Quantum optics and quantum information processing with superconducting circuits

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Alexandre Blais
Université de Sherbrooke, Canada

Sherbrooke's circuit QED theory group
Félix Beaudoin, Adam B. Bolduc, Maxime Boissonneault, Jérôme Bourassa, Samuel Boutin, Andy Ferris, Kevin Lalumière, Clemens Mueller, Matt Woolley
Former members: Marcus da Silva, Gabrielle Denhez

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Microwave-photon antibunching without 'clicks'

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Quantum Device Lab, ETH Zurich
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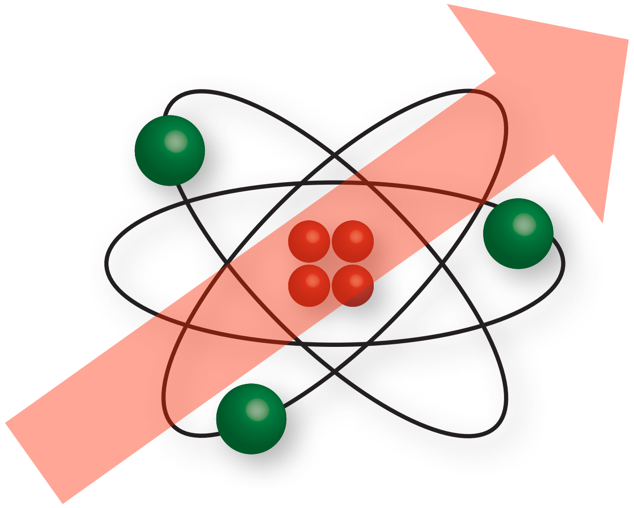
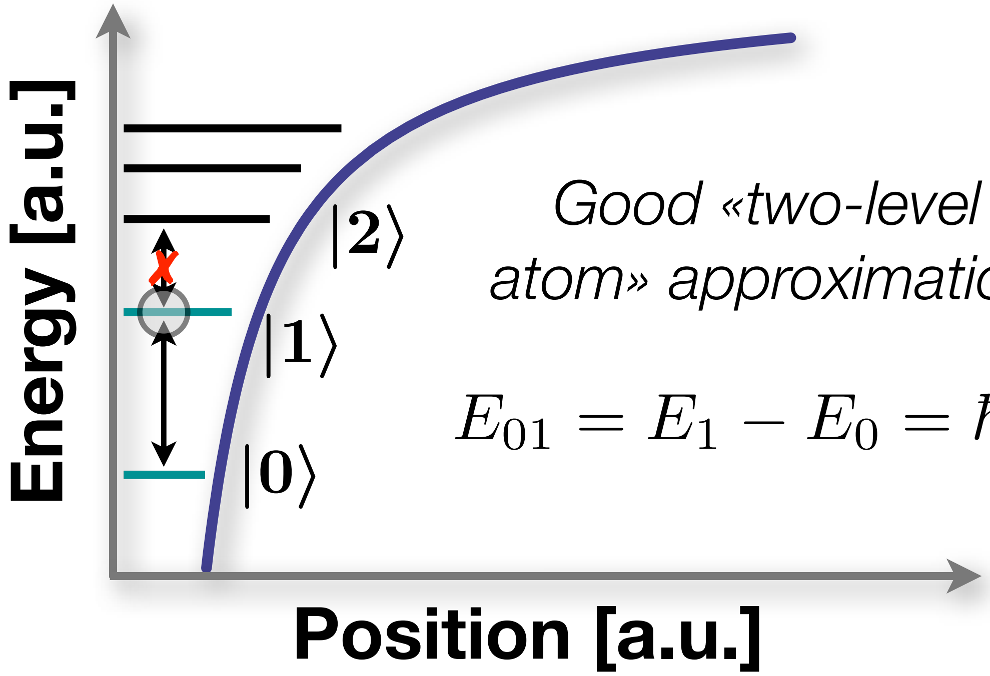
Nature’s atoms





Good «two-level atom» approximation

$$E_{01} = E_1 - E_0 = \hbar\omega_{01}$$

- Control internal state by shining laser tuned at the transition frequency

$$H = -\vec{d} \cdot \vec{E}(t) \quad \text{with} \quad E(t) = E_0 \cos \omega_{01} t$$

- Hyperfine levels of ^{9}Be$_+$ have long decay and coherence times

$$T_1 \sim \text{a few years} \qquad T_2 \gtrsim 10 \text{ seconds}$$

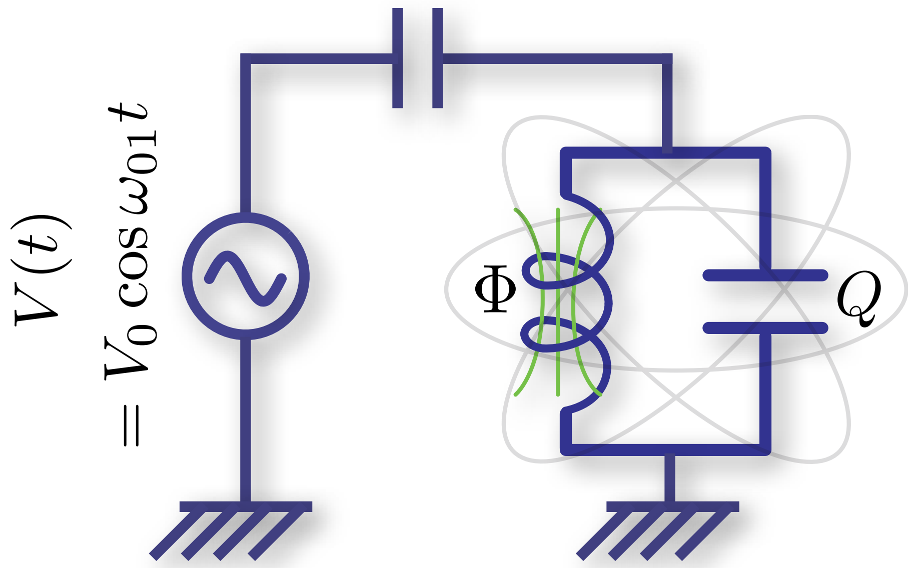
- Reasonably short π-pulse time

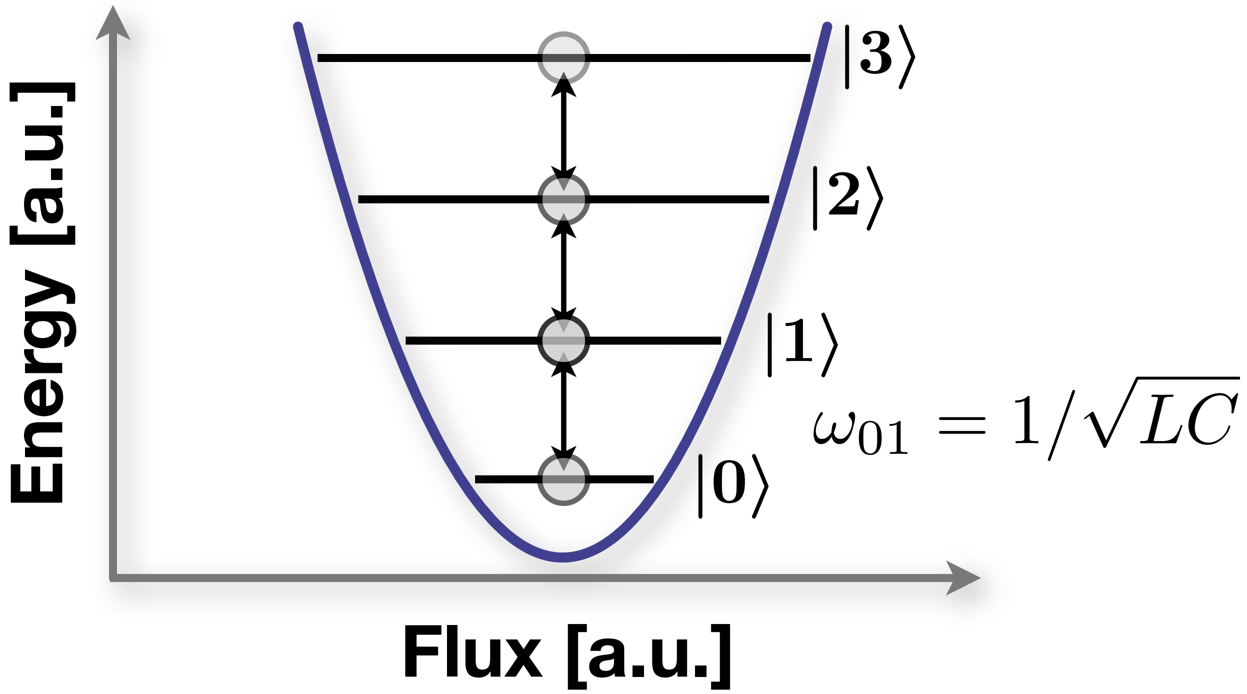
$$T_\pi \sim 5 \ \mu\text{s}$$

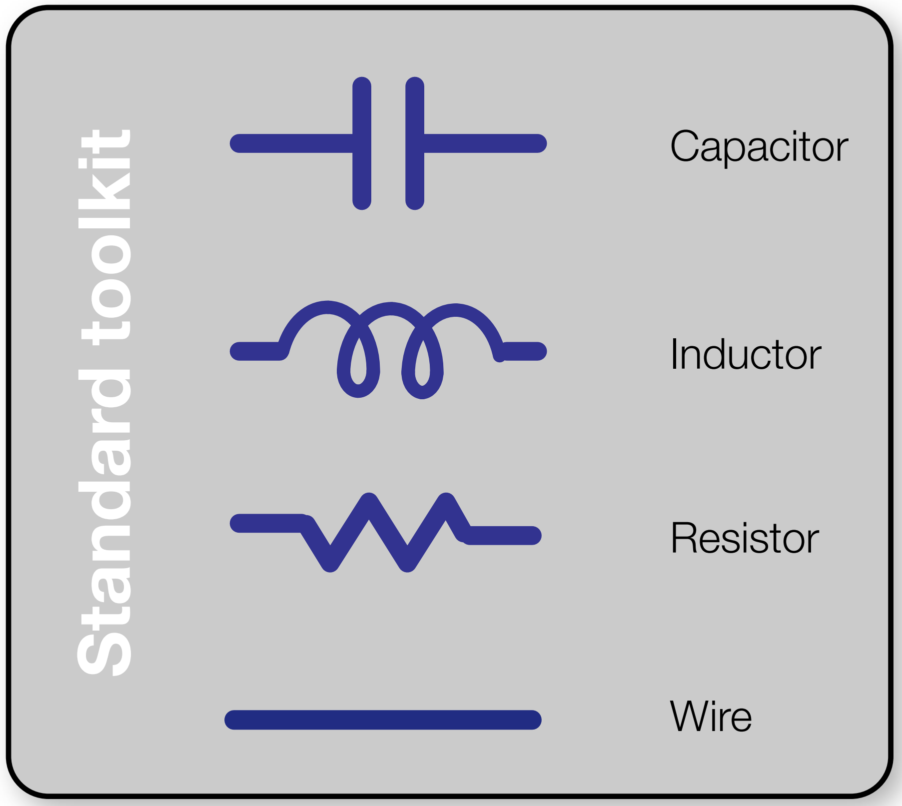
- Low error per gates: ~ 0.48%

T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J. L. O’Brien, Nature **464**, 45 (2010)

Artificial atoms: a toolkit

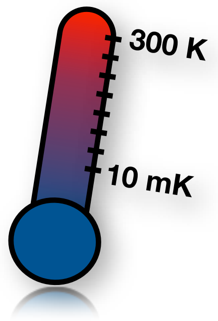






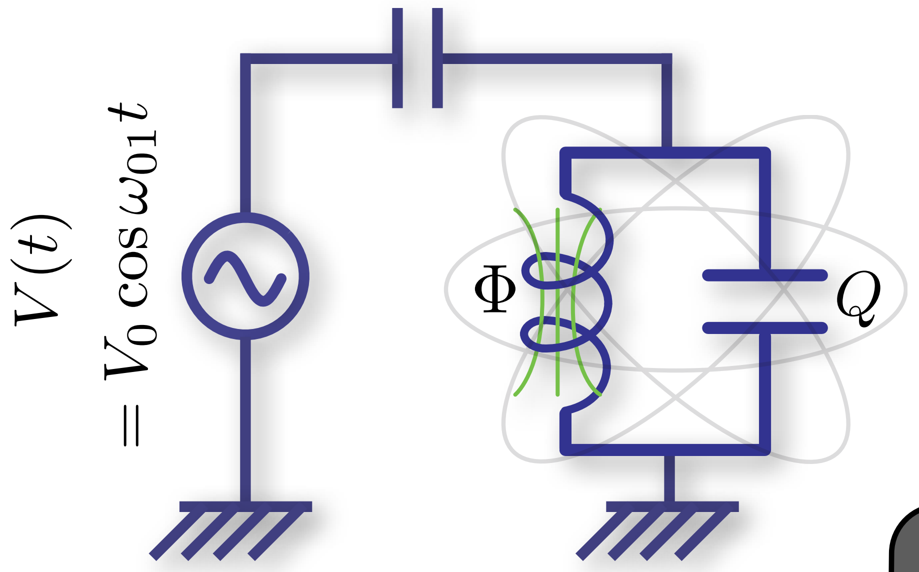
- Simple initialization to ground state

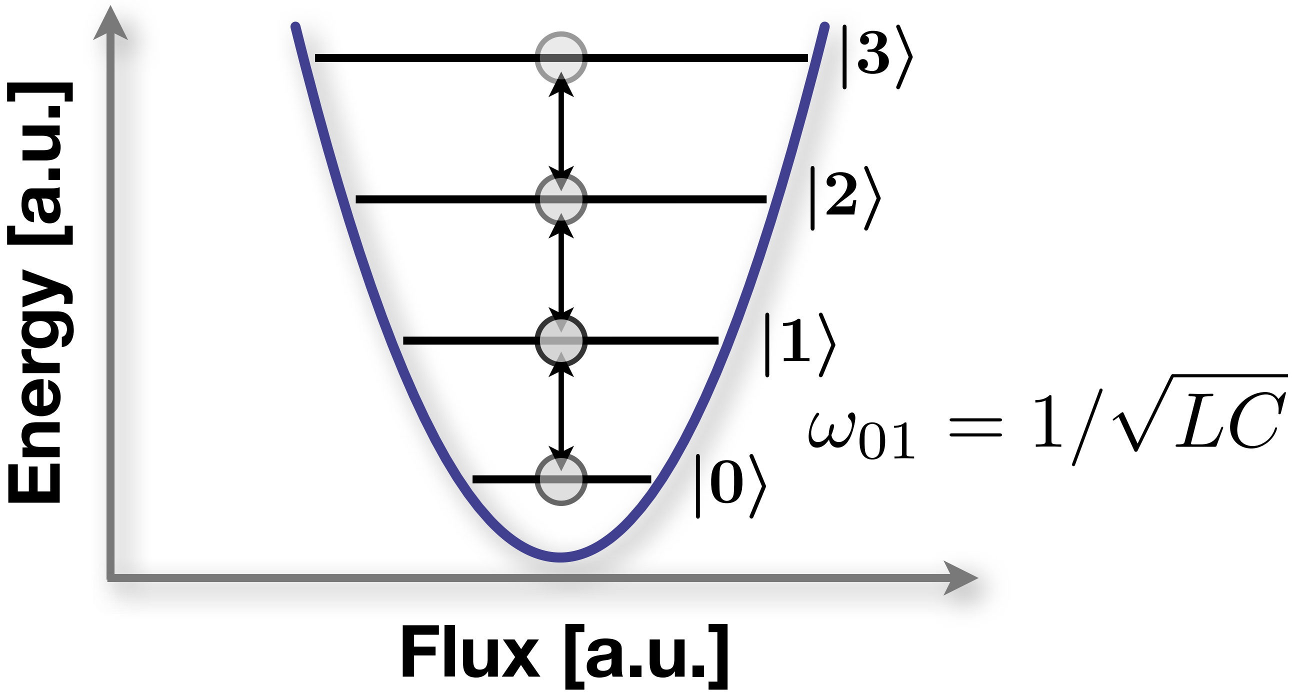
$$\omega_{01} = 1/\sqrt{LC} \sim 10\ \mathrm{GHz}$$
$$\sim 0.5\ \mathrm{K}$$



- Not a good «two-level» atom...

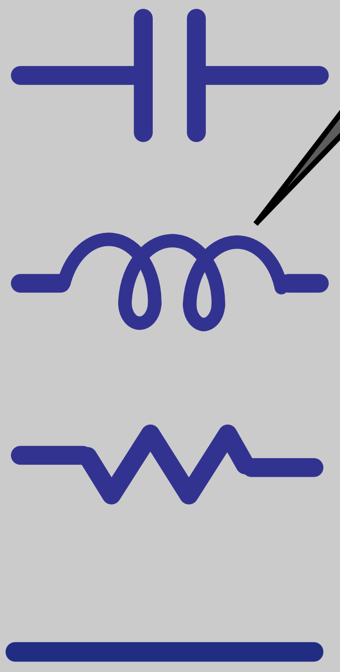
Artificial atoms: potential shaping



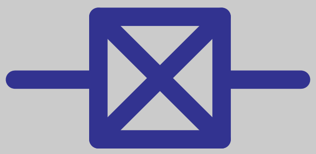


$I = \Phi/L$

Standard toolkit



Josephson junctions

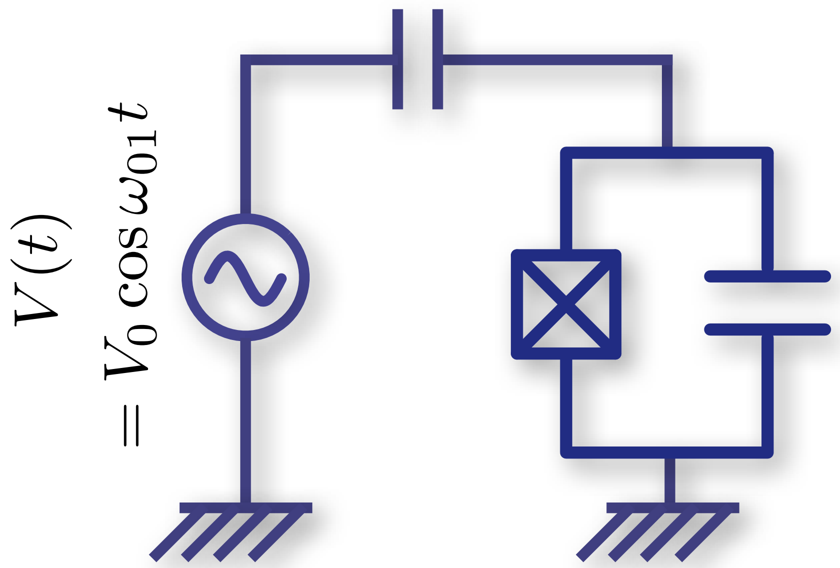


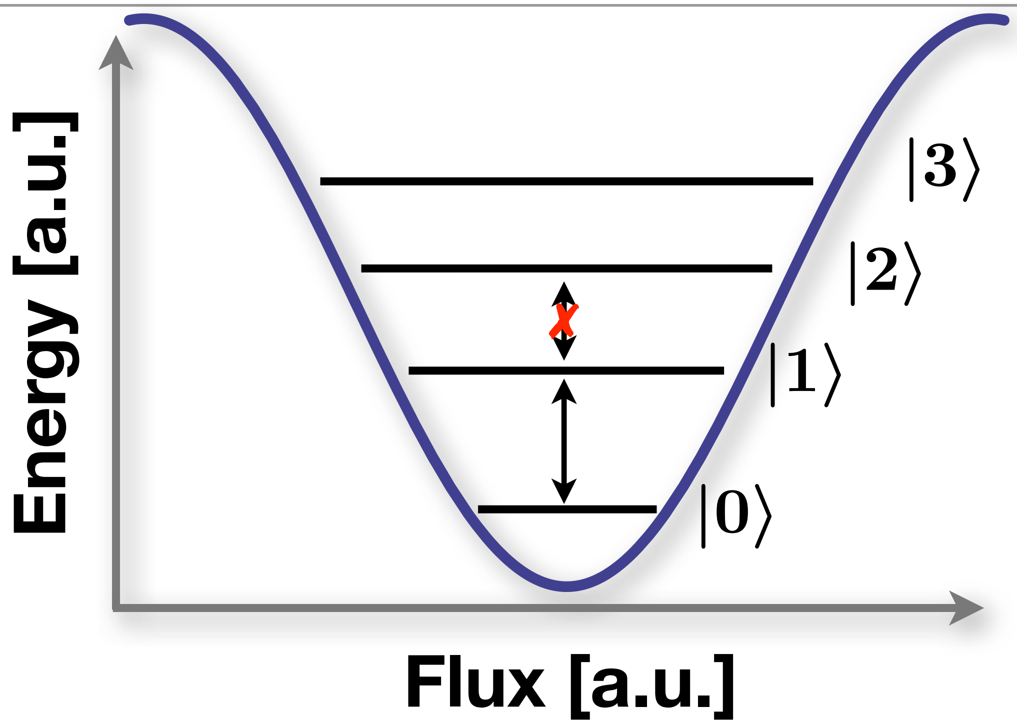
$$I = I_0 \sin(2\pi\Phi/\Phi_0)$$

$$L_J(\Phi) = \left(\frac{\partial I}{\partial \Phi}\right)^{-1}$$

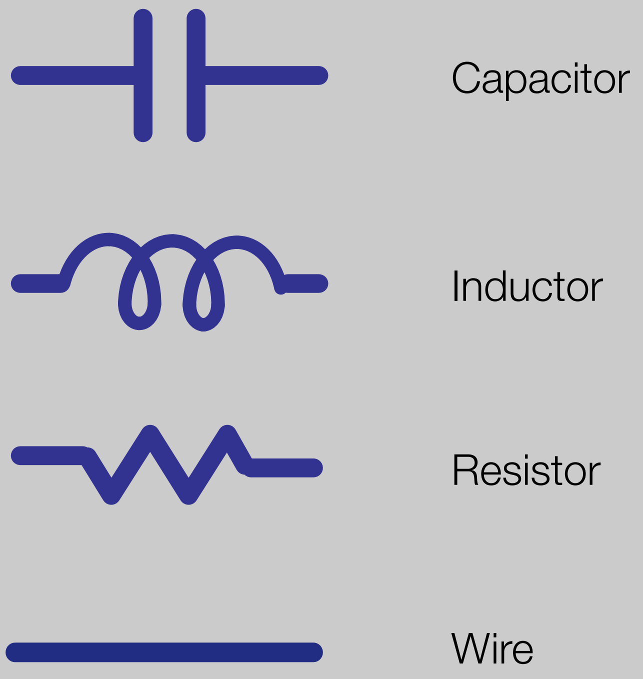
$$= \frac{\Phi_0}{2\pi I_0} \frac{1}{\cos(2\pi\Phi/\Phi_0)}$$

Artificial atoms: potential shaping





Standard toolkit



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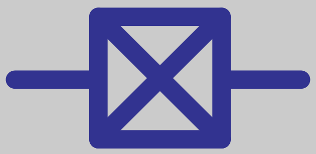

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$$L_J(\Phi) = \left(\frac{\partial I}{\partial \Phi}\right)^{-1}$$

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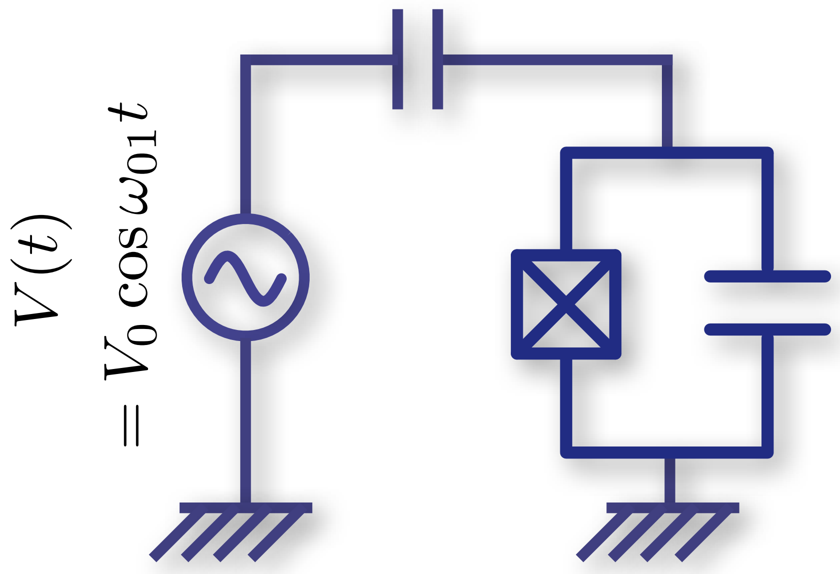
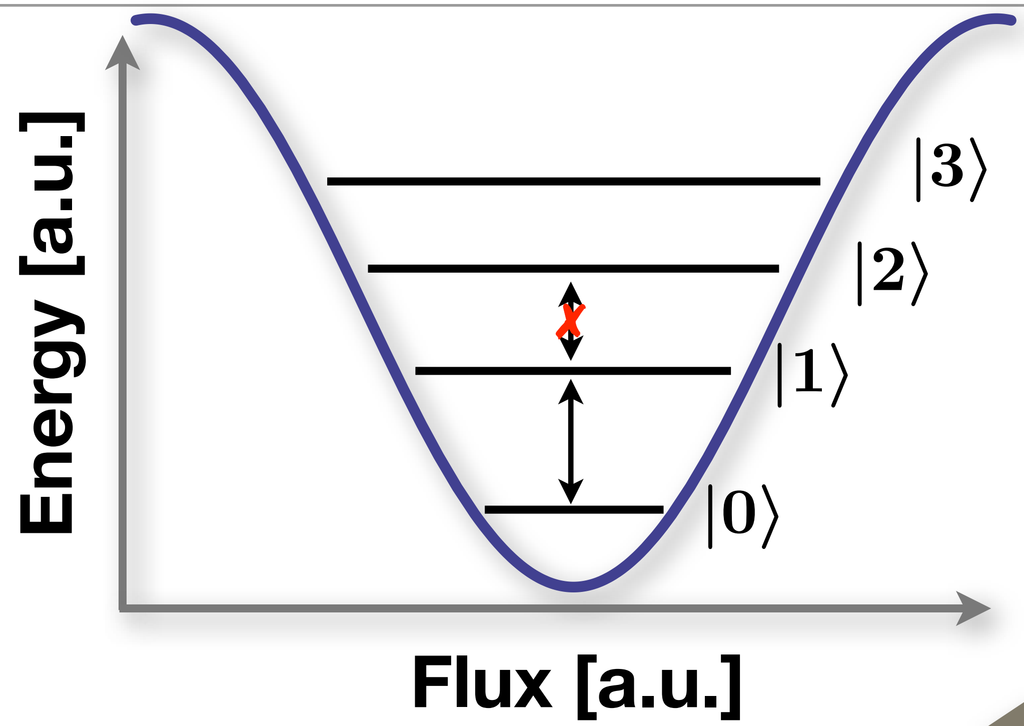
Artificial atoms: fast and coherent



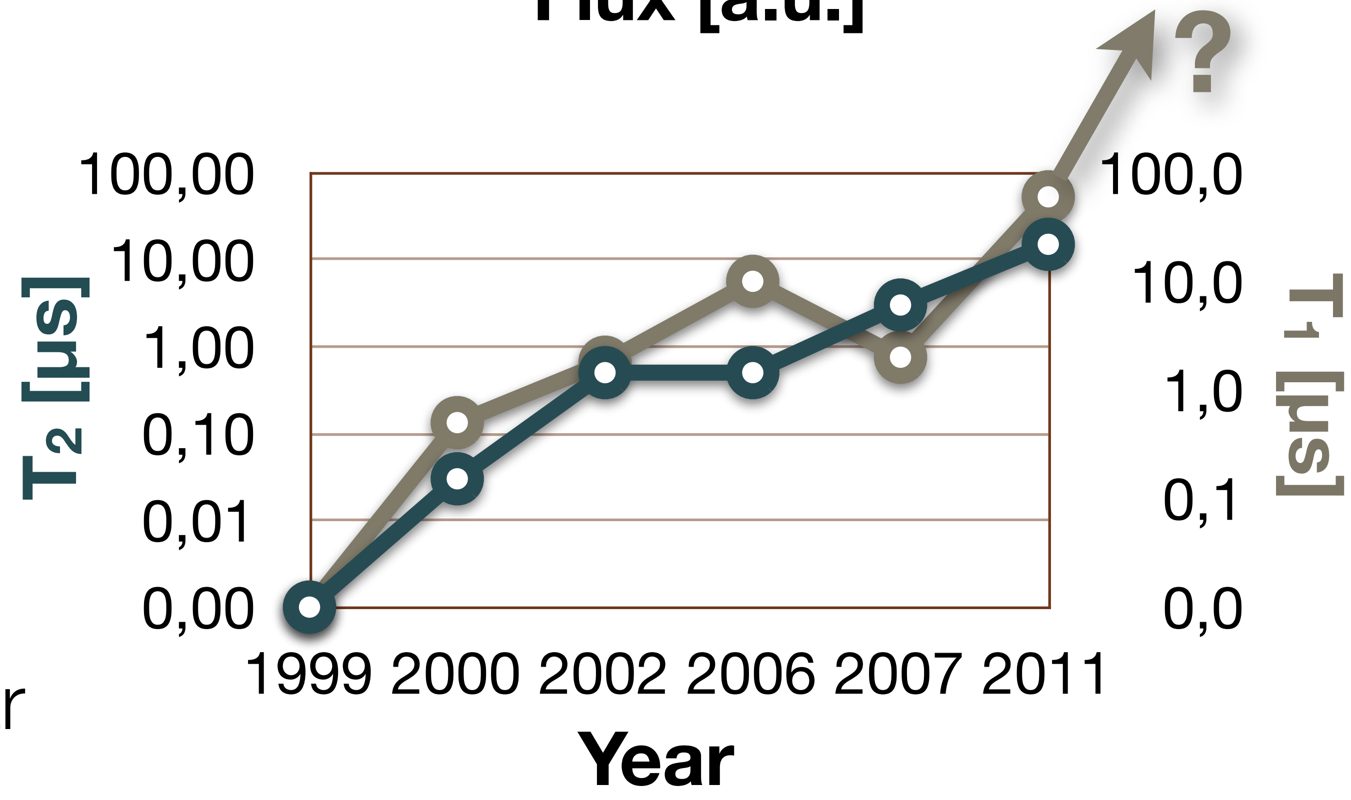


- Very short π-pulse time

$$T_\pi \sim 4 - 20\ \mathrm{ns}$$

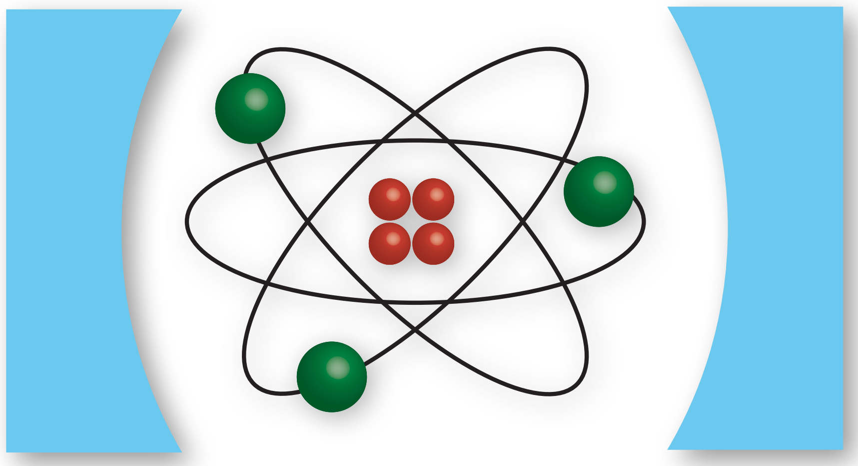
- Big improvements in relaxation and dephasing times

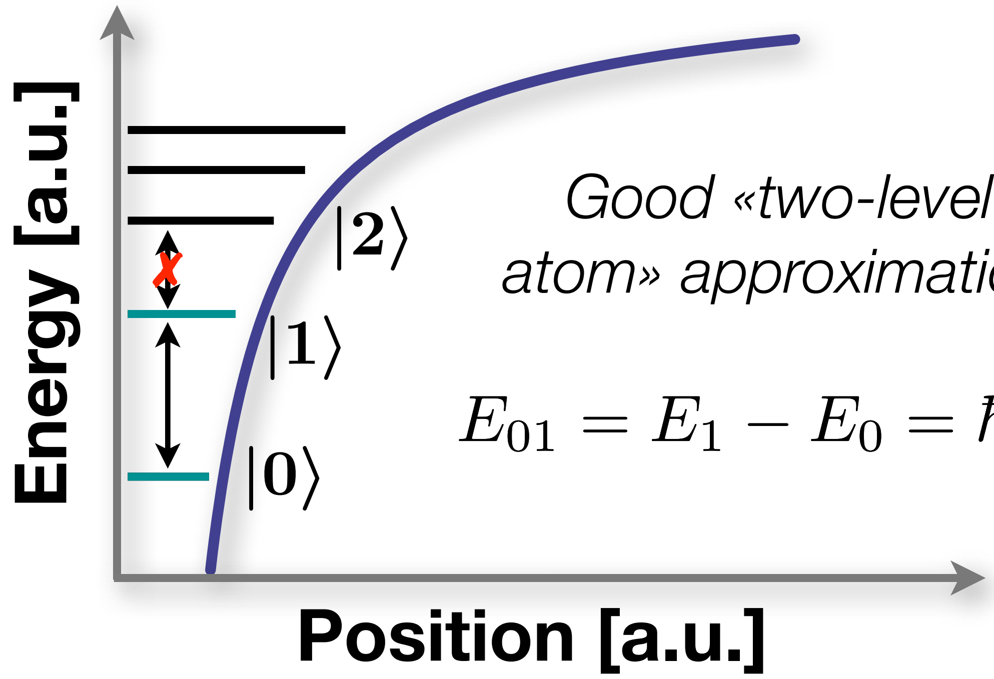
- Error per gates of 0.25%, similar to trapped ion results



Short pulse: J. M Chow *et al*, Phys. Rev. A **82**, 040305(R) (2010)
Long coherence: H. Paik *et al*, arXiv:1105.4652v2 (2011)

From atomic physics to quantum optics





Good «two-level atom» approximation

$$E_{01} = E_1 - E_0 = \hbar\omega_{01}$$

- Control internal state by shining laser at the transition frequency

$$H = \underbrace{-\vec{d} \cdot \vec{E}}_{g}(t) \quad \text{with} \quad E(t) = E_0 \cos \omega_{01} t$$

- Can the field of a single photon, or even *vacuum fluctuations,* have a large effect?

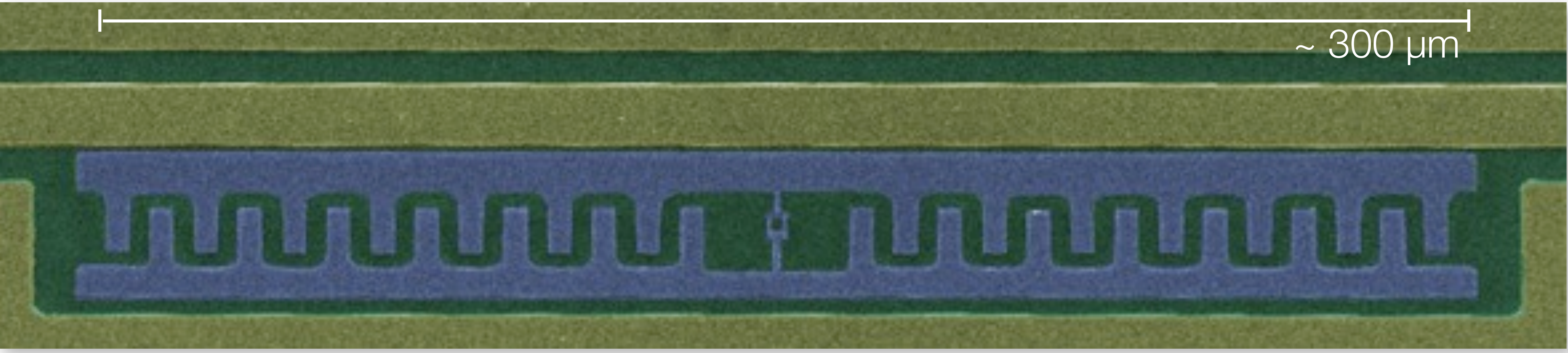
Cavity QED

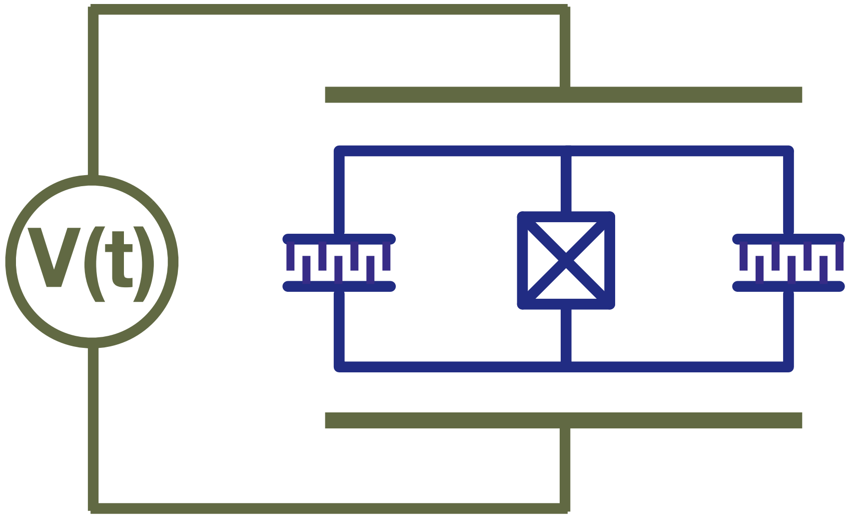
1) Work with large atoms (d)
2) Confine the field (E)

Exploring the Quantum: Atoms, Cavities, and Photons, S. Haroche and J.-M. Raimond (2006)

From cavity to *circuit* QED

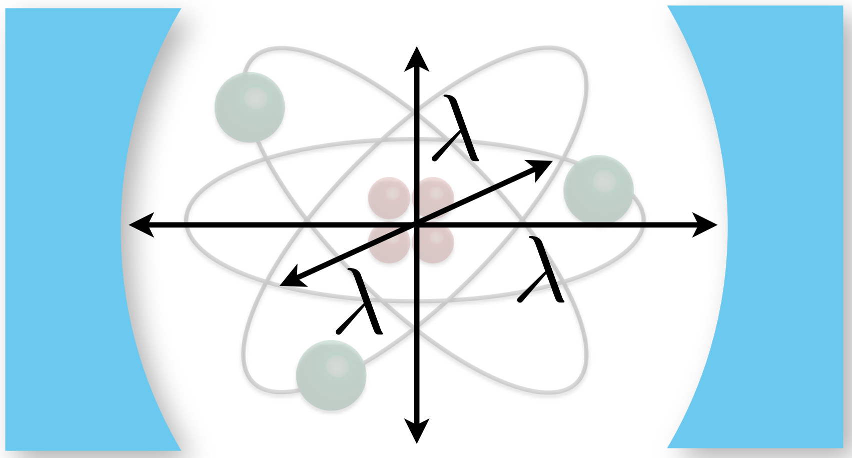
- Artificial atoms are ***large***



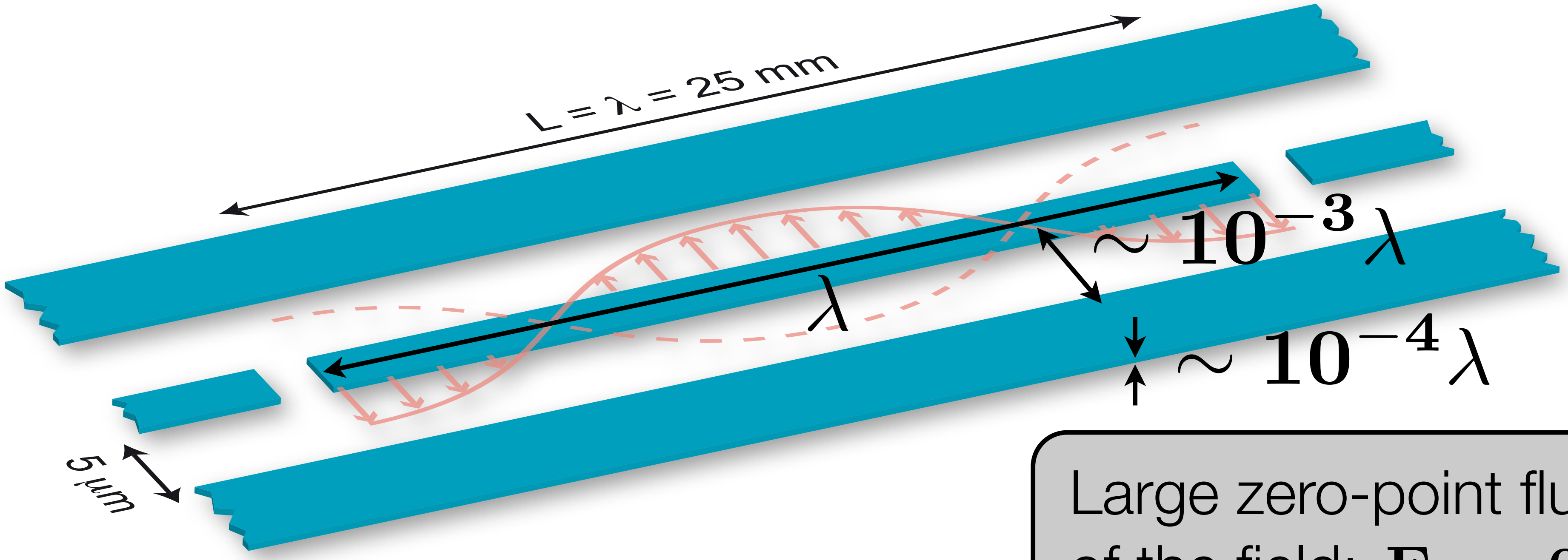


From cavity to *circuit* QED

- E-field can be tightly confined



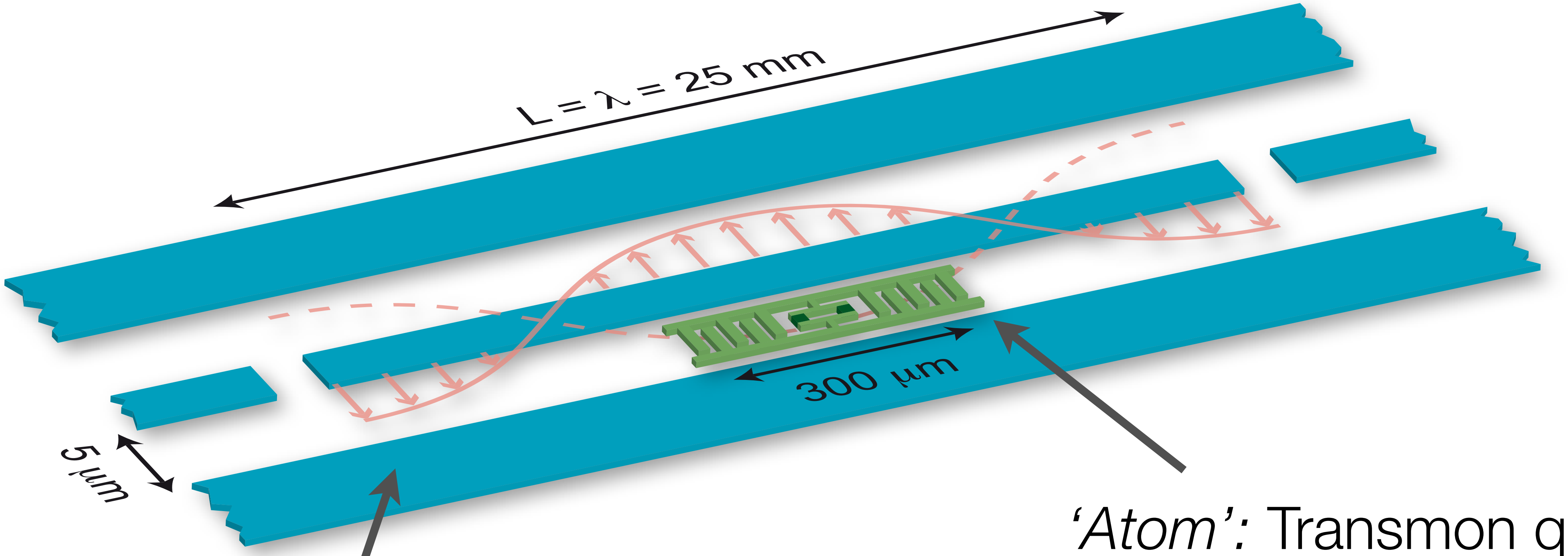
$$\mathbf{E} \propto \sqrt{\mathbf{1}/\lambda^{\mathbf{3}}}$$



Large zero-point fluctuations of the field: $\mathbf{E_0} \sim \mathbf{0.2\ V/m}$

Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)

From cavity to *circuit* QED



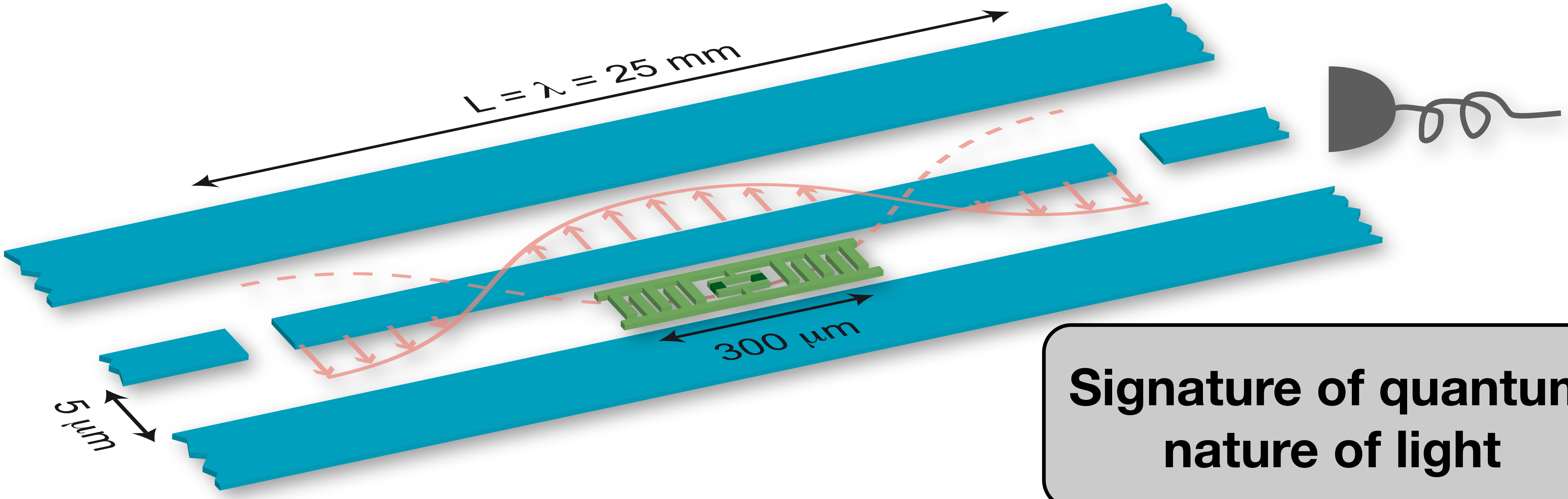
'Atom': Transmon qubit of transition frequency ω_a and long coherence time

'Cavity': Superconducting coplanar transmission-line resonator of fundamental mode frequency ω_r

$$\boxed{\begin{array}{c} g_{\text{circuit}}/2\pi \sim [0-1]\ \text{GHz} \\ g_{\text{cavity}}/2\pi \sim 50\ \text{kHz} \end{array}}$$

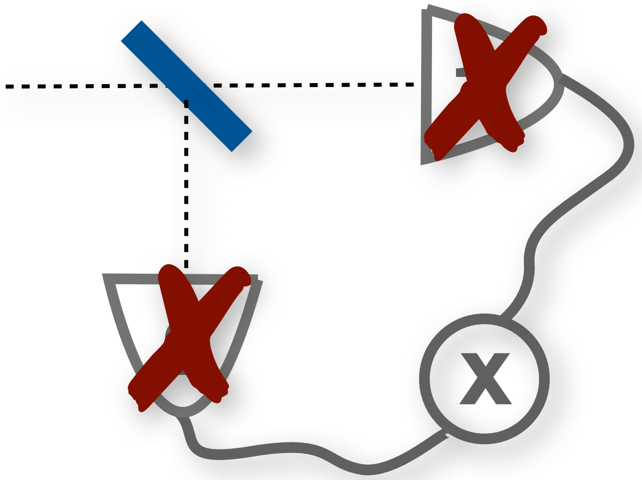
Proposal: Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)
First realization: Wallraff, Schuster, Blais, Frunzio, Huang, Majer, Kumar, Girvin & Schoelkopf. Nature **431**, 162 (2004)
Ultra-strong coupling: Bourassa, Gambetta, Abdumalikov, Astafiev, Nakamura & Blais. Phys. Rev. A **80**, 032109 (2009)

Quantum optics with circuit QED

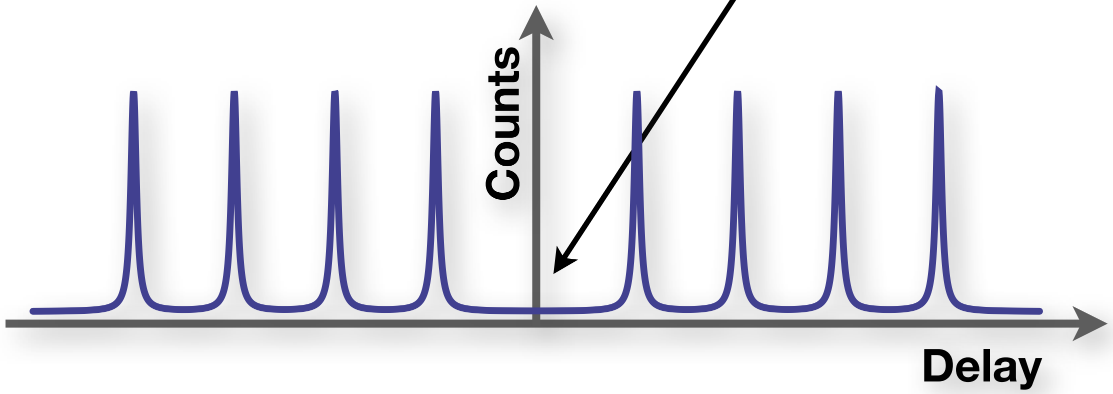


Signature of quantum nature of light

- How to characterize this single microwave-photon source?



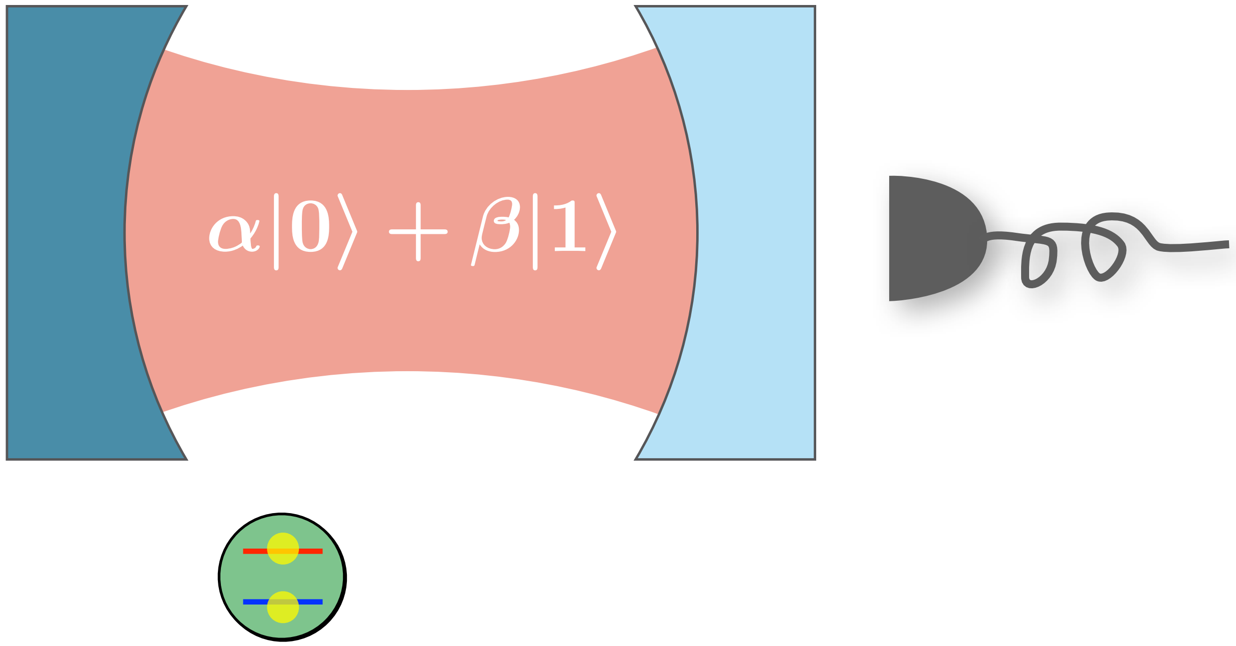
t	n_1	n_2	x
Δt	1	0	0
2Δt	0	1	0
3Δt	0	1	0
:	:	:	:



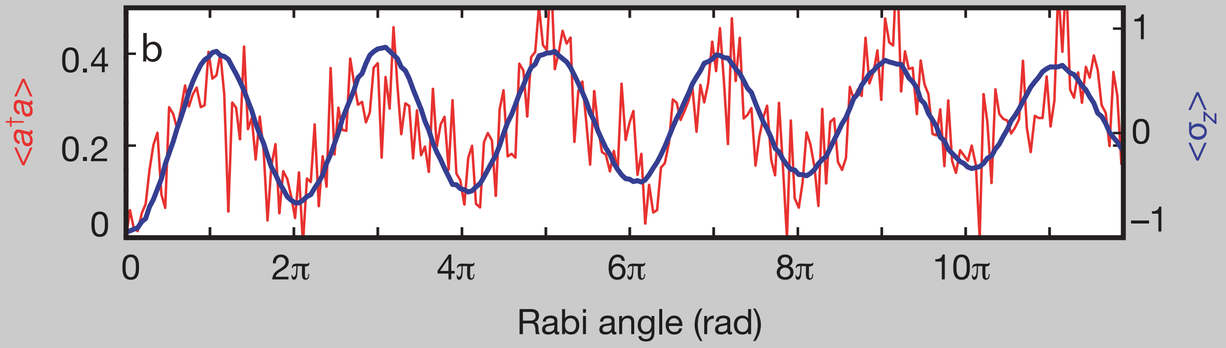
$$G^{(2)}(\tau) = \langle a^\dagger(t+\tau)a^\dagger(t)a(t+\tau)a(t)\rangle$$

D. F. Walls and G. J. Milburn. Quantum Optics (2008)

On-demand single microwave-photon source

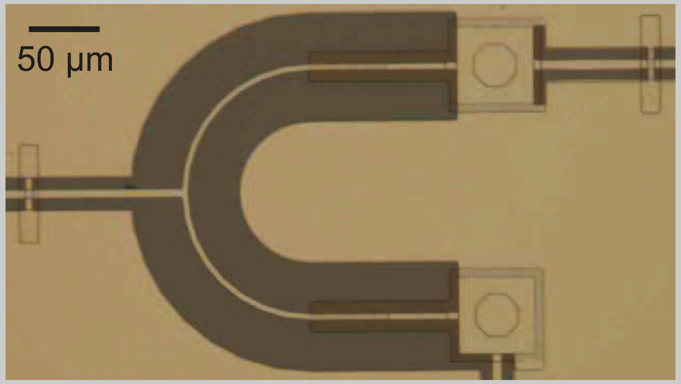


On-demand single microwave photon source



A. Houck et al. Nature **449**, 328 (2007)

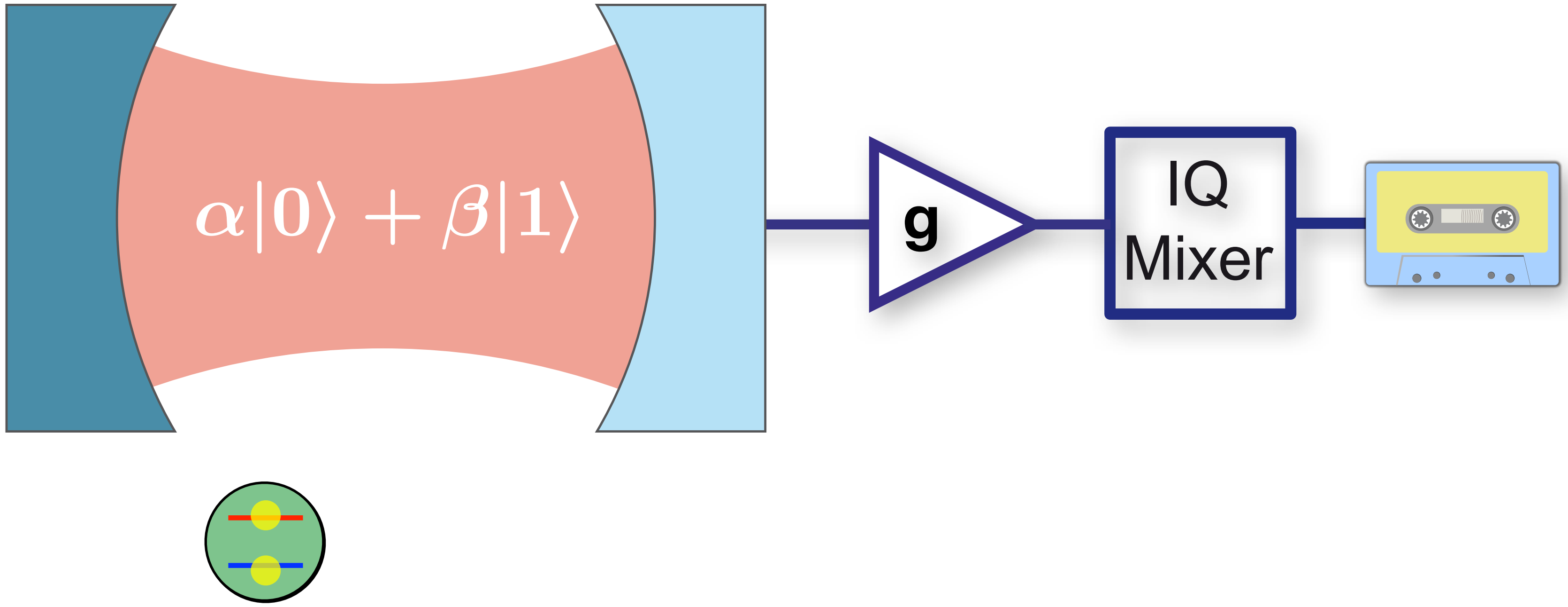
First experimental steps towards single microwave-photon detectors



Y.-F. Chen *et al*. arXiv:1011.4329

D. Bozyigit, ..., M. P. da Silva, A. Blais and A. Wallraff. Nature Physics **7**, 154 (2011)

On-demand single microwave-photon source



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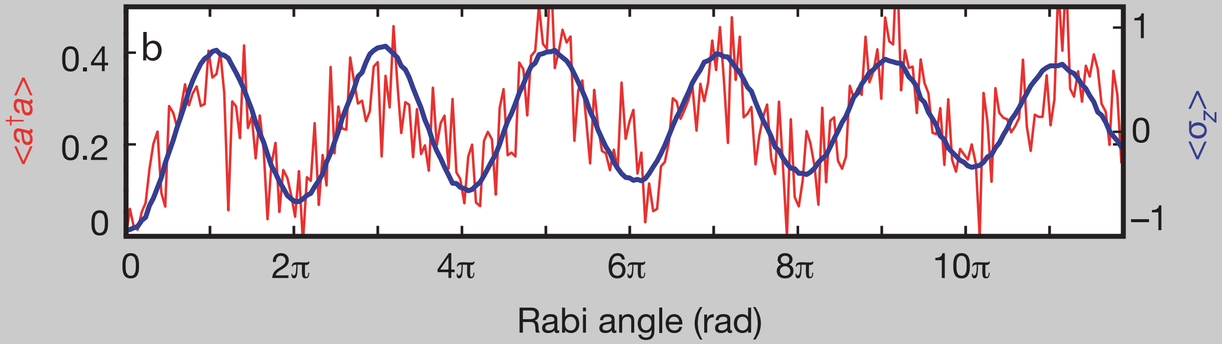

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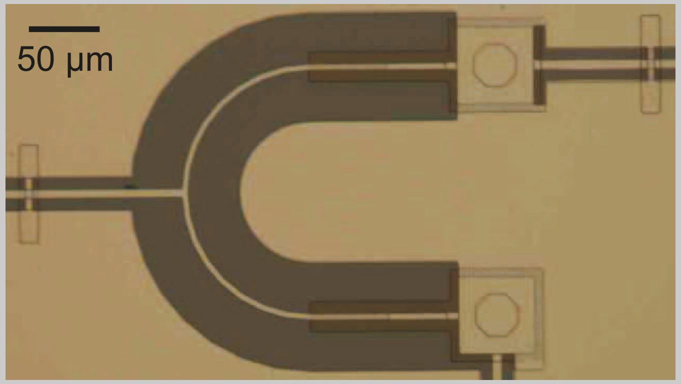
First experimental steps towards single microwave-photon detectors



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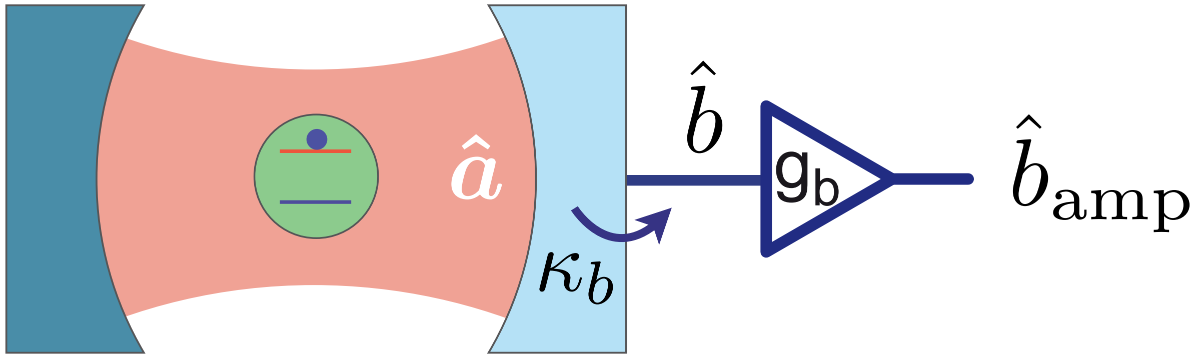
Quantum mechanics of microwave measurements

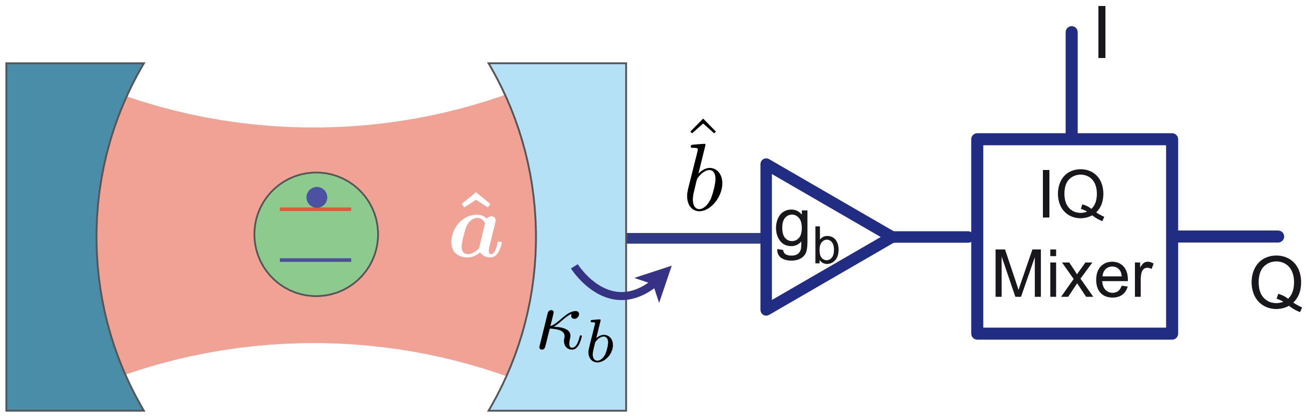


Output field: $\hat{b}(t) = \sqrt{\kappa_b}\hat{a}(t) - \hat{b}_{\mathrm{in}}(t)$

Amplification: $b_{\mathrm{amp}}(t) \overset{?}{=} g_b b(t) \;\; \Rightarrow [b_{\mathrm{amp}}(t), b^{\dagger}_{\mathrm{amp}}(t)] = g_b^2$

C. W. Gardiner and M. J. Collett, Phys. Rev. A **31**, 3761 (1985); C. M. Caves, Phys. Rev. D **26**, 1817 (1982)
B. Yurke and J. S. Denker, Phys. Rev. A **29**, 1419 (1984); A. Clerk *et al.*, Rev. Mod. Phys. **82**, 1155 (2010)

Quantum mechanics of microwave measurements



Output field: $\hat{b}(t) = \sqrt{\kappa_b}\hat{a}(t) - \hat{b}_{\mathrm{in}}(t)$

Amplification: $b_{\mathrm{amp}}(t) = g_b b(t) + \sqrt{g_b^2 - 1}d_b^\dagger(t)$

↖ Added noise

with $\langle d_b^\dagger(t) d_b(t') \rangle = N_T \delta(t - t')$

C. W. Gardiner and M. J. Collett, Phys. Rev. A **31**, 3761 (1985); C. M. Caves, Phys. Rev. D **26**, 1817 (1982)
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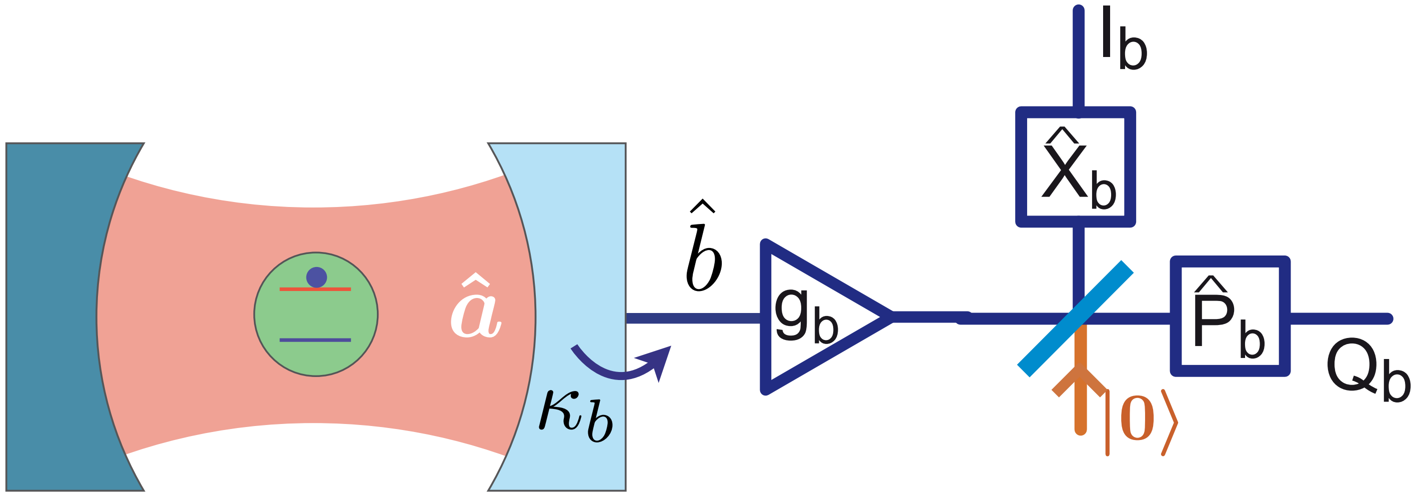

$X_b \propto (b^\dagger + b)$
$P_b \propto i(b^\dagger - b)$

Output field: $\hat{b}(t) = \sqrt{\kappa_b}\,\hat{a}(t) - \hat{b}_{\mathrm{in}}(t)$

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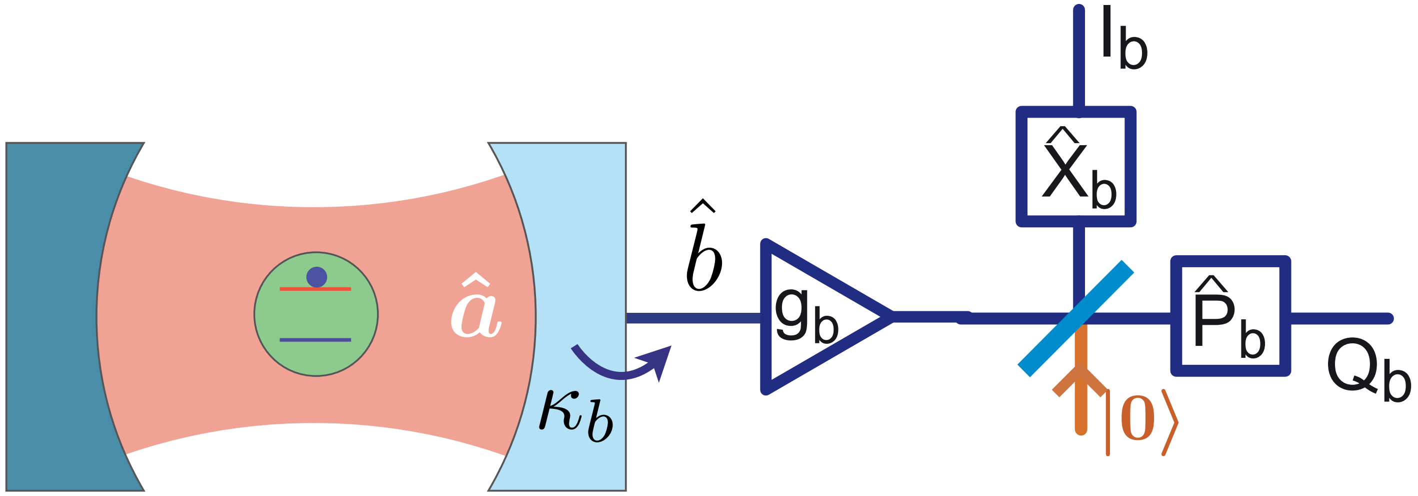
Beam-splitter: added vacuum noise and commuting outputs

C. W. Gardiner and M. J. Collett, Phys. Rev. A **31**, 3761 (1985); C. M. Caves, Phys. Rev. D **26**, 1817 (1982)
B. Yurke and J. S. Denker, Phys. Rev. A **29**, 1419 (1984); A. Clerk *et al*., Rev. Mod. Phys. **82**, 1155 (2010)

Complex envelope



$X_b \propto (b^\dagger + b)$
$P_b \propto i(b^\dagger - b)$

Complex envelope:
$$\begin{aligned}\hat{S}_b(t) &= \hat{X}_b(t) + i\hat{P}_b(t)\\ &= g_b\hat{b}(t) + \hat{N}_b(t)\\ &= g_b\sqrt{\kappa_b}\,\hat{a}(t) + \hat{N}'_b(t)\end{aligned}$$

Digitalized using FPGA electronics with a 10 ns time resolution $\ll 1/\kappa$

Beam-splitter: Noise rejection

$$X_b \propto (b^\dagger + b)$$
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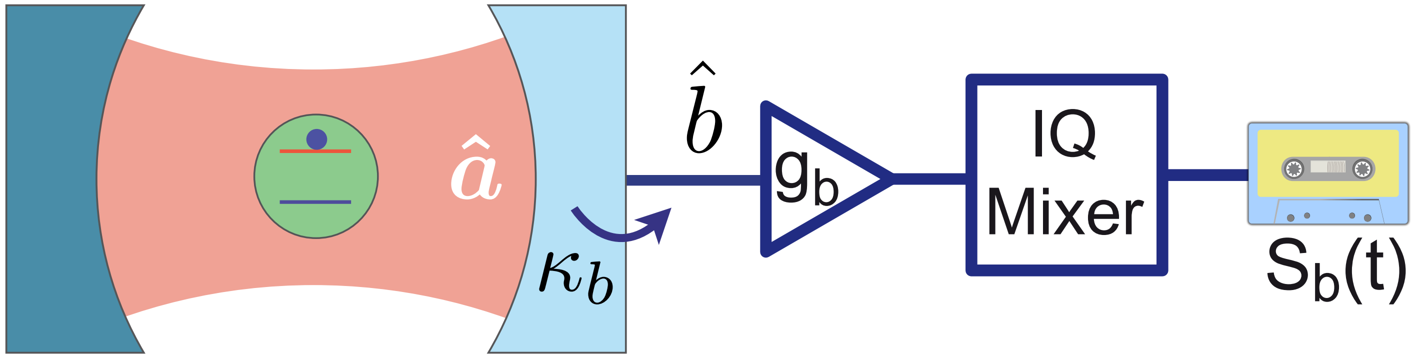

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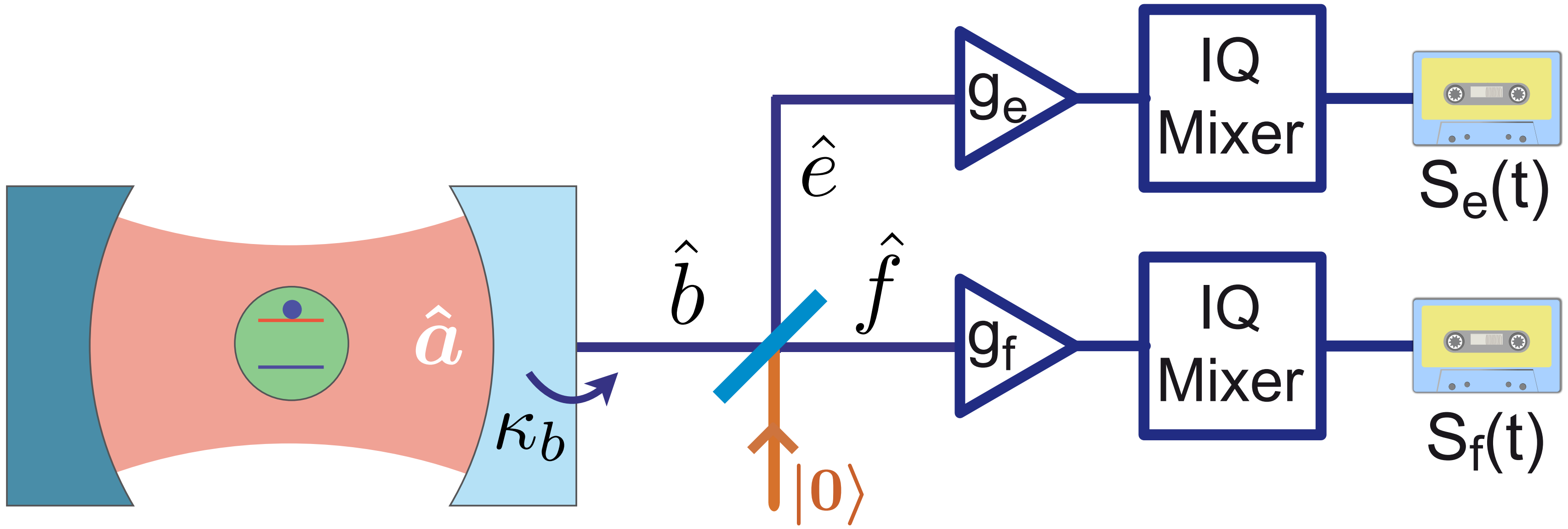


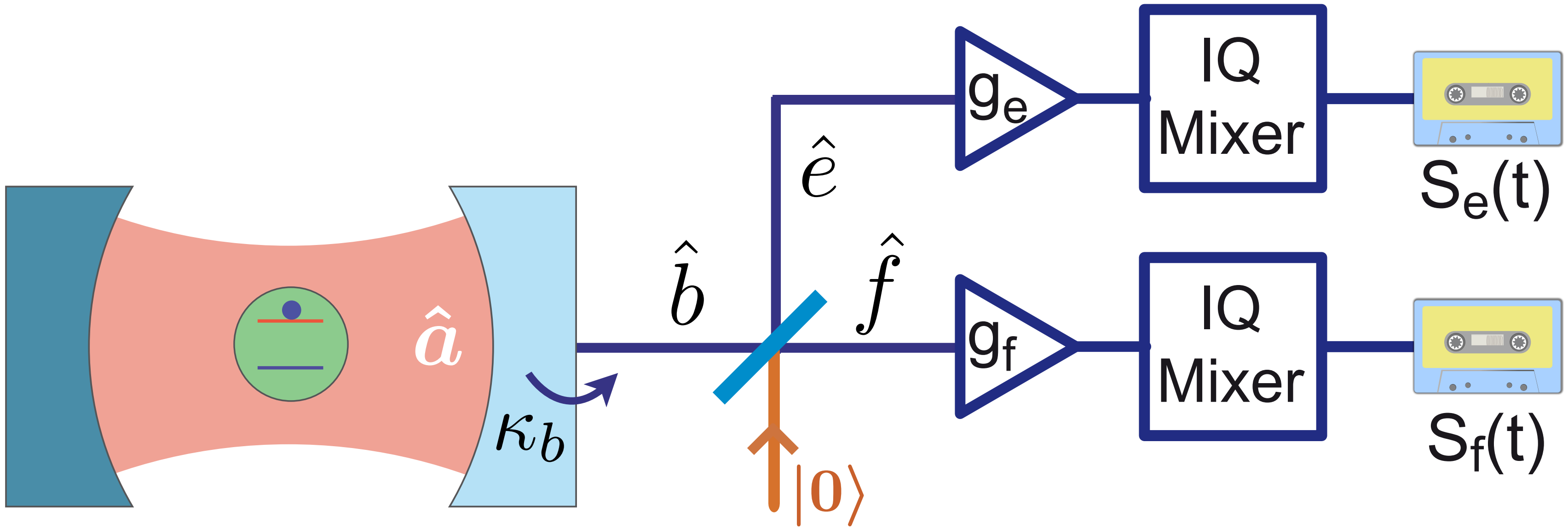
Rejection of uncorrelated noise

Complex envelope:

$$\begin{aligned}\hat{S}_b(t) &= \hat{X}_b(t) + i\hat{P}_b(t)\\ &= g_b\hat{b}(t) + \hat{N}_b(t)\\ &= g_b\sqrt{\kappa_b}\hat{a}(t) + \hat{N}_b'(t)\end{aligned}$$

Digitalized using FPGA electronics with a 10 ns time resolution $\ll 1/\kappa$

Same-time averages



Same-time averages:

Quadrature $\langle \hat{S}_e(t) \rangle \longrightarrow \langle \hat{a}(t) \rangle$

Cross-power $\langle \hat{S}_e^\dagger(t) \hat{S}_f(t) \rangle \longrightarrow \langle \hat{a}^\dagger(t) \hat{a}(t) \rangle$

M. P. da Silva, D. Bozyigit, A. Wallraff, A. Blais. Phys. Rev. A **82**, 043804 (2010)
D. Bozyigit, ..., M. P. da Silva, A. Blais and A. Wallraff. Nature Physics **7**, 154 (2011)

Protocol

Repeat ~ $10^{6\text{-}9}$ times

1. Cool to ground state

$$|\psi_1\rangle = |g\rangle \otimes |0\rangle$$

2. Prepare arbitrary qubit state

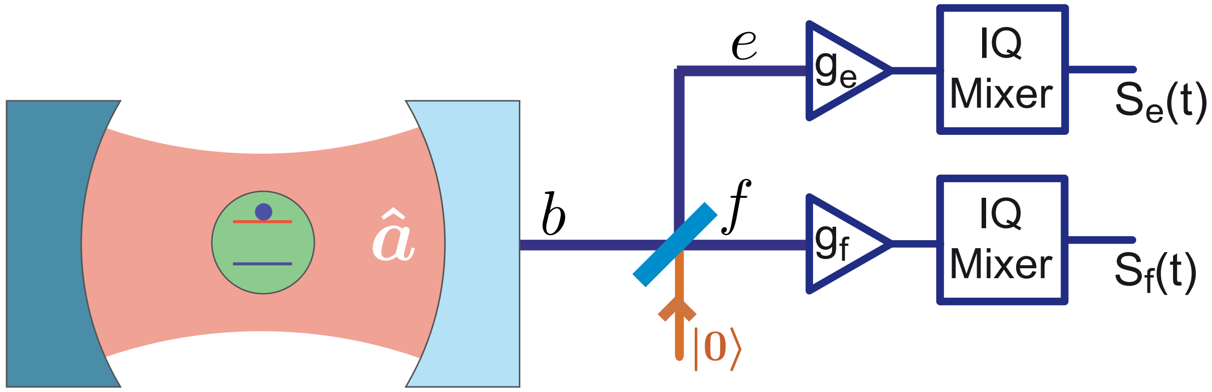
$$|\psi_2\rangle = (\alpha|g\rangle + \beta|e\rangle) \otimes |0\rangle$$

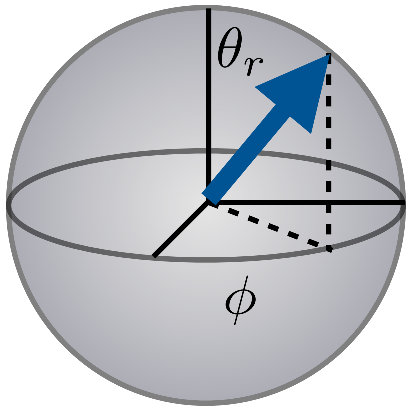
3. Transfer state to resonator

$$|\psi_3\rangle = |g\rangle \otimes (\alpha|0\rangle + \beta|1\rangle)$$

4. Measure quadratures, extract $S_{e,f}(t)$
   and calculate desired quantity

5. Average results





$$\alpha = \cos(\theta_r/2)$$
$$\beta = \sin(\theta_r/2)e^{i\phi}$$

M. P. da Silva, D. Bozyigit, A. Wallraff, A. Blais. Phys. Rev. A **82**, 043804 (2010)
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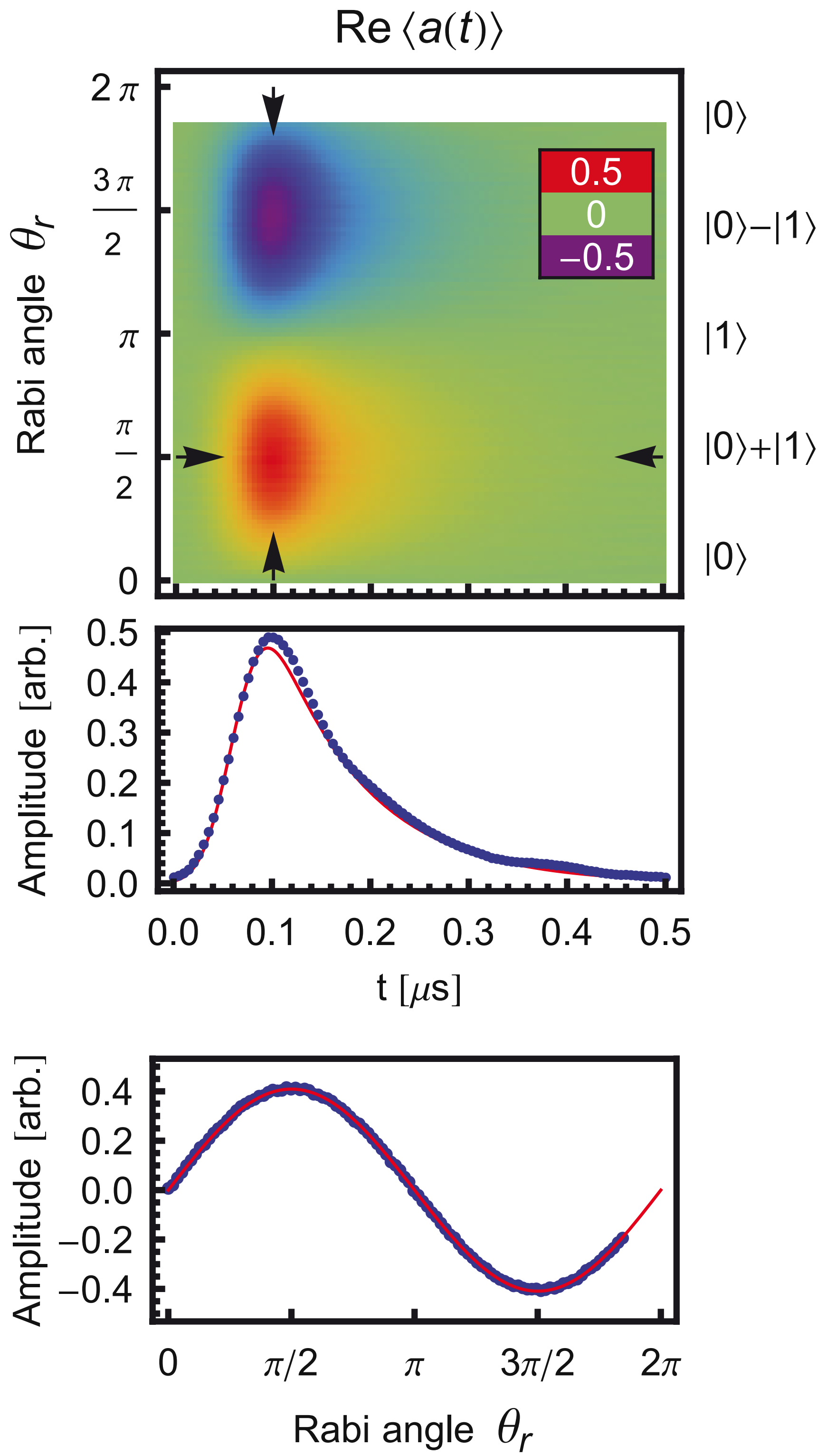
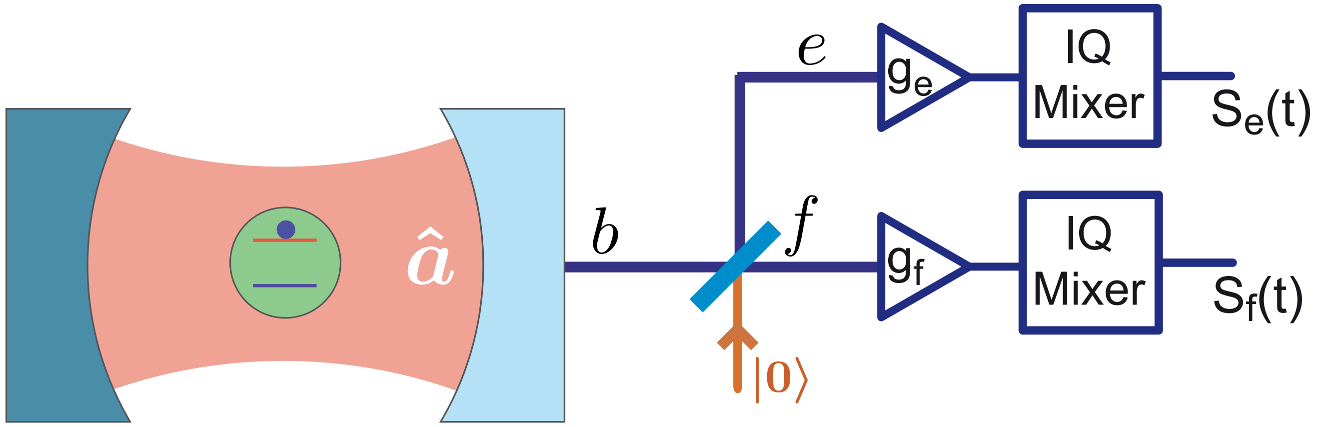


$$|\psi\rangle = (\alpha|0\rangle + \beta|1\rangle)$$

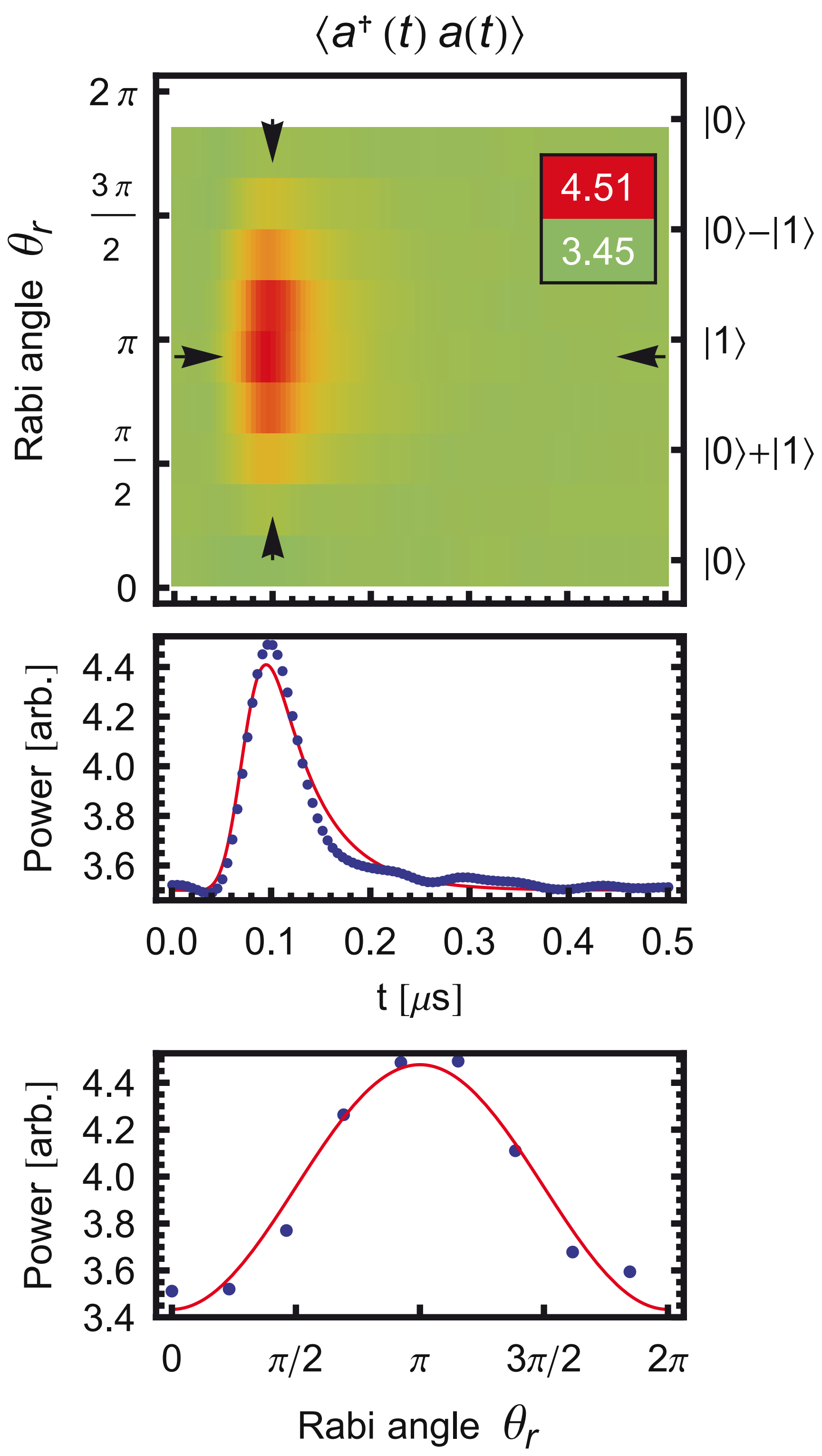
$$\langle \hat{S}_e(t)\rangle \propto \langle \hat{a}(t)\rangle = \alpha^*\beta\, e^{-\kappa t/2}$$

$$\propto \sin(\theta_r)e^{-\kappa t/2}/2$$



See also: A. A. Houck *et al.* Nature **449**, 328 (2007)
M. P. da Silva, D. Bozyigit, A. Wallraff, A. Blais. Phys. Rev. A **82**, 043804 (2010)
D. Bozyigit, ..., M. P. da Silva, A. Blais and A. Wallraff. Nature Physics **7**, 154 (2011)

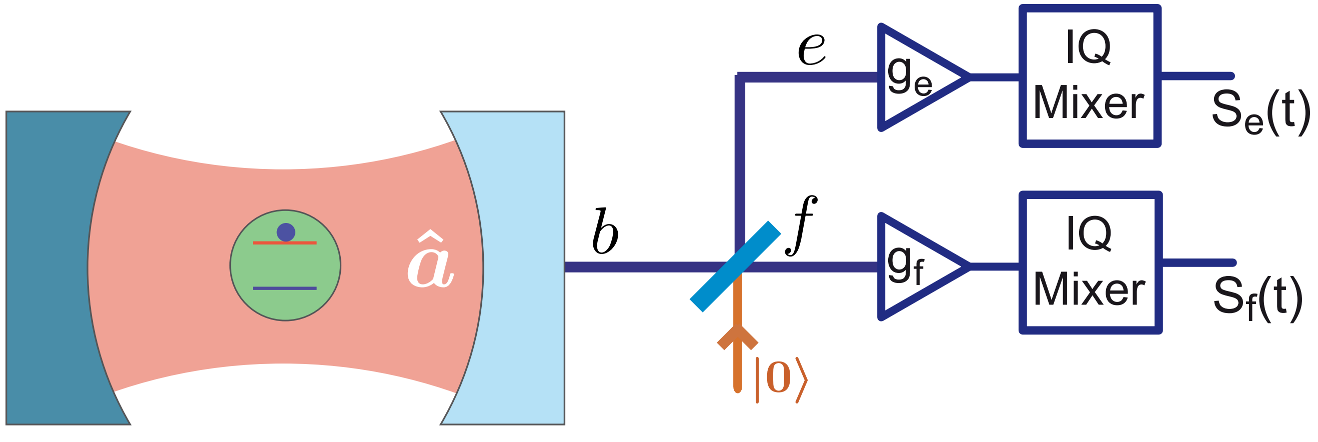
Same-time averages



$$|\psi\rangle = (\alpha|0\rangle + \beta|1\rangle)$$

$$\begin{aligned}\langle \hat{S}_e^\dagger(t)\hat{S}_f(t)\rangle &\propto \langle \hat{a}^\dagger(t)\hat{a}(t)\rangle + P(N_{ef}) \\ &= |\beta|^2\, e^{-\kappa t} + P(N_{ef})\end{aligned}$$

Can be (mostly) subtracted away with measurements in the ground state



See also: A. A. Houck *et al.* Nature **449**, 328 (2007)
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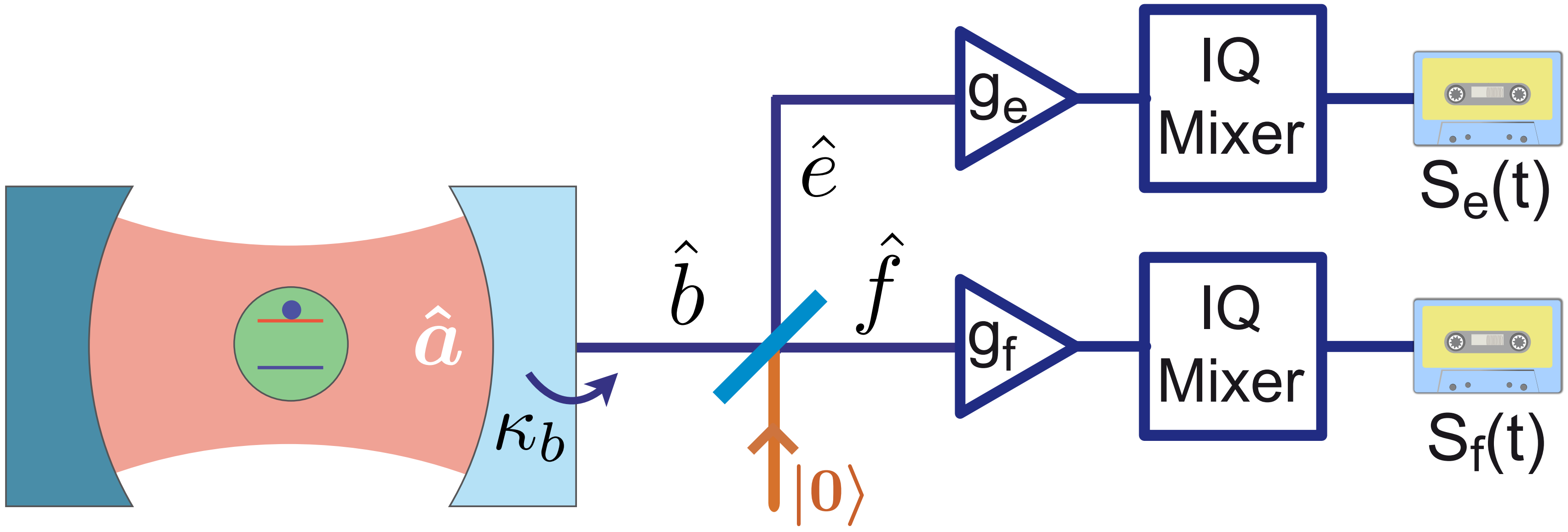
Two-time averages



Two-time correlation functions:

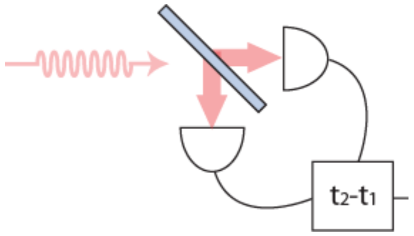
$$\langle \hat{S}_e^\dagger(t)\hat{S}_f(t+\tau)\rangle = \frac{\sqrt{g_e g_f}}{2} G^{(1)}(t,t+\tau) + \bar{N}_{ef}\delta(\tau) \qquad G^{(1)}(\tau) = \langle a^\dagger(t)a(t+\tau)\rangle$$

$$\langle \hat{S}_e^\dagger(t)\hat{S}_e^\dagger(t+\tau)\hat{S}_f(t+\tau)\hat{S}_f(t)\rangle = \frac{g_e g_f}{4} G^{(2)}(t,t+\tau) + G^{(2)}_{\text{noise}}(t,t+\tau)$$

$$+\frac{\sqrt{g_e g_f}}{2}\bar{N}_{ef}\left[\delta(\tau)G^{(1)}(t+\tau,t)\delta(0)G^{(1)}(t+\tau,t+\tau) + \delta(0)G^{(1)}(t,t) + \delta(\tau)G^{(1)}(t,t+\tau)\right]$$

M. P. da Silva, D. Bozyigit, A. Wallraff, A. Blais. Phys. Rev. A **82**, 043804 (2010)
D. Bozyigit, ..., M. P. da Silva, A. Blais and A. Wallraff. Nature Physics **7**, 154 (2011)
See also: Menzel et al., Phys. Rev. Lett. 105, 100401 (2010); Mariantoni et al., Phys. Rev. Lett. 105, 133601 (2010)

Two-time correlation functions: $G^{(2)}(\tau)$



Second order cross-correlation:

$$\langle \hat{S}_e^\dagger(t)\hat{S}_e^\dagger(t+\tau)\hat{S}_f(t+\tau)\hat{S}_f(t)\rangle = \frac{g_e g_f}{4} G^{(2)}(t,t+\tau) + G^{(2)}_{\text{noise}}(t,t+\tau)$$

$$+\frac{\sqrt{g_e g_f}}{2}\bar{N}_{ef}\left[\delta(\tau)G^{(1)}(t+\tau,t)\delta(0)G^{(1)}(t+\tau,t+\tau)+\delta(0)G^{(1)}(t,t)+\delta(\tau)G^{(1)}(t,t+\tau)\right]$$

$$G^{(2)}(\tau) = \langle a^\dagger(t+\tau)a^\dagger(t)a(t+\tau)a(t)\rangle$$

Pulsed single-microwave photon source

- Pulse delay: $t_p = 512 \text{ ns} \gg 1/\kappa,\ 1/T_1$

- Expected results: $G^2(\tau = nt_p) \propto \sin^4(\theta_r/2)$

$$G^2(0) = 0$$

M. P. da Silva, D. Bozyigit, A. Wallraff, A. Blais. Phys. Rev. A **82**, 043804 (2010)
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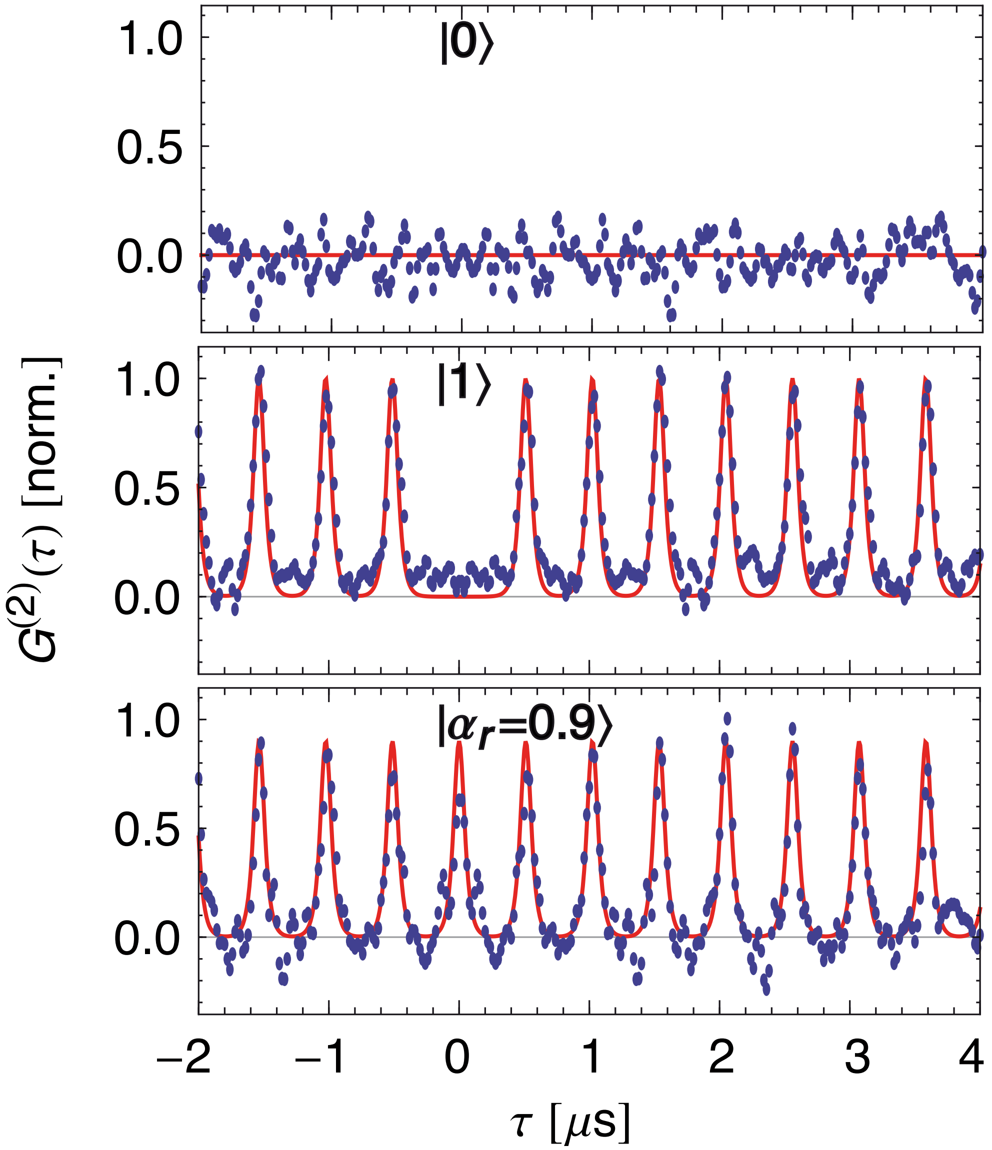
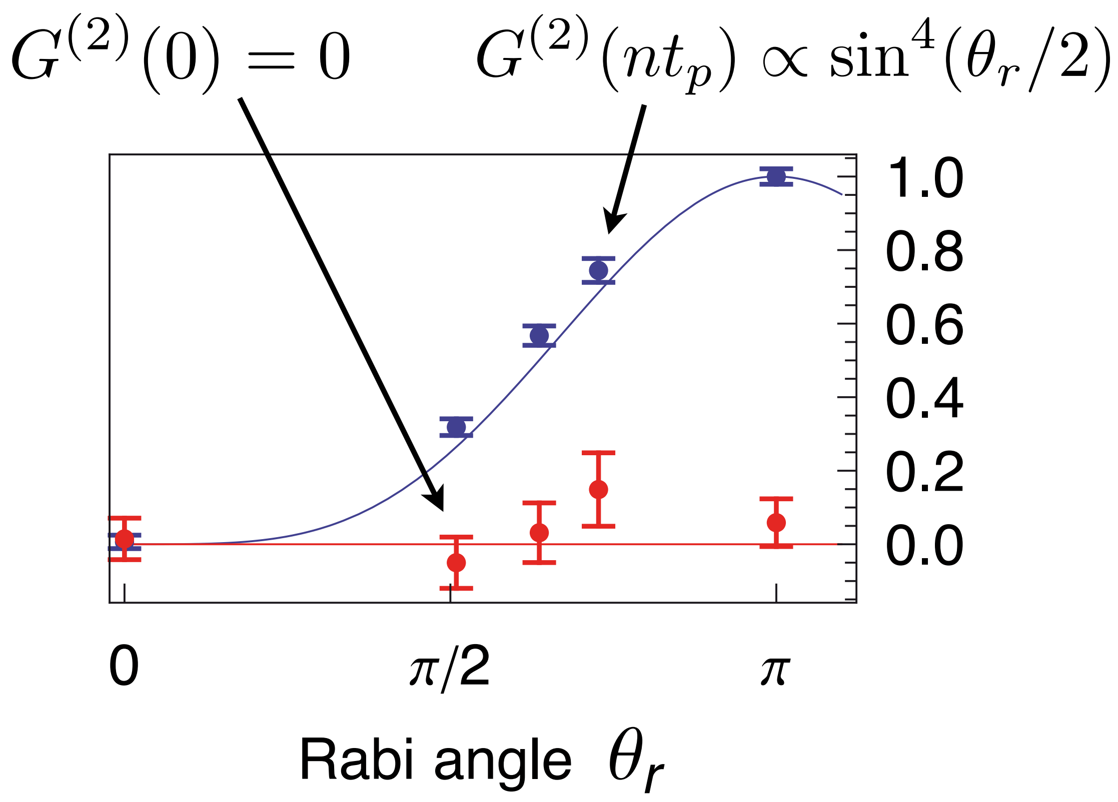
Two-time correlation functions: $G^{(2)}(\tau)$




$G^{(2)}(0) = 0$

$G^{(2)}(nt_p) \propto \sin^4(\theta_r/2)$

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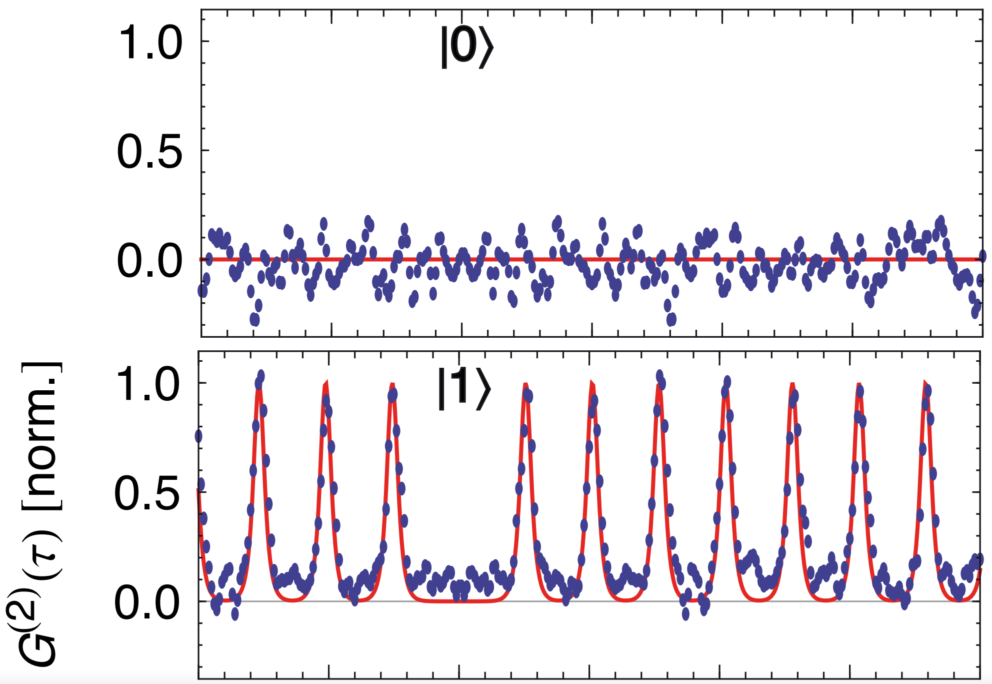
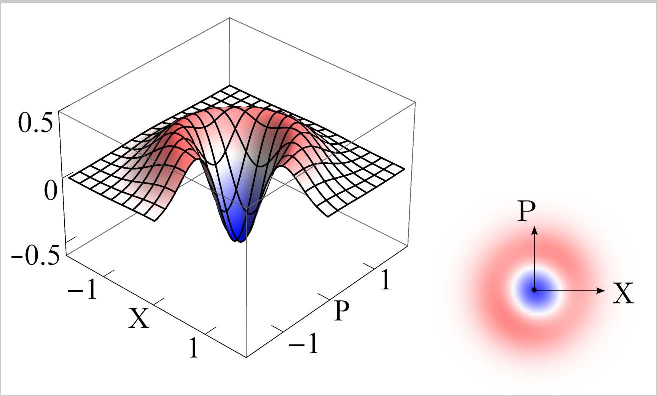
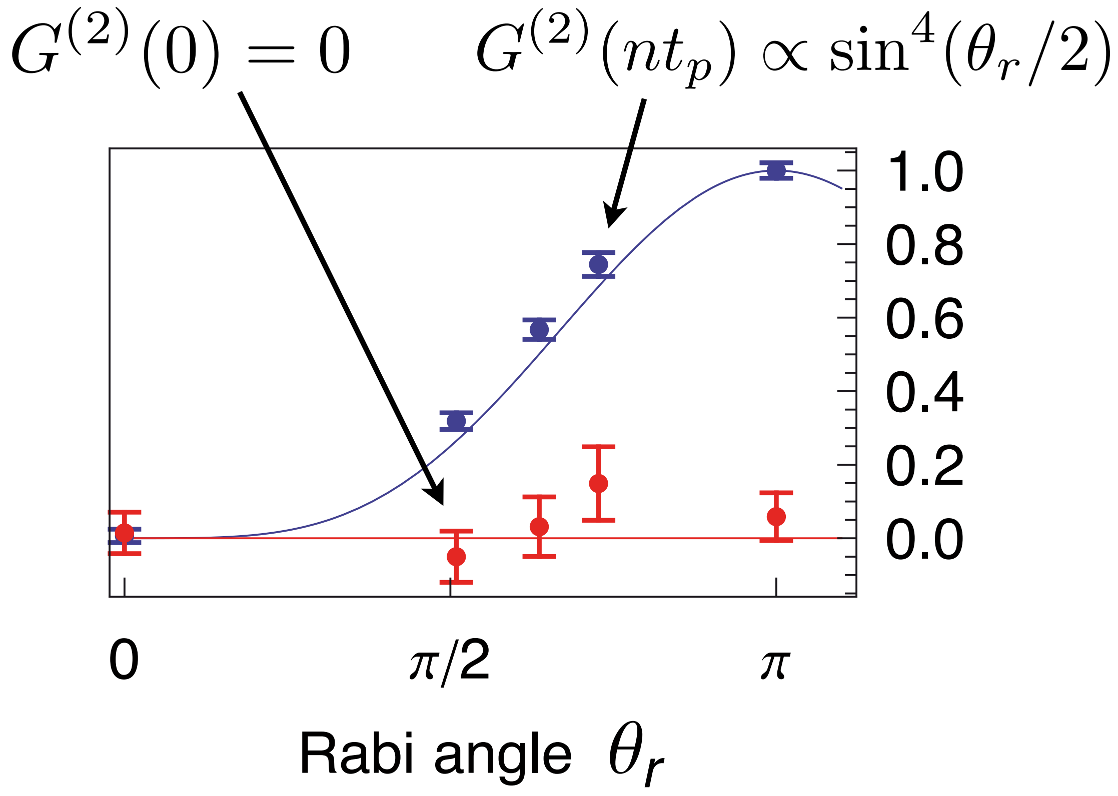
Two-time correlation functions: $G^{(2)}(\tau)$



Wigner function reconstruction of itinerant microwave photon



C. Eichler *et al*, Phys. Rev. Lett. **106**, 220503 (2011)


$G^{(2)}(0) = 0$

$G^{(2)}(nt_p) \propto \sin^4(\theta_r/2)$

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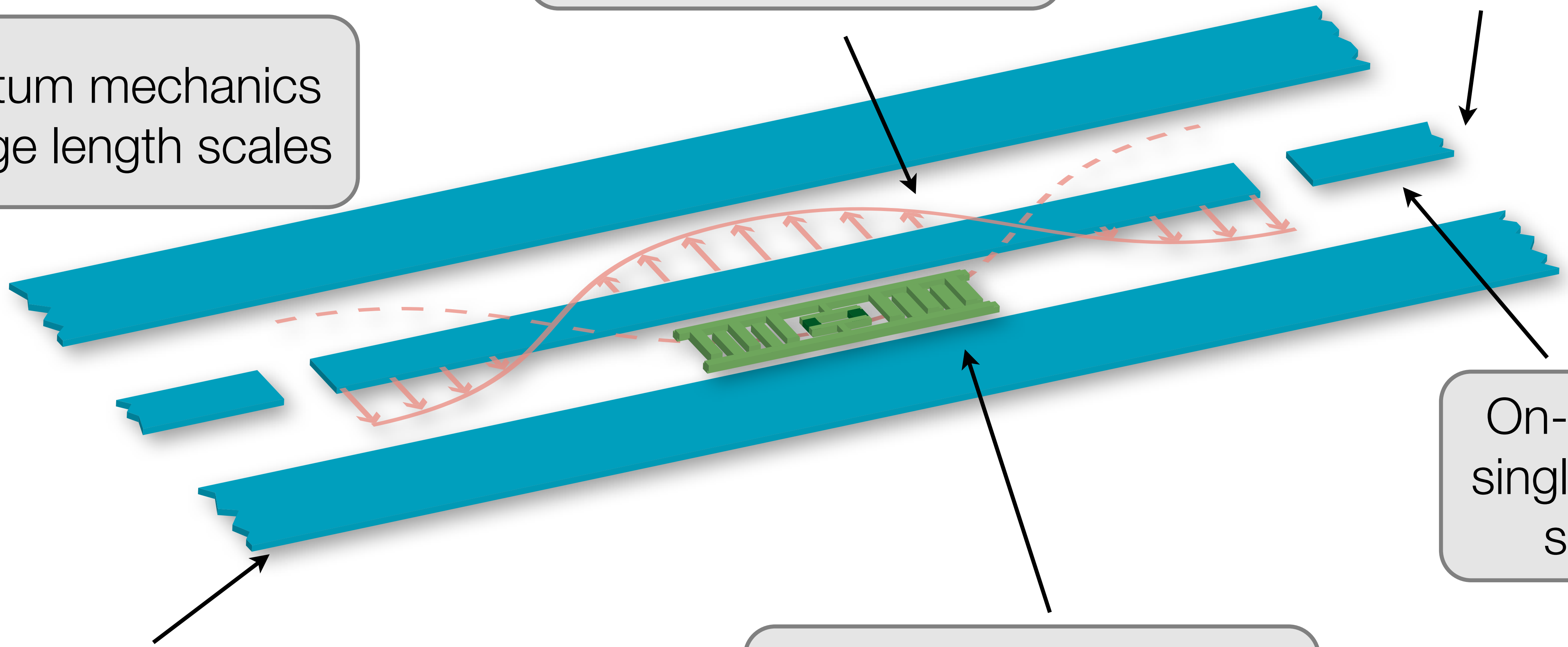
Summary



Quantum information processing

Antibunching: Quantum nature of microwave light demonstrated

Correlations characterize output field

Quantum mechanics on large length scales

On-demand single photon source

Superconducting high-Q resonator

Transmon qubits with long coherence times

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