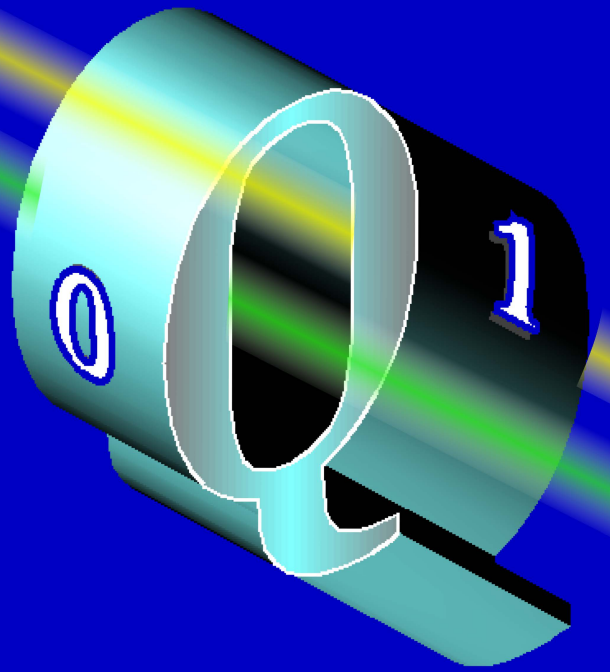
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2018.
Invited presentation ED6-5-INV was given at ISS 2017, December 13-15, 2017, Tokyo, Japan.

Coherent superconducting circuits and quantum information – 30 years' advancements

ISS 2017



12/15/2017, Tokyo

Jaw-Shen Tsai

Tokyo University of Science/Riken

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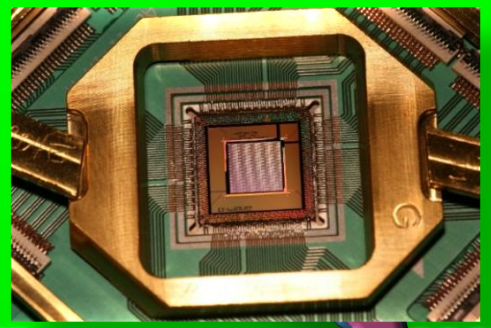
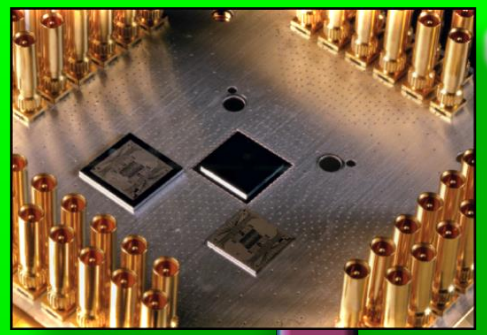
Superconducting Quantum Circuits – A Family Tree

Time

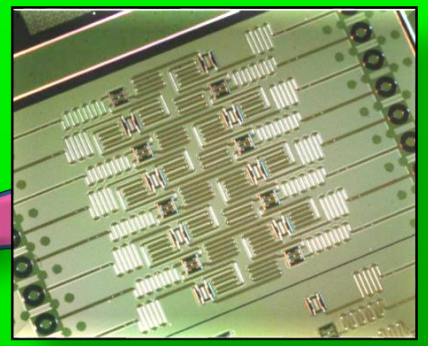


D-Wave 2000 Qubits 2017
(Flux Qubit)

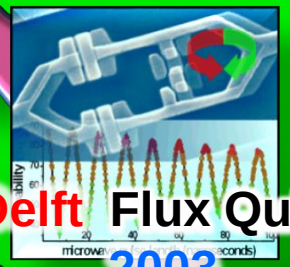


Google 22-Charge Qubits 2017
(Transmon)

Regetti
Northrop-Grumman
Lockheed Martin

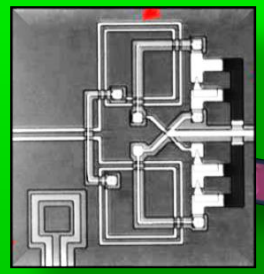


IBM 17 Charge Qubit, 2017
Cloud Quantum Computing
(Transmon)

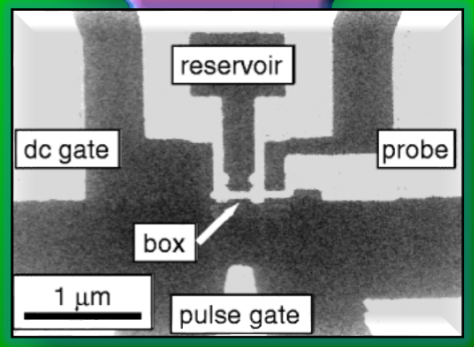


Delft Flux Qubit
2003

NTT



Kansas/NIST
Phase Qubit
2001/2002



NEC
Charge Qubit
Dynamic: 1999 Nakamura, Pashkin, Tsai
Adiabatic: 1997 Nakamura, Chen, Tsai

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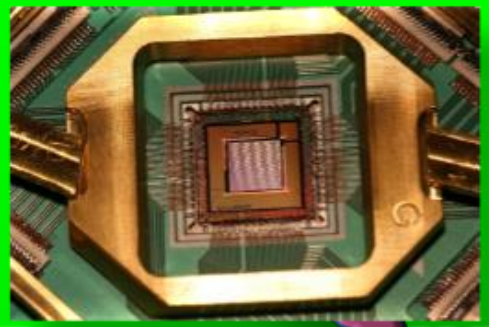
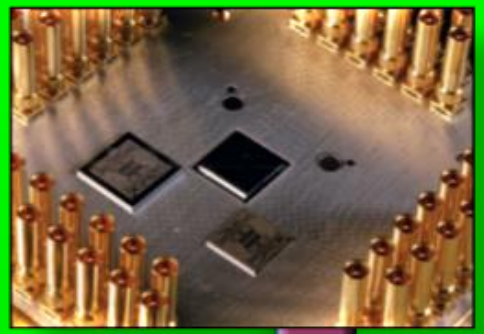
Superconducting Quantum Circuits – A Family Tree

Time

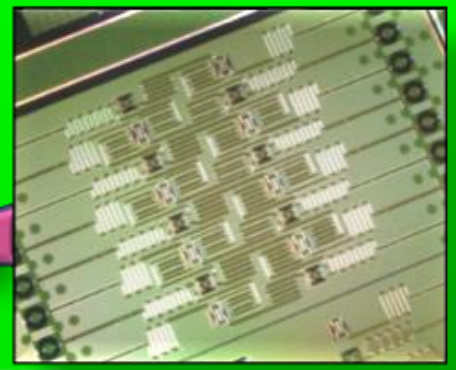


D-Wave 2000 Qubits 2017
(Flux Qubit)



Google 22-Charge Qubits 2017
(Transmon)

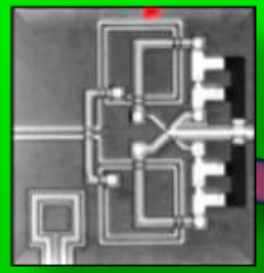
Regetti
Northrop-Grumman
Lockheed Martin



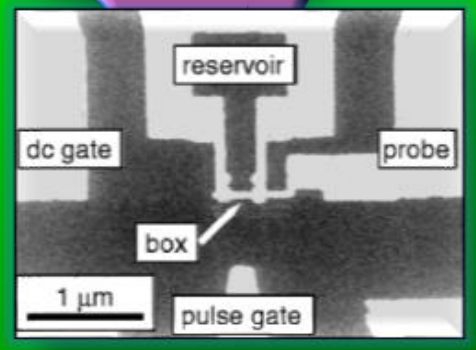
IBM 17 Charge Qubit, 2017
Cloud Quantum Computing
(Transmon)

Delft Flux Qubit
2003

NTT



Kansas/NIST
Phase Qubit
2001/2002



NEC Charge Qubit, 1999
Nakamura, Pashkin, Tsai

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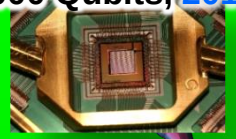
Quantum Computing – A Family Tree

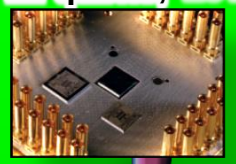
30 Years

Quantum Era

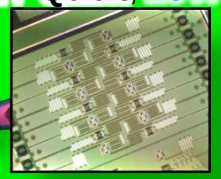
Annealing
2000 Qubits, 2017



22 qubits, 2017

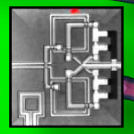


17 Qubit, 2017

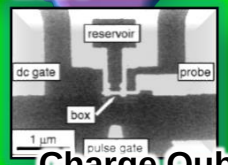


Coherent Quantum Phase Slip
2012

Phase Qubit
2001/2002



Flux Qubit
2003



Charge Qubit
1999/1997

NMR 7bit 1998

Ion trap/Cavity QED 1995

Charge number

D. Averin

Single-electron tunneling 1985

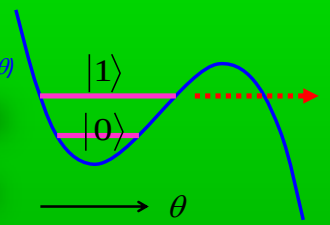
1st ISS 1987
HTC1986

K. Likharev

Bloch oscillation in Josephson junction 1984

Universality/ Topological protection 1983

Energy level quantization 1984



Macroscopic quantum tunneling 1981

2eV = hν

SQUID 1964

Josephson Effect
1962

Josephson

Phase

Quantum Information Theory

Grover: Database search 1997

Shor: Prime number factorization 1994

Deutsch & Jozsa: quantum algorithm1992

Deutsch:
Quantum Turing machine model 1985

Feynman:
Possibility of quantum mechanics 1982

Landauer & Bennet: 1960s
Reversible computing

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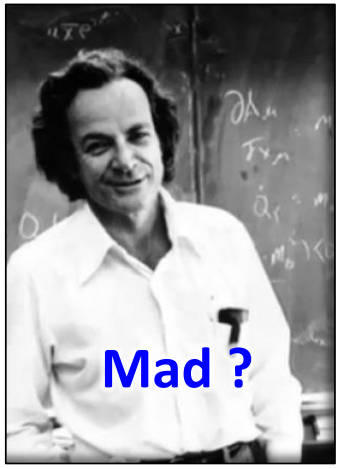
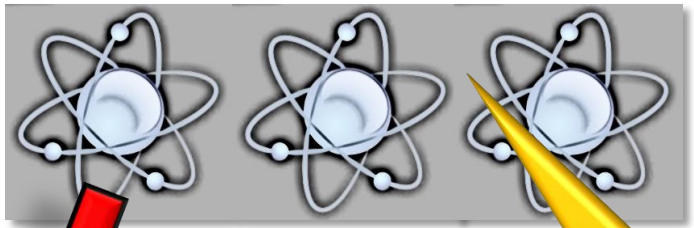
Feynman Lecture @ gakusyuin University, Tokyo (1984)



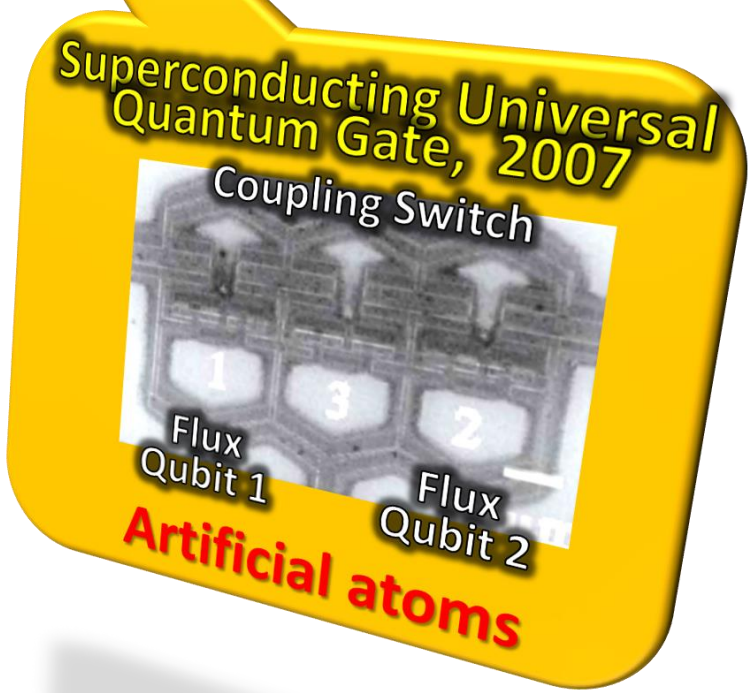
Title: "Computer of the future"



Future Transistor
(3 atoms)

To my great surprise,
23 years later,
we made similar device!

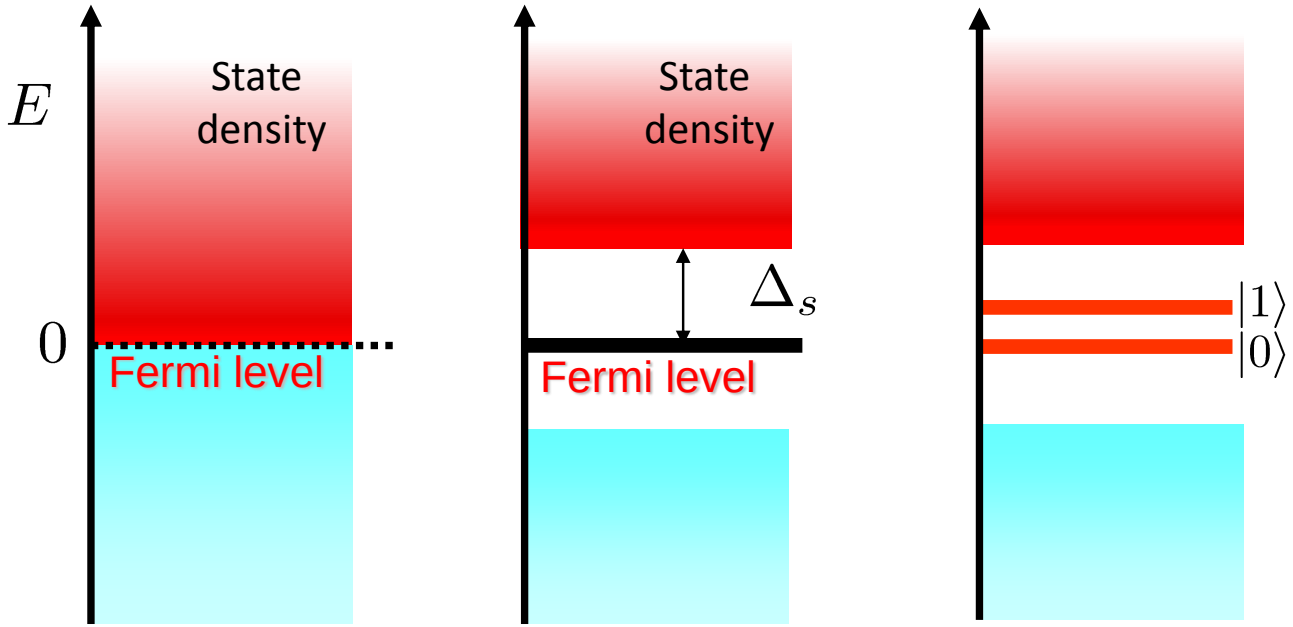
Quantum wind tunnel:
Quantum simulation (analog)
Quantum computing (digital)



Superconducting qubit

- *single non-degenerate **macroscopic ground state***
- *elimination of low-energy excitations*
- *degrees of freedom reduce to two: **phase & number***

Superconductor	~ 1 meV
Qubit	~ 10 μeV



normal metal superconductor

Qubit via
Josephson junction
Resonance: L, C
(secondary quantum states)

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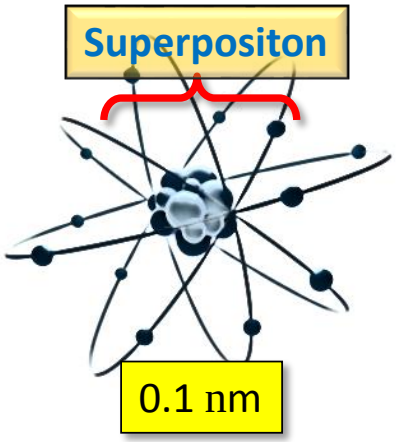
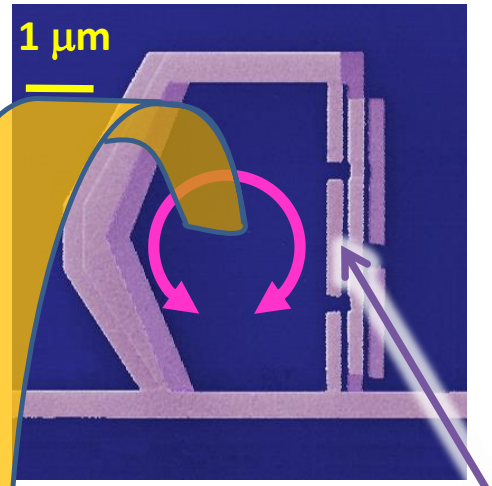
Quantum Superposition

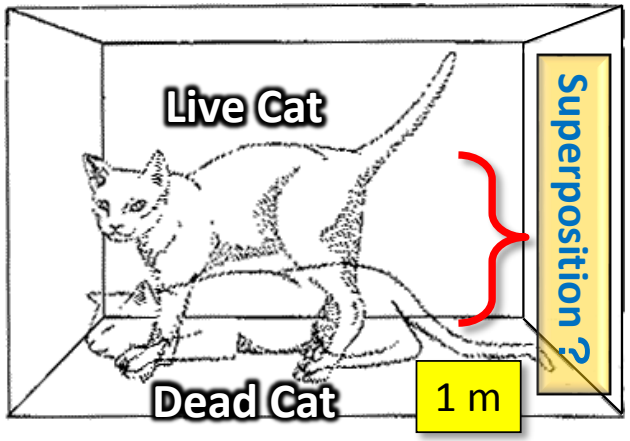
Micro : Atomic Orbits



Superconducting System



Macro : Cat



Clockwise Current Counter-clockwise Current

Superposition

Permanent current in superconducting loop

~ 10^8 electrons involved current
Quantum Coherence Realized in Macroscopic System (1999)

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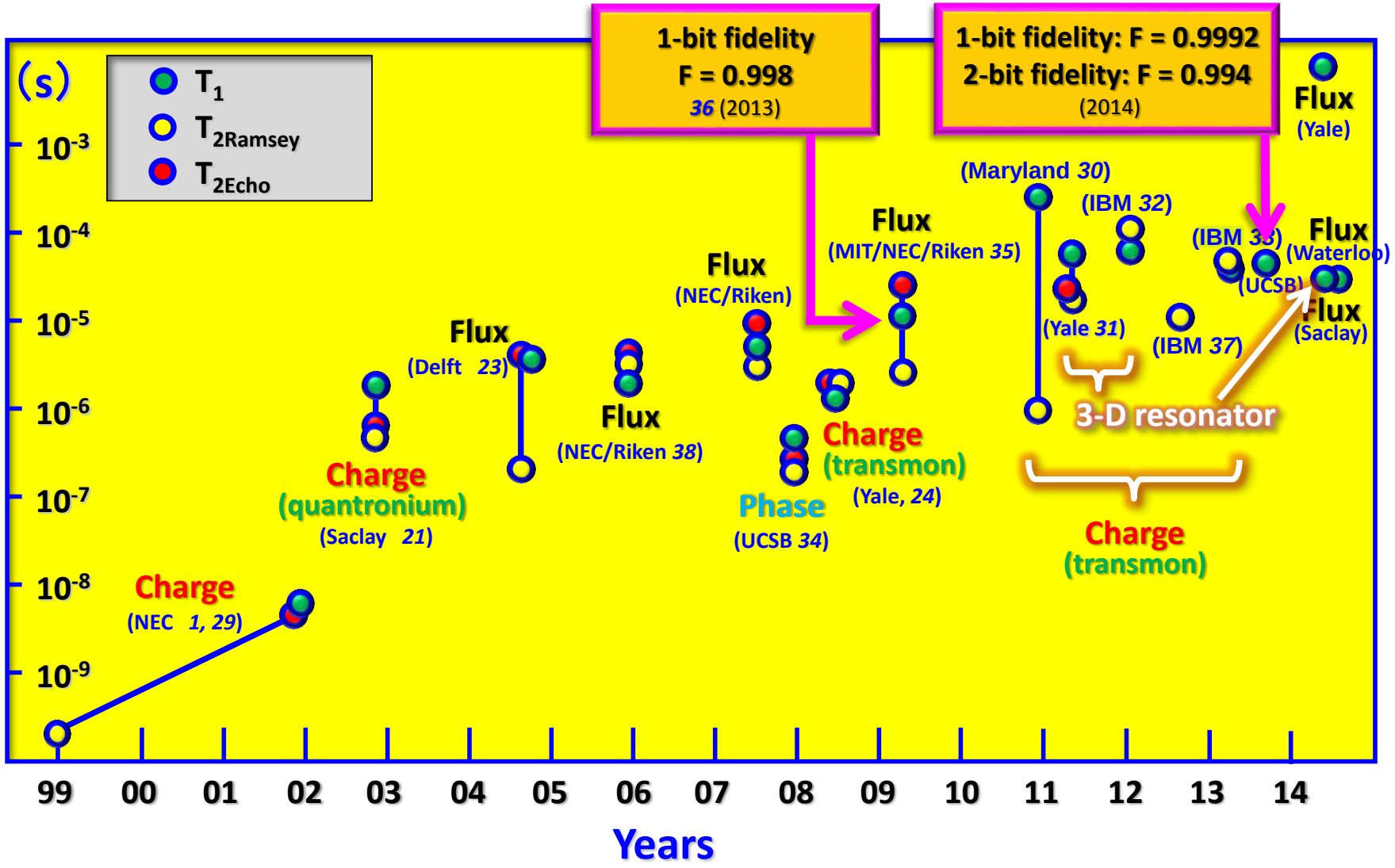
Progress in Decoherence time *for Josephson Qubits*

Good enough for fault tolerance



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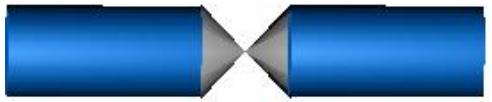
Josephson junction

Secondary Macroscopic Quantum effect

Multi-energy state (cf. solitary BCS state)

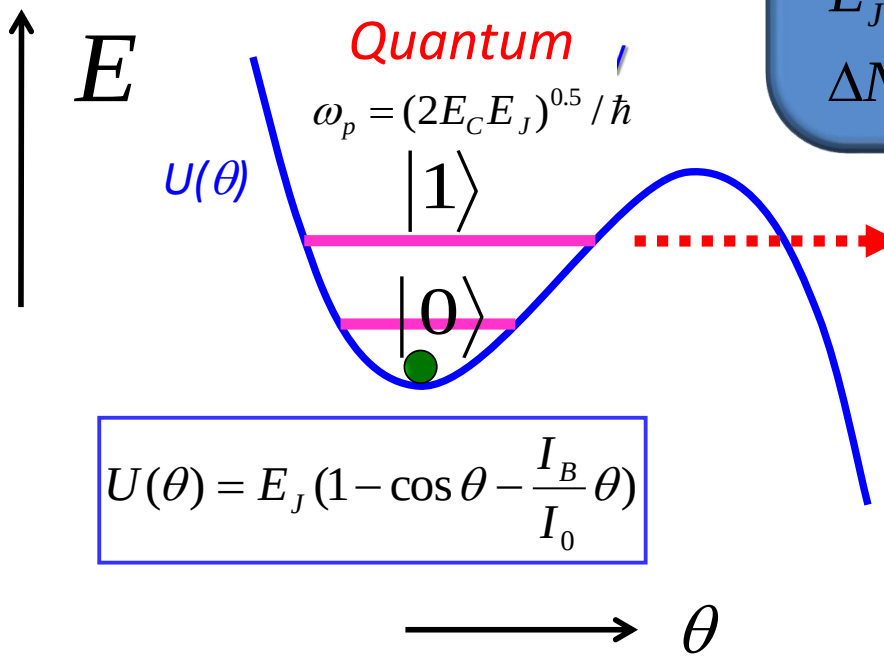


$$H = E_C N^2 + E_J(1-\cos\theta)$$

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

$$E_J = I_0\Phi_0$$

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



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

Macroscopic Tunneling

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

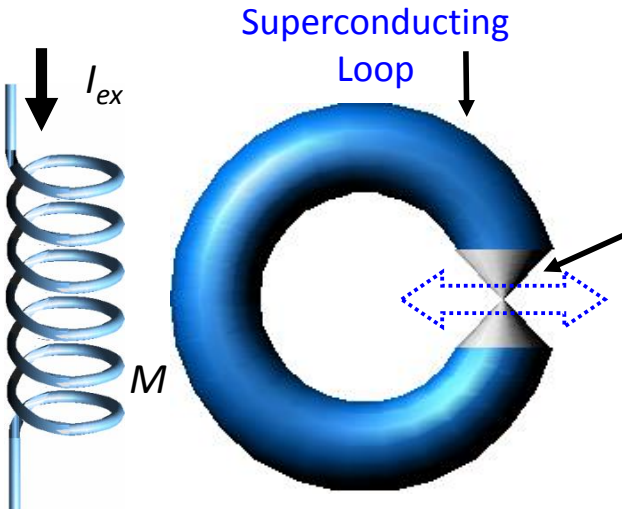
Level Quantization

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

Flux Quantum State

$$H = -\frac{1}{2}(\varepsilon_\Phi \sigma_Z + \Delta \sigma_X)$$

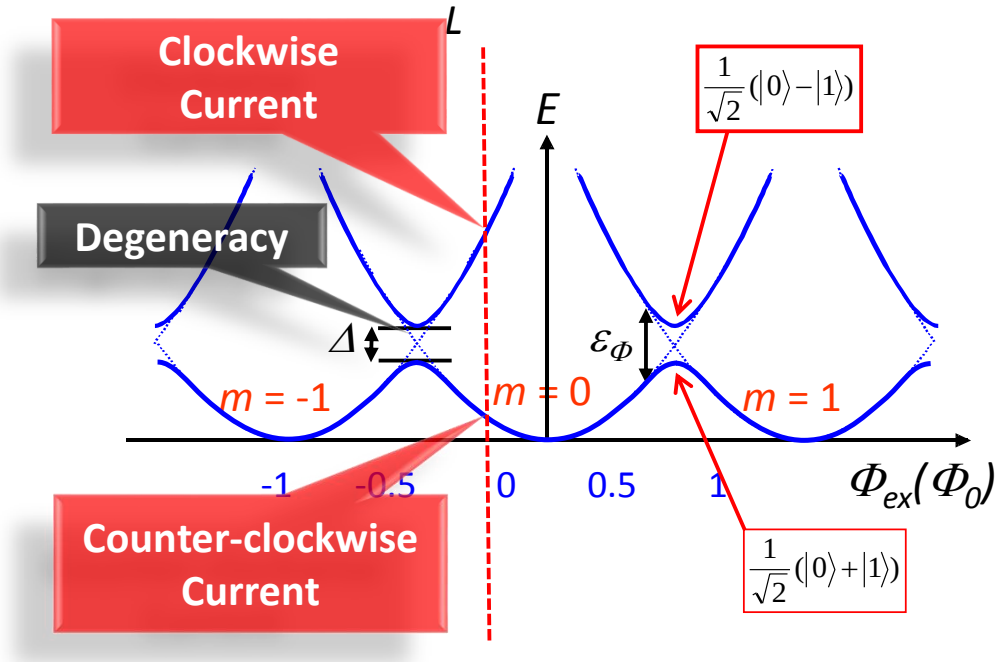
$$\varepsilon_\Phi = \frac{(m\Phi_0 - \Phi_{ex})^2}{2L} - \frac{((m+1)\Phi_0 - \Phi_{ex})^2}{2L} = \frac{\Phi_0^{\,2}}{2L}\left(\frac{2\Phi_{ex}}{\Phi_0} - 1\right)$$

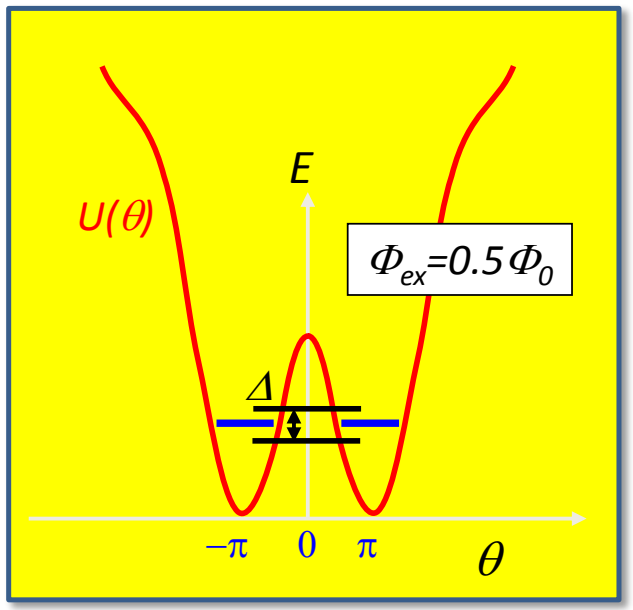


Josephson Junction

Φ_0 Coherent Tunneling

$E_J >> E_c$

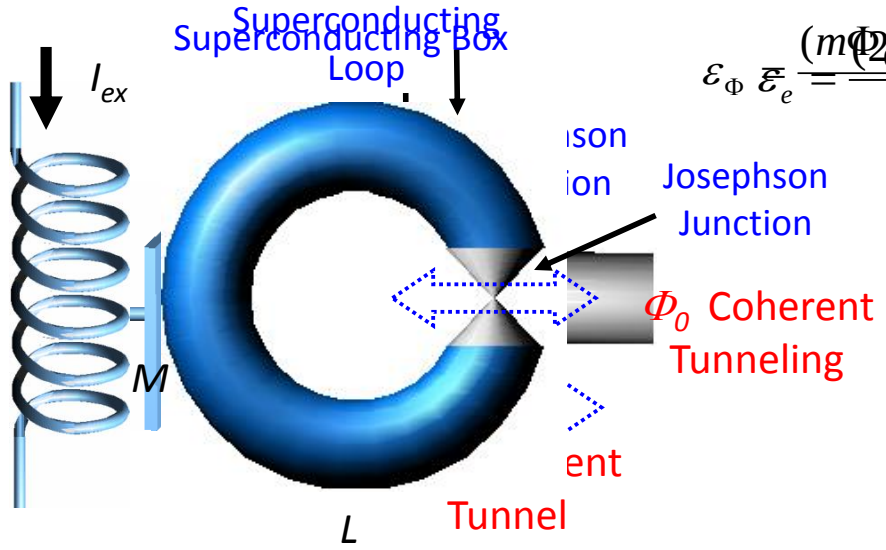




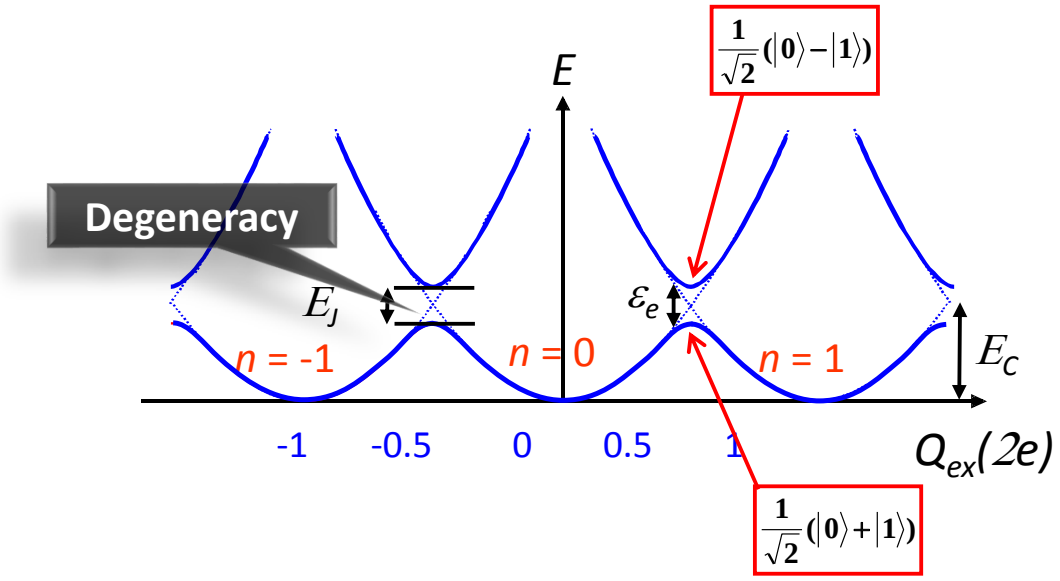
Flux quantum state

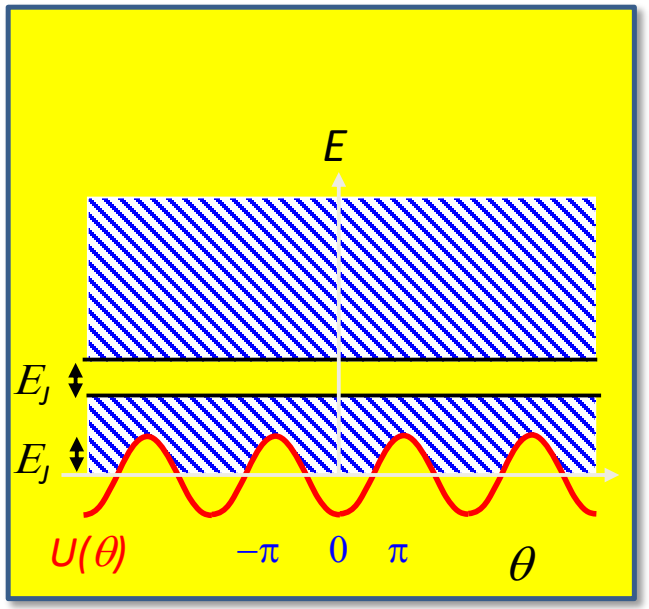
$$H = \frac{1}{2}(\varepsilon_\Phi \sigma_Z + \Delta \sigma_X) \quad H = \frac{1}{2}(\varepsilon_e \sigma_Z + E_J \sigma_X)$$

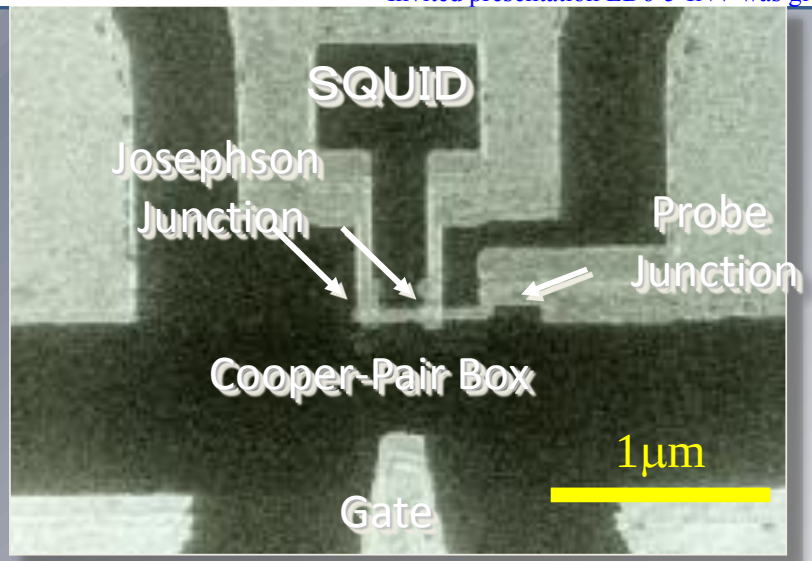
$$\varepsilon_\Phi = \frac{(m\Phi_0 - \Phi_{ex})^2}{2LC} = \frac{((m+1)\Phi_0 - \Phi_{ex})^2}{2LC} = \frac{\Phi_0^2}{2LC}\left(\frac{2\Phi_{ex}}{\Phi_0} - 1\right)^2 \quad \varepsilon_e = 4E_C(2n_{ex} - 1)^2$$



$E_J \gg E_C$



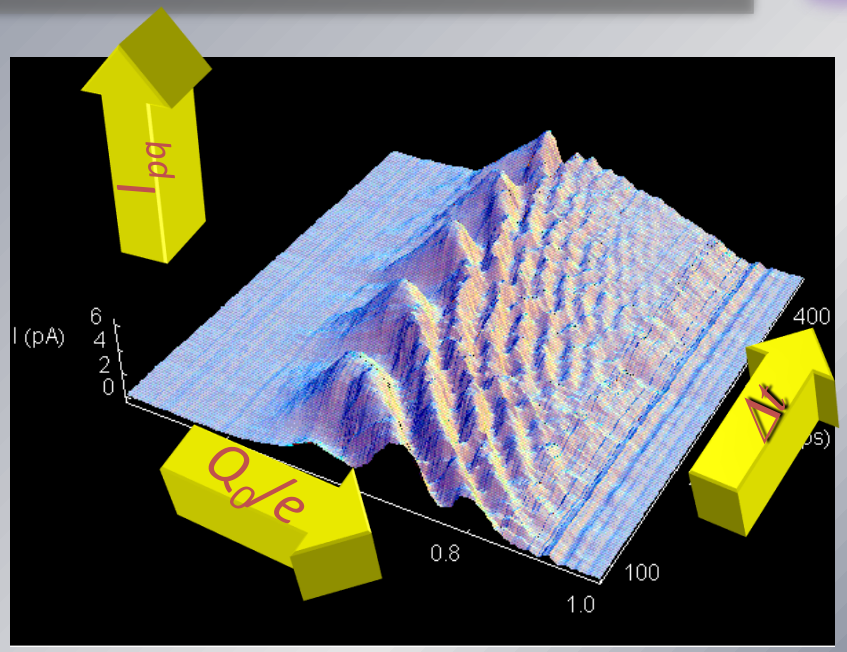




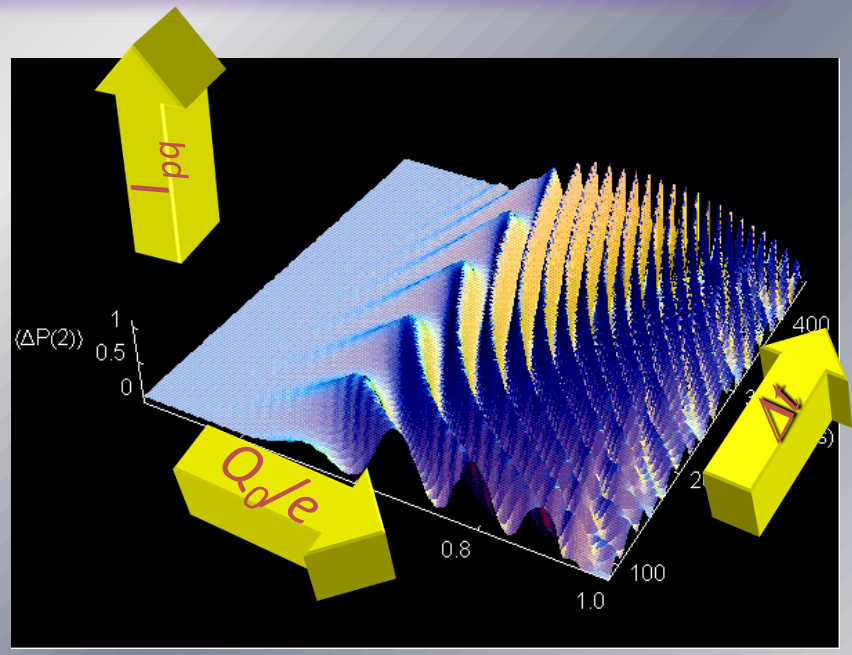
Charge Qubit

Nature, 398, 786, 1999

Creation of superposition state in macroscopic system with phase factor

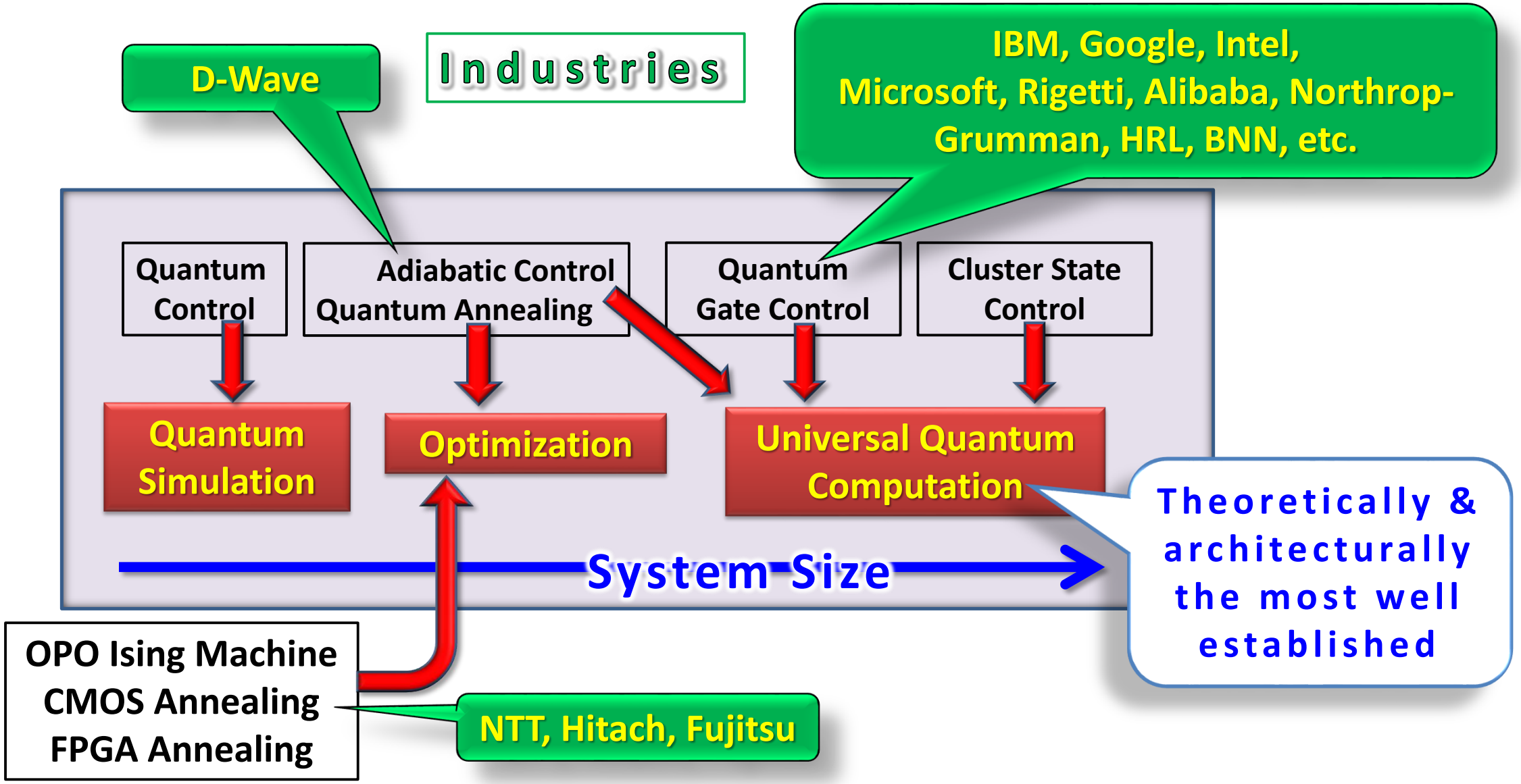


Experiment



Simulation

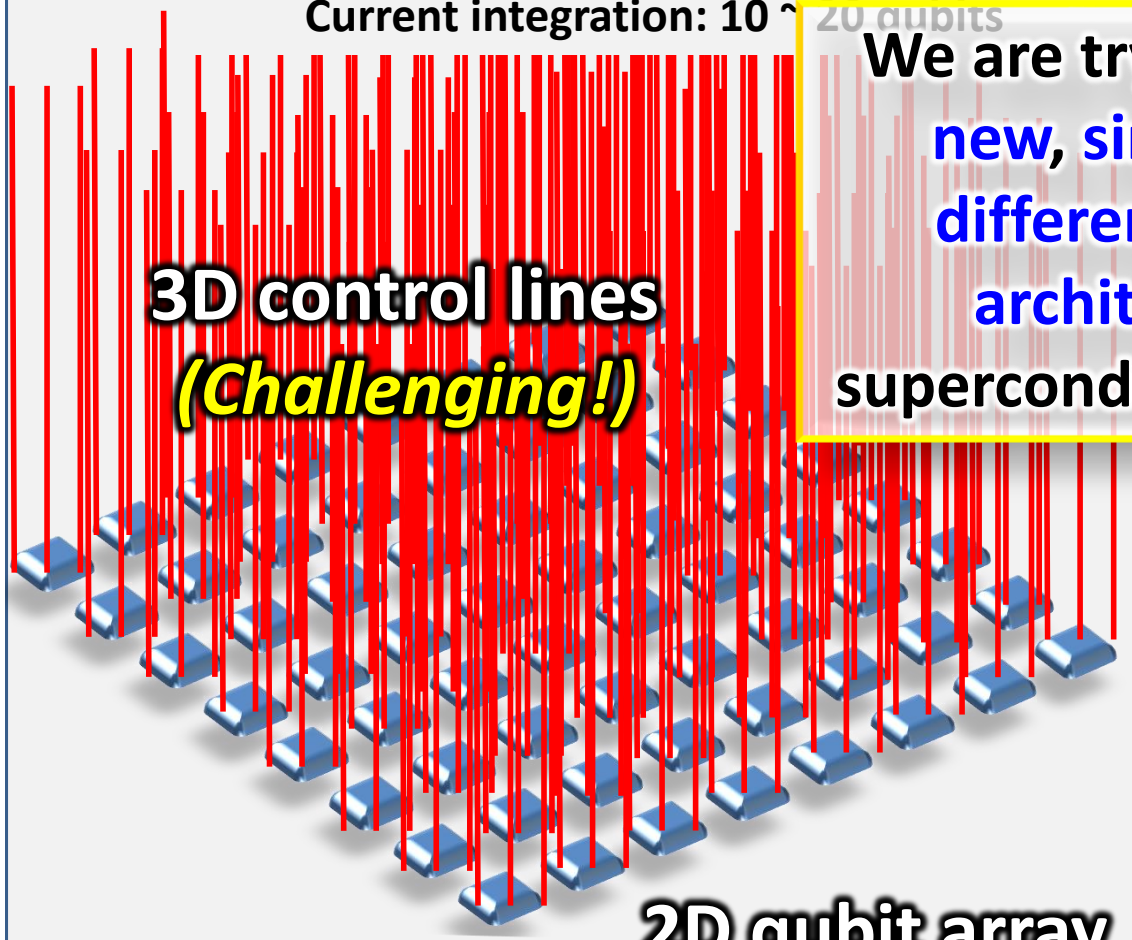
Family of Quantum Information Processing



Gate Model

Superconducting system:
IBM (50~100), Google (50), Intel (50~100),
Rigetti (100), Microsoft (1000) etc
Current integration: 10 ~ 20 qubits

3D control lines
(Challenging!)



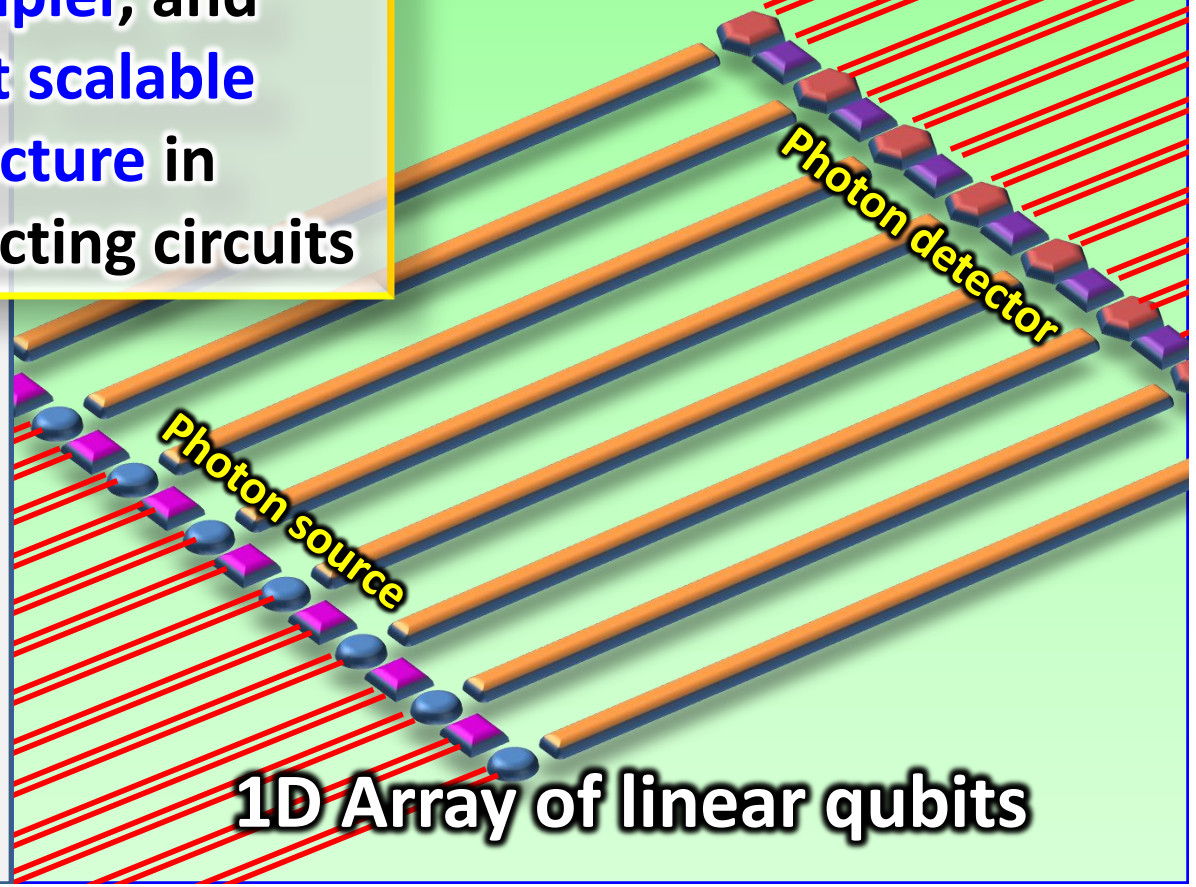
2D qubit array

We are trying to find a **new**, **simpler**, and **different scalable architecture** in superconducting circuits

One-way Model

Our proposal

2D control lines
(Much easier!)



1D Array of linear qubits

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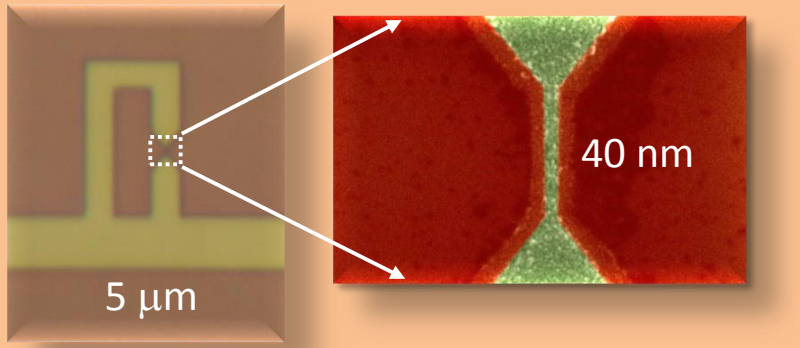
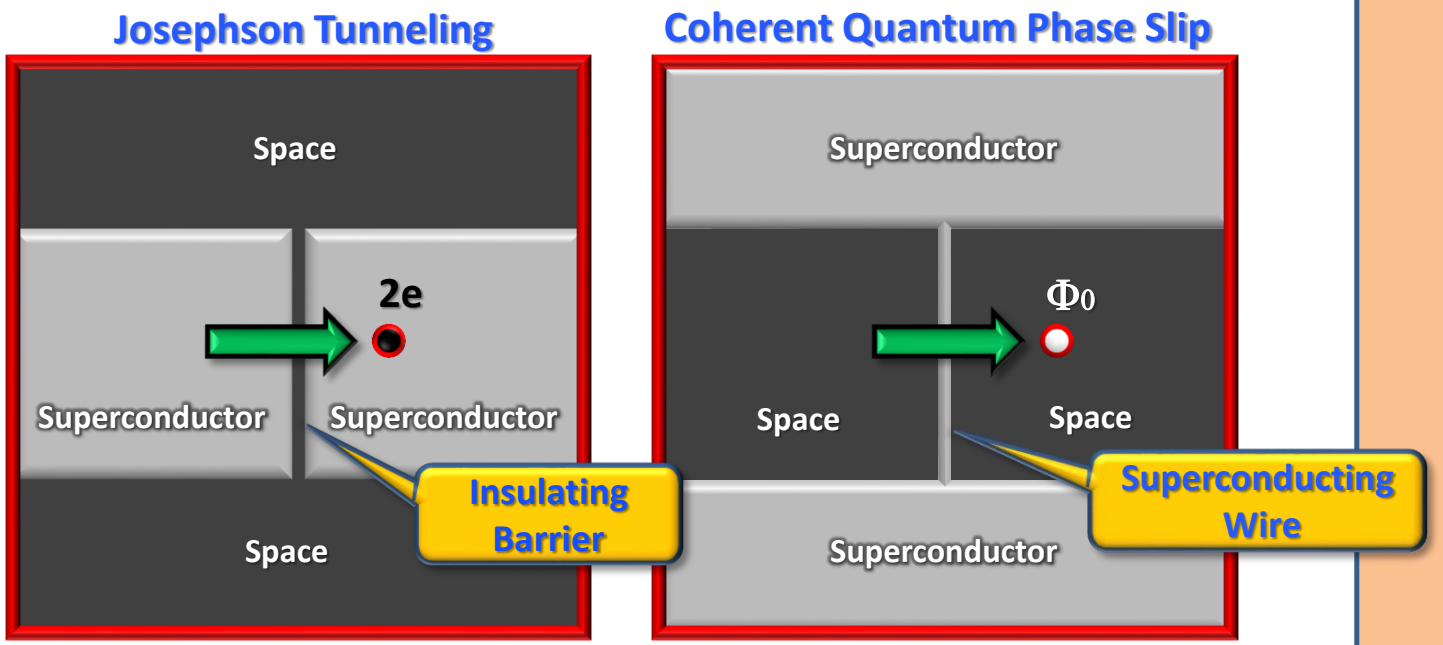
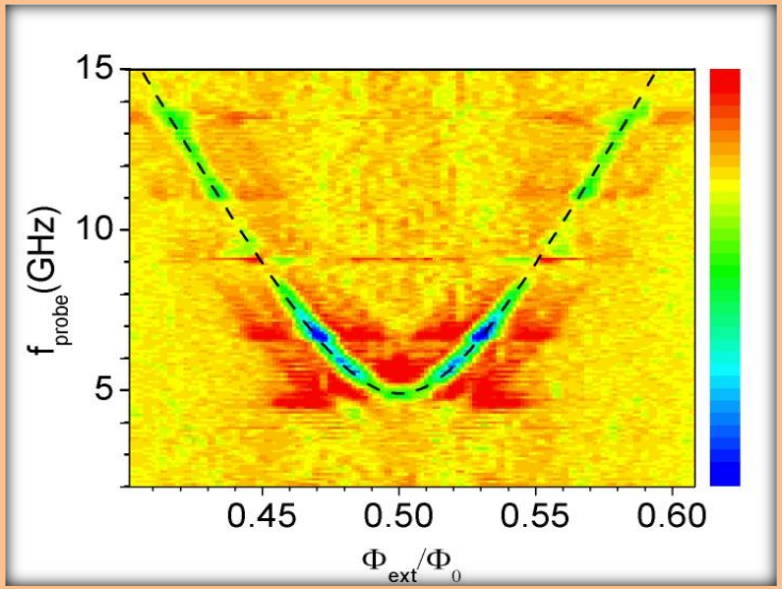
Coherent Quantum Phase Slip in Superconducting Wire

Astafiev et al, Nature 2012

- **Exact quantum dual** to *Josephson tunneling*
  (Coulomb blockade is a "partial" dual)







15

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Electrical Quantum Standards (triangle)

Voltage :
Josephson Effect
(*Nobel 1973*)

$$V = \frac{h\nu}{2e}$$

Accuracy:
$< 3 \times 10^{-19}$

$$I = \frac{V}{R}$$

Resistance :
Quantized Hall Effect
(*Nobel 1985*)

$$R = \frac{h}{e^2}$$

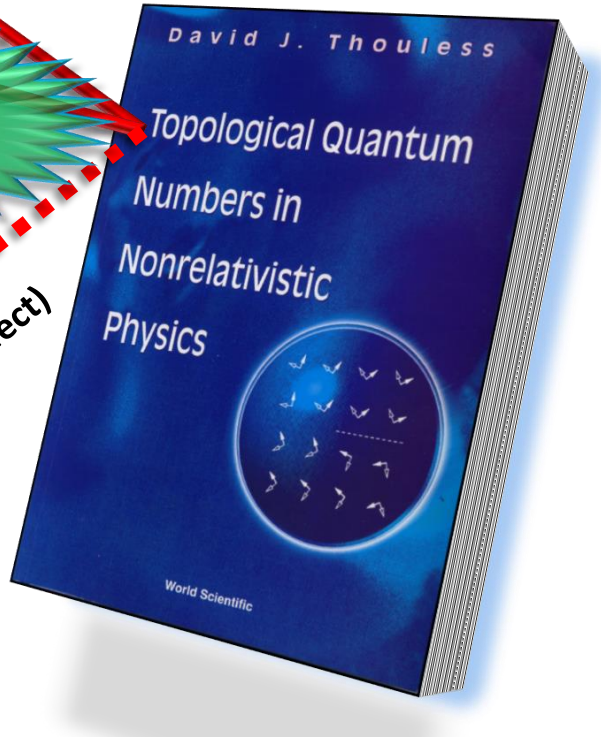
Topological Protection !

$$I = 2e\nu$$

COMPETITION

Current :
- ***Coherent quantum phase slip***
- ***SINIS pump***
- ***Semiconductor pump***
- ***SET pump, Turnstile***

??? (Conjugate to Josephson Effect)



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