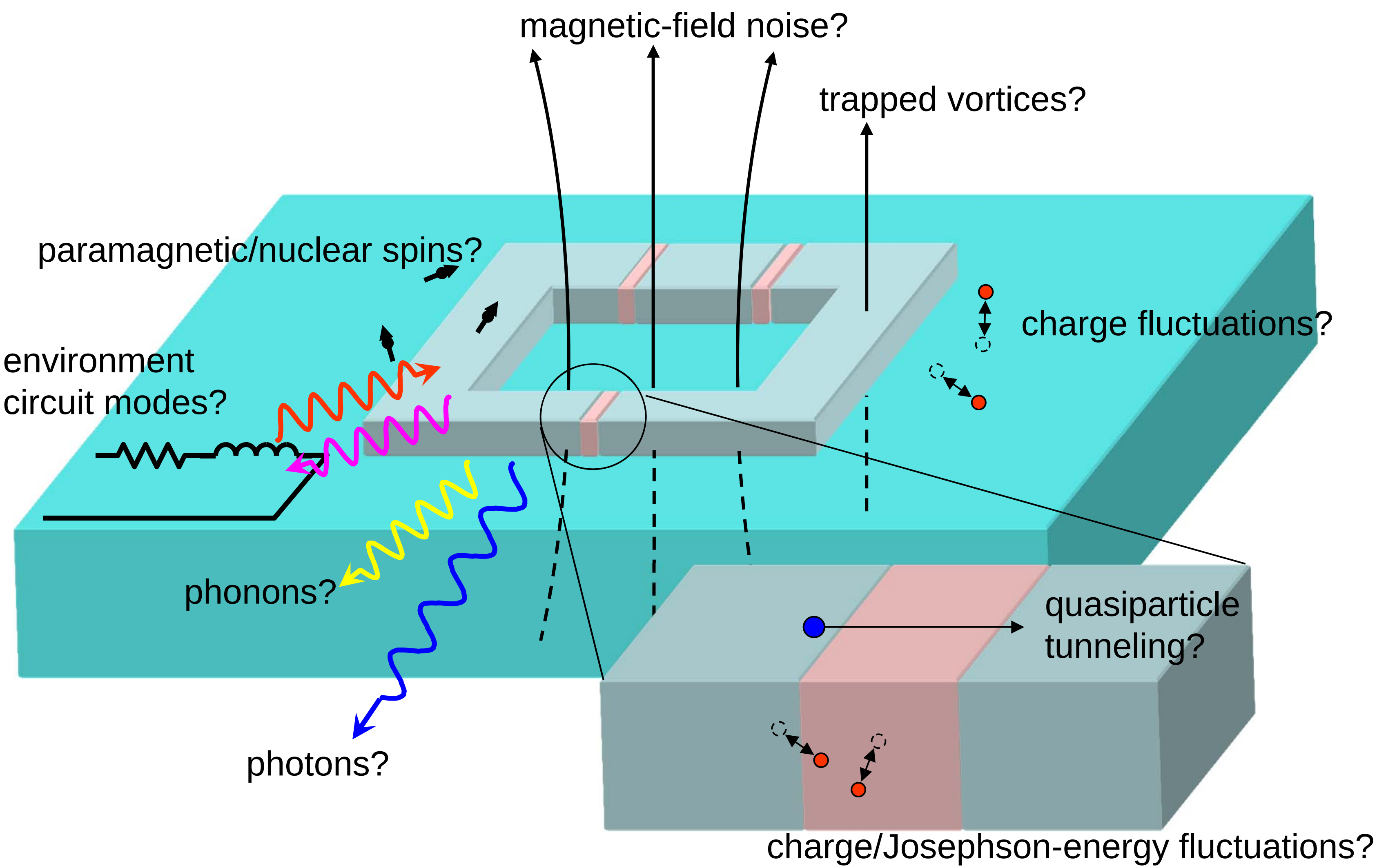
Sources of Decoherence

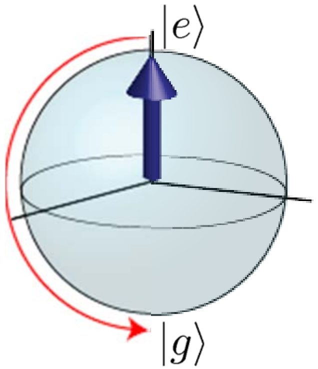


G. Ithier *et al.*, *Phys. Rev. B* **72**, 134519 (2005)

Relaxation and dephasing (T_1 and T_2)

- T_1: energy relaxation time

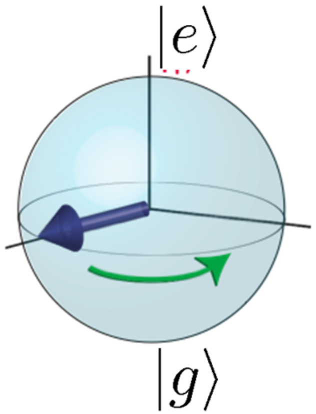
depolarization, decay



perturbation orthogonal to quantization axis ($\propto \sigma_{x,y}$); e.g. fast charge fluctuations causing transitions

- T_2: dephasing time

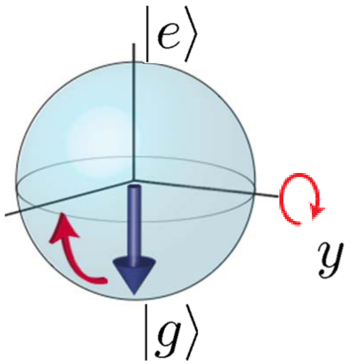
dephasing

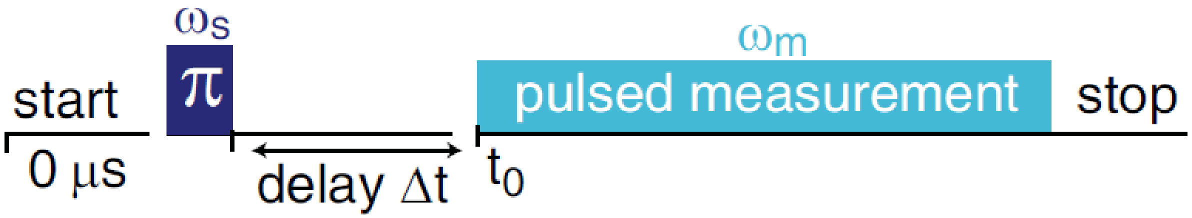


slow perturbation along quantization axis ($\propto \sigma_z$); e.g. magnetic flux noise causing phase randomization

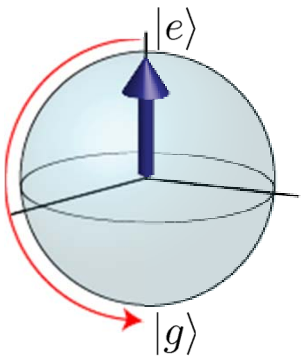
Relaxation Time (T1) Measurement

pulse scheme:



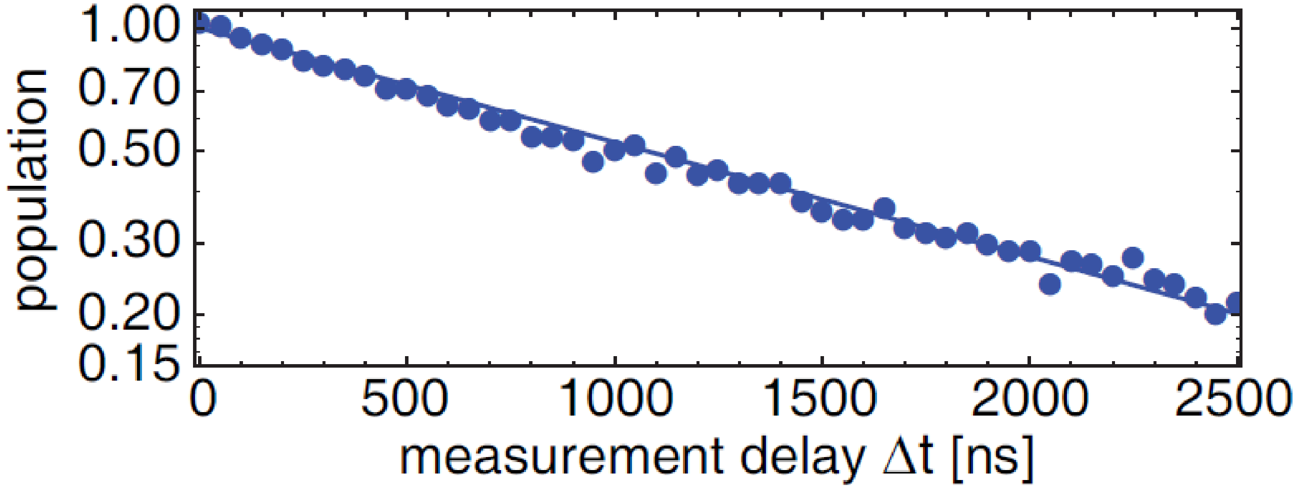


decay



log-plot

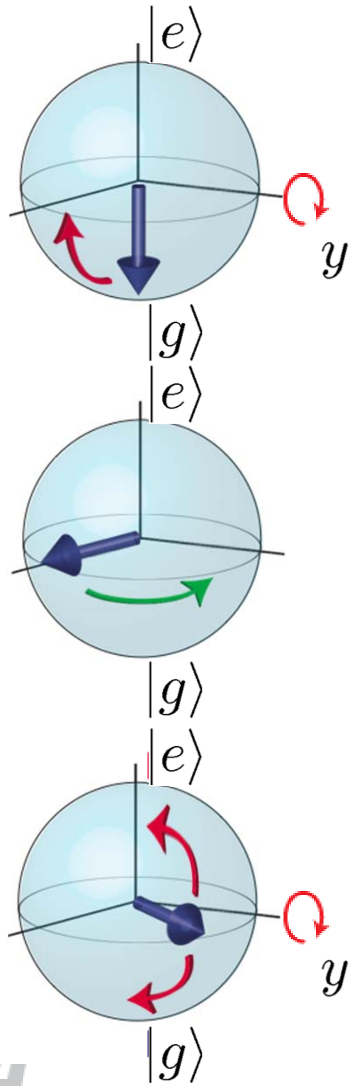
T_1=1.2 us

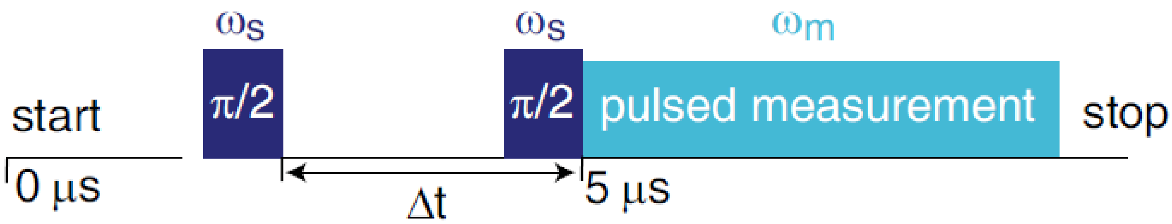


R. Bianchetti, QUDEV, ETH Zurich (2010)

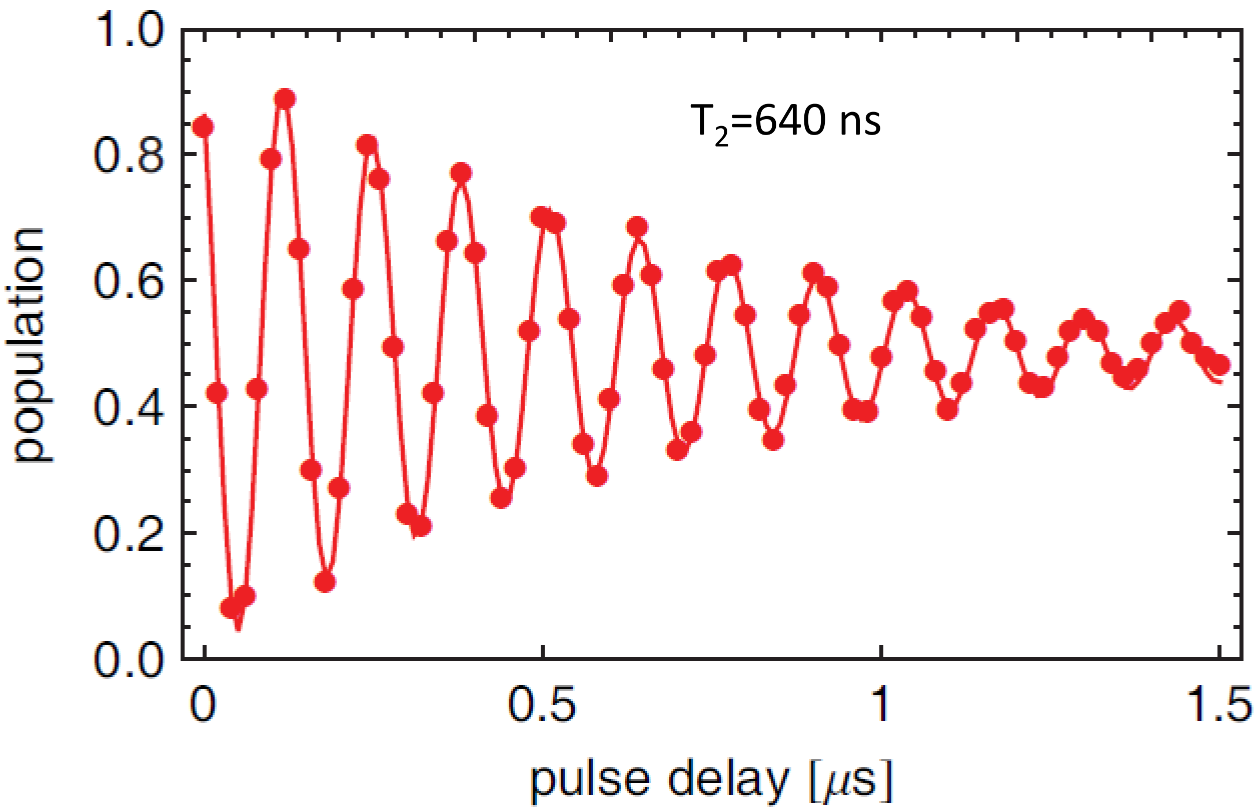
Coherence Time (T2) Measurement: Ramsey Fringes

pulse scheme:





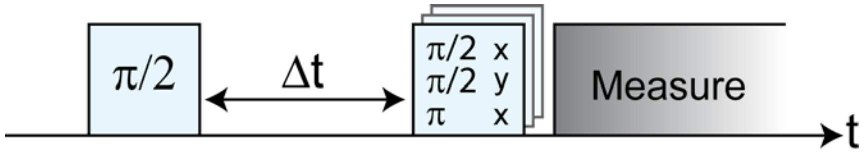
Ramsey fringes:

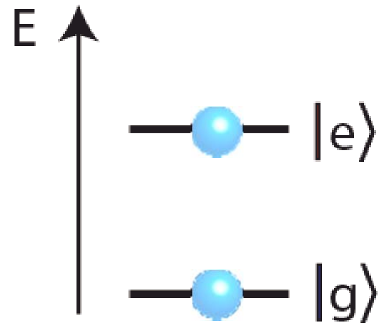


R. Bianchetti, QUDEV, ETH Zurich (2010)

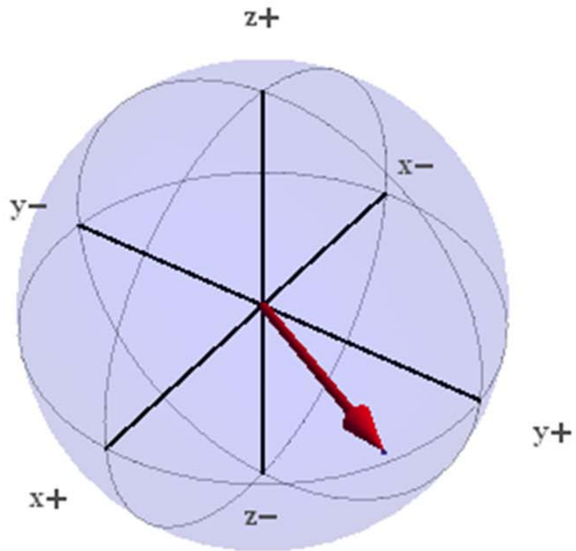
Tomography of Ramsey Experiment

pulse sequence:

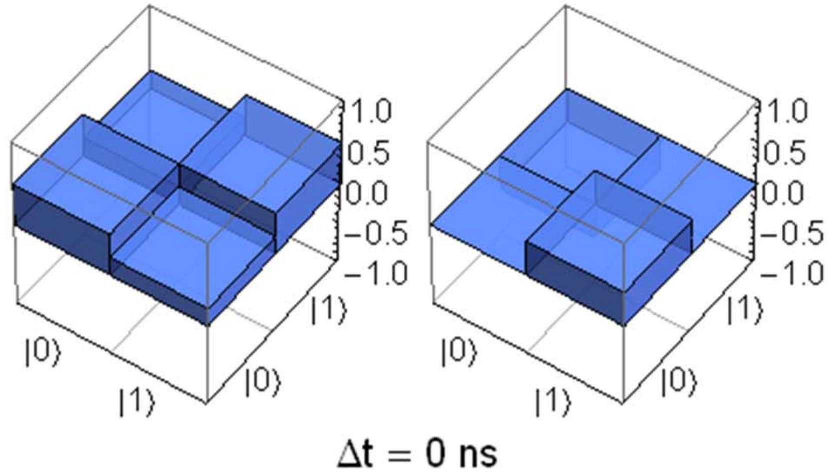




experimental Bloch vector:



experimental density matrix:



L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

Strategies to Reduce Decoherence

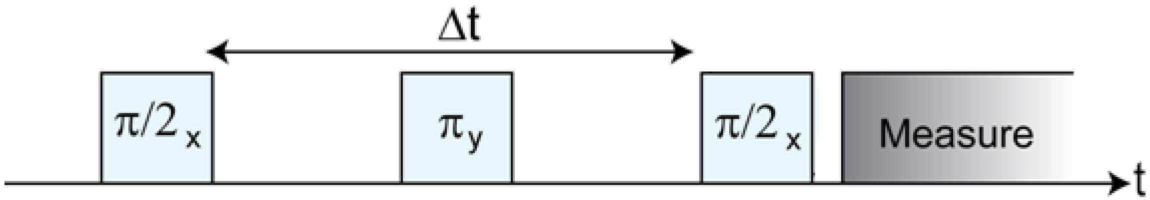
- remove sources of decoherence
  - improve materials

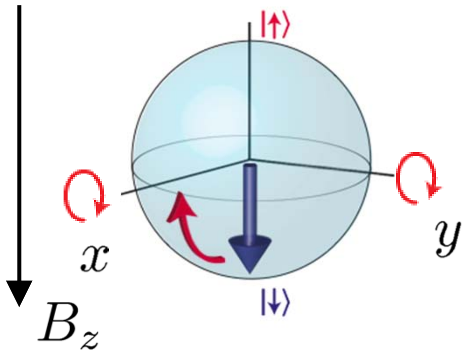
- reduce sensitivity of quantum systems to specific sources of decoherence (e.g. transmon design)
  - make use of symmetries in design and operation

- use dynamic methods to counteract specific sources of decoherence
  - spin echo
  - geometric manipulations

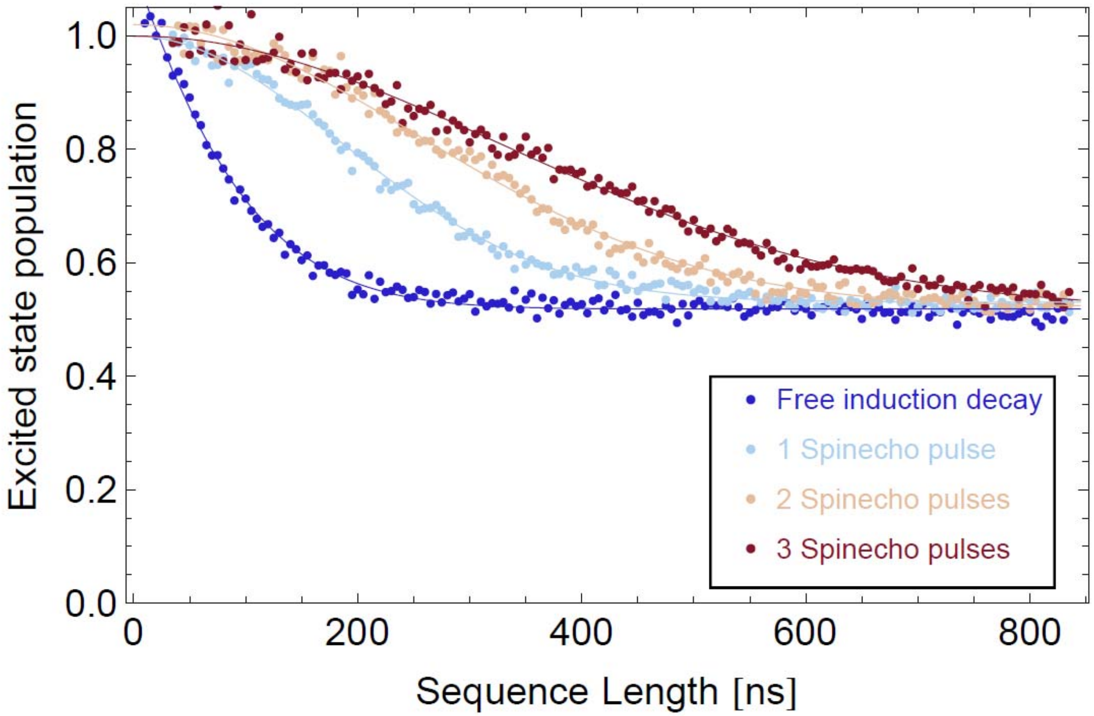
Reduce Decoherence Dynamically: Spin Echo

pulse scheme:





result:



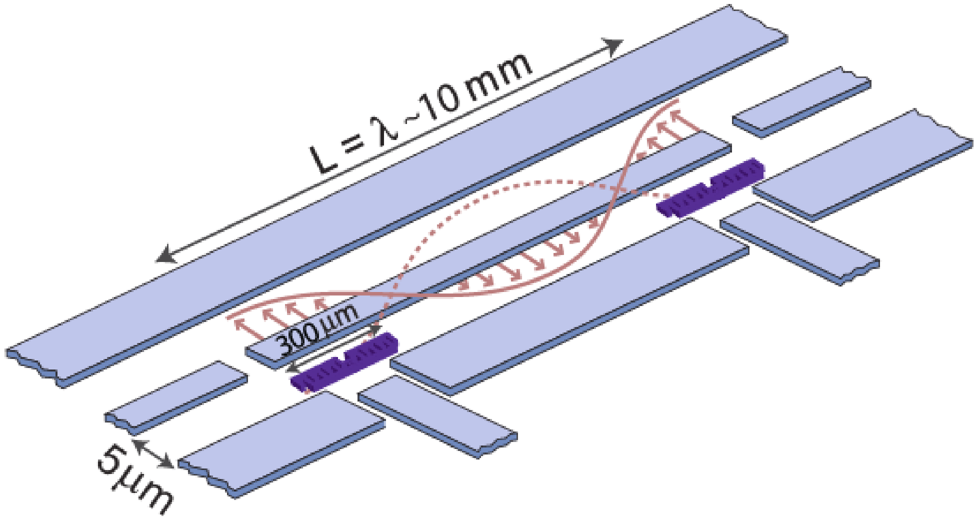
- refocusing
- elimination of low frequency fluctuations
- increased effective coherence time

[Lars Steffen *et al.* (2009)
P. J. Leek, J. Fink *et al.*, *Science* **318**, 1889 (2007)]

Coupling Superconducting Qubits and Generation of Entanglement

Entangling two distant qubits

transmission line resonator can be used as a **'quantum bus'** to create an **entangled** state

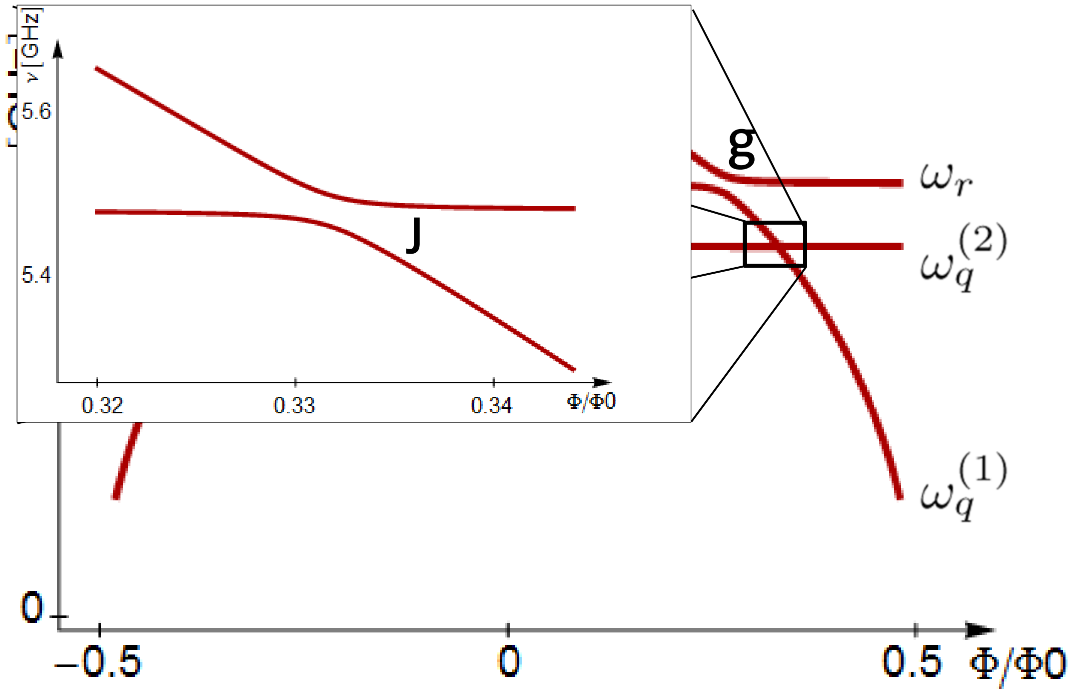


Dispersive two-qubit J-coupling

qubit 1: transition frequency: $\omega_q \approx \sqrt{8E_C E_J} = \sqrt{8E_C E_{J,max}\,|\cos(\pi\Phi/\Phi_0)|}$

qubit 2: constant frequency (5.5 GHz)

resonator:
- direct coupling (g ~ 130 MHz)
- mediated J-coupling (J ~ 20 MHz)



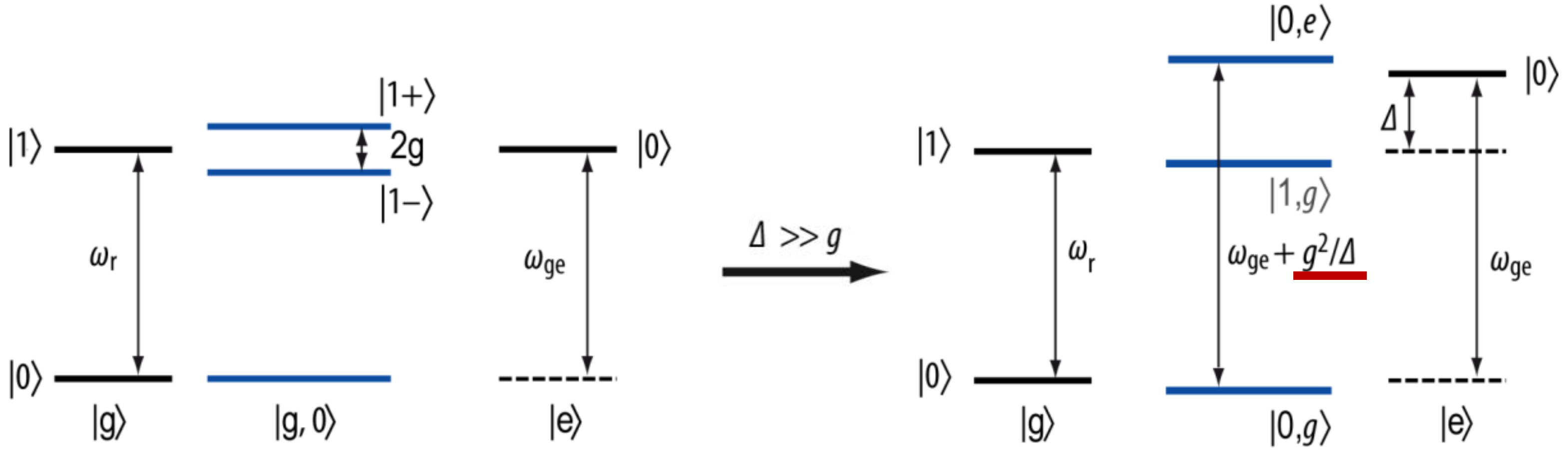
[Majer *et al.*, Nature 449 (2007)]

Dispersive regime – single qubit

resonant:

qubit detuned from resonance:

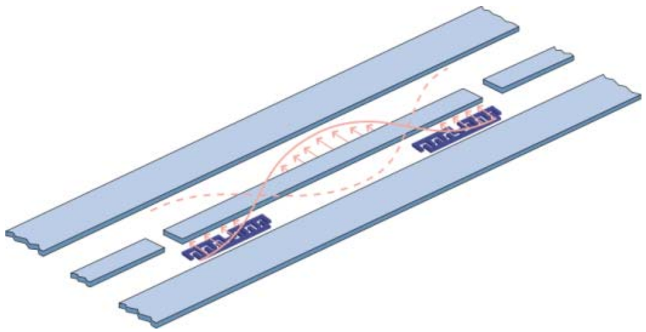
$\Delta = |\omega_{ge} - \omega_r| \gg g$



$$H \approx \hbar\left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right)a^\dagger a + \frac{\hbar}{2}\left(\omega_{ge} + \frac{g^2}{\Delta}\right)\sigma_z$$

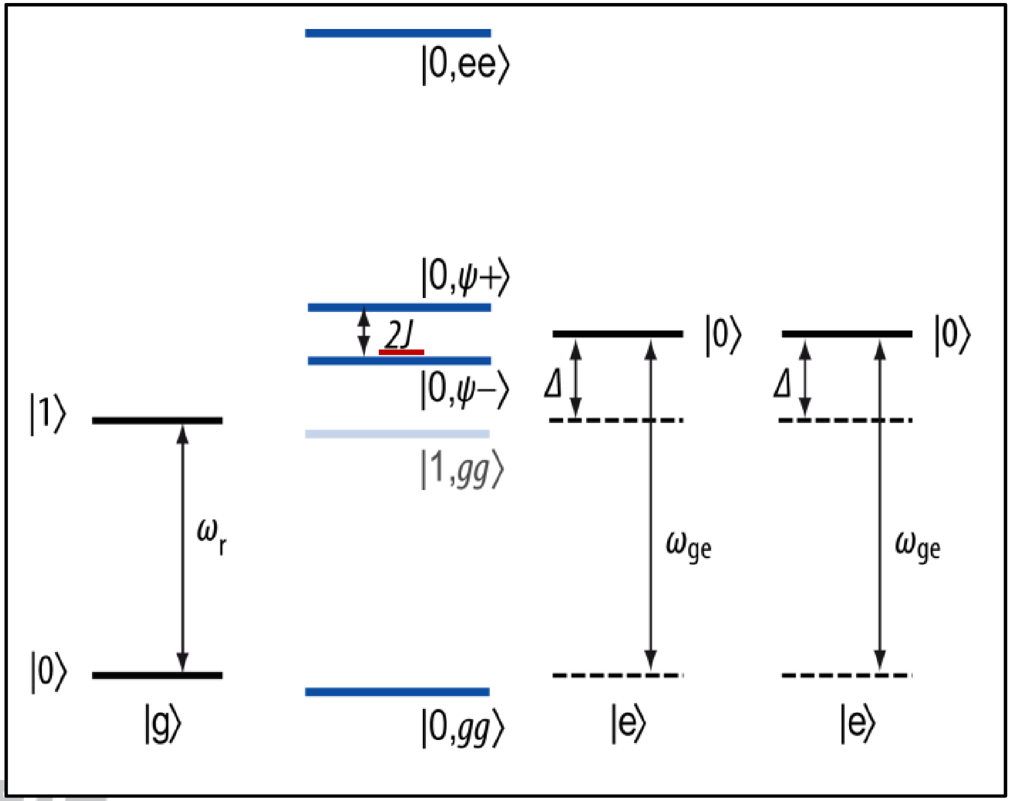
Lamb-Shift (level shift caused by interaction of atom with vacuum field)

Dispersive regime – 2 qubits



$$H = H_0 + J\left(\sigma_{+1}\sigma_{-2} + \sigma_{-2}\sigma_{+1}\right)$$

transverse exchange (J-) coupling
mediated by virtual photons



$$H_0 = \hbar(\omega_r + \sum_{j=1,2} \chi_j \sigma_{zj}) a^\dagger a + \frac{\hbar}{2} \sum_{j=1,2} (\omega_{aj} + \chi_j)\sigma_{zj}$$

coupling strength determined by qubit-cavity coupling g_j and detuning $\Delta = \omega_a - \omega_r$:

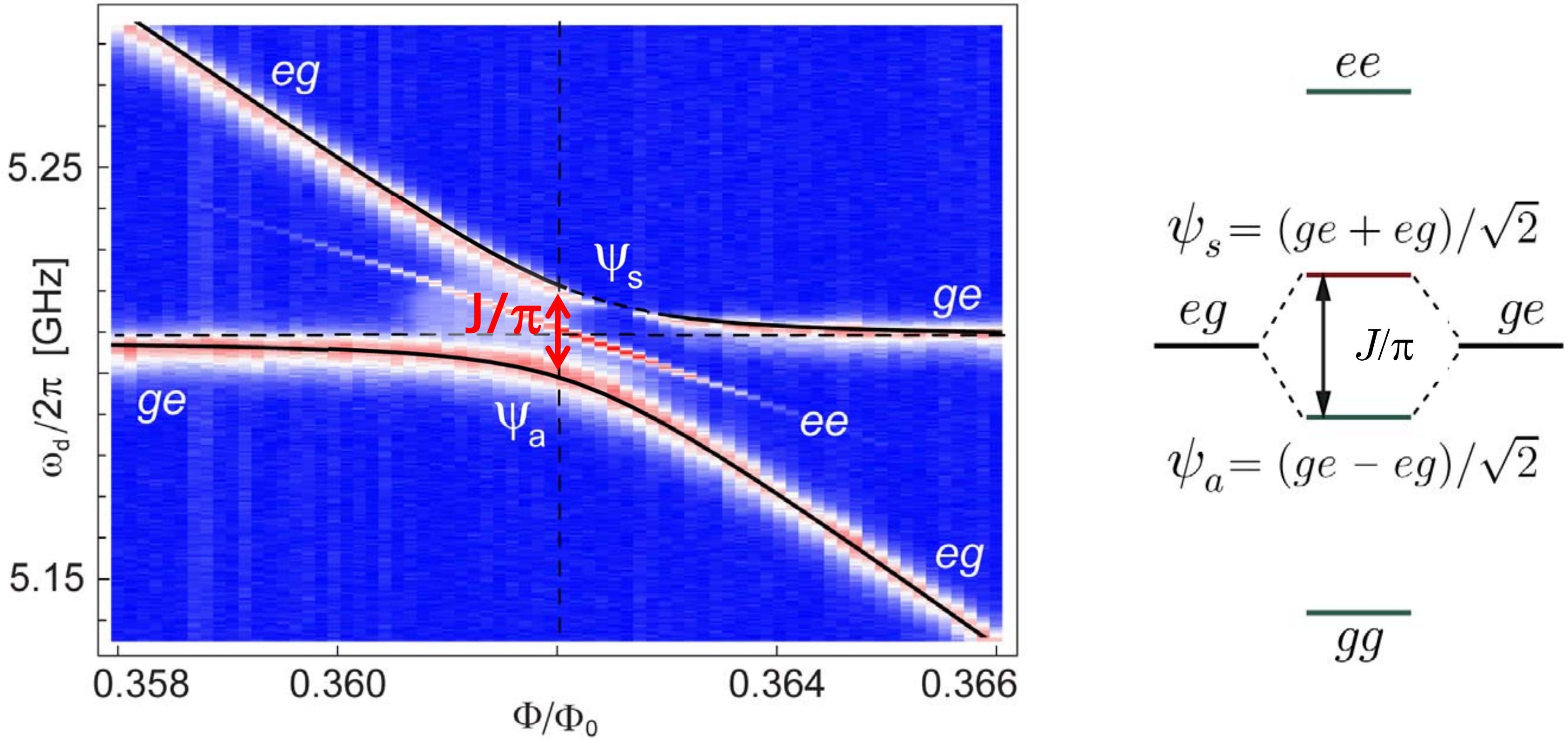
$$J = \frac{g_1 g_2}{\Delta}$$

qubit eigenstates (Bell states):

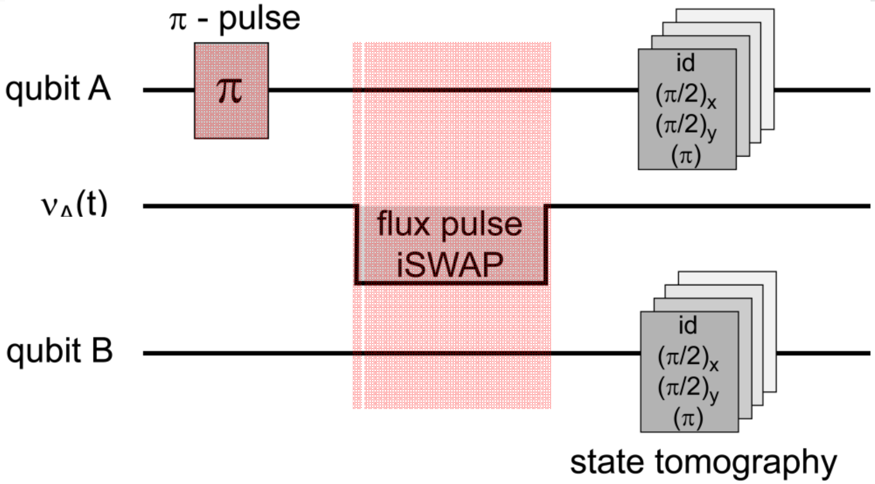
$$|\psi+\rangle = (|eg\rangle + |ge\rangle)/\sqrt{2}$$
$$|\psi-\rangle = (|eg\rangle - |ge\rangle)/\sqrt{2}$$

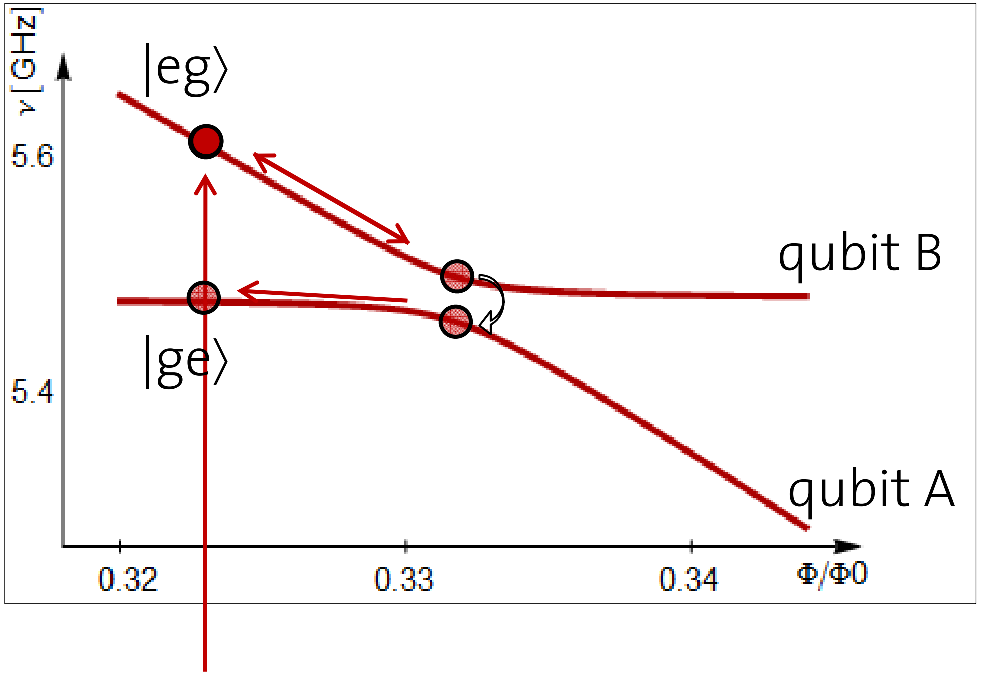
Avoided level crossing

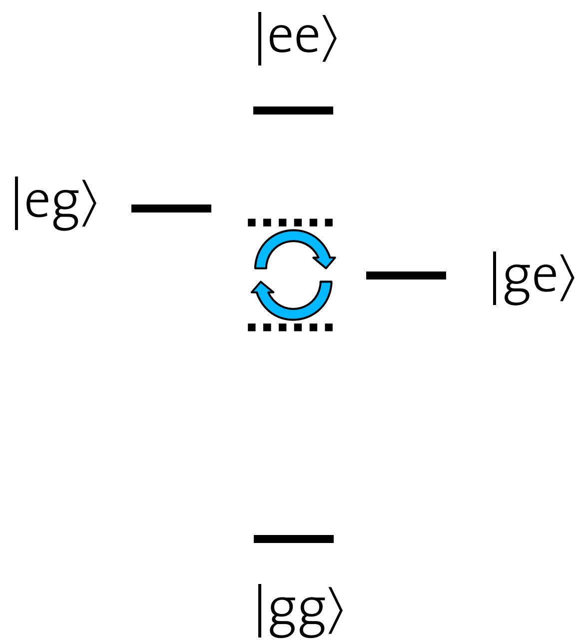
qubit A swept across resonance with fixed qubit B
cavity mediated coupling leads to an avoided crossing



2-qubit gate: iSWAP gate using ge ↔ eg transitions

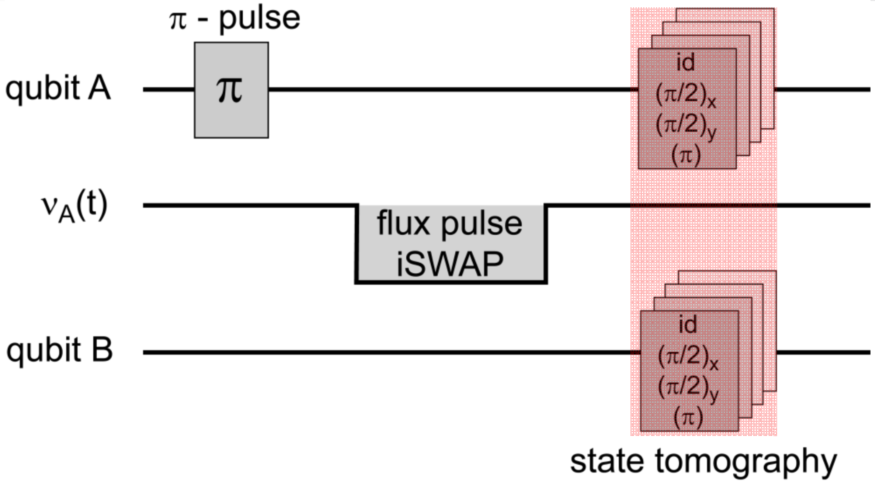






Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

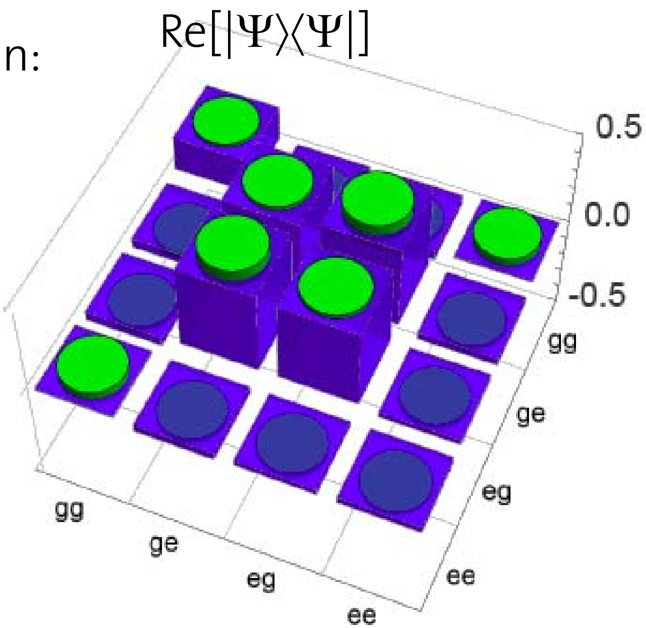
2-qubit gate: iSWAP gate using ge $\leftrightarrow$ eg transitions

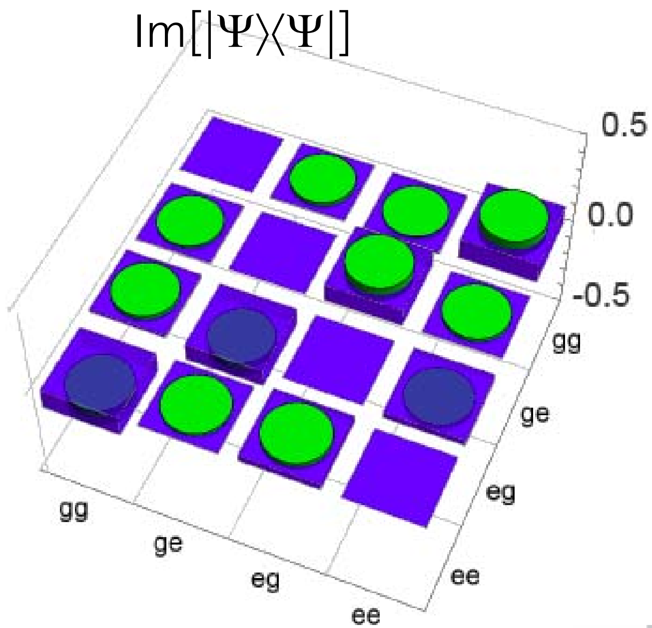


$$|gg\rangle \xrightarrow{\pi_A} |eg\rangle$$
$$\xrightarrow{iSWAP} \frac{1}{\sqrt{2}}\left(|eg\rangle - i|ge\rangle\right)$$

+ local phase transformation:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|eg\rangle + |ge\rangle\right)$$

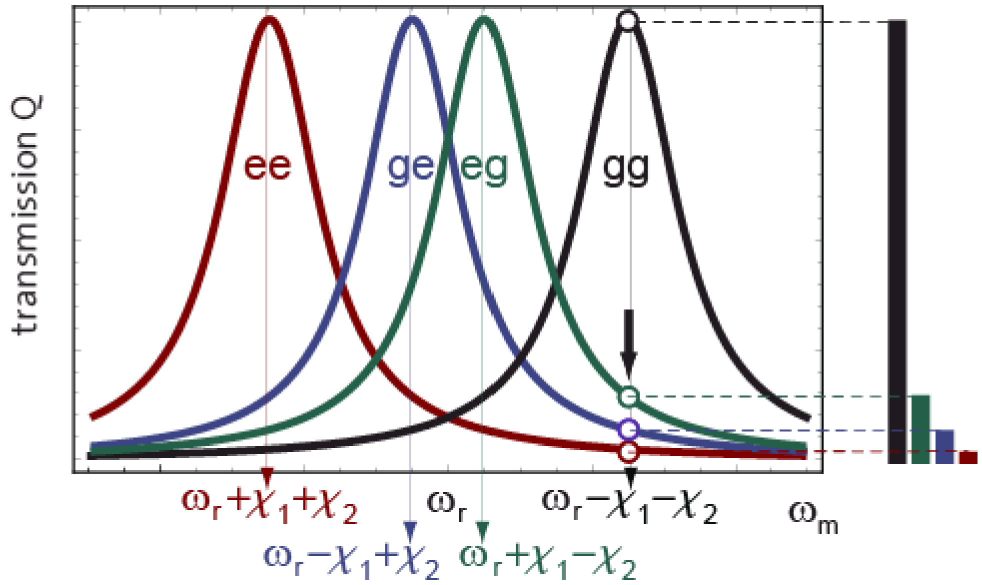




Dispersive read-out of two qubits

dispersive two-qubit/resonator Hamiltonian describes qubit-state dependent shift of resonance frequency ($\delta\omega_r = \pm\ \chi_1 \pm\ \chi_2$)

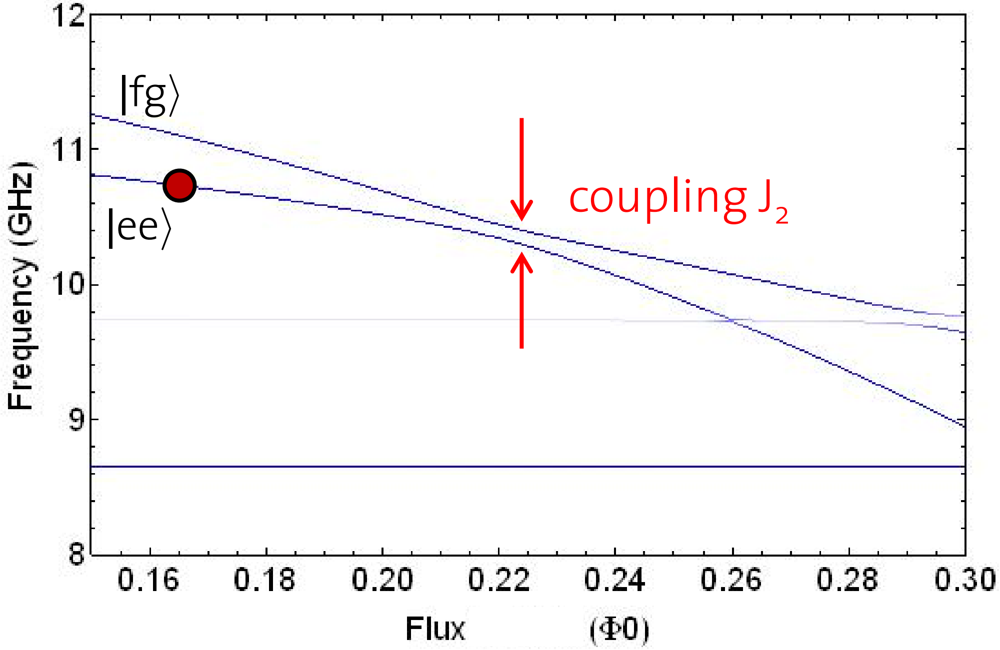
$$H_0 = \hbar(\omega_r + \underbrace{\chi_1\sigma_{z1} + \chi_2\sigma_{z2}}_{\delta\omega_r})a^\dagger a + \frac{\hbar}{2}\sum_{j=1,2}(\omega_{aj} + \chi_j)\sigma_{zj} \qquad \chi = \frac{g^2}{\Delta}$$



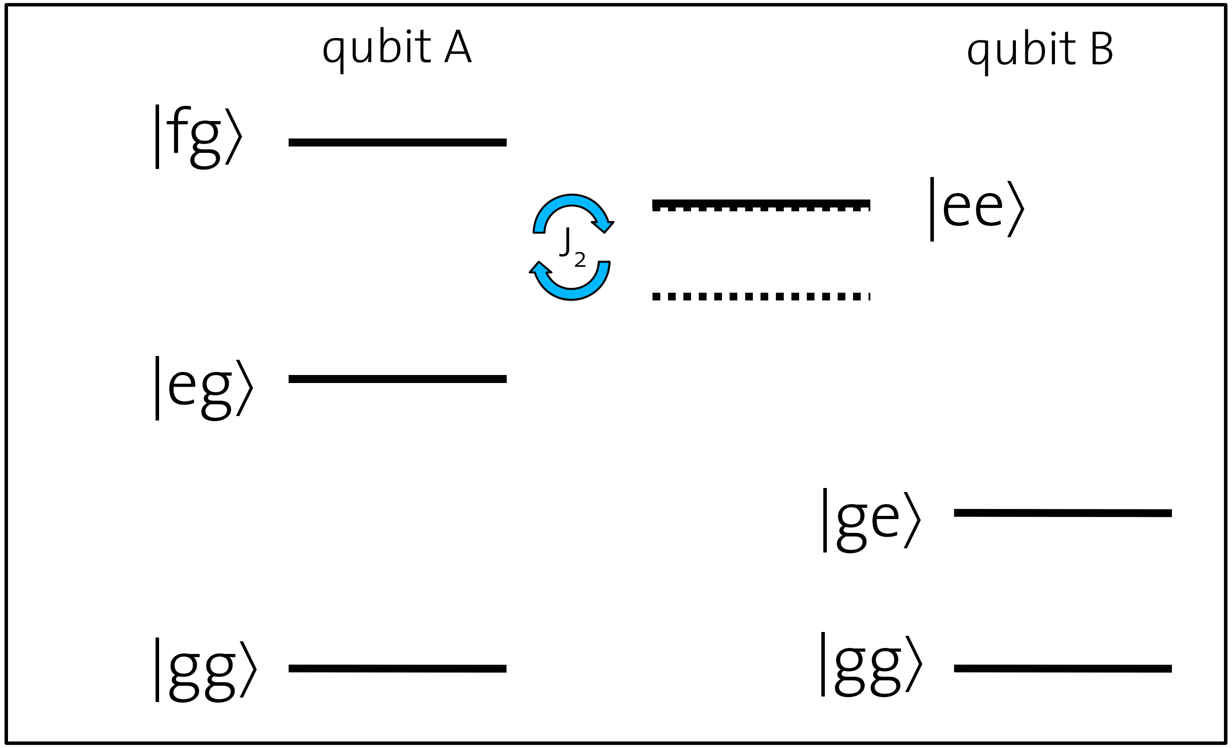
transmission amplitude reflects two-qubit state

2-qubit gate: C-Phase gate using ee $\leftrightarrow$ fg transitions

- ee-level interacts with fg-level
- coupling strength J_2~ 40-80 MHz (g ~ 300 MHz)
- fast, non-adiabatic tuning of qubits into resonance
- 2π - rotation after $t=\pi/J_2$
- $|ee\rangle$ -state picks up phase $e^{i2\pi/2} = -1$



2-qubit gate: C-Phase gate using ee <-> fg transitions



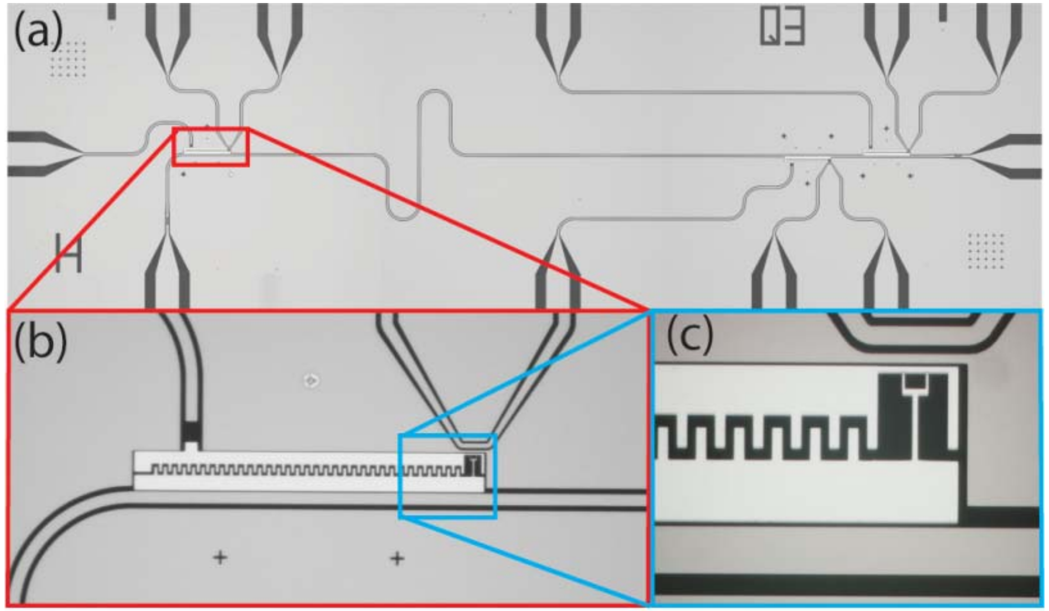
gate operation:

$$|ee\rangle \longrightarrow -|ee\rangle$$
$$|ge\rangle \longrightarrow |ge\rangle$$
$$|eg\rangle \longrightarrow |eg\rangle$$
$$|gg\rangle \longrightarrow |gg\rangle$$

C-Phase = universal 2-qubit gate

$$U_{CPhase} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

ETH Quantum processor platform with 3-Qubits



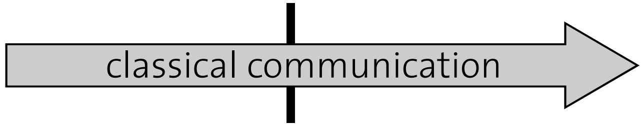
- Full individual coherent qubit control via local charge and flux lines
- Large coupling strength to resonator g ~ 300 - 350 MHz
- Transmon coherences times: T_1 ~ 0.8 - 1.2 μs, T_2 ~ 0.4 – 0.7μs.

[Baur, Fedorov, Steffen, SF, da Silva, Wallraff. arXiv:1107.4774]

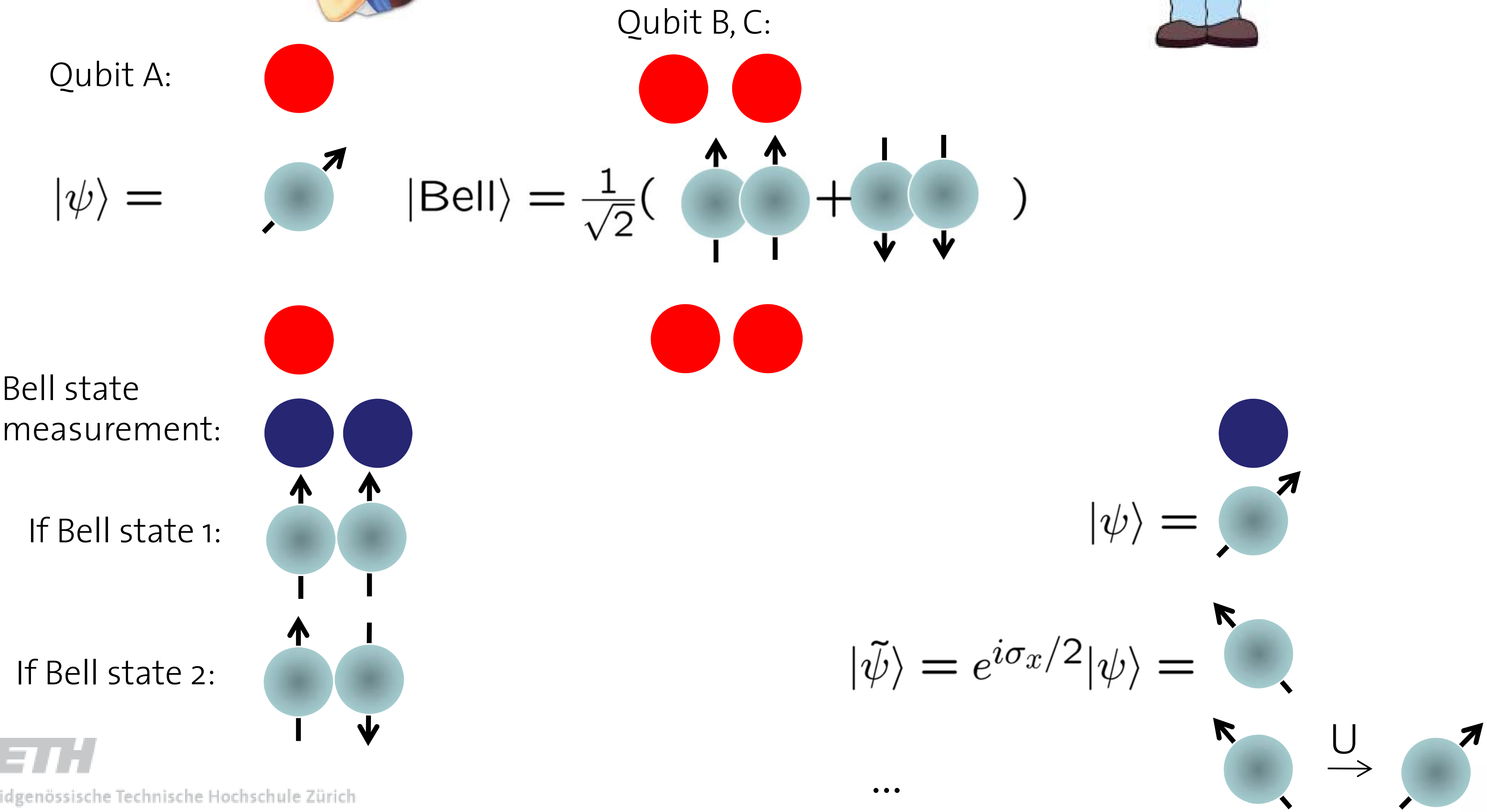
Quantum Teleportation

Alice

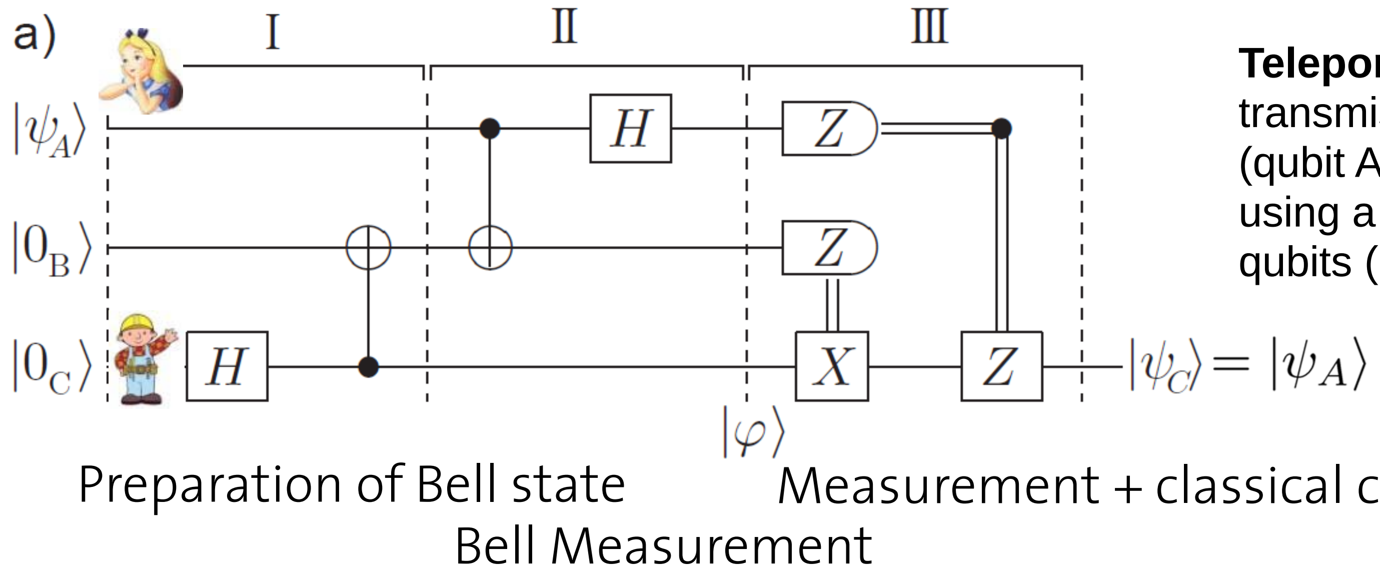
No local interaction!



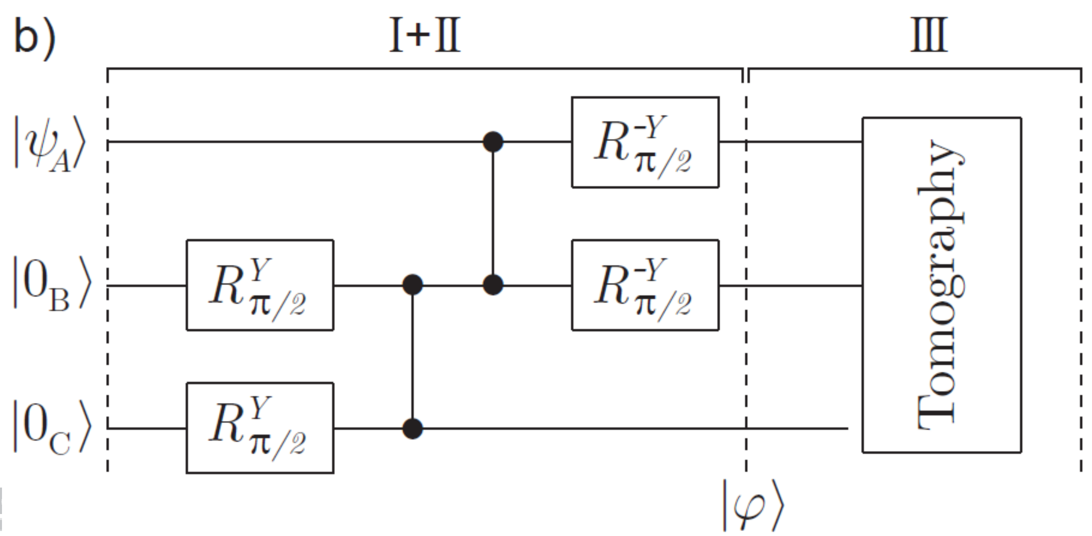
Bob



Teleportation Circuit



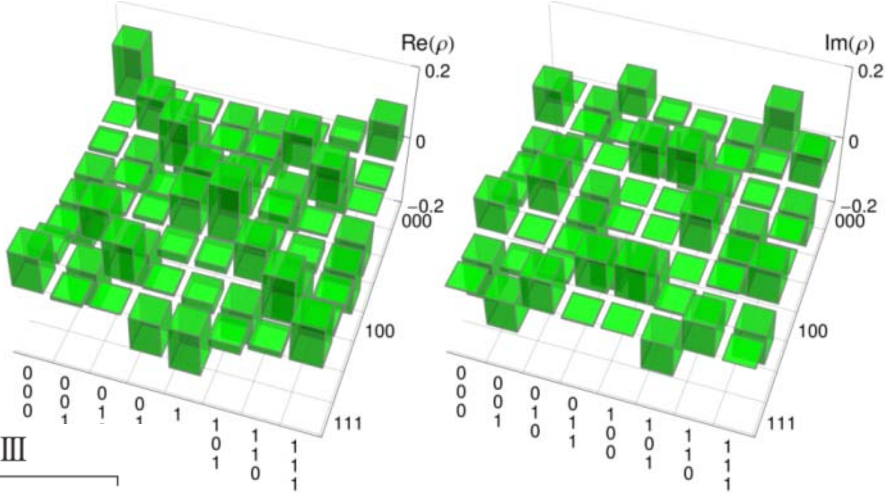
Teleportation:
transmission of quantum bit (qubit A) from Alice to Bob using a pair of entangled qubits (qubits B+C)



implemented three qubit tomography at step III

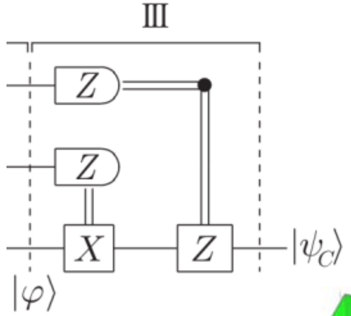
State tomography of the entangled 3-qubit state

Example: State to be teleported on qubit A is $|\Psi\rangle = \frac{1}{\sqrt{2}}(|g\rangle + i|e\rangle)$

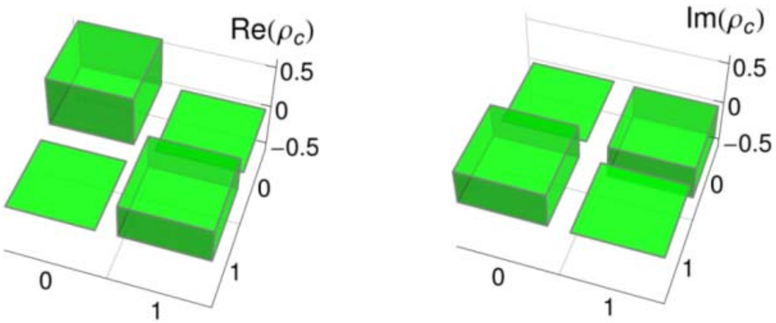


$$\begin{aligned}|\varphi\rangle = \{ & |g_A g_B\rangle \otimes |\Psi\rangle_C \\ & + |g_A e_B\rangle \otimes \sigma_x |\Psi\rangle_C \\ & + |e_A g_B\rangle \otimes \sigma_z |\Psi\rangle_C \\ & + |e_A e_B\rangle \otimes (-\sigma_z \sigma_x) |\Psi\rangle_C \}\end{aligned}$$

$$\rho = |\varphi\rangle\langle\varphi|$$



Simulating measurement of qubit A and B with projection on $|g_A g_B\rangle$:



$$\begin{aligned}\rho_C &= \langle g_A g_B | \rho | g_A g_B \rangle \\ &= |\Psi\rangle\langle\Psi|\end{aligned}$$

fidelity 88%

[Baur, Fedorov, Steffen, Filipp, da Silva, Wallraff. arXiv:1107.4774]

DiVincenzo Criteria fulfilled for Superconducting Qubits

for Implementing a Quantum Computer in the standard (circuit approach) to quantum information processing (QIP):

#1. A scalable physical system with well-characterized qubits. ✓
#2. The ability to initialize the state of the qubits. ✓
#3. Long (relative) decoherence times, much longer than the gate-operation time. ✓
#4. A universal set of quantum gates. ✓
#5. A qubit-specific measurement capability. ✓

plus two criteria requiring the possibility to transmit information:

#6. The ability to interconvert stationary and mobile (or flying) qubits. ✓
#7. The ability to faithfully transmit flying qubits between specified locations. ✓