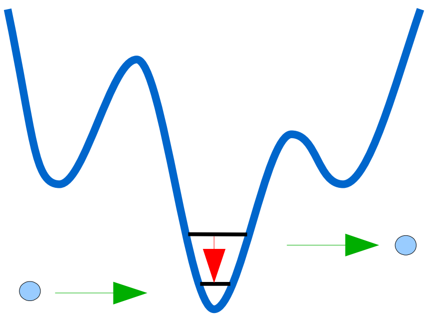


# Trapping quasiparticles in superconducting qubits

G. Catelani

| Yale: | Jülich/Aachen: | CEA Saclay: | MIT: |
|---|---|---|---|
| L. Glazman | G. Viola(Chalmers) | P. Bertet | S. Gustavsson |
| R. Schoelkopf | R. Riwar | M. Stern | W. Oliver |
| M. Devoret | A. Hosseinkani | (Bar Ilan) | |

# Outline

- intro & background

- single-junction qubits:
  - theory
  - transmon experiments (w/ theory):
    - thermal quasiparticles
    - parity switching & dephasing

- quasiparticle dynamics:
  - vortices
  - normal-metal traps

- summary

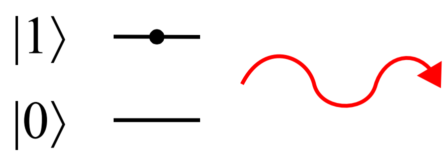
# Qubits for quantum computation

**Qubit**: coherent, controllable two-level system

**Q**: how coherent?

**A**: coherence time much longer than gate operation time
(error correction is possible if ratio $>10^2$ - $10^4$)

Relaxation limits coherence:




decay rate $\Gamma_{1\to 0} \sim 1/T_1$

- one of five requirements: DiVincenzo criteria [Fortschr. Phys. **48**, 711 (2000)]
  (initialization, quantum gates, measurement, scalability)

Physical qubits:

- natural systems (trapped ions & neutral atoms, nuclear spins in molecules, photons, ...)
- solid state devices (charge/spin of electrons in quantum dots, NV centers in diamond, P in Si, superconducting devices, ...)

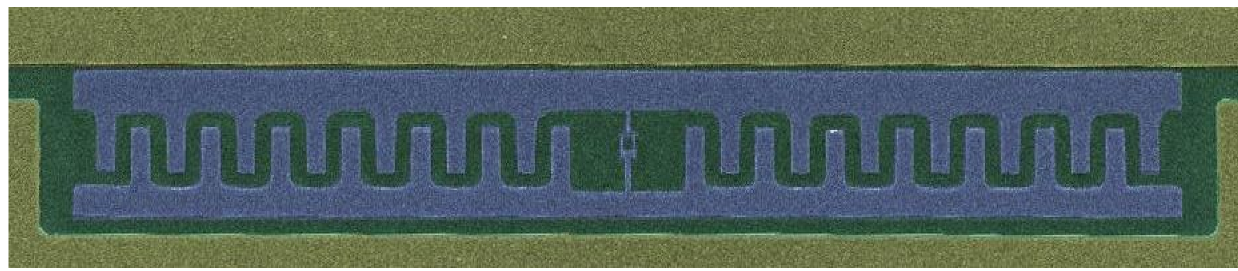
# Superconducting qubits

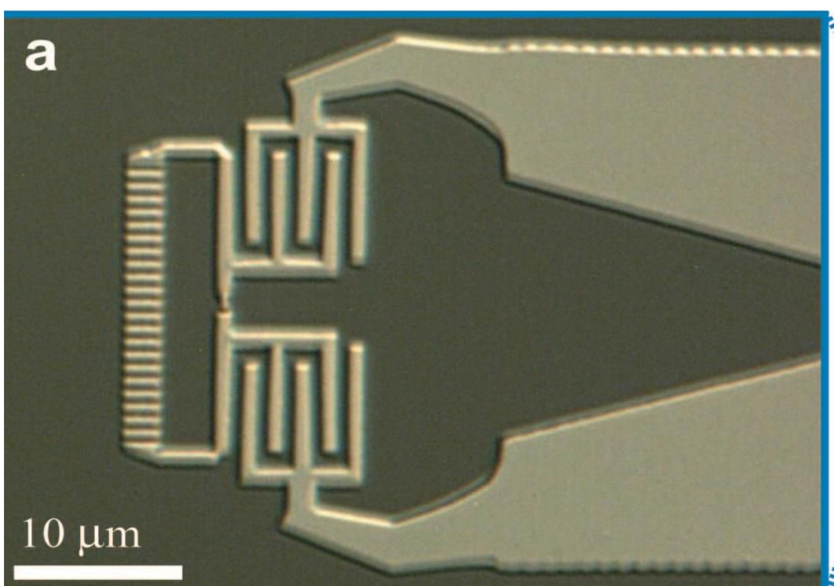
Many flavors:

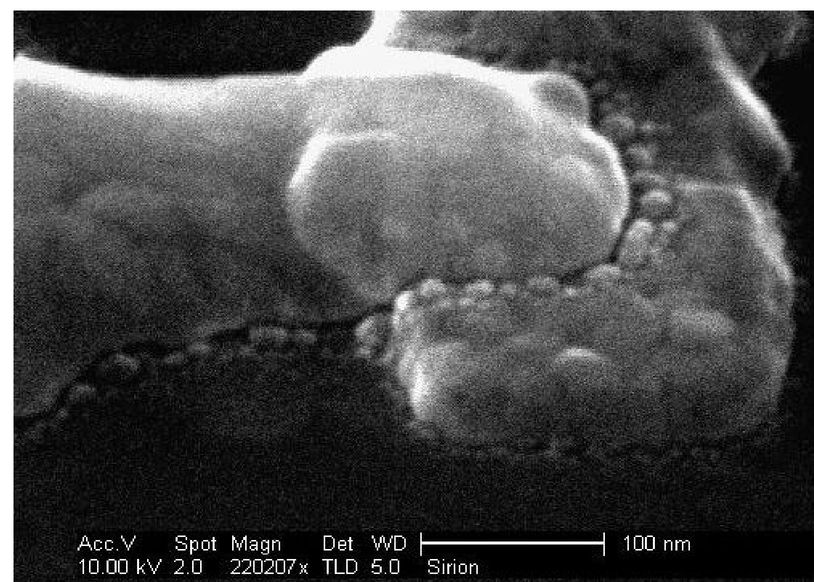
- Cooper pair box
- phase qubit
- flux qubit
- quantronium
- transmon
- fluxonium
- ...

two basic ingredients:

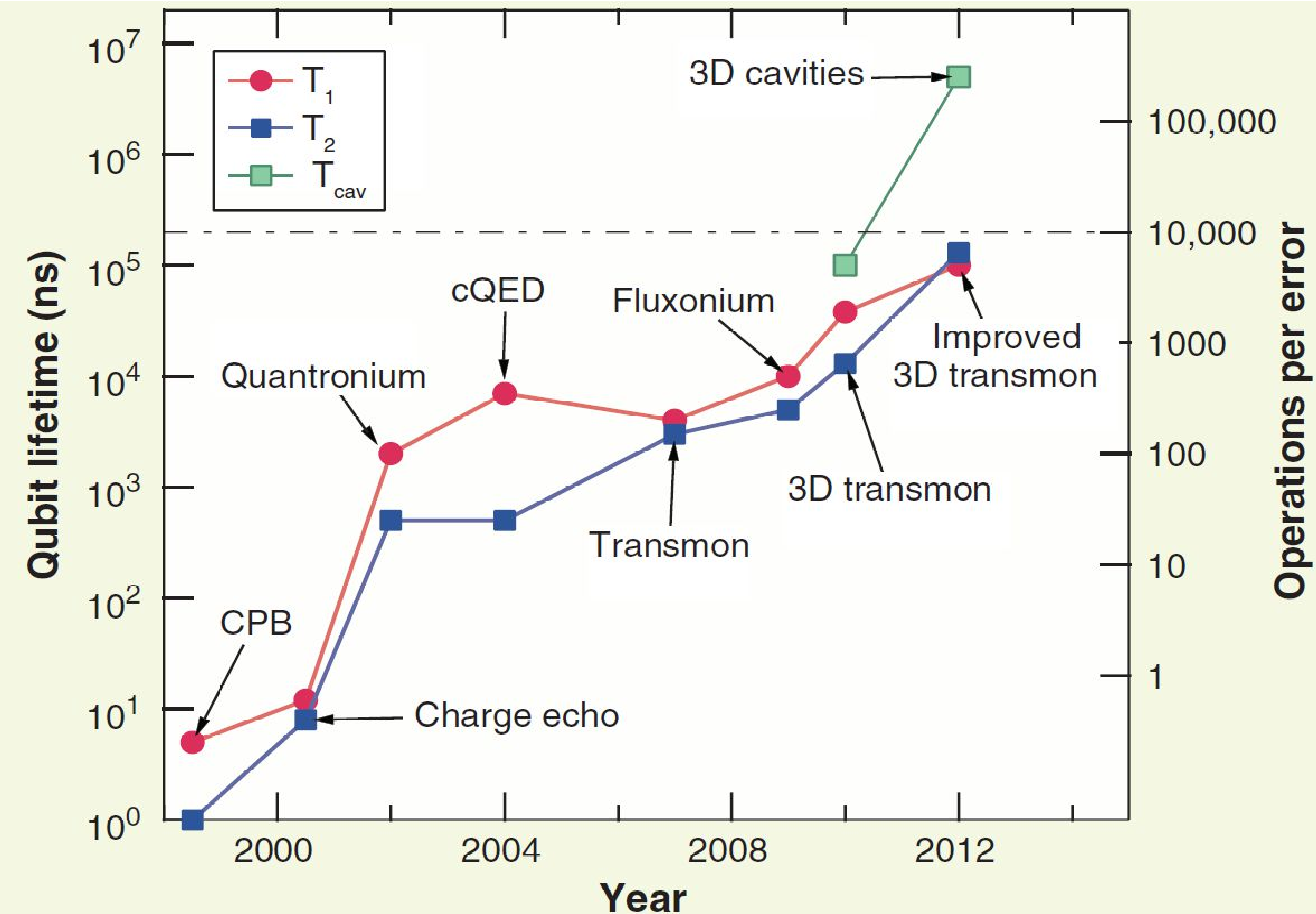
- superconductor (Al, Nb)
- tunnel junction ($AlO_x$)





# Qubit coherence times




quality factor $Q_i = \omega T_i\,, \qquad \omega \sim 40\ \mathrm{GHz}$

M.H. Devoret & R.J. Schoelkopf
Science **339**, 1169 (2013)

# Relaxation in superconducting qubits

- Possible relaxation mechanisms:

*extrinsic*

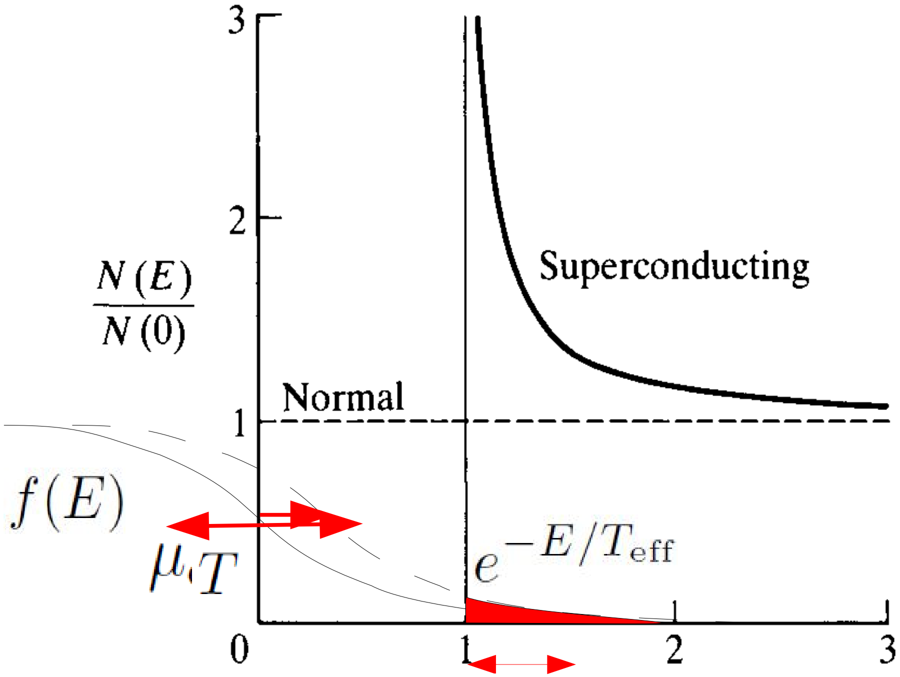
| | |
|---|---|
| • radiation | light-matter interaction, driving & read-out |
| • dielectric losses (substrate, surfaces,TLS,...) | material properties, fabrication process |
| • quasiparticles | *intrinsic* excitations in a superconductor |

**Q**: are QPs a limiting factor in current experiments?

# QPs in a bulk superconductor

density of states:

$$\frac{N_s(E)}{N(0)} = \frac{d\xi}{dE} = \begin{cases} \frac{E}{(E^2-\Delta^2)^{1/2}} & (E>\Delta) \\ 0 & (E<\Delta) \end{cases}$$




$T_{\rm eff}$ : characteristic QP energy (non-equilibrium)

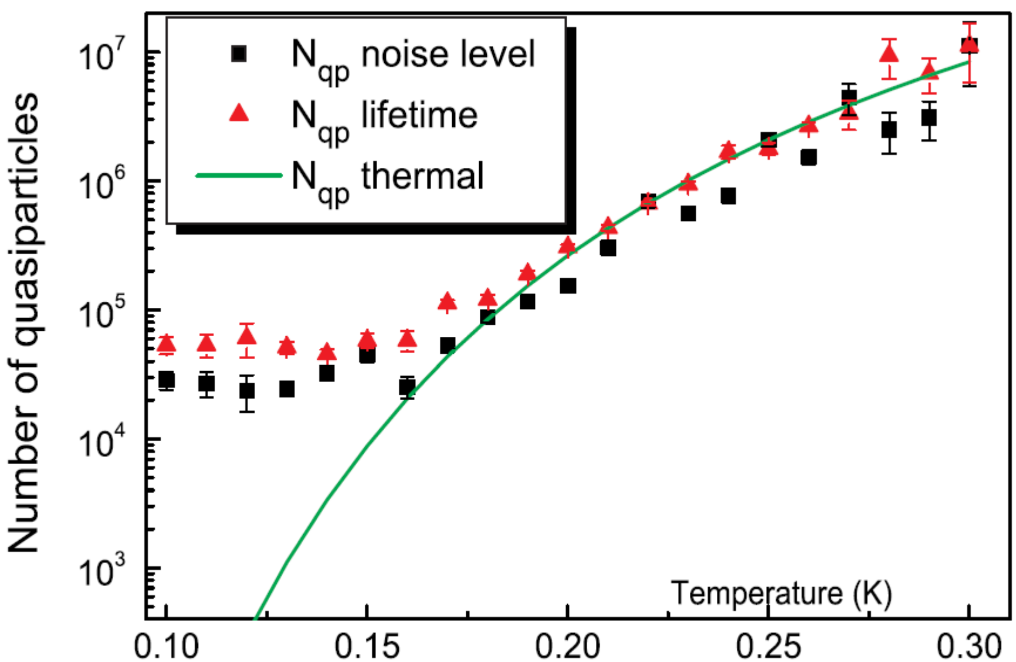
low energies: $T_{\rm eff} \ll \Delta$

AC losses: $\sigma'(\omega) \propto n_{\rm qp}$

$$n_{\rm qp} = 4N(0)\int_\Delta^\infty dE \frac{E}{\sqrt{E^2-\Delta^2}} f(E)$$

low frequencies: $\omega \ll \Delta$

generalization of Mattis-Bardeen formula
PRB **82**, 134502 (2010)

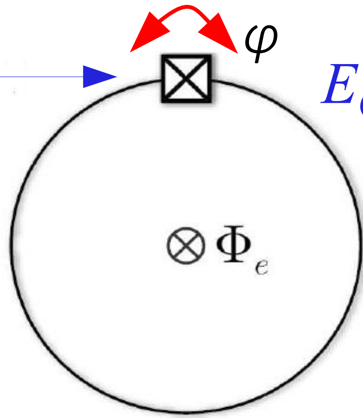



Klapwijk group, PRL **106**, 167004 (2011)

# Single-junction qubit (no QPs)

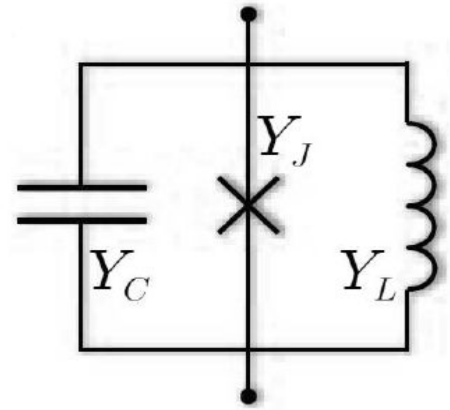
tunnel junction

superconducting loop + flux




$E_C$, $E_J$

$E_L$




ideal circuit elements

qubit Hamiltonian (quantum dynamics of ***phase difference***)

$$\hat{H}_\varphi = 4E_C\left(\hat{N} - n_g\right)^2 - E_J \cos\hat{\varphi} + \frac{1}{2}E_L(\hat{\varphi} - 2\pi\Phi_e/\Phi_0)^2$$

charging energy (~$1/C$) | Josephson energy | inductive energy (~$1/L$)

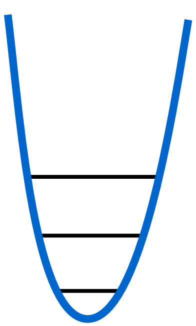
number operator: $\hat{N} = -id/d\varphi$

flux quantum: $\Phi_0 = h/2e$

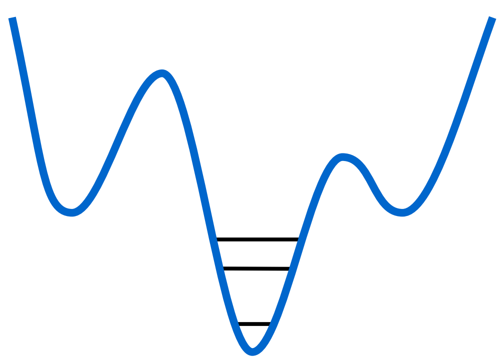
external flux: $\Phi_e$

gate voltage: $n_g$

$E_J = 0$



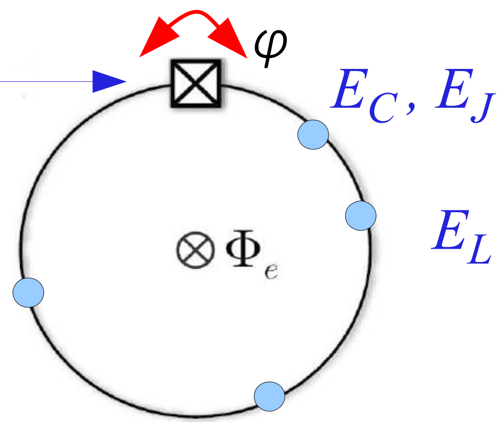
$E_J \neq 0$

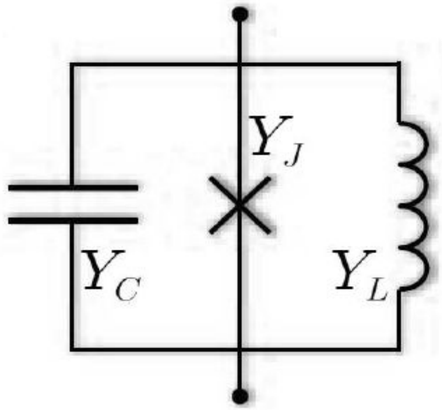


# Single-junction qubit (with QPs)

tunnel junction

superconducting loop + flux




lossy junction

$$\hat{H} = \hat{H}_\varphi + \hat{H}_{\rm qp} + \hat{H}_T$$

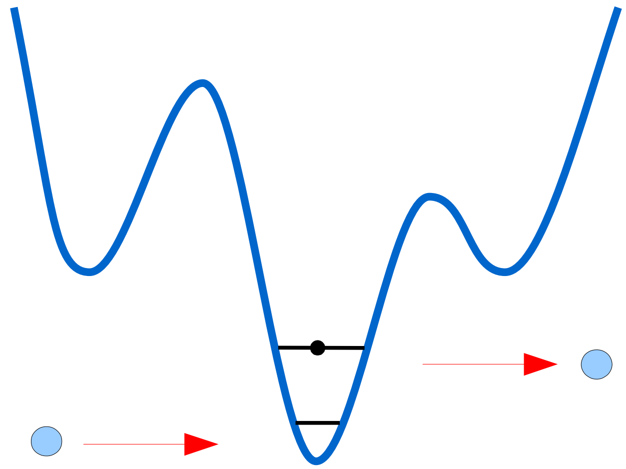
qubit Hamiltonian $\hat{H}_\varphi = 4E_C\left(\hat{N} - n_g\right)^2 - E_J \cos\hat{\varphi} + \frac{1}{2}E_L(\hat{\varphi} - 2\pi\Phi_e/\Phi_0)^2$

qp Hamiltonian $\hat{H}_{\rm qp} = \sum_k E_k \hat{\gamma}_k^\dagger \hat{\gamma}_k \quad E_k = \sqrt{\xi_k^2 + \Delta^2}$

non-degenerate gas of excitations above gap

qp tunneling $\hat{H}_T \sim \tilde{t} \sum \left(i \sin\frac{\hat{\varphi}}{2}\right) \hat{\gamma}_L^\dagger \hat{\gamma}_R + \text{H.c.}$

# Transition rates and relaxation



$$\hat{H} = \hat{H}_\varphi + \hat{H}_{\rm qp} + \underline{\hat{H}_T}$$

perturbation

$$\hat{H}_T \sim \tilde{t} \sum \left( i \sin \frac{\hat{\varphi}}{2} \right) \hat{\gamma}_L^\dagger \hat{\gamma}_R + {\rm H.c.}$$

$$\omega_{if} = E_i - E_f$$

Fermi golden rule:

$$\Gamma_{i \to f} = 2\pi \sum_{\{\lambda\}_{\rm qp}} \langle\langle |\langle f, \{\lambda\}_{\rm qp} | H_T | i, \{\eta\}_{\rm qp} \rangle|^2 \delta\left(E_{\lambda,{\rm qp}} - E_{\eta,{\rm qp}} - \omega_{if}\right) \rangle\rangle_{\rm qp}$$

qubit (phase) states

qp states

quantum statistical averaging

qp and phase dynamics separate:

$$\Gamma_{i \to f} = \left| \langle f | \sin \frac{\hat{\varphi}}{2} | i \rangle \right|^2 S_{\rm qp}(\omega_{if})$$

non-linear qubit-qp interaction

qp current spectral density

cold qp $T_{\rm eff} \ll \omega_{if}$

$$S_{\rm qp}(\omega) \propto \frac{1}{\sqrt{\omega}} x_{\rm qp} \propto {\rm Re}\, Y_{\rm qp}^{hf}$$

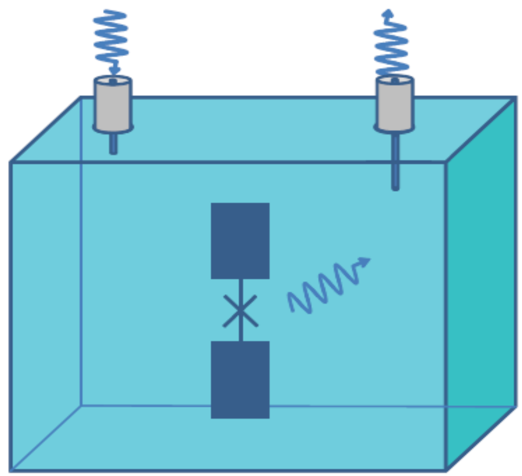
qp density (normalized)

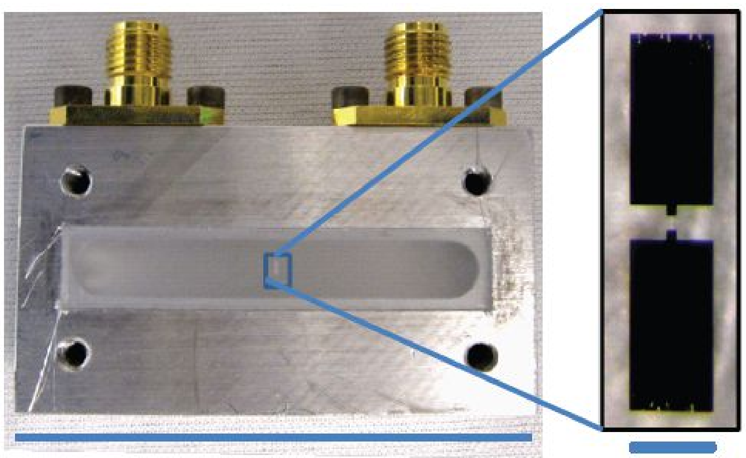
admittance (magnitude)

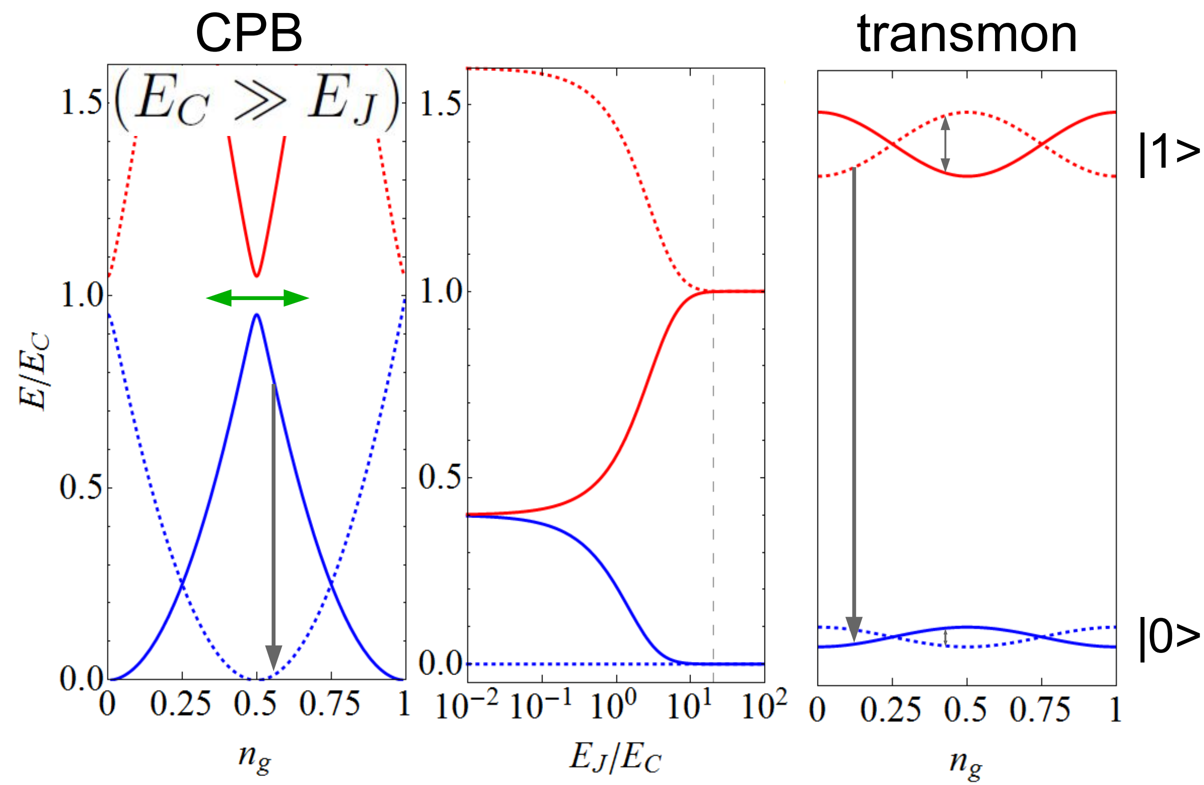
# 3D Transmon

$$\hat{H}_\varphi = 4E_C\left(\hat{N} - \cancel{n_g}\right)^2 - E_J \cos\hat{\varphi} + \cancel{\frac{1}{2}E_L(\hat{\varphi} - 2\pi\Phi_e/\Phi_0)^2}$$

$$E_C \ll E_J$$





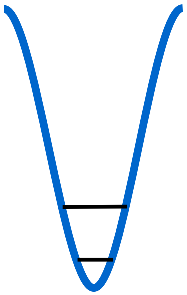

- charge noise
- quasiparticle poisoning

Lutchyn, Glazman, Larkin, PRB **72**, 014517 (2005)

Koch *et al.*, PRA **76**, 042319 (2007)

# Transmon exp. 1: thermal qp

$E_L = 0$



$\varphi_0 = 0$

$\omega_{10} = \omega_p$

transition rate:

$$\Gamma_{1\to 0} = \omega_p \frac{x_{\rm qp}}{2\pi}\sqrt{\frac{2\Delta}{\omega_p}}\,2$$

$$x_{\rm qp} = x_{eq} + x_{ne}$$

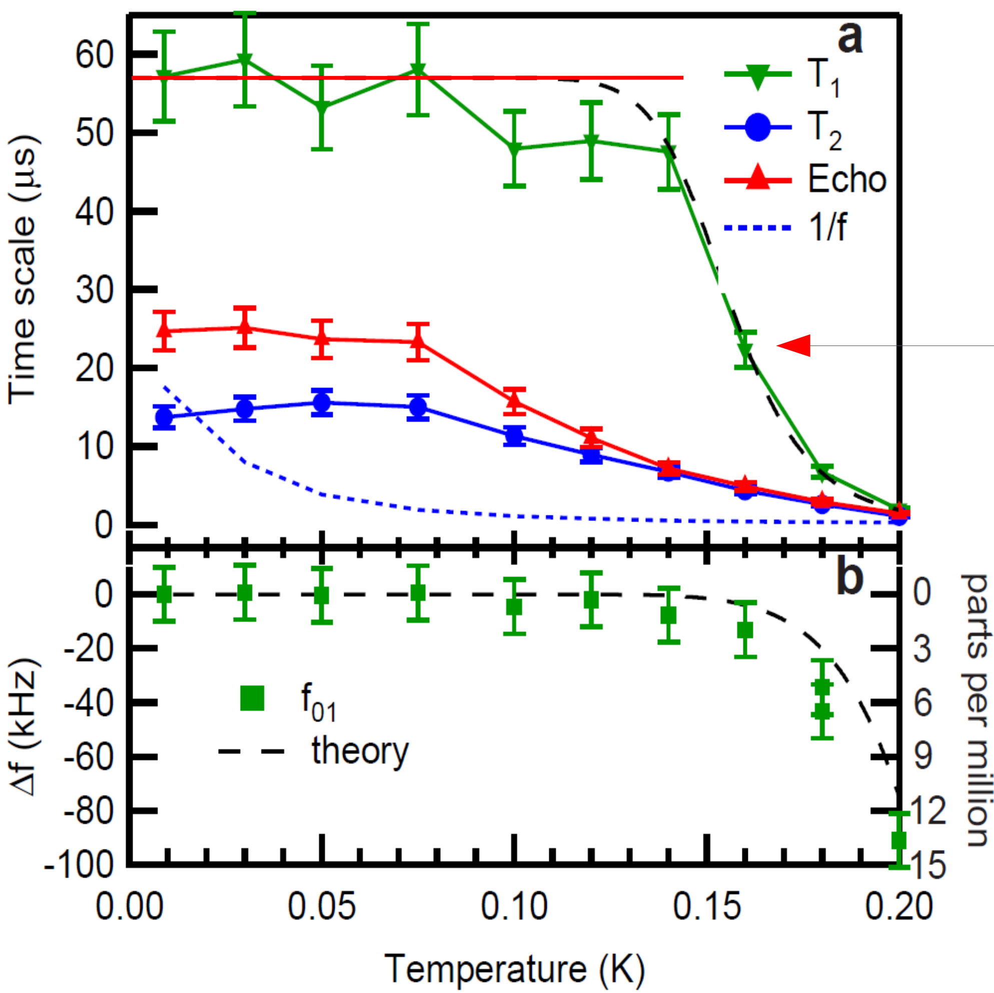
non-equilibrium qp density < $4\mathrm{x}10^{-7}$

thermal qp density

$$x_{eq} = \sqrt{\frac{2\pi T}{\Delta}}\,e^{-\Delta/T}$$

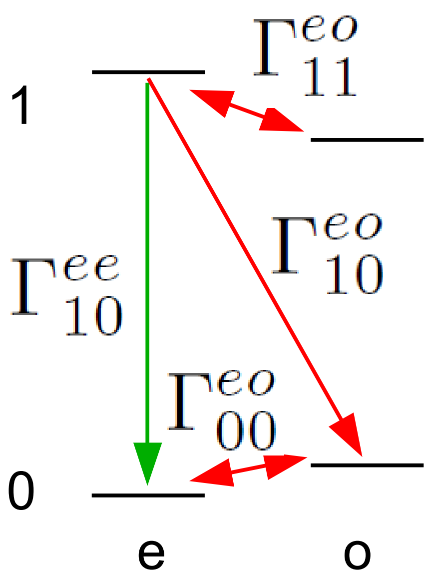
frequency shift:

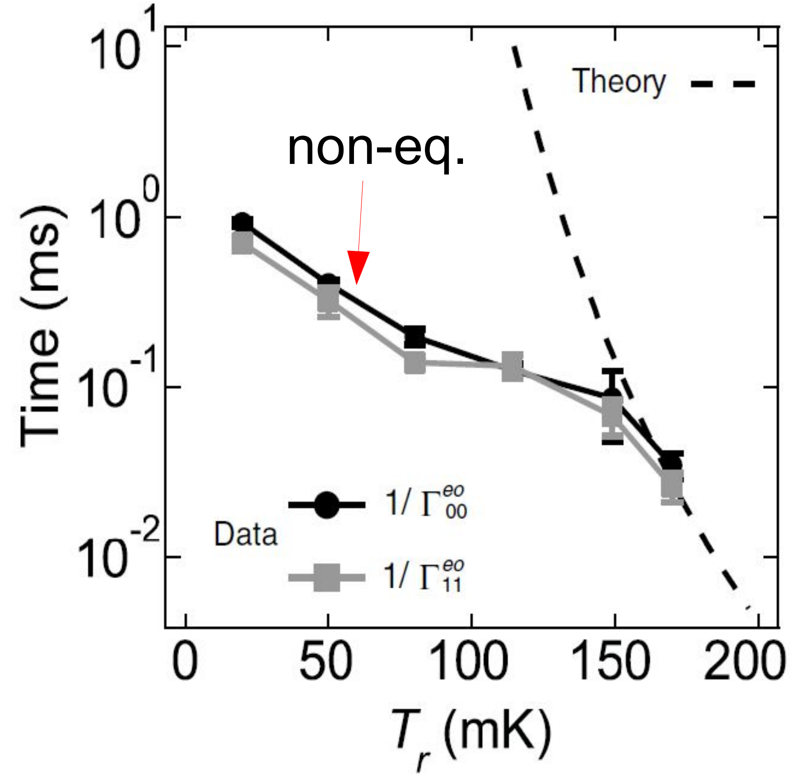
$$\mathrm{Re}\,\delta\omega(T) = -\frac{1}{2}\omega_p x_{eq}\left(\frac{1}{\pi}\sqrt{\frac{2\Delta}{\omega_p}} + 1\right)$$

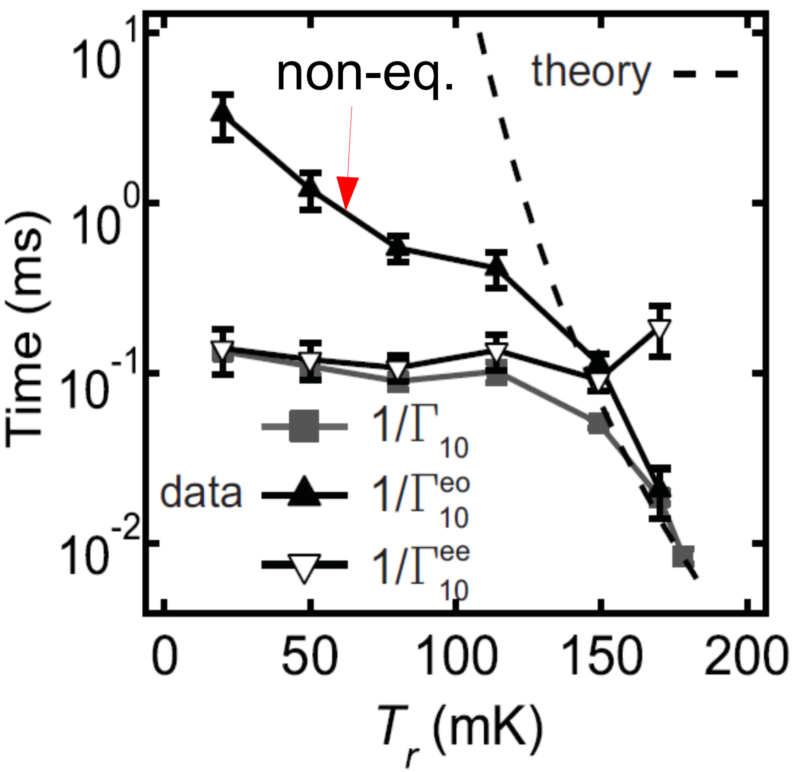



Phys. Rev. Lett. **107**, 240501 (2011)

# Transmon exp. 2: parity switching




small splitting $\varepsilon \ll T_{\rm eff}$

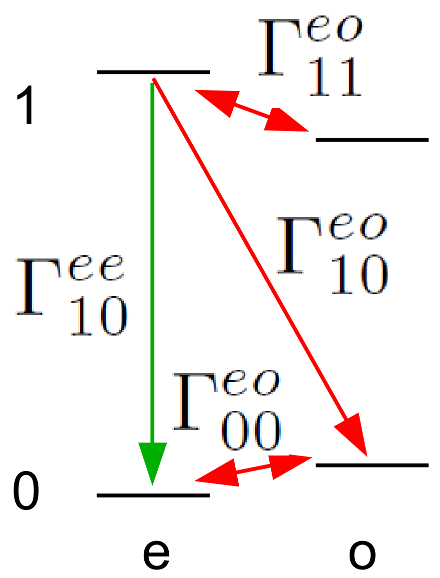
$$\Gamma_{ii}^{eo} \simeq \Gamma_{ii}^{oe} \propto |c_i|^2 \qquad c_i = \langle i\, e|\cos\frac{\hat{\varphi}}{2}|i\, o\rangle$$

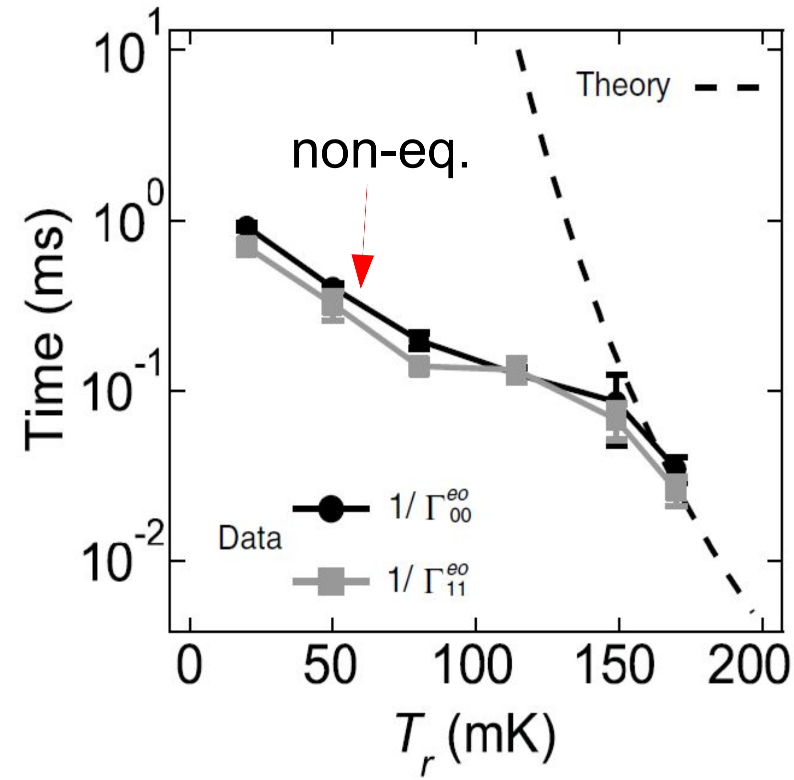
$$\frac{\Gamma_{11}^{oe}}{\Gamma_{00}^{eo}} \approx 1 - 2\sqrt{\frac{E_C}{8E_J}} - 3\frac{E_C}{8E_J}$$

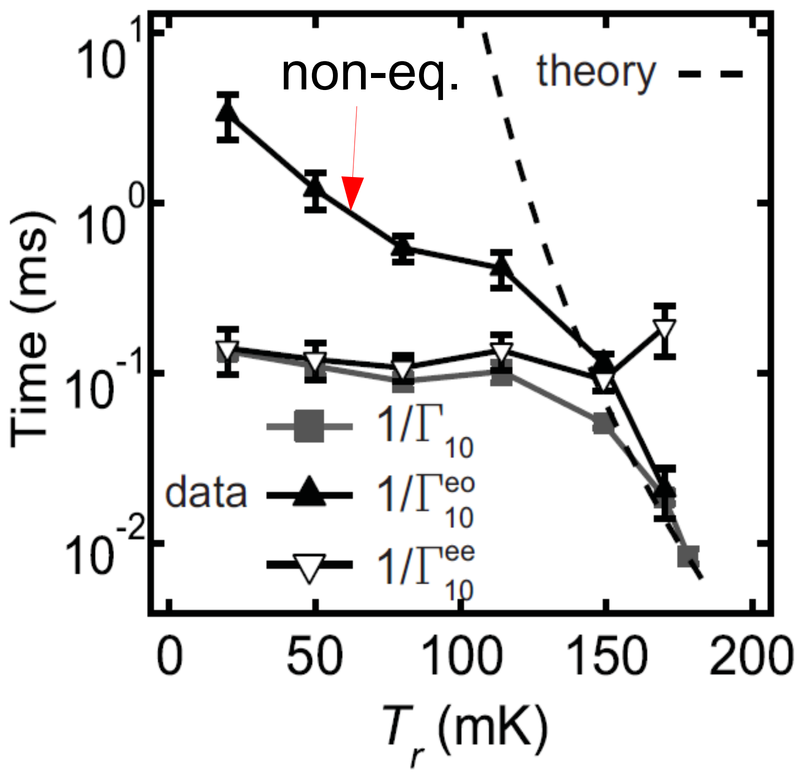
D. Riste' *et al.*, Nat. Commun. **4**, 1913 (2013)

PRB **89**, 094522 (2014)

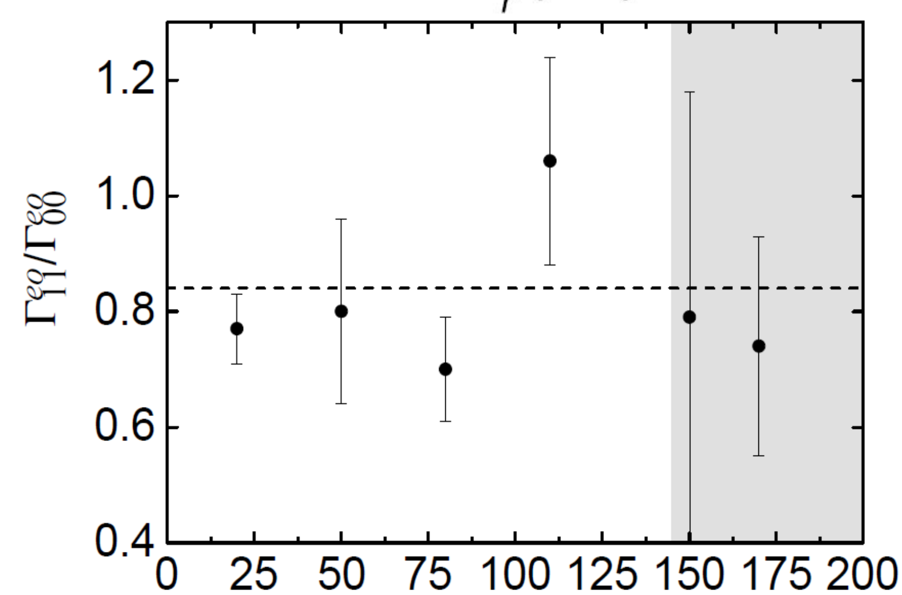
# Transmon exp. 2: parity switching



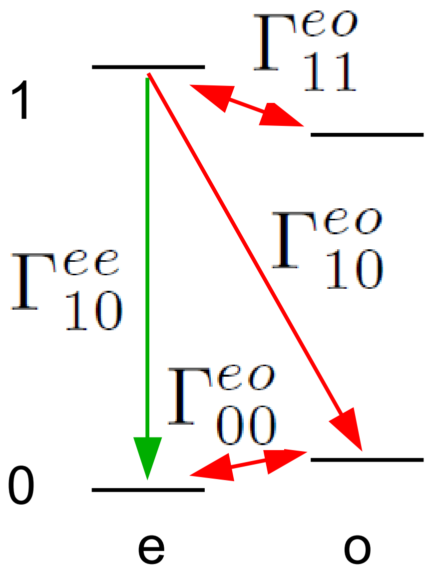



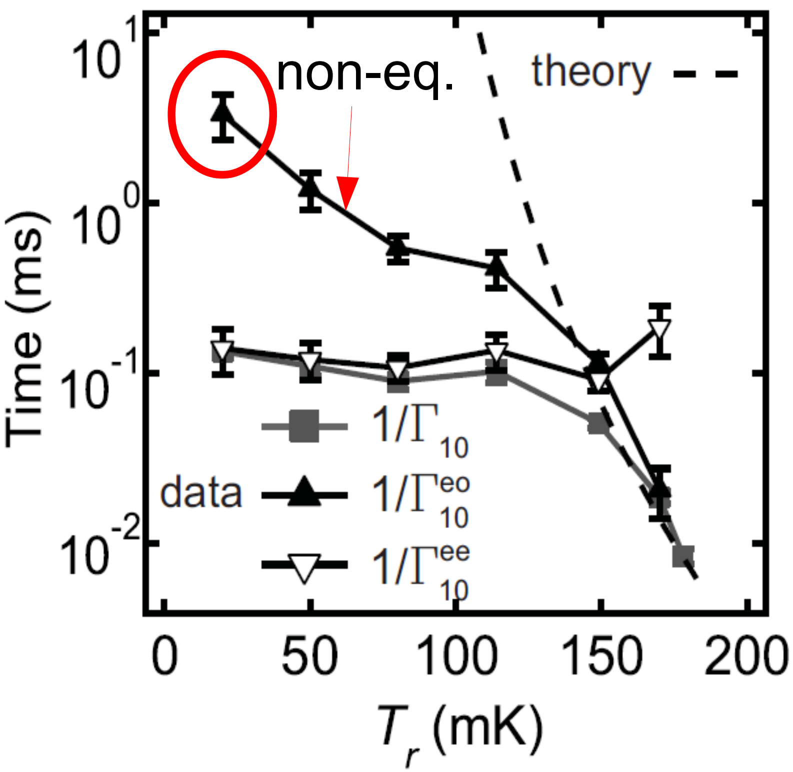

D. Riste' *et al.*, Nat. Commun. **4**, 1913 (2013)



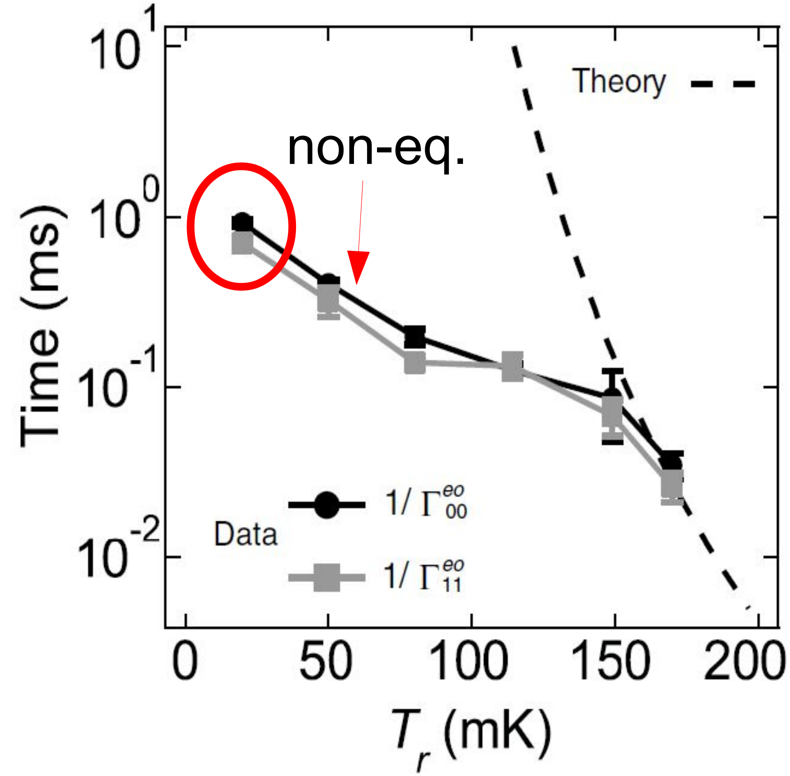

$T$ [mK] PRB **89**, 094522 (2014)

# Dephasing in transmon




D. Riste' *et al.*, Nat. Commun. **4**, 1913 (2013)




coherence time

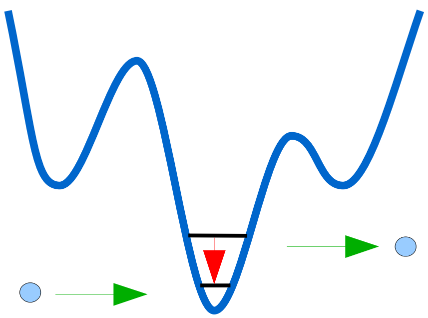
$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

may be dominated by parity switching dephasing

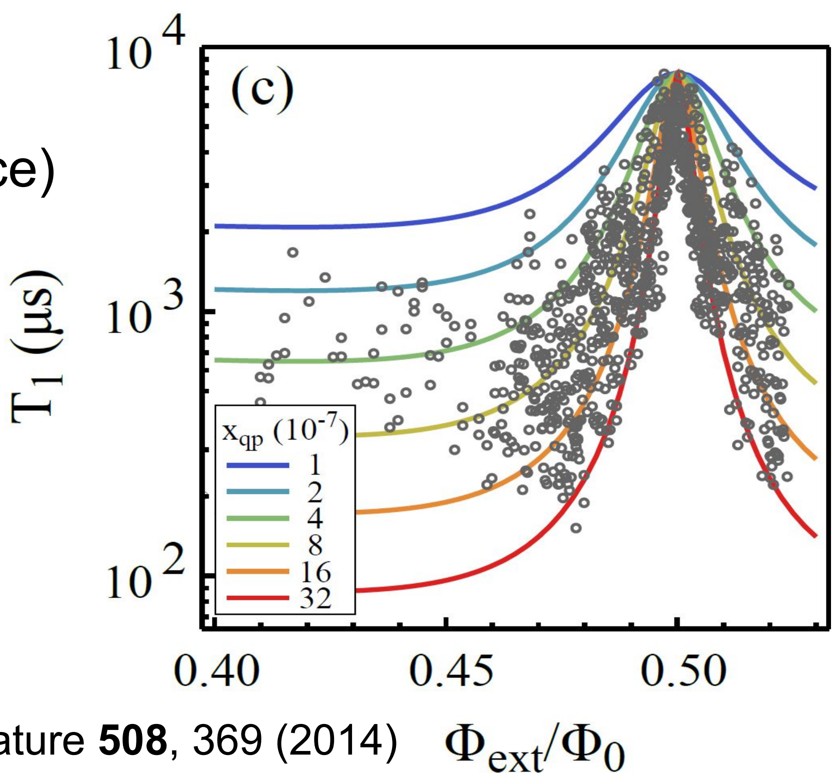
$$\frac{1}{T_\phi} \simeq \Gamma_p > \frac{1}{2T_1}$$

PRB **89**, 094522 (2014)

# Partial summary



- evidence for out-of-equilibrium qp
- qp effects on qubits:
  - relaxation
  - pure dephasing
  - frequency shift
- experimental test with transmons:
  - relaxation by thermal qp
  - parity switching
- other tests:
  - fluxonium (qp interference)
  - phase qubit
  - flux qubit




Nature **508**, 369 (2014)

# Transmon exp. 3: qp dynamics

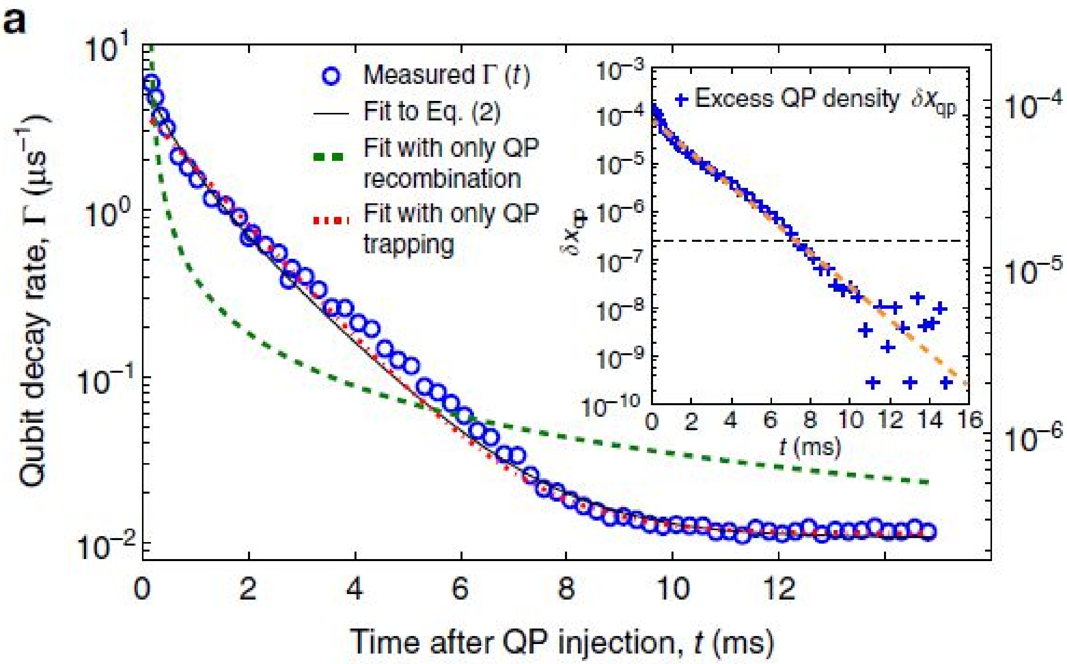
- study qp dynamics using $\Gamma_{10} \propto x_{\mathrm{qp}}$
- phenomenology of dynamics

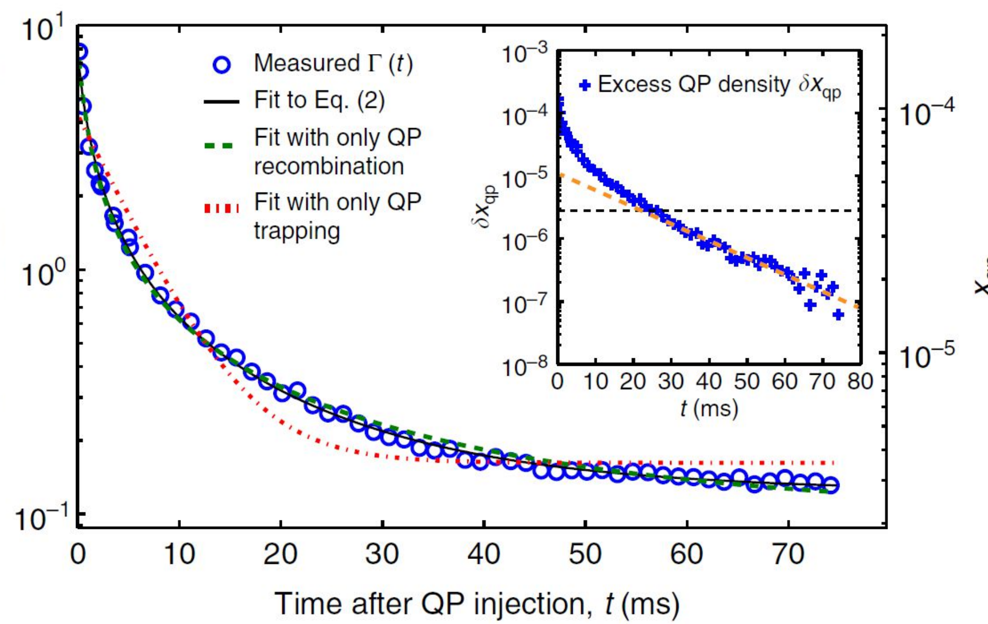
$$\frac{dx_{\mathrm{qp}}}{dt} = -r\,x_{\mathrm{qp}}^2 - s\,x_{\mathrm{qp}} + g$$

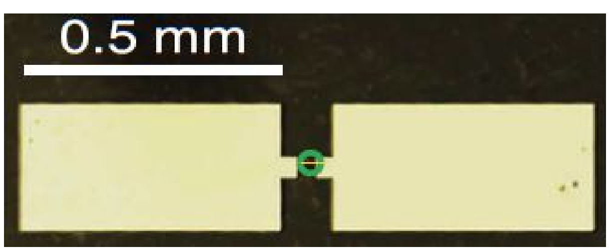
recombination → $-r\,x_{\mathrm{qp}}^2$

trapping → $-s\,x_{\mathrm{qp}}$

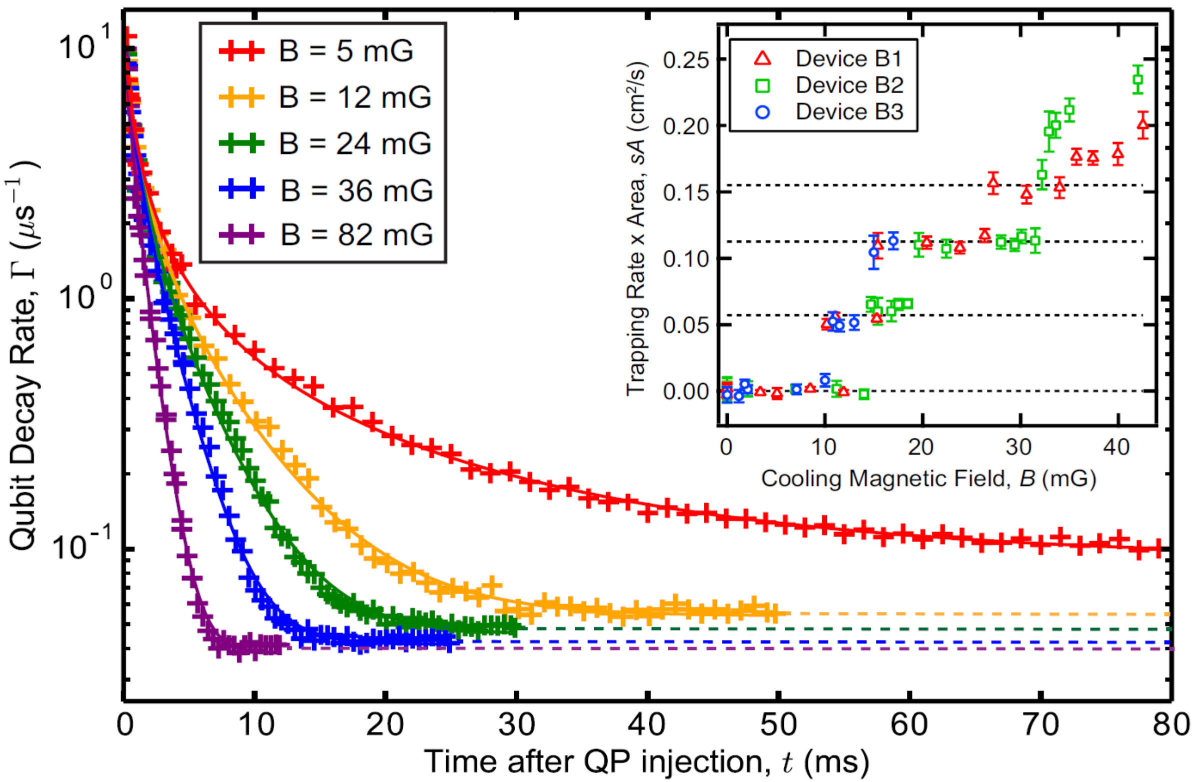
generation → $g$

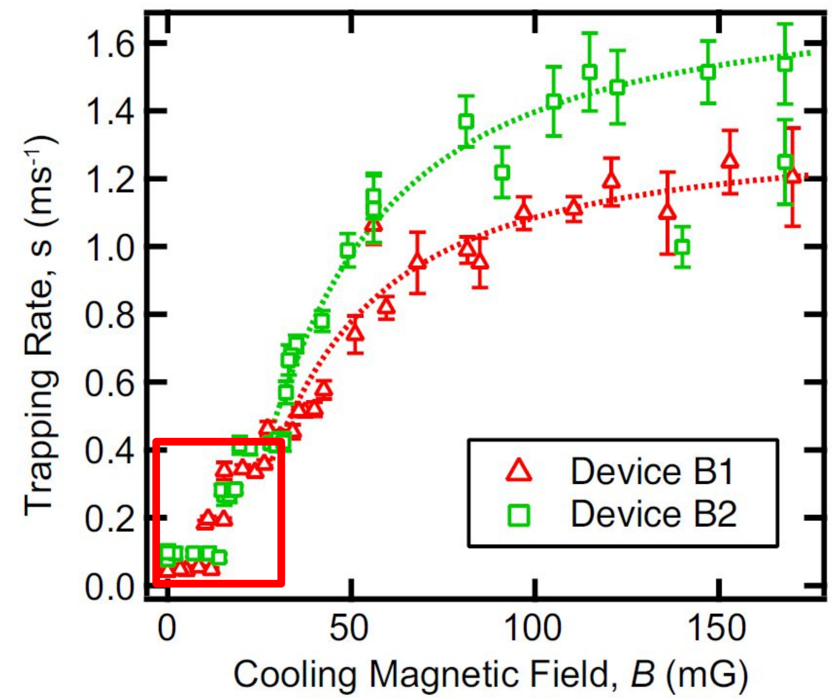


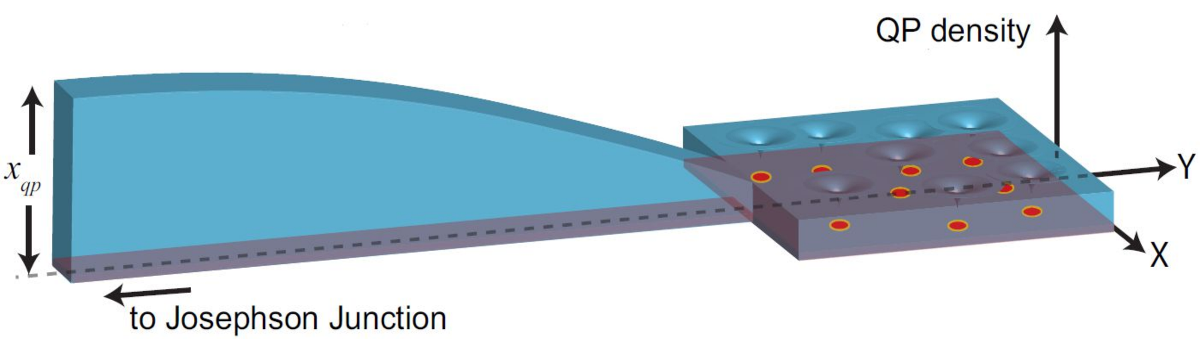



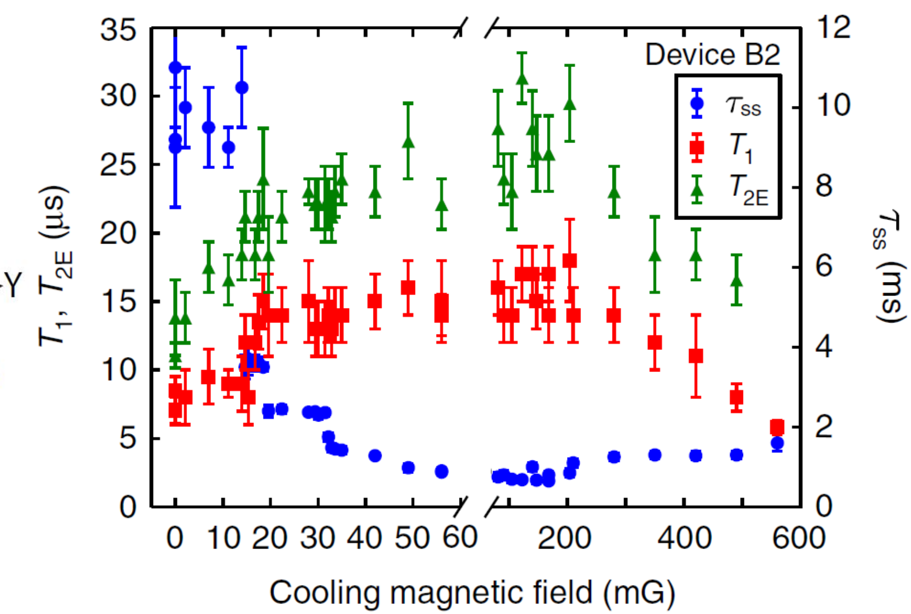




# Transmon exp. 3: qp dynamics



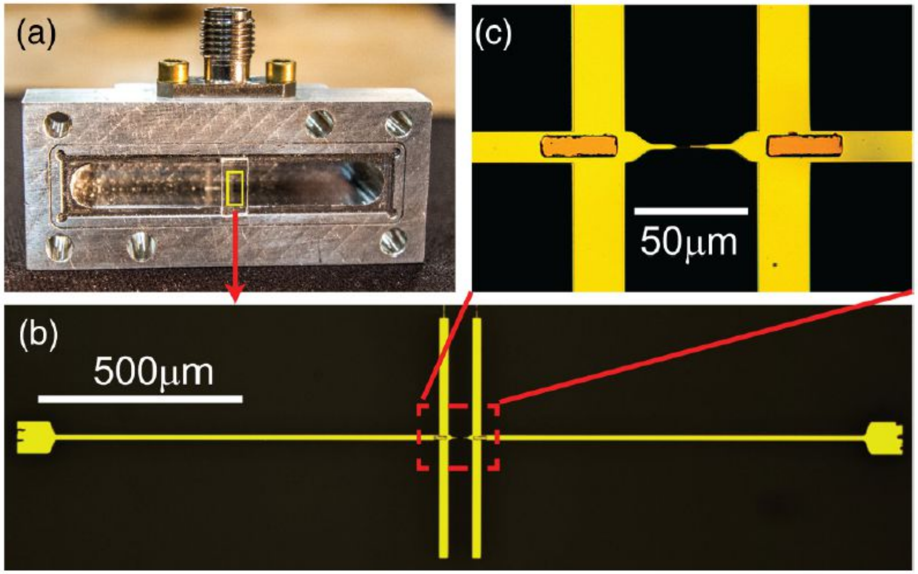



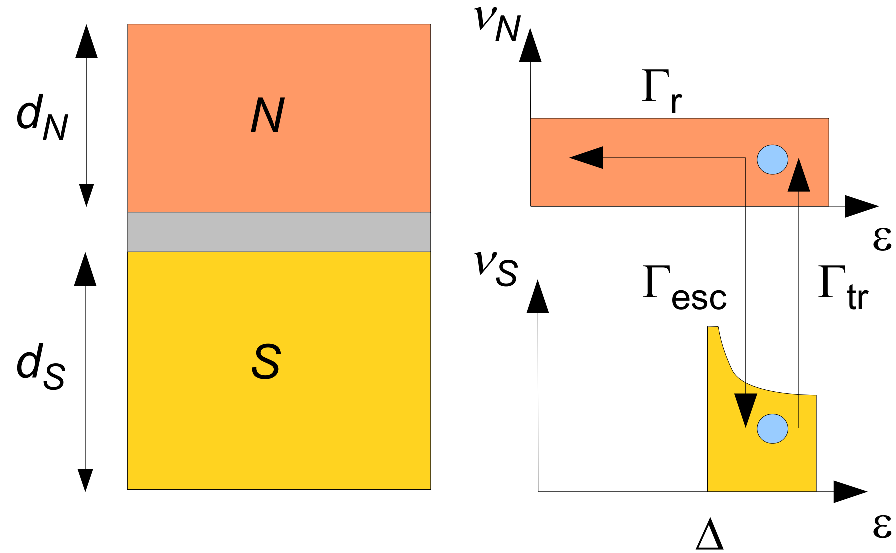




Nat. Commun. **5**, 5836 (2014)

# Transmon exp. 4: normal-metal traps




1. tunneling from S to N, rate $\Gamma_{tr}$

2a. relaxation to energy below the gap, rate $\Gamma_r$

2b. escape from N to S, rate $\Gamma_{esc}$

} need relaxation faster than escape for trapping to work

Problem: $\Gamma_{esc} \sim \nu_S(\varepsilon) = \frac{\epsilon}{\sqrt{\epsilon^2 - \Delta^2}}$ diverges near the gap (!)

...but averaging over energies gives finite effective trapping rate $\Gamma_{eff}$

- fast relaxation $\Gamma_r \gg \sqrt{\frac{\Delta}{T_{eff}}}\Gamma_{esc} \longrightarrow \Gamma_{eff} \approx \Gamma_{tr}$
- slow relaxation $\Gamma_r \lesssim \sqrt{\frac{\Delta}{T_{eff}}}\Gamma_{esc} \longrightarrow \Gamma_{eff} \approx \sqrt{\frac{T_{eff}}{\Delta}}\Gamma_r$

# Effective trapping and diffusion

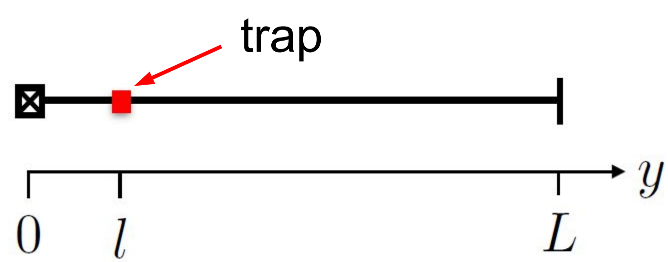
Quasiparticle dynamics: $$\dot{x}_{qp} = -r x_{qp}^2 - s_b x_{qp} + g$$ recombination, bulk trapping, generation

$$+ D_{qp} \nabla^2 x_{qp} - a(x,y)\Gamma_{eff} x_{qp}$$ diffusion, trap

long-time behavior:

- exponential decay $x_{qp}(t) \sim e^{-t/\tau_w}$
- rate & density profile depend on geometry

1D example ($l \ll L$):




equation for decay rate:

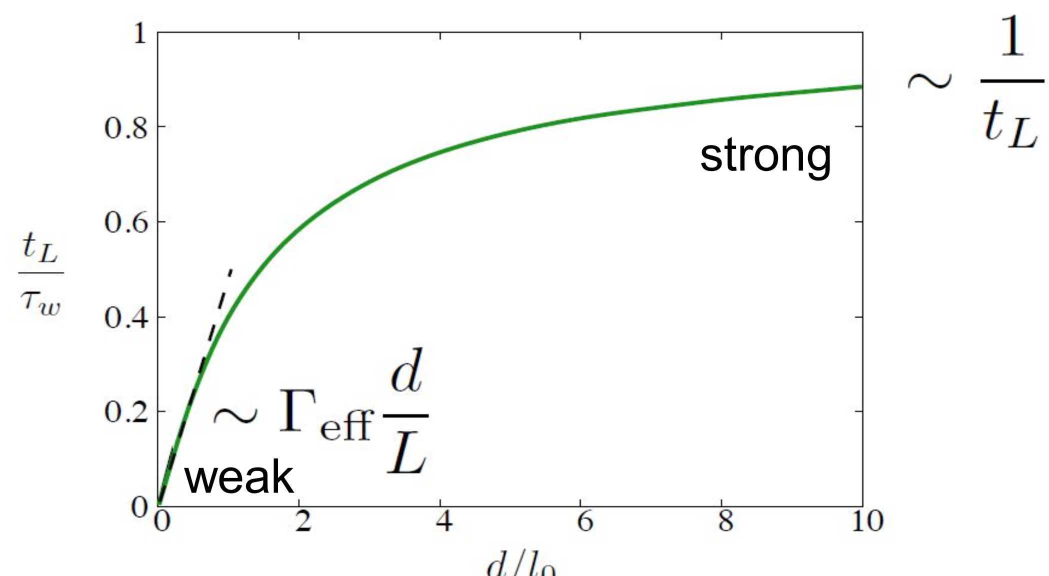
$$\cot\left(\frac{\pi}{2}\frac{t_L^2}{\tau_w^2}\right) = \frac{l_0}{d}\frac{t_L^2}{\tau_w^2}$$

diffusion time

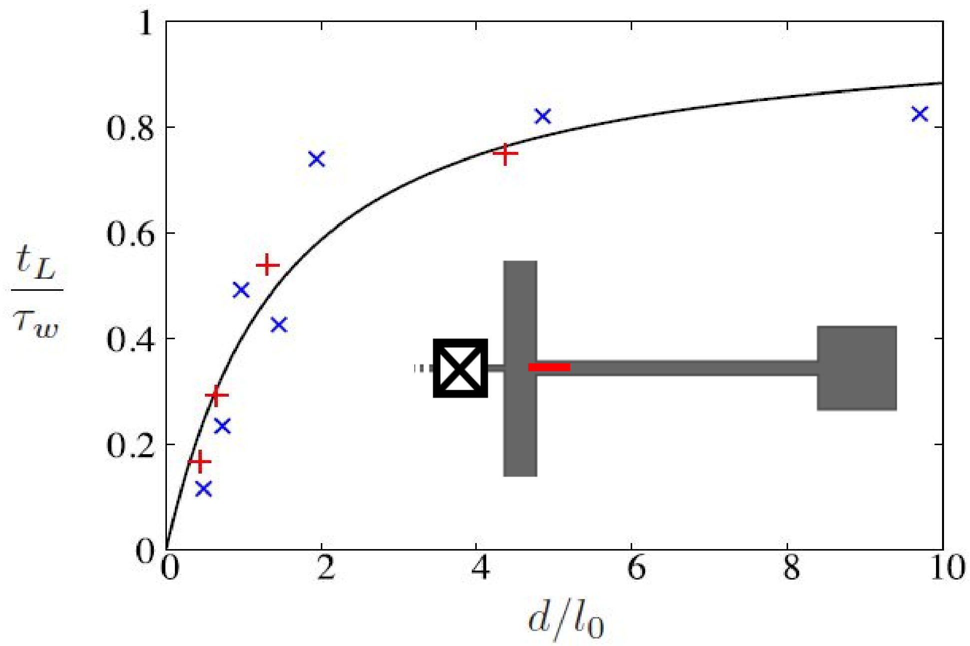
$$t_L \equiv \frac{4L^2}{\pi^2 D_{qp}}$$

"critical" length

$$l_0 \equiv \frac{\pi}{2}\frac{D_{qp}}{L\Gamma_{eff}}$$



# Transmon exp. 4: normal-metal traps

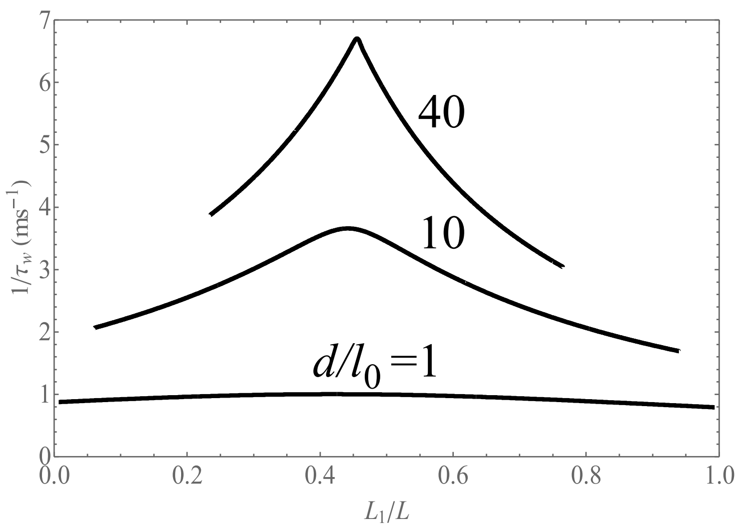



$$\Gamma_{\text{eff}} \approx 242\text{kHz} \quad T_{\text{fr}} = 13mK$$

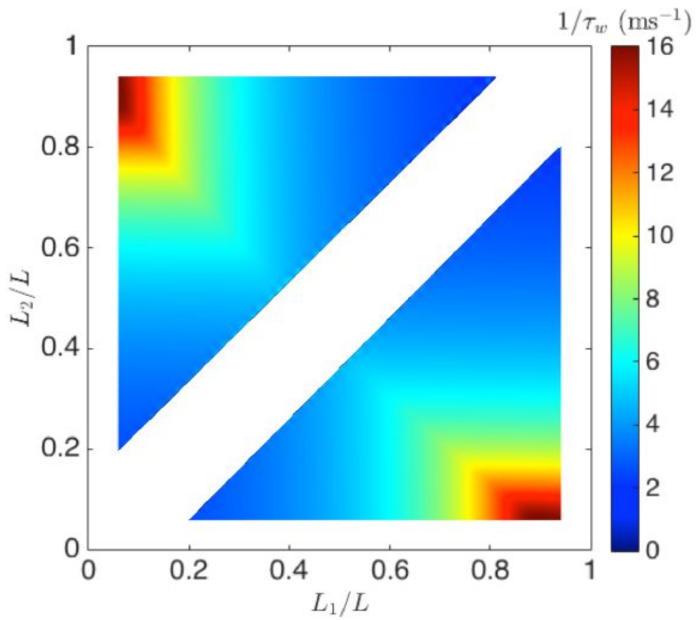
$$\Gamma_{\text{eff}} \approx 374\text{kHz} \quad T_{\text{fr}} = 50mK$$

- slow relaxation $\Gamma_{\text{eff}} \approx \sqrt{\frac{T_{\text{eff}}}{\Delta}}\Gamma_{\text{r}}$

Phys. Rev. B **94**, 104516 (2016)

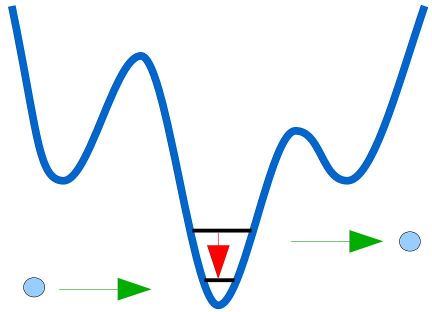



optimal placement for 1 trap




2 traps

- Estimate losses
- Proximity effect



# Summary

- theory of qubit relaxation, dephasing, and frequency shift due to quasiparticles
- valid in and out of equilibrium
- tested in various experiments:
  - transmon
  - fluxonium (qp interference)
  - phase qubit
  - flux qubit
- quasiparticles dynamics & trapping
  - vortices
  - normal islands
- multi-qubit systems, nanowire junctions, atomic point contacts, ...