Superconducting Qubits Readout

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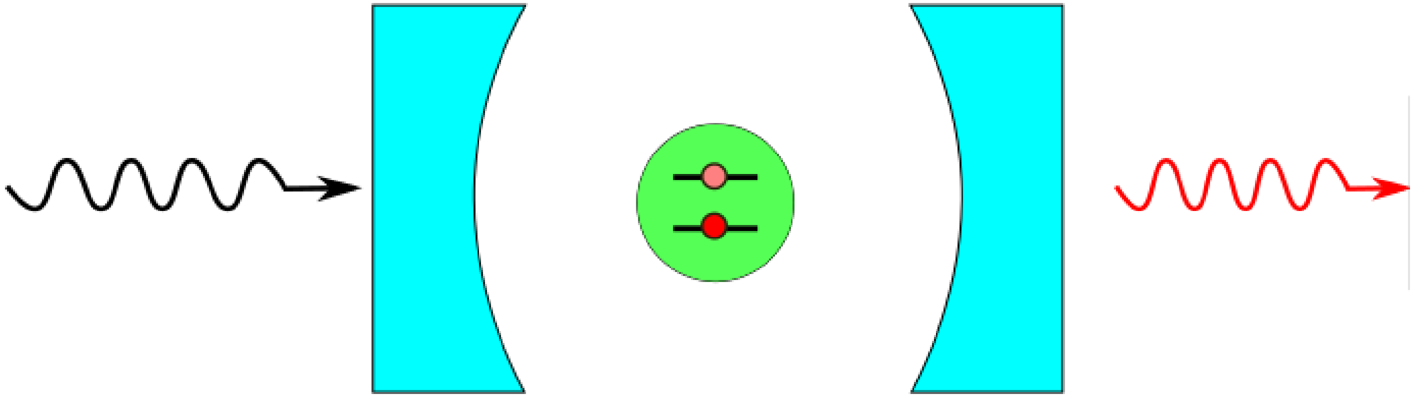
Motivation

- Properties we want for a QM-measurement:
  - Projective
  - Non-demolition (QND)
  - High SNR
  - Faster than life- and coherence time (T_1, T_2)
  - High fidelity

Setup

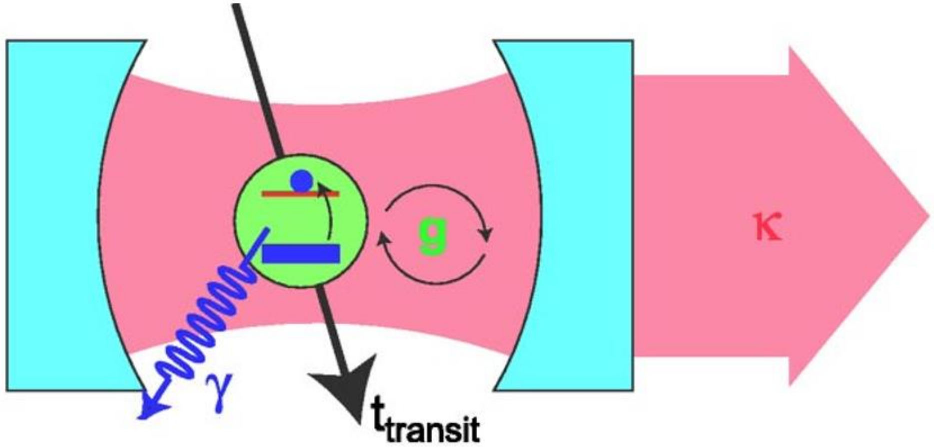


- Put qubit inside cavity
- Measure the transmitted / reflected radiation of the cavity

→ Transform quantum qubit state to macroscopic observable

- This is analogous to e.g. Stern-Gerlach

CQED introduction



- Two-level atom inside cavity
- Jaynes-Cummings Hamiltonian:

$$H = \underbrace{\boxed{\hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right)}}_{\text{Cavity field}} + \underbrace{\boxed{\frac{\hbar\omega_q}{2}\boldsymbol{\sigma}^z}}_{\text{qubit}} + \underbrace{\boxed{\hbar g\left(a^\dagger\boldsymbol{\sigma}^- + \boldsymbol{\sigma}^+ a\right)}}_{\text{coupling}} + \underbrace{\boxed{H_\kappa + H_\gamma}}_{\text{environment}}$$

- Coupling strength: $g = \frac{\mathcal{E}_{rms} d}{\hbar}$
- Detuning: $\Delta := \omega_q - \omega_r$
- Cavity and qubit to photon decay rate: κ, γ

A. Blais et al., PRA 69, 062320 (2004)

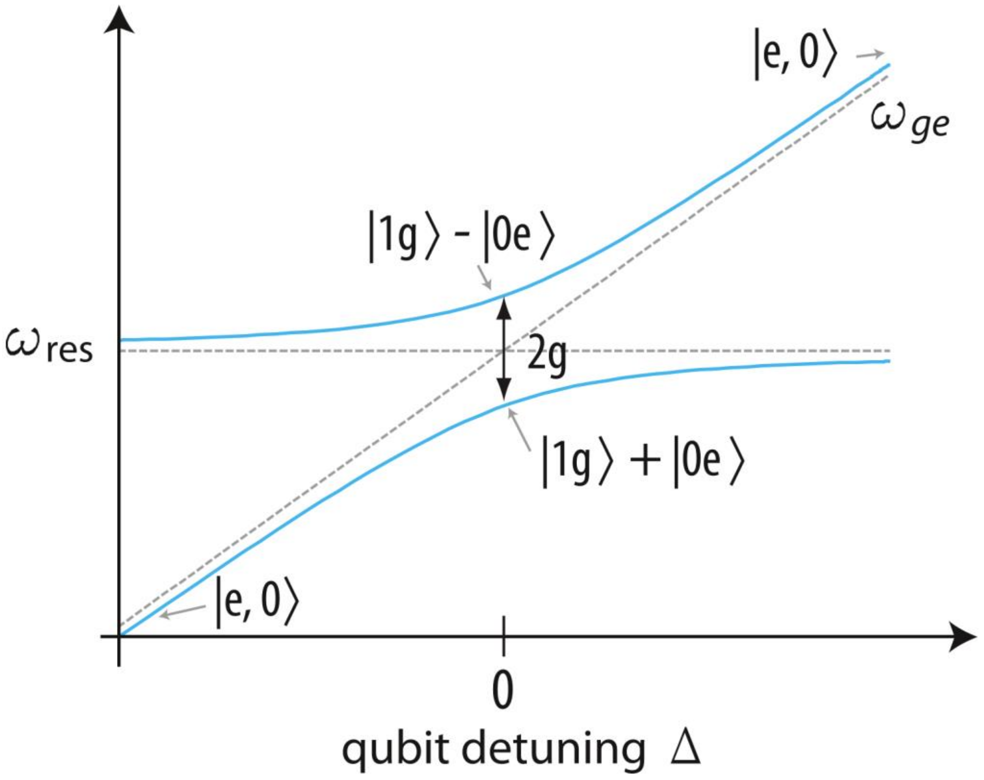
CQED introduction

- Neglecting damping, exact diagonalization of Jaynes-Cummings Hamiltonian yields «dressed» (entangled) states:

$$|+, n\rangle = \cos(\theta_n)\,|e, n\rangle + \sin(\theta_n)\,|g, n+1\rangle$$
$$|-, n\rangle = -\sin(\theta_n)\,|e, n\rangle + \cos(\theta_n)\,|g, n+1\rangle$$

$$E_{\pm,n} = (n+1)\hbar\omega_r \pm \frac{\hbar}{2}\sqrt{4g^2(n+1) + \Delta^2}$$

$$\tan(2\theta_n) = \frac{2g\sqrt{n+1}}{\Delta}$$

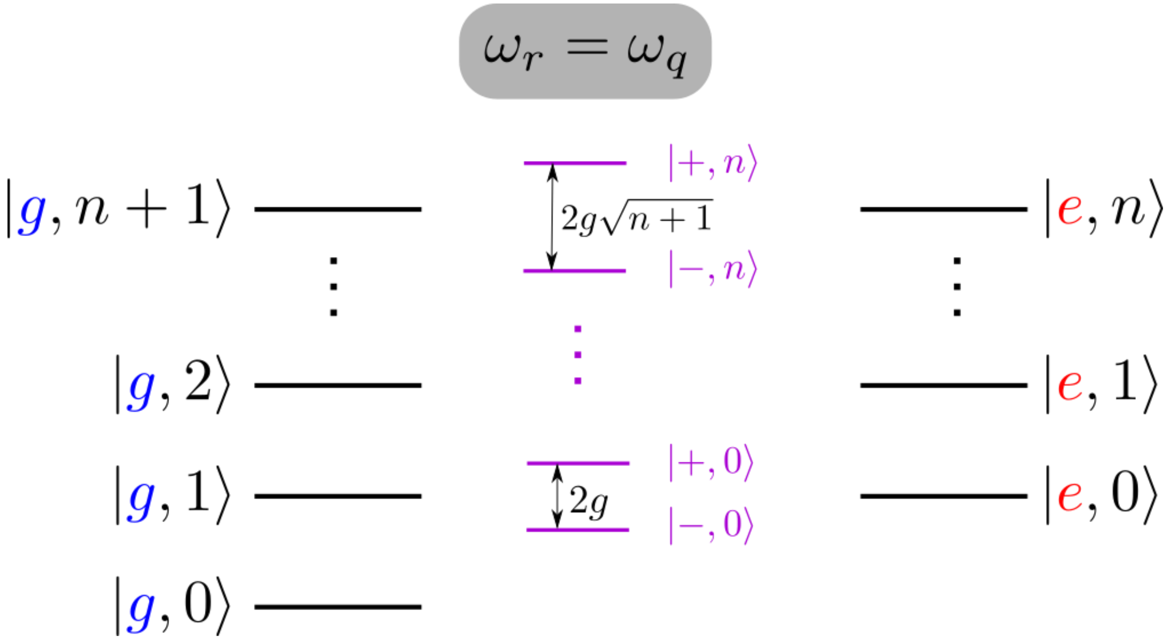


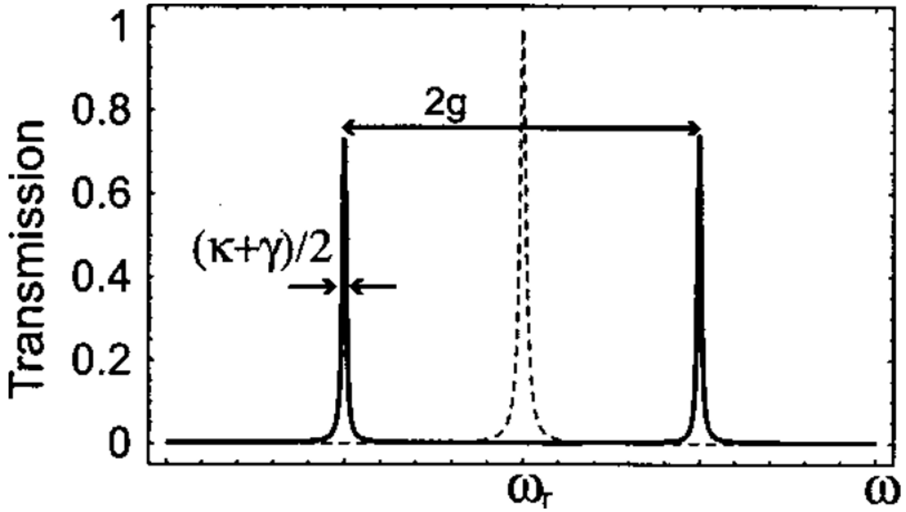
C. Eichler, Ph.D. thesis, ETH Zurich (2013)

CQED introduction

Case 1: zero detuning

- Strong coupling limit: $g \gg \kappa, \gamma$
- Energy spectrum:





A. Blais et al., PRA 69, 062320 (2004)

CQED introduction

Case 2: large detuning (dispersive regime)

$$\omega_r = \omega_q - \Delta$$

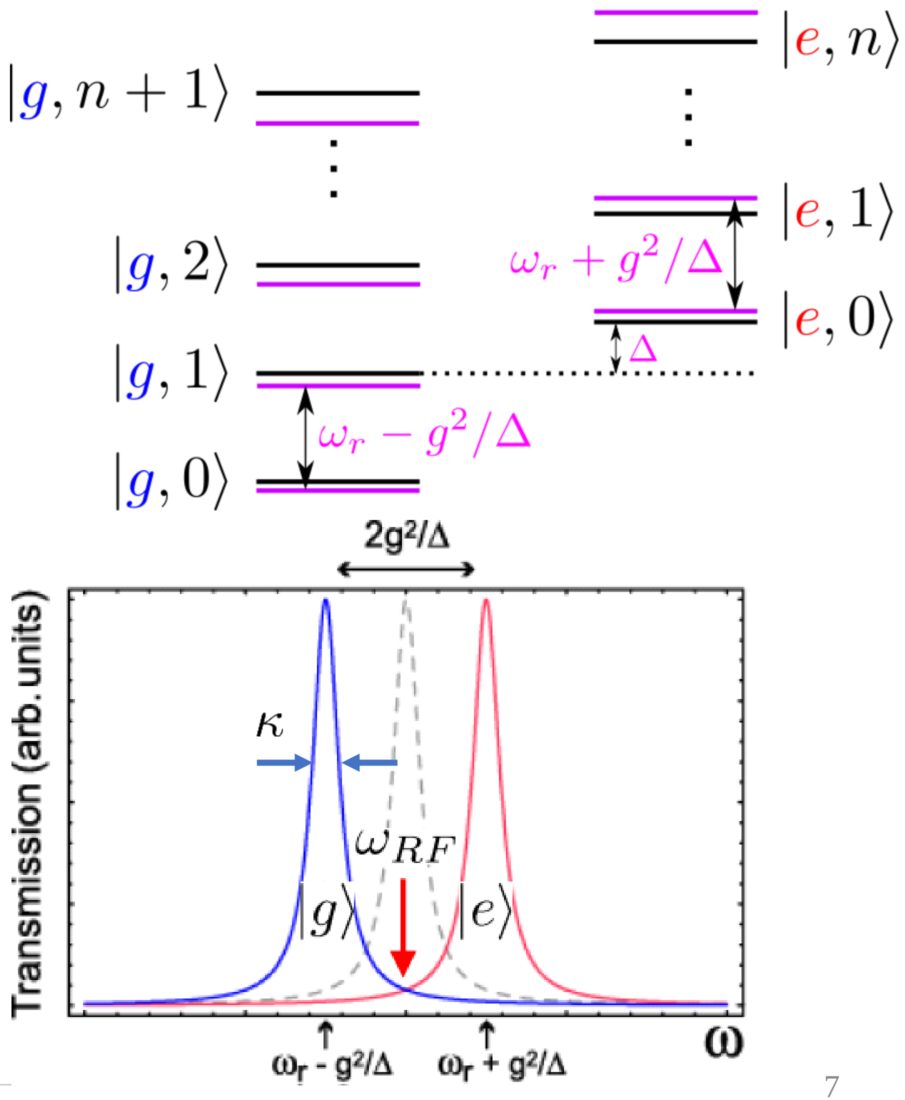
$$\frac{g}{\Delta} \ll 1 \Rightarrow \begin{array}{l} |+,n\rangle \rightarrow |e,n\rangle \\ |-,n\rangle \rightarrow |g,n+1\rangle \end{array}$$

→ qubit states become eigenstates

→ qubit flip suppressed as $\sim \epsilon \frac{g}{\Delta}$

- Also qubit lifetime enhancement; $\frac{\gamma}{\kappa} \rightarrow 0$
- Schrieffer-Wolff transformation:

$$UHU^\dagger \approx \hbar \underbrace{\left(\omega_r + \frac{g^2}{\Delta}\sigma^z\right)}_{\omega_r(\sigma^z)} a^\dagger a + \frac{\hbar}{2}\left(\omega_q + \frac{g^2}{\Delta}\right)\sigma^z$$



CQED introduction

Case 2: large detuning (dispersive regime)

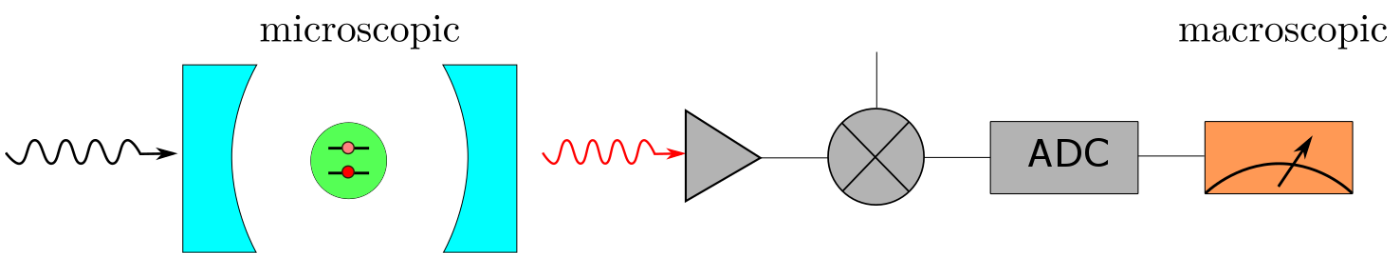
- Schrieffer-Wolff transformation is an approximate diagonalization of Hamiltonian
- Interaction Hamiltonian now commutes with qubit Hamiltonian

→ no qubit flip

→ non-demolition measurement (QND)

Dispersive Readout of Qubits

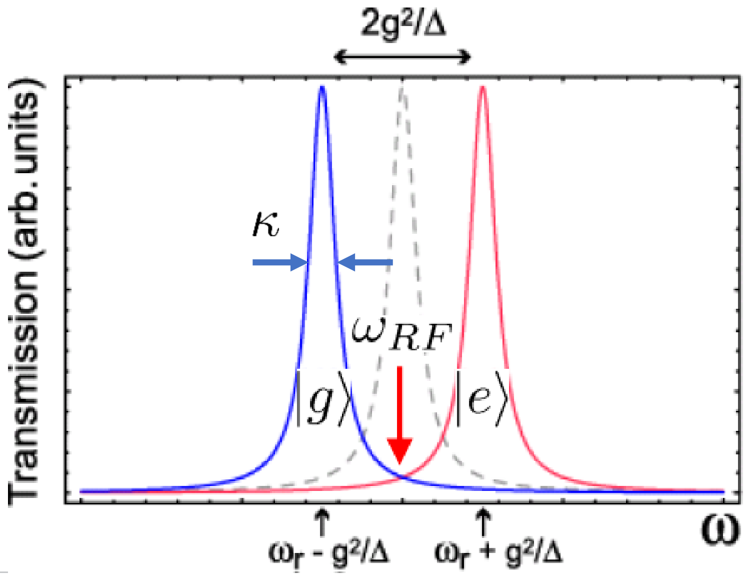
Measurement Strategies

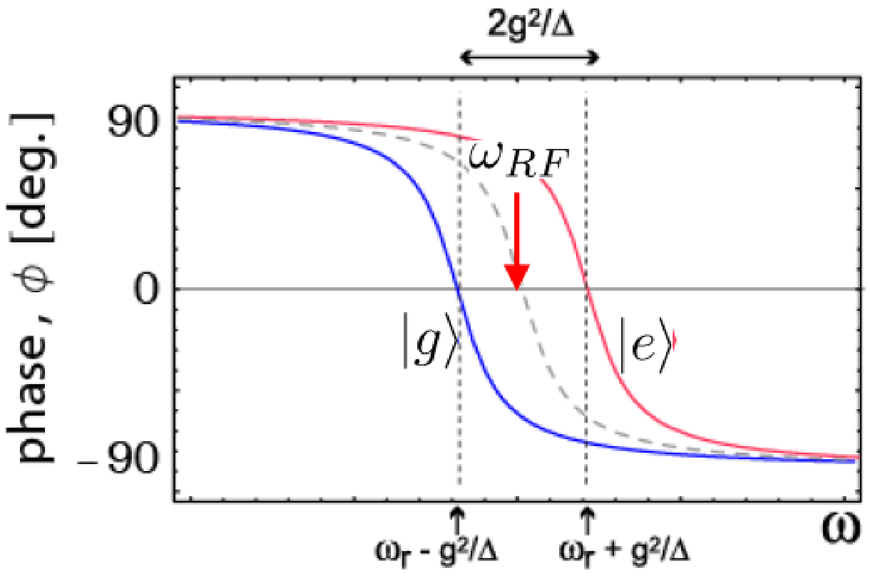


- The transmission spectrum presents a peak of width κ at $\omega_r - g^2/\Delta$ or $\omega_r + g^2/\Delta$, depending on the qubit state

- The phase jumps in the spectrum are shifted, depending on the qubit state

- Two measurement strategies
  1. Choose $\omega_d = \omega_r \pm g^2/\Delta$ and measure transmission amplitude.
  2. Choose $\omega_d = \omega_r$ and measure the phase of the transmitted waves.



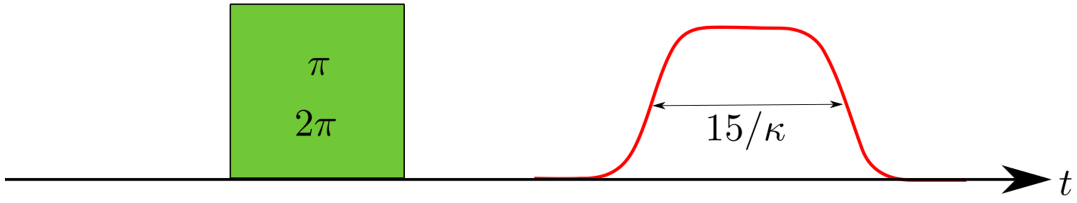


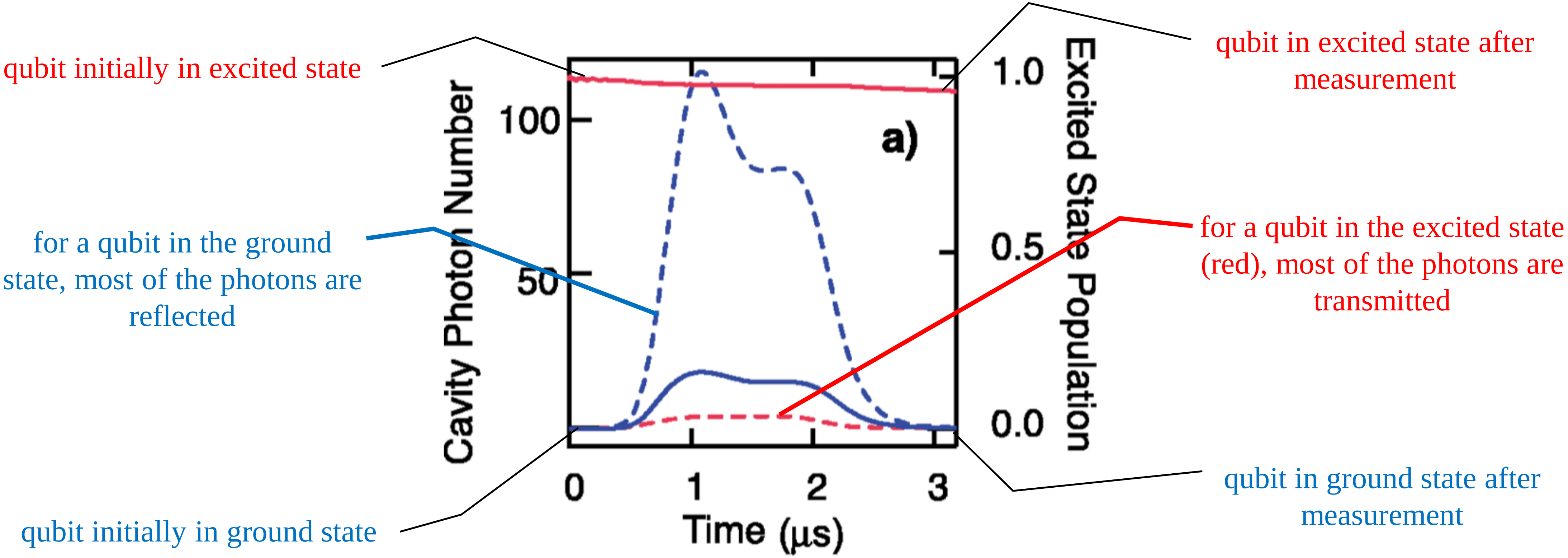
A. Blais et al., PRA 69, 062320 (2004)

Dispersive Readout of Qubits

Measuring Transmission Amplitude (Simulation)

- Qubit prepared in ground or excited state
- Measurement pulse duration ~15/κ
- Drive frequency is $\omega_d = \omega_r + g^2/\Delta$
- Hyperbolic tangent rise and fall



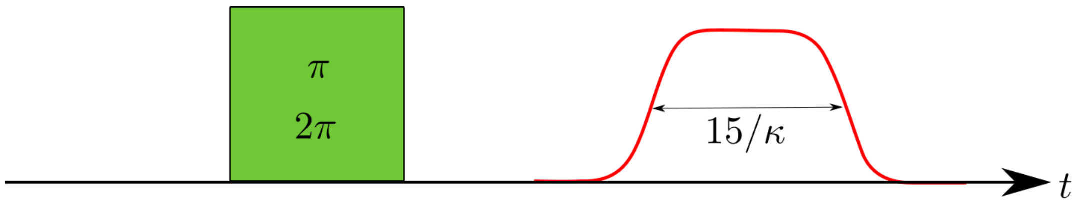


A. Blais et al., PRA 69, 062320 (2004)

Dispersive Readout of Qubits

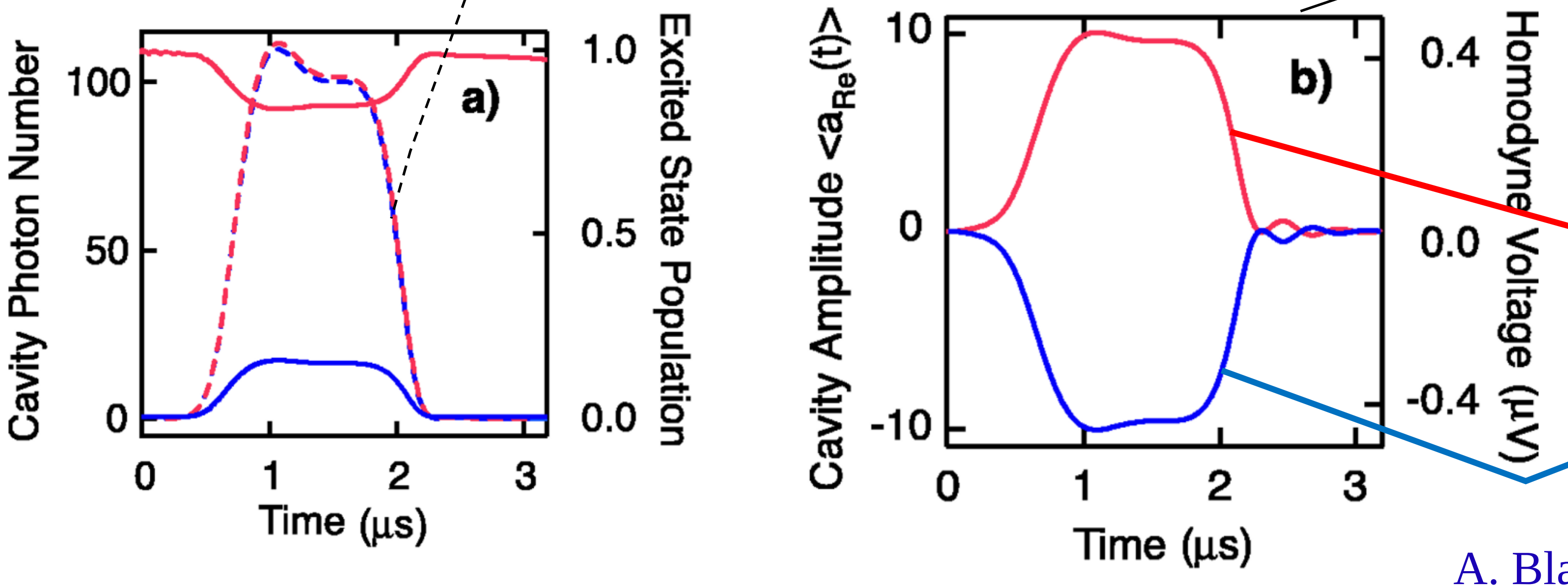
Measuring Phase Shift (Simulation)

- Qubit prepared in ground or excited state
- Measurement pulse duration ~15/κ
- Drive frequency is $\omega_d = \omega_r$
- Hyperbolic tangent rise and fall



no information can be extracted from the transmission amplitude

both axes can be related to the phase of the transmitted wave



qubit in the excited state

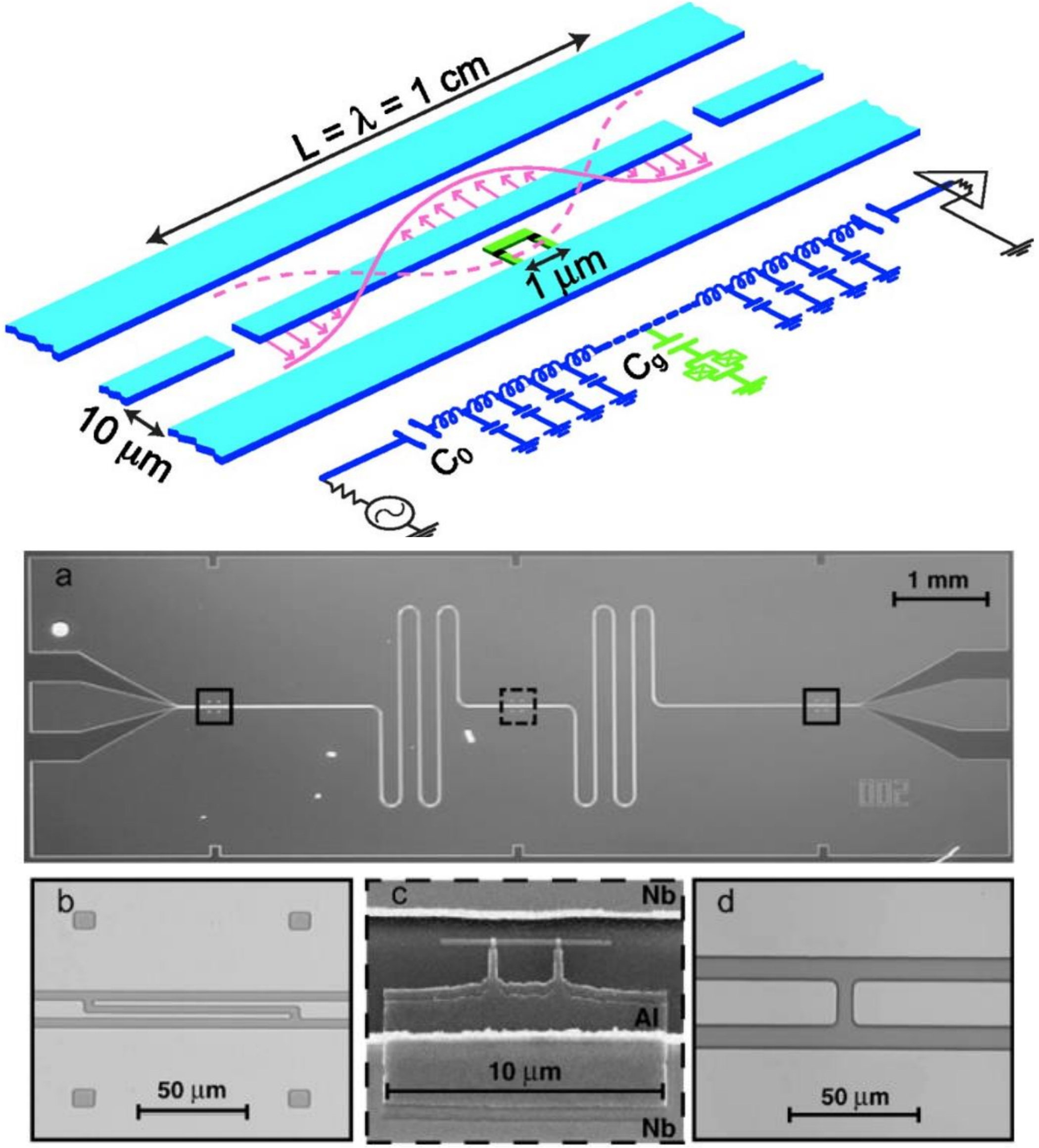
qubit in the ground state

A. Blais et al., PRA 69, 062320 (2004)

Cavity Quantum Electrodynamics for SC Circuits

Design Example

- 1D transmission line resonator: superconducting coplanar waveguide, geometry defines resonance frequency ω_r
- Small effective volume of the resonator allow large coupling strength, as the electric fields are some ~100 times larger than in 3D microwave resonators
- Resonator is coupled via capacitive gaps (Fig. b, d) to input and output. Their design defines κ
- Qubit (here two Cooper-pair boxes) is capacitively coupled to the resonator where the fields reach maxima for strong interaction g
- Qubit is tuned by external flux and controlled by gate voltage. Control detuning Δ and qubit state



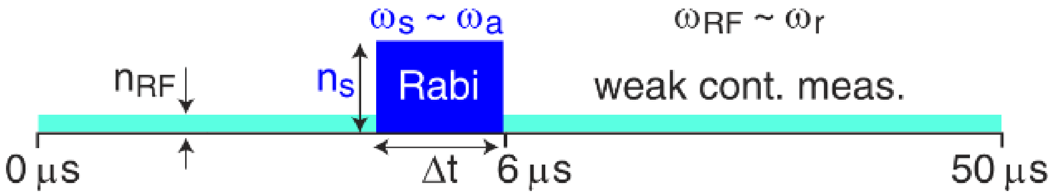
A. Blais et al., PRA 69, 062320 (2004)
L. Frunzio et al., IEEE Vol. 15, No. 2, 1051-8223 (2005)

Dispersive Readout of Qubits

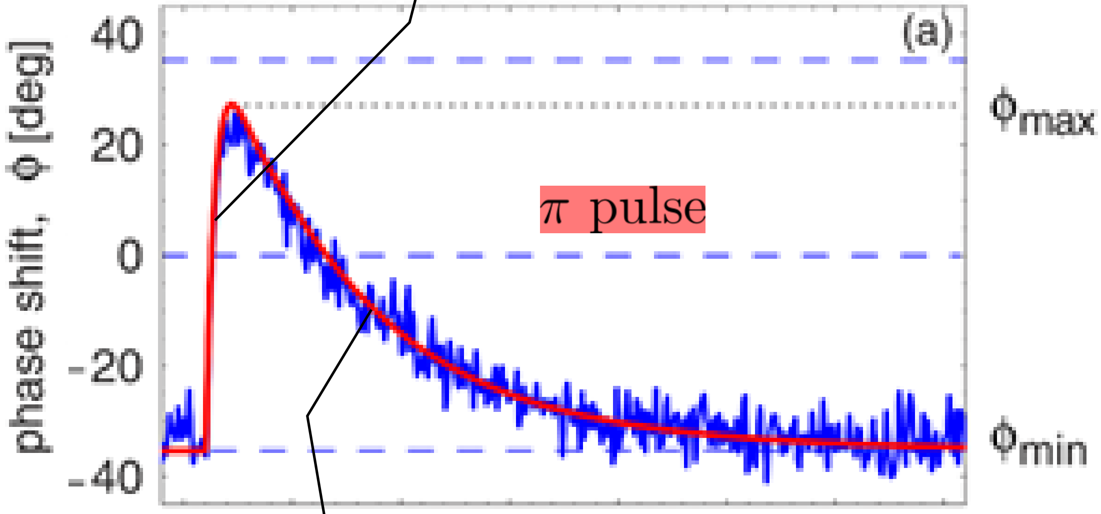
Example: Rabi oscillations

- Weak continuous measurement of the phase of the transmitted wave
- Drive frequency close to resonator frequency

$\omega_d \approx \omega_r$



finite response time of the resonator ~1/κ



finite qubit lifetime T_1

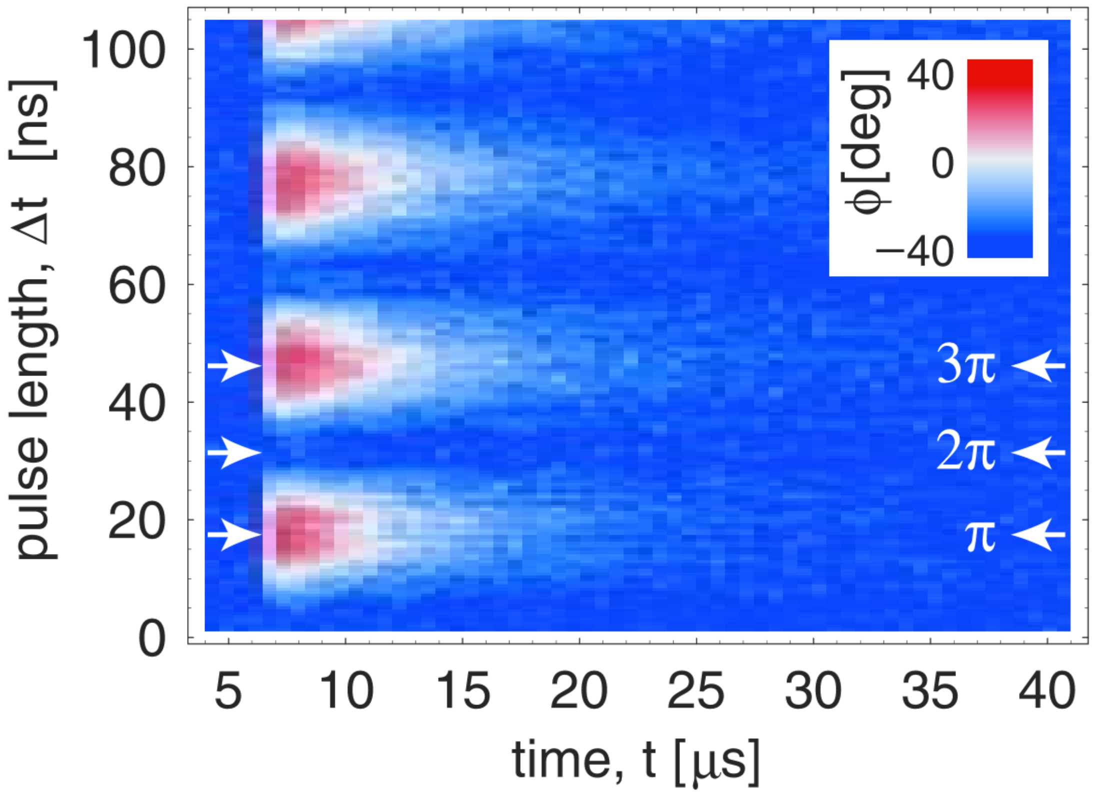
- Signal to Noise Ratio SNR=0.1
- Average over 5×10^4 times
- Projective character of the measurement is lost

A. Wallraff et al., PRL 95, 060501 (2005)

Dispersive Readout of Qubits

Example: Rabi oscillations

- Does the signal really correspond to the qubit state?
- Measurement duration of order T_1: we need to average
- Why don't we just increase the number of photons?
  Approximation of the Hamiltonian is no longer valid. We start driving qubit transitions!
- Ideally: single shot measurement
  - Reduce noise
  - Reduce measurement time
  - Increase qubit lifetime
  - Increase interaction strength



A. Wallraff et al., PRL 95, 060501 (2005)

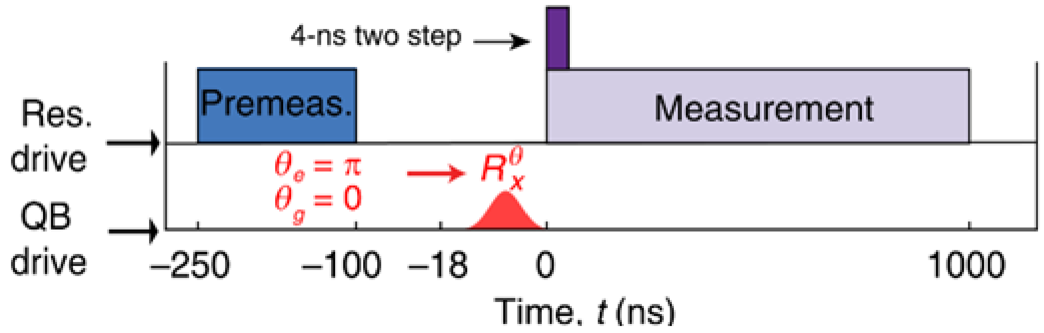
Recent progress

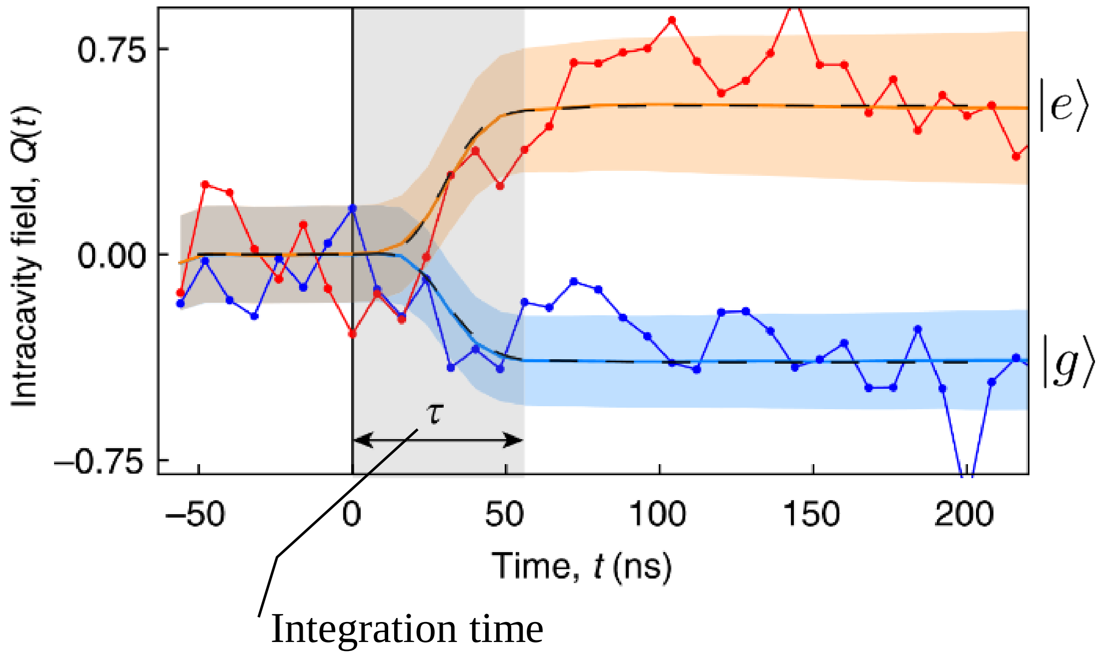
in dispersive qubit readout

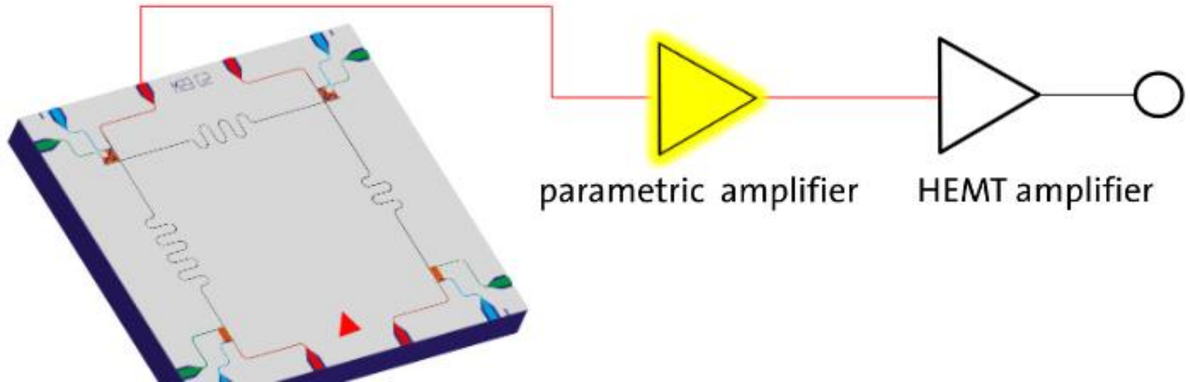
- Additional tools (e.g. parametric amplifier, special readout tones, …) were developed to increase readout fidelity, measuring multiple qubits simultaneously and decrease qubit decay during measurements

- Single-shot dispersive readout: One single measurement allows state determination with high fidelity

- Provides projective measurement







T. Walter et al., Phys. Rev. Applied **7**, 054020 (2017)

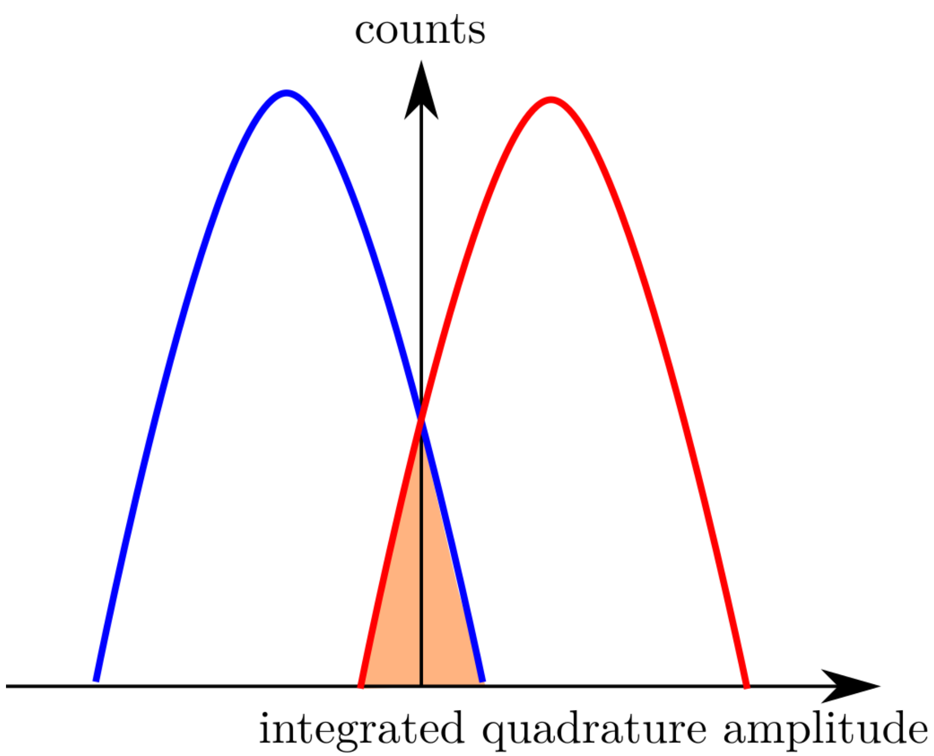
Recent progress

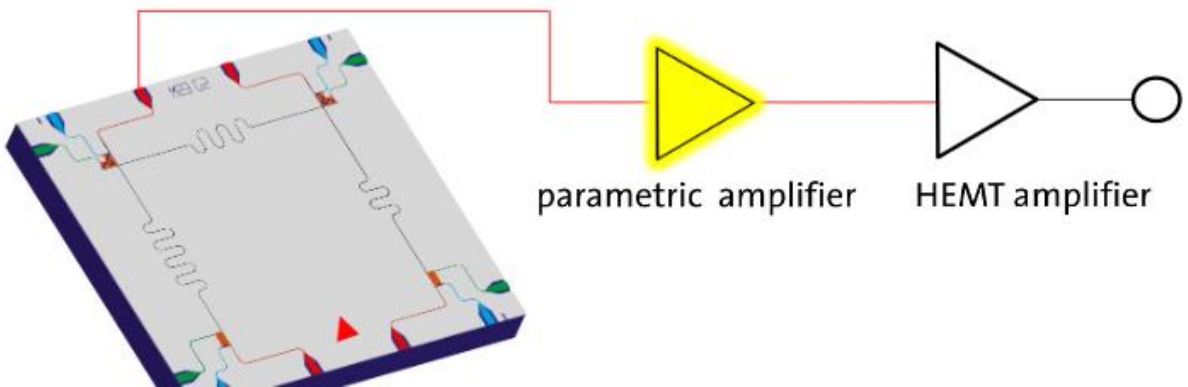
in dispersive qubit readout

- Extract fidelity from statistic

$$F = 1 - P(e|g) - P(g|e)$$

- Choose integration time properly
  - Too short: state trajectories are not clearly separated
  - Too long: spontaneous emission, thermal excitations, readout-induced transitions





T. Walter et al., Phys. Rev. Applied **7**, 054020 (2017)

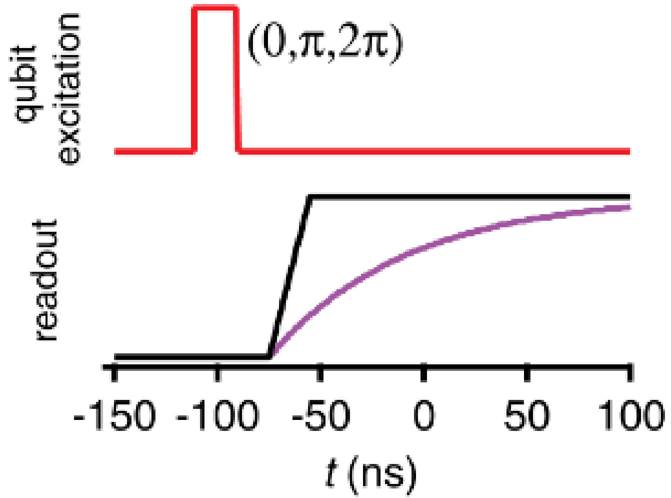
Recent progress

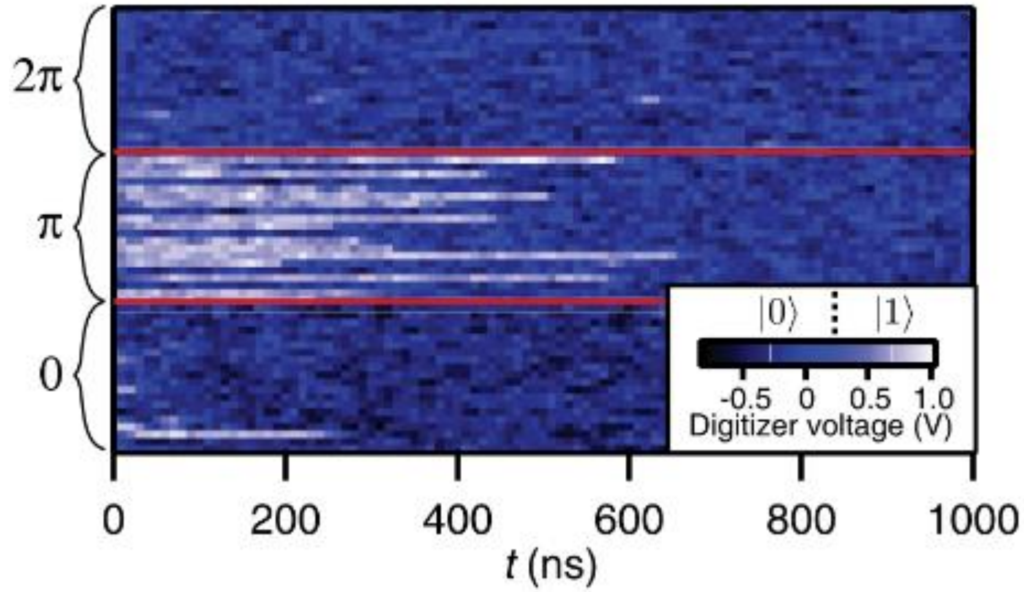
in dispersive qubit readout

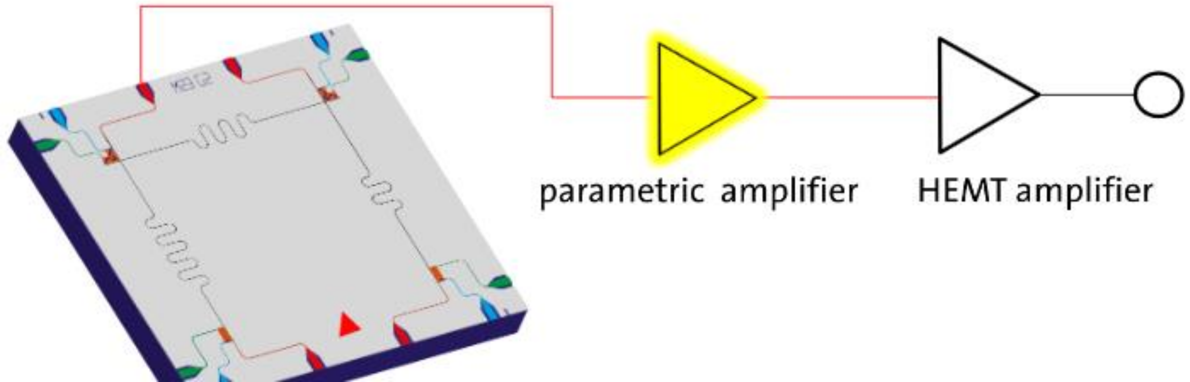
- Time scale of measurement much faster than T_1
- QND measurement scheme, allowing repetitions

- 20 single shot traces
- Realtime observation of quantum jumps

- Continuous error correction







R. Vijay et al., Phys. Rev. Lett. 106, 110502 (2011)

References

[1] A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, J. Majer, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, *Approaching unit visibility for control of a superconducting qubit with dispersive readout*, Phys. Rev. Lett. **95**, 060501 (2005), URL https://link.aps.org/doi/10.1103/PhysRevLett.95.060501.

[2] A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, *Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation*, Phys. Rev. A **69**, 062320 (2004), URL https://link.aps.org/doi/10.1103/PhysRevA.69.062320.

[3] R. Vijay, D. H. Slichter, and I. Siddiqi, *Observation of quantum jumps in a superconducting artificial atom*, Phys. Rev. Lett. **106**, 110502 (2011), URL https://link.aps.org/doi/10.1103/PhysRevLett.106.110502.

[4] T. Walter, P. Kurpiers, S. Gasparinetti, P. Magnard, A. Potočnik, Y. Salathé, M. Pechal, M. Mondal, M. Oppliger, C. Eichler, and A. Wallraff, *Rapid high-fidelity single-shot dispersive readout of superconducting qubits*, Phys. Rev. Applied **7**, 054020 (2017), URL https://link.aps.org/doi/10.1103/PhysRevApplied.7.054020.