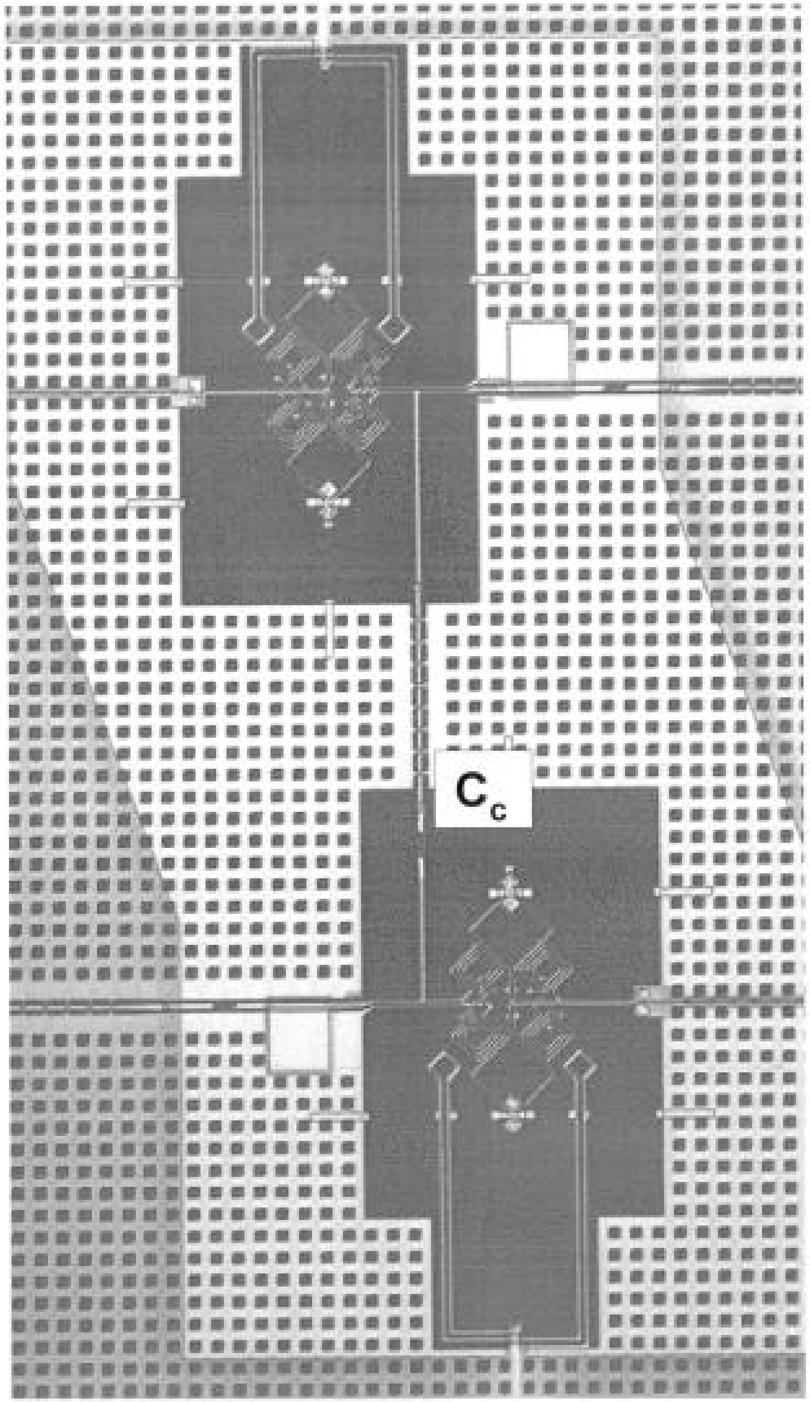
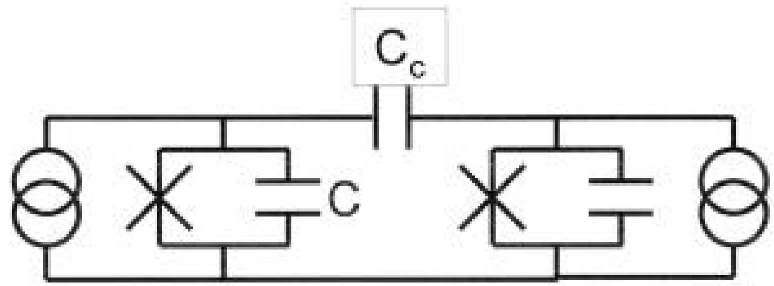


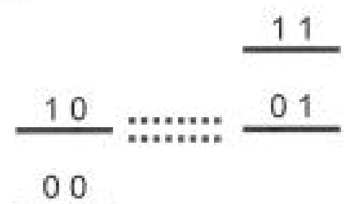
Coupled Qubits

Straightforward to implement:
- simple coupling
- tunable
- fast readout
  - simultaneous measurement



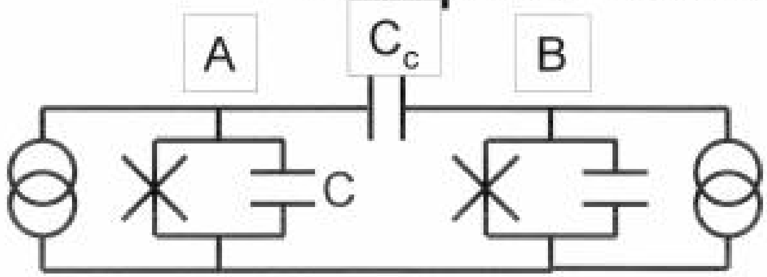
$$S/2=\frac{C_c}{C}\hbar\omega_{10}\left(|01\rangle\langle 10|+|10\rangle\langle 01|\right)$$

On Resonance:

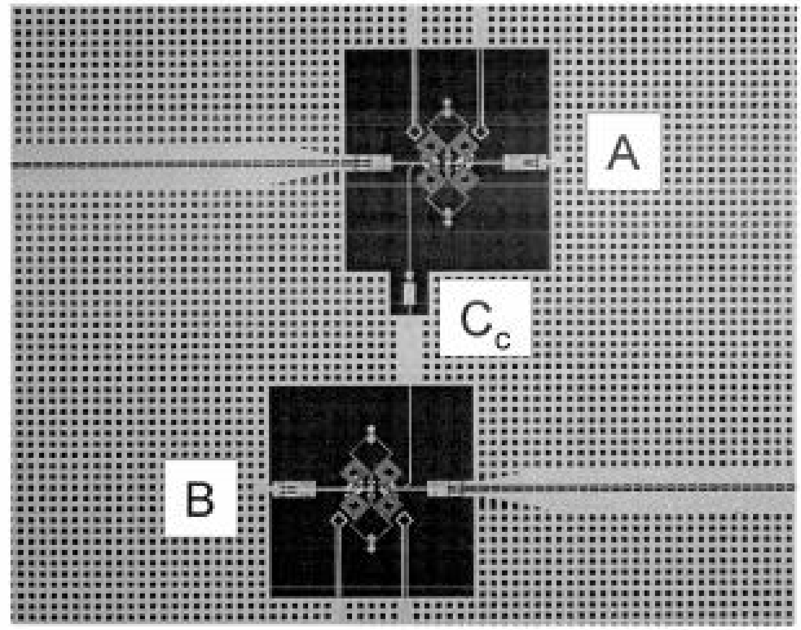


eg. UMaryland

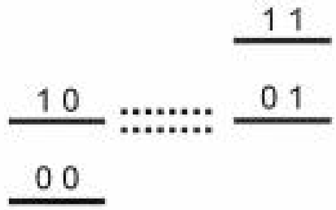
Coupled Qubits: Spectroscopy



$$H_{int} = \frac{C_c}{C}\hbar\omega_{10}\left(|01\rangle\langle10| + |10\rangle\langle01|\right)$$

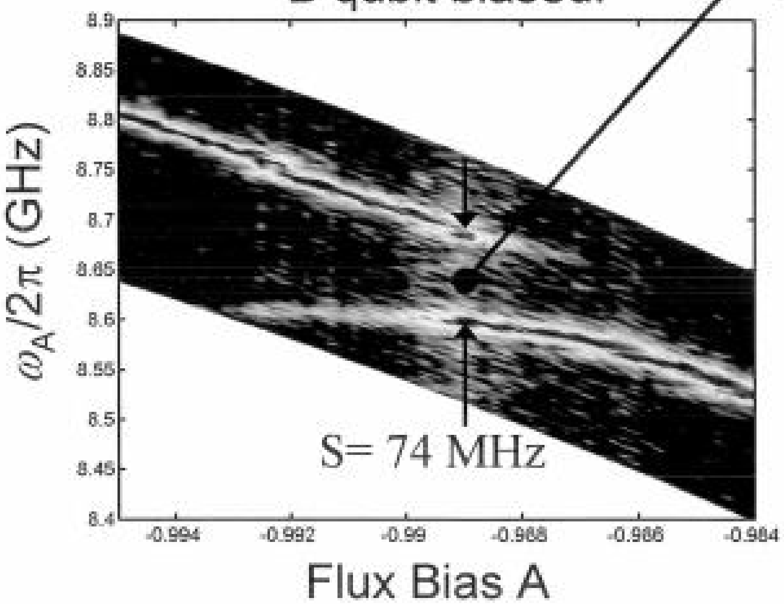


Resonant:

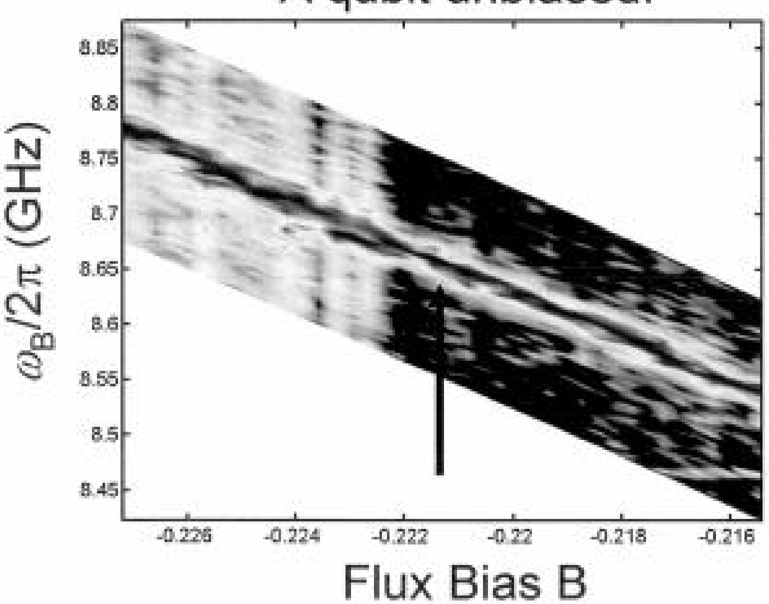


Moves with bias on B

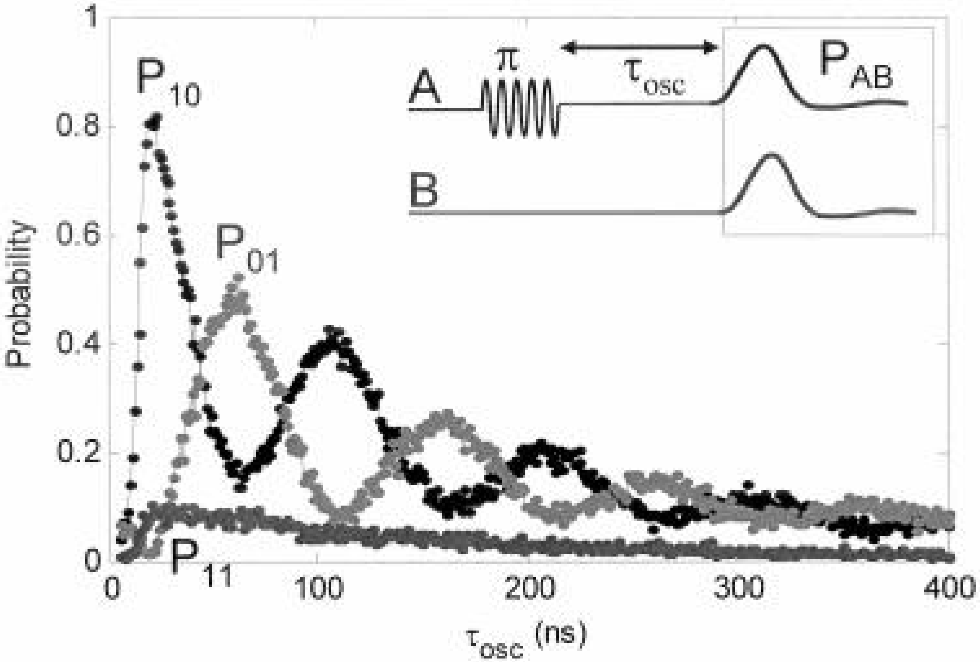
B qubit biased:

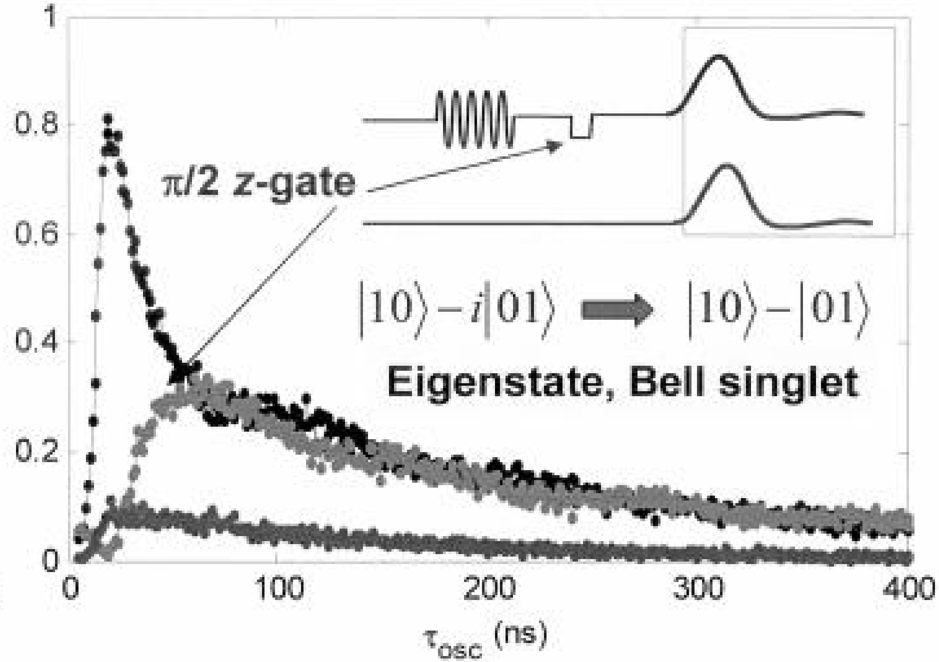


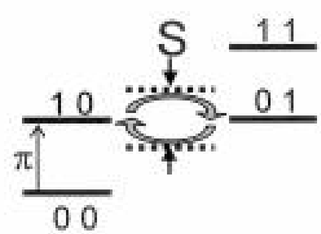
A qubit unbiased:



Simultaneous Measure of Coupled Qubits: i-SWAP gate

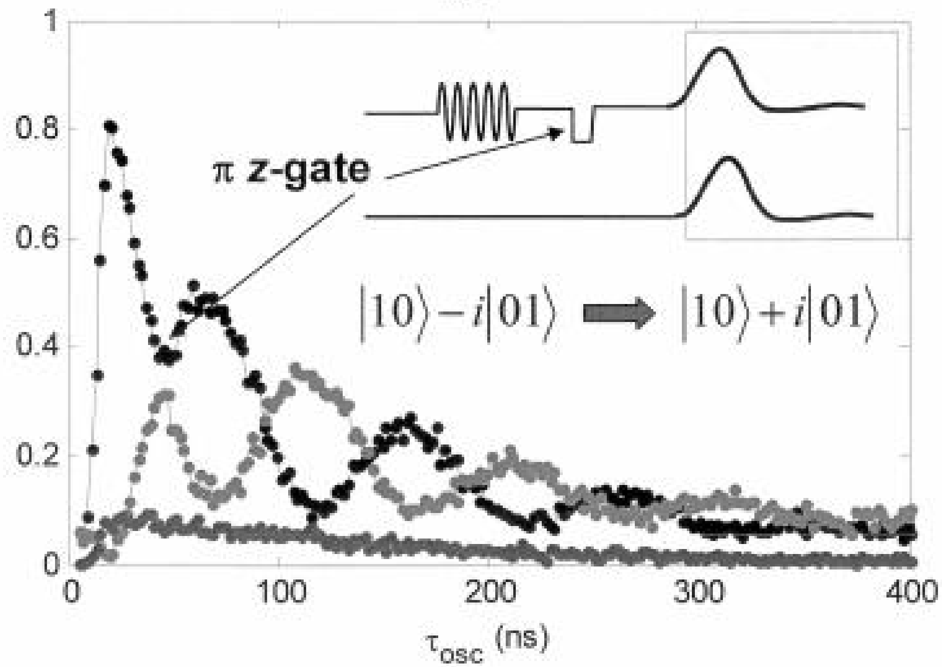






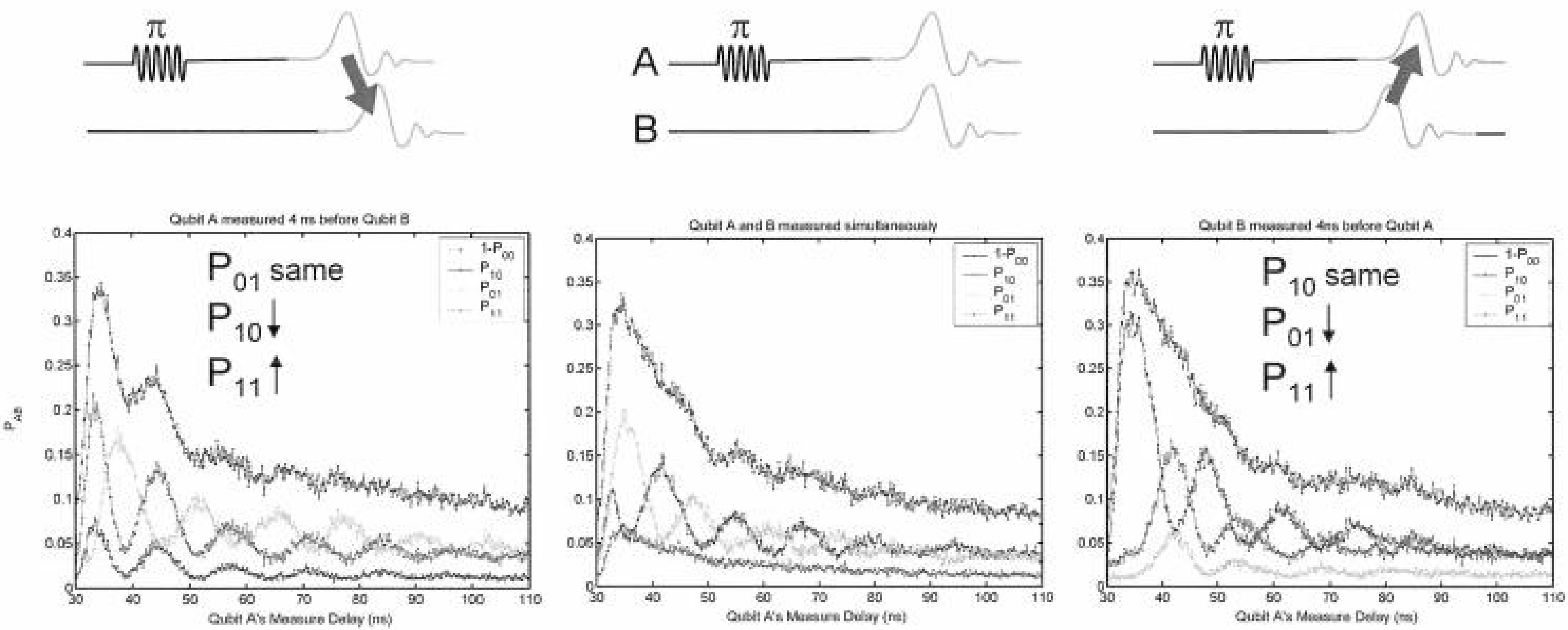
$$|\Psi\rangle = \tfrac{1}{2}\big(|10\rangle + |01\rangle\big) + \tfrac{1}{2}\big(|10\rangle - |01\rangle\big)e^{-iS\tau_{osc}}$$
$$= |10\rangle\cos(S\tau_{osc}/2) - i|01\rangle\sin(S\tau_{osc}/2)$$

i-SWAP gate



Cross Coupling when Measurement is Delayed

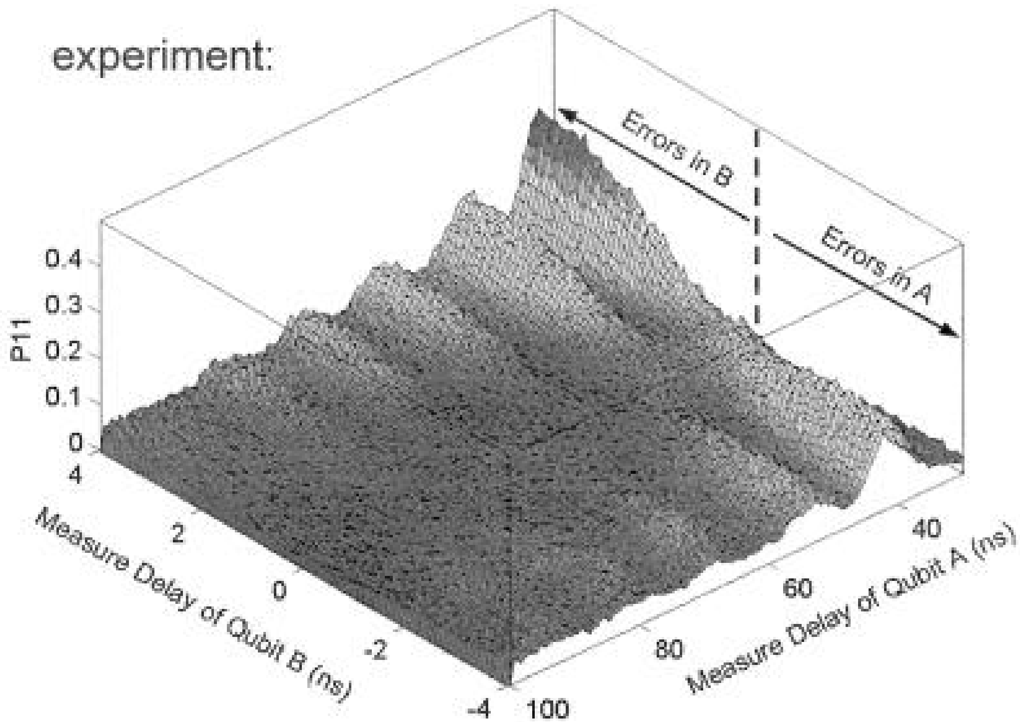
Fixed Coupling: Qubit gate easy to make,
During measurement coupling still on !
Measurement of 1 state dissipates energy



When measure 1 state:
pumps energy into 2nd qubit,
producing 0 -> 1 transition

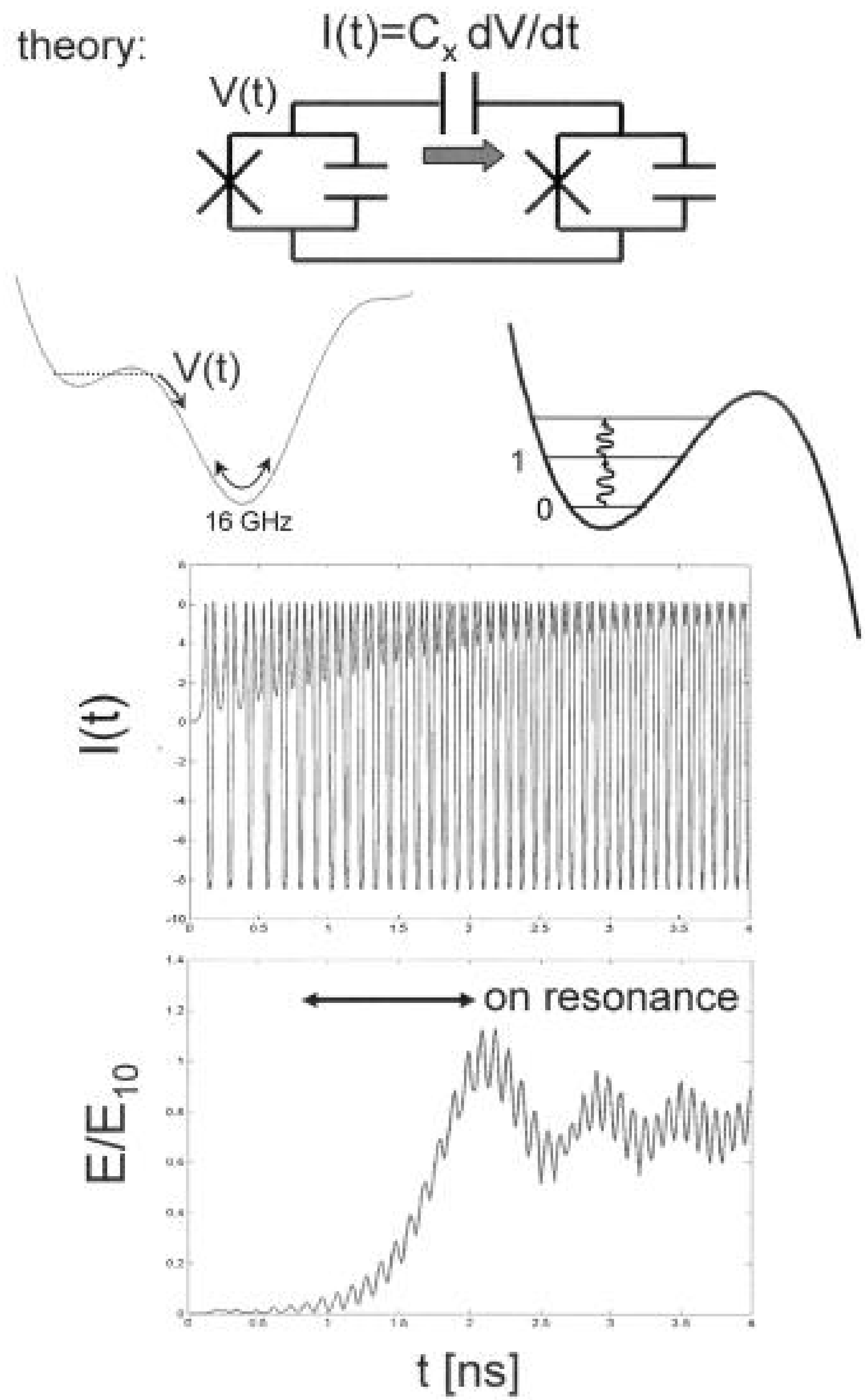
Time Scale of Measurement Crosstalk

experiment:



Small crosstalk for misalignment <1 ns

theory:



Density Matrix

— outer prod. of wavefn

$$\rho = \sum_i p_i \, |\psi_i\rangle\langle\psi_i|$$

$\uparrow$ Classical prob. sum over pure states

eg. $\psi = \frac{1}{\sqrt{2}}|01\rangle + |10\rangle$; coher. state

$$\rho_{coh.} = \frac{1}{2}(|01\rangle + |10\rangle)(\langle 01| + \langle 10|$$

$$= \frac{1}{2}(|01\rangle\langle 01| + |10\rangle\langle 10| \quad \text{diag.}$$

$$+ |01\rangle\langle 10| + |10\rangle\langle 01|) \quad \text{off diag.}$$

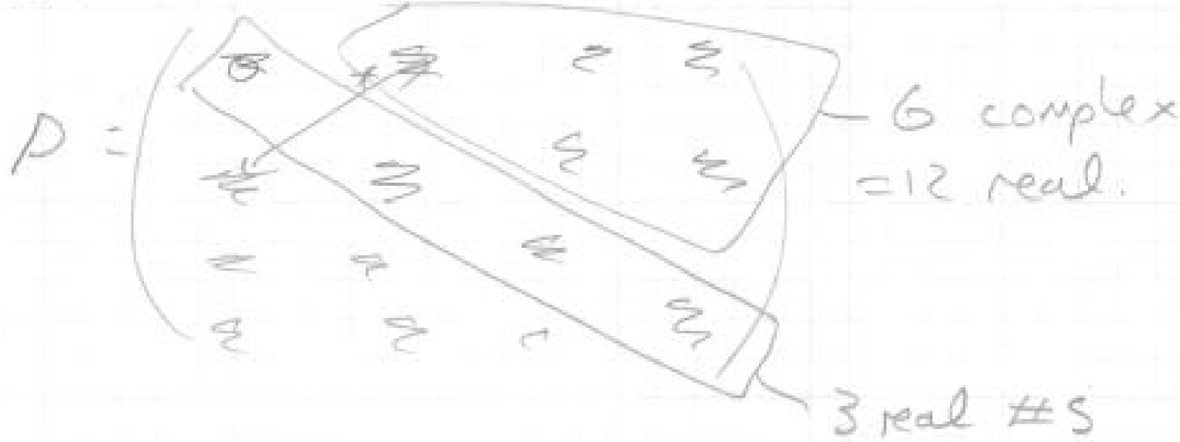
eg. $\frac{1}{2}$ prob $|01\rangle$; $|10\rangle$

$$\rho_{uncoh} = \frac{1}{2}(|01\rangle\langle 01| + |10\rangle\langle 10|)$$

$$\rho = \begin{array}{c} \langle 00| \quad \langle 01| \quad \langle 10| \quad \langle 11| \\ \begin{pmatrix} \; & \; & \; & \; \\ & 1/2 & 1/2 & \\ & 1/2 & 1/2 & \\ & & & \end{pmatrix} \end{array} \begin{array}{l} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{array}$$

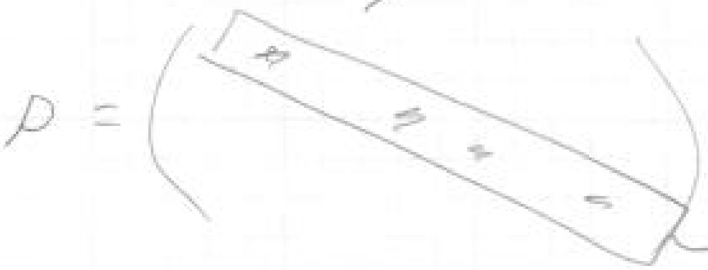
off diag ($=$ diag) $\Rightarrow$ coh. state.

ρ is Hermetian



15 real #'s describe state!

Meas. of ρ



In z-basis, Meas. These 3 #'s ($\Sigma = 1$; normalized).

How to meas. off diag → Need to rotate them in with X_{90}, Y_{90} pulses (meas in X, Y basis) as with 1 qubit.

9 experiments $U_{rotate} = (I, X, \text{or } Y)^{(1)} \otimes (I, X, \text{or } Y)^{(2)}$

$\rho' = U_{rot} \rho U_{rot}^{+}$; then meas. diagonal elements.

Issue: It would be *nice* if could rotate *only* a off diag into diag; but get linear sum of off diag. So have to do Math to invert.

9 experiments; 3 diag elements ⇒ 27 linear equations of all 15 ρ elements.

Overconstrained (good!).
Use least squares fit;
In MATLAB, 1 line of code!

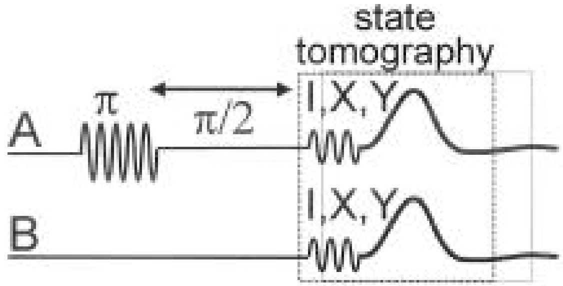
1 qubit: 3 exps → 3 ρ elements
2 qubits: 9 exps → 15 ρ elements; overconstrai

⋮

8 qubits: Reduce # of experiments. (Innsbruck)
Matrix inversion is hardest

$U_I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ $U_x = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -i \\ -i & 1 \end{pmatrix}$; $U_Y = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}$

Tomography: Direct Proof of Entanglement

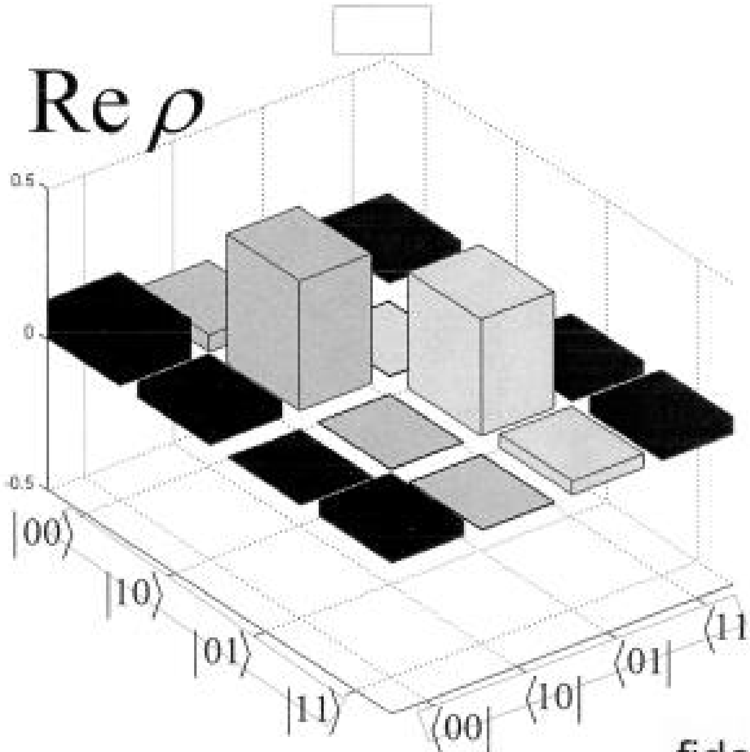


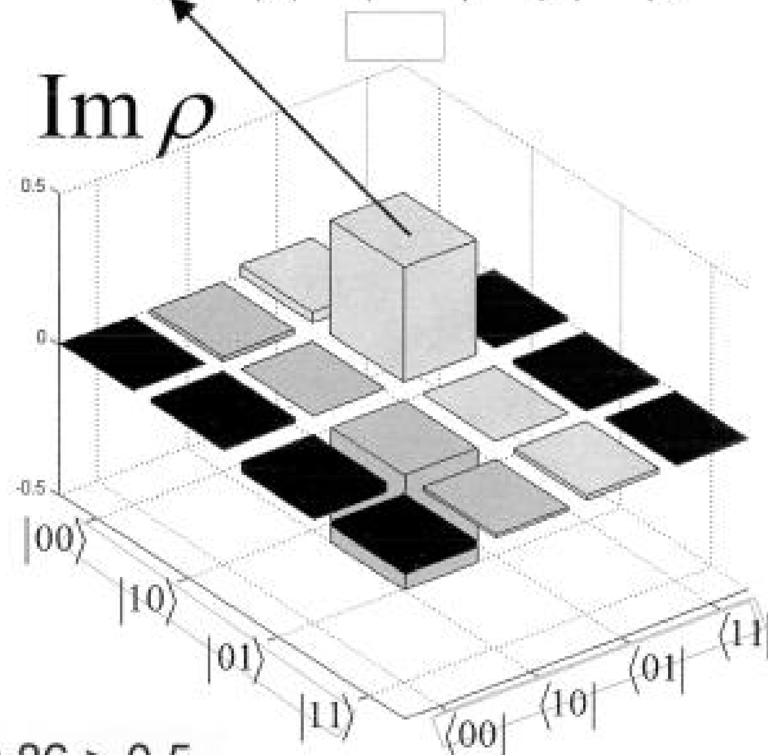
$$|10\rangle - i|01\rangle$$

$$\rho_{\mathrm{incoh}} = (1/2)(|10\rangle\langle 10| + |01\rangle\langle 01|)$$

$$\rho_{\mathrm{coh}} \equiv (|10\rangle - i|01\rangle)(\langle 10| + i\langle 01|)$$

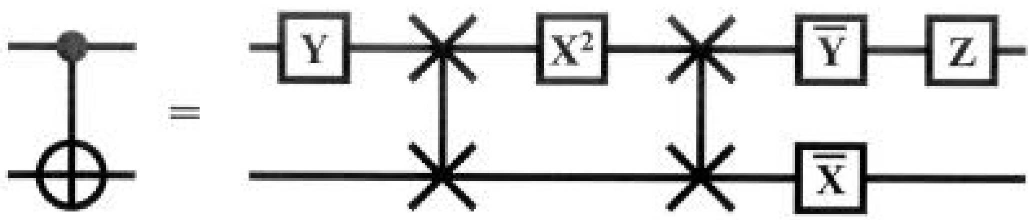
$$= (1/2)(|10\rangle\langle 10| + |01\rangle\langle 01| + i|10\rangle\langle 01| - i|01\rangle\langle 10|)$$





fidelity = 0.86 > 0.5
expect = 0.87

CNOT Gate

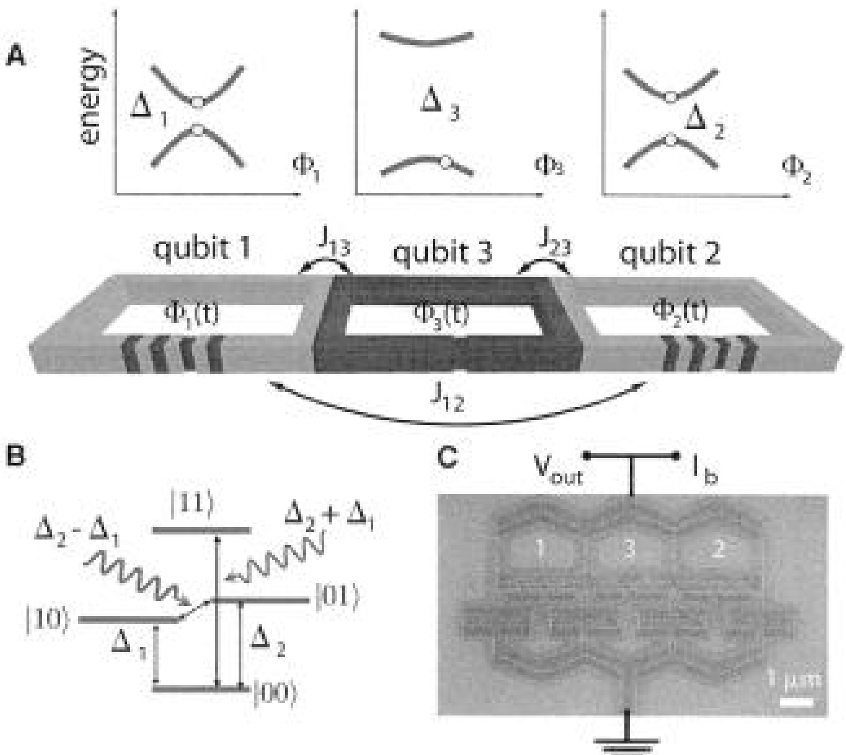


$\sqrt{\text{i-SWAP}}$ is a universal gate

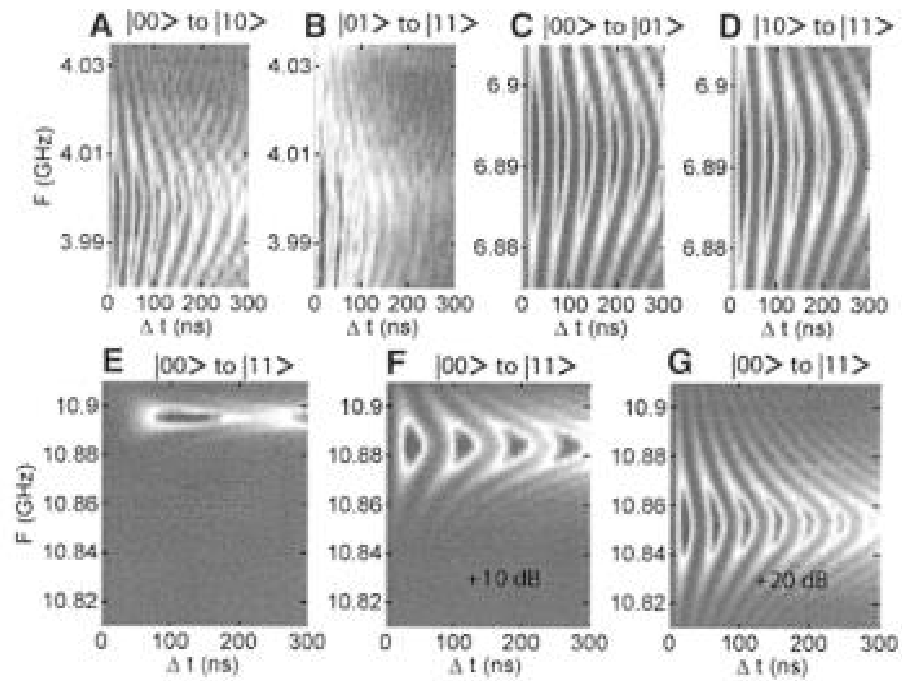
(General qubit coupling uses this sequence !)

Degeneracy Point: Parametric Coupling (NEC)

Coupling more difficult at degeneracy point -
Must modulate M with time to couple



Common µwave drive



On/off ratio = 20
20 ns gate time
Visibility ~ 40%