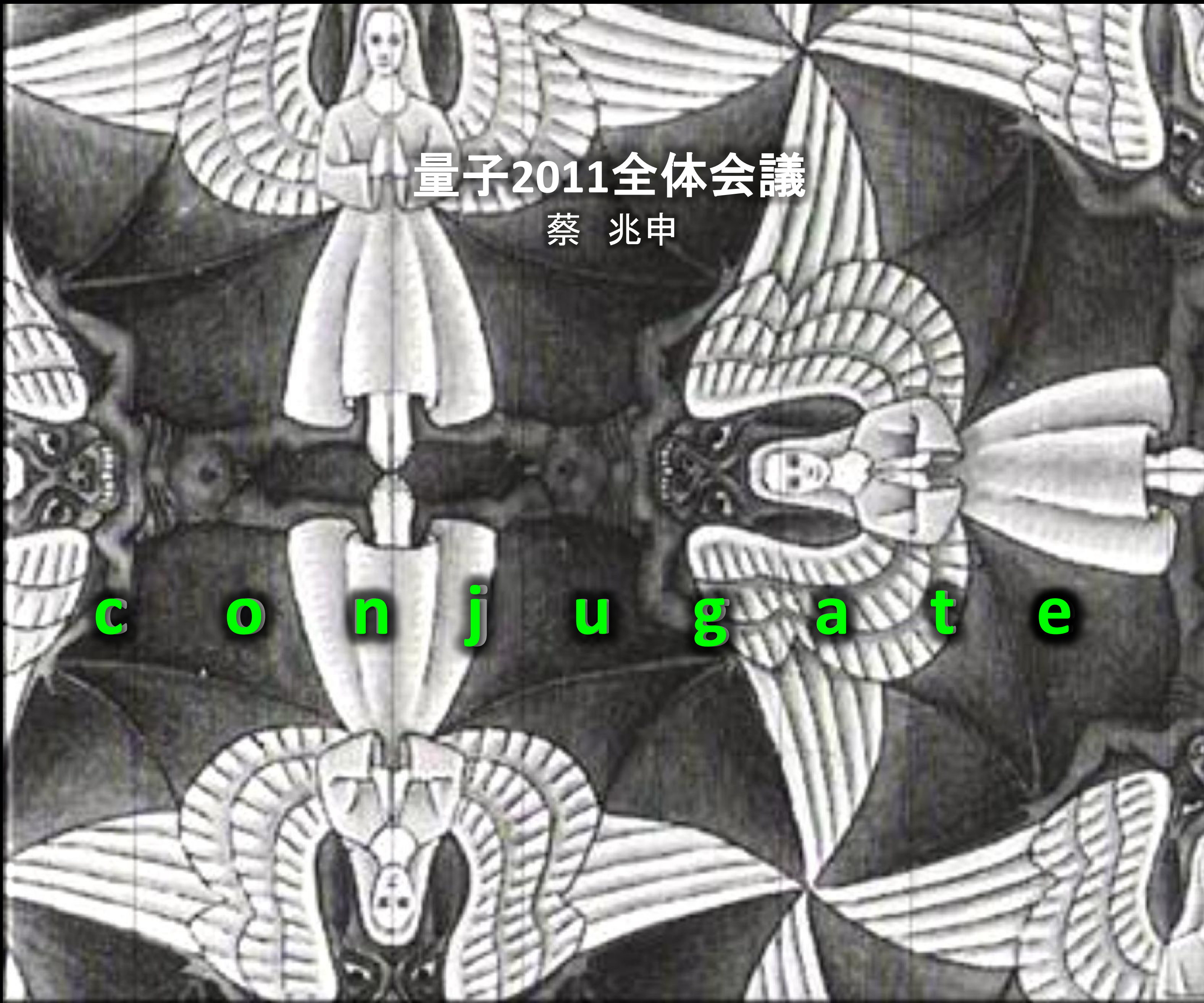
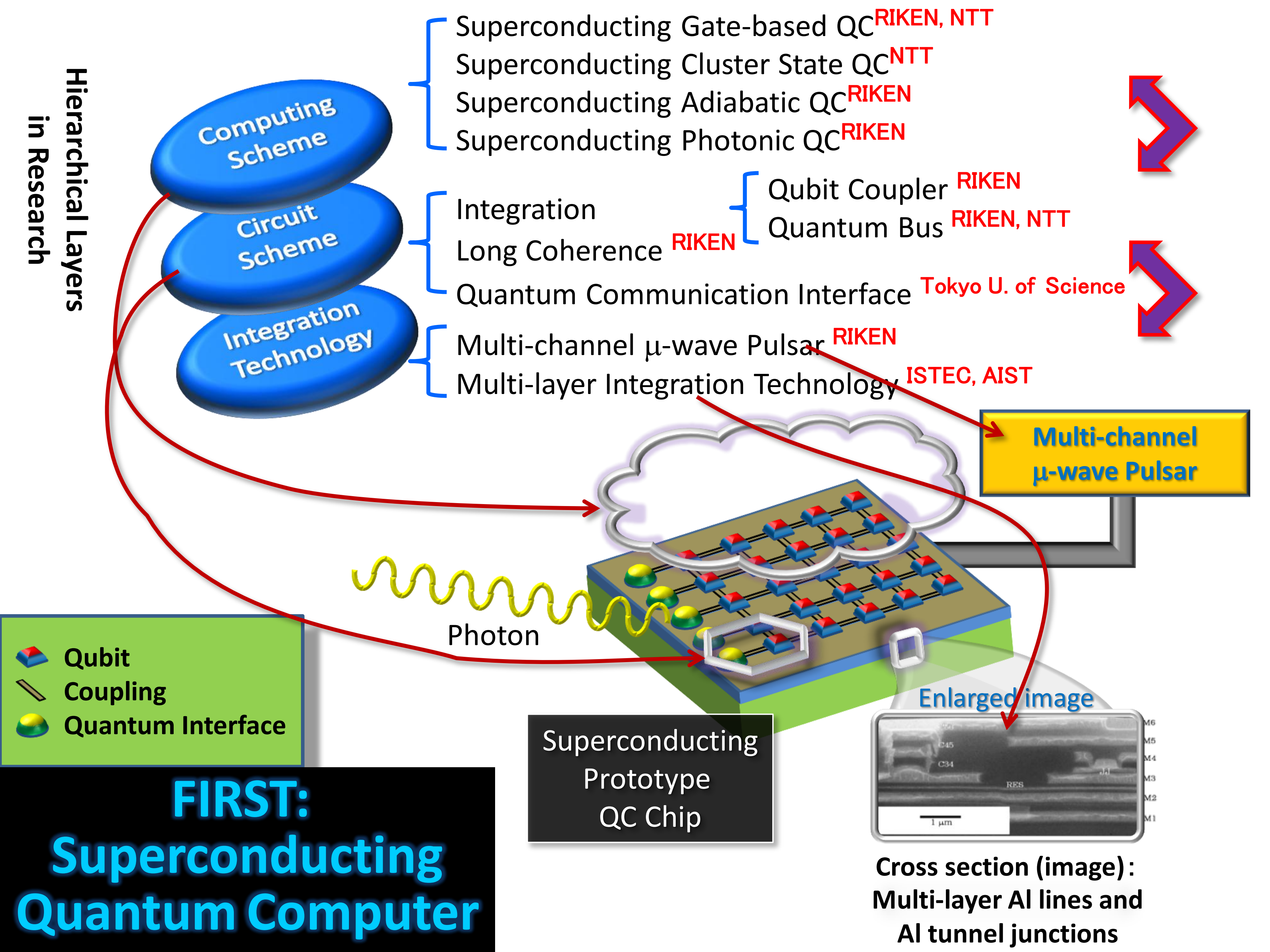
Observation of Coherent Quantum Phase Slip



M.C. Escher *Angels and devils (detail), 1941*



Hierarchical Layers in Research
Computing Scheme
Circuit Scheme
Integration Technology
Superconducting Gate-based QC RIKEN, NTT
Superconducting Cluster State QC NTT
Superconducting Adiabatic QC RIKEN
Superconducting Photonic QC RIKEN
Integration
Long Coherence RIKEN
Qubit Coupler RIKEN
Quantum Bus RIKEN, NTT
Quantum Communication Interface Tokyo U. of Science
Multi-channel μ-wave Pulsar RIKEN
Multi-layer Integration Technology ISTEC, AIST
Multi-channel μ-wave Pulsar
Photon
Qubit
Coupling
Quantum Interface
Superconducting Prototype QC Chip
Enlarged image
Cross section (image): Multi-layer Al lines and Al tunnel junctions
FIRST: Superconducting Quantum Computer

Superconducting Quantum Cybernetics

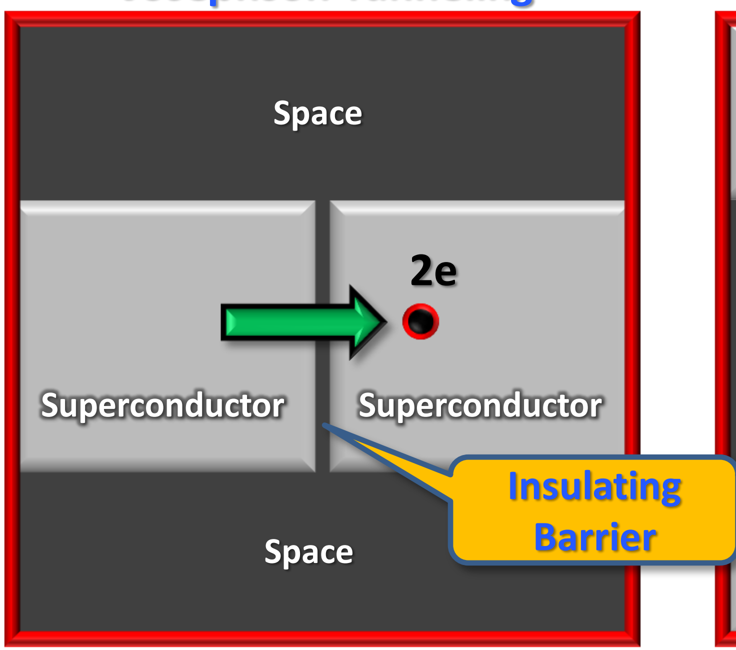
Quantum Optics with Superconducting Atom
Parallel Current Pumpimg
Discrete Andreev Reflection Observation
Quantum Nanomechanics
Scalable Coupling Scheme
Quantum Phase Slip?

Observation of Coherent Quantum Phase Slip

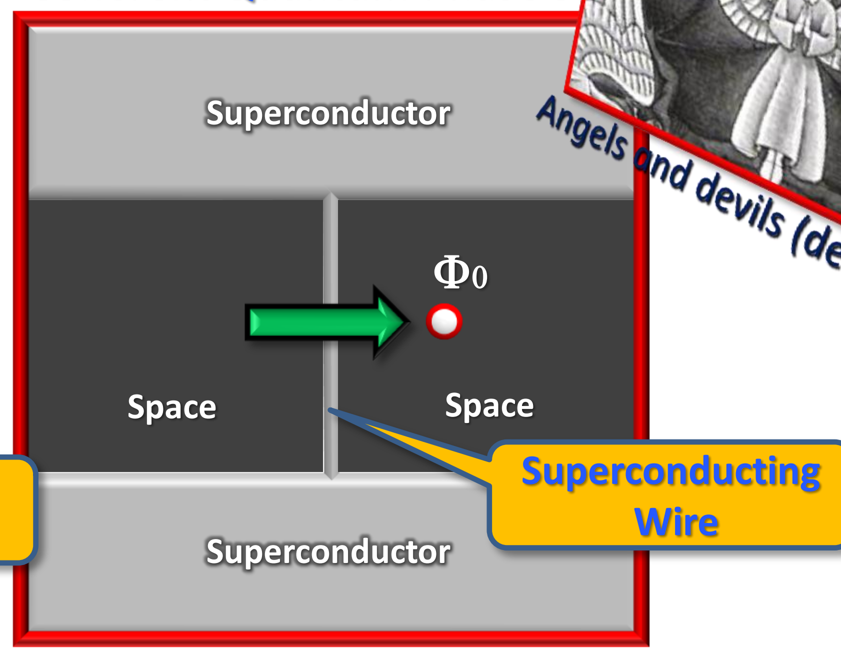
Riken/NEC: O. V. Astafiev, S. Kafanov, Yu. A. Pashkin, & J. S. Tsai
Rutgars: L. B. Ioffe
Jyveskyla: K. Yu. Arutyunov
Weizmann: D. Shahar, O. Cohen

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

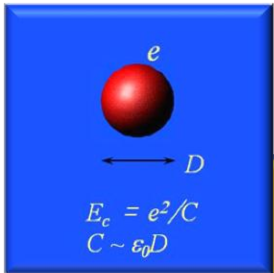
Josephson Tunneling

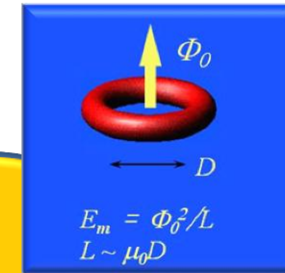


Coherent Quantum Phase Sli



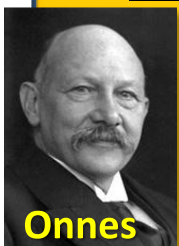
A Brief History of Superconductivity





Electric

1911: Supercurrent, (*Nobel 1913*)



1957: BCS Theory, (*Nobel 1972*)

1962: Josephson Effect, (*Nobel 1973*)

Magnetic

1933: Meissner Effect,

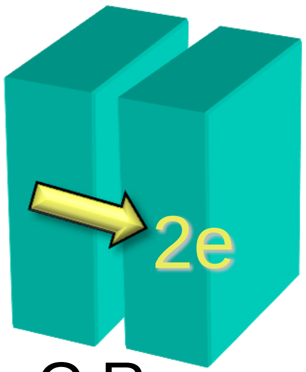
1952 : Abrikosov Vortex (*Novel 2003*)

Exact duality

2011: Coherent Quantum Phase Slip (CQPS)

Coulomb Blockade of Tunneling

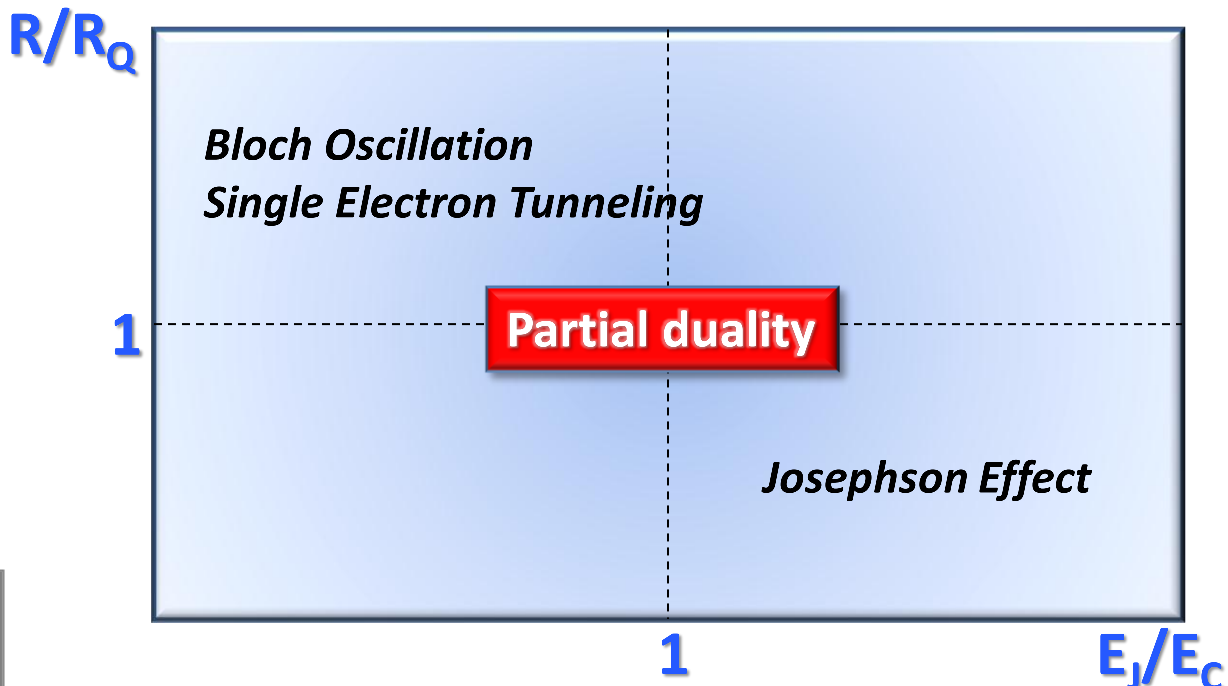
tunnel junction



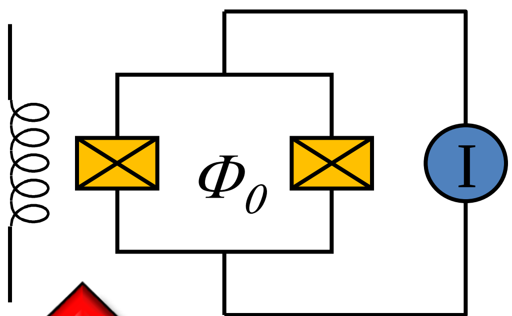
C,R

$$E_C \equiv \frac{e^2}{2C} > k_B T$$

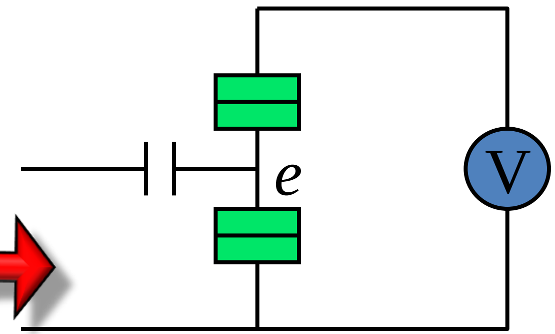
$$R_Q \equiv \frac{h}{4e^2} << R$$



Josephson Electronics	*Single Electronics*
flux quanta (***phase***)	charge (***number***)
Current bias	voltage bias
parallel element	serial element
inductive coupling	capacitive coupling



Partial duality



DC SQUID	Single Elect. Transistor
RF SQUID	Single Elect. Box
Josephson Memory	Single Elect. Trap
SFQ device	Single Elect. Turnstile
Resistively Couple Device	Resistively Coupled SET

Exact duality

Mooij, Nazarov. *Nature Physics* **2,** 169-172 (2006)

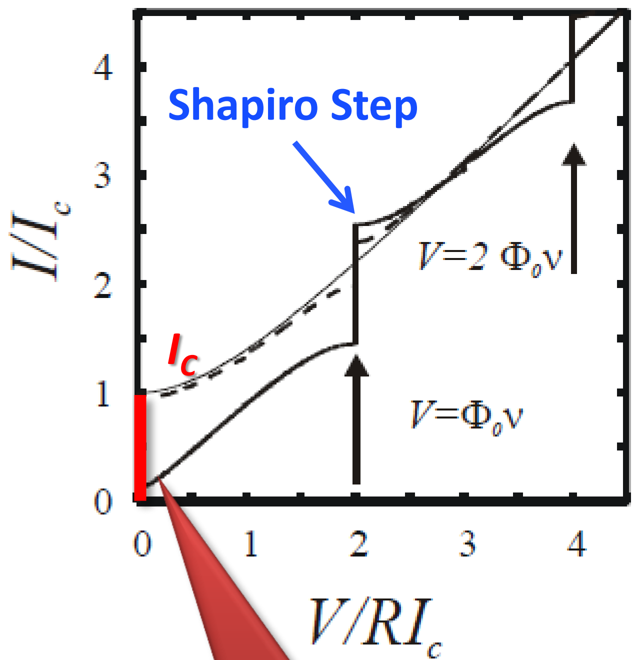
ϕ = Phase across junction

$[q, \phi] = -i$

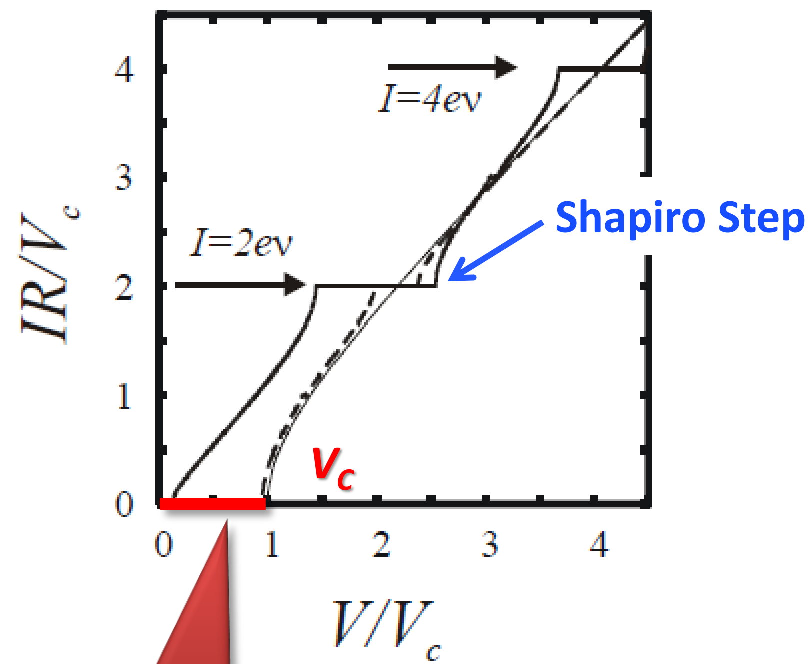
q = Cooper-pair transferred (continuous number)

Josephson Current: $I_c \sin\phi$
Kinetic Inductance: $\Phi_0(2\pi I_c \cos\phi)^{-1}$
Shapiro Step: $\Delta V = n\Phi_0 \nu$

CQPS Voltage: $V_c \sin(2\pi q)$
Kinetic Capacitance: $2e(2\pi V_c \cos(2\pi q))^{-1}$
Shapiro Step: $\Delta I = n2e\nu$



Supercurrent

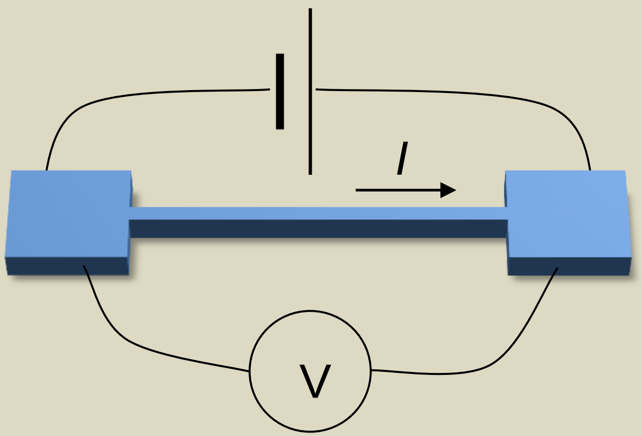


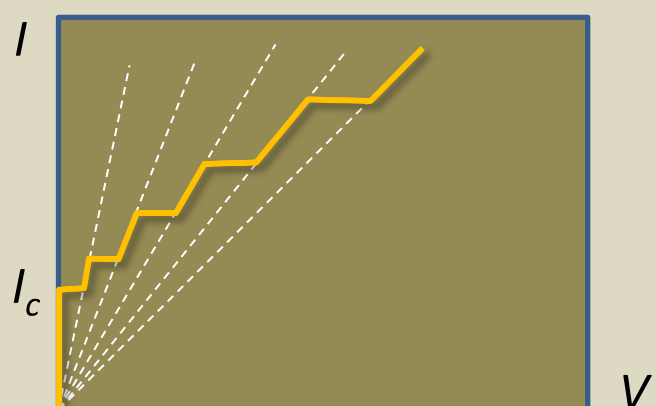
CQPS voltage

Phase-slip in superconducting nanowires

Thermal phase slip:

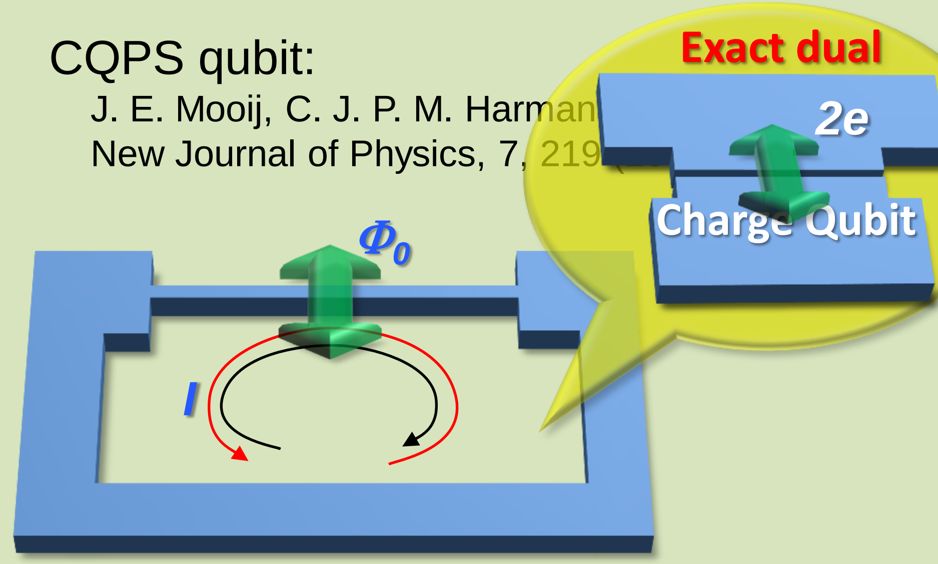
Finite voltage
across superconducting wires





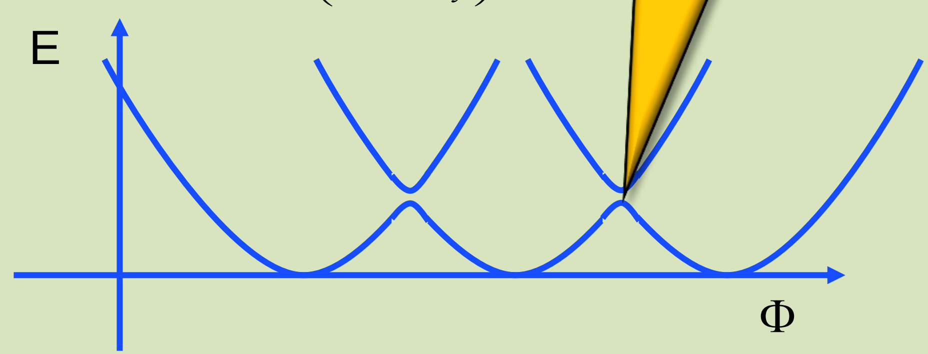
Coherent Quantum Phase-Slip

CQPS qubit:
J. E. Mooij, C. J. P. M. Harman
New Journal of Physics, 7, 219



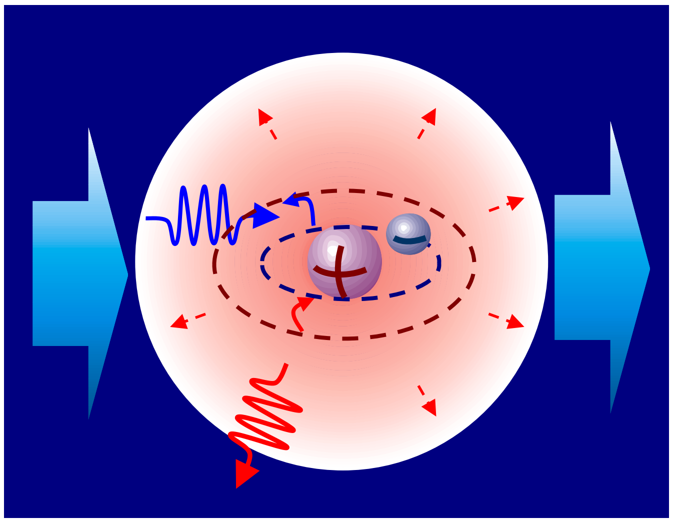
$$\Gamma_{cqps} = \alpha \exp\left(-\beta \frac{R_n}{R_\xi}\right)$$

$$\Delta = \hbar\Gamma_{cqps}$$

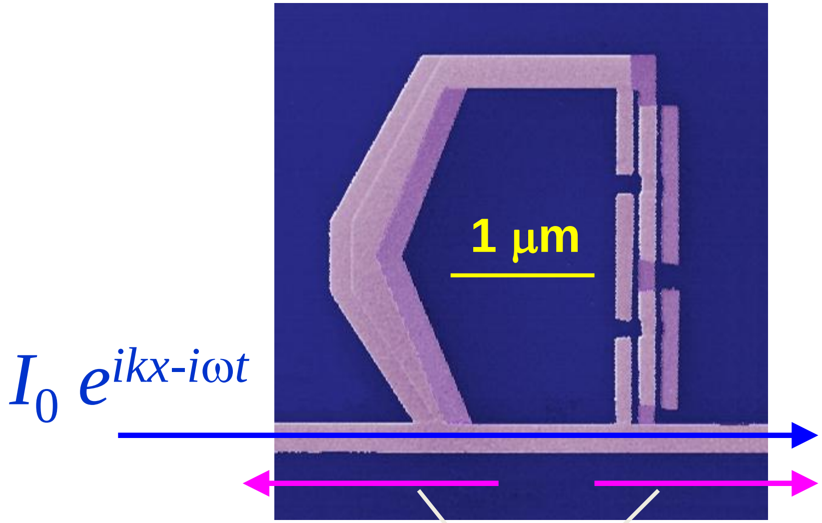


Atom in open space

Light scattering by an atom



MW scattering by a macroscopic quantum scatterer (10^{10} Al atoms)



Dipole moment $\langle \phi(t) \rangle = \phi_p \langle \sigma^- \rangle e^{-i\omega t}$

Matrix element $\phi_p = MI_p$

$$I_{sc}(x,t) = i\frac{\hbar\Gamma}{\phi_p}\langle \sigma^- \rangle e^{ik|x| - i\omega t}$$

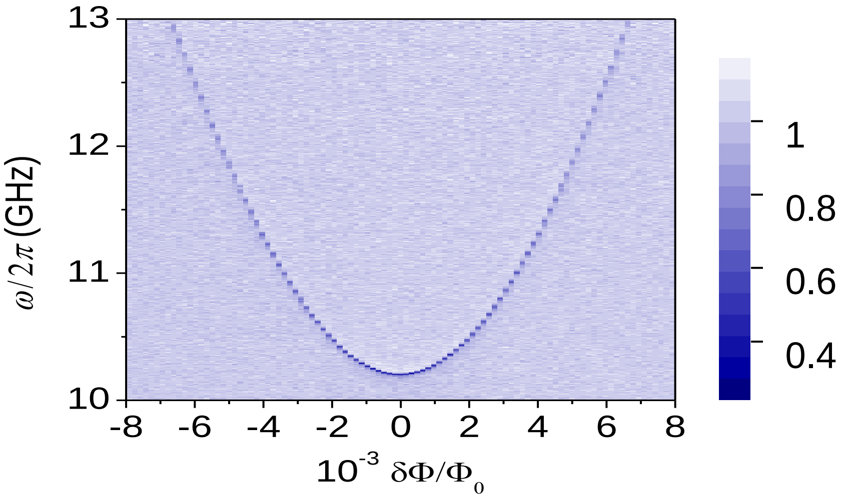
Natural atoms are weakly coupled to electromagnetic waves (weak scattering)

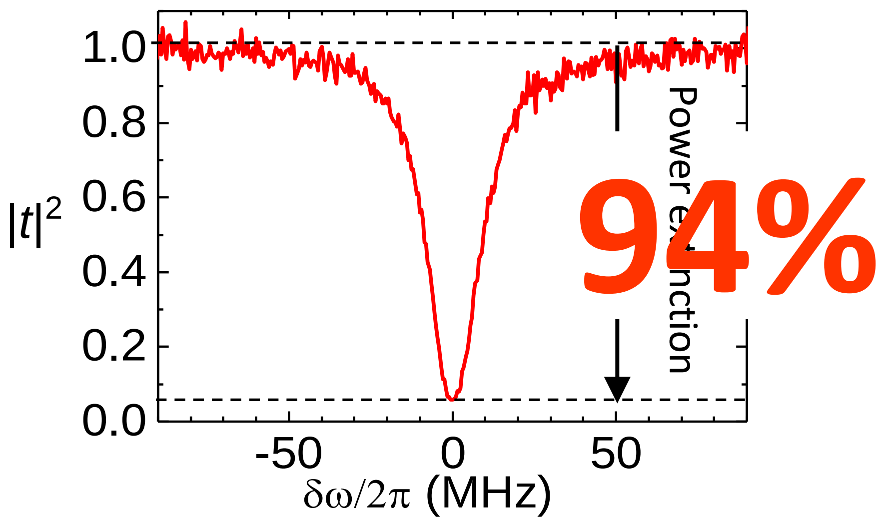
Artificial atoms are strongly coupled to electromagnetic waves

Strong scattering of propagating waves

Resonance fluorescence:
Extinction at the degeneracy point

Direct transmission spectroscopy





Previous record in optical systems was
12%

The artificial atom strongly interacts with modes of 1D open space

⇓

Promising candidate for quantum information processing

O. Astafiev, A. M. Zagoskin, A. A. Abdumalikov, Yu. A. Pashkin, T. Yamamoto, K. Inomata, Y. Nakamura, and J. S. Tsai. Resonance fluorescence of a single artificial atom. Science. 327 (2010).

Thank you for your attention