Solid State Quantum Computing

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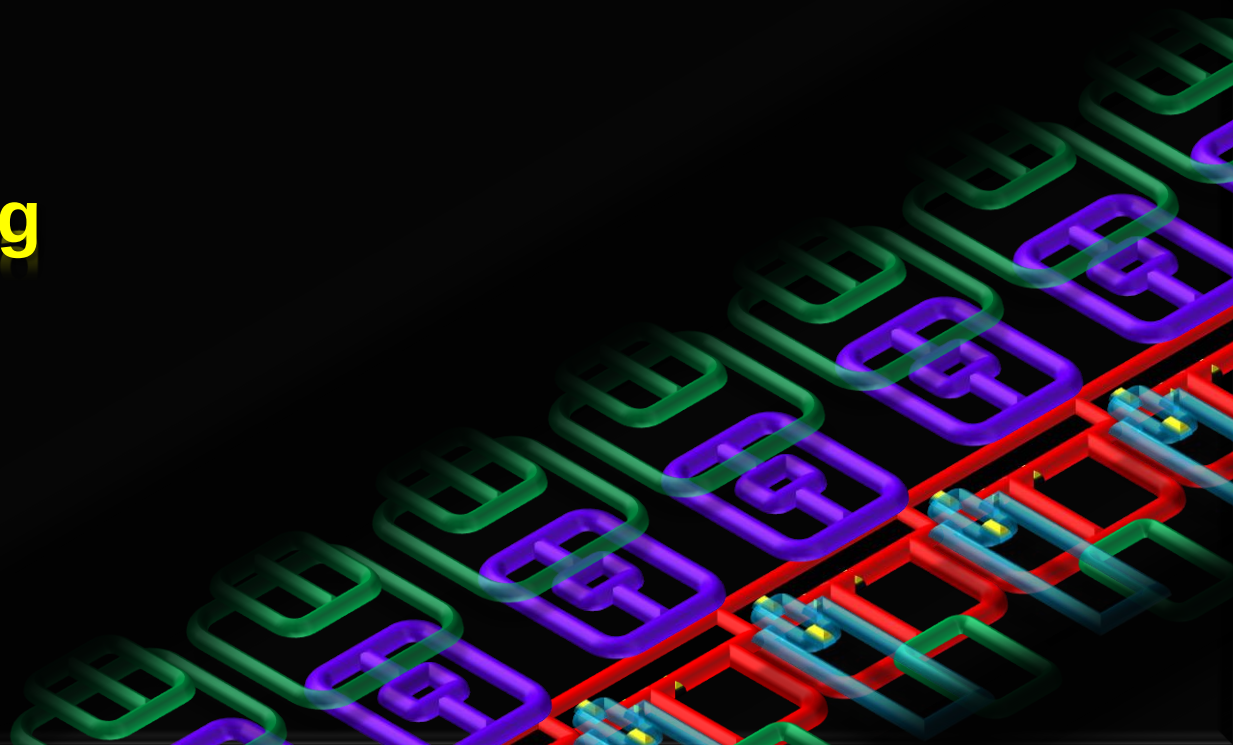
NEC/Riken

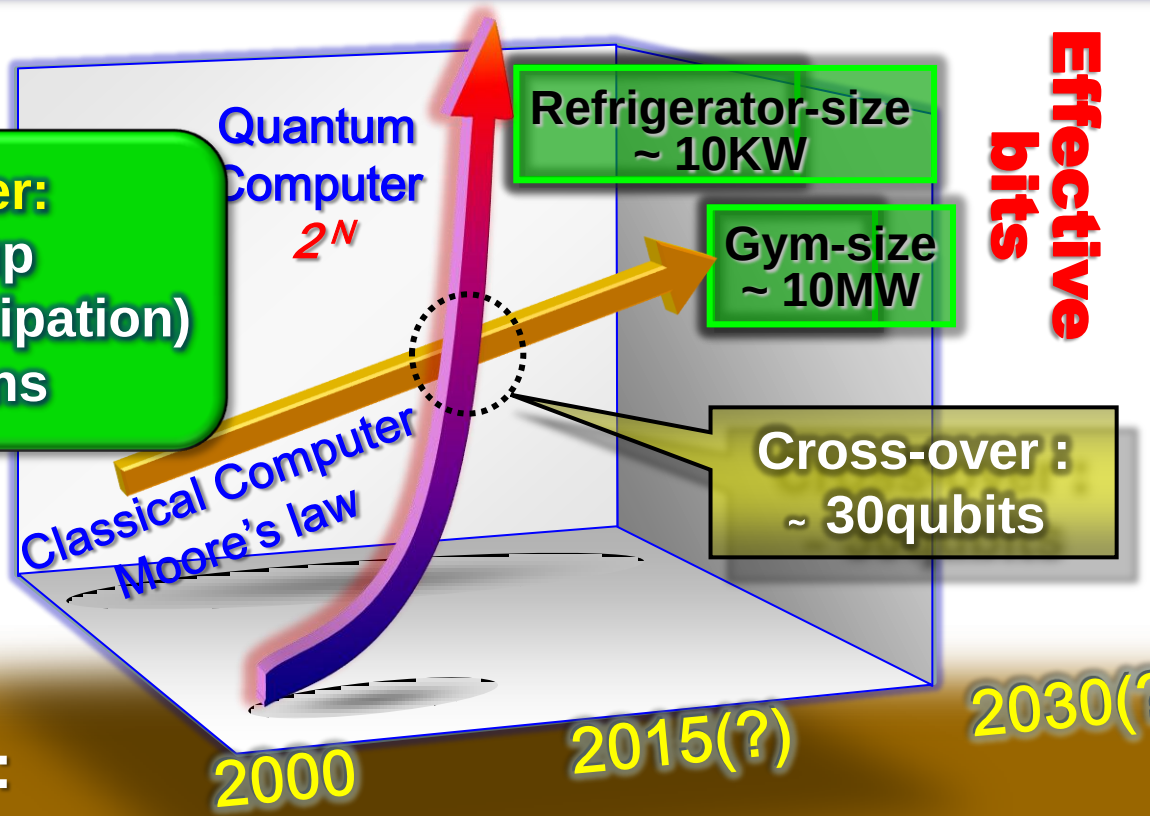
NANO-TEC, Athens, 10/13/2011

Decoherence
Integration Scaling

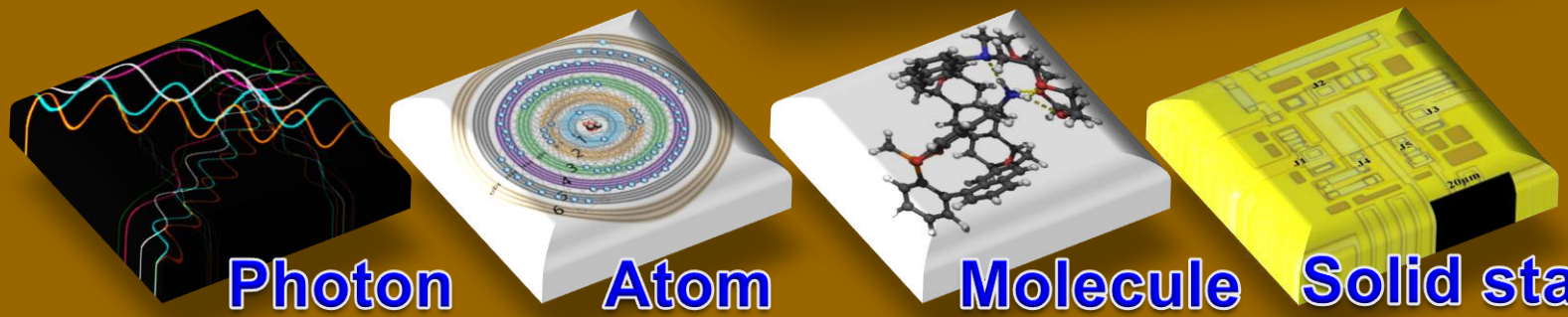


New Paradigm of Computing

Quantum Computer:
- Exponential speed up
- Low energy (no dissipation)
- Not for all applications



Physical realizations:



TRANSMISSION

LONG LIFE, UNIFORMITY

INTEGRATION, DESIGN/CONTROL FREEDOM

What can quantum computing (QC) do?

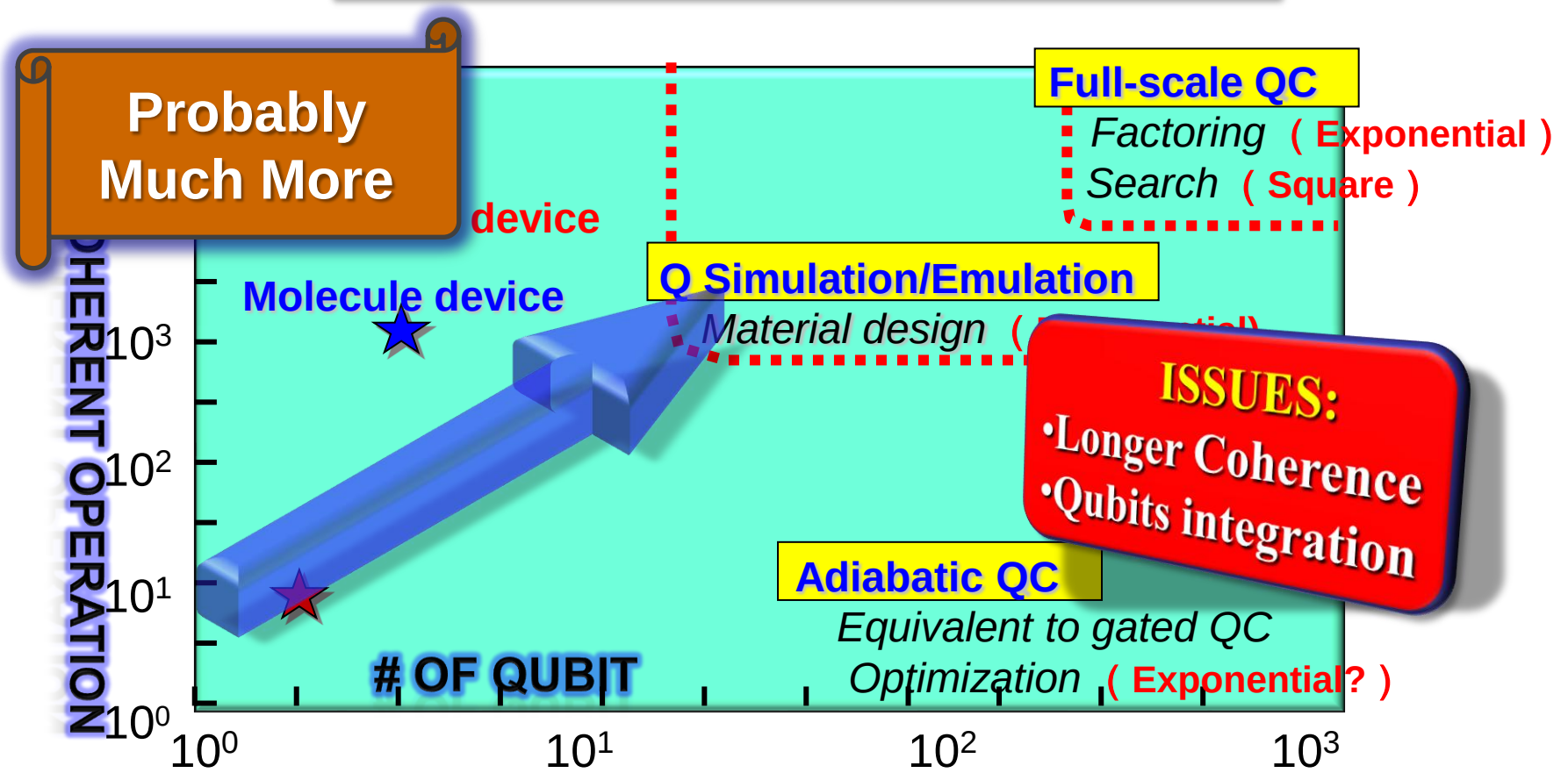
Hypothetical Quantum Computer

Breaking SSL128 (RSA1024):

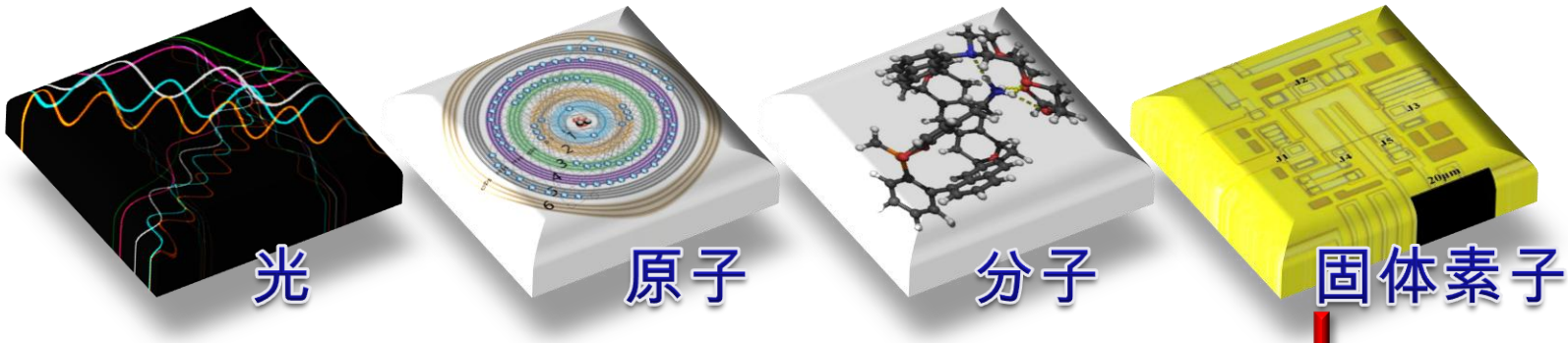
Number of qubit: 3ln(1024) X 7 (QEC) = ~ 20000 qubits

Computing time: 1024^3 X 10^4 (QEC) X 10 (connection) X GHz^{-1} = ~ 30h

C f : Supercomputer (35MW) : 3 M years



量子ビットの実現



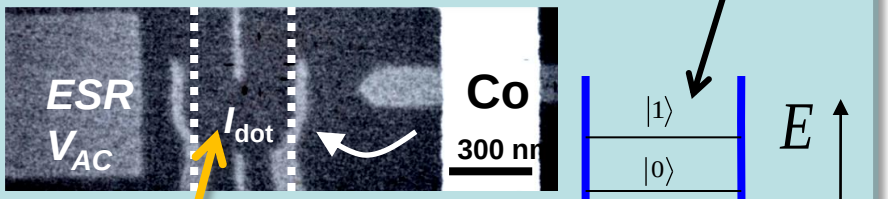
特

固体素子： 集積化、設計自由度、制

分子： 長寿命 均 送

半導体
量子ドット

超伝導体
ジョセフソン
接合



量子ドット

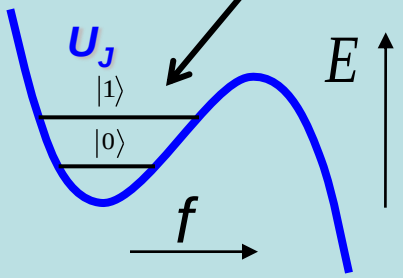
単電子状態

スピン量子ビットX

自由度： スピン、電荷数、ポーラロン

ジョセフソン接合

巨視的状態



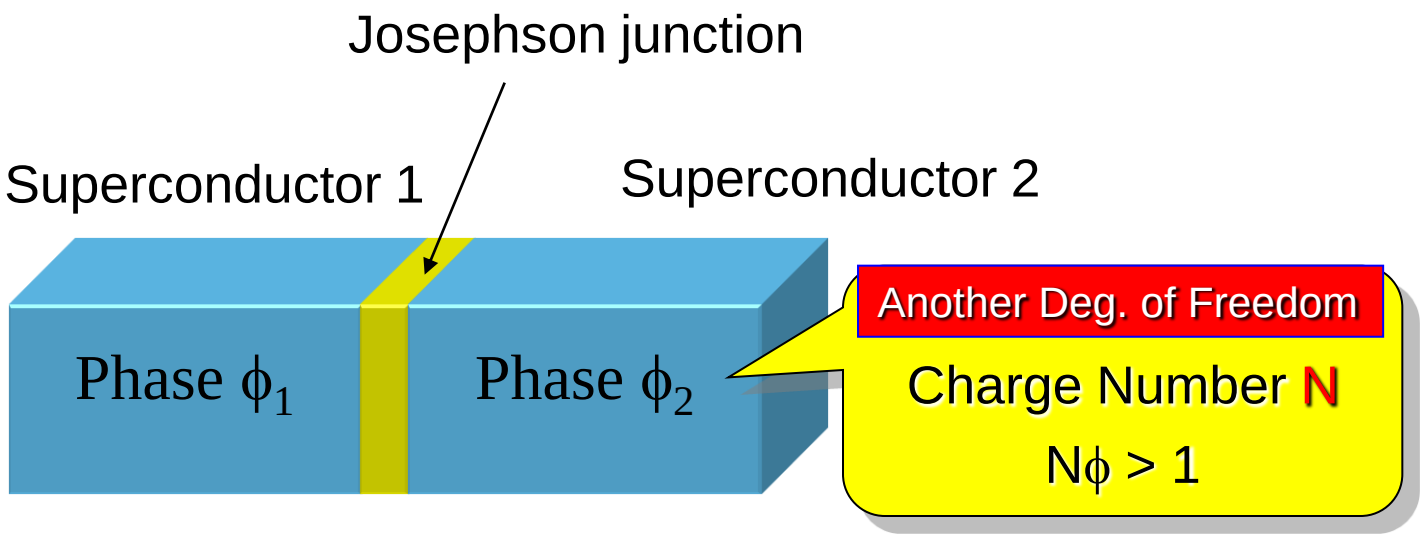
位相量子ビット

自由度： 位相差・磁束、電荷

A Macroscopic System

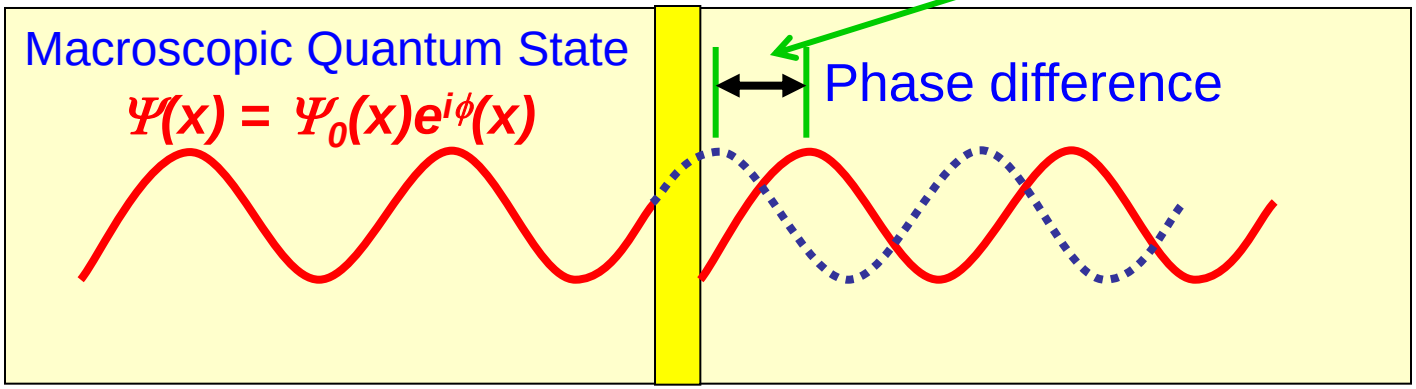
Macroscopic order parameter

$\psi(x) = \psi_0(x)e^{i\phi(x)}$



Supercurrent $\propto$ $I_0 \sin(\phi_1 - \phi_2)$

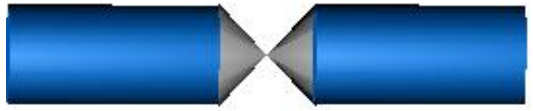
$$V = \frac{h}{2e}\frac{d\varphi}{dt}$$



Josephson junction

Secondary Macroscopic Quantum effect

Multi-energy state (cf. solitary BCS state)



$$C, \quad L_J = \frac{\Phi_0}{2\pi I_C \cos\theta}$$

Aharmonic oscillator

$$H = E_C N^2 + E_J(1-\cos\theta)$$

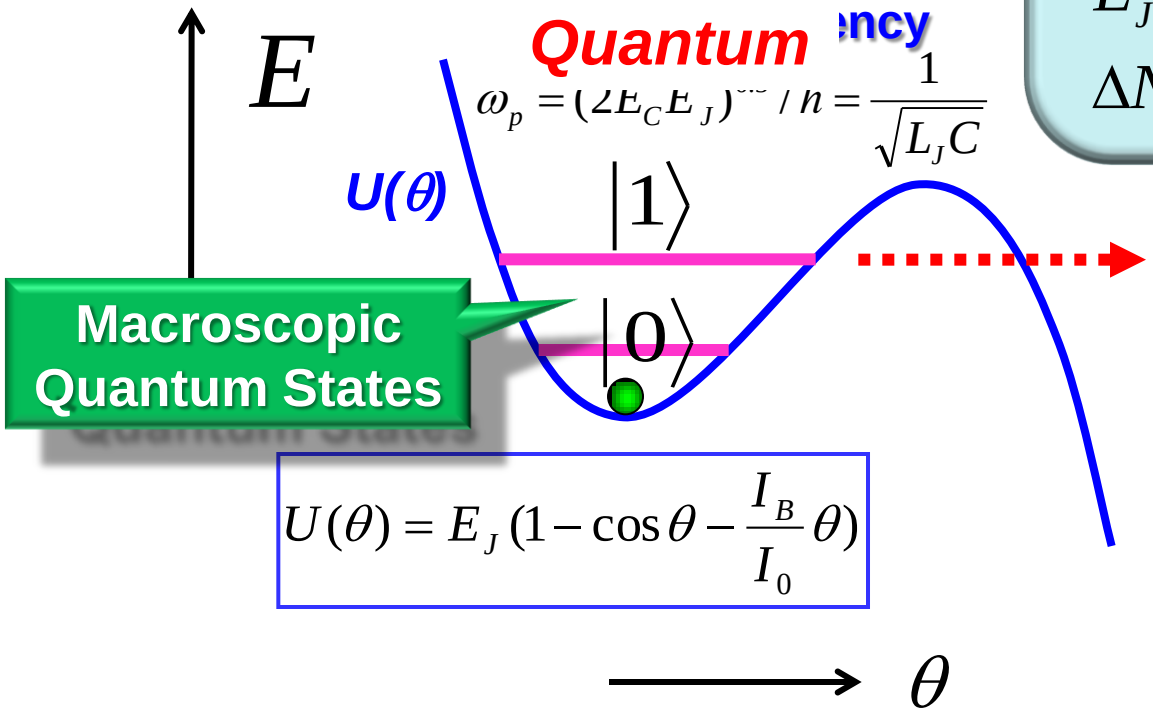
$$E_C = \frac{2e^2}{C}$$

$$E_J = I_0 \Phi_0$$

$$\Delta N \cdot \Delta\theta \geq 1/2$$

Quantum

$$\omega_p = (2E_C E_J)^{1/2} / n = \frac{1}{\sqrt{L_J C}}$$



Macroscopic Quantum States

$$U(\theta) = E_J\left(1-\cos\theta - \frac{I_B}{I_0}\theta\right)$$

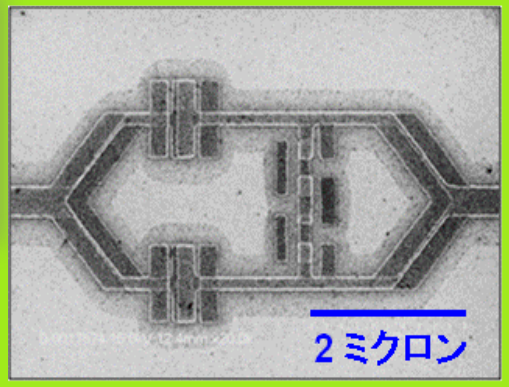
Macroscopic Tunneling

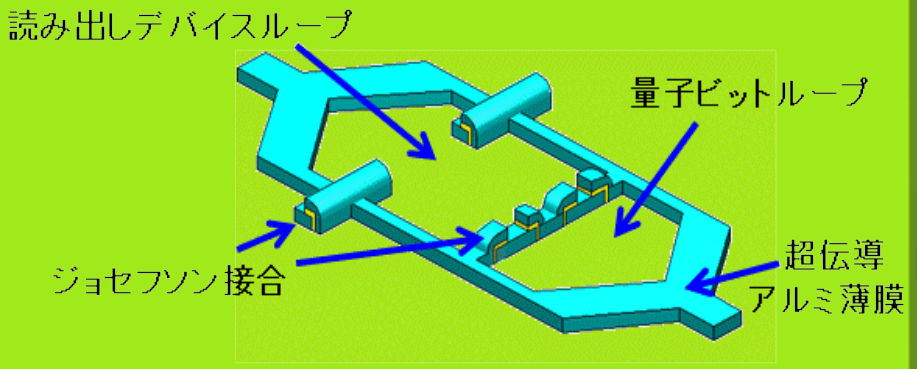
Phys. Rev. Lett. ***47****, 265 (1981)*

Level Quantization

Phys. Rev. Lett. 55, 1543 (1985)

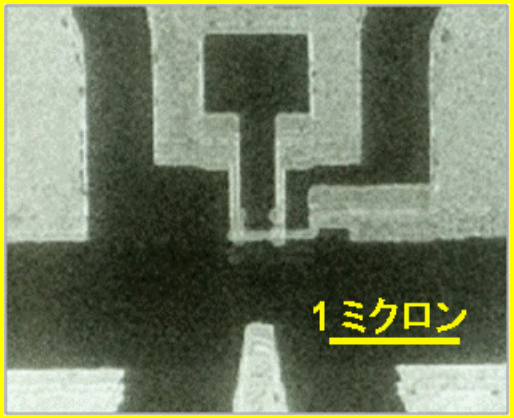
超伝導
磁束
量子ビット

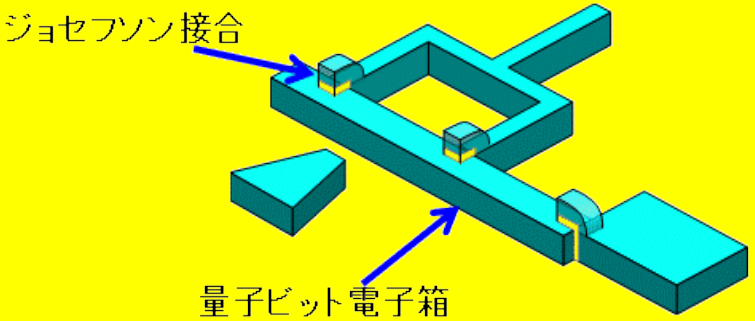




量子状態(例):
- 「0」状態: 量子ビットループに時計回りの永久電流
- 「1」状態: 量子ビットループに反時計回りの永久電流

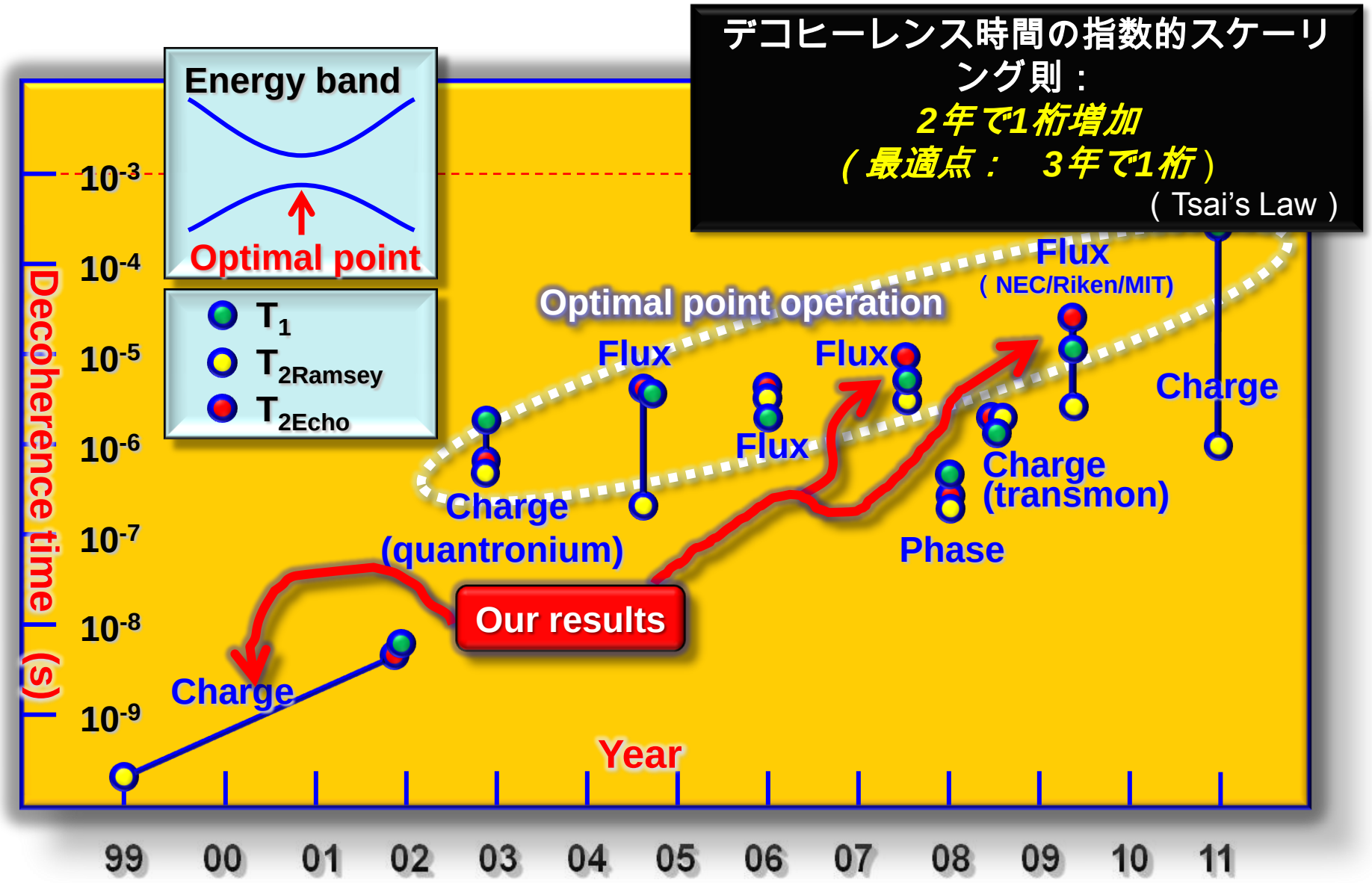
超伝導
電荷
量子ビット





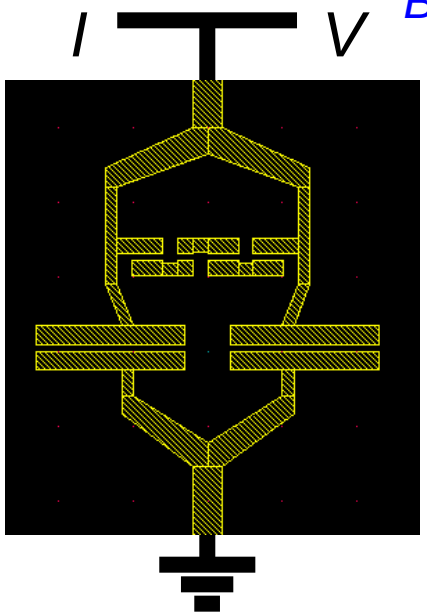
量子状態(例):
- 「0」状態: 量子ビット電子箱に余剰電子がない
- 「1」状態: 量子ビット電子箱に余剰な電子対が一つある

Progress in Decoherence time for Josephson Qubits



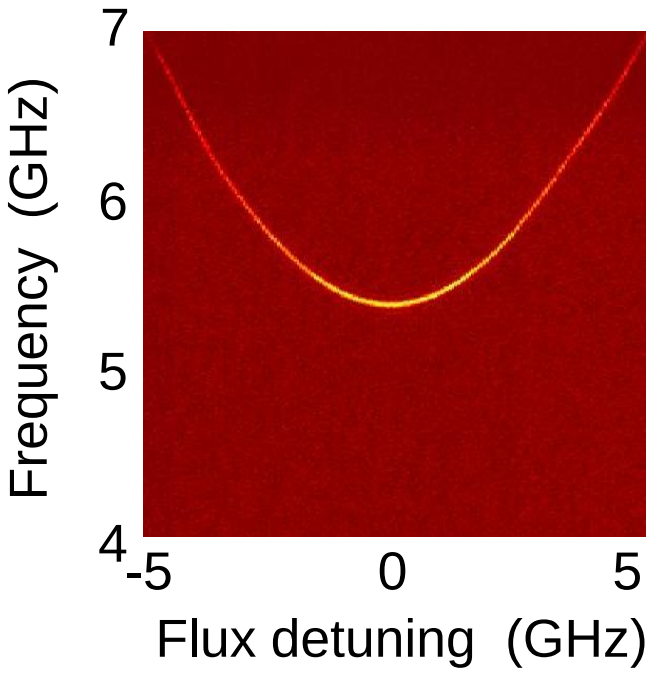
Long decoherence sample (with MIT)

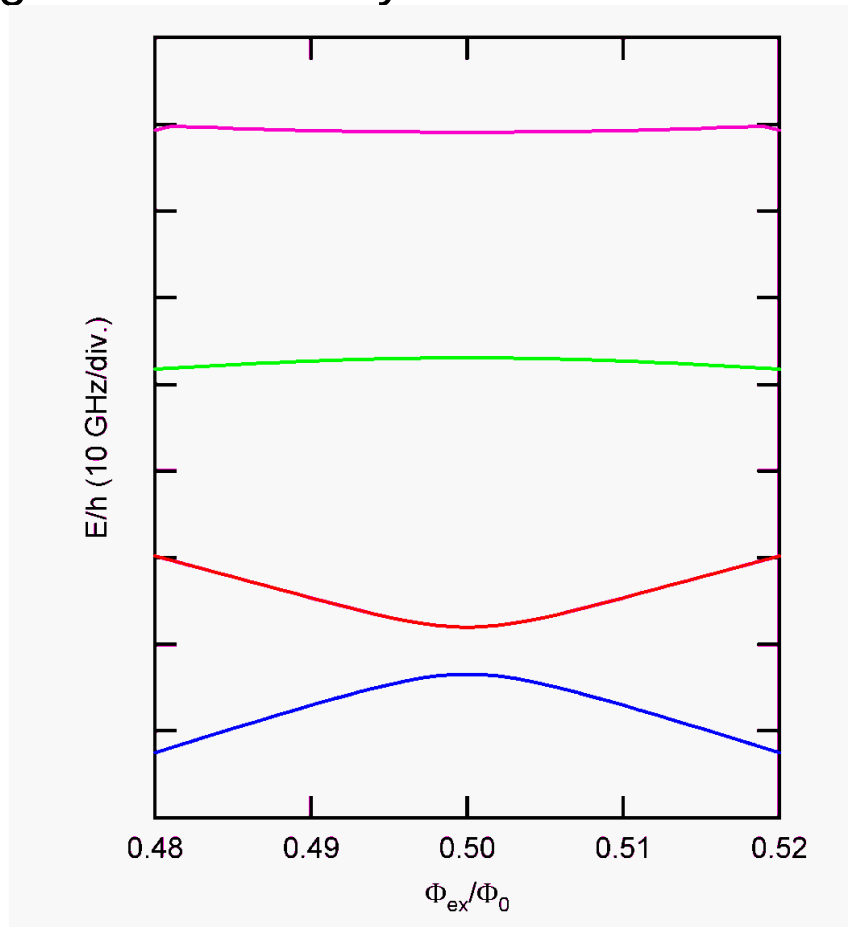
Bylander et al, **Nature Physics**, doi:10.1038/nphys1994, 2



Aluminum 4JJ flux qubit on SiO_2/Si

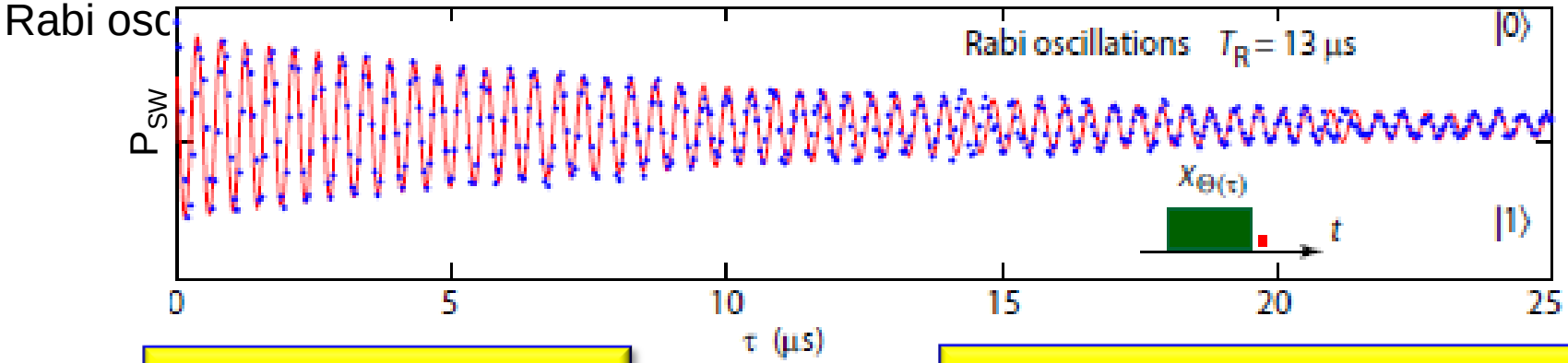
- Δ/h = 5.4 GHz
- I_P = 180 nA
- Large anharmonicity ~ 5
- E_J/h ~ 210 GHz
- E_C/h ~ 4 GHz
- α ~ 0.54



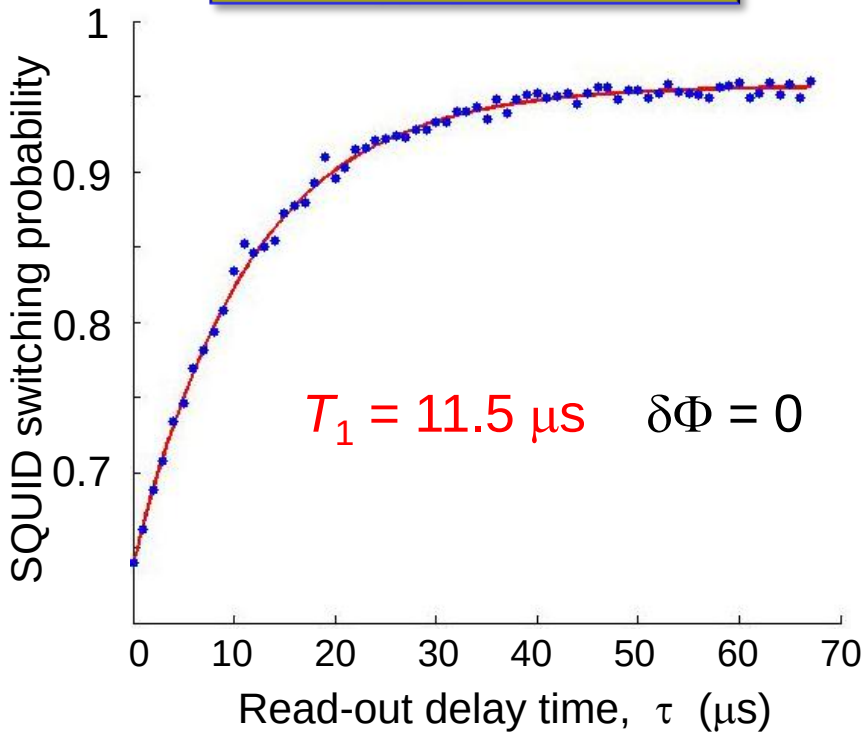


T_1 and T_2^{echo} at optimal point (with MIT)

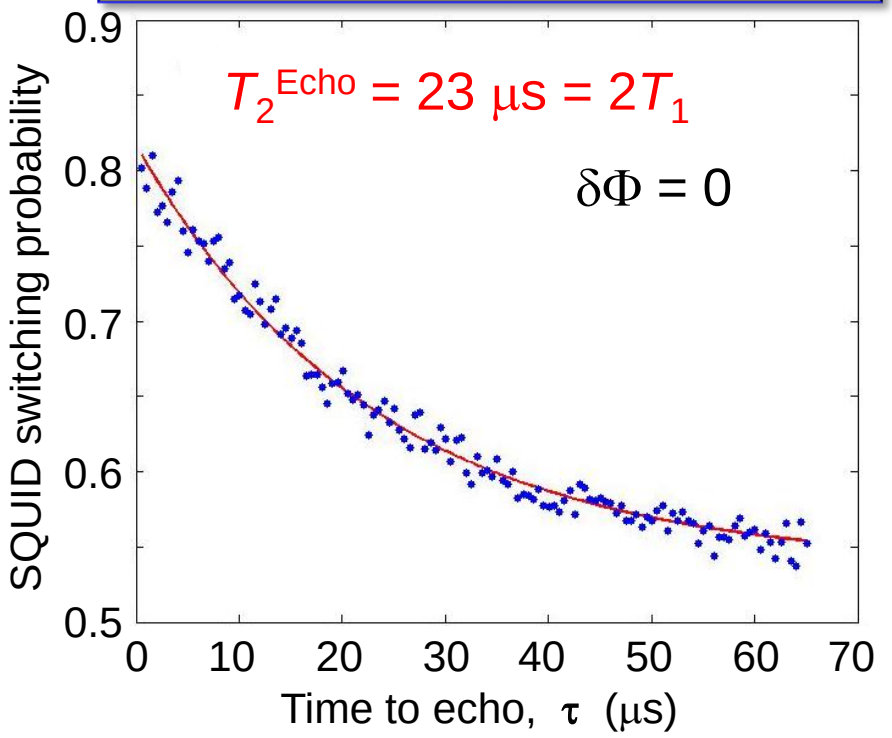
Bylander et al, **Nature Physics**, doi:10.1038/nphys1994, 2

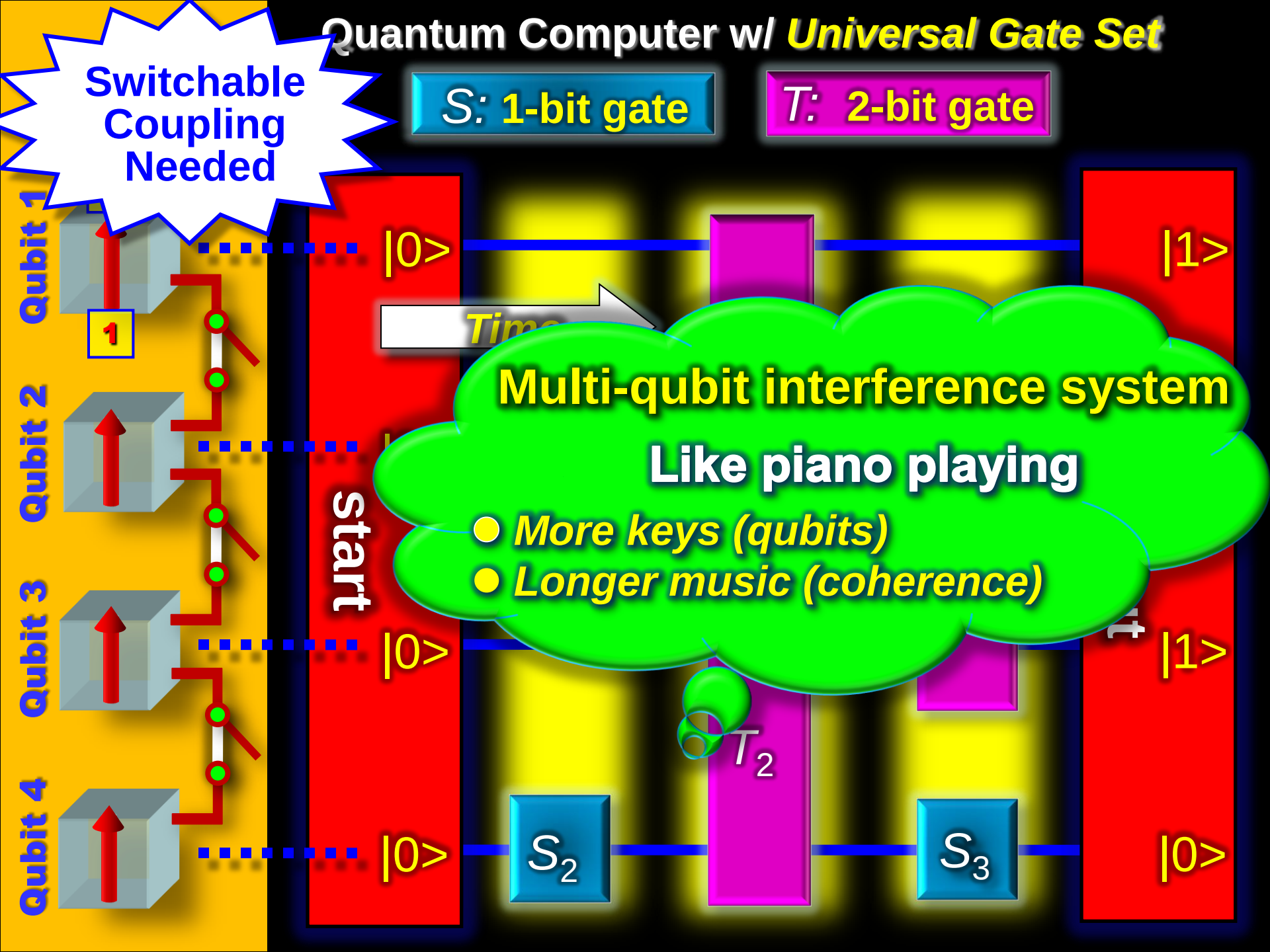


Q = $\omega_{01}T_1$ ~ 390,000



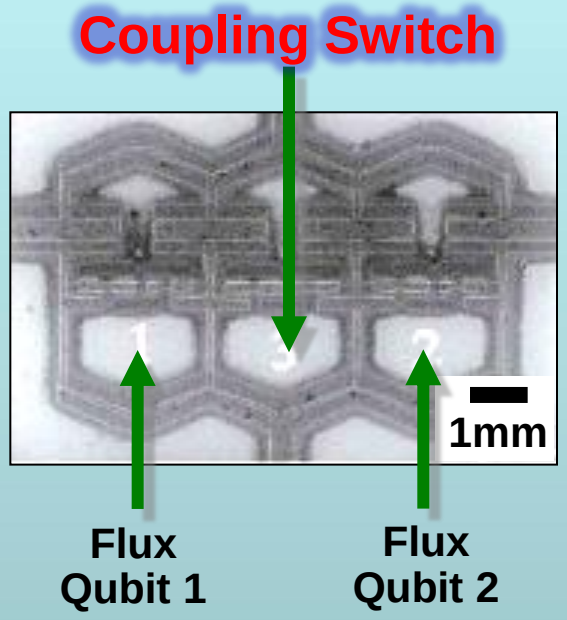
Pure dephasing time ~ 0.1ms




Quantum Computer w/ Universal Gate Set
Switchable Coupling Needed
S: 1-bit gate
T: 2-bit gate
Qubit 1
Qubit 2
Qubit 3
Qubit 4
1
start
|0>
|0>
|0>
|1>
|1>
|0>
Time
Multi-qubit interference system
Like piano playing
More keys (qubits)
Longer music (coherence)
T2
S2
S3

Progress in Scaling Up for Josephson Qubits

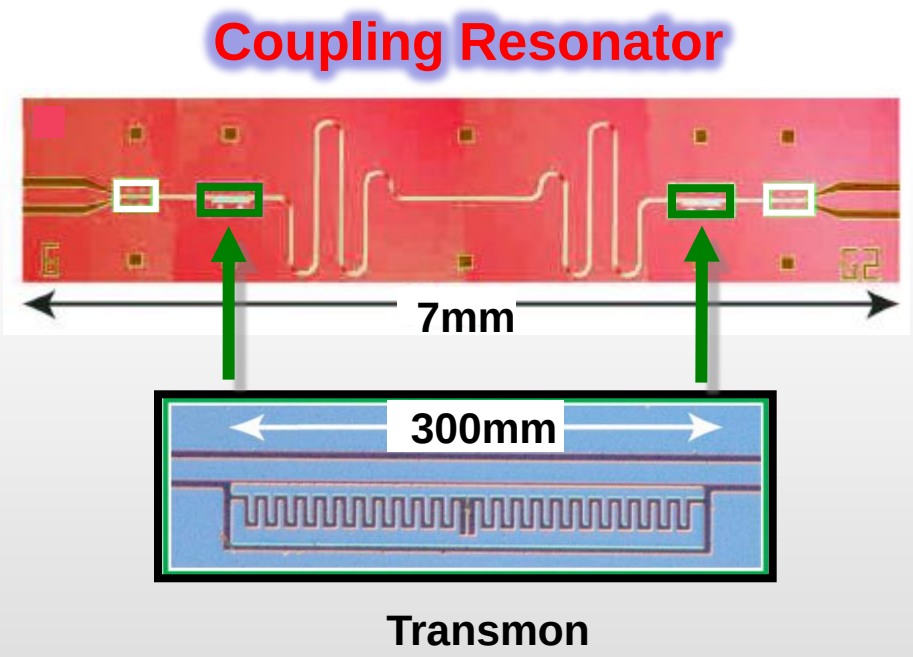
Adjustable Coupling Energy



Optimal point operation

Flux qubit:
Science, 316, 723 (2007)

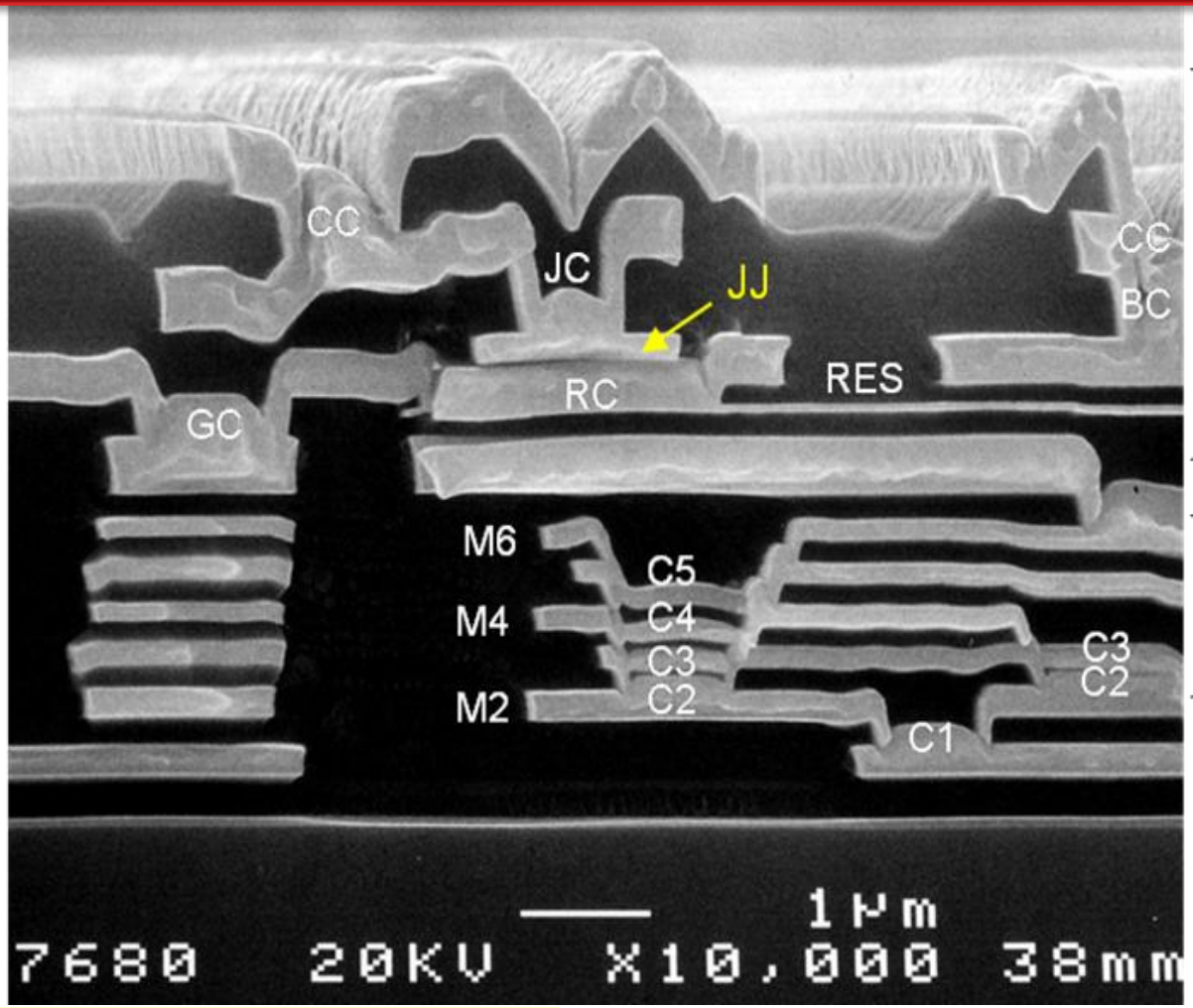
Fixed Coupling + non-adiabatic detuning



Phase qubit: Nature, 449, 438 (2007)
Charge qubit: Nature, 449, 443 (2007)

10-Nb-layer Josephson chip by the ISTEC

New effort to realize Al multi-layer qubits with EBL



The number of Nb layers: 10
J_c: 10 kA/cm^2
Sheet resistance ($R_{\square}$): 2.4 Ω

Minimum JJ size: 1×1 μm
Minimum line width: 1 μm
Stacked contact

超伝動量子万能ゲート計算理研，NTT

ター状態計算NTT

子計算理研

口波光子量子計算理研

量子ビット結合器理研

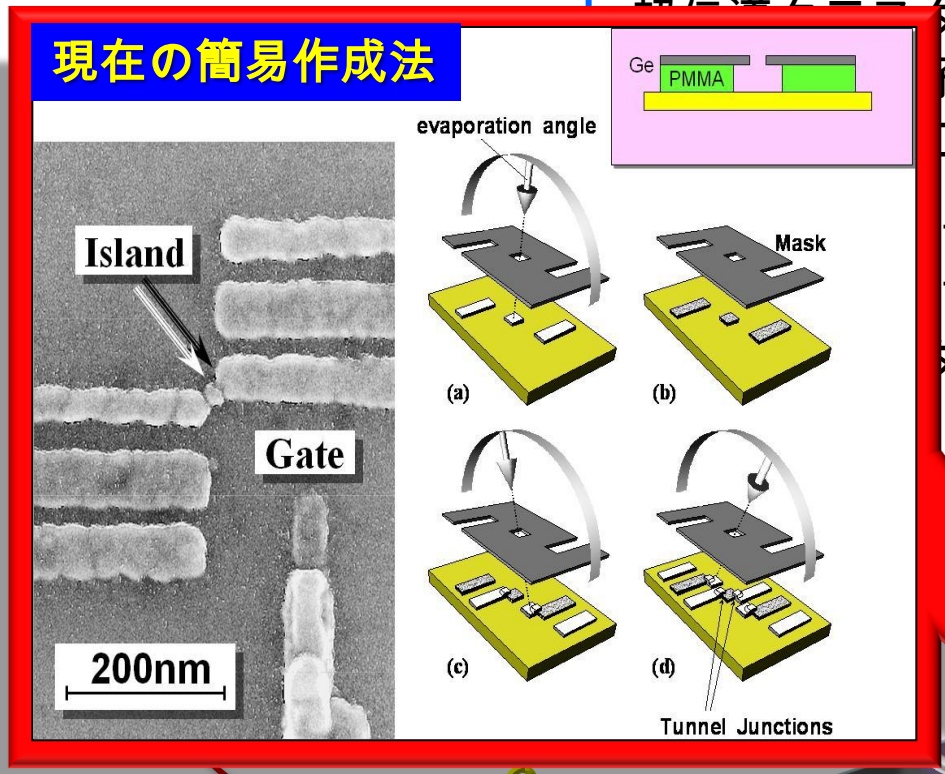
量子バス理研，NTT

ターフェイス東京理科大

パルサー理研

術理研

最先端Pjターゲッ
（4年）

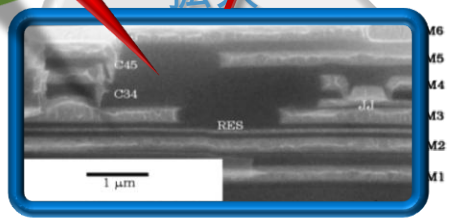


多チャンネル
マイクロ波パル
サー

光子

超伝導プロトタイプ
量子計算チップ

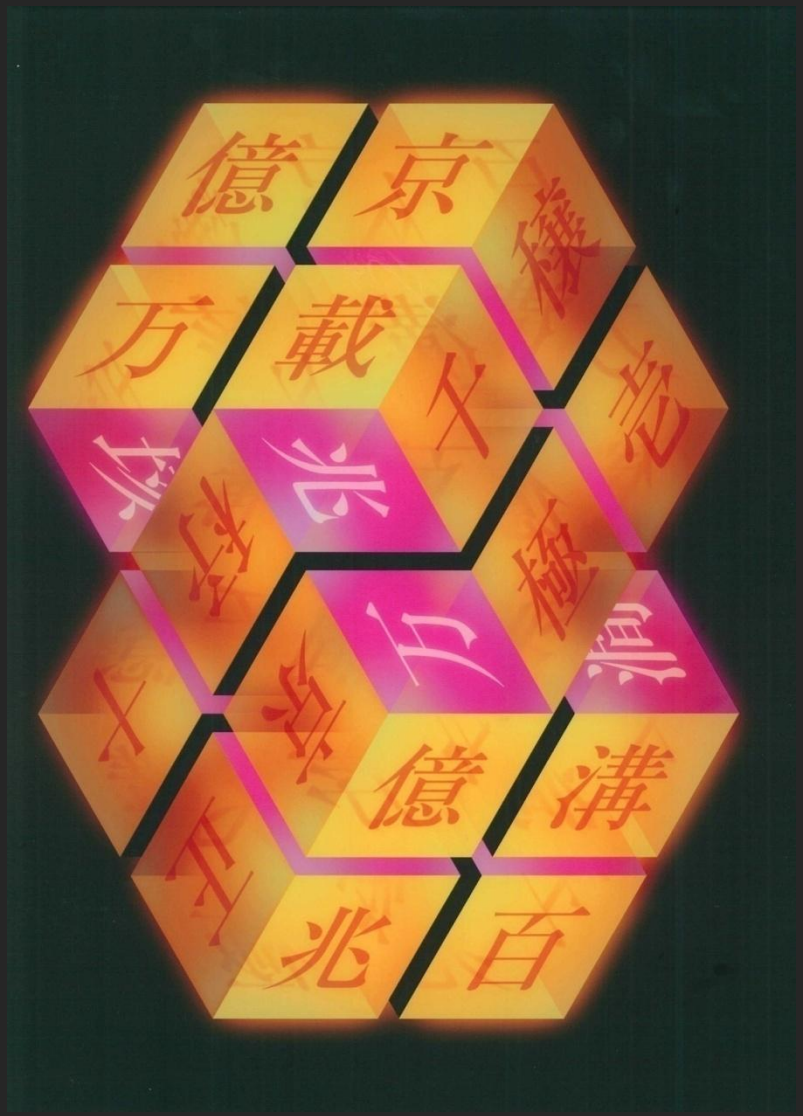
拡大



集積回路断面図(イメージ)：
多層のAl超伝導配線とAlトンネル接合より構成

量子ビット
ビット間結合
量子インターフェイス

壱： 10^{0}
十： 10^{1}
百： 10^{2}
千： 10^{3}
万： 10^{4}
憶： 10^{8}
兆： 10^{12}
京： 10^{16}
垓： 10^{20}
抒： 10^{24}
穣： 10^{28}
溝： 10^{32}
澗： 10^{36}
正： 10^{40}
載： 10^{44}
極： 10^{48} ~ 2^{150}



Thank you for your Attention