Coherence and Decoherence in Mesoscopic Transport

Tobias Brandes (Manchester)

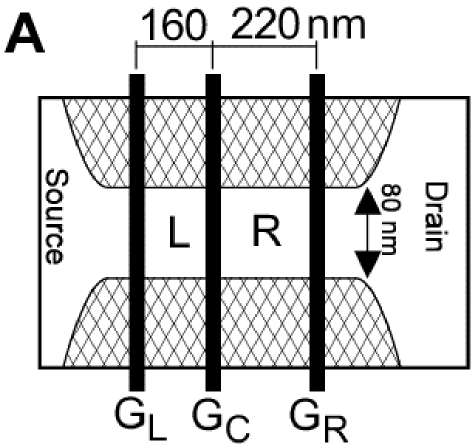
- Quantum Mechanical Transport
- Quantum Noise, Dissipation
- Nanomechanics, Quantum Optics and Mesoscopics
- Non-equilibrium in Driven Systems

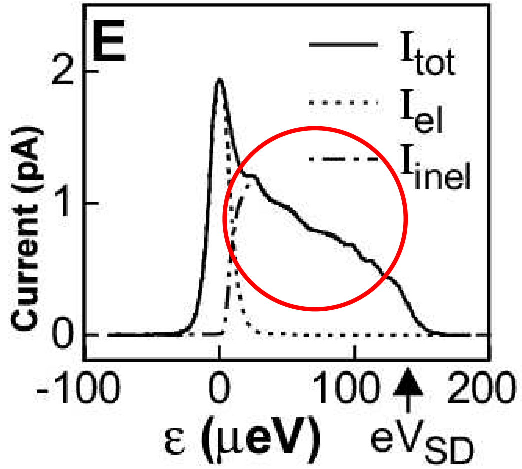
'Coherent and Collective Quantum Optical Effects in Mesoscopic Systems', (TB 2004, Phys. Rep., cond-mat/0409771)

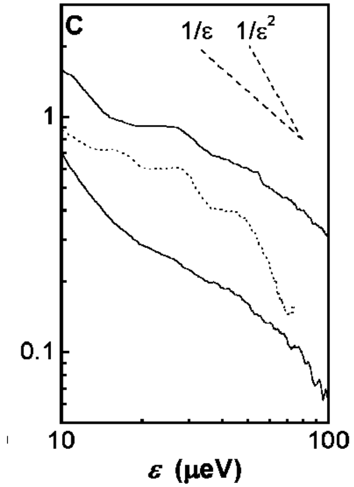
Electronic Transport

1956 'transistor' 1972 'BCS' 1973 'tunneling phenomena in semiconductors and superconductor' 1977 'electronic structure' 1985 'quantized Hall effect' 1987 'superconductivity in ceramic materials' 1998 'quantum fluid with fractionally charged excitations' 2003 'superconductors and superfluids'

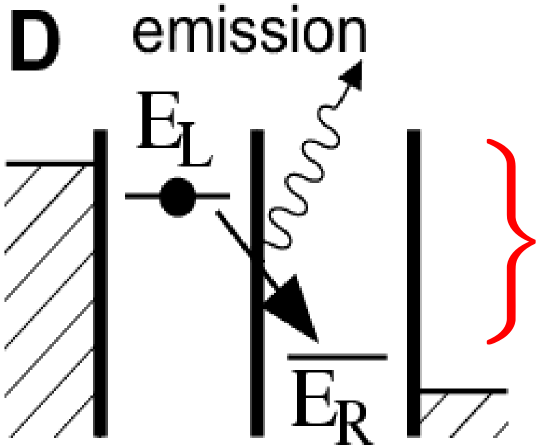
- Aspects:
  - Correlations
  - Non-Equilibrium
  - Quantum-Coherence / Decoherence
- Low-dimensional quantum systems, coupled to external world
  - d=2,1,0
  - (d=0) charge and spin-qubits: quantum dots, Cooper-Pair-Box, ...



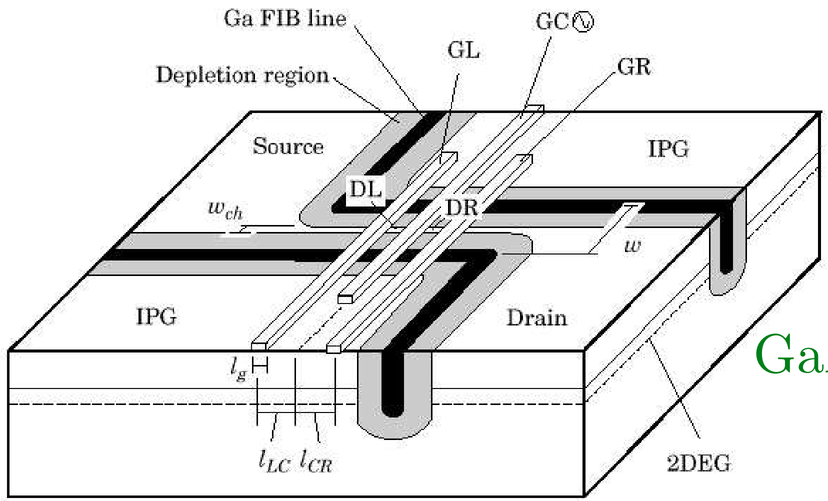




$\propto \varepsilon^{1+2\alpha}$



ε

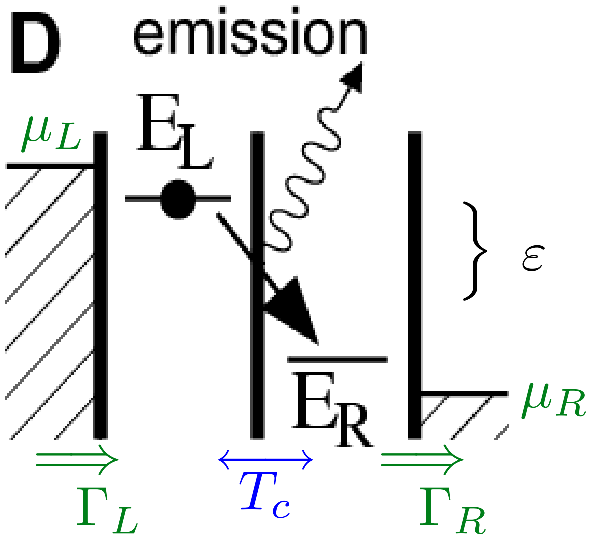


GaAs/AlGaAs

Spontaneous Emission
of Phonons, T=23 mK

T. Fujisawa, T. H. Oosterkamp, W. G. van der Wiel, B. W. Broer, R. Aguado, S. Tarucha, and L. P. Kouwenhoven, Science **282**, 932 (1998)

- ‘Canonical Model’: Transport, Coulomb-Blockade, Quantum Coherence, Dissipation.



3 states $|L\rangle$, $|R\rangle$, $|0\rangle$.

$\hat{\sigma}_z \equiv |L\rangle\langle L| - |R\rangle\langle R|, \quad \hat{\sigma}_x \equiv |L\rangle\langle R| + |R\rangle\langle L|.$

$$\begin{aligned} \mathcal{H} &= \mathcal{H}_{SB} + \mathcal{H}_{res} + \mathcal{H}_T \\ \mathcal{H}_T &= \sum_{k_\alpha} (V_k^\alpha c_{k_\alpha}^\dagger |0\rangle\langle\alpha| + H.c.), \alpha = L, R \\ \mathcal{H}_{SB} &= \left[\frac{\varepsilon(t)}{2} + \sum_{\mathbf{Q}} \frac{g_Q}{2}\left(a_{-\mathbf{Q}} + a_{\mathbf{Q}}^\dagger\right)\right]\hat{\sigma}_z + T_c(t)\hat{\sigma}_x + \mathcal{H}_B. \end{aligned}$$

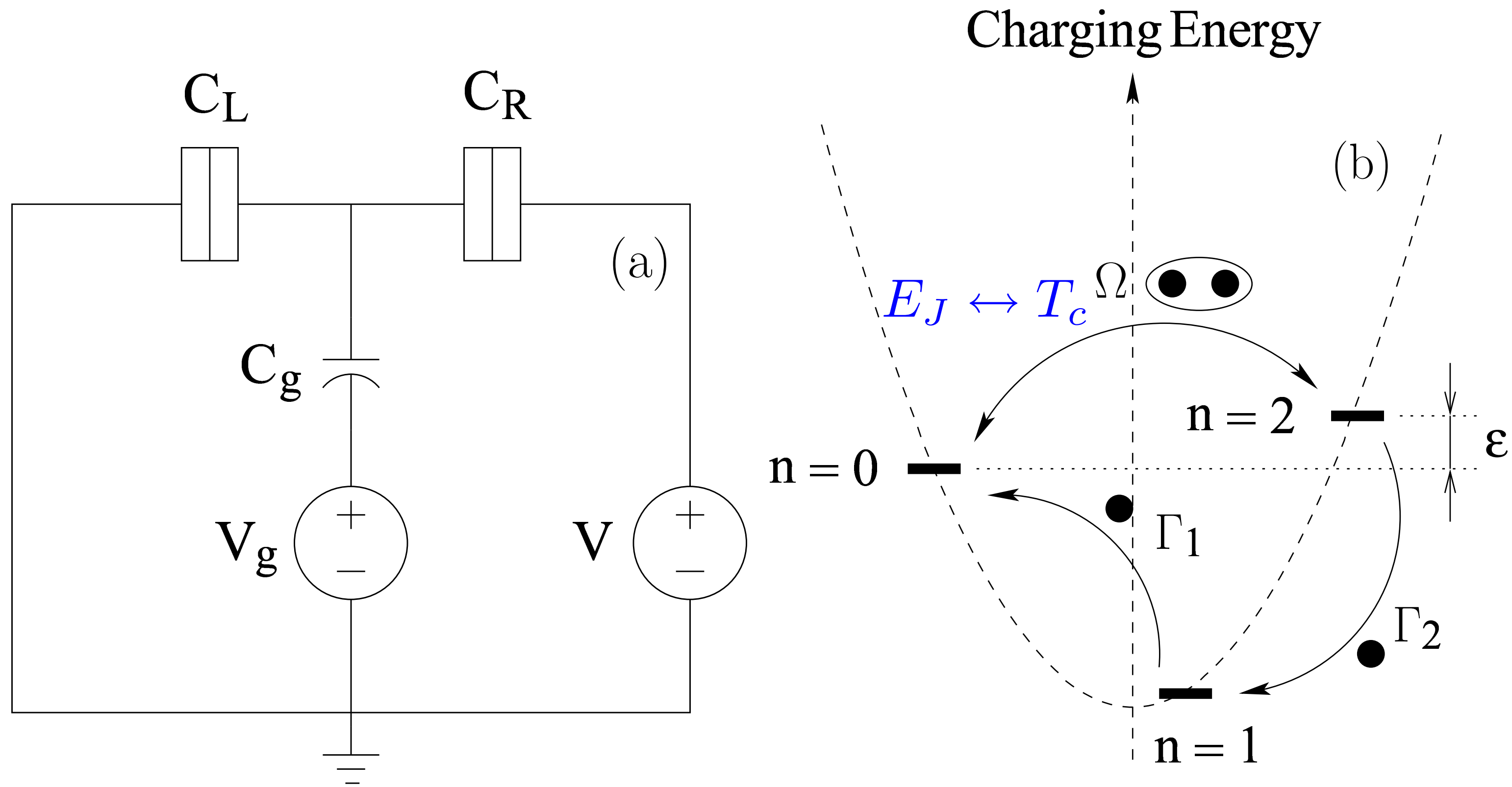
Loc-Deloc Transition at $\alpha = 1$, *Leggett et al 87*

- ‘Internal’ Parameter $\varepsilon(t), T_c(t)$;

$$J(\omega) \equiv \sum_{\mathbf{Q}} |g_Q|^2 \delta(\omega - \omega_Q) = \begin{cases} 2\alpha\omega_{\text{ph}}^{1-s}\omega^s e^{-\frac{\omega}{\omega_c}} \\ \text{microscopic model: } \textit{Phonons...} \end{cases}$$

- ‘External’ parameters μ_L, μ_R, $\Gamma_\alpha(\varepsilon) = 2\pi \sum_{k_\alpha} |V_k^\alpha|^2 \delta(\varepsilon - \varepsilon_{k_\alpha})$, $\alpha = L/R$.

Analogy with SSET (superconducting single electron transistor), $E_C \gg E_J$:

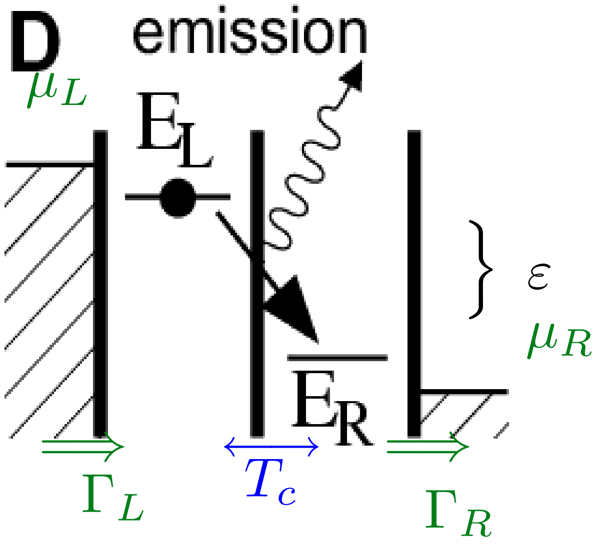


M.-S. Choi, F. Plastina, R. Fazio, PRB **67**, 045105 (2003)

$|L\rangle \leftrightarrow 0,\ |R\rangle \leftrightarrow 2,\ |0\rangle \leftrightarrow 1$

EXP: Y. Nakamura, Yu. A. Pashkin, and J. S. Tsai, Nature **398**, 786 (1999).

Formulation



- EOM for reduced density operator

$$\langle \mathbf{A}(t)\rangle = \langle \mathbf{A}(0)\rangle + \int_0^t dt' \left\{ M(t,t') \langle \mathbf{A}(t')\rangle + \Gamma_L \mathbf{e}_1 \right\}.$$

- $\mu_L - \mu_R \to \infty$ (Gurvitz, Prager 1996, Stoof, Nazarov 1996, Gurvitz 1998.)

- 'Memory Kernel'

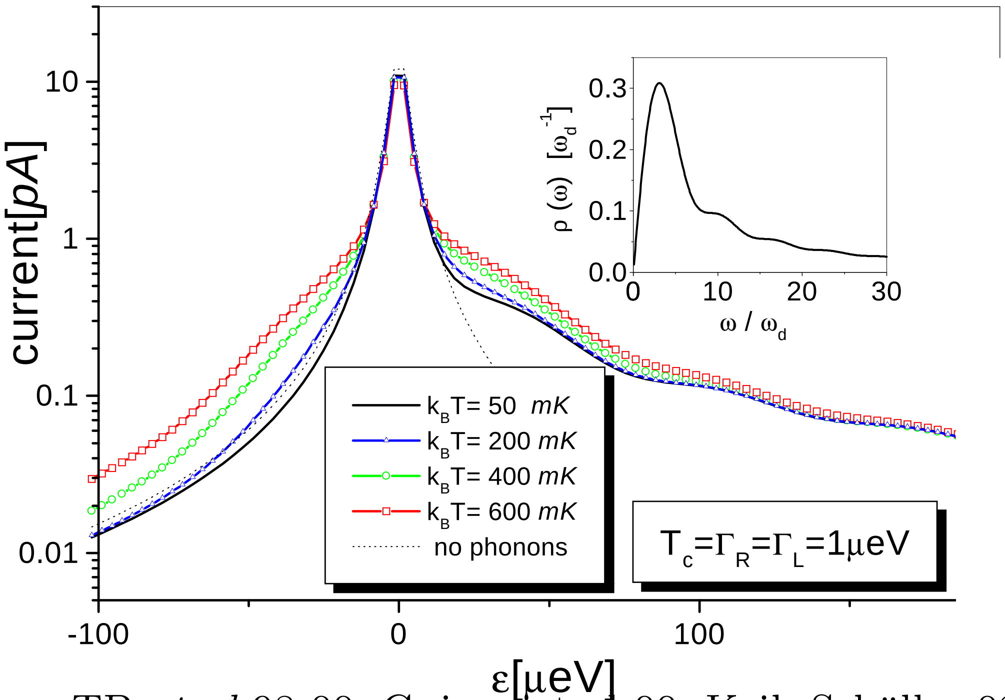
$$z\hat{M}(z) = \begin{bmatrix} -\hat{G} & \hat{T}_c \\ \hat{D}_z & \hat{\Sigma}_z \end{bmatrix}, \quad \hat{G} \equiv \begin{pmatrix} \Gamma_L & \Gamma_L \\ 0 & \Gamma_R \end{pmatrix}, \quad \hat{T}_c \equiv iT_c(\sigma_x - 1)$$

- Blocks $\hat{D}_z$, $\hat{\Sigma}_z$: Dephasing, Relaxation $\begin{cases} \text{PER} \\ \text{POL} \end{cases}$

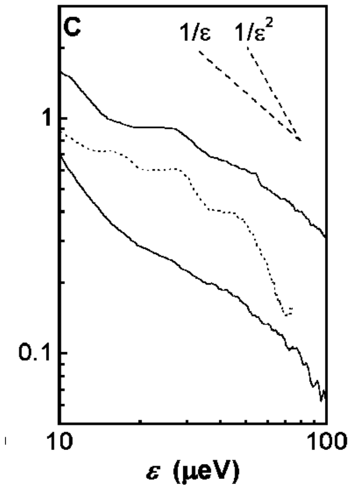
- Polaron-Transformation (POL) $\equiv$ NIBA (non-interacting blib approximation): calculate $\hat{D}_z$ and $\hat{\Sigma}_z$ using bosonic correlation function

$$C_\varepsilon^{[*]}(z) \equiv \int_0^\infty dt e^{-zt} e^{[-]i\varepsilon t} \exp(-\int_0^\infty d\omega \frac{J(\omega)}{\omega^2} \left[(1-\cos\omega t)\coth\left(\frac{\beta\omega}{2}\right) \pm i \sin\omega t\right]).$$

- Polaron tunneling $\rightsquigarrow$ 'boson shake-up' effect
- $\mathrm{Re}[C_\varepsilon(z)]|_{z=\pm i\omega} = \pi P(\varepsilon \mp \omega)$: P(E)-Theory.



TB *et al* 98-00; Guinea et al 00; Keil, Schöller 02



T. Fujisawa, T. H. Oosterkamp, W. G. van der Wiel, B. W. Broer, R. Aguado, S. Tarucha, and L. P. Kouwenhoven, Science **282**, 932 (1998)

$\propto \varepsilon^{1+2\alpha}, \alpha \approx 0.1$

PHYSICAL REVIEW B VOLUME 46, NUMBER 19 15 NOVEMBER 1992-I

Scattering theory of current and intensity noise correlations in conductors and wave guides

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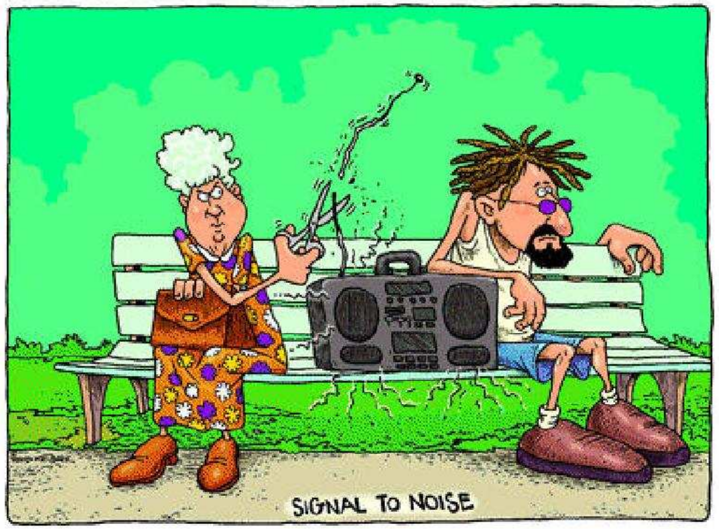
(Received 16 June 1992)

- Quantum Mechanical Transport
- Quantum Noise
- Nanomechanics, Quantum Optics and Mesoscopi
- Non-equilibrium in Driven Systems



R. Landauer : 'the noise is the signal'.

'Whether noise is a nuisance or a signal may depend on whom you ask' C. Beenakker, C. Schönenberger Physics Today 2003.

Quantum Noise: particle statistics, quantum coherence, dissipation, entanglement $\leftrightarrow$ equilibrium noise

Quantum Noise in presence of CB, Q-coherence + dissipation?

- Noise-Spectrum with current conservation $I_L - I_R = \dot{Q}$, $I = aI_L + bI_R$,

$$\mathcal{S}_{\mathcal{I}}(\omega) \equiv \int_{-\infty}^{\infty} d\tau e^{i\omega\tau} \langle \{\Delta\hat{I}(\tau), \Delta\hat{I}(0)\} \rangle = \underline{aS_{I_L}(\omega) + bS_{I_R}(\omega)} - ab\omega^2 \underline{S_Q(\omega)}$$

- $\underline{S_{I_R}(\omega)}$ using 'Full Counting Statistics' ($\leftrightarrow$ Quantum Jump Approach) ,

$$\dot{n}_0^{(n)} = -\Gamma_L n_0^{(n)} + \Gamma_R n_R^{(n-1)}, \quad \dot{n}_{L/R}^{(n)} = \pm\Gamma_{L/R} n_0^{(n)} \pm iT_c \left(p^{(n)} - [p^{(n)}]^\dagger\right), \quad \text{etc.}$$

- $\underline{S_Q(\omega)}$ using resolvent $[z - z\hat{M}(z)]^{-1}$.

Explicitly for model with charge degrees of freedom L, R

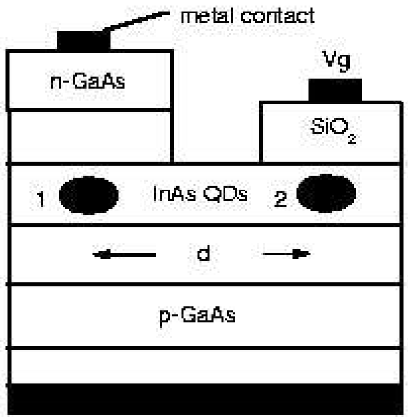
$$S_{I_R}(\omega) = 2eI\left\{1 + \Gamma_R\left[\hat{n}_R(-i\omega) + \hat{n}_R(i\omega)\right]\right\}$$

$$z\hat{n}_R(z) = \frac{\Gamma_L g_+(z)}{\{z + \Gamma_R + g_-(z)\}(z + \Gamma_L) + (z + \Gamma_R + \Gamma_L)g_+(z)}$$

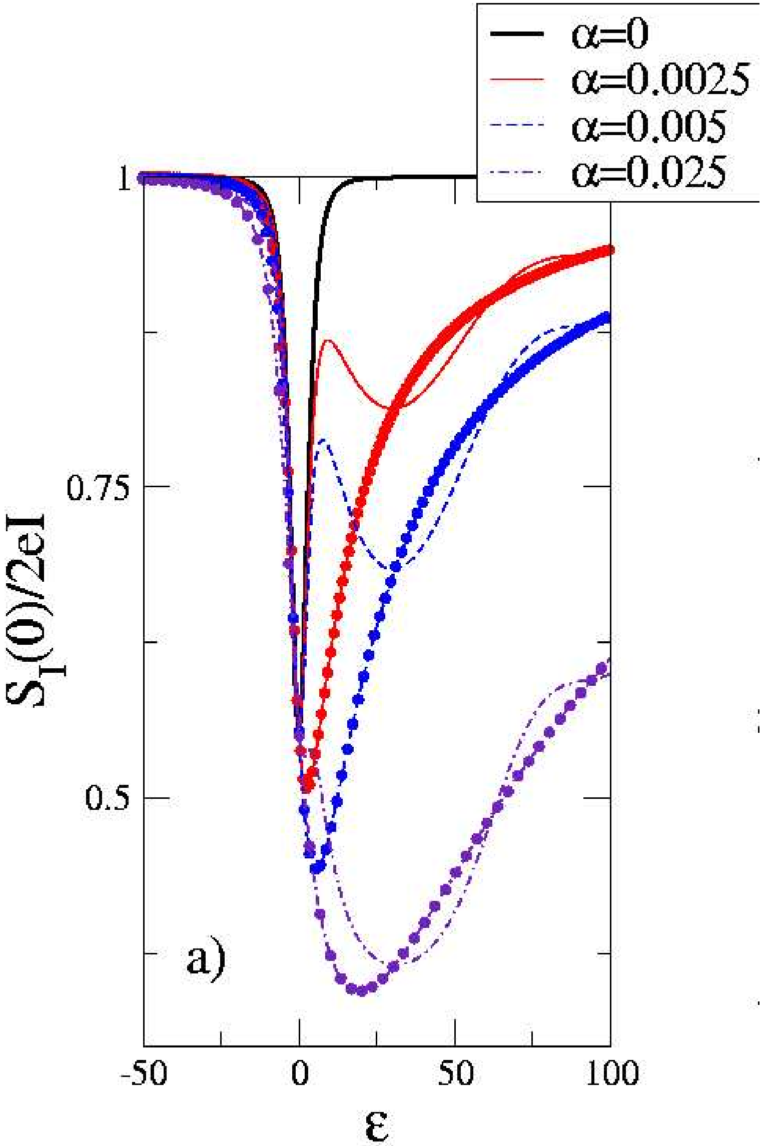
$$g_{+[-]}(z) = \pm iT_c(\mathbf{e}_1 - \mathbf{e}_2)\left[z - \hat{\Sigma}_z\right]^{-1}\hat{D}_z\mathbf{e}_{1[2]}.$$

R. Aguado, TB, Phys. Rev. Lett. **92**, 206601 (2004), Eur. Phys. J. B **40**, 357 (2004).

Extension to coupled excitonic quantum dots: Y. N. Chen, D. S. Chuu, T. Brandes, PRL **90**, 166802 (2003); Y. N. Chen, T. Brandes, C. M. Li, and D. S. Chuu, PRB **69**, 245323 (2004).



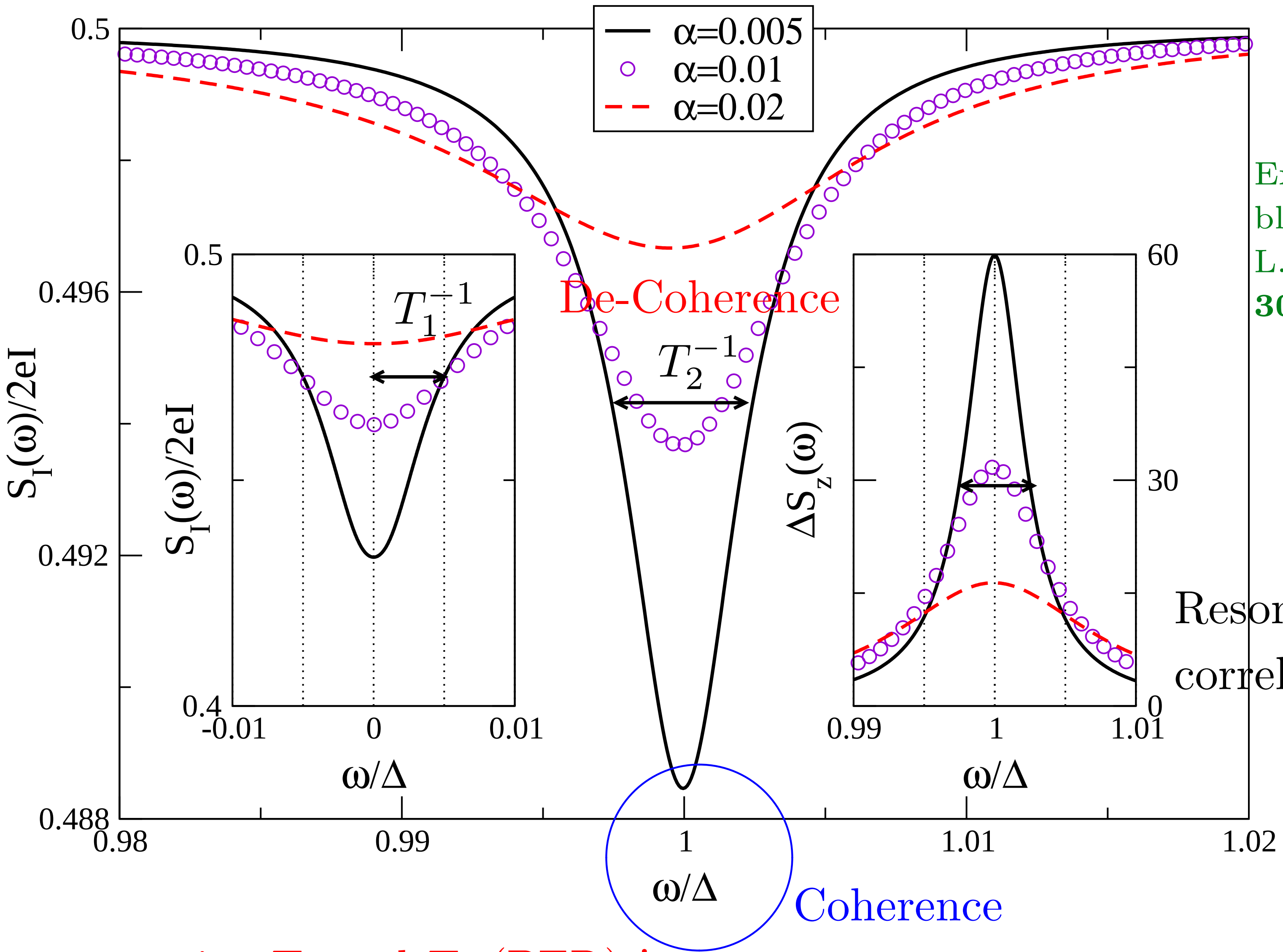
Fano Factor



- Interaction ($U \to \infty$) $\rightsquigarrow$ no Khlus-Lesovik form ‘$T(1-T)$’.
- ($\alpha = 0$) coherence suppresses noise: minimum at $\varepsilon = 0$.
- ($\alpha = 0$) large $|\varepsilon|$ ‘localises’ charge (L oder R).
- ($\alpha \neq 0$) for $\varepsilon > 0$: dissipation suppresses noise (like in disordered metallic systems, A. Shimizu, M. Ueda (1992)). Maximal for $\gamma_p = \Gamma_R$.

frequency dependent noise spectrum

R. Aguado, TB, Phys. Rev. Lett. **92**, 206601 (2004), Eur. Phys. J. B **40**, 357 (2004).



Exp. Cooper-Pair Box: R. Deblock, E. Onac, L. Gurevich, L. P. Kouwenhoven, Science **301**, 203 (2003)

Resonance as Pseudo-Spin-correlation function

contains T_1 und T_2 (PER) !

VOLUME 91, NUMBER 22 PHYSICAL REVIEW LETTERS week ending 28 NOVEMBER 2003

Coherent Manipulation of Electronic States in a Double Quantum Dot

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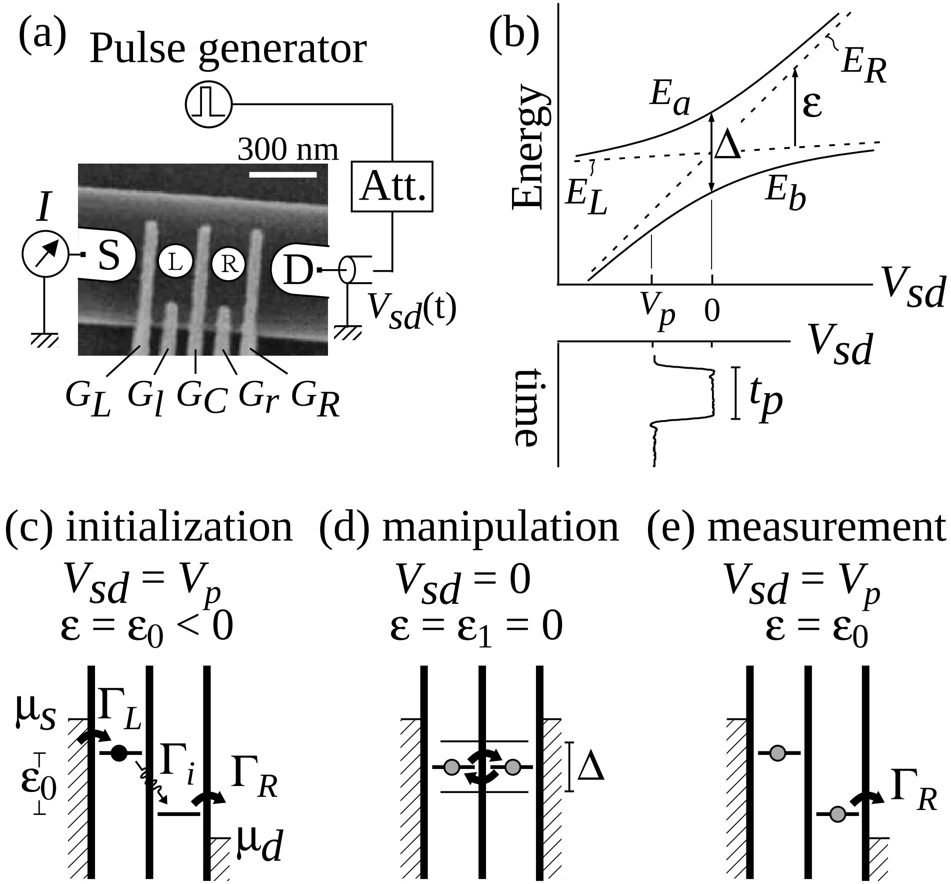
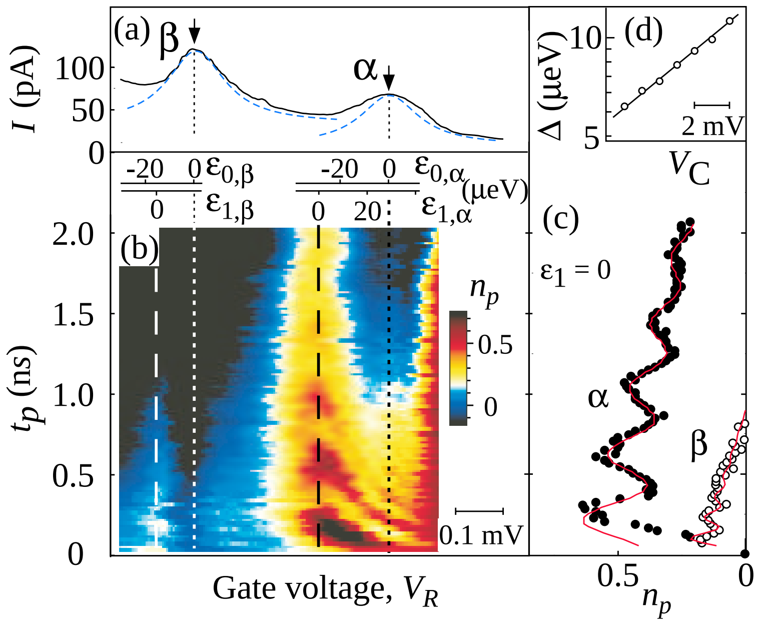
[1]NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, 243-0198, Japan



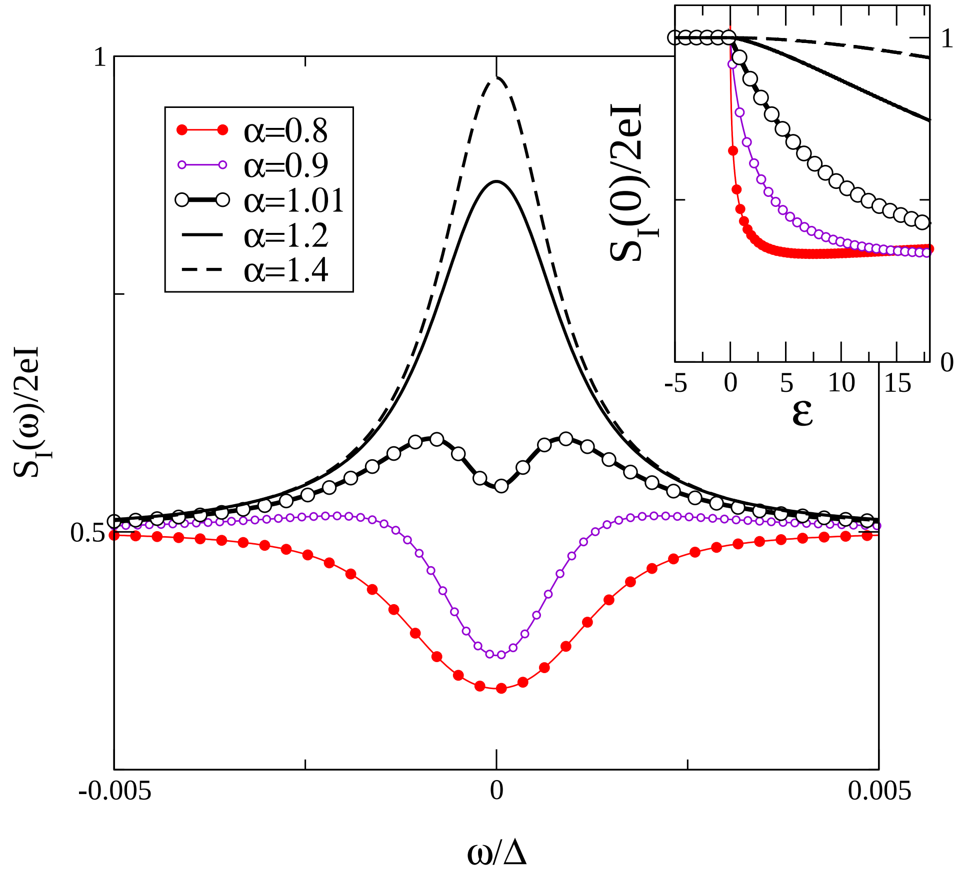


cf. TB, T. Vorrath, PRB **66**, 075341 (2003); U. Hartmann, F. K. Wilhelm, PRB **67**, 161307 (2003).

- Localisation-Delocalisation transition in $\mathcal{H}_{\text{SB}}$ at $\alpha = 1$

  Spin $1/2$: S. Chakravarty (1982); A. J. Bray, M. A. Moore, (1982)

  Spin $> 1/2$: T. Vorrath, TB 2003.
- visible in noise spectrum !
- Polaron as new quasi-particle $\rightsquigarrow$ polaron-noise $\rightsquigarrow$ Poisson-regime for $\alpha > 1$.



- Quantum Mechanical Transport
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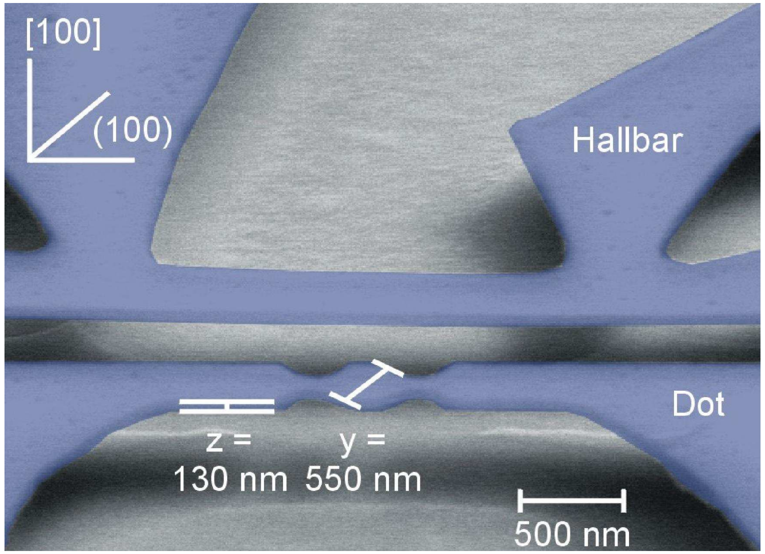
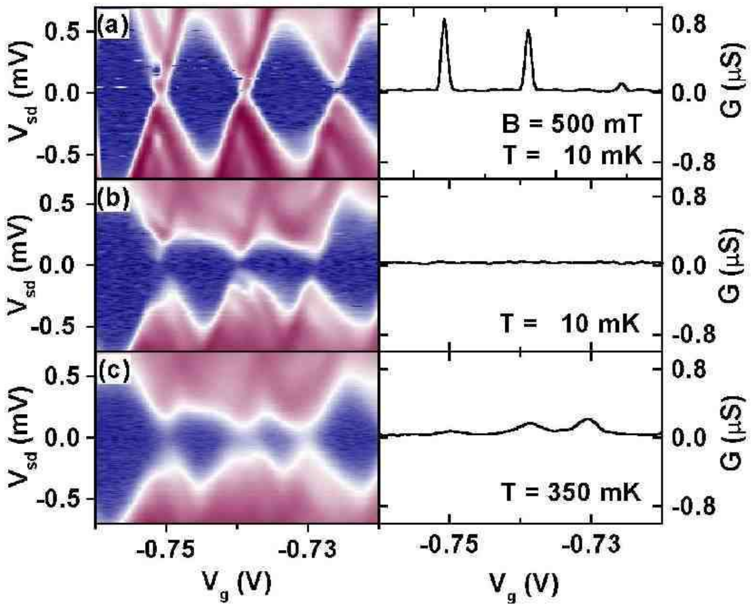
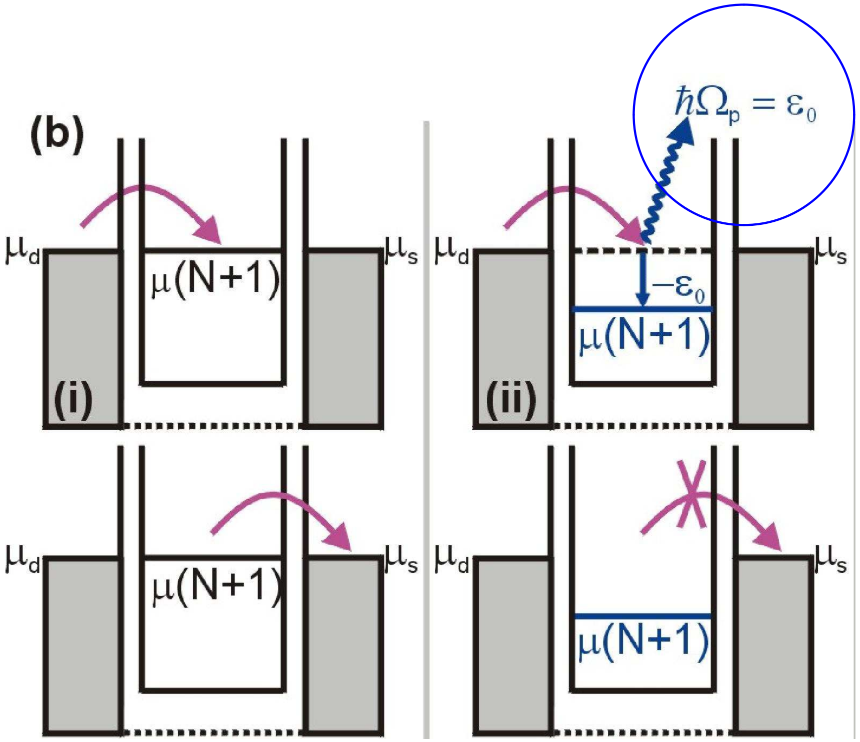
Resonator modes

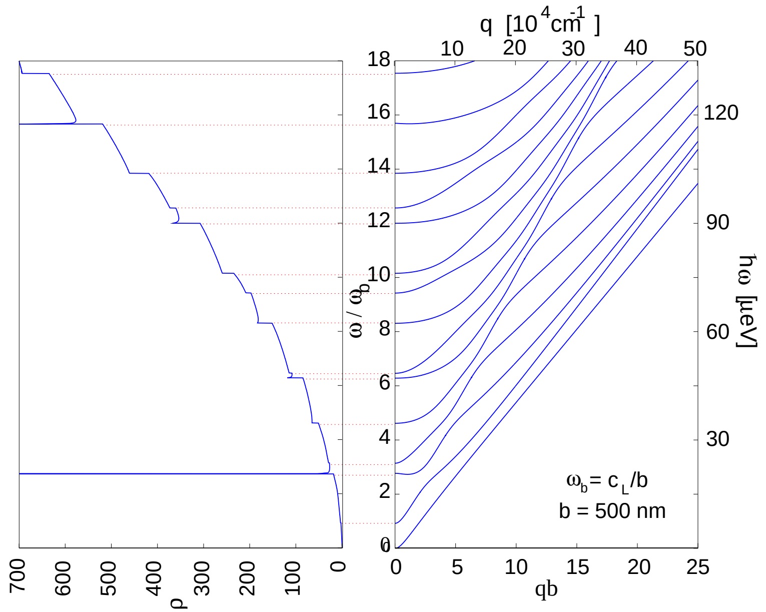
Strong coupling to resonator modes

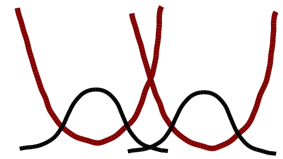




- free-standing quantum dots
- 'recoil effect', 'phonon blockade': mechanism ? (E. M. Weig, J. Kirschbaum, R. H. Blick, TB, W. Wegscheider, M. Bichler, and J. P. Kotthaus, PRL **92**, 046804 (2004).)







- Franck-Condon Effect: electron tunneling → electrostatic force on resonator,

$$\mathcal{H} = \left[\varepsilon + g(a+a^\dagger)\right]\hat{n}_{\rm d} + \mathcal{H}_{res} + \mathcal{H}_T + \Omega a^\dagger a$$

$$\rightarrow \quad \text{tunneling} \quad \propto c_k d^\dagger e^{-g(a-a^\dagger)}$$

- resonator model: Rayleigh-Lamb equations for thin plate ⇝ van-Hove-Singularity in phononic DOS, good agreement with $\Omega_{\rm p}$; S. Debald, TB, B. Kramer PRB **66**, 041301(R)(2002).
- coupling too weak for Franck-Condon? Dissipation ?
- LIFTING of PB by magnetic field: resonance between excitation energy and phonon energy $\hbar\Omega_{\rm p}$.

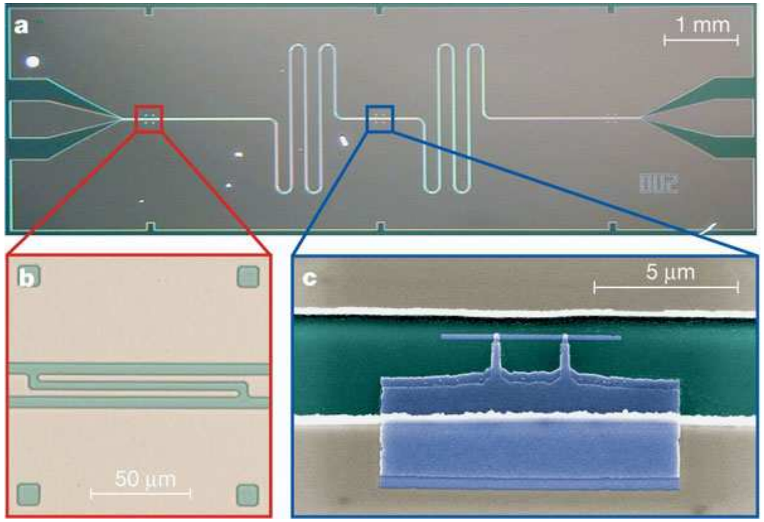
Strong coupling by image charge effect:

- Dot charged by single electron tunneling $\rightarrow$ image charge in nearby gate $\rightarrow$ attractive force on resonator, oscillations around new equilibrium $\mathbf{u}_0(\mathbf{r}) \propto \hat{n}_d$.
- Harmonic expansion of resonator Lagrangian around $\mathbf{u}_0(\mathbf{r}) \rightarrow$ Hamiltonian

$$\mathcal{H}_{\text{dot,resonator}} = \sum_{\mathbf{k}} \left[\Omega_{\mathbf{k}} a_{\mathbf{k}}^{\dagger} a_{\mathbf{k}} + g_{\mathbf{k}} \left(a_{\mathbf{k}}^{\dagger} + a_{\mathbf{k}} \right) \hat{n}_d + \Delta_{\mathbf{k}} \hat{n}_d \right].$$

- $P(E)$-theory with continuum of resonator modes $\mathbf{k}$ and 'large' $g_{\mathbf{k}} \propto e^2 \int d\mathbf{r} \mathbf{u}_0(\mathbf{r}) e^{i\mathbf{kr}} \rightarrow$ Franck-Condon effect, PB.
- Role of resonator
  - strong coupling due to image charges
  - provides typical $\omega = \omega_{\text{vH}}$ via van-Hove singularity $\rightarrow$ effective boson spectral density $J(\omega) \approx J_{\text{background}}(\omega) + g_{\text{vH}}^2 \delta(\omega - \omega_{\text{vH}})$.
- LIFTING of PB by Rabi-Oscillations to excited state. Co-tunneling ?

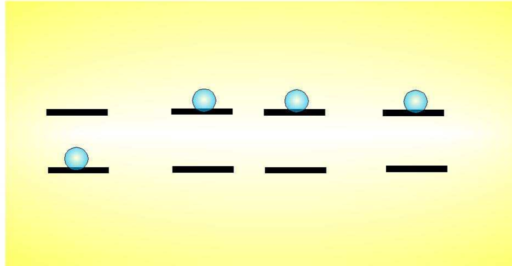
Strong Coupling to Resonator Modes II:



- coherent coupling between single photons and charge degree of freedoms
- wave guides (resonators), Josephson contacs: Cooper-Pair-Box (A. Wallraff, D. Schuster, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Kumar, S. M. Girvin, and R. J. Schoelkopf, Nature (London) **431**, 162 (2004).)
- transmission spectrum, two resonances $\pm\nu_{\text{Rabi}}$.

Scaling $\rightsquigarrow$ collective quantum optical models, entanglement, chaos, phase transitions TB *et al* 2000-.

Single-mode superradiance (Dicke) mode

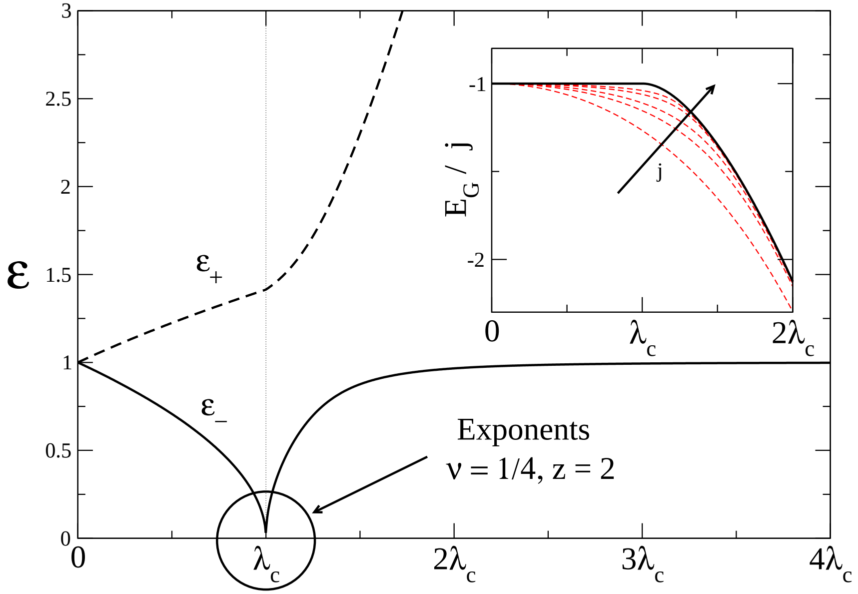


- N 2-level systems coupled to cavity boson.

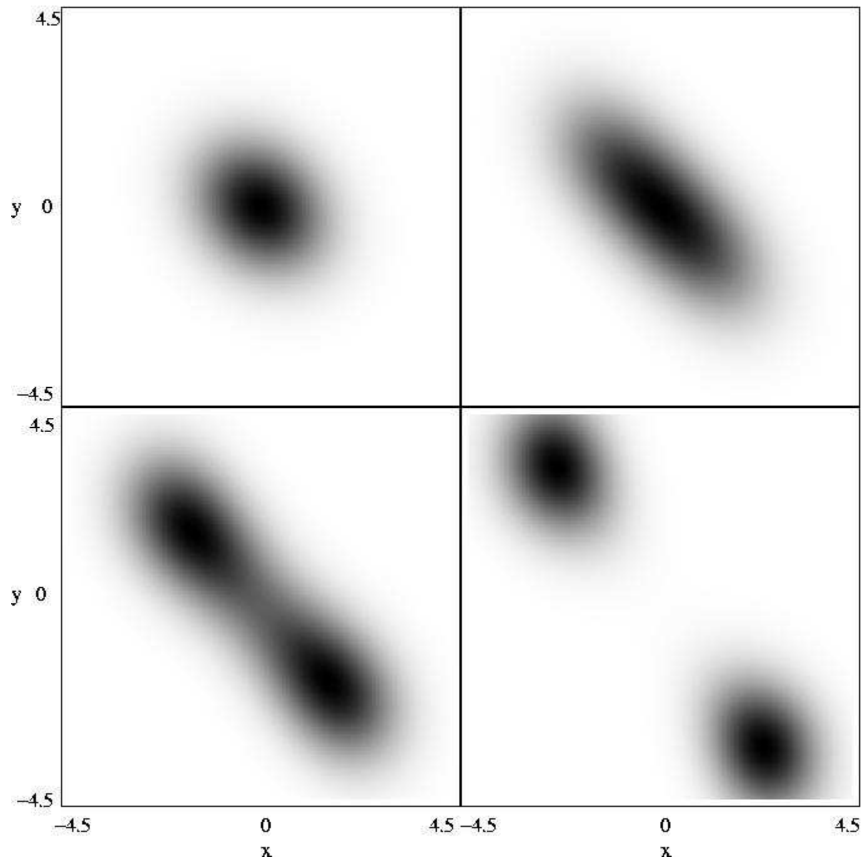
$$
\begin{aligned}
\mathcal{H}_{\text{Dicke}} &= \frac{\omega_0}{2}\sum_{i=1}^{N}\hat{\sigma}_{z,i} + \frac{\lambda}{\sqrt{N}}\sum_{i=1}^{N}\hat{\sigma}_{x,i}\left(a^\dagger + a\right) + \omega a^\dagger a, \quad j = \quad , \\
&= \omega_0 J_z + \frac{\lambda}{\sqrt{2j}}\left(a^\dagger + a\right)\left(J_+ + J_-\right) + \omega a^\dagger a, \quad [J_z, J_\pm] = \pm J_\pm .
\end{aligned}
$$

- $N = 1$: Rabi-Hamiltonian: cavity QED, nano-electromechanics...
- $N \to \infty$: $T = 0$-phase transition from $\langle a^\dagger a\rangle = 0$ to $\langle a^\dagger a\rangle \neq 0$ at $\lambda_c = \sqrt{\omega\omega_0}/2$. Exactly solvable K. Hepp and E. Lieb, Ann. Phys. **76**, 360 (1973).
- $N < \infty$: quantum chaos; Kus 85; Graham, Höhnerbach 86; Lewenkopf et al 91; level statistics $P(S)$, classical chaos; C. Emary, TB, Phys. Rev. Lett. **90**, 044101 (2003); Phys. Rev. E **67**, 066203 (2003)
- entanglement of spin pairs, or field and matter

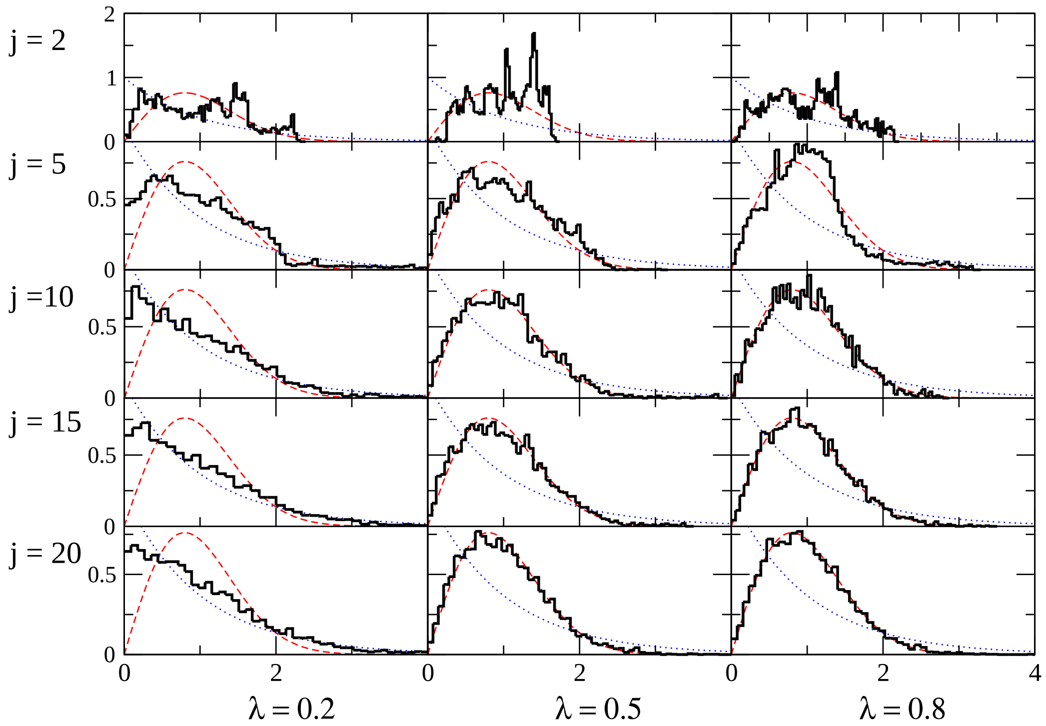
C. Emary, TB, Phys. Rev. Lett. **90**, 044101 (2003); Phys. Rev. E **67**, 066203 (2003)

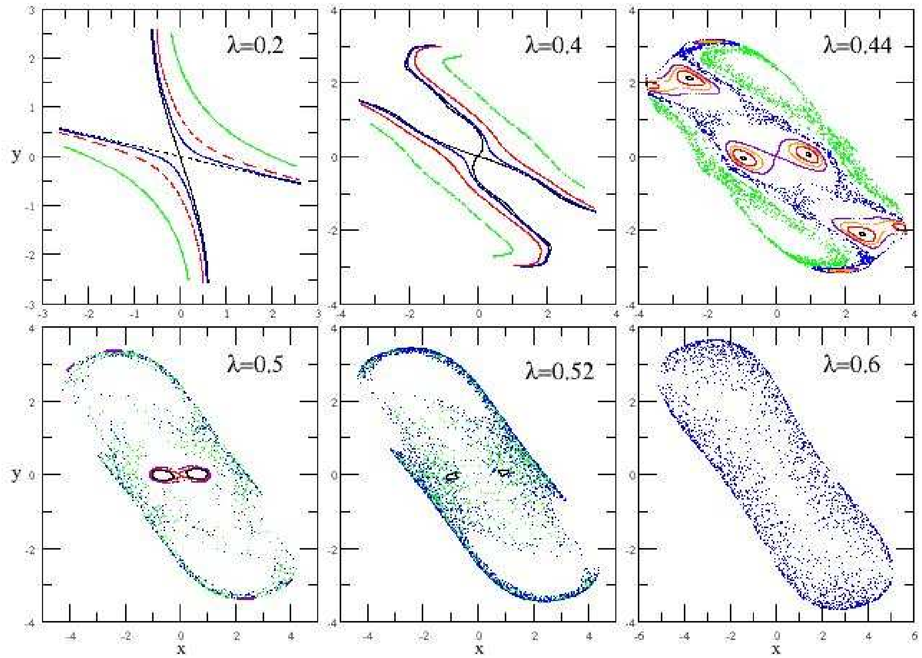


- HP transformation $J_z = (b^\dagger b - j)$, $J_+ = b^\dagger\sqrt{2j - b^\dagger b}$.
- effective Hamiltonians for $j = N/2 \to \infty$.
- GS energy E_G; collective excitation energies $\varepsilon_\pm$.



- Bifurcation in GS wave function for $\lambda > \lambda_c$.
- $x \equiv \frac{1}{\sqrt{2\omega}}\left(a^\dagger + a\right)$ (Photon), $y \equiv \frac{1}{\sqrt{2\omega_0}}\left(b^\dagger + b\right)$ ('Atom')





- Level spacing distribution $P(S)$.
- Transition from Poisson (localised) to Wigner-Dyson (delocalised). ↔ metal insulator transition.
- Classical Hamiltonian via HP trafo and canonical x-y representation.
- 'cat' corresponds to double attractor. C. Emary, TB 2003; X.-W. Hou, B. Hu 2004; G. Levine, V. N. Muthukumar, 2004; A. P. Hines, C. M. Dawson, R. H. McKenzie, G. J. Milburn , 2004.

Entanglement

letters to nature

Scaling of entanglement close to a quantum phase transition

A. Osterloh*†, Luigi Amico*†, G. Falci*† & Rosario Fazio†‡

$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$

Entanglement

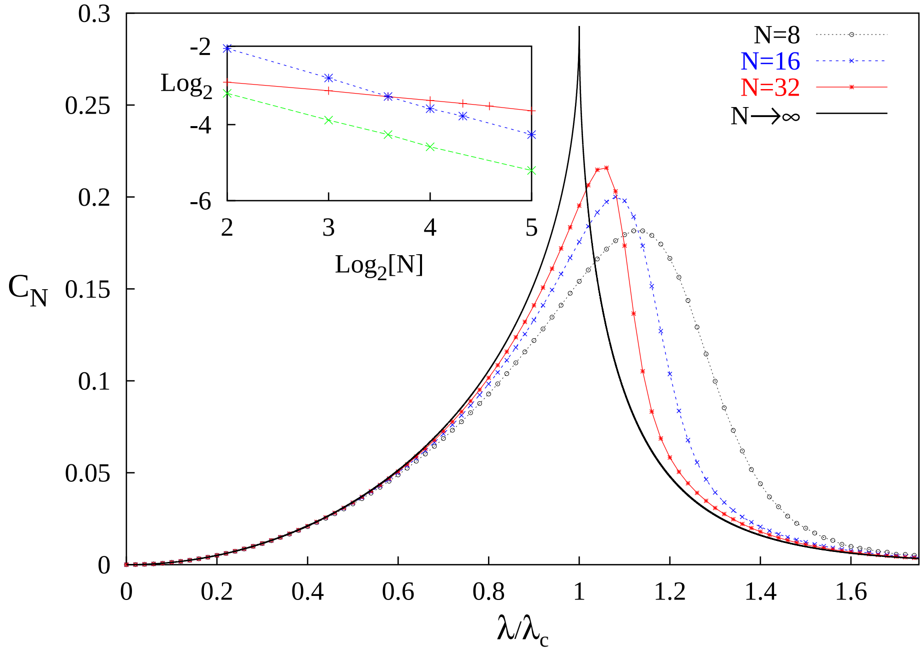
- 'History' Spin-$\frac{1}{2}$ XY-model on ferromagnetic chain,

$$H = -\lambda(1+\gamma)\sum_{i=1}^{N}\sigma_i^x\sigma_{i+1}^x - \lambda(1-\gamma)\sum_{i=1}^{N}\sigma_i^y\sigma_{i+1}^y - \sum_{i=1}^{N}\sigma_i^z,$$

A. Osterloh, L. Amico, G. Falci, R. Fazio; nature **416**, 608 (2002); T. Osborne, M. A. Nielsen, Phys. Rev. A **66**, 032110 (2002).

- $\mathcal{H}_{\rm Lipkin} = -\frac{2\lambda}{N}\left(J_x^2 + \gamma J_y^2\right) - 2J_z$ J. Vidal *et al.*
- pairwise entanglement of spins, critical behavior, scaling for $N < \infty$.

$\Leftrightarrow$ Dicke model $\mathcal{H}_{\rm Dicke} = \omega_0 J_z + \frac{\lambda}{\sqrt{N}}\left(a^\dagger + a\right)\left(J_+ + J_-\right) + \omega a^\dagger a.$



- Scaling $C_N = NC$ necessary.
- Exploit S_N symmetry.
- Concurrence $\leftrightarrow$ momentum squeezing

$$C_\infty = 1 - \frac{1+\mu}{\omega_0}(\Delta p_y)^2,$$

mit $\mu_{\lambda<\lambda_c} = 1$, $\mu_{\lambda>\lambda_c} = (\lambda_c/\lambda)^2$.

$$C_\infty^{x\leq 1} = 1 - \frac{1}{2}\left[\sqrt{1+x} + \sqrt{1-x}\right], \quad x \equiv \lambda/\lambda_c$$

$$C_\infty^{x\geq 1} = 1 - \frac{1}{\sqrt{2}x^2}\left[\sin^2\gamma\sqrt{1+x^4-\sqrt{(1-x^4)^2+4}} + \cos^2\gamma\sqrt{1+x^4+\sqrt{(1-x^4)^2+4}}\right]$$

$$2\gamma = \arctan[2/(x^2-1)] \quad \text{in SR phase.}$$

- $N < \infty$: $\lambda^{\mathrm{M}} - \lambda_c \propto N^{-0.68\pm 0.1}$, $C_N^{\mathrm{M}}(\lambda_c) - C_N \propto N^{-0.25\pm 0.01}$.
- Comparison with $\mathcal{H}_{\mathrm{Lipkin}} = -\frac{2\lambda}{N}\left(J_x^2 + \gamma J_y^2\right) - 2J_z$: Exponents! J. Vidal *et al*

- Quantum Mechanical Transport
- Quantum Noise, Dissipation
- Nanomechanics, Quantum Optics and Mesoscopics
- Non-equilibrium in Driven Systems

‘Controllable Non-equilibrium’

- Electronic (dc) transport in presence of time-dependent (ac) fields $\mathbf{E}(\mathbf{x}) \cos \Omega t$.
- plethora of methods
  - cubic response
  - Boltzmann equation (semi-classic)
  - Green’s functions
  - Floquet transport theory

Boltzmann equation (semi-classics):

- $\mathbf{E}(\mathbf{q}, t)$ 'probe-field' in linear response
- $\mathbf{E}_0(t)$ 'pump-field' exact

$$\begin{aligned}
\mathbf{j}(\mathbf{q}, t) &\equiv \frac{e}{L^d} \sum_{\mathbf{k}} \mathbf{v}_{\mathbf{k}} f(\mathbf{q}, \mathbf{k}, t) = \frac{e^2}{L^d m} \sum_{\mathbf{k}} \left[\mathbf{k} - \frac{e}{c} \mathbf{A}^e(t) \right] (-\partial_{\mathbf{k}} f_0(\mathbf{k})) \times \\
&\times \int_0^t dt' \, \mathbf{E}(\mathbf{q}, t') \exp \left\{ - \int_{t'}^t ds \, g \left[\mathbf{k} + e \int_0^s dt'' \, \mathbf{E}_0(t'') \right] \right\} - \frac{e^2}{mc} n_e \mathbf{A}^e(t) \\
g(\mathbf{k}) &\equiv \tau^{-1}(\mathbf{k}) + i \mathbf{v}_{\mathbf{k}} \mathbf{q},
\end{aligned}$$

TB, Europhys. Lett **33**, 629 (1996).

- Modification of scattering potentials, 'Intracollisional Field Effect': relevant for zero-resistance ac-QHE !?

  J. Inarrea, G. Platero, cond-mat/0409708.

Green's functions

$$
\begin{aligned}
G(t_1,t_2) &= \begin{pmatrix} G^T(t_1,t_2) & -G^<(t_1,t_2) \\ G^>(t_1,t_2) & -G^{\tilde{T}}(t_1,t_2) \end{pmatrix} \\
G(\omega,N) &= G^0(\omega,N) + \sum_{N_1 N_2} G^0\left(\omega + \frac{N_1 - N}{2}\Omega, N_1\right) \\
&\times \Sigma\left(\omega + \frac{N_1 - N_2}{2}\Omega, N - N_1 - N_2\right) G\left(\omega + \frac{N - N_2}{2}\Omega, N_2\right).
\end{aligned}
$$

- screening, photo side-bands.

TB, Phys. Rev. B **56**, 1213 (1997); Annalen der Physik 7, 120 (1998), TB, J. Robinson, phys. stat. sol. (b) **234**, 378 (2002)

Transport Floquet theory of driven quantum systems: charge qubits

$\varepsilon + \Delta \cos \Omega t$

$$\mathcal{H}(t) = \left[\frac{\varepsilon(t)}{2} + \sum_{\mathbf{Q}} \frac{g_Q}{2} \left(a_{-\mathbf{Q}} + a^{\dagger}_{\mathbf{Q}} \right) \right] \hat{\sigma}_z + T_c \hat{\sigma}_x + \mathcal{H}_B + \mathcal{H}_{res} + \mathcal{H}_T$$

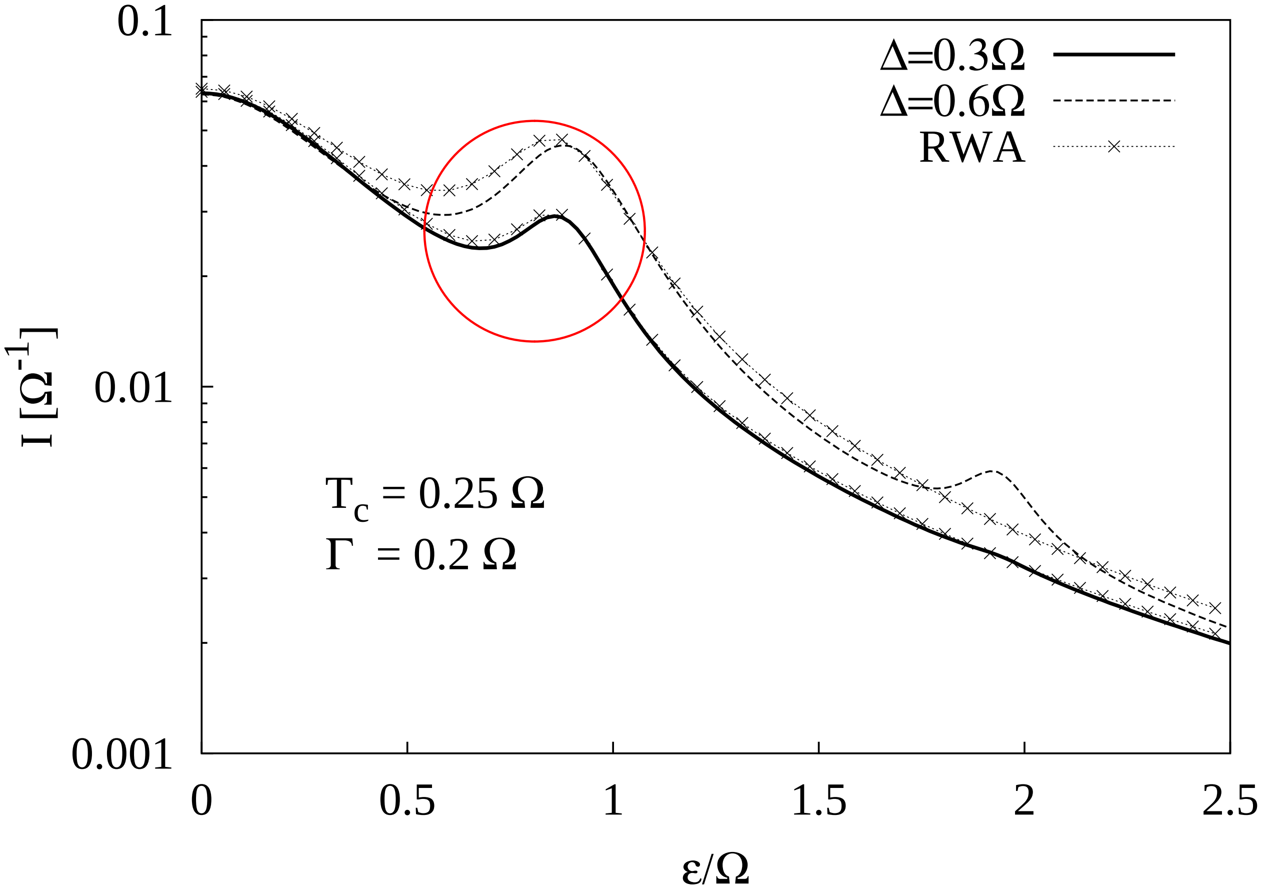
- limiting cases:
  - $\mathcal{H}_B = 0$, perturbation theory in T_c: P. K. Tien, J. R. Gordon 1963
  - $\mathcal{H}_{res} + \mathcal{H}_T \equiv 0$ M. Grifoni, P. Hänggi 1998,...
- Methode: Fourier components of reduced density operator $\rho(t) \longrightarrow$ stationary current via

$$\begin{aligned} K_m(-im'\Omega) &= i^{-m} T_c^2 \sum_n \left[J_n\left(\frac{\Delta}{\Omega}\right) J_{n-m}\left(\frac{\Delta}{\Omega}\right) \hat{D}_{\varepsilon+(m'-n)\Omega} + J_n\left(\frac{\Delta}{\Omega}\right) J_{n+m}\left(\frac{\Delta}{\Omega}\right) \hat{D}^*_{\varepsilon-(m'+n)\Omega} \right] \\ G_m(-im'\Omega) &= i^{-m} T_c^2 \sum_n \left[J_n\left(\frac{\Delta}{\Omega}\right) J_{n-m}\left(\frac{\Delta}{\Omega}\right) \hat{E}_{\varepsilon+(m'-n)\Omega} + J_n\left(\frac{\Delta}{\Omega}\right) J_{n+m}\left(\frac{\Delta}{\Omega}\right) \hat{E}^*_{\varepsilon-(m'+n)\Omega} \right]. \end{aligned}$$

↑ *Dynamical Localisation*

$$\hat{D}_\varepsilon(z) \equiv \frac{1}{\hat{C}_\varepsilon(z)^{-1} + \Gamma_R/2}$$

↑ *Dissipation*



Bloch-Siegert shift for larger ac amplitudes Δ.

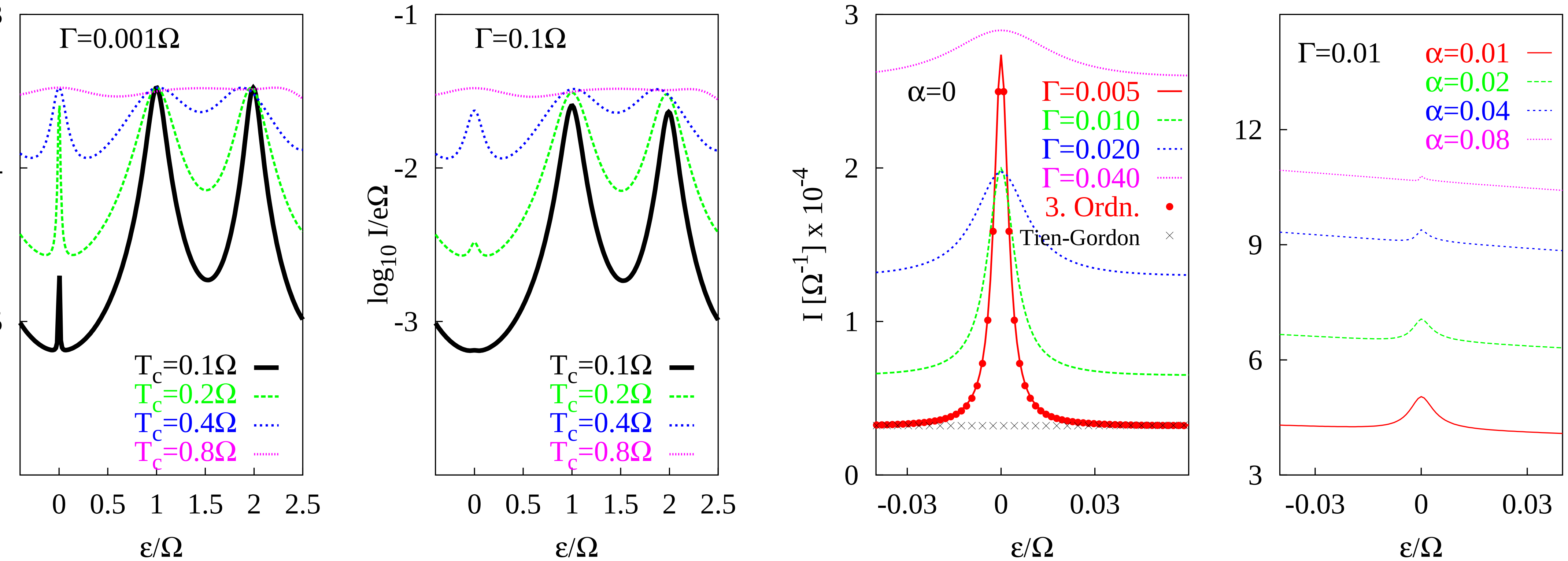
TB, R. Aguado, G.Platero, PRB **69**, 205326 (2004).

Resonance at $\varepsilon = \sqrt{\Omega^2 - 4T_c^2}$: quantum coherence.

EXP: R. H. Blick, D. W. van der Weide, R. J. Haug, K. Eberl; PRL **81**, 689 (1998); T. H. Oosterkamp, T. Fujisawa, W. G. van der Wiel, K. Ishibashi, R. V. Hijman, S. Tarucha, L. P. Kouwenhoven, nature **395**, 873 (1998).

dynamical localisation: $T_c \to T_c J_0(\Delta/\Omega)$ (Tien-Gordon)...

- Tien-Gordon becomes *wrong for large* T_c. 6. order $T_c \longrightarrow$ Barata, Wreszinski, PRL **84**, 2112 (2000).

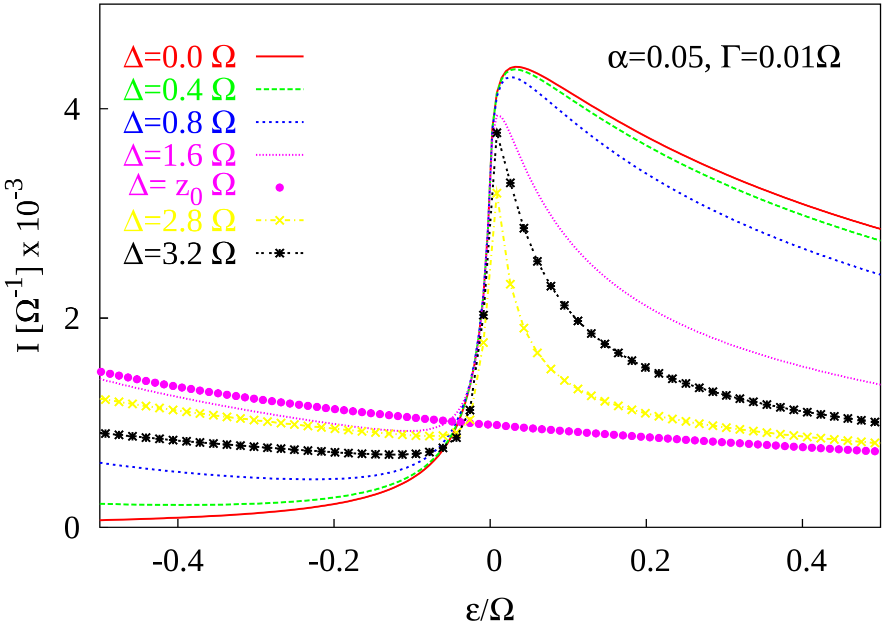


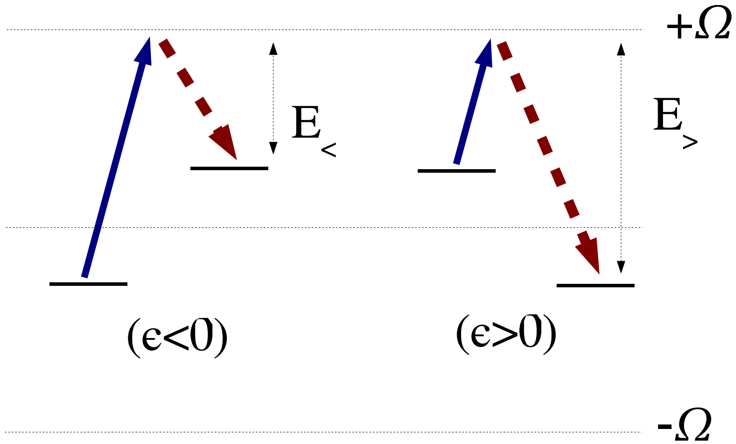
'coherent lifting' of dynamical localisation ...

...disappears at *stronger dissipation*

TB, R. Aguado, G.Platero, PRB **69**, 205326 (2004).

Dissipation and ac fields





- dynamical localisation destroys asymmetry between spontaneous emission and absorption.
- $P(E) \propto E^{2\alpha-1} e^{-E/\omega_c} \rightsquigarrow P(E_<) > P(E_>)$.

Summary

- electronic transport: correlations, non-equilibrium   quantum coherence / decoherence
- quantum noise, non-equilibrium, driven systems.
- Nanomechanics. Quantum Optics and Mesoscopics: Entanglement, Quantum Chaos, Phase Transitions.

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Coherent and Collective Quantum Optical Effects in Mesoscopic Systems, (TB, Physics Reports 2004, cond-mat/0409771)