Équipe de recherche en Physique de l'Information Quantique

Quantum information processing with superconducting circuits

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UNIVERSITÉ DE SHERBROOKE

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Motivations: A physicist point of view

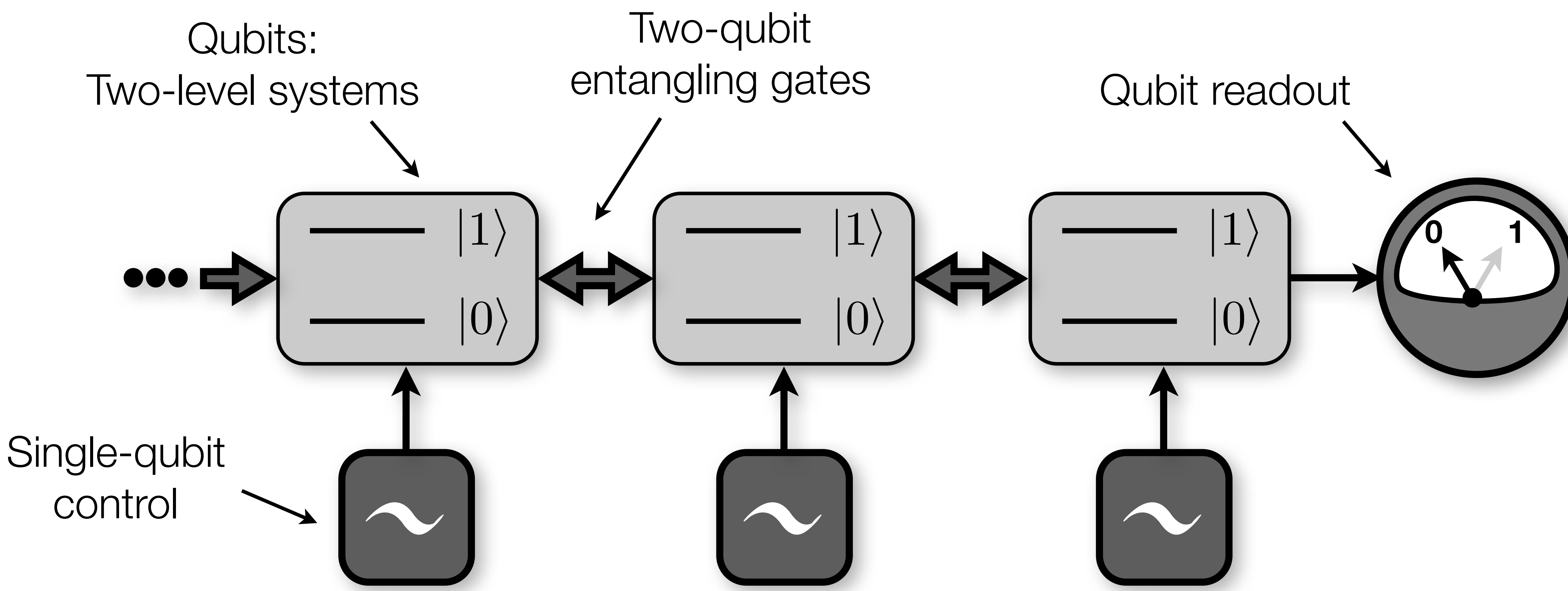
(Really) Long term goals:

- Large scale quantum computation
- Solve computationally hard (and interesting!) problems

Current goals:

- Quantum mechanics of big objects
- Understanding decoherence and quantum measurement
- Control of open quantum system
- Does quantum mechanics break down at large scales?

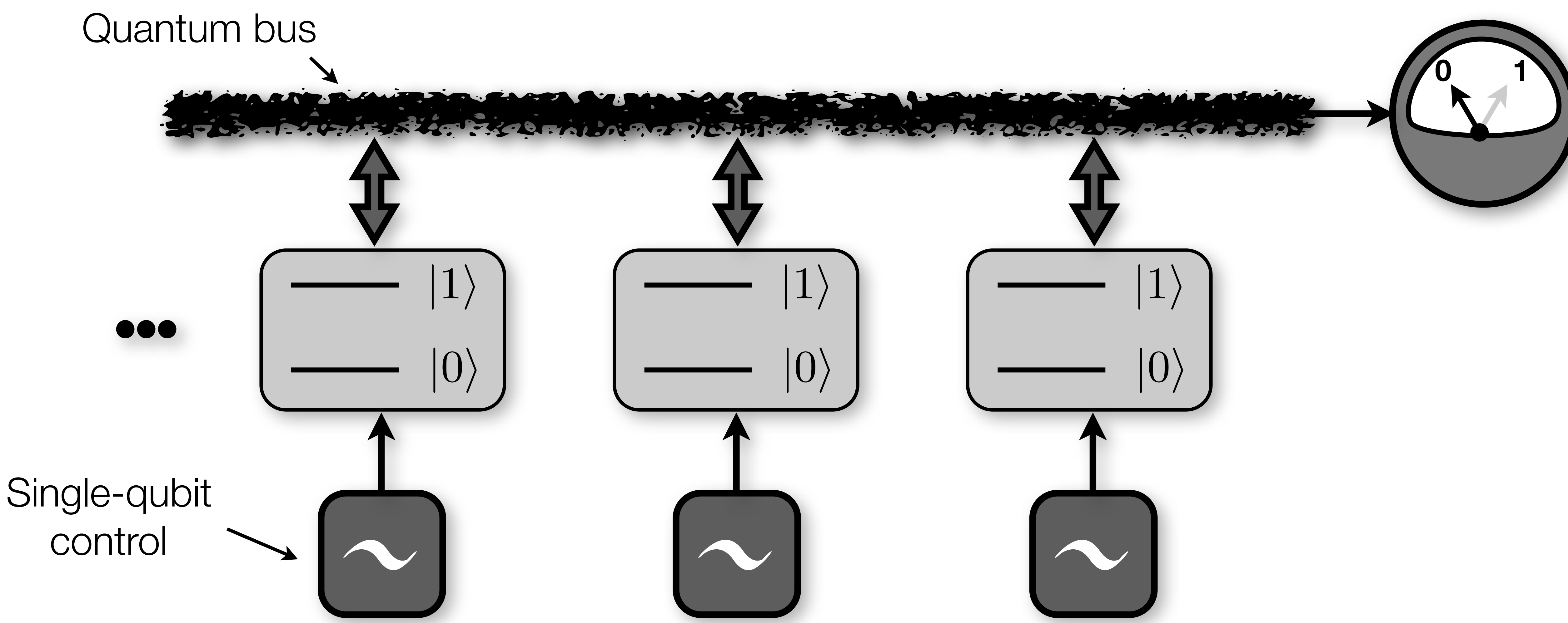
Quantum information processing: the challenge



- Conflicting requirements: *long* coherence, *fast* control and readout

D. DiVincenzo, Fortschritte der Physik **48**, 771 (2000)

Quantum information processing: the challenge



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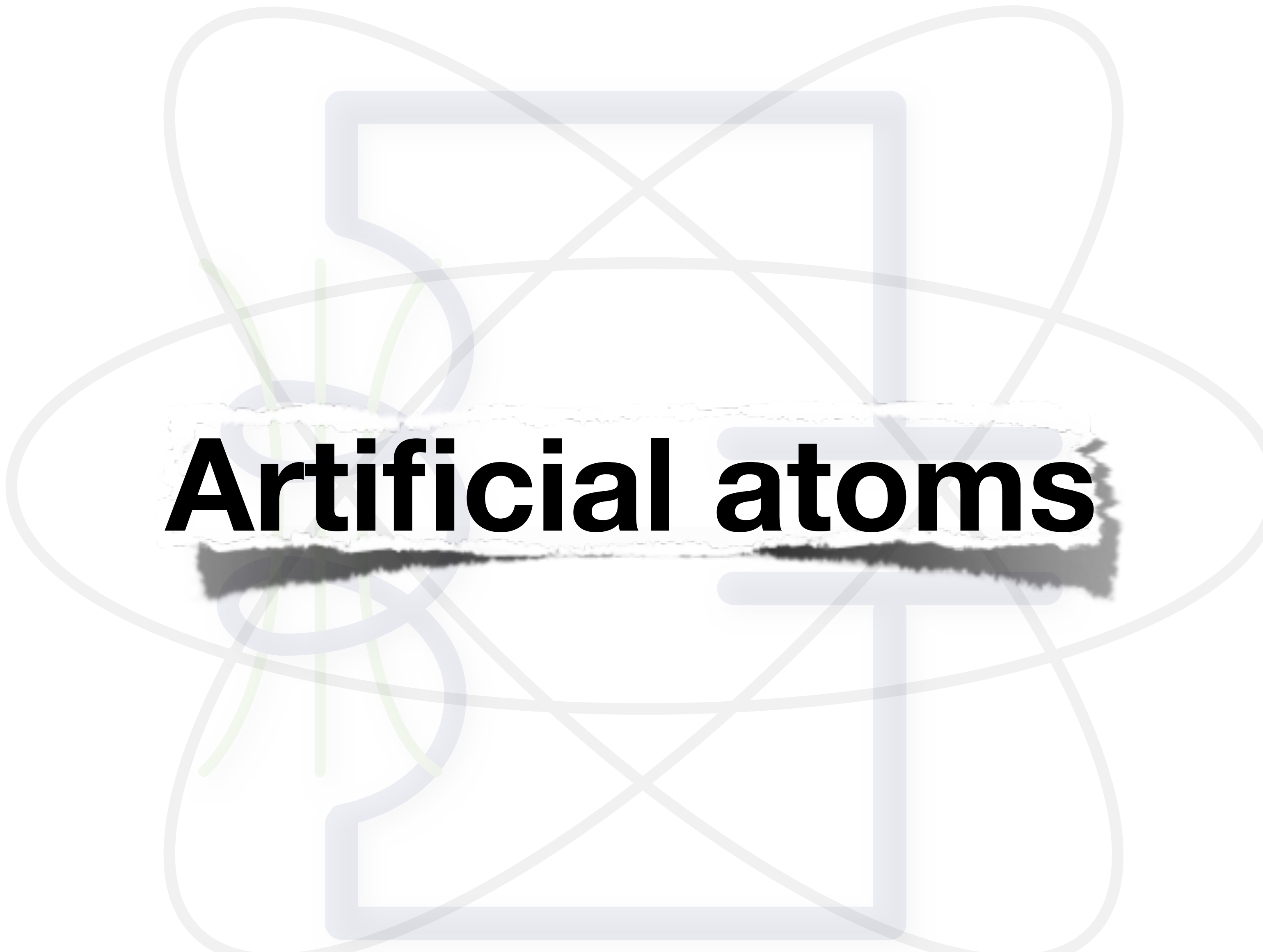
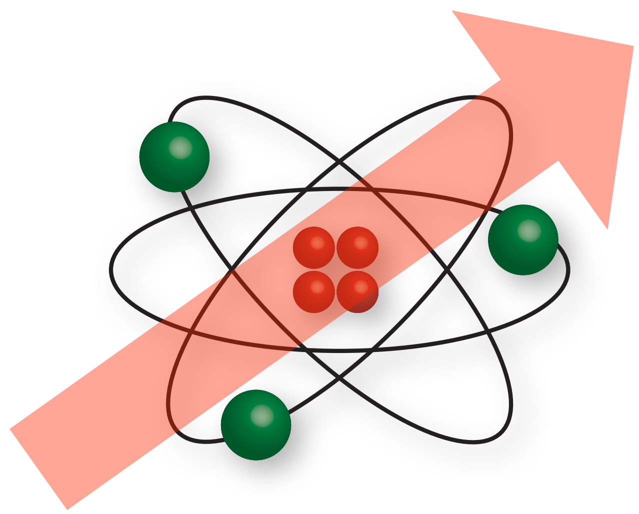
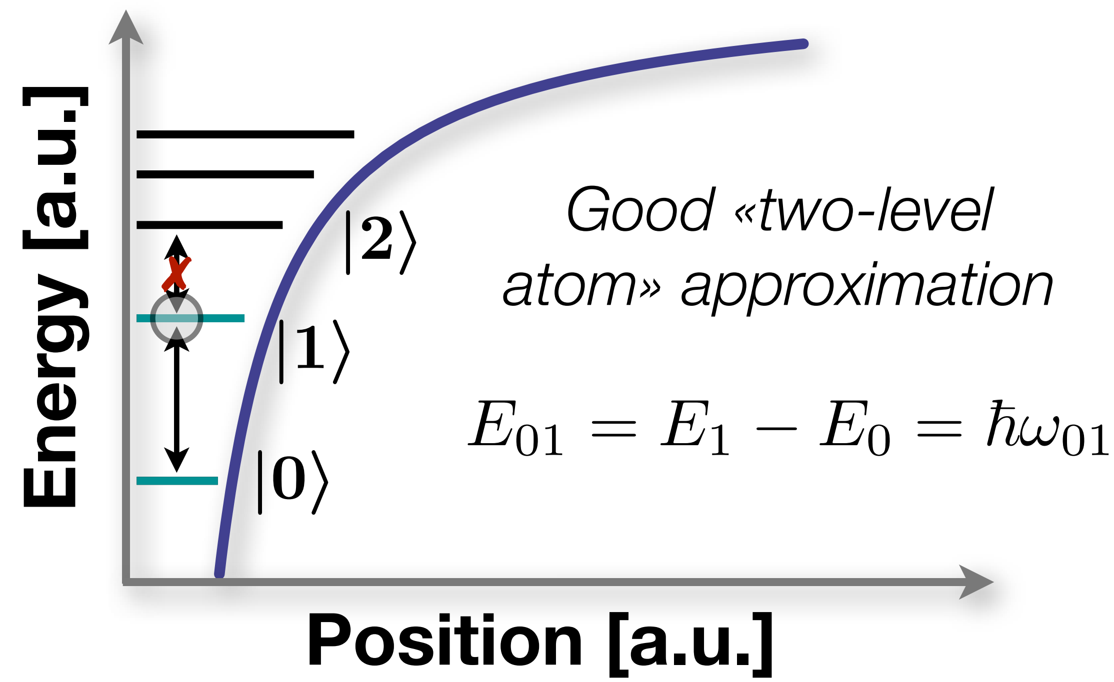
Artificial atoms



Nature's atoms





- 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 $^9Be_+$ have long decay and coherence times

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

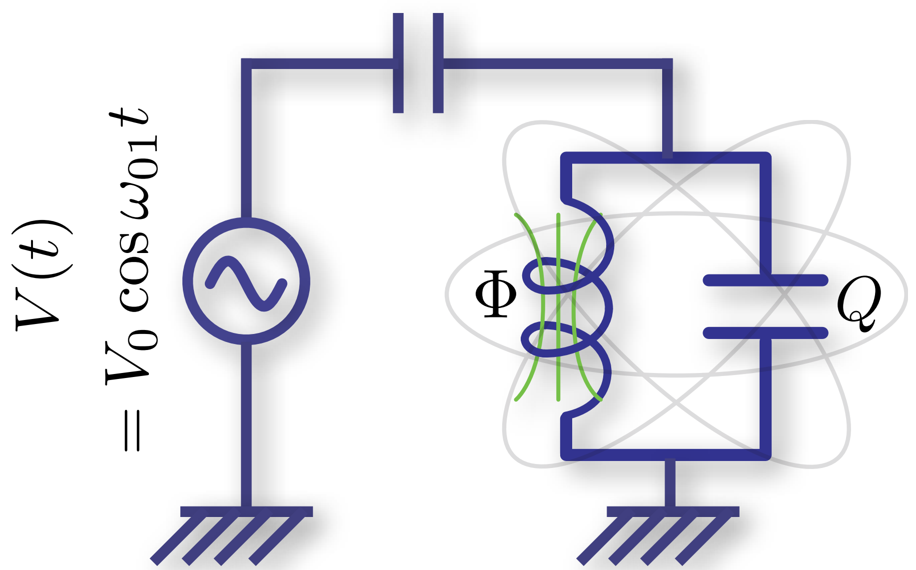
- Reasonably short π-pulse time

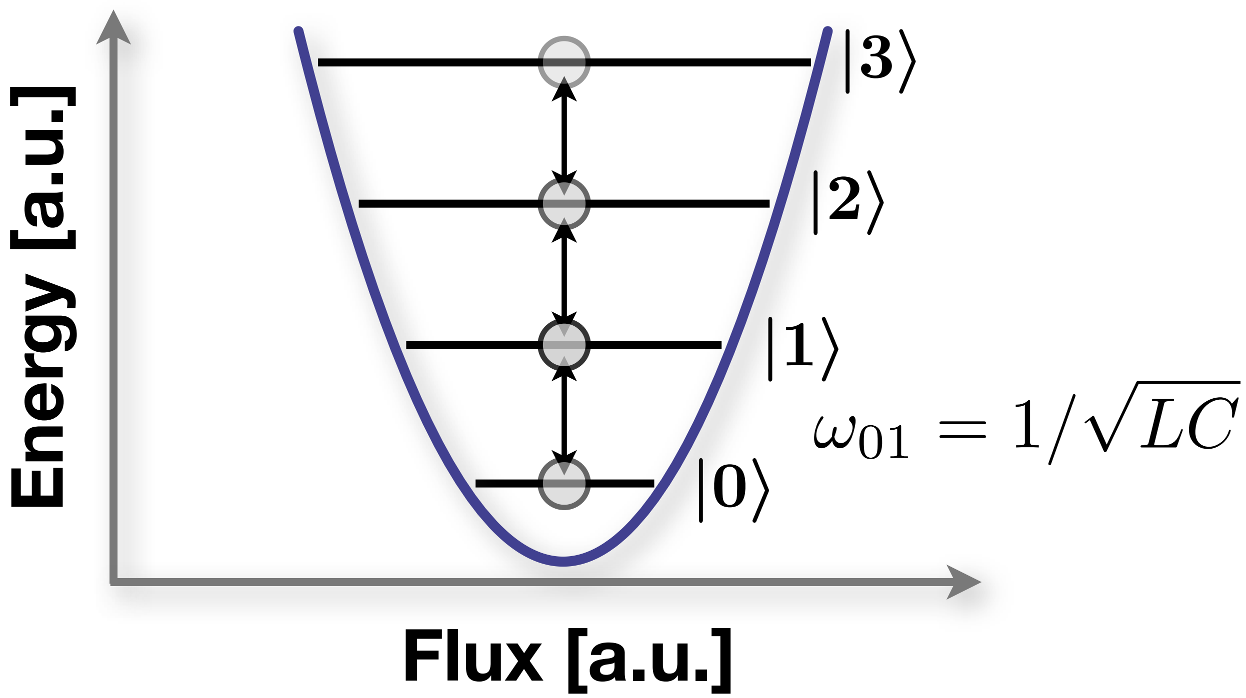
$$T_\pi \sim 5\ \mu\text{s}$$

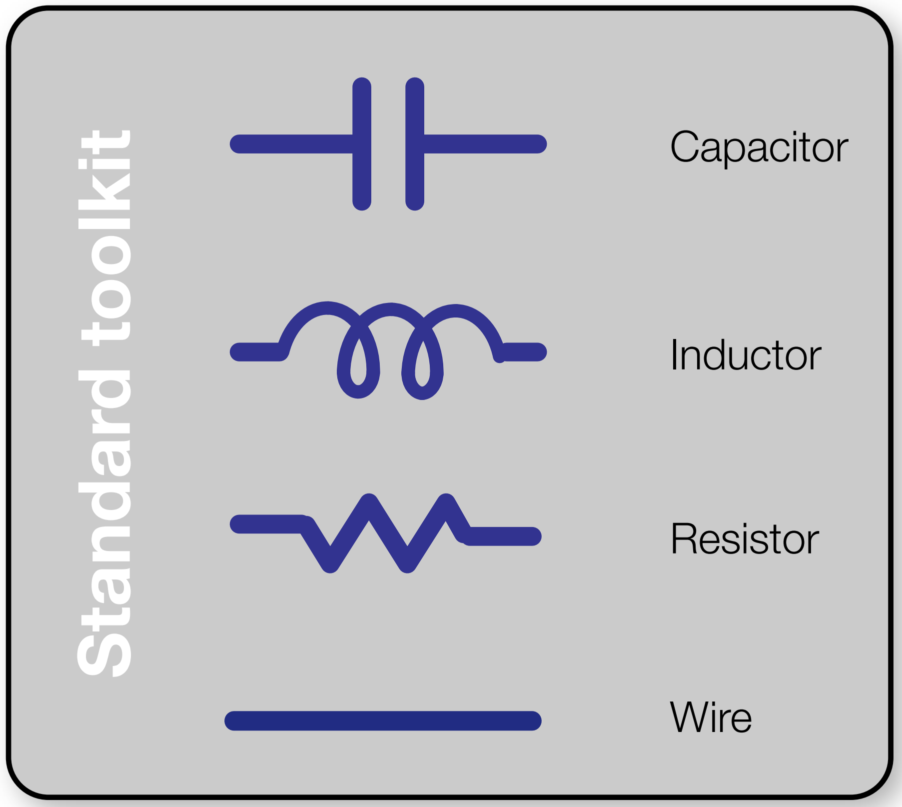
- Low error per gates: ~ 0.48%

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

Artificial atoms: a toolkit

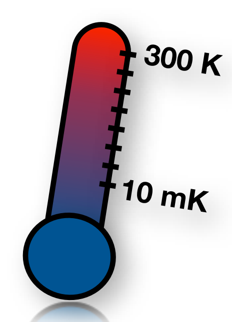






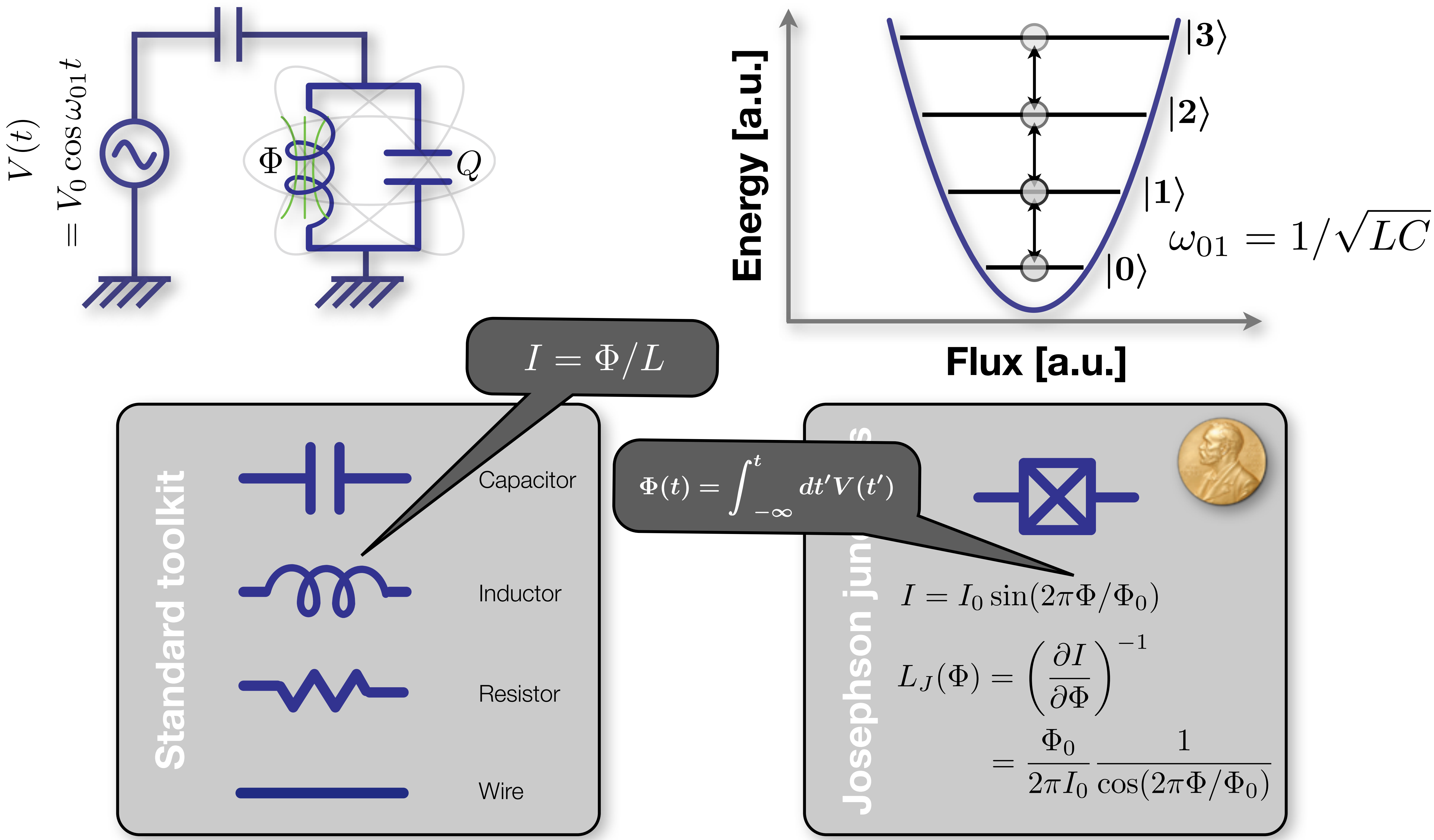
- Initialization to the ground state is simple

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

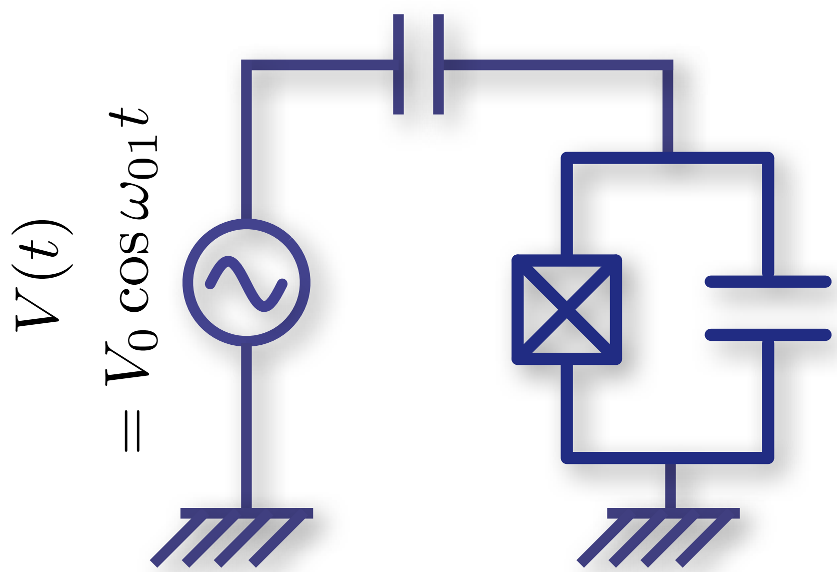


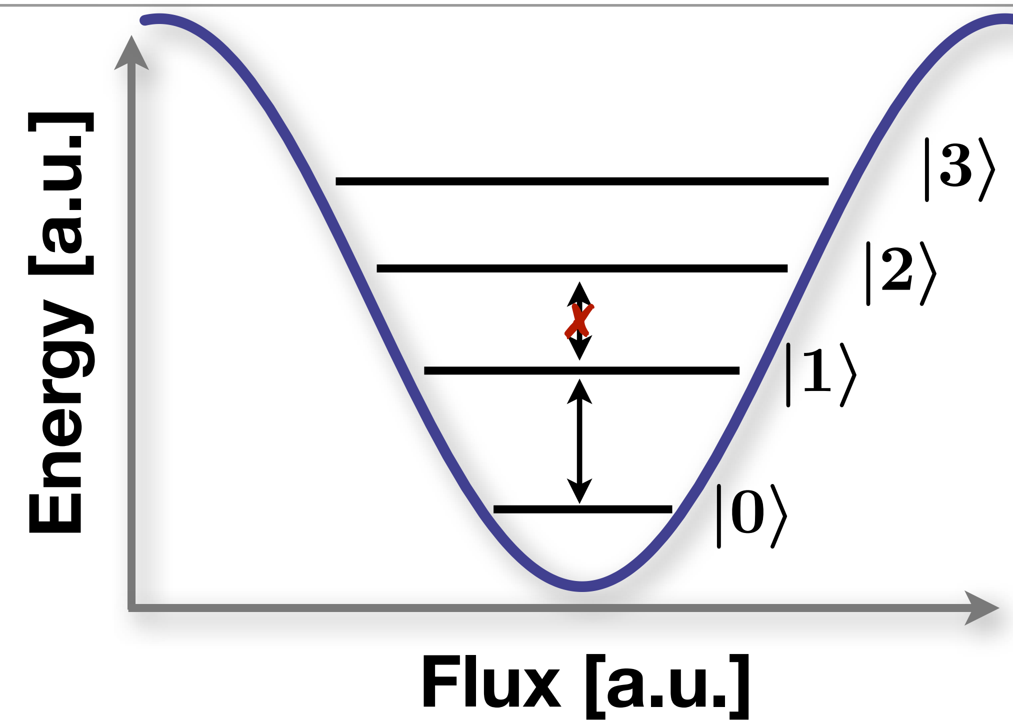
- Not a good «two-level» atom...

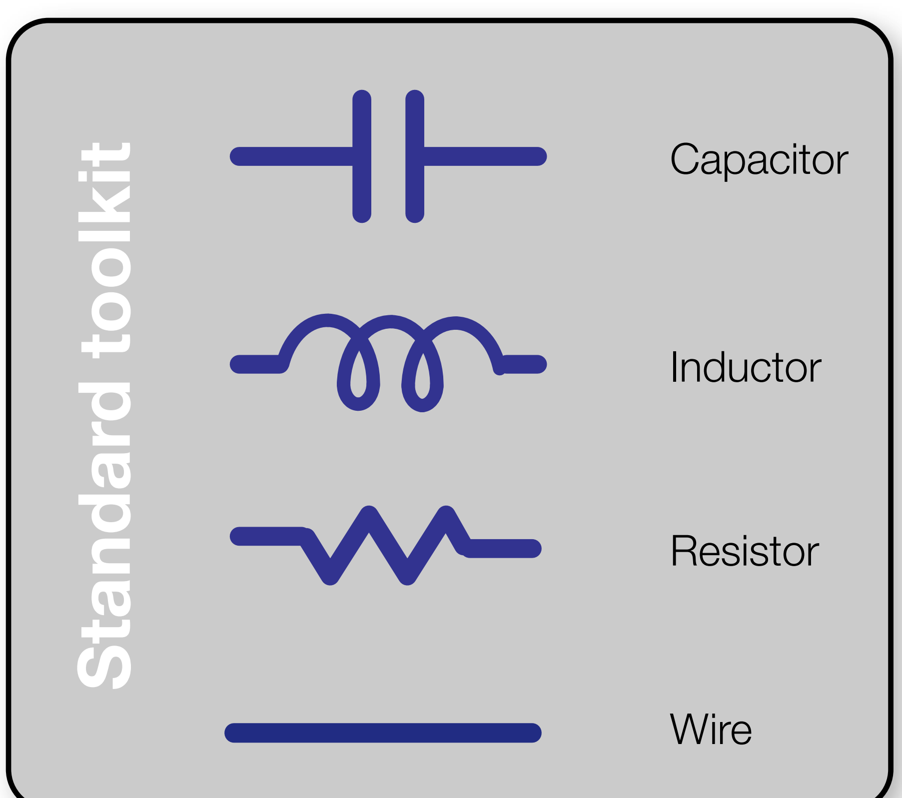
Artificial atoms: potential shaping



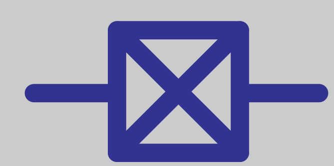
Artificial atoms: potential shaping







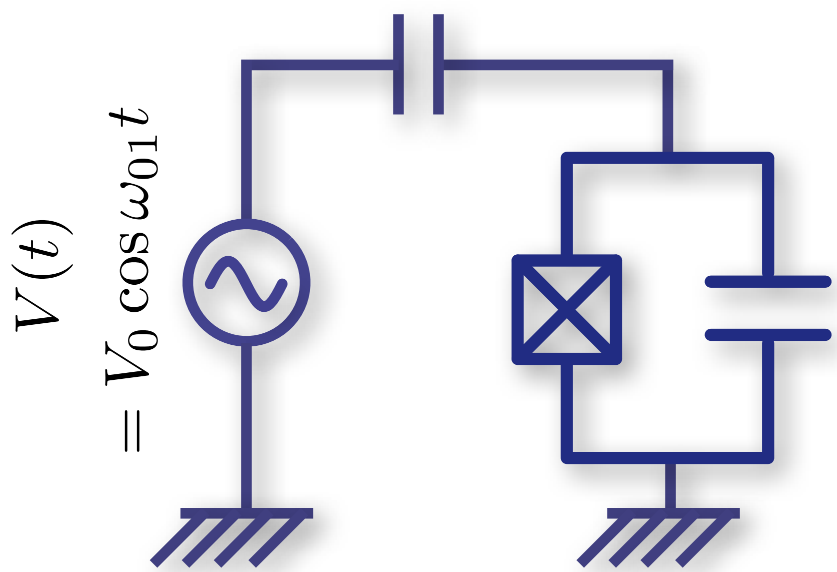
Josephson junctions

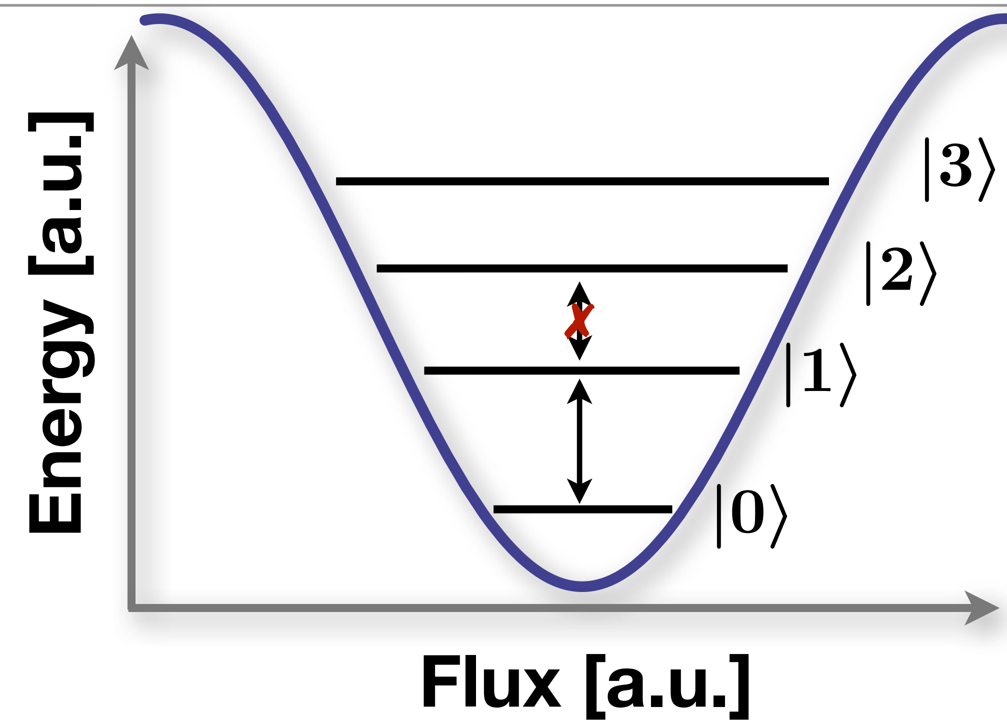


$$I = I_0 \sin(2\pi\Phi/\Phi_0)$$

$$L_J(\Phi) = \left(\frac{\partial I}{\partial \Phi}\right)^{-1} = \frac{\Phi_0}{2\pi I_0} \frac{1}{\cos(2\pi\Phi/\Phi_0)}$$

Artificial atoms: fast and coherent

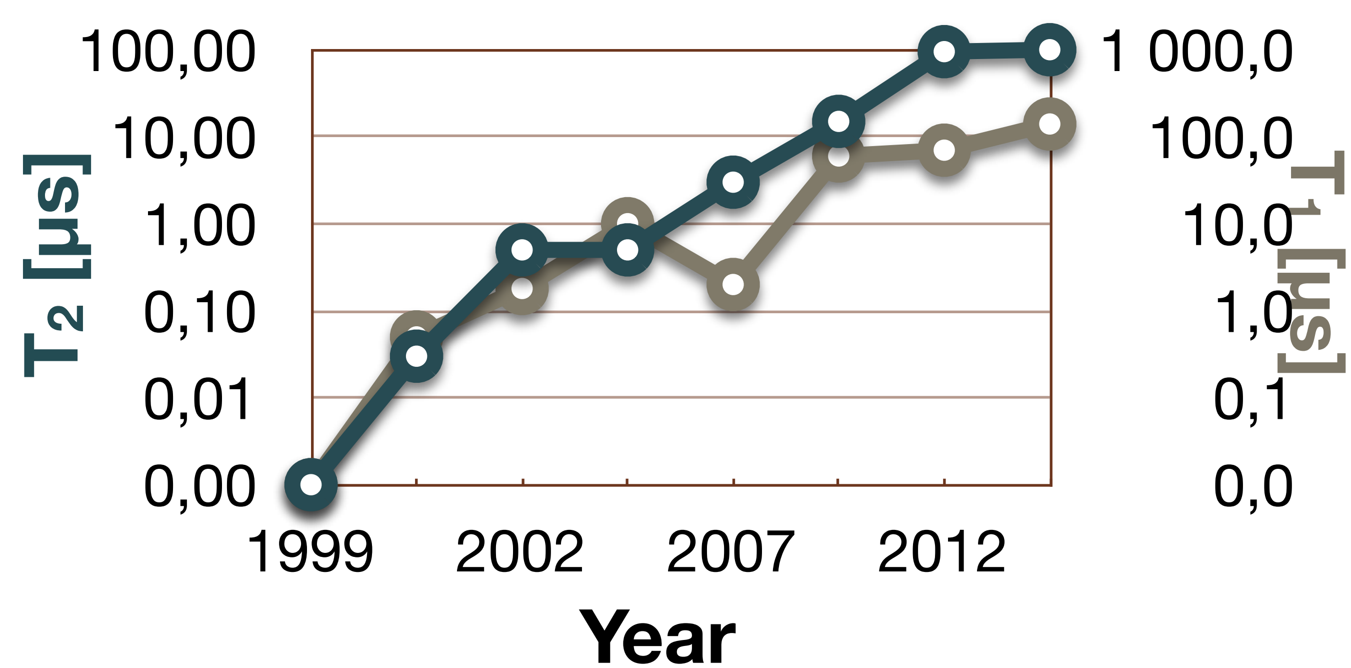




- Very short π-pulse time

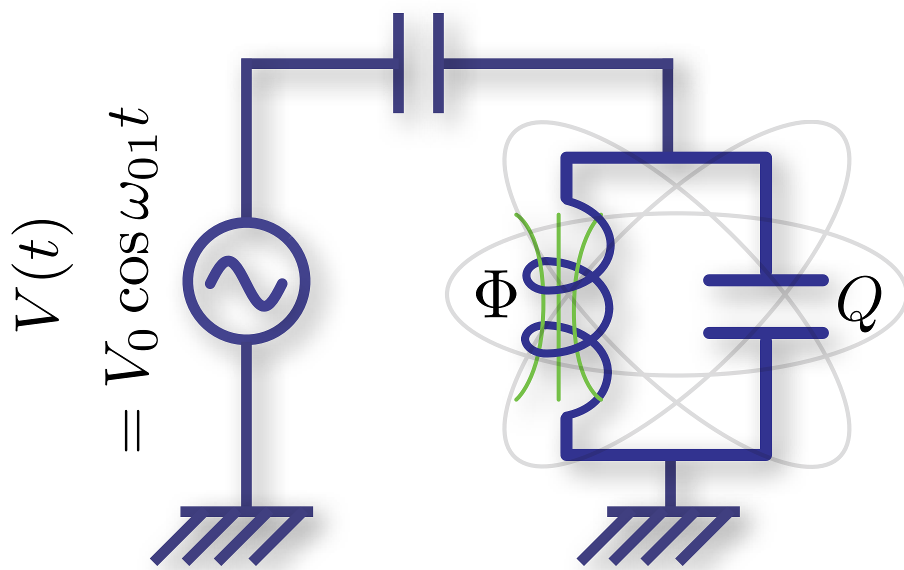
$$T_\pi \sim 4 - 20 \text{ ns}$$

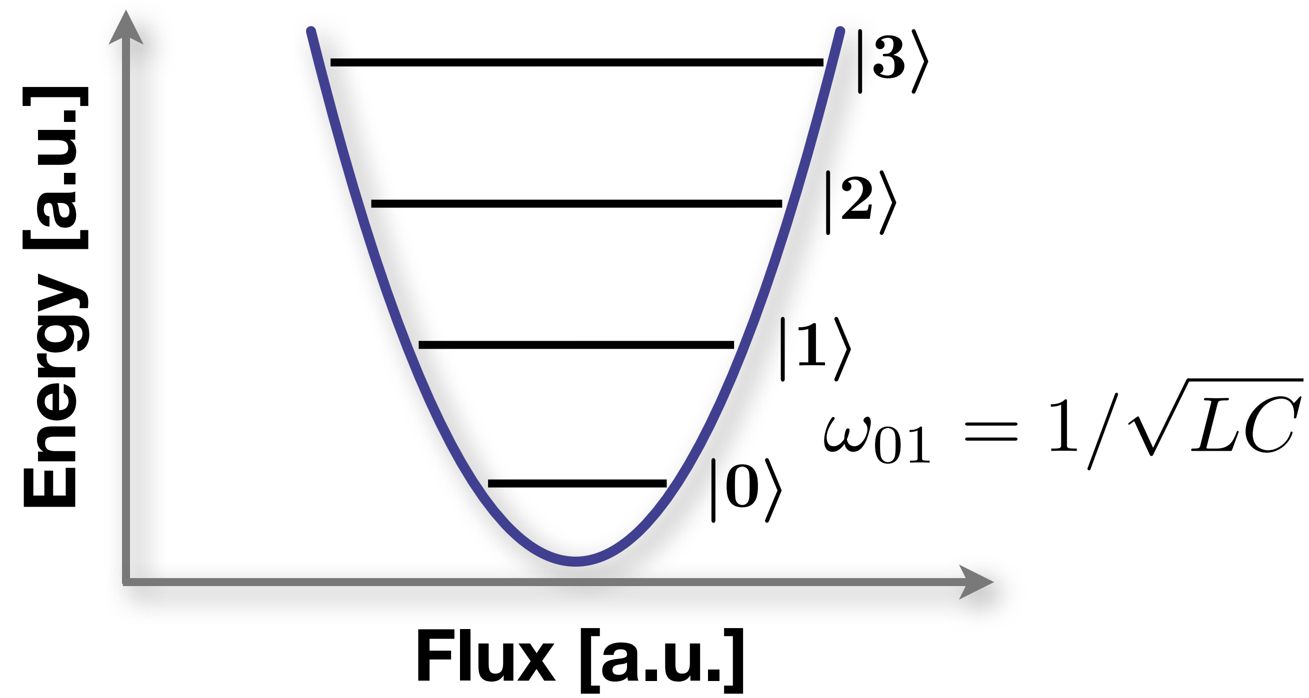
- Big improvements in relaxation and dephasing times in last 10 years
- Error per gates of 0.2%, similar to trapped ion results



Low error per gates: E. Magesan *et al*, Phys. Rev. Lett. **109**, 080505 (2012)
Long T_1 and T_2: H. Paik *et al*, Phys. Rev. Lett. **107**, 240501 (2011)

Back to basic: the harmonic oscillator





$$\hat{H} = \frac{\hat{Q}^2}{2C} + \frac{1}{2} C \omega_{01}^2 \hat{\Phi}^2$$

Kinetic energy **Potential energy**

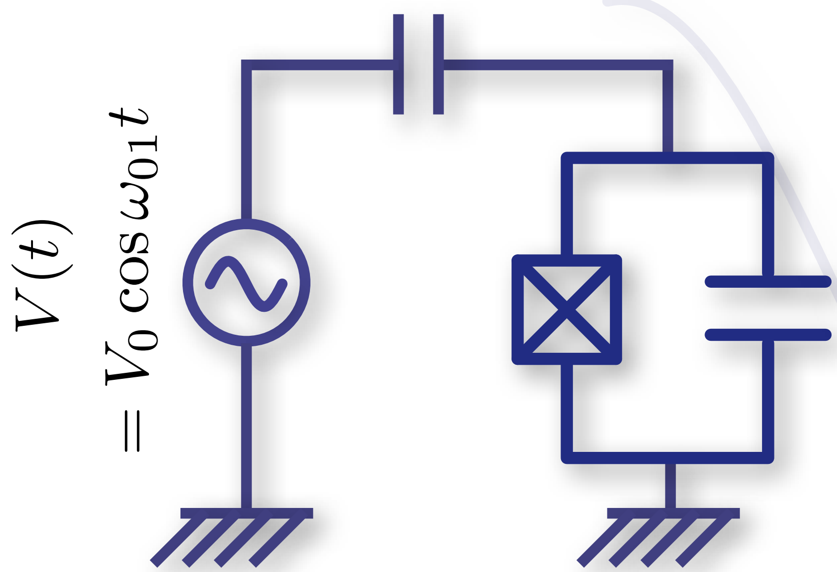
$$\hat{Q} = i\sqrt{\frac{\hbar}{2Z_0}}(\hat{a}^\dagger - \hat{a})$$

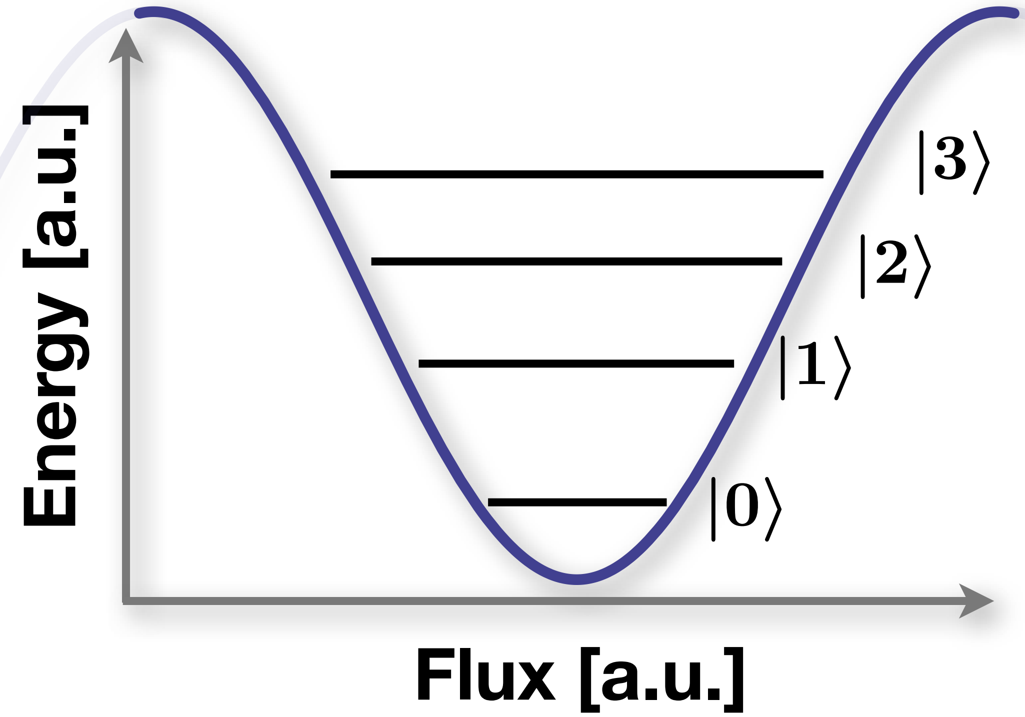
$$\hat{\Phi} = \sqrt{\frac{\hbar Z_0}{2}}(\hat{a}^\dagger + \hat{a})$$

$$Z_0 = \sqrt{\frac{L}{C}}$$

$$\hat{H} = \hbar\omega_{01}(\hat{a}^\dagger \hat{a} + 1/2)$$

Josephson energy

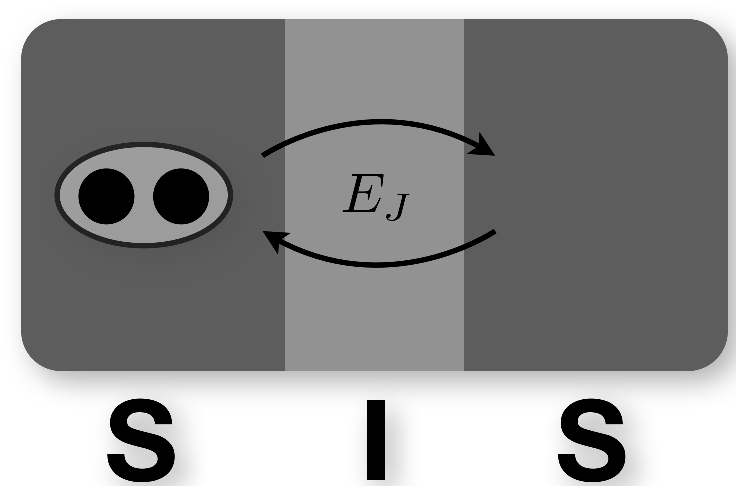




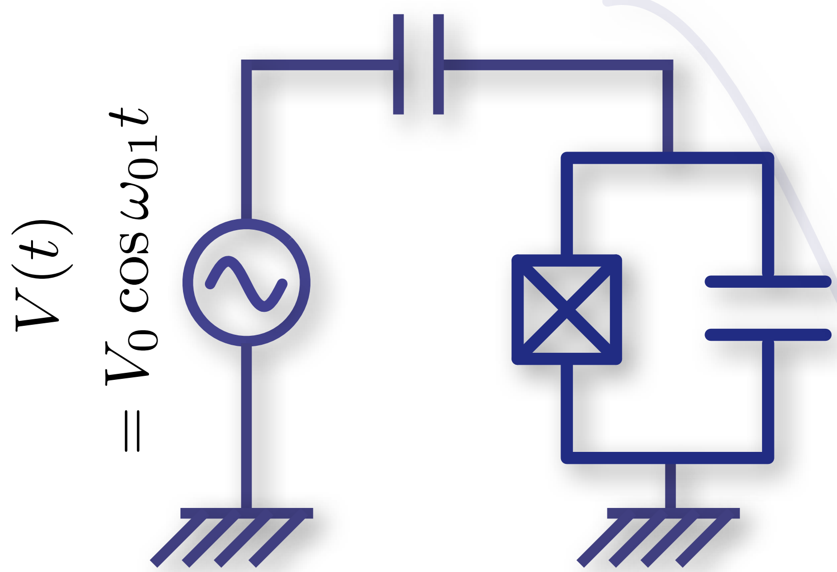
$$E = \int dt V(t) I(t)$$

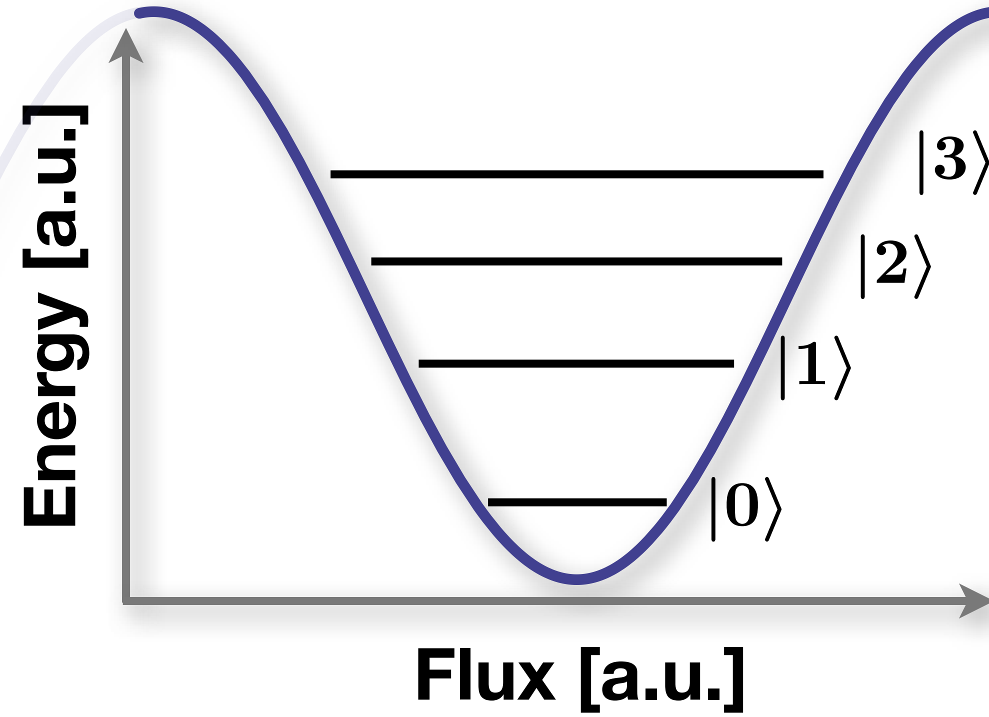
$$= \int \cancel{dt} \left(\frac{d\Phi}{\cancel{dt}} \right) \left(I_0 \sin \frac{2\pi\Phi}{\Phi_0} \right)$$

$$= -E_J \cos \frac{2\pi\Phi}{\Phi_0}$$



Josephson energy





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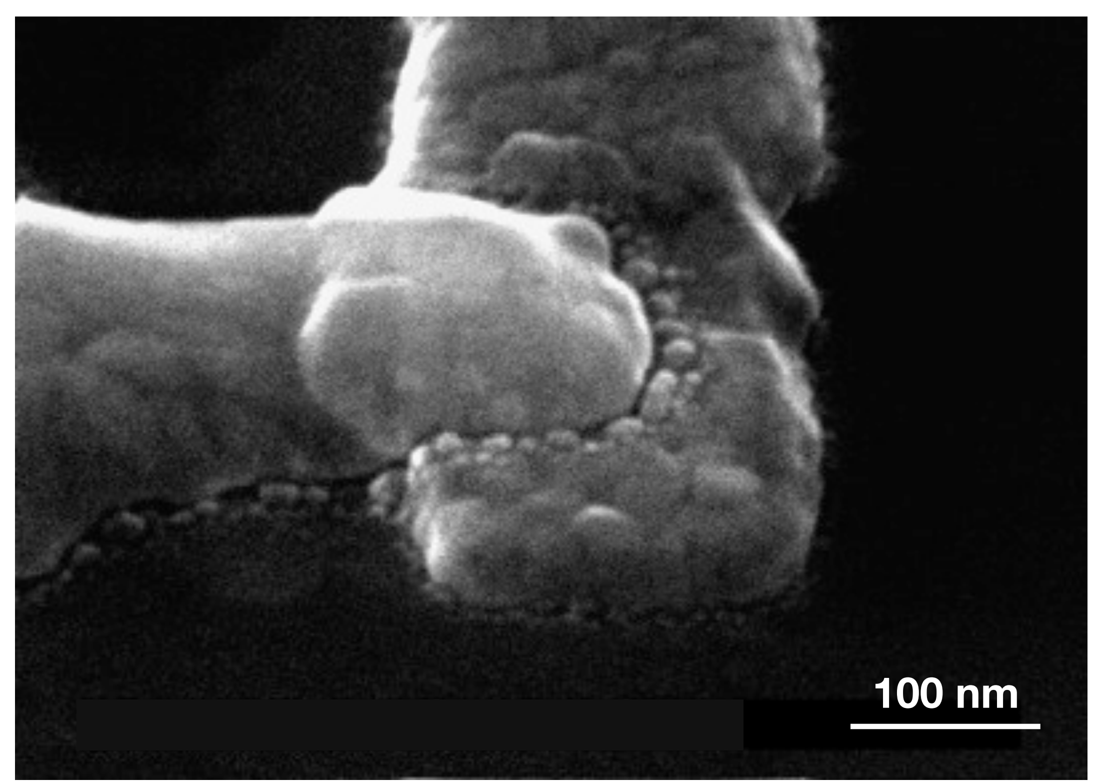
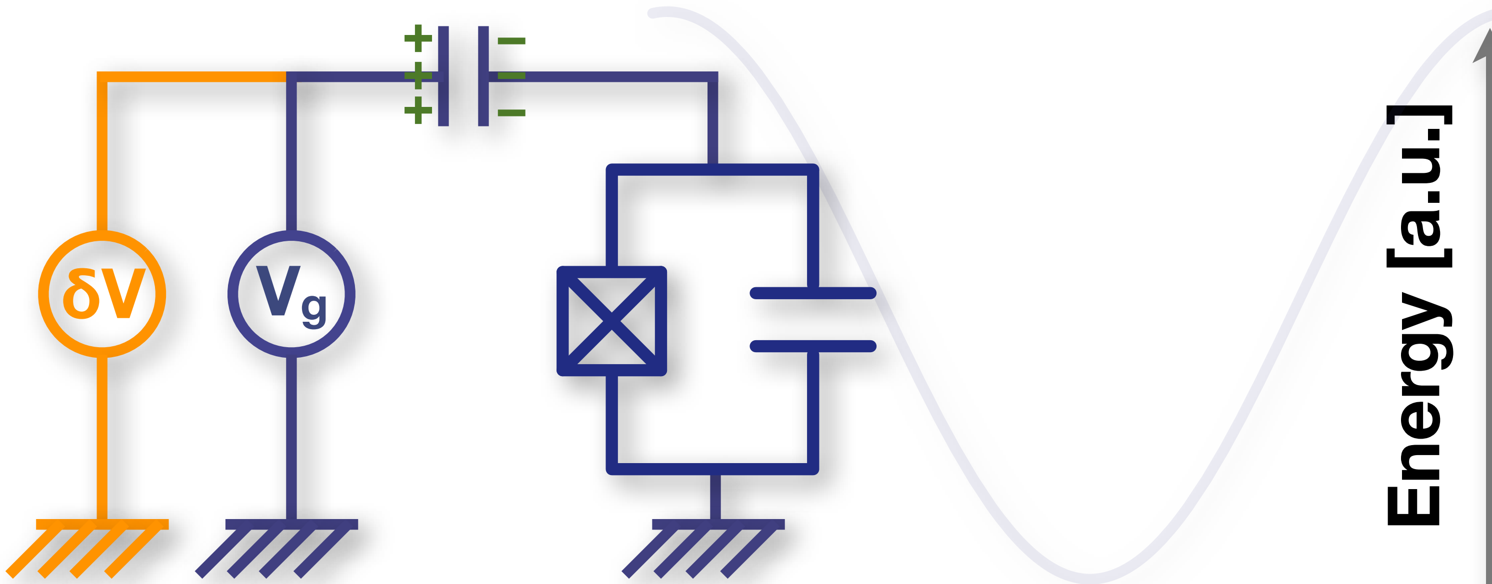
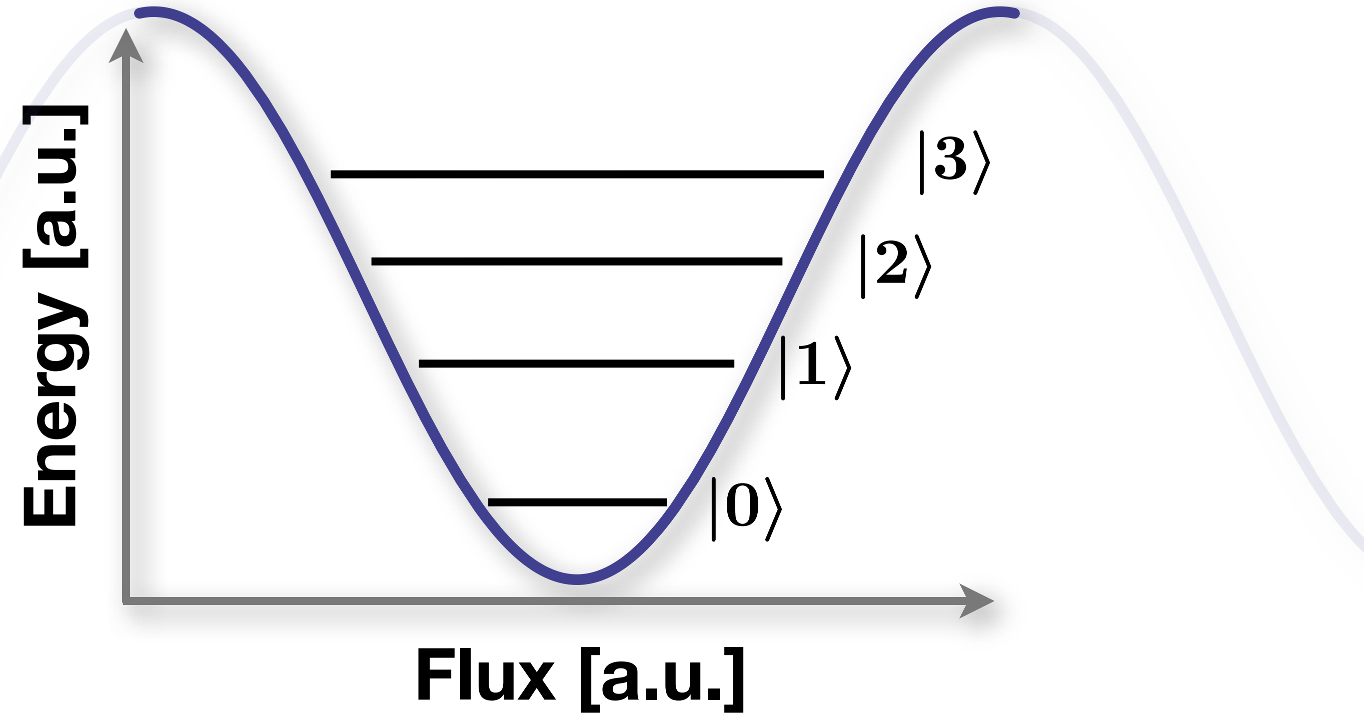


Hamiltonian of a superconducting qubit





$$H = \frac{\hat{Q}^2}{2C} - E_J \cos\frac{2\pi\hat{\Phi}}{\Phi_0}$$

$$= \frac{(2e)^2}{2C}\hat{n}^2 - E_J\cos\hat{\phi}$$

$$= 4E_C(\hat{n} - n_g)^2 - E_J\cos\hat{\phi}$$

Optimal choice of E_J/E_C?

Interlude: eigenvalues and eigenstates

Find E_k and $|\psi_k\rangle$ satisfying $\hat{H}|\psi_k\rangle = E_k|\psi_k\rangle$

$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos\hat{\phi}$$

In the phase basis, $\hat{\phi}|\phi\rangle = \phi|\phi\rangle$, need to solve:

$$\langle\phi|\hat{H}|\psi_k\rangle = E_k\langle\phi|\psi_k\rangle = E_k\psi_k(\phi)$$

$$\hat{n} \to -i\frac{\partial}{\partial\phi}$$

$$\left(\hat{P} \to -i\hbar\frac{\partial}{\partial x}\right)$$

$$\Rightarrow \quad \left[4Ec\left(-i\frac{\partial}{\partial\phi} - n_g\right)^2 - E_J\cos\phi\right]\psi_k(\phi) = E_k\psi_k(\phi)$$

```
DSolve[4 Ec (-ψk''[ϕ] + ⅈ ng ψk'[ϕ] + ng^2 ψk[ϕ]) - Ej Cos[ϕ] ψk[ϕ] == Ek ψk[ϕ], ψk[ϕ], ϕ]
```

```
ψk[ϕ] = e^(1/2 ⅈ ϕ ng) (C[1] MathieuC[Ek/Ec - 3 ng^2, -Ej/(2 Ec), ϕ/2] + C[2] MathieuS[Ek/Ec - 3 ng^2, -Ej/(2 Ec), ϕ/2])
```

J. Koch et al. Phys. Rev. A **76**, 042319 (2007)

Interlude: eigenvalues and eigenstates

Find E_k and $|\psi_k\rangle$ satisfying $\hat{H}|\psi_k\rangle = E_k|\psi_k\rangle$

$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos\hat{\phi}$$

In the charge basis, $\hat{n}|n\rangle = n|n\rangle$, *H* takes the form:

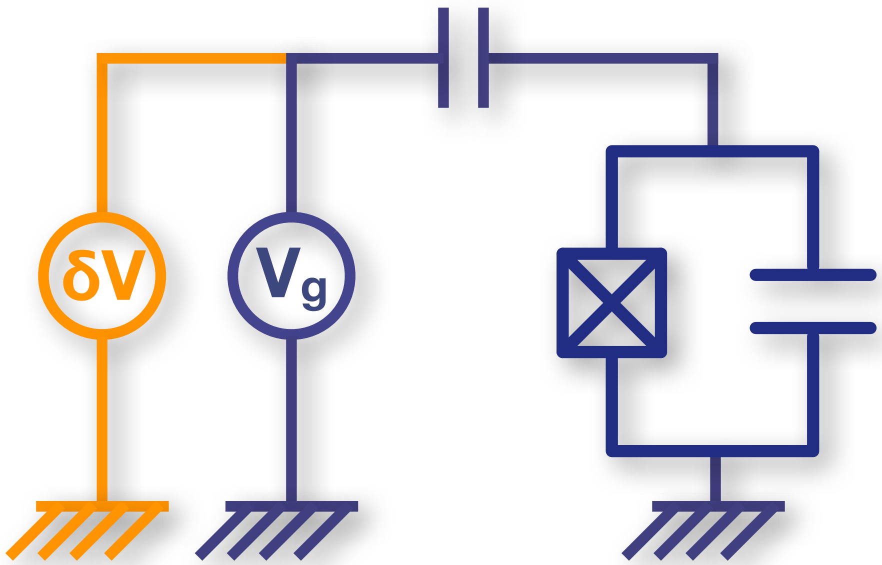
$$H = \sum_{n=-\infty}^{\infty} \left[4E_C(n - n_g)^2 |n\rangle\langle n| - \frac{E_J}{2}(|n\rangle\langle n+1| + |n+1\rangle\langle n| \right]$$

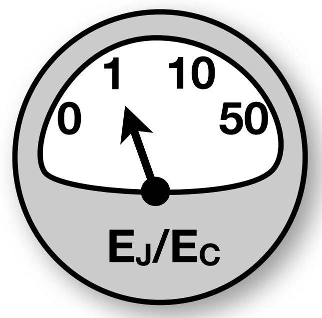
Truncating the Hilbert space:

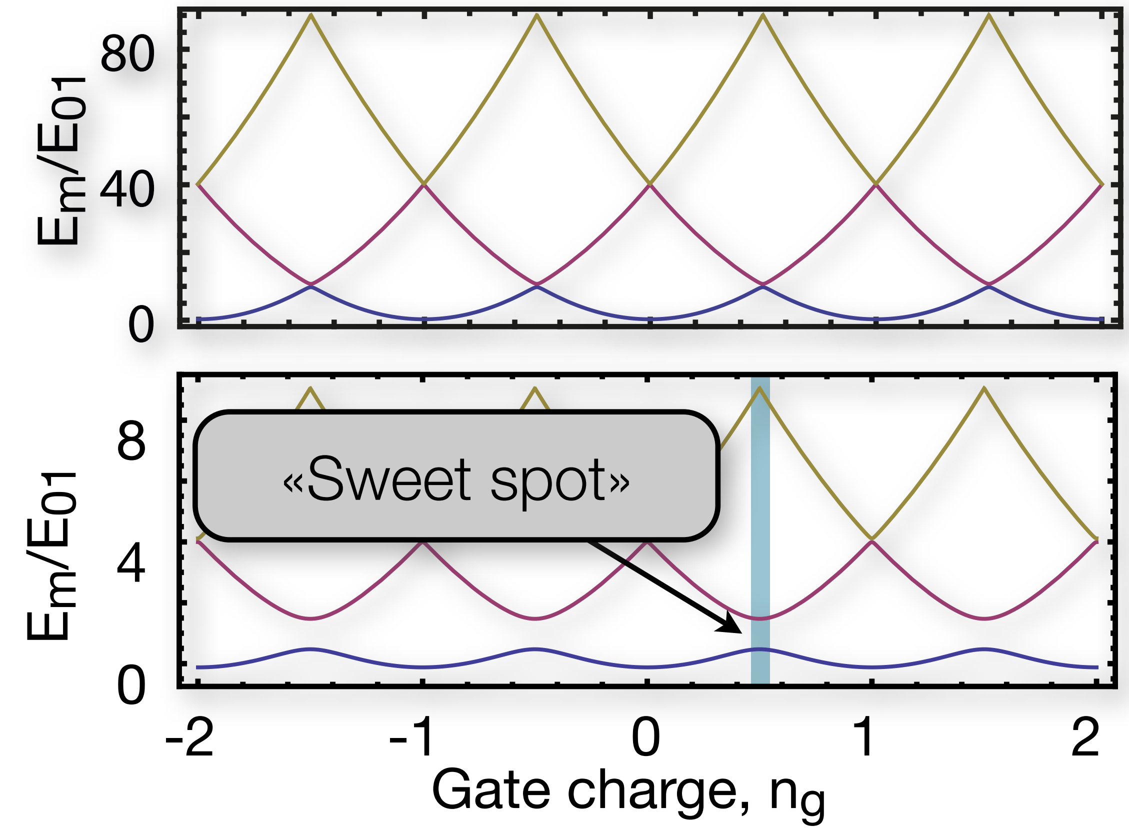
$$\text{H} = \begin{pmatrix} 4\,\text{Ec}\,(-2-\text{ng})^2 & -\frac{\text{Ej}}{2} & 0 & 0 & 0 \\ -\frac{\text{Ej}}{2} & 4\,\text{Ec}\,(-1-\text{ng})^2 & -\frac{\text{Ej}}{2} & 0 & 0 \\ 0 & -\frac{\text{Ej}}{2} & 4\,\text{Ec}\,\text{ng}^2 & -\frac{\text{Ej}}{2} & 0 \\ 0 & 0 & -\frac{\text{Ej}}{2} & 4\,\text{Ec}\,(1-\text{ng})^2 & -\frac{\text{Ej}}{2} \\ 0 & 0 & 0 & -\frac{\text{Ej}}{2} & 4\,\text{Ec}\,(2-\text{ng})^2 \end{pmatrix}$$

```
{evalues, evectors} = Eigensystem[H];
```

Superconducting qubits: transmon regime



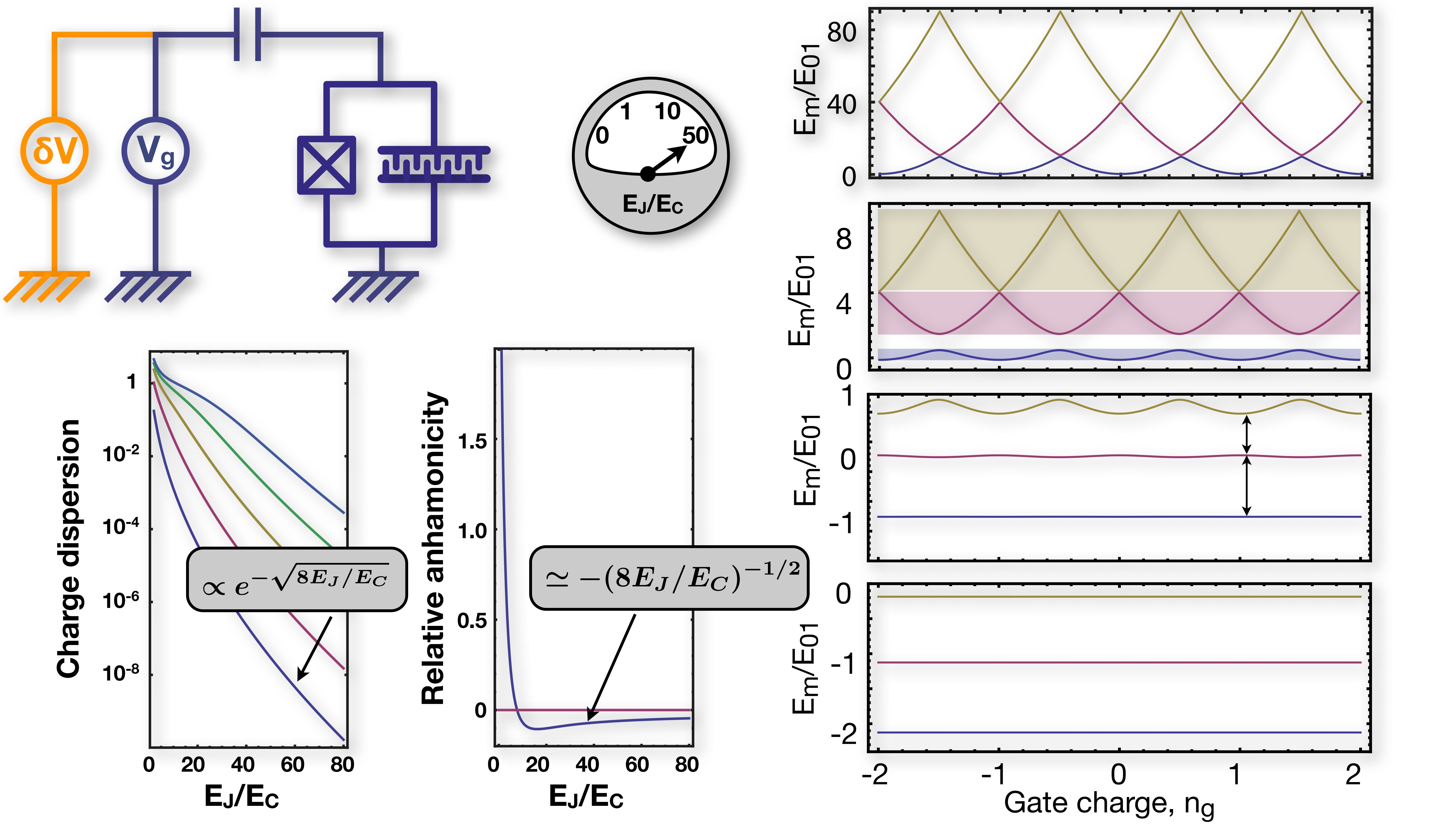




Small variations in n_g yields large variation in energy: dephasing due to charge noise

Charge qubit: A. Shnirman et al. Phys. Rev. Lett. **79** 2371 (1997); V. Bouchiat et al. Physica Scripta **T76** 165 (1998)
Sweet spot: D. Vion et al. Science **296**, 886 (2002); Transmon: J. Koch et al. Phys. Rev. A **76**, 042319 (2007)

Superconducting qubits: transmon regime



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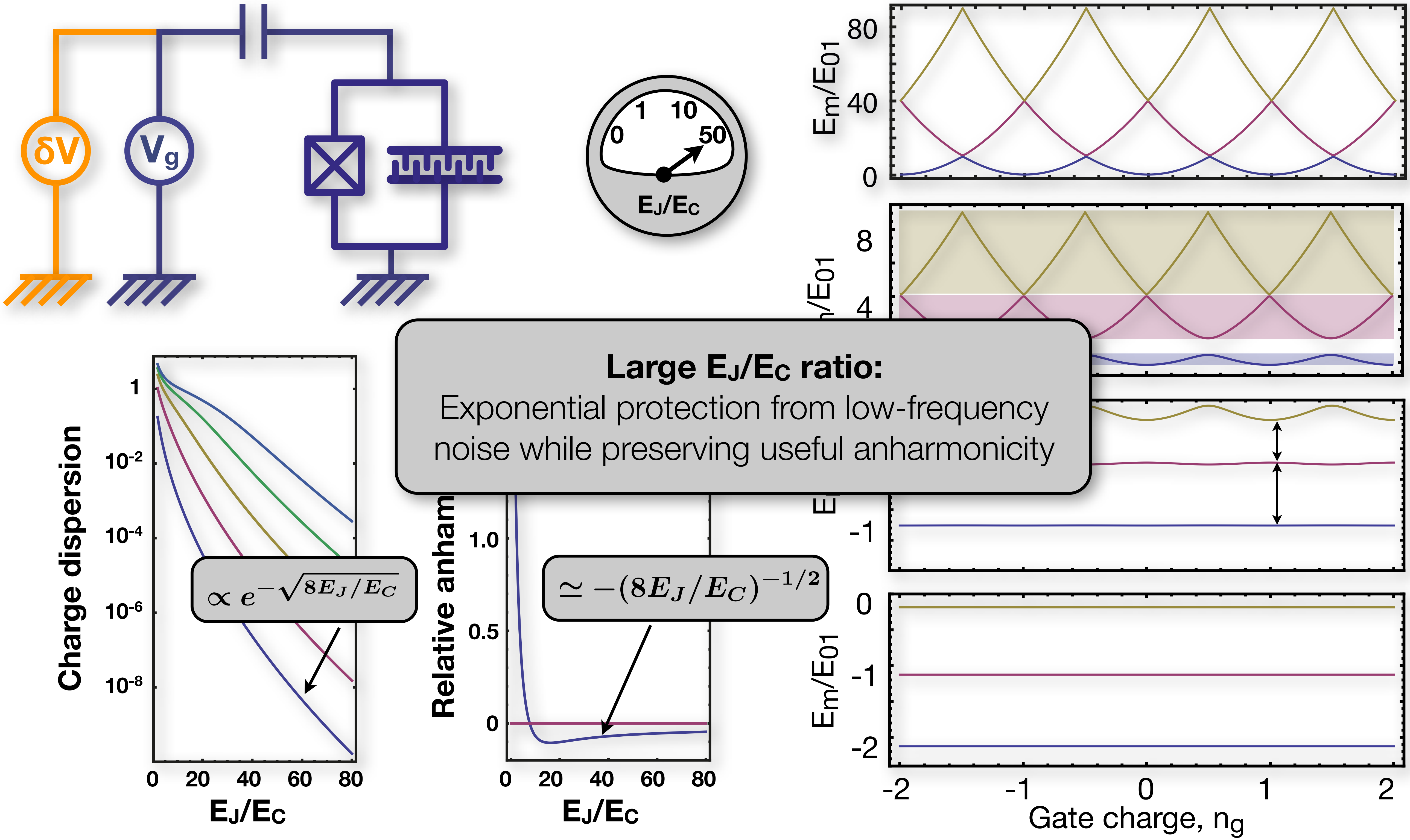
Superconducting qubits: transmon regime



Large E_J/E_C ratio:
Exponential protection from low-frequency noise while preserving useful anharmonicity

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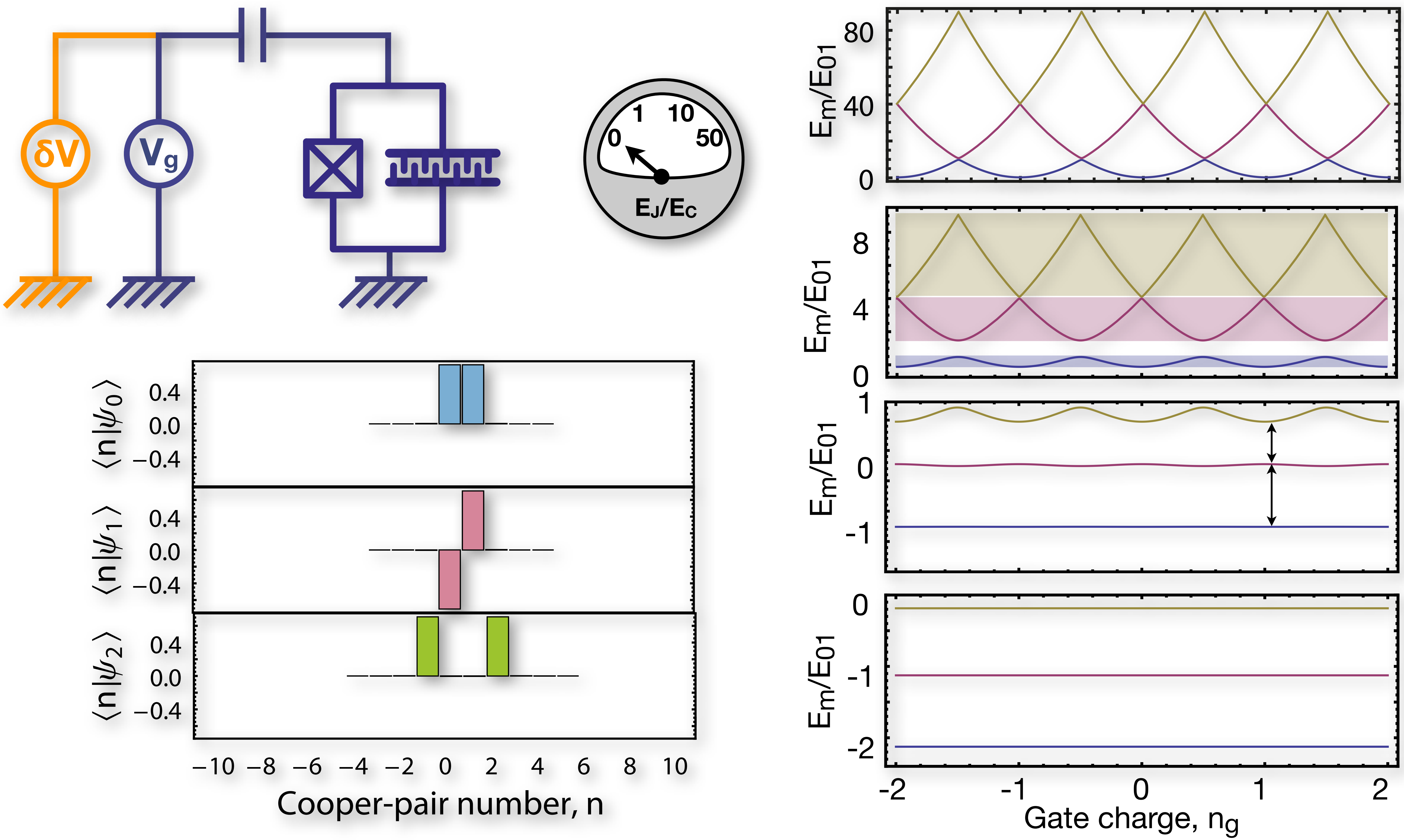
Superconducting qubits: transmon regime



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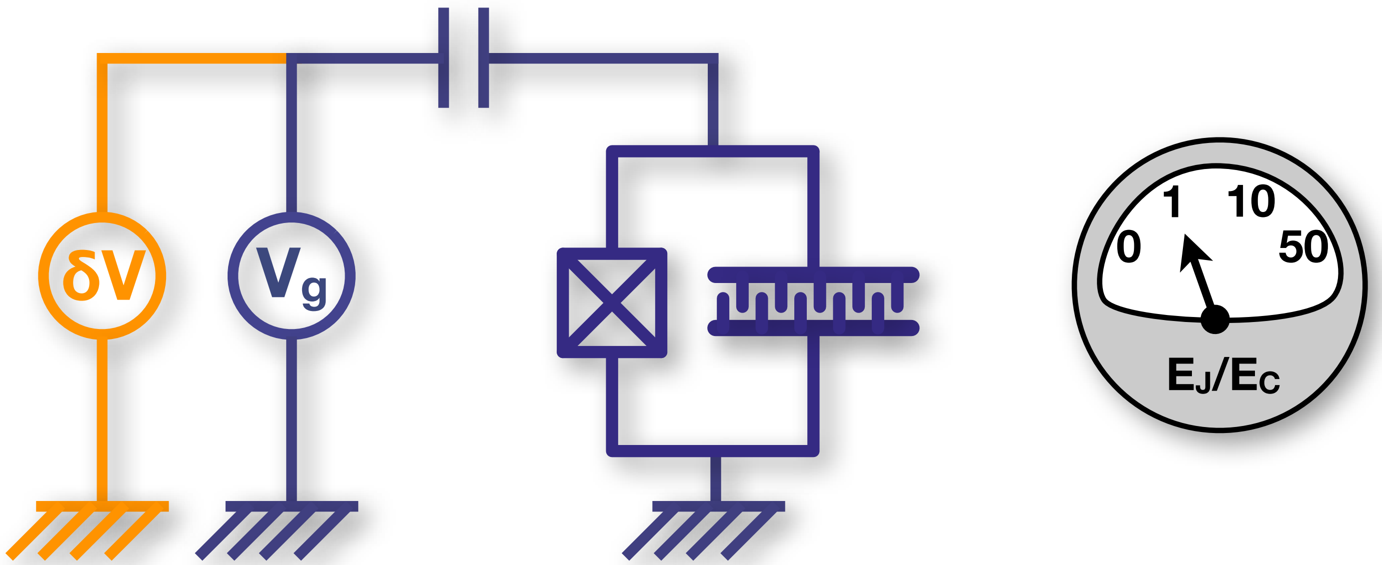
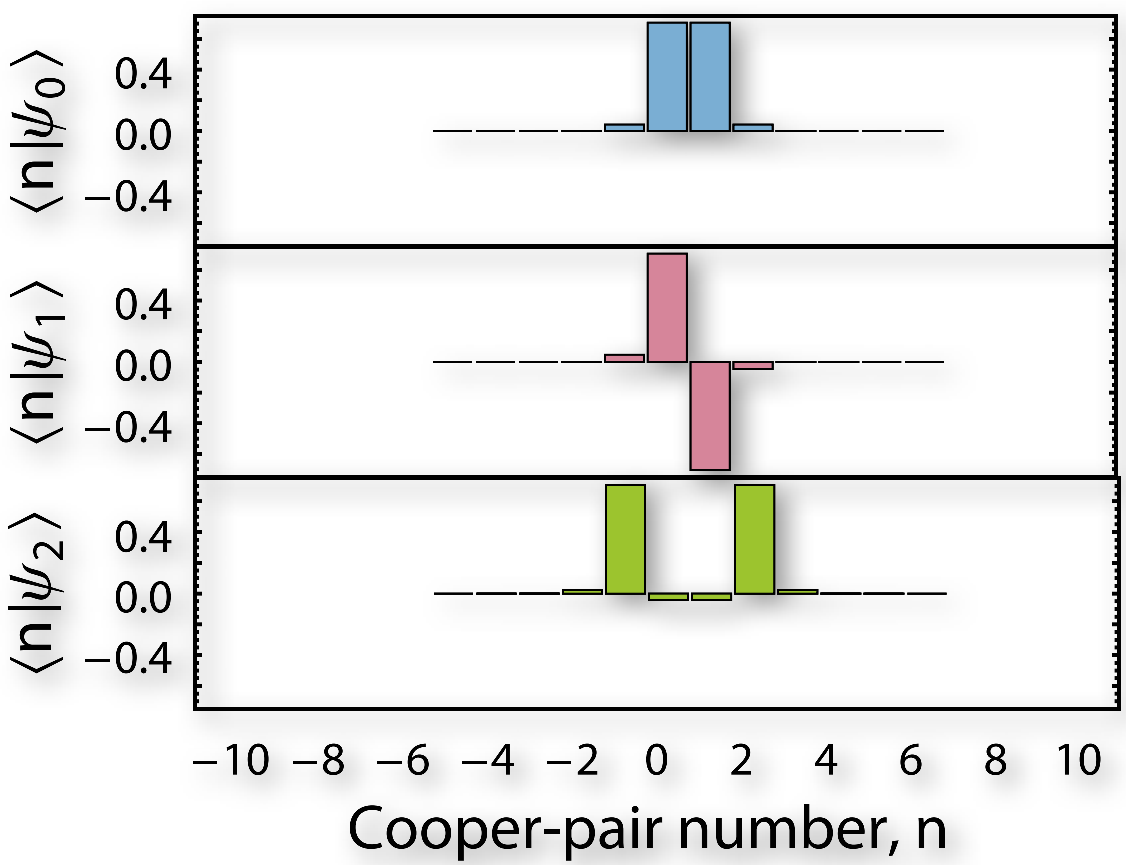
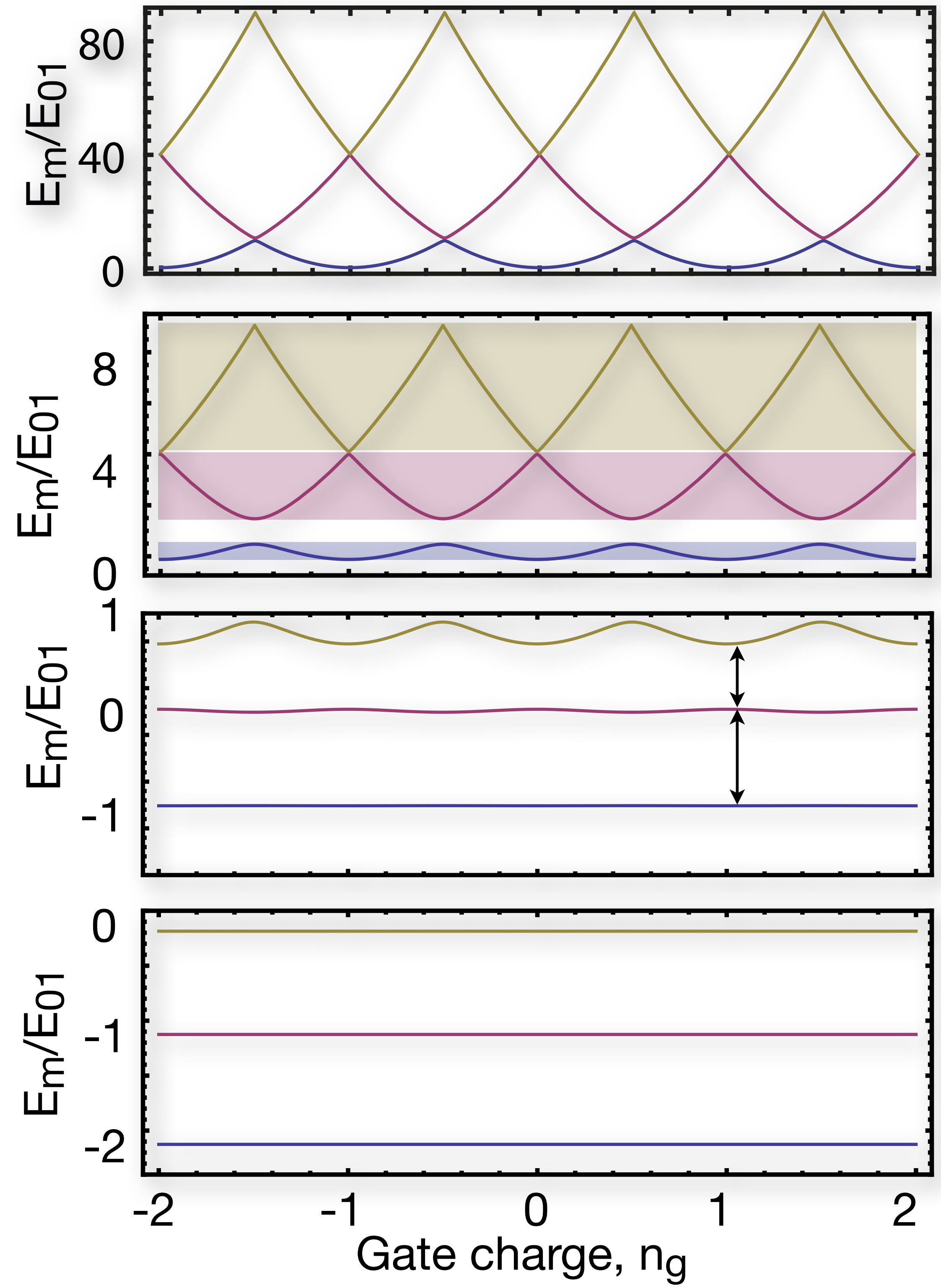
Superconducting qubits: transmon regime







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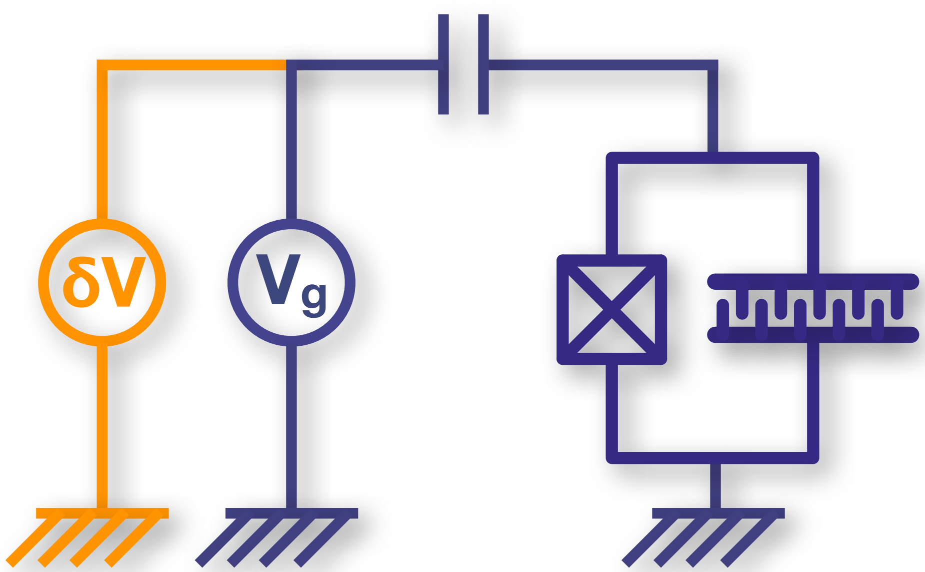
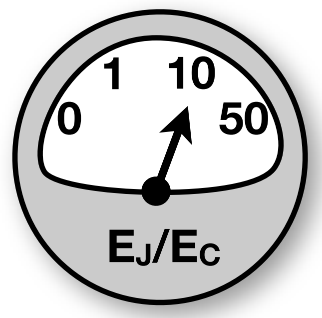
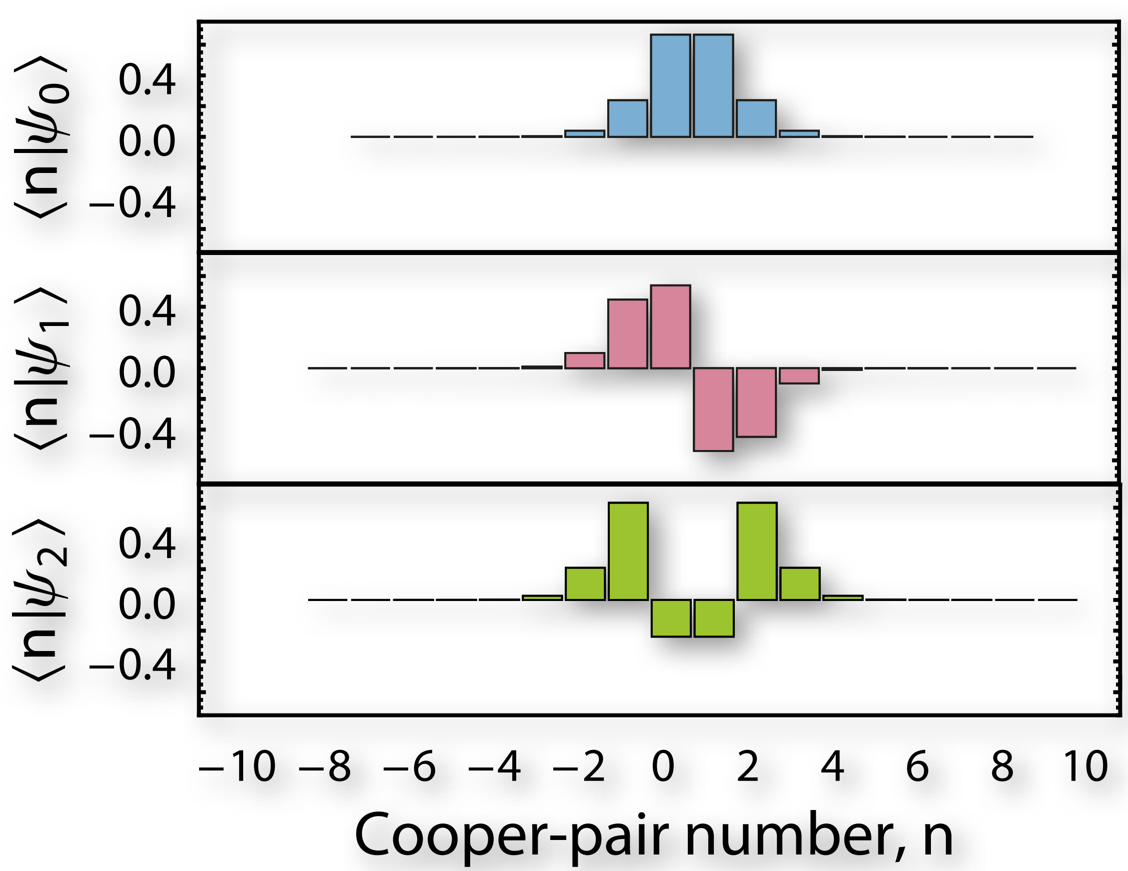
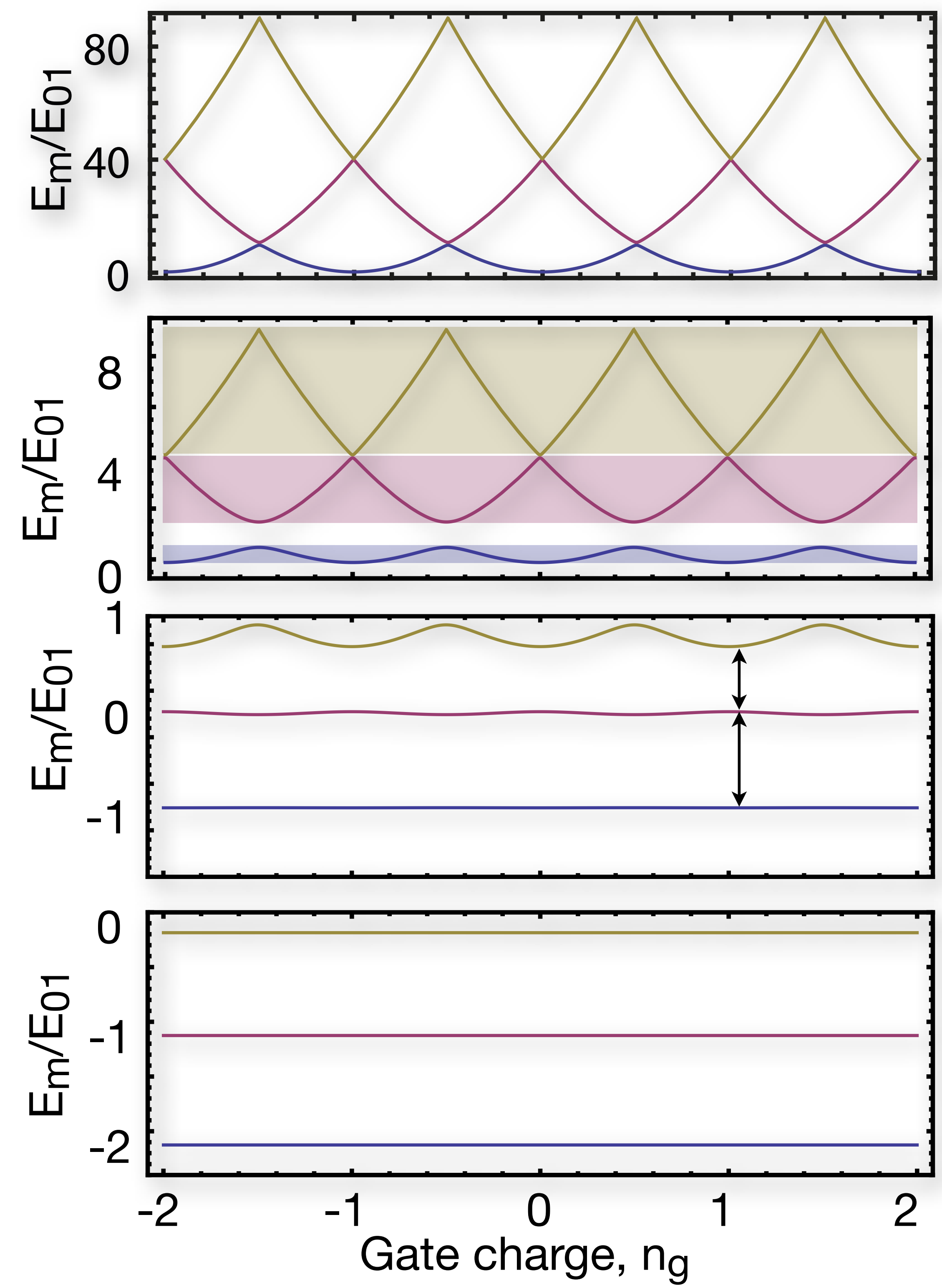
Superconducting qubits: transmon regime









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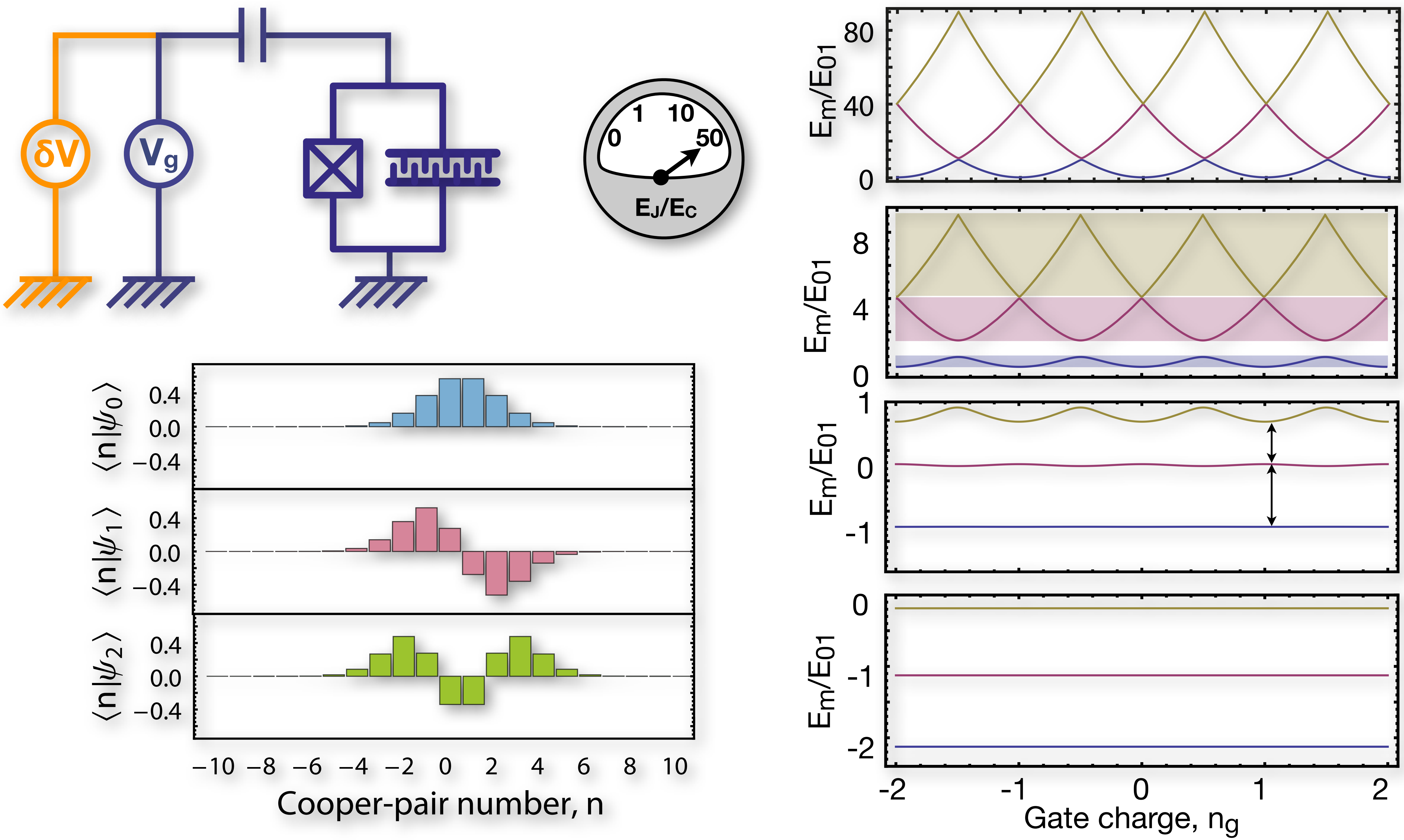
Superconducting qubits: transmon regime



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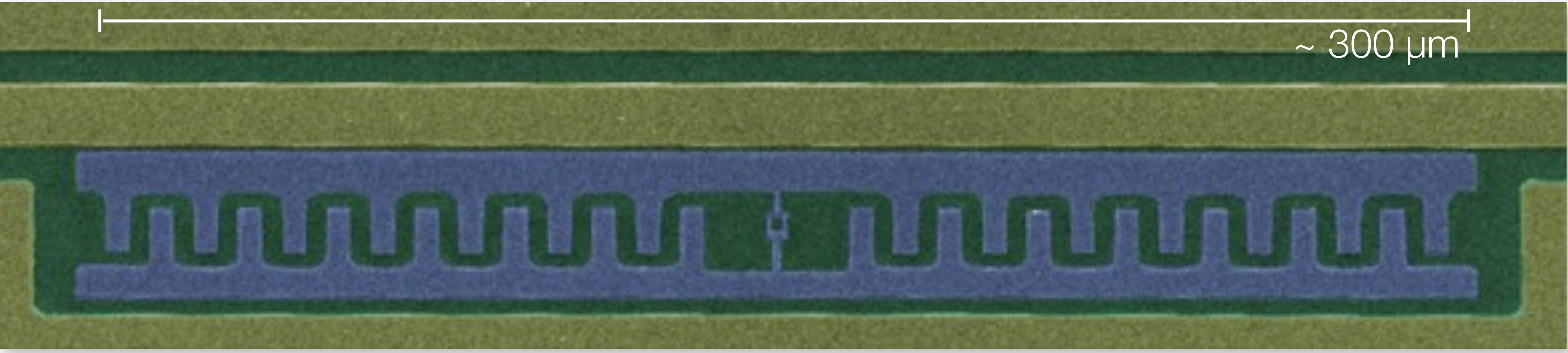
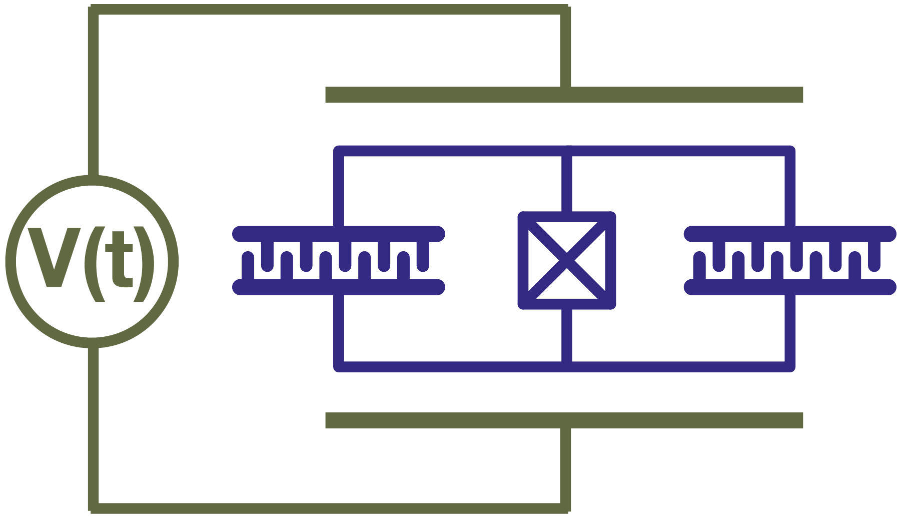
Superconducting qubits: transmon regime





J. Koch et al. Phys. Rev. A **76**, 042319 (2007)

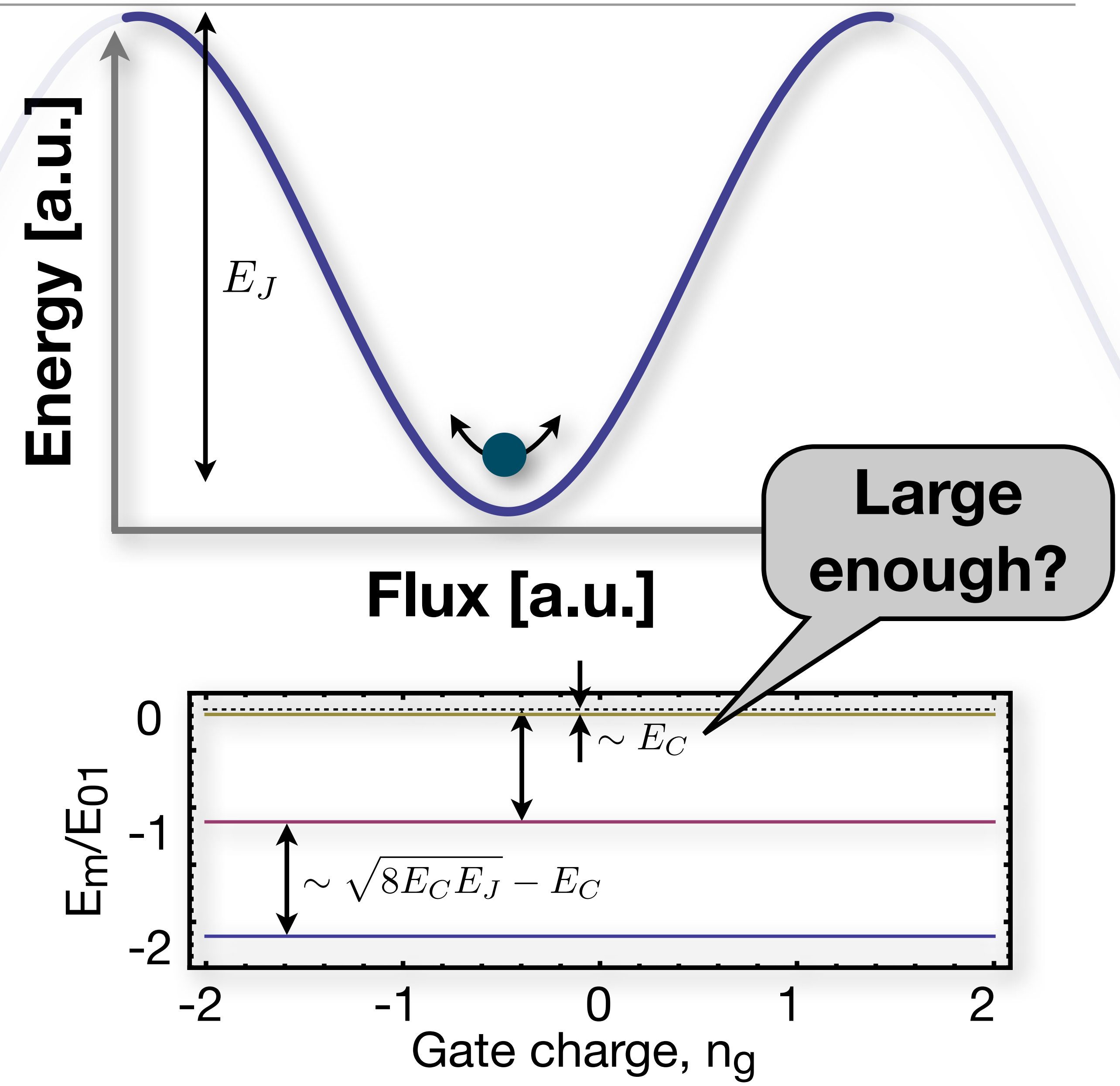
Transmon regime: anharmonic oscillator

$$
\begin{aligned}
H &= 4E_C\hat{n}^2 - E_J\cos\hat{\phi} \\
&\approx 4E_C\hat{n}^2 + \frac{1}{2}E_J\hat{\phi}^2 - \frac{1}{24}E_J\hat{\phi}^4 \\
&\equiv \frac{\hat{n}^2}{2C'} + \frac{\hat{\phi}^2}{2L'} - \frac{1}{24}E_J\hat{\phi}^4
\end{aligned}
$$

$$\hat{n} = i\sqrt{\hbar}\left(\frac{E_J}{32E_C}\right)^{1/4}(\hat{b}^\dagger - \hat{b})$$

$$\hat{\phi} = \sqrt{\hbar}\left(\frac{2E_C}{E_J}\right)^{1/4}(\hat{b}^\dagger + \hat{b})$$

$$
\begin{aligned}
H &\approx \sqrt{8E_CE_J}\hat{b}^\dagger\hat{b} - \frac{E_C}{2}(\hat{b}^\dagger\hat{b}^\dagger\hat{b}\hat{b} + 2\hat{b}^\dagger\hat{b}) \\
&= (\sqrt{8E_CE_J} - E_C)\hat{b}^\dagger\hat{b} - \frac{E_C}{2}\hat{b}^\dagger\hat{b}^\dagger\hat{b}\hat{b}
\end{aligned}
$$

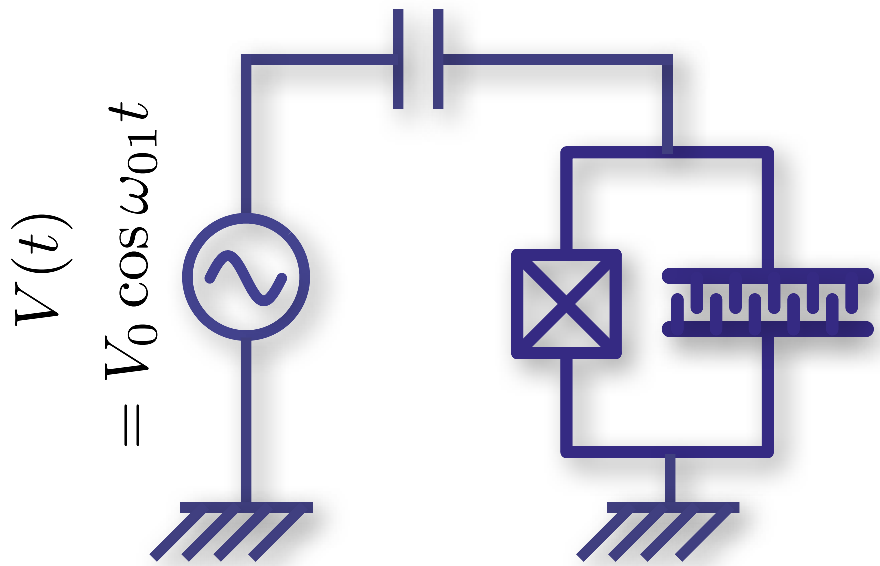


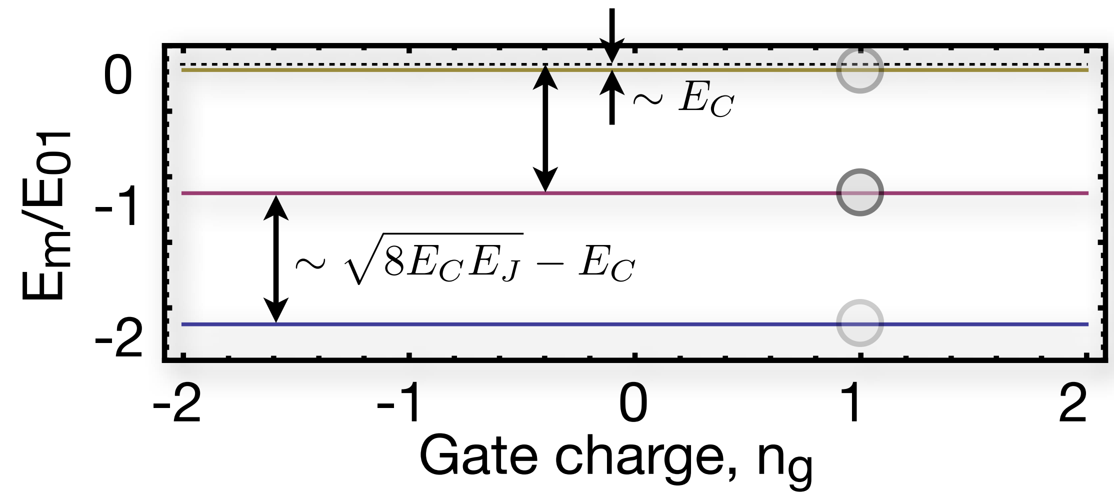
Typical values:

$E_J \sim 20$ GHz

$E_C \sim 400$ MHz

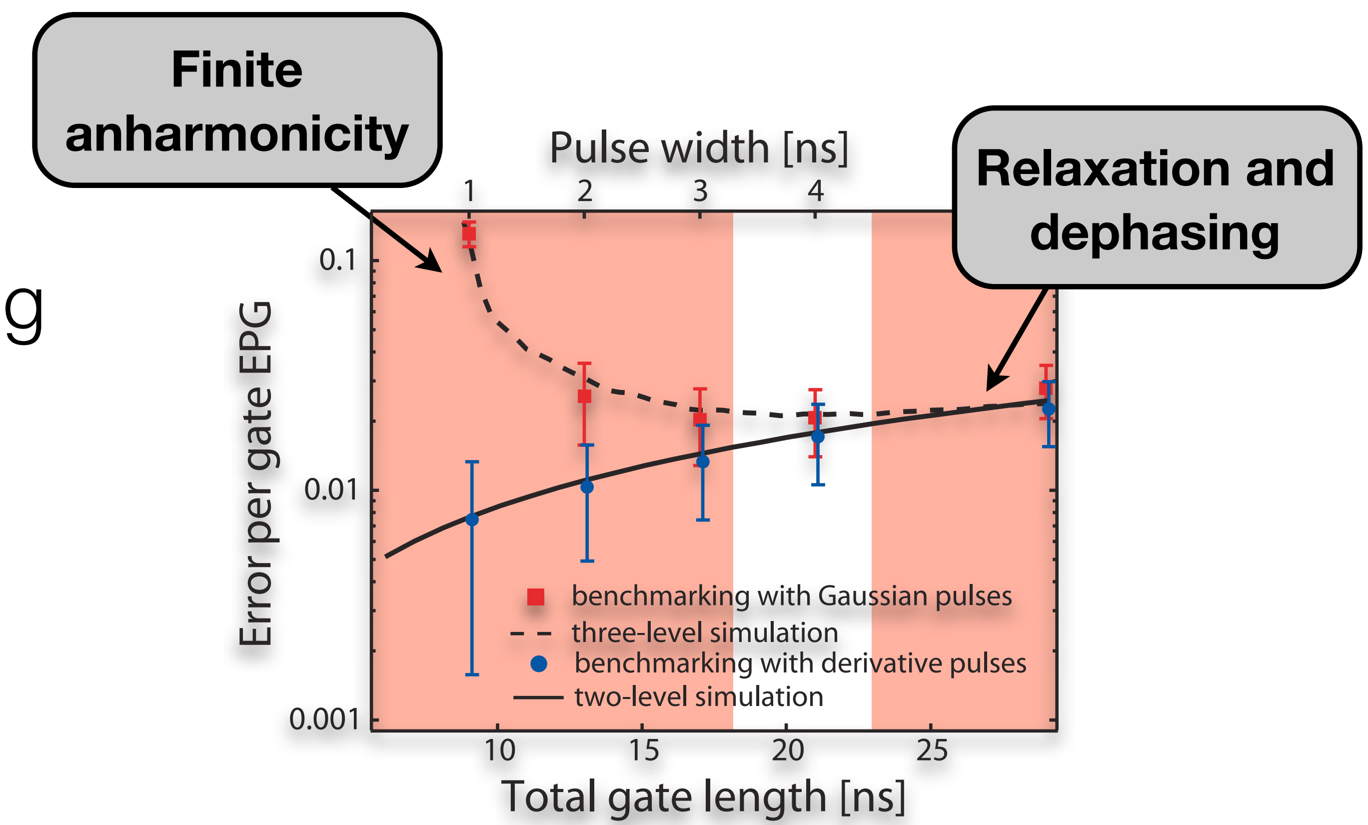
Coherent control





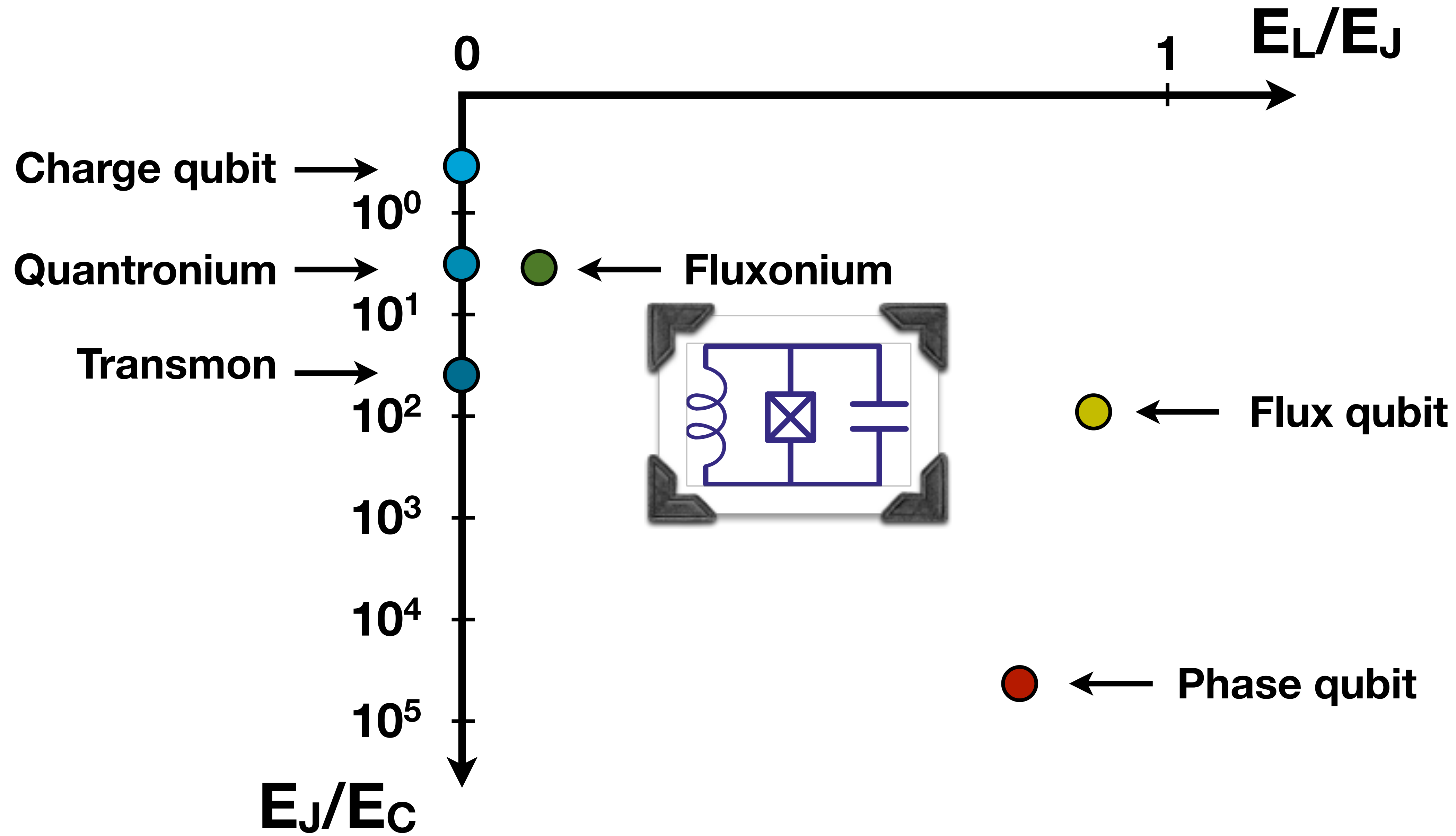
- Leakage reduction by pulse shaping

- Error per gates of 0.2%, similar to trapped ions results

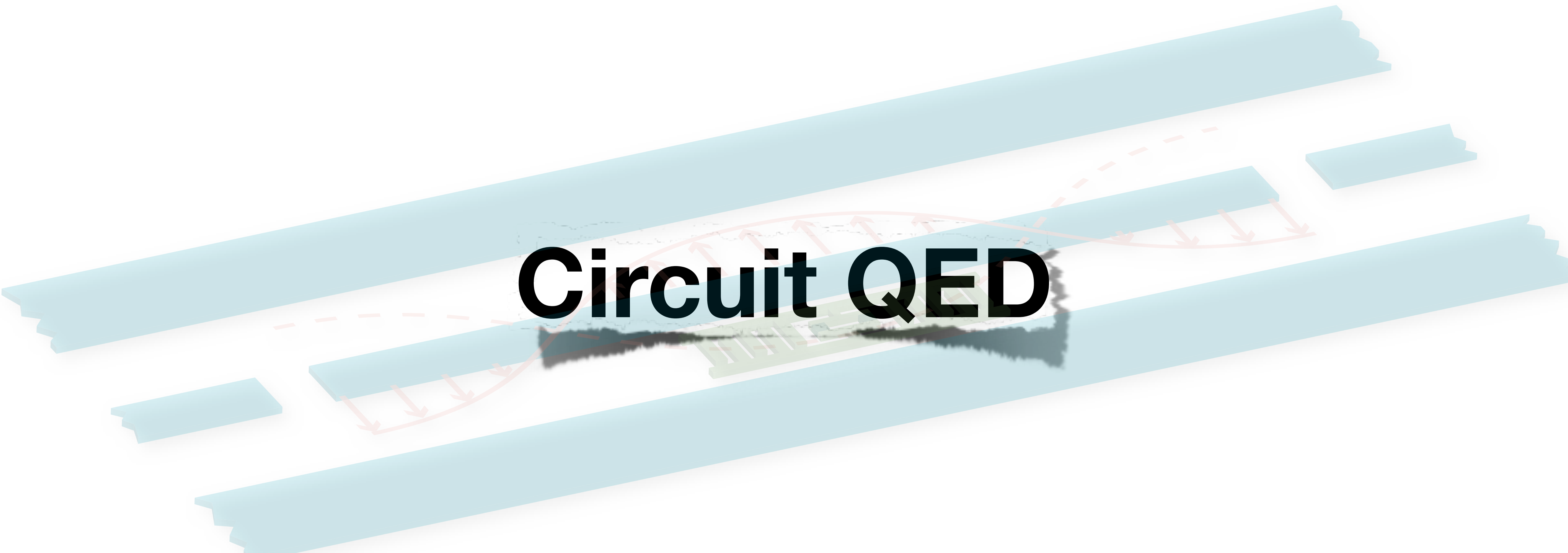


Pulse shaping theory: F. Motzoi *et al*. Phys. Rev. Lett. **103**, 110501 (2009)
Exp: J. M. Chow *et al*. Phys. Rev. A **82**, 040305 (2010); E. Magesan et al, Phys. Rev. Lett. **109**, 080505 (2012)

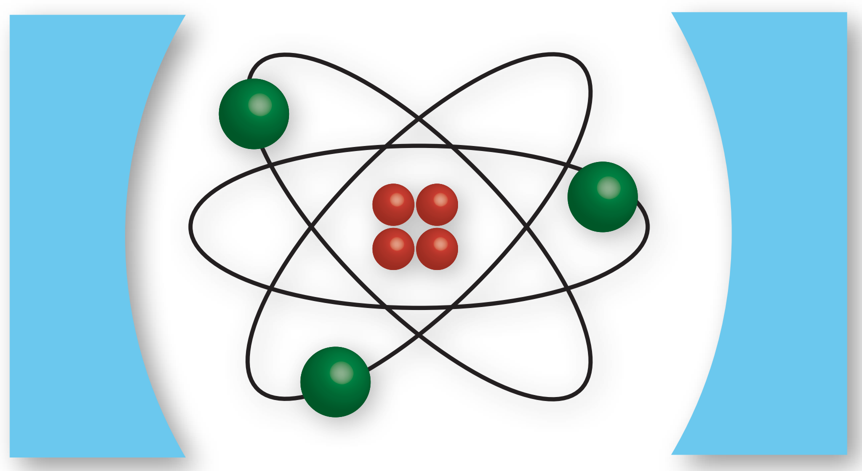
Superconducting qubits, a family tree

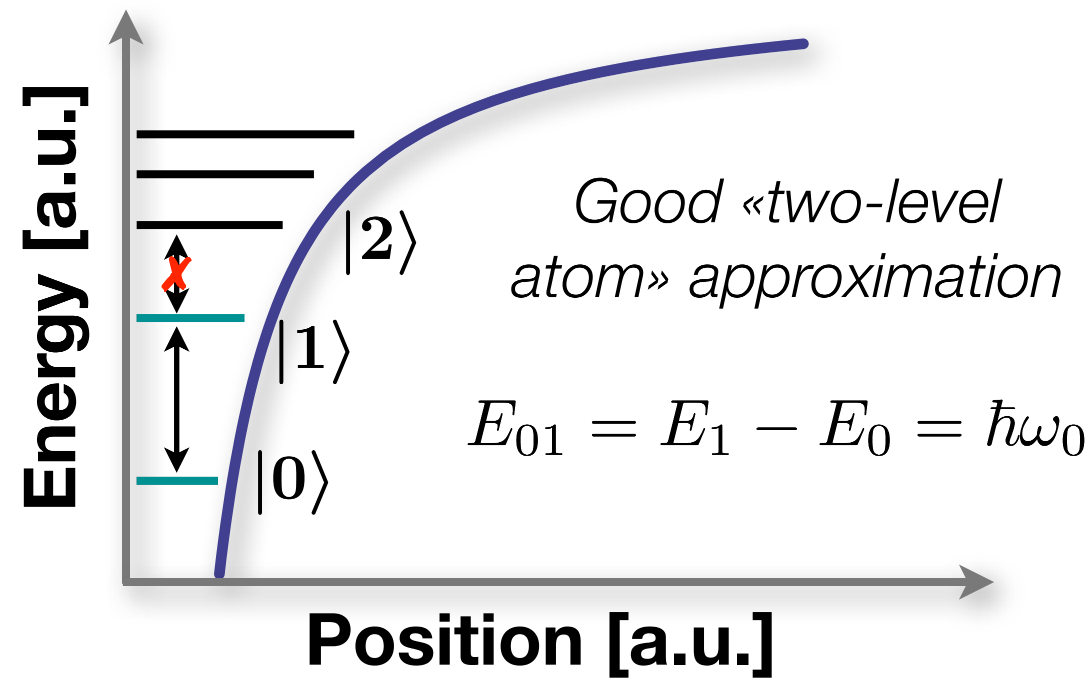


Circuit QED



From atomic physics to quantum optics





- Control internal state by shining laser at the transition frequency

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

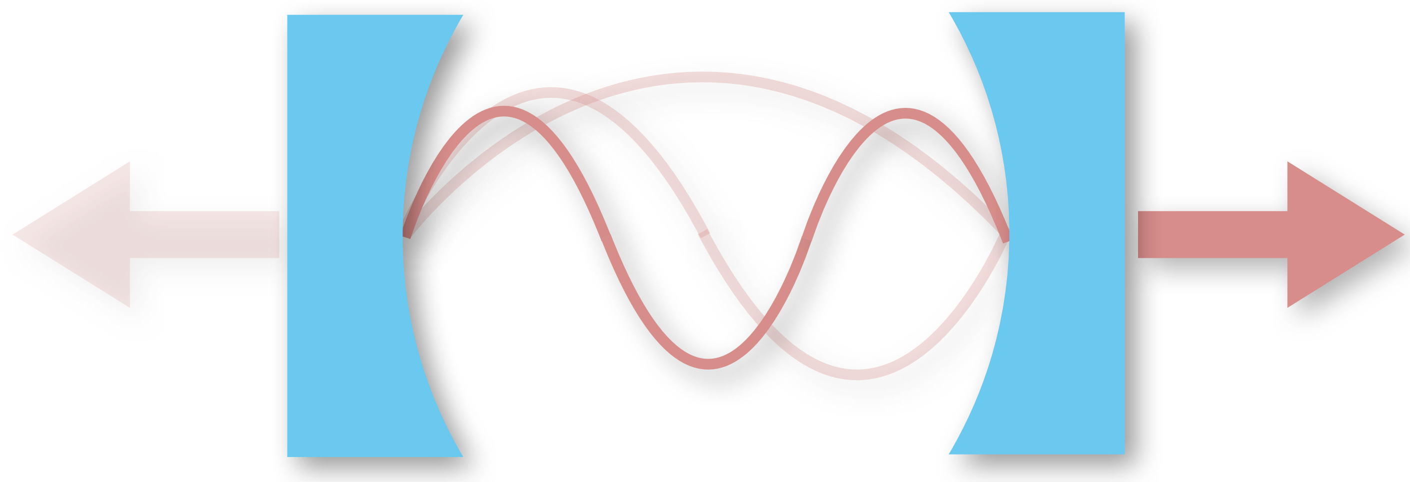
- Can the field of a single photon, or even *vacuum fluctuations,* have a large effect?

Cavity QED

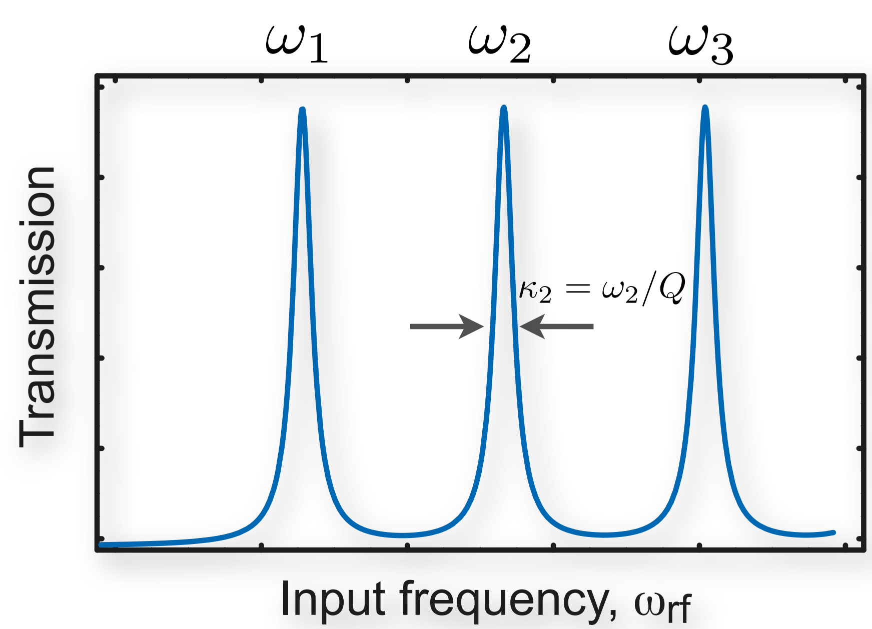
1) Work with large atoms (d)
2) Confine the field (E)

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

Fabry–Pérot resonator



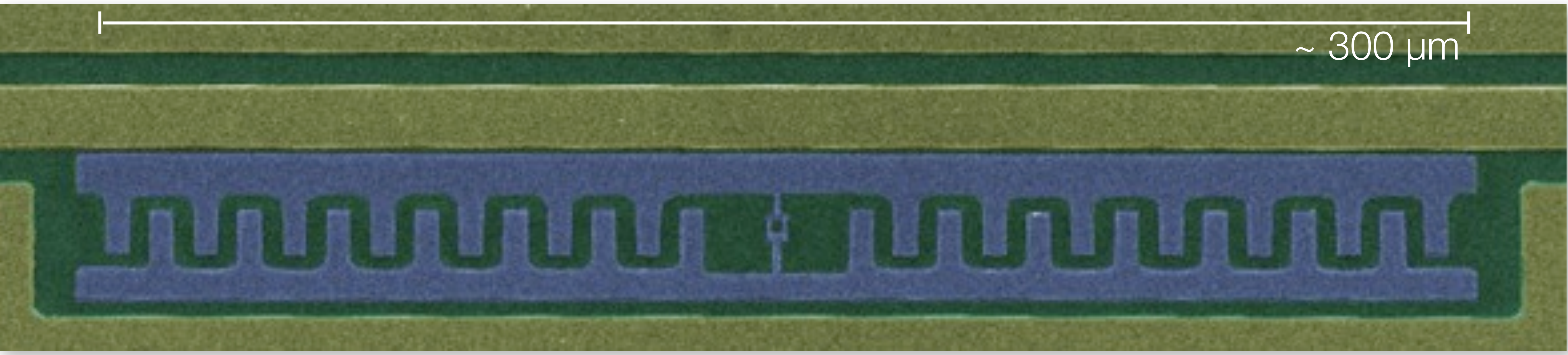
- Transmission vs input frequency:

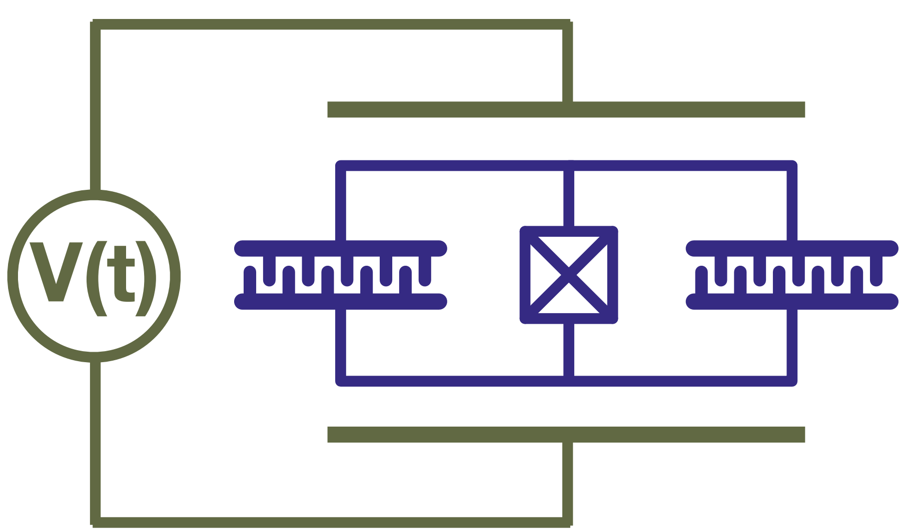


Exploring the Quantum: Atoms, Cavities, and Photons, S. Haroche and J.-M. Raimond (2006)

From cavity to *circuit* QED

- Artificial atoms are ***large***





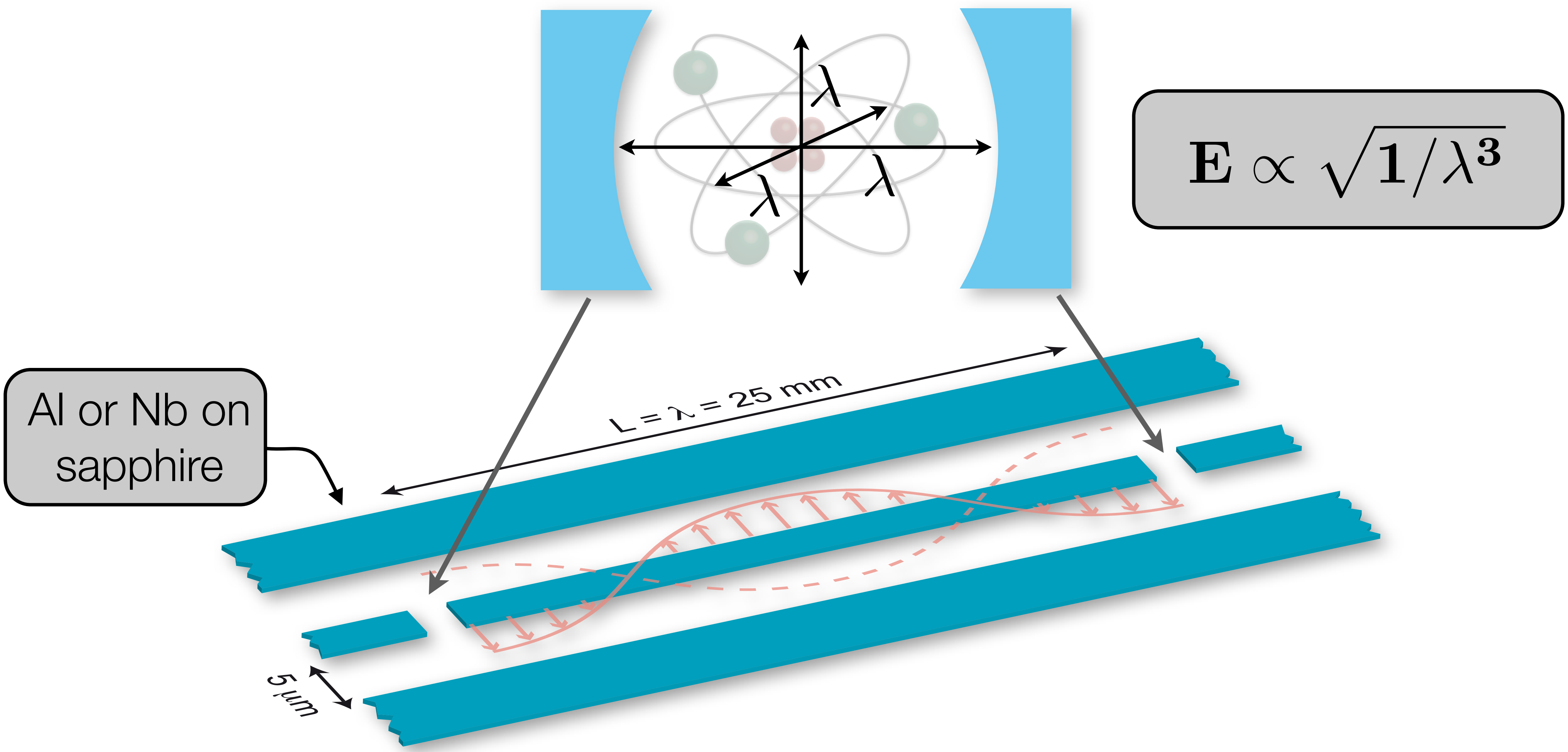
Artificial atoms have
***large** dipole moments*

↓

Fast gates

From cavity to *circuit* QED

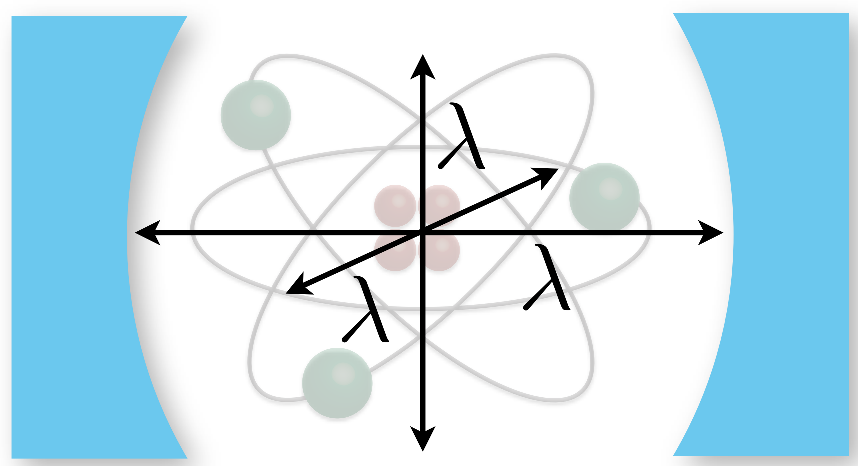
- E-field can be tightly confined



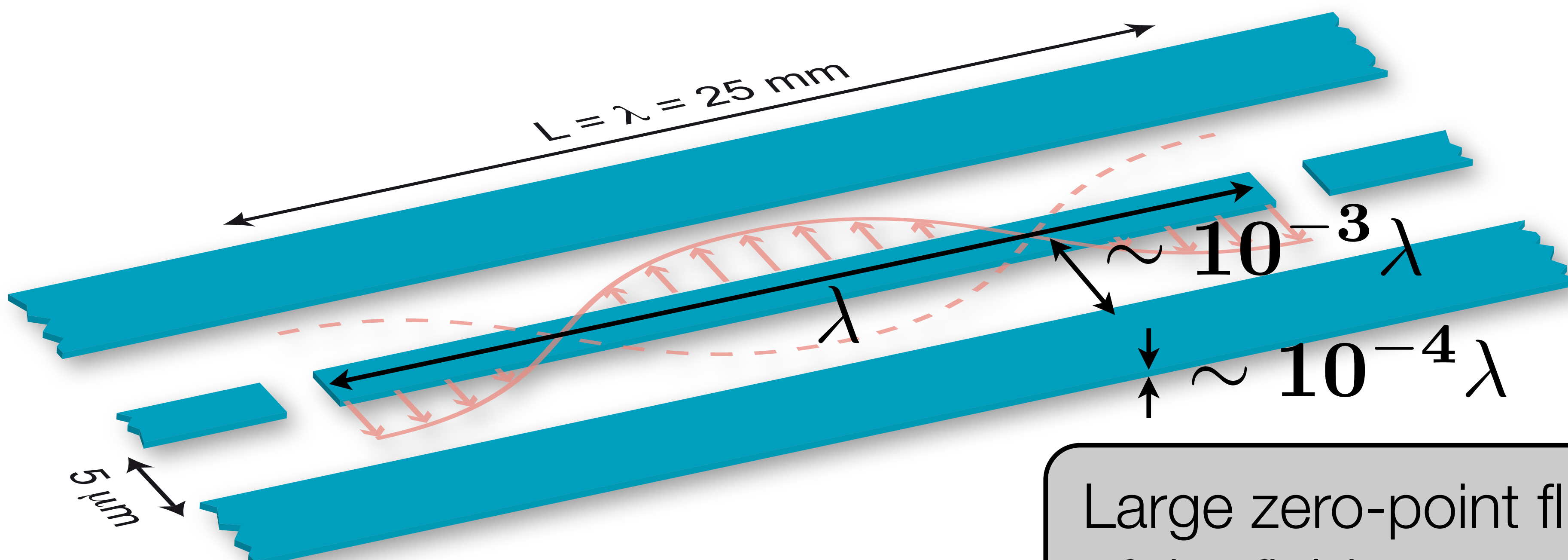
Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)

From cavity to *circuit* QED

- E-field can be tightly confined



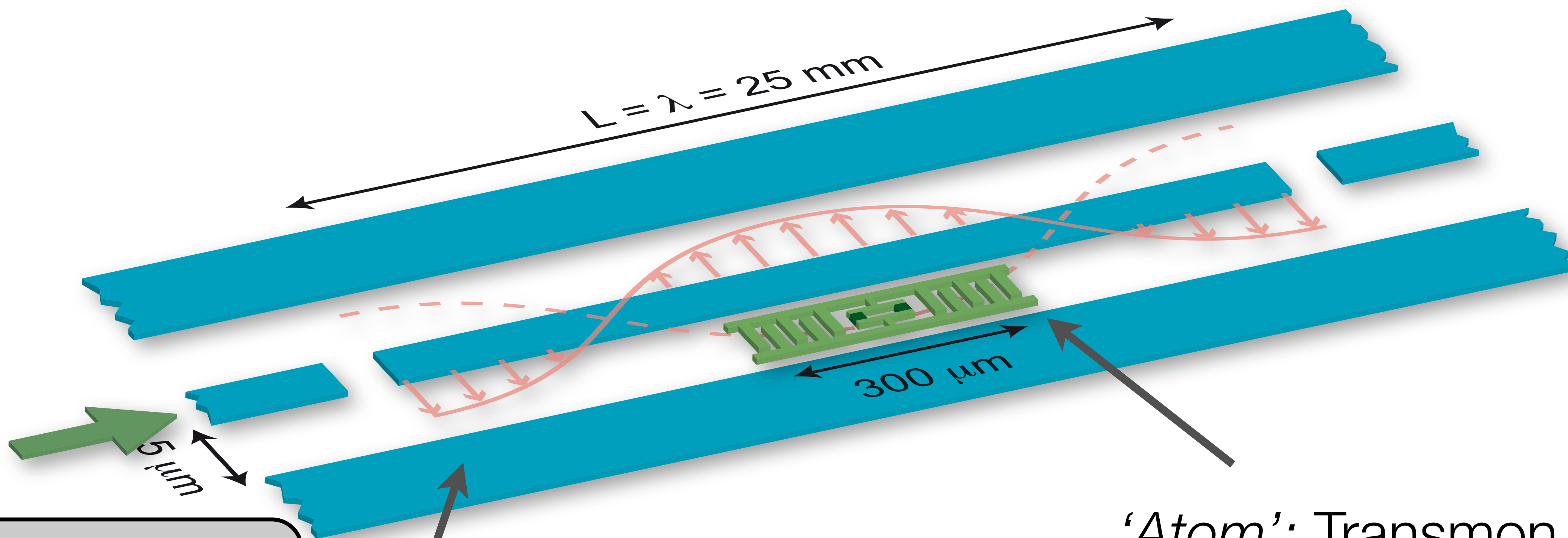
$$\mathbf{E} \propto \sqrt{1/\lambda^3}$$



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

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

From cavity to *circuit* QED



Irradiation at atomic transition frequency: coherent control

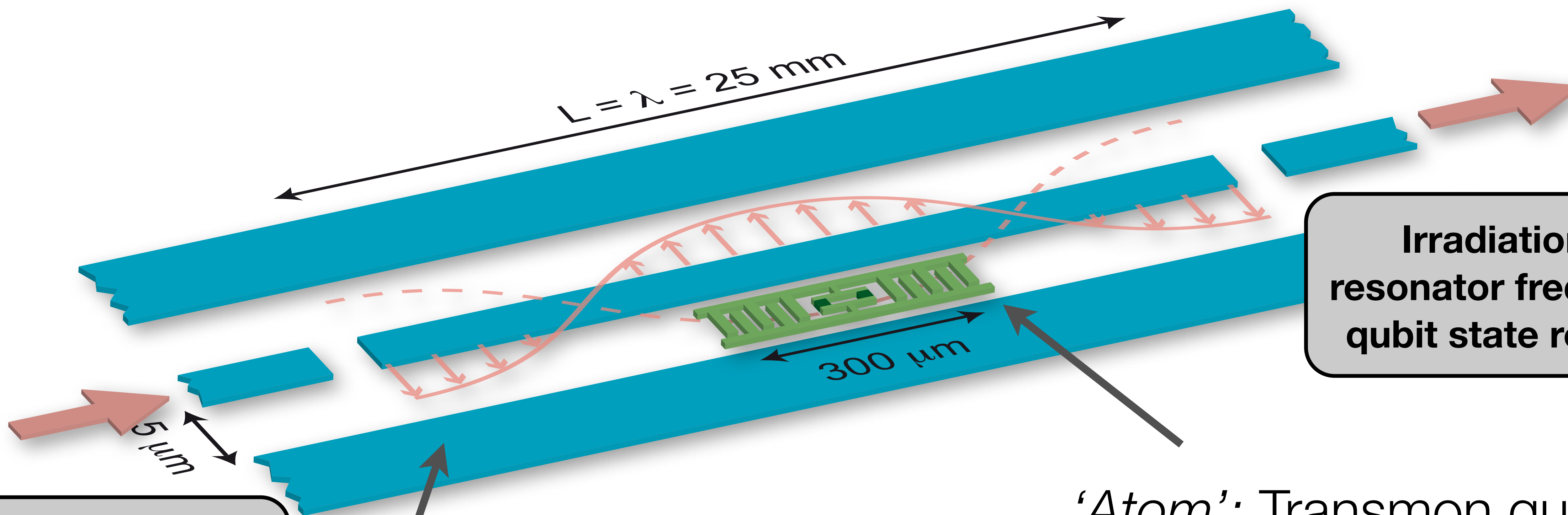
'Cavity': Superconducting coplanar transmission-line resonator of fundamental mode frequency ω_r

'Atom': Transmon qubit of transition frequency ω_{01} and long coherence time

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

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)
Ultrastrong coupling: Bourassa, Gambetta, Abdumalikov, Astafiev, Nakamura, Blais. Phys. Rev. A **80**, 032109 (2009)

From cavity to *circuit* QED



Irradiation at resonator frequency: qubit state readout

Irradiation at atomic transition frequency: coherent control

'Atom': Transmon qubit of transition frequency ω_{01} and long coherence time

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

$$g_{\text{circuit}}/2\pi \sim [0-1]\ \text{GHz}$$
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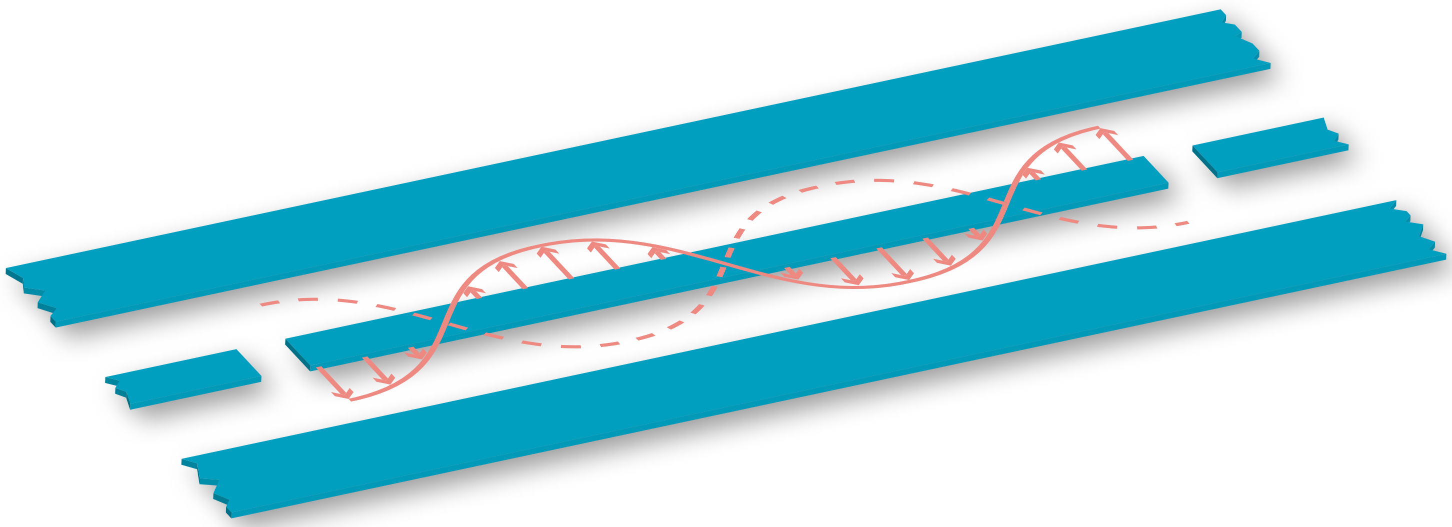
Resonator: One-mode approximation



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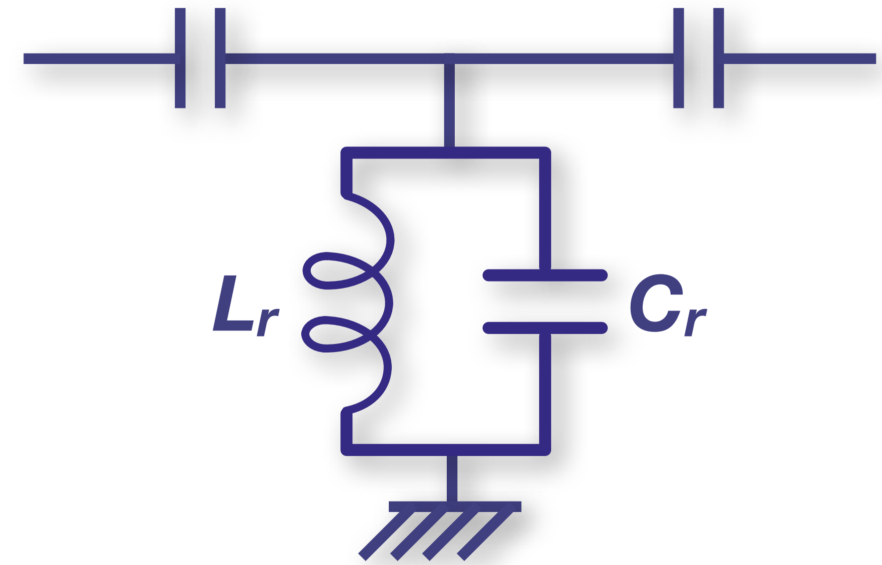
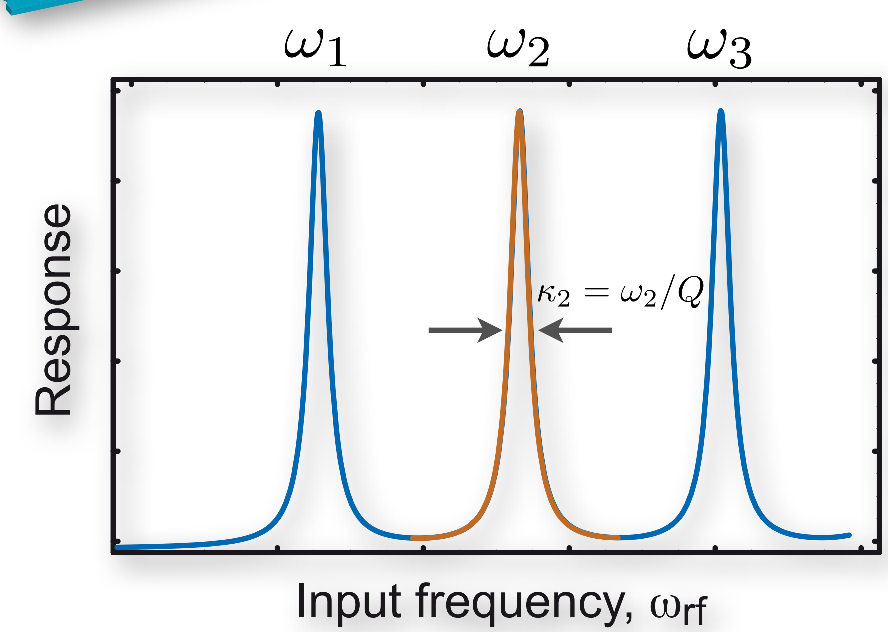




$$\omega_r = \sqrt{1/L_r C_r}$$
$$\kappa = \omega_r/Q$$

Voltage across the resonator:

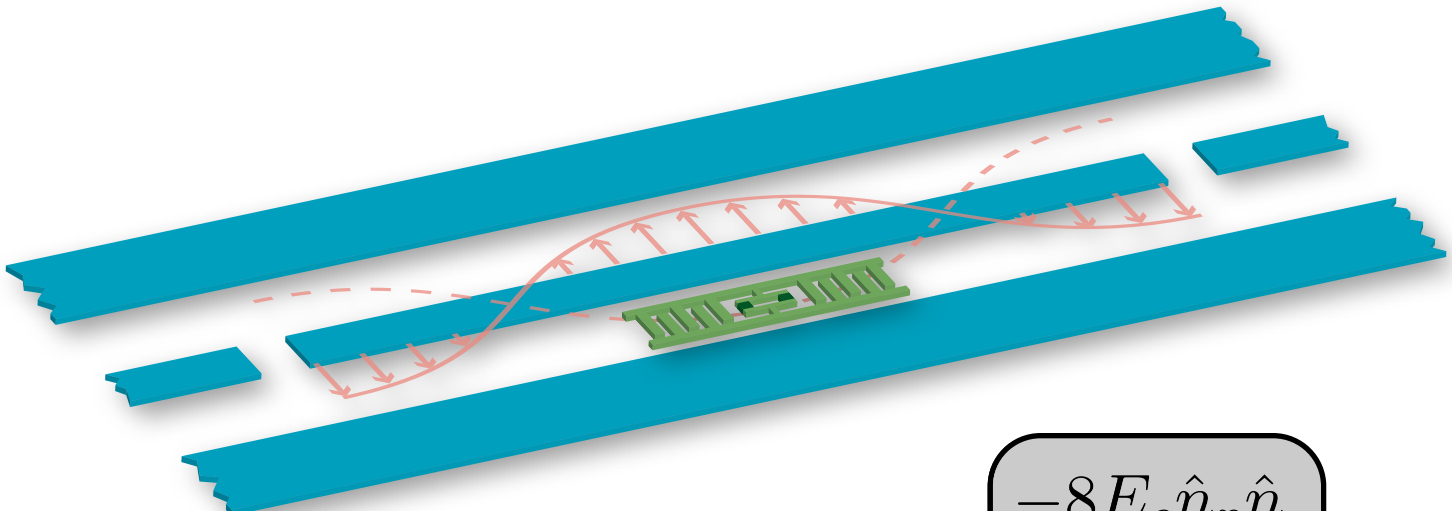
$$\hat{V}_r = \hat{Q}_r/C_r \quad \langle 0|\hat{V}_r|0\rangle = 0$$

$$\sqrt{\langle 0|\hat{V}_r^2|0\rangle} = \sqrt{\frac{\hbar\omega_r}{2C_r}} \sim 1\ \mu\text{V}$$

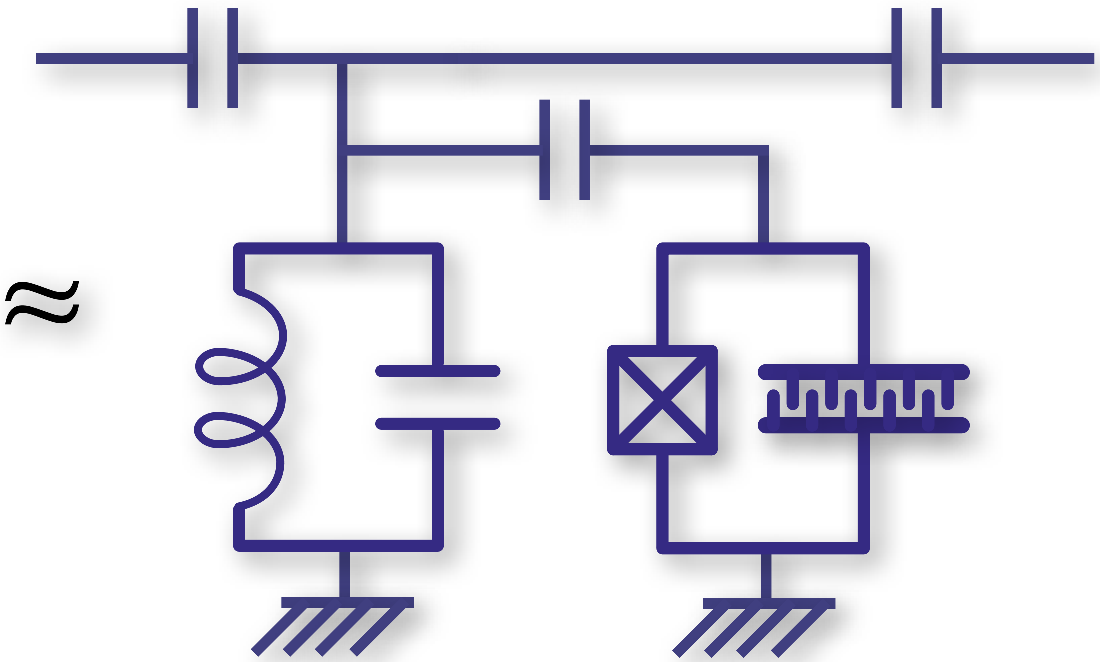
Zero-point field fluctuations:

$$E_0 = \frac{\Delta\hat{V}_r}{d} \sim \frac{1\ \mu\text{V}}{5\ \mu\text{m}} \sim 0.2\ \text{V/m}$$

Bringing it all together: Jaynes-Cummings model



$\approx$



$-8E_c\hat{n}_r\hat{n}$

$$\hat{H} = \left(\frac{\hat{Q}_r^2}{2C_r} + \frac{\hat{\Phi}_r^2}{2L_r}\right) + \left(4E_C[\hat{n} - \hat{n}_r]^2 - E_J\cos\hat{\phi}\right)$$

$$= \omega_r\hat{a}^\dagger\hat{a} + \left(\omega_{01}\hat{b}^\dagger\hat{b} - \frac{E_c}{2}\hat{b}^\dagger\hat{b}^\dagger\hat{b}\hat{b}\right) - g(\hat{a}^\dagger - \hat{a})(\hat{b}^\dagger - \hat{b})$$

TLS approx.

$$= \omega_r\hat{a}^\dagger\hat{a} + \frac{\omega_{01}}{2}\hat{\sigma}_z - g(\hat{a}^\dagger - \hat{a})(\hat{\sigma}_+ - \hat{\sigma}_-)$$

RWA

$$\approx \omega_r\hat{a}^\dagger\hat{a} + \frac{\omega_{01}}{2}\hat{\sigma}_z + g(\hat{a}^\dagger\hat{\sigma}_- + \hat{a}\hat{\sigma}_+)$$

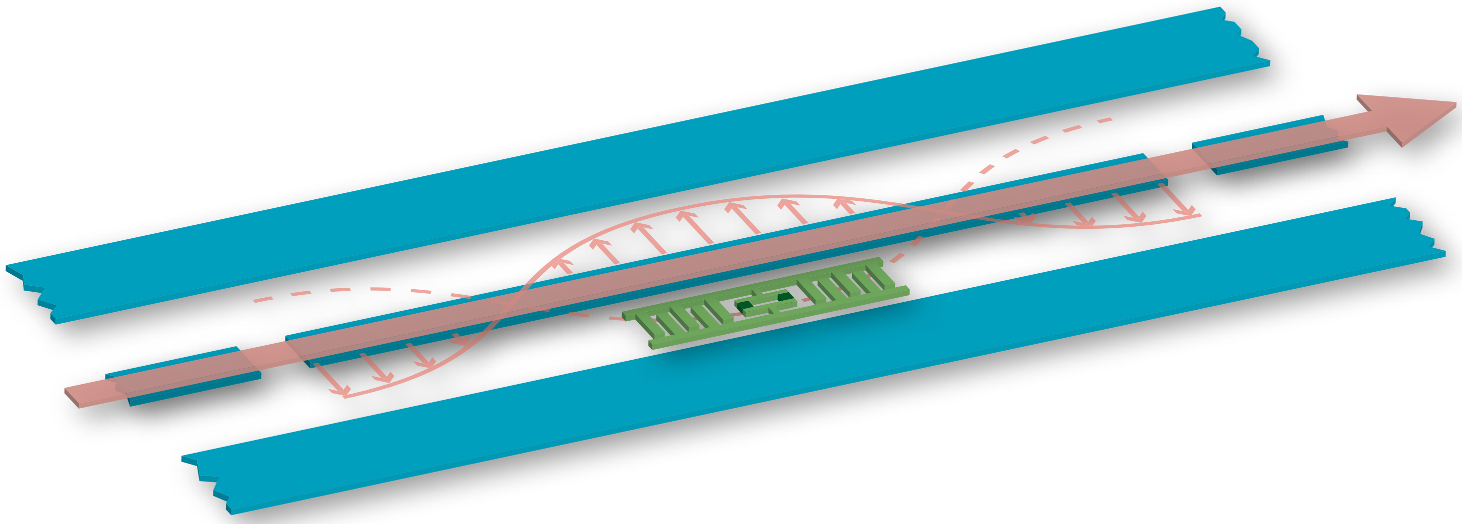
Energy exchange between ‘light’ and ‘matter’ at rate *2g*

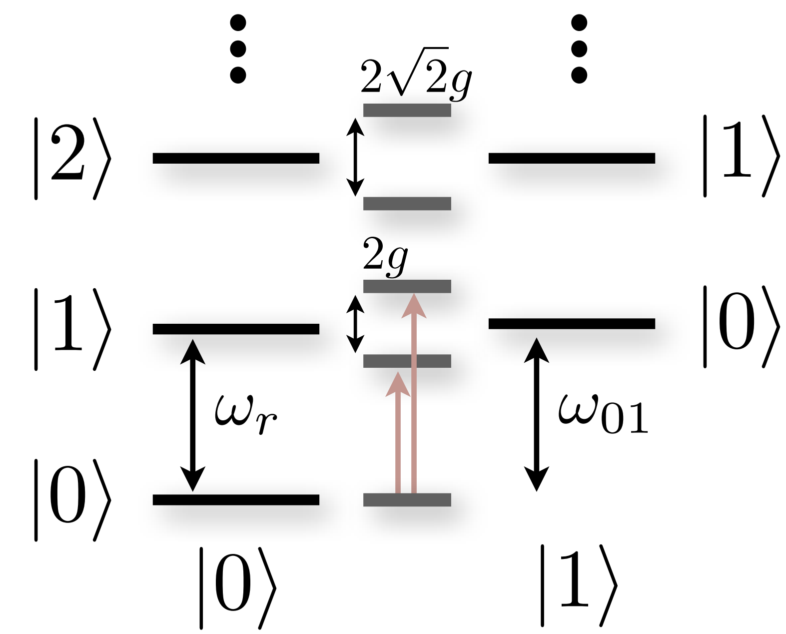
$g_{\text{circuit}}/2\pi \sim [0-1]$ GHz

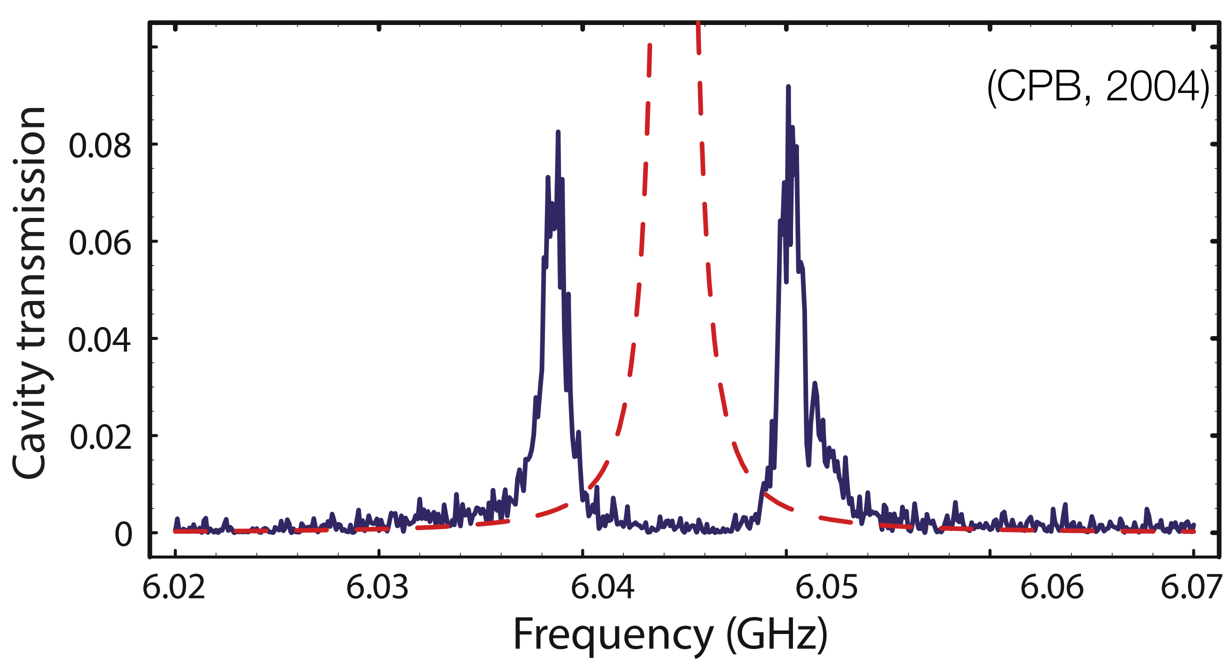
$g_{\text{cavity}}/2\pi \sim 50$ kHz

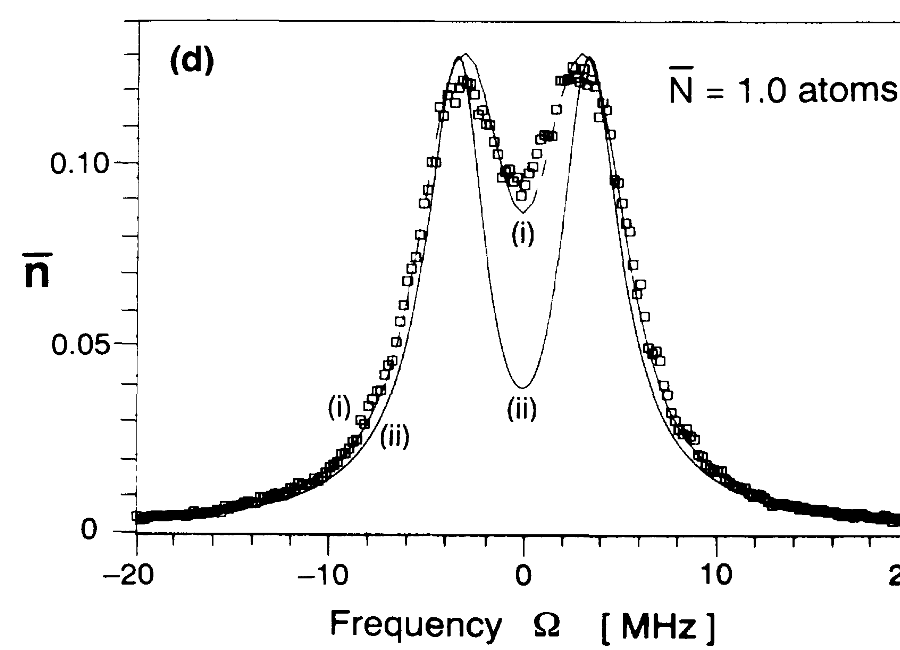
Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)

Jaynes-Cummings Hamiltonian





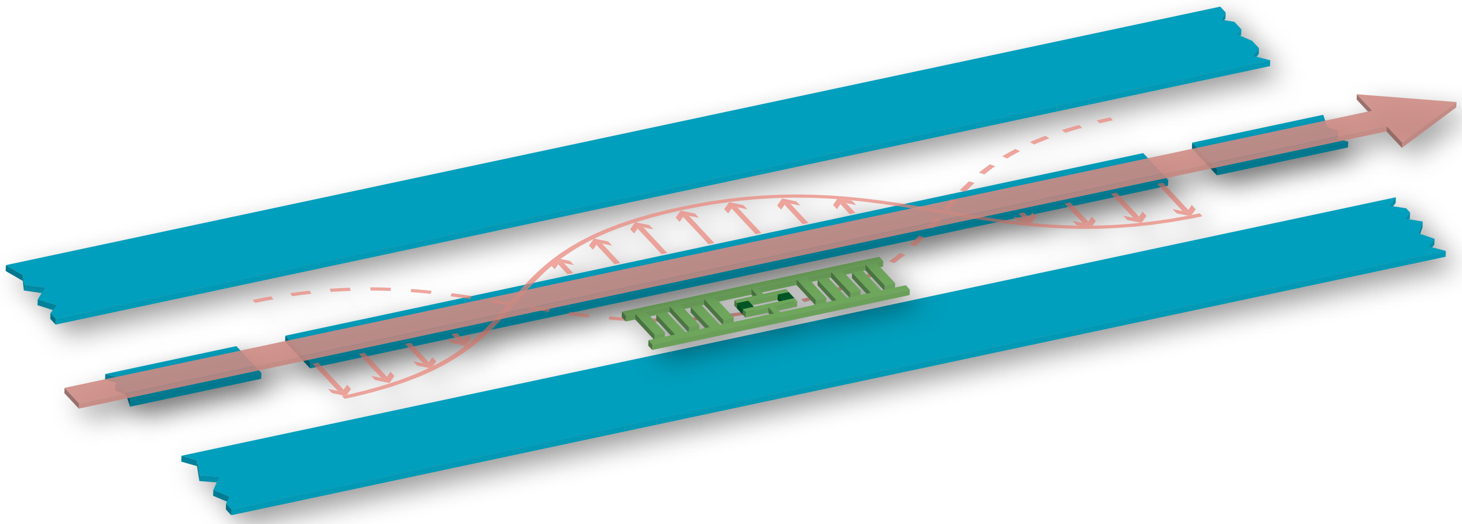


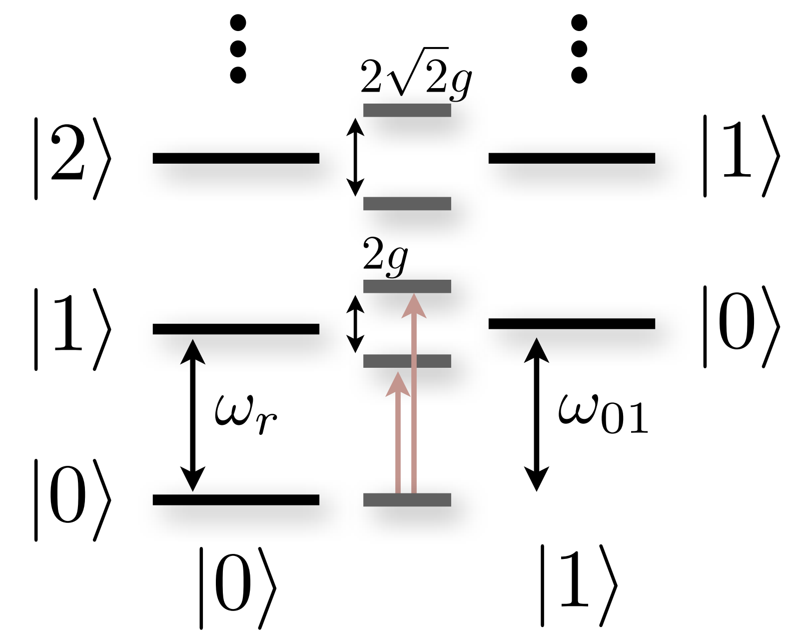


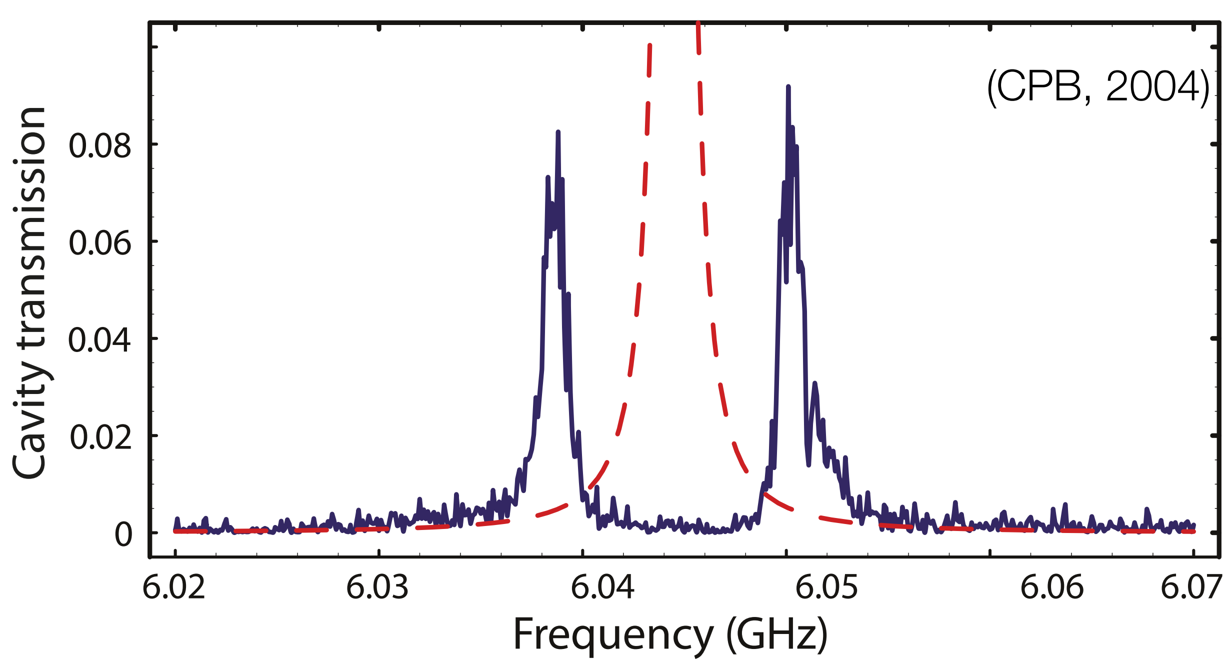
Circuit QED: Wallraff, Schuster, Blais, Frunzio, Huang, Majer, Kumar, Girvin & Schoelkopf. Nature 431, 162 (2004)

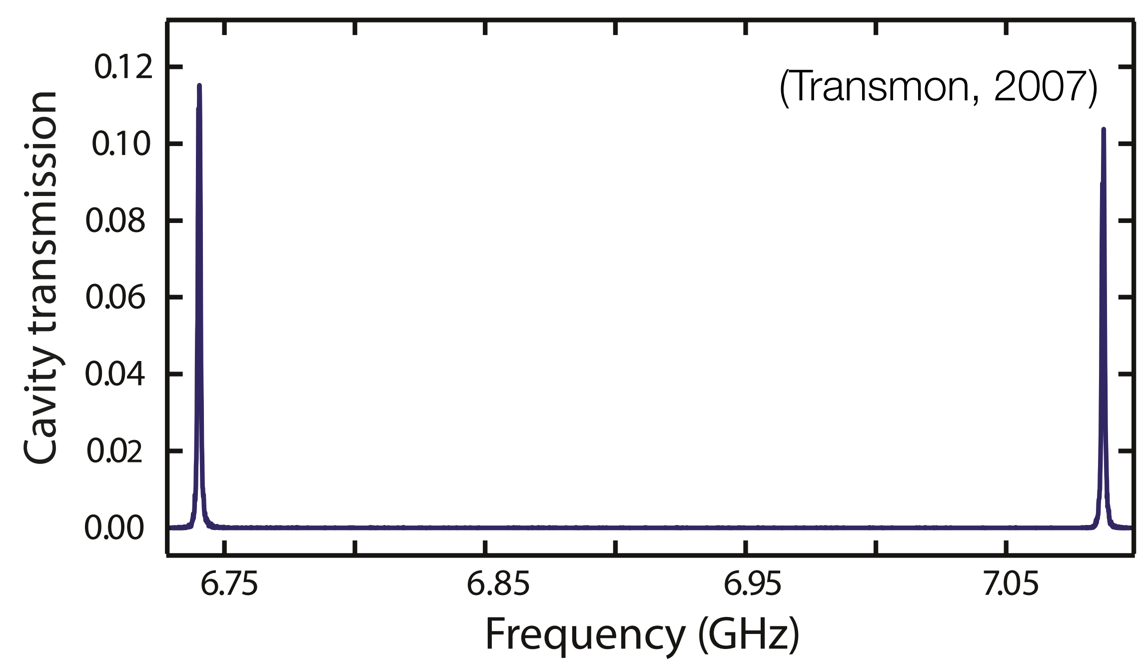
Cavity QED: R. J. Thompson, G. Rempe and H. J. Kimble, PRL **68**, 1132 (1992)

Jaynes-Cummings Hamiltonian









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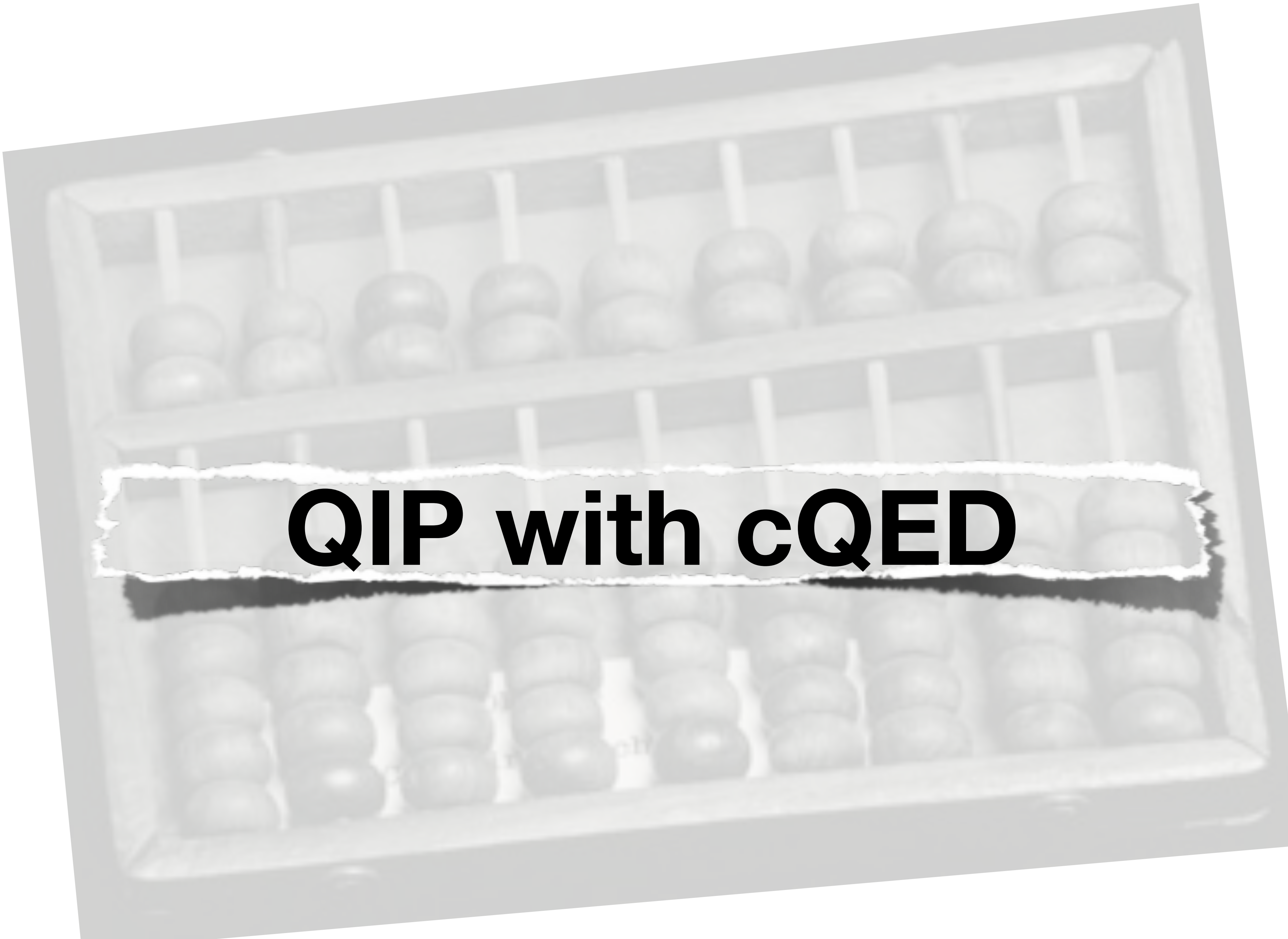
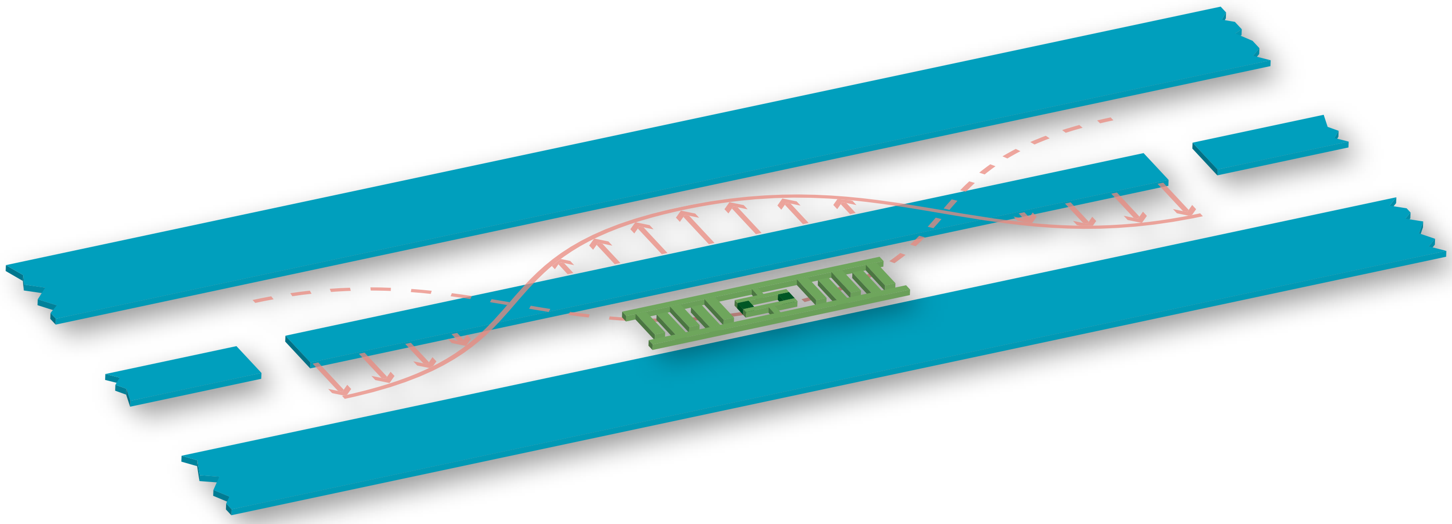
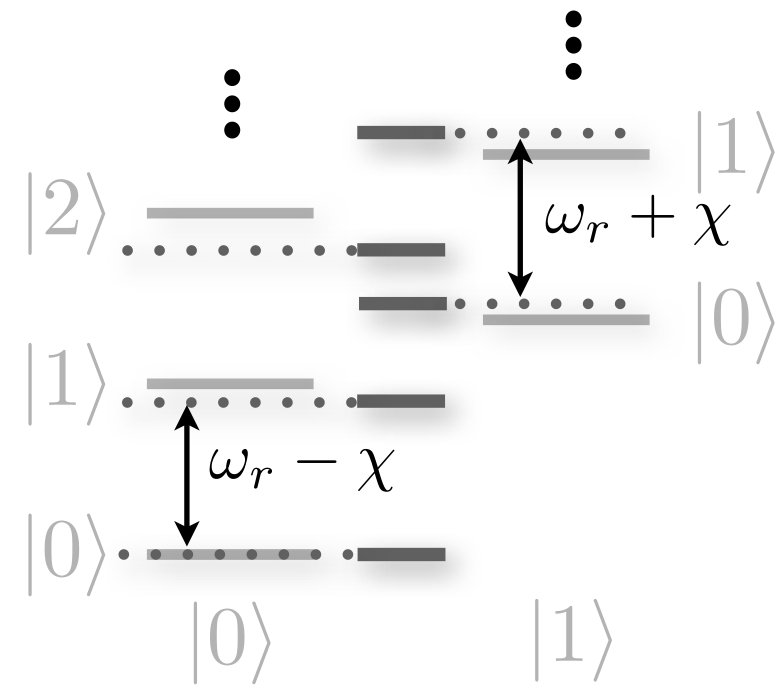


QIP with cQED

Dispersive regime of the JC Hamiltonian





Dispersive interaction: $H \approx (\omega_r + \chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} + \frac{\tilde{\omega}_{01}}{2}\hat{\sigma}_z$

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

Resonator frequency

Dispersive interaction strength
$\chi = g^2/\Delta$

Qubit transition frequency

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

Dispersive regime of the JC Hamiltonian

Dispersive interaction: $H \approx (\omega_r + \chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} + \frac{\tilde{\omega}_{01}}{2}\hat{\sigma}_z$

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

Resonator frequency

Dispersive interaction strength

$\chi = g^2/\Delta$

Qubit transition frequency

Operator perturbation theory:

$$H = \omega_r a^\dagger a + \frac{\omega_a}{2}\sigma_z + g(a^\dagger\sigma_- + a\sigma_+)$$

$$H_{\text{eff}} = e^{-\lambda X} H e^{\lambda X} = H + \lambda[H, X] + \frac{\lambda^2}{2!}[[H, X], X] + \frac{\lambda^3}{3!}[[[H, X], X], X] + \cdots$$

Choose X and λ such as to cancel non-diagonal term to second order:

$$X = a^\dagger\sigma_- - a\sigma_+ \qquad \lambda = -g/\Delta$$

Dispersive regime: Qubit readout

Dispersive interaction: $H \approx (\omega_r + \chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} + \frac{\tilde{\omega}_{01}}{2}\hat{\sigma}_z$

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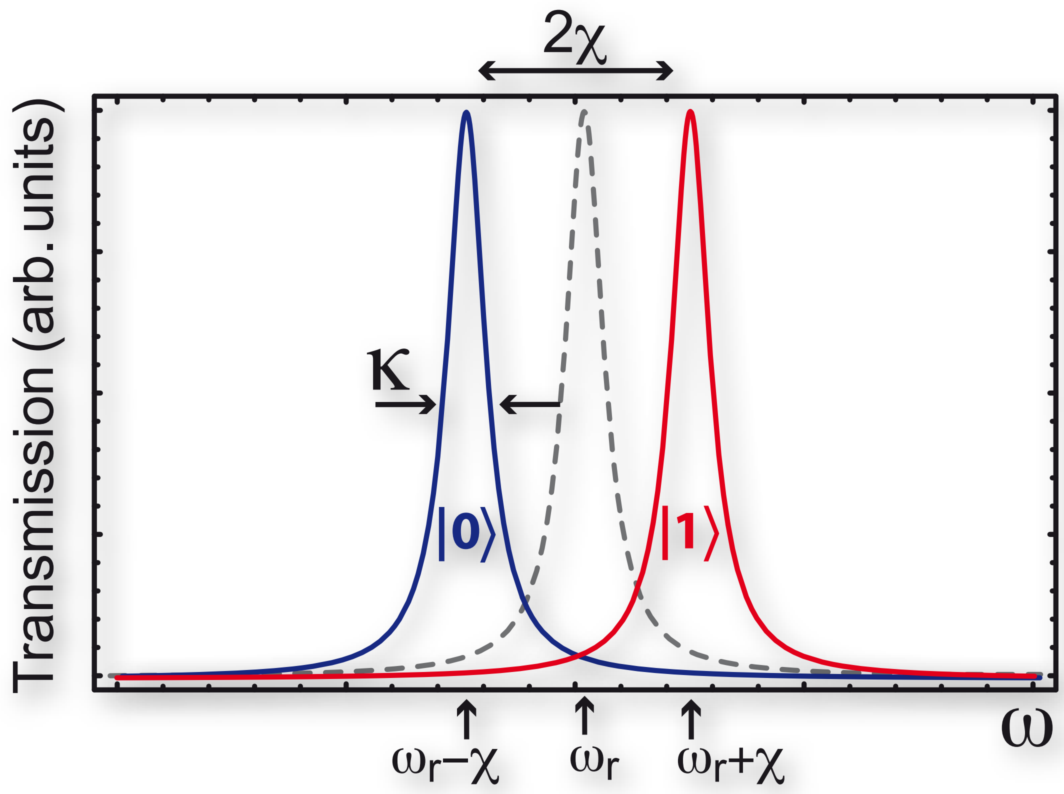

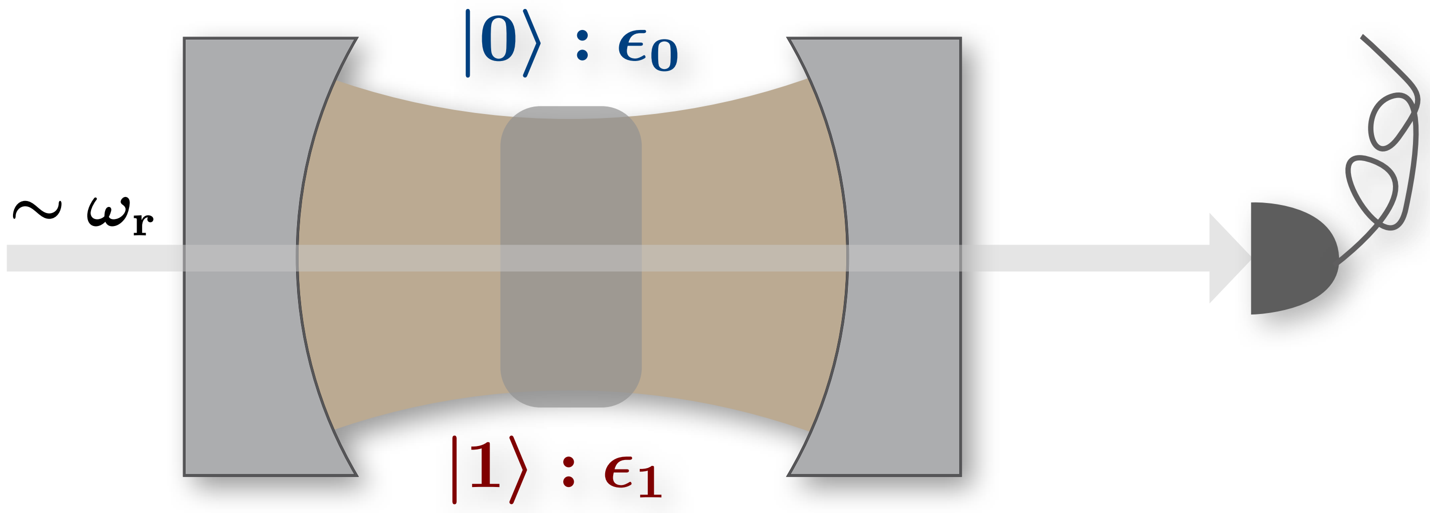

Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)

Dispersive regime: Qubit readout

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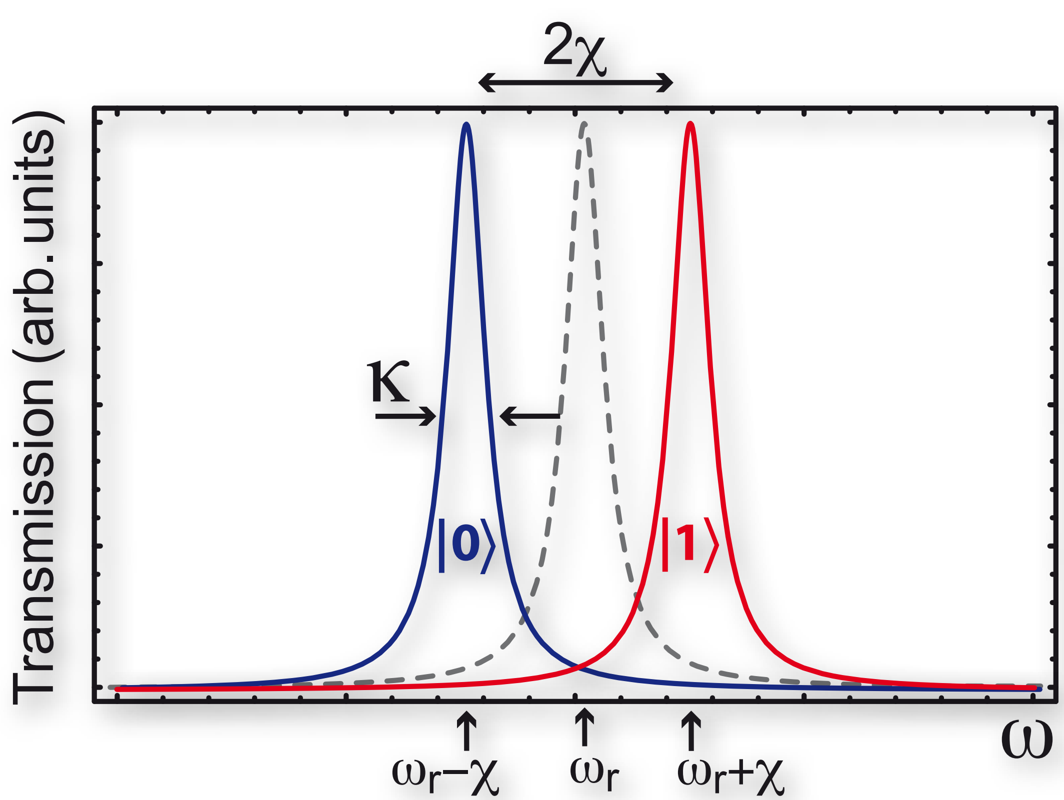
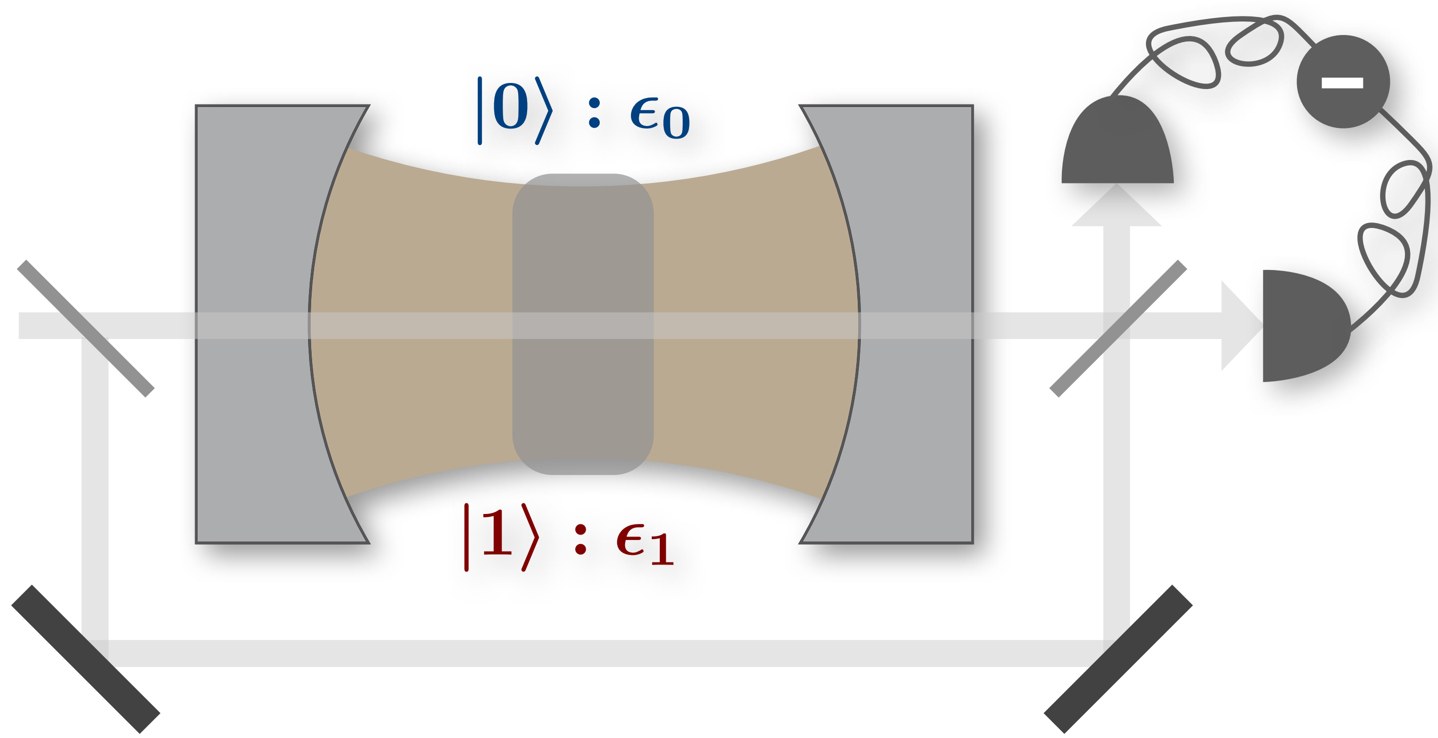




Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)

Dispersive regime: Single-qubit gates

Dispersive interaction: $H \approx (\omega_r + \chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} + \frac{\tilde{\omega}_{01}}{2}\hat{\sigma}_z$

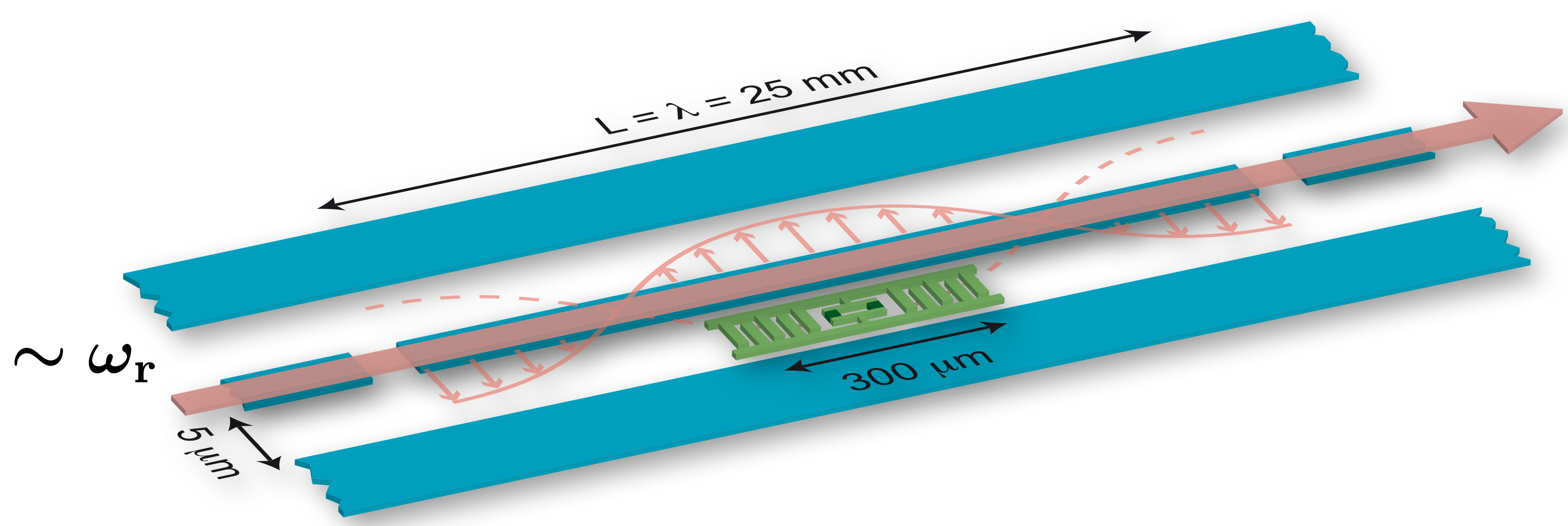
$(|\Delta| = |\omega_{01} - \omega_r| \gg g)$

Resonator frequency

Dispersive interaction strength

$\chi = g^2/\Delta$

Qubit transition frequency



A. Wallraff *et al*. Phys. Rev. Lett. **95**, 060501 (2005).

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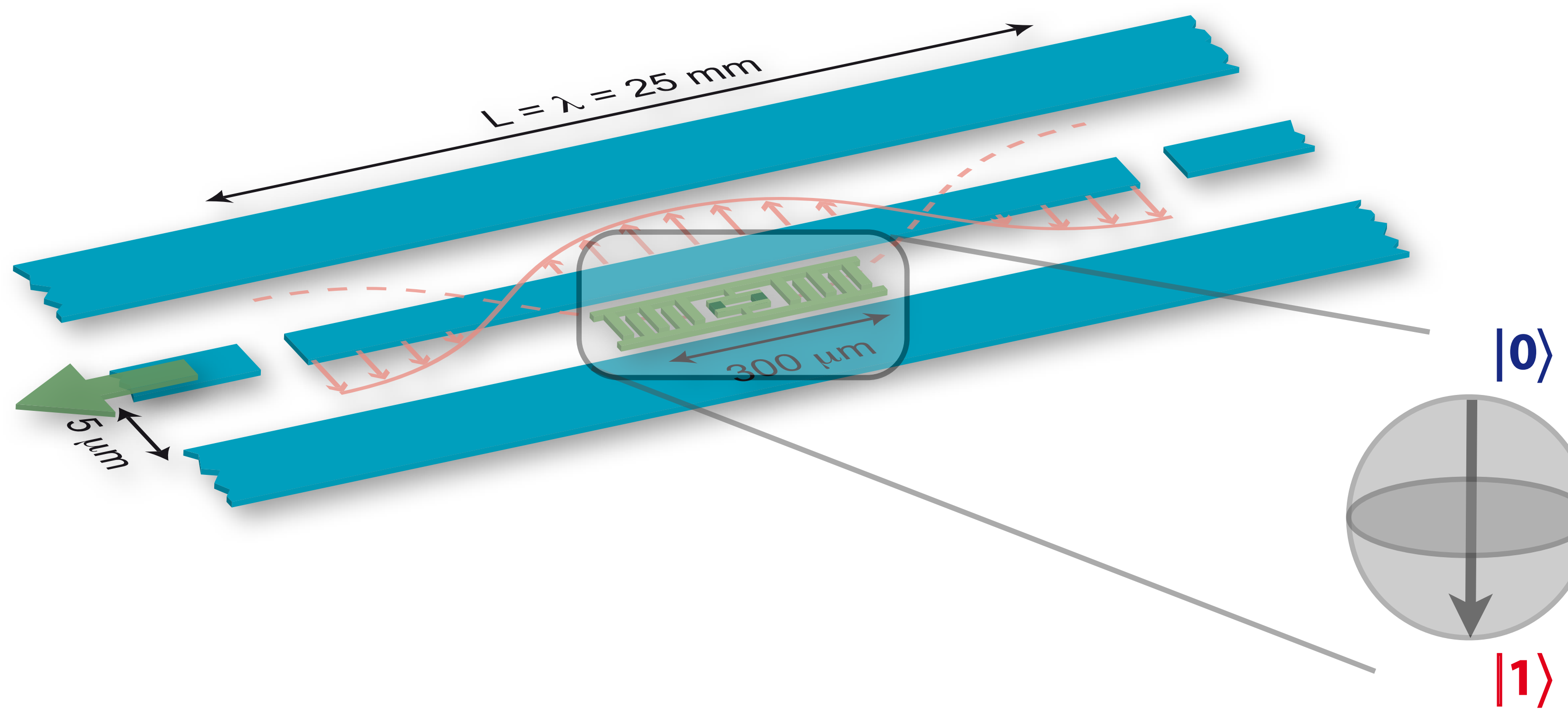
$(|\Delta| = |\omega_{01} - \omega_r| \gg g)$

Resonator frequency

Dispersive interaction strength
$\chi = g^2/\Delta$

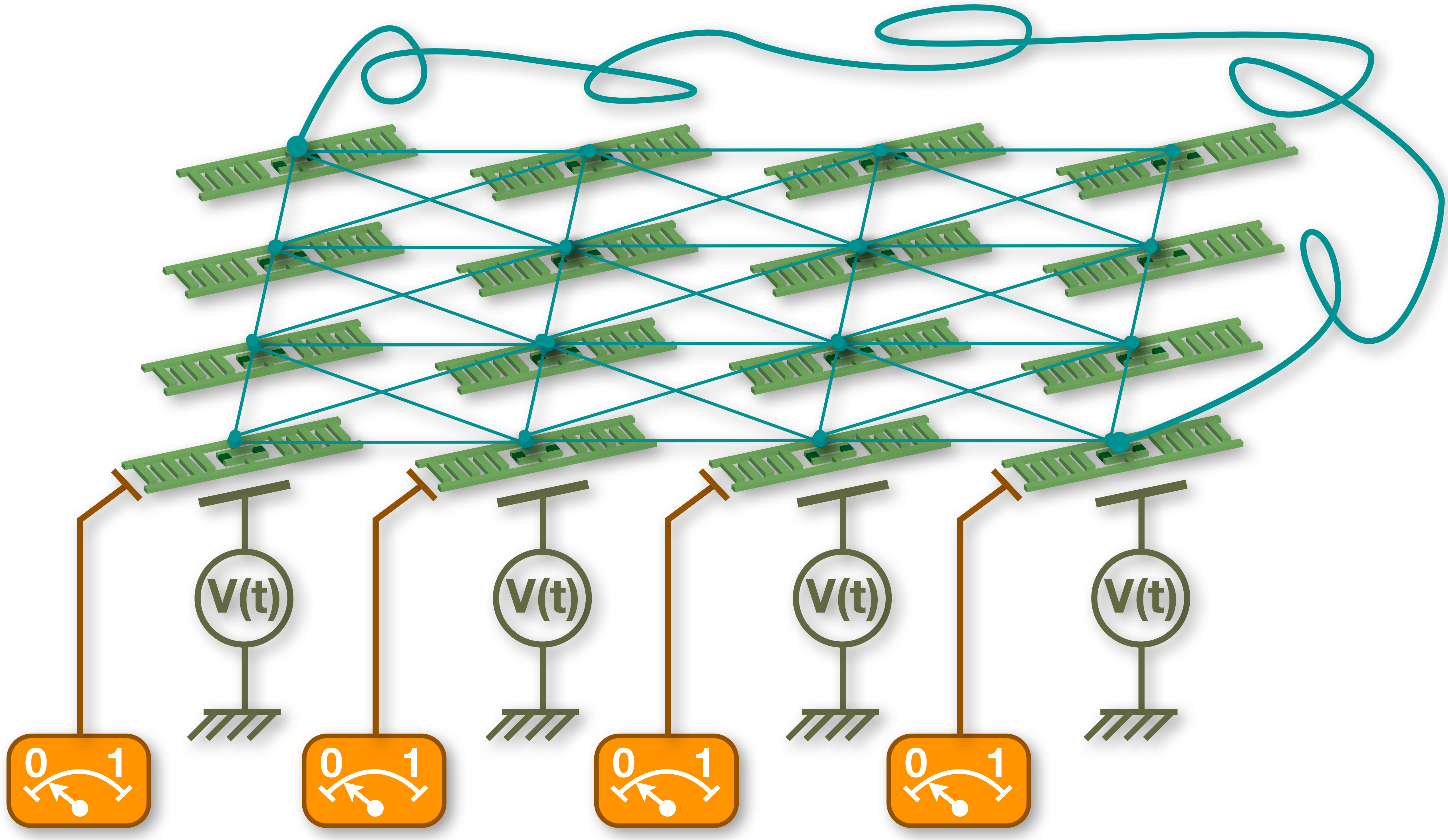
Qubit transition frequency



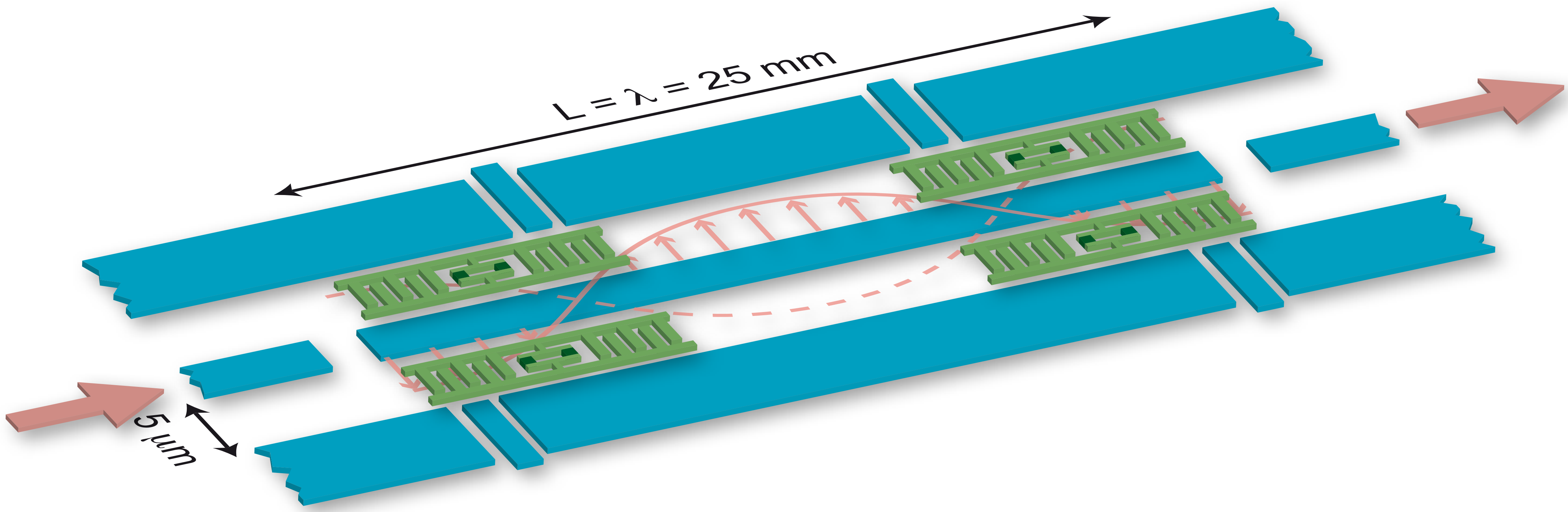
A. Wallraff *et al*. Phys. Rev. Lett. **95**, 060501 (2005).

Quantum information processing with circuit QED

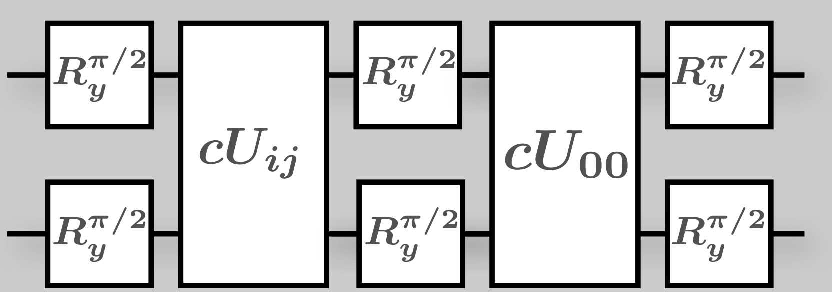
without



Quantum information processing with circuit QED



First two-qubit quantum algorithms implemented in a solid-state quantum information processor



L. DiCarlo *et al*, Nature **460**, 240 (2009)

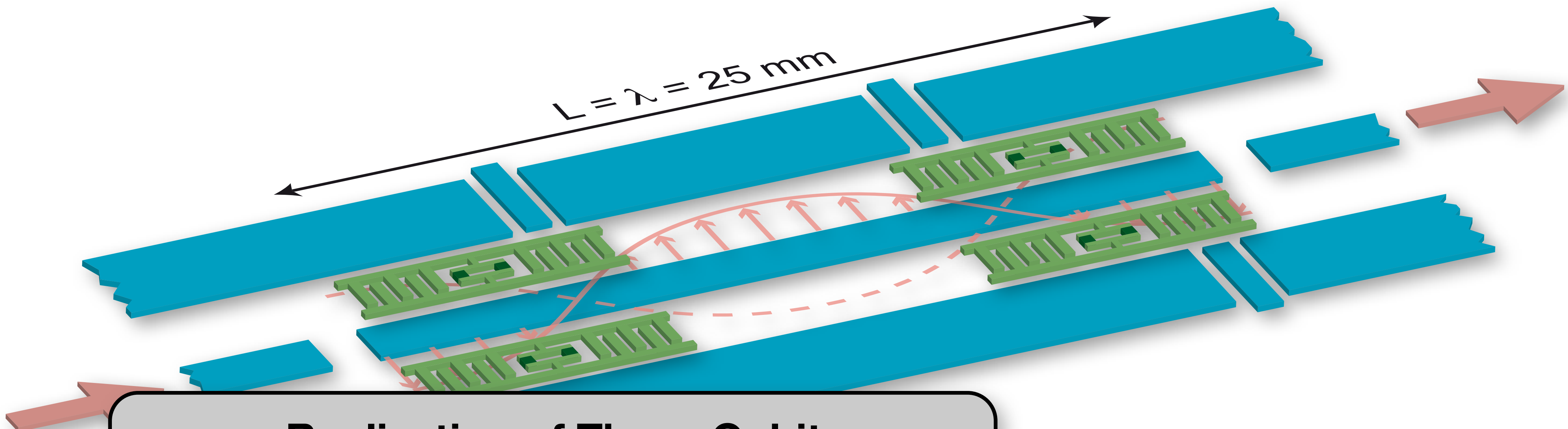
3-qubit entanglement generated with 88% fidelity

$$|\mathbf{GHZ}\rangle = \frac{1}{\sqrt{2}}\left(|000\rangle + |111\rangle\right)$$

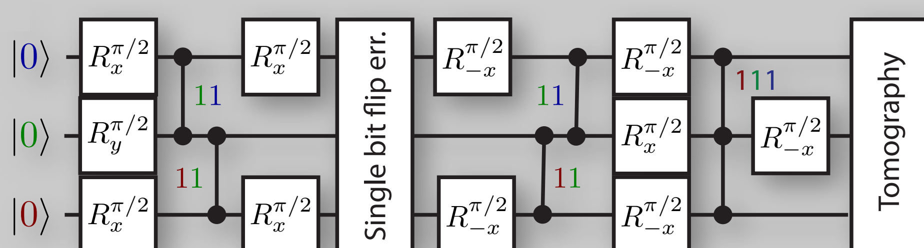
L. DiCarlo *et al*, Nature **467**, 574 (2010)

Quantum gates: A. Blais *et al*, Phys. Rev. A **75**, 032329 (2007)
Multi-qubit readout: S. Filipp *et al*, Phys. Rev. Lett. **102**, 200402 (2009)

Quantum information processing with circuit QED



Realization of Three-Qubit Quantum Error Correction



M. D. Reed *et al*, Nature **482**, 382 (2011)

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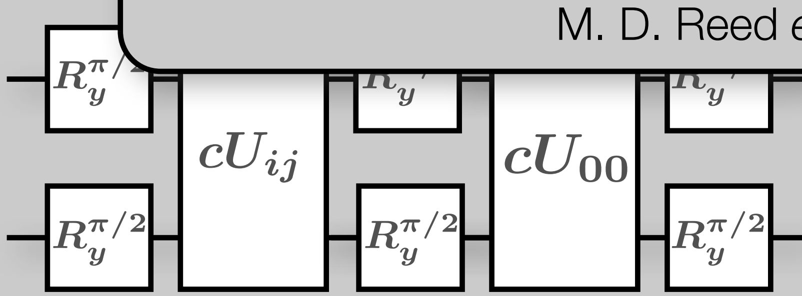

L. DiCarlo *et al*, Nature **460**, 240 (2009)

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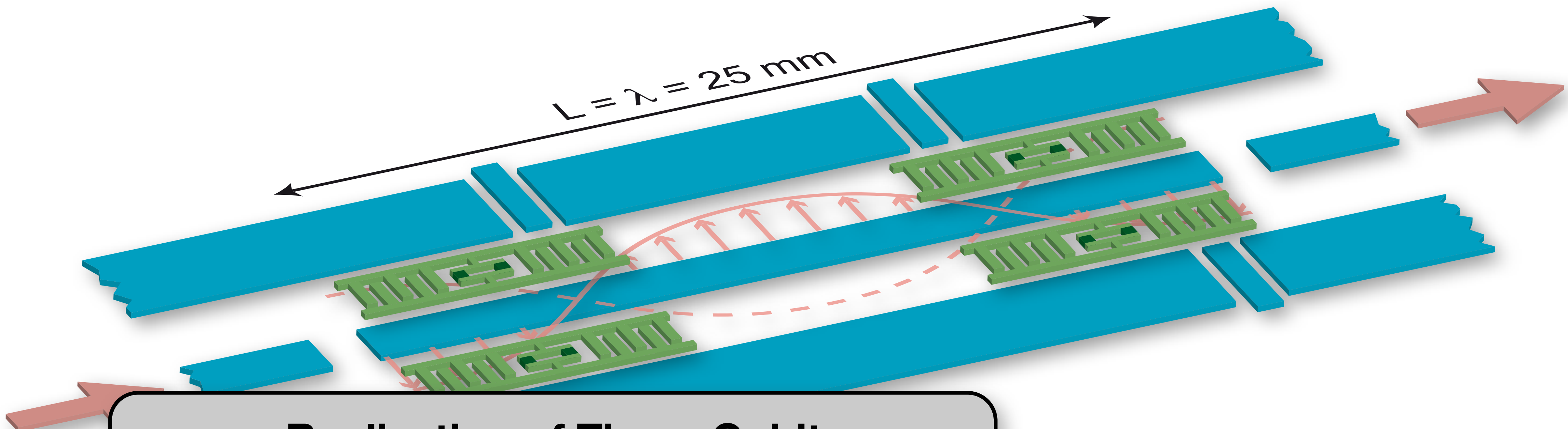
Quantum information processing with circuit QED



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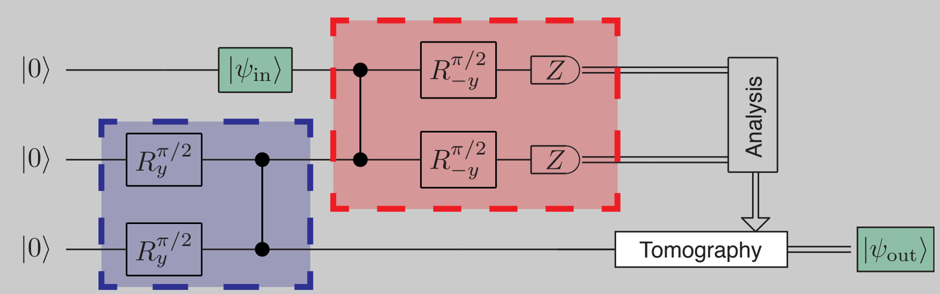
Realization of Three-Qubit Quantum Error Correction

Realization of quantum teleportation



L. DiCarlo

L. Steffen *et al*, ArXiV: arXiv:1302.5621

...ment generated ...% fidelity

$$... |000\rangle + |111\rangle)$$

...o *et al*, Nature **467**, 574 (2010)

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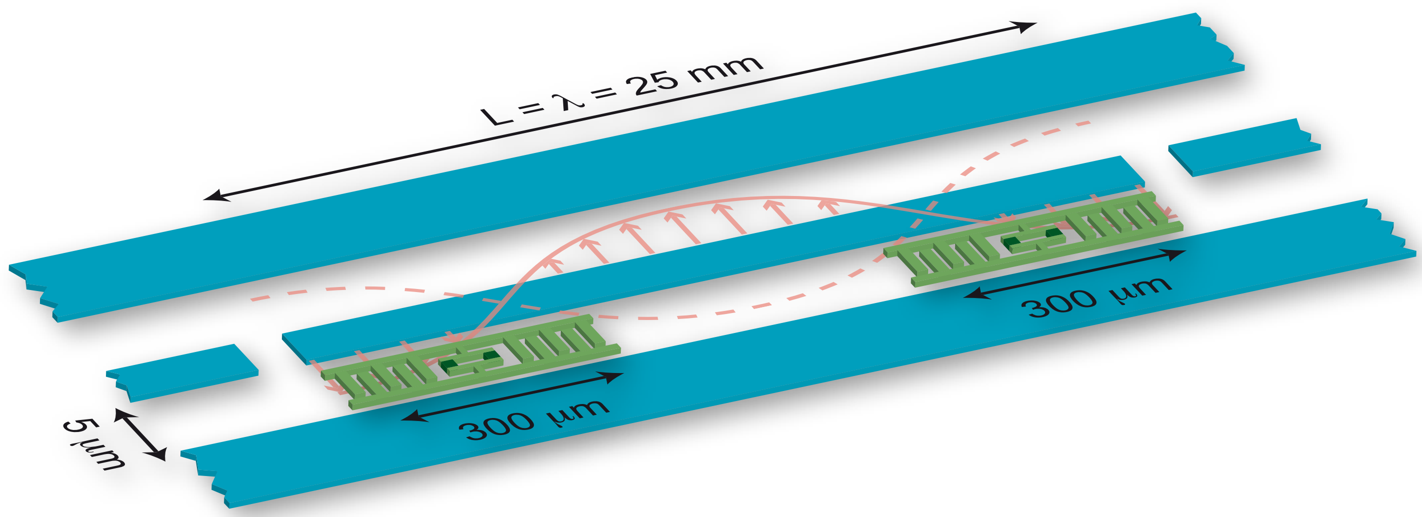
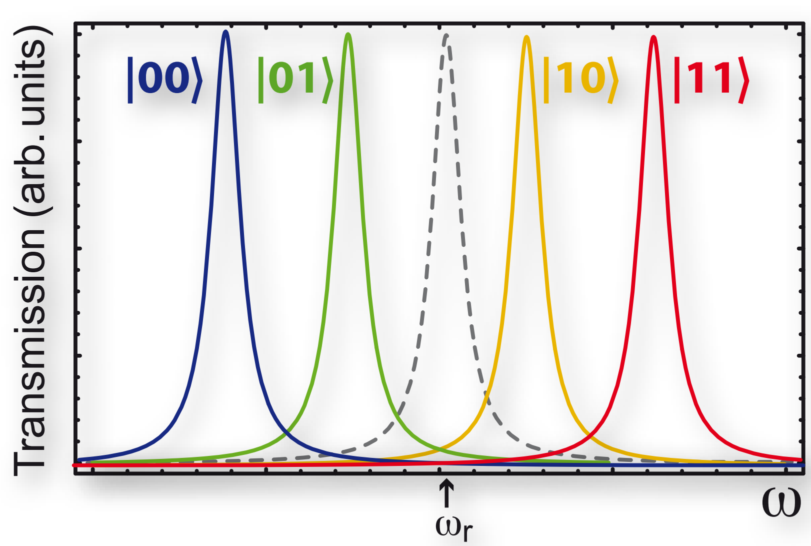
Multi-qubit readout: S. Filipp *et al*, Phys. Rev. Lett. **102**, 200402 (2009)

Multi-qubit circuit QED



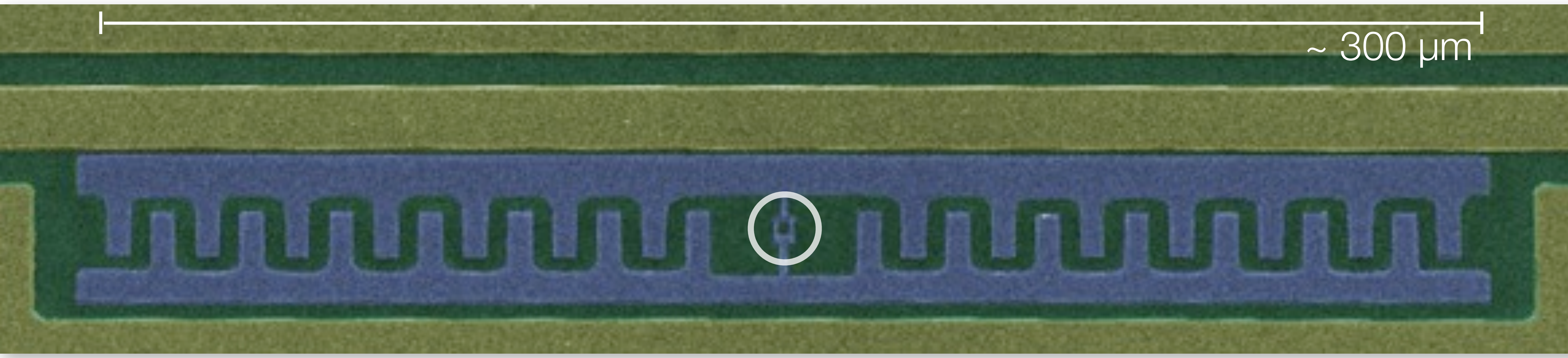
Dispersive interaction: $H = (\omega_r + \hat{\chi})\, a^\dagger a + \frac{\omega_{a1}}{2}\sigma_{z1} + \frac{\omega_{a2}}{2}\sigma_{z2}$

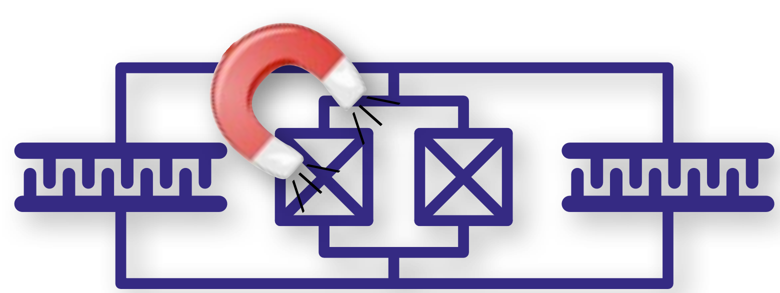
$$\hat{\chi} = \chi_1 \sigma_{z1} + \chi_2 \sigma_{z2}$$



- Simultaneous qubit readout
- Single-qubit gates in parallel
- Weak measurement

Superconducting qubits: transmon regime

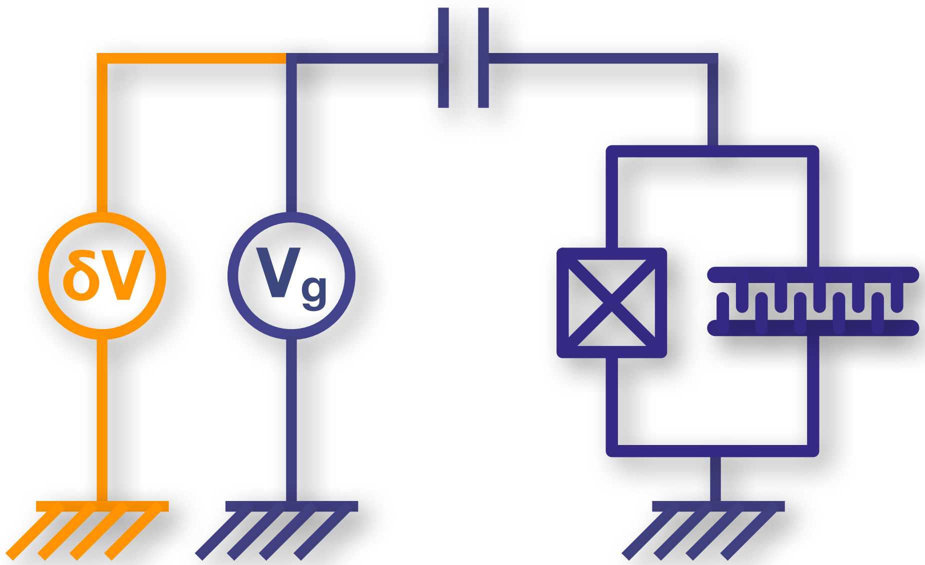


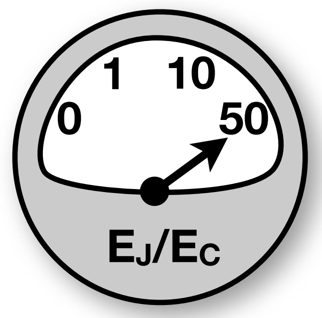


Qubit transition frequency can be changed by ~ 1 GHz in a few ns

J. Koch et al. Phys. Rev. A **76**, 042319 (2007)

Flux dispersion

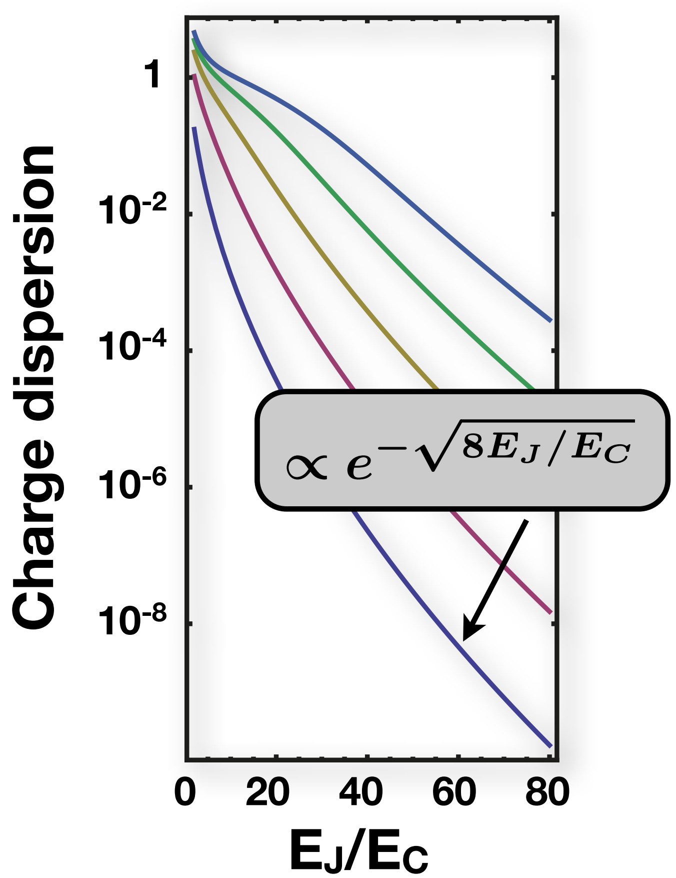


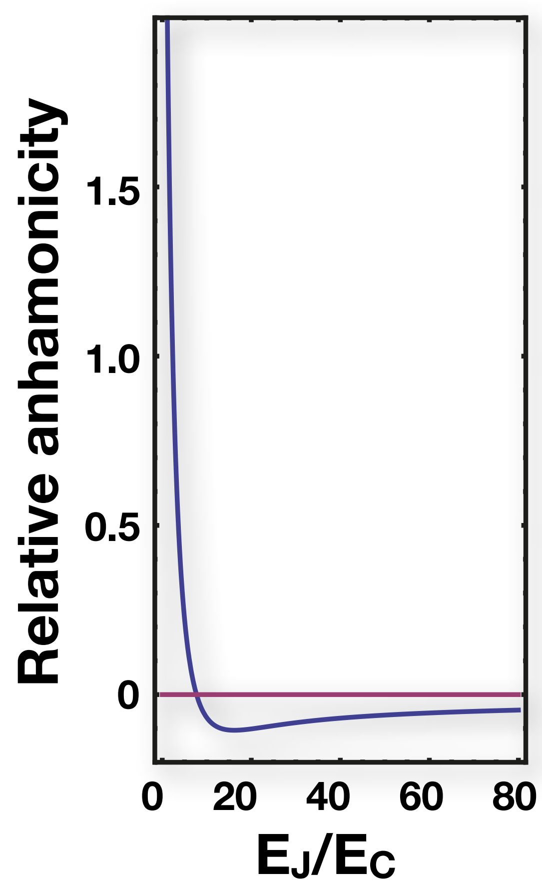


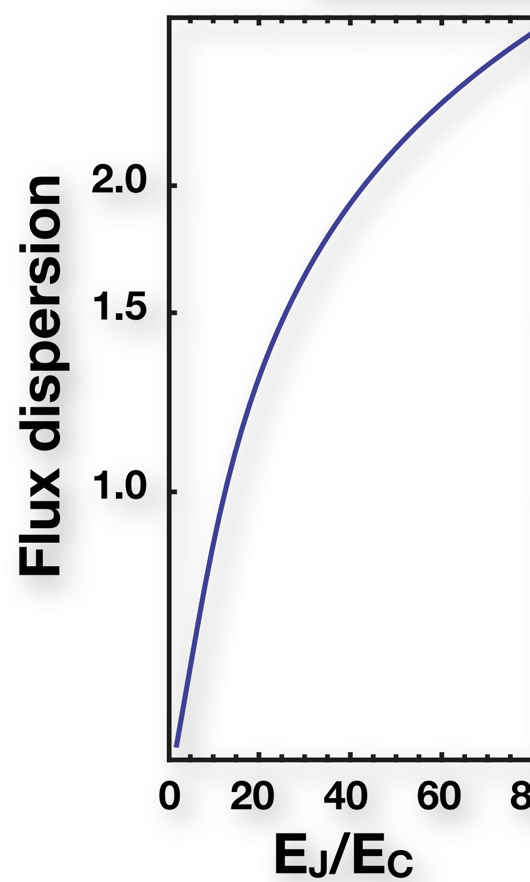
$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos\hat{\phi}$$

Flux in the SQUID loop:

$$E_J \to E_J \cos\left(\frac{\pi\Phi_x}{\Phi_0}\right)$$

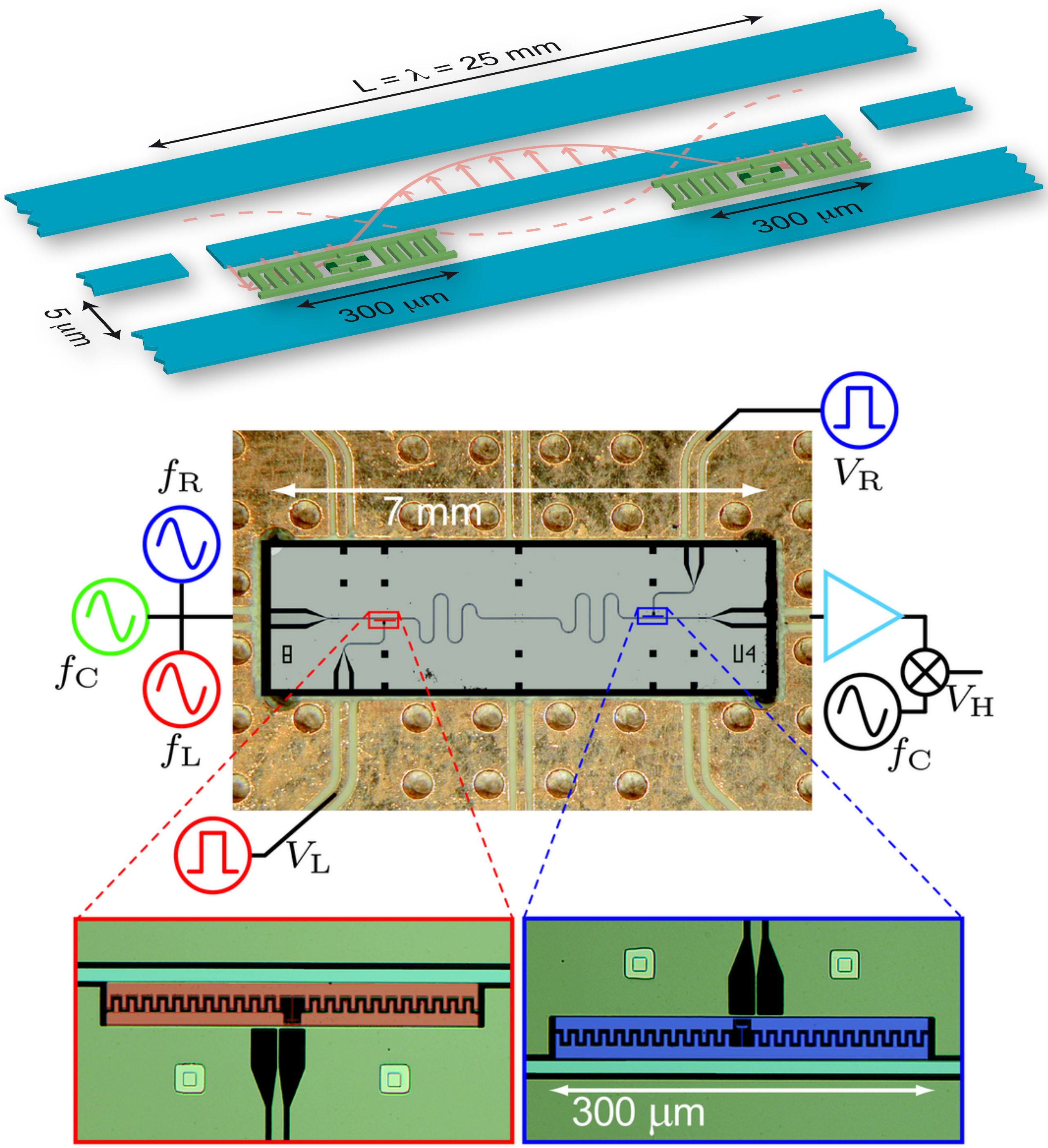






Sweet spot: D. Vion et al. Science **296**, 886 (2002); Transmon: J. Koch et al. Phys. Rev. A **76**, 042319 (2007)

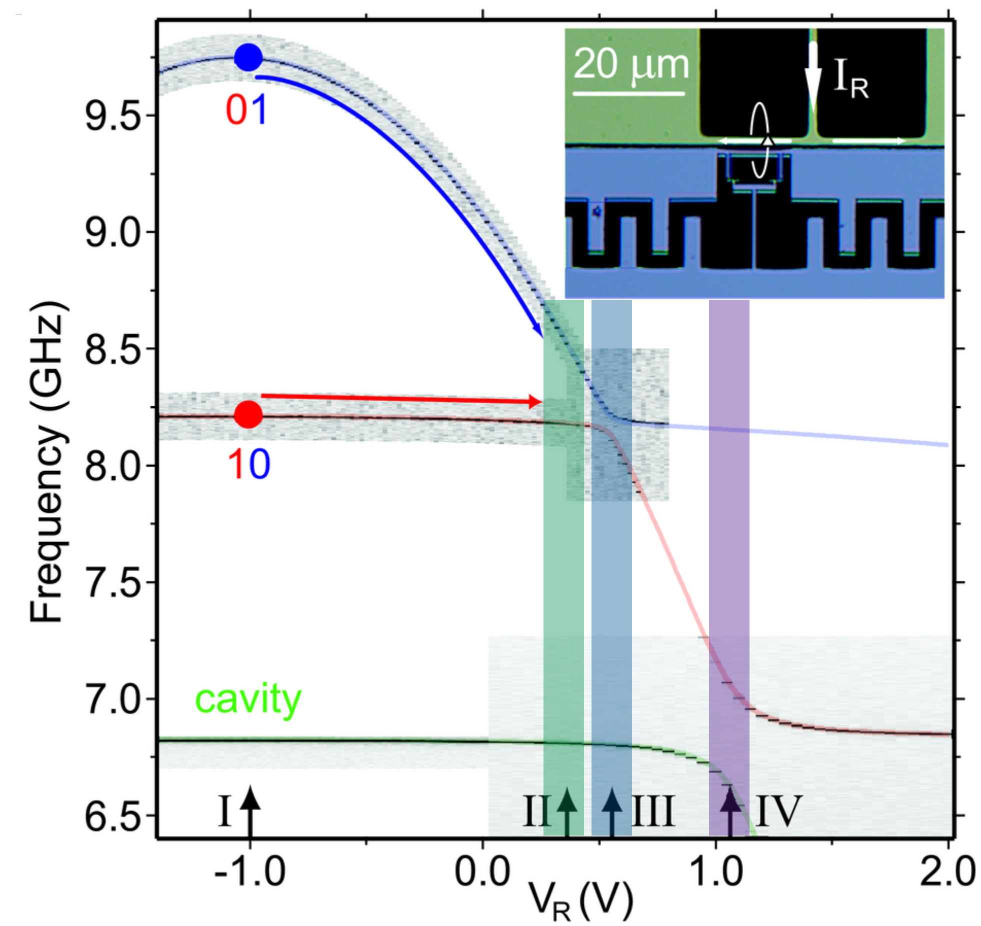
Generating highly entangled states



T_{1L}~1.3 µs
T_{2L}~1.8 µs

T_{1R}~0.8 µs
T_{2R}~1.2 µs

Flux-tunable frequencies:



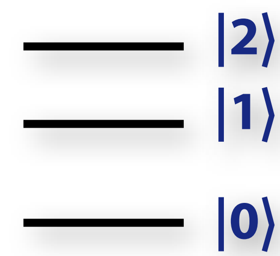
Quantum bus
J. Majer *et al.* Nature **449**, 443 (2007)

Vacuum Rabi Splitting
Wallraff *et al*. Nature **431**, 162 (2004)

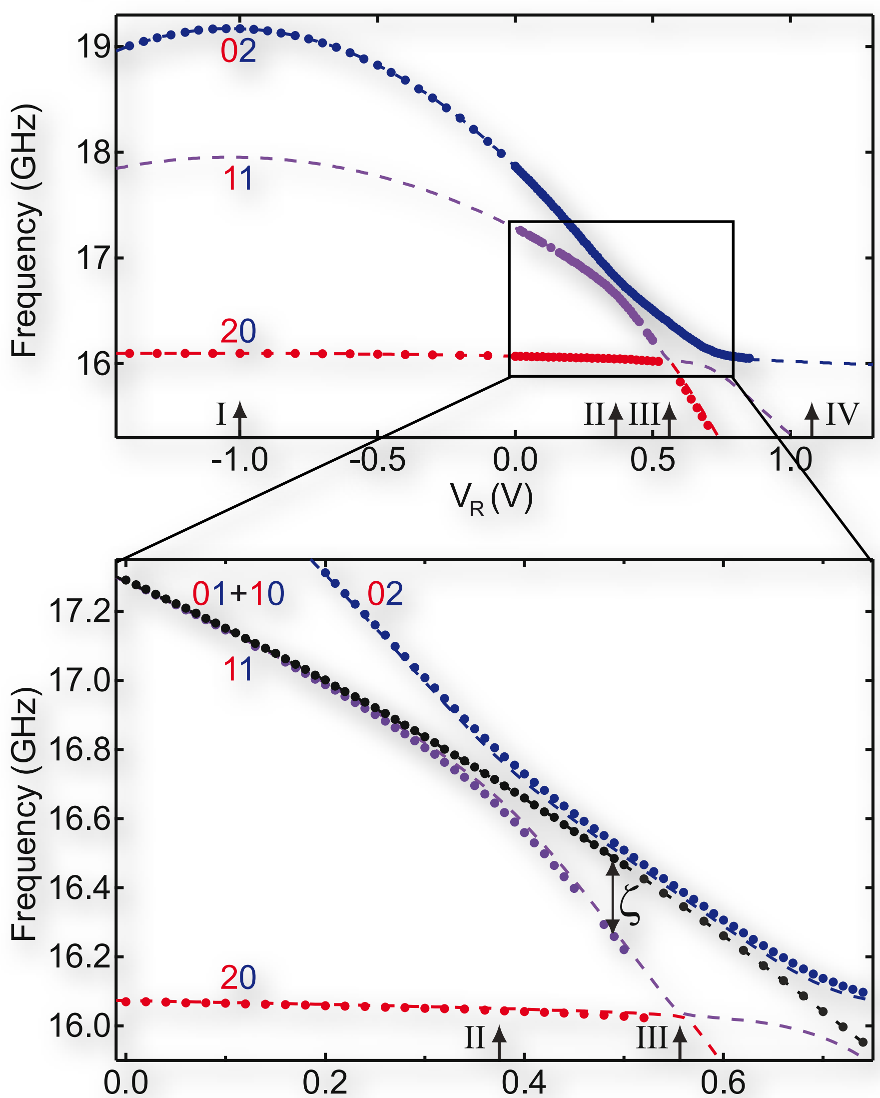
L. DiCarlo *et al.* Nature **460**, 240 (2009)

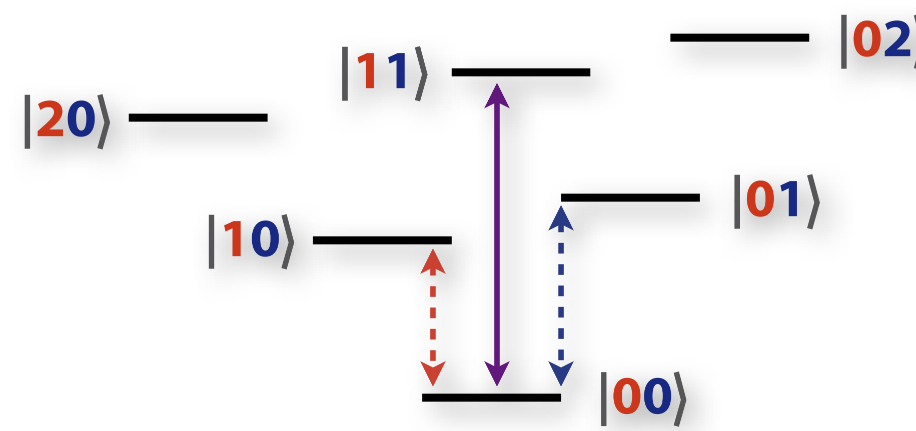
Generating highly entangled states

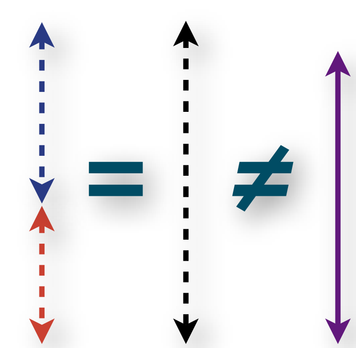
Transmon qubit: a slightly anharmonic oscillator



|02⟩ - |11⟩ avoided crossing:



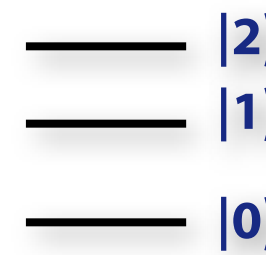




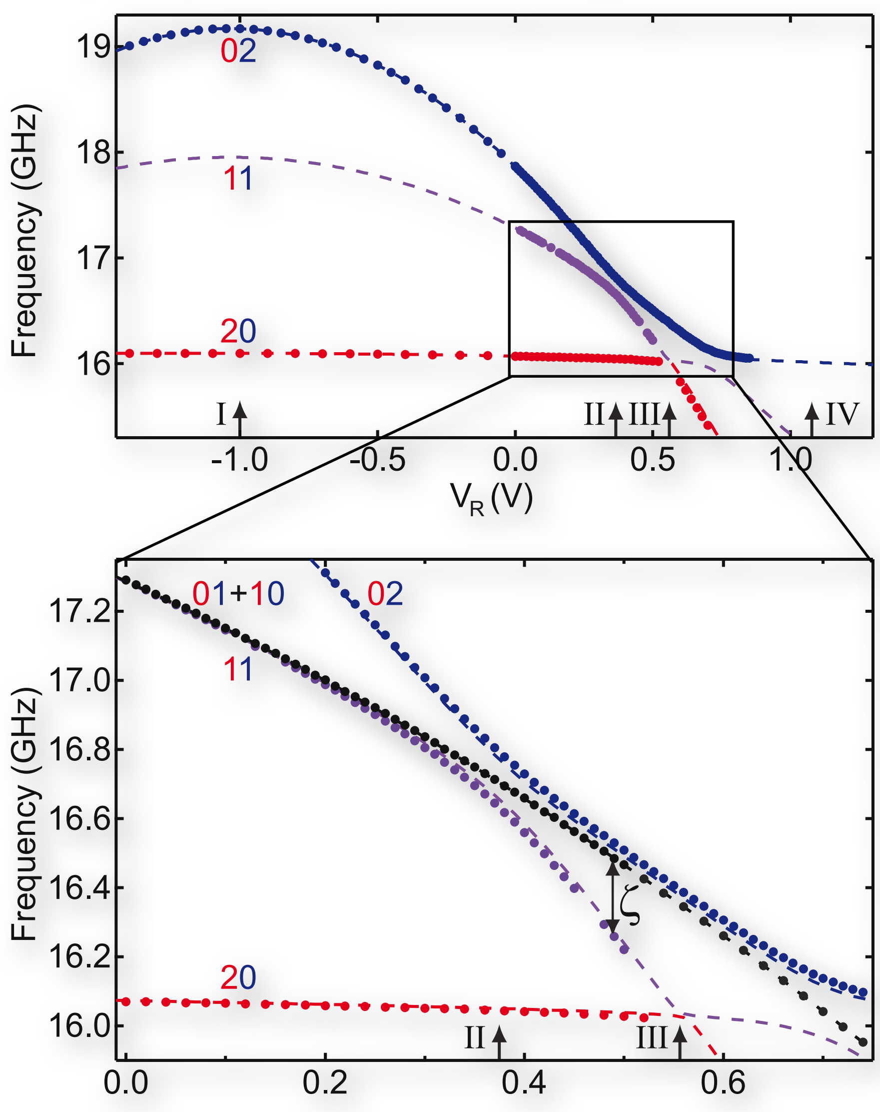
L. DiCarlo *et al.* Nature **460**, 240 (2009)

Generating highly entangled states

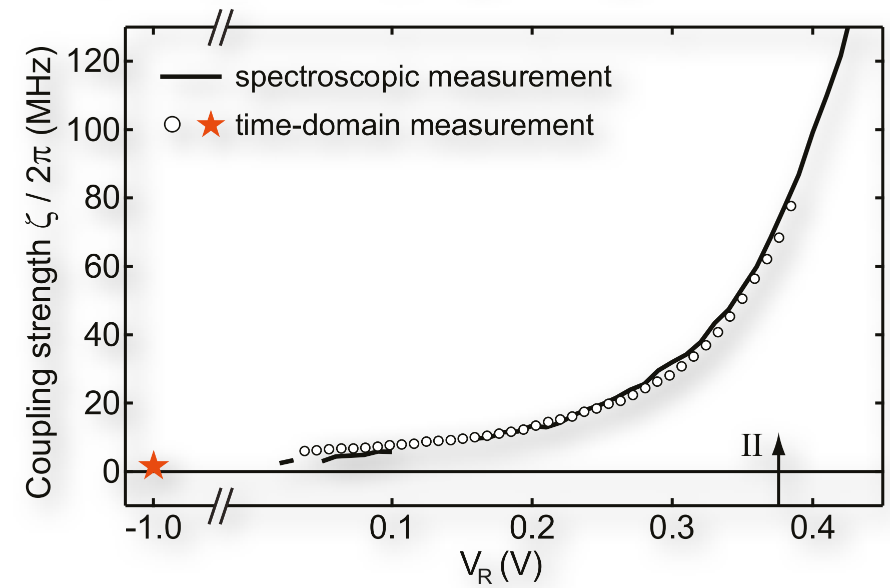
Transmon qubit: a slightly anharmonic oscillator



|02⟩-|11⟩ avoided crossing:



Qubit-qubit coupling strength:



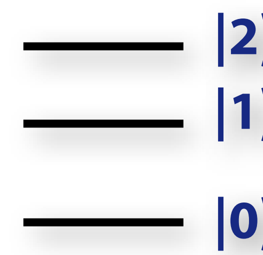
Conditional phase gate:

$$
cU = \begin{pmatrix} e^{i\phi_{00}} & 0 & 0 & 0 \\ 0 & e^{i\phi_{01}} & 0 & 0 \\ 0 & 0 & e^{i\phi_{10}} & 0 \\ 0 & 0 & 0 & e^{i\phi_{11}} \end{pmatrix}
$$

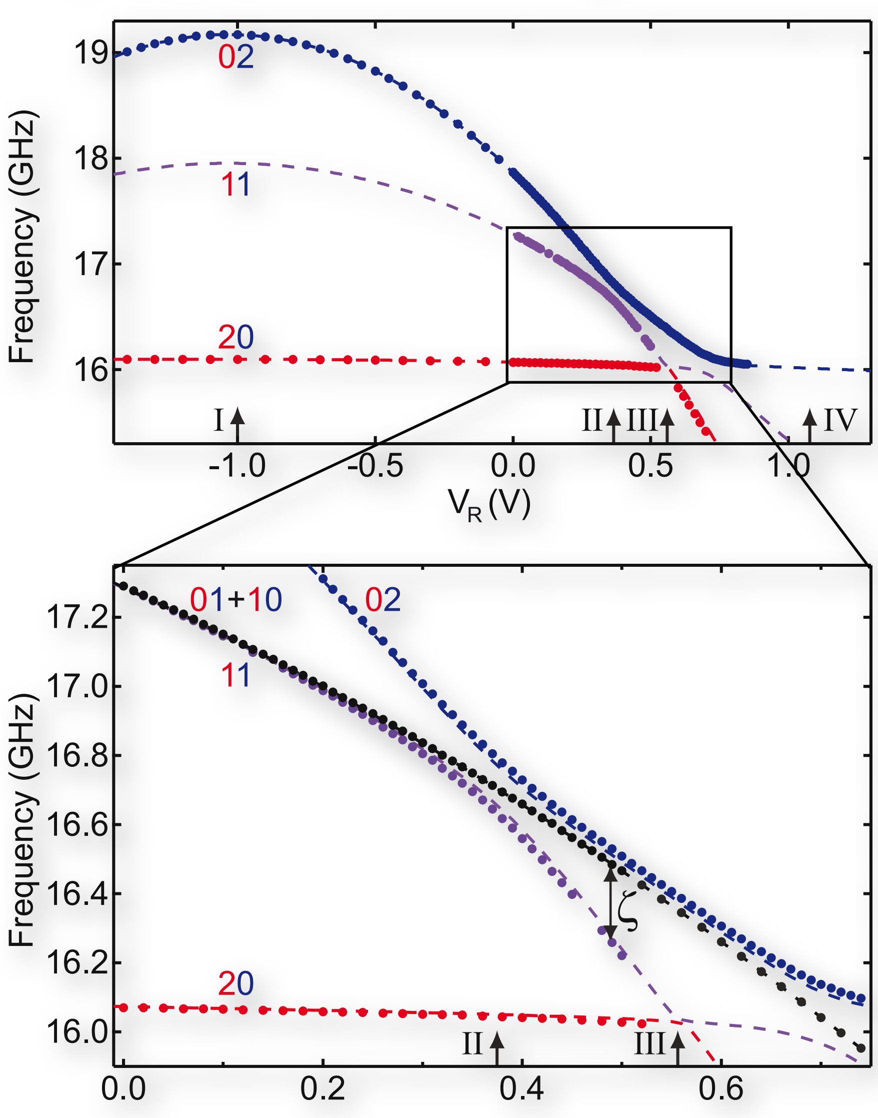
L. DiCarlo *et al.* Nature **460**, 240 (2009)

Generating highly entangled states

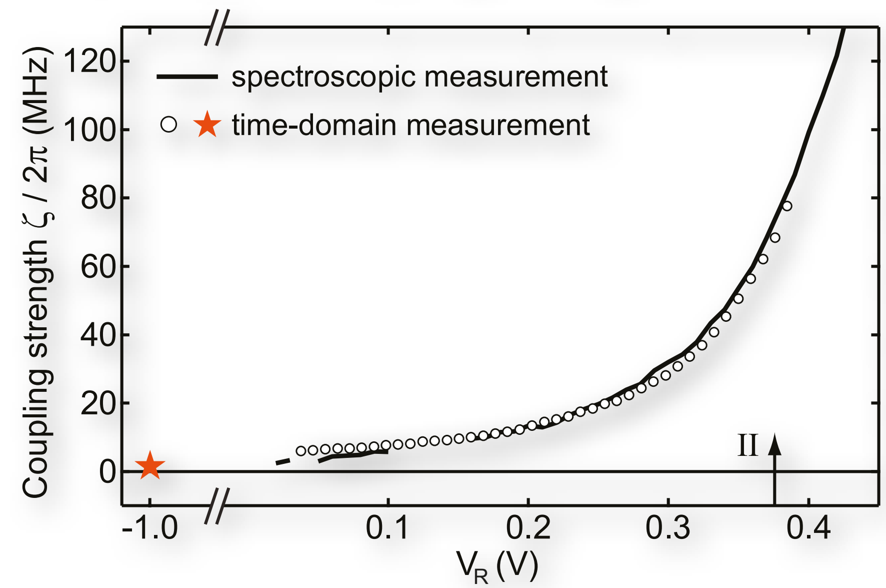
Transmon qubit: a slightly anharmonic oscillator



|02⟩ - |11⟩ avoided crossing:



Qubit-qubit coupling strength:



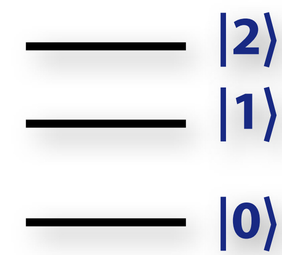
Conditional phase gate:

$$cU_{11} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

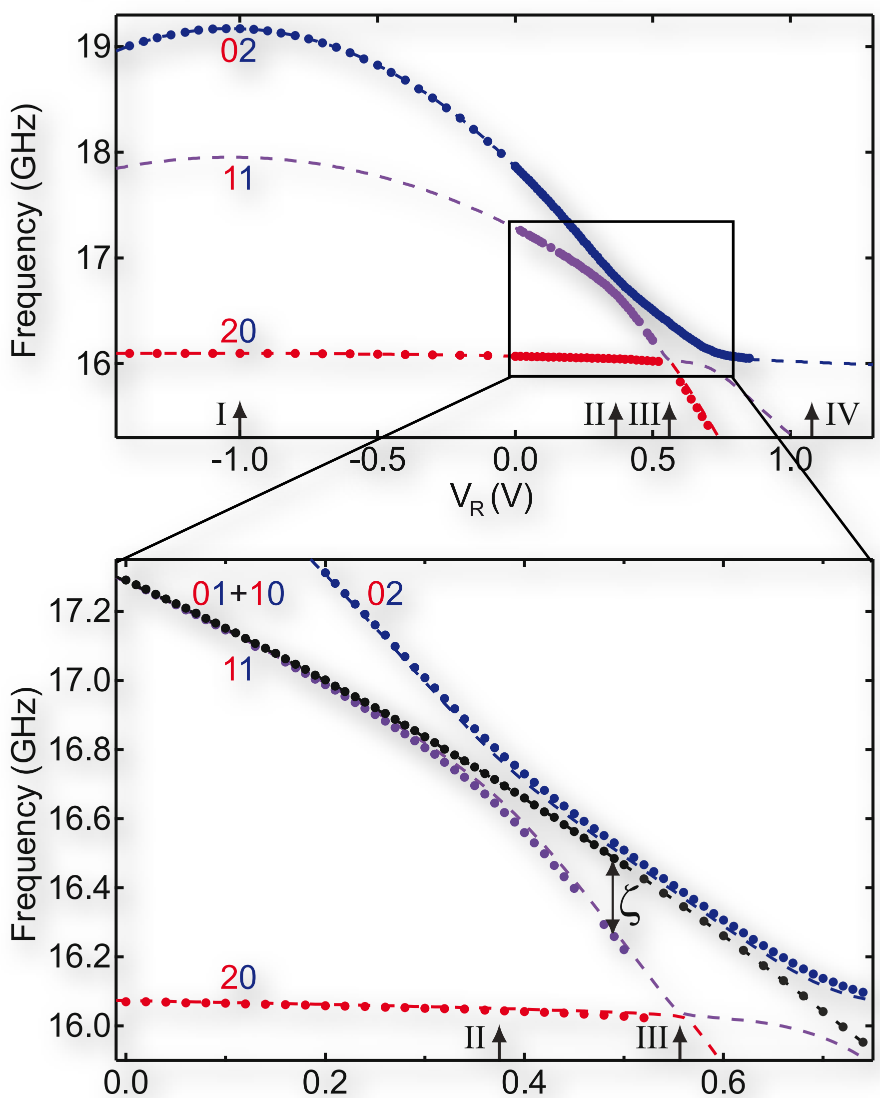
L. DiCarlo *et al.* Nature **460**, 240 (2009)

Generating highly entangled states

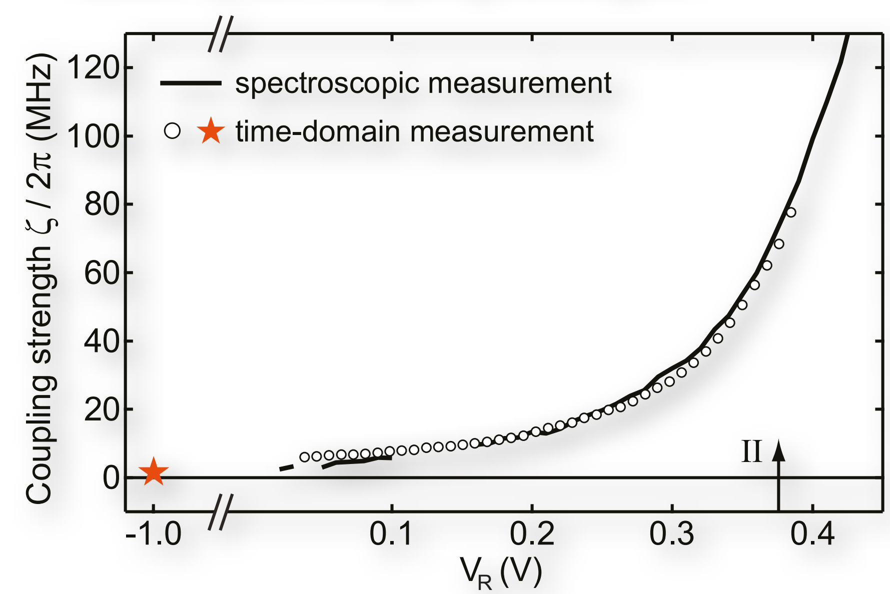
Transmon qubit: a slightly anharmonic oscillator



|02⟩-|11⟩ avoided crossing:



Qubit-qubit coupling strength:



Conditional phase gate:

$$cU_{10} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

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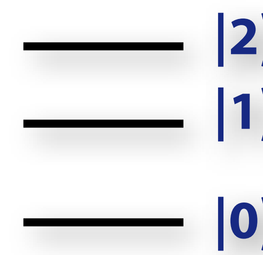
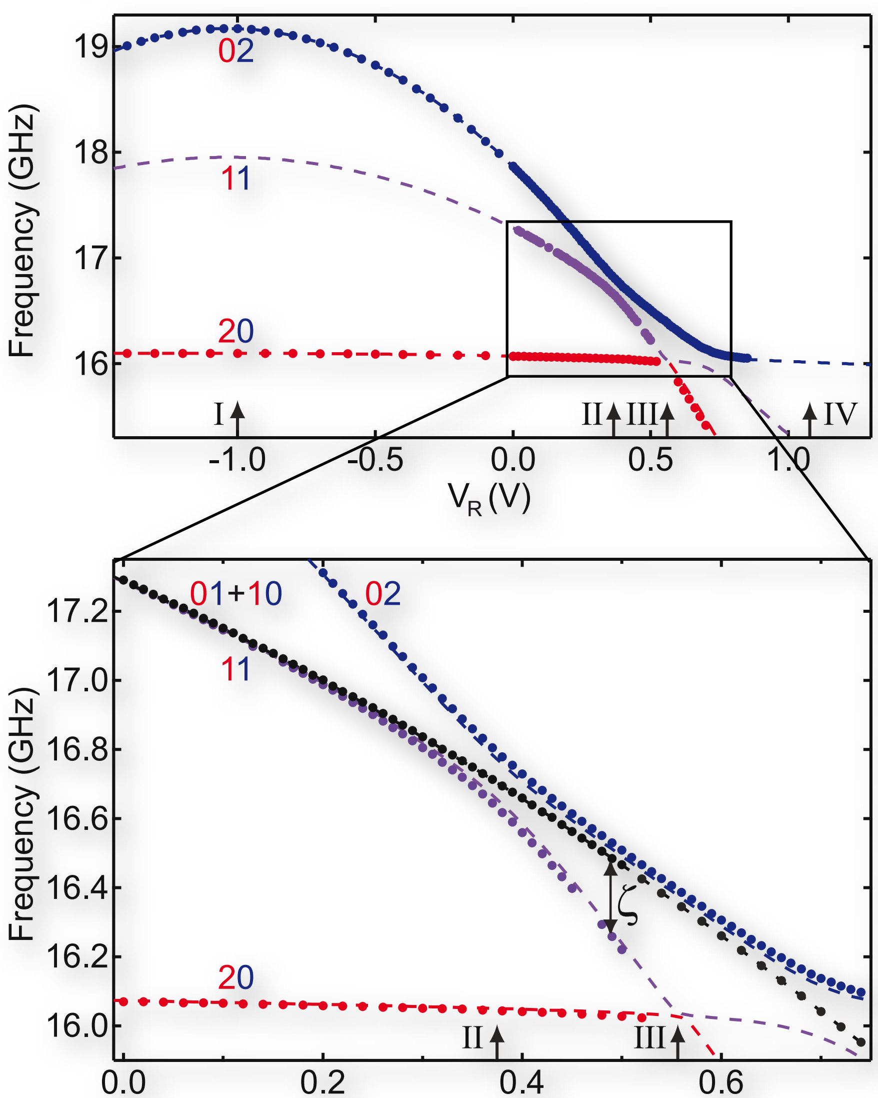
Generating highly entangled states

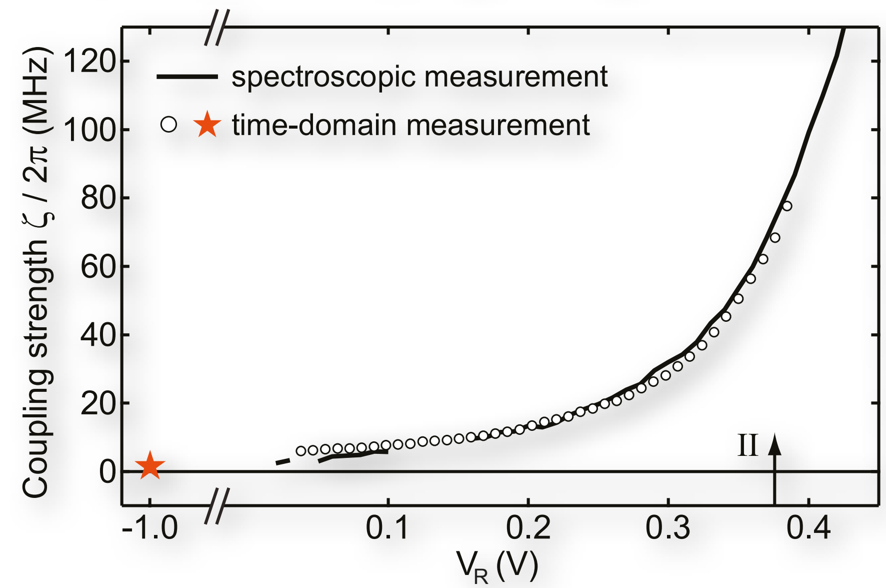
Transmon qubit: a slightly anharmonic oscillator



|02⟩-|11⟩ avoided crossing:



Qubit-qubit coupling strength:



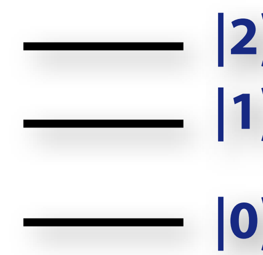
Conditional phase gate:

$$cU_{01} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

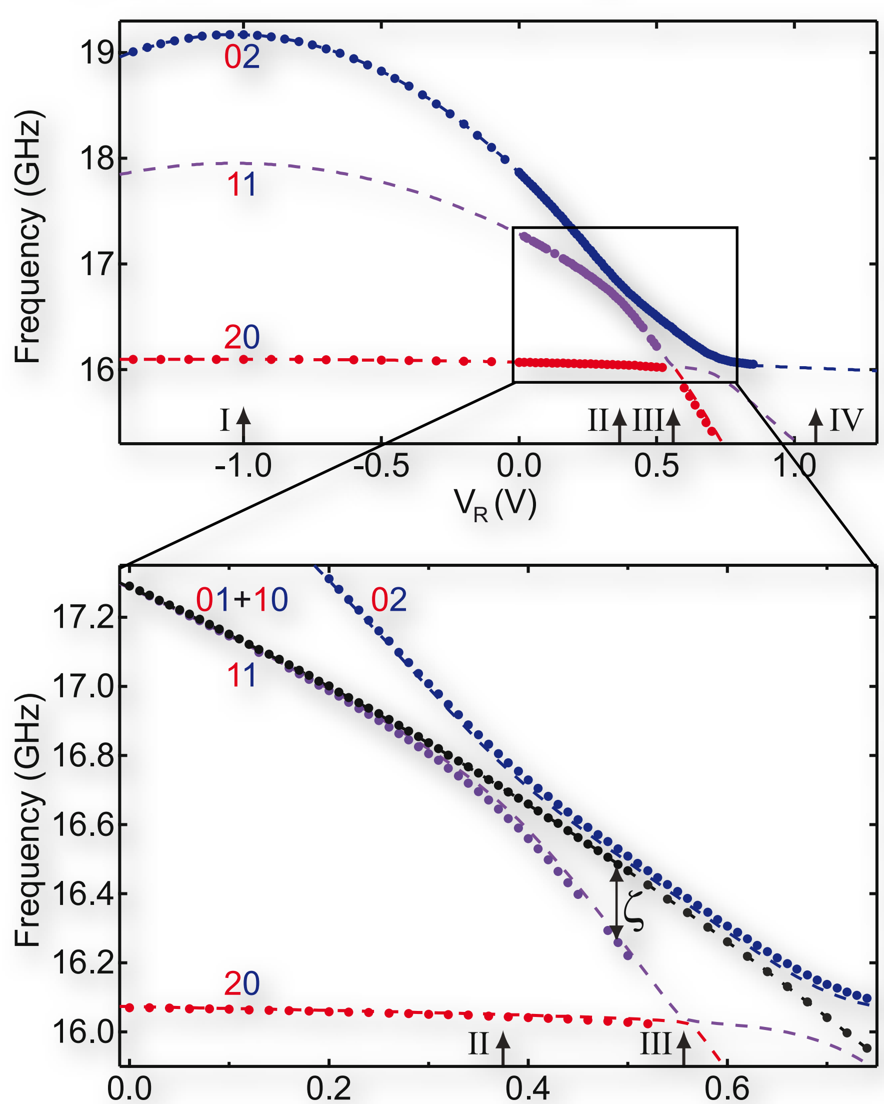
L. DiCarlo *et al.* Nature **460**, 240 (2009)

Generating highly entangled states

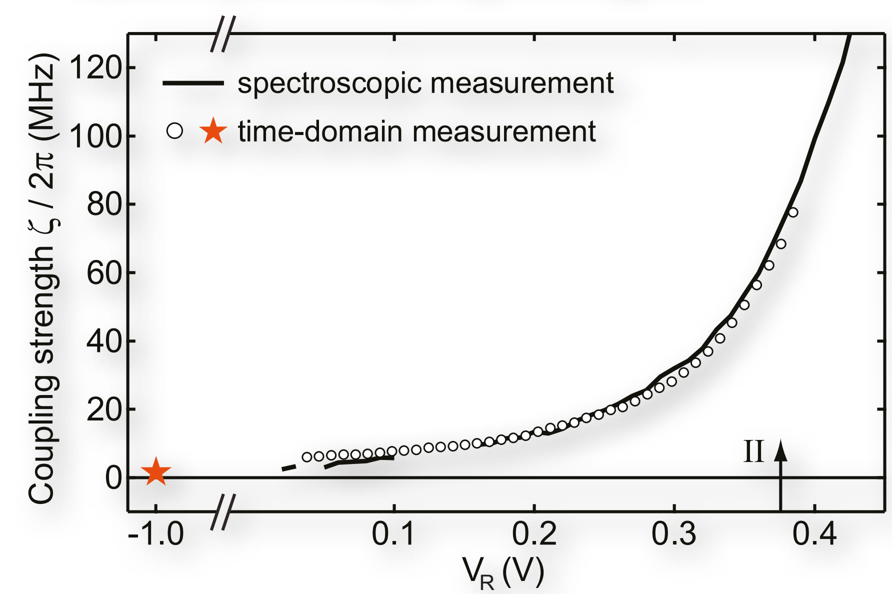
Transmon qubit: a slightly anharmonic oscillator



|02⟩ - |11⟩ avoided crossing:



Qubit-qubit coupling strength:

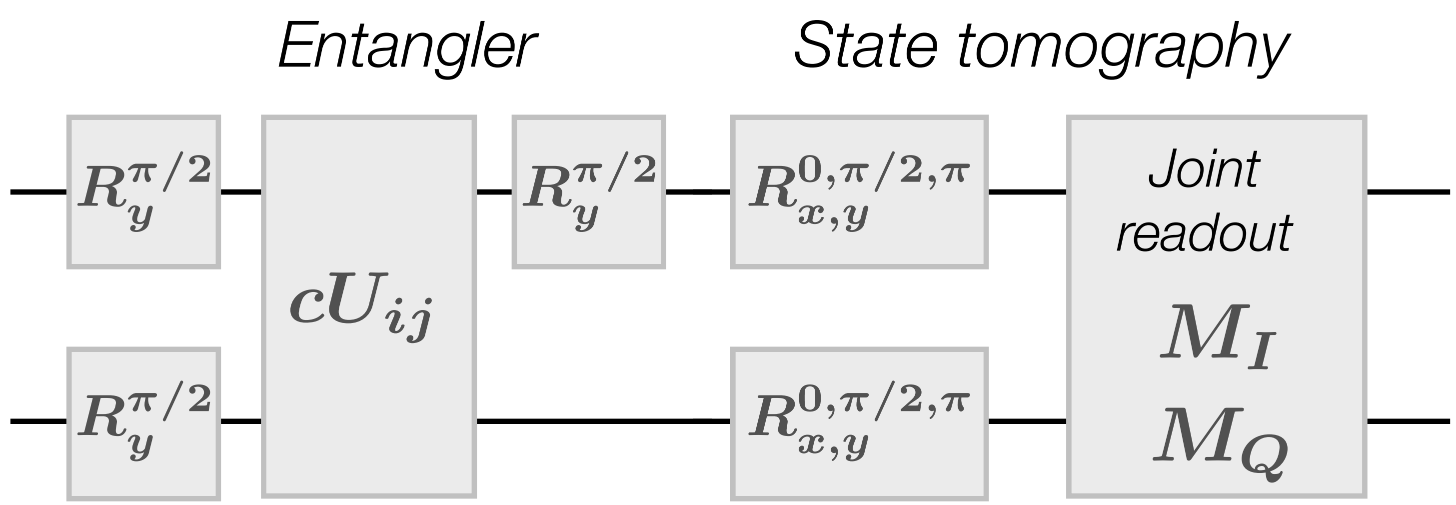


Conditional phase gate:

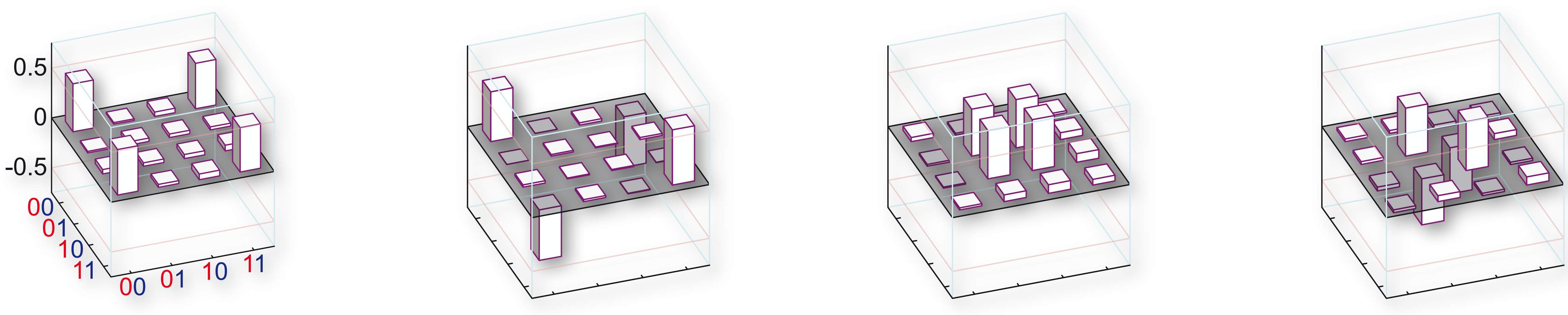
$$cU_{00} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

L. DiCarlo *et al.* Nature **460**, 240 (2009)

Generating highly entangled states



$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ $|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$ $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$ $|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$



F = 0.91±0.01
C = 0.88±0.02

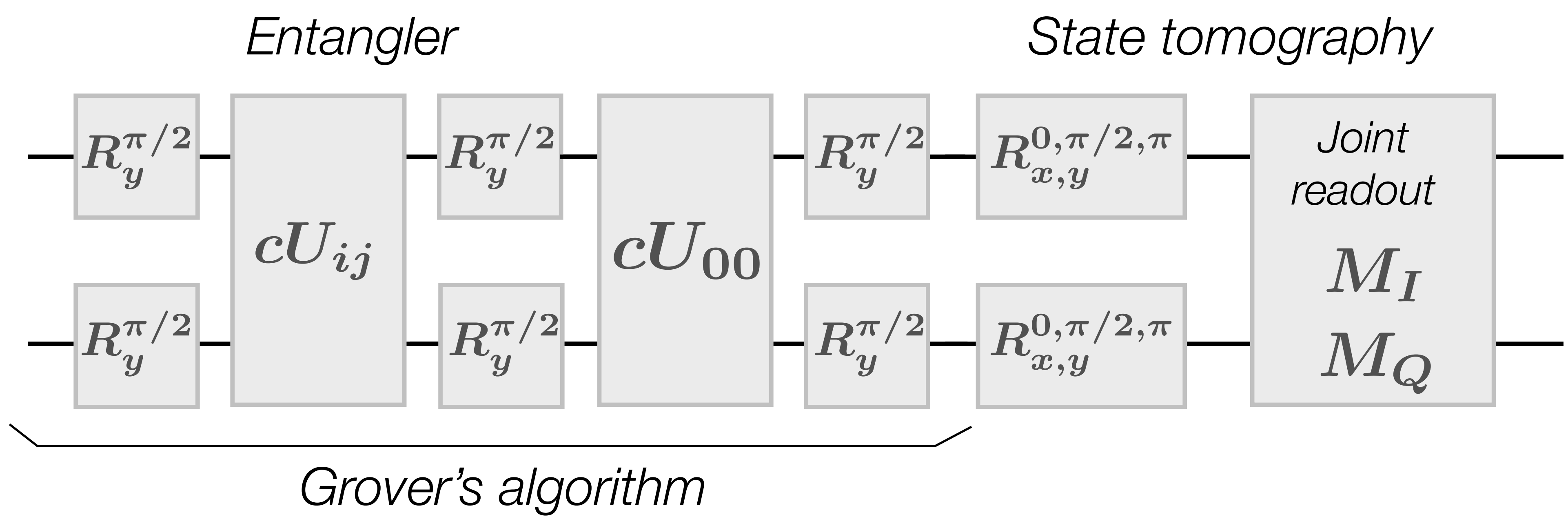
F = 0.94±0.01
C = 0.94±0.01

F = 0.90±0.01
C = 0.86±0.02

F = 0.87±0.02
C = 0.81±0.04

L. DiCarlo *et al.* Nature **460**, 240 (2009)

Quantum searching

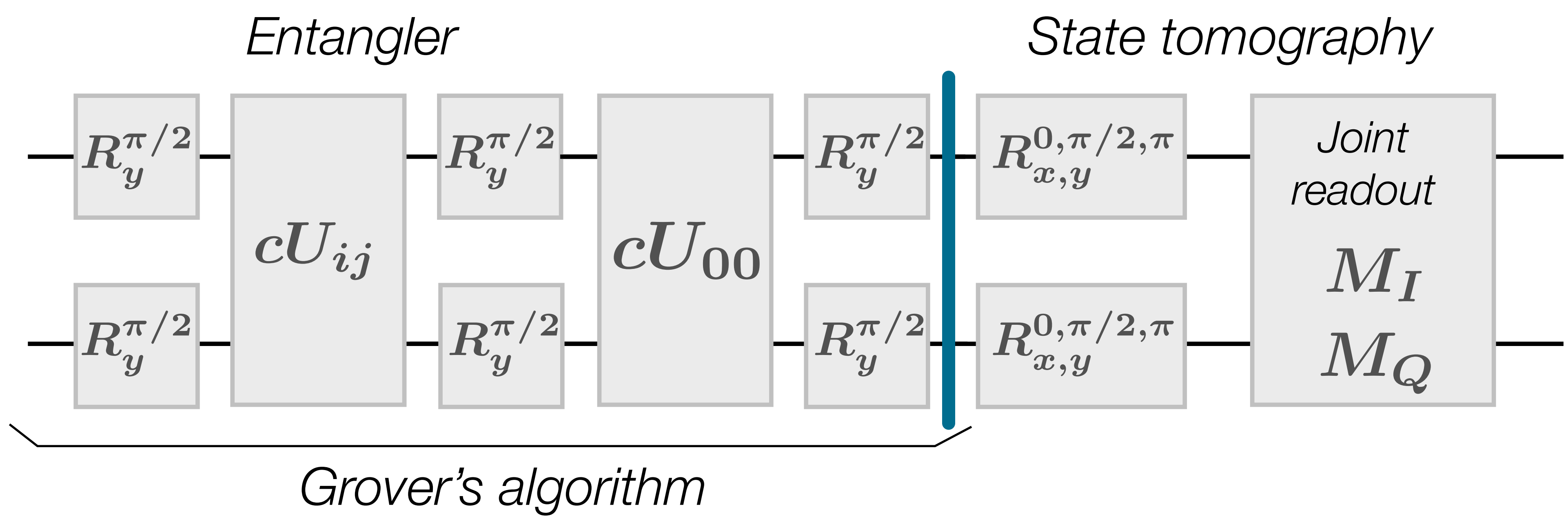


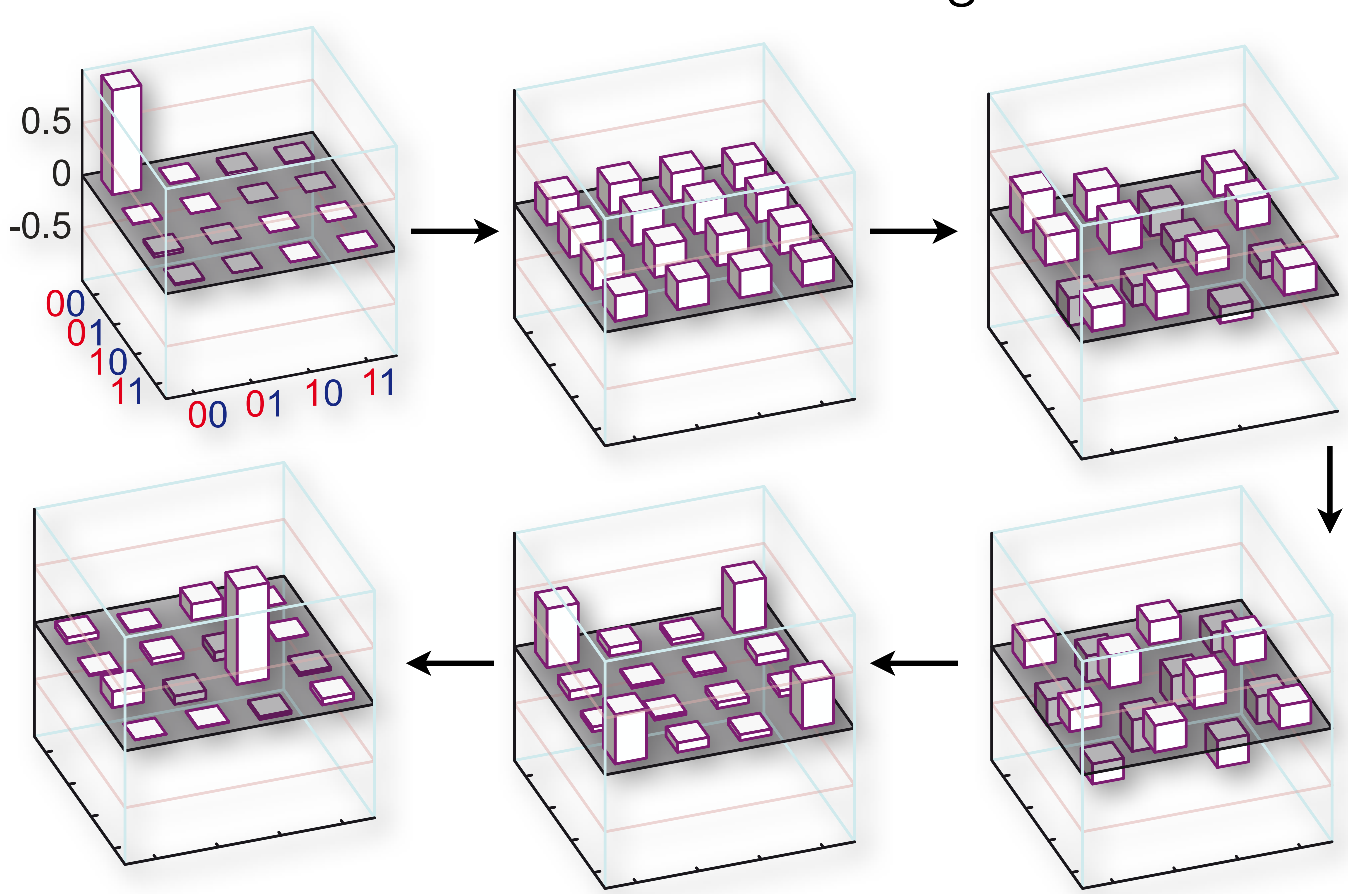
Determine x_0 in the set x = {00,01,10,11} which is such that

$$f_{ij}(x) = \begin{cases} -1 & x = x_0 \\ +1 & \text{otherwise} \end{cases}$$

Classical: O(N)
Quantum: O(√N)

Quantum searching





Fidelity = 0.85

(Consistent with T_1)

Deutsch–Jozsa algorithm also implemented

L. DiCarlo *et al.* Nature **460**, 240 (2009)

Qubit readout in cQED

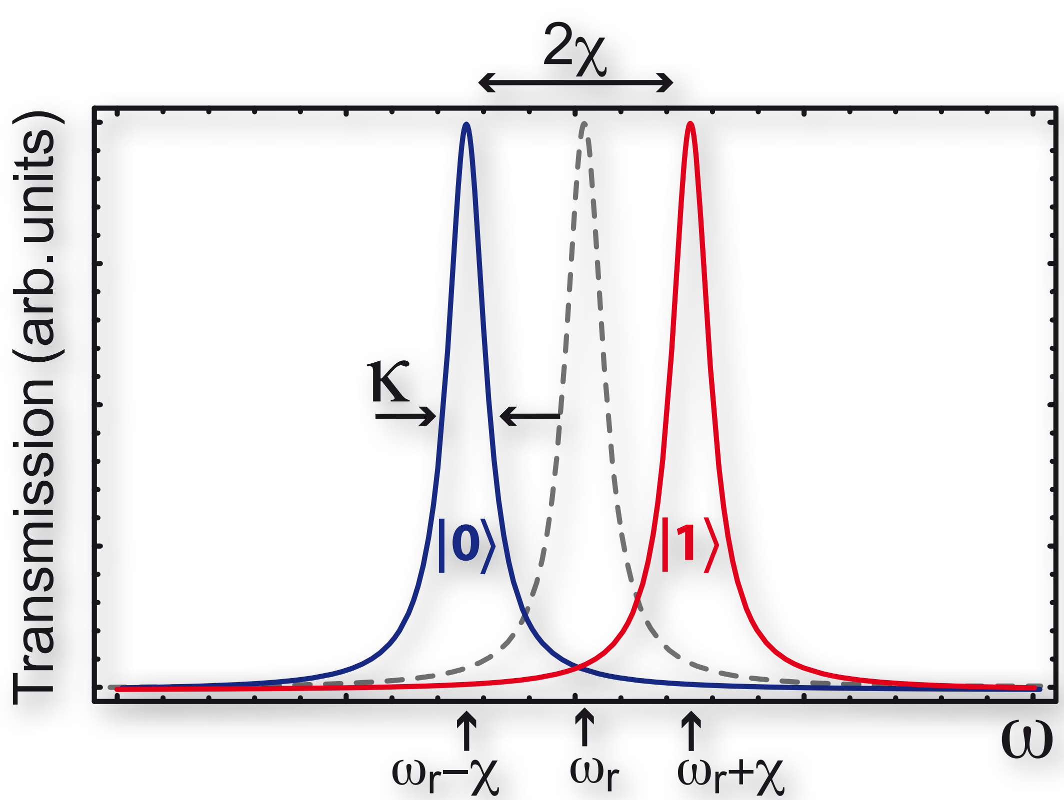
Dispersive regime: Qubit readout $|\Delta| = |\omega_{01} - \omega_r| \gg g$

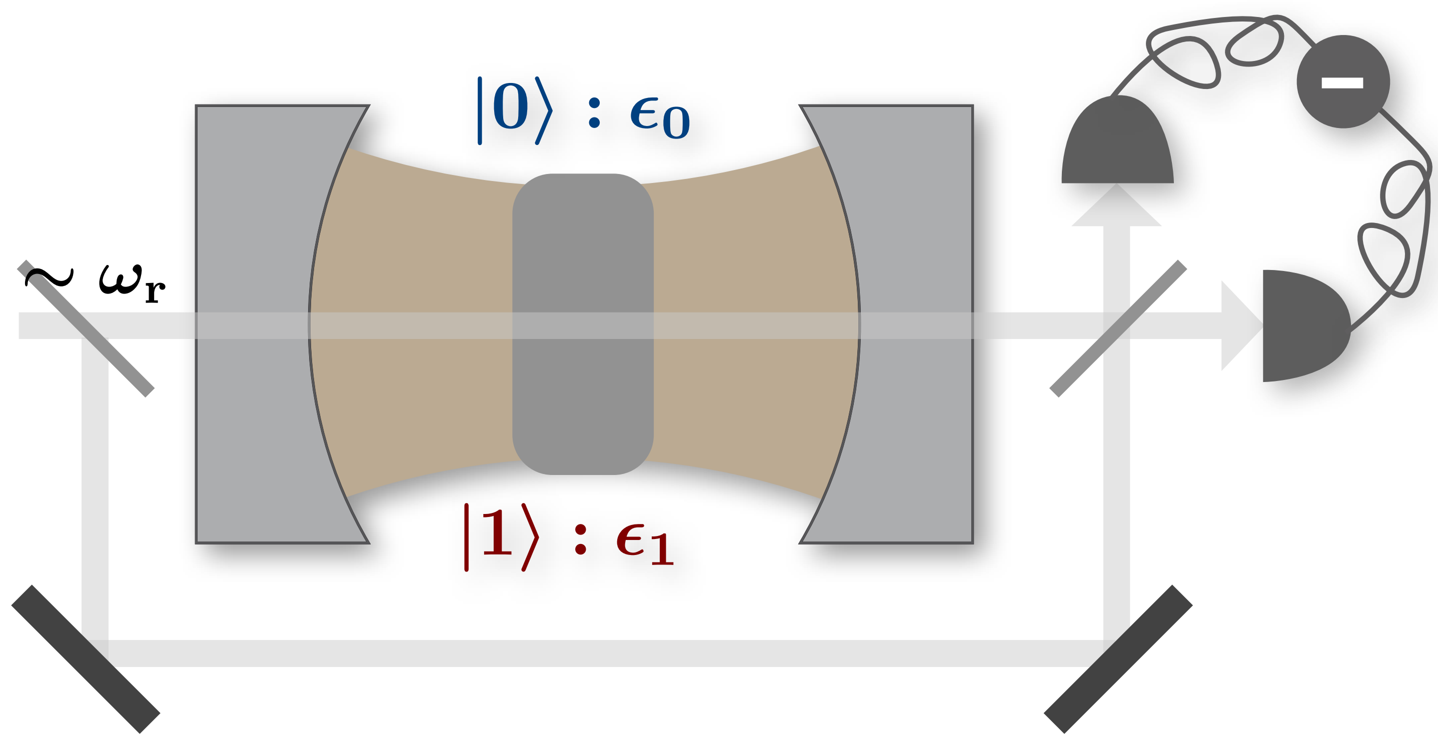
Dispersive interaction: $H \approx (\omega_r + \chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} + \frac{\tilde{\omega}_{01}}{2}\hat{\sigma}_z$

Resonator frequency

Dispersive interaction strength
$\chi = g^2/\Delta$

Qubit transition frequency

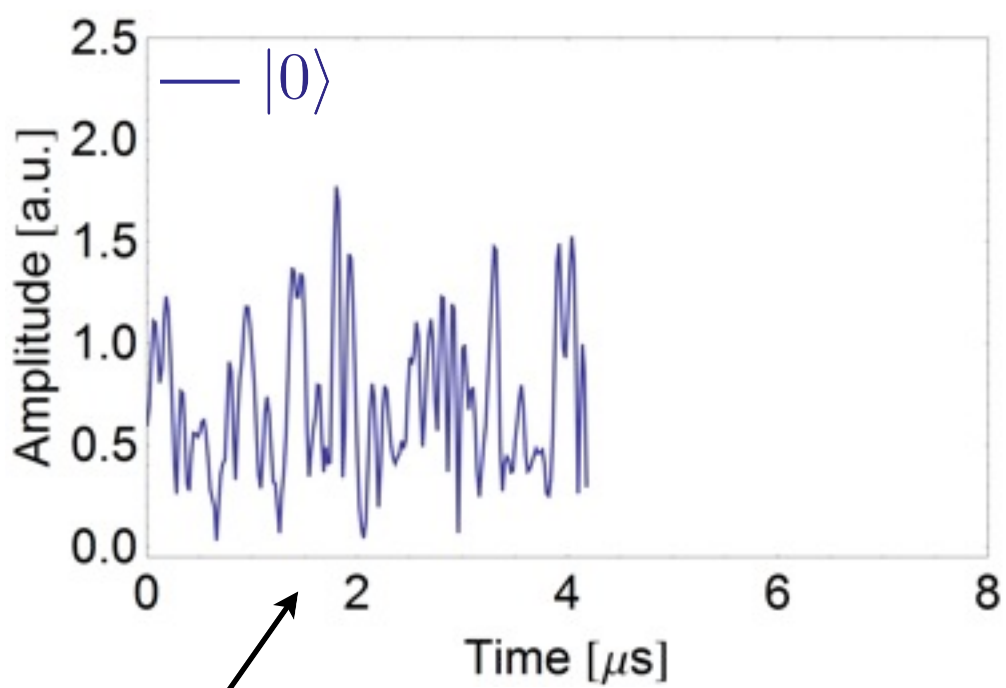




Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)

Signal-to-noise ratio

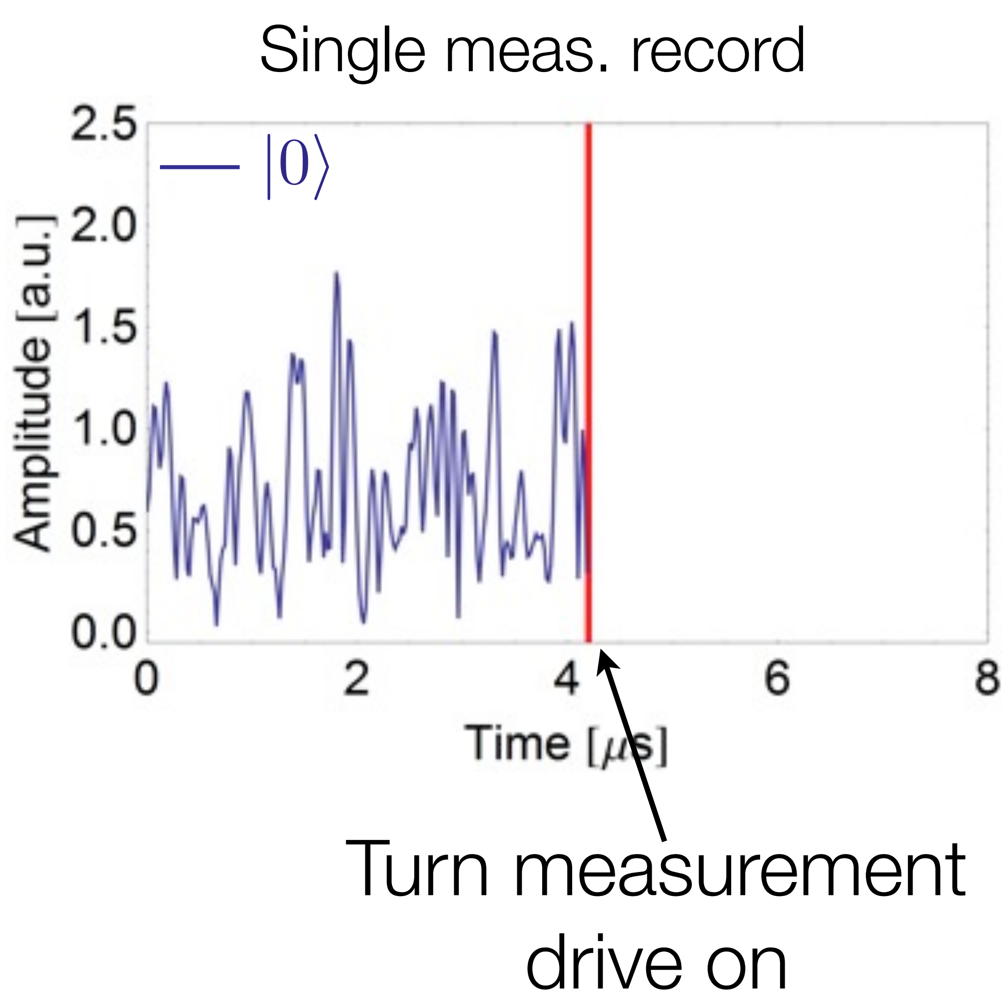
Single meas. record



Measurement drive off:
noise

Data: A. Wallraff's group @ ETH Zurich; See also: R. Bianchetti et al. Phys. Rev. A **80**, 043840 (2009)

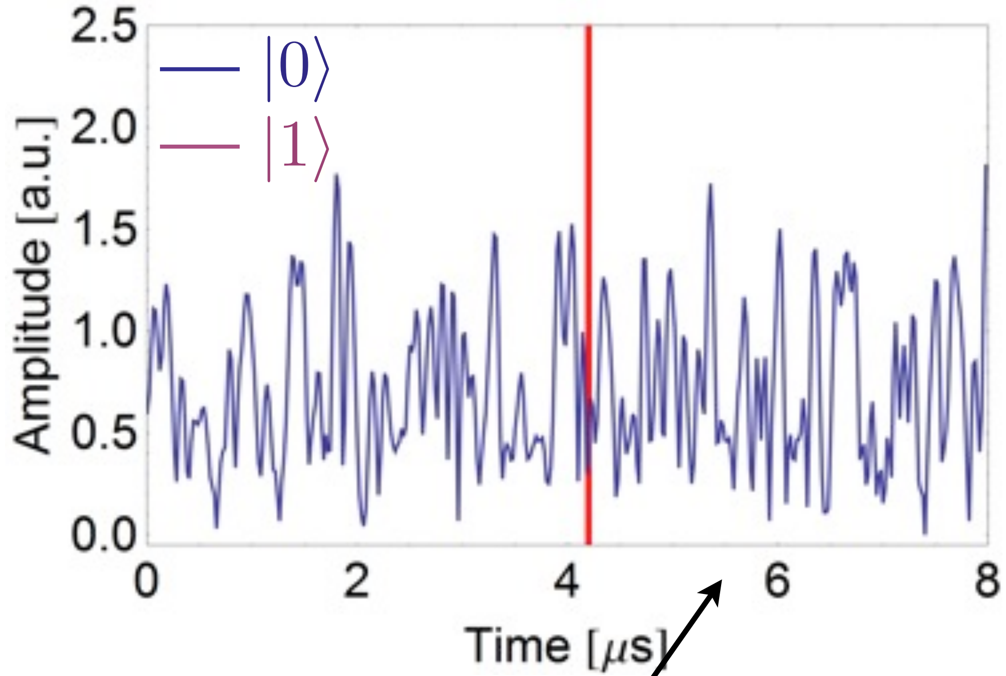
Signal-to-noise ratio



Data: A. Wallraff's group @ ETH Zurich; See also: R. Bianchetti et al. Phys. Rev. A **80**, 043840 (2009)

Signal-to-noise ratio

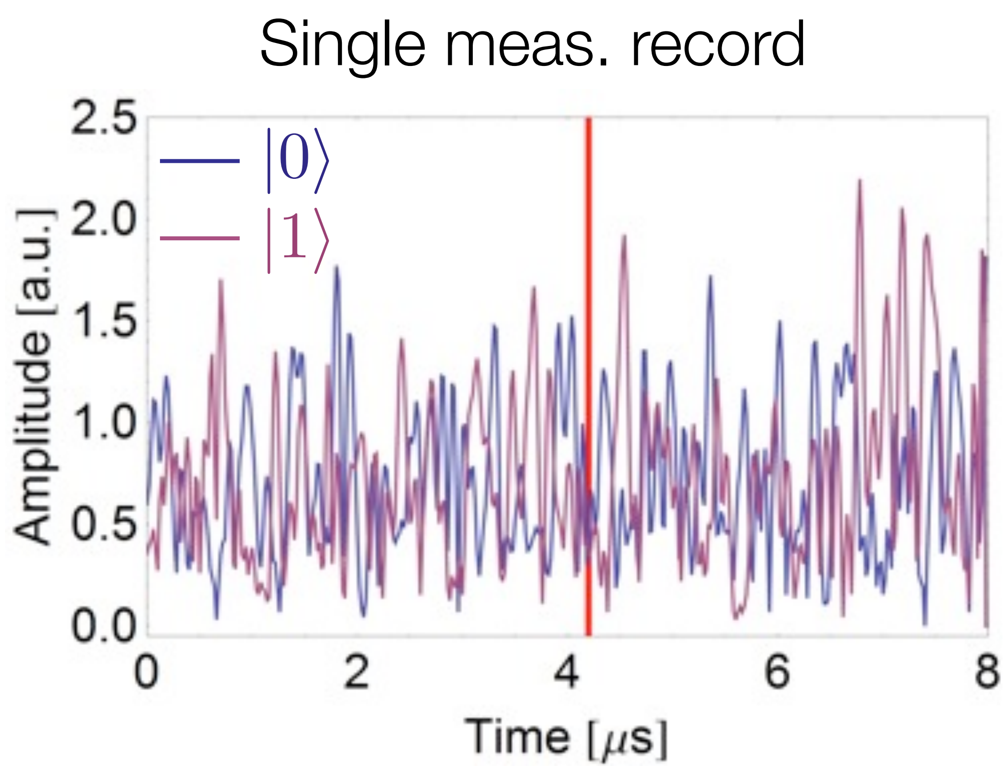
Single meas. record

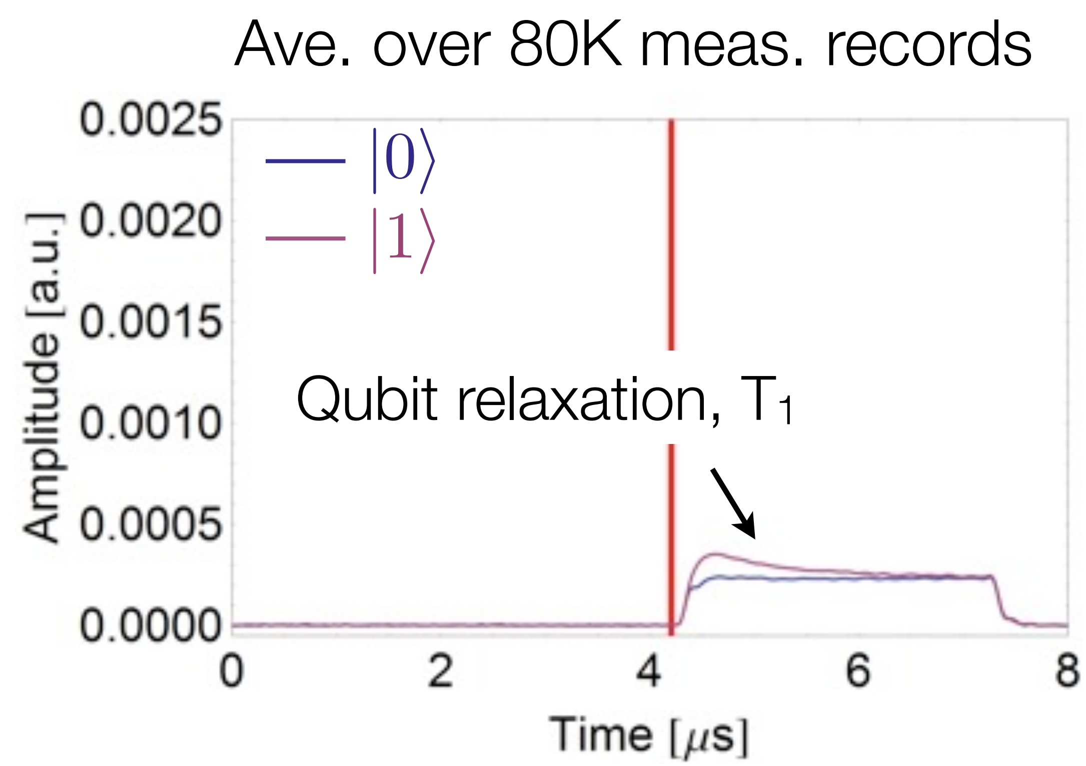


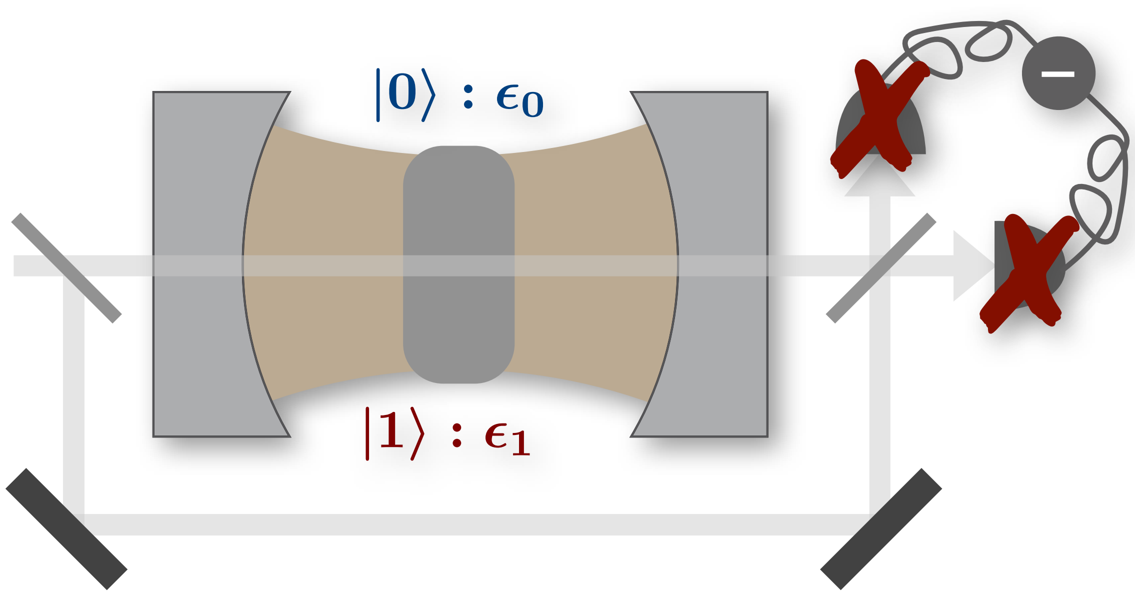
Measurement drive on:
noise + signal (?!?)

Data: A. Wallraff's group @ ETH Zurich; See also: R. Bianchetti et al. Phys. Rev. A **80**, 043840 (2009)

Signal-to-noise ratio





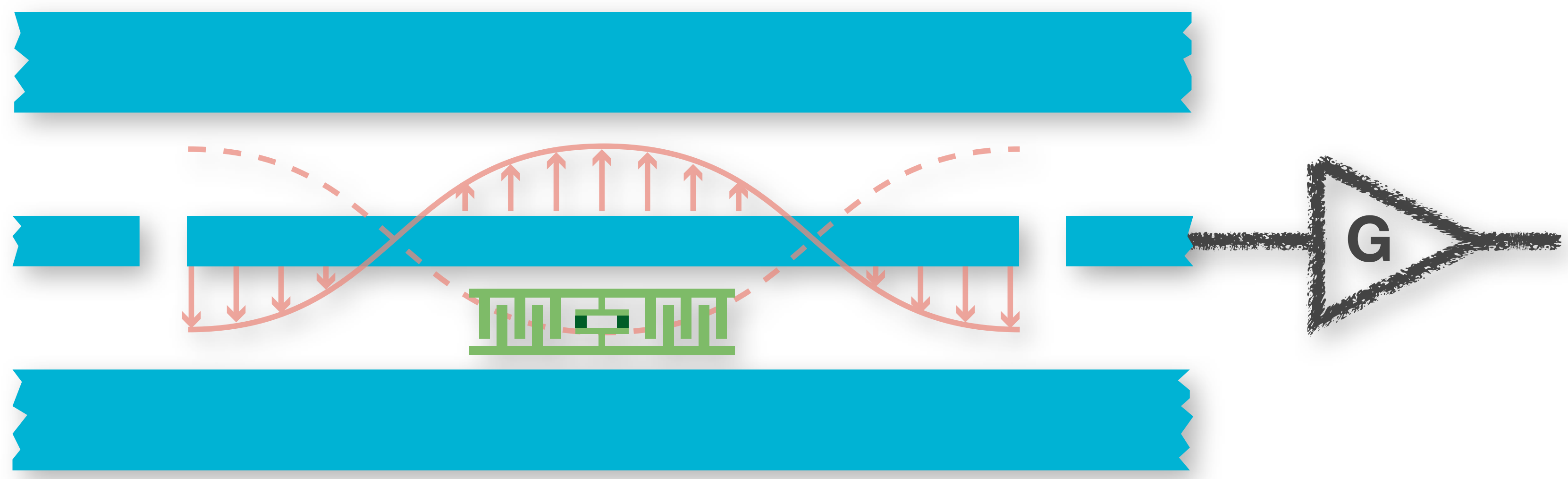


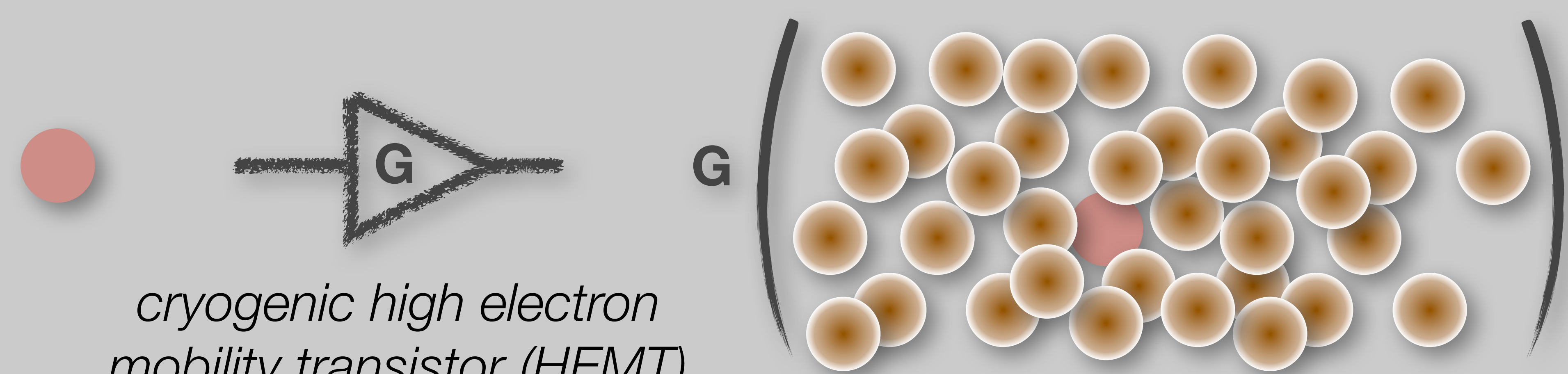
μw-photons have too little energy...

$$\frac{\nu_{\text{opt.}}}{\nu_{\mu\text{w}}} \sim \frac{500\ \text{THz}}{5\ \text{GHz}} \sim 10^5$$

Data: A. Wallraff's group @ ETH Zurich; See also: R. Bianchetti et al. Phys. Rev. A **80**, 043840 (2009)

Linear amplifiers





cryogenic high electron mobility transistor (HEMT)

~ 40 noise photons...

Phase-space representation

Coherent states: $a|\alpha\rangle = \alpha|\alpha\rangle\,,\quad |\alpha\rangle = e^{i|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n}}|n\rangle$ *with* $a^\dagger a|n\rangle = n|n\rangle$

Both basis coincide for vacuum state: $|\alpha = 0\rangle = |n = 0\rangle$

Pictorial representation?

State fidelity: $F = |\langle\psi|\psi_0\rangle|^2$

(How close is ψ to ψ_0?)

Q-function: $Q_{\alpha_0}(\alpha) = \frac{1}{\pi}|\langle\alpha|\alpha_0\rangle|^2$

(How close is α to α_0?)

Phase-space representation

Q-function: Q

$$\hat{Q} = i\sqrt{\frac{\hbar}{2Z_0}}(\hat{a}^\dagger - \hat{a}) \quad \hat{\Phi} = \sqrt{\frac{\hbar Z_0}{2}}(\hat{a}^\dagger + \hat{a})$$

$$\hat{a} = \sqrt{\frac{2}{\hbar Z_0}}\left(\hat{\Phi} + iZ_0\hat{Q}\right)$$

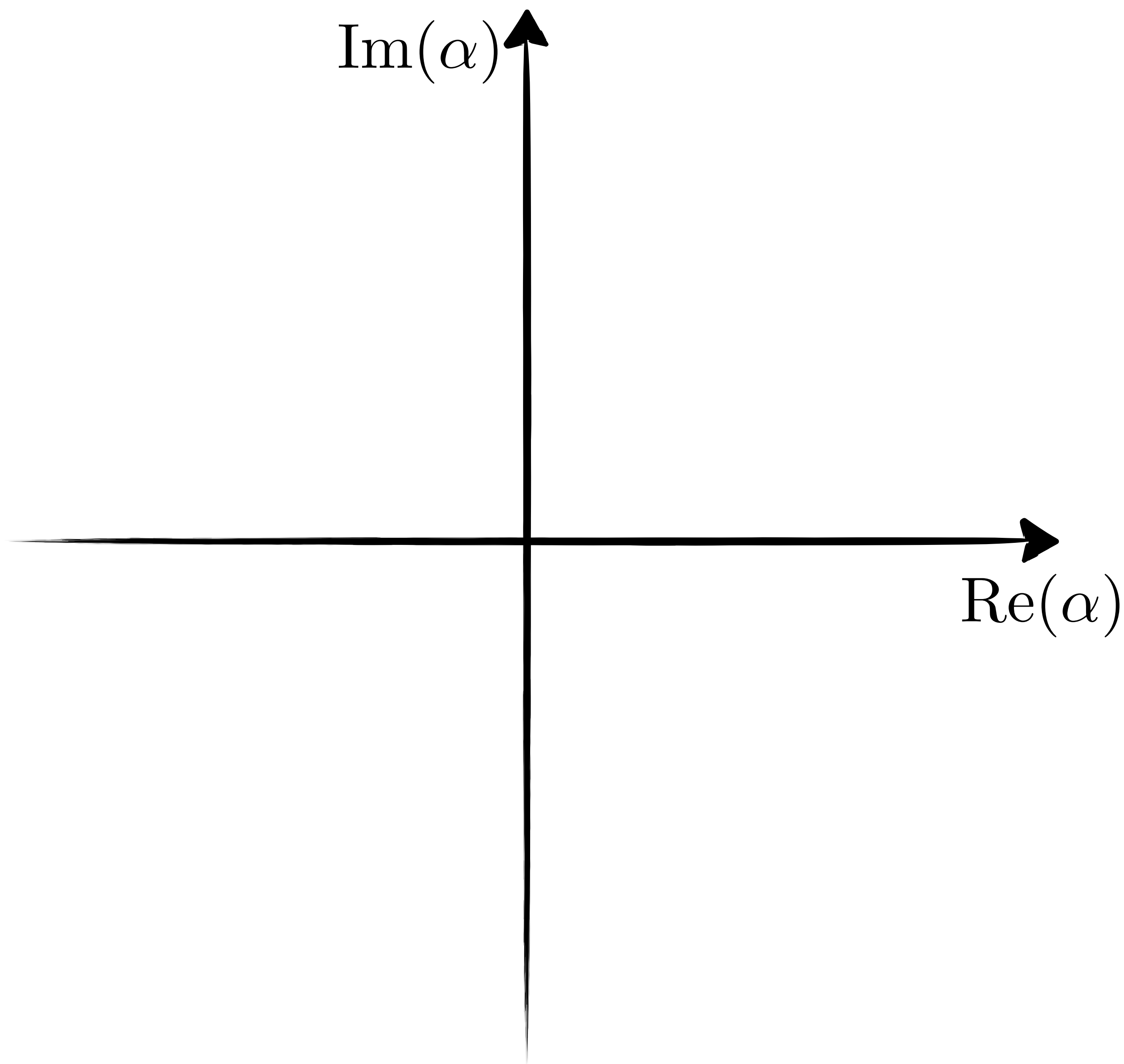
$$\equiv \frac{1}{\sqrt{2}}(\hat{X} + i\hat{P})$$

$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle \quad \rightarrow \quad \langle\alpha|\hat{a}|\alpha\rangle = \alpha$$

$$\Rightarrow \begin{cases} \mathrm{Re}(\alpha) = \langle\hat{X}\rangle/\sqrt{2} \\ \mathrm{Im}(\alpha) = \langle\hat{P}\rangle/\sqrt{2} \end{cases}$$

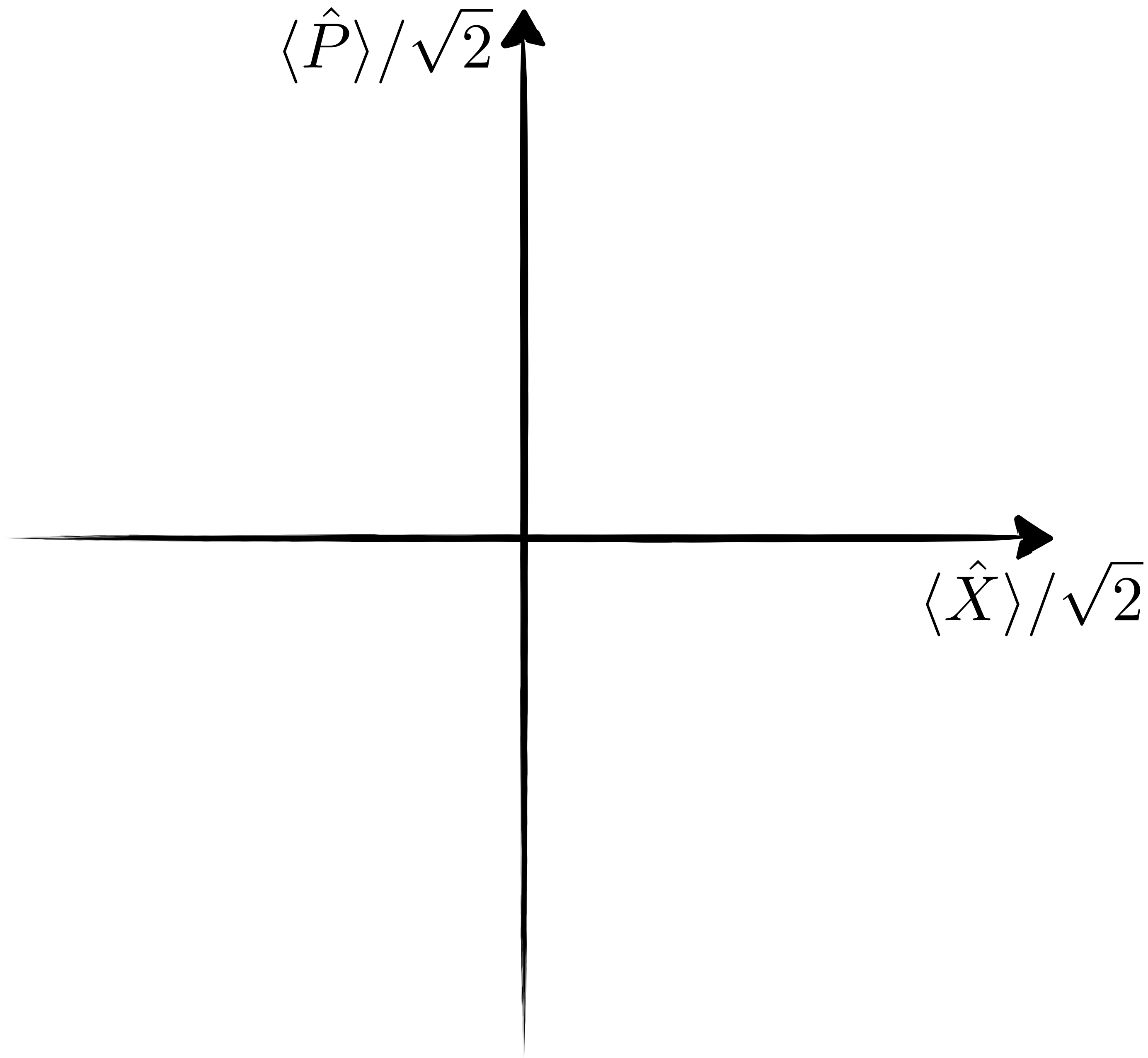
Phase-space representation

Q-function: $Q_{\alpha_0}(\alpha) = \frac{1}{\pi}|\langle\alpha|\alpha_0\rangle|^2$



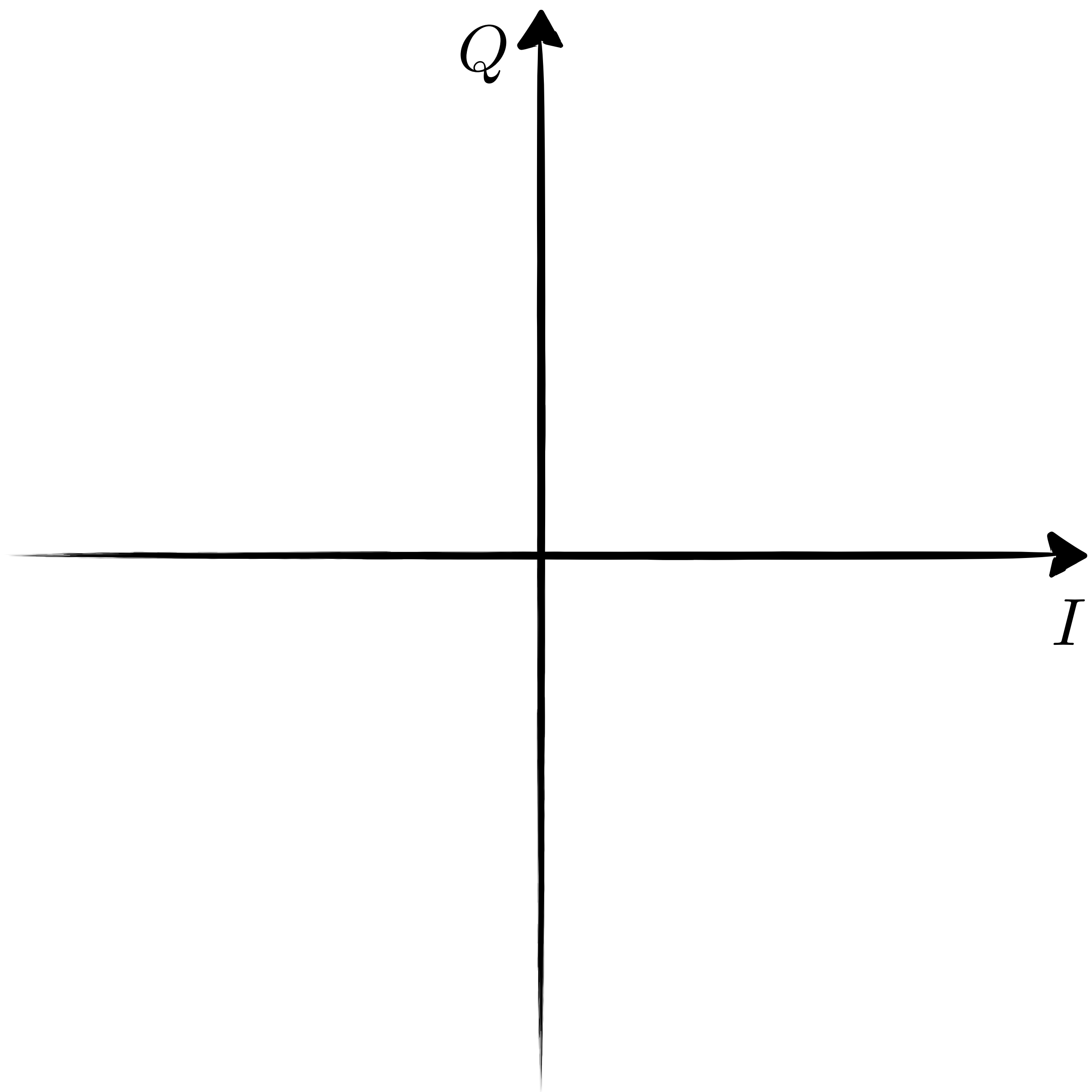
Phase-space representation

Q-function: $Q_{\alpha_0}(\alpha) = \frac{1}{\pi}|\langle\alpha|\alpha_0\rangle|^2$



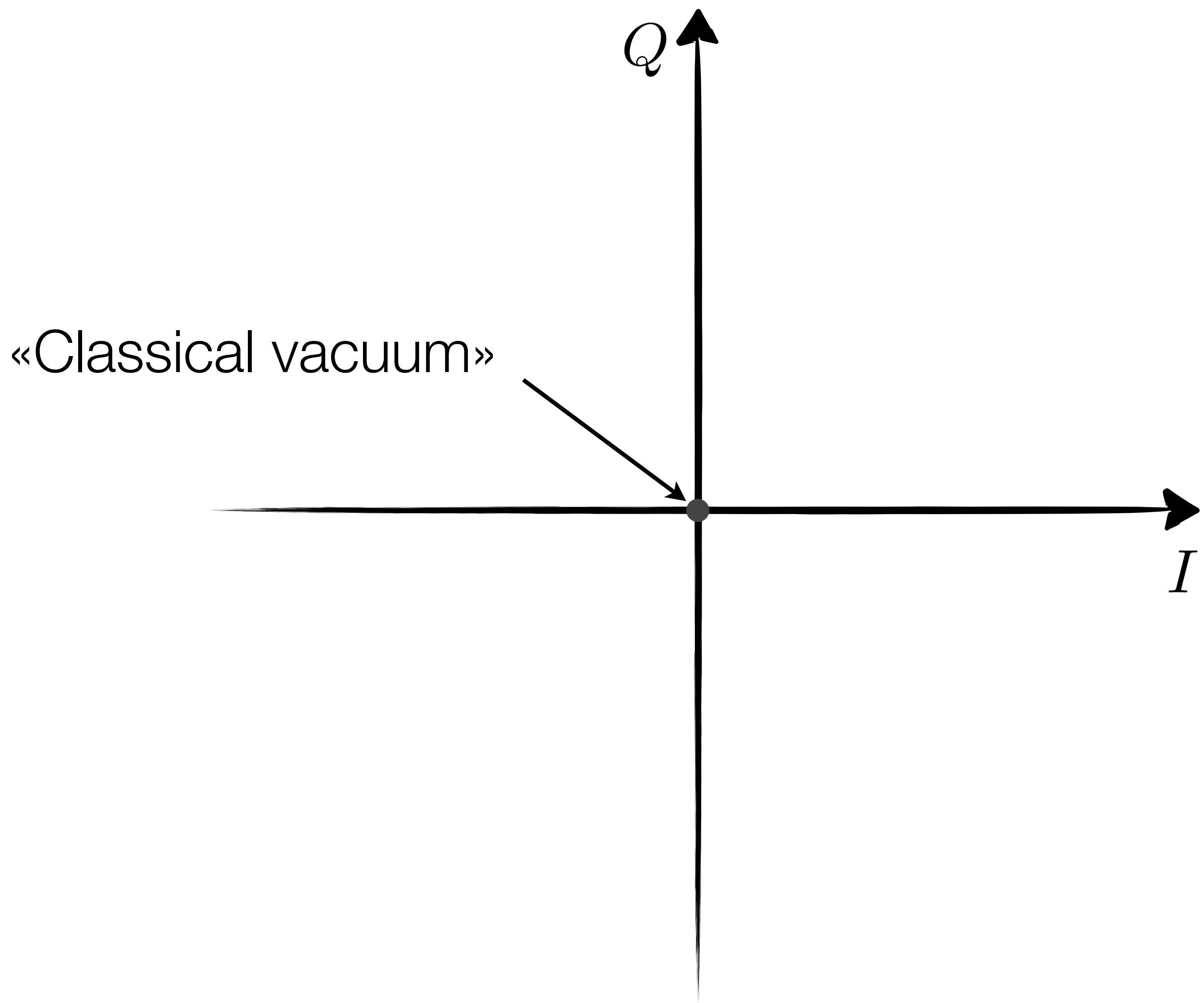
Phase-space representation

Q-function: $Q_{\alpha_0}(\alpha) = \frac{1}{\pi}|\langle\alpha|\alpha_0\rangle|^2$



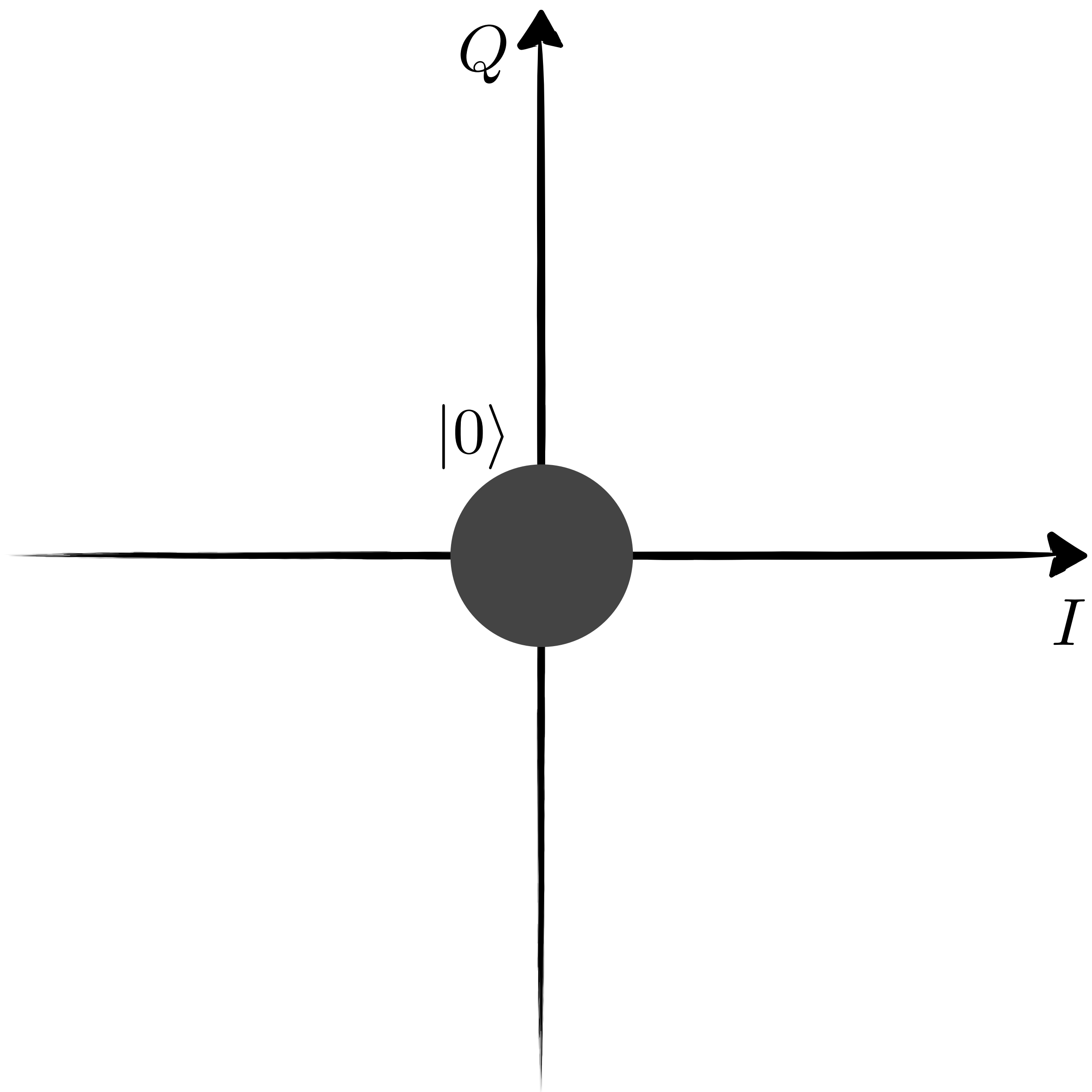
Phase-space representation

Q-function: $Q_{\alpha_0}(\alpha) = \dfrac{1}{\pi}|\langle\alpha|\alpha_0\rangle|^2$



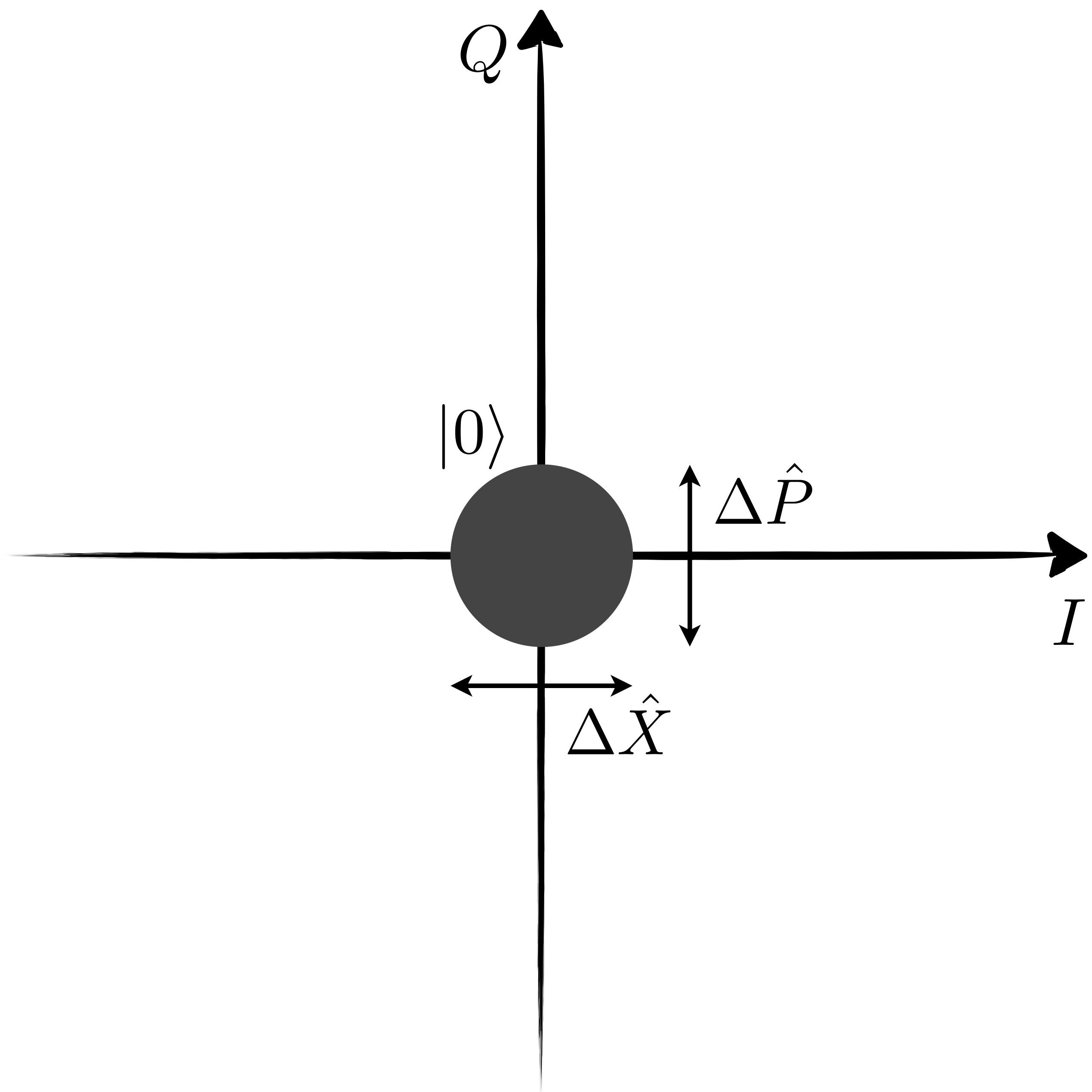
Phase-space representation

Q-function: $Q_{\alpha_0}(\alpha) = \frac{1}{\pi}|\langle\alpha|\alpha_0\rangle|^2$



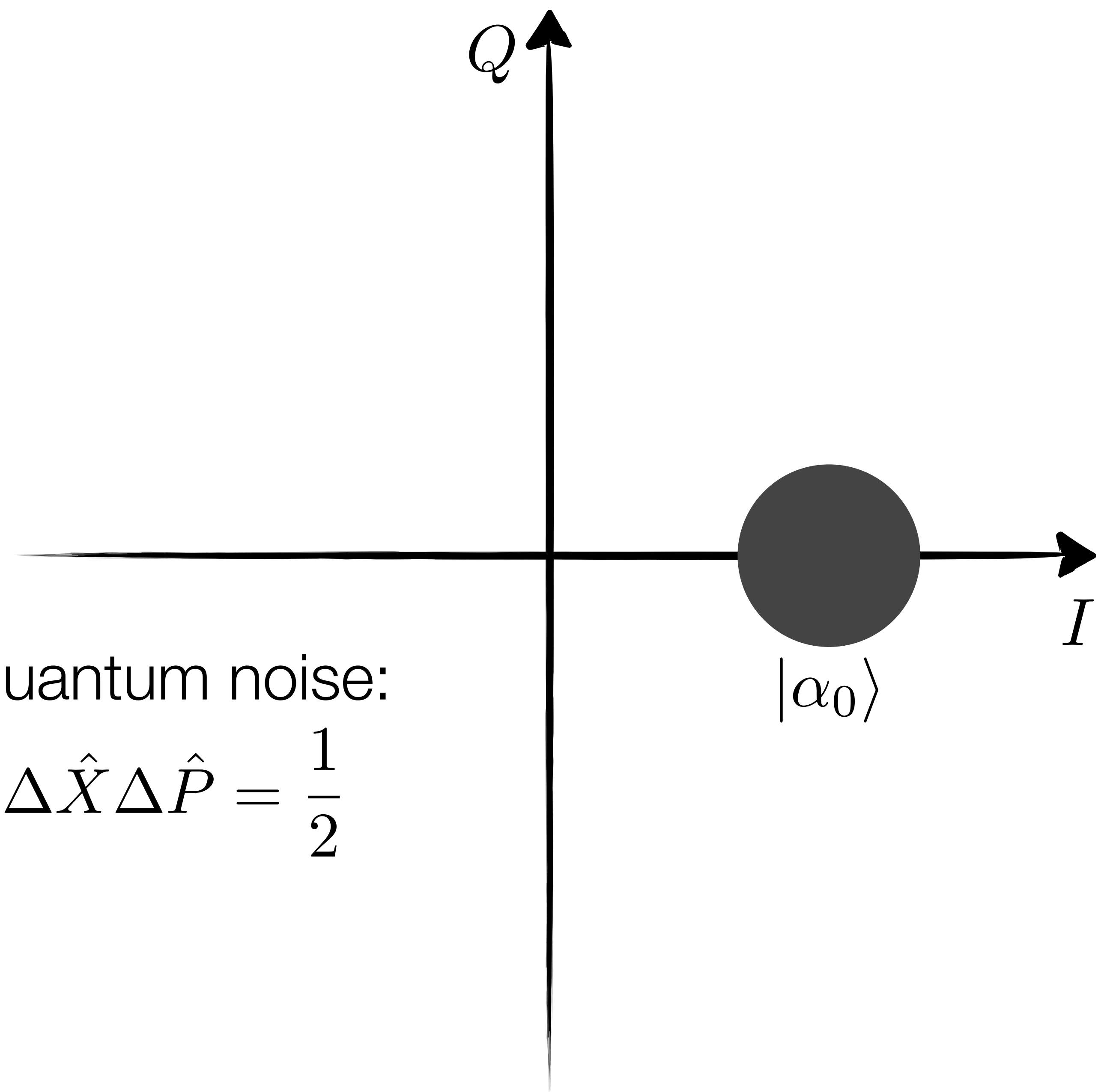
Phase-space representation

Q-function: $Q_{\alpha_0}(\alpha) = \frac{1}{\pi}|\langle\alpha|\alpha_0\rangle|^2$



Phase-space representation

Q-function: $Q_{\alpha_0}(\alpha) = \frac{1}{\pi}|\langle\alpha|\alpha_0\rangle|^2$

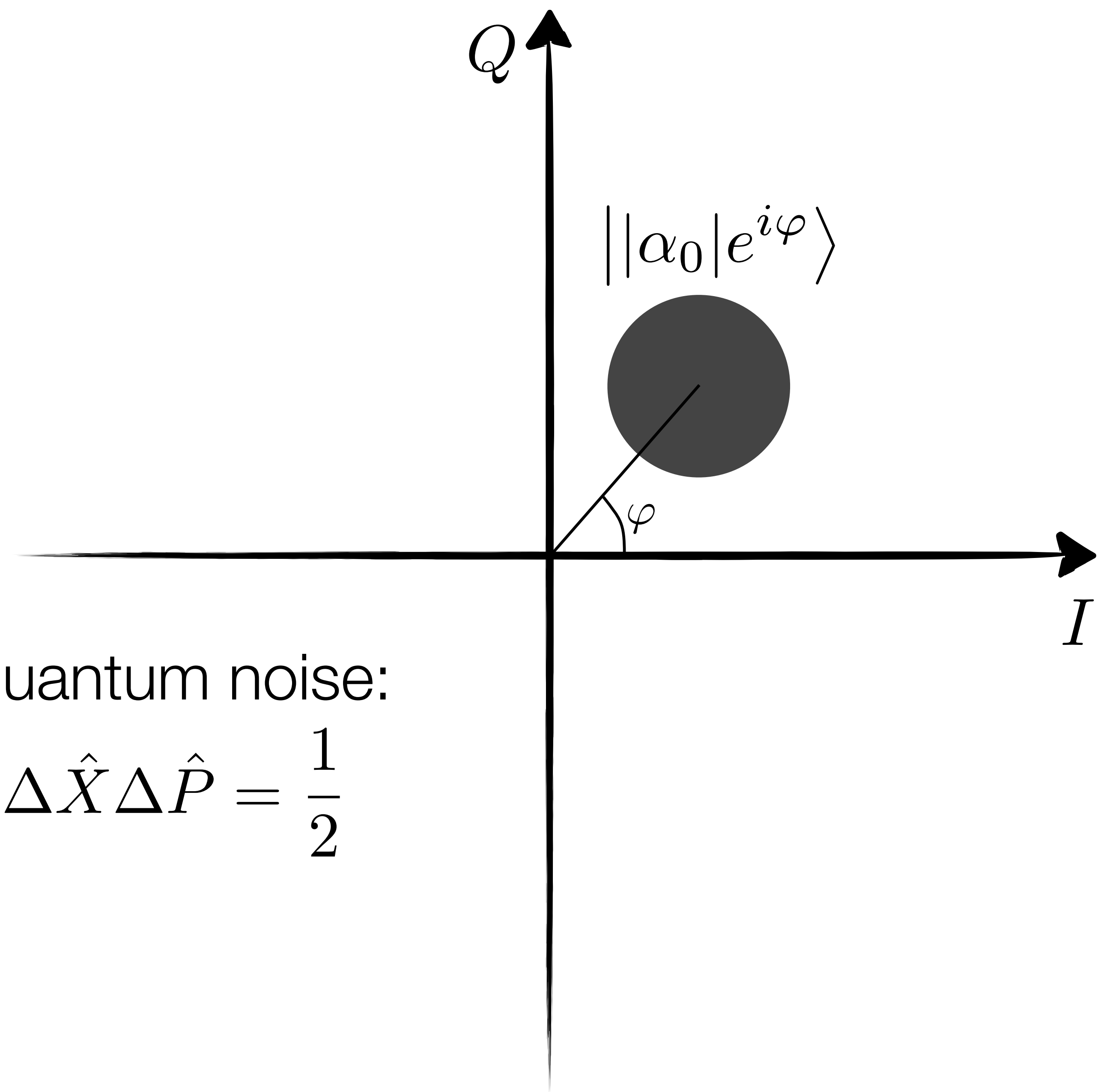


Quantum noise:

$$\Delta\hat{X}\Delta\hat{P} = \frac{1}{2}$$

Phase-space representation

Q-function: $Q_{\alpha_0}(\alpha) = \frac{1}{\pi}|\langle\alpha|\alpha_0\rangle|^2$

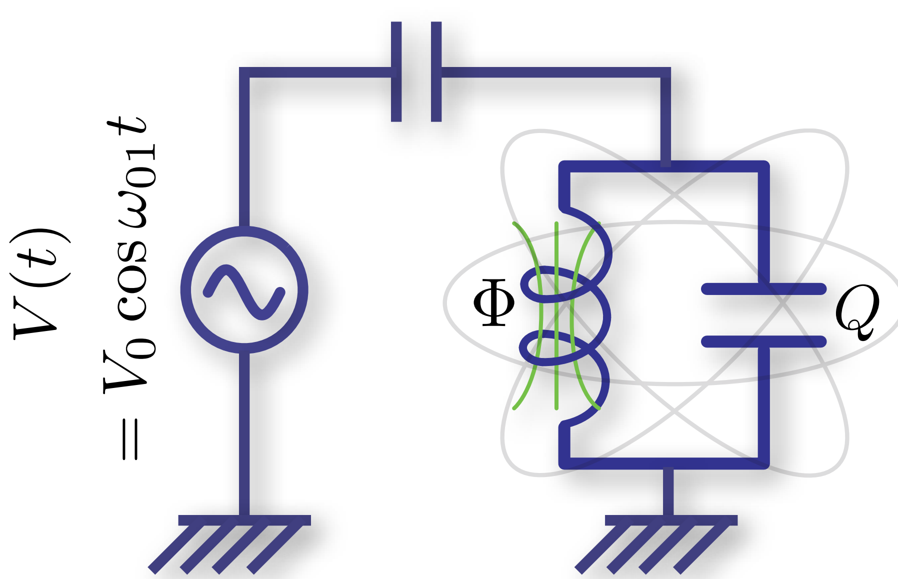


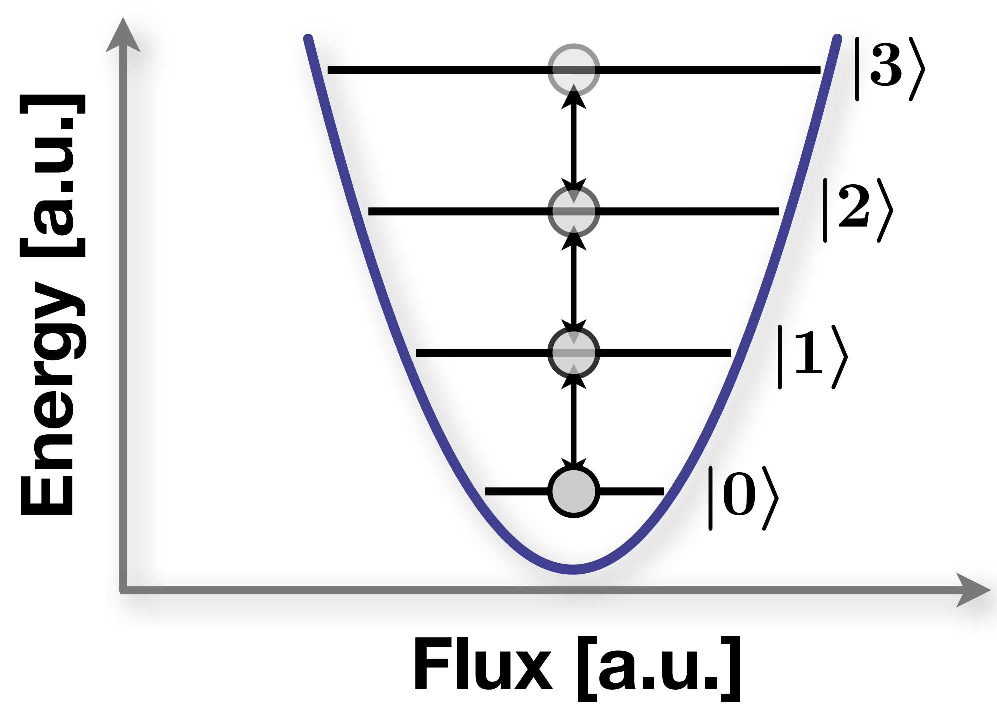
Quantum noise:

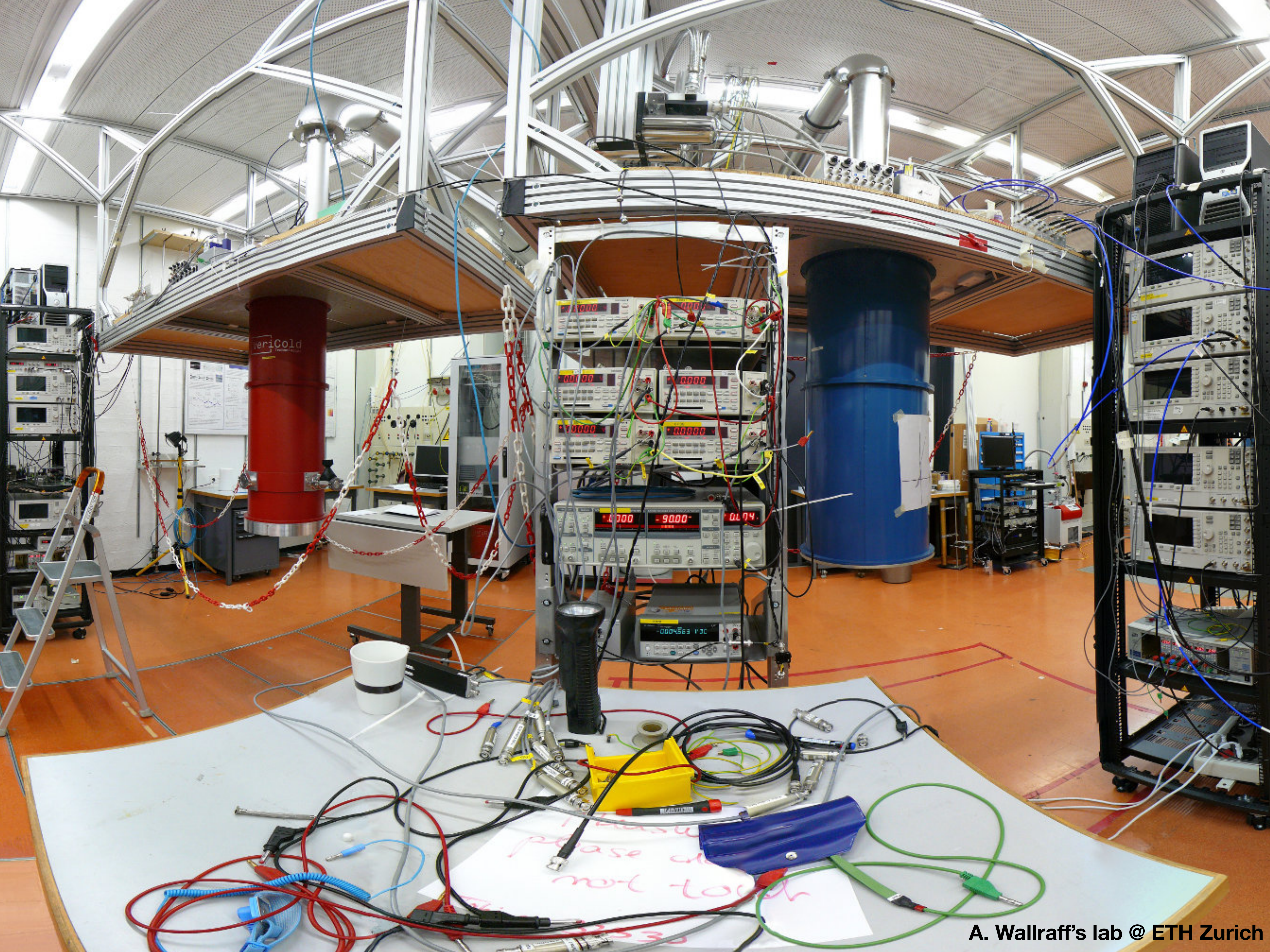
$$\Delta\hat{X}\Delta\hat{P} = \frac{1}{2}$$

How to prepare a coherent state of light?

Coherent state: Steady-state of driven damped harmonic oscillator







A. Wallraff's lab @ ETH Zurich

Dispersive regime: Qubit readout

Dispersive interaction: $H \approx (\omega_r + \chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} + \frac{\tilde{\omega}_{01}}{2}\hat{\sigma}_z \longrightarrow \hat{H}_{\text{int}} = \chi\hat{a}^\dagger\hat{a}\hat{\sigma}_z$

$$(c_0|0\rangle + c_1|1\rangle) \otimes |\alpha\rangle = e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}(c_0|0\rangle|n\rangle + c_1|1\rangle|n\rangle)$$

$$\to e^{-i\chi t\hat{a}^\dagger\hat{a}\hat{\sigma}_z} e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}(c_0|0\rangle|n\rangle + c_1|1\rangle|n\rangle)$$

$$= e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}(c_0e^{+i\chi tn}|0\rangle|n\rangle + c_1e^{-i\chi tn}|1\rangle|n\rangle)$$

$$= c_0|0\rangle e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{(\alpha e^{+i\chi t})^n}{\sqrt{n!}}|n\rangle + c_1|1\rangle e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{(\alpha e^{-i\chi t})^n}{\sqrt{n!}}|n\rangle$$

$$= c_0|0\rangle|\alpha e^{+i\chi t}\rangle + c_1|1\rangle|\alpha e^{-i\chi t}\rangle$$

Dispersive regime: Qubit readout

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$$\rightarrow e^{-i\chi t \ldots}$$

Qubit-state dependent coherent states!

$$= e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}(c_0 e^{+i\chi t n}|0\rangle|n\rangle + c_1 e^{-i\chi t n}|1\rangle|n\rangle)$$

$$= c_0|0\rangle e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{(\alpha e^{+i\chi t})^n}{\sqrt{n!}}|n\rangle + c_1|1\rangle e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{(\alpha e^{-i\chi t})^n}{\sqrt{n!}}|n\rangle$$

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Dispersive regime: Qubit readout

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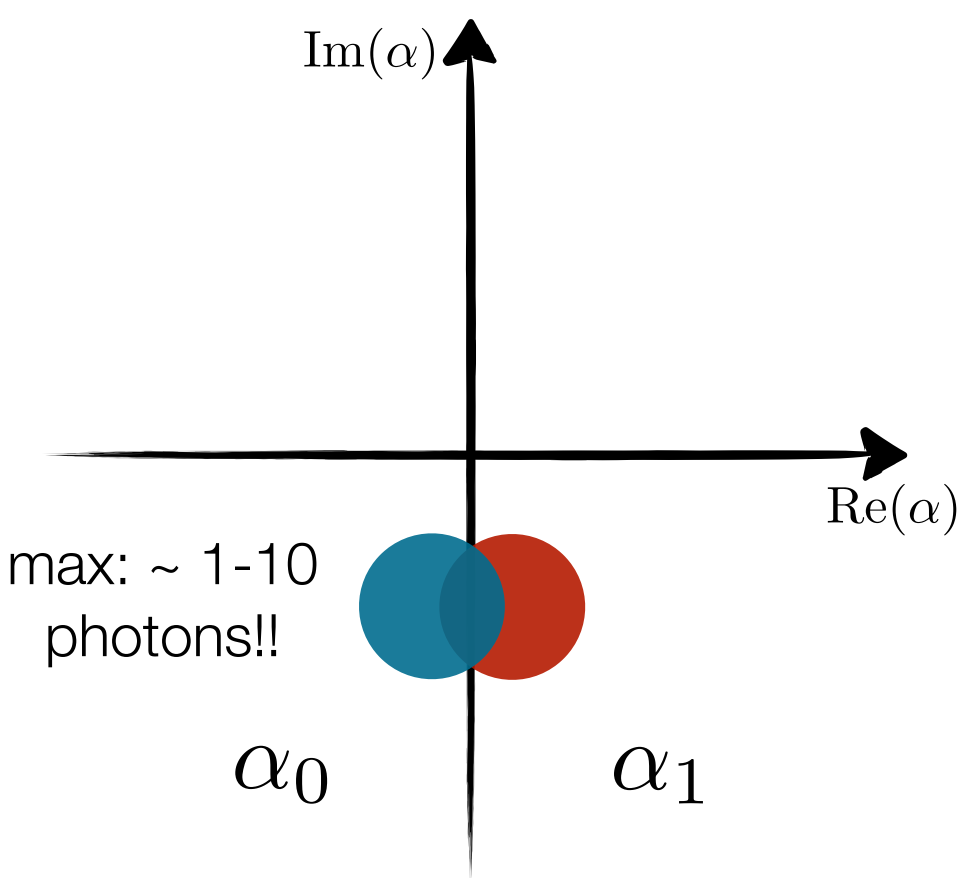
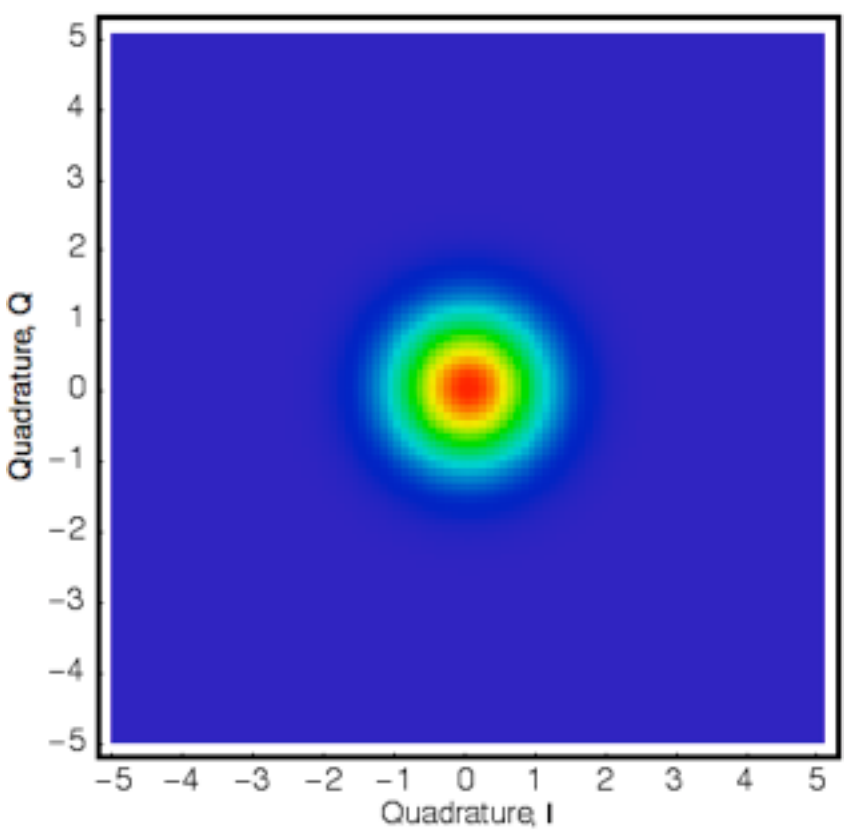
$$(c_0|0\rangle + c_1|1\rangle) \otimes |\alpha\rangle \rightarrow c_0|0\rangle|\alpha e^{+i\chi t}\rangle + c_1|1\rangle|\alpha e^{-i\chi t}\rangle$$



Numerical simulation:



Dispersive regime: Qubit readout

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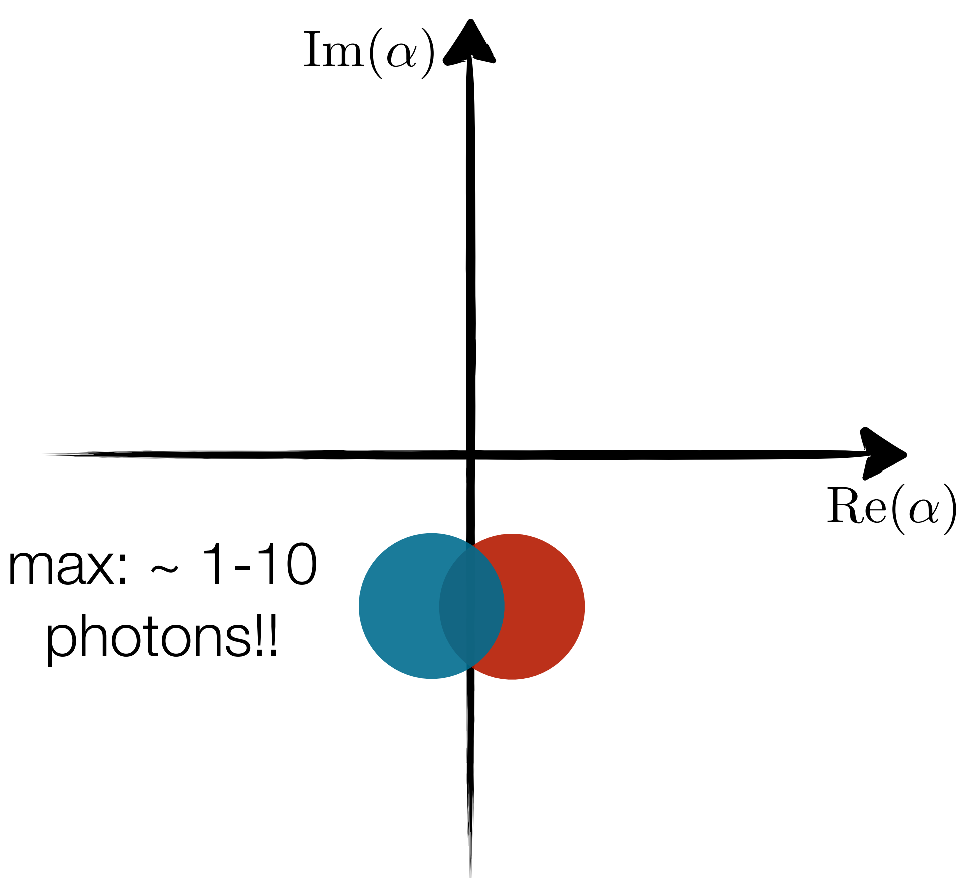
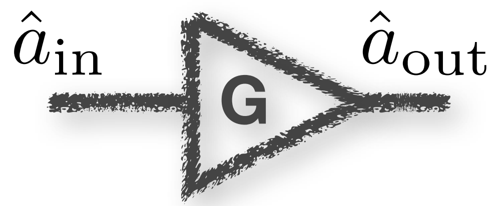


Need to amplify:

- No «click» detectors
- Need to further separate the pointer states

Quantum limit to amplification



Linear amplification: $\langle \hat{a}_{\rm out} \rangle = \sqrt{G} \langle \hat{a}_{\rm in} \rangle$

$\Rightarrow \; \hat{a}_{\rm out} \stackrel{?}{=} \sqrt{G}\hat{a}_{\rm in} + \hat{h}$ $\qquad [\hat{a}_{\rm out}, \hat{a}^\dagger_{\rm out}] = 1$ $\qquad \langle \hat{h} \rangle = 0$ (it's noise)

$$[\hat{h}, \hat{h}^\dagger] = 1 - G$$

Noise at the amplifier output:

$$(\Delta a_{\rm out})^2 = G(\Delta a_{\rm in})^2 + \frac{1}{2}\left\langle \left\{ \hat{h}, \hat{h}^\dagger \right\} \right\rangle \geq G(\Delta a_{\rm in})^2 + \frac{1}{2}|G-1|$$

Noise at the output as equivalent noise at the input; large gain limit :

$$(\Delta a_{\rm out})^2 / G \geq (\Delta a_{\rm in})^2 + \frac{1}{2}$$

C. M. Caves, Phys. Rev. D **26**, 1817 (1982)
Review: A. Clerk *et al*., Rev. Mod. Phys. **82**, 1155 (2010)

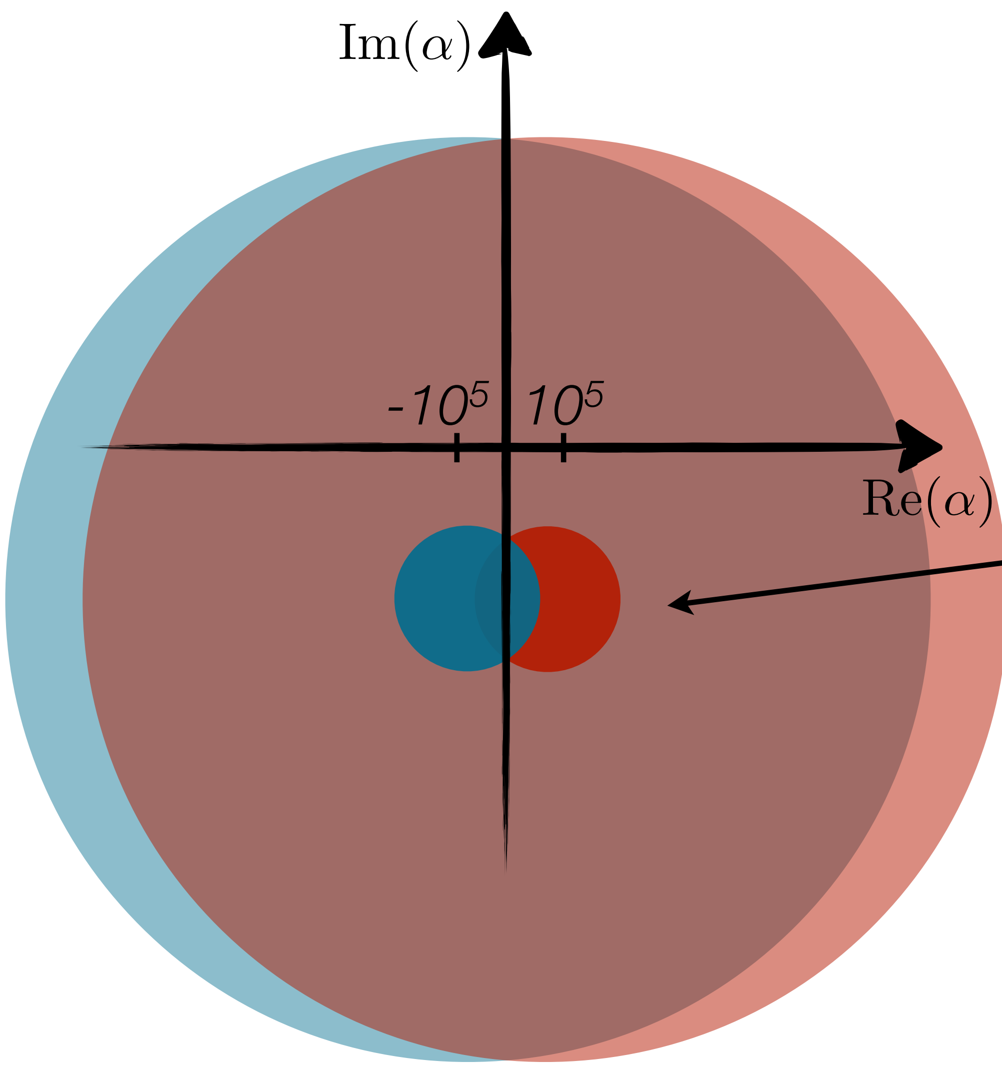
Quantum limit to amplification

$$\hat{a}_{\text{out}} = \sqrt{G}\hat{a}_{\text{in}} + \hat{h}$$

Noise at the output as equivalent noise at the input; large gain limit :

$$(\Delta a_{\text{out}})^2/G \geq (\Delta a_{\text{in}})^2 + \frac{1}{2}$$

Linear amplifier with large gain must add at least half a photon of noise.

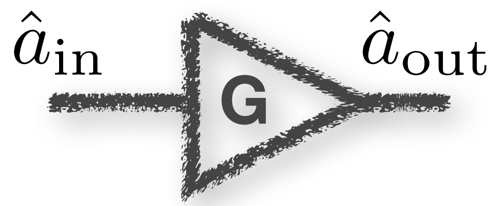


40 dB gain + quantum noise

40 dB gain + 40 photons of noise

C. M. Caves, Phys. Rev. D **26**, 1817 (1982)
Review: A. Clerk *et al.*, Rev. Mod. Phys. **82**, 1155 (2010)

Quantum limit to amplification



Linear amplification: $\langle \hat{a}_{\mathrm{out}} \rangle = \sqrt{G} \langle \hat{a}_{\mathrm{in}} \rangle$

$\Rightarrow \ \hat{a}_{\mathrm{out}} = \sqrt{G}\hat{a}_{\mathrm{in}} + \hat{h}$ $\quad [\hat{a}_{\mathrm{out}}, \hat{a}^{\dagger}_{\mathrm{out}}] = 1$ $\quad \langle \hat{h} \rangle = 0$ (it's noise)

$\hat{a}_{\mathrm{out}} = \sqrt{G}\hat{a}_{\mathrm{in}}$ $\quad \hat{a}^{\dagger}_{\mathrm{out}} = \hat{a}^{\dagger}_{\mathrm{in}}/\sqrt{G}$ $\quad [\hat{a}_{\mathrm{out}}, \hat{a}^{\dagger}_{\mathrm{out}}] = 1$

C. M. Caves, Phys. Rev. D **26**, 1817 (1982)
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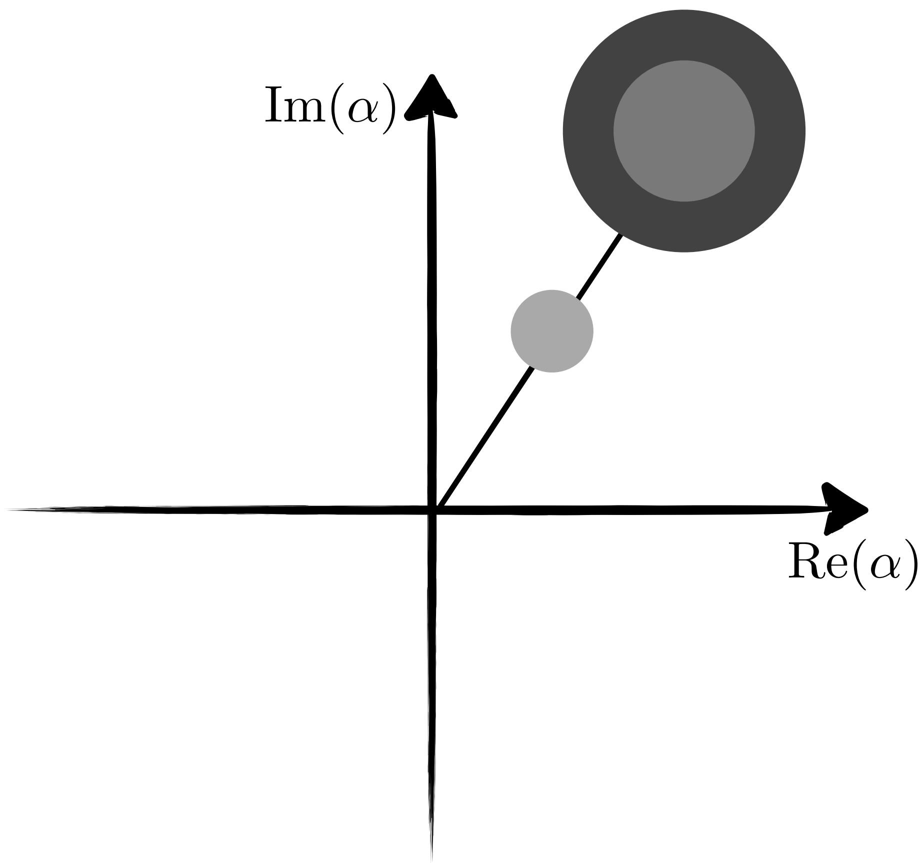
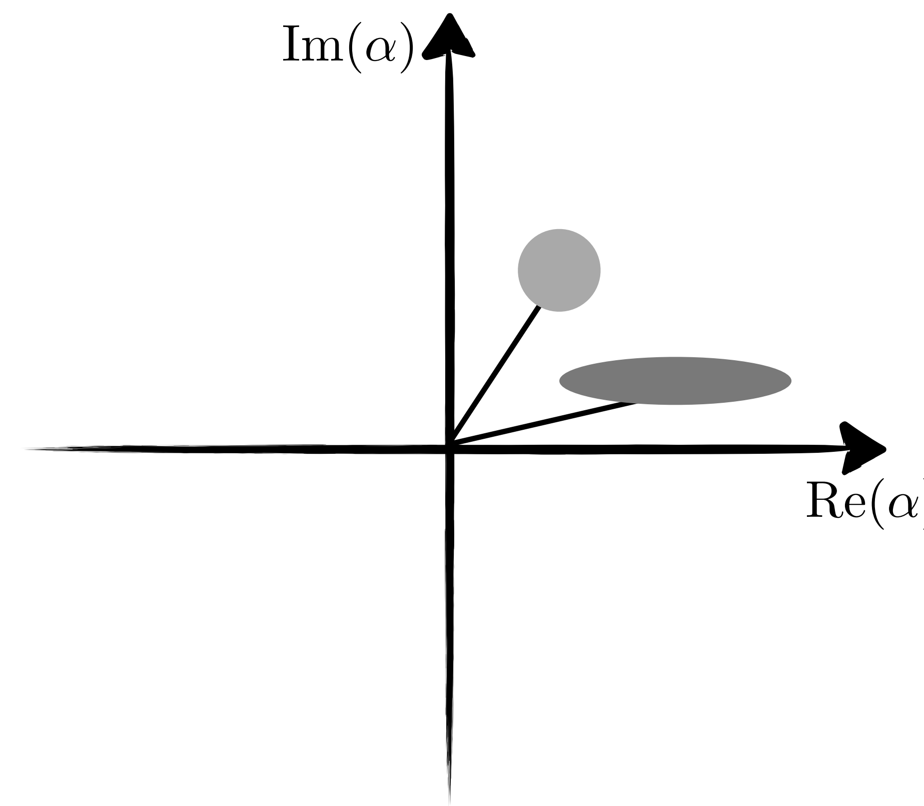
Quantum limit to amplification

$$\hat{a}_{\text{out}} = \sqrt{G}\hat{a}_{\text{in}} + \hat{h}$$



Phase insensitive
(phase preserving)

$$\hat{a}_{\text{out}} = \sqrt{G}\hat{a}_{\text{in}} \qquad \hat{a}^{\dagger}_{\text{out}} = \hat{a}^{\dagger}_{\text{in}}/\sqrt{G}$$

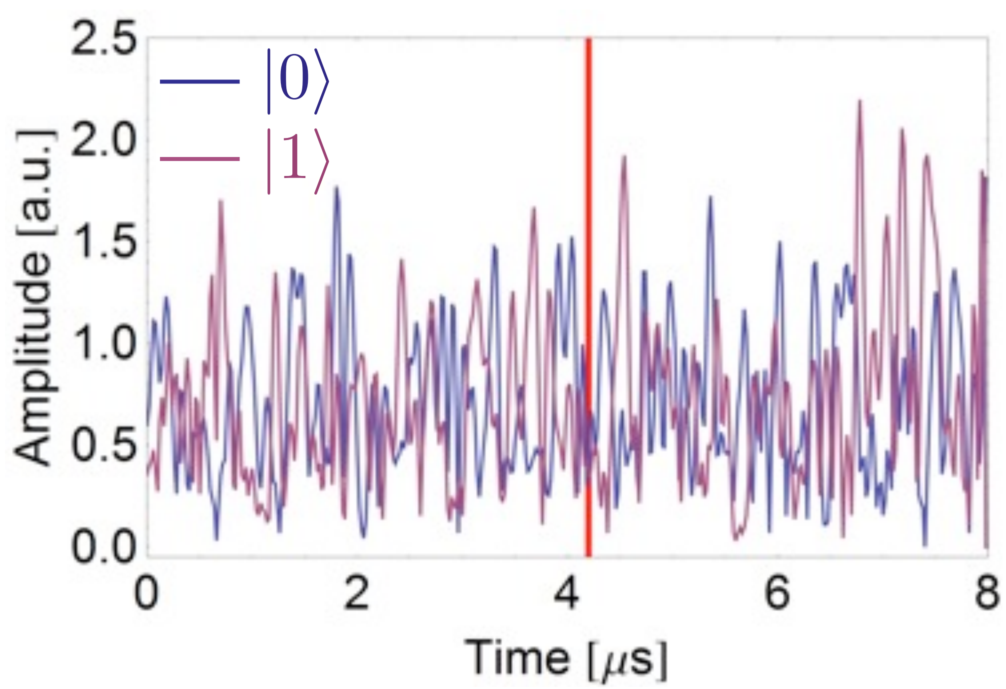


Phase sensitive
(phase non-preserving)

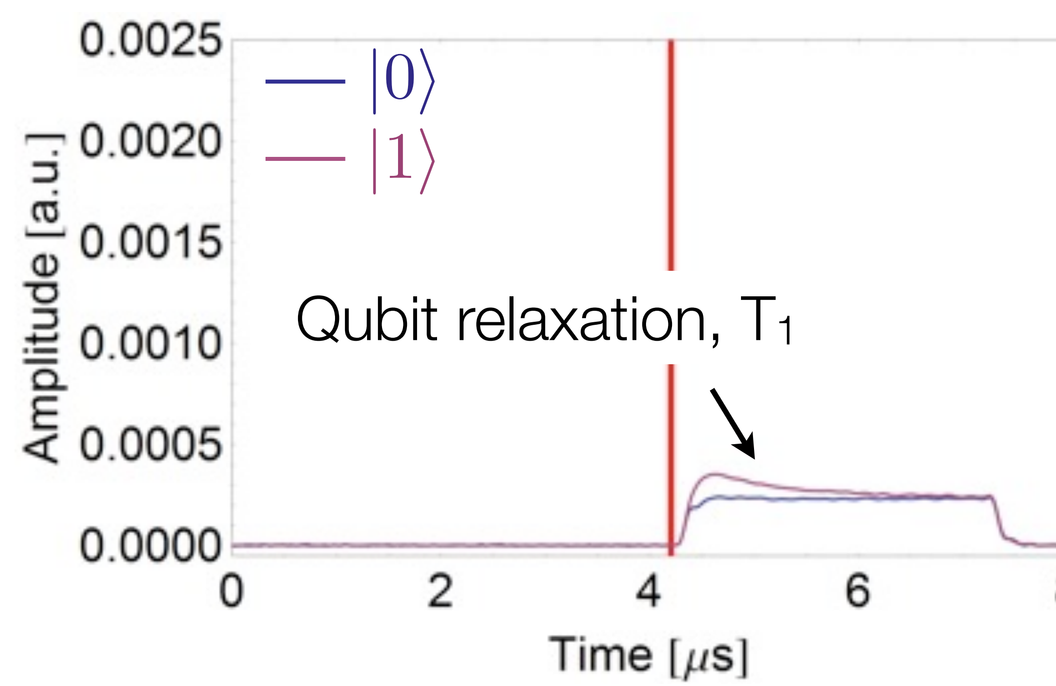
C. M. Caves, Phys. Rev. D **26**, 1817 (1982)
Review: A. Clerk *et al*., Rev. Mod. Phys. **82**, 1155 (2010)

Signal-to-noise ratio

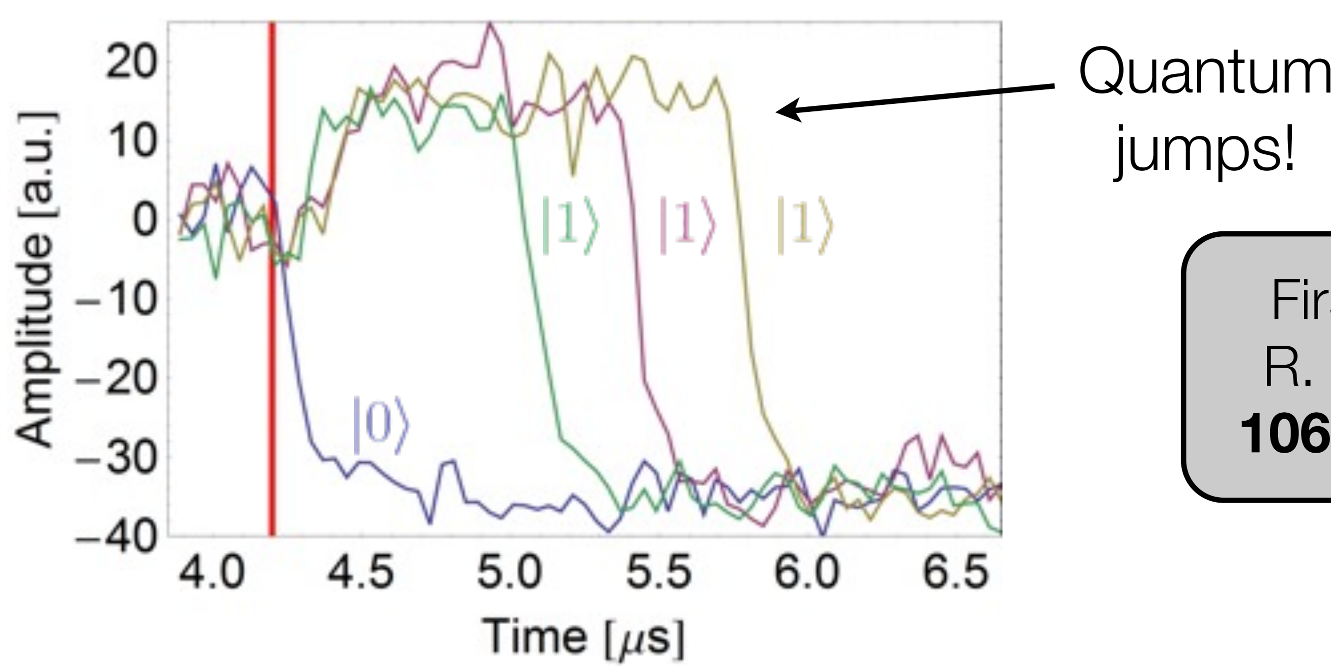
Single meas. record



Ave. over 80K meas. records

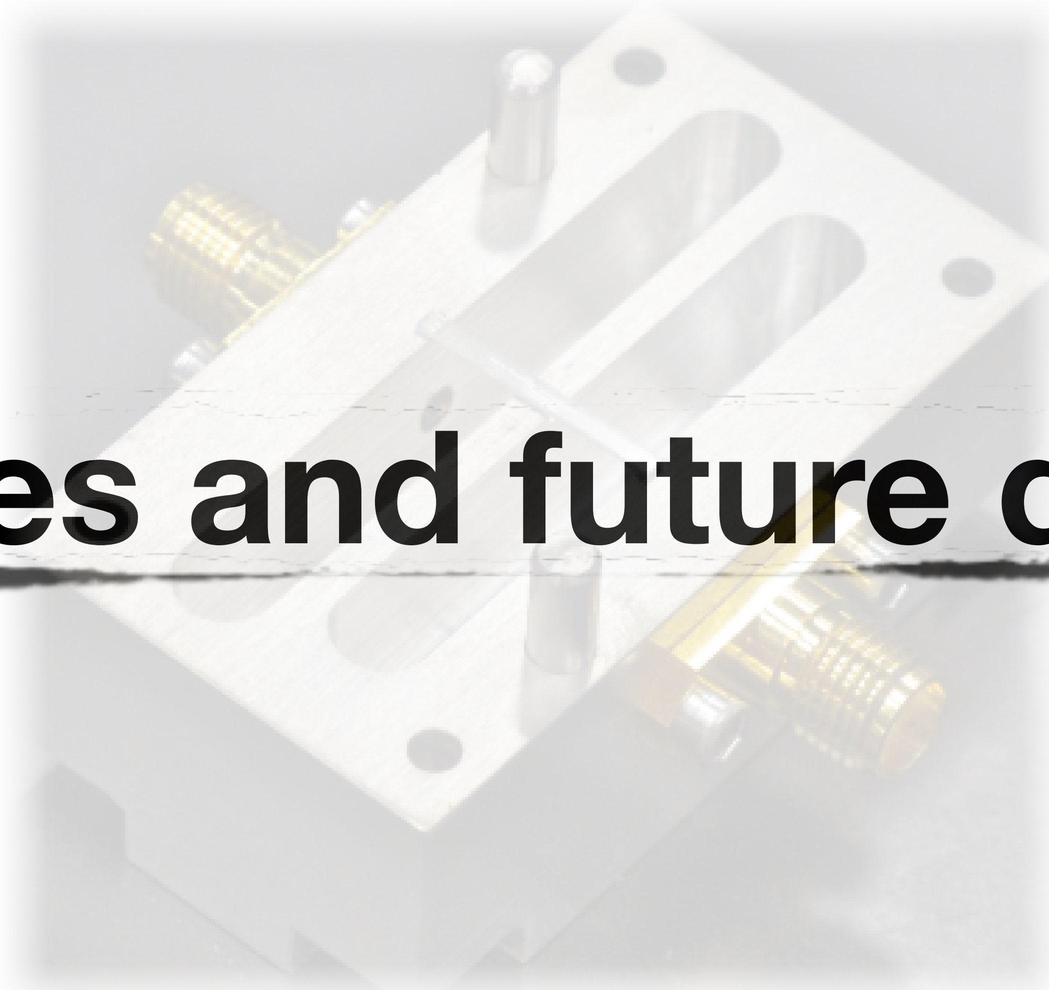


Single meas.
with JJ amp



First observation:
R. Vijay et al. PRL
106, 110502 (2011)

Data: A. Wallraff's group @ ETH Zurich; See also: R. Bianchetti et al. Phys. Rev. A **80**, 043840 (2009)



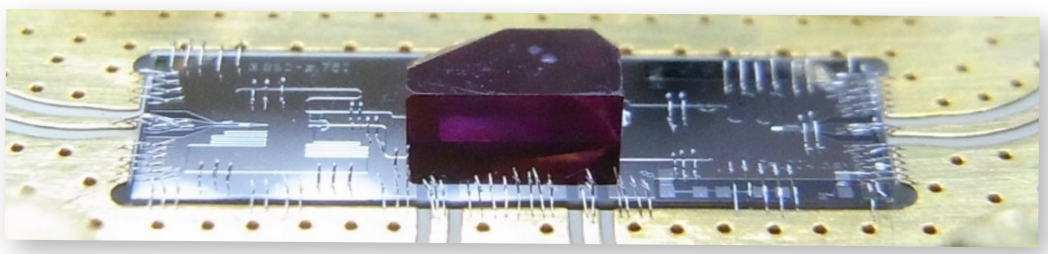
Challenges and future directions

Future directions and challenges

Hybrid systems

- Coupling to NV centers, rare earths, quantum dots...
- Quantum memory + fast gates

Credit: Quantronics group



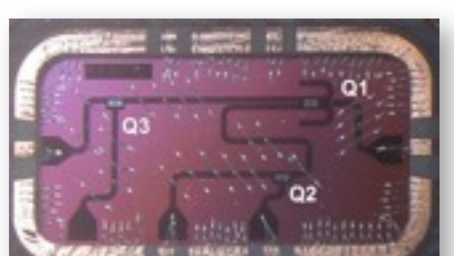
Strong nonlinearities

- ***New*** regimes of quantum optics
  - Single photon Kerr nonlinearities several orders of magnitude larger than in optics
- Improving qubit readout

Quantum information processing

- Keep improving T_1
- Understand and improve qubit readout
- Scalable architecture: multi-resonators

Credit: IBM

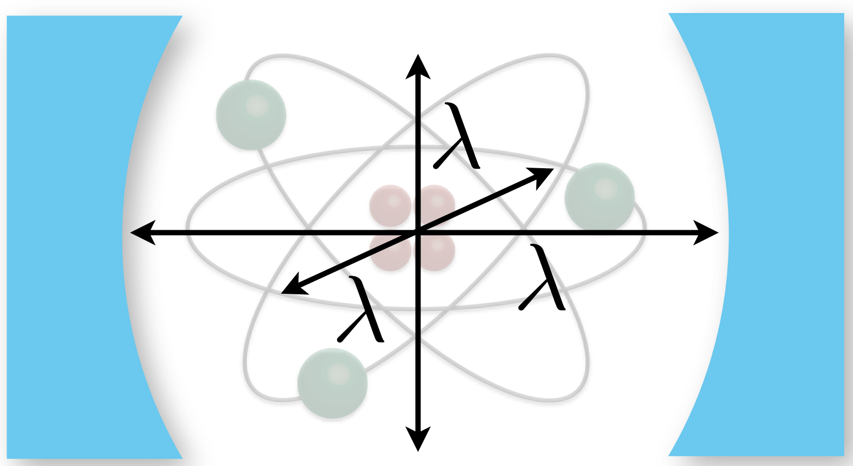


New tools for discoveries

- Probes of noise at high frequencies
- Quantum sensing: sensitive magnetometers, ...
- What else?!

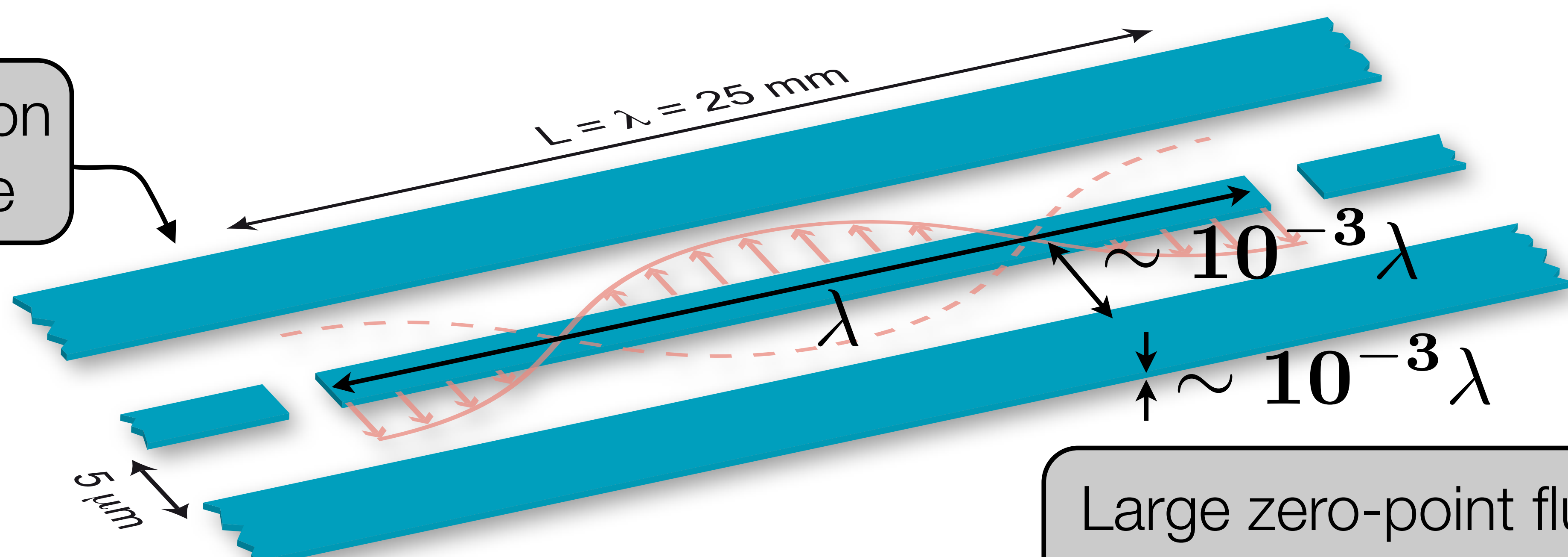
From cavity to *circuit* QED

- E-field can be tightly confined



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

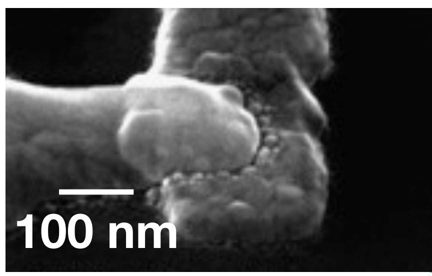
Al or Nb on sapphire

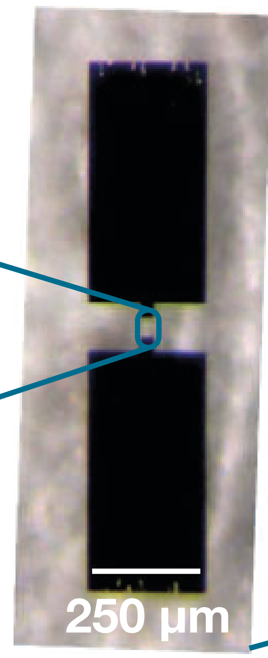


Large zero-point fluctuations of the field: $\mathbf{E_0 \sim 0.2\ V/m}$

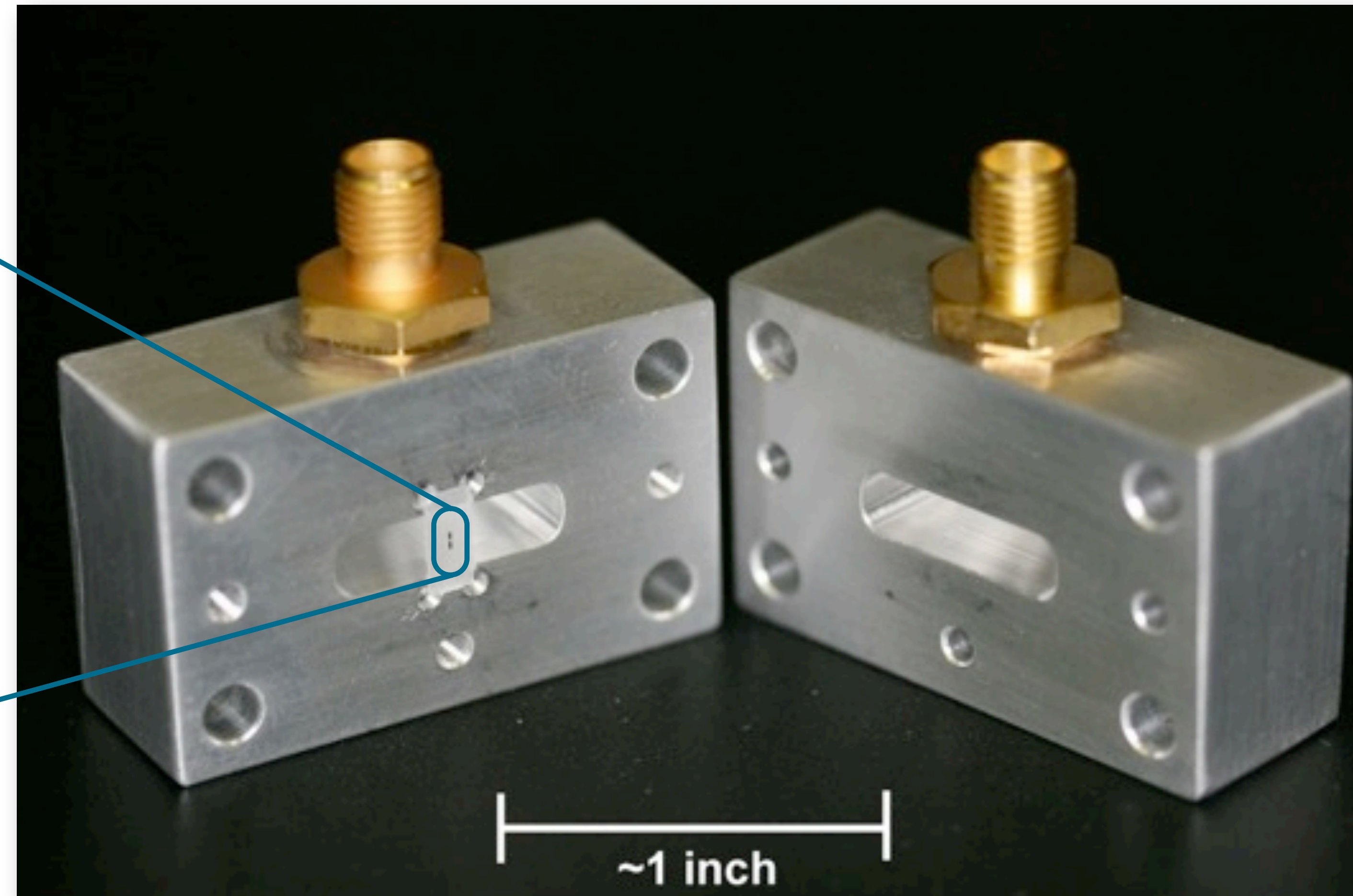
Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)

Circuit QED goes ***3D***





Large dipole moment



Weak electric fields

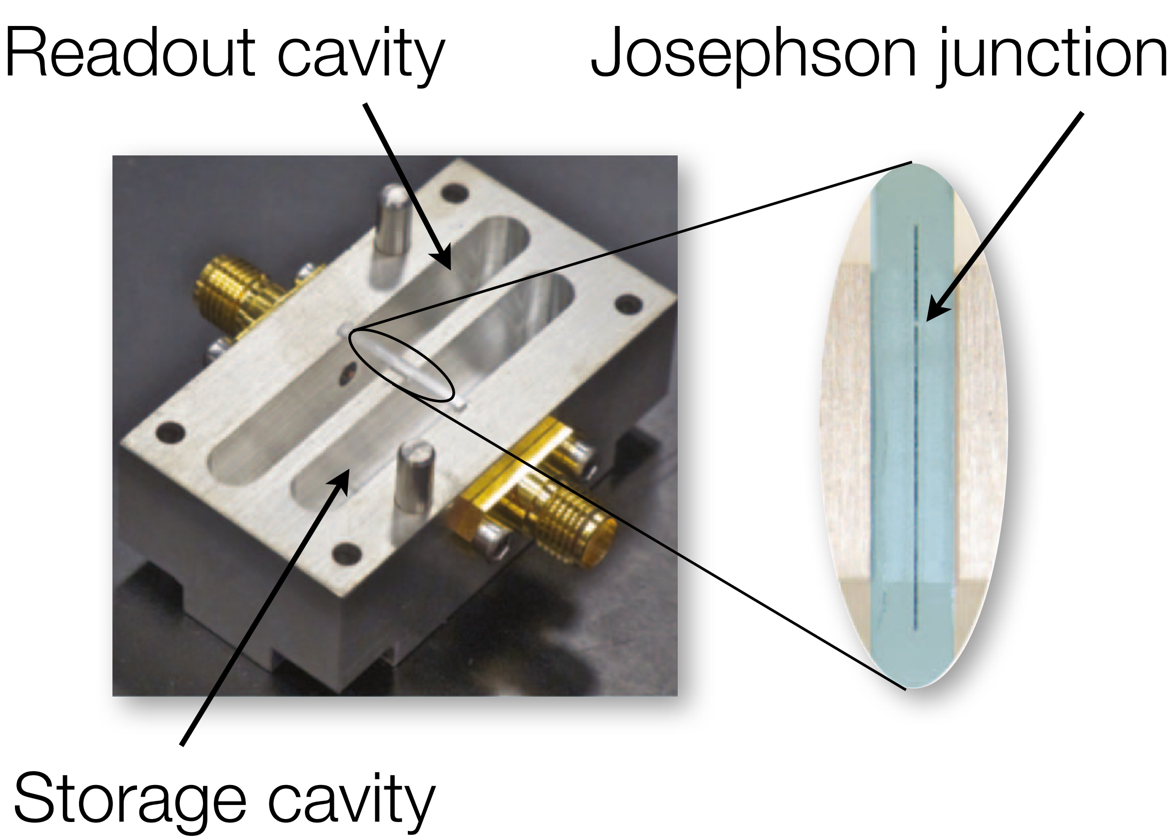
Light-matter interaction: $g = d \cdot E$ unchanged!

Current best values: $T_1 = 70\ \mu s$ and $T_2^* = 95\ \mu s$

H. Paik *et al*, Phys. Rev. Lett. **107**, 240501 (2011)

Circuit QED goes ***3D***

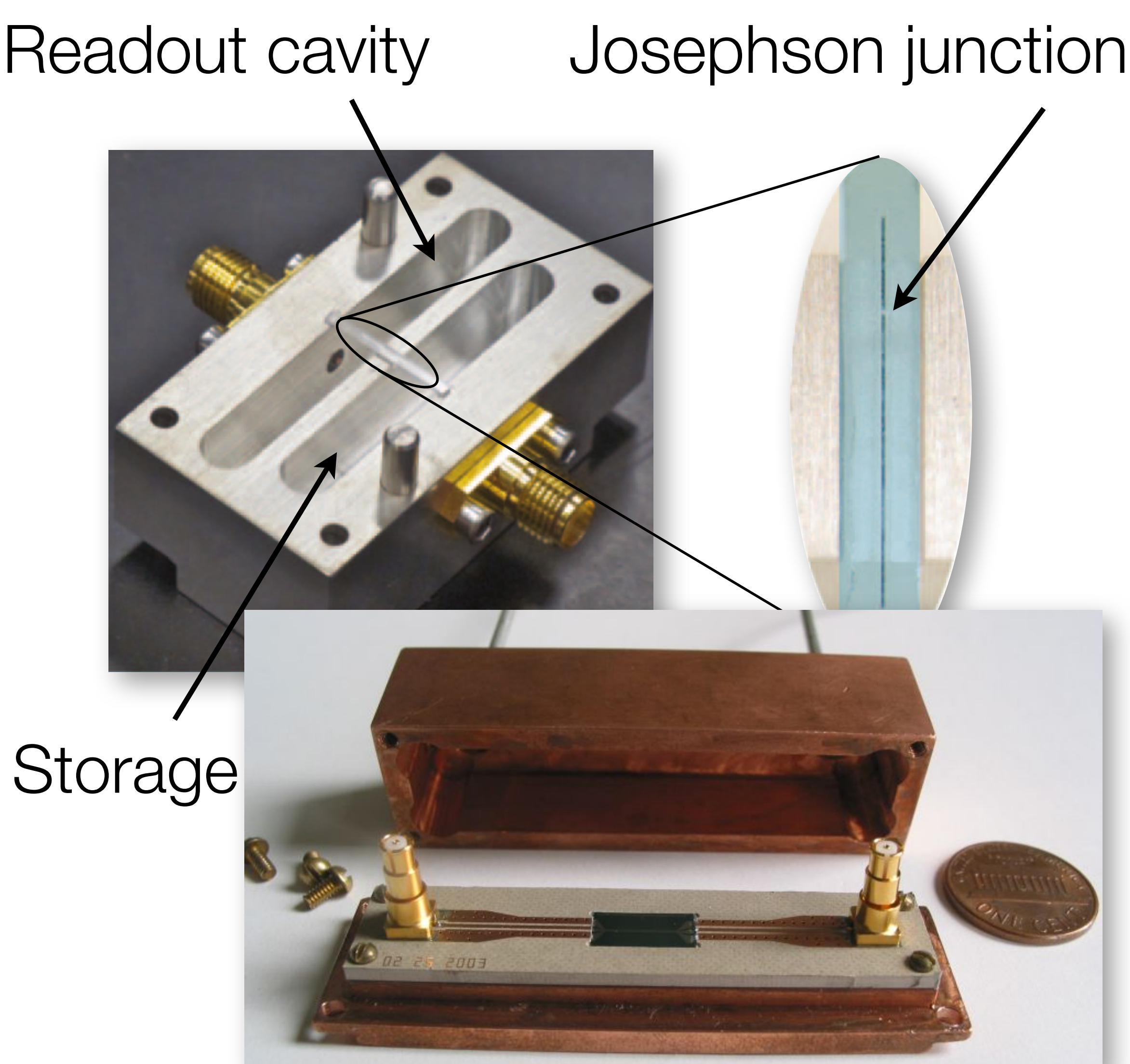
First steps towards scaling-up



G. Kirchmair *et al*, Nature. 495, 205 (2013)

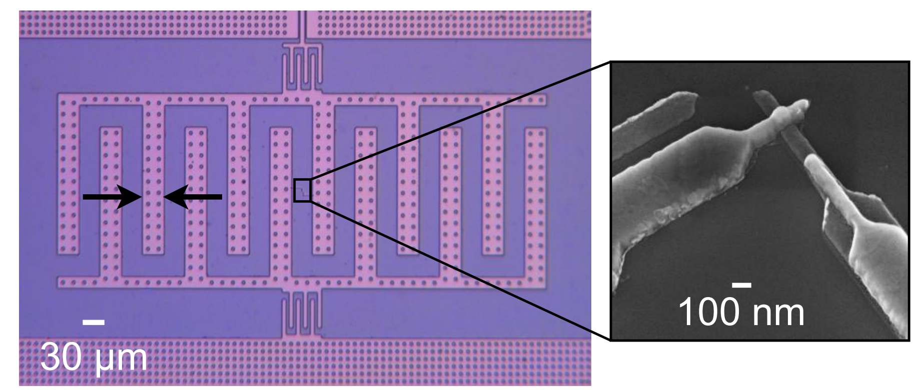
Circuit QED goes ***3D***

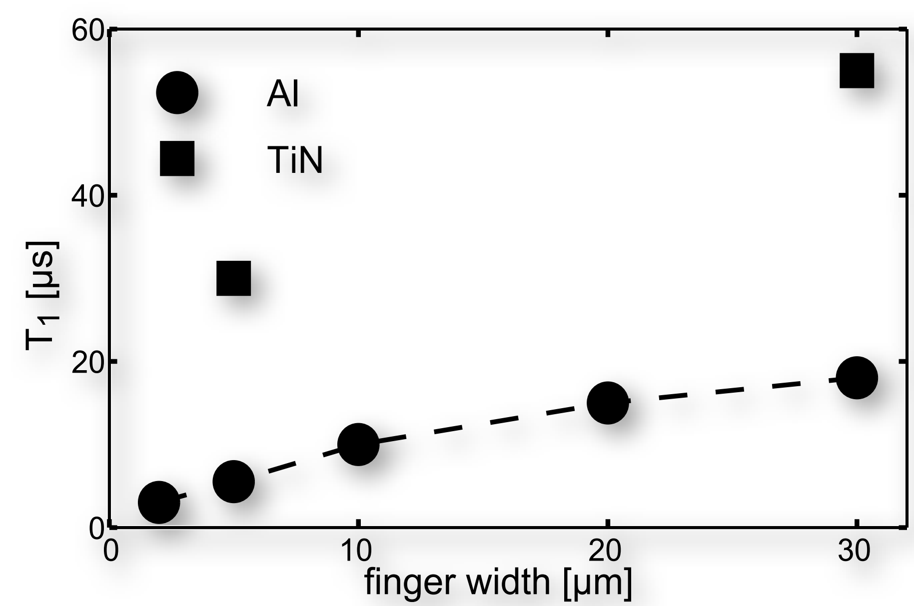
First steps towards scaling-up



G. Kirchmair *et al*, Nature. 495, 205 (2013)

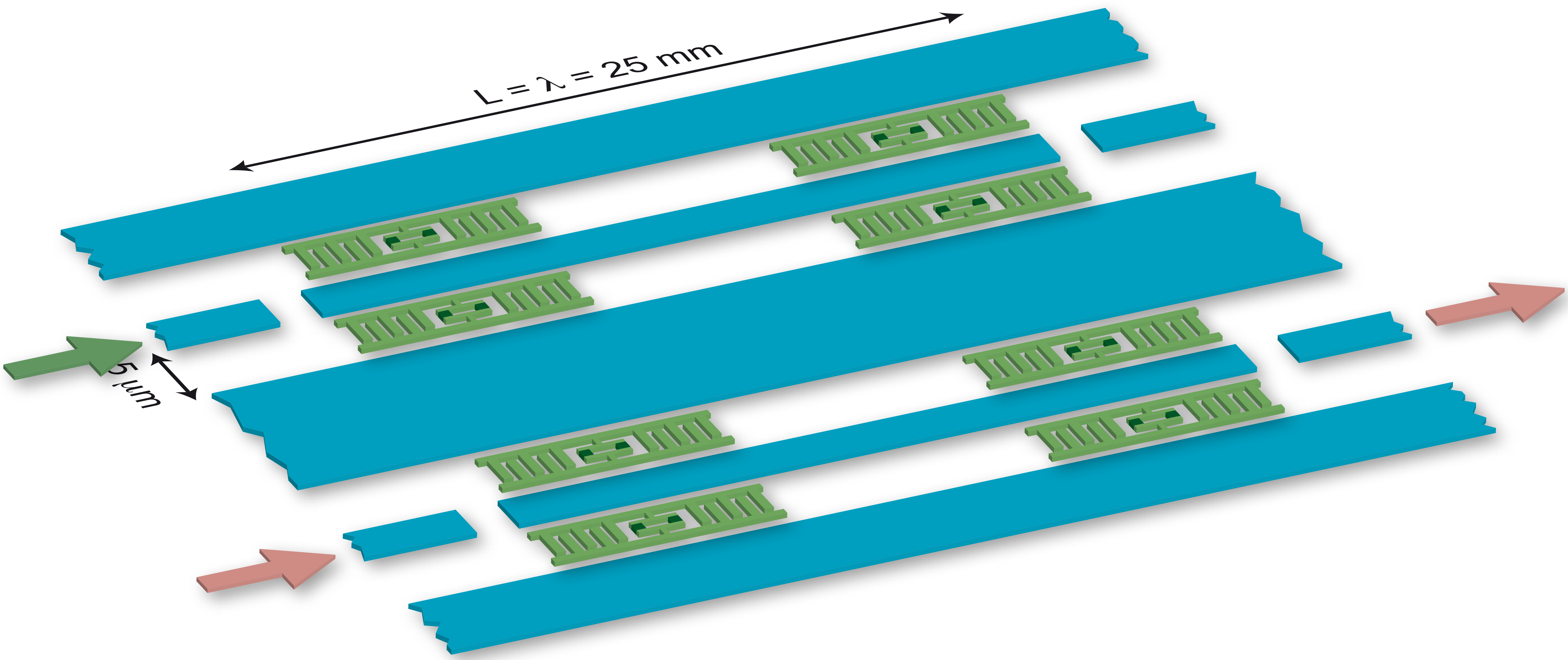
... and back to 2D



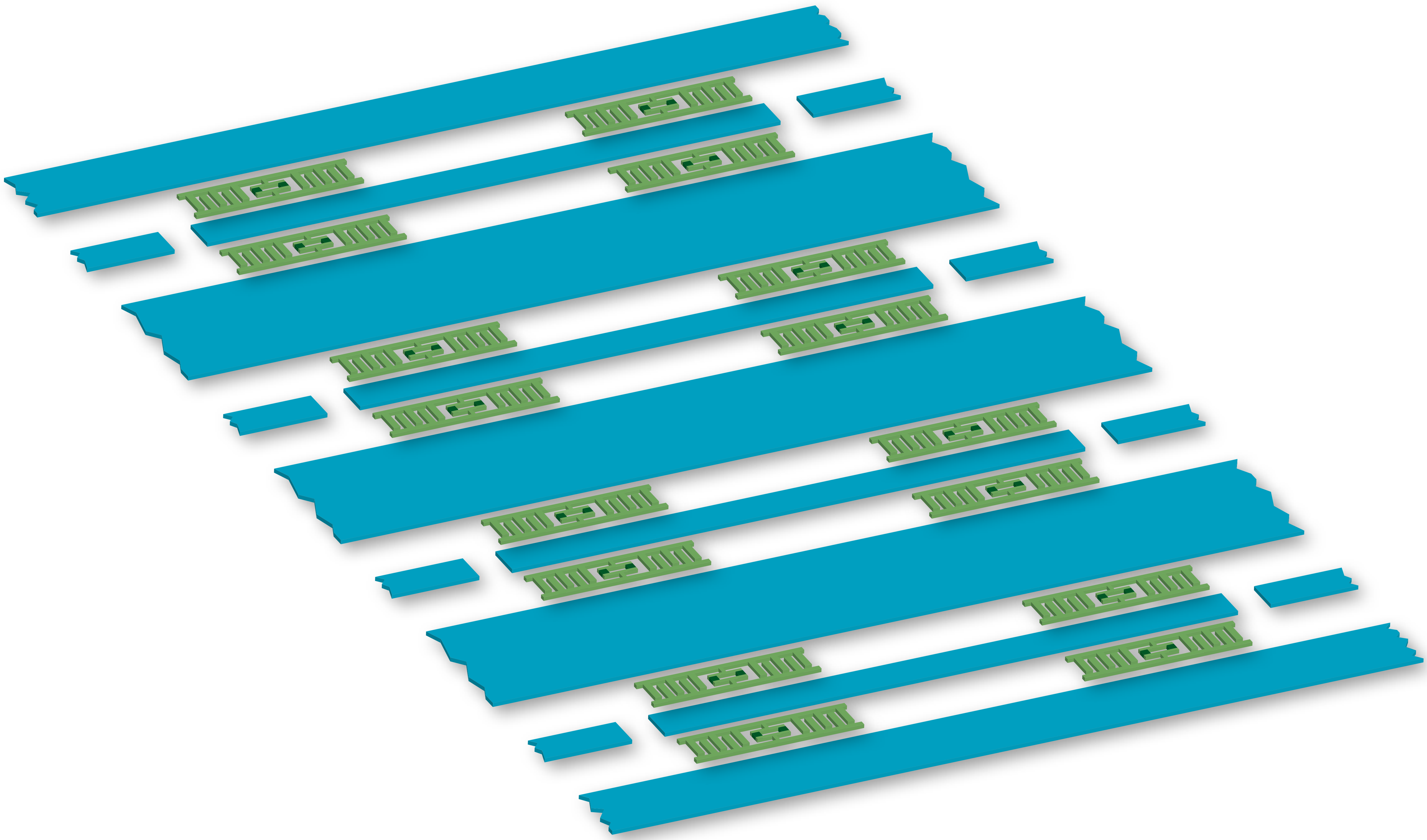


J. Chang *et al*, arXiv:1303.407 (2013)

Towards a scalable architecture

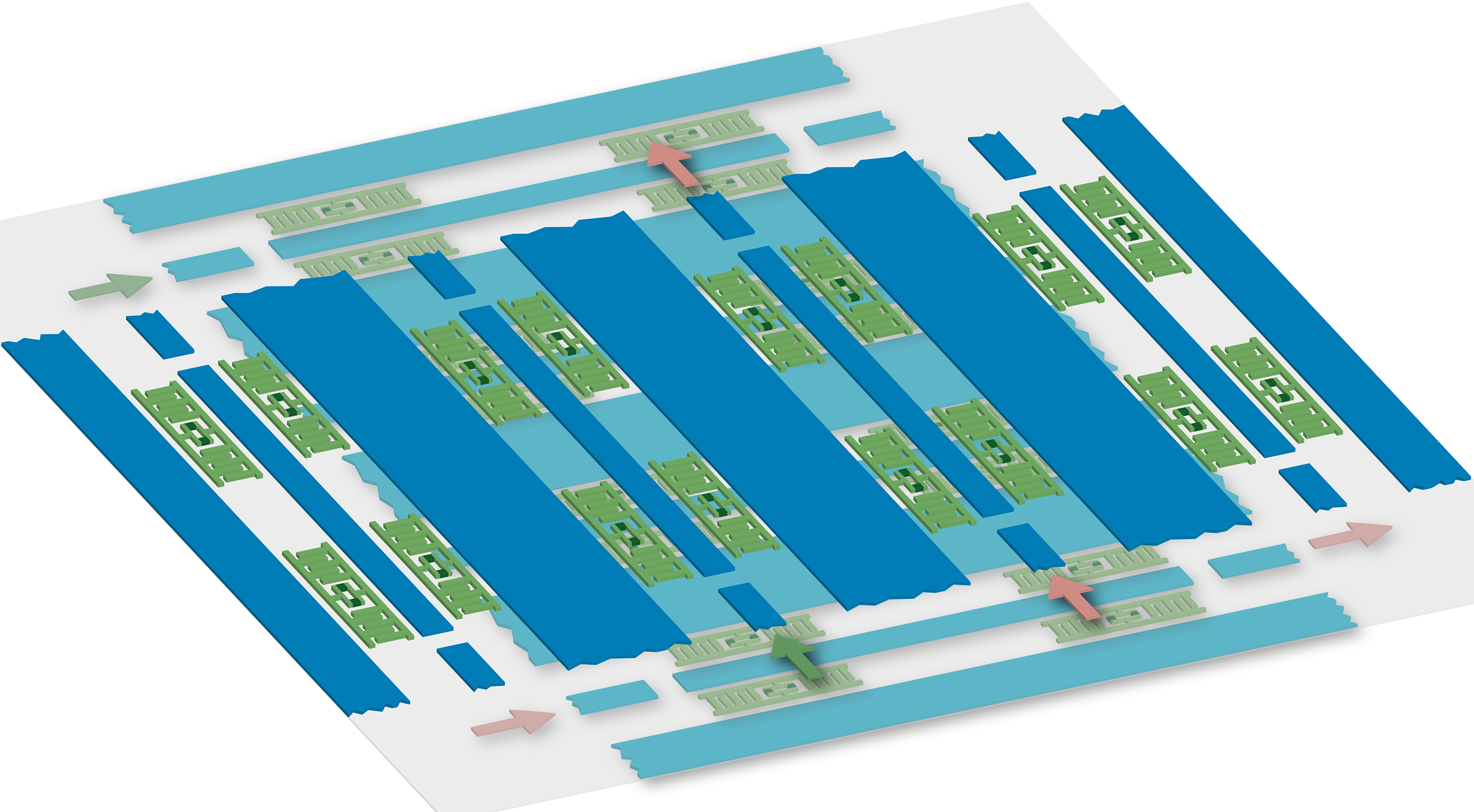


Towards a scalable architecture



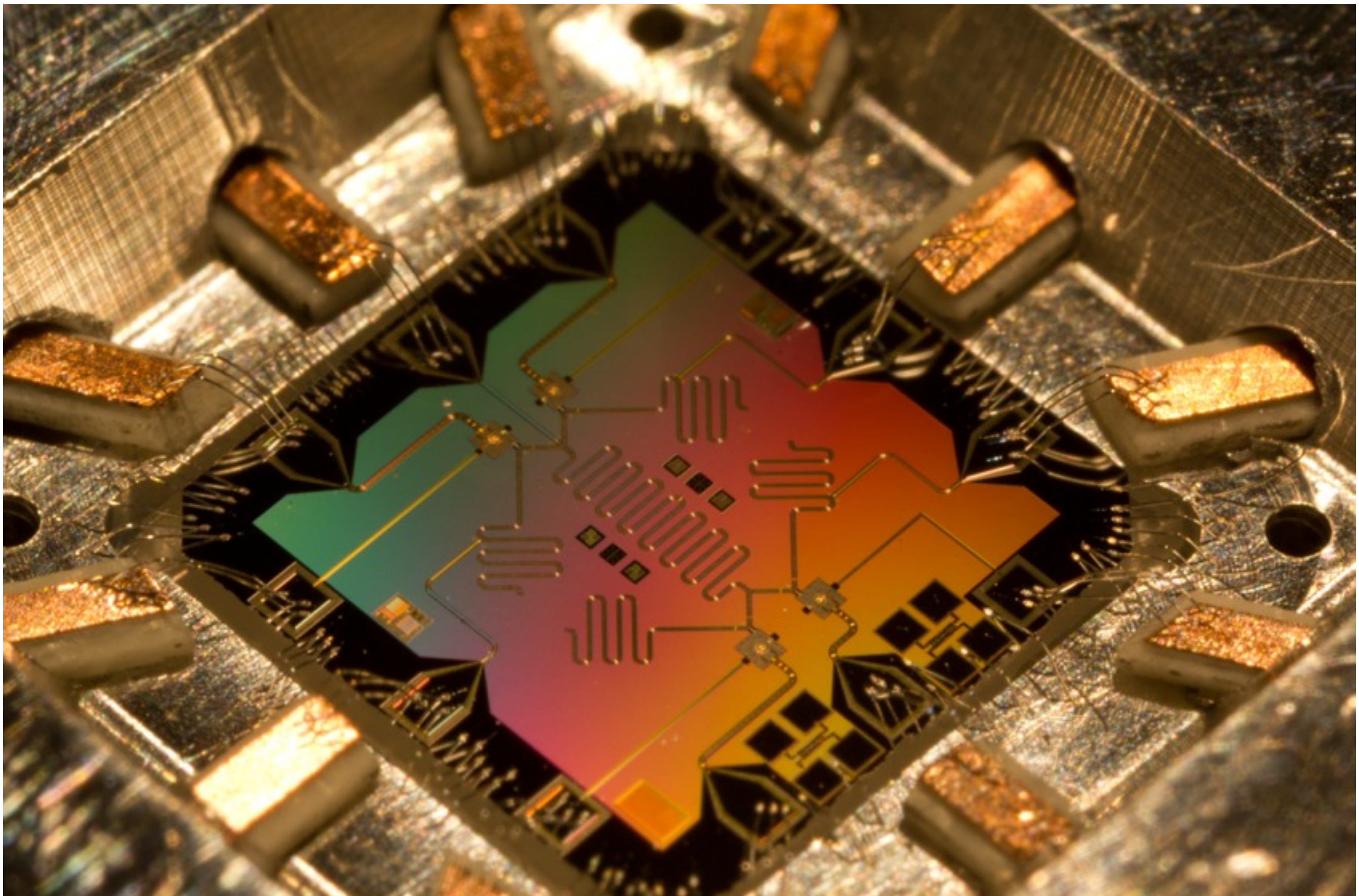
F. Helmer *et al,* Europhys. Lett. **85**, 50007 (2009)

Towards a scalable architecture



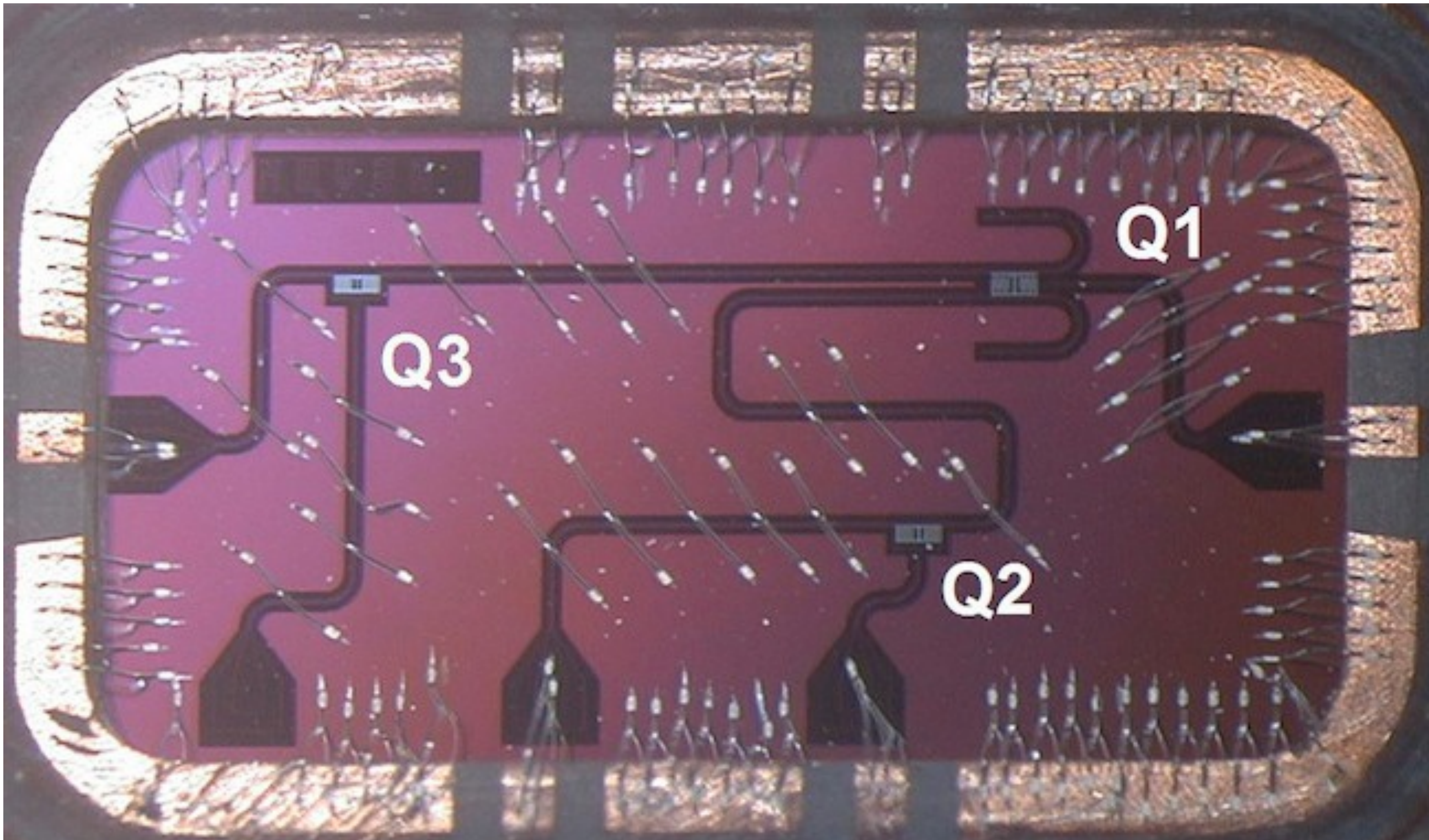
F. Helmer *et al,* Europhys. Lett. **85**, 50007 (2009)

Towards a scalable architecture



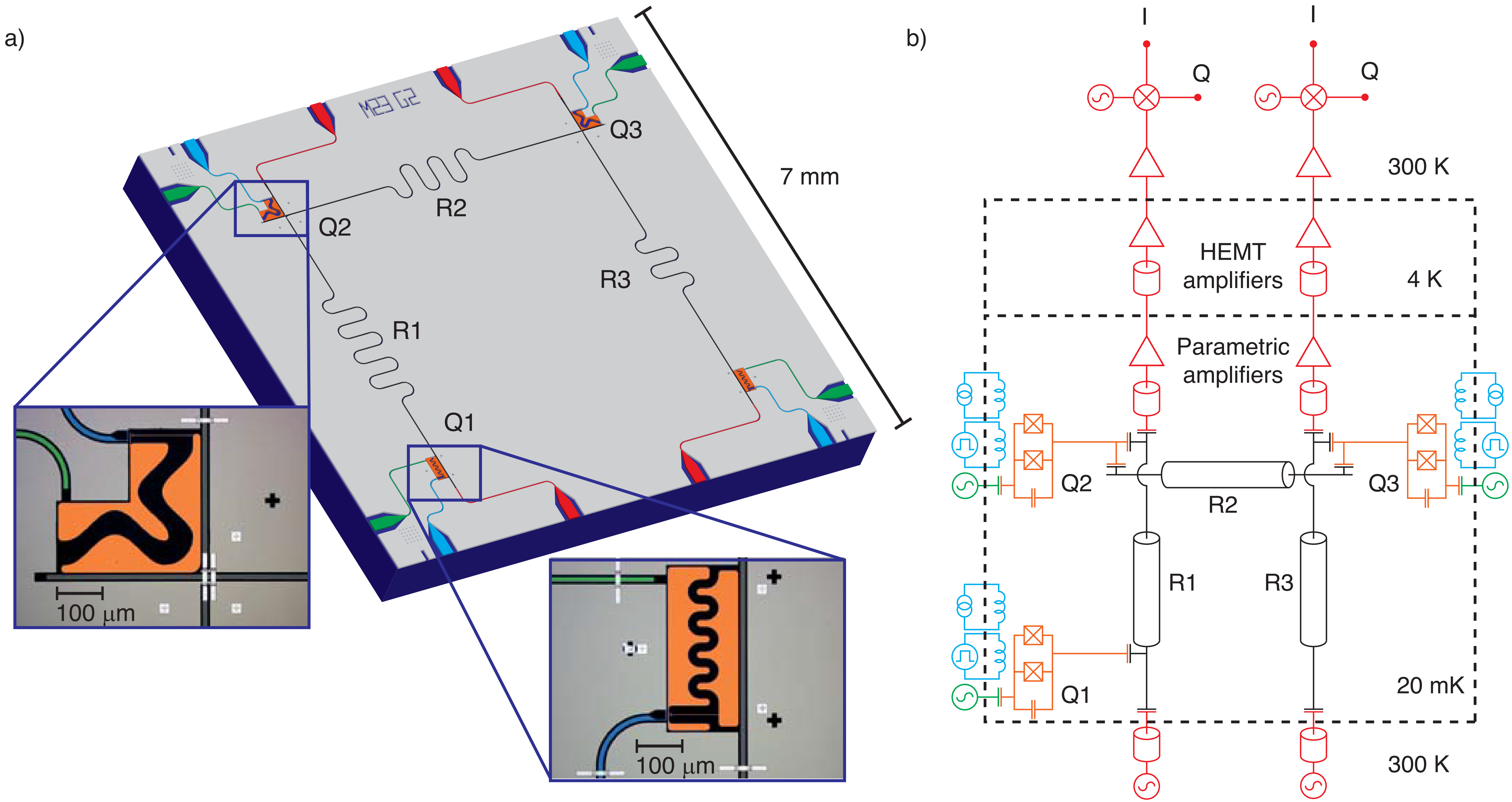
Credit: UCSB

Towards a scalable architecture



Credit: IBM

Towards a scalable architecture



Credit: ETH Zurich

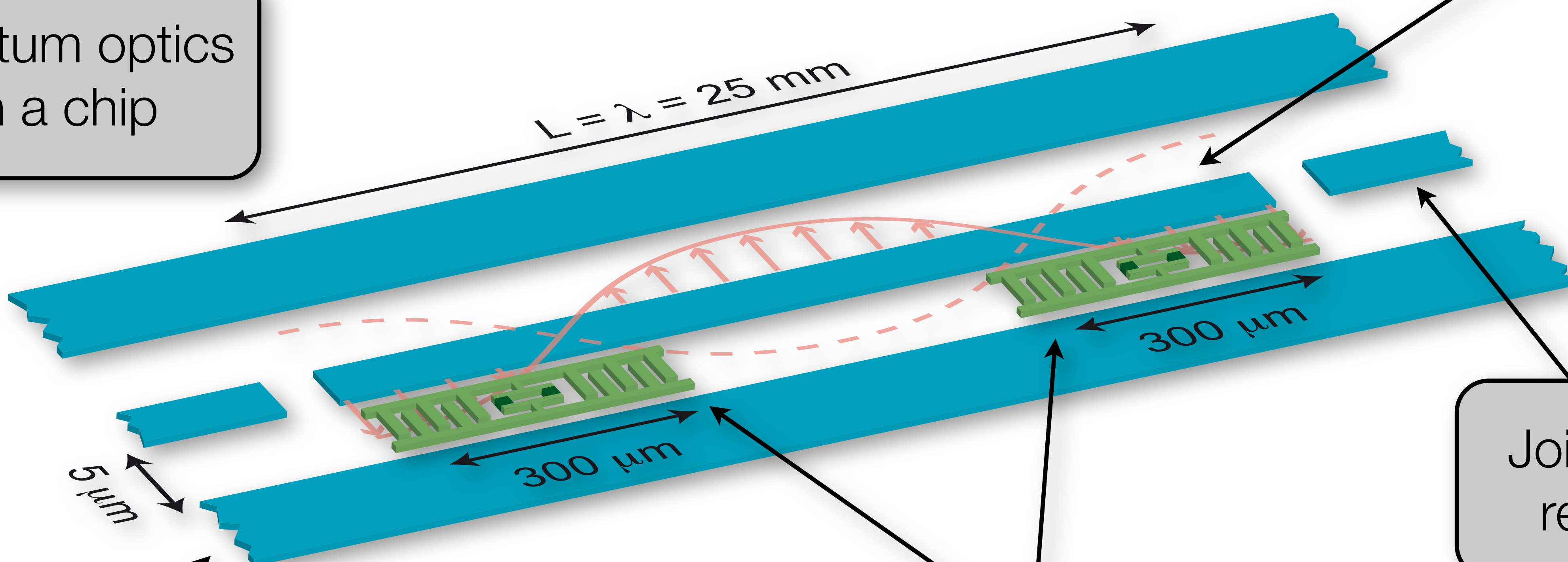
Summary

Exploring quantum mechanics on large length scales

Quantum protocols implemented in solid-state quantum processor

Quantum bus mediating qubit-qubit interaction

Quantum optics on a chip



Joint qubit readout

Superconducting high-Q resonator

Superconducting qubits with long coherence times

CIFAR CANADIAN INSTITUTE for ADVANCED RESEARCH
CRSNG NSERC
ALFRED P. SLOAN FOUNDATION
INTRIQ