Superinductors and Superinductor-Based Qubits

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Lev Gor'kov Memorial Conference, June 25,2019

40 years ago:

D.E. Khmelnitskii and L.P. Gor’kov
AbrahamsFest @ Rutgers 2007

A.I. Larkin
@ Weizmann
1993

L.P. Gor'kov, A.I. Larkin, D.E. Khmelnitskii
PARTICLE CONDUCTIVITY IN A TWO-DIMENSIONAL RANDOM POTENTIAL.
JETP Letters 30, 228 (1979)

Outline

Fast forward to superconductor-based quantum computing:

- **State-of-the-art superconducting qubits**
- **Superinductors and Superinductor-based qubits**

Qubit Performance: Two Main Parameters

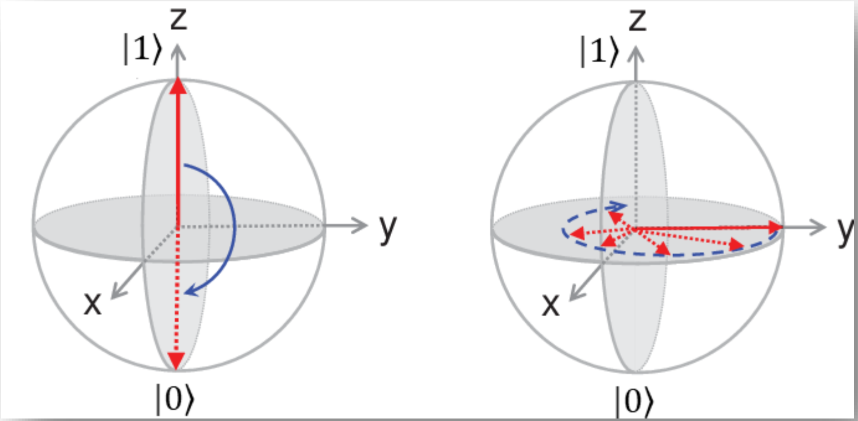
Low error rate: $\varepsilon \equiv \frac{t_g}{t_C}$

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

$t_C = min(T_1, T_\varphi)$ - the coherence time

T_1 – the relaxation time

Spontaneous decay, coupling to high-frequency noises with $\omega \sim \omega_0$



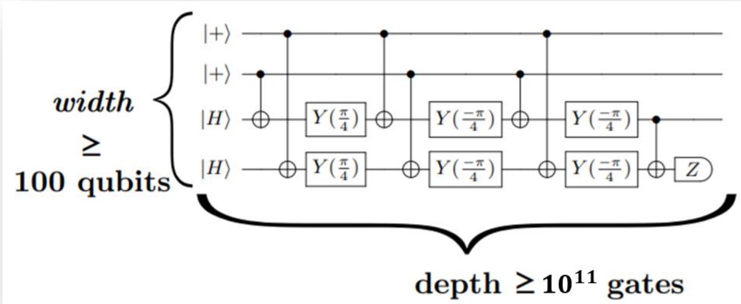
T_φ - the dephasing time

Random walk of the phase due to low-frequency fluctuations of E_{01}

Short gate time: t_g - requires strong non-linearity $t_g > \frac{h}{\delta}$ $\delta \equiv E_{21} - E_{10}$

In superconducting qubits, the non-linearity is provided by **Josephson junctions**.

Universal Digital QC: "Logical – Physical" Gap



The depth required for Shor's algorithm $\sim 10^{11}$ gates –
the error rate of a logical qubit should be $< 10^{-11}$.

Logical qubit

$\varepsilon \sim 10^{-11}$

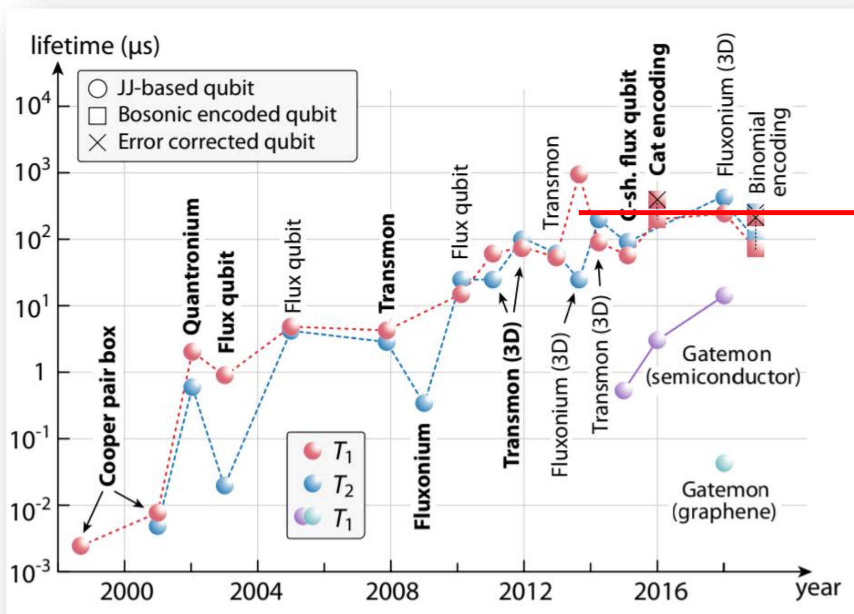
Error corrections

Physical qubit

$\varepsilon \sim 10^{-4}$

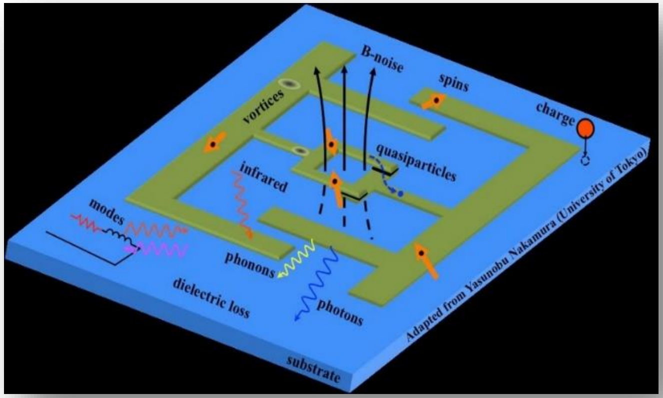
(much higher for two-qubit gates in multi-qubit circuits)

Superconducting qubits



Insignificant progress over the past 5 years

M. Kjaergaard et al., arXiv:1905.13641



Noises in Superconducting Qubits

$$\hat{H} = \frac{E_C}{2}(\hat{n} - n_g)^2 - \frac{E_J}{2}\cos\varphi + \frac{E_L}{2}(\phi - 2\pi\Phi_{ext}/\Phi_0)^2$$

$$E_C = \frac{e^2}{2C} \qquad E_J = \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{1}{L_J} \qquad E_L = \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{1}{L}$$

$$E_{01} = E_{01}(E_J, E_C, n_g, \Phi, \dots.)$$

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

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

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

High-f noises: relaxation

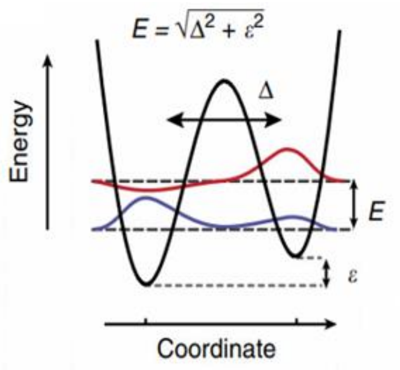
Low-f noises: dephasing

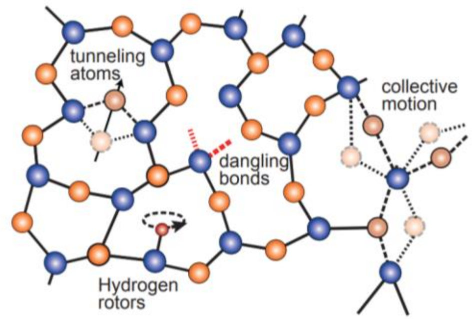
Main source of fluctuations:

two-level systems (TLS) in the qubit environment

which remain active even at mK temperatures!

Two Level Systems

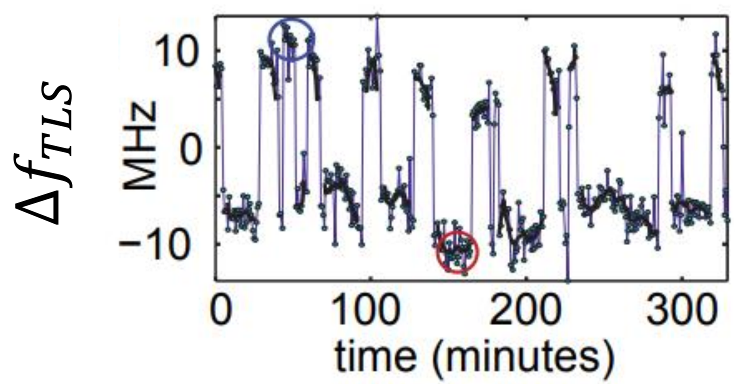


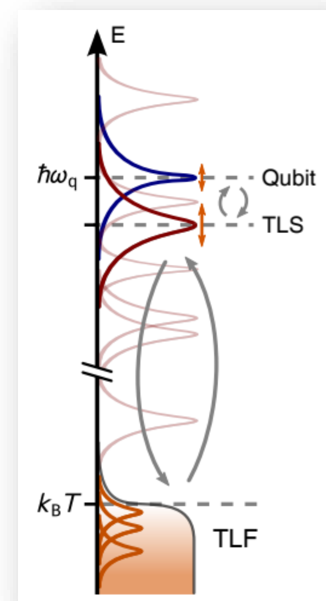


Microscopic sources of TLS remain elusive.

TLS → ***Two-Level Fluctuators*** $E \leq k_B T$ ($1/f$ noise, decoherence)

TLS → ***Coherent TLS*** $E \gg k_B T$ (resonance coupling to qubits)



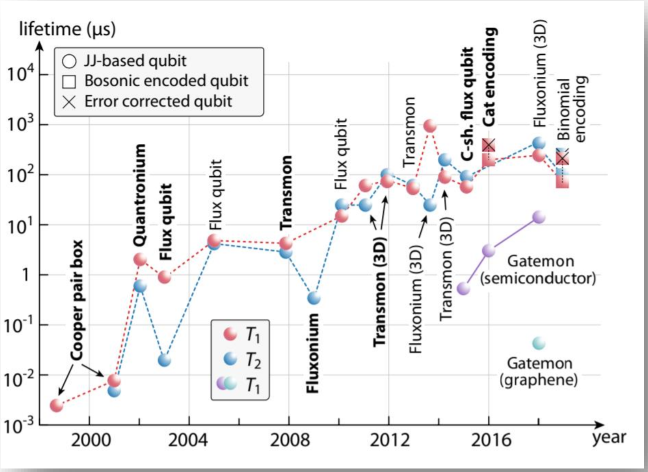


Dipole-dipole interactions

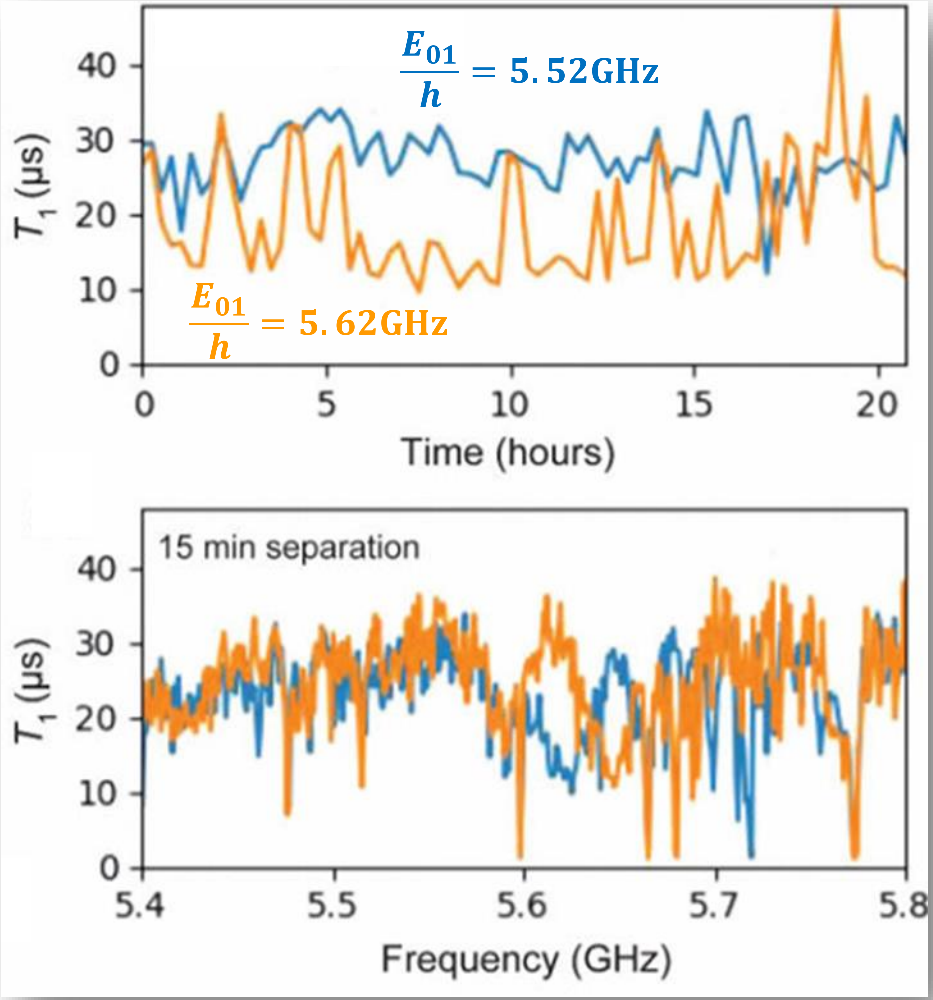
"Telegraph" noise in the resonance frequency of a coherent TLS due to interactions with two-level fluctuators.

C. Müller, J.H. Cole, J. Lisenfeld. **arXiv:1705.01108**

Best vs. Typical



Best

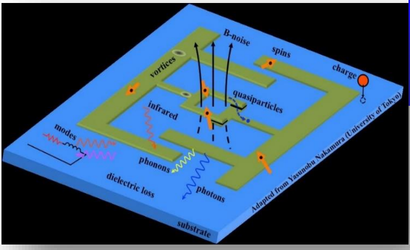


Typical

For many-qubit circuits,

the ***smallest*** $T1$ matters!

P. Klimov *et al.*, *PRL* **121**, 090502 (2018)



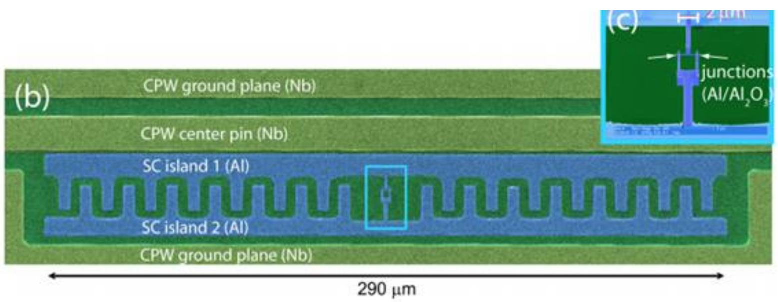
Coherence Improvement

$$\Gamma_1^{\lambda} \sim \langle 0|\hat{\lambda}|1\rangle^2 S_{\lambda}(\omega_{01}) \qquad \Gamma_2^{\lambda} \sim \left(\frac{\partial \omega_{01}}{\partial \lambda}\right)^2 S_{\lambda}(0)$$

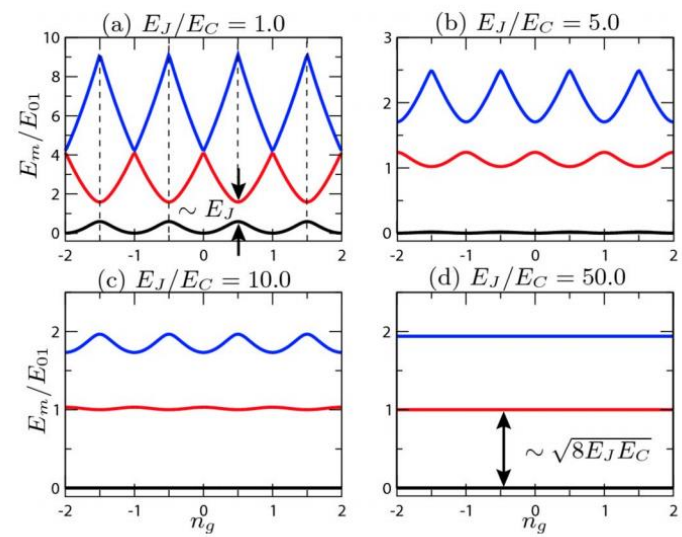
Recipe: (a) reduce noises, (b) increase quantum fluctuations of λ (by reducing E_{λ}),

(c) reduce matrix elements $\langle 0|\hat{\lambda}|1\rangle$.

Transmon (Yale, 2007)



Large shunt capacitor in parallel with the JJ reduces E_C.



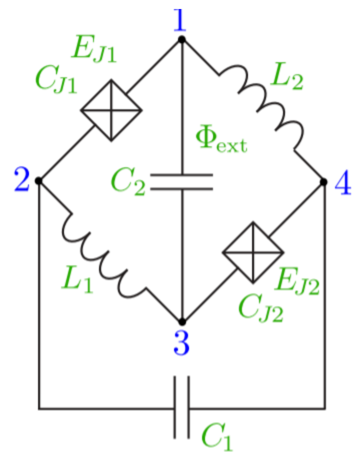
Large E_J/E_C:
- sensitivity to the charge noise drops exponentially,
- the anharmonicity decreases algebraically.

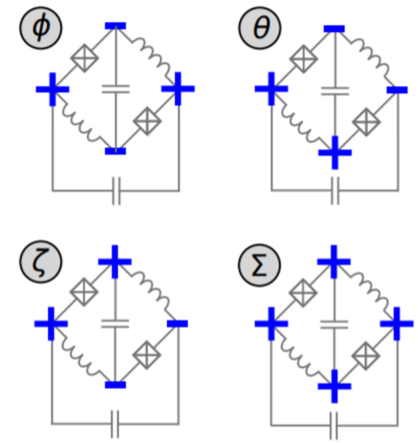
A qubit with **more than one** effective degrees of freedom may offer more robust quantum states.

Theoretical Proposals: Protected “0 - π” Qubit

A. Kitaev et al.

degenerate logical states
with exponentially small overlap





Quantum information is encoded in two near-degenerate logical states.

Suppression of relaxation and dephasing due to exponentially small overlap of logical wave functions and very low flux and charge dispersion.

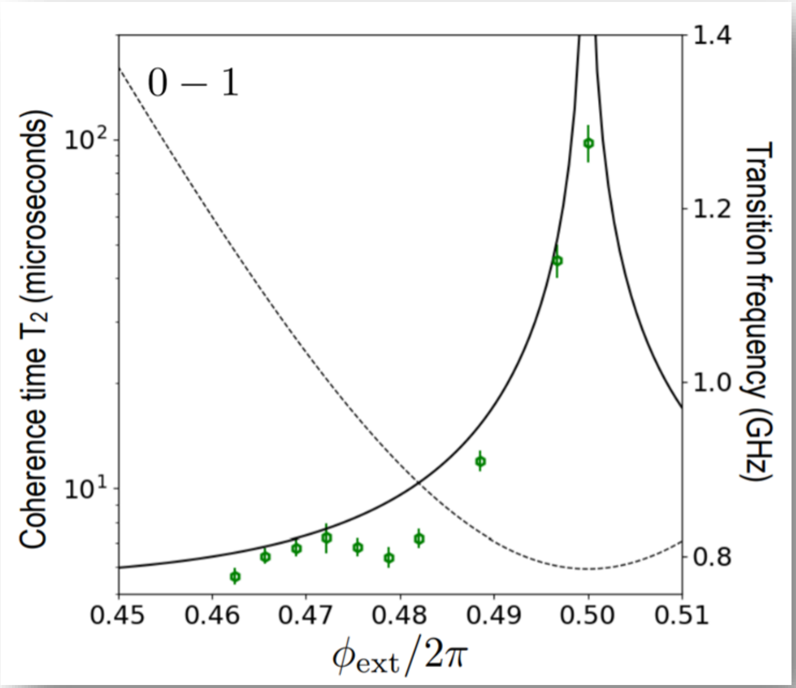
The fully protected regime exploits a degree of freedom with large quantum fluctuations. This requires an impedance $Z \gg R_Q$.

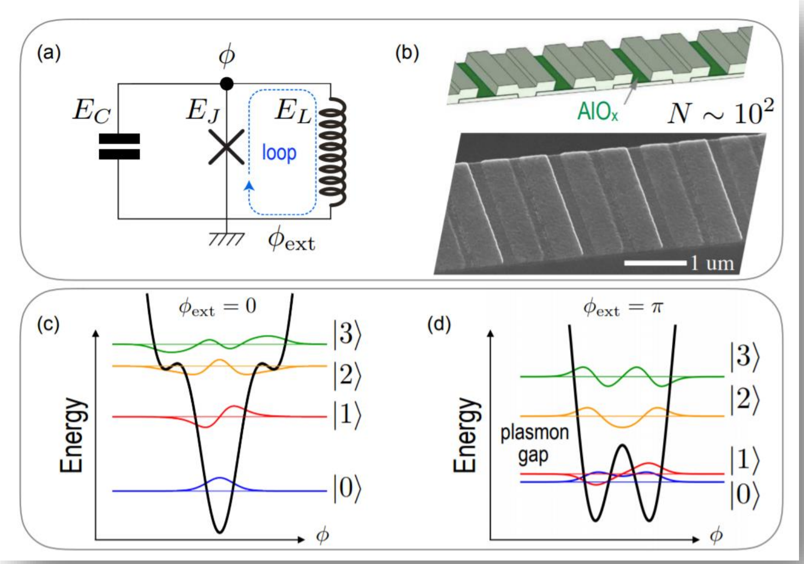
$$E_L = \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{1}{L} \qquad \frac{E_L}{h} \sim 0.01 GHz \qquad L \sim 10 \mu H \ \textbf{(!)}$$

P. Groszkowski *et al., New J. Phys*. **20** (2018)

"Heavy" Fluxonium

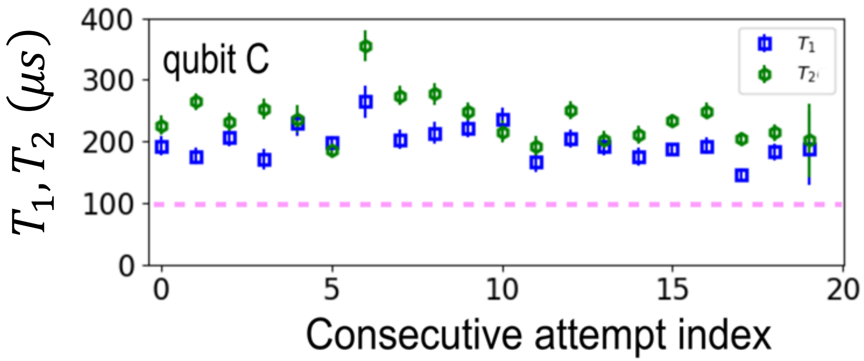
V. Manucharyan et al.





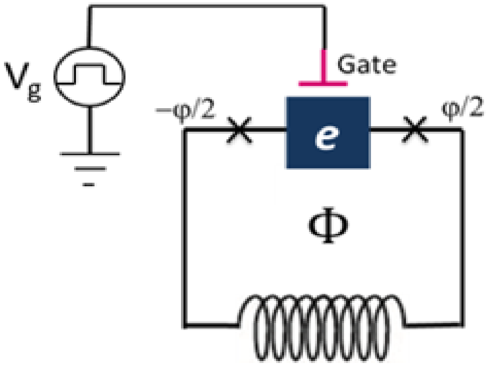
$L \sim (0.1 - 0.2)\mu H$

The effective loss tangent of the inductance must be in the 10^{-8} range in order to reach the coherence times reported in this experiment.



L.B. Nguyen *et al.,* arXiv: 1810.11006 (2018)

Tunable Parity-Protected Qubits



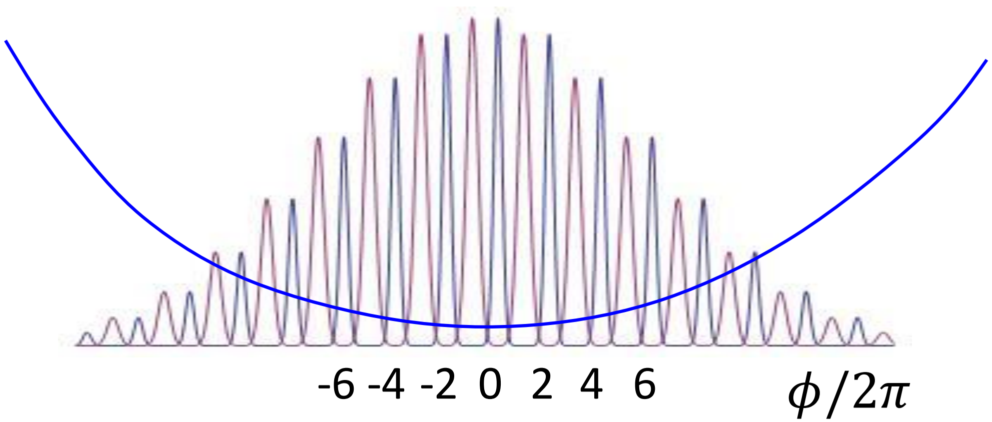
Lev Ioffe et al.

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

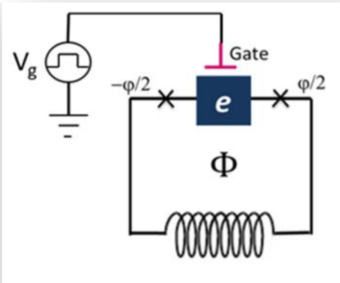
Decay is suppressed exponentially if parity is protected.

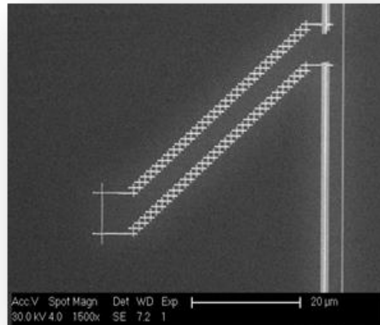
Fast tunability (at an expense of T_2 reduction). T_1 is large, which significantly simplifies the problem of error corrections.

$$q = e \qquad V_{\pm} = \frac{1}{2} E_L (\phi - \phi_{ext})^2 \pm E_J \cos\left(\frac{\phi}{2}\right)$$

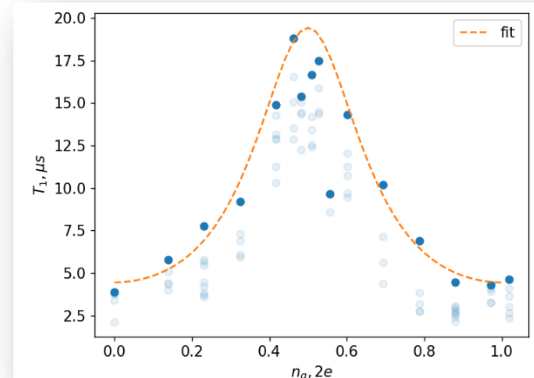


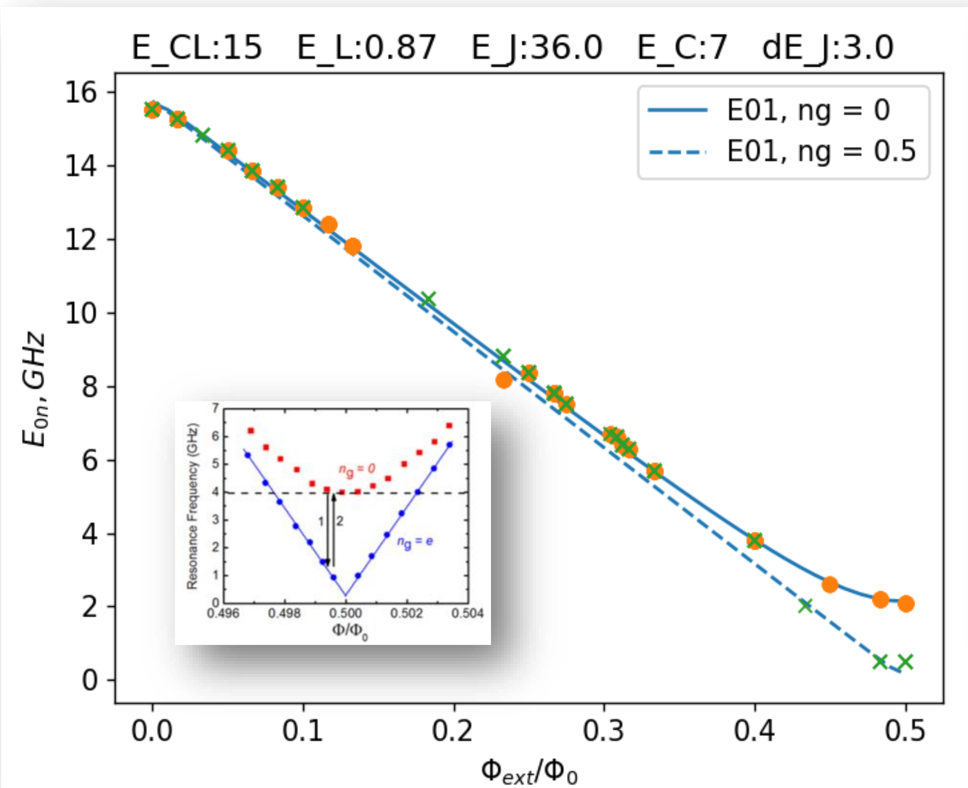
Fluxon-Parity-Protected Qubits

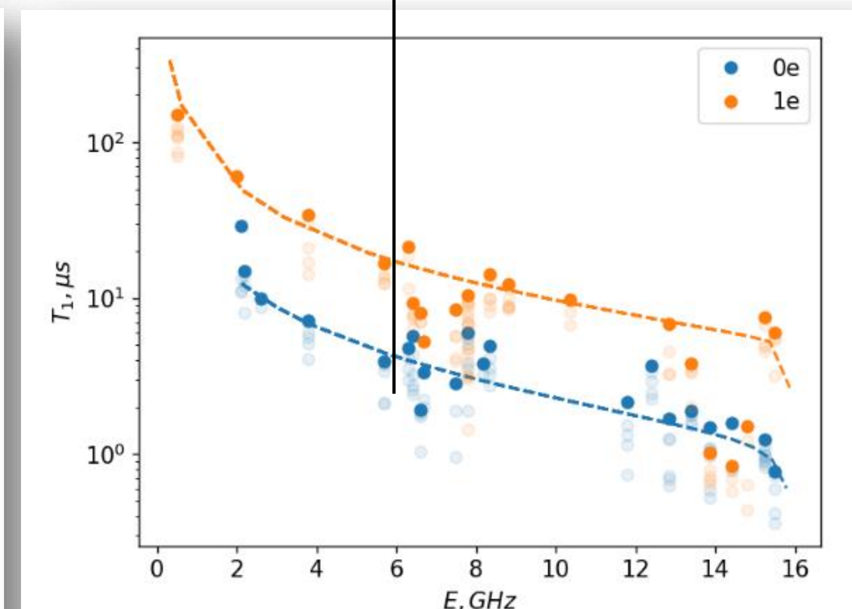




M. Bell *et al.,* (2019)





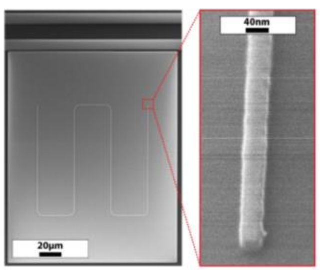


Implementation of Superinductors

non-dissipative (superconducting) elements with large inductance and small stray capacitance, such that the impedance $Z = \sqrt{L/C} \gg R_Q \equiv \frac{h}{(2e)^2} \approx 6.5k\Omega$.

Z of conventional "geometric" inductors is limited by the "vacuum" impedance $Z_0 = \sqrt{\mu_0/\varepsilon_0} = 377\Omega \ll R_Q$.

Solution: to use the kinetic inductance L_K of superconductors



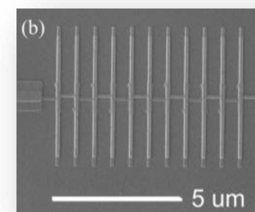
NbN
D. Niepce et al., arXiv: 1802.01723

ultra-narrow wires of disordered superconductors

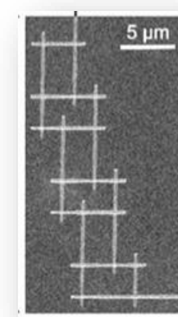
$$L_K = \frac{1}{W} \cdot \frac{\hbar R_{N\square}}{\pi\, \Delta}$$

Josephson arrays with small stray capacitance

$$L_J = \frac{\hbar R_N}{\pi\, \Delta}$$



*Manucharyan et at., Science **326**, 113 (2009)*
*Masluk et al., PRL **109**, 137002 (2012)*



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

$$R_{N\square} = 1\ k\Omega \quad \rightarrow \quad L_{K\square} \sim 1\ nH$$

Limitations

ultra-narrow wires of disordered superconductors

$$L_K = \frac{1}{W} \cdot \frac{\hbar R_{N\square}}{\pi\,\Delta}$$

***Upper limit on $R_{N\square}$*:**

disorder-driven SIT

Josephson arrays with small stray capacitance

$$L_J = \frac{\hbar R_N}{\pi\,\Delta}$$

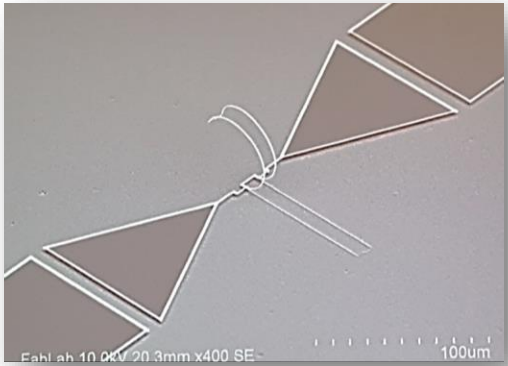
***Upper limit on R_N*:**

high rate of quantum phase slips

$$\propto exp\left(-\sqrt{\frac{E_J}{E_C}}\right) \propto exp\left(-\sqrt{\frac{\alpha}{R_N}}\right).$$

***Upper limit on Z*:**

stray capacitances



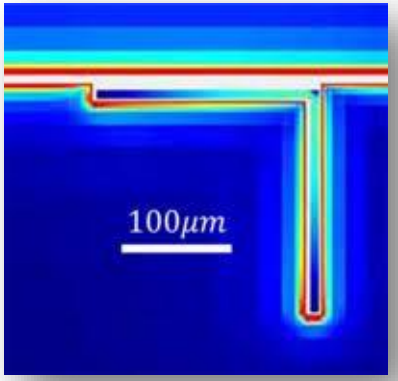
Manucharyan et al., 2018

High - L_K Superinductors

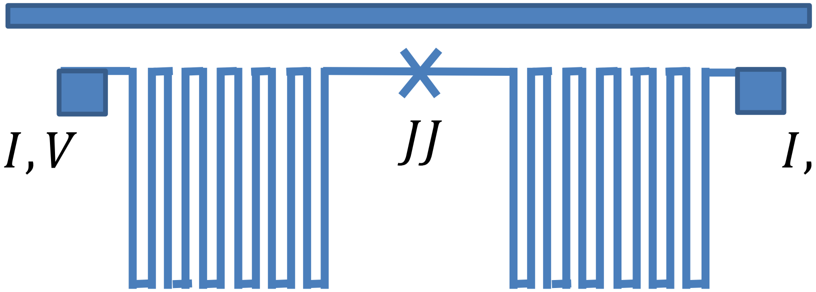
Granular Al films deposited by magnetron sputtering of pure Al in $Ar + O_2$ atmosphere.

Two main issues:

- losses near SIT
- minimization of stray capacitance

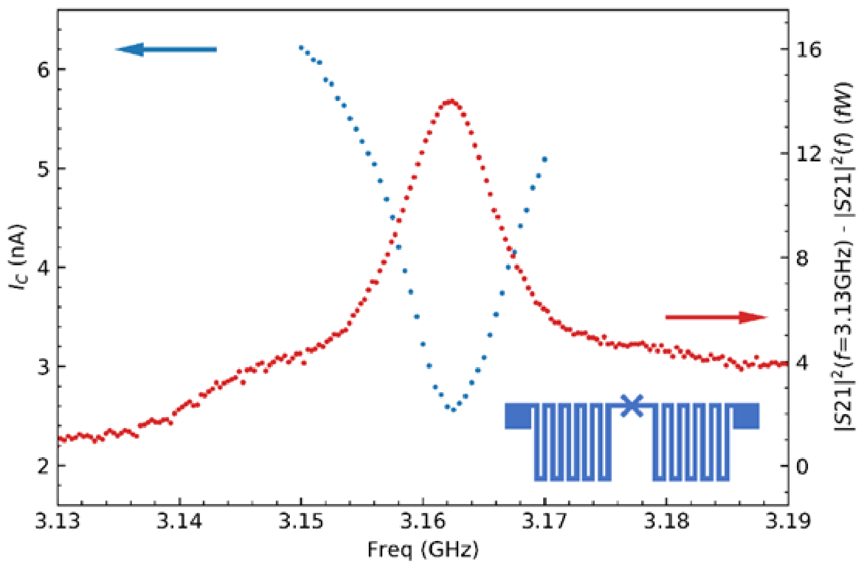


Half-λ microwave resonators



JJ as an indicator of MW currents

Meandered Nanowires

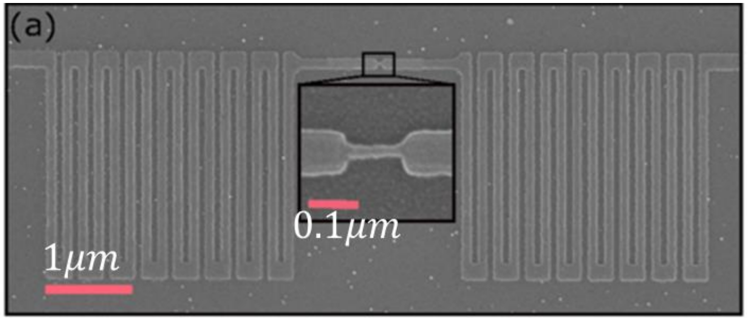


W.-S. Lu et al., to be published

Meandered nanowires $20 \times 20\mu m^2$

Device	***type***	f_r *GHz*	f_r^{sim} *GHz*	Z *kΩ*
1	junction+ meanders	3.30	3.46	27.5
2	junction+ meanders	3.16	3.78	22.9
3	CPB+ meanders	12.6	13.8	10.1

Total L up to $2\mu H$, good agreement with simulations based on the Mattis-Bardeen theory.



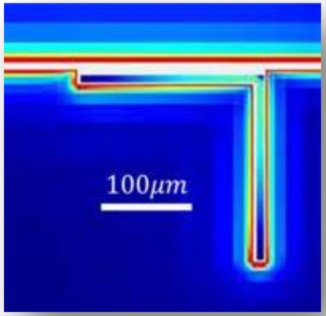
S. de Graaf et al., Phys. Rev. B **99**, 205115 (2019)

TiN nanowires

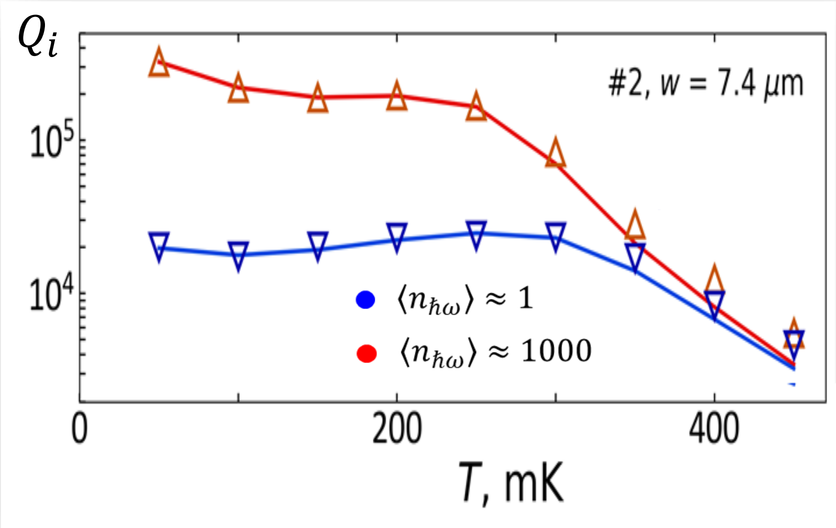
$$W = 0.1\mu m, R_\square = 3\text{k}\Omega, L_K \approx 2\mu H$$

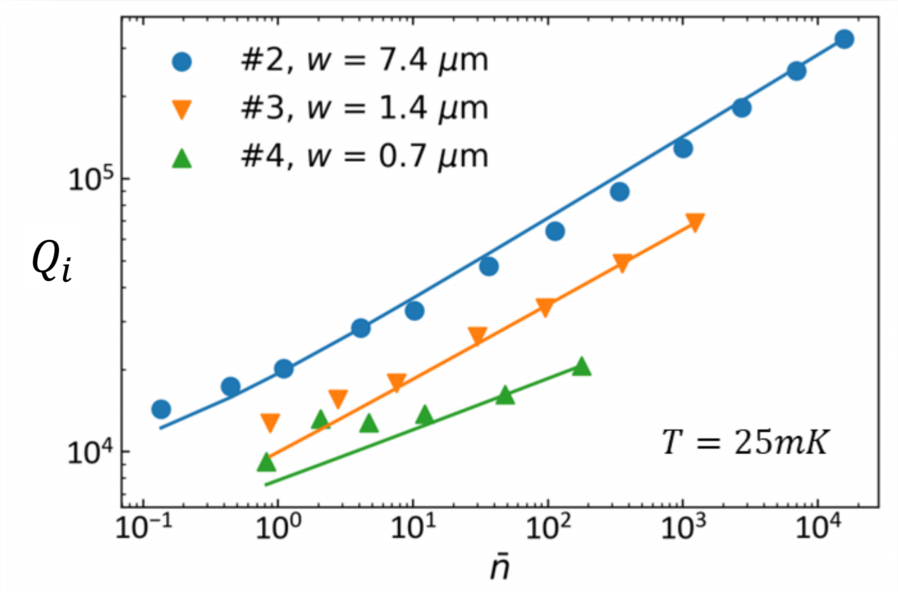
$Z \sim 200\text{k}\Omega$ (!)

Microresonators fabricated from $AlOx$ films



Half-λ CPW microresonators ($c^* \sim \frac{c}{100}$, $\frac{\lambda}{2} \approx 200\ \mu m$ at $f_r = 5GHz$) with impedance up to 5 $k\Omega$.

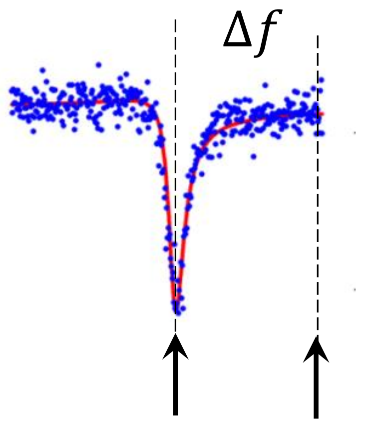


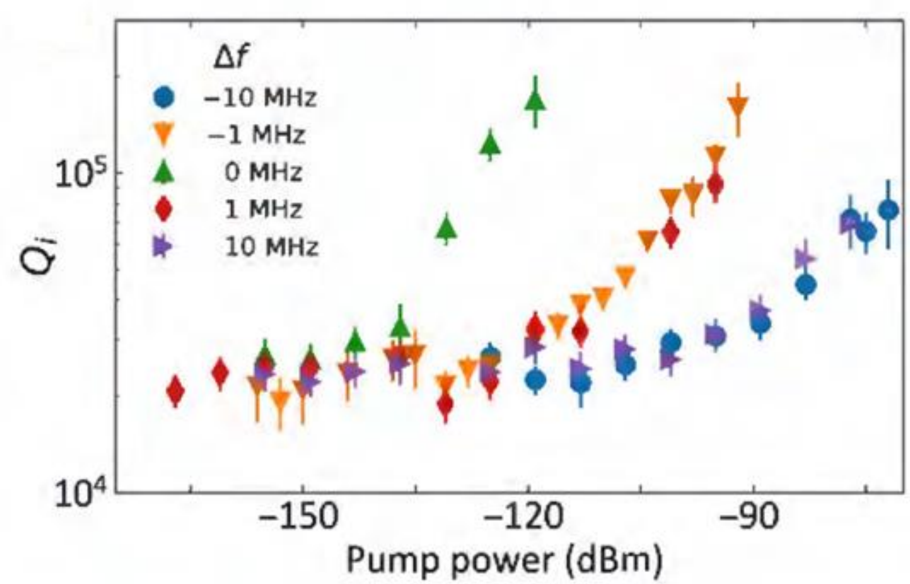


The resonator intrinsic losses at $T < 0.3K$ are determined by coupling to the TLS in the environment.

W. Zhang *et al.*, *Phys. Rev. Appl.* **11**, 011003 (2019)

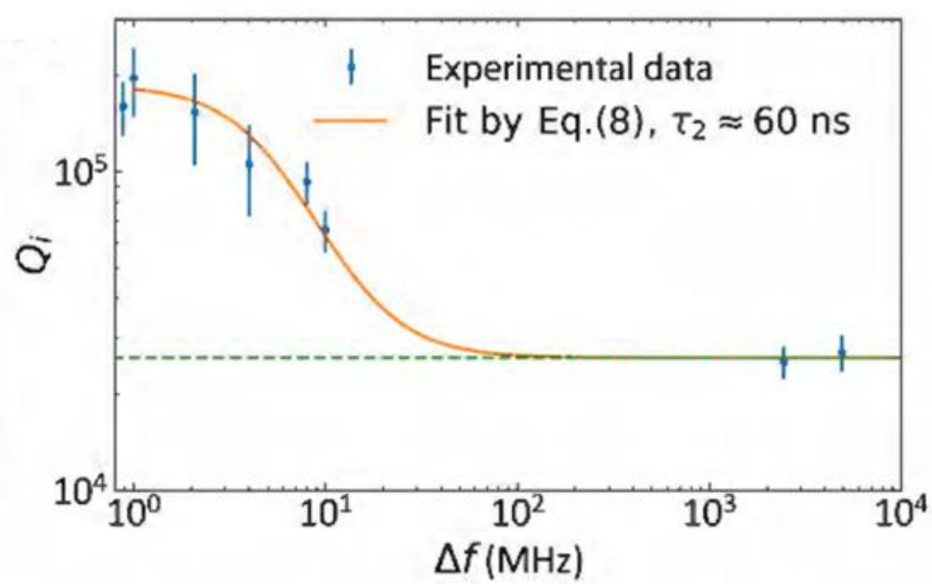
Hole Burning in the TLS Spectrum





Q_i is a universal function of $\langle n_{\hbar\omega} \rangle$ if $|f_{pump} - f_{r1}| \leq 10MHz.$

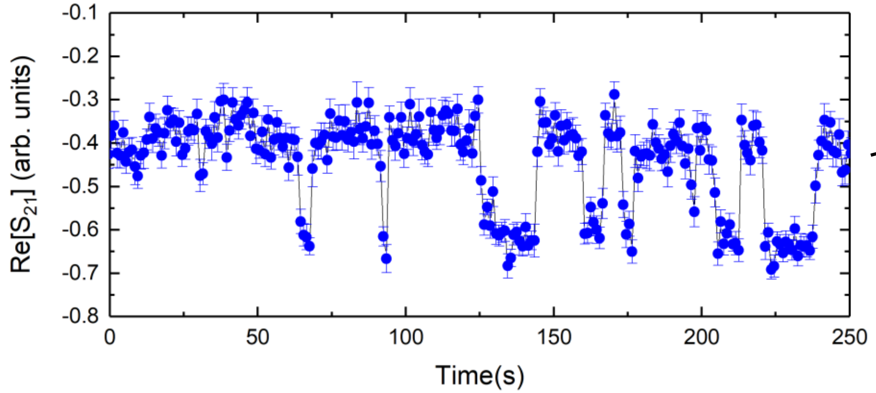
The spectral diffusion range corresponds to the TLS dephasing time $\sim 60\ ns$.

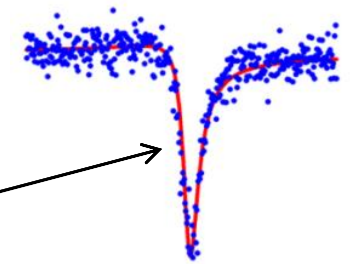


W. Zhang *et al., Phys. Rev. Appl.* **11**, 011003 (2019)

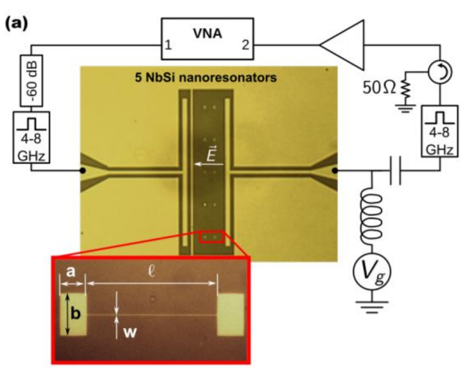
$AlOx$ Microresonators: TLS-induced telegraph noise

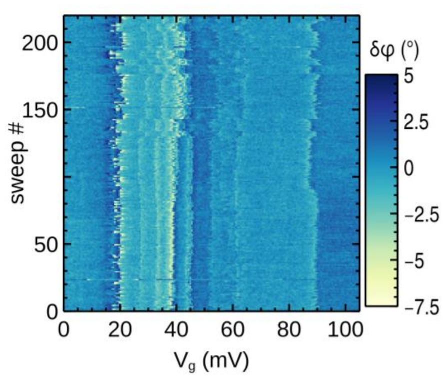
Telegraph noise in $AlOx$ high-impedance microresonators: the kinetic inductance of sub-$\boldsymbol{\mu m}$ $AlOx$ nanowires is affected by TLS, and this results in jitter of the resonance frequency.





W. Zhang et al. *Phys. Rev. Applied* **11**, 011003 (2019)





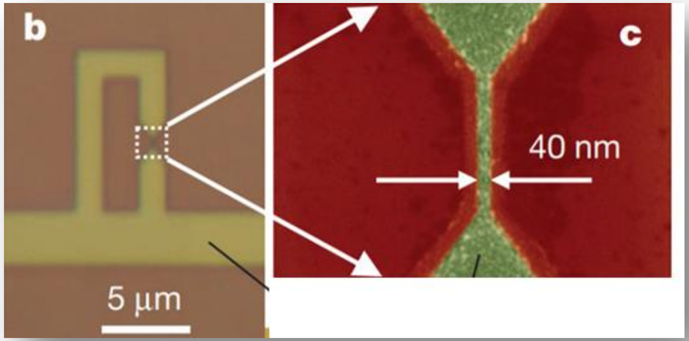
Conclusion: microresonators can be used as a platform for express-analysis of TLS-induced losses and f_r jitter.

Jitter in nanowire resonators made of NbSi.

H. le Sueur et al., arXiv:1810.12801

Some Consequences

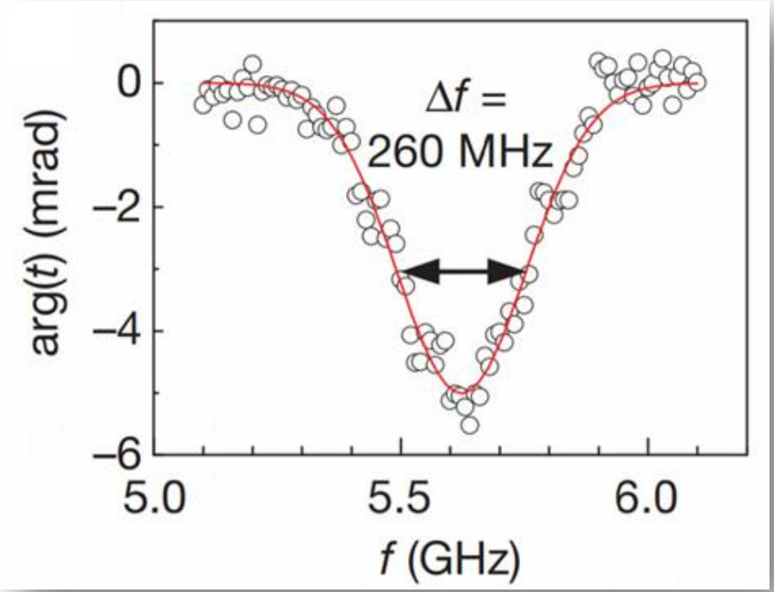
- The TLS-induced local dynamic "gating" may explain poor coherence of the qubits based on coherent phase slips.



InOx, ALD-grown TiN , NbN and TiN.

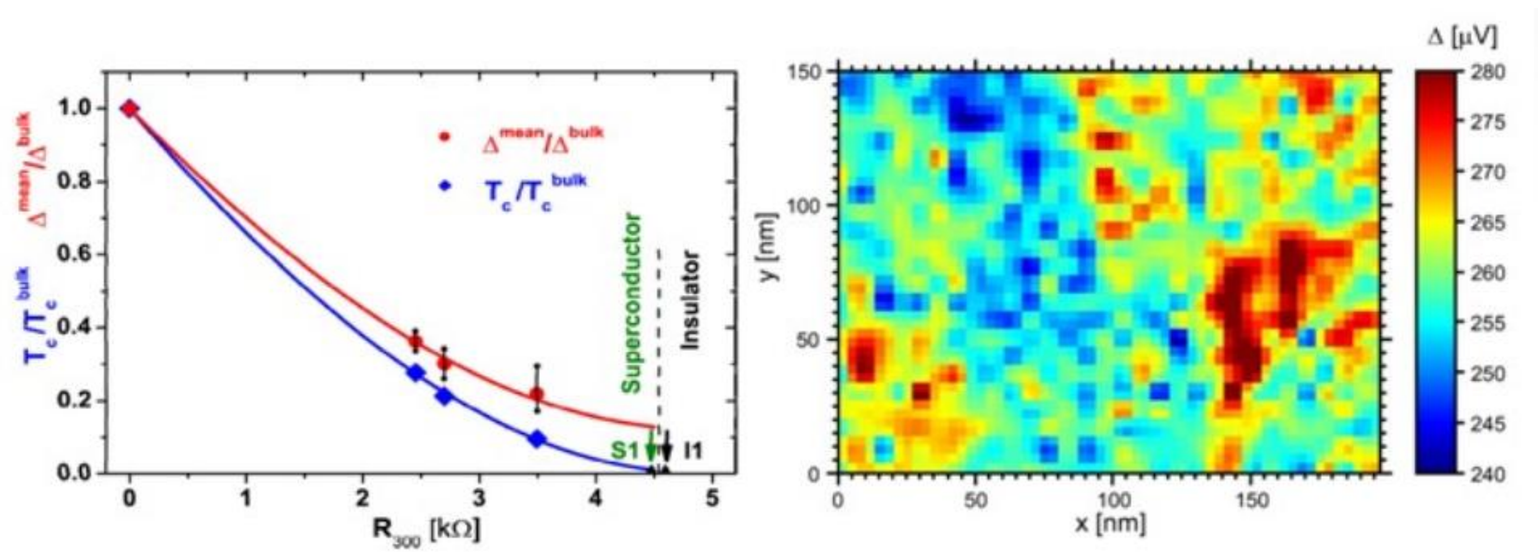
O. Astafiev *et al.*, *Nature* **484**, 355 (2012)
J. Peltonen et al., Phys. Rev. B **88**, 220506(R) (2013)

$Q \sim 20$



Some Consequences (cont'd)

- No such thing as "quenched" disorder: the local dynamic "gating" might affect the results of the STM experiments with superinductors, especially the 2D superconductors close to the SIT.



B. Sacépé et al., *PRL* **101**, 157006 (2008)

Conclusion

Superinductors enable:

- dominance of the quantum fluctuations of the phase over that of the charge;
- novel platform for the TLS study;
- novel qubits with improved coherence;
- ultra-small amplifiers and microwave resonators;
- analog simulators of many-body systems;

and many more.