

# Coupling qubits with a cavity bus

Tim Albers & Bart Giethoorn

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# Overview

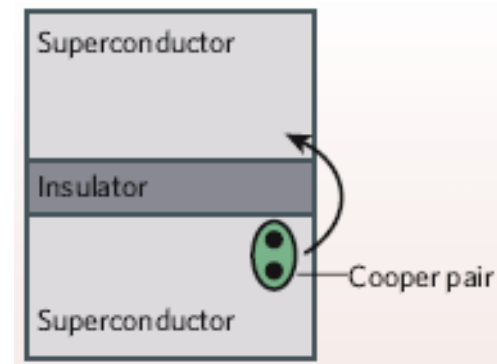
- Introduction
- Theory
- Phase qubit bus (Sillanpaa et al.)
- Charge qubit bus (Majer et al.)
- Summary

# Introduction

- Current achievements
  - Qubits realized (phase, charge, flux)
  - Coupling qubit to photon
- Motivation
  - Coupled qubits necessary for quantum computing
  - Local coupling limits size

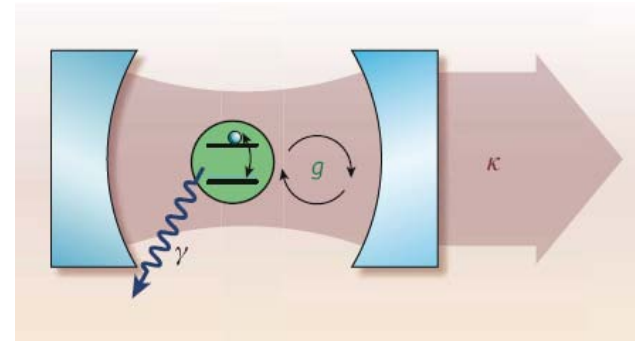
# Theory – Superconducting qubits

- $[\delta, Q] = i2e$
- $E_j \leftrightarrow E_c$
- Three types



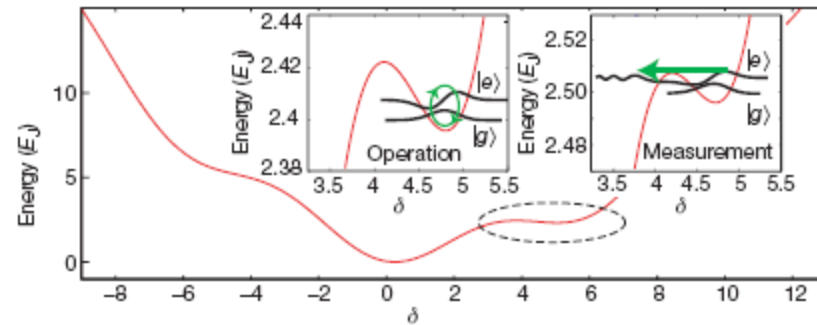
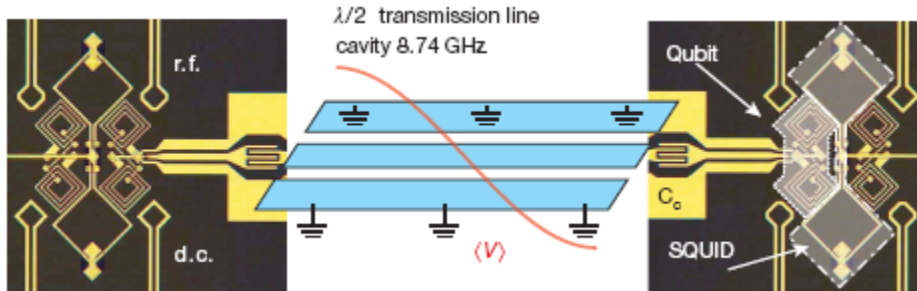
# Theory – Coupling qubit-photon

- $g = d E_0 / \hbar$
- On resonance: Vacuum Rabi splitting



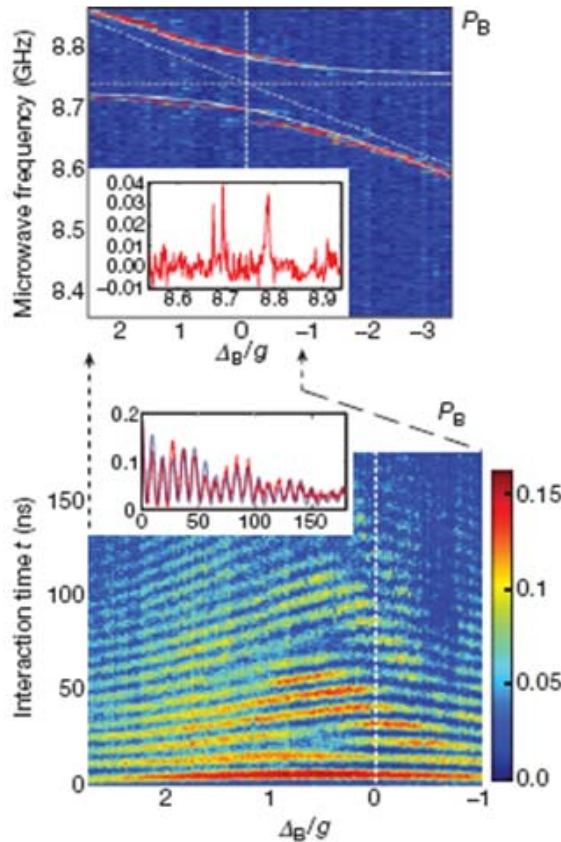
(Schoelkopf & Girvin, 2008)

# Phase qubit - Setup



(Sillanpaa et al. 2007)

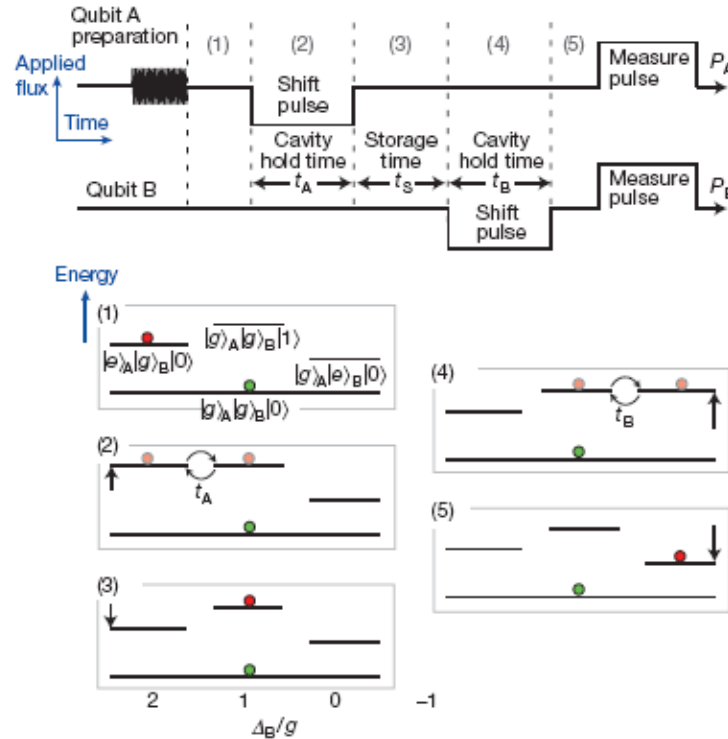
# Phase qubit - Verification strong coupling



- Single qubit-cavity interaction
- $g_{a,b} > \gamma_{a,b} > \kappa$
- Rabi oscillations
- Vacuum Rabi splitting

(Sillanpaa et al. 2007)

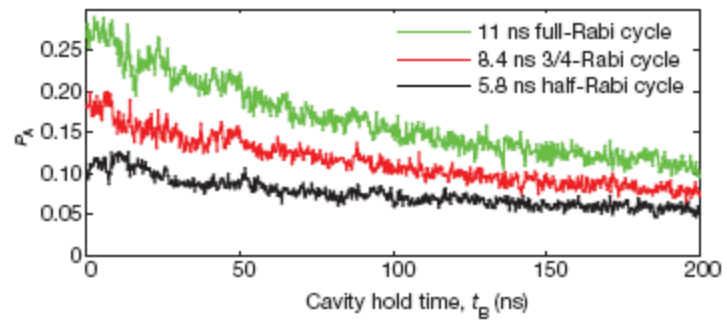
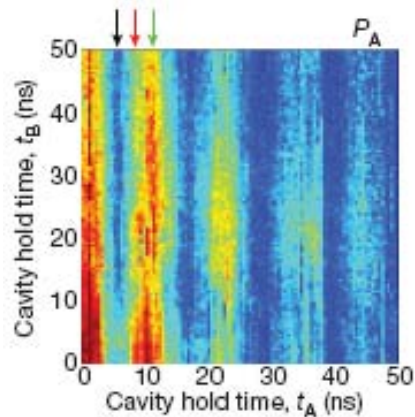
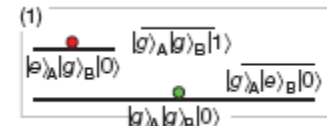
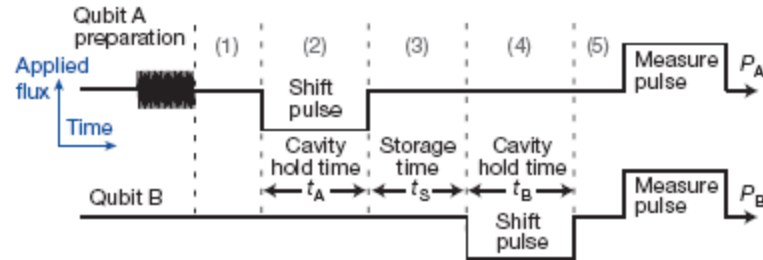
# Phase qubit - Experiment



(Sillanpaa et al. 2007)

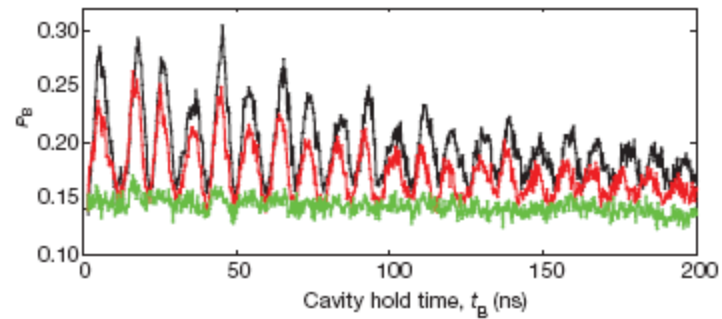
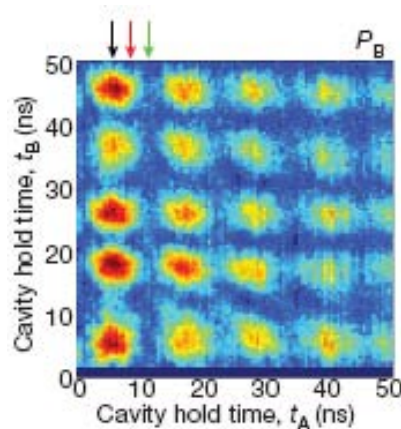
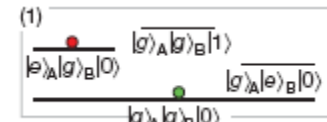
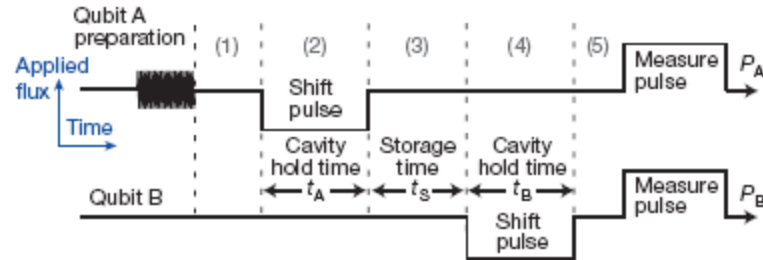


# Phase qubit - Results



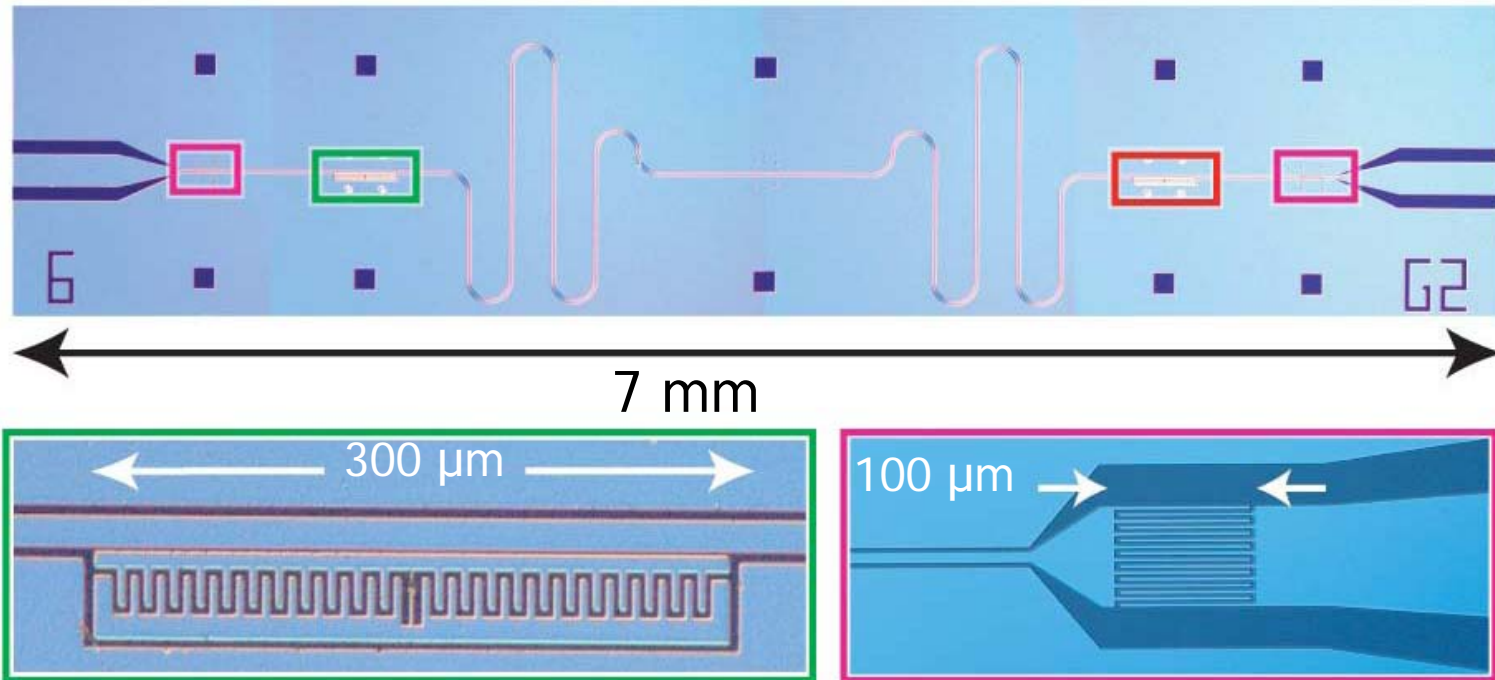
(Sillanpaa et al. 2007)

# Phase qubit – Results (2)



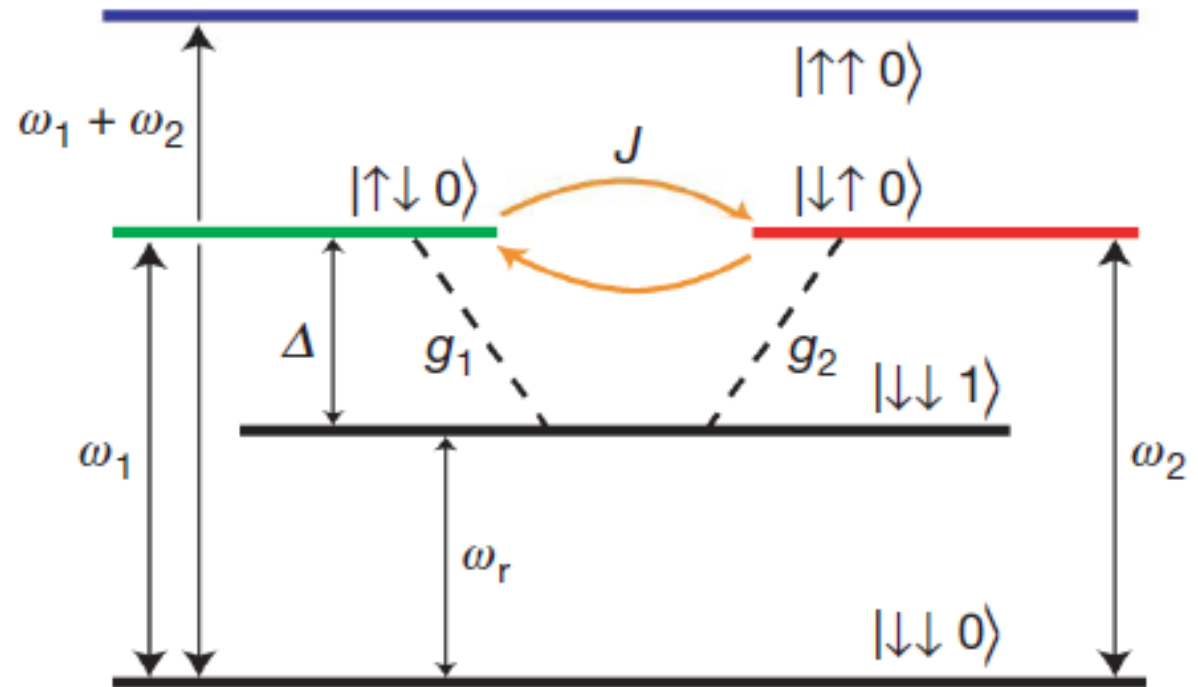
(Sillanpaa et al. 2007)

# Charge-phase qubit - Sample



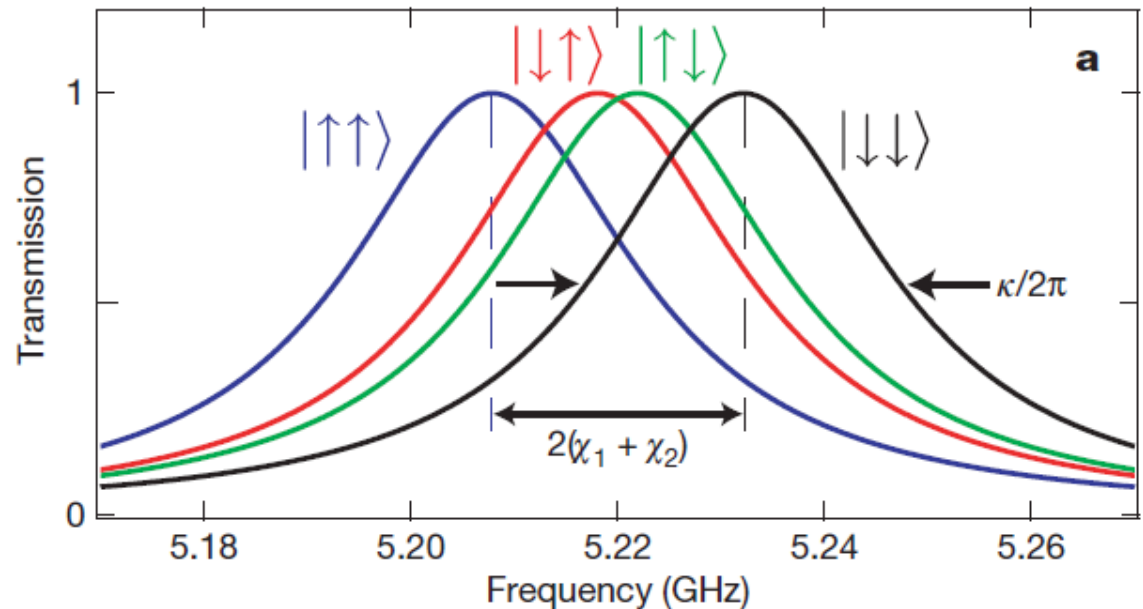
# Charge-phase qubit- Dispersive limit

- Dispersive limit:  $|\Delta_{1,2}| = |\omega_{1,2} - \omega_r| \gg g_{1,2}$



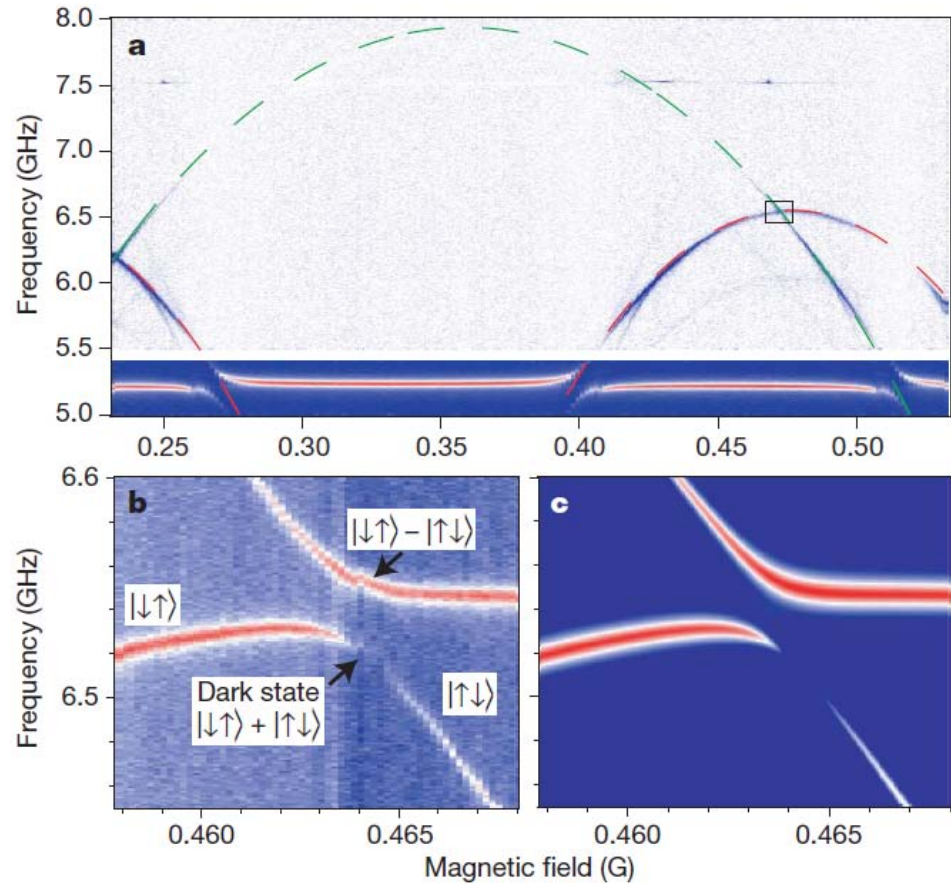
# Charge-phase qubit- Dispersive limit

- Qubit-state-dependent shift  $\pm X_{1,2}$  of the cavity frequency



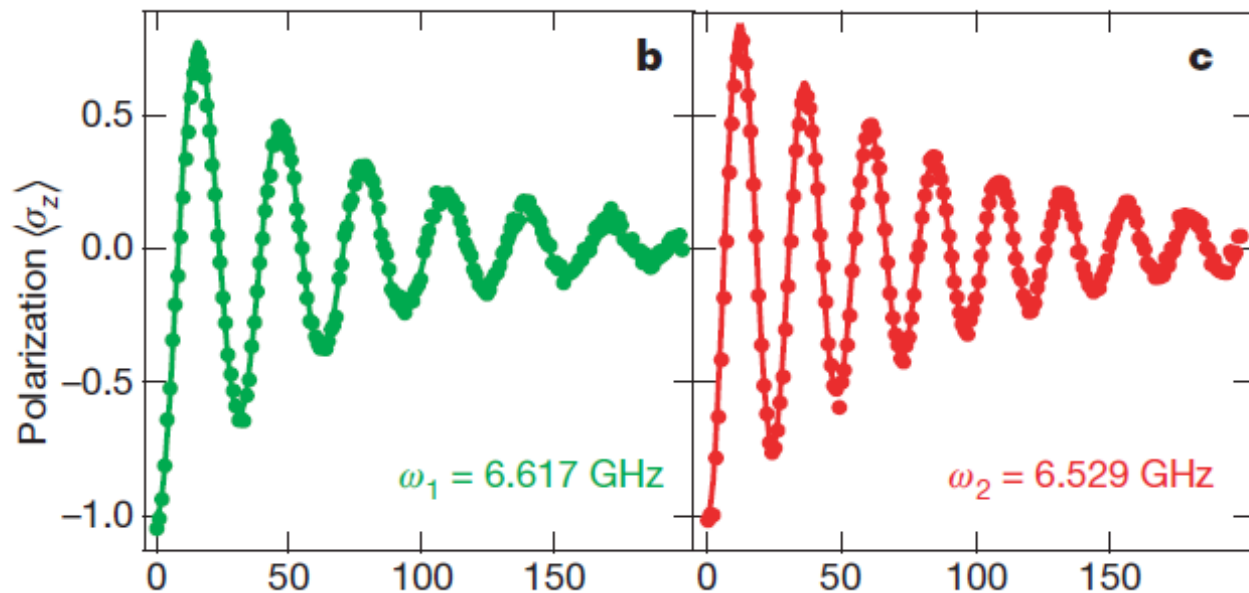
# Charge-phase qubit- Cavity transmission

- Coherent interaction
- Dark state



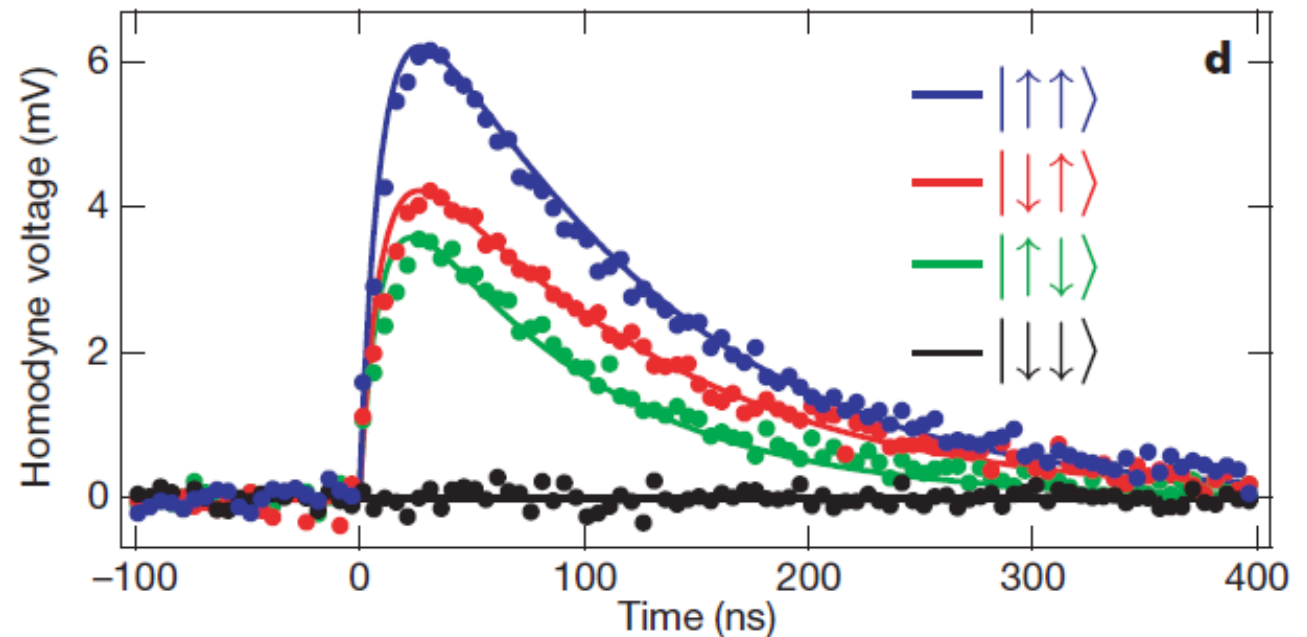
# Charge-phase qubit- Rabi oscillations

- Qubit-qubit coupling negligible
- Coupling does not affect single-qubit operations



# Charge-phase qubit- Read out

- Response of the cavity after  $\pi$ -pulse
- Able to distinguish 4 states





# Summary

- Phase qubit bus
  - Coupling through a cavity achieved
  - Coupling is coherent
- Charge-phase qubit bus
  - Able to couple over distance