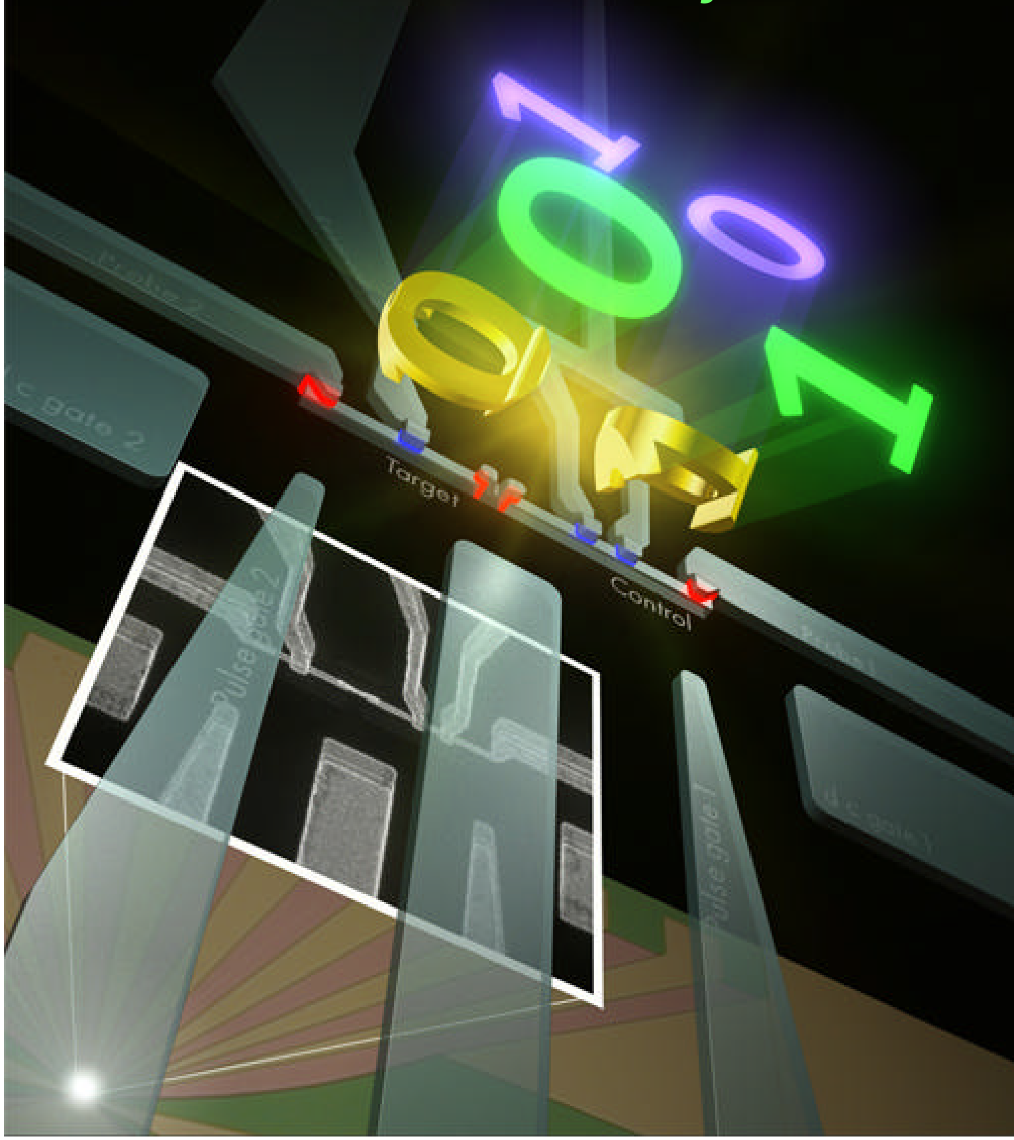
RECENT PROGRESSES IN SUPERCONDUCTING QUBITS

MIT Stanford Berkeley Nano Forum, Stanford, June 16, 2004



J. S. Tsai, NEC/Riken

Single-Shot Measurement

EFFICIENCY ~90%

VISIBILITY ~70%

Noise for T_1 & T_1

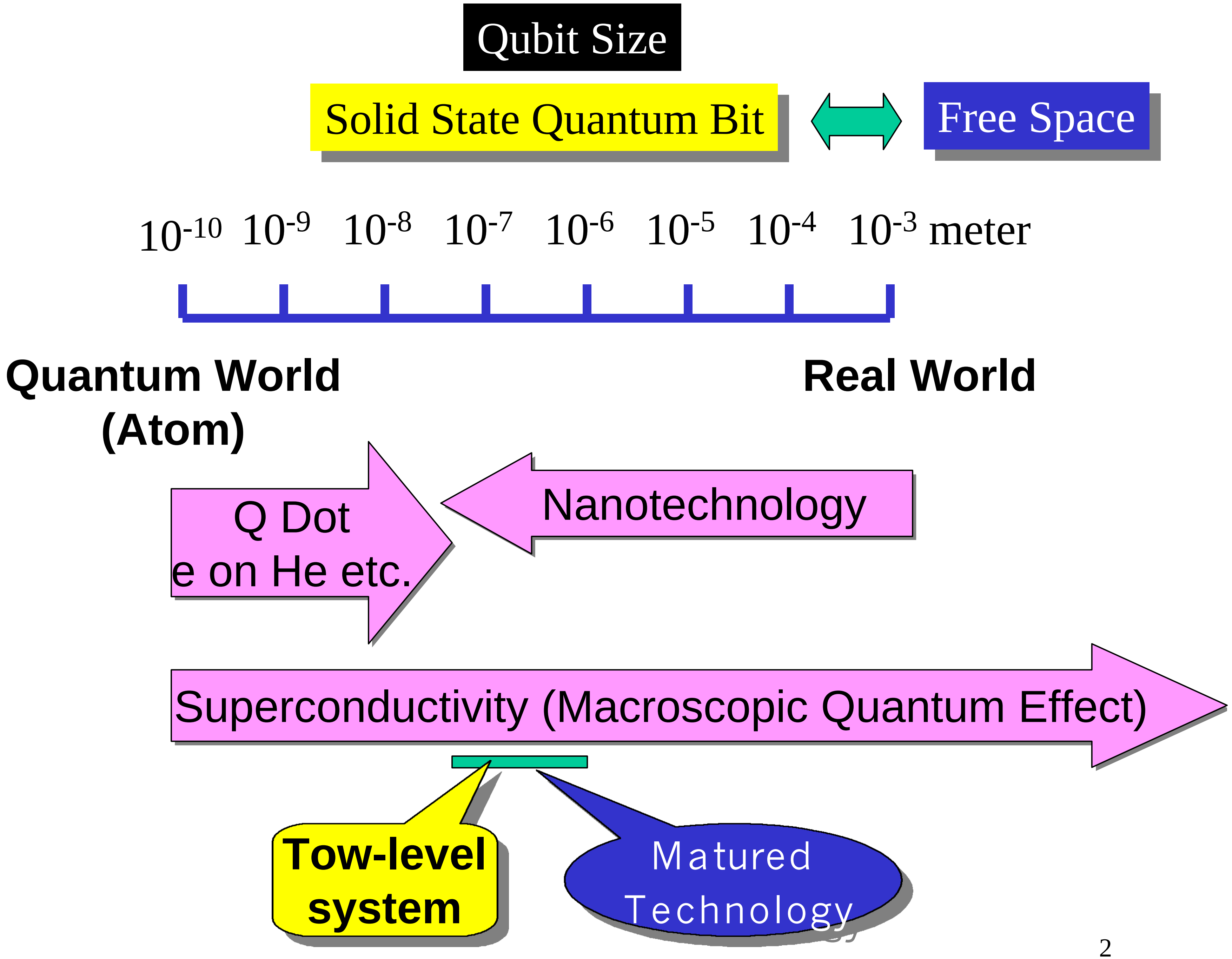
O. Astafiev et al, Cond-mat/0402619

Coupled Oscillation

Yu. Pashkin et al, Nature, 421, 823, 03

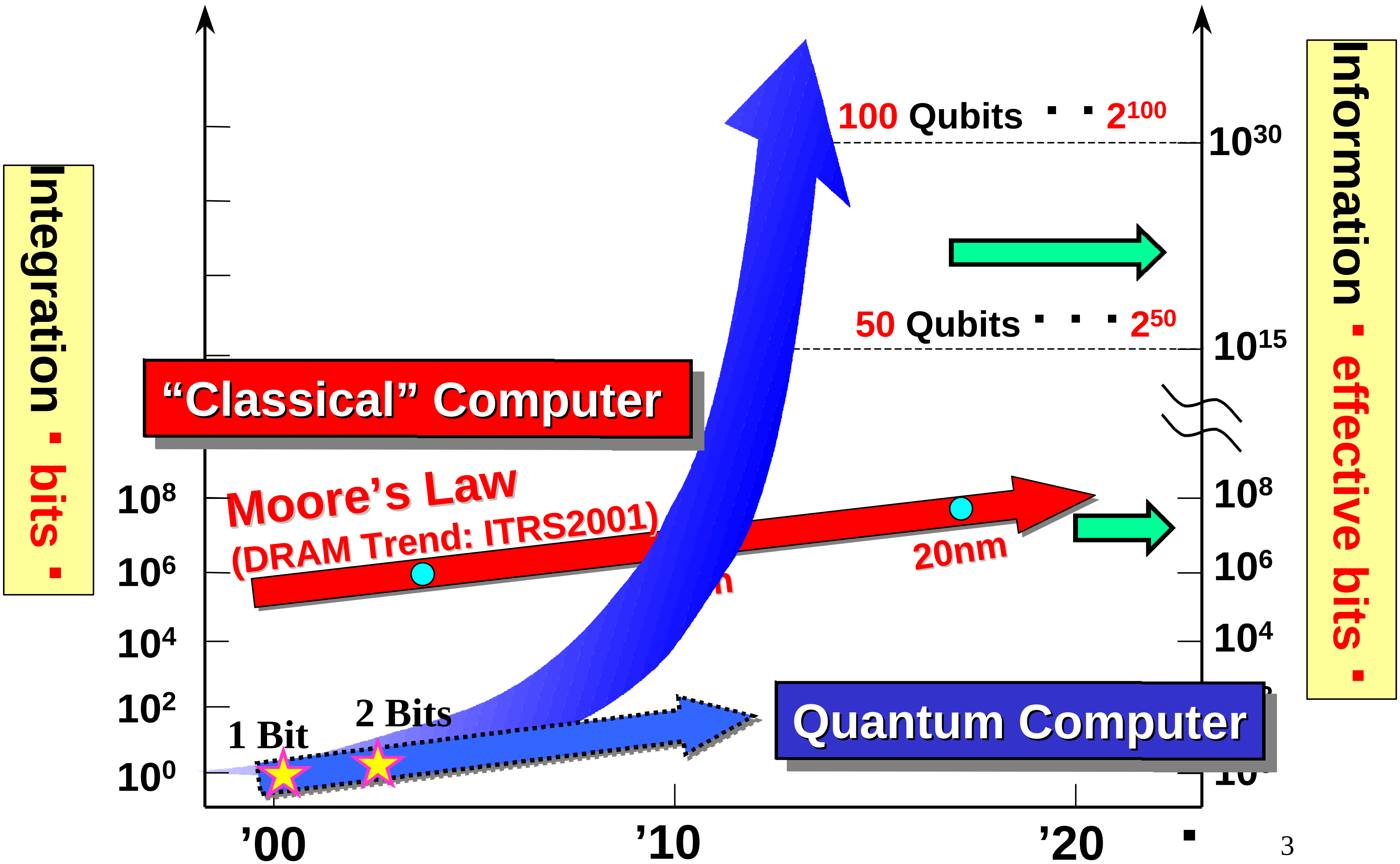
CNOT Operation

T. Yamamoto et al, Nature, 425, 941, 03



Qubit Size
Solid State Quantum Bit
Free Space
10-10 10-9 10-8 10-7 10-6 10-5 10-4 10-3 meter
Quantum World (Atom)
Real World
Q Dot
e on He etc.
Nanotechnology
Superconductivity (Macroscopic Quantum Effect)
Tow-level system
Matured Technology

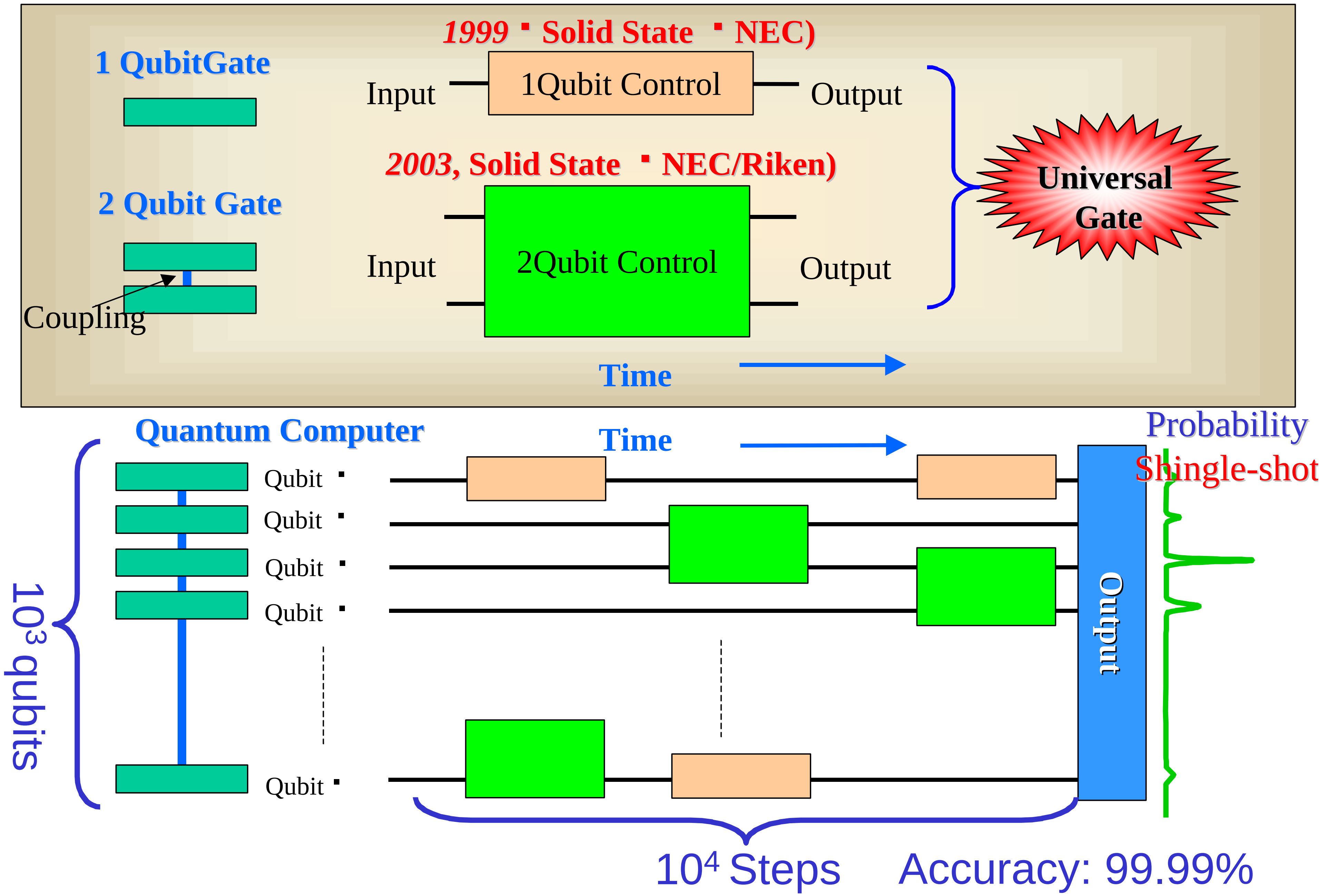
New Paradigm for Computing

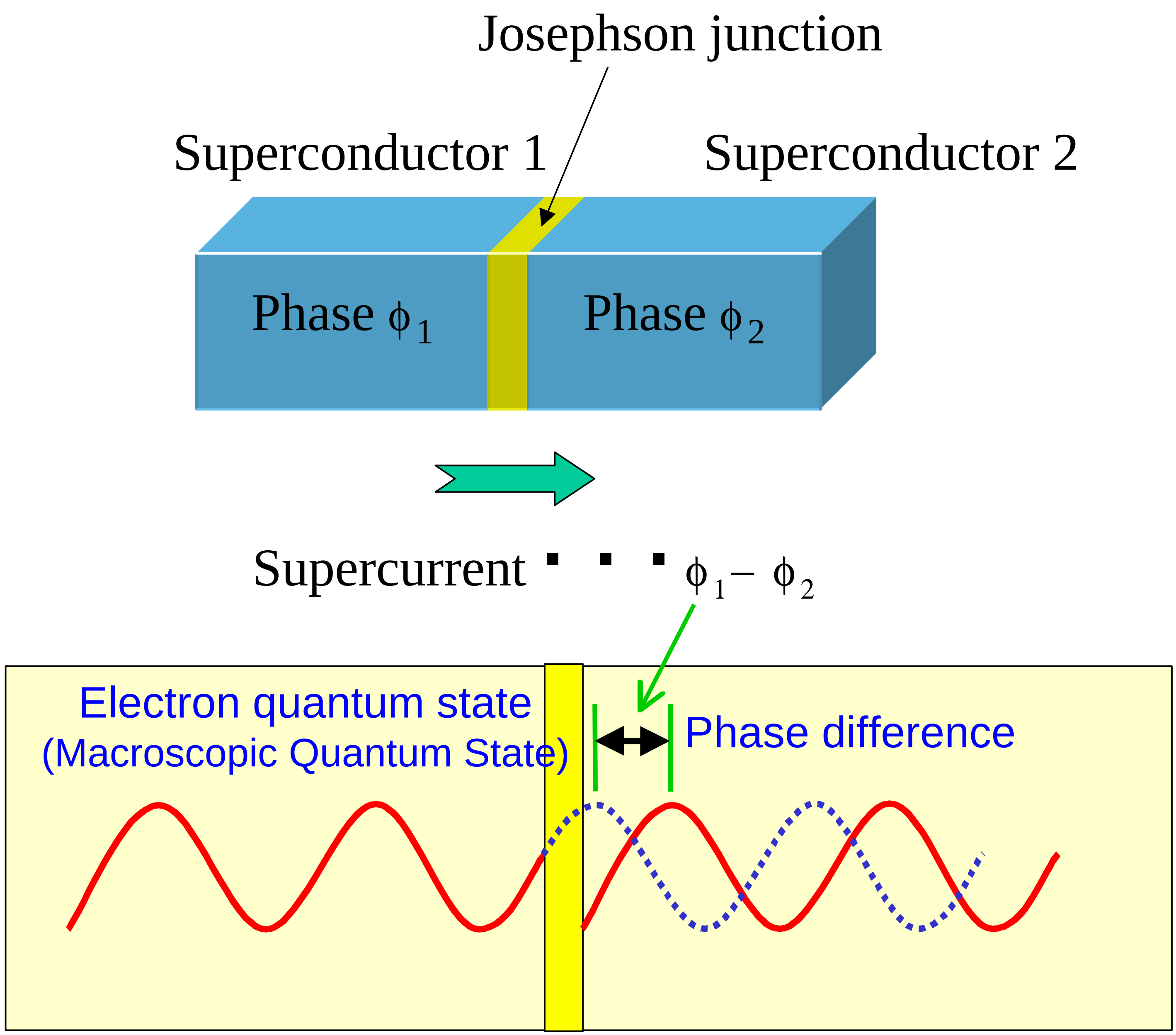


Physical Qubit

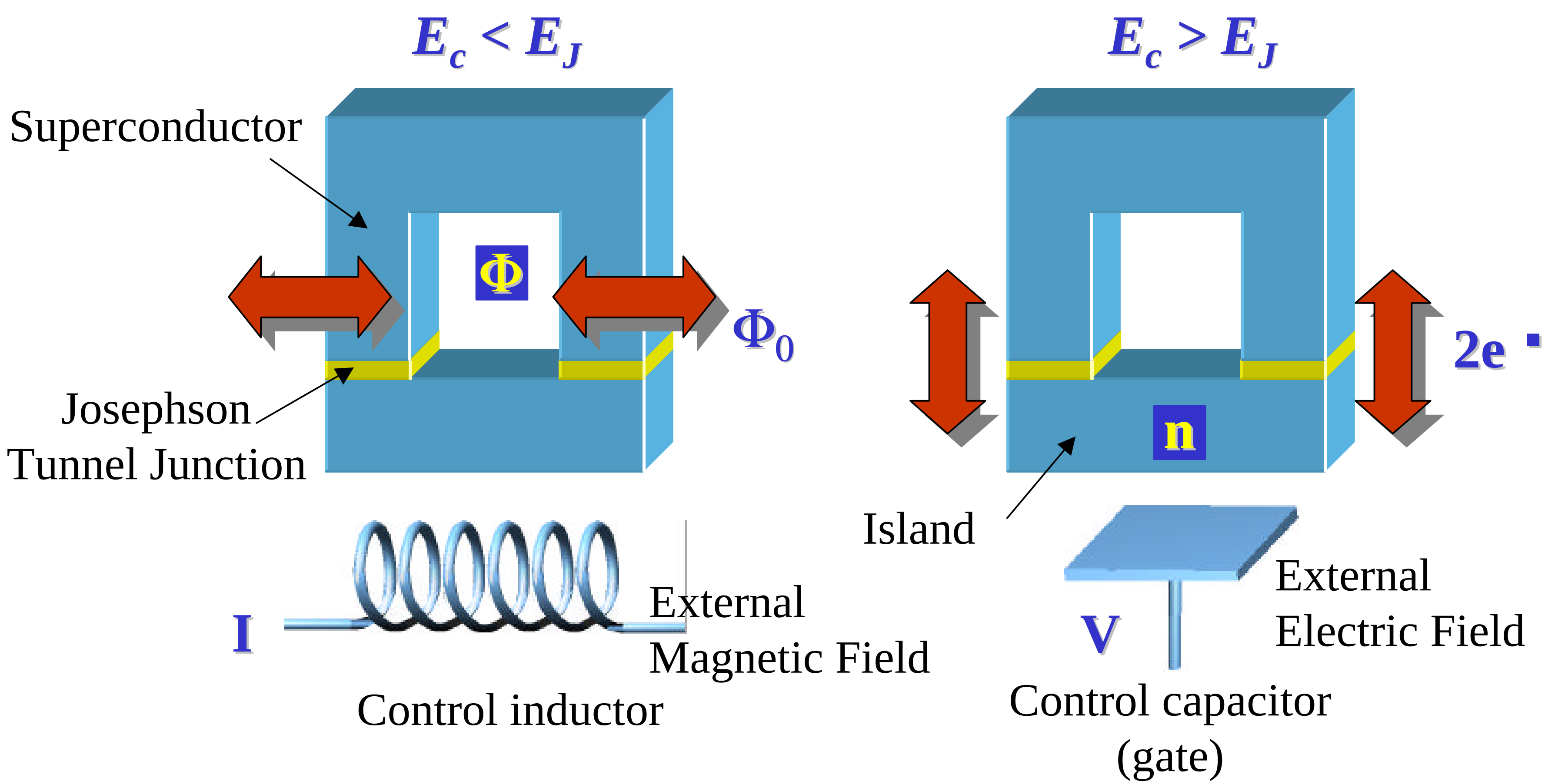
Ion Trap	(Wineland et al.: NIST, '95)	2 qubit	Microscopic system
	(Sackett et al.: NIST, 00)	4 qubit	
Cavity QED	(Kimble et al: Caltech, '95)	2 qubit	
NMR	(Chuang et al: IBM et al., '01)	7 qubit	
Small Josephson junction			
Charge	(NEC, 99)	1 qubit	Macroscopic (solid state) system
Phase	(Kansas, NIST, 02)	1 qubit	
Charge	(Scaly, Chalmers, 02)	1 qubit	
Phase/Flux	(Delft, 02)	1 qubit	
Charge	(NEC/Riken, 02)	2 qubit	
Quantum Dot			
Exciton	(Michigan, NTT)	1 qubit	
Charge	(NTT)	1 qubit	

Structure of Quantum Computer

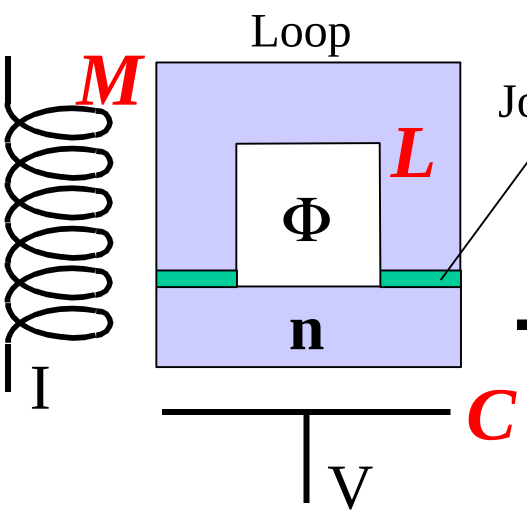


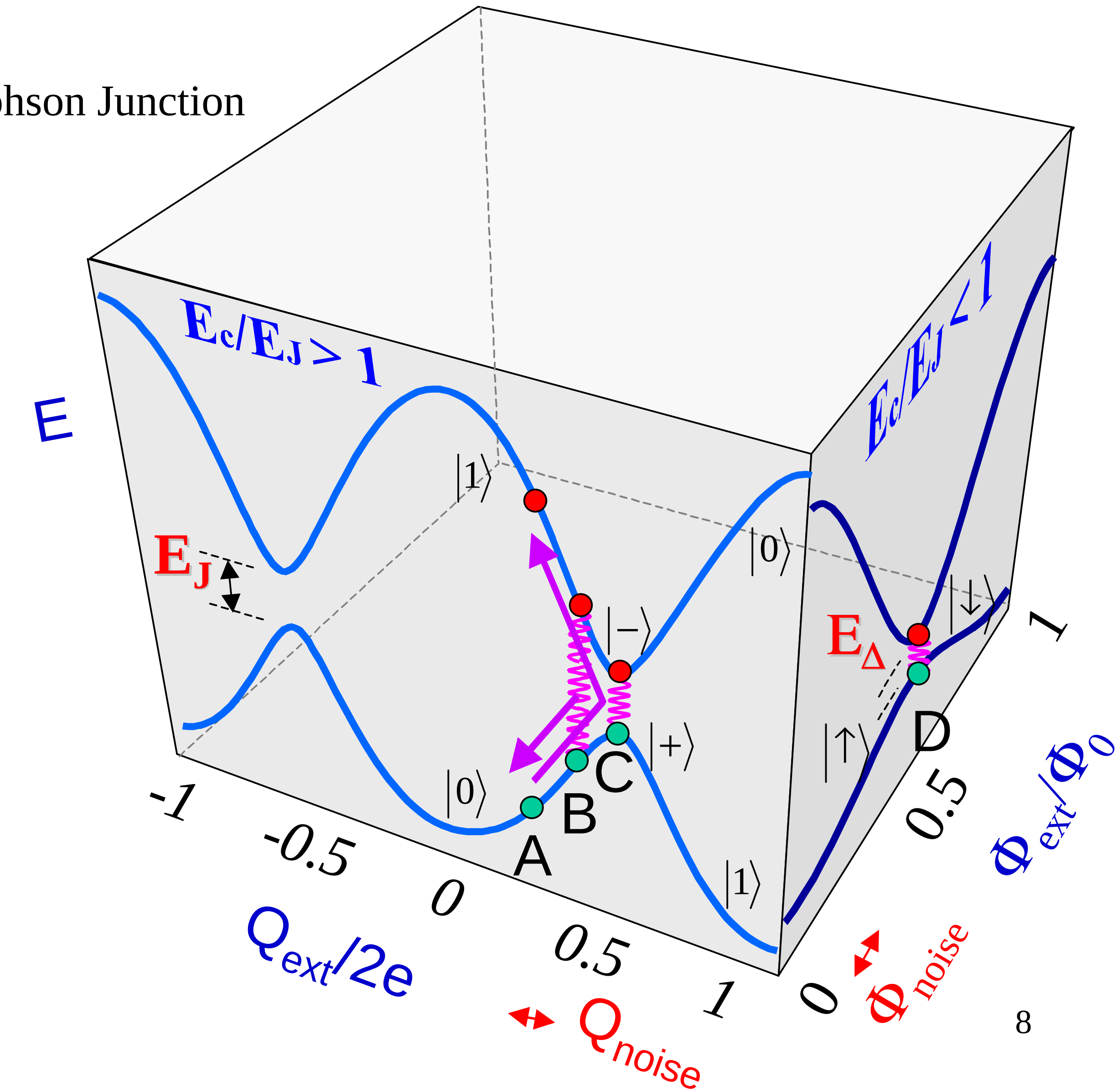

Josephson junction
Superconductor 1
Superconductor 2
Phase ϕ1
Phase ϕ2
Supercurrent ・・・ϕ1 − ϕ2
Electron quantum state
(Macroscopic Quantum State)
Phase difference

Flux qubit   Charge qubit



$$E = E_C\left(n - \frac{CV_g}{2e}\right)^2 - E_J\cos\left(\frac{p\Phi}{\Phi_0}\right)\cos\left(\frac{f_1+f_2}{2}\right) + \frac{1}{2L}(\Phi-\Phi_{ex})^2$$





A: NEC '99

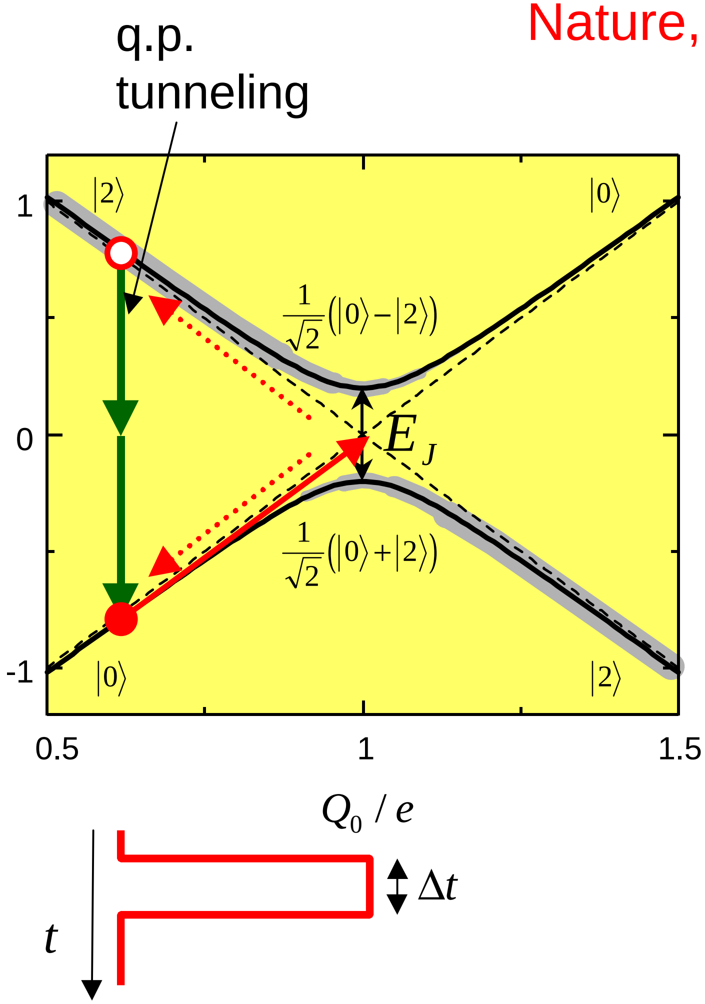
B: NEC '01

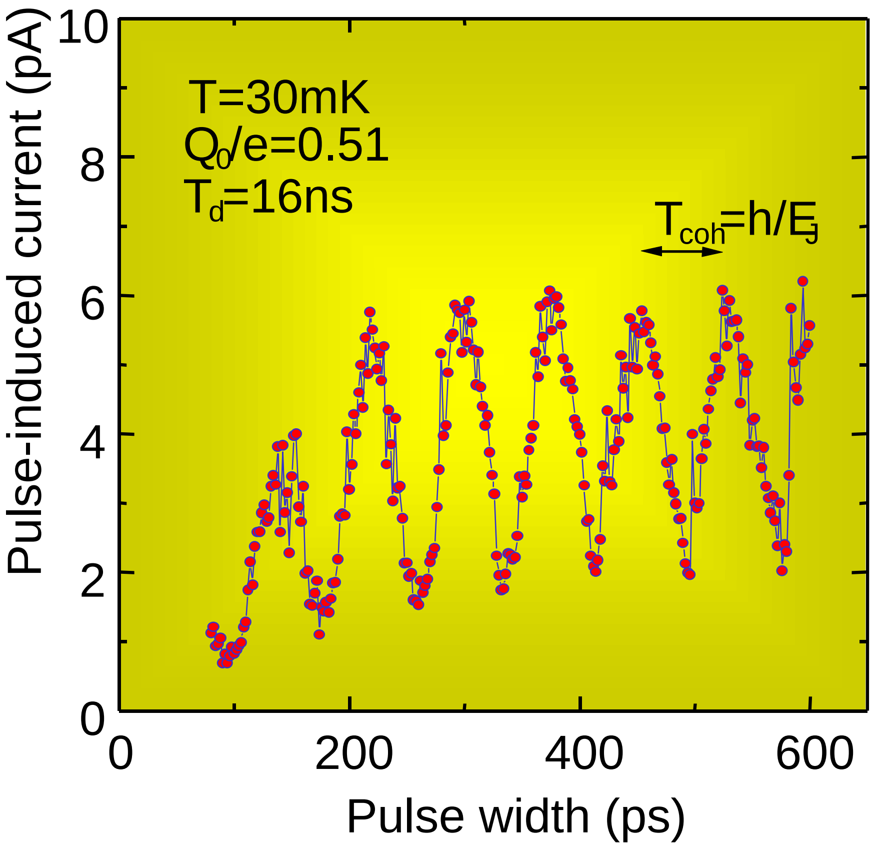
C: Saclay '02

D: Delft '03

Qubit Control Experiment

Nature, 398, 786, 1999

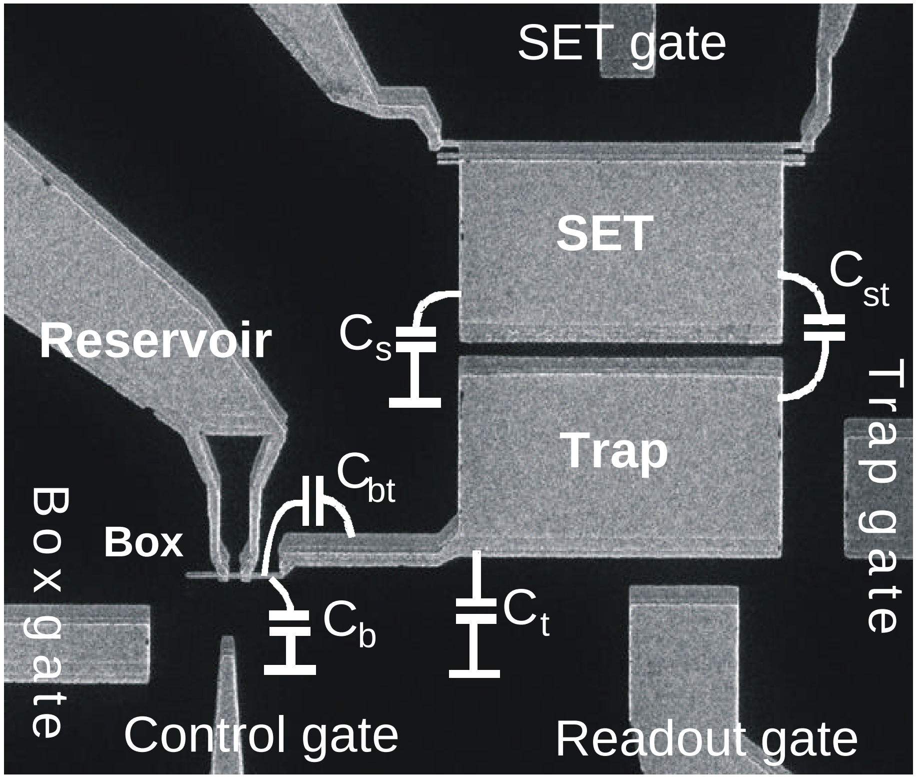




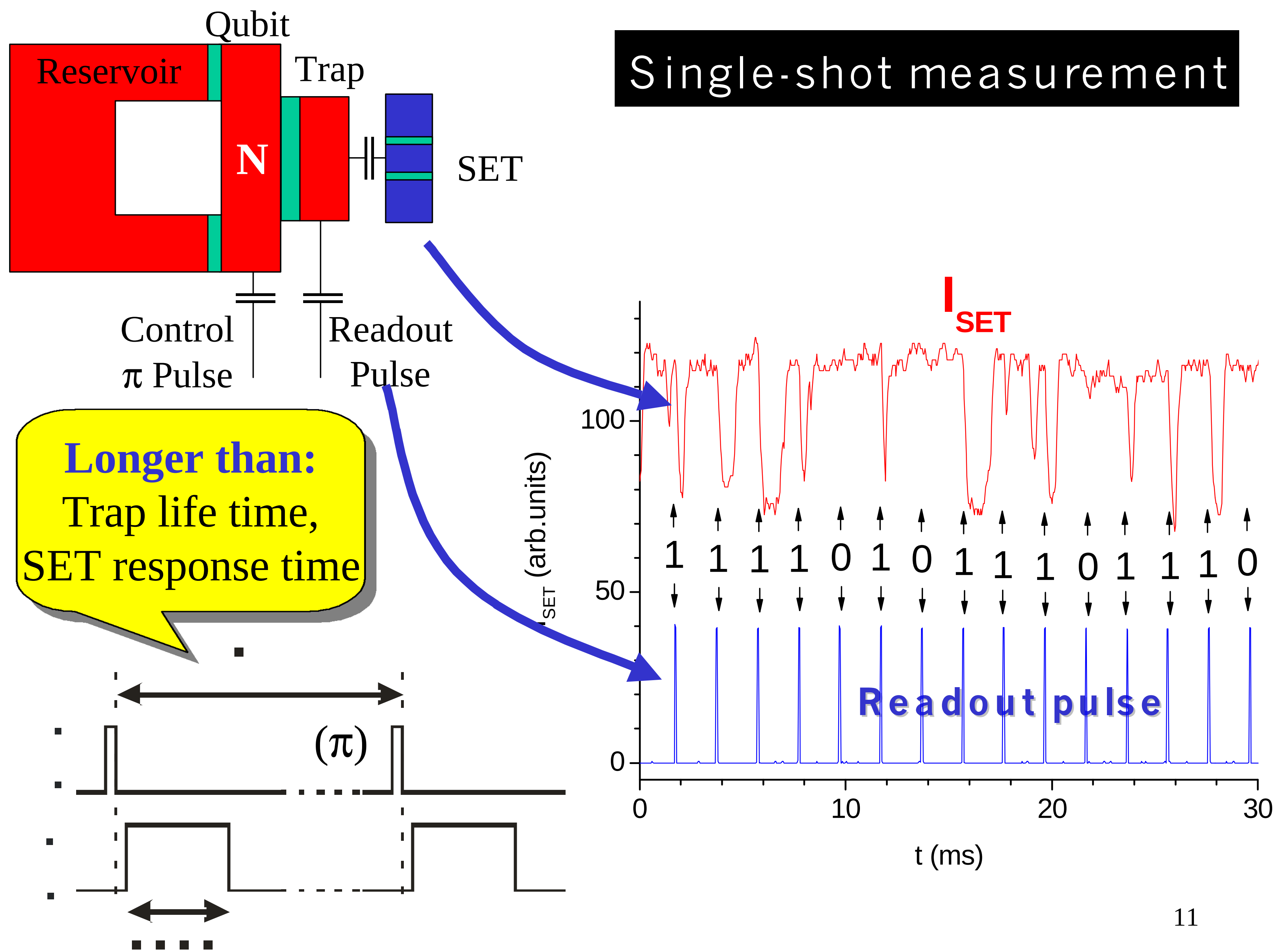
Non-adiabatic gate operation

Also done:
2-pulse interference
3-pulse echo

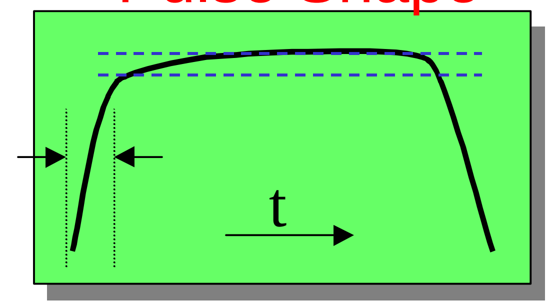
Single Shot Measurement Scheme (mask design)
Single-electron trap + SET



Single-shot measurement



Pulse Shape

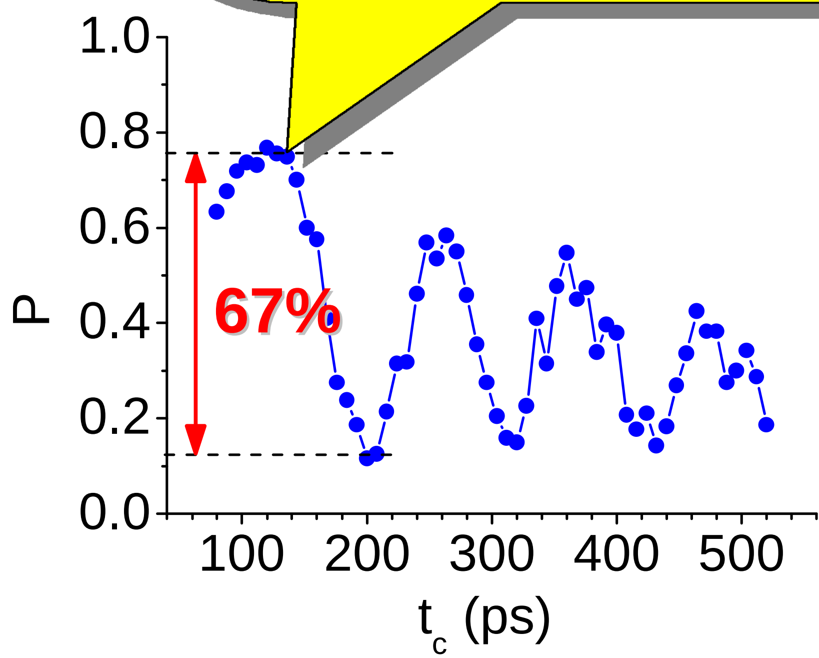


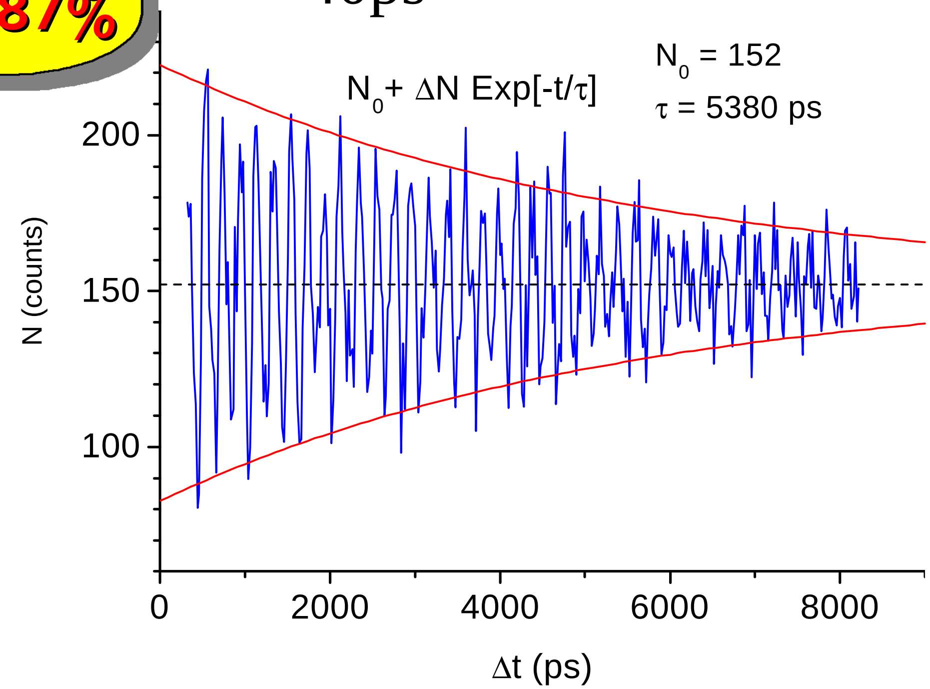
Amplitude depends on:

efficiency of **π pulse: 84%**

x

efficiency of **Readout: 87%**



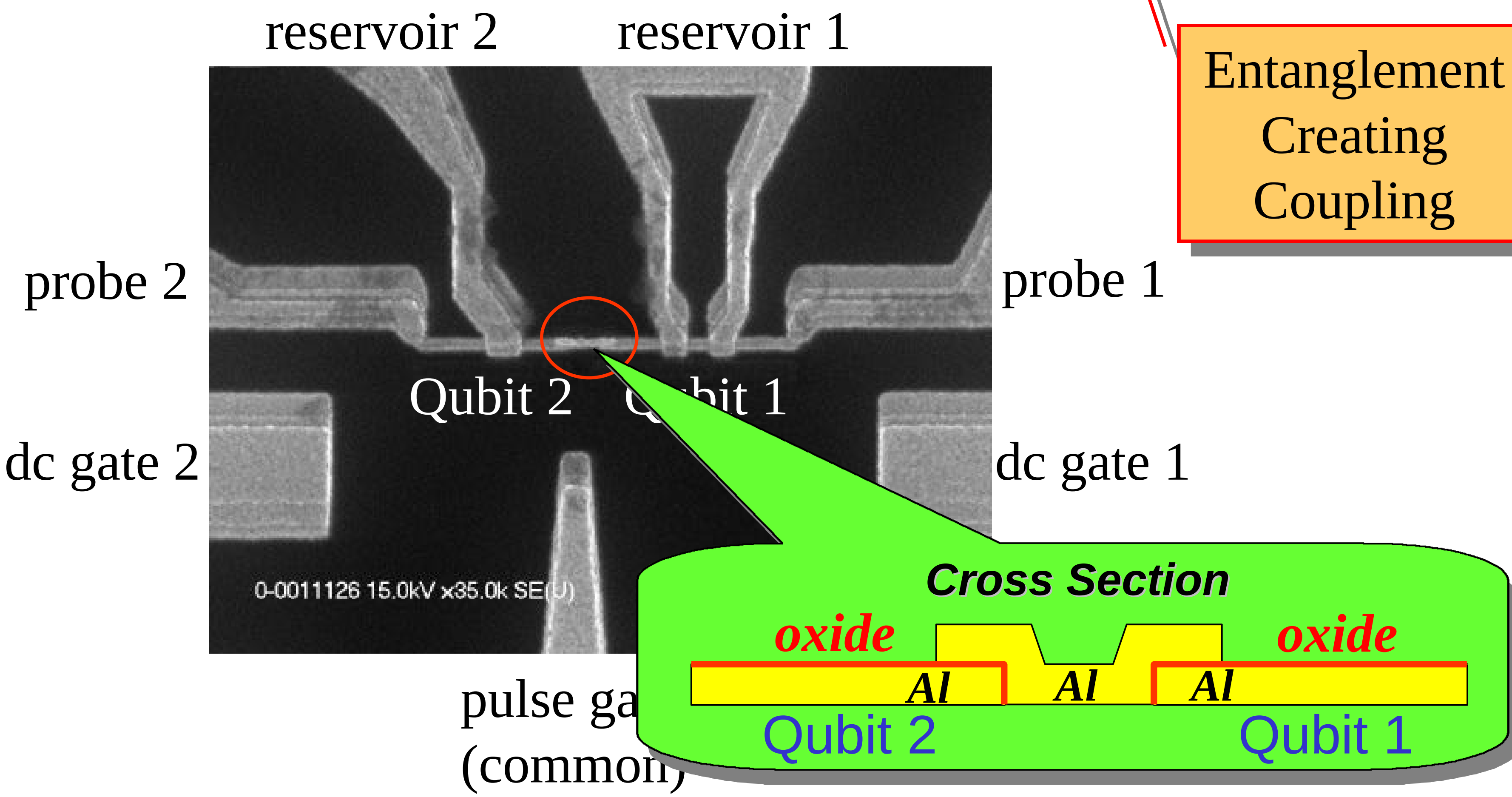


Total count: 327

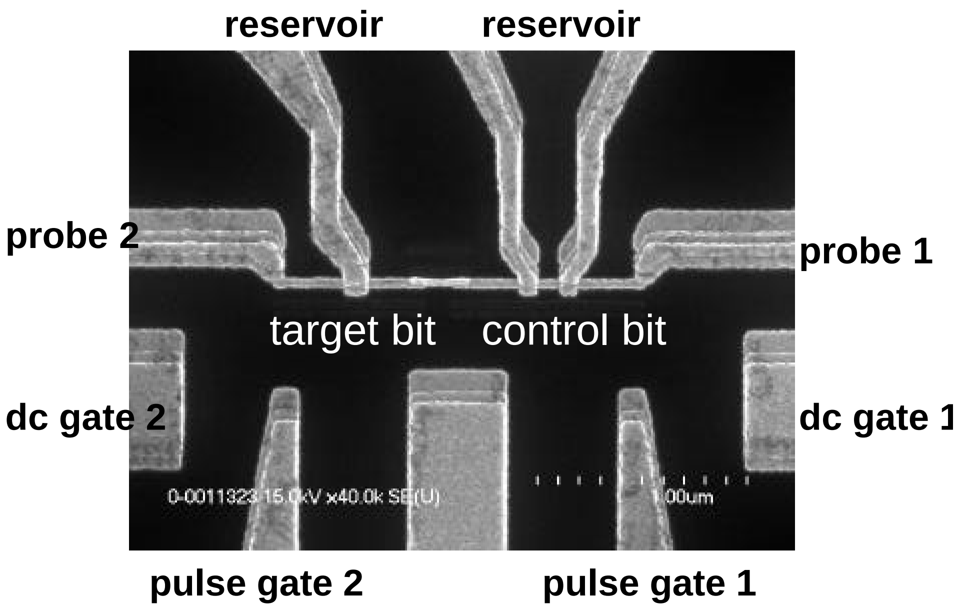
Coupled 2 Qubits - capacitive coupling

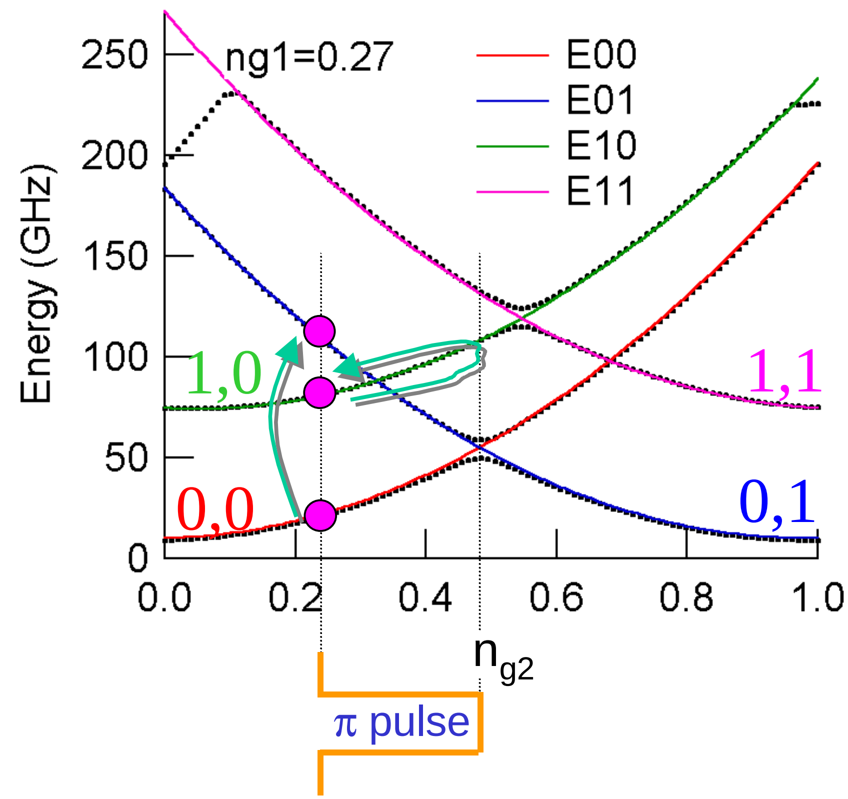
$$
\begin{aligned}
H(n_{g1}, n_{g2}) \;=\; \sum_{n_1, n_2 = 0,1} & \Big[4E_{c1}(n_1 - n_{g1})^2 + 4E_{c2}(n_2 - n_{g2})^2 \\
& + E_m (n_1 - n_{g1})(n_2 - n_{g2}) \Big] |n_1 n_2\rangle\langle n_1 n_2| \\
& - \frac{E_{J1}}{2}\Big(|00\rangle\langle 10| + |01\rangle\langle 11| + H.C. \Big) \\
& - \frac{E_{J2}}{2}\Big(|00\rangle\langle 01| + |10\rangle\langle 11| + H.C. \Big)
\end{aligned}
$$

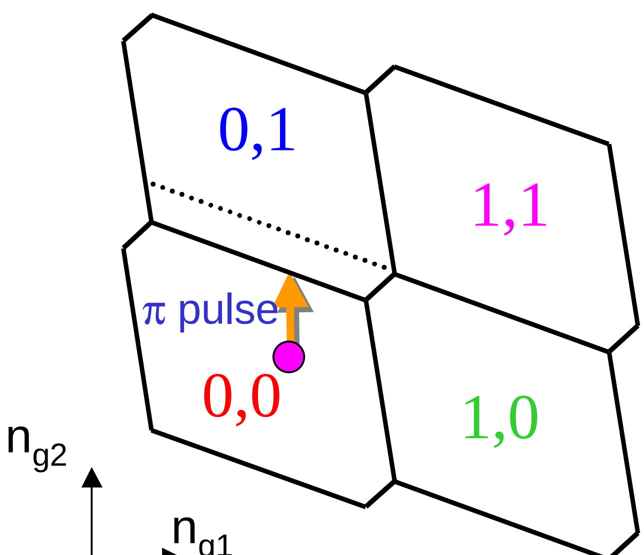
Entanglement Creating Coupling



Demonstration of controlled-NOT gate operation





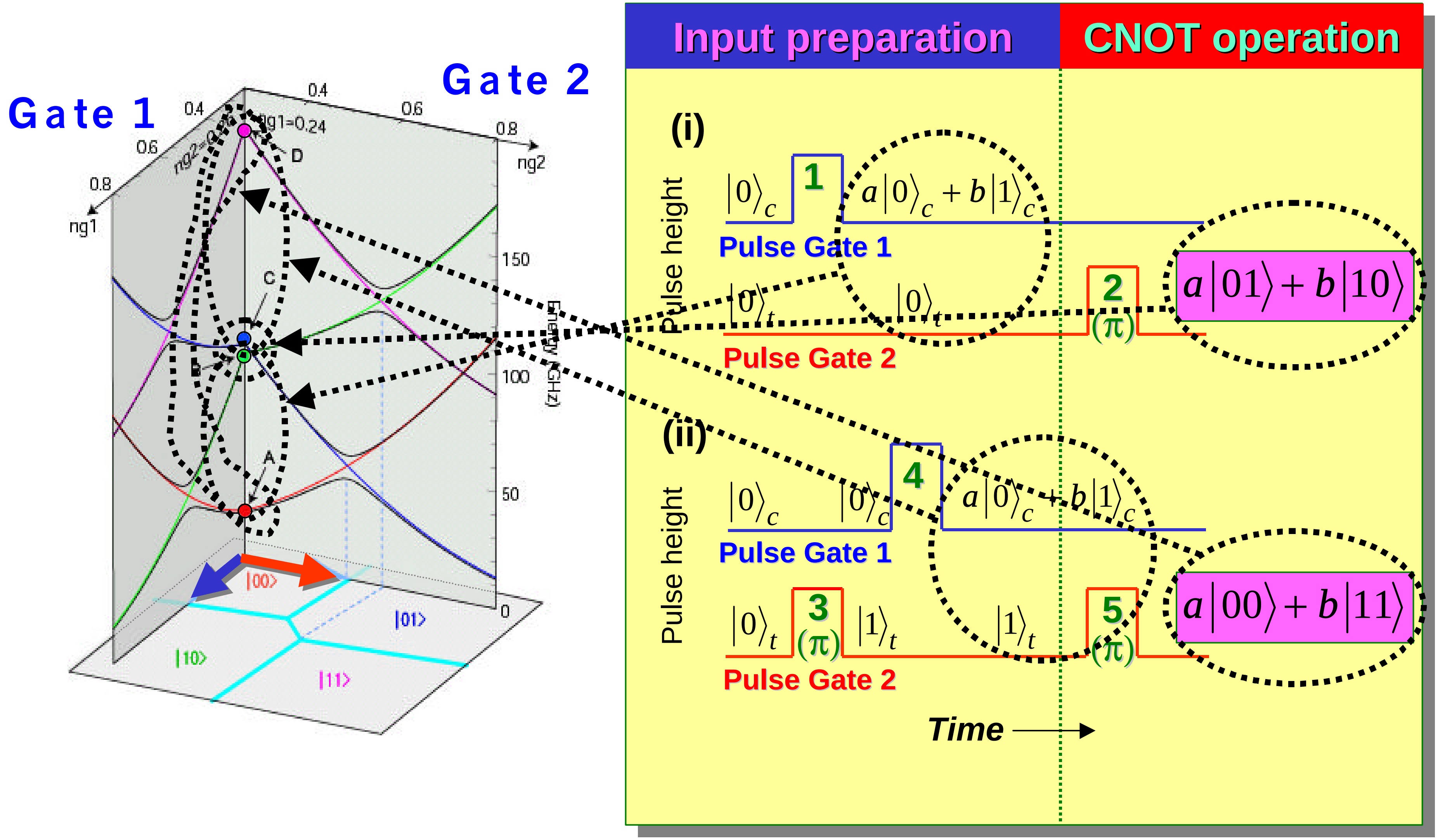


control target

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

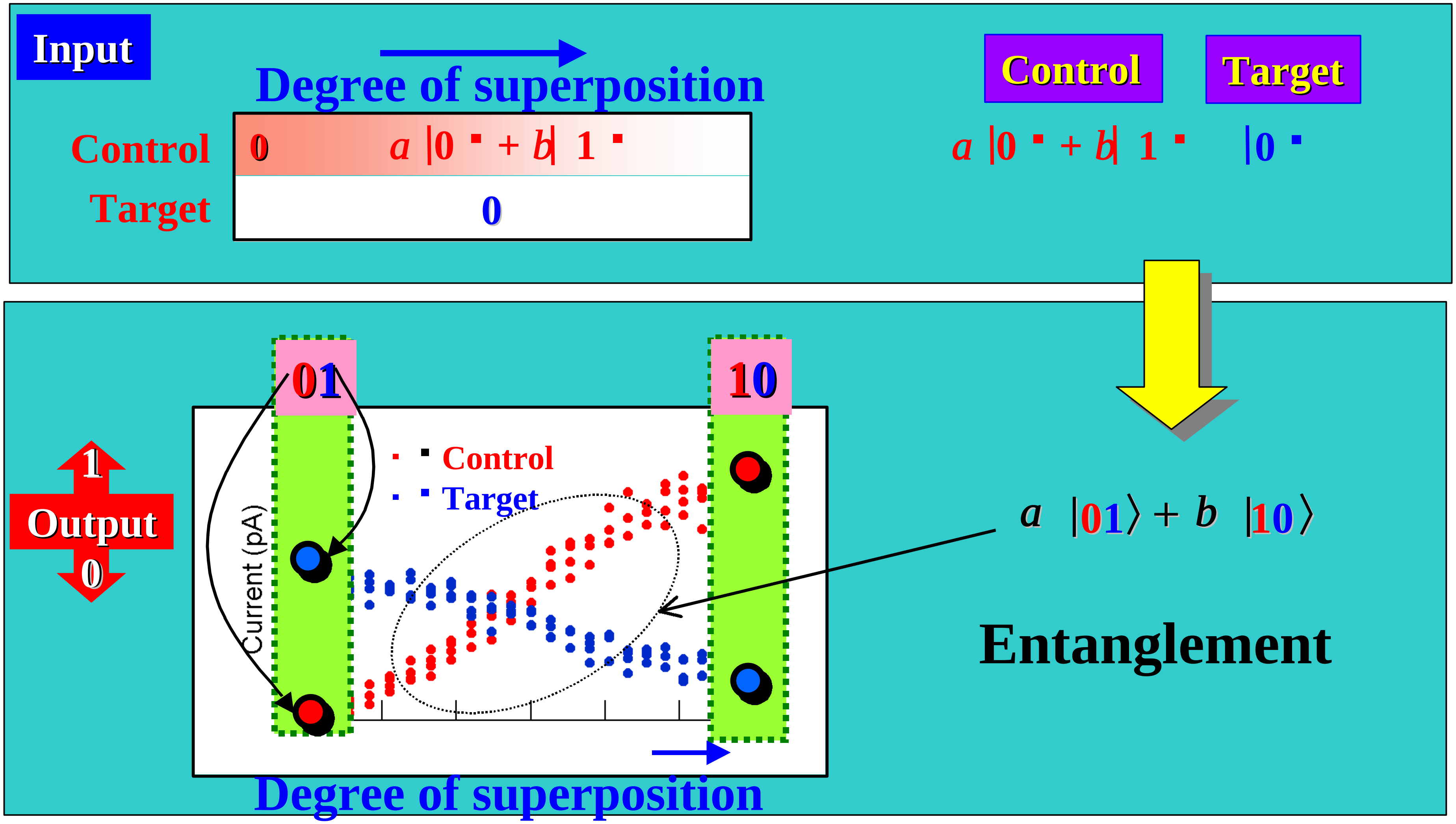
$$|00\rangle \longrightarrow |01\rangle$$

conditional operation !



Outside of the co-resonance:
No coherence between **(00 and 11)**, **(01 and 10)**

Result 1



Control

Target

Input	Output
00	01
10	10

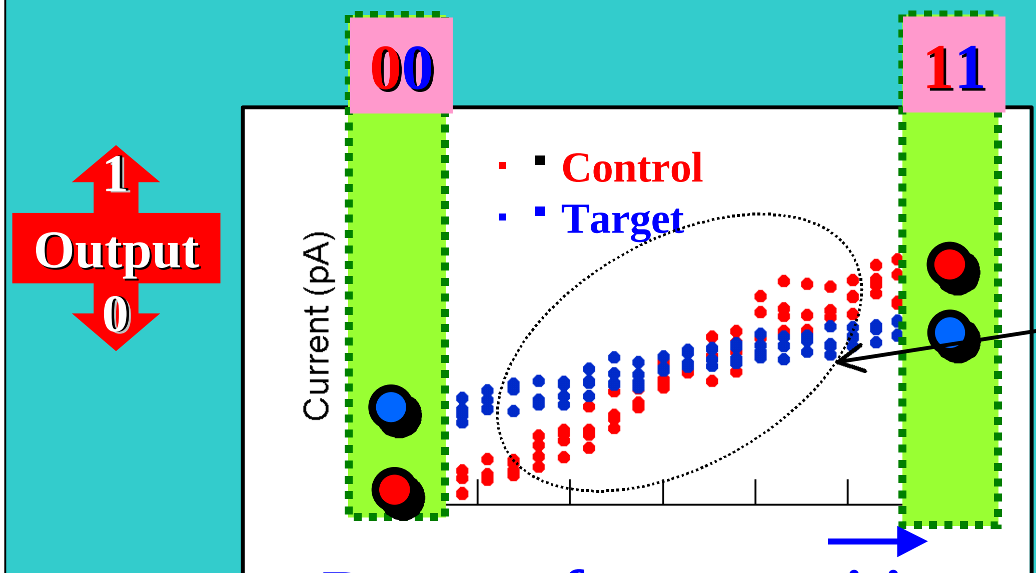
Result 2

Input

Degree of superposition

Control	0 $a|0\rangle + b|1\rangle$
Target	1

Control	Target
$a|0\rangle + b|1\rangle$	$|1\rangle$



Degree of superposition

$a\,|00\rangle + b\,|11\rangle$

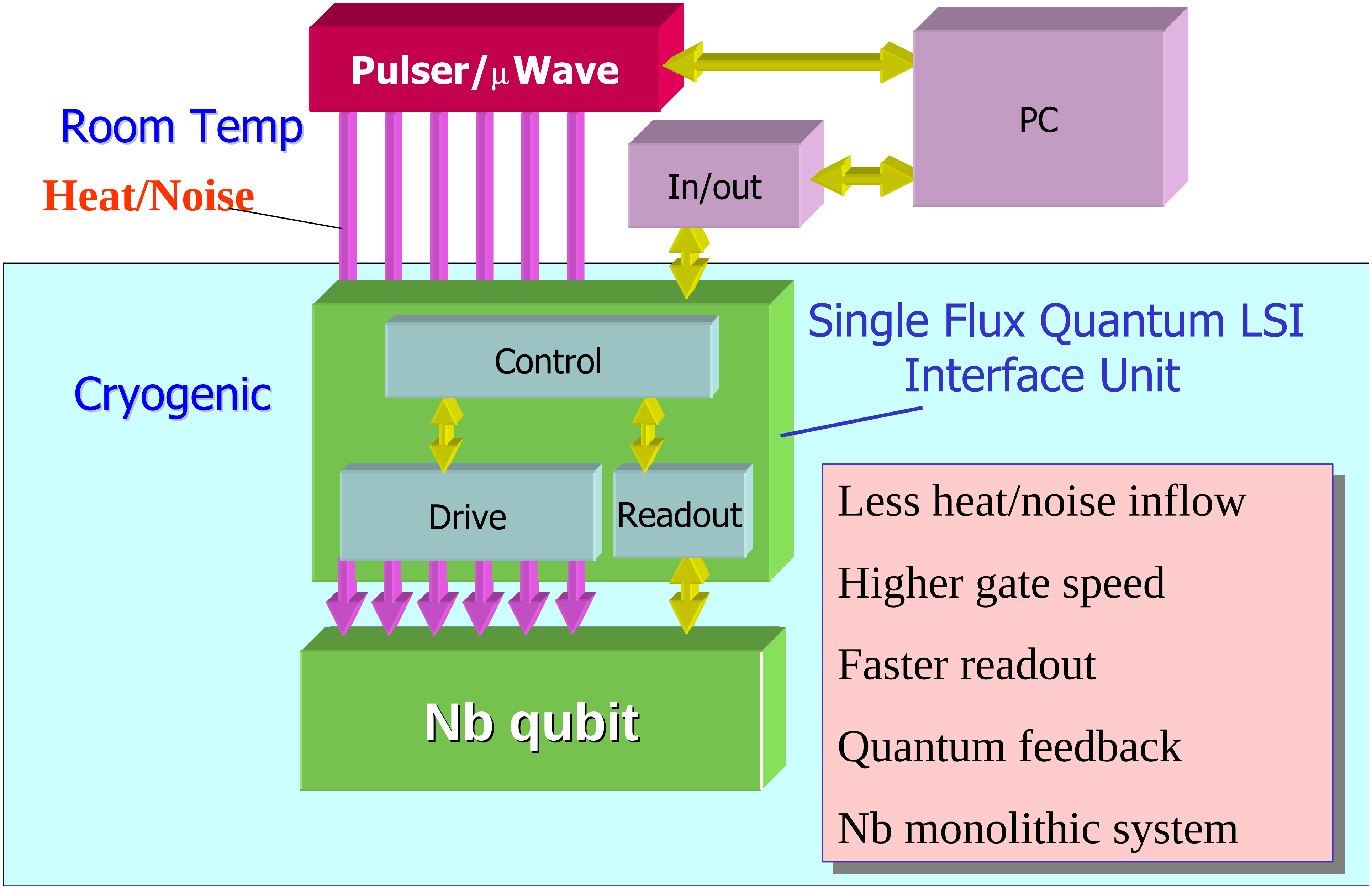
Entanglement

Control

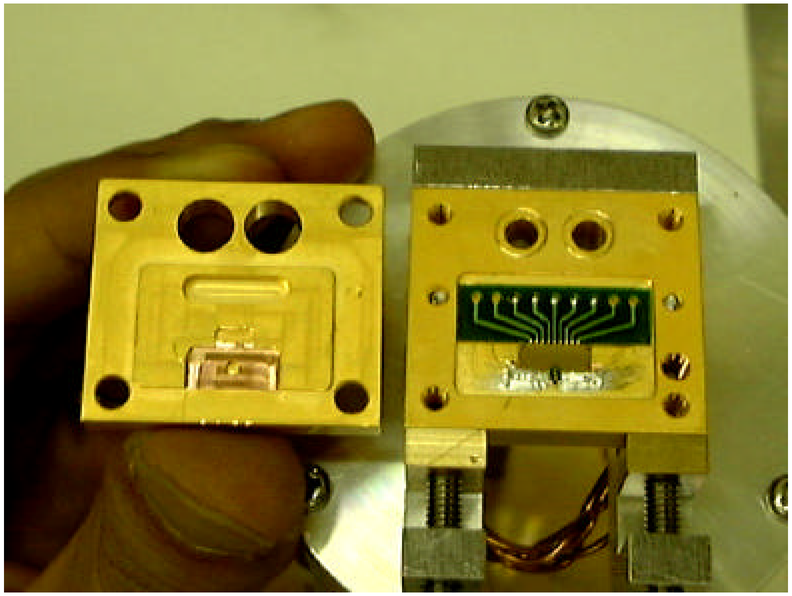
Target

Input	Output
01	00
11	11

Superconducting qubit system



- Less heat/noise inflow
- Higher gate speed
- Faster readout
- Quantum feedback
- Nb monolithic system



SUMMARY

COHERENTLY COUPLED

2-QUBIT

MACROSCOPIC-ENTANGLEMENT CREATION

CNOT OPERATION

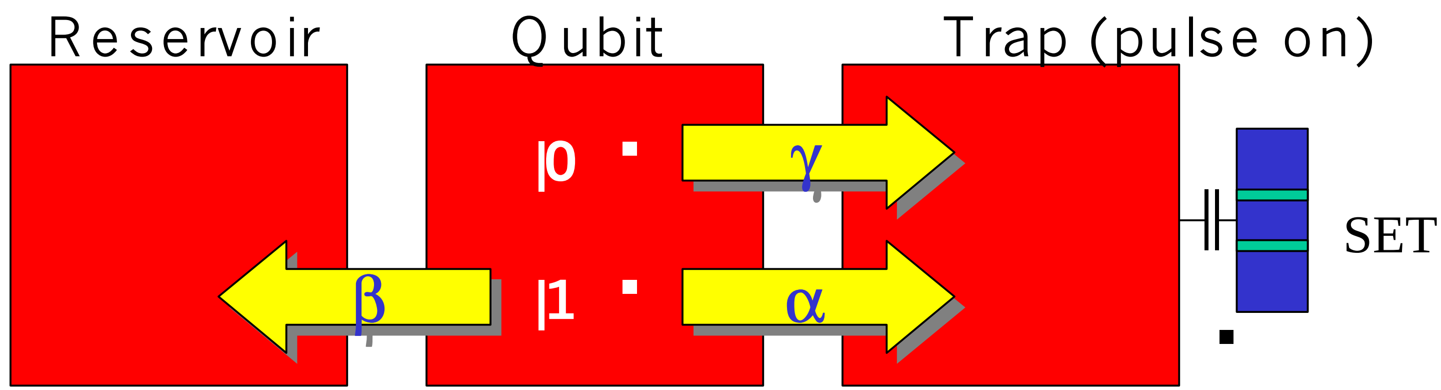
Single-**S**HOT **M**EASUREMENT

EFFICIENCY~90%

UNSOLVED **I**SSUES:

DECOHERENCE/RELAXIATION

INTEGRATON



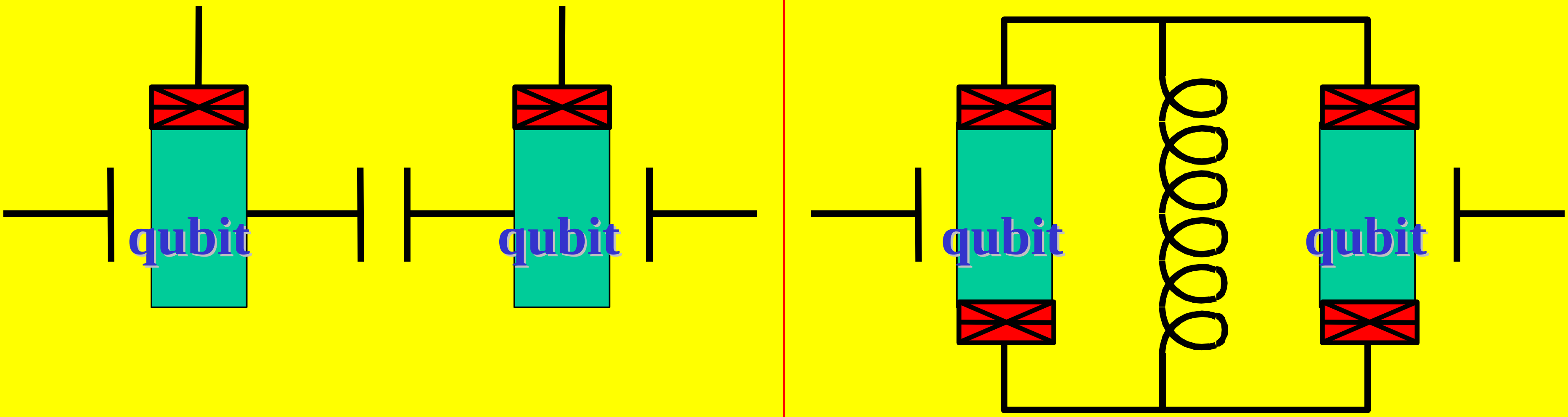
$\beta^{-1} = \mathbf{T_1}$

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	$P_1 P_p - (1 - P_0) \approx 67\%$

P_p=84% (fitted); t_{RD} = 300ns

Coupling Charge Qubits

JQ You, et al.
PRL, 89, 197902-1, 2002



$\sigma_z \sigma_z$

$\sigma_x \sigma_x$