Parity-Protected Qubits

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Outline:

- **Quantum Effects in Superconducting Circuits**
- **Superconducting Qubits**
- **Parity-Protected Josephson Circuits**
  - **Charge-pairing devices**
  - **Fluxon-pairing devices**

"Localization, Interactions, and Superconductivity", Chernogolovka, July1, 2015

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Josephson Junctions:
non-linear and *non-dissipative* elements at low *T*

Macroscopic many-particle condensate wavefunction:

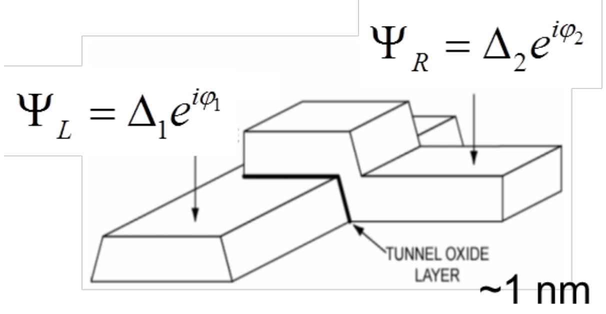
$$\Psi(r,t) = |\Psi(r,t)| \exp[i\varphi(r,t)]$$

amplitude phase

DC J. effect

$$I_S = I_C \sin\phi \quad \varphi = \varphi_1 - \varphi_2$$

I_S - the supercurrent, I_C - the crit. current



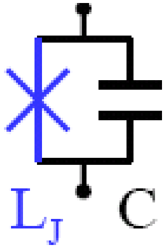
AC J. effect

$$V = \frac{\hbar}{2e}\frac{d\varphi}{dt}$$

$$L_J = \frac{L_{J0}}{\cos\varphi} \qquad L_{J0} = \frac{\hbar}{2eI_C}$$

Josephson inductance – the inertia of Cooper pairs.

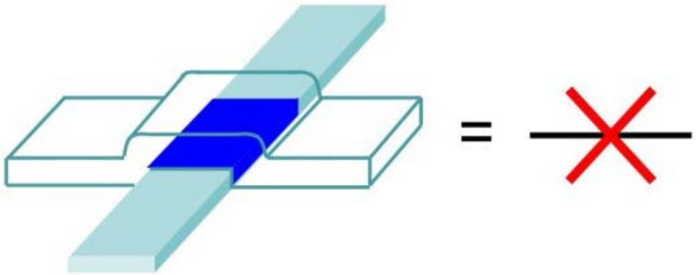
$I_C = 10nA \rightarrow 1\mu H$, the inductance as of a 1-m-long wire!



The Josephson junction is a non-dissipative (at $T \rightarrow 0$) nonlinear **inductor** shunted by a **capacitor**

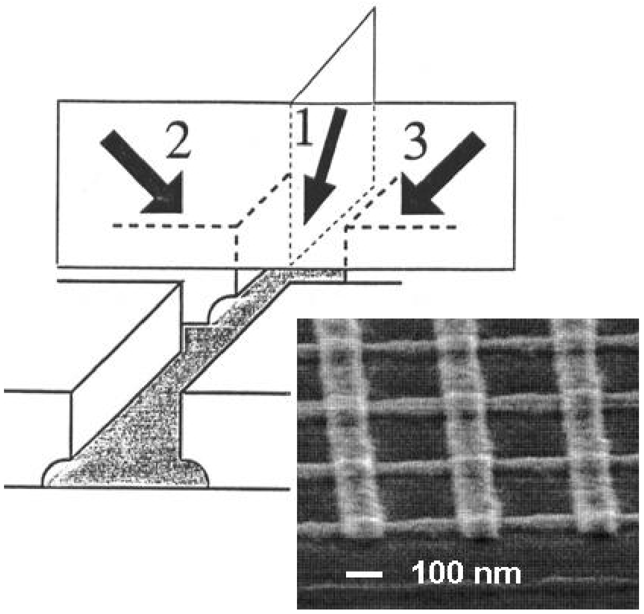
$\Rightarrow$ ***a non-linear non-dissipative oscillator***.

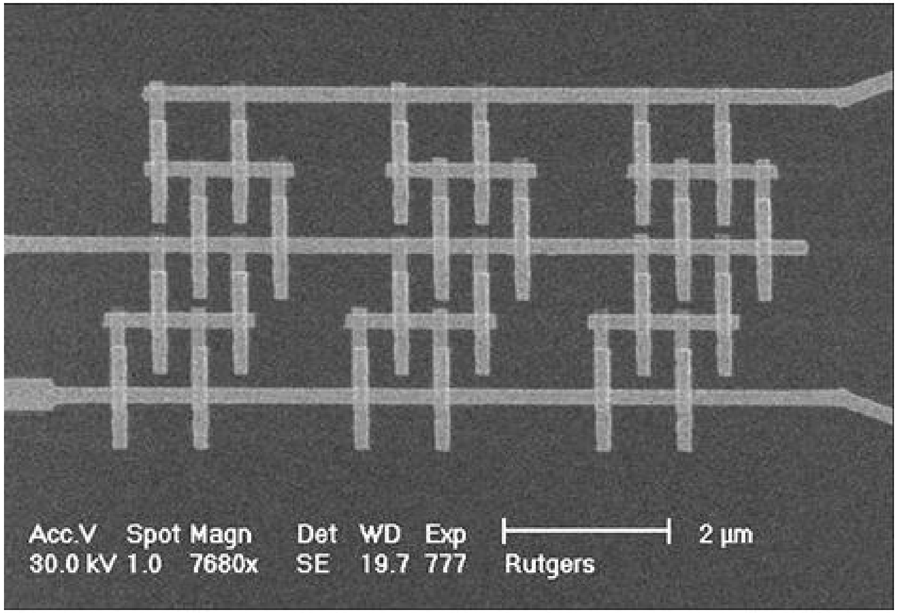
Fabrication



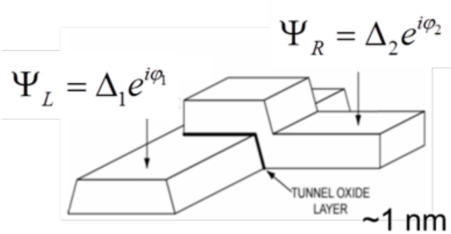
Al → superconducting electronics

Si → semiconductor electronics





Characteristic Energies



Josephson energy

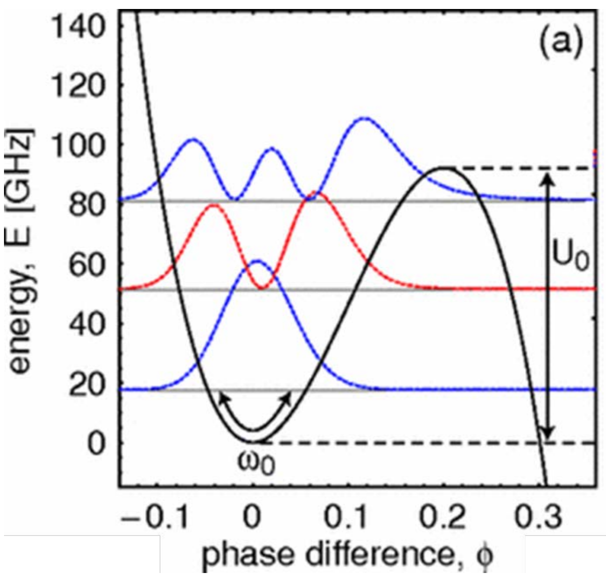
$$E_J = \frac{\Phi_0^{\,2}}{2L_J}$$

Charging energy

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

$$\omega_{p0} \equiv \frac{1}{\sqrt{L_J C_J}} = \frac{1}{\hbar}\sqrt{8E_J E_C}$$

– the plasma frequency (typically $\sim 60GHz = 3K$)



Josephson junction impedance:

$$Z_J \equiv \sqrt{\frac{L_J}{C_J}} \approx 1k\Omega\sqrt{\frac{8E_C}{E_J}}$$

- *tunable,* E_J/E_C ~ (JJ area)^2

Quantum Fluctuations in Nano-Scale JJs

Charge and phase are quantum variables.

$$\hat{H} = E_C\left(\hat{n} - n_0\right)^2 - E_{J0}\cos\varphi - I\varphi$$

current

$$\hat{n} = i\frac{\partial}{\partial\varphi}$$

n – the number of Cooper pairs

- motion of a "particle" with coordinate $\boldsymbol{\varphi}$ and mass $\propto$ $\boldsymbol{C_J}$

cf. $$H(x,p) = \frac{p^2}{2m} + V(x)$$

$$\left[\hat{n},\hat{\varphi}\right] = -i$$

The uncertainty relation for a superconductor:

$$\Delta n \cdot \Delta\varphi \geq 1$$

$$E_J << E_C$$

$\boldsymbol{n}$ is well defined, $\boldsymbol{\varphi}$ strongly fluctuates

(the ***Coulomb blockade*** regime).

$$E_J >> E_C$$

$\boldsymbol{\varphi}$ is well defined, $\boldsymbol{n}$ strongly fluctuates

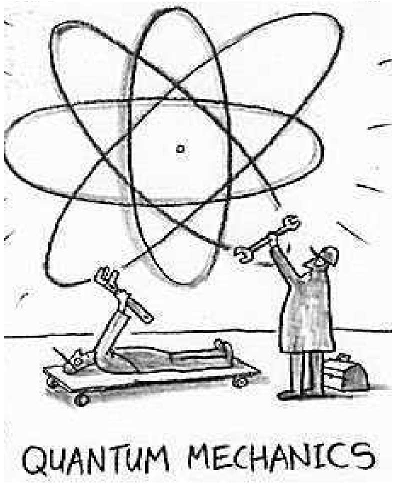
(the "classical" ***Josephson*** regime).

Conventional superconducting electronics:

classical behavior of the collective quantum variable φ

Quantum superconducting electronics:

quantum behavior of the quantum variables φ and n



Google: quantum engineers

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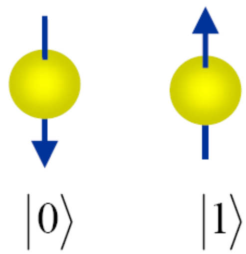
DiVincenzo Criteria

- **A scalable physical system with well-defined qubits.**
- **The ability to initialize all qubits in a simple initial state,**
  e.g. $|\mathbf{00000..}\rangle$**.**
- **Decoherence time >>> gate operation time.**
- **A universal set of quantum gates.**
- **Ability to measure qubits.**

Quantum Bits

- two-level systems which behave quantum mechanically (preserve coherence) for sufficiently long time.

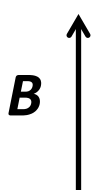
Quantum states

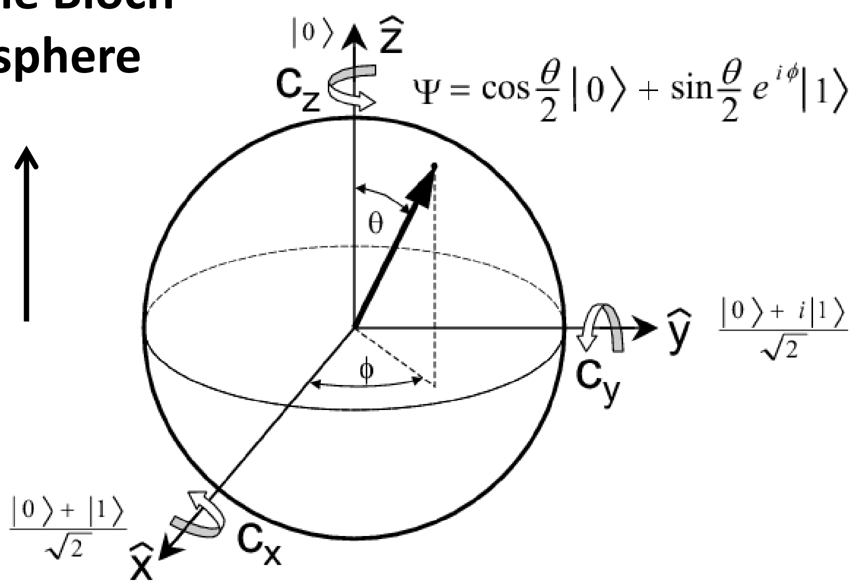


Wavefunction

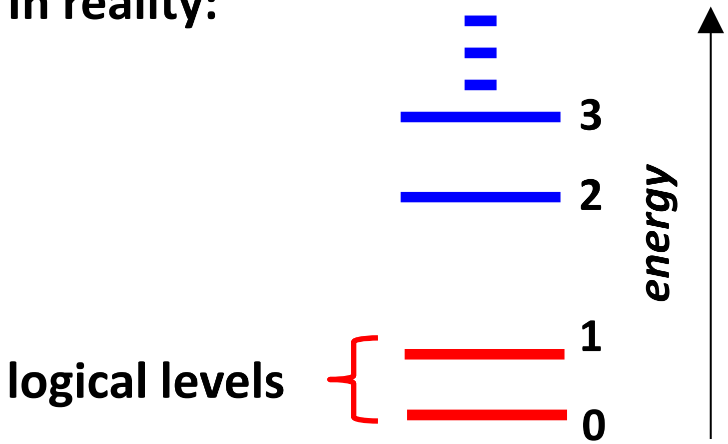
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

The Bloch sphere





In reality:



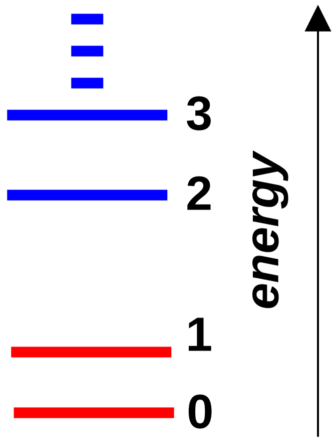
anharmonicity $\boldsymbol{\delta \equiv E_{12} - E_{01}}$

- the stronger the better

$\boldsymbol{\delta}$ determines ***the shortest operation time*** of a qubit:

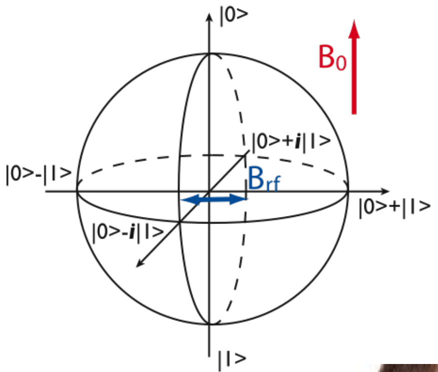
$$\boldsymbol{t_0 > \frac{h}{\delta}}$$

Noises in Superconducting Qubits



$$E_{01} = E_{01}(E_J, E_C, q, \varphi, \dots.)$$

$$\hat{H} = E_C\,(\hat{n} - n_g)^2 - E_J \cos\left(2\pi\frac{\Phi}{\Phi_0}\right) + \cdots + \frac{parasitic}{coupling}$$



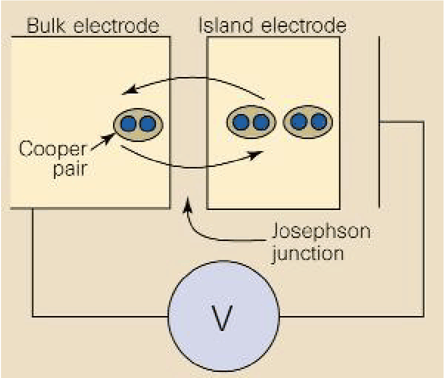
$$n_g = n_{g\,stat} + \delta n_g(t)$$ ***Charge noise***

$$\Phi = \Phi_{stat} + \delta\Phi(t)$$ ***Flux noise***

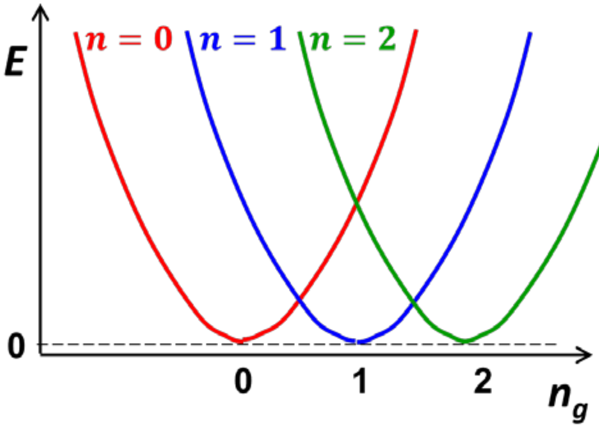
$$E_J = E_{J\,stat} + \delta E_J(t)$$ ***Crit. current fluctuations***

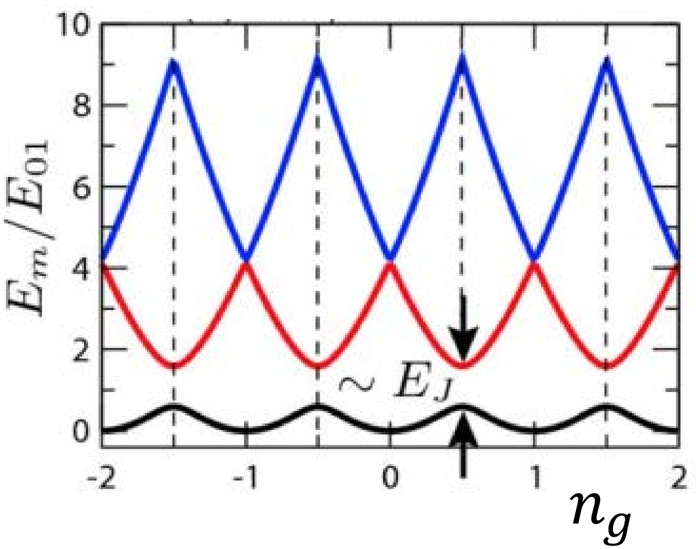
Task: to build a solid-state (= scalable) system with a "two-level" Hamiltonian where undesirable couplings are kept at _ppm_ (!) level

Cooper pair box

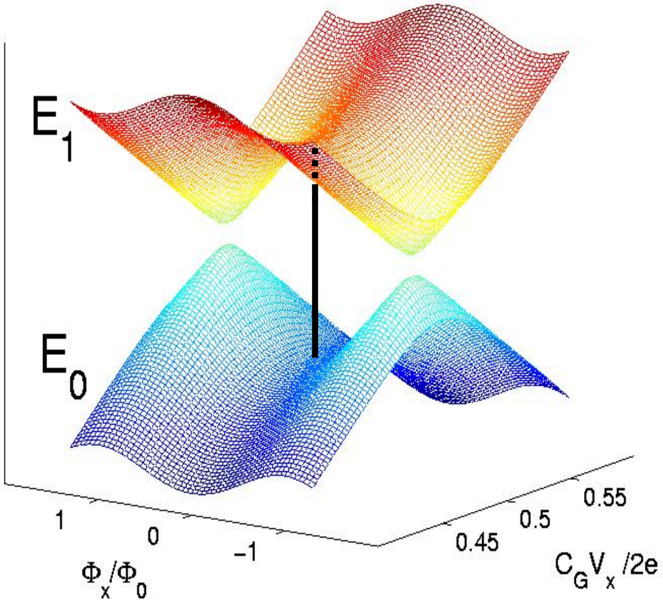


$$\hat{H} = E_C\left(\hat{n} - n_g\right)^2 - E_J\cos\varphi$$



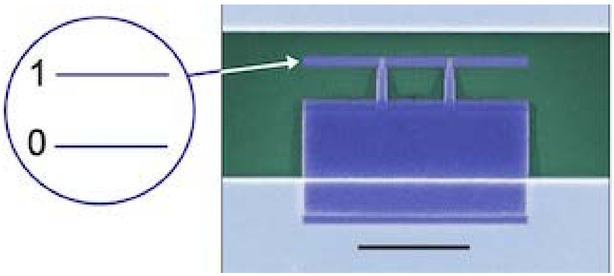


$$n_g = n_{g\,stat} + \delta n_g(t)$$



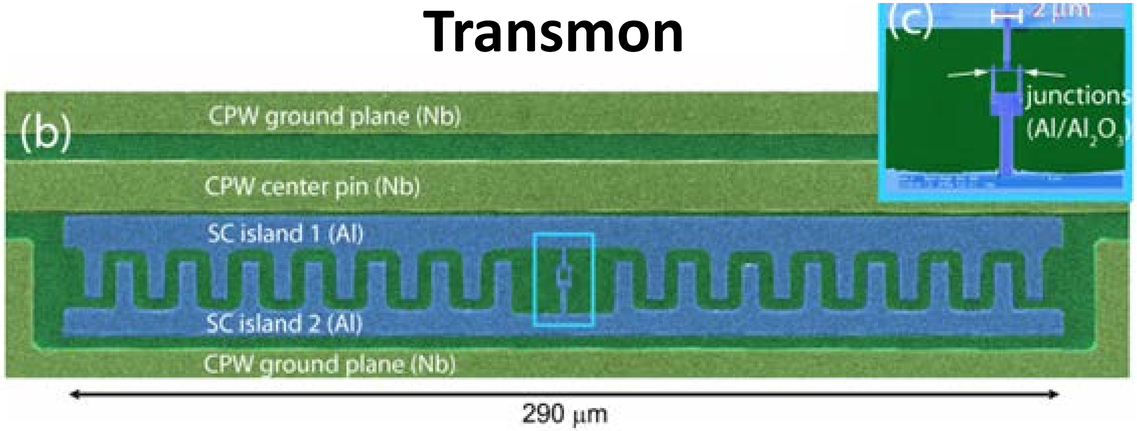
Vion *et al.*, CEA Saclay, '02

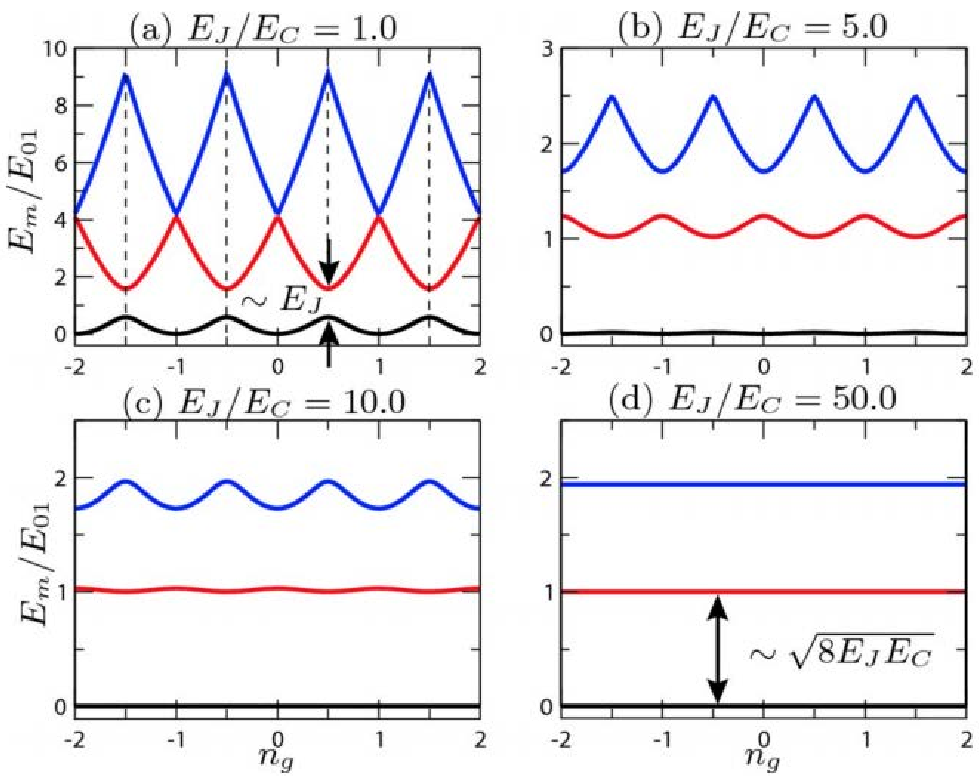
From Charge Qubit to Transmon (Yale 2007)



Charge qubit

Transmon





Increase of E_J/E_C:

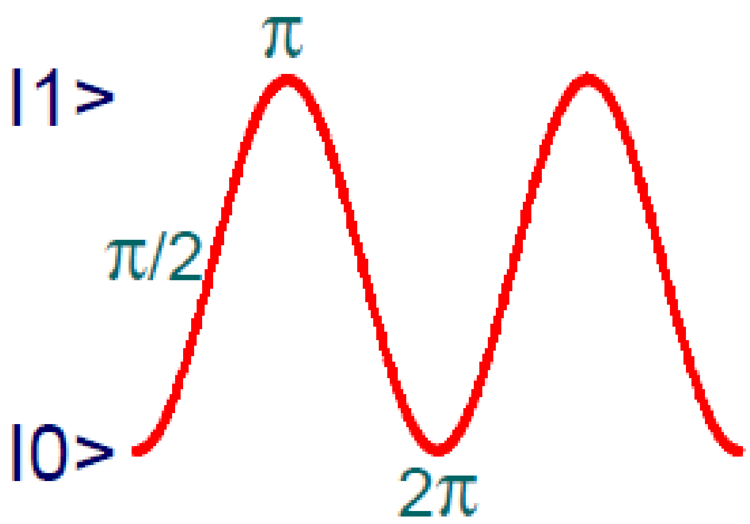
- sensitivity to the charge noise drops exponentially,
- the anharmonicity decreases algebraically.

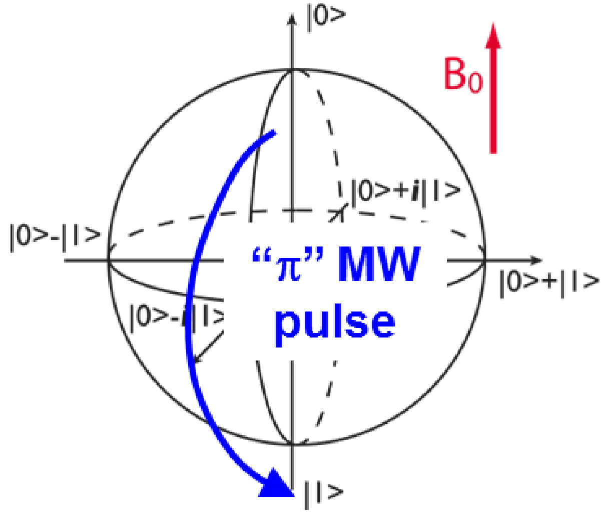
This eliminates the need for tuning to a charge sweet spot.

Quantum Manipulations

Rabi oscillations

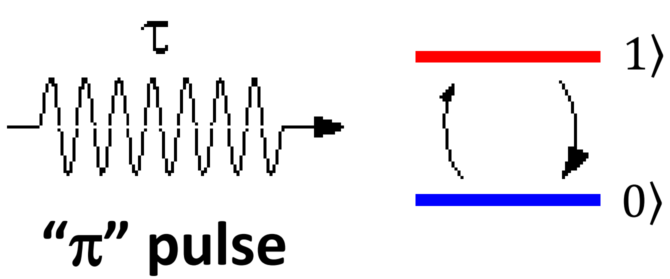
resonant EM wave $\boldsymbol{\omega = E_{01}/\hbar}$





Rabi frequency ∝ MW amplitude

Rabi flop:

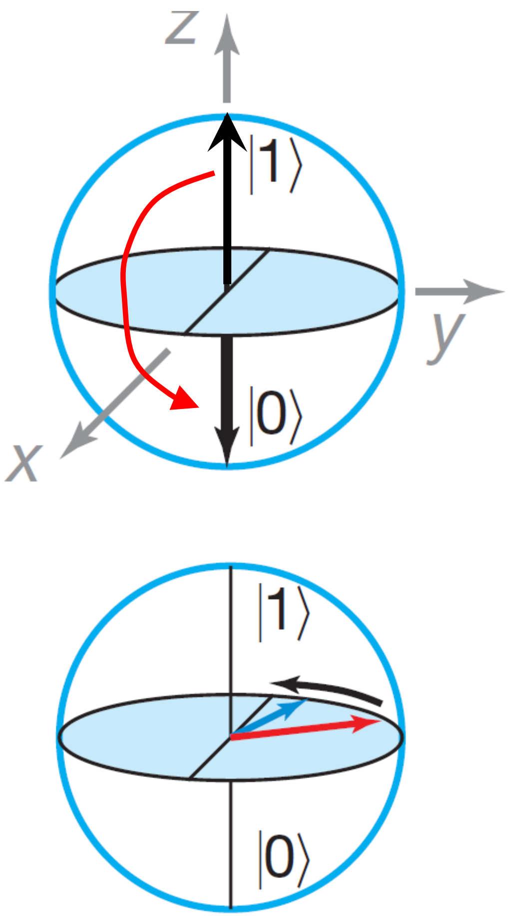


$$\tau_0 \geq 100/2\pi f_{01}$$

$$f_{01} = 5GHz$$

$$\tau_0 \sim 10ns$$

Decoherence : Energy Relaxation + Dephasing



$\alpha|0\rangle + \beta|1\rangle$

T_1 = Relaxation time

spontaneous decay, coupling to high-frequency noises

T_φ = Dephasing time

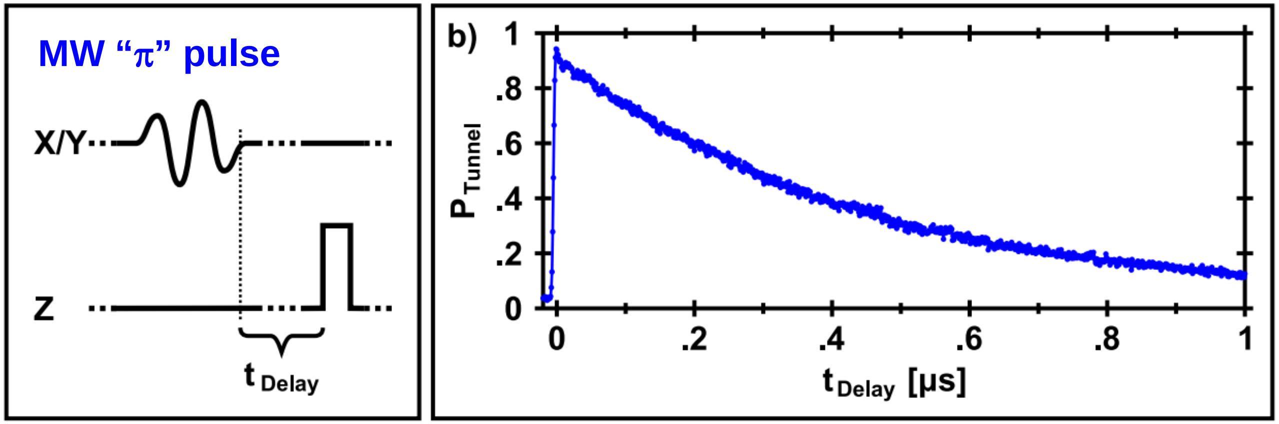
Coupling to low-frequency noises

$$T_2 = \left(\frac{1}{2T_1} + \frac{1}{T_\varphi}\right)^{-1}$$

$$e^{i(E_1 - E_0)t} = e^{i\hbar\omega_{01}t}$$

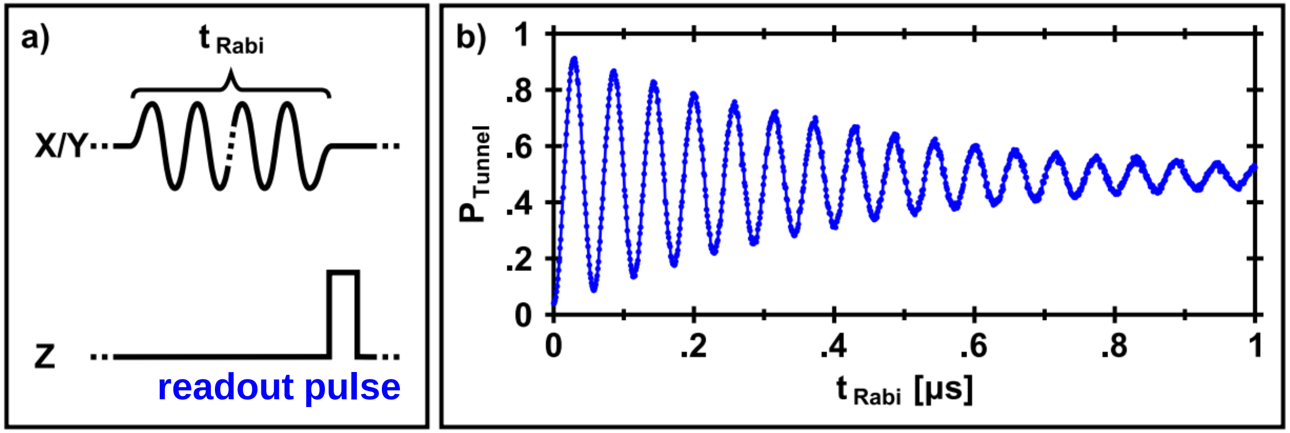
Measurements of T1 and T2

Energy Relaxation (T_1)



M. Ansmann, Ph.D. thesis, '09

Rabi Oscillation (T_2)



Sufficiently Long Decoherence Time?

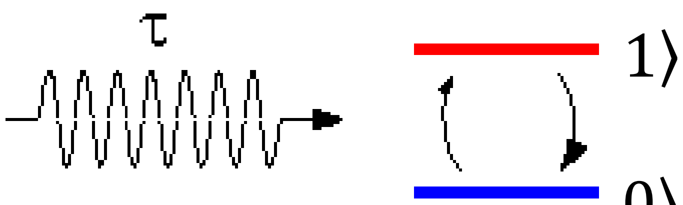
The error rate : $\boxed{\varepsilon \equiv \frac{\tau_0}{T_2}}$

T_2 **- the decoherence time**

τ_0 - **the time of longest operation**

For implementation of error-correction codes (with realistic redundancy) $\varepsilon < 10^{-4}$

Rabi flop:



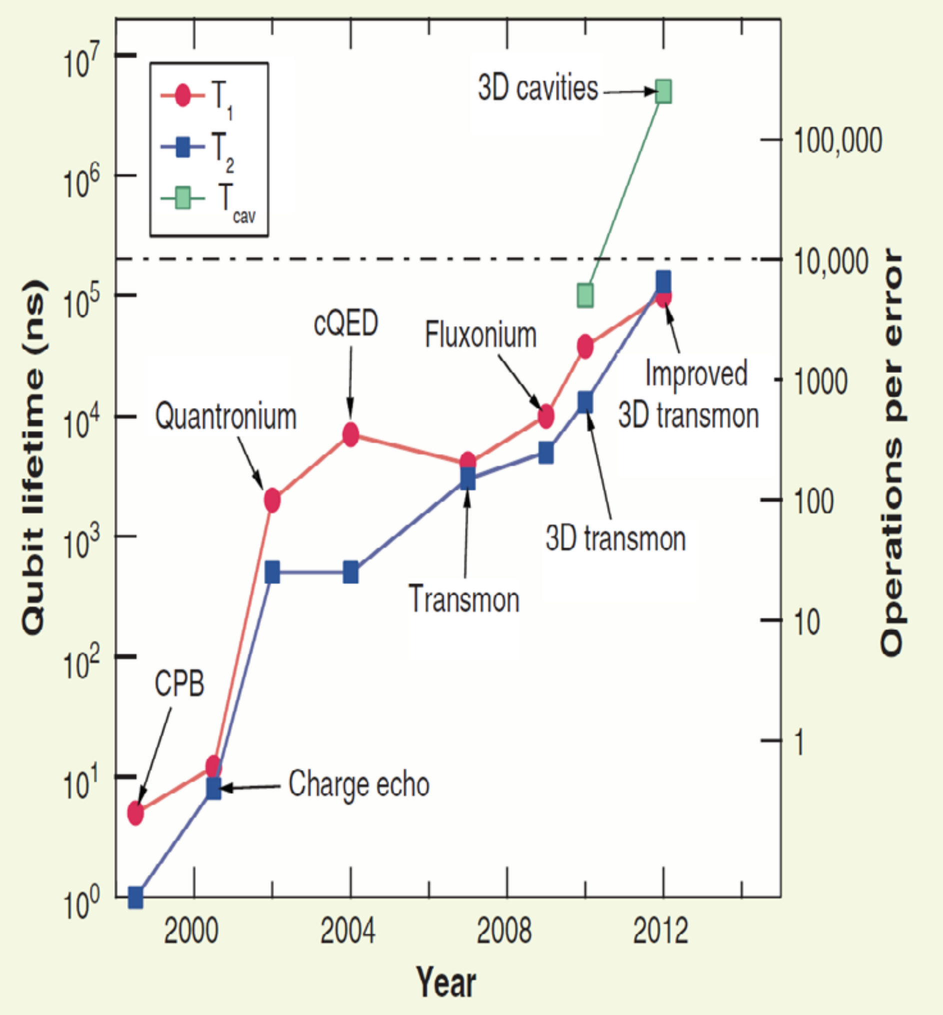
"π" pulse

$\tau_0 \geq 100/\omega_{01}$

$$\Longrightarrow \quad Q \equiv \omega_{01} T_2 > \mathbf{10^6}$$

State of the Art

"Moore's Law" for superconducting qubits



Devoret & Schoelkopf, Science 2013

Single qubit gates: $\varepsilon \equiv \dfrac{\tau_0}{T_2} \sim 10^{-4}$

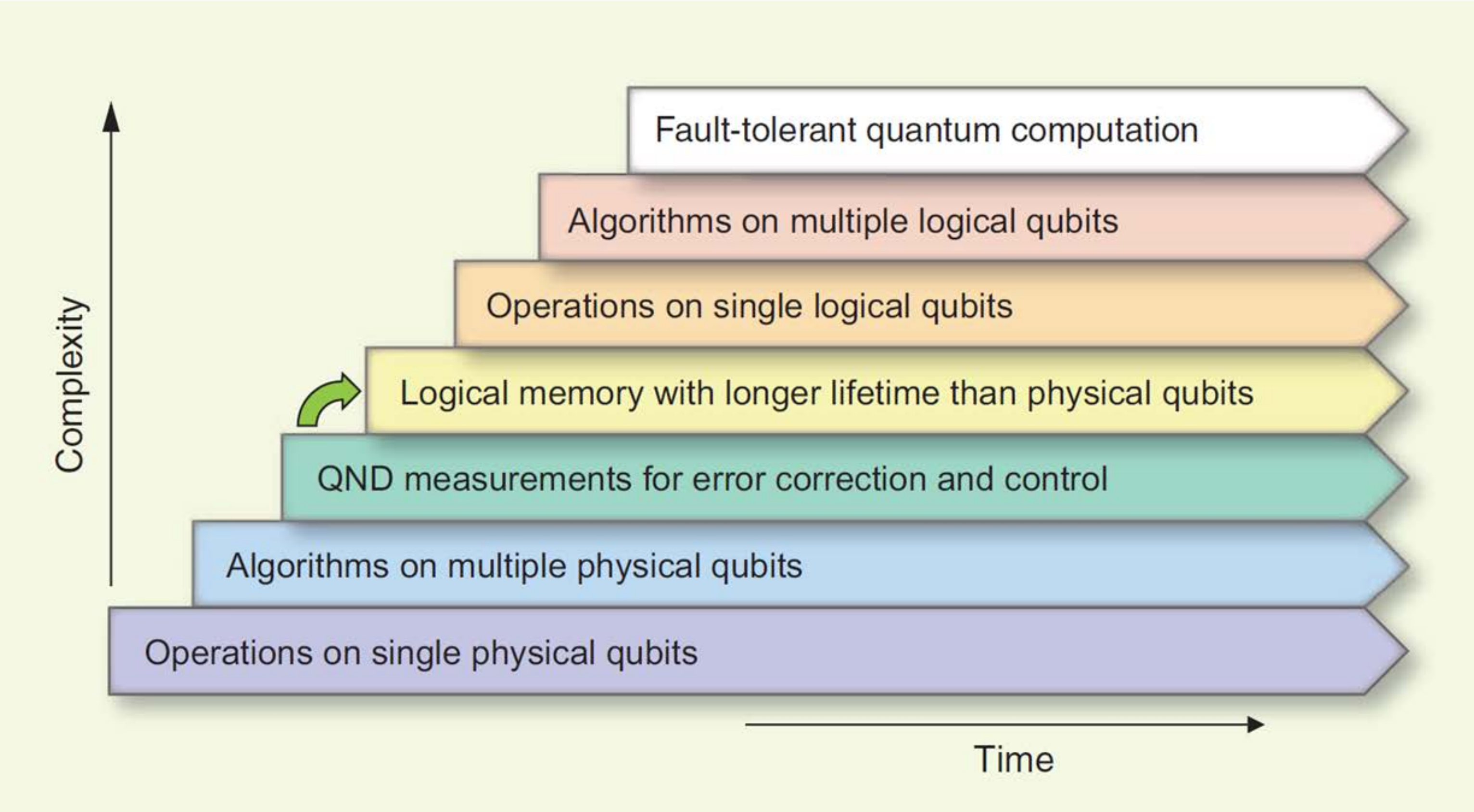
Two-qubit gates:

$T_2 \approx 40\ \mu s \qquad \tau_0 \approx 40\ ns$

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

Martinis' Group, UCSB/Google

State of the Art (cont'd)



Devoret & Schoelkopf, Science 2013

The next step $\rightarrow$ logical (fault-tolerant) qubit.

Major bottleneck is the enormous overhead because the accuracy of physical (faulty) qubits is too close to (or even below?) the threshold.

QC – still in the early stages, but…

Martinis (UCSB $\rightarrow$ Google): "We're somewhere between the invention of the transistor and the invention of the integrated circuit."

even this is not obvious yet

- ❑ **the number of people working on the superconducting QC in the industry is already a few hundred ("quantum engineers").**

- ❑ **Funding – hundreds $M (Google: $100M/five years)**

IBM'S $3 BILLION INVESTMENT IN SYNTHETIC BRAINS AND QUANTUM COMPUTING

IBM THINKS THE FUTURE BELONGS TO COMPUTERS THAT MIMIC THE HUMAN BRAIN AND USE QUANTUM PHYSICS...AND THEY'RE BETTING $3 BILLION ON IT.

BY NEAL UNGERLEIDER

IBM is unveiling a massive $3 billion research and development round on Wednesday, investing in weird, science fiction-like technologies—and, in the process, essentially staking Big Blue's long-term survival on big data and cognitive computing.

Over the next five years, IBM will invest a significant amount of their total revenue in technologies like non-silicon computer chips, quantum computing research, and computers that mimic the human brain.

Lockheed Martin

BBN (Raytheon)

HRL in Malibu

Northrop Grumman

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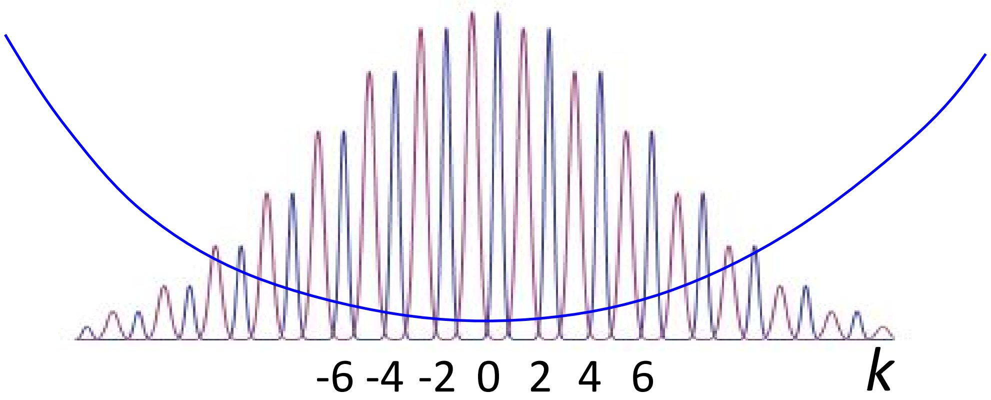
Parity-Protected Qubits

The goal: to engineer two (almost degenerate) quantum states ***indistinguishable*** by the environment.

Gottesman, Kitaev & Preskill (2001)



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

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

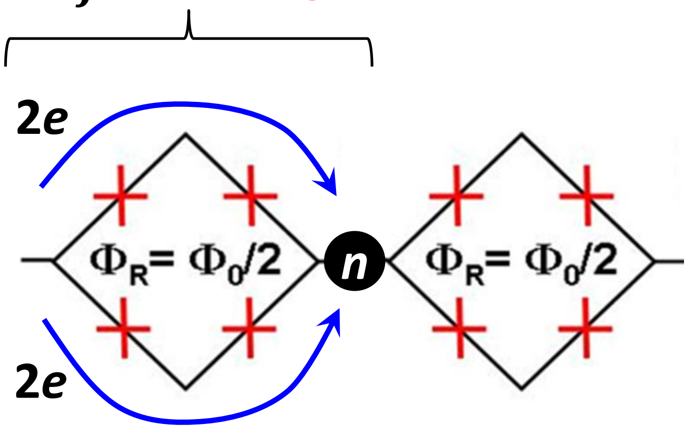
- **parity protection**

- Decay is suppressed if parity is protected. ⟸ $T_1 = \infty$
- Dephasing is suppressed if the envelope decays slowly so that wave functions are not easily distinguishable. ⟸ $long\ T_2$

★ (Some) fault tolerant rotations – protected from noise in the control pulses.

Charge Pairing

$E_J^* cos(2\phi)$

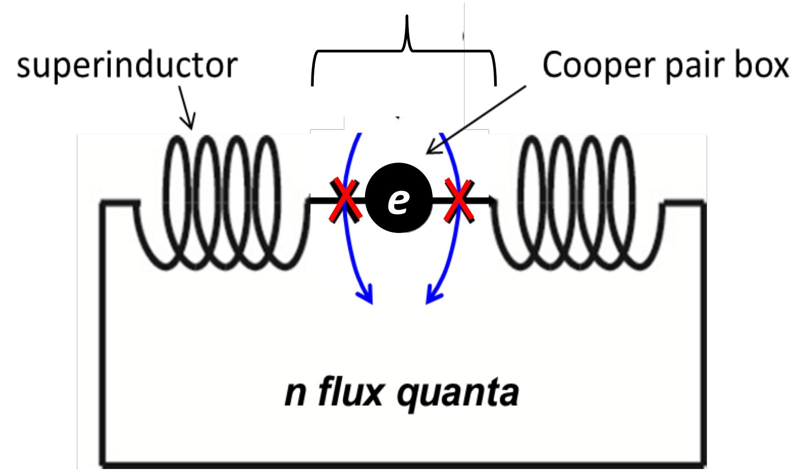


Correlated tunneling of TWO Cooper pairs

$\cos(\phi)$ **term is suppressed by destructive interference (Aharonov-Bohm phase)**

Flux Pairing

$2E_J cos(\phi/2)$



Correlated tunneling of TWO flux quanta

$\cos(\phi)$ **term is suppressed by destructive interference (Aharonov-Casher phase)**

The parity is protected by SYMMETRY

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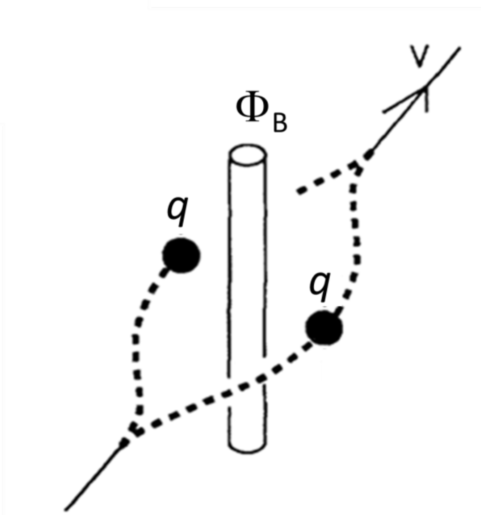
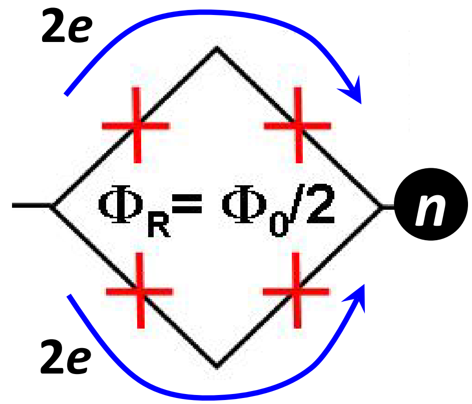
Josephson $cos(2\varphi)$ element ("Josephson "rhombus")



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

Aharonov-Bohm phase: the wave function of a charge ***q*** moving around a magnetic flux Φ_B acquires a topological phase shift

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



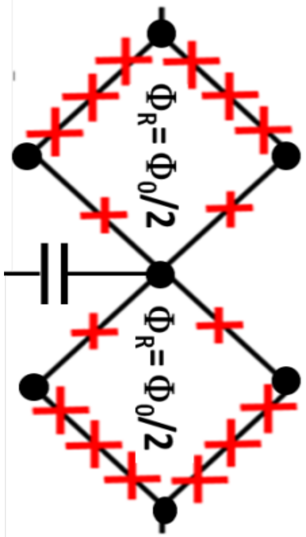
Ioffe, Doucot, Feigel'man *et. al.* (2002 – present)

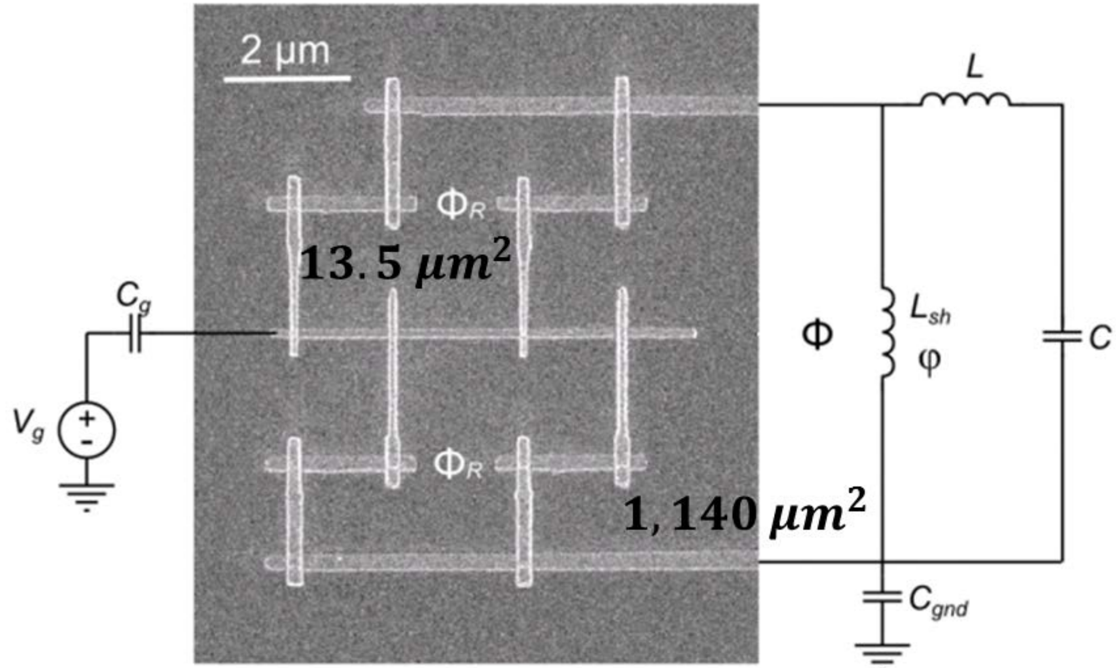
Parity protection ($k \not\to k+1$) due to destructive interference.

Correlated tunneling of **TWO** Cooper pairs

S. Gladchenko, D. Olaya, E. Dupont-Ferrier, B. Douçot, L.B. Ioffe, and MEG. *Nat. Phys.* **5**, 48 (2009).

Device and Readout

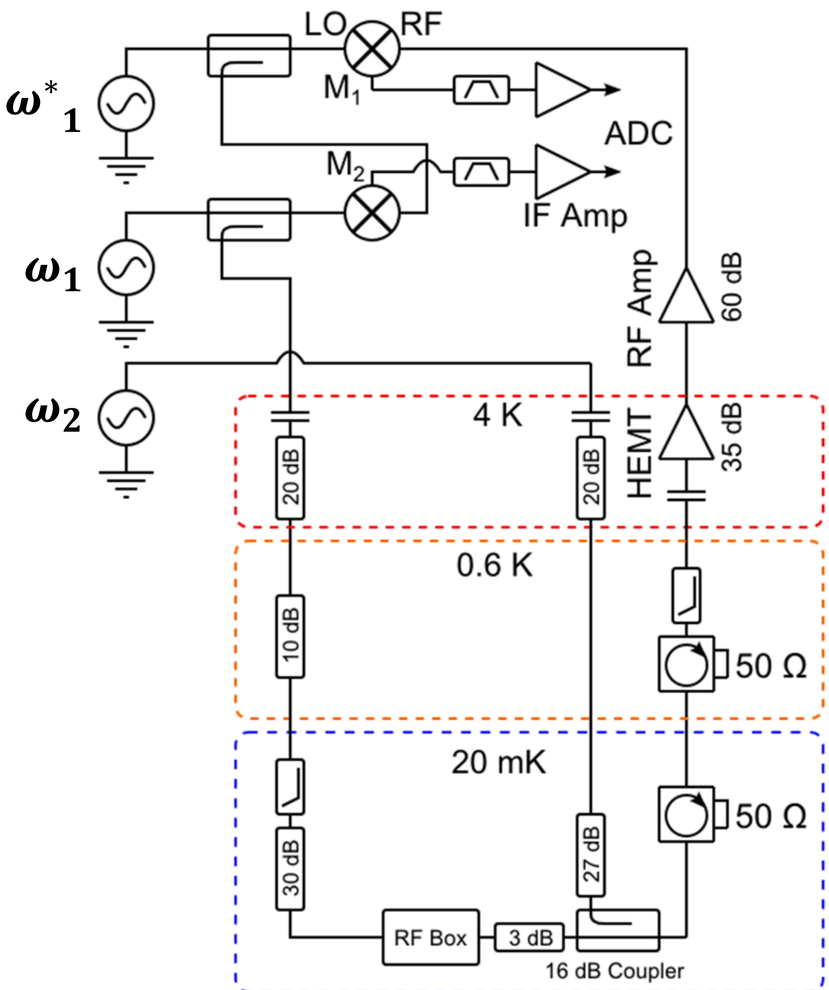


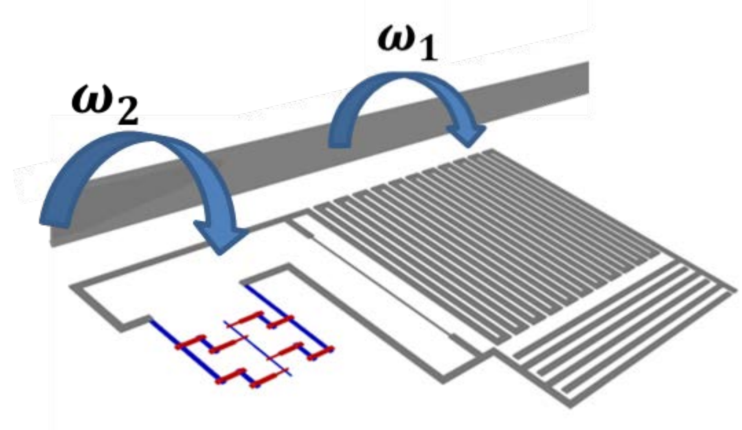


Two experimental "knobs":

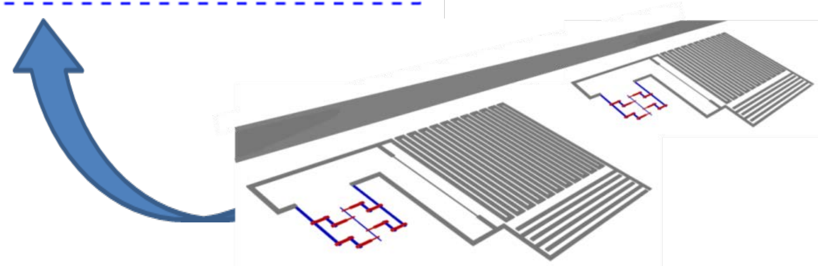
- the gate voltage controls n_g on the central island;
- the flux in the "phase" loop controls φ across the chain.

Microwave Measurements



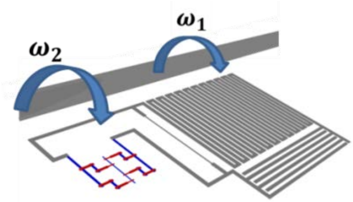


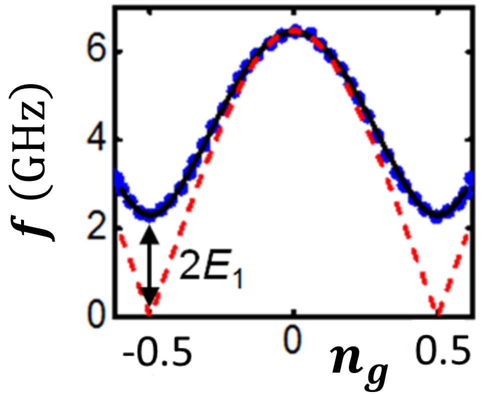
the device is coupled to the read-out *LC* resonator



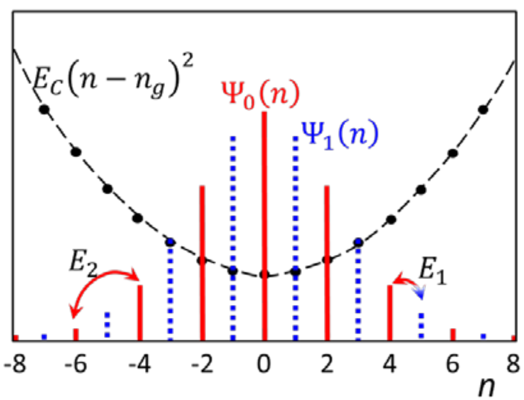
Multiplexing: several devices with systematically varied parameters.

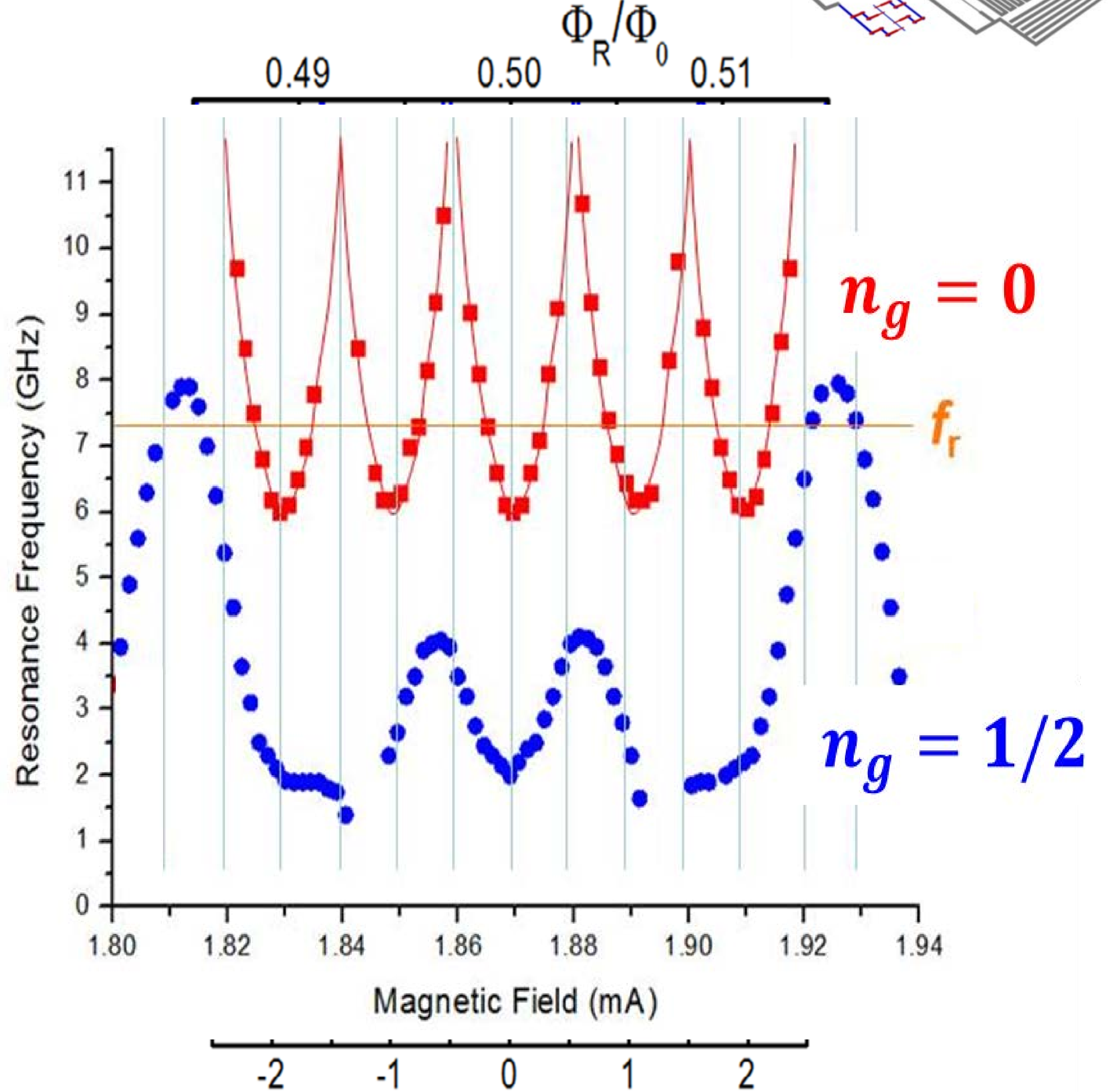
Spectroscopy





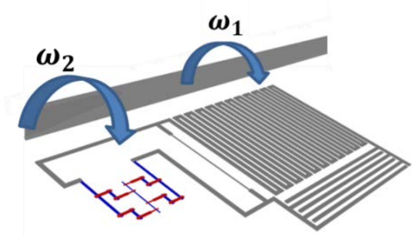
$\varphi = 0$





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

Spectroscopy

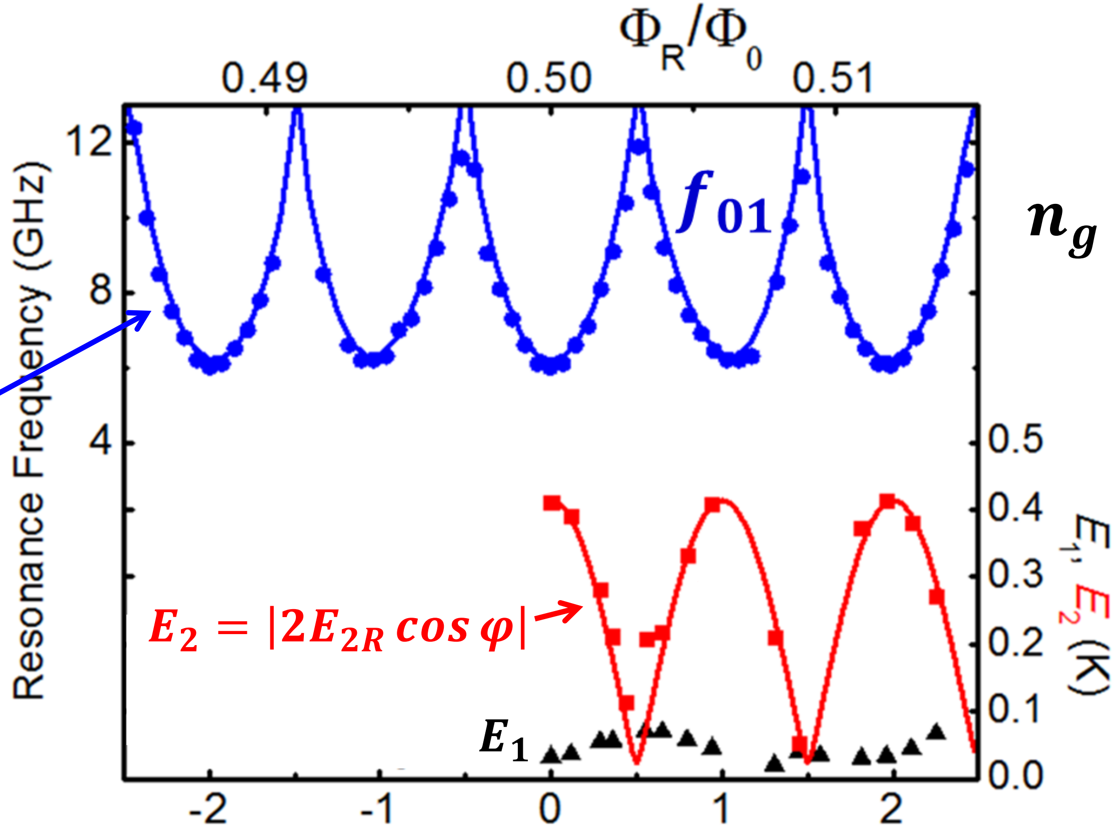


$$E_{01} \propto g^{0.5} exp(-g)\cos(\pi n_g)\omega_p$$

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

$$\omega_p = 4\sqrt{E_2 E_C}$$

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



$\boldsymbol{n_g = 0}$

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

$$\boxed{E_2(max) = 8.5GHz}$$

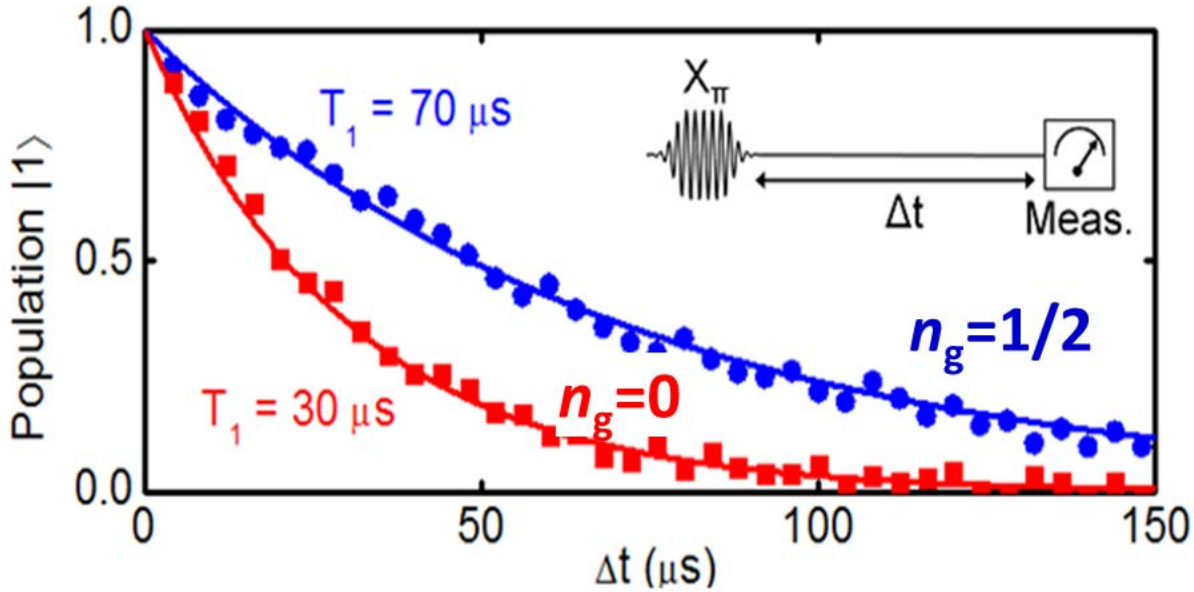
$$E_C \approx 15GHz$$

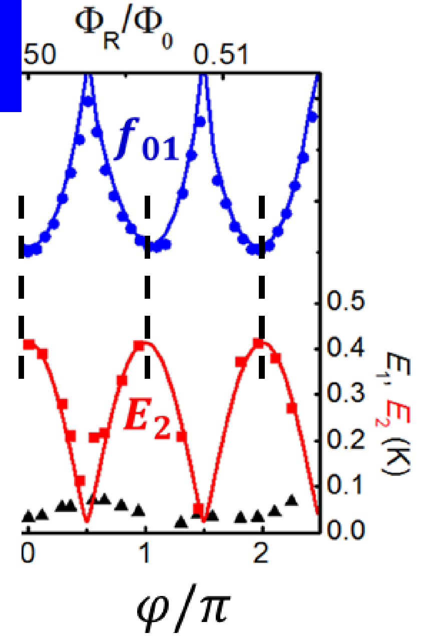
$$\boxed{E_1 = 0.75GHz}$$

Time-Domain Measurements

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

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



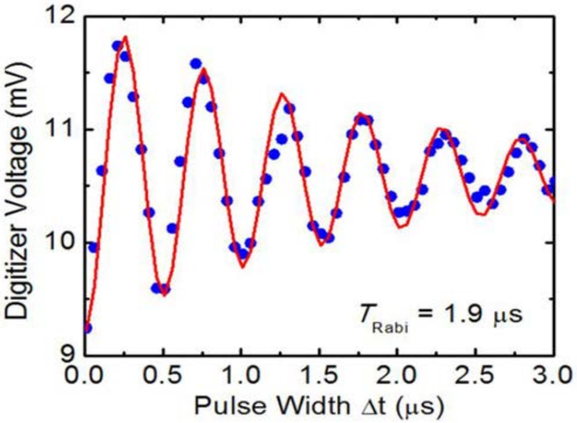


$$\boldsymbol{Q \equiv \omega_{01} T_1 \approx 1 \cdot 10^6}$$

Improvement by 2 orders of magnitude
(compared to a similar unprotected circuit)

M. Bell, J. Paramanandam, L. Ioffe, and MEG. *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 that causes fluctuations of E_1 ($E_1 \neq 0$, relatively small g).

Next steps:

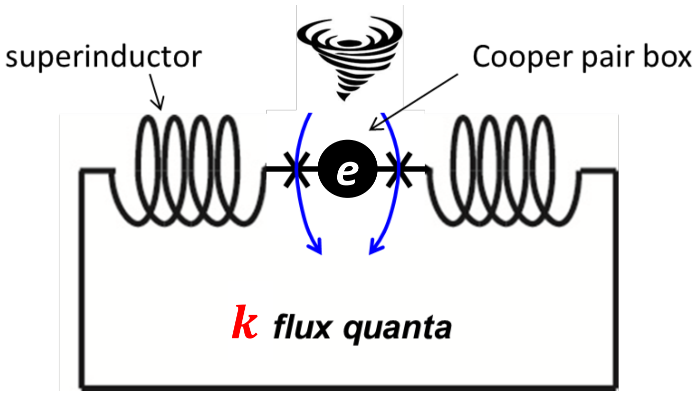
- **eliminate the asymmetry**
- **increase E_2/E_C**

Outline:

- Quantum Effects in Superconducting Circuits
- Superconducting Qubits
- Parity-Protected Josephson Circuits
  - Charge-pairing devices
  - **Fluxon-pairing devices**

Flux-Pairing Qubit [Josephson $cos(\varphi/2)$ element]

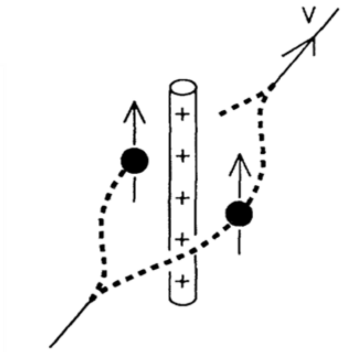
Ioffe, Doucot 2012



Discrete variable: $2\pi k$

Parity protection ($k \not\to k+1$) due to destructive interference.

Correlated tunneling of TWO fluxons



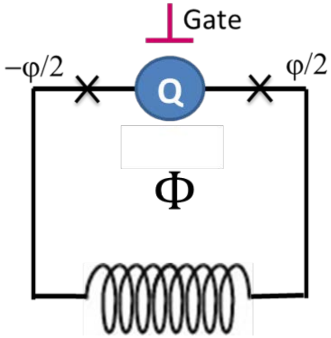
Y. Aharonov & A. Casher, *PRL* 53, 319 (1984)

***Aharonov-Casher phase*: the wave function of a magnetic dipole μ moving around a line charge acquires a topological phase shift proportional to the line charge density**

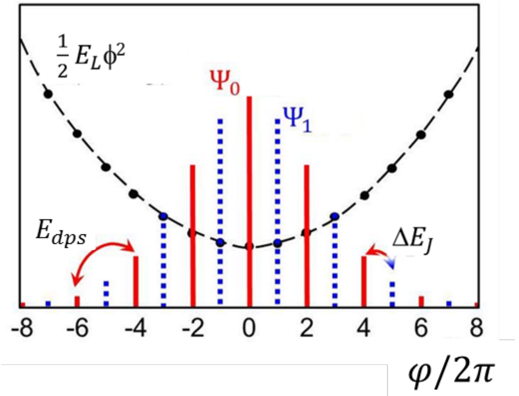
$$\Delta\varphi_{AC} = \frac{1}{\hbar c^2}\oint [\mu \times E] \cdot dl$$

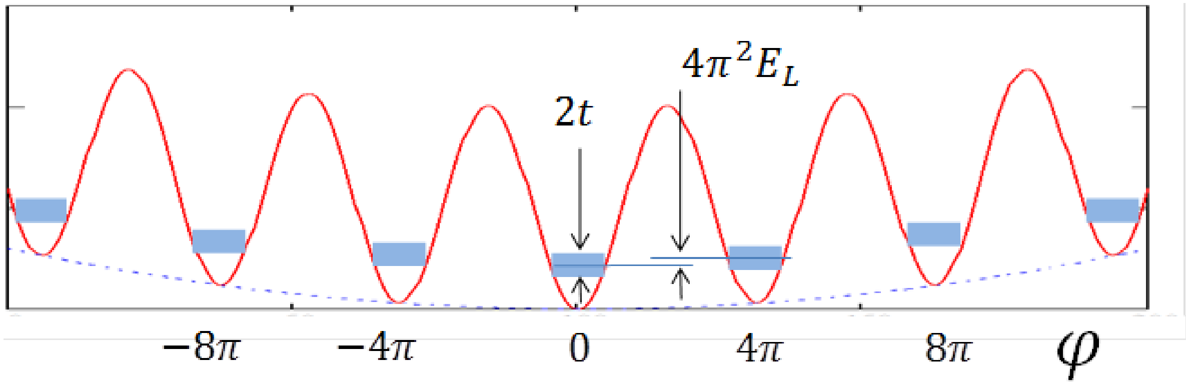
$$= \frac{1}{\hbar}\oint (\mu \cdot B)_{part} dt$$

Flux-Pairing Qubits



$$H = -E_J \cos\left(\frac{\varphi}{2}\right)\sigma^x + 4E_{CL}q^2 + \frac{1}{2}E_L\left(\varphi - 2\pi\frac{\Phi}{\Phi_0}\right)^2 \qquad E_L = \left(\frac{\Phi_0}{2\pi}\right)^2\frac{1}{L}$$





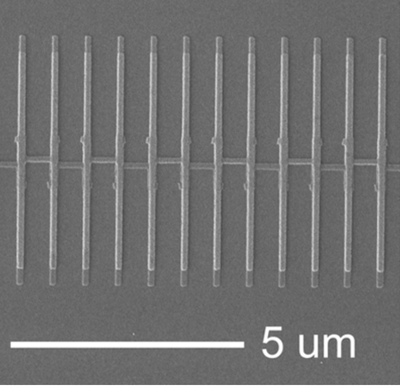
Large quantum fluctuations of phase ($\langle n^2\rangle \gg 1$): $\boxed{E_{dps} \gg 4\pi^2 E_L}$

Implementation of the fault tolerant flux-pairing qubit:

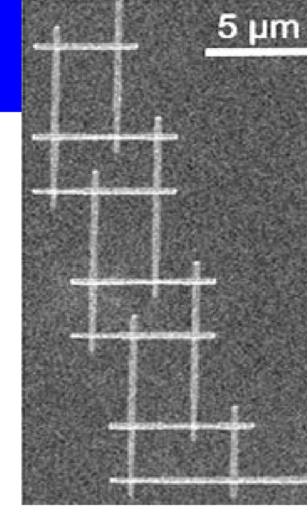
1. Superinductance $(\sim 3 - 10\ \mu\text{H})$
2. High rate of double phase slips ($\frac{E_J}{E_C} \leq 0.2$)

Fluxonium:

$L = 0.3\mu H$



Superinductor



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

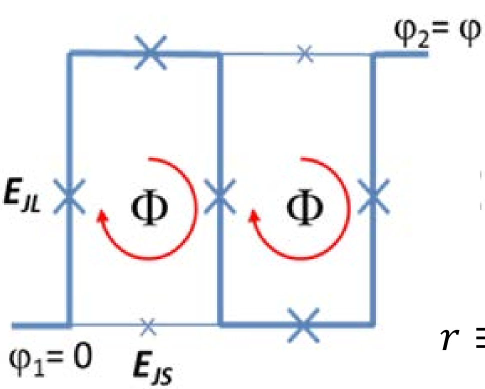
No dissipation and dephasing

Chain of junctions with $\frac{E_J}{E_C} \gg 1: \quad \boldsymbol{L = 0.3\mu H}$

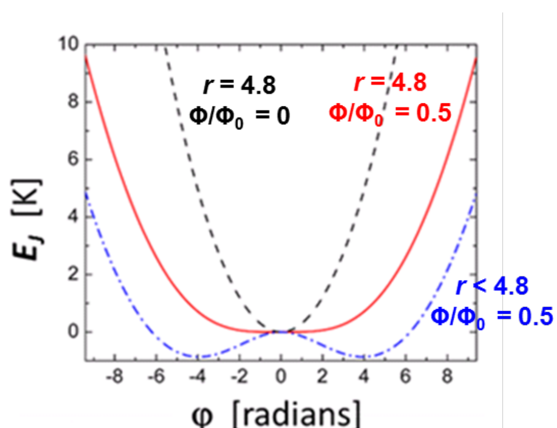
V. E. Manucharyan, J. Koch, L. Glazman, M. H. Devoret. Science 326, 113 (2009).

Chain of asymmetric SQUIDs : $\boldsymbol{L(\Phi = \Phi_0/2) = 3\mu H}$

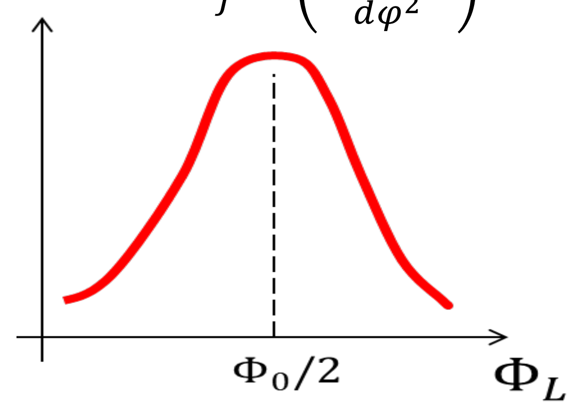
M. Bell, I. Sadovskyy, L. Ioffe, A. Kitaev, and MEG. ***PRL*** **109, 137003 (2012).**



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

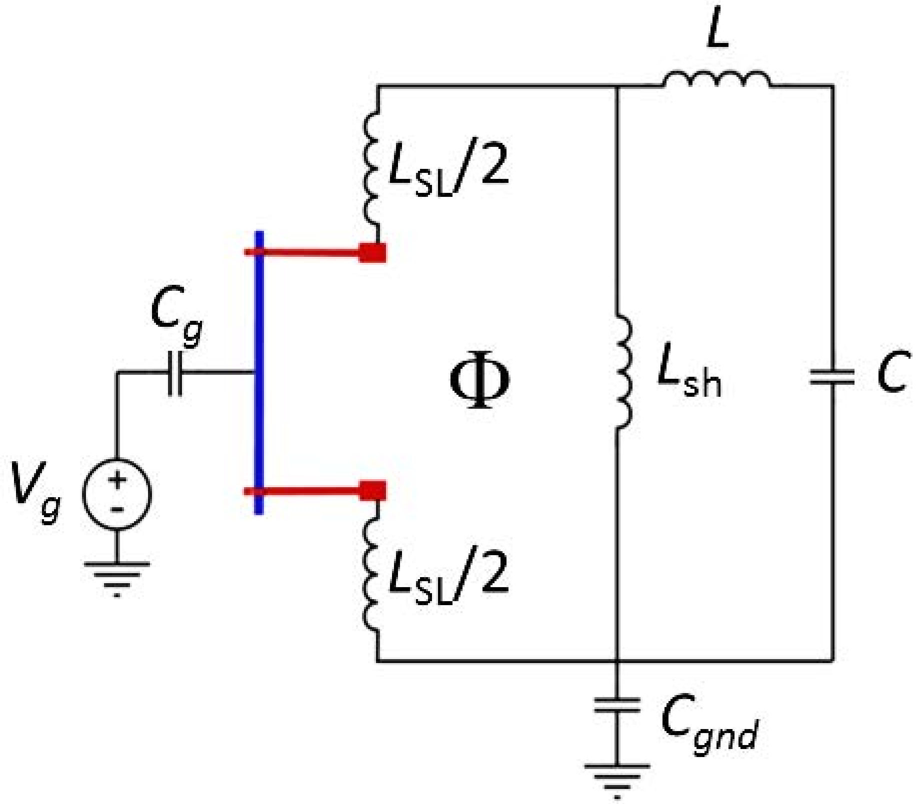


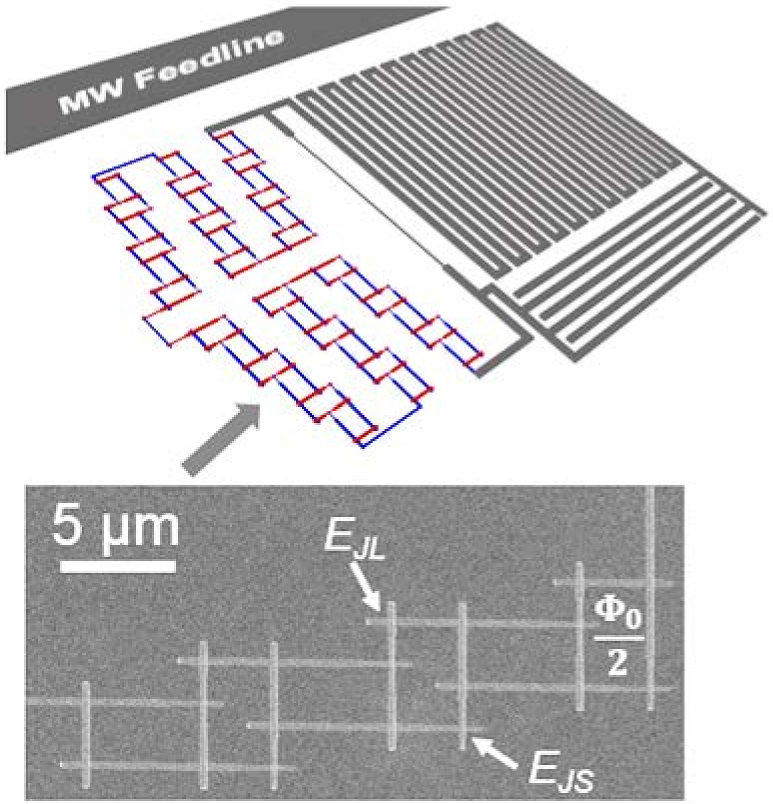
$$L_J \propto \left(\frac{d^2 E_J(\varphi)}{d\varphi^2}\right)^{-1}$$

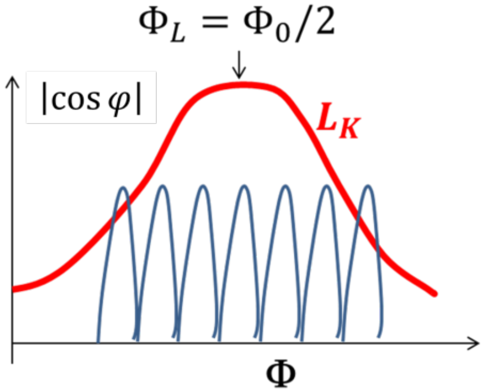


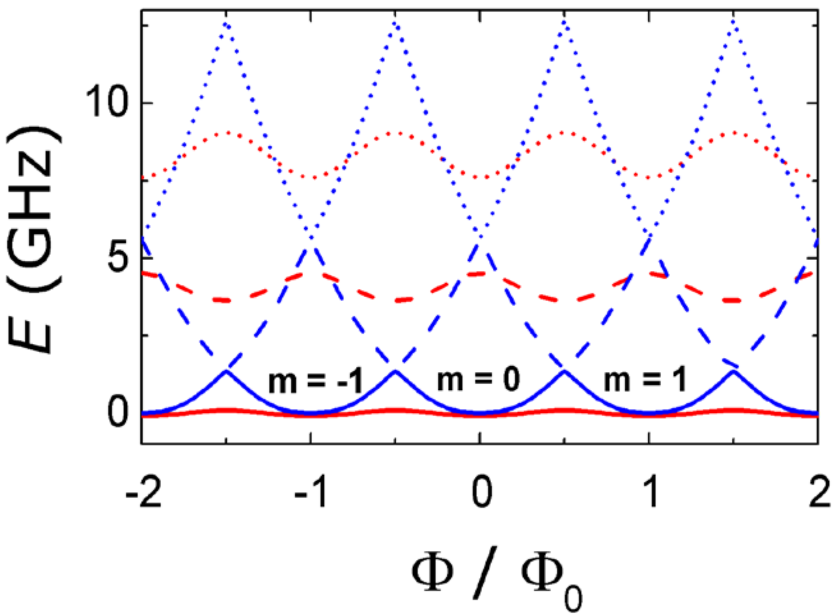
Specific to our design: ***tunable inductance and non-linearity.***

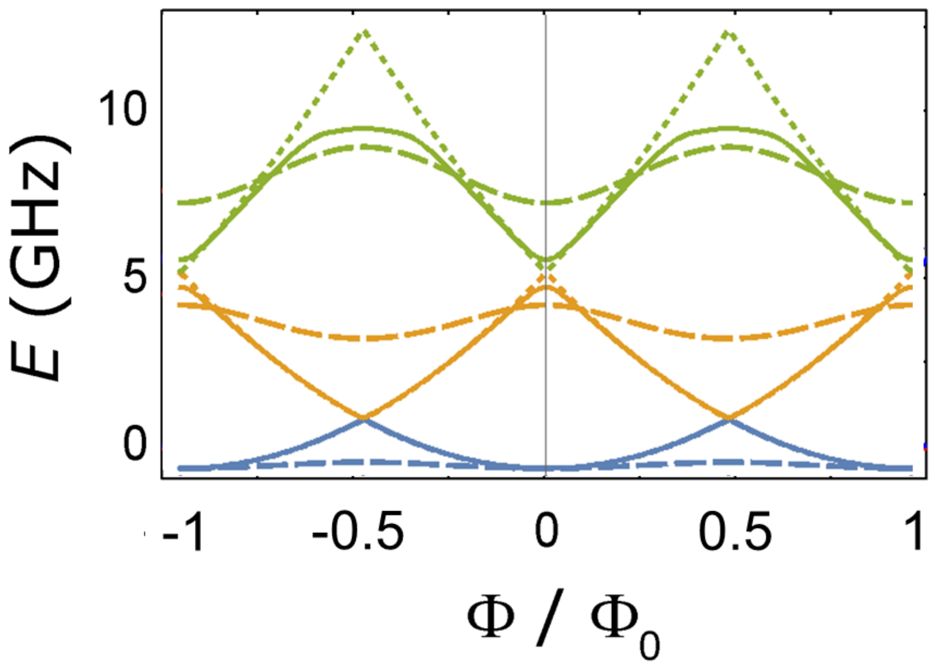
CPB + Superinductor



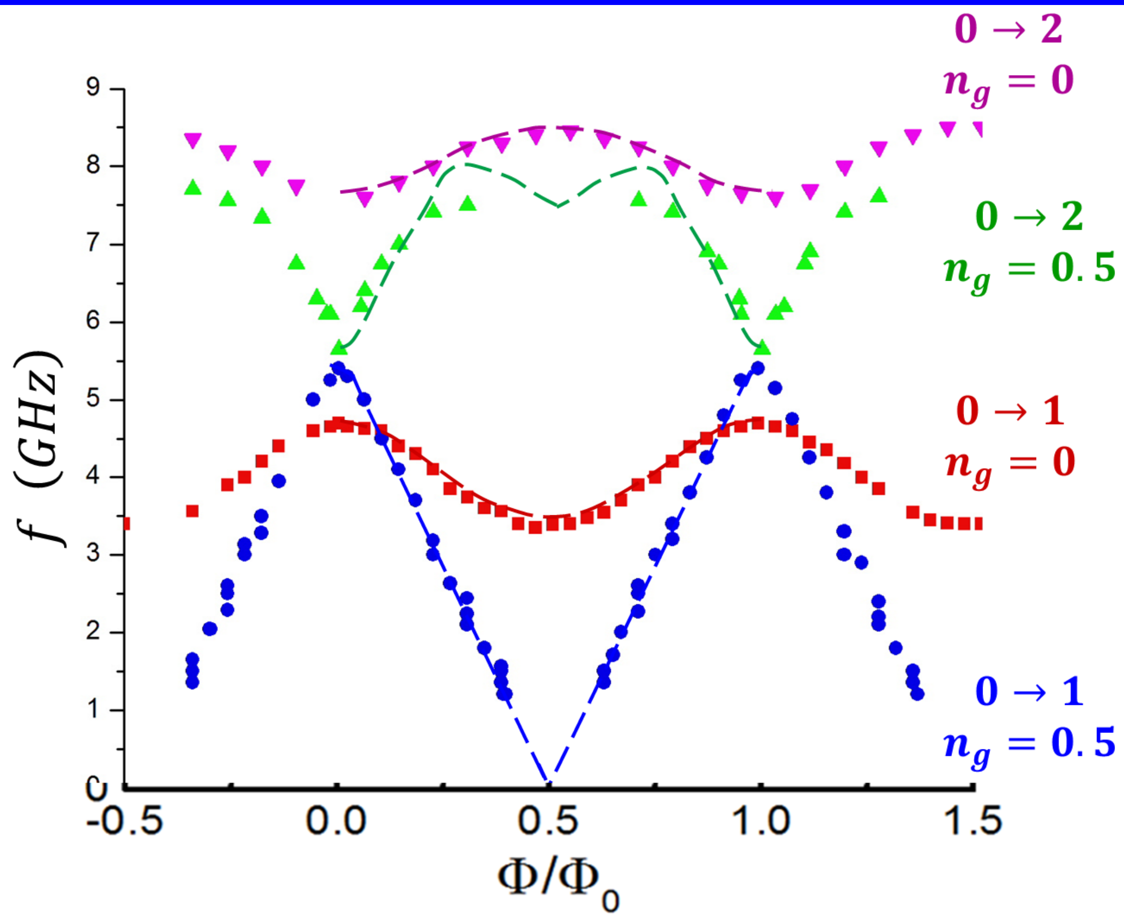





10
5
0
E (GHz)
m = -1
m = 0
m = 1
-2
-1
0
1
2
Φ / Φ0


10
5
0
E (GHz)
-1
-0.5
0
0.5
1
Φ / Φ0

Spectroscopic Evidence of Aharonov-Casher Effect



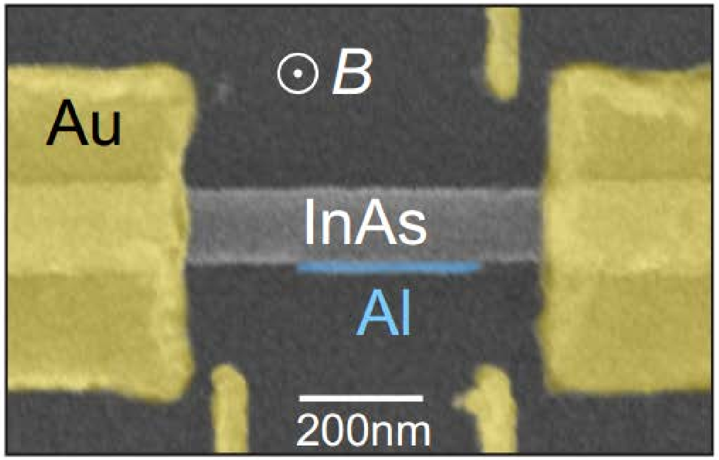
M.T. Bell, W.Zhang, L.B. Ioffe, MEG. arXiv:1504.05602

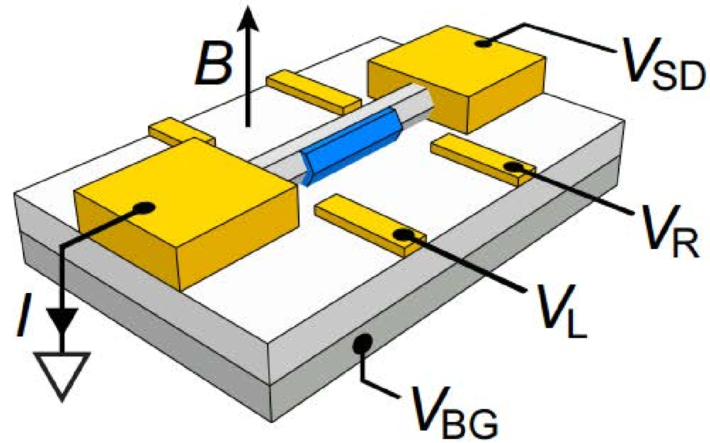
Linear dependence $E_{01}(\Phi)$ at n_g = 0.5 (complete suppression of single and double phase slips):

- identical small junctions

- clear spectroscopic evidence of Aharonov-Casher effect

Marcus' Lab (Copenhagen)





Fine tuning of E_J: symmetry protection

Fast (1 ns) switching: fault-tolerant operations

Summary

- **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:**
  - improvement of coherence in rhombi chains (larger E_J/E_C) ;
  - optimization of the parameters of the flux-pairing qubits (smaller E_L and larger E_{dps}).