* **484**, no. 7394 (2012): 355-358.
- *Nature Physics* **14**, no. 6 (2018): 590-594.
- *Nature* **608**, 45–49 (2022).

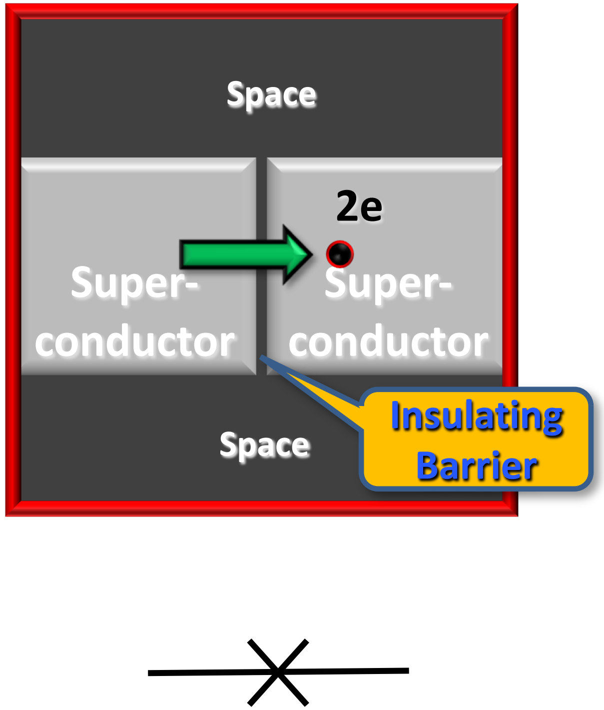
Coherent Phase Slip effect

Josephson Effect: Cooper pair tunneling

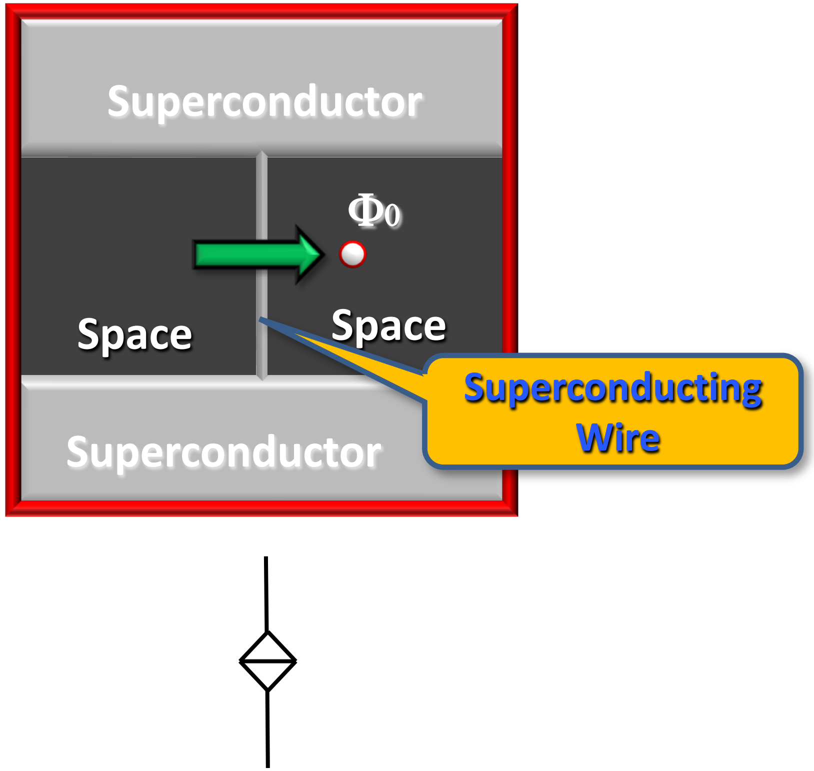
CQPS: magnetic flux quanta tunneling (phase slips)

CQPS is dual to the Josephson effect

Cooper pair tunneling

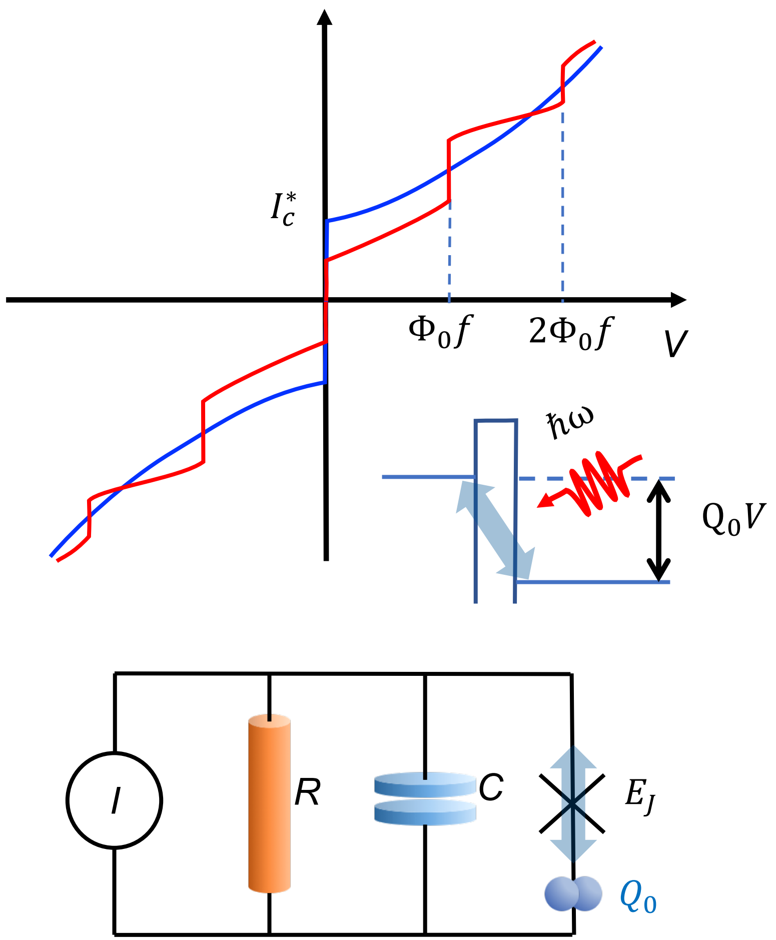


Flux tunneling

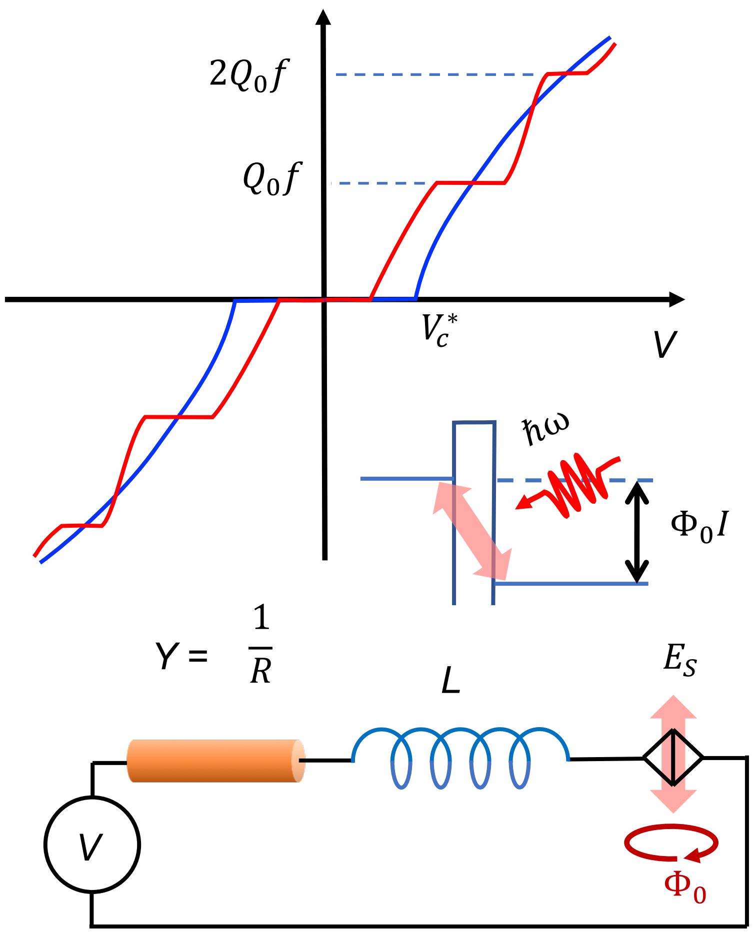


Duality between the Josephson effect and CQPS

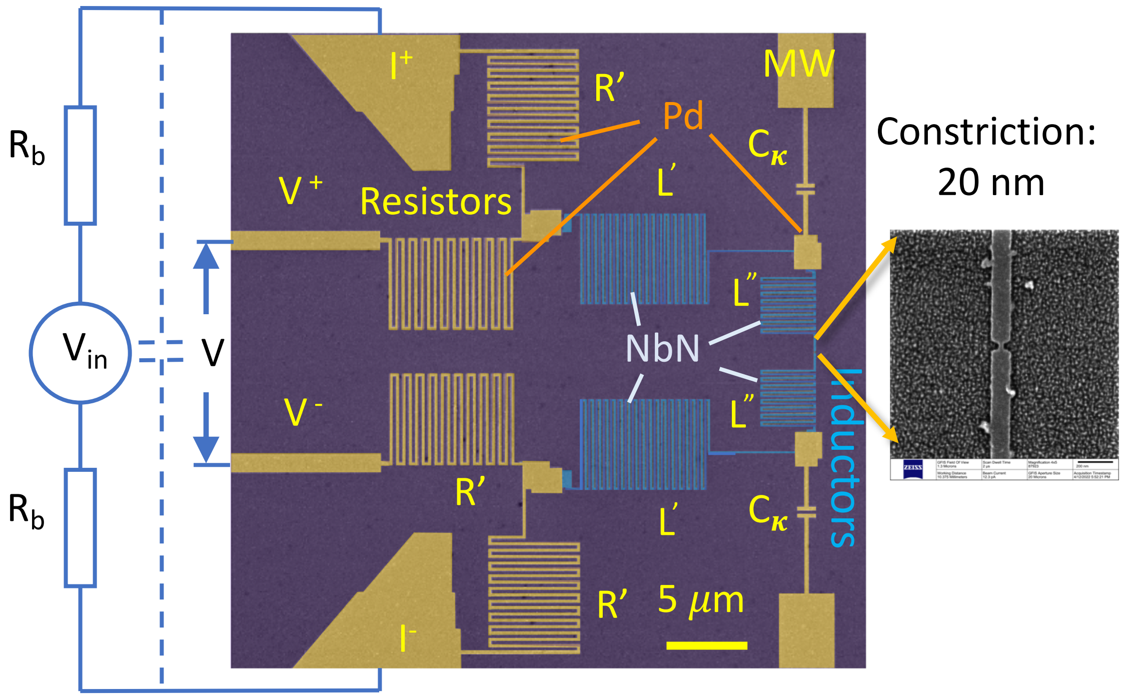
Josephson junction

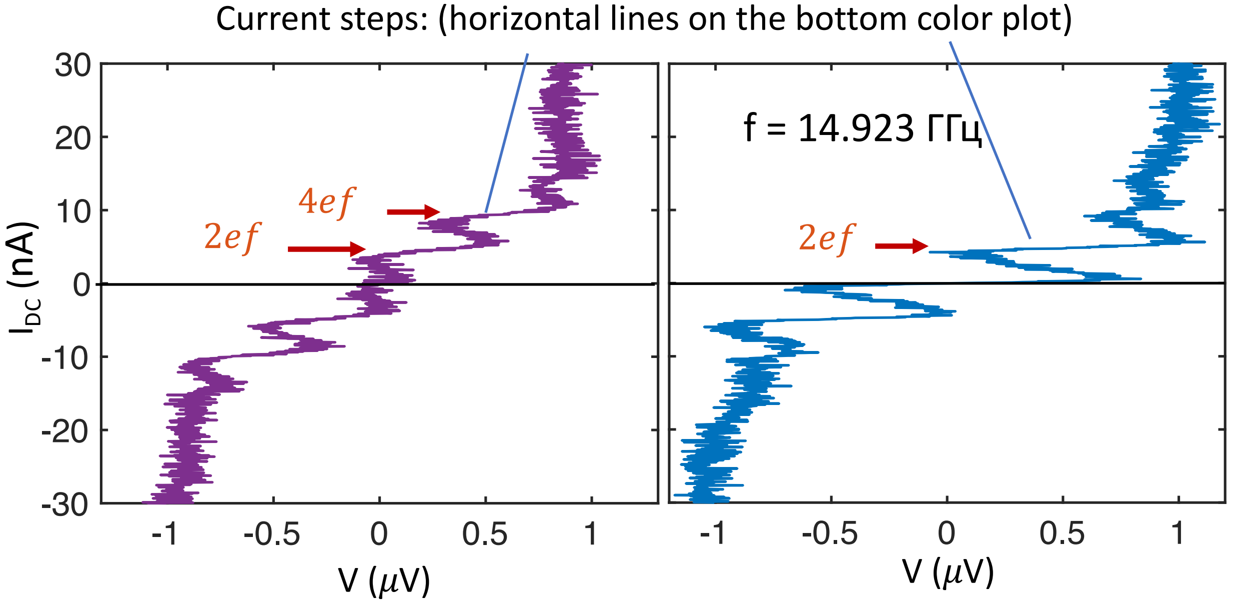


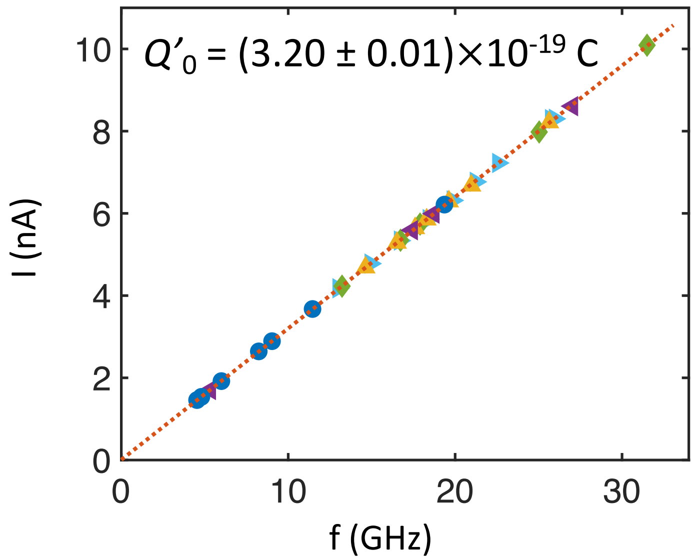
CQPS

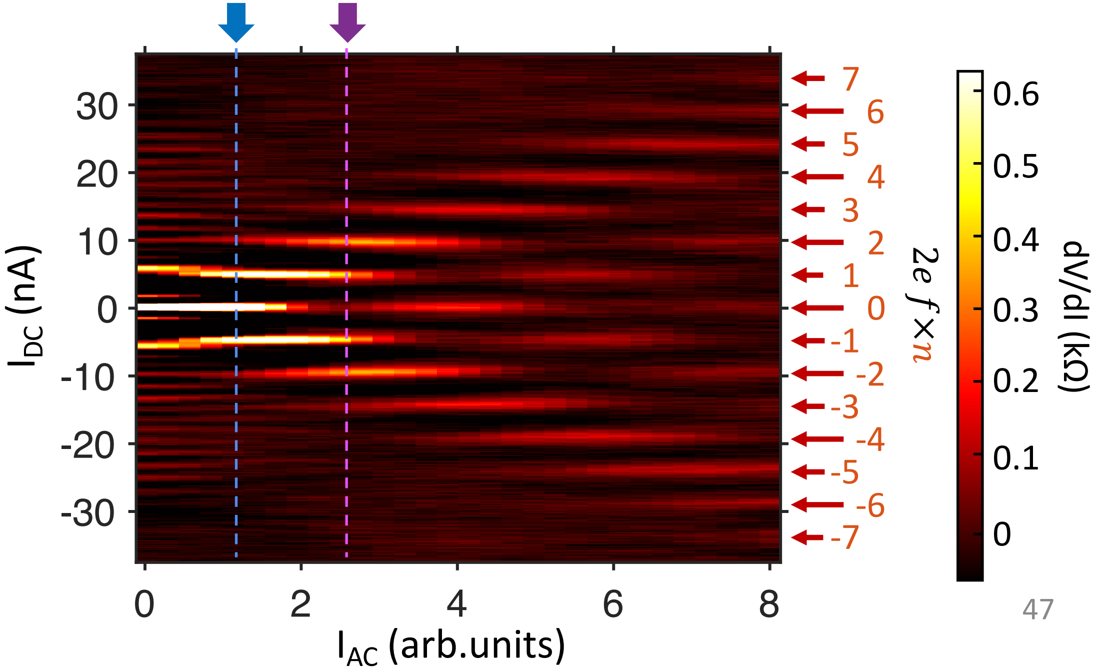


AC CQPS effect









Quantum metrology: current standard

Josephson effect ⇔ Coherent Quantum Phase slip Effect

Shapiro steps:
Voltage standards $V_n = n\Phi_0 f$

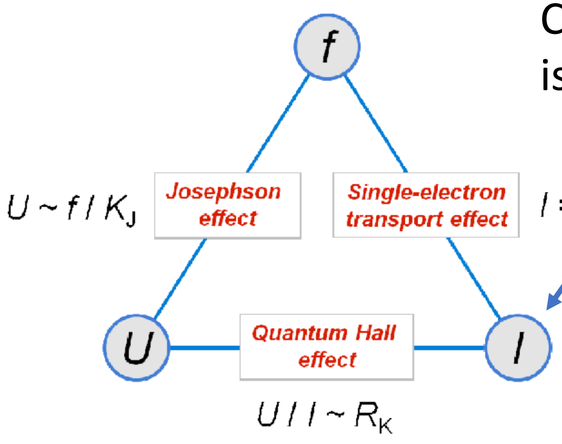
Quantum Hall effect (resistances steps)
Resistance standard $R_n = n\frac{h}{e^2}$

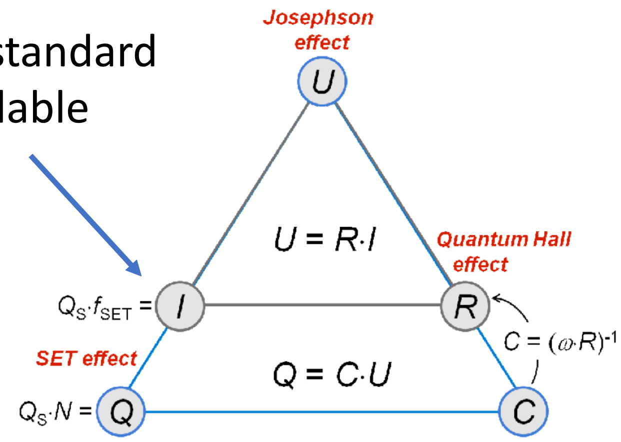
Inverse Shapiro steps:
Current standards: $I_n = nQ_0 f$

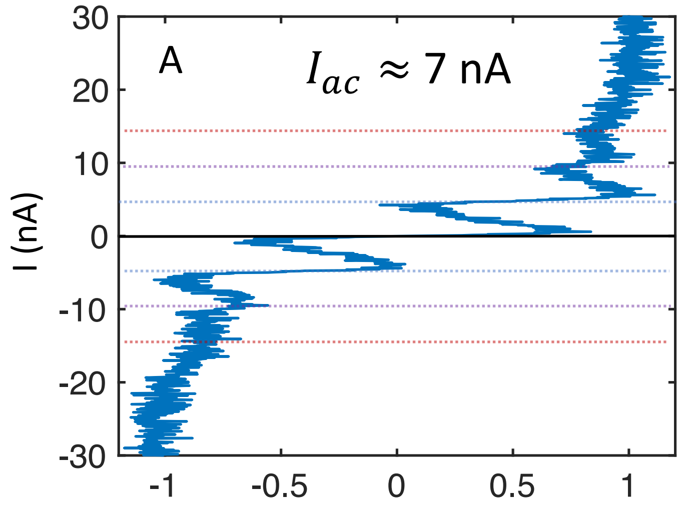
$Q_0 = 2e$

Metrology triangle

Current standard
is unavailable







Conclusion

- Superconducting Quantum Technologies:
  wide range of research directions and applications (MW photonics)
- We are doing a research in the following directions:
  - Quantum processors (simulators)
  - Quantum optics in the MW range
  - Quantum acoustics
  - Quantum sensing and metrology