Parity-Protected Josephson Qubits

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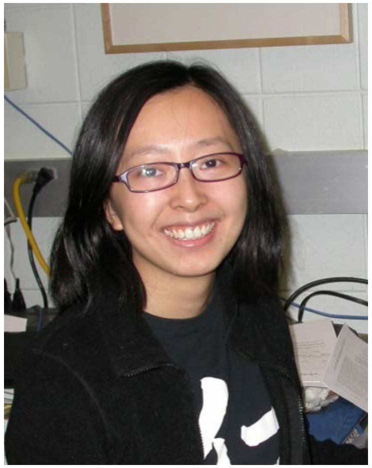


Chernogolovka, June 2016

The State University of New Jersey
Rutgers
Department of Physics and Astronomy

Outline

- Qubits: state of the art
- Idea of Parity-Based Protection
- Charge-Pairing Qubits
- Flux-Pairing Qubits
- Superinductors

Main Idea

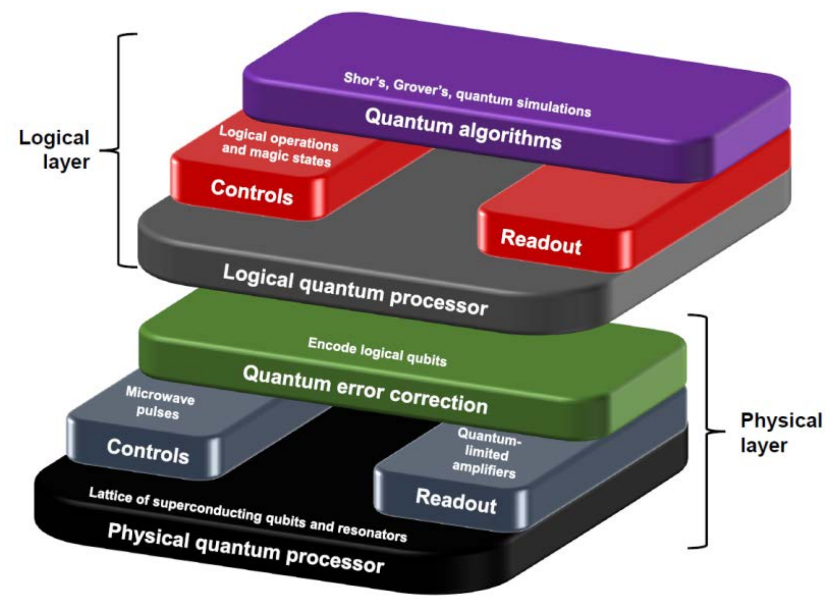
Physical (faulty) qubit: a two-level quantum system that satisfies DiVincenzo criteria.

Logical (fault-tolerant) qubit: a collection of *N* physical qubits that can correct for arbitrary errors in a single qubit by running error correction codes.

error correction codes

faulty physical qubits → fault-tolerant logical qubit

The "fault tolerance" theorem: once *a sufficient low error rate* of physical qubits is attained, there is a strategy for correcting errors so that one can carry out indefinitely long computations.



Physical Qubits: error rate and speed

The error rate : $\boxed{\varepsilon \equiv \dfrac{\tau_0}{\tau_d}}$

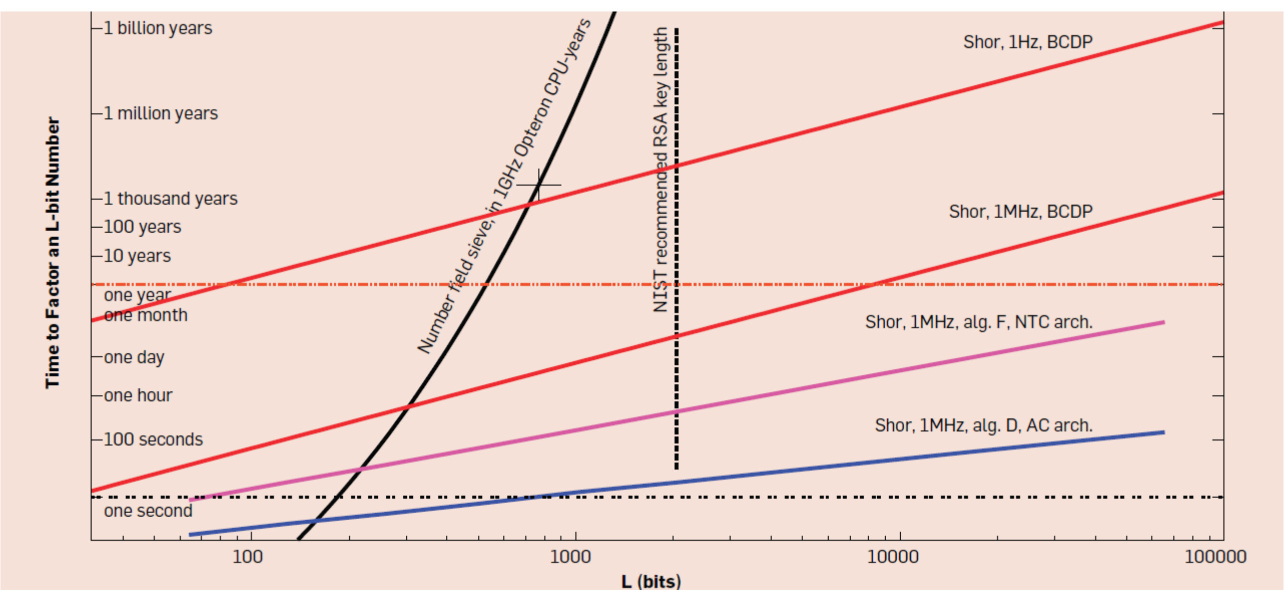
τ_0 - the longest time for one- and two-qubit gates

$$\tau_d \approx \min\left(T_1, T_\varphi\right)$$

Threshold values of $\boldsymbol{\varepsilon}$ for different ECCs:

Earlier codes (Steane, Bacon-Shor): $\boldsymbol{\varepsilon \approx 10^{-5}}$

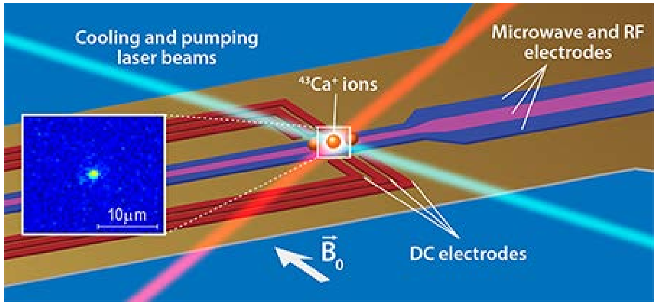
Surface correction code (Kitaev *et al.*): $\boldsymbol{\varepsilon \approx 10^{-2}}$



QC "speed" below 1MHz is not practical.

Van Meter & Horsman, *Communications of the ACM* 56, 84 (2013)

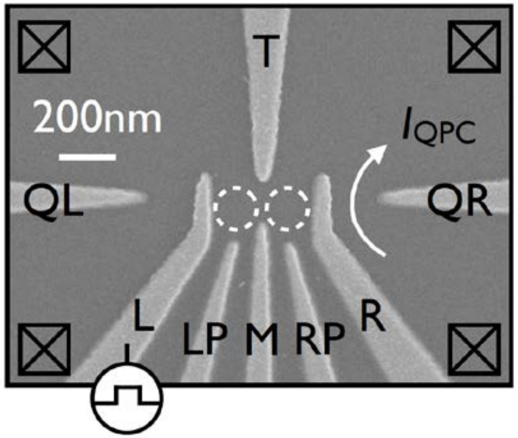
Qubit Implementations (Isolation ⇔ Speed)



Trapped $^{43}Ca^{+}$ ions

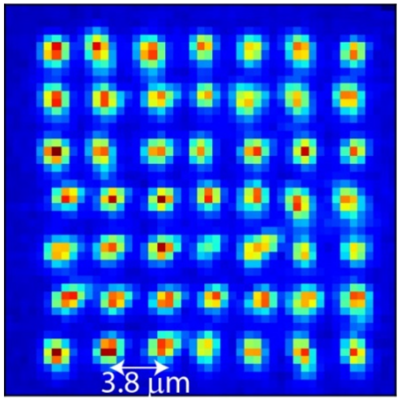
Single-shot readout fidelity 99.93%
Single-qubit gate fidelity 99.9999%
Harty *et al.*, *PRL* 113, 220501 (2014)

Trapped ions,
neutral atoms,
quantum dots,
superconducting
qubits,
etc.



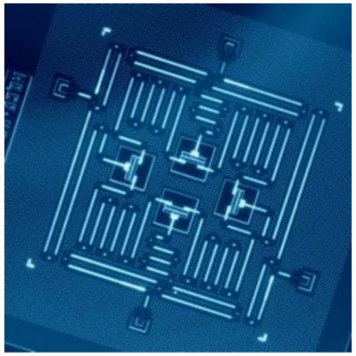
Quantum dots

Single-qubit gate fidelity > 99.5%
Kim *et. al.*, *Nat.QI* 1, 15004 (2015)



Trapped Cs atoms

Single-qubit gate fidelity 99.83%
Xia *et al.*, *PRL* 114, 100503 (2015)



Superconducting qubits

Single-qubit gate fidelity > 99.95%

Two-qubit gate fidelity 99.5%

State-of-the-art:
Gambetta et al., arXiv:1510.0437

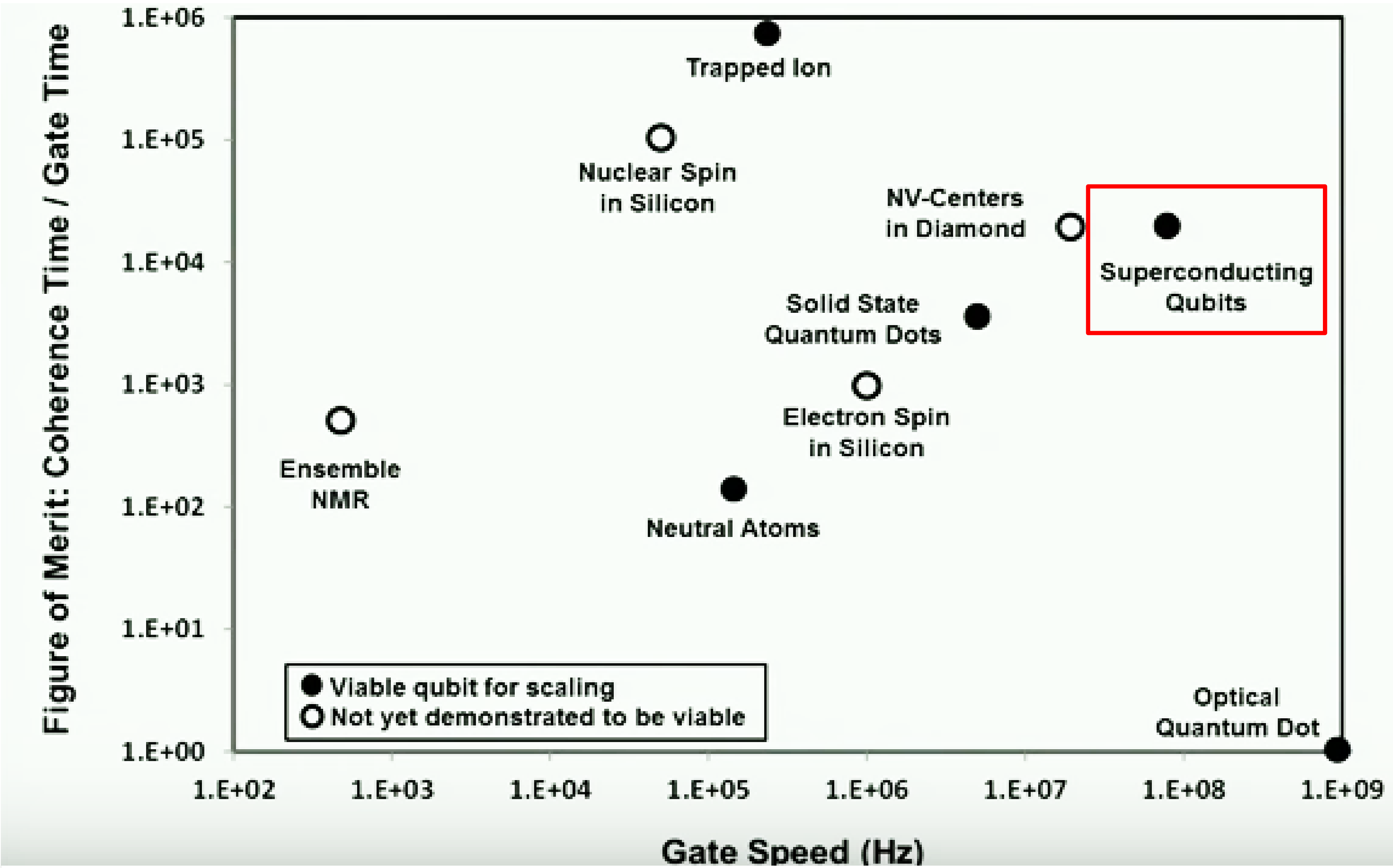
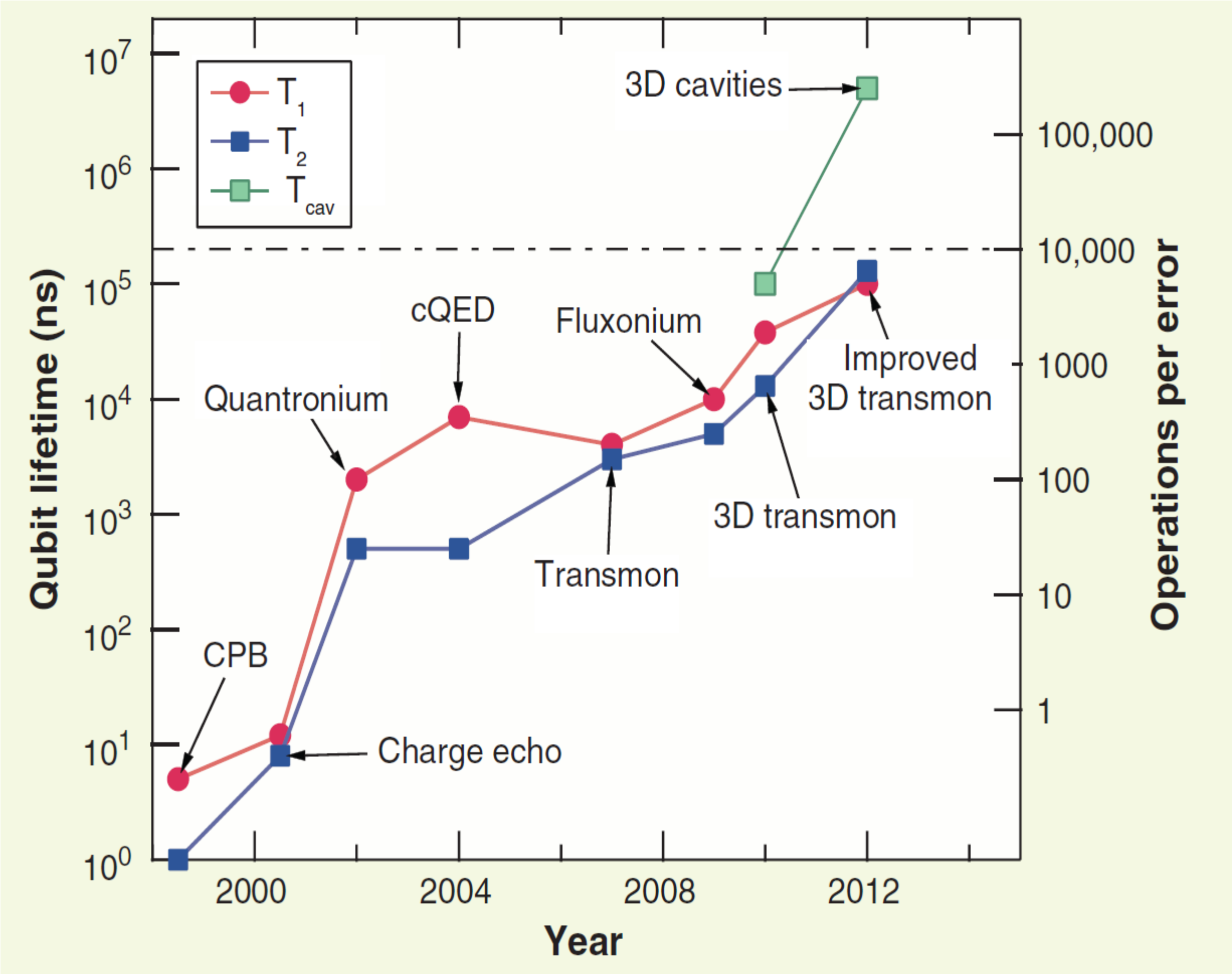


Figure of Merit: Coherence Time / Gate Time
Gate Speed (Hz)
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
1.E+09
Trapped Ion
Nuclear Spin in Silicon
NV-Centers in Diamond
Superconducting Qubits
Solid State Quantum Dots
Electron Spin in Silicon
Ensemble NMR
Neutral Atoms
Optical Quantum Dot
Viable qubit for scaling
Not yet demonstrated to be viable

Superconducting Qubits: State of the Art



Devoret & Schoelkopf, Science 2013

Single-qubit gates:

$$\varepsilon \equiv \frac{\tau_0}{T_2} \sim 10^{-4}$$

Two-qubit gates:

$$T_2 \approx 40\ \mu s$$

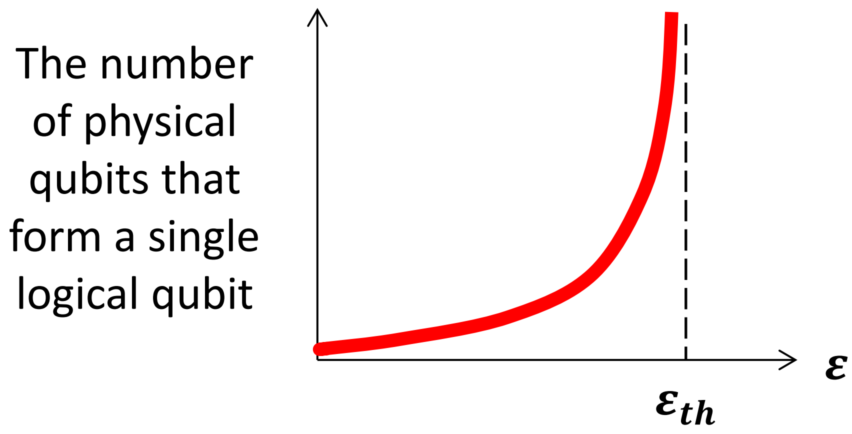
$$\tau_0 \approx 40\ ns$$

Martinis' Group, UCSB/Google

$$\varepsilon = 1 \times 10^{-3}$$

Physical Qubit vs. Logical Qubit

How many physical qubits does it take to build a single logical qubit?



The threshold error rate for *the surface error codes* is $\sim 1\%$. If the error rate is 1/10 of ε_{th}, «a reasonably fault-tolerant logical qubit ... takes $\mathbf{10^3 - 10^4}$ physical qubits».

Physical qubits are macroscopic ($\geq 100\ \mu m$), areal density $\sim 10^6$ times less than computer chips - enormous impact on the large scale architecture.

Martinis (UCSB and Google): "We're somewhere between the invention of the transistor and the invention of the integrated circuit" – **not yet…**

Main Message

Although simple physical qubit designs (e.g. transmon) are very attractive, they do not eliminate enormous complexity of logical qubits.

Any design that may help to reduce the complexity of the final product (i.e. the logical qubit) is worth considering.

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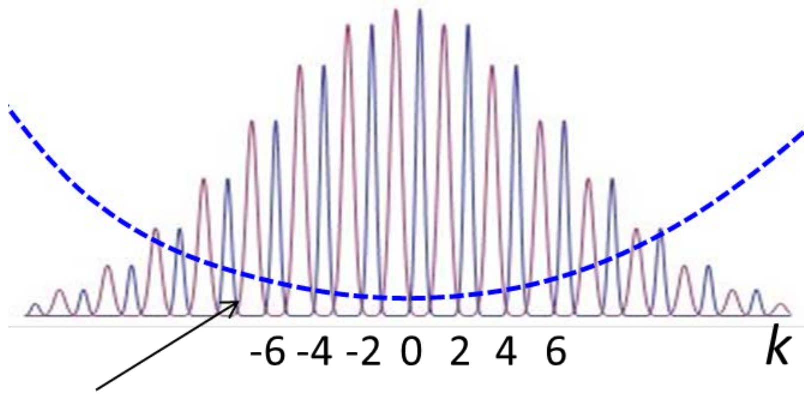
- Idea of Parity-Based Protection
- Charge-Pairing Qubits
- Flux-Pairing Qubits
- Superinductors

Parity Protected Qubits



g – the number of discrete components of the lowest-energy even (odd) states

The goal: to engineer two quantum states *indistinguishable* by the environment.

$$H = K\,(X^n + X^{-n}) + V\,k^2$$

k – discrete variable

n=2 - parity protection

$$X^{\pm 2}|k\rangle = |k \pm 2\rangle$$

The two-level approximation Hamiltonian

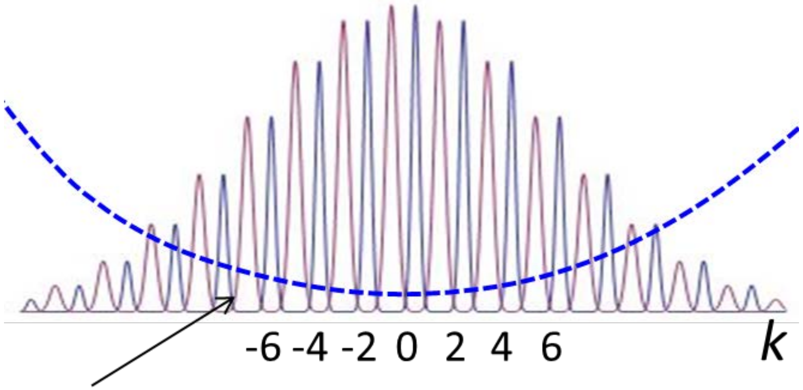
$$H = \frac{E_{01}}{2}\sigma_z + \frac{E^*}{2}\sigma_x$$

the rate of parity violation

Two almost degenerate low-energy states: $E_{01} \propto exp(-g)$

Protection against “k” noises $\propto$ $exp(-\alpha g)$

Parity Protected Qubits, cont'd

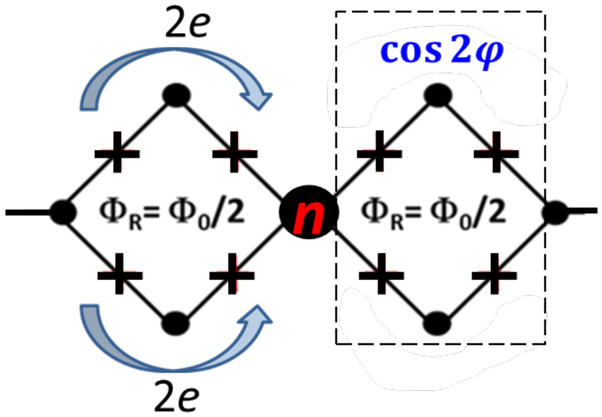


g – the number of discrete components of the lowest-energy even (odd) states

- Decay is suppressed if parity is protected ($E^* = 0$). ⟵ $T_1 = \infty$
- Coupling to "k" noises is suppressed if the envelope decays slowly (large g). ⟵ $long\ T_2$
- ★ Some fault tolerant rotations can be realized by fast changes of *V*(t) – protection from the gate pulse noise.

Charge Pairing Qubit

Correlated tunneling of TWO Cooper pairs



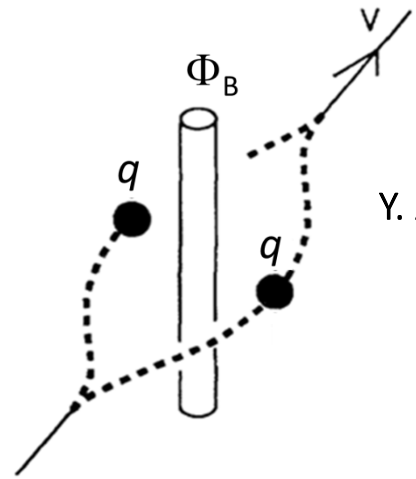
Discrete variable: number of Cooper pairs on the central island

Parity protection (cancellation of "single-particle" tunneling) due to destructive AB interference

Gladchenko *et al*. *Nat. Phys.* **5**, 48 (2009)

Bell *et al*. *PRL* **112**, 167001 (2014)

Aharonov-Bohm phase



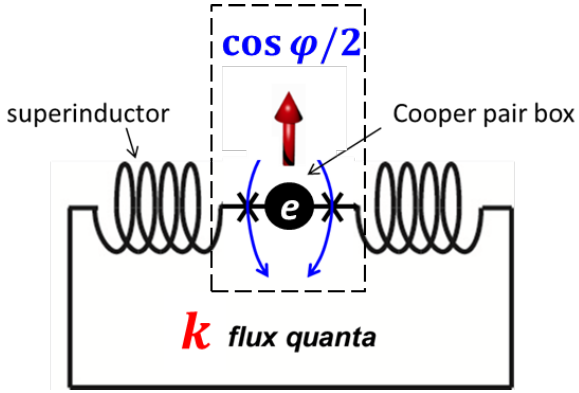
Y. Aharonov & D. Bohm, *PR* **115**, 485 (1959)

The wave function of a charge q moving around a magnetic flux Φ_B acquires a topological phase shift

$$\Delta\varphi_{AB} = \frac{q}{\hbar}\oint A \cdot dl = \frac{2e}{\hbar}\Phi_B$$

Flux(on) Pairing Qubit

Correlated tunneling of TWO fluxons



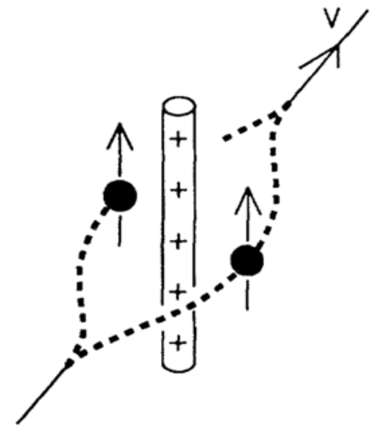
Discrete variable: number of flux quanta in the loop

Parity protection (cancellation of "single-particle" tunneling) due to destructive AC interference

Bell *et al*. *PRL* **109**, 137003 (2012)

Bell *et al*. *PRL* **116**, 107002 (2016)

Aharonov-Casher phase



Y. Aharonov & A. Casher, *PRL* **53**, 319 (1984)

The wave function of a particle with magnetic dipole moment μ moving in 2D around a line charge acquires a topological phase shift proportional to the line charge density.

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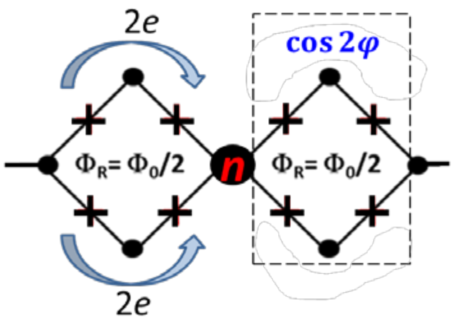
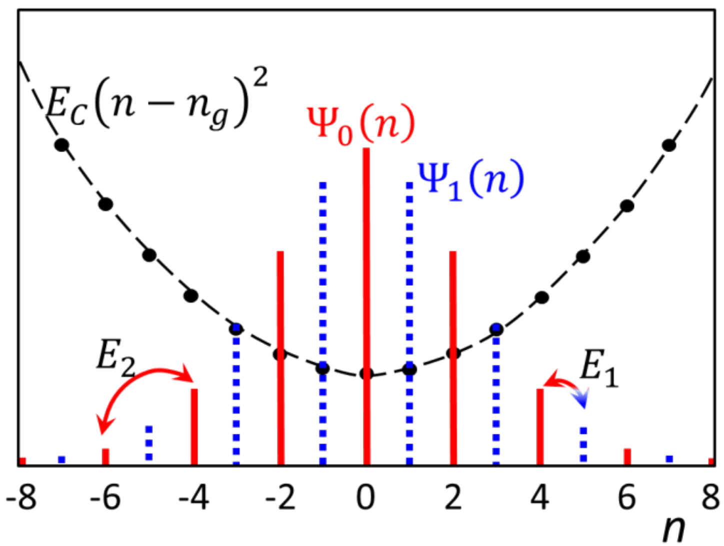
Charge-Pairing Qubits (discrete variable - Cooper pairs number)



Ioffe, Doucot, Feigel'man *et. al.* (2002 –present)

$$H = -2E_2 \cos 2\varphi - 2E_1 \cos\varphi + E_C\left(\hat{n} - n_g\right)^2$$



The two-level approximation Hamiltonian

$$H = \frac{E_{01}}{2}\sigma_z + \frac{E^*}{2}\sigma_x$$

Perfect symmetry ($E_1 = 0$):

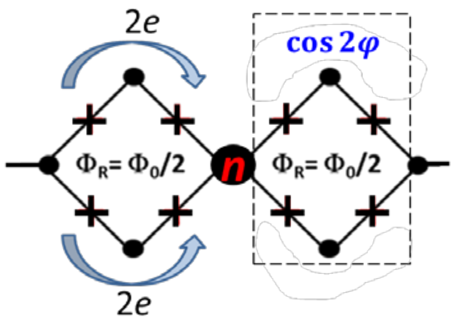
$$E_{01} \propto \omega_p exp(-g)\cos\left(\pi n_g\right)$$

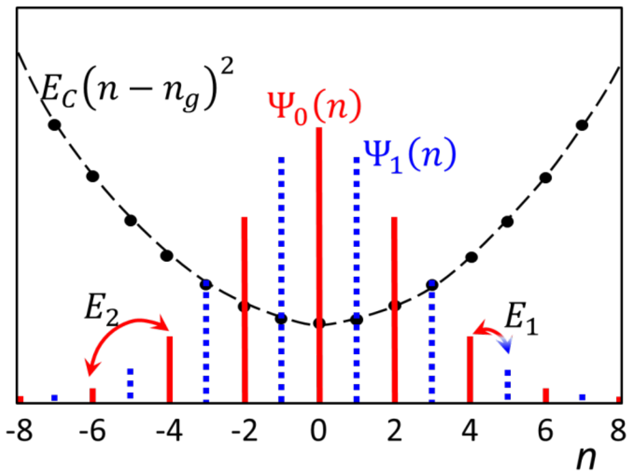
$$g = 4\sqrt{E_2/E_C}$$

$$\omega_p = 4\sqrt{E_2 E_C}$$ - plasma frequency

Required: $E_2 \gg E_C$

Decoupling from noises





The two-level approximation Hamiltonian

$$H = \frac{E_{01}}{2}\sigma_z + \frac{E^*}{2}\sigma_x$$

Perfect symmetry ($E_1 = 0$):

Energy relaxation is suppressed (very long T_1)

Coupling to the charge noise is exp. small $\propto exp(-g)sin(\pi n_g)$

Parity violation: single Cooper pair hopping (non-zero E_1).

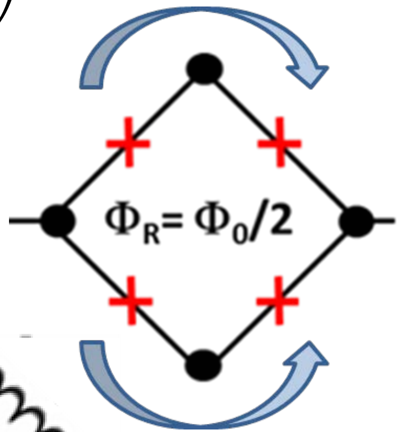
Sources of parity violation: rhombus asymmetry, flux noise.

To suppress coupling to the flux noise , the rhombi chain should be longer.

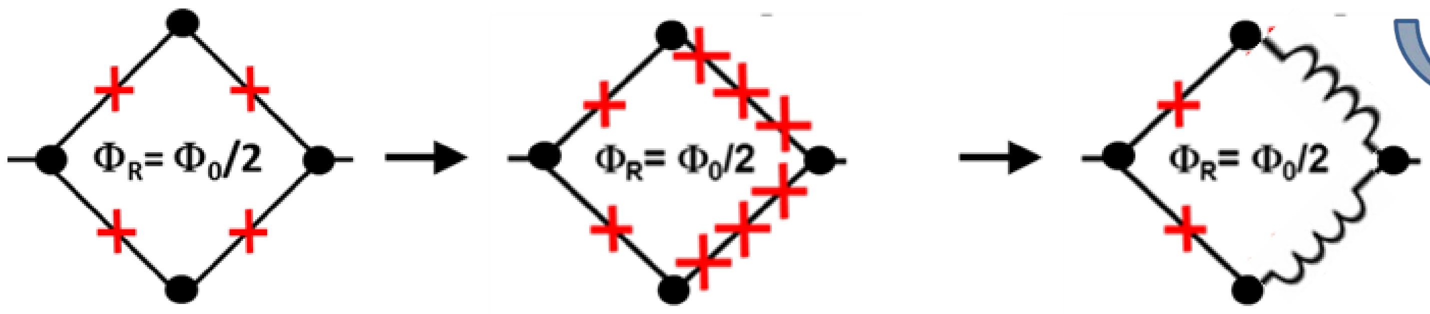
Problem of Offset Charges

Optimal $\frac{E_J}{E_C} \approx 3 - 4$

Phase slip rate $\propto \exp\left(-\alpha\sqrt{\frac{E_J}{E_C}}\right)$



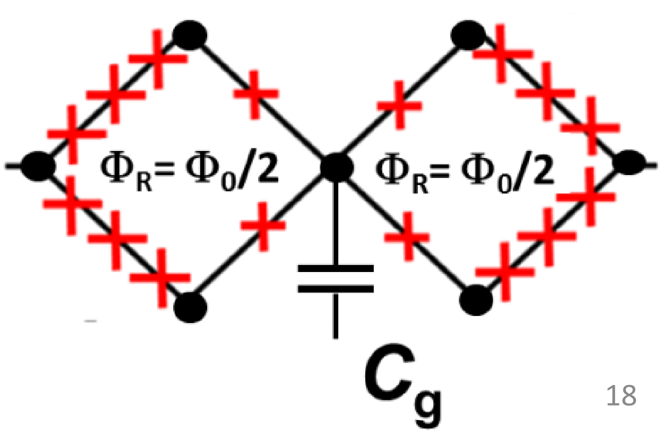
Phase slips + uncontrollable offset charges on unbiased islands $\Rightarrow$ Symmetry breaking



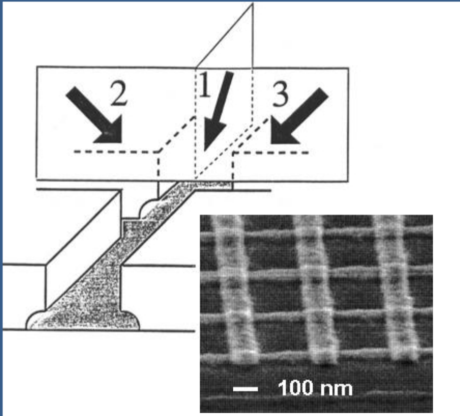
E_{JL}/E_{JS} ~ 3-4 implies E_{JL}/E_{CL} ~ 30-50

no phase slips across larger junctions

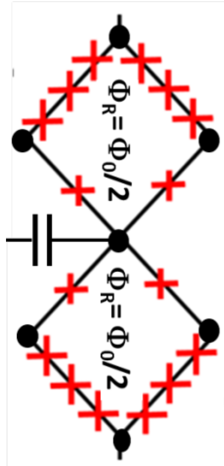
chain of 3-4 larger junctions is equivalent to a (classical) inductor

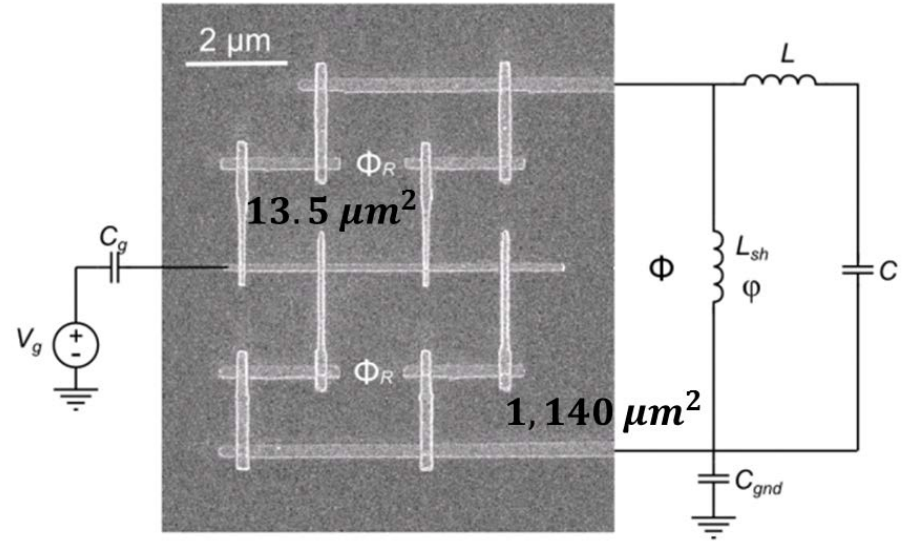


Device and Readout



Multi- angle deposition of Al through a shadow mask.





Small JJ: $0.13 \times 0.14\ \mu m^2$

Large JJ: $0.25 \times 0.25\ \mu m^2$

Global magnetic field:

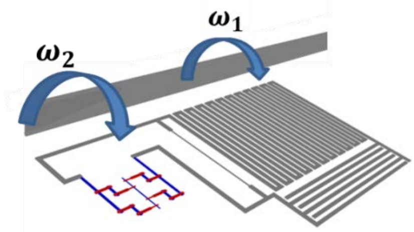
$$\Phi_R \approx \Phi_0/2 \qquad E_1 \approx 0$$

$$\varphi = 2\pi \frac{\Phi}{\Phi_0}$$ - phase difference across the chain

Two experimental "knobs":

- the gate voltage controls n_g on the central island;
- the flux in the "phase" loop controls φ across the chain.

Spectroscopic Measurements



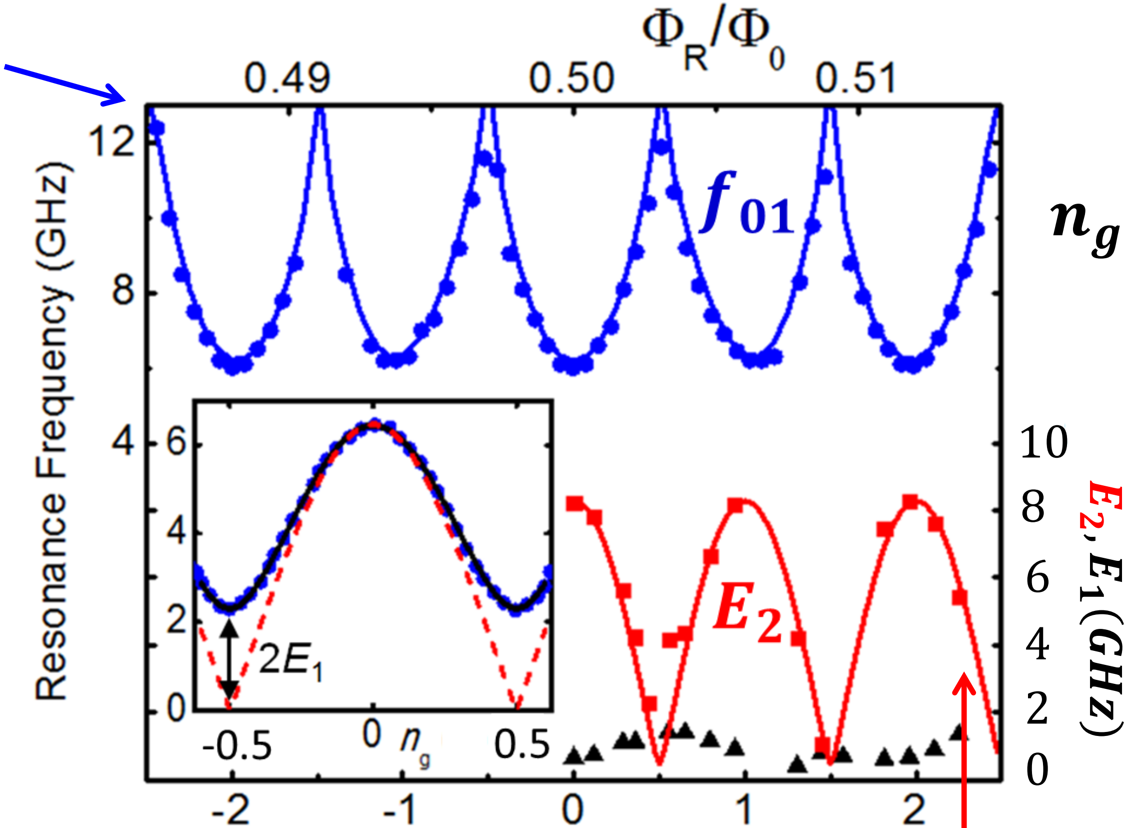
$$E_{01}{}^{*} = \sqrt{E_{01}{}^{2} + (2E_1)^2}$$

$E_2(max) = 8.5GHz$

$E_C \approx 15GHz$

$E_1 = 0.75GHz$

$\Delta E_{2R} \leq 0.1 E_{2R}$

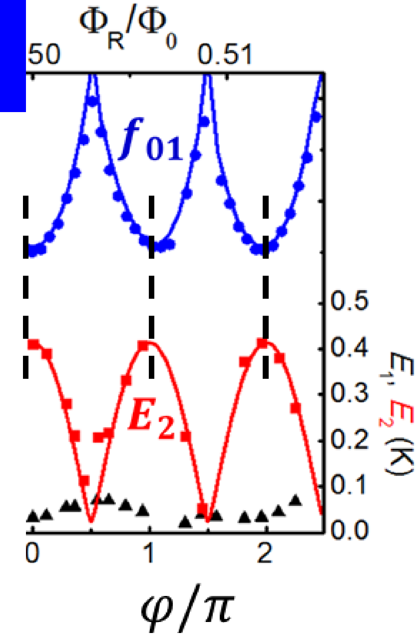


$n_g = 0$

$$\varphi/\pi = 2\frac{\Phi}{\Phi_0}$$

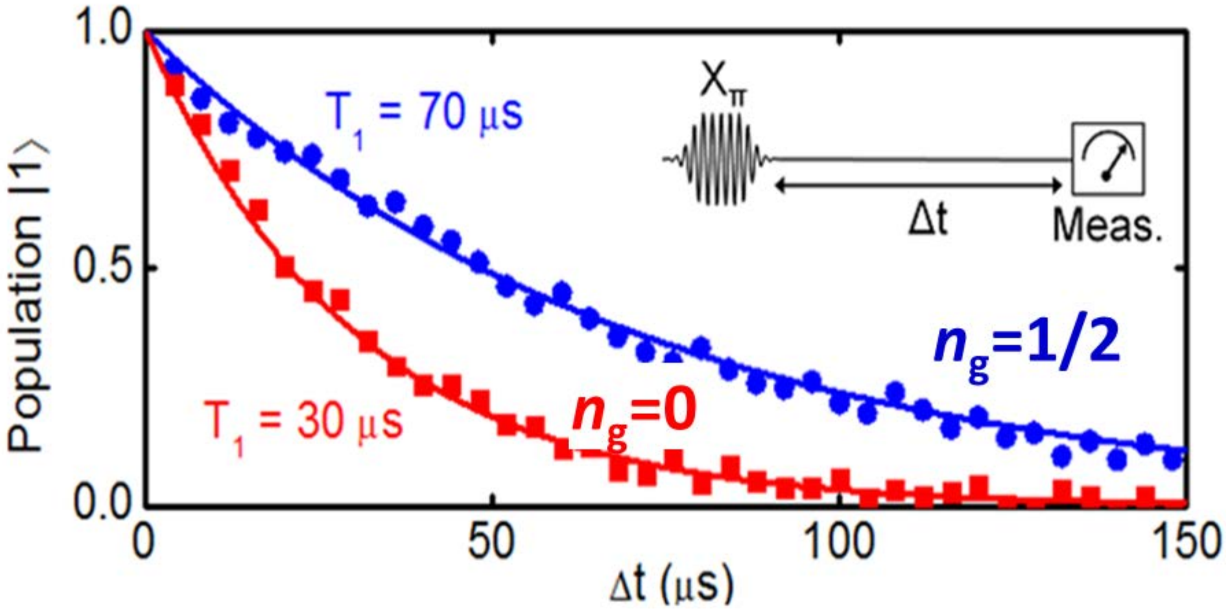
$E_2(\varphi) = |2E_{2R} \cos \varphi|$

Time-Domain Measurements



Optimal regime: $\max E_2, \min E_1 \rightarrow$

$\varphi = n\pi \quad (\min E_{01})$

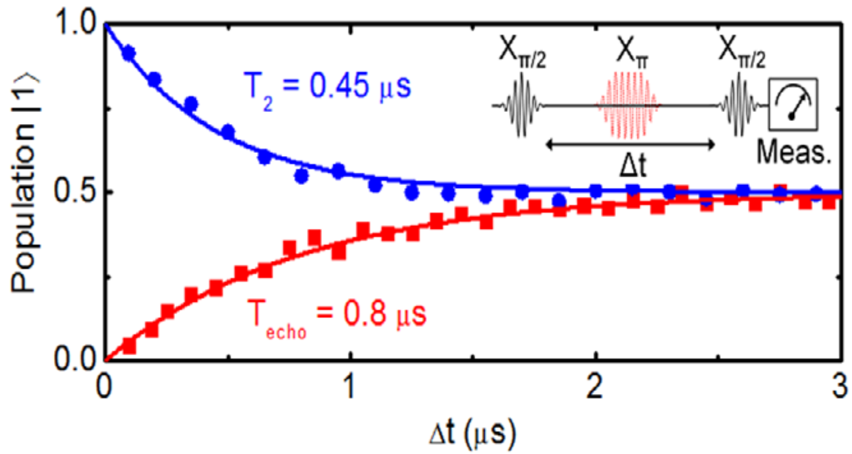


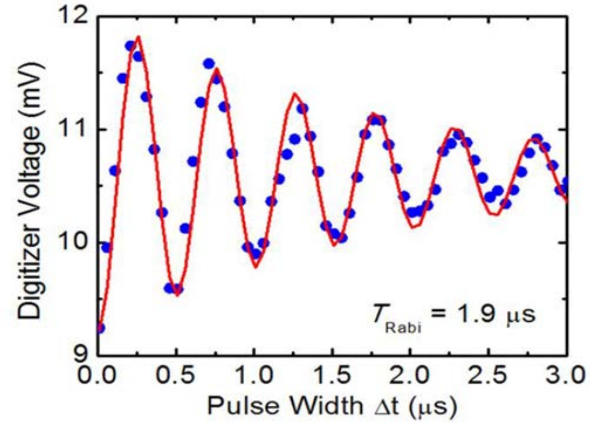
$$Q \equiv \omega_{01} T_1 \approx 1 \cdot 10^6$$

At $n_g = 0$ the effect of charge noise and dielectric losses is negligibly small. Primary source of decay: coupling to the transmission line and readout resonator.

M. Bell et al. *PRL* **112**, 167001 (2014)

Dephasing Time





$$\Gamma_2{}^{\Phi} = \sqrt{\frac{log(E_1/\Omega_0)}{2\pi}}\left(\frac{2E_1}{E_{01}}\right)(2\delta E_1)$$

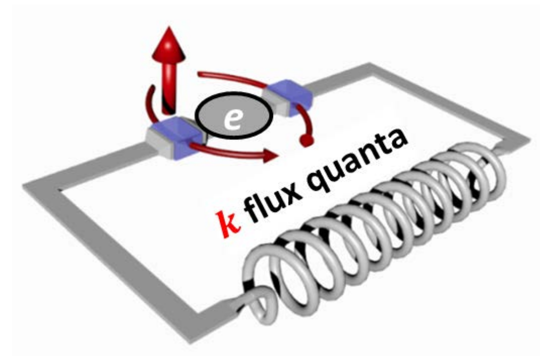
δE_1 - fluctuations of E_1 caused by the 1/f flux noise

Primary source of dephasing:
flux noise in the rhombi loops.

- Reduction of asymmetry
- Increase of E_2/E_C
- Alternative implementation of $\cos 2\varphi$ elements

The toolbox for protected qubits:
$\cos(2\varphi)$, $cos(\varphi/2)$, super-*L*

- ❑ Idea of Parity-Based Protection
- ❑ **Flux-Pairing Qubits**
- ❑ Charge-Pairing Qubits
- ❑ Superinductors



- ❑ Qubits: state of the art
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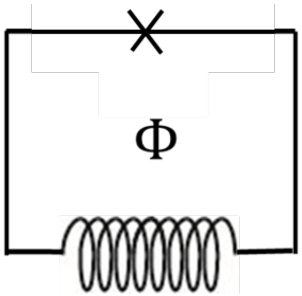
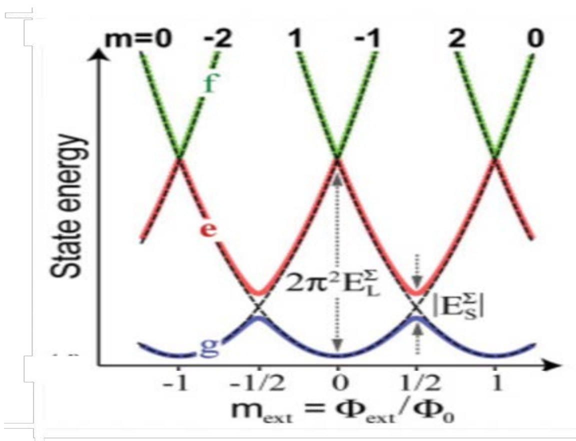
"$\cos(\varphi) - L$" and "$\cos(\varphi/2) - L$" Qubits

Fluxonium (Manucharyan *et al*. 2009)



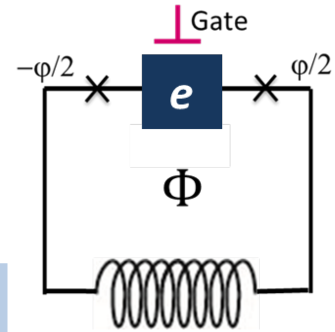
$$E_L = \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{1}{L}$$



single fluxon tunneling

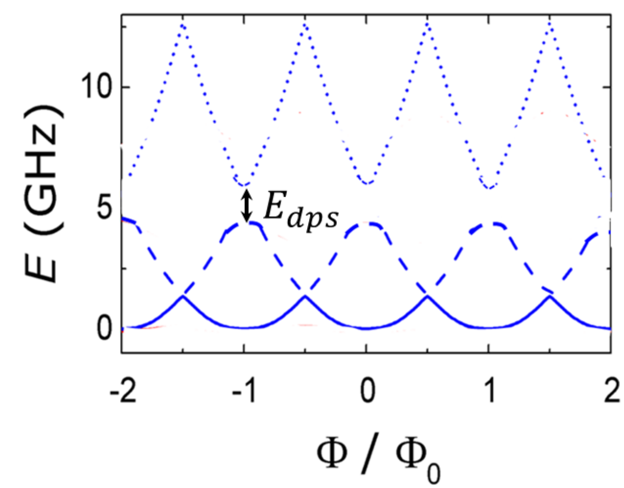
$$E_{sps} \propto \omega_p exp\left(-\sqrt{\frac{8E_J}{E_C{}^*}}\right)$$

Flux-pairing Qubit



$q = e$

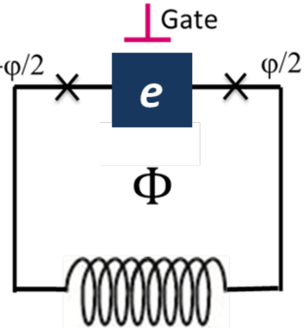
$\boldsymbol{E_L \gtrsim E_{dps}}$



double fluxon tunneling

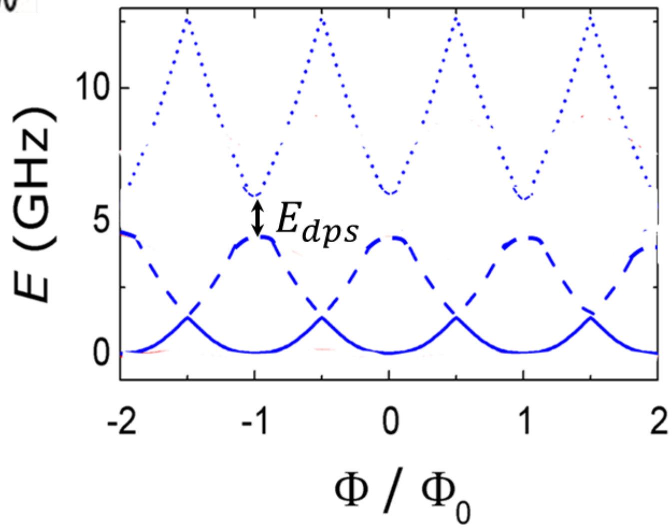
$$E_{dps} \propto \omega_p exp\left(-2\sqrt{\frac{8E_J}{E_C{}^*}}\right)$$

$$\omega_p = \sqrt{8E_J E_C{}^*}$$

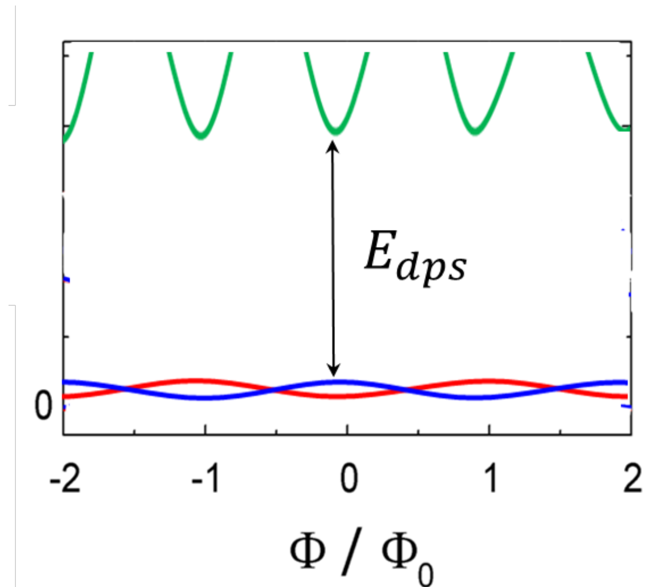


Flux-Pairing Qubit ($q=e$)

$$E_L \gtrsim E_{dps}$$



$$E_L \ll E_{dps}$$

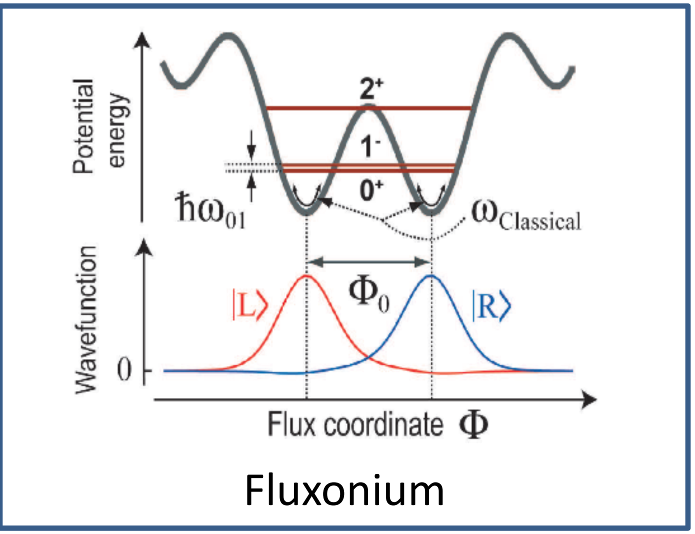


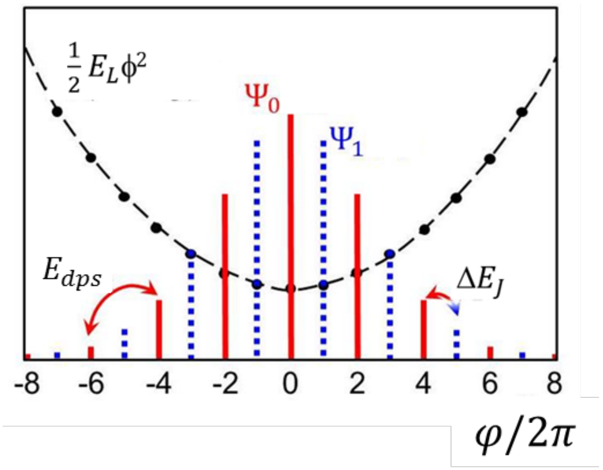
$$H = -\left(\frac{E_L{}^*}{2}\sigma_z + \frac{E_{sps}}{2}\sigma_x\right)$$

$$E_L{}^* = E_L(1 - 2\Phi/\Phi_0)$$

$$E_L{}^* = E_L exp\left(-\sqrt{\frac{E_{dps}}{E_L}}\right)$$

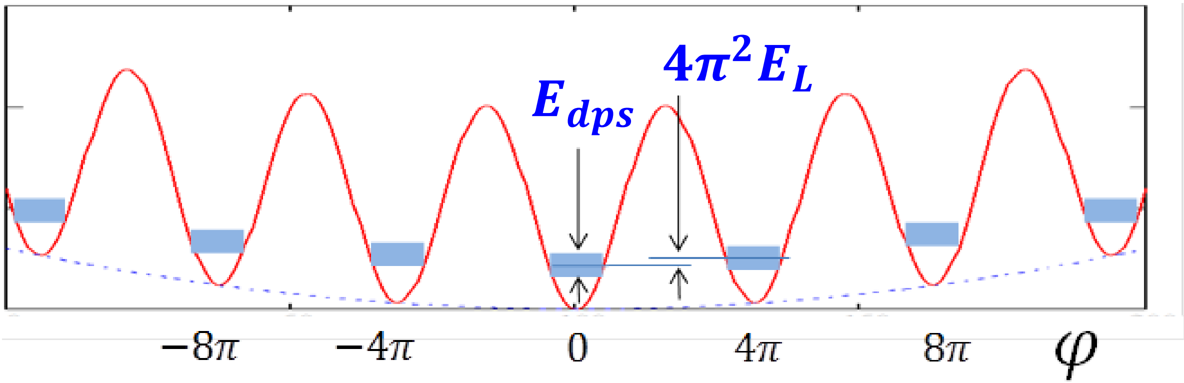
Flux-Pairing Qubit ($E_L \ll E_{dps}$)





Large quantum fluctuations of phase ($\langle k^2\rangle \gg 1$):

$$\boxed{E_{dps} \gg 4\pi^2 E_L}$$



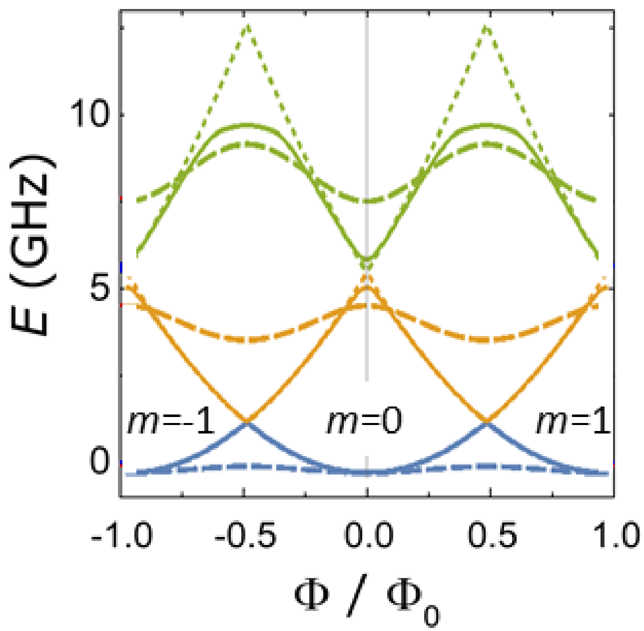
Implementation of the fault tolerant flux-pairing qubit:

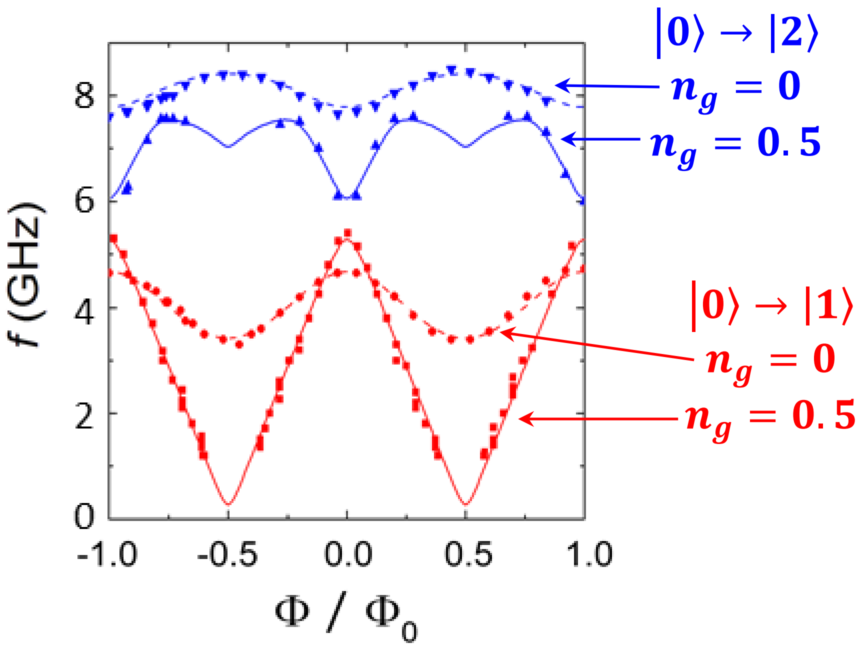
1. Superinductance $\sim$10 μH (!)
2. High rate of double phase slips ($\frac{E_J}{E_C} \leq 0.2$)

Fluxonium:

$L = 0.3\mu H$

Spectroscopic Evidence of Aharonov-Casher Effect





Bell *et al*. *PRL* **116**, 107002 (2016)

Complete suppression of single phase slips at n_g = 0.5 -
clear spectroscopic evidence of the Aharonov-Casher effect

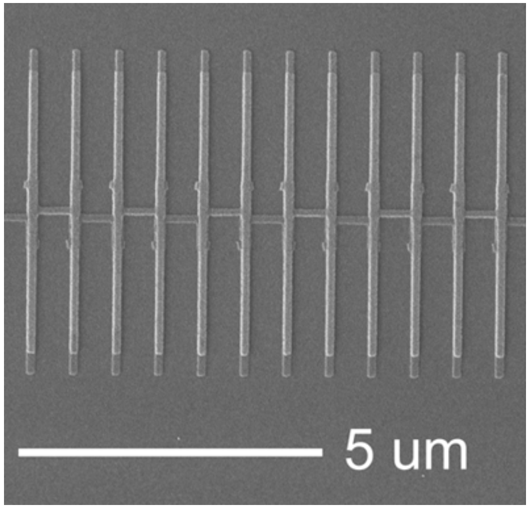
- Decrease E_L down to ~ 1 mK ($L \geq 10$ µH) without decreasing the superinductor self-mode frequency .
- Increase the rate of double phase slips ($\frac{E_J}{E_C} \leq 0.2$).

- ❑ Qubits: state of the art
- ❑ Idea of Parity-Based Protection
- ❑ Charge-Pairing Qubits
- ❑ Flux-Pairing Qubits
- ❑ Superinductors

Superinductors

Impedance Z >> $R_Q \equiv \frac{h}{(2e)^2} \approx 6.5k\Omega$

No dissipation and dephasing

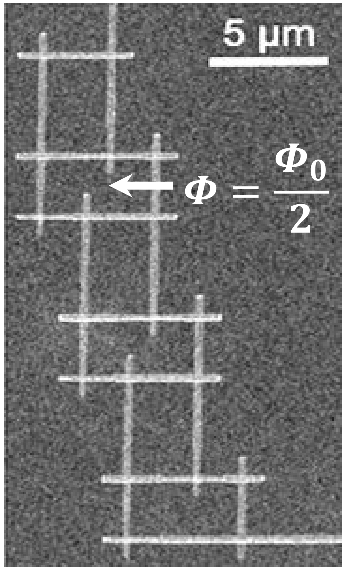


Chain of junctions with $\frac{E_J}{E_C} \gg 1$

$\boldsymbol{L = 0.3\mu H}$

Manucharyan *et al.*
Science 326, 113 (2009)

Masluk *et al.*
PRL 109, 137002 (2012).



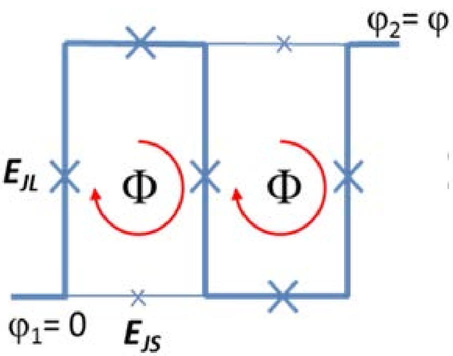
Chain of asymmetric SQUIDs

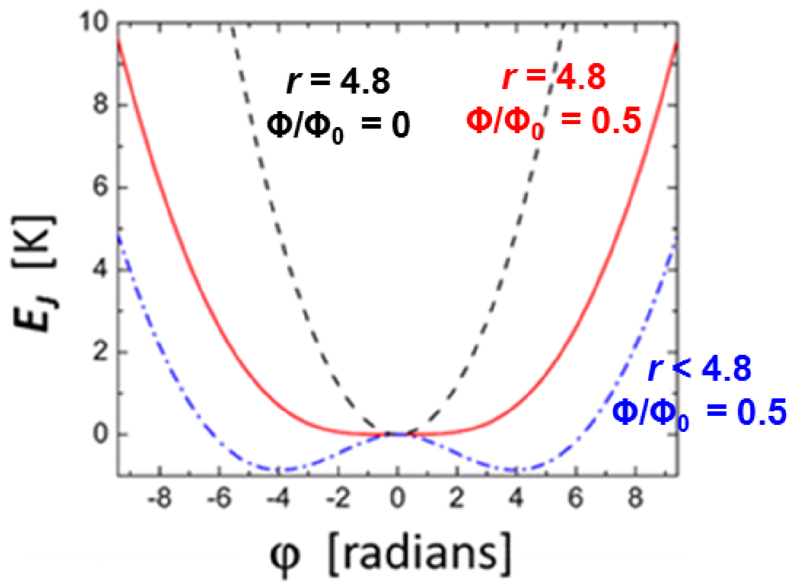
$\boldsymbol{L(\Phi = \Phi_0/2) = 3\mu H}$

Bell *et al.*
PRL 109, 137003 (2012)

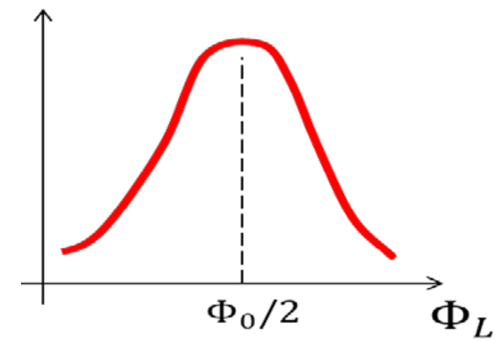
Specific to our design: *tunable inductance and non-linearity.*

Tunable Nonlinear Superinductor





$$L_J \propto \left(\frac{d^2 E_J(\varphi)}{d\varphi^2}\right)^{-1}$$

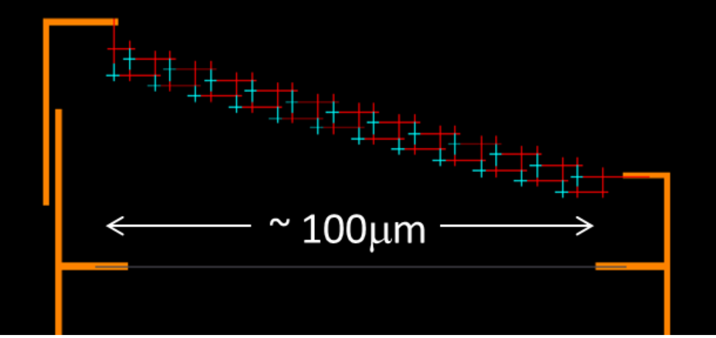


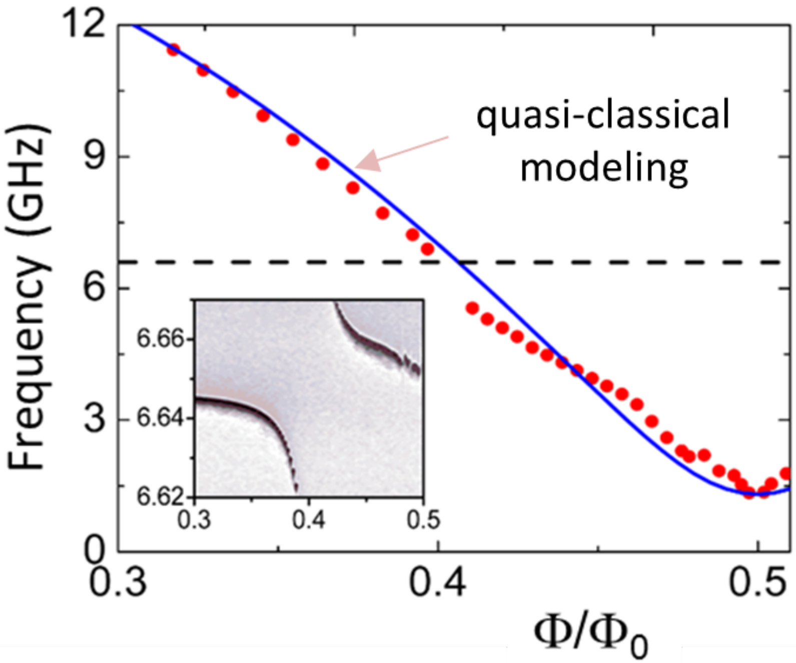
$$\boldsymbol{r} \equiv \frac{\boldsymbol{E_{JL}}}{\boldsymbol{E_{JS}}}$$

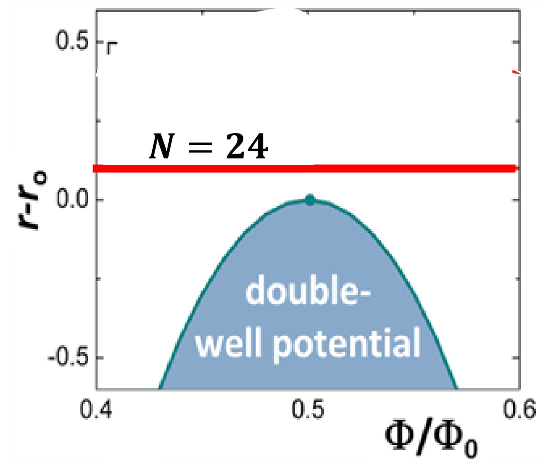
For the optimal ***r*** value, $E_J(\varphi)$ becomes "flat" at Φ=1/2Φ_0, and the "classical" L_J diverges.

- the ladder backbone is formed by the junctions with $E_{CL} \ll E_{JL}$ - the phase slip rate is exponentially small;
- Potential can be varied from a single well to double well either by changing E_{JL}/E_{JS} or by changing the flux.

Ladders with 24 unit cells





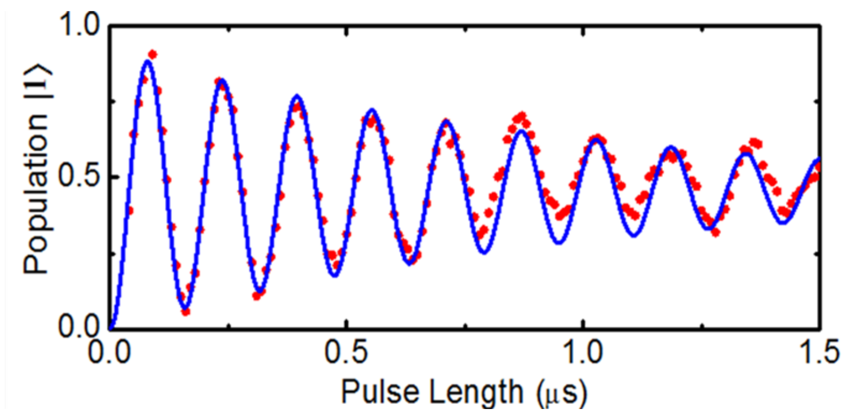


$$L_K(\Phi = \Phi_0/2) = 3\mu H$$

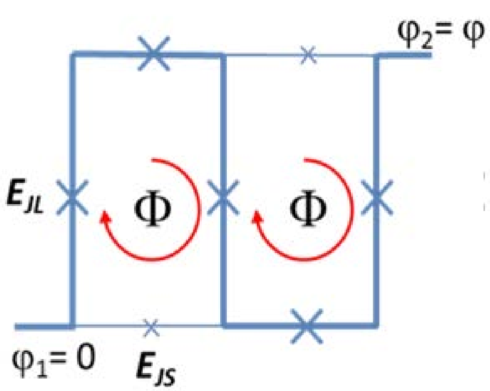
- this is the inductance of a 3-meter-long wire!

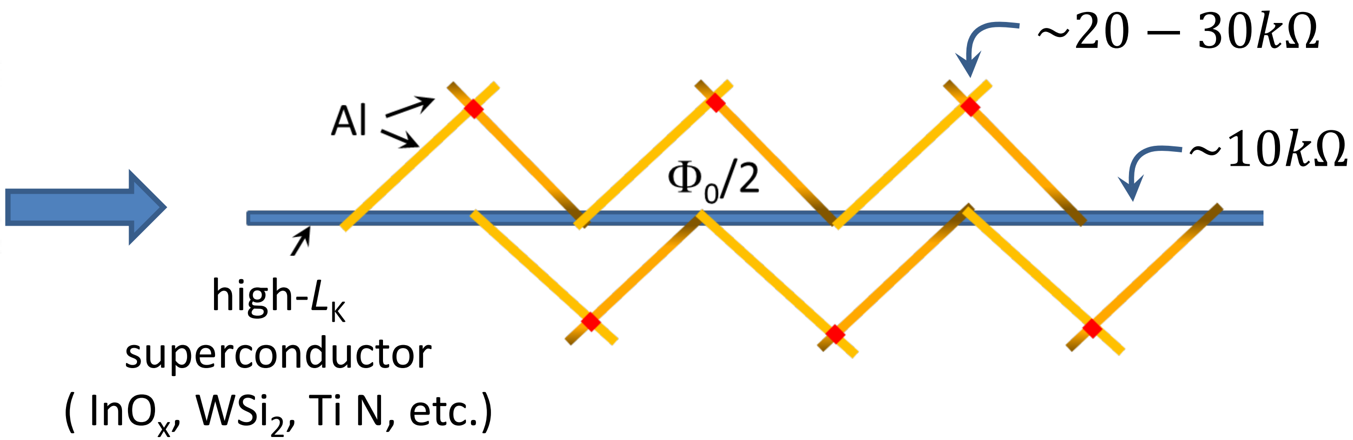
$$Z(3GHz) = 50k\Omega > R_Q \equiv \frac{h}{(2e)^2}$$

Bell *et al. PRL* 109, 137003 (2012).

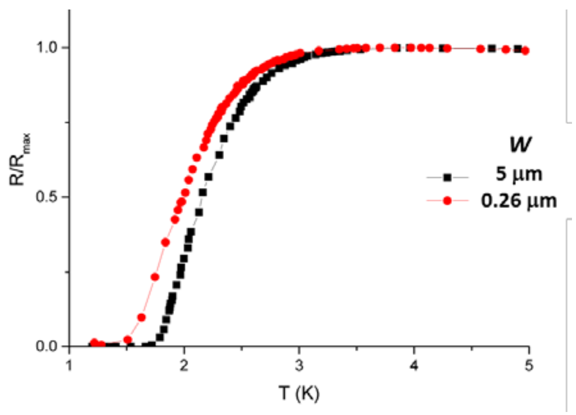


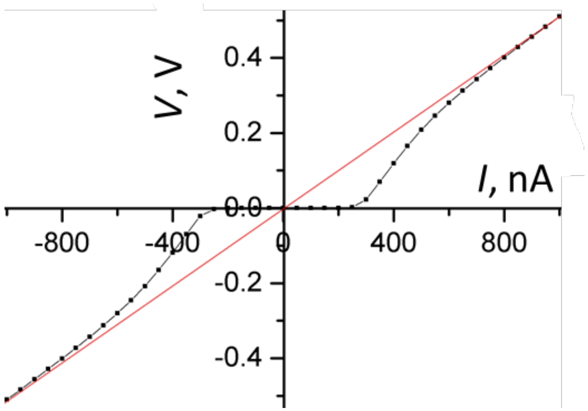
Collaboration with Sacépé Lab (Grenoble)





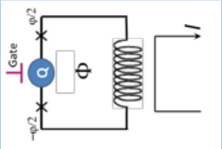
InOx films: $R_{\square} = 2.5k\Omega, W = 0.26\mu m, T_C \approx 1.5K$





- increase the SL inductance without decreasing the resonance frequency of the superinductor

- fast control of the superinductance for fault-tolerant operations



- implement superinductor-based traveling wave parametric amplifiers;

Bell and Samolov, Phys. Rev. Applied ***4****, 024014 (2015)*

- use 1D chains of asymmetric SQUIDs as a platform for the study of 1D quantum phase transitions.

Summary

The toolbox for protected qubits:

$\mathbf{cos(2\varphi)}$, $\boldsymbol{cos(\varphi/2)}$, super-*L*

- Charge- (flux-) pairing qubits offer the possibility of coherence protection and fault-tolerant operations.
- Observed:
  - suppression of energy relaxation in a minimalistic rhombi chain;
  - spectroscopic evidence of Aharonov-Casher effect in flux-pairing devices.
- Current work:
  - optimization of the parameters of the flux-pairing qubits (smaller E_L and larger E_{dps});
  - development of better superinductors (for applied projects as well as a novel tool to study 1D QPTs).