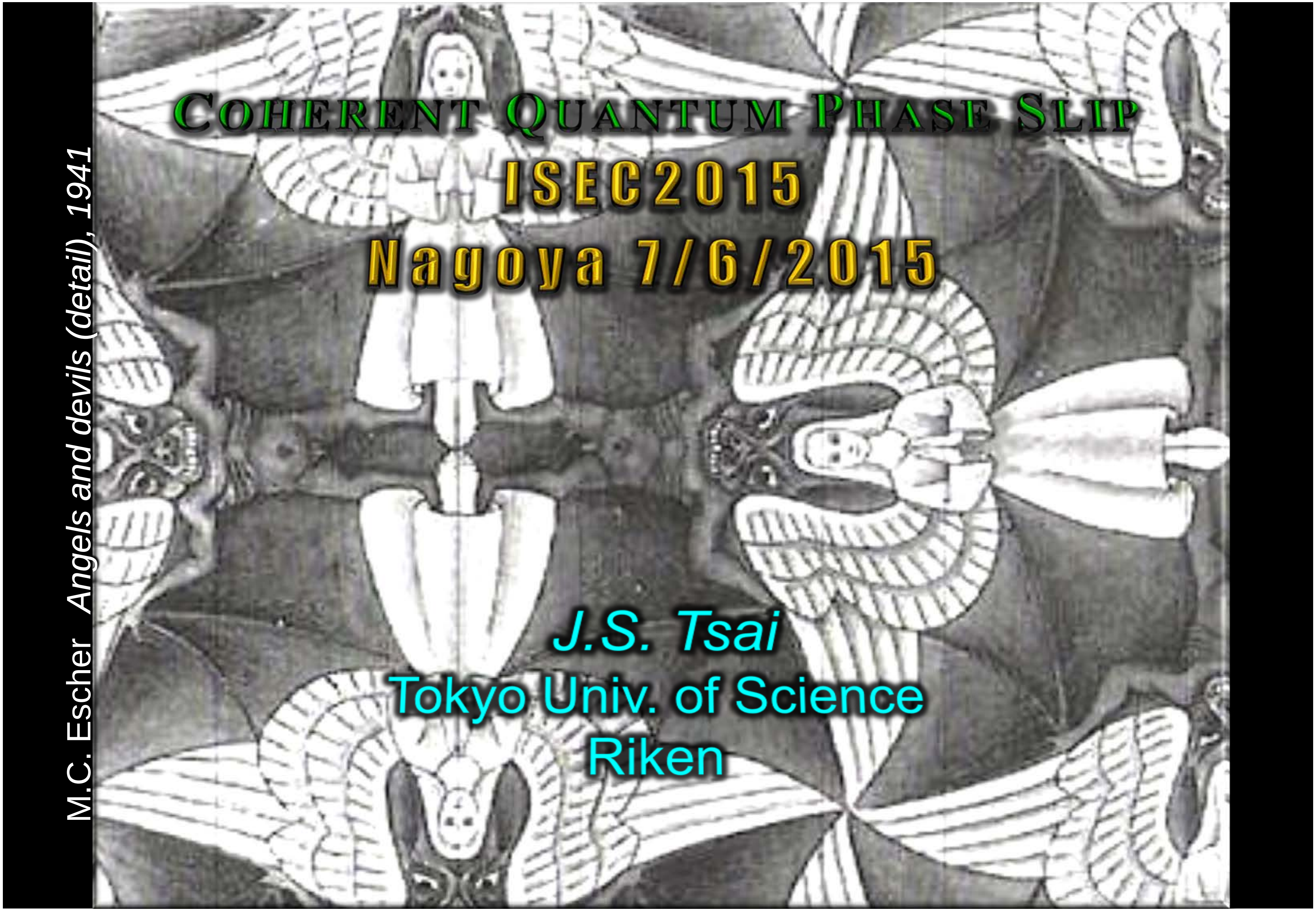
IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) July 2015.
Plenary Presentation PL1 given at ISEC 2015, Nagoya, Japan, July 6 – 9, 2015.

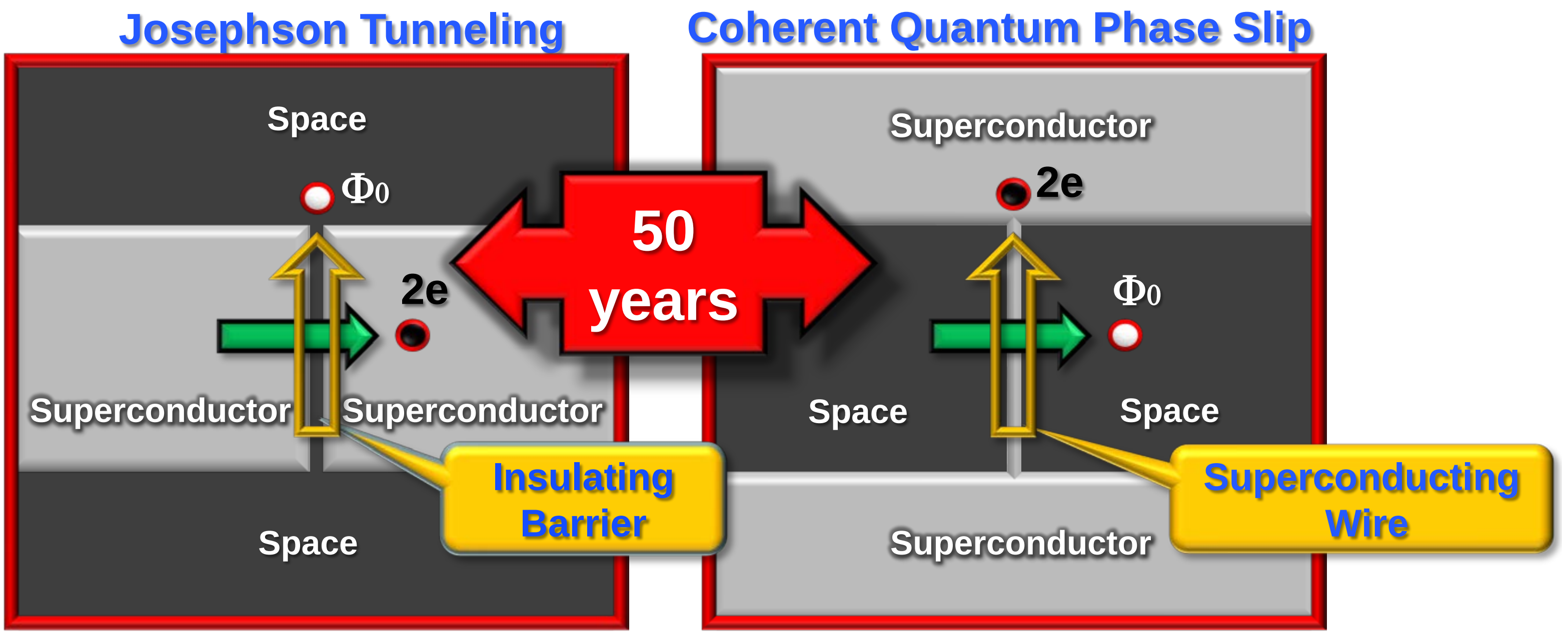


Coherent Quantum Phase Slip:

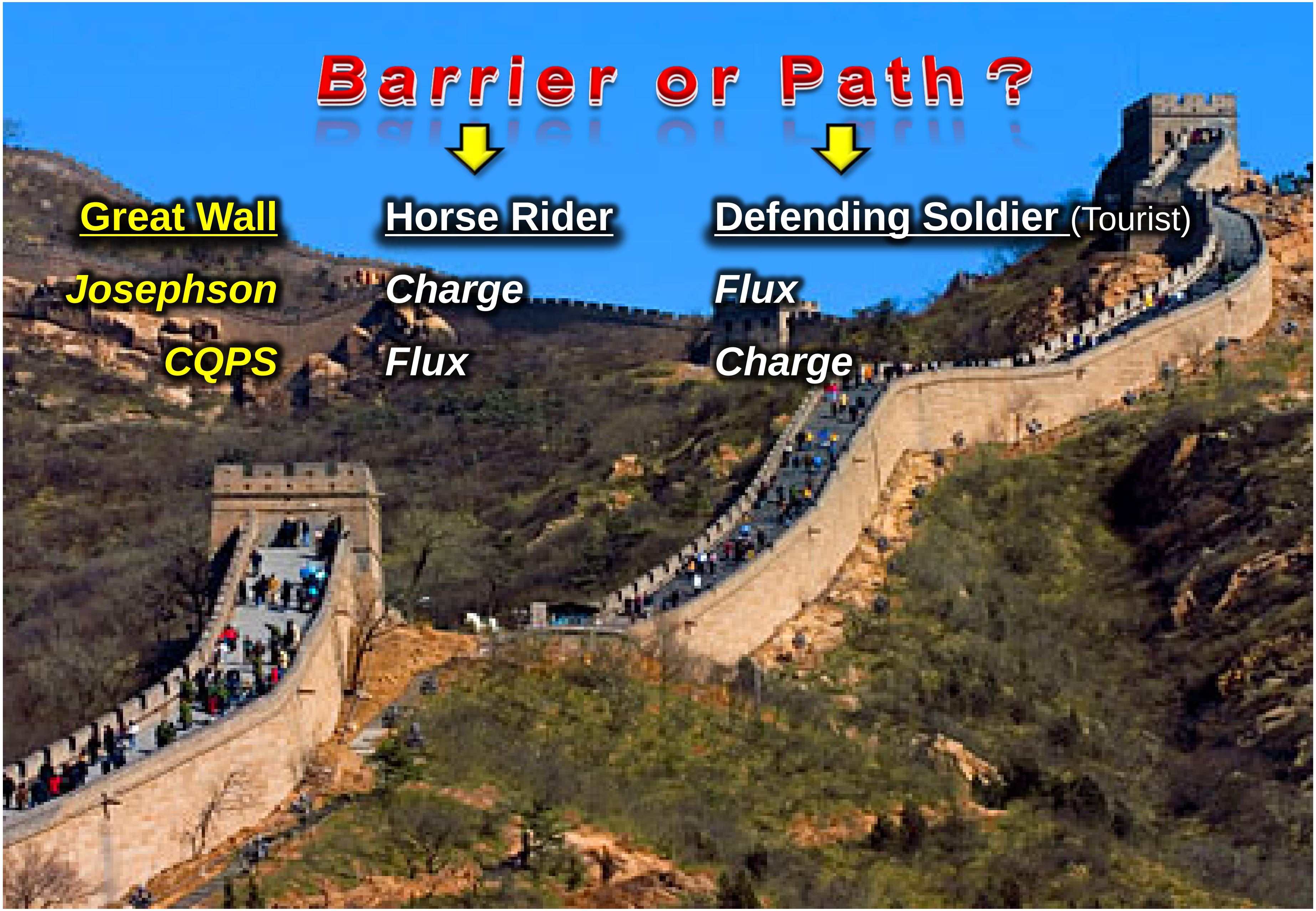
Exact quantum dual to ***Josephson Tunneling***

(Coulomb blockade is a "partial" dual)

Degree of freedom in superconductor: Phase and Charge



Nature doi: 10.1038/nature 10930, 2012


Barrier or Path ?
Great Wall
Horse Rider
Defending Soldier (Tourist)
Josephson
Charge
Flux
CQPS
Flux
Charge

Exact duality

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

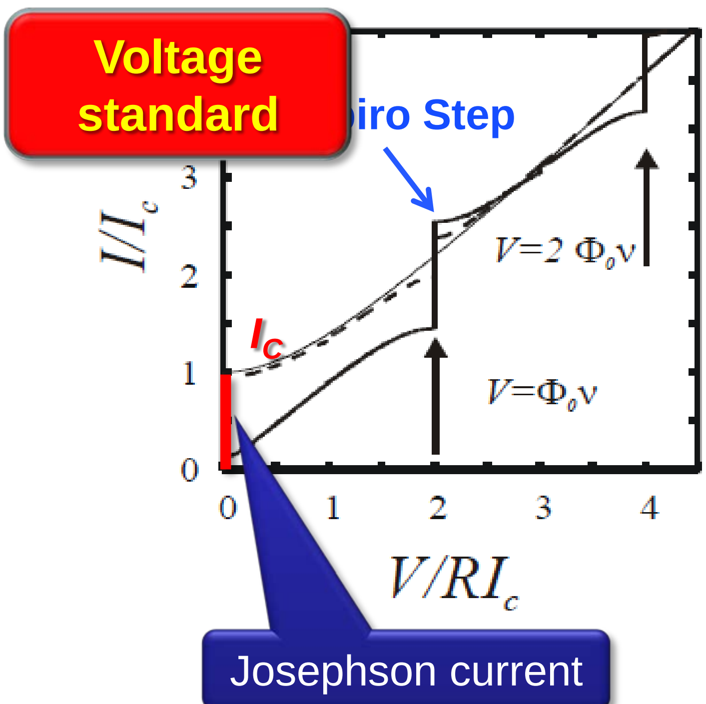
ϕ = Phase across junction

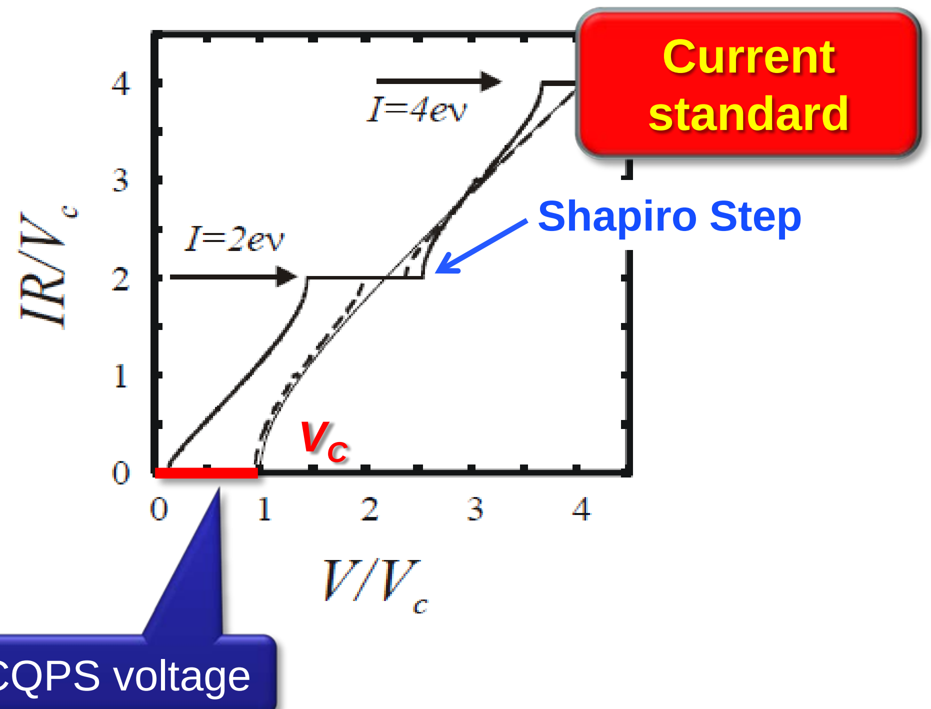
$[q, \phi] = -i$

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: $\Delta V = n\Phi_0 \nu$

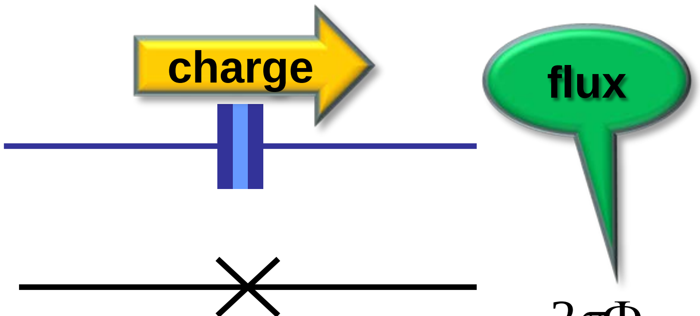
CQPS Voltage: $V_c \sin(2\pi q)$
Kinetic Capacitance: $2e(2\pi V_c \cos(2\pi q))^{-1}$
Shapiro Step: $\Delta I = n2e\nu$





Duality to the Josephson Effect

Josephson junction

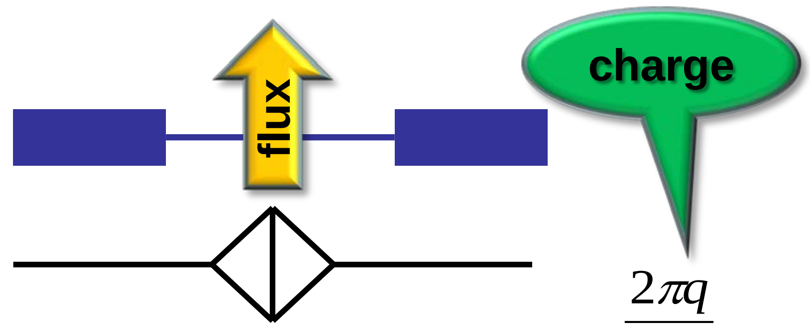


$$\frac{2\pi\Phi}{\Phi_0}$$

$$E_J = E_{J0}\cos\varphi$$

$$\frac{1}{L_J} = \left(\frac{2\pi}{\Phi_0}\right)^2 \frac{\partial^2 E_J}{\partial \varphi^2} \sim E_{J0}$$

Quantum phase-slip junction



$$\frac{2\pi q}{2e}$$

$$E_{CQPS} = E_0 \cos\chi$$

$$\frac{1}{C_k} = \left(\frac{2\pi}{2e}\right)^2 \frac{\partial^2 E_{CQPS}}{\partial \chi^2} \sim E_0$$

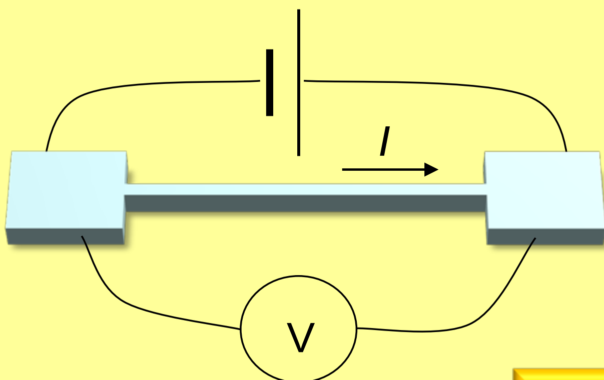
$Z \leftrightarrow Y \quad L \leftrightarrow C \quad \Phi_0 \leftrightarrow 2e$

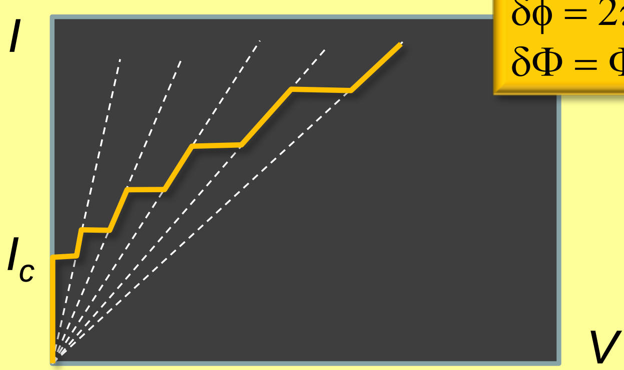
The CQPS is completely dual to the Josephson effect

Phase-slip in superconducting nanowires

Thermal phase slip:

Finite voltage
across superconducting wires

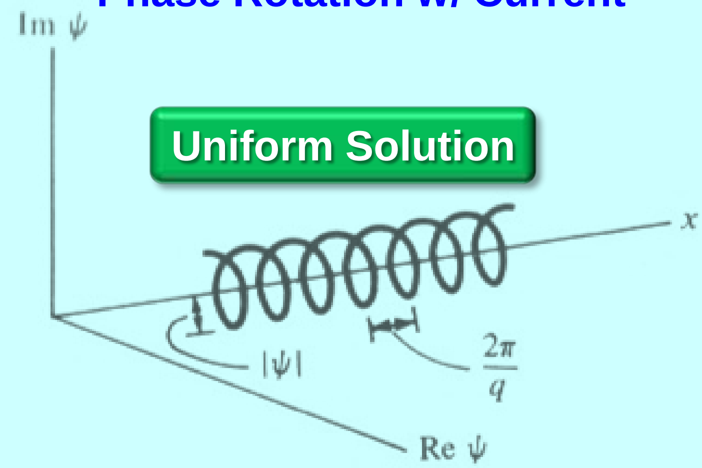




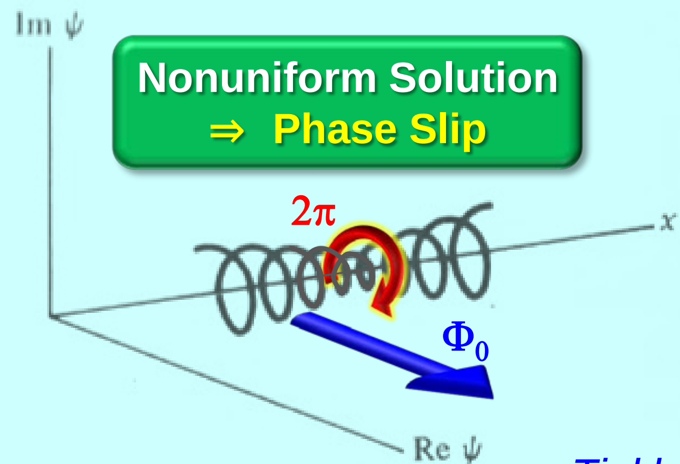
$\delta\phi = 2\pi$
$\delta\Phi = \Phi_0$

Complex GL wavefunction ψ in 1-D
Phase Rotation w/ Current

Uniform Solution



Nonuniform Solution
⇒ Phase Slip



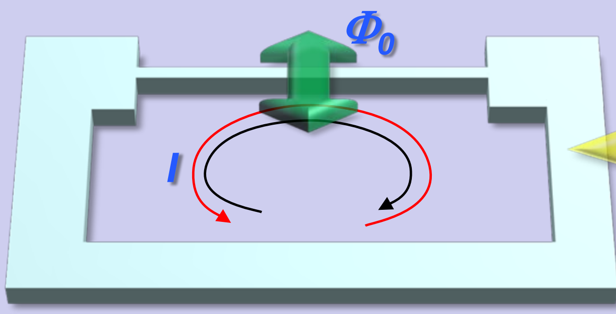
Tinkham

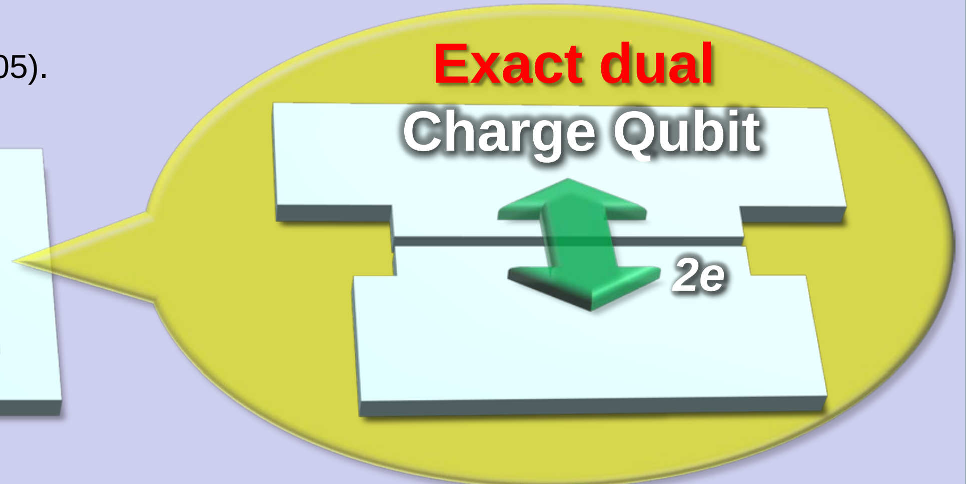
Phase-slip in superconducting nanowires

Coherent Quantum Phase-Slip

CQPS Qubit:

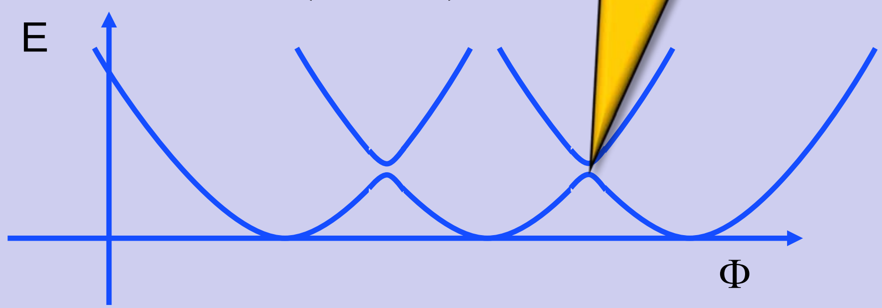
J. E. Mooij, C. J. P. M. Harmans,
New Journal of Physics, 7, 219 (2005).





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

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



Superconducting qubits

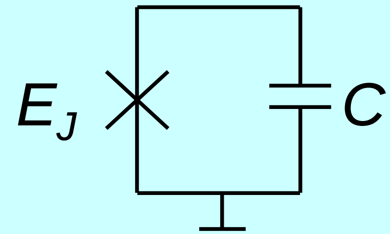
- Quantized charge: $2e$: $|N\rangle$, $|N+1\rangle$
- Quantized flux: Φ_0: $|\downarrow\rangle$, $|\uparrow\rangle$

Charging energy: $E_c = 4e^2/C$
Josephson (tunneling) energy: E_J
Magnetic energy: $E_L = \Phi_0^2/L$
Phase-slip energy: E_S

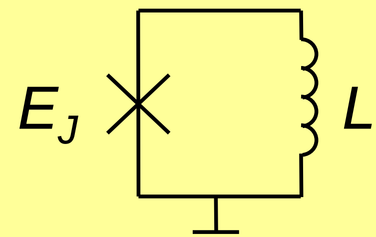
Necessary condition: $E_{qubit} \gg kT$

- Charge qubit: $E_C \gg E_J$
- Flux qubits: $E_J \gg E_c$
- Phase-slip qubit: $E_L \gg E_S$

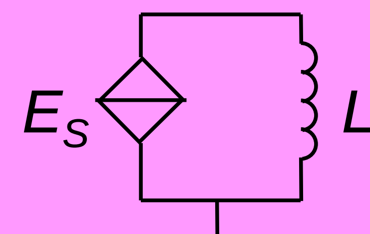
Charge qubit



Flux qubit

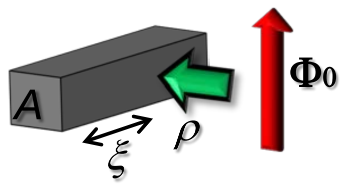


Phase-slip qubit

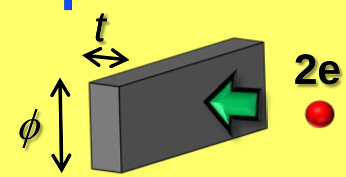


Device characteristics

CQPS: superconducting wire



Josephson : insulator



CQPS energy

$$E_{cqps} \propto \alpha \exp(-\beta \frac{R_Q A}{\rho \xi})$$

Josephson energy

$$E_J \propto \alpha' \exp(-\beta' t \sqrt{\phi})$$

A: cross sectional area
ρ: resistivity (<Tc)
ξ: coherence length

Inductive energy

$$E_k = \frac{\Phi_0^{\,2}}{L}$$

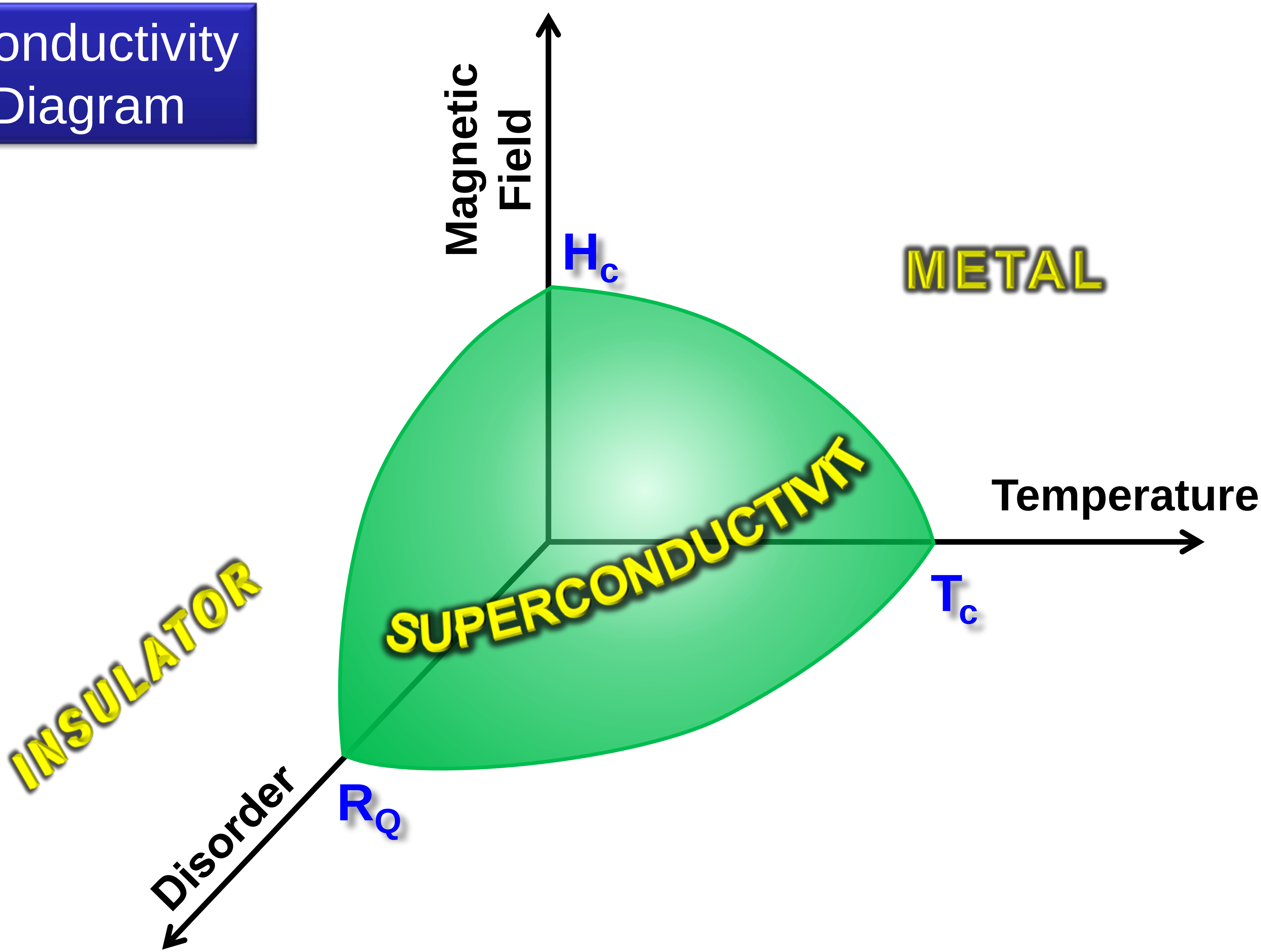
$$L_{\square} = 0.14 \frac{hR_{\square}}{k_B T}$$

$$E_k >> E_{cqps} > k_B T$$

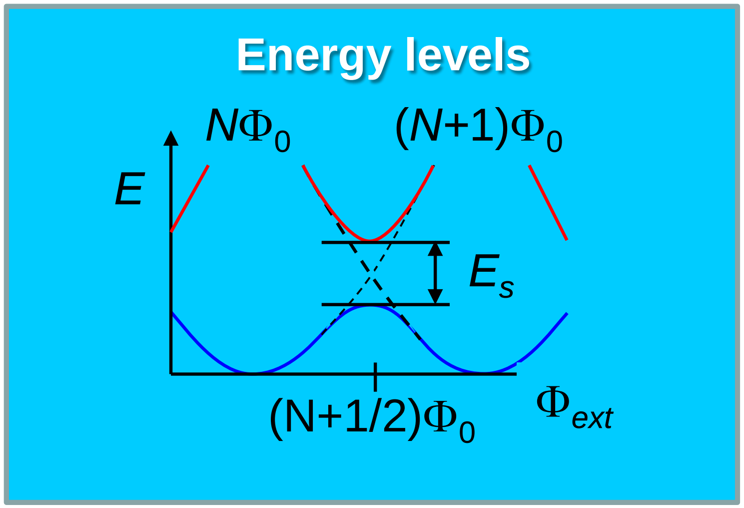
Disordered superconductor for large *ρ*

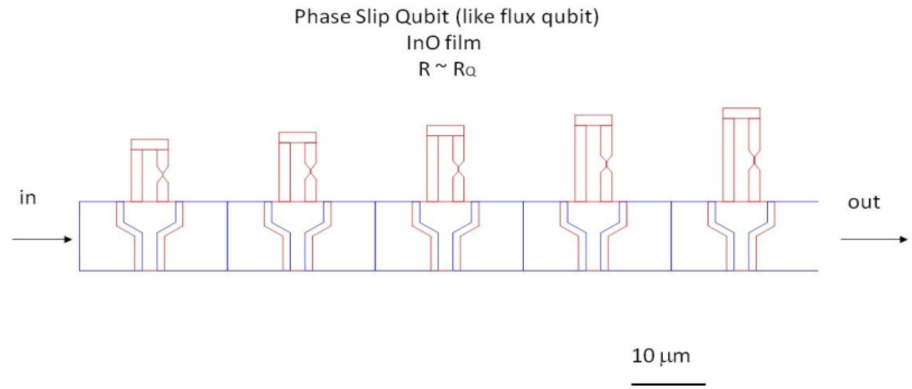
InO_x film
t = 35 nm
T_c = 2.7K
$R_{\square}$ =1.7kΩ

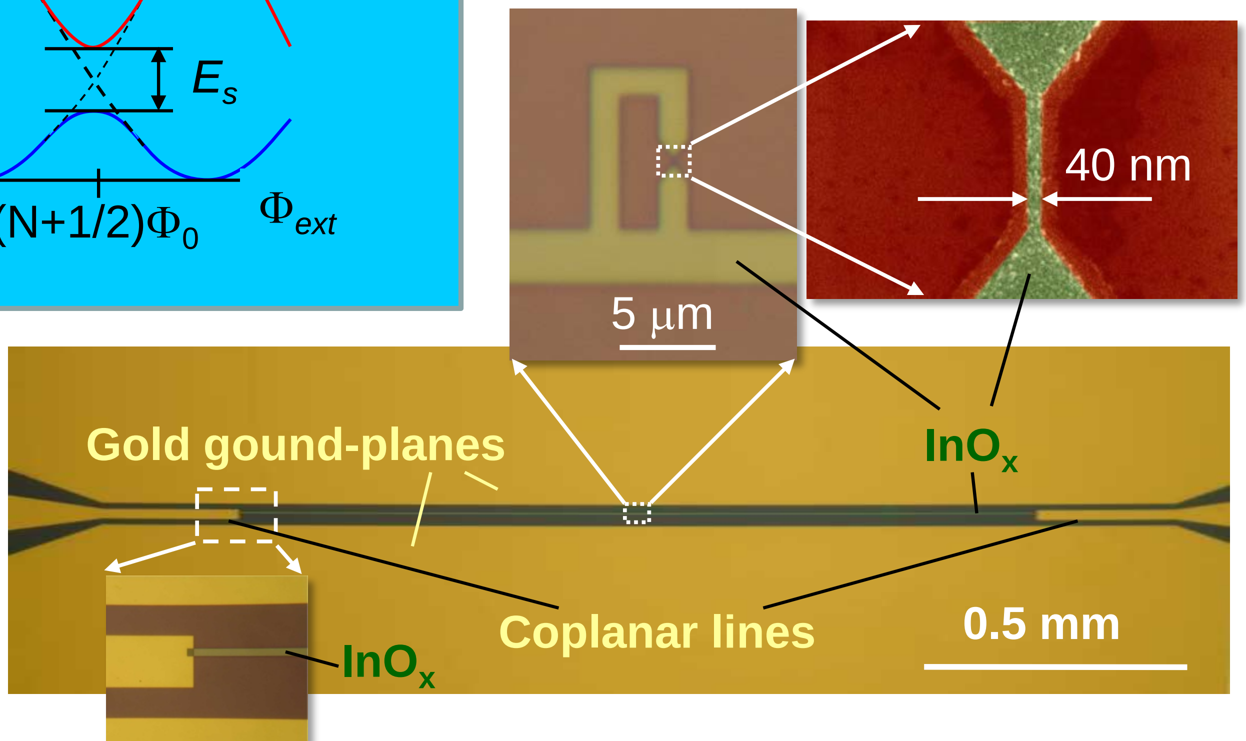
Superconductivity Phase Diagram



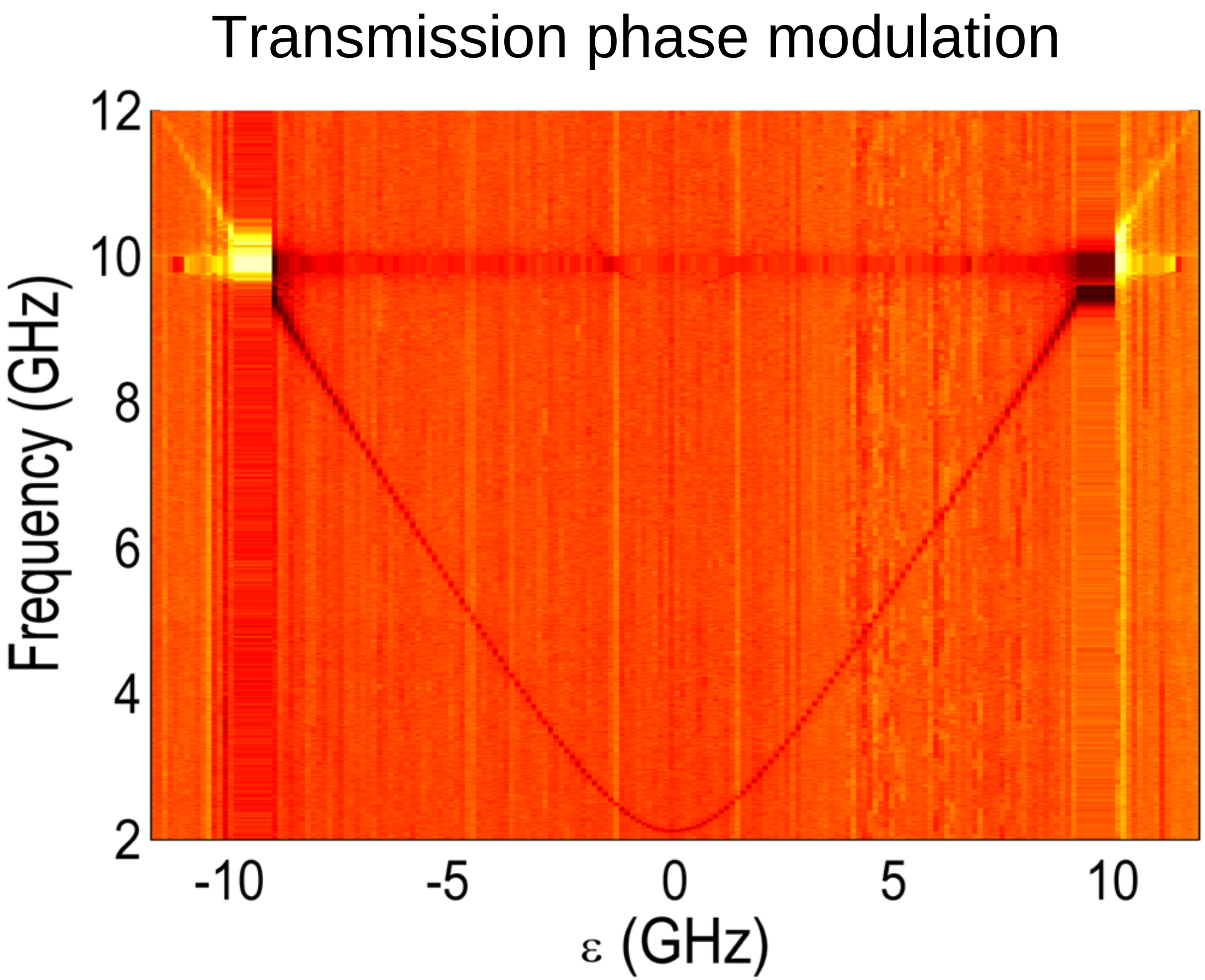
Device configuration
CQPS flux qubit + resonator

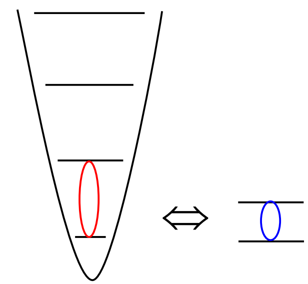


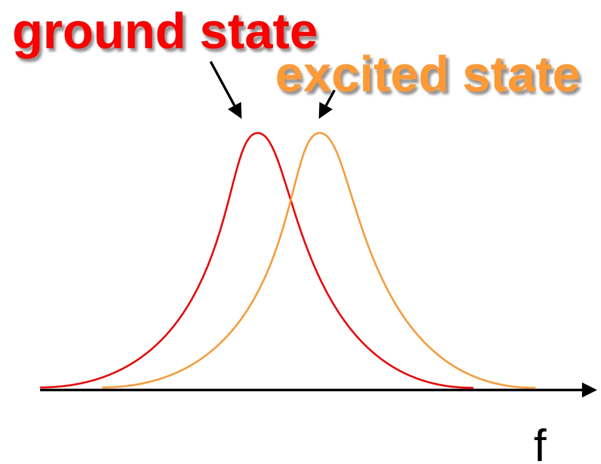




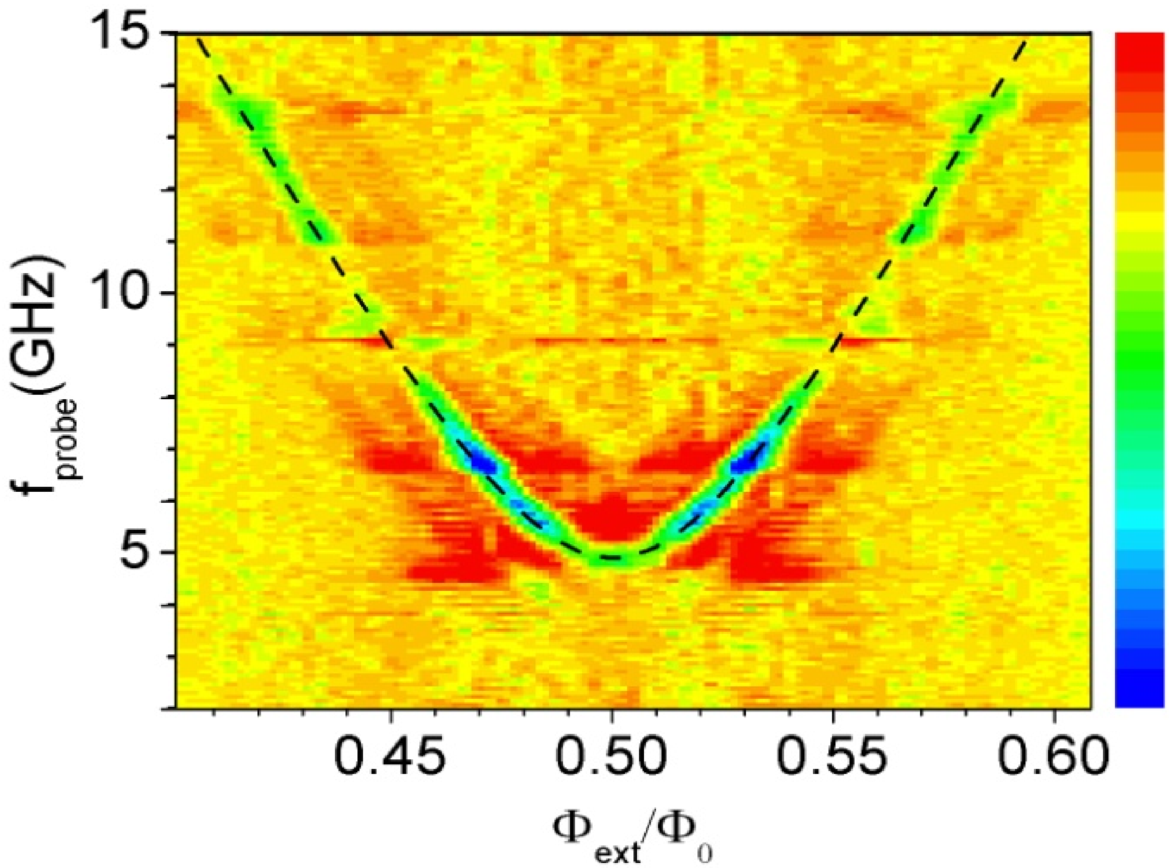
Transmission at the resonator resonance under qubit excitation





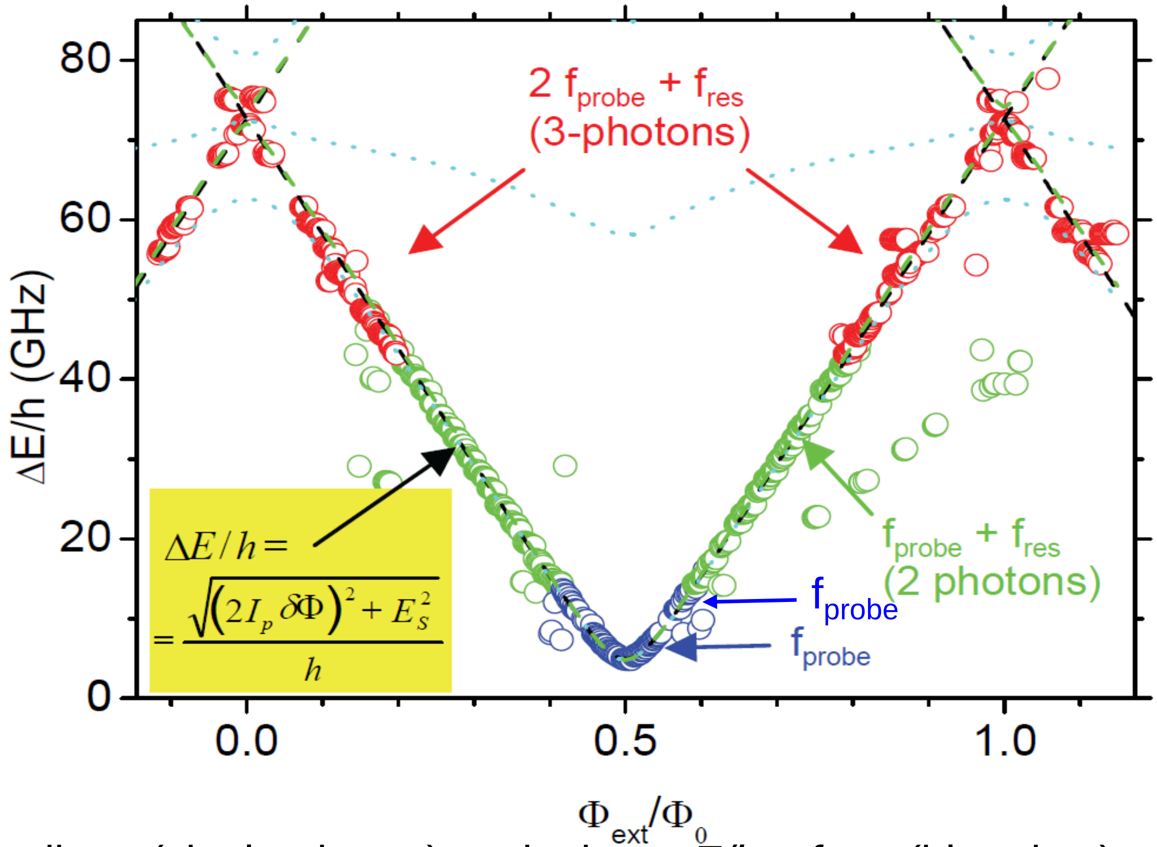


Two-level spectroscopy



The dashed line is a fit to the energy splitting with E_S/h = 4.9 GHz, I_p = 24 nA.

Spectroscopy of the system in a wide ranges

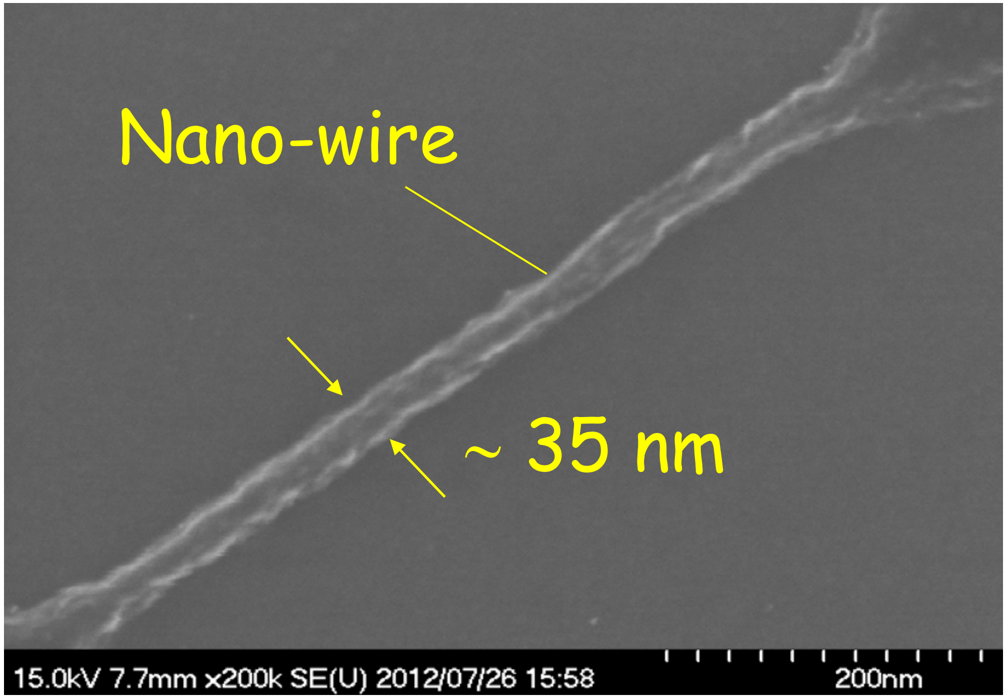


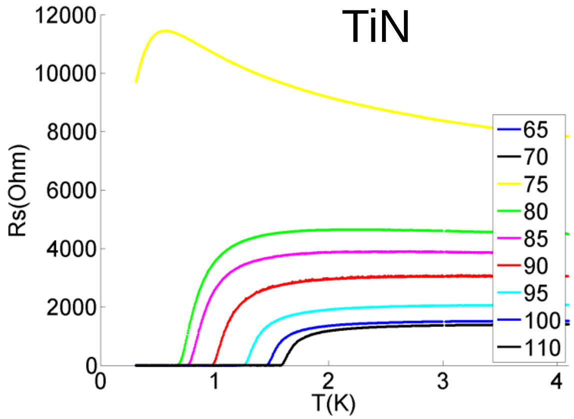
direct (single-photon) excitation, $\Delta E/h = f_{probe}$ (blue dots)
two-photon process, $\Delta E/h = f_{probe} + f_4$ (green dots)
three-photon process $\Delta E/h = 2\, f_{probe} + f_4$ (red dots)
$f_{probe} \leq 35$ GHz,
The dashed line: calculated with **E_S = 4.9 GHz and I_p = 24 nA**

CQPS in other materials

Requirements: $R_\square$ > 1 kΩ, suppressed Tc

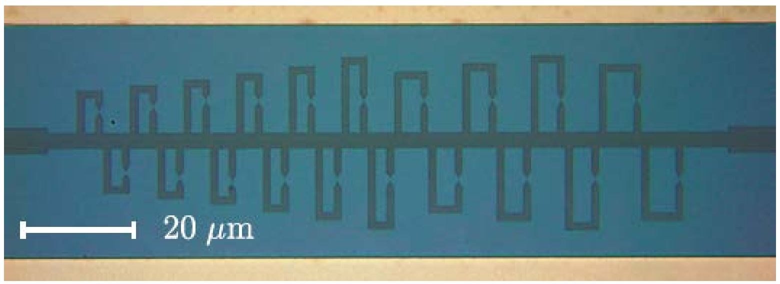
- ALD grown TiN films, $R_\square$ ~ 3 kΩ *(TU Delft, Klapwijk's group)*
- Spattered NbN films, $R_\square$ ~ 2 kΩ *(MSPU, Goltsman's group)*

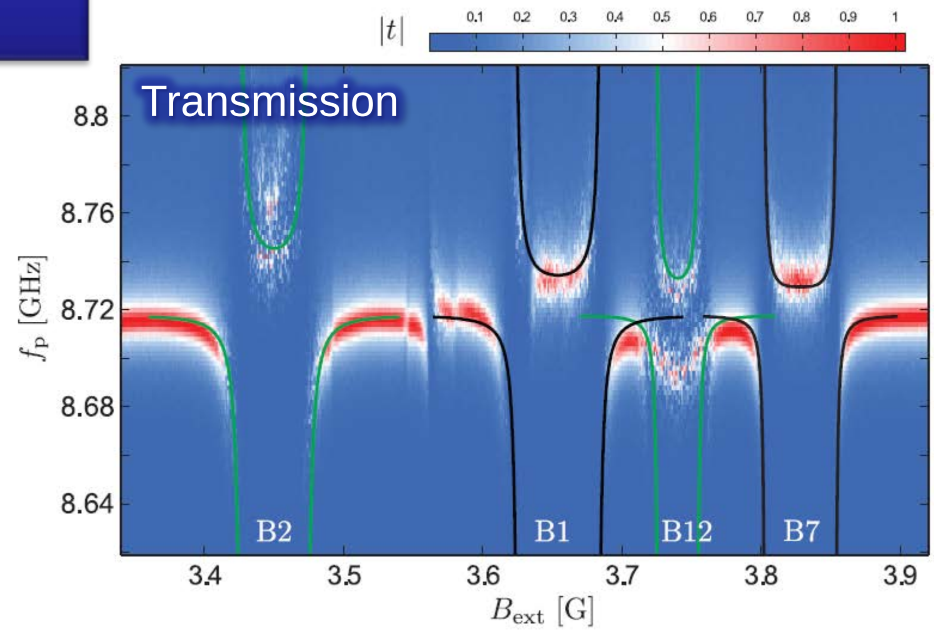


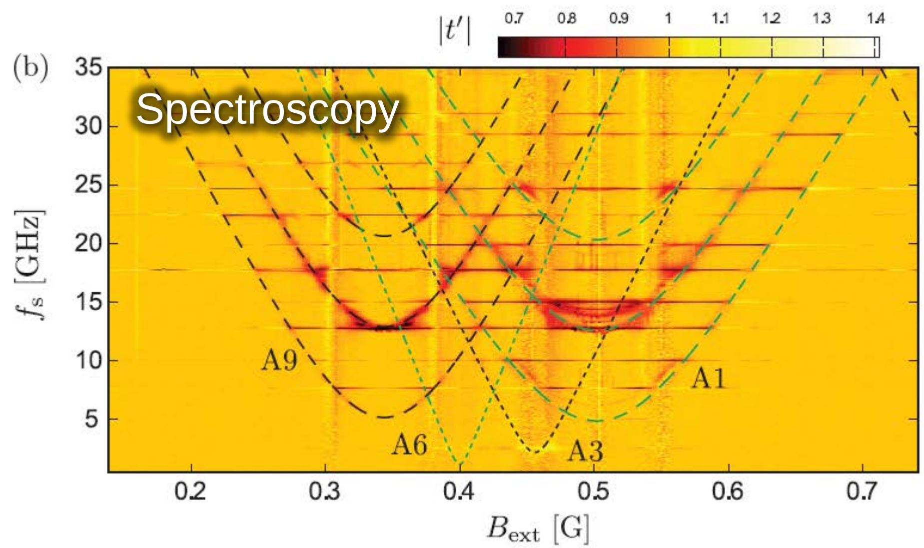


NbN film qubits

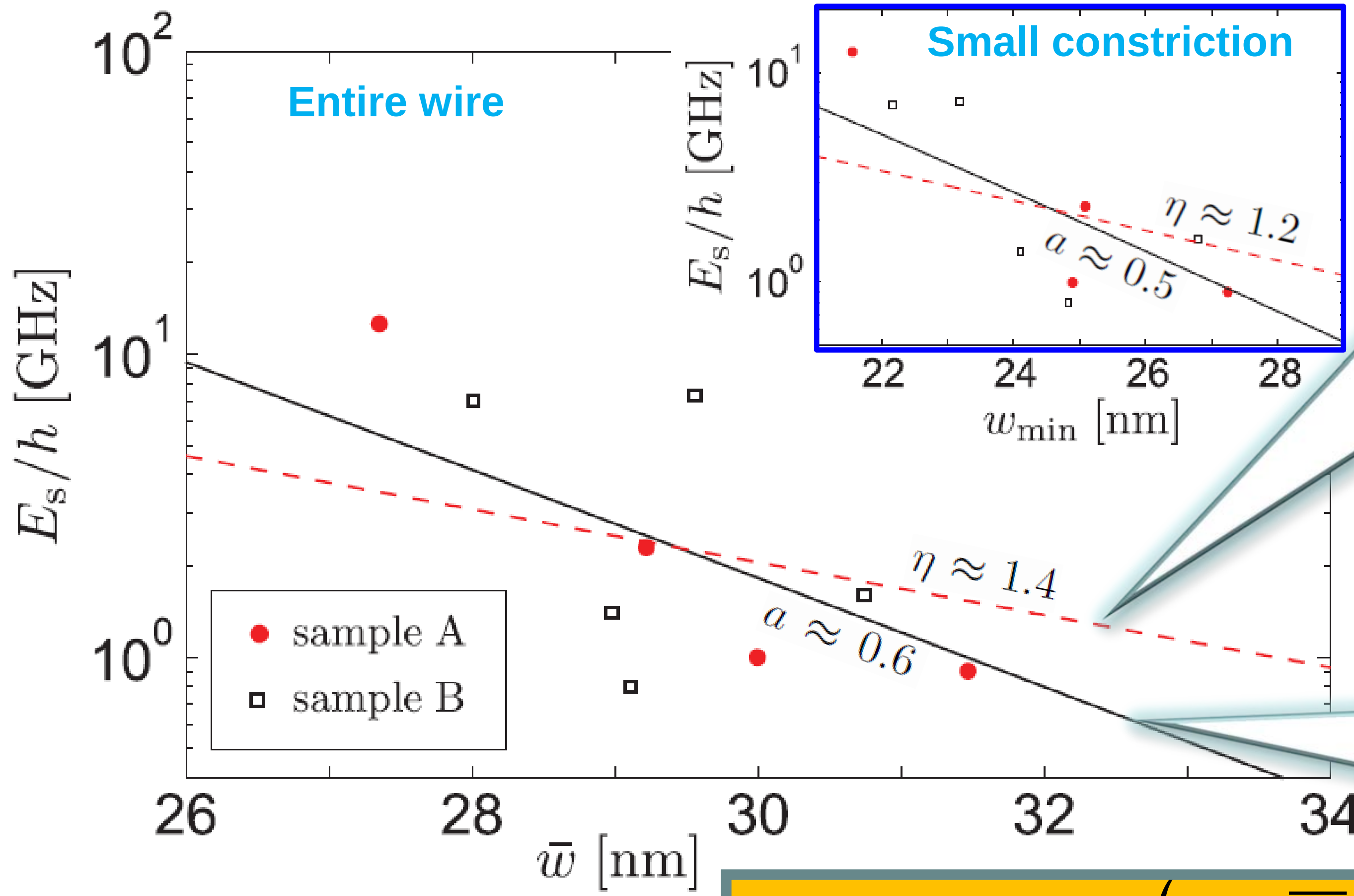
20 qubits in a resonator







NbN film qubits: width dependence



Disordered Superconductor

$$E_0 = \rho\sqrt{l/\bar{w}}$$
$$\kappa = \eta\sqrt{\nu_p \rho}$$
$$\rho = (\hbar/2e)^2 L_\square^{-1}$$
$$\nu_p = 1/(2e^2 R_\square D)$$

BCS

$$E_0 = \Delta(R_Q/R_\square) l \bar{w} \xi^{-2}$$
$$\kappa = a(R_Q/R_\square)\xi^{-1}$$

$$E_S = E_0 \exp\left(-\kappa\bar{\omega}\right)$$

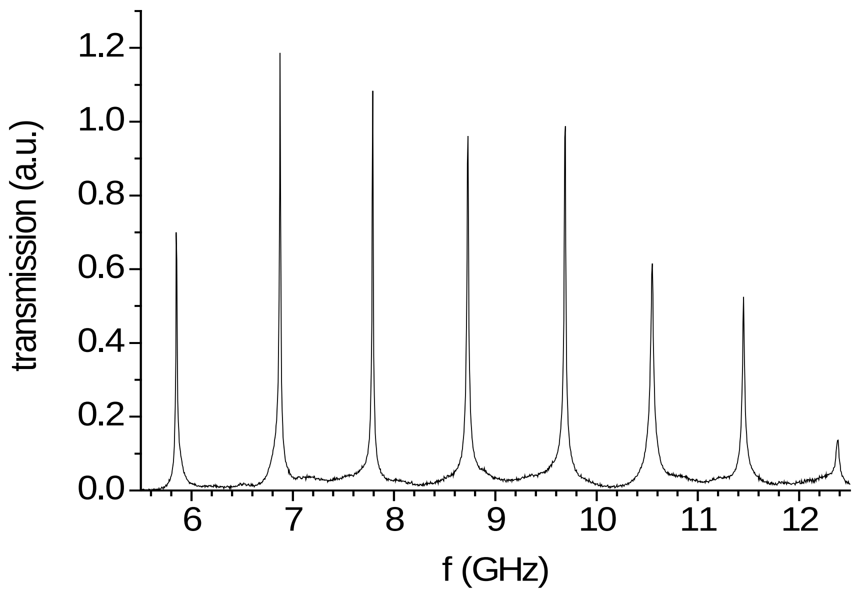
$l = 500$ nm
$R_\square \approx 2$ kΩ
$L_\square \approx 1.3$ nH
$D \approx 0.45$ cm^2/s
$\xi = 4$ nm

Peltonen et al, Phys. Rev. B 88, 220506(R) (2013)

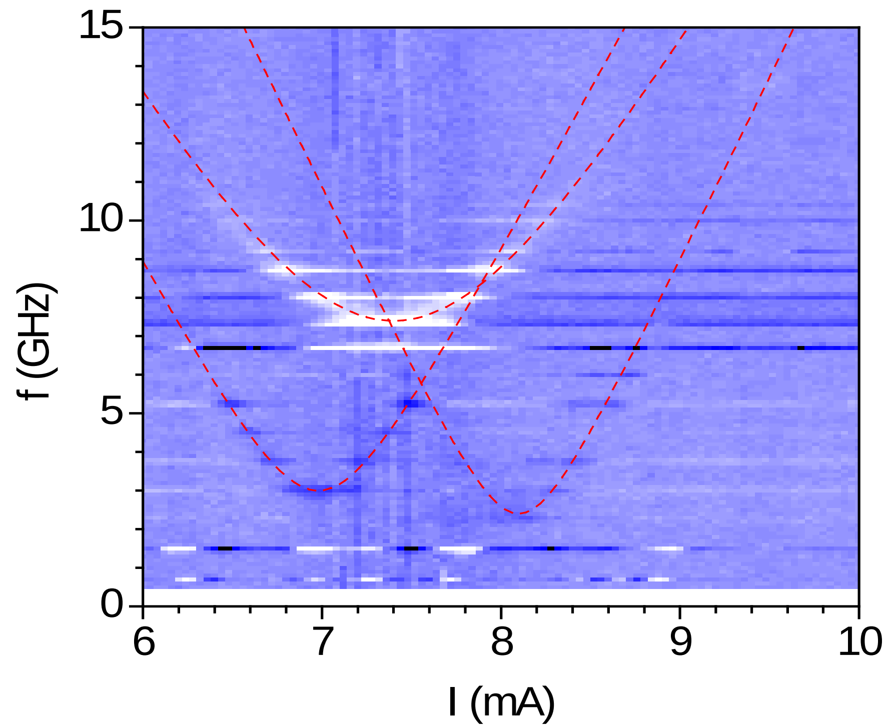
TiN qubits

In MW measurements $T_c \approx 0.8$ K
L ≈ 1.6 nH/sq

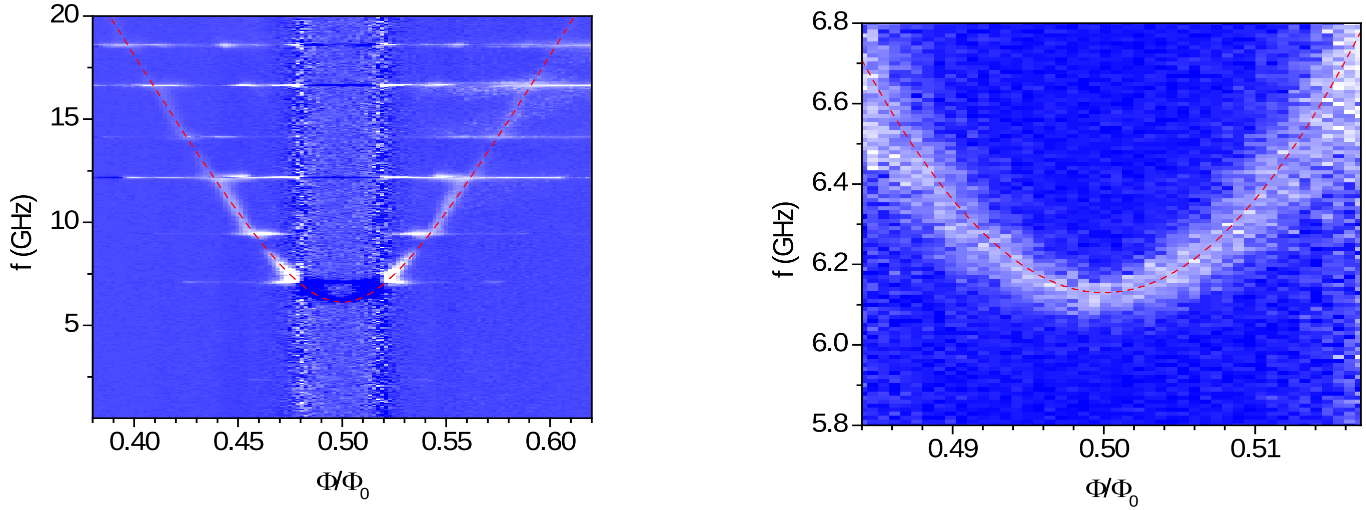
Transmission through 1.5 mm
Length coplanar resonator



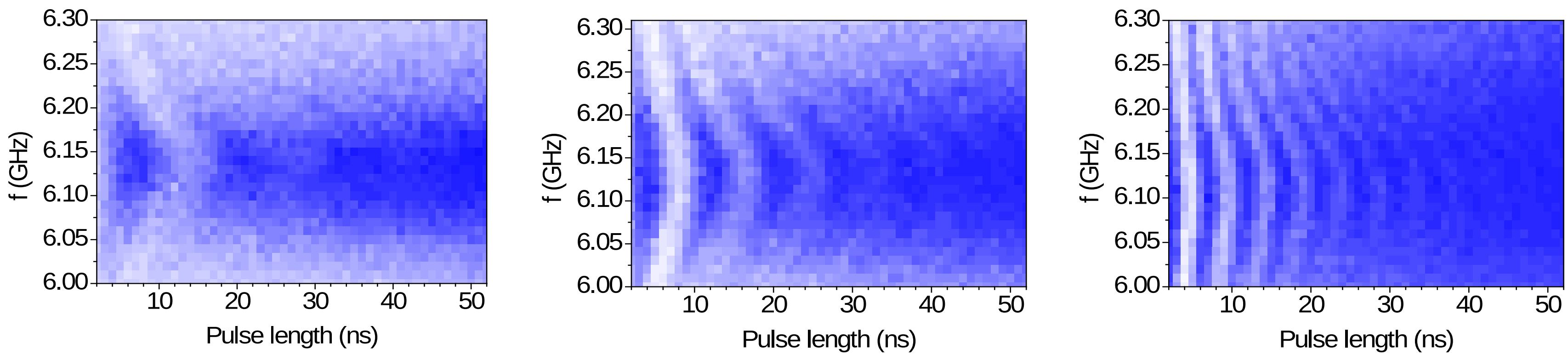
Spectroscopy



NbN qubits: Dynamics



Quantum oscillations



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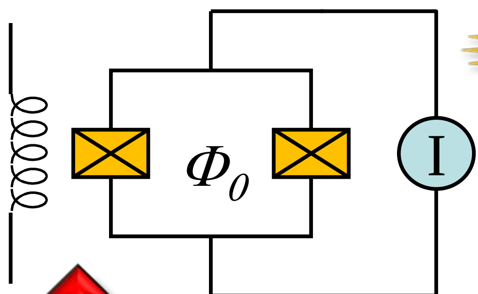
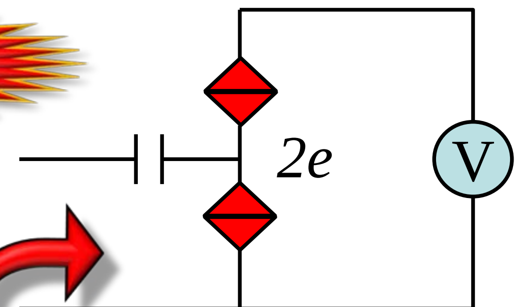
Josephson Electronics		***Single Electronics***
flux quanta (***phase***)	⟷	charge (***number***)
current	⟷	voltage bias
parallel element	⟷	serial element
inductive coupling	⟷	capacitive coupling

Exact duality



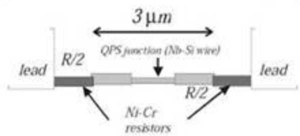


Advantage!
Switching time
t ~ L/R ~ ps

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

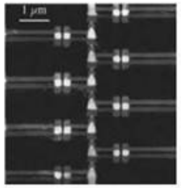
QUANTUM CURRENT STANDARD: Electron Pump $I = ef$

Quantum Phase Slip



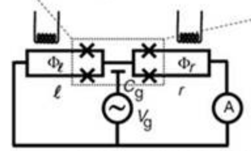
J.E. Mooij and Yu. V. Nazarov et al., Nature Phys. 2, 169 (2006)
O. V. Astafiev et al., Nature 484, 355 (2012)

Single electron transistor



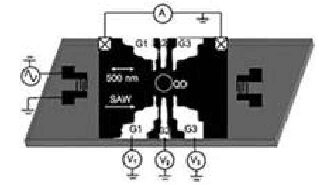
Keller et al., APL 69, 1804 (1996)

Cooper pair sluice



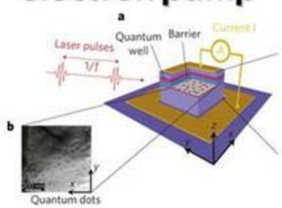
Niskanen et al., PRL 91 177003 (2003)

Surface acoustic wave

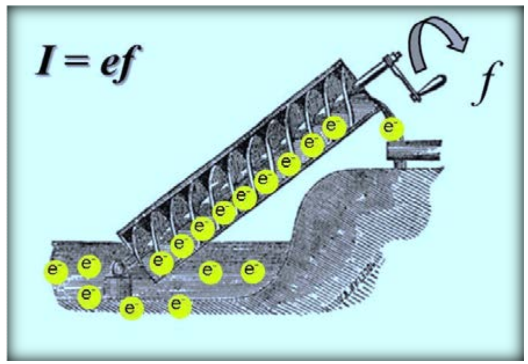


J. Ebbecke et al., APL 84, 4319 (2004)

Optically driven electron pump

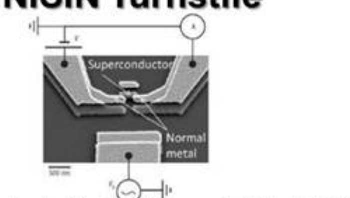


L. Nevou et al., Nature Phys. 7, 423 (2011)



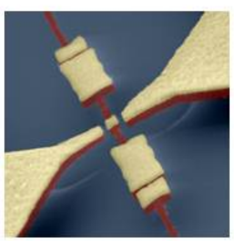
10 – 100pA with 10^{-7}

NISIN Turnstile



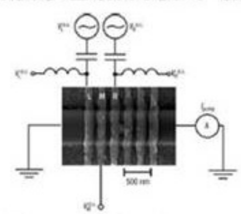
Pekola et al., Nature Phys. 4, 120 (2007)

Nanomechanical single-electron shuttle



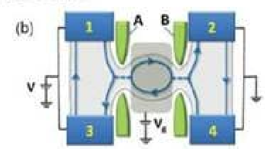
Daniel R. Koenig et al., Nature Nano. 3, 482 (2008)

Tunable Barrier Pumping



M.D. Blumenthal et al., Nature Phys. 3, 343 (2007)

Nonlocal electron hole turnstile



F. Battista and Samuelsson, PRB 125324 (2011).

Electrical Quantum Standards (triangle)

Voltage:
Josephson Effect
(*Nobel 1973*)


Josephson

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

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

Resistance:
Quantized Hall Effect
(*Nobel 1985*)


von Klitzing

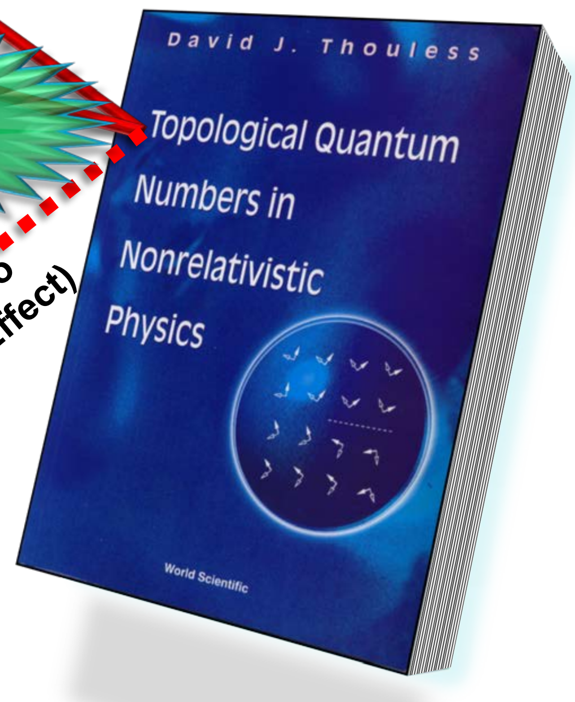
$$R = \frac{h}{e^2}$$

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

$$I = 2e\nu$$

Topological Protection !

??? (Conjugate to Josephson Effect)



COMPETITION

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

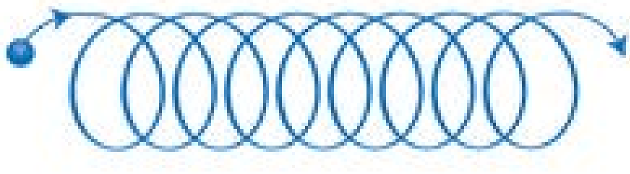
Topological Protection

Phase rotation

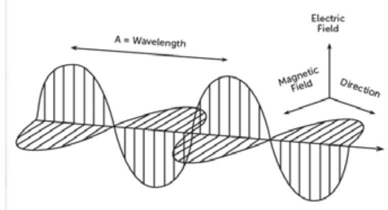
Time

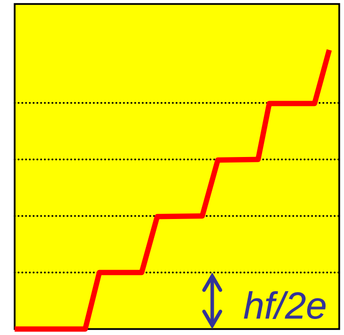
Macroscopic Phase ϕ

$d\phi/dt = V/\Phi_0$



Phase lock w/ External Microwave



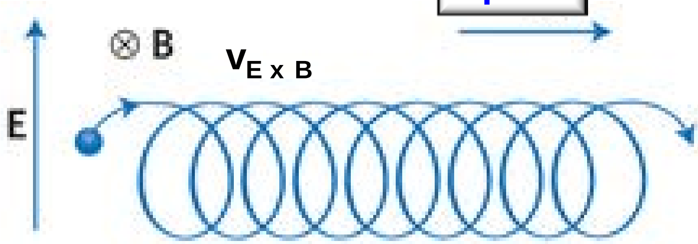


Josephson

Cyclotron orbits

Space

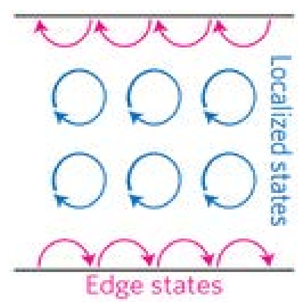
Electron Orbit

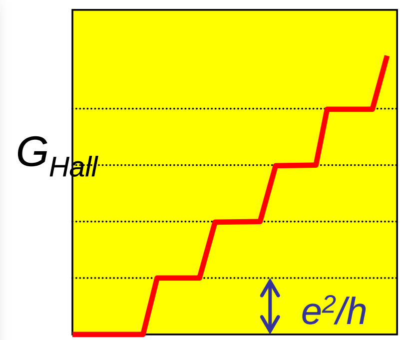


Landau level

$$E_n = \hbar\omega_c(n + 1/2)$$

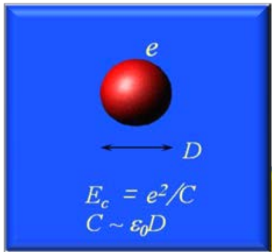
$$\omega_c = eB/m$$

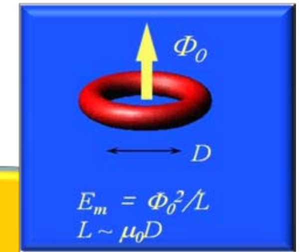




Quantized Hall

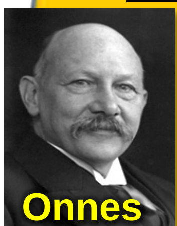
A Brief History of Superconductivity





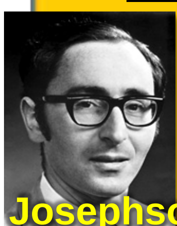
Electric

1911: **Supercurrent**, (*Nobel 1913*)



1957: **BCS Theory**, (*Nobel 1972*)

1962: **Josephson Effect**, (*Nobel 1973*)

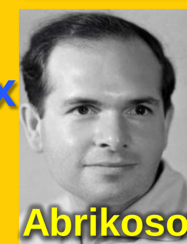


1999: **Macroscopic Quantum Coherence** (Josephson qubit)

Magnetic

1933: **Meissner Effect**

1952: **Abrikosov Vortex** (*Nobel 2003*)

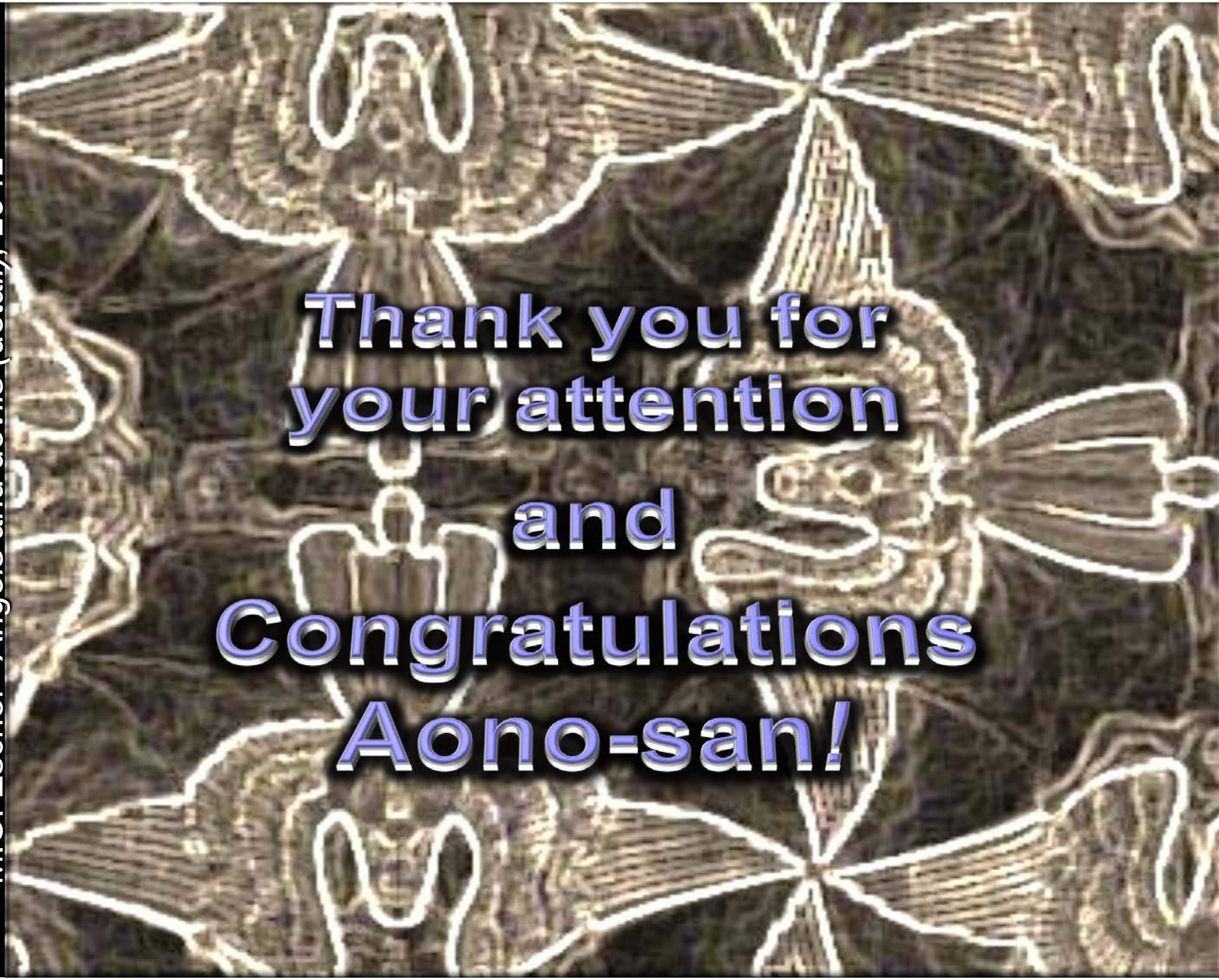


Exact duality

2012: **Coherent Quantum Phase Slip (CQPS)**

Conclusion

- Coherent Quantum Phase Slip has been experimentally demonstrated
- Phase-slip qubit has been realized in thin highly disordered films of InO_x , NbN and TiN
- DC characterization is underway



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