An artificial atom in a transmission line as quantum sensor

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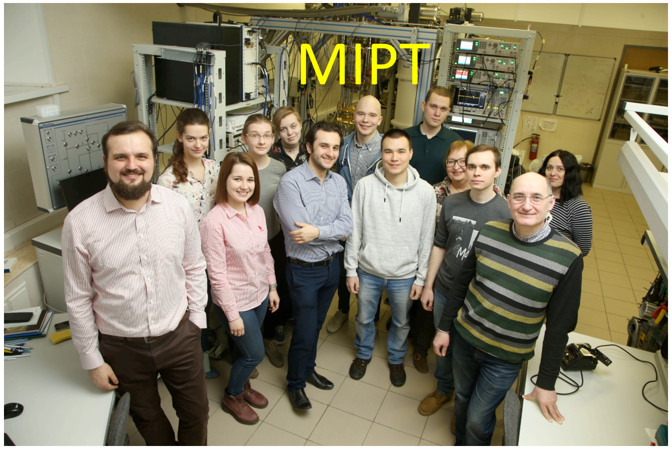
National Physical Laboratory (NPL), UK
Moscow Institute of Physics and Technology (MIPT), Russia

Jukka Pekola birthday anniversary.
Congratulations!

RHUL, NPL, MIPT groups



Labs have been setup starting from 2014:

Cryogenic
- He free dilution fridges up to 10 mK (RHUL, NPL, MIPT)

RHUL Fabrication
- New clean room ~300 m^2 (RHUL)
- EBL: JEOL 8100FS (RHUL)
- Evaporator dedicated for Josephson junctions
- …

Microwave equipment
- Network and spectrum analyzers
- MW, pulse, AW generators
- …

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

Research topics (Superconducting Quantum Technology):
- Quantum optics with artificial atoms
- On-chip quantum electronics
- Quantum meta-materials
- Quantum metrology: Coherent Quantum Phase Slips (CQPS)

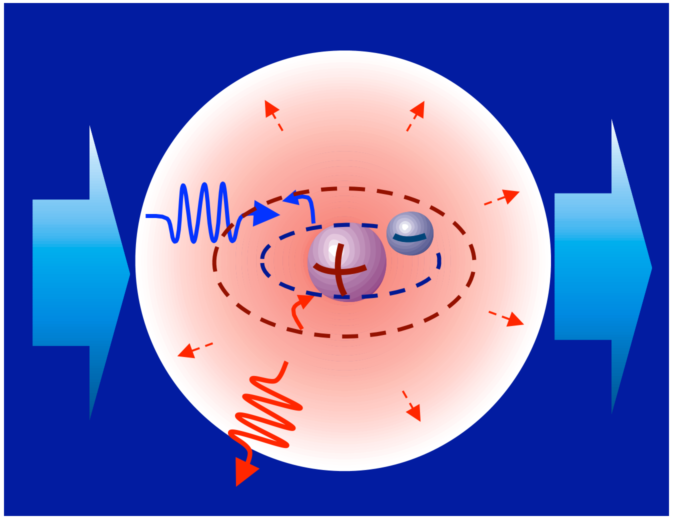
UK Center for Superconducting and Hybrid Quantum Technologies: £10M (EPSRC+RHUL)

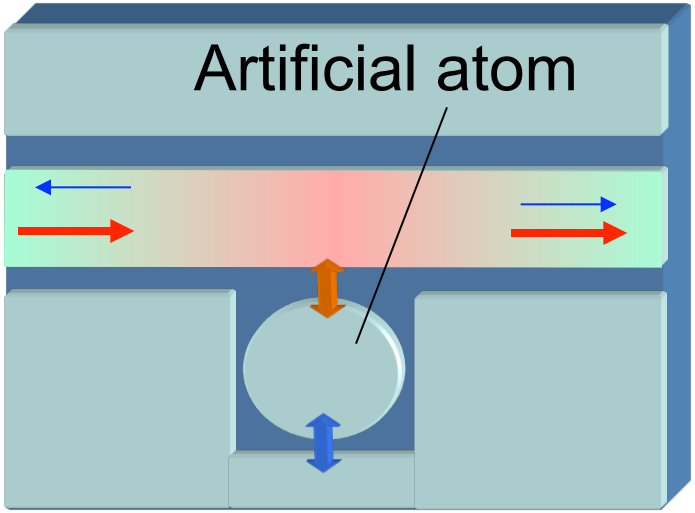
Outline

- Artificial atoms in a 1D transmission line
- Quantum optical effects with a single artificial atom in an open space
- Tunable on-demand single-photon source
- Absolute power meter with a two-level atom
- Quantum wave mixing on a two-level atom
- Quantum mixing on a three-level atom
- Quantum regime of a phonon resonator with SAWs (CQAD)

Atom in open space

Light scattering by an atom





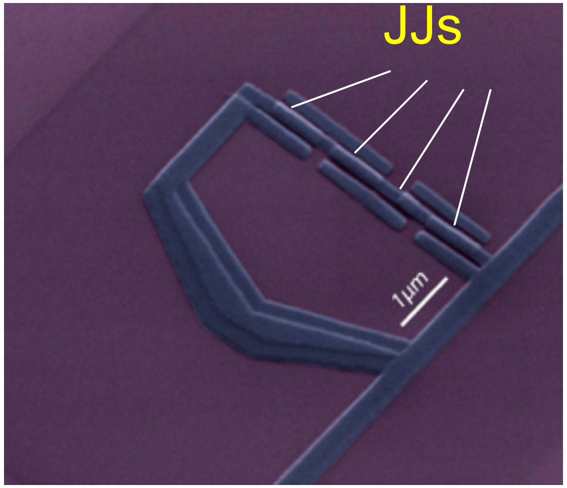
Natural atoms are weakly coupled to electromagnetic waves (weak scattering)

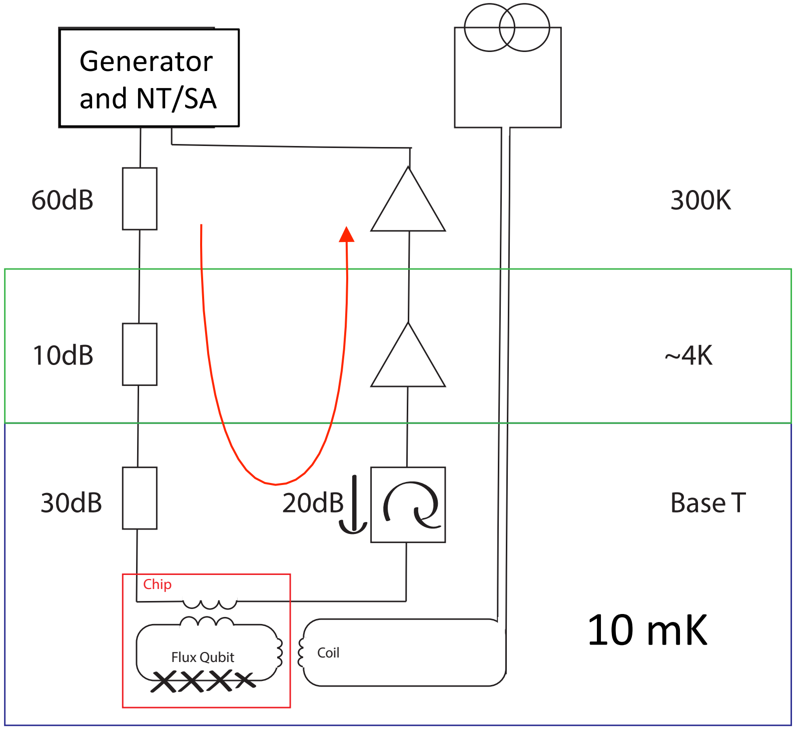
Artificial atoms are strongly coupled to electromagnetic waves

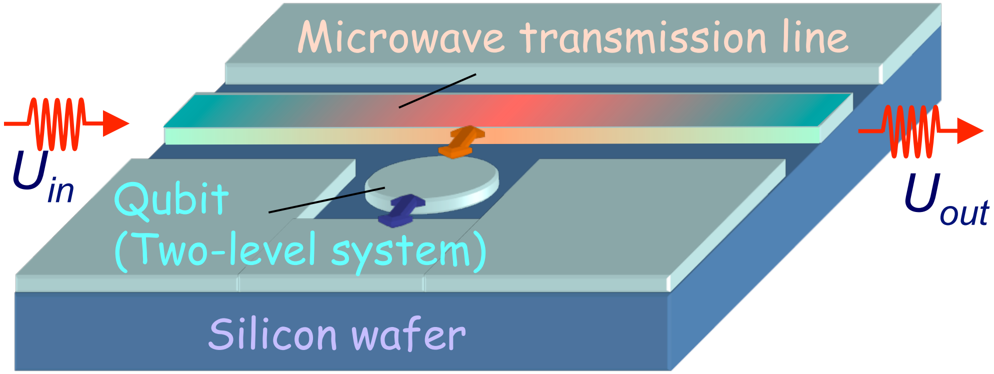
Strong scattering of propagating waves

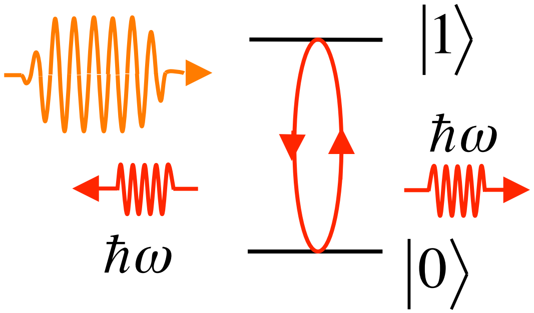
A series of promising applications

Measurements of Artificial Atoms in the open 1D space



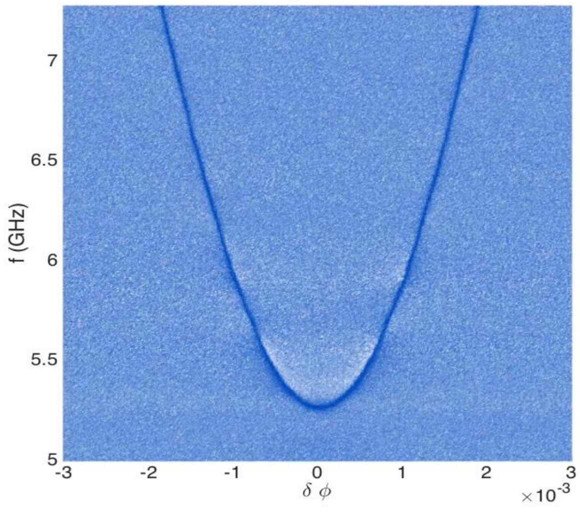


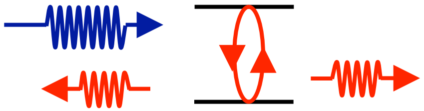




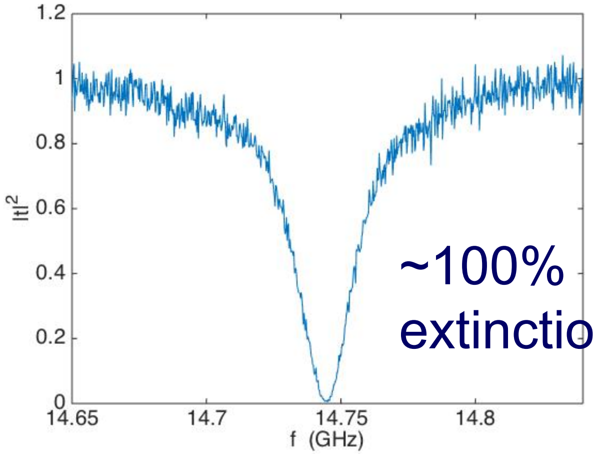
Resonance Fluorescence with a single atom: Elastic and inelastic scattering

Transmission amplitude



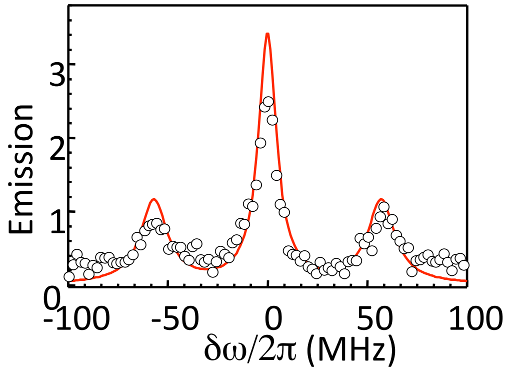


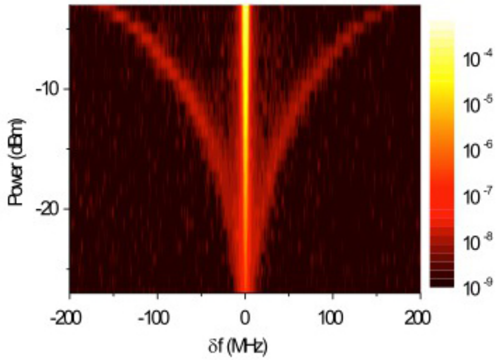
Normalized transmission power



~100% extinction

Inelastic scattering





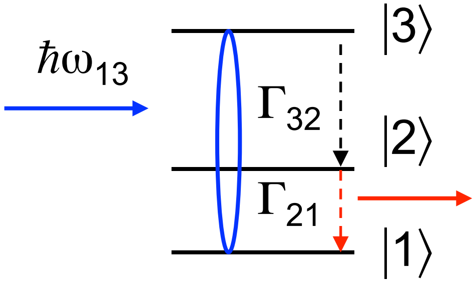
$$I_{emit}(t) = i\frac{\hbar\Gamma}{\phi_p}\langle\sigma^-\rangle e^{-i\omega t}$$

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

⇓

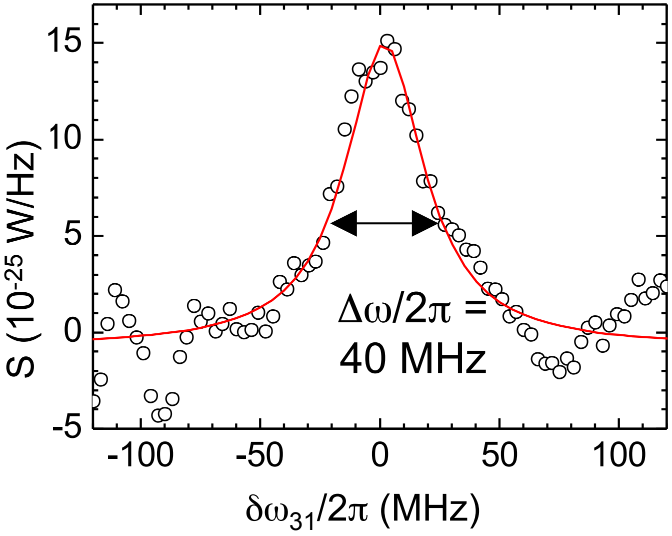
Promising candidate for quantum information processing

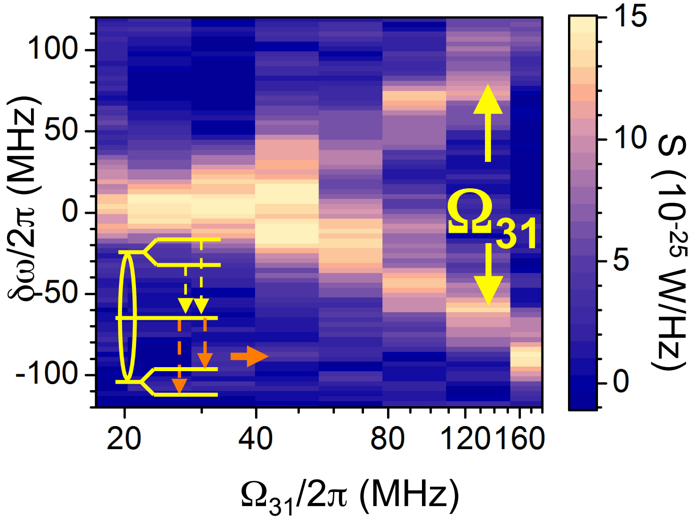
Spontaneous emission



Noise spectral density (*weak driving limit*)

$$S(f) = \frac{\hbar\omega\Gamma_{21}}{2}\frac{\gamma_{21}}{\gamma_{21}^2 + \delta\omega^2}$$

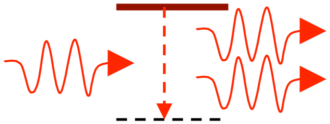


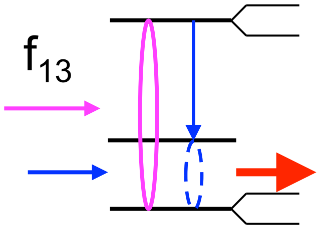


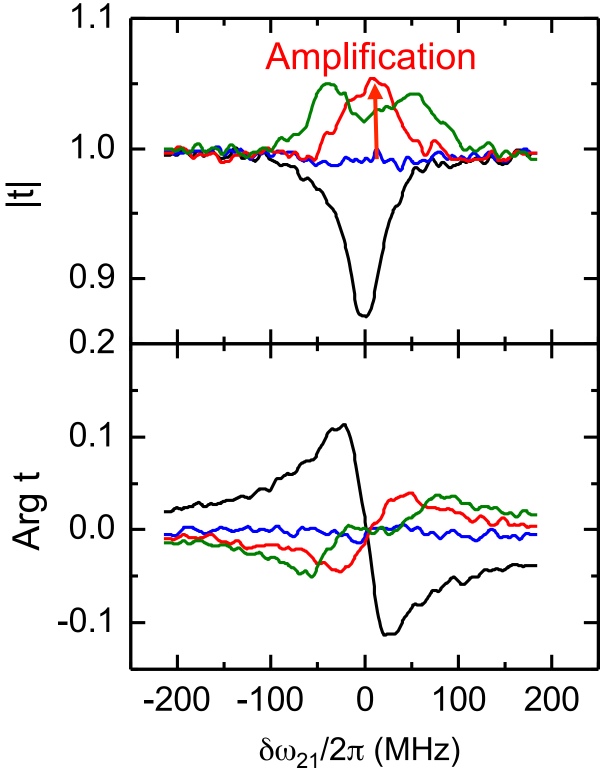
Noise level of the 4K amplifier is 10^{-22} W/Hz!

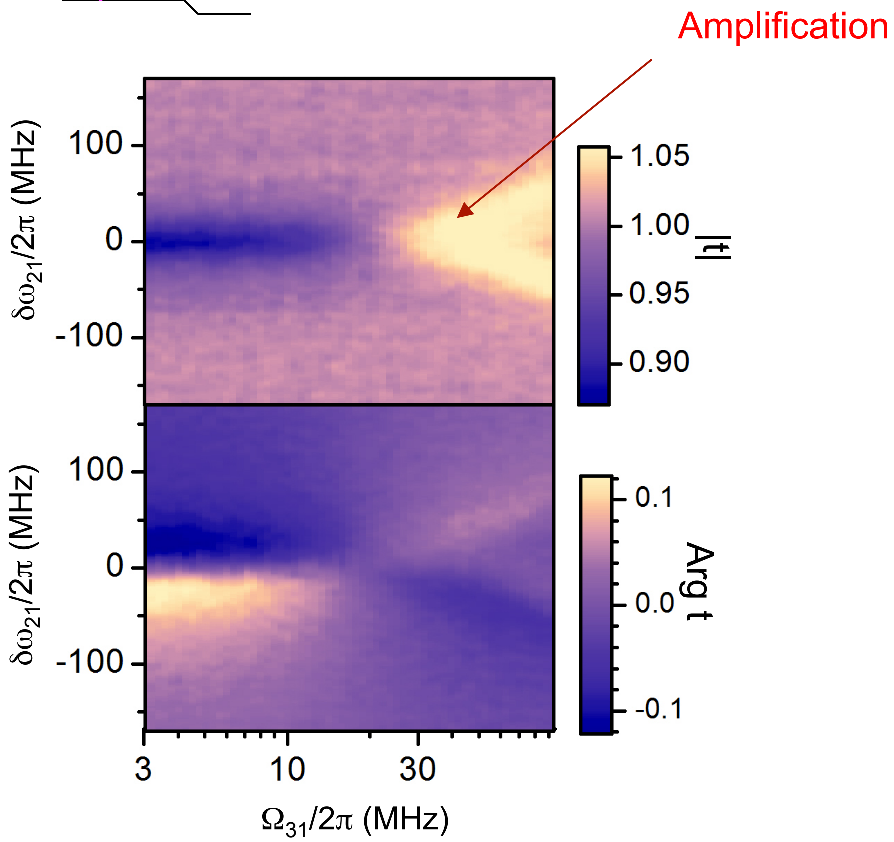
Several lasing schemes have been demonstrated with the artificial atoms

Stimulated emission
(single-atom on-chip quantum amplifier)



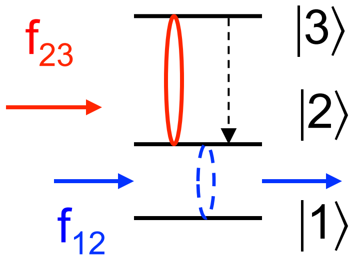





Amplification

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).

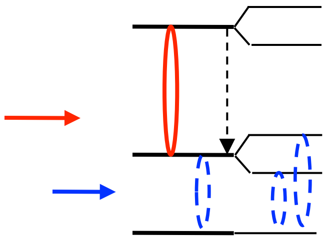
Electromagnetically induced transparency



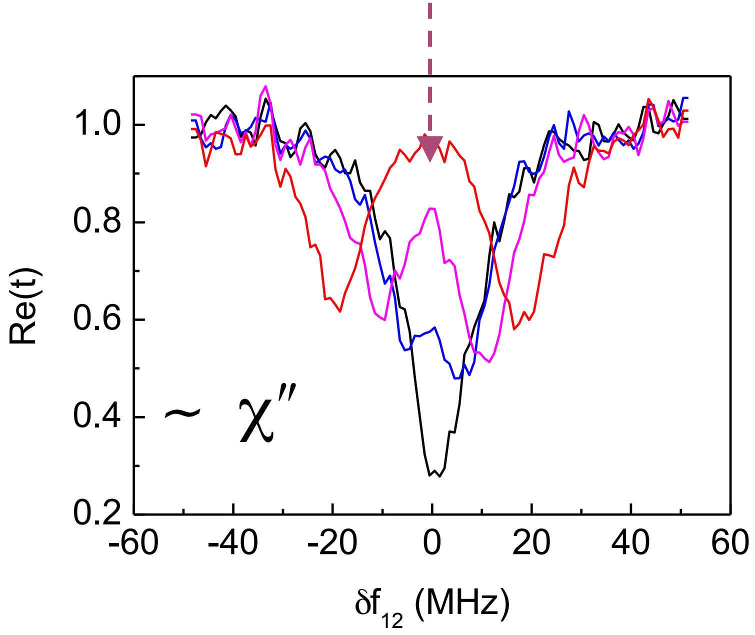
$$\chi = \chi' + i\chi''$$

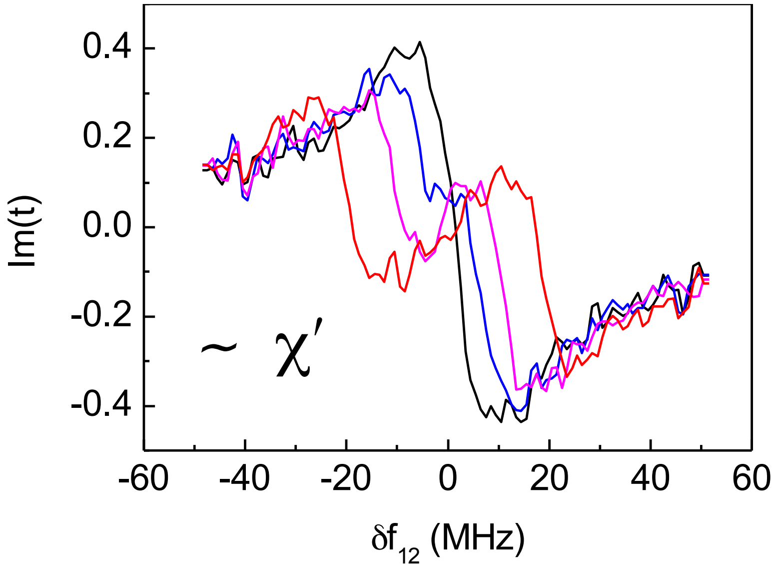
$\alpha|1\rangle + \beta|2\rangle + \gamma|3\rangle$

Dark state (no absorption) $\beta = 0$



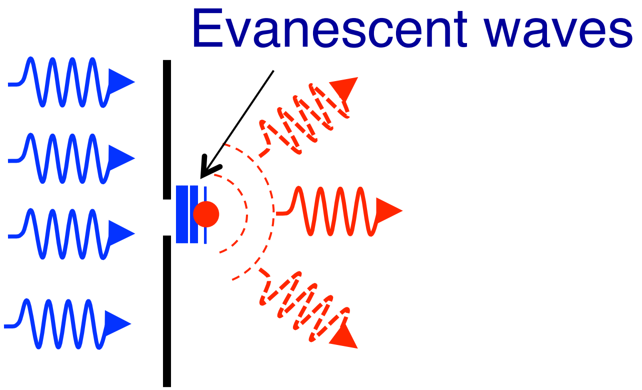
Induced transparency

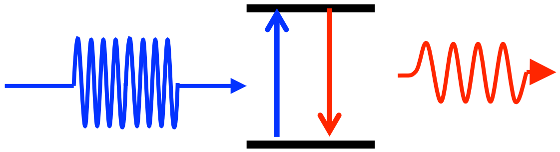


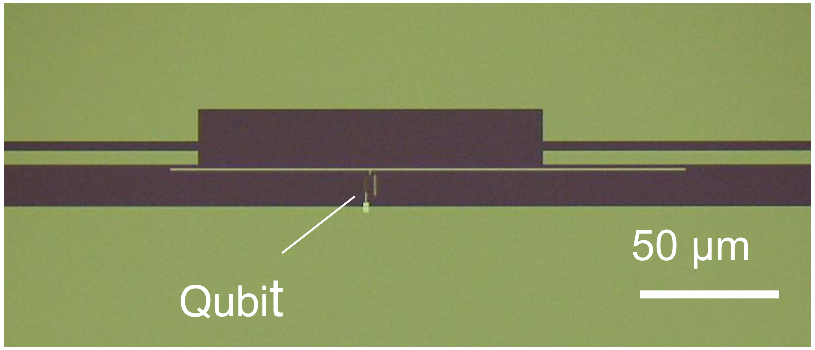


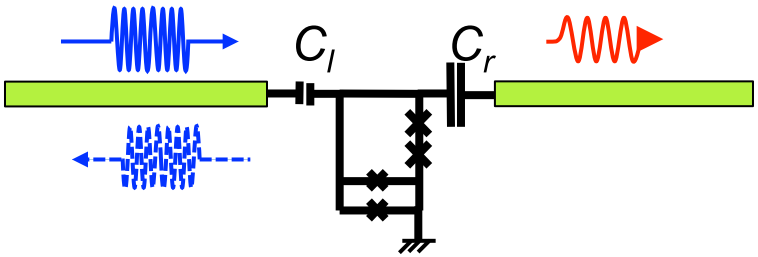
A. A. Abdumalikov, O. V. Astafiev, A. M. Zagoskin, Yu.A. Pashkin, T. Yamamoto, K. Inomata, Y. Nakamura, and J.S. Tsai. Electromagnetically Induced Transparency on a Single Artificial Atom. *Phys. Rev. Lett.* **104**, 193601 (2010).

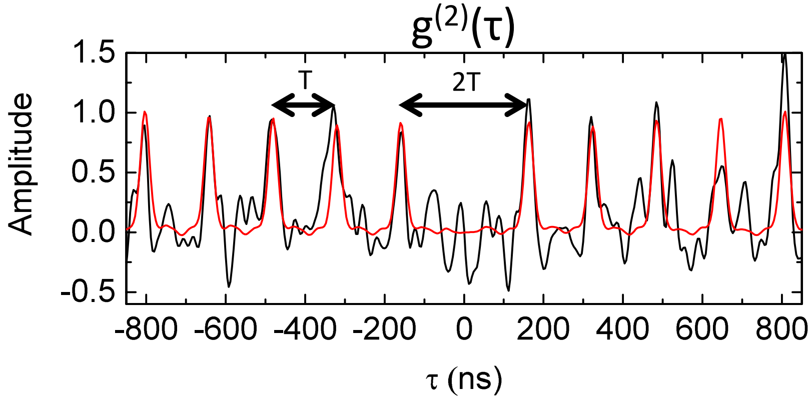
On-demand microwave photon source









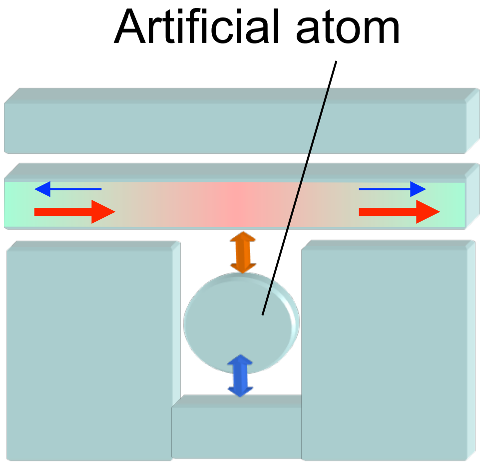


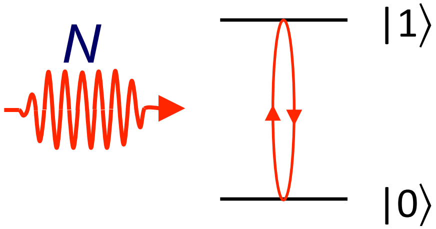
Recently achieved efficiency is 98%

Z. H. Peng, S. E. de Graaf, J. S. Tsai &
O. V. Astafiev. *Nature Comm.* **7**, 12588 (2016)

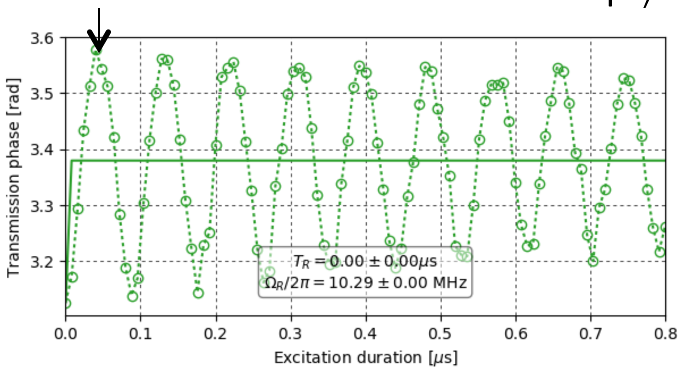
Quantum sensor of power

The artificial atom strongly interacts with the transmitted microwave: All photons interact with the atom





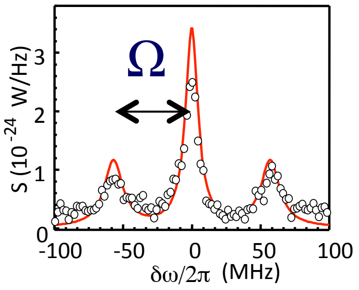
π-pulse



Ω - Rabi frequency => the frequency of probability oscillations

Γ_1 is the atomic relaxation time => photon emission rate

Number of photons in the *π*-pulse is $N = \frac{\Omega}{\Gamma_1}$



In continuous driving regime the power is $P = \frac{\Omega^2}{\Gamma_1}\hbar\omega$

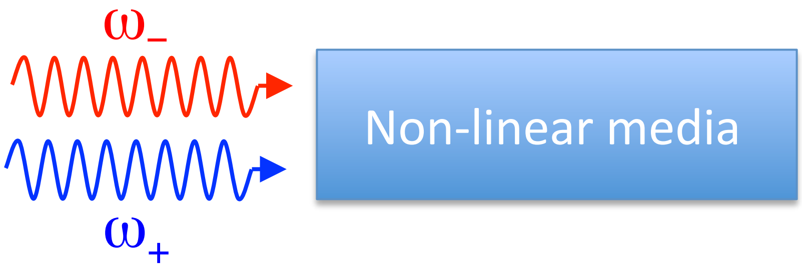
There are no optical analogs

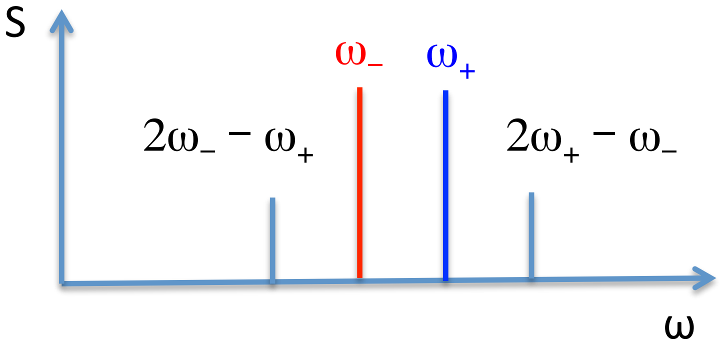
Applications in quantum computing, low temperature experiments, etc.

Quantum wave mixing

A new insight into statistics of coherent states

Classical four-wave mixing

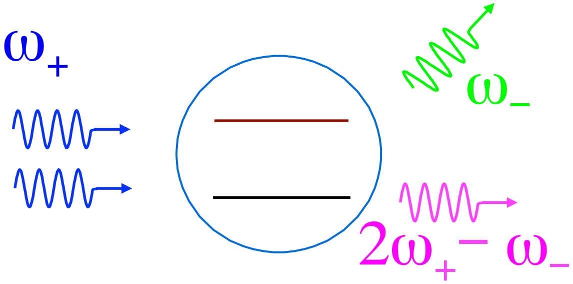




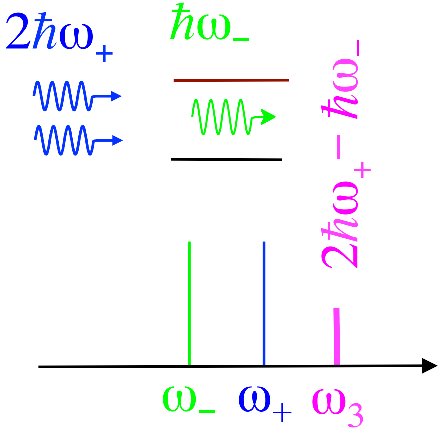
Four-wave mixing is a result of third-order nonlinearity

$\omega_3 = \omega_1 - 2\omega_0$

$$a_+ a_-^{\dagger} a_+ b_3^+$$



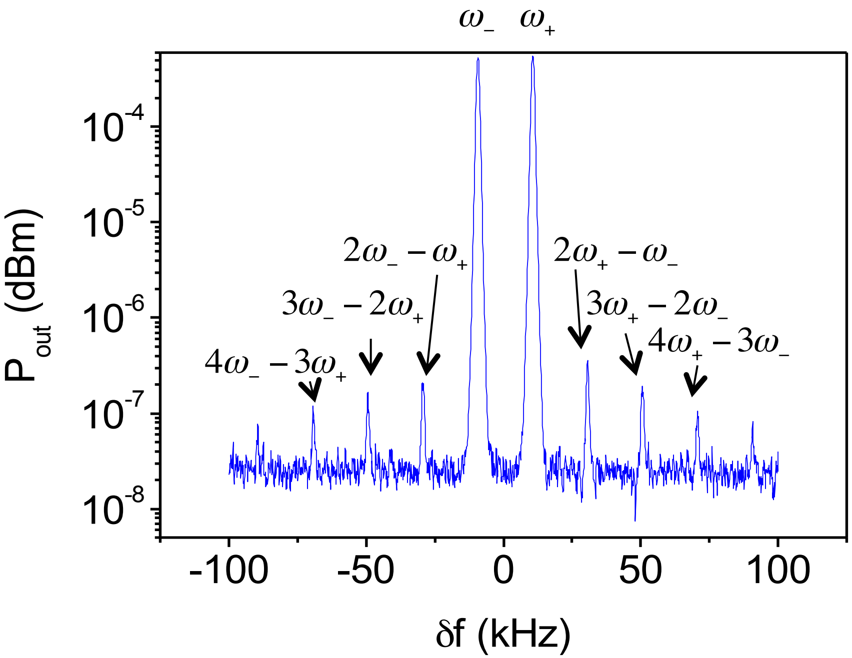
Spectrum



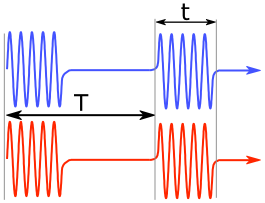
Two-level system: one scattering process at a time

Frequency mixing on a quantum system

Multi-photon mixing (continuous waves)

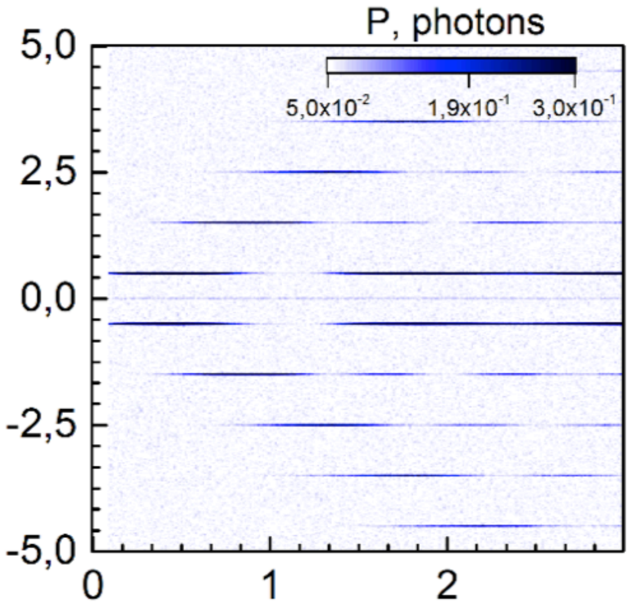


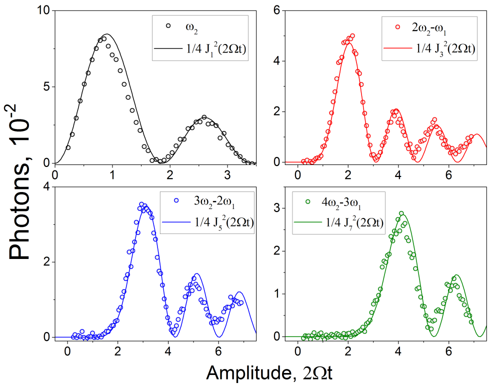
$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$



Harmonic quantum oscillations =>
=> Bessel function oscillations

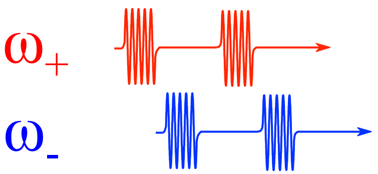
Time-frequency quantum oscillations



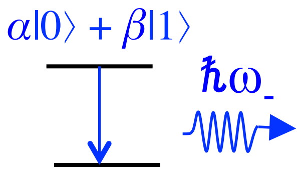


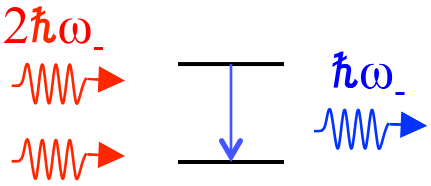
Quantum mixing

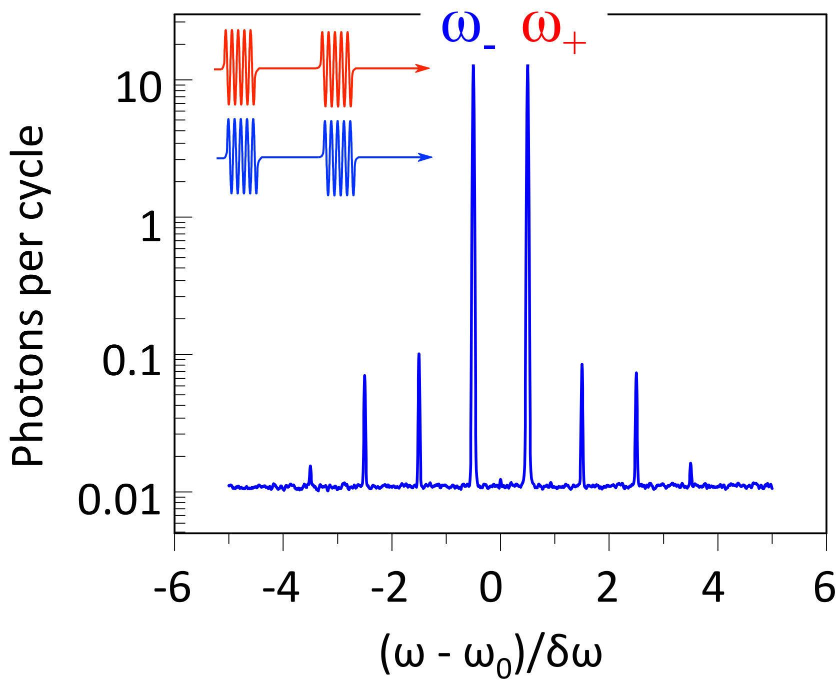
Broken time-symmetry

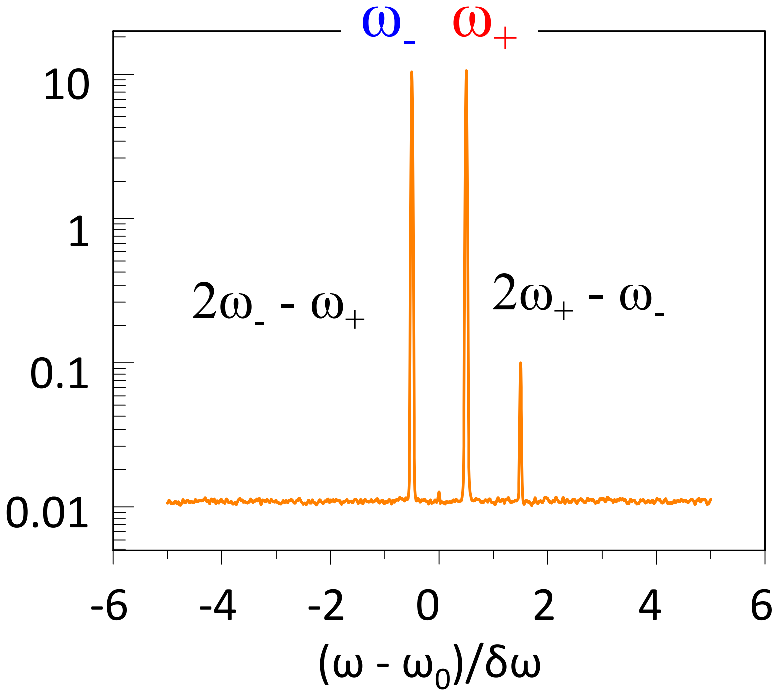


Two-level system emits maximum one photon at a time





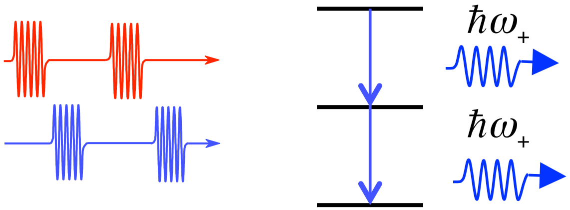




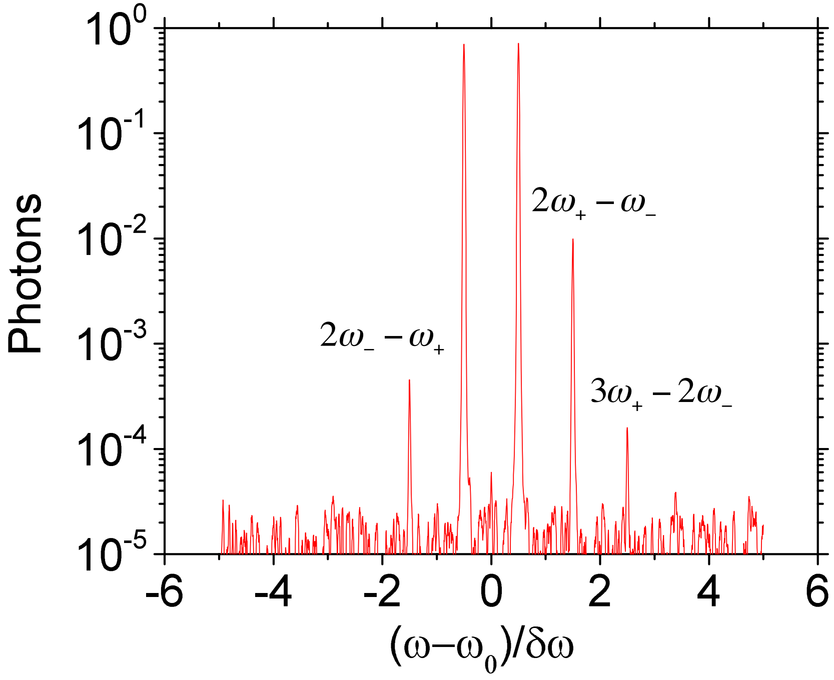
A. Yu. Dmitriev, R. Shaikhaidarov, V. N. Antonov, T. Hönigl-Decrinis, O. V. Astafiev. Nature Comm., 8, 1352 (2017).

Quantum mixing with two-photon superposed state

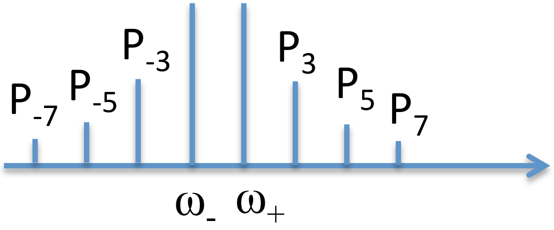
Three-level system emits up to two photons



$$\alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle$$



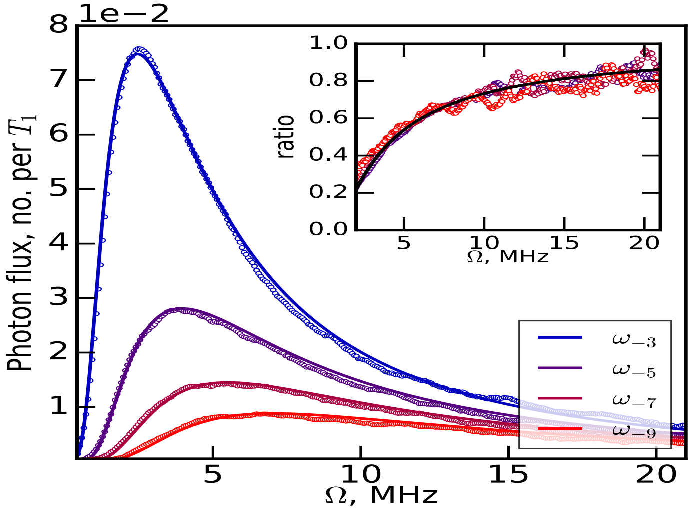
Continuous wave mixing on a single artificial atom
Photon statistics in coherent states

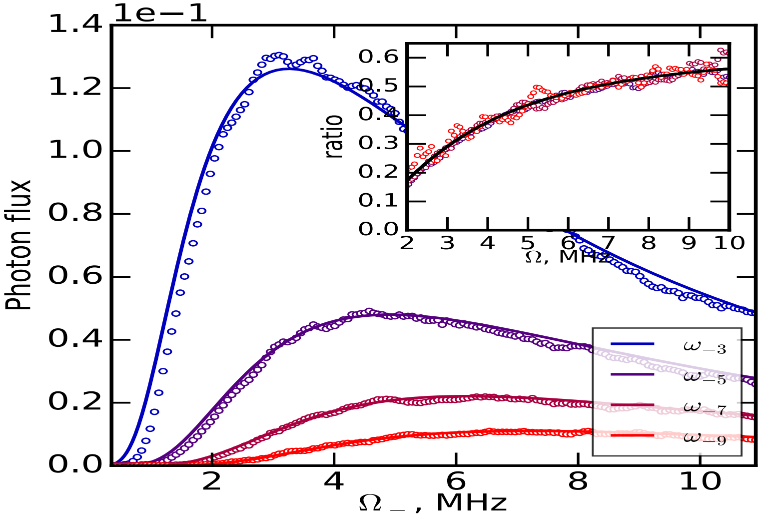


$$V^{sc}_{\pm(2p+1)} = \frac{(-1)^p\,\Gamma_1 \tan\theta}{\Lambda}\left(V_{\mp}\tan\frac{\theta}{2} - V_{\pm}\right)\tan^p\frac{\theta}{2}$$

$$\lambda = \Gamma_2 + i\Delta\omega \qquad \sin\theta = \frac{2\Omega_-\Omega_+}{\Gamma_1|\lambda|^2 + \Gamma_2\left(\Omega_-^2 + \Omega_+^2\right)} \qquad \Lambda^{-1} = \frac{\lambda\Gamma_1}{4\Gamma_2\Omega_-\Omega_+}$$

Weak drive: $N_{2p+1} \approx N_-^{p+1} N_+^p$ $\quad \left\langle a_3^\dagger \right\rangle \sim \left\langle a_- a_+^\dagger a_- \right\rangle \quad \left\langle a_{+5}^\dagger \right\rangle \sim \left\langle a_- a_+^\dagger a_- a_+^\dagger a_- \right\rangle$ …

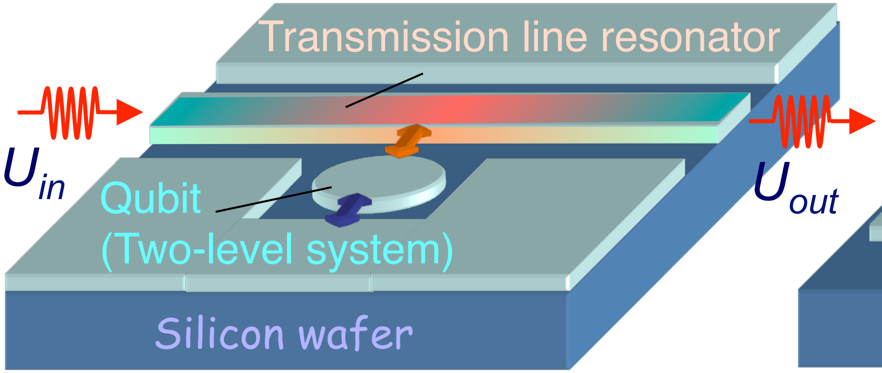


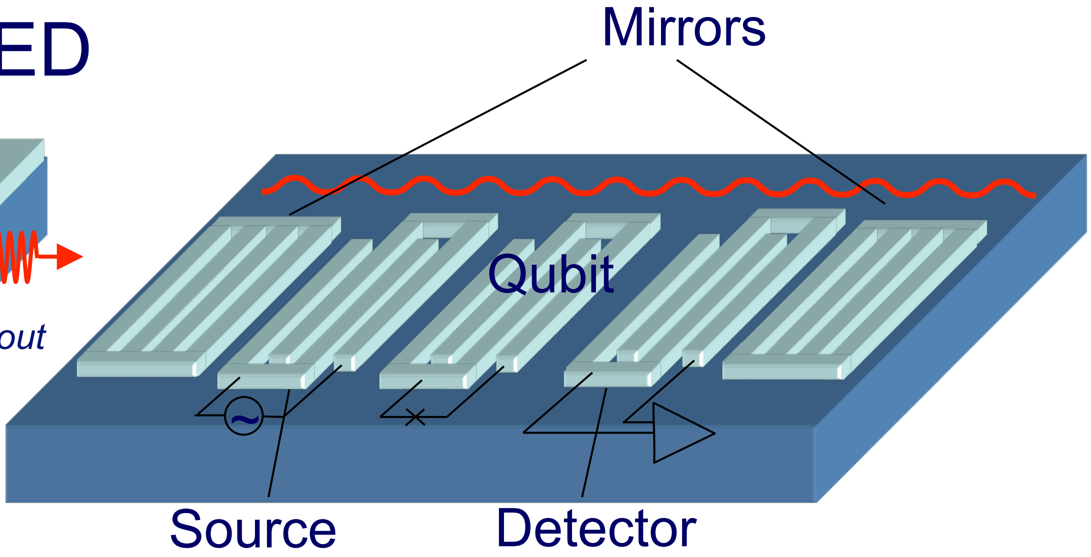


Quantum Acoustodynamics
Coupling of a superconducting two-level system to a quantized vacuum mode of a surface acoustic wave (SAW) resonator

Why Acoustics?

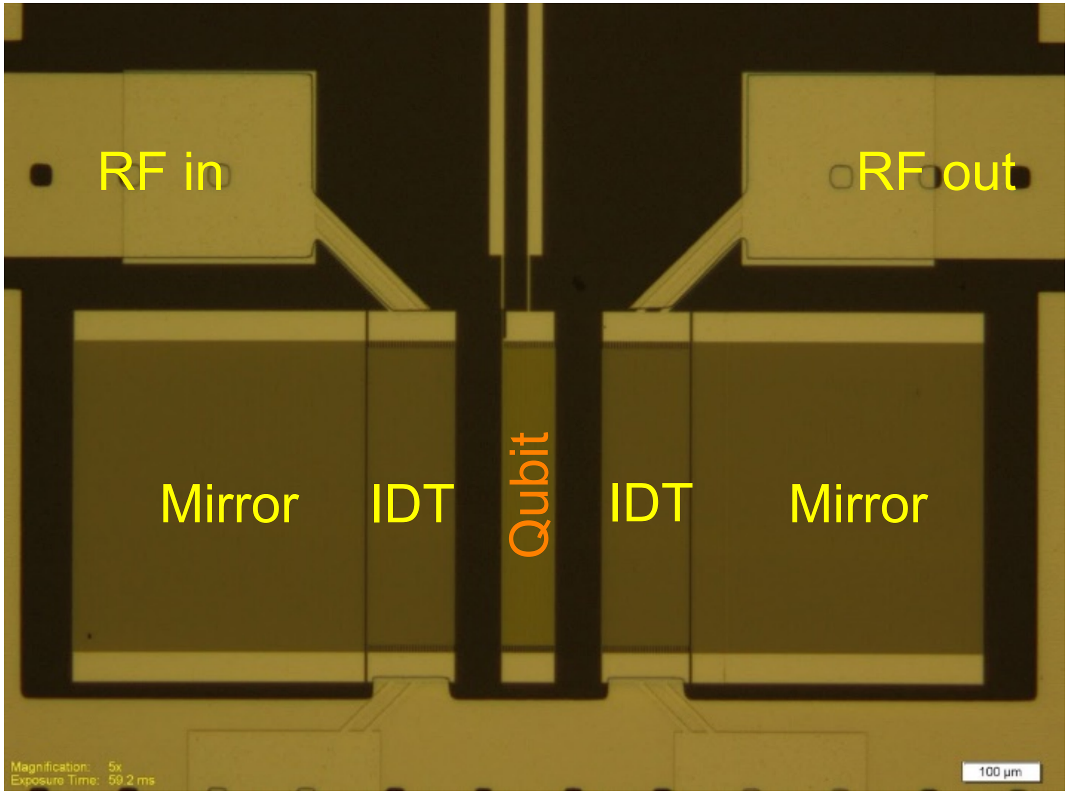
Cavity and Circuit QED



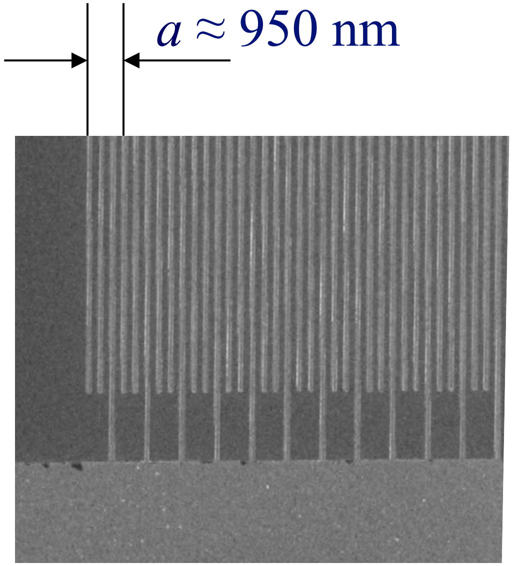


- Quantum mechanics becomes true quantum mechanics
- New physics
- Speed of sound 3000 m/s => compact elements
- 2D-geometry

Device geometry



Split gate geometry



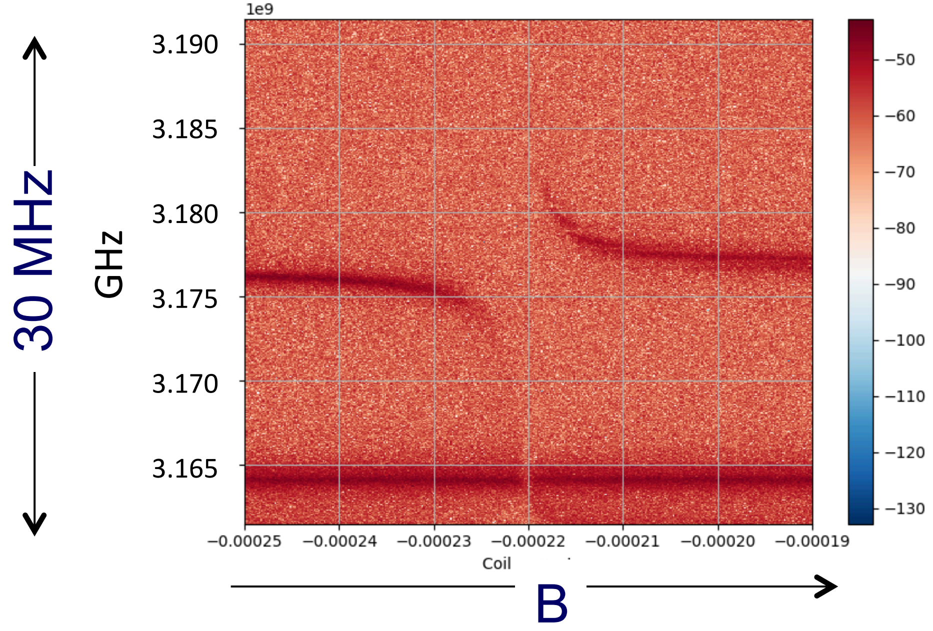
Technologically extremely challenging

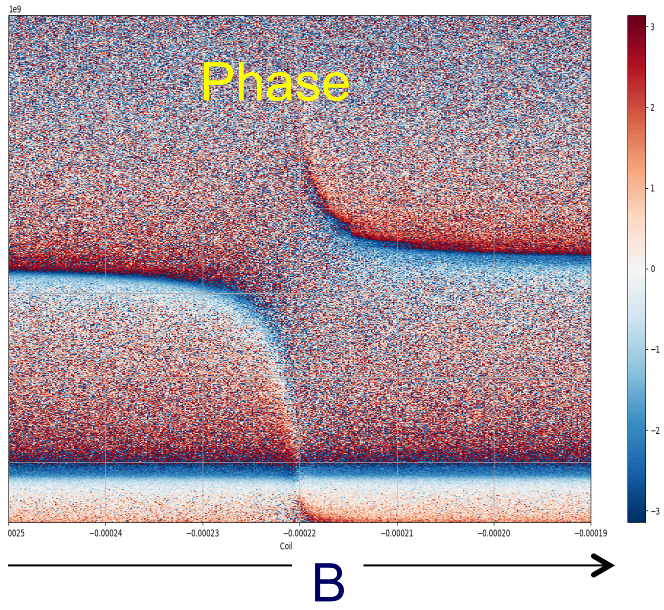
Interaction between an artificial atom and a SAW resonator

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).

Conclusion

- Strong coupling of an artificial atom to a transmission line is easily achievable
- An artificial atom in an open 1D space is an interesting system with reach physics
- Quantum wave mixing is a new physical phenomenon
- QWM allows to verify photon statistics in classical and non-classical coherent and superposed states
- A quantum regime of SAW resonator has been demonstrated