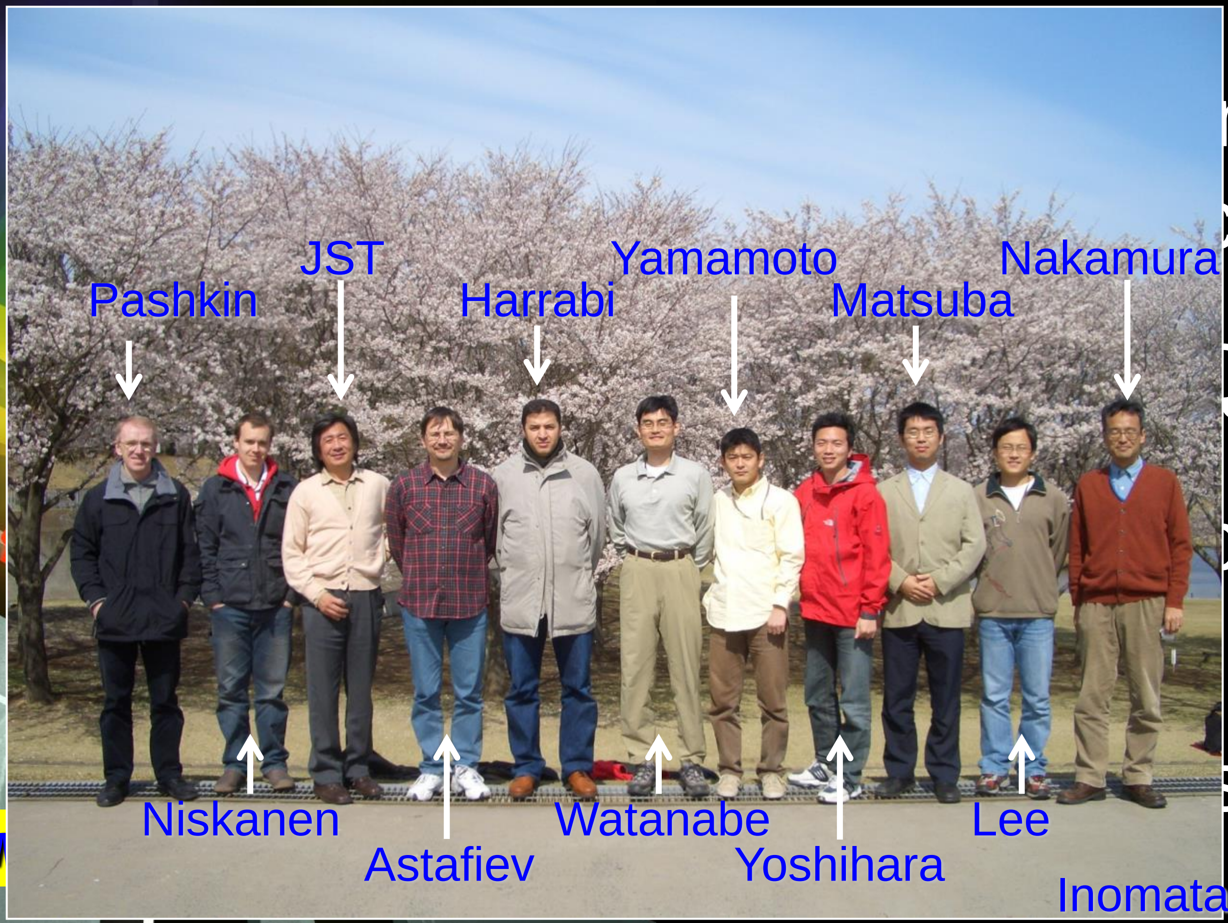
# "IMAGING" QUANTUM COHERENCE AND BYOND: SUPERCONDUCTING MULTI-QUBIT SYSTEM

*The Brijuni Conference,* Imaging the Space and Time, August 30, 2006

*J. S. Tsai, NEC/RIKEN/CREST*




n

c System

Qubits

bits

sues:

*Scaling up*

# Quantum Coherence Helps Imaging

***Examples:***

**NMR/MRI**
**Optical Holography**
**Electron Beam Holography**
**Scanning SQUID magnetometer**
**Manetocardiography (MKG)**
**Magnetoencephalography (MEG)**
***and more***

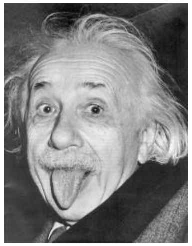
***However:***

**Measurement *kills* coherence**

**⇒ Projection measurement**

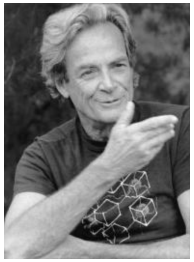
**Cf: Quantum Non-Demolition Measurement (QND)**

$$\Psi \neq \Psi_1 \Psi_2, \quad cf: \Psi = \frac{1}{\sqrt{2}}(\Psi_1 \Psi_2 + \Psi_2 \Psi_1)$$



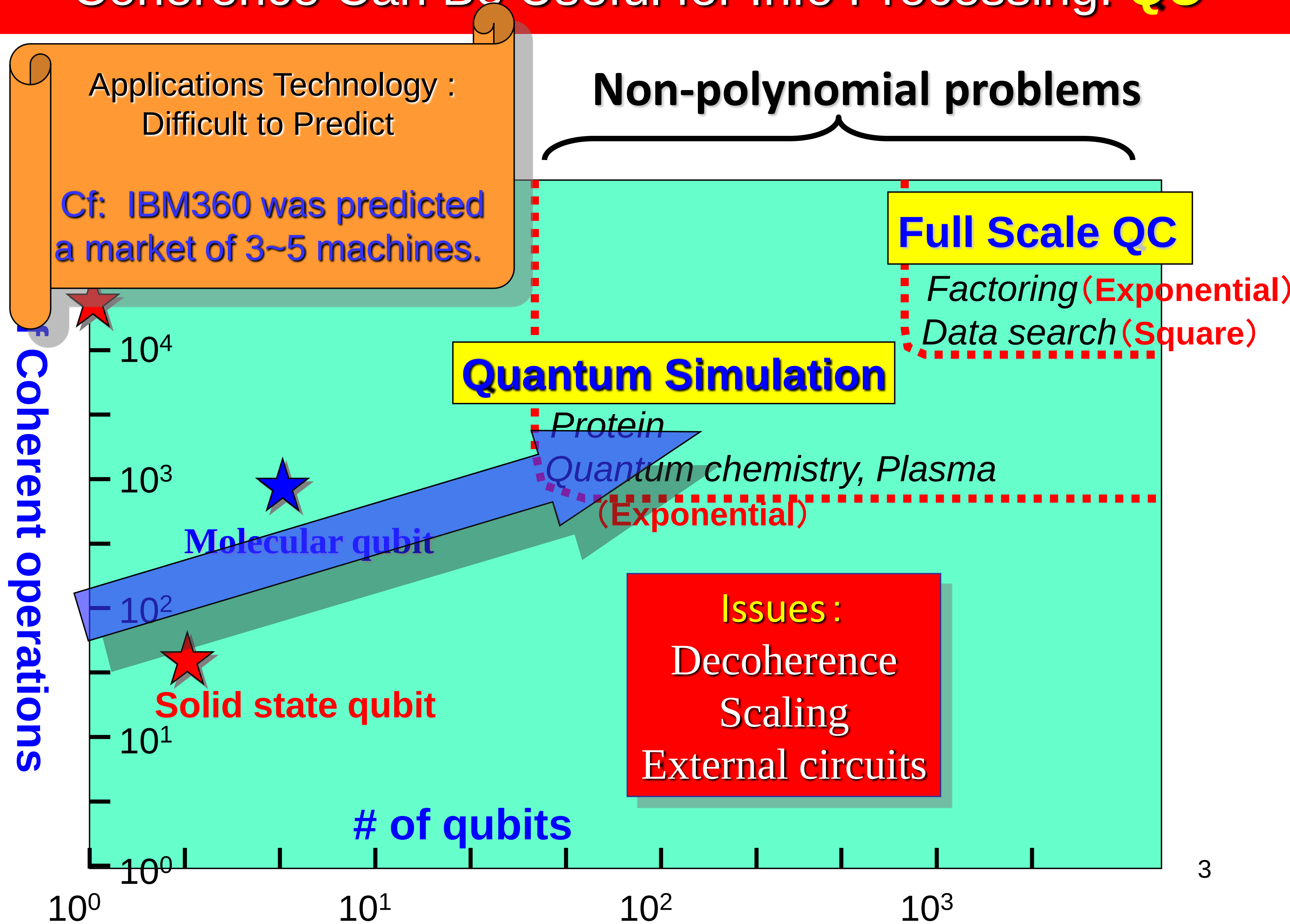
## Quantum Coherence (entanglement)

- Einstein: "Spooky action at a distance" **WRONG**
- Feynman "Can never be understood" **MAY NOT BE SO**



**If it was such a *revolution* in idea,**
**can it help something more dramatically?**
**Use it more *dynamically*, beyond mere quantization & interference?**

# Coherence Can Be Useful for Info Processing: QC

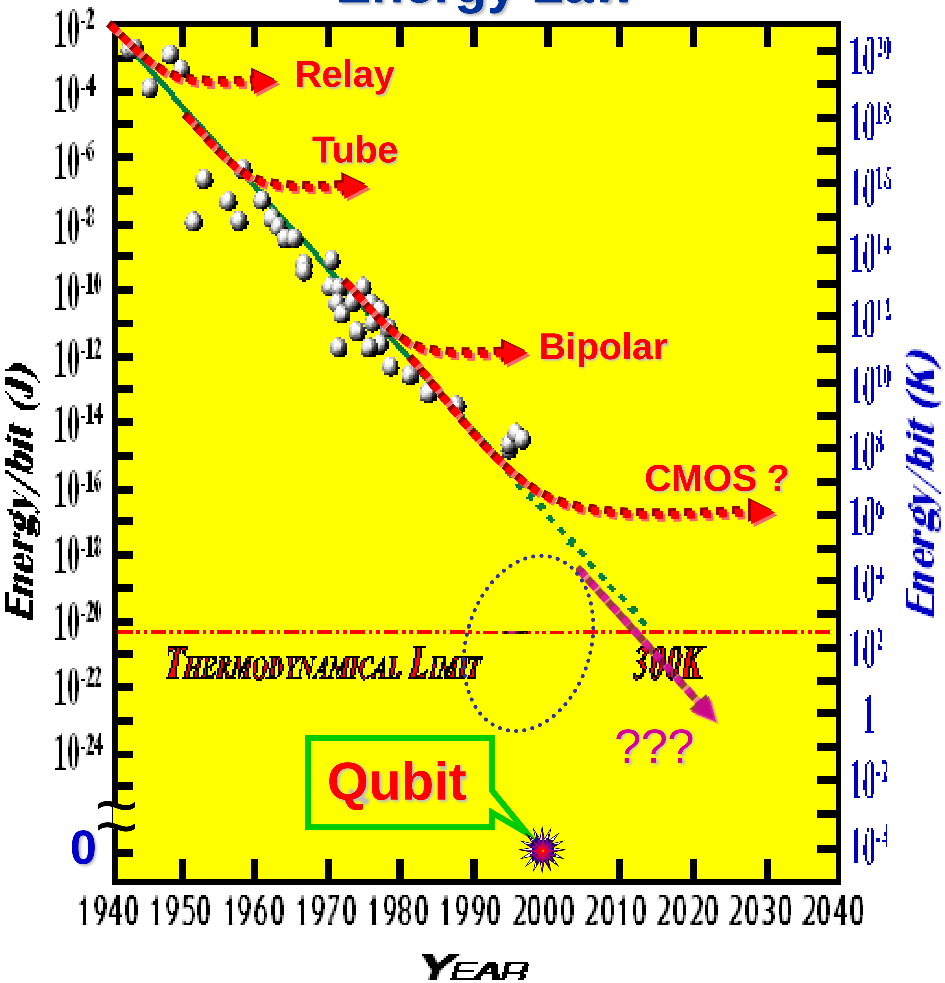


# Trend in Electronics (digital)

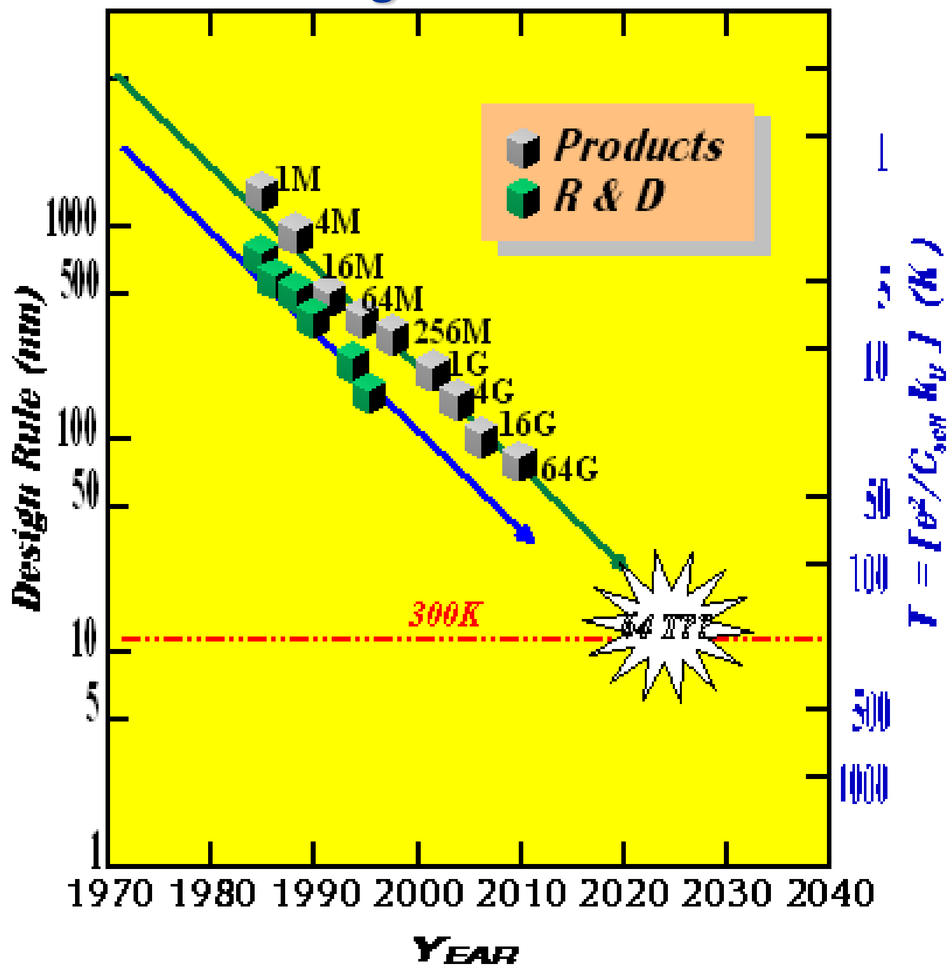
## Decreasing Energy/bit ⇒ *Less Time & Power*

## Increasing Integration ⇒ *More Information*

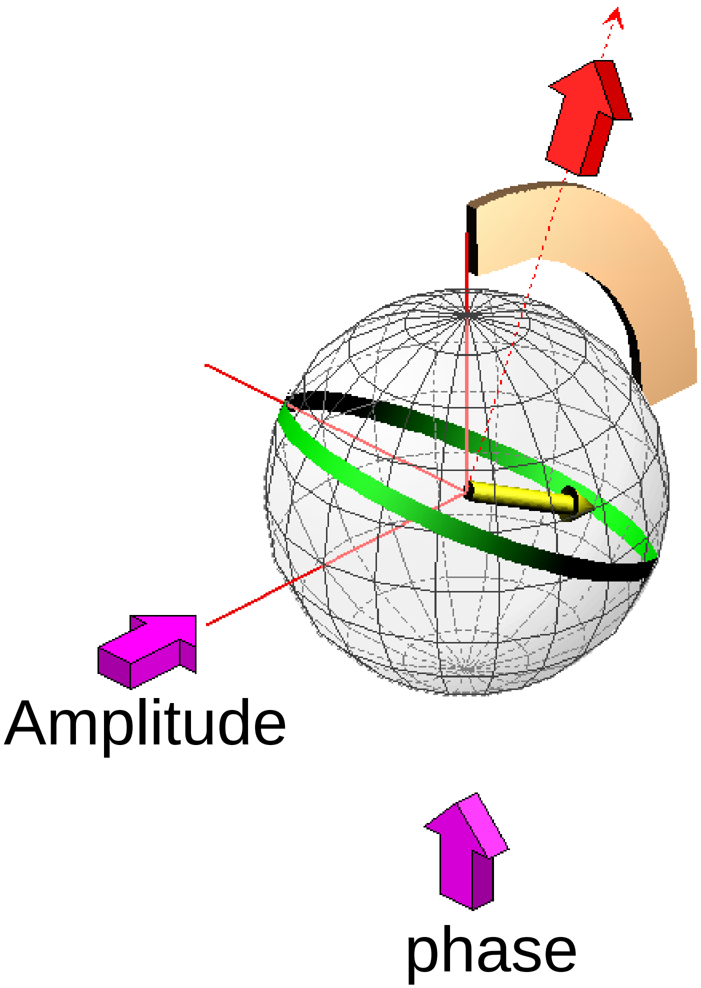
**Energy Law**




**Integration Law**



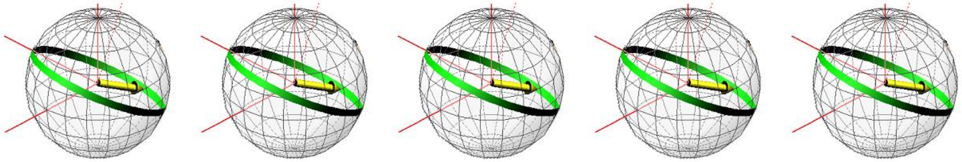
# Qubit:
# *½ spin model*




- **Long decoherence time**

$$T_2^{-1} = 0.5T_1^{-1} + T_\phi^{-1}$$

- **Many qubits**

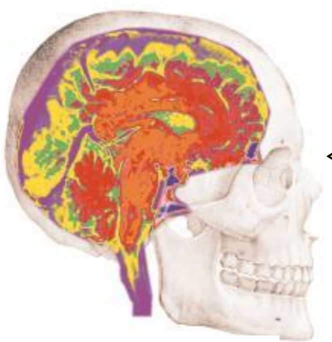


# Imaging Information Processors

Imaging Diagnostics

Input

Output

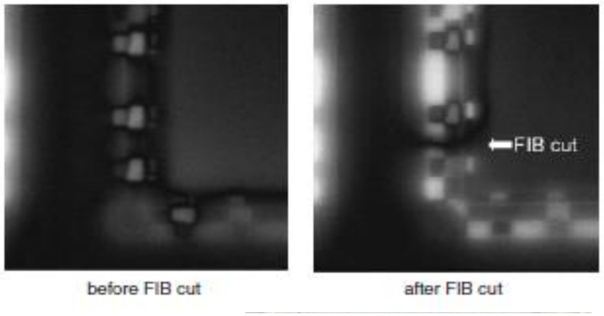


MRI image

Imaging Diagnostics

Input

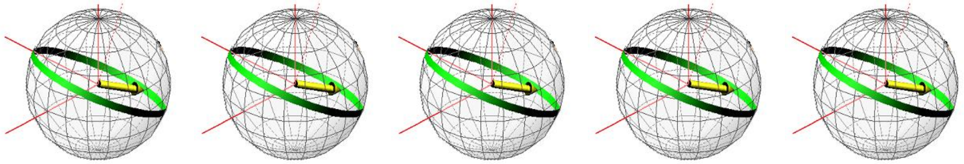
Output




Scanning laser SQUID
(Cortices of K. Nikawa)

**Imaging Quantum Computer:**

Can only be tapped at the ***end*** of calculation ⇒ ***Readout (0,1)***



Or do error correction in the ***middle*** of calculation:

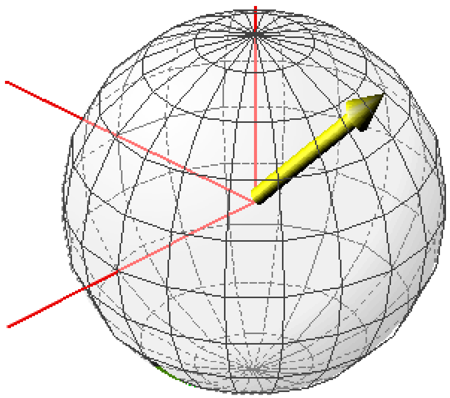
***Readout*** (projection) ⇒ ***Feedback*** (coherence)

# QUBIT READOUT

**(Imaging in space and time)**

$\alpha\,|0\rangle + \beta\, e^{i\phi}\,|1\rangle$

$|1\rangle$



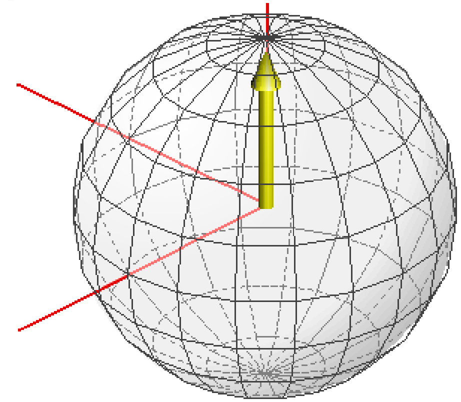
$|0\rangle$

**Observation**

Probability $|\beta|^2$

$|1\rangle$

$|1\rangle$

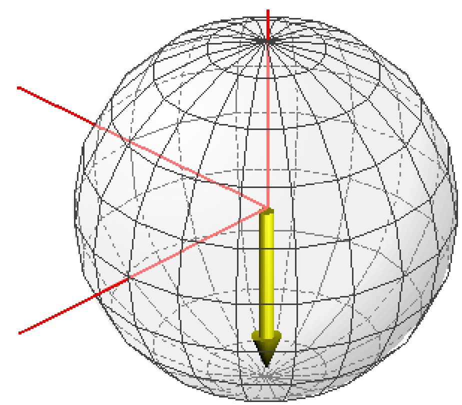


$|0\rangle$

$|0\rangle$

Probability $|\alpha|^2$

$|1\rangle$



$|0\rangle$

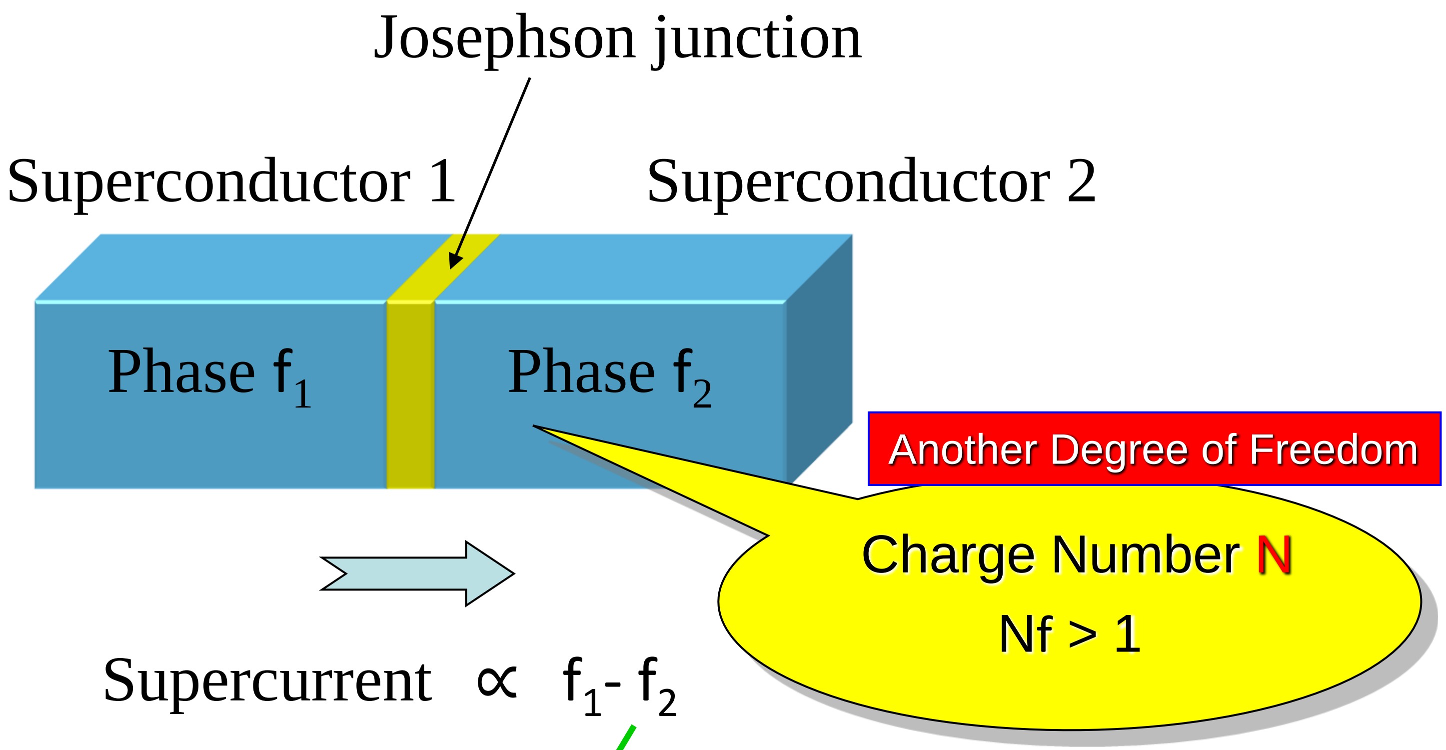
**Different from Classical Picture**

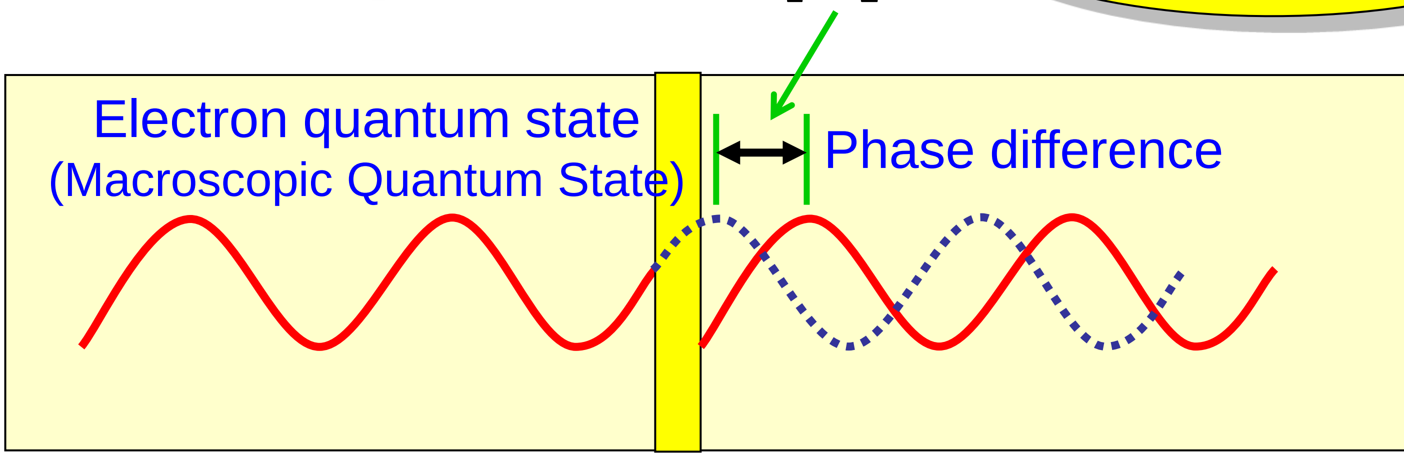
**Amplitude ⇒ *Averaging* many events**

**Phase ⇒ *Interference***

**Tomography**

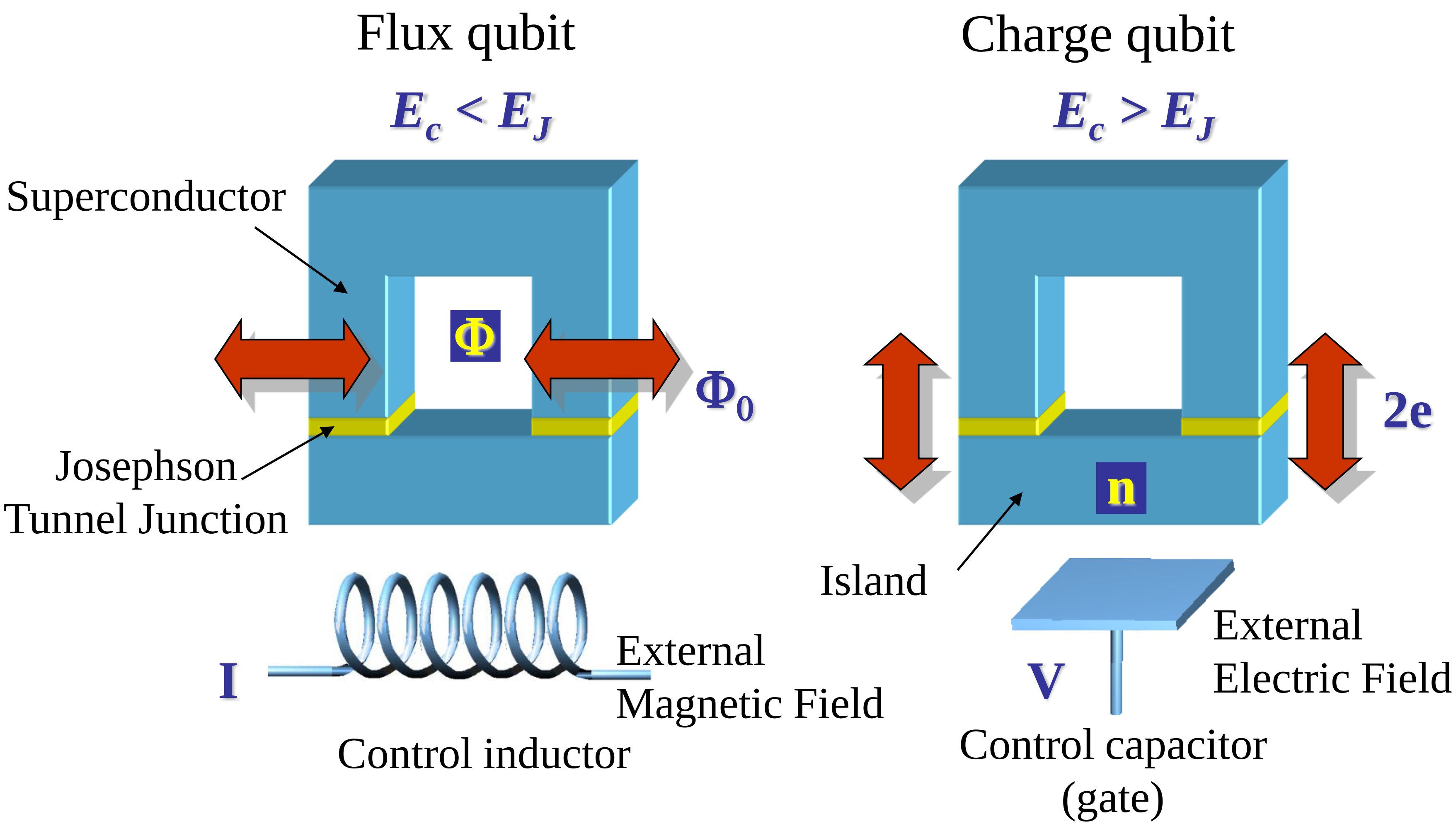
***(Cf: X ray)***



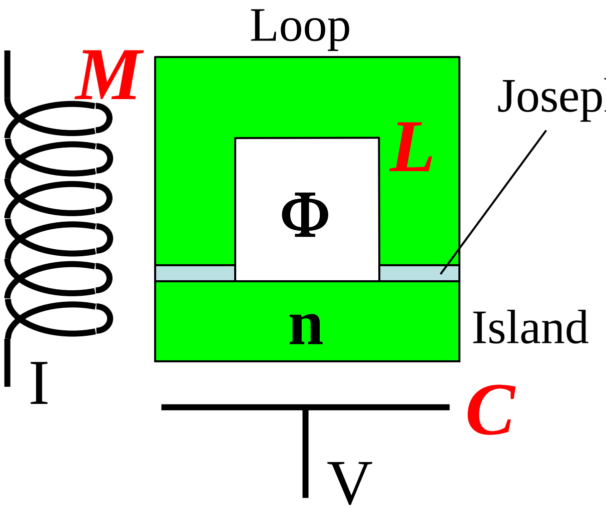



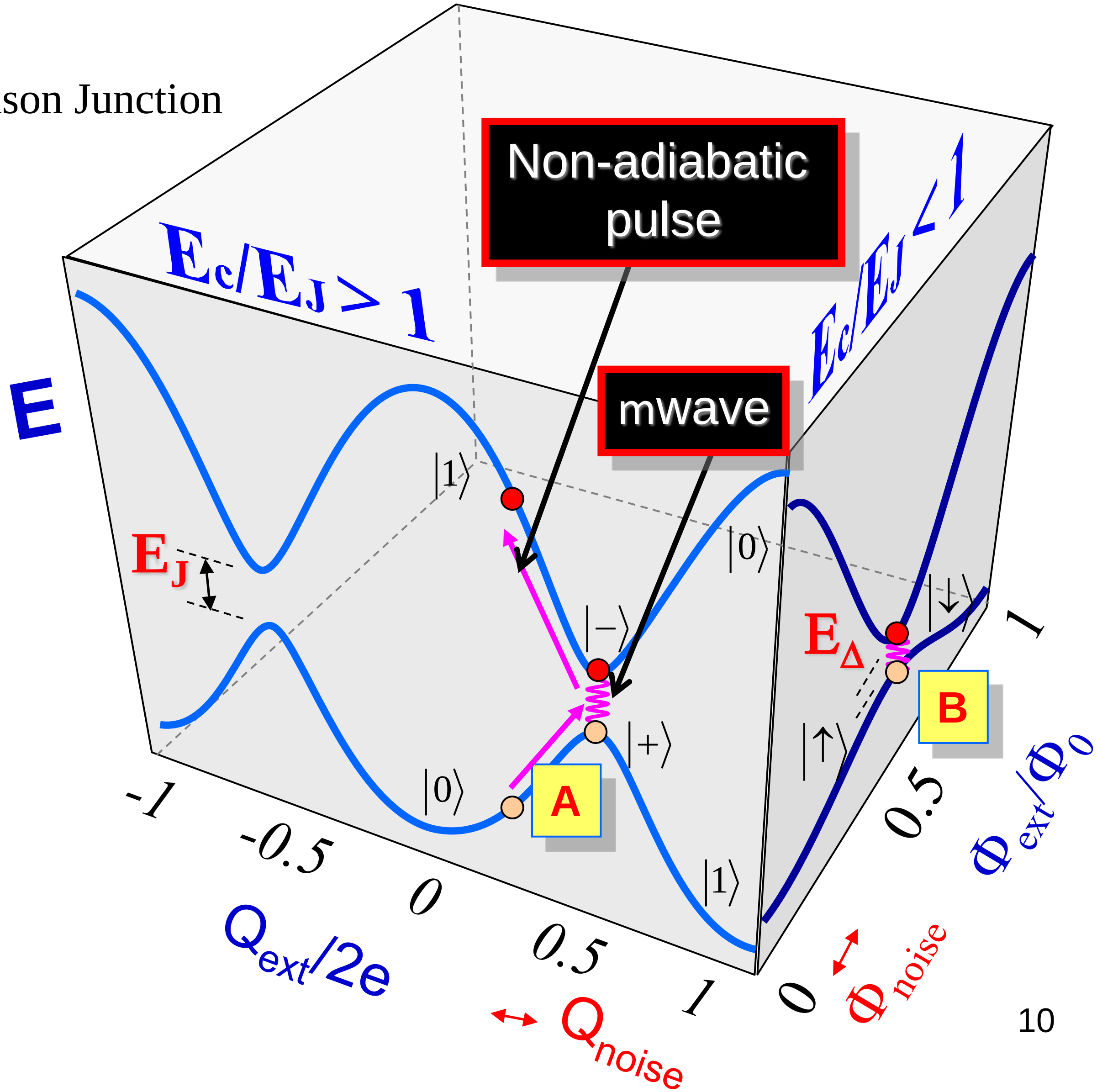

**Josephson relation:** $$\frac{d(\phi_1 - \phi_2)}{dt} = \frac{2e}{\hbar}V$$ **accurate to $\underline{1/10^{20}}$ !**

# Josephson Junction Qubits



# 2 Strategies for Operation Point
## Optimized operation: **Flat energy bands**



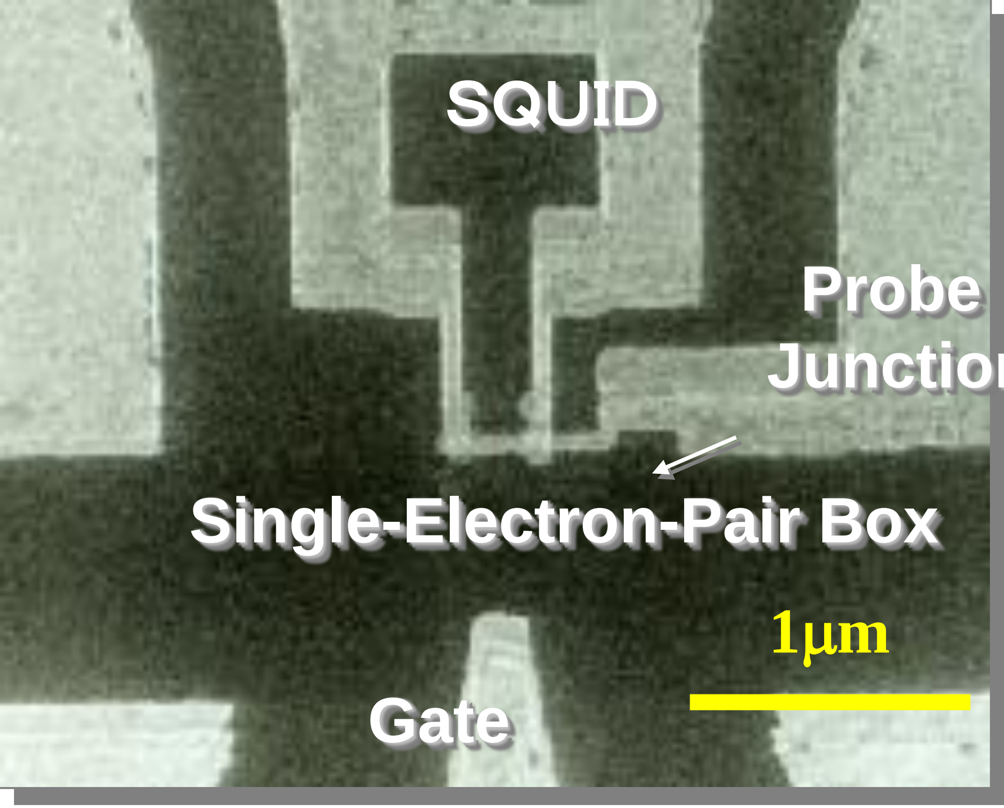




**2 Physics**

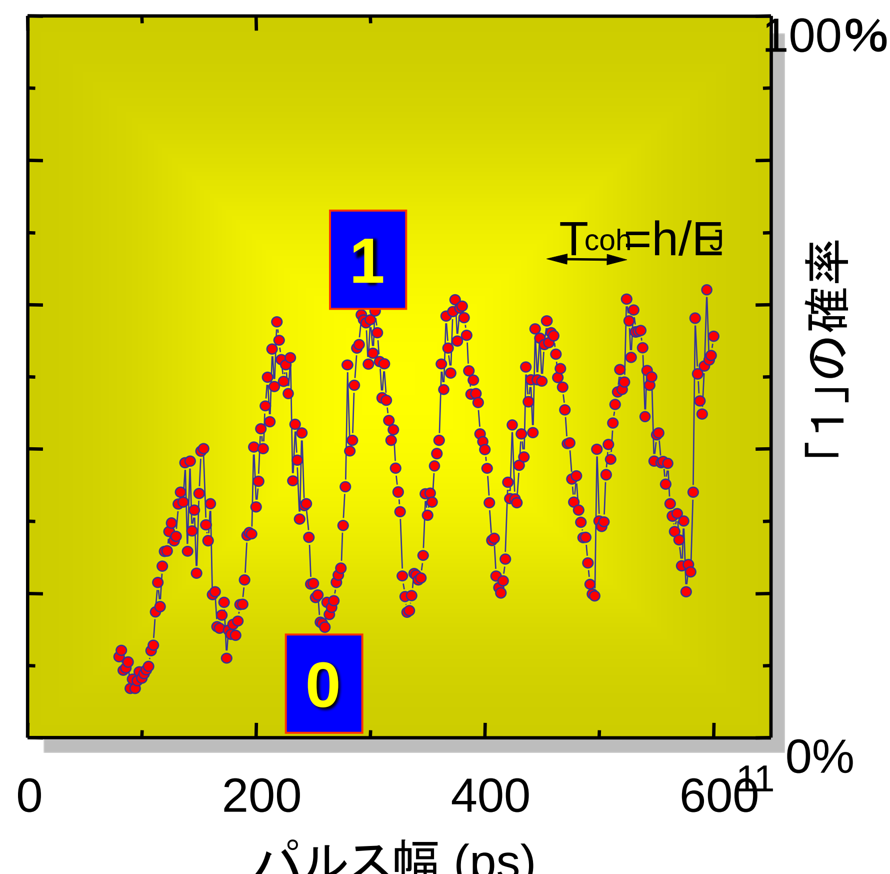
A: Charge tunnel

B: Phase tunnel

# Charge Qubit



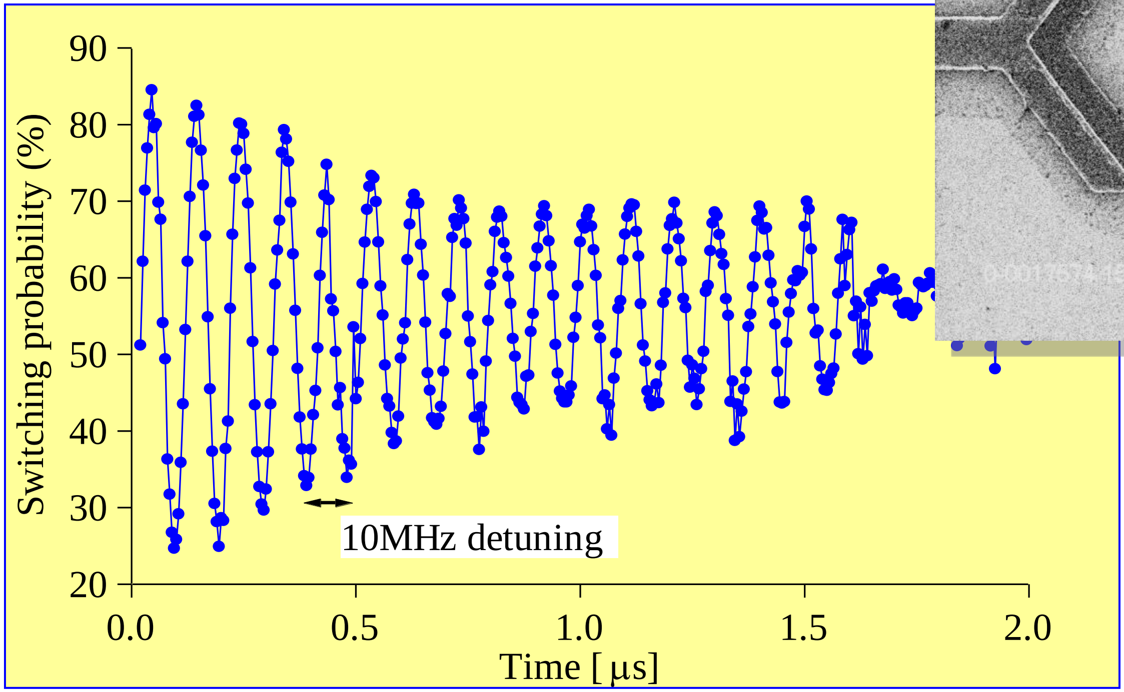

Average measurement

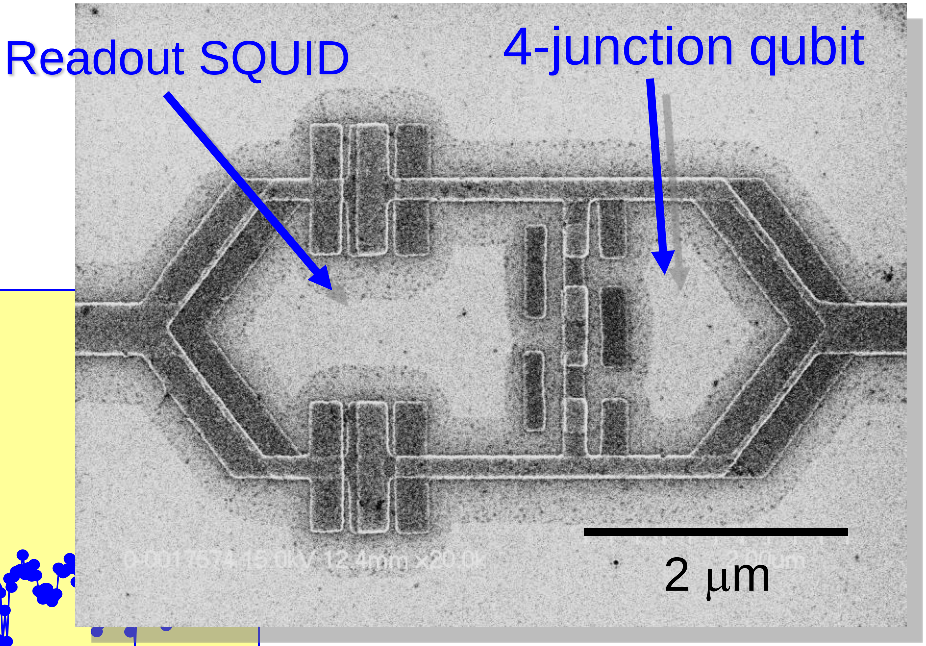



Nature, 398, 786, 1999

# Ramsey oscillations of flux qubit

- single qubit
- microwave pulse control
- SQUID switching current readout

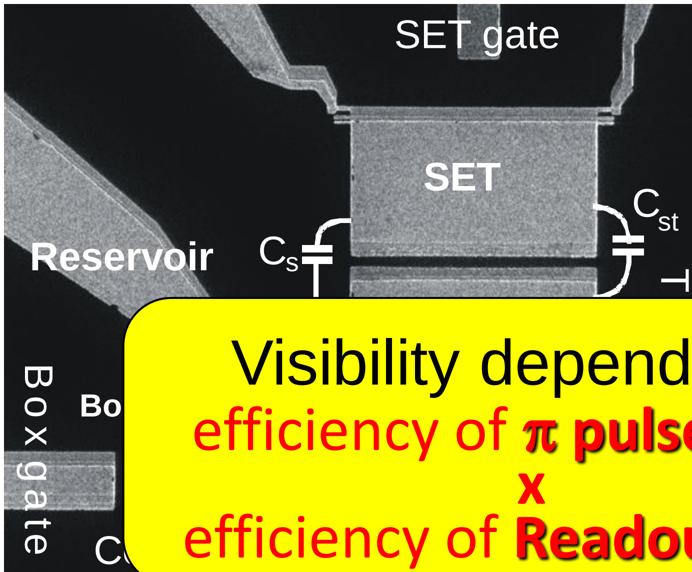


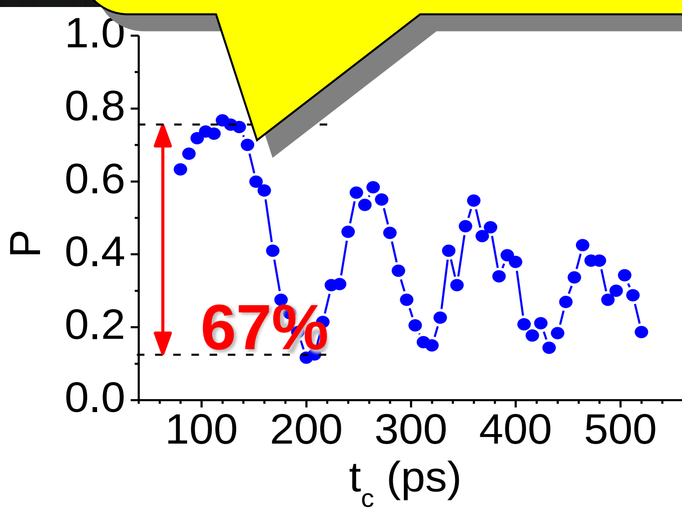
# Single-Shot Readout : Charge qubit

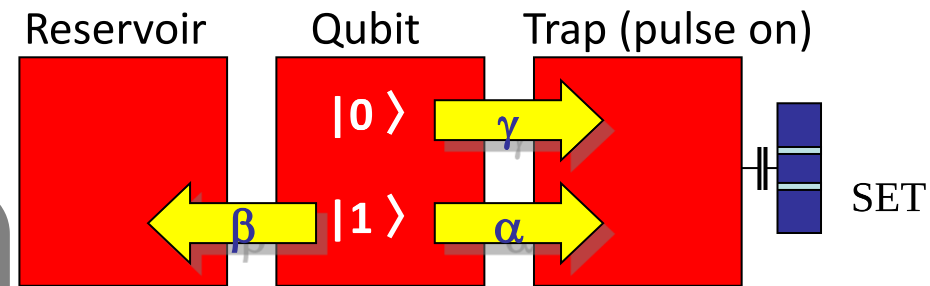
## IMPORTANCE: required for quantum algorithm

Astafiev et al, Phys. Rev. B (RC) 69, 180507, 2004



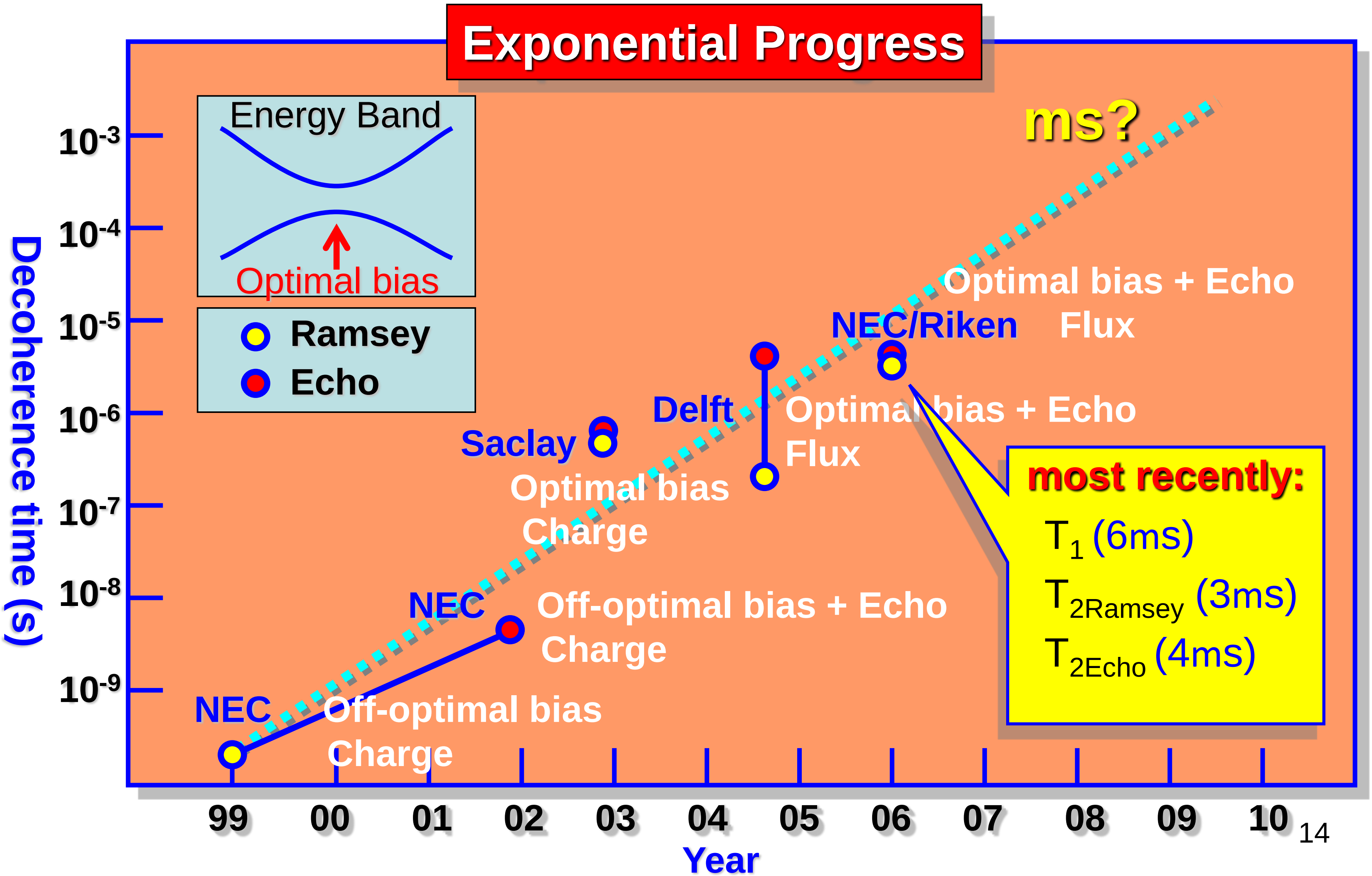

Visibility depends on:
efficiency of π pulse: 84%
x
efficiency of Readout: 87%




| | |
|---|---|
| Detection efficiency of \|0〉 | $P_0 = 1 - \gamma\, t_{RD} \approx 93\ \%$ |
| Detection efficiency of \|1〉 | $P_1 = \dfrac{\alpha + \beta\gamma\, t_{RD}}{\alpha + \beta} \approx 87\ \%$ |
| Visibility | $P_1 P_\pi - (1 - P_0) \approx 67\ \%$ |

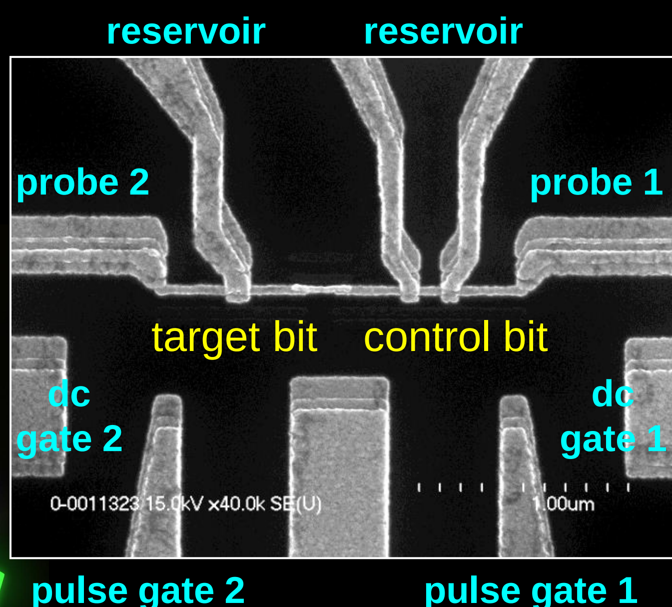
# Progress in Decoherence time *for Josephson Qubits*



# QUANTUM CNOT GATE

- FIRST SOLID STATE QUANTUM LOGIC GATE
- UNIVERSAL GATE OF QC ( Together with 1-qubit control)

*Yamamoto et al, Nature, 425, 941, 2003*




**Truth Table**

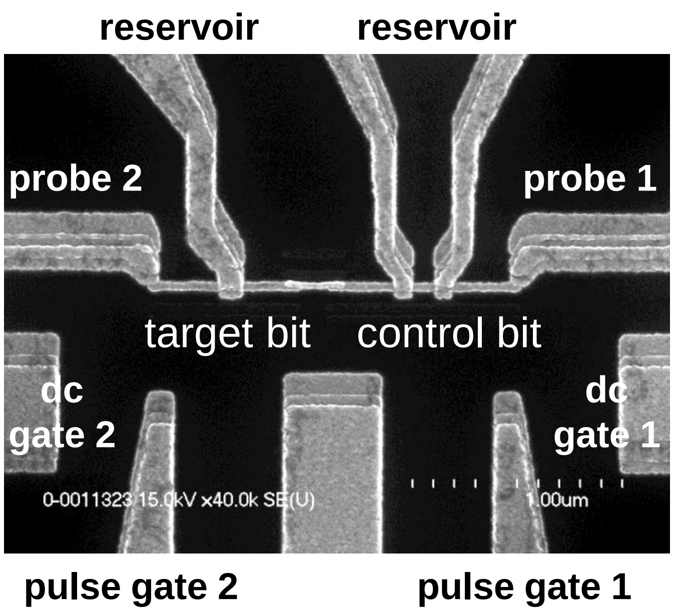
| Before CNOT | | After CNOT | |
|---|---|---|---|
| Control | Target | Control | Target |
| \|0> | \|0> | \|0> | \|1> |
| \|0> | \|1> | \|0> | \|0> |
| \|1> | \|0> | \|1> | \|0> |
| \|1> | \|1> | \|1> | \|1> |
| a\|0>+b\|1> | \|0> | a\|01> + b\|10> | |
| a\|0>+b\|1> | \|1> | a\|00> + b\|11> | |

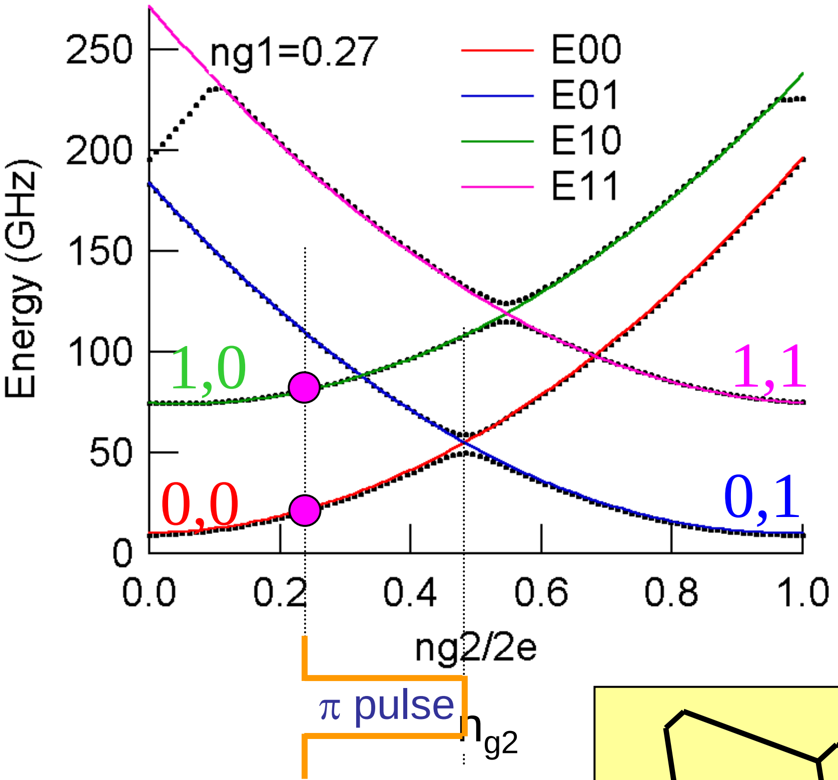
**Entanglement**

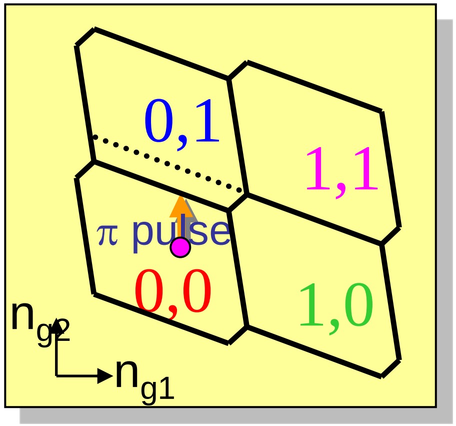
**Weak point: Coupling always ON**

# *Demonstration of controlled-NOT gate operation*

***Yamamoto et al, Nature, 425, 941, 2003***



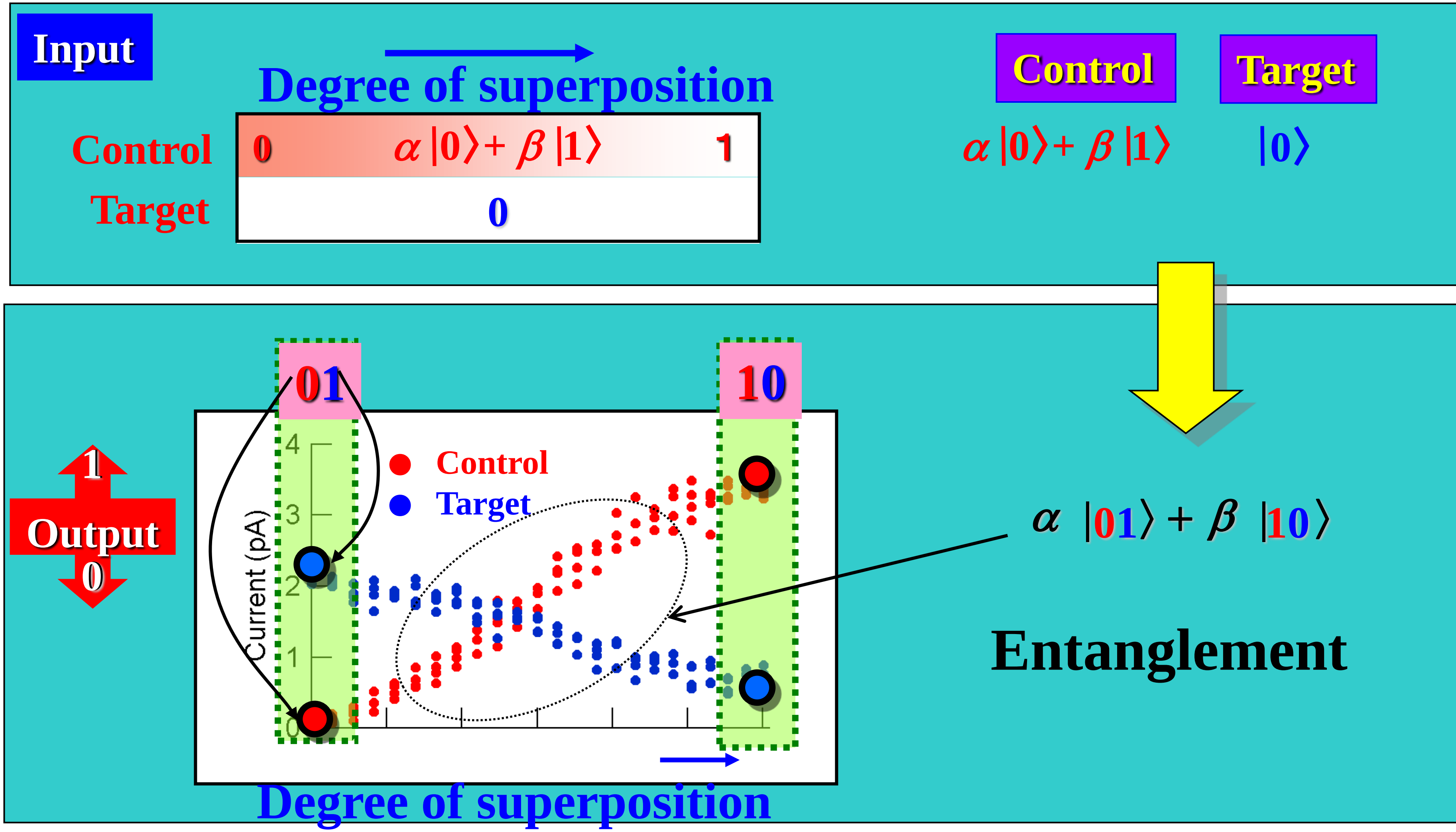

control target

$$|10\rangle \longrightarrow |10\rangle$$

$$|00\rangle \longrightarrow |01\rangle$$

conditional operation !

# Result 1

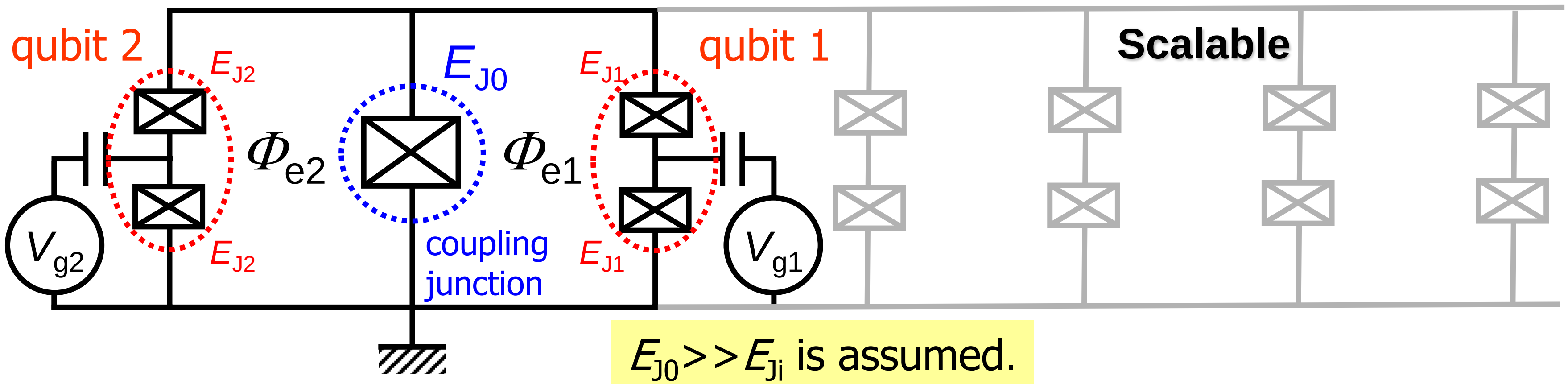



Control
Target

| Input | Output |
|---|---|
| 00 | 01 |
| 10 | 10 |

# *L*-coupled split CPB charge qubits

J. Q. You *et al.*, PRL, 89, 197902-1, 2002




$E_{J0}>>E_{Ji}$ is assumed.

charging energy    Josephson energy    tunable coupling

$$H = -\frac{1}{2}\sum_{i=1}^{2}\left[E_{ci}(1-n_{gi})\ \sigma_{zi} + 2E_{Ji}^{*}\cos(\frac{\pi\Phi_e}{\Phi_0})\ \sigma_{xi}\right] + \chi\ \sigma_{x1}\ \sigma_{x2}$$

$$\chi = L_J I_{c1}\sin(\frac{\pi\Phi_{e1}}{\Phi_0}) I_{c2}\sin(\frac{\pi\Phi_{e2}}{\Phi_0})$$

Coupling is controlled by external magnetic field.

$\Phi_e=0$ → $\chi=0$, no coupling

$\Phi_{e1}, \Phi_{e2}\neq 0$ → finite coupling (maximum@$0.5\Phi_0$)

# Josephson Qubits:

Macroscopic Coherence CAN BE:

- Controlled (~few % error)
- Maintained (~few microseconds)
- Readout (~ accuracy better than 90%)

Universal Gate Demonstrated

- CNOT

Adjustable Coupling BEING PURSUED

Future Prospective?