Coupled Superconducting Phase Qubits

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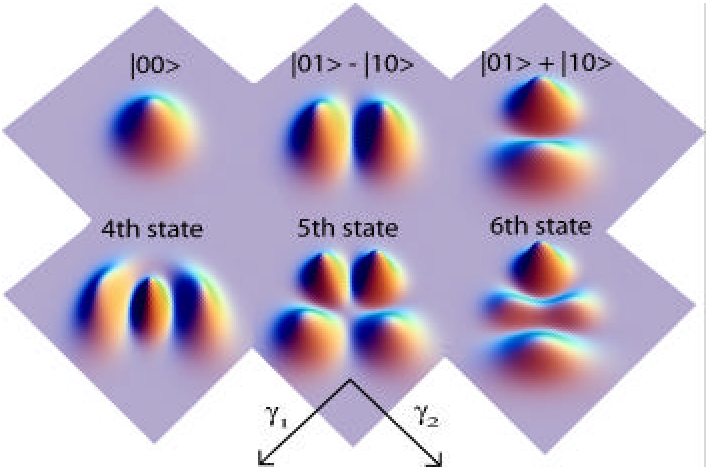

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Center for Superconductivity Research

Outline- Coupled Phase Qubits

- Single **large** (e.g. 10 μm^2 junction, C_J ~ 5 pF) current-biased Josephson-junction (CBJJ) **phase** qubits. (NIST, Kansas, Maryland)

- What happens when you capacitively couple two CBJJ qubits separated by ~ 1 mm?

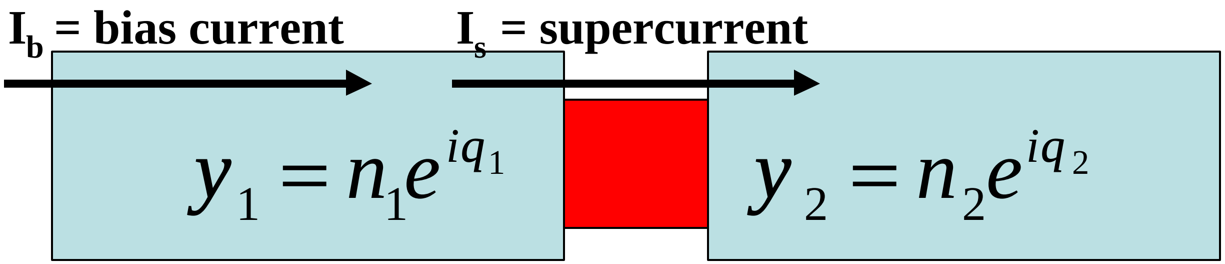
- Next challenges: Longer coherence times!, measuring coherent oscillations, measuring correlations.

Motivation

- What makes CBJJ phase qubits attractive?
  - Single phase qubit QM established, MQT/MQC
  - Solid state scalability.
  - Tunable coupling and energy levels.
  - Easily controlled (wires).
  - Prepare in ground state.
  - High fidelity gates possible in principle.
  - Easily measured.
  - Good experiments testing important fundamental physics.

- Serious challenges to meet:
  - Match (in large phase qubit) the impressive *charge* and *flux* qubit results (NEC, Yale, Saclay, SUNY, Delft, MIT, IBM, etc…)
  - Much longer coherence time (*better isolation*, less noise).
  - Measuring coherent oscillations and quantum correlations.

Dynamics of tunnel junction phase:



(collective variable ~ 10^9 pairs)

Josephson relations:

$$I_s(t) = I_c \sin g(t)$$

$$V(t) = \frac{Q(t)}{C_J} = \left(\frac{\Phi_0}{2p}\right)\frac{dg(t)}{dt}$$

$$g = (q_1 - q_2) + \frac{2e}{\hbar}\int A \cdot dx$$

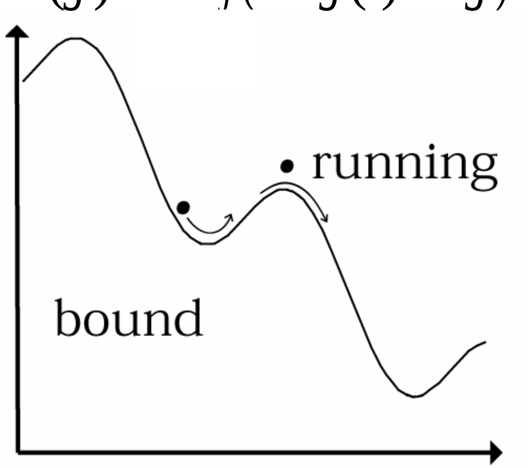
Equations of motion:

$$\frac{d^2 g(t)}{dt^2} = -\left(\frac{8E_C E_J}{\hbar^2}\right)\frac{d}{dg}U(g)$$

$$E_J = I_c \Phi_0 / 2p \gg E_C = e^2 / 2C_J$$

$$\Phi_0 = \frac{h}{2e}$$

$$U(g) = -E_J\left(\cos g(t) + Jg\right)$$



Bound: g(t) oscillates at plasma frequency ω_p :
AC voltage across junction but no DC voltage.

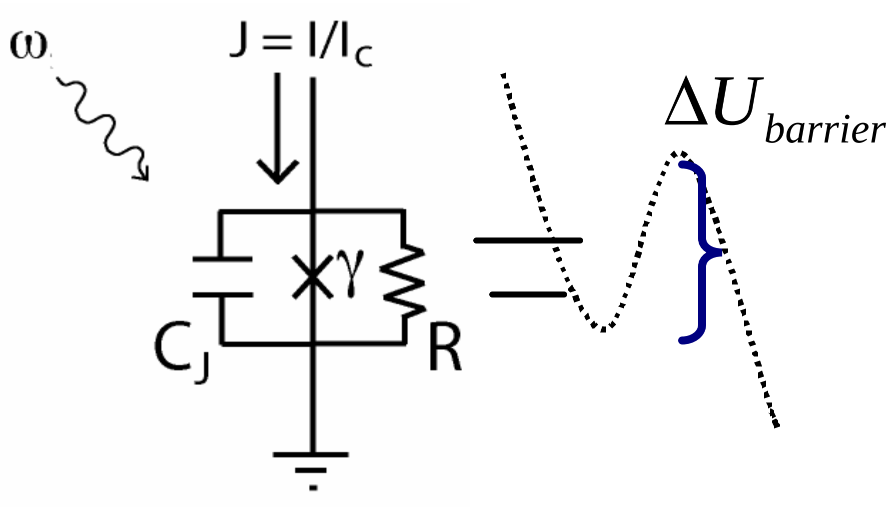
$$w_p(J) = \sqrt{8E_J E_C}\left(1 - J^2\right)^{1/4} / \hbar$$

If g(t) makes it past barrier it switches to a finite DC voltage running state.

Single junction control and Hamiltonian

$$N \cong \frac{\Delta U_{barrier}}{\hbar w_p(J)} = \frac{2^{3/4}}{3}\left(\frac{E_J}{E_C}\right)^{1/2}(1-J)^{5/4}$$

When N > 1 there exist metastable bound states in each well; phase qubit regime.



Single junction control

- **J = I/I$_C$ = normalized bias current: J controls tilt of washboard; J > 1 no wells**
- **Microwaves.**
- **Magnetic field** ? **critical current**

Canonical momentum:

$$H(p,g) = 4E_C p^2/\hbar^2 + U(g)$$

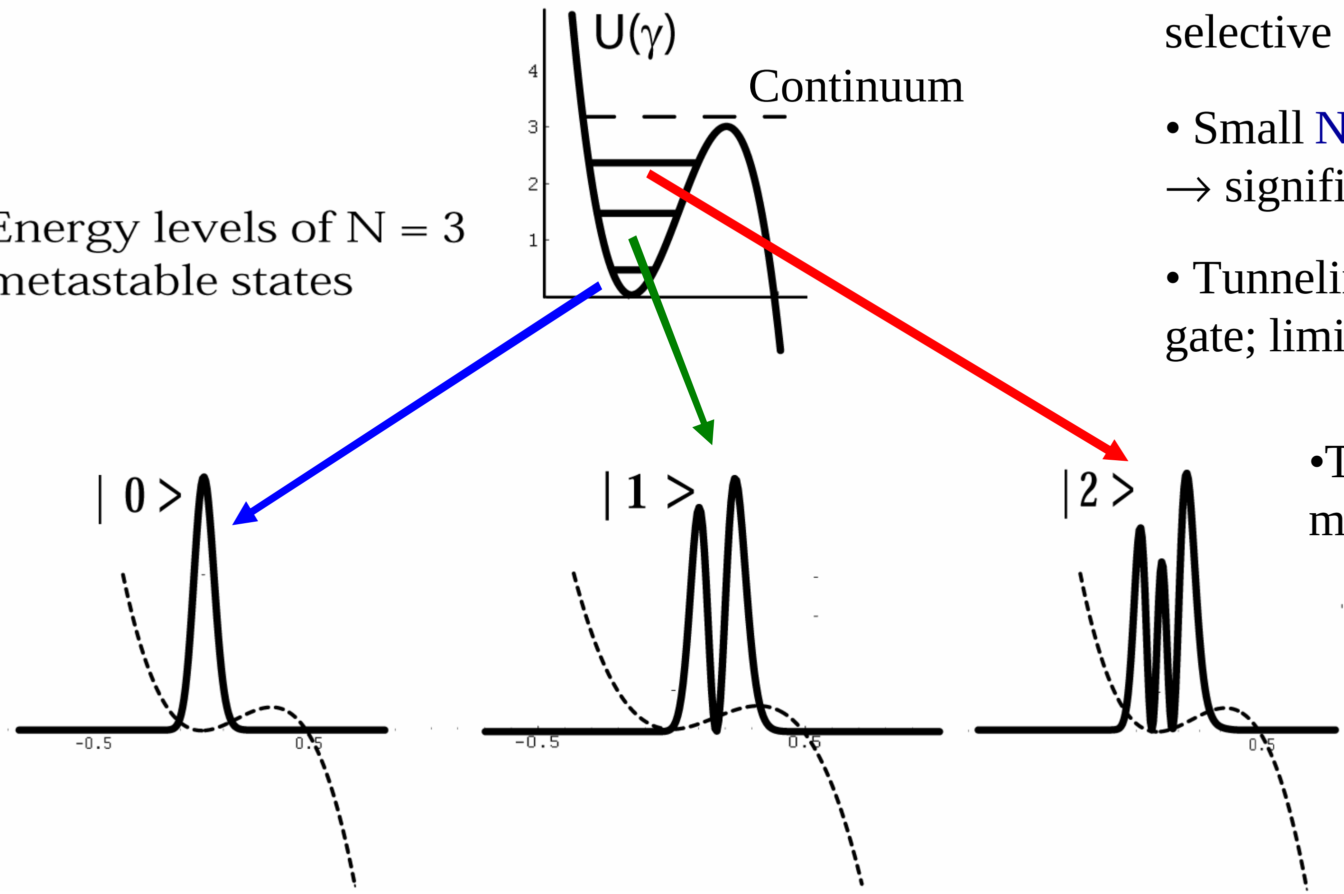
$$U(g) = -E_J\left(\cos g(t) + Jg\right)$$

$$p = \left(\frac{\Phi_0}{2p}\right)^2 C_J \frac{dg}{dt} = \frac{\hbar Q}{2e}$$

μ Number of pairs

Single junction quantum states

Energy levels of N = 3 metastable states

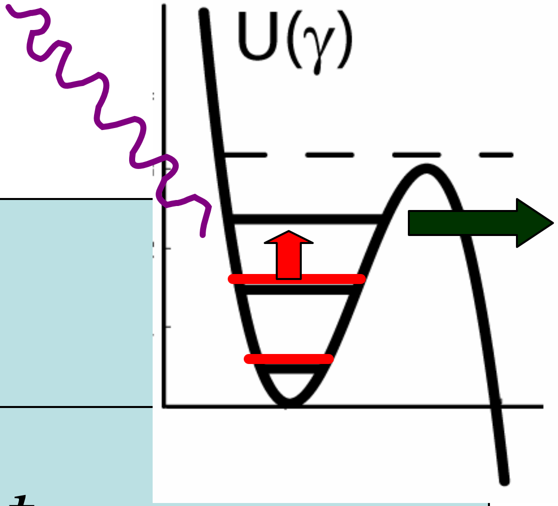


- Small N → anharmonic → selective level transitions.
- Small N → strong nonlinearity → significant tunneling.
- Tunneling limits fidelity of any gate; limits how small N can be.
- Tunneling used for state measurement/readout.

- **Not a 2 level system; and other states aren’t negligible.**

N @ 4 - 5 good compromise.

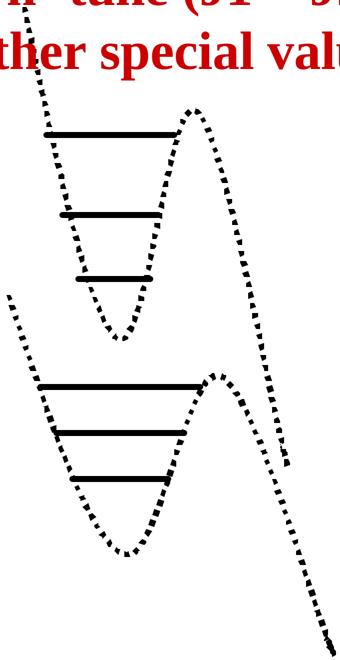
Readout / Measurement

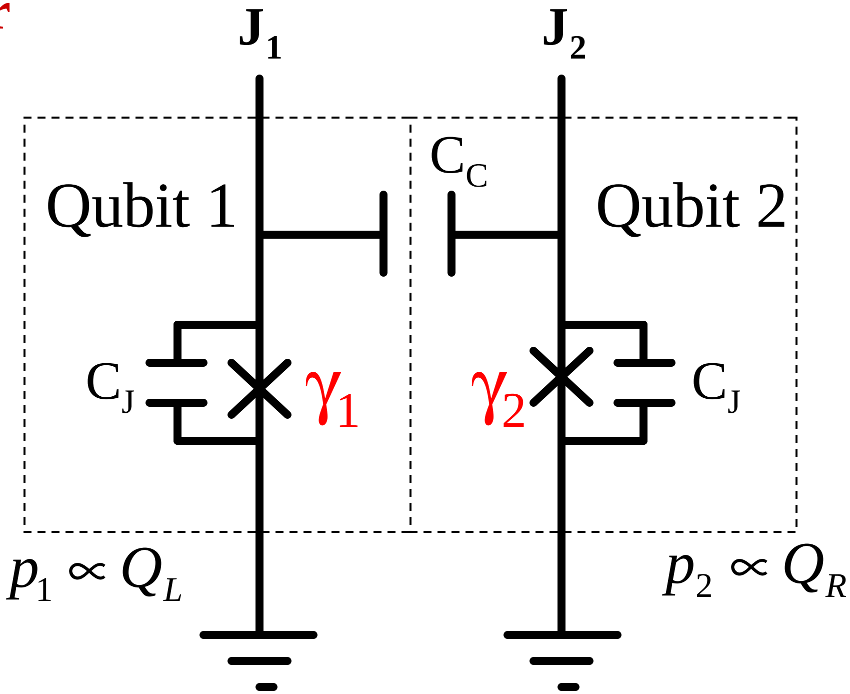


Qubit states are $\left|0\right\rangle$ and $\left|1\right\rangle$.
Pump with microwaves at $w_{21} = \left(E_2 - E_1\right)/\hbar$
If state is $\left|0\right\rangle$, no transition since $\left(E_1 - E_0\right) \neq \left(E_2 - E_1\right)$.
If state is $\left|1\right\rangle$, microwaves drive $\left|1\right\rangle \rightarrow \left|2\right\rangle$
$\left|2\right\rangle$ quickly tunnels out of well (switches) giving measurable DC voltage across junction

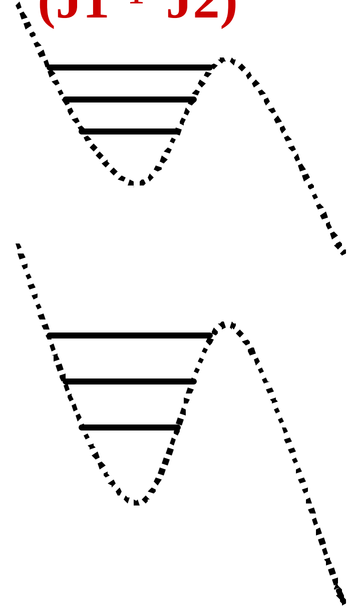
Two capacitively coupled qubits

On- tune (J1 = J2, or other special values)





Off- tune (J1 ¹ J2)



$$H = \frac{4E_C}{(1+z)\hbar^2}\left(p_1{}^2 + p_2{}^2 + 2zp_1p_2\right) - E_J\left(\cos g_1 + J_1 g_1 + \cos g_2 + J_2 g_2\right)$$

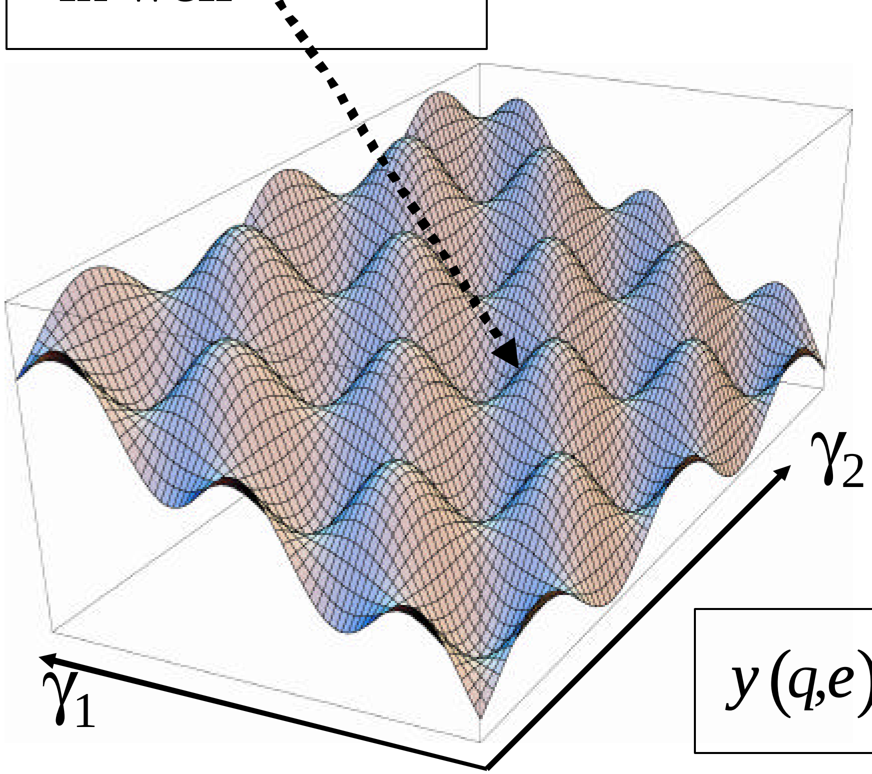
Kinetic energy; Potential energy

$$z = \frac{C_C}{C_C + C_J} = \text{Coupling parameter.}$$

Momentum coupling: Electrostatic energy

Numerical solution of the 2D Schrödinger equation: split operator method.

Metastable states localized in well



Split-operator methods:

• Computes wave function on a lattice.

• Using imaginary time gives metastable stationary states.

• Using real time gives evolution including tunneling.

• Works for general nonlinear potentials.

• Highly accurate and proven method; unitary to machine precision.

• How is works:

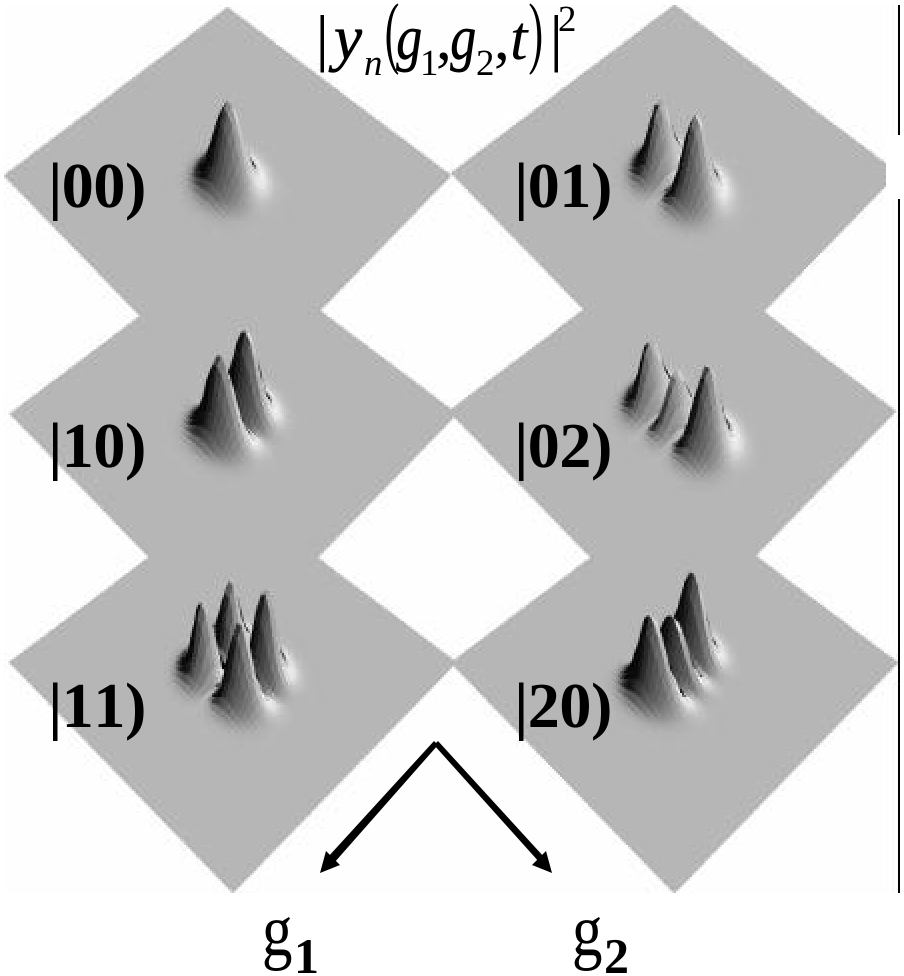
$$y(q,e) = e^{-iV(q)e/2} \underset{(p\to q)}{FFT} e^{-iT(p)e} \underset{(q\to p)}{FFT} e^{-iV(q)e/2} y(q,0)$$

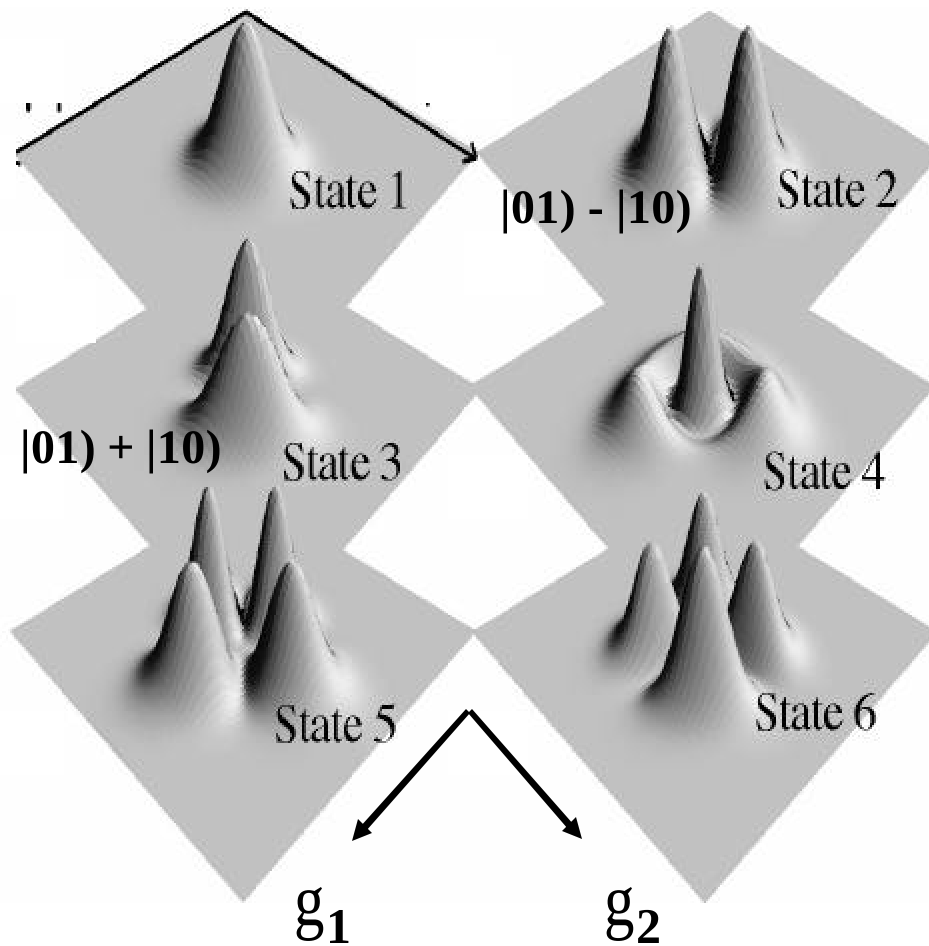
Numerically computed quantum states:

(CJ = 4.3 pF, IC = 13.3 μA, N = 3)

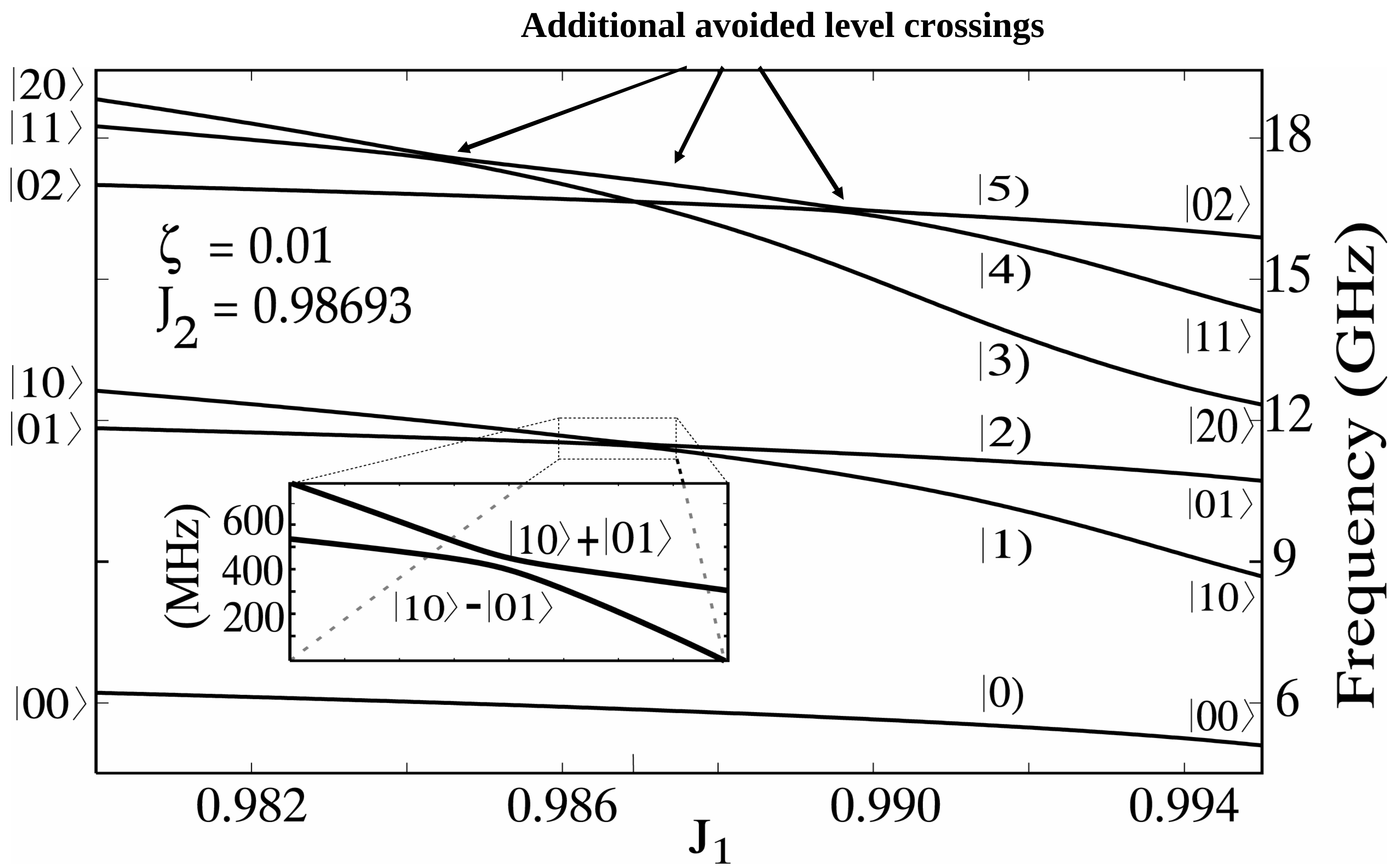
$$z = \frac{C_C}{C_C + C_J} = 0.01$$

J1 1 J2 : Detuned **J1 = J2 : Tuned**





Energy levels versus bias current: small coupling



Not 2-level system: |0,1,2,...⟩ x |0,1,2,...⟩ = { |00⟩ , |01⟩ , |10⟩ , |20⟩ , |11⟩, |02⟩ ,… }

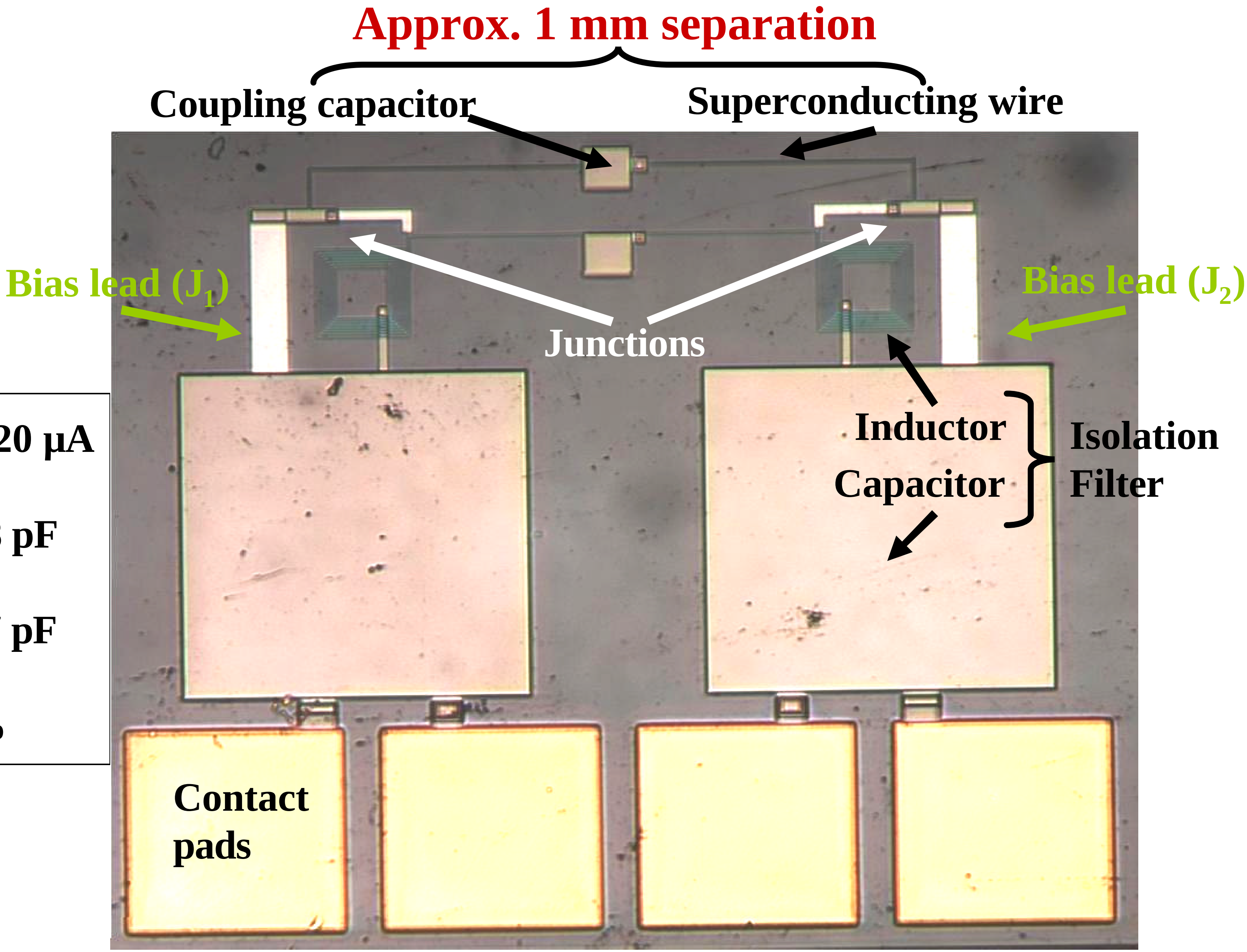
Two qubit chip (Hypres): Large Nb-AlOx-Nb junction: 100 μm^2 area

I_C = 10-20 μA

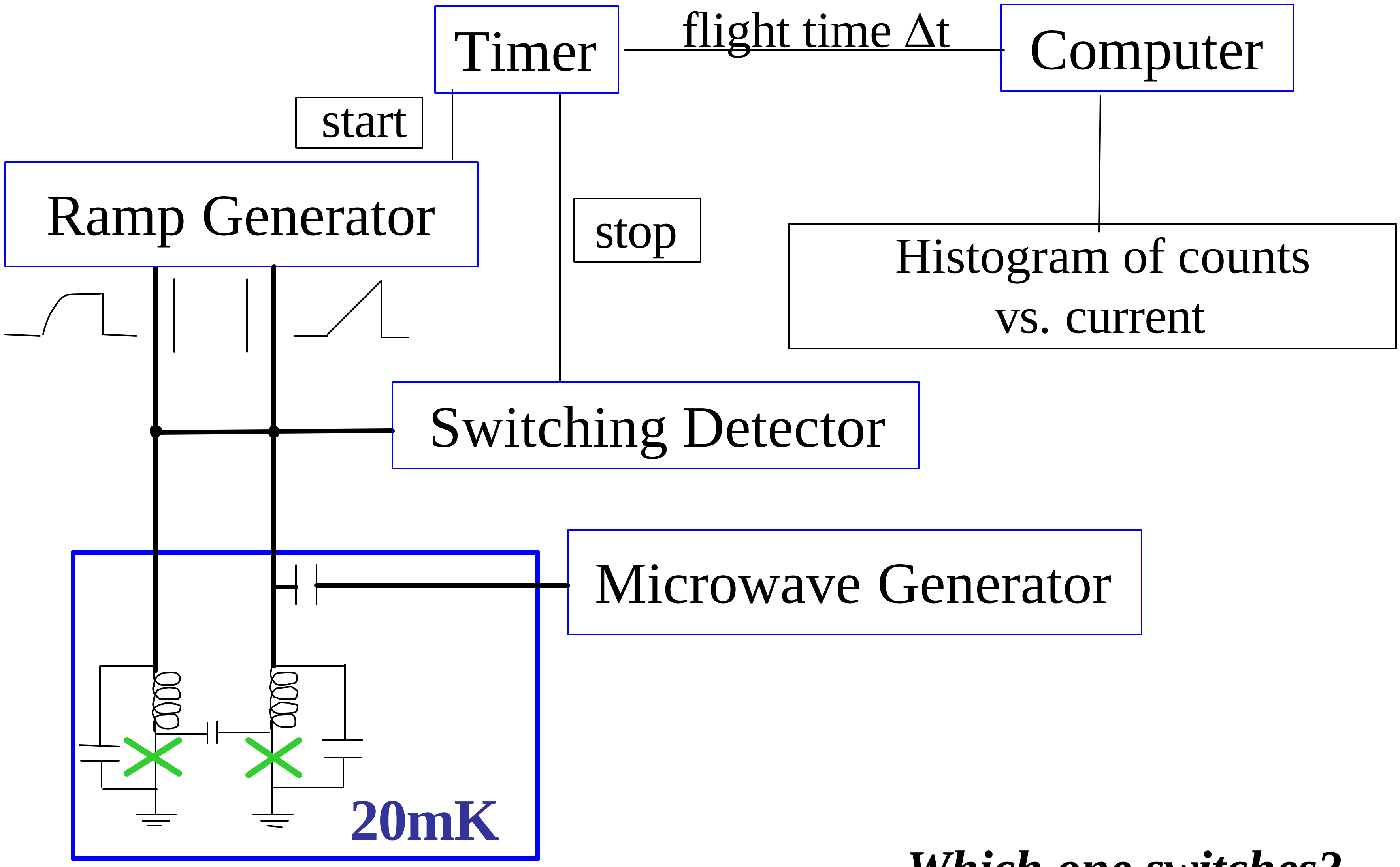
CJ = 4.8 pF

C_C = 0.7 pF

z = 13%

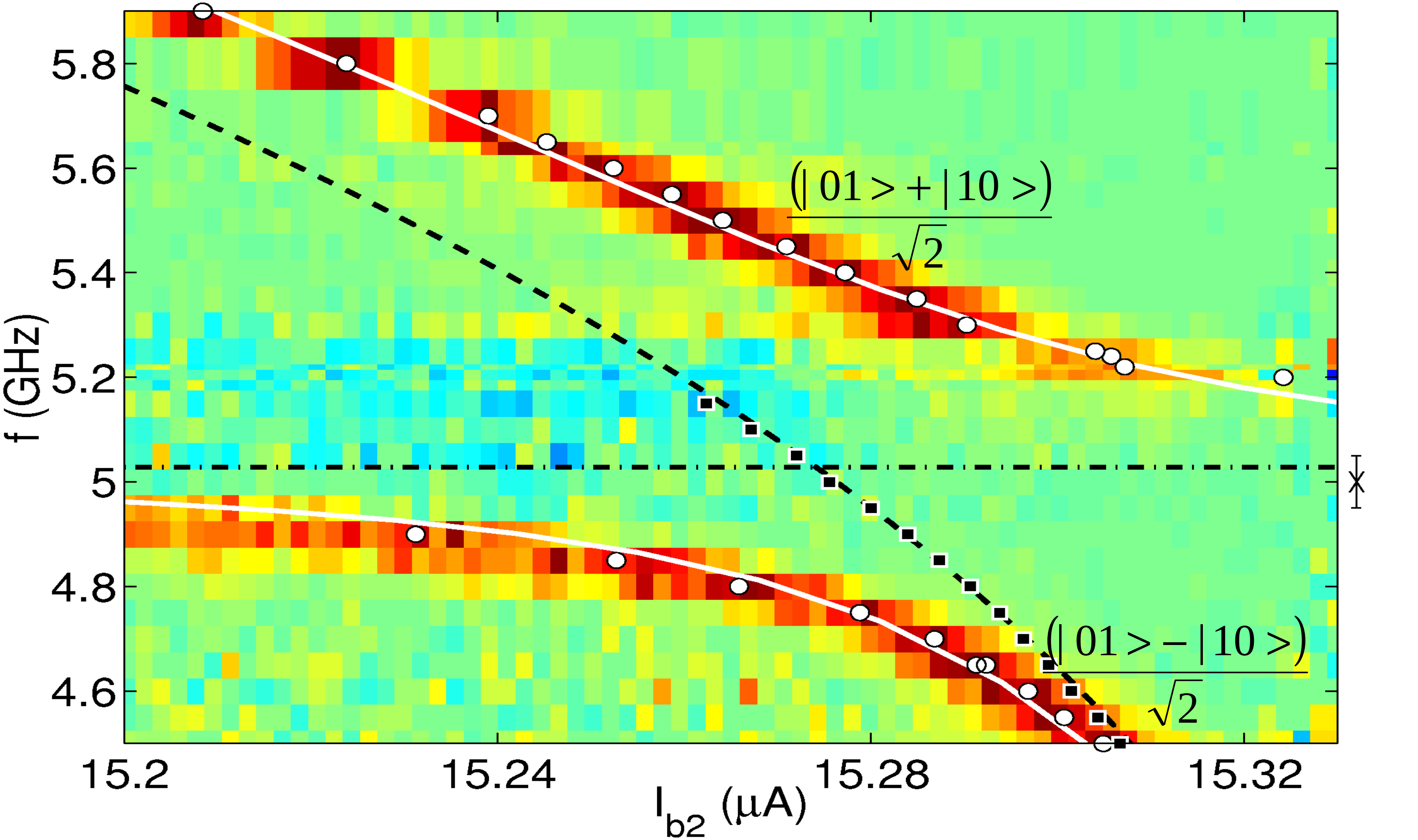


2-qubit spectroscopy method



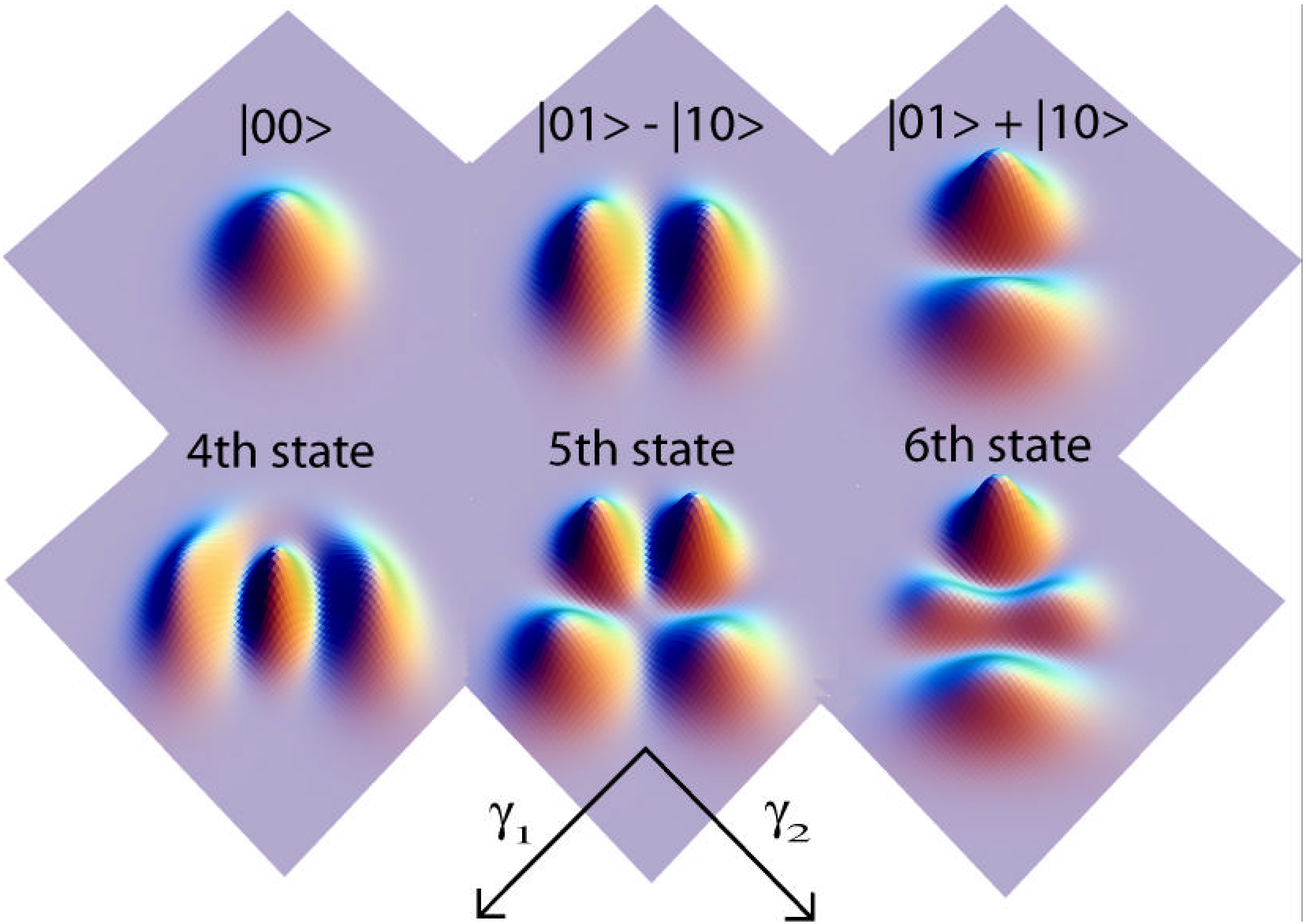
Which one switches?

Two qubit chip



Berkley et al., Science, May 15, 2003.

First 6 states computed with experiment junction parameters



Coherence and other qualitative features

- **Decoherence times may be estimated from widths of escape histograms: ranges from 2 - 6 ns.**
- **However, no excess decoherence from coupling.**
- **The 2 - 6 ns coherence time appears to be limited by low frequency current noise. Developing better isolation schemes should improve this (*how much*?).**
- **A little more coherence and many fundamental experiments are possible; QC will need a lot more coherence.**
- **Levels do not move with power, but new lines appear.**
- **If treated classical avoided levels appear but (because Hamiltonian is nonlinear) not in same place.**

Conclusions

• Capacitively coupled Josephson-junctions phase qubits are tunable qubits with effective coupling controlled by bias currents.
(Johnson et al. PRB 67 020509 (2003); cond-mat/0210278.)

• First test for coupled system passed: spectroscopy in excellent agreement with Schrödinger equation for nonlinear Hamiltonian, including quantum power dependence and MQT behavior. ***(Berkley et al. Science, May 15, 2003)***

• Even more stringent experimental tests on the horizon. Increasing coherence is vital, there are a number of isolation schemes that should at least help in this regard. Coherent oscillations, ultimately correlations, must be measured.

• Next Fred Strauch is going to discuss quantum dynamics and show that good quantum gates should be possible; not immediately obvious with this system.
(Strauch et al., quant-ph/0303002)