Dynamics of quasiparticle trapping in Andreev bound states

Alfredo Levy Yeyati

D. G. Olivares, ALY , L. Bretheau, C. Girit, H. Pothier, C. Urbina

Phys. Rev. B 89, 104504 (2014)

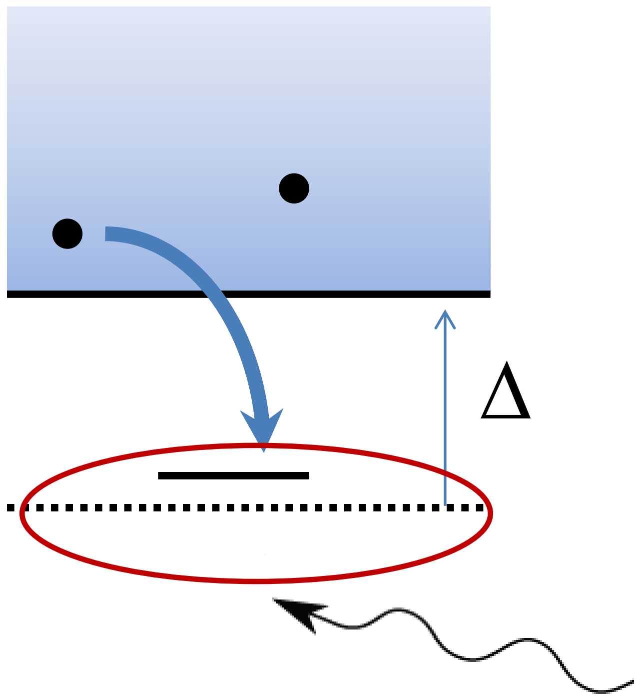
A. Zazunov, A. Brunetti, R. Egger & ALY

Phys. Rev. B 90, 104508 (2014)

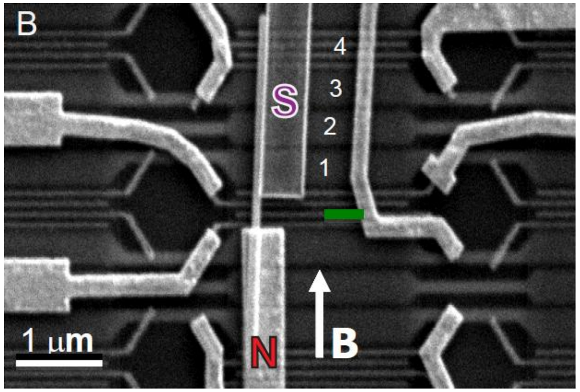
30 years of Quantronics

Paris, 22/6/15

qp poisoning

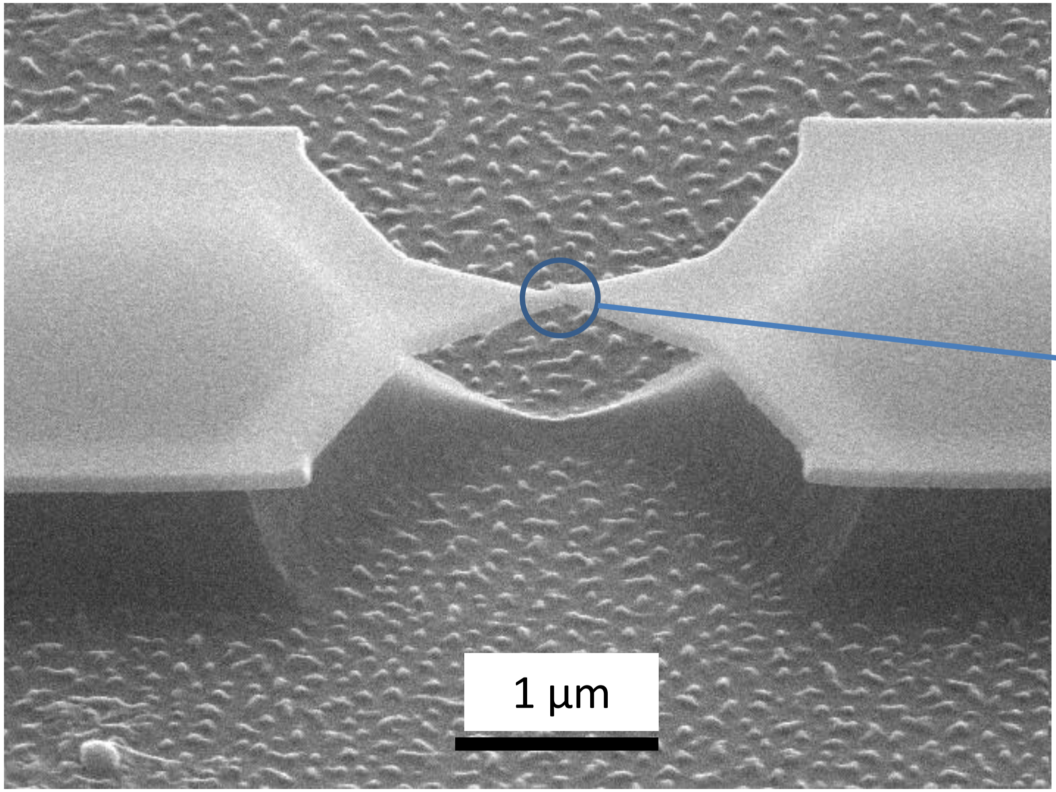


Superconducting qubits



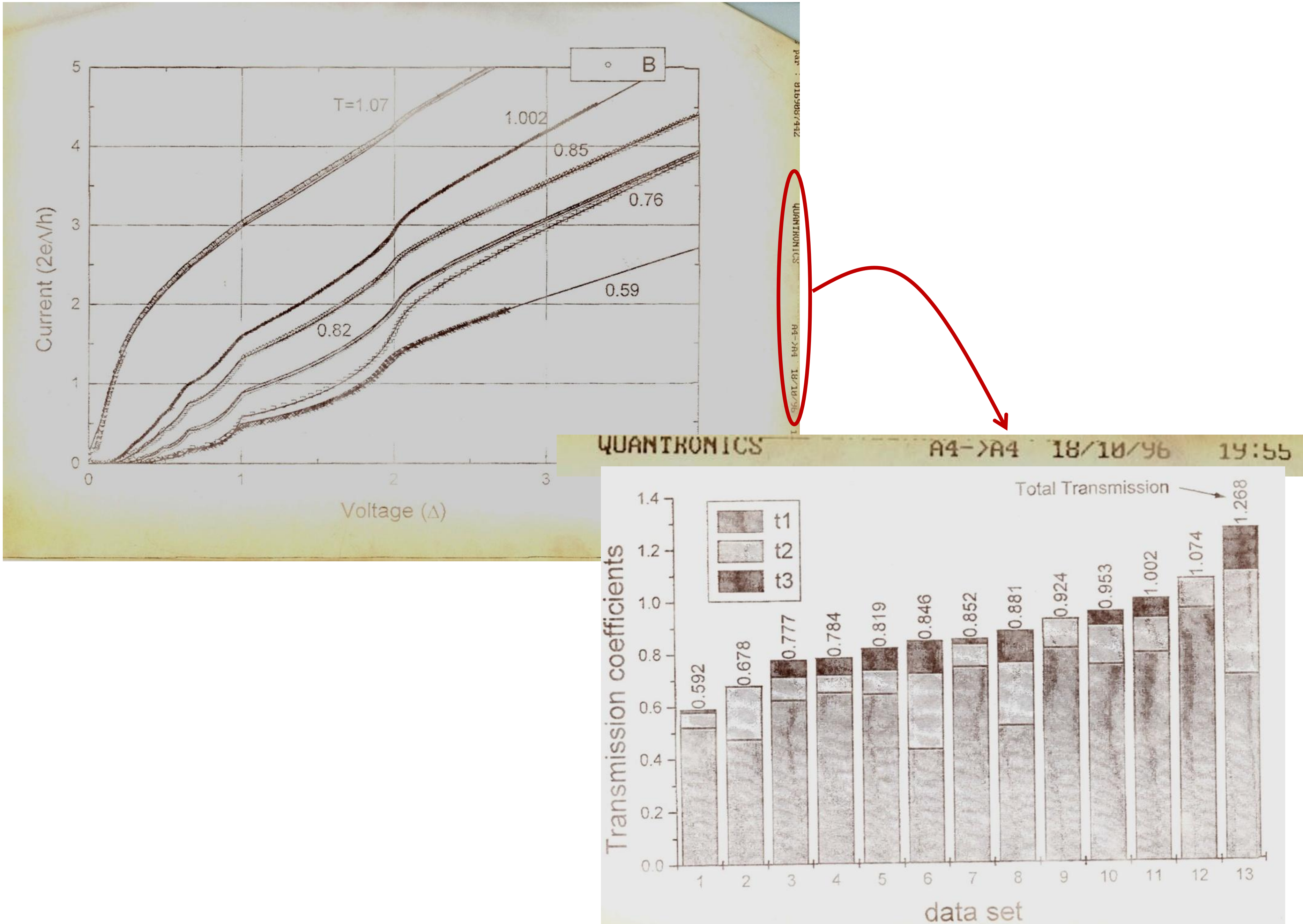
Hybrid nanostructures ("Majorana" wires)

Superconducting atomic contacts

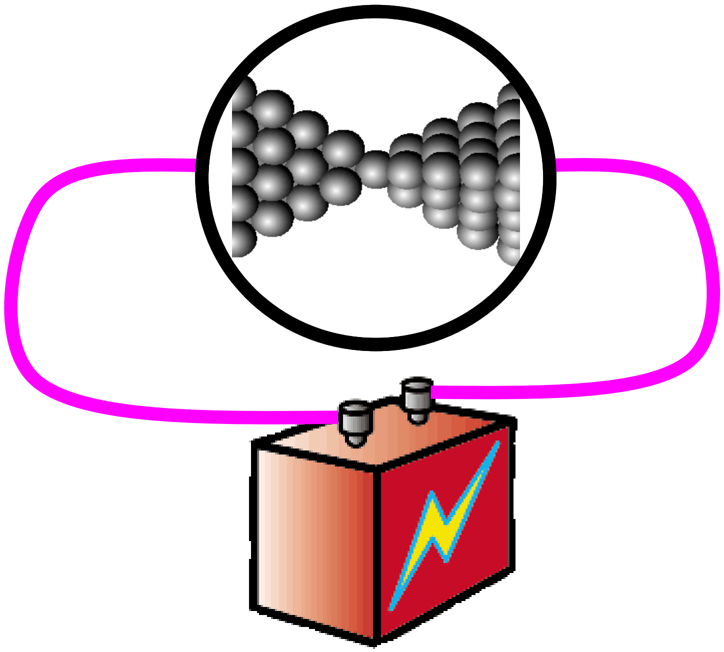


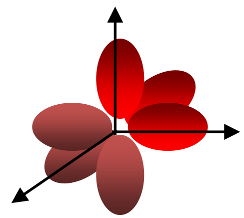
Few conduction channels

$\{\tau_n\}$


B
T=1.07
1.002
0.85
0.76
0.82
0.59
Current (2eΔ/h)
Voltage (Δ)
0
1
2
3
4
5
QUANTRONICS A4->A4 18/10/96 19:55
Total Transmission
t1
t2
t3
0.592
0.678
0.777
0.784
0.819
0.846
0.852
0.881
0.924
0.953
1.002
1.074
1.268
Transmission coefficients
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1
2
3
4
5
6
7
8
9
10
11
12
13
data set

(Almost) 20 years of collaboration with Quantronics

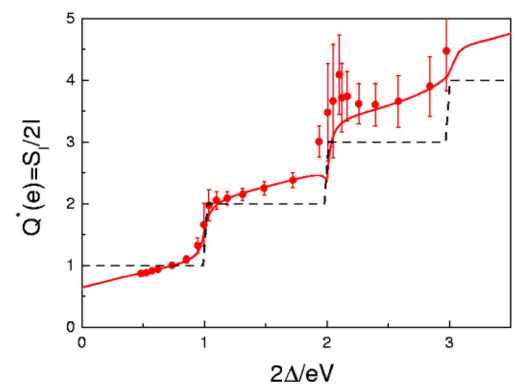




$\{\tau_n\}$

Valence orbital Structure and PIN code

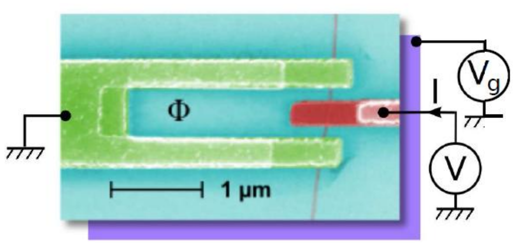
Scheer et al. Nature (1998)



Noise in MAR regime

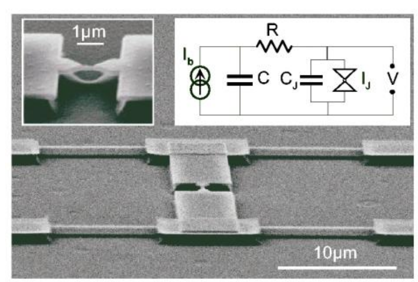
Cuevas et al. PRL (1999)
Cron et al. PRL (2001)

Andreev bound states in CNT



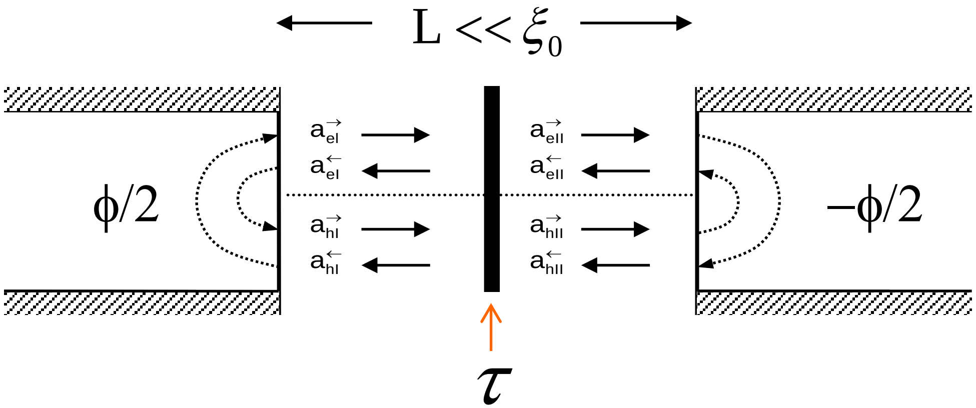
J.D. Pillet et al. NP (2010)

Coulomb blockade & Environmental effects



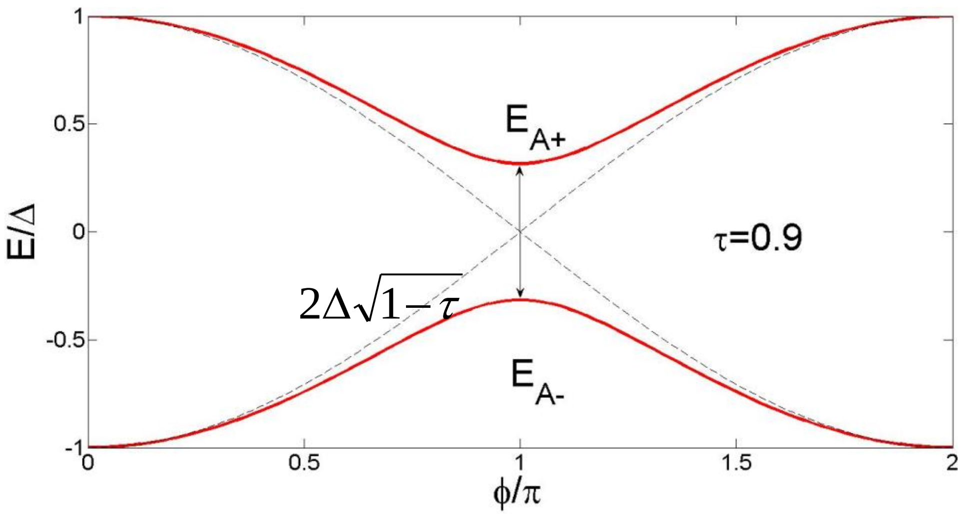
Goffman et al. PRL (2000)
ALY et al. PRL (2001)
Cron et al. PRL (2001)
Chauvin et al. PRL (2007)

Andreev states in a point contact



$$E_{A\pm} = \pm \Delta \sqrt{1 - \tau \sin^2\left(\frac{\phi}{2}\right)}$$

Furusaki and Tsukada (1991)
Beenakker (1992)



supercurrent

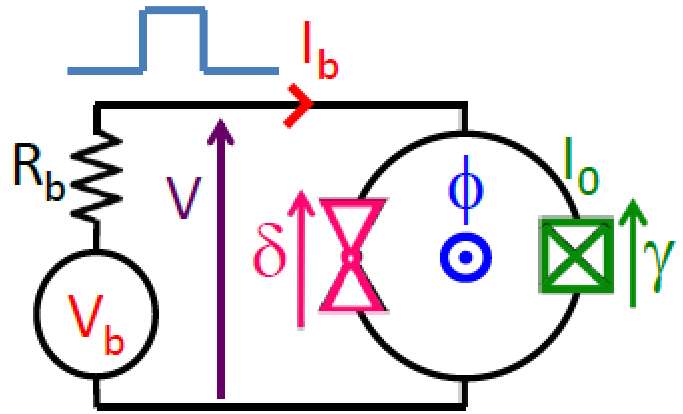
$$I_s = \frac{e\Delta}{2\hbar} \frac{\tau \sin(\phi)}{\sqrt{1 - \tau \sin^2\left(\frac{\phi}{2}\right)}} (n_- - n_+)$$

Short junction limit:
No contribution from continuum!

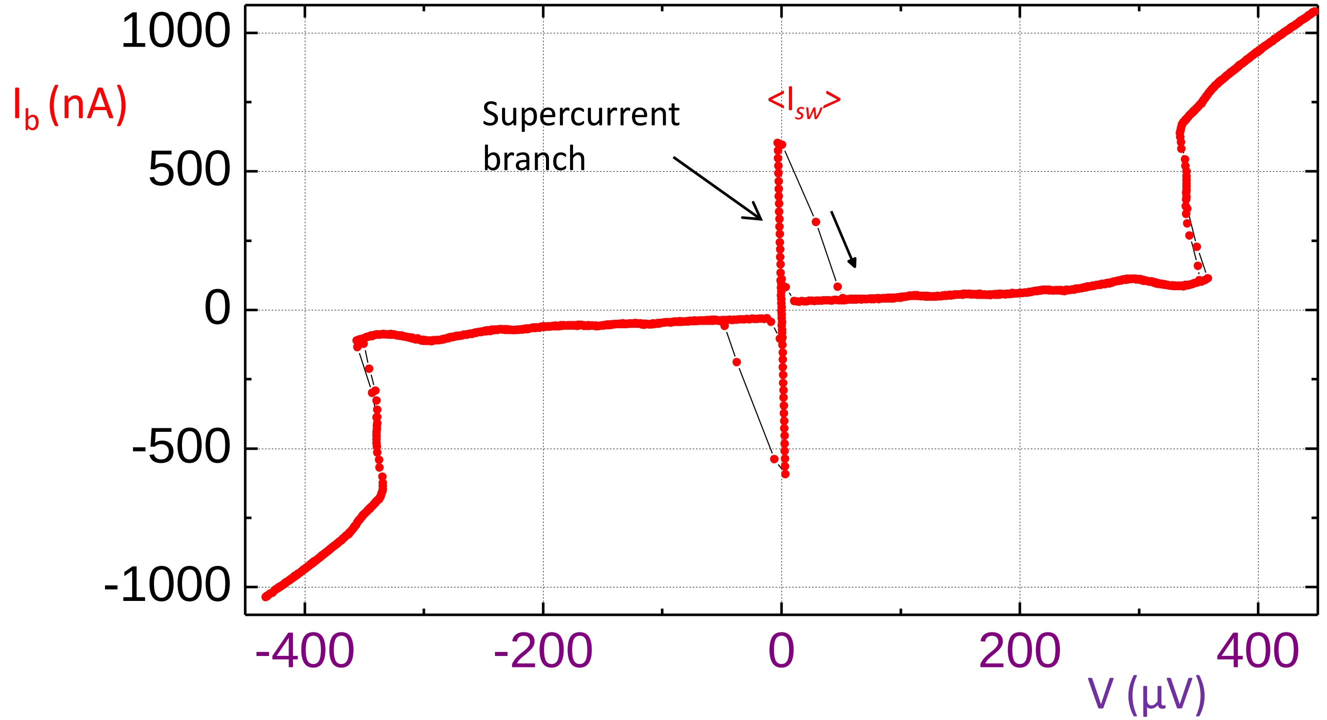
Switching experiments

*M. Zgirski et al. PRL **106**, 257003 (2011)*

Atomic SQUID



$$I_0 >> \frac{e\Delta}{\hbar}$$



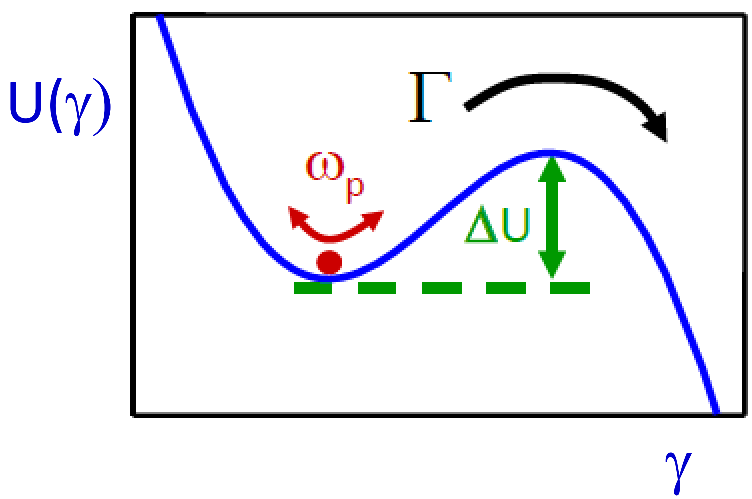
“Extended” tilted washboard potential theory

$$U = -\varphi_0 I_b \gamma - \varphi_0 I_0 \cos\gamma \quad - \quad \sum_i E_A(\tau_i, \gamma + \varphi)$$

Junction « tilted-washboard » potential

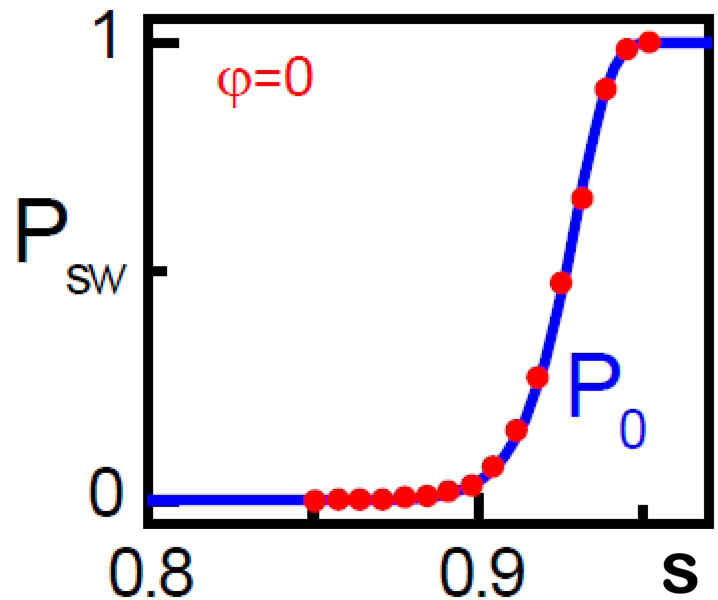
Atomic contact contribution

(assuming g.s.)



$$\Gamma = \frac{\omega_p(s)}{2\pi} \exp\left(-\frac{\Delta U(s)}{k_B T}\right)$$

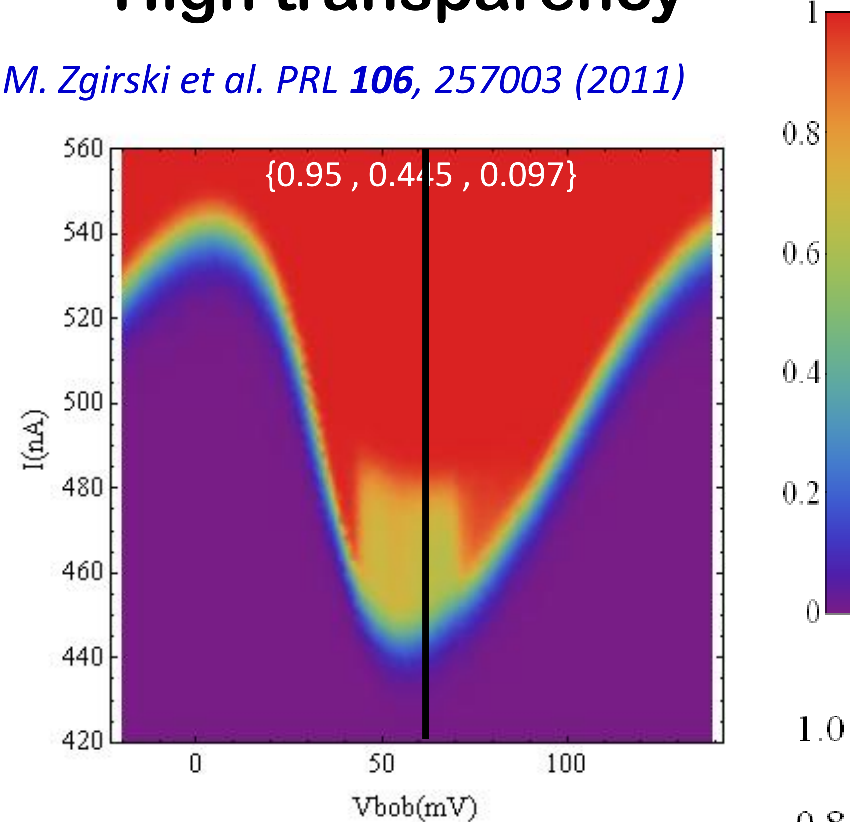
$$s = \frac{I_b}{I_0}$$ size of applied current pulse



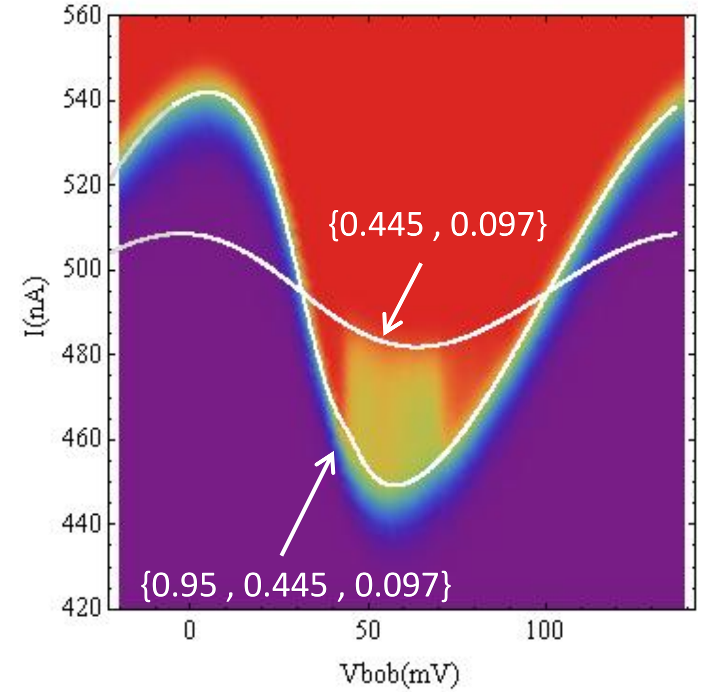
M.F. Goffman, R. Cron, ALY, P. Joyez, M.H. Devoret, D. Esteve and C. Urbina; PRL ***85****, 170 (2000)*

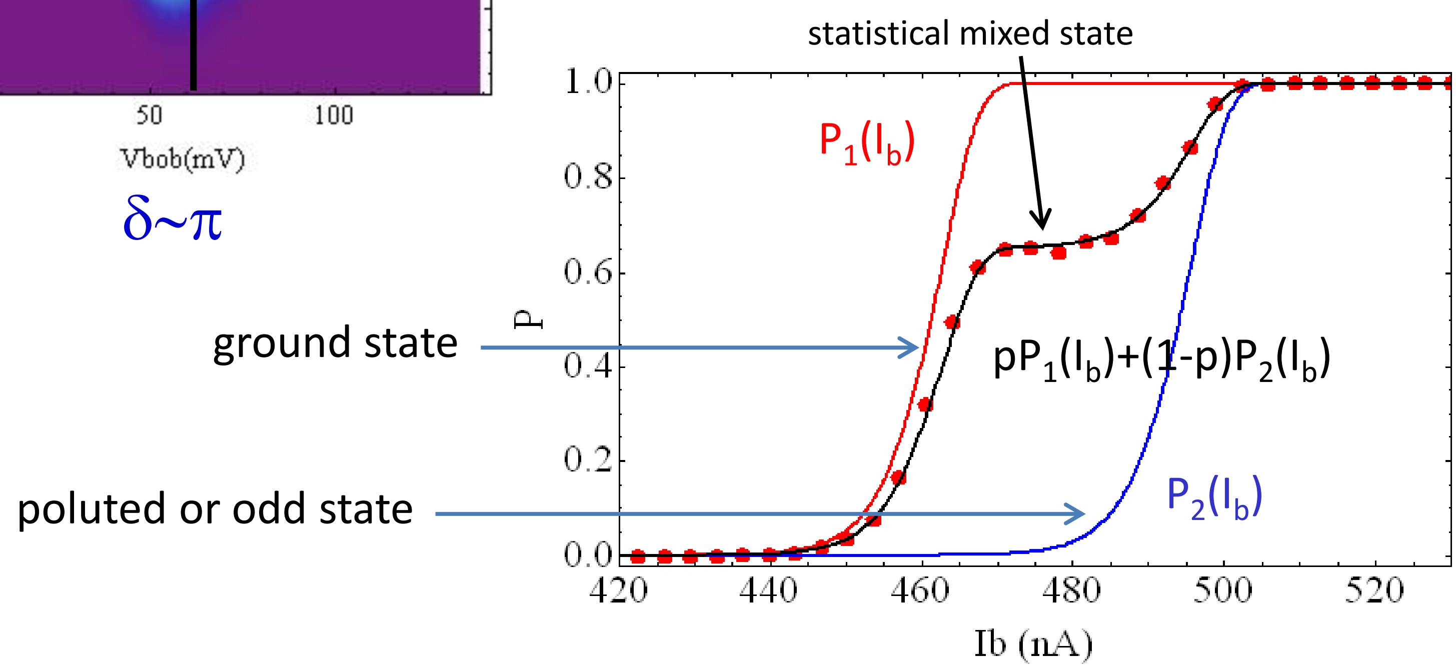
High transparency

*M. Zgirski et al. PRL **106**, 257003 (2011)*

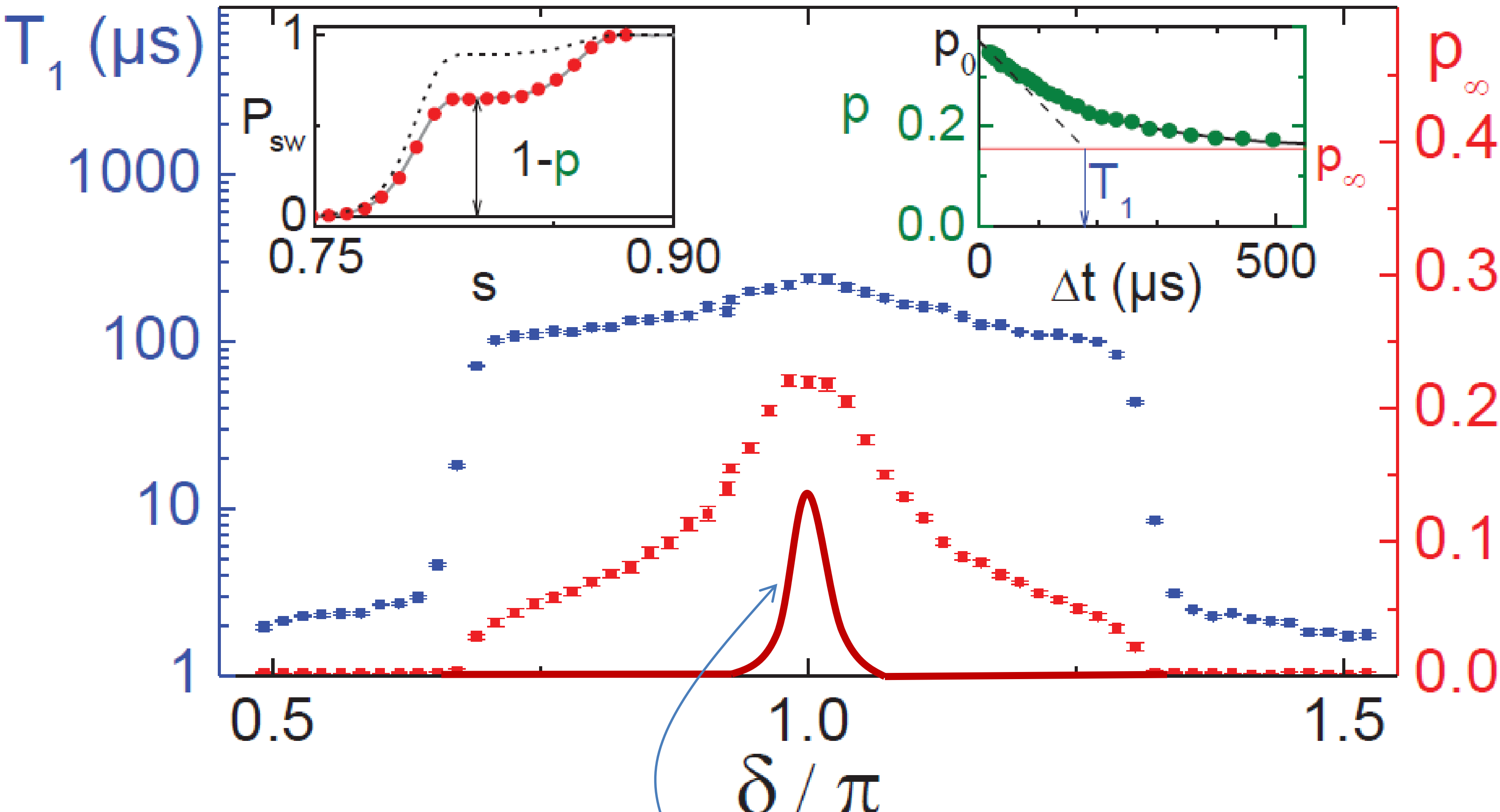


$\delta \sim \pi$





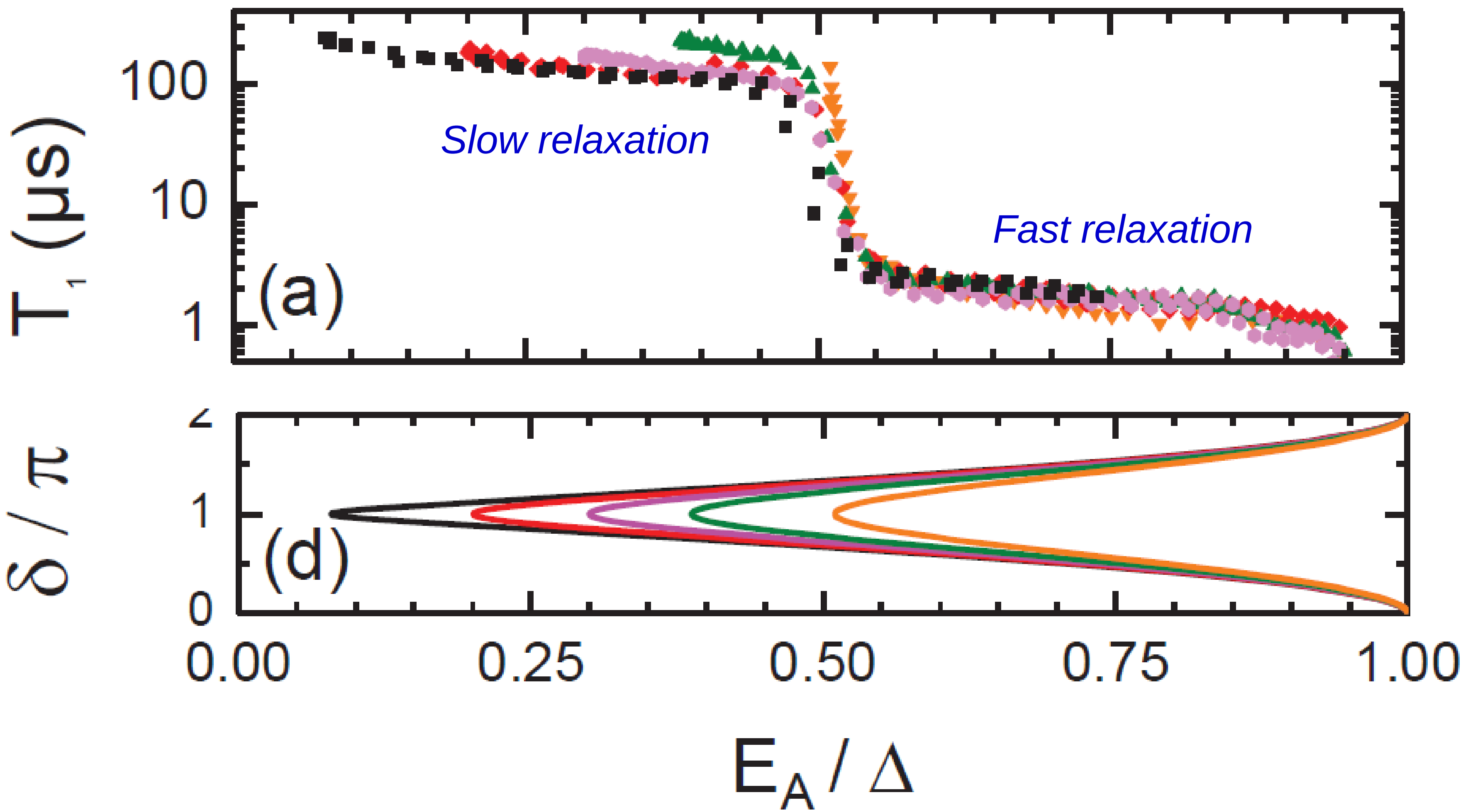
Relaxation time and stationary probability



$T \approx 30\,\mathrm{mK}$

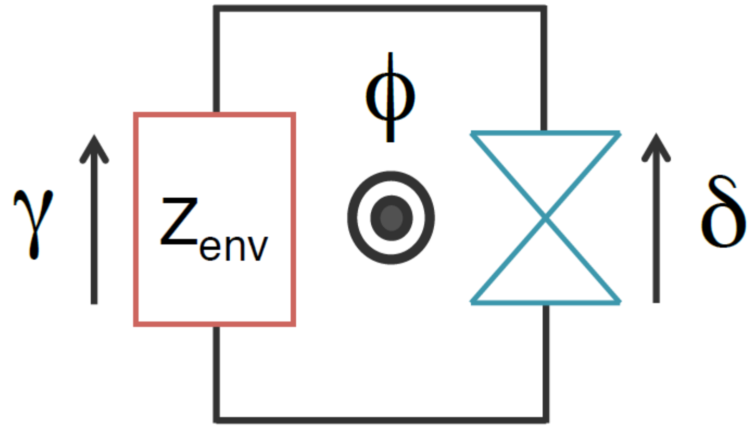
$$p_{eq} = 2 f(E_A, T) f(-E_A, T)$$

Approximate "Universality"



Theory of qp trapping?

Theoretical model



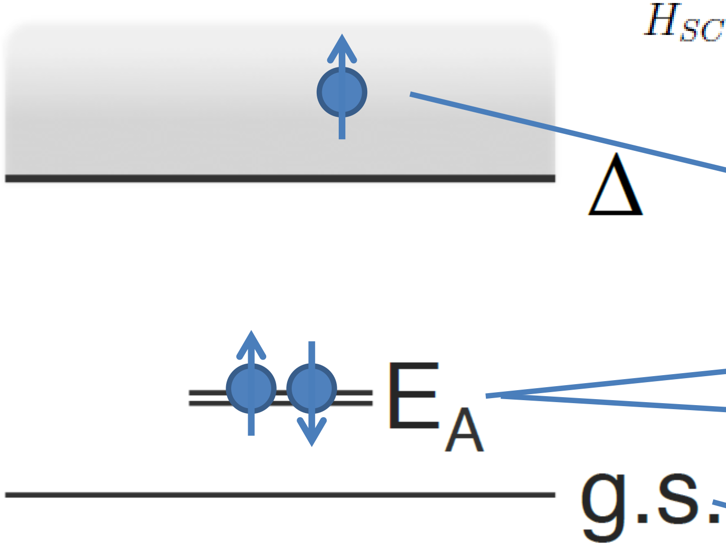
$$\hat{H} = \hat{H}_{SC}(\hat{\delta}) + \hat{H}_{\text{env}}(\hat{\gamma})$$

$$\text{Re}(Z_{\text{env}}) \ll R_Q$$

$$\hat{H} \simeq \hat{H}_{\text{env}}(\hat{\gamma}) + \hat{H}_{SC}(\varphi) + \varphi_0 \hat{\gamma} \hat{I}(\varphi)$$

$$\hat{I} = \varphi_0^{-1} \partial \hat{H}_{SC} / \partial \delta \qquad \varphi_0 = \hbar / 2e$$

$$\hat{H}_{SC}(\varphi) = -E_A(\varphi) + \sum_{\sigma} E_A(\varphi) \gamma^{\dagger}_{A,\sigma} \gamma_{A,\sigma} + \sum_{k,\eta,\sigma} E_k \gamma^{\dagger}_{k,\eta,\sigma} \gamma_{k,\eta,\sigma}$$



$\gamma^{\dagger}_{k,\eta,\sigma} |\Psi_0\rangle$

$\gamma^{\dagger}_{A,\sigma} |\Psi_0\rangle$ odd

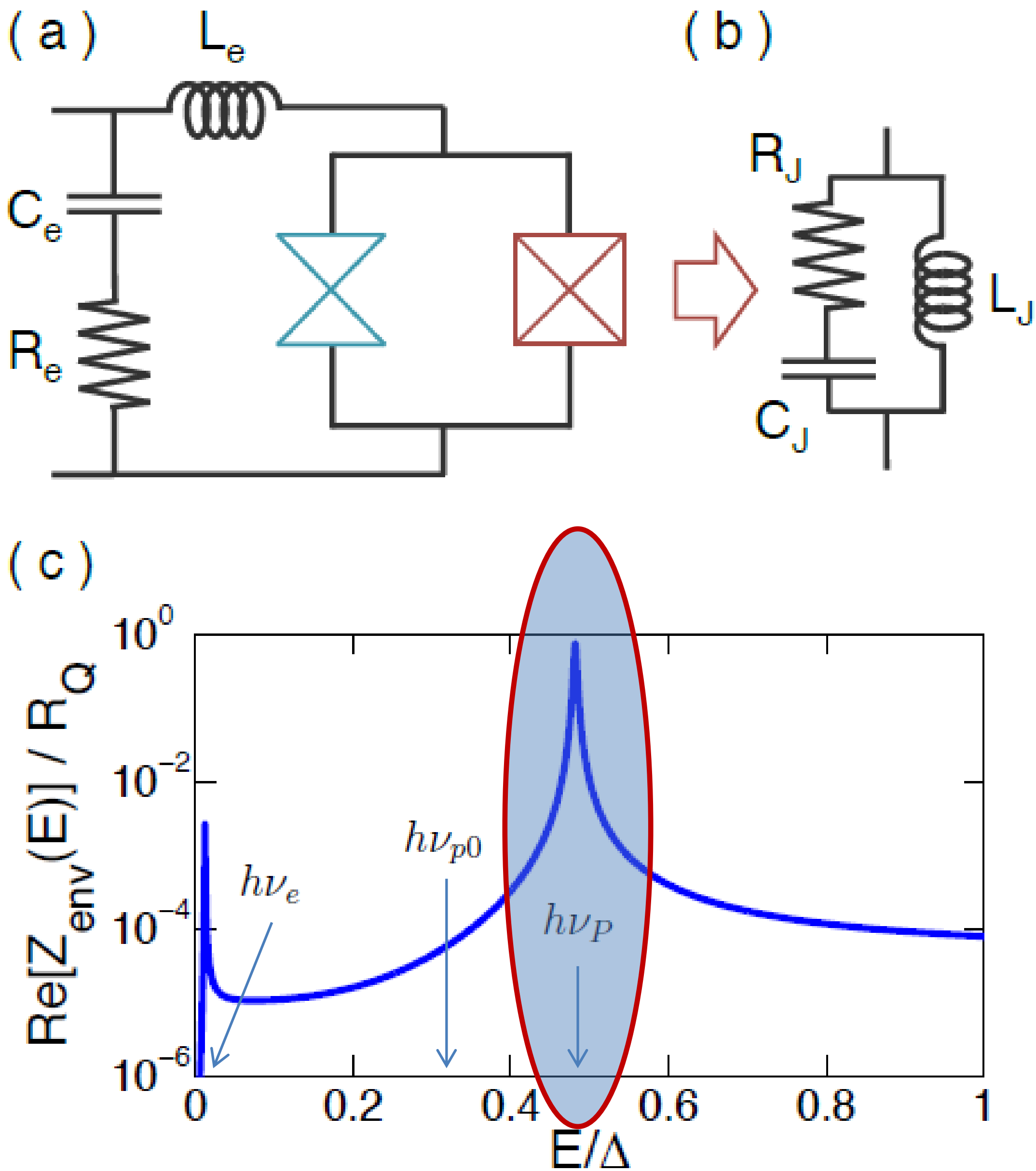
even*

$\gamma^{\dagger}_{A,\uparrow} \gamma^{\dagger}_{A,\downarrow} |\Psi_0\rangle$

$|\Psi_0\rangle$ even

$\gamma_{\alpha,\sigma} |\Psi_0\rangle = 0$

Description of the EM environment



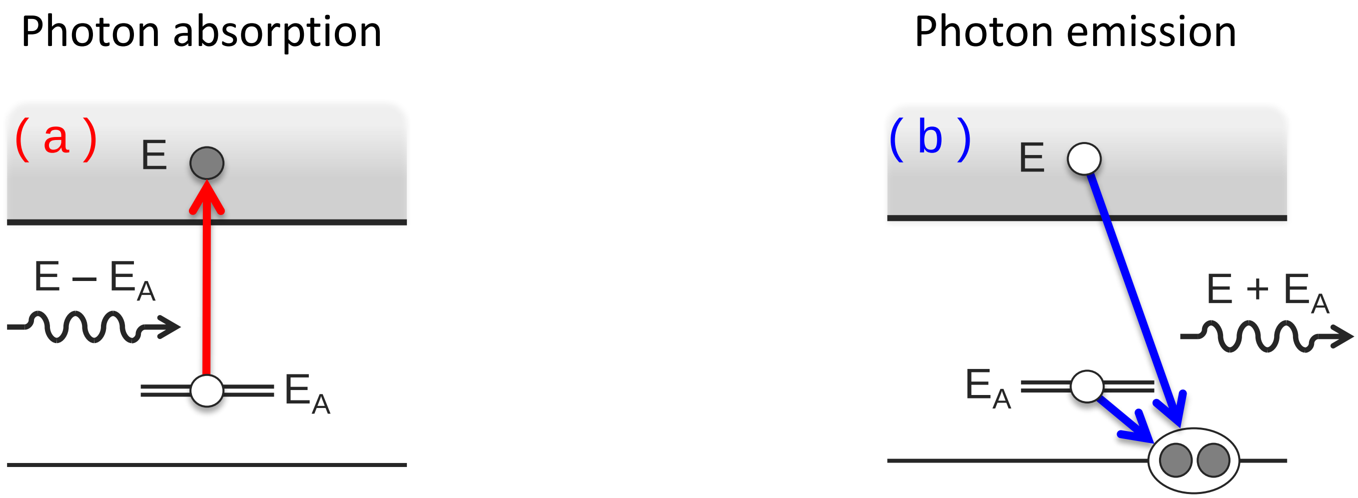
$$\nu_e = \frac{1}{2\pi}(L_e C_e)^{-1/2}$$

$$\nu_{p0} = \frac{1}{2\pi}(L_J C_J)^{-1/2}$$

$$\nu_P = \frac{1}{2\pi}\sqrt{\frac{L_J^{-1} + L_e^{-1}}{C_J}}$$

$$Q \simeq 100$$

Transition rates: from an initial odd state



$$\Gamma^{(a)}_{\mathrm{out}} = \frac{2\pi}{\hbar}\sum_{k,\eta}\left|\left\langle \Psi_0 \left| \gamma_{k,\eta,\sigma}\varphi_0 \hat{I}\gamma^{\dagger}_{A,\sigma}\right| \Psi_0\right\rangle\right|^2 D\left(E_k - E_A(\delta)\right) f_{\mathrm{BE}}\left(E, T_{\mathrm{env}}\right)\left(1 - f_{\mathrm{FD}}(E_k, T_{\mathrm{qp}})\right)$$

$$D(E) = \frac{\mathrm{Re}\left\{Z_{\mathrm{env}}(E)\right\}}{E R_Q}$$

Ingold-Nazarov, Single Charge Tunneling Plenum 1992

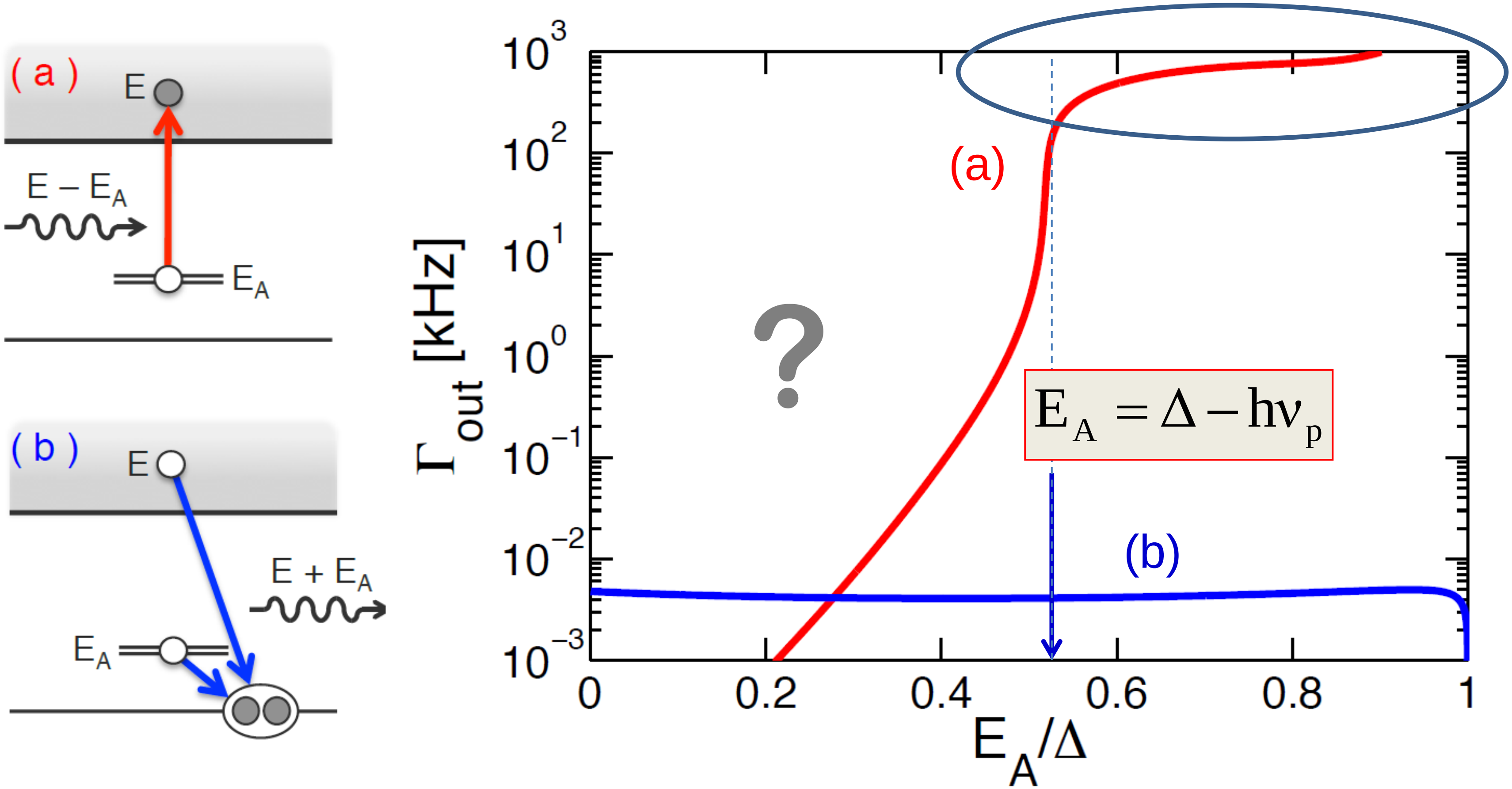
$$\Gamma^{(a)}_{\mathrm{out}} = \frac{8\Delta}{h}\int_{\Delta}^{\infty} dE\, D\left(E - E_A\right) g\left(E, E_A\right) f_{\mathrm{BE}}\left(E - E_A, T_{\mathrm{env}}\right)\left(1 - f_{\mathrm{FD}}\left(E, T_{\mathrm{qp}}\right)\right)$$

matrix elements for perfect transmission

$$g\left(E, E_A\right) = \frac{\sqrt{\left(E^2 - \Delta^2\right)\left(\Delta^2 - E_A^2\right)}}{\Delta\left(E - E_A\right)}$$

Untrapping rates

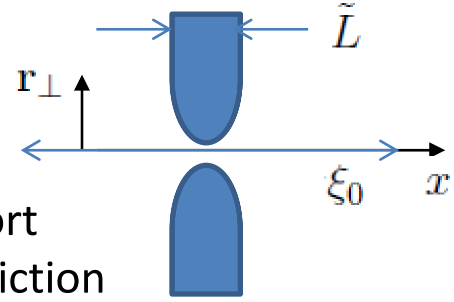
Consistent with observed T_1~1μs (fast relaxation)



Electron-phonon mechanism

$$\hat{H}_{\text{e-ph}} = \tilde{\gamma} \int d\mathbf{r} \sum_{\sigma} \Psi_{\sigma}^{\dagger}(\mathbf{r}) \Psi_{\sigma}(\mathbf{r}) \hat{\phi}(\mathbf{r})$$

$$\hat{\phi}(\mathbf{r}) = \sum_{\mathbf{q}} \sqrt{\frac{h\nu_{\mathbf{q}}}{2V}} \left(b_{\mathbf{q}} e^{i\mathbf{q}\mathbf{r}} + b_{\mathbf{q}}^{\dagger} e^{-i\mathbf{q}\mathbf{r}}\right)$$



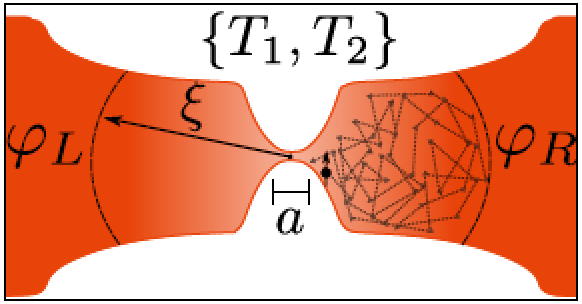
Short constriction

A. Zazunov et al. PRB (2005)

$$\Gamma_{\text{out}}^{(a)} = \kappa_{\text{e-ph}} \Delta^3 \left(\frac{\tilde{L}}{\xi_0}\right)^2 \int_{\Delta}^{\infty} \frac{dE}{\Delta} \left(\frac{E - E_A}{\Delta}\right)^3 g(E, -E_A)\, f_{\text{BE}}(E - E_A, T_{\text{ph}}) \left(1 - f_{\text{FD}}(E, T_{\text{qp}})\right)$$

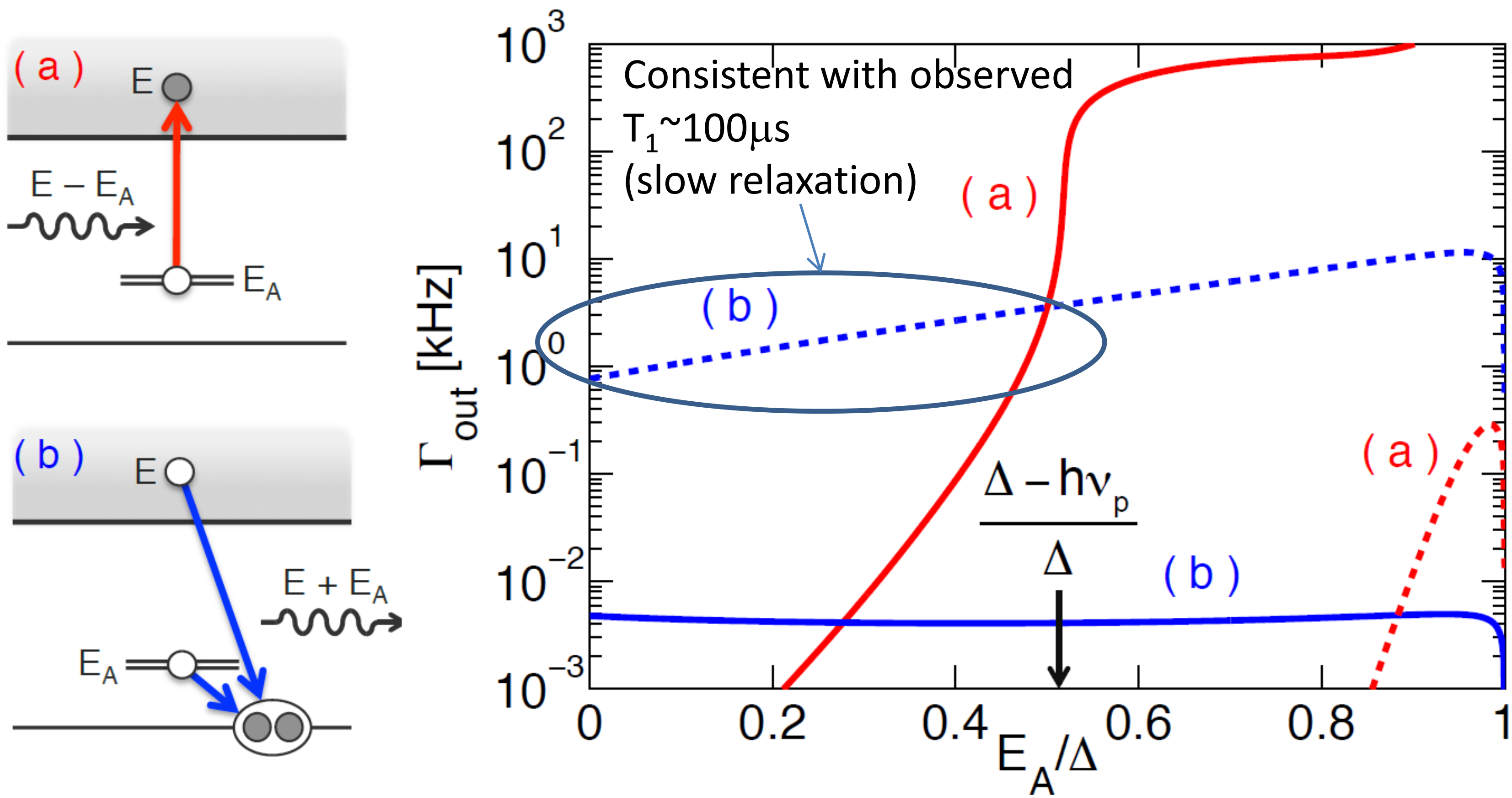
$$\kappa_{\text{e-ph}} \Delta^3 = \frac{16\tilde{\gamma}^2 \Delta^3}{\pi^2 \hbar^4 c_s^3} \sim 10 \text{ GHz}$$

$$\left(\frac{\tilde{L}}{\xi_0}\right)^2 \sim 10^{-2} \qquad \Gamma_{\text{out}}(E_A = 0) \sim 1\text{kHz}$$



Padurariu-Nazarov
EPL **100**, 57006 (2012)

Untrapping rates

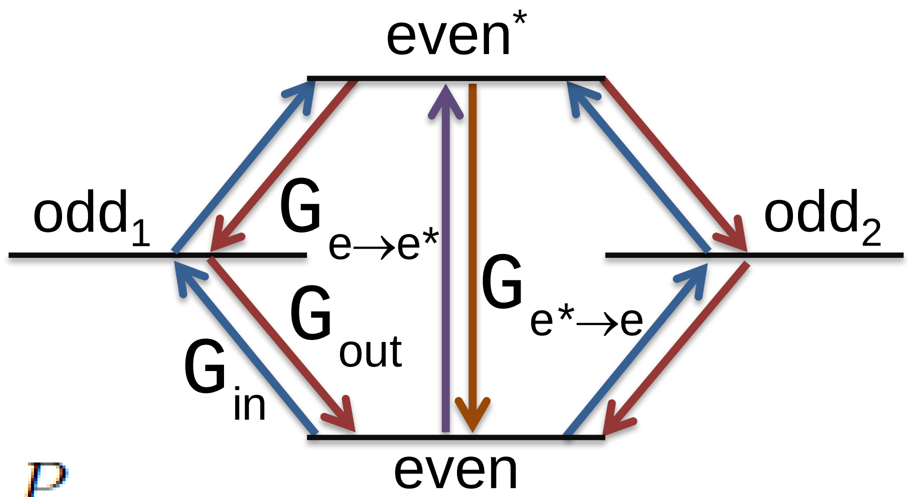


$$k_B T_{\mathrm{qp}} = 0.09\Delta \sim k_B T_{\mathrm{env}} \quad > k_B T_{\mathrm{ph}} = 0.016\Delta$$

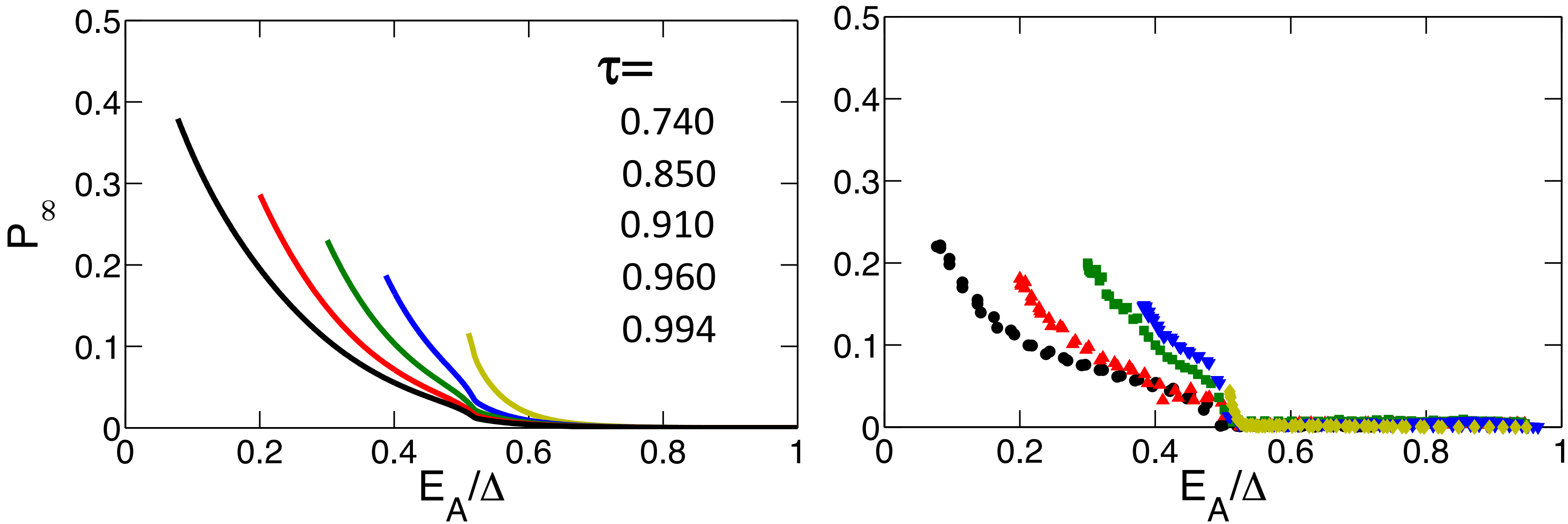
Corresponds to a few tens of noneq qps per μm^3

$T \approx 30$ mK

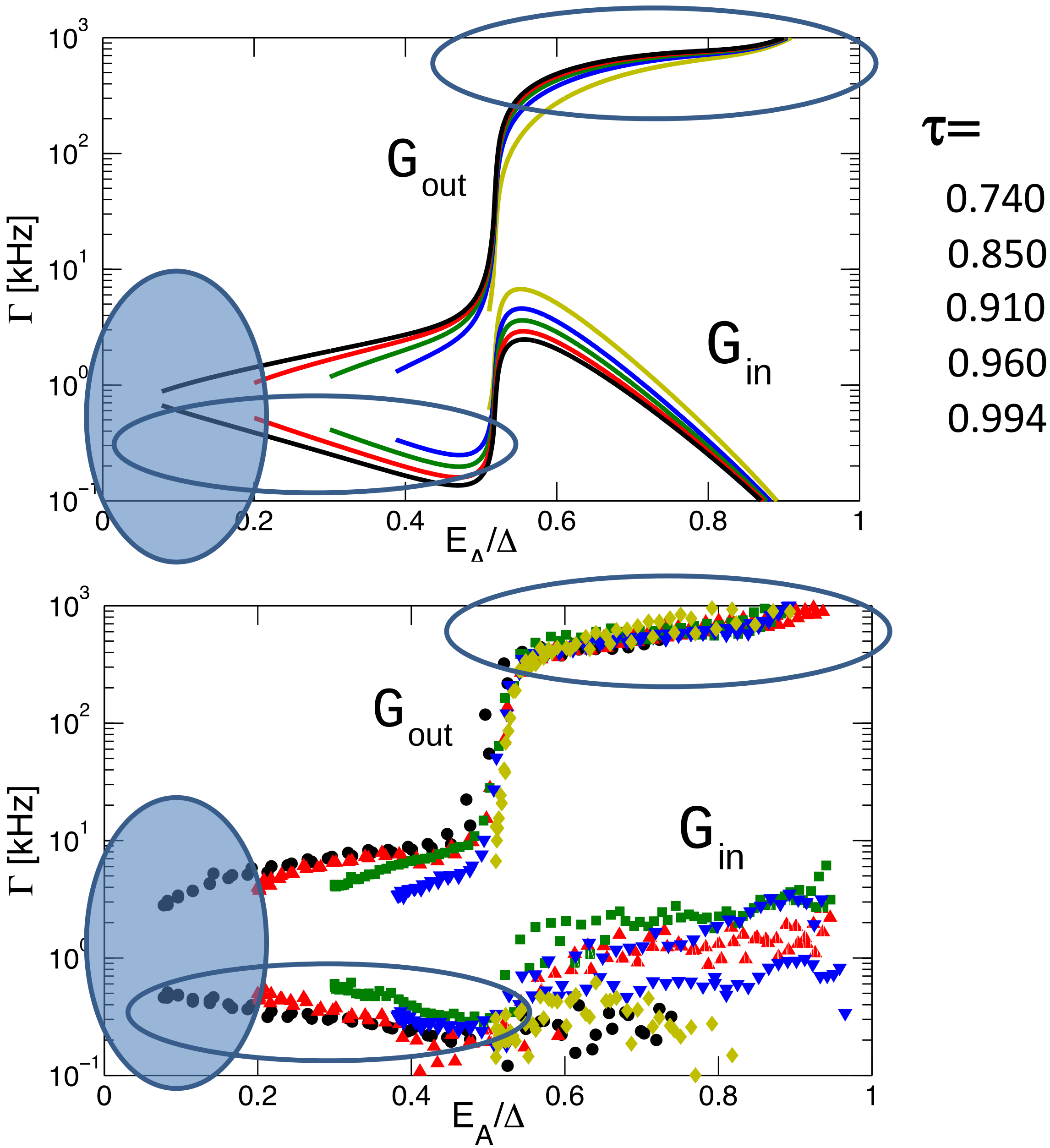
Rate equations and stationary probabilties



$$P_{\rm odd} \equiv P_\infty$$

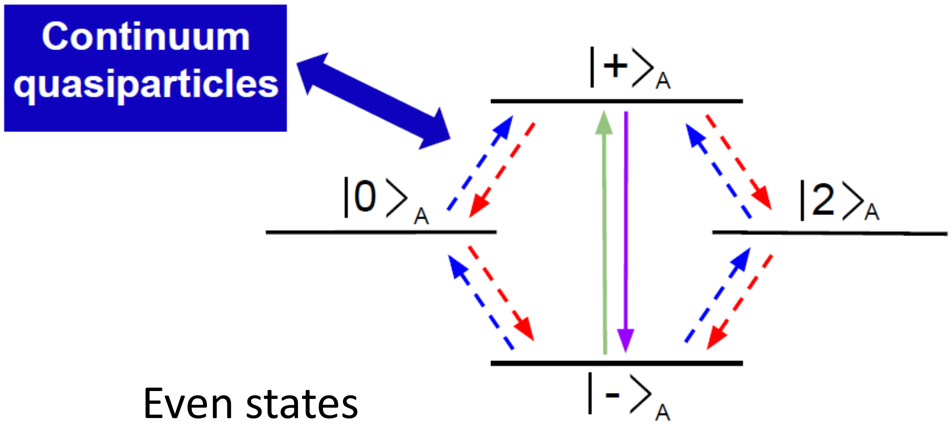


Trapping-untrapping rates: theory vs exp



A. Zazunov, A. Brunetti, R. Egger & ALY
Phys. Rev. B 90, 104508 (2014)

Generalized rate equations



Odd states

$$\dot{P}_0 = -\sum_{p,\eta=\pm} \left[\Gamma_{p,\eta} n_p P_0 - \Gamma_{\eta,p}(1-n_p) P_\eta\right]$$

$$\dot{P}_2 = -\sum_{p,\eta} \left[\Gamma_{\eta,p}(1-n_p) P_2 - \Gamma_{p,-\eta} n_p P_\eta\right]$$

Even states

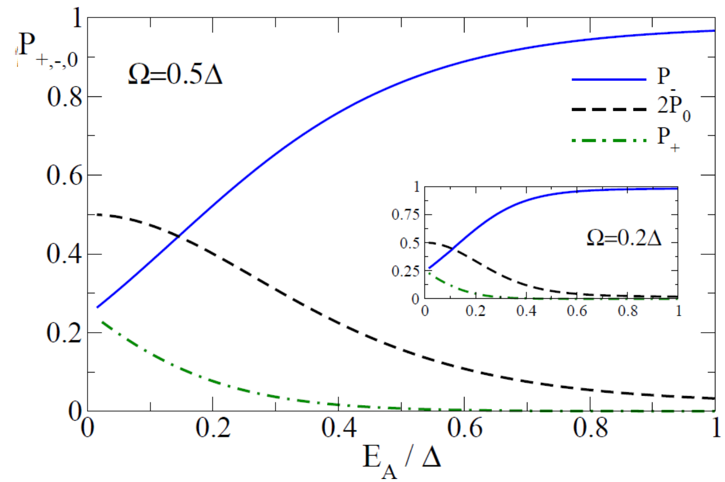
$$\dot{P}_\eta = -\Gamma_{\eta,-\eta} P_\eta + \Gamma_{-\eta,\eta} P_{-\eta} - \sum_p \left[n_p \left(\Gamma_{p,-\eta} P_\eta - \Gamma_{p,\eta} P_0\right) + (1-n_p)\left(\Gamma_{\eta,p} P_\eta - \Gamma_{-\eta,p} P_2\right)\right]$$

Continuum states

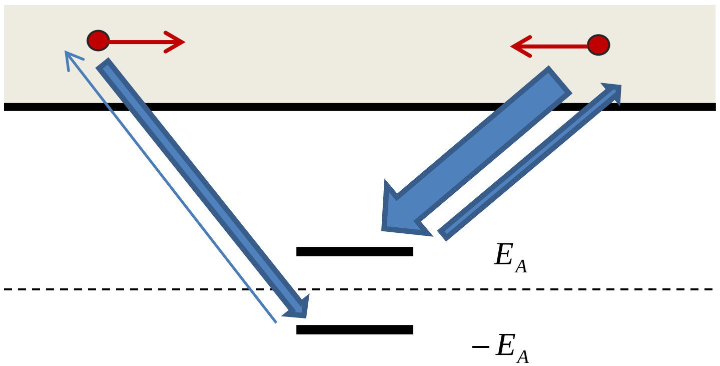
$$\partial_t n_p = -\sum_{\eta=\pm} \left[\Gamma_{p,\eta}(1-n_\eta) n_p - \Gamma_{\eta,p}(1-n_p) n_\eta\right]$$

$$\Gamma_{\nu\nu'} = \frac{2\pi}{\hbar} \left|\mathcal{I}_{\nu\nu'}\right|^2 \left[1 + n_B\left(E_\nu - E_{\nu'}\right)\right] J\left(E_\nu - E_{\nu'}\right)$$

$$J(\omega) = \frac{\lambda^2 \eta_d}{2\pi} \left(\frac{1}{(\omega-\Omega)^2 + \eta_d^2/4} - \frac{1}{(\omega+\Omega)^2 + \eta_d^2/4} \right)$$



Charge imbalance



(perfect transmission case)

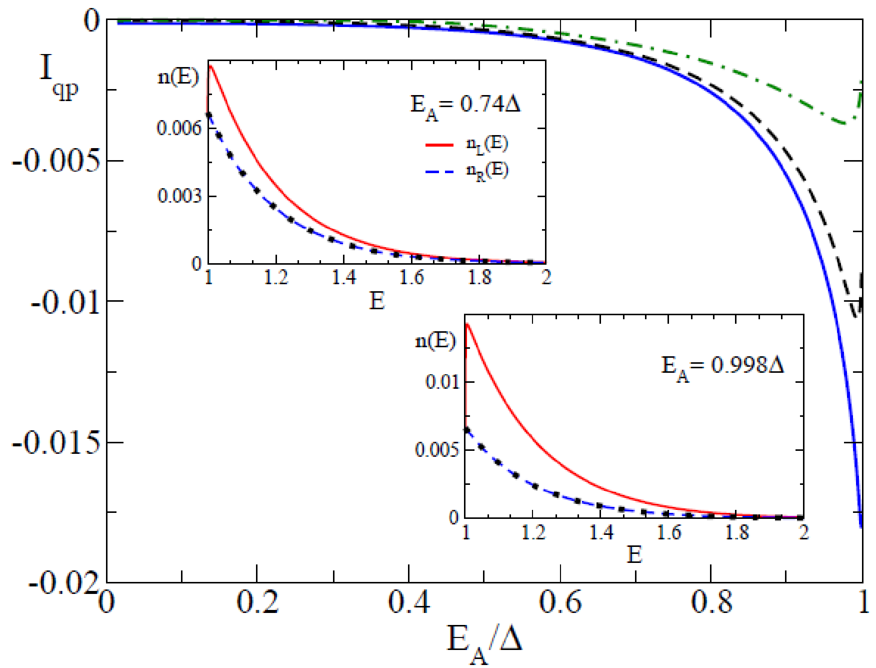
Continuum states: $p=(E,s)$

$s=1$ qe, right
$s=2$ qh, right
$s=3$ qe, left
$s=4$ qh, left

$$n_{(E,s=1)} = n_{(E,s=4)} = n_R(E),$$
$$n_{(E,s=2)} = n_{(E,s=3)} = n_L(E).$$

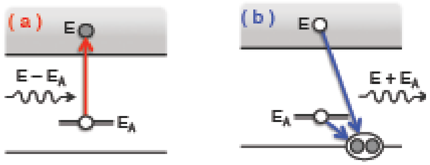
$$I_{\rm qp} = \frac{e}{\pi\hbar}\int_{|E|\geq\Delta} dE\ j_{\rm qp}(E)\left[n_R(E) - n_L(E)\right],$$

$$j_{\rm qp}(E) = \frac{|E|\sqrt{E^2-\Delta^2}}{E^2-E_A^2},$$



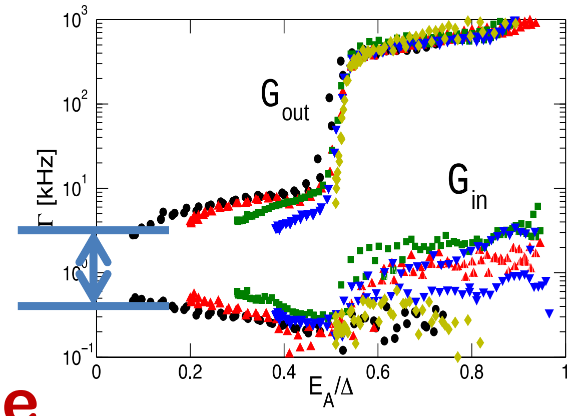
Summary and outlook

Trapping dynamics: photons vs phonons



Only semi-quantitative agreement:

gap between Γ_{out} and Γ_{in} is an open issue



Backaction on qps: charge-imbalance

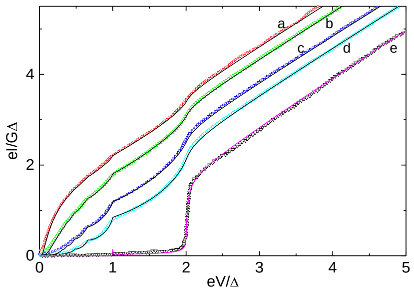
*Riwar et al. JPCM **27**, 095701 (2015)*

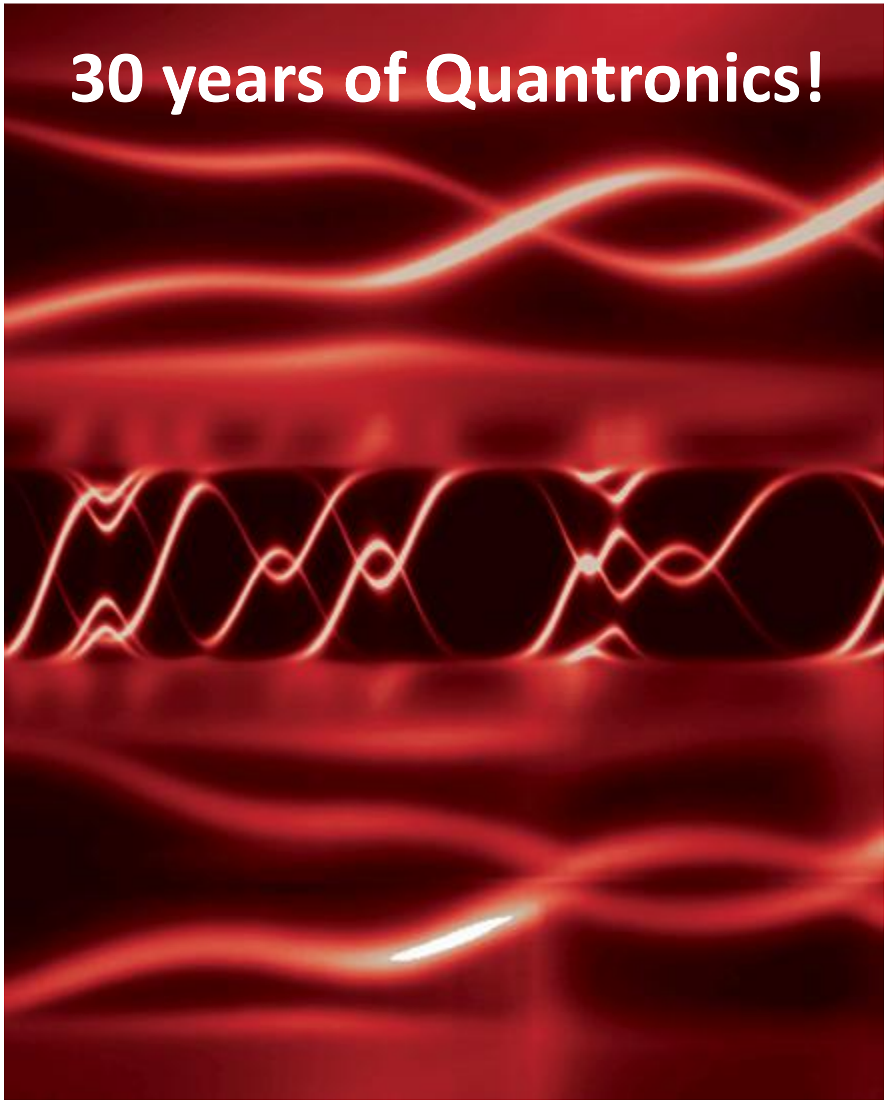
ABS: extremely sensitive qp detectors

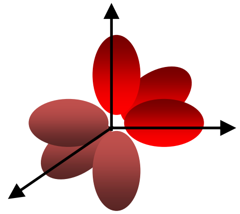
*Levenson-Falk et al. PRL **112**, 047002 (2014)*

Work in progress: qp poisoning in Topological junctions

Thank you for







$\{\tau_n\}$