Interaction Effects in Disordered Conductors

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Dima Golubev

Artem Galaktionov

Outline

- Introduction and motivation
- Short coherent conductors: Weak Coulomb blockade
- Short coherent conductors: interaction correction and shot noise
- Interactions and higher current cumulants
- Transport and interactions in quantum dots and arrays: universal model for ANY diffusive conductor
- Weak localization and decoherence at T=0

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Coulomb interaction + disorder

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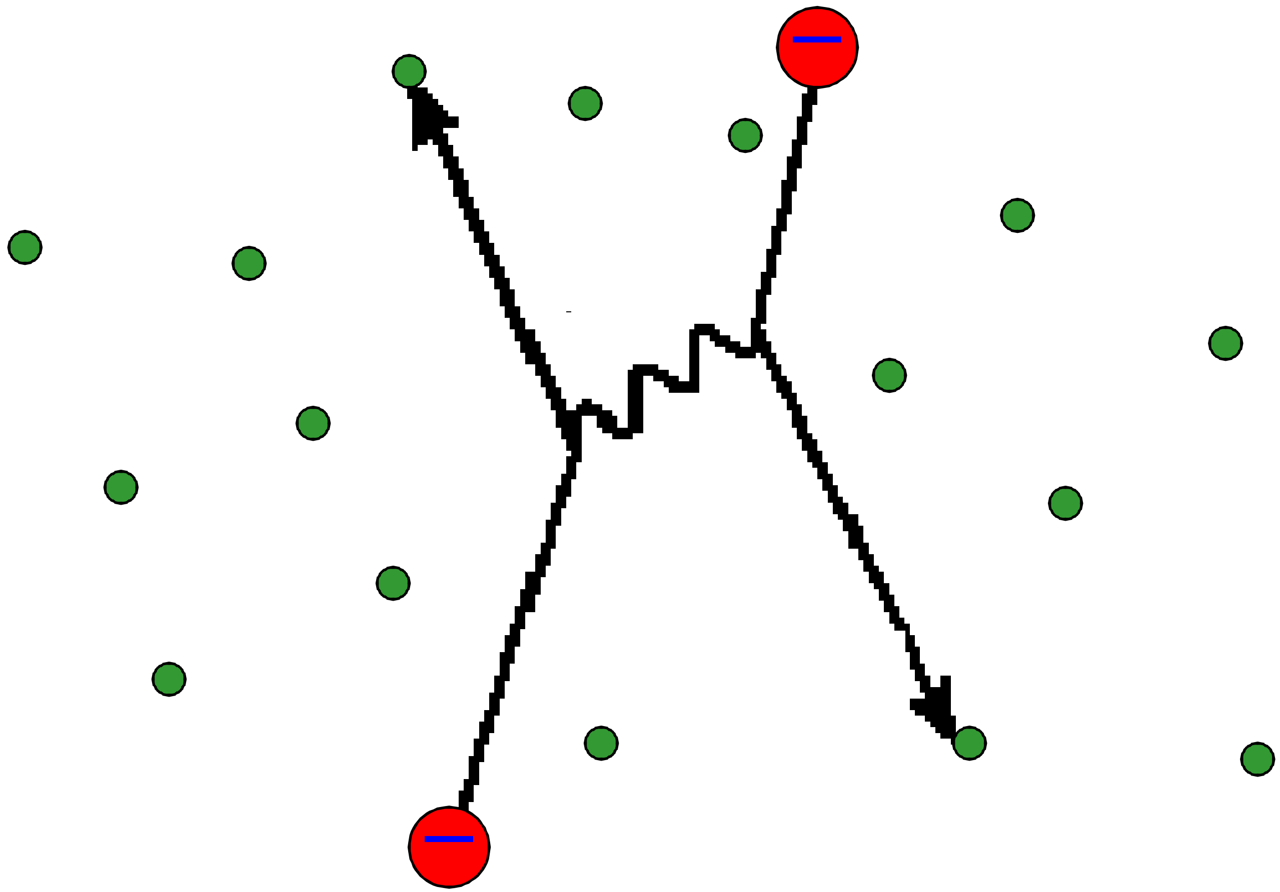
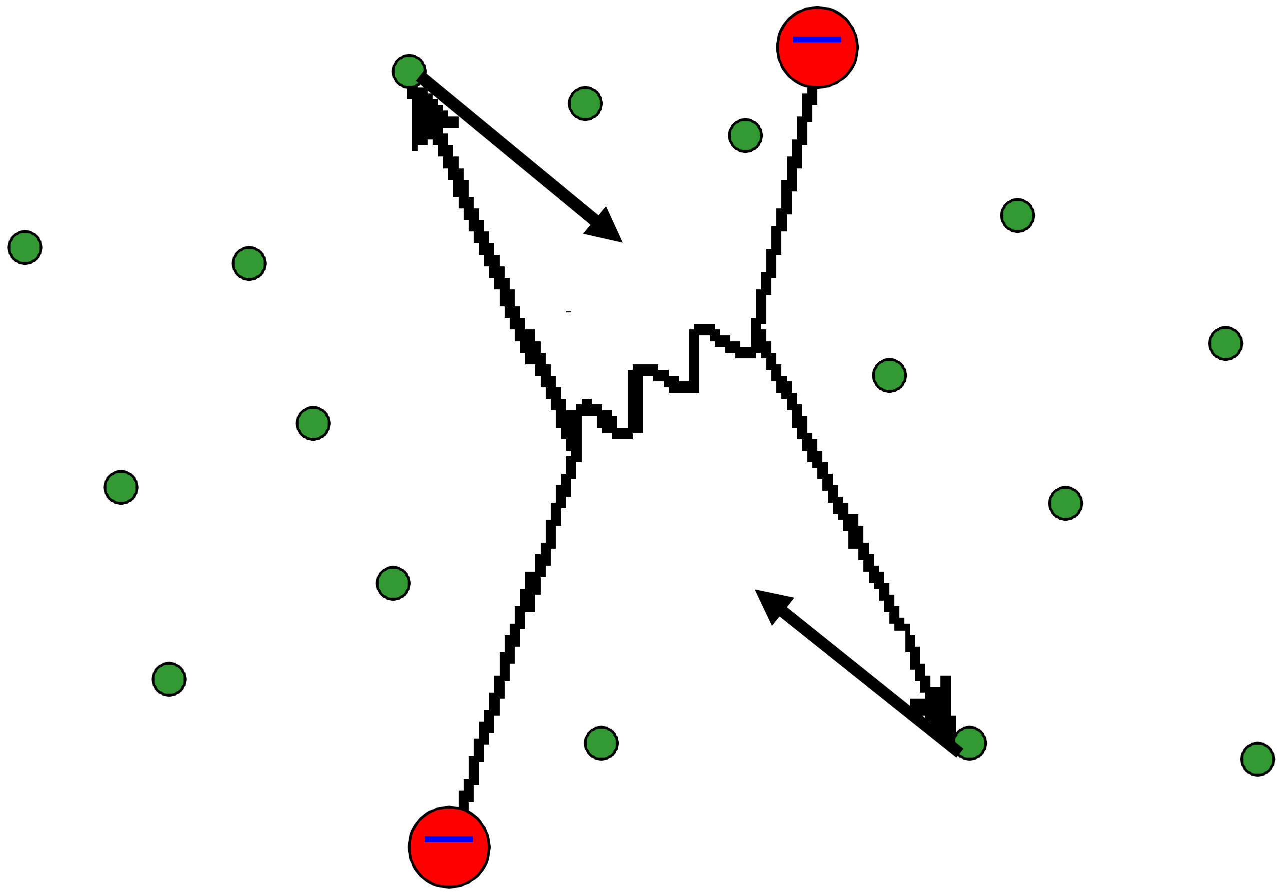
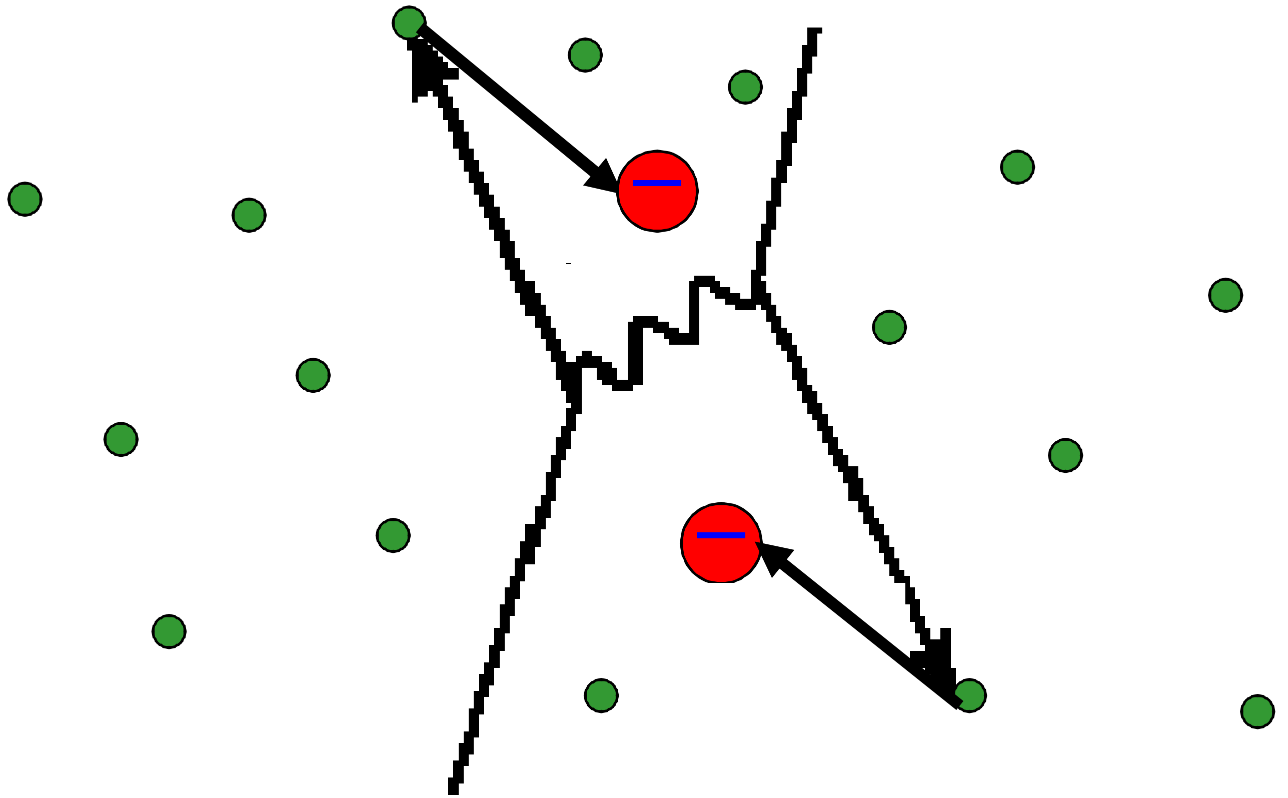


Coulomb interaction + disorder



Coulomb interaction + disorder




G=dI/dV

)

$$G(T) = G_{\text{Drude}} - \delta G_{\text{int}} - \delta G_{\text{WL}}$$

Interaction correction

Weak localization correction

$$G(T) = G_{\mathsf{Drude}} - \delta G_{\mathsf{int}} - \delta G_{\mathsf{WL}}$$

- $\frac{\delta G_{\mathsf{int}}}{G_{\mathsf{Drude}}} \sim \frac{L_{\mathsf{T}}}{L_{\mathsf{loc}}}, \qquad L_{\mathsf{T}} \sim \sqrt{\frac{D}{T}}, \qquad L_{\mathsf{loc}} \sim Nl$

- $\frac{\delta G_{\mathsf{WL}}}{G_{\mathsf{Drude}}} \sim \frac{L_{\varphi}}{L_{\mathsf{loc}}}, \qquad L_{\varphi} \sim L_{\mathsf{loc}}^{1/3} L_{\mathsf{T}}^{2/3},$

$$G(T) = G_{\text{Drude}} - \delta G_{\text{int}} - \delta G_{\text{WL}}$$

- $\frac{\delta G_{\text{int}}}{G_{\text{Drude}}} \sim \frac{L_{\text{T}}}{L_{\text{loc}}}, \qquad L_{\text{T}} \sim \sqrt{\frac{D}{T}}, \qquad L_{\text{loc}} \sim Nl$
- $\frac{\delta G_{\text{WL}}}{G_{\text{Drude}}} \sim \frac{L_{\varphi}}{L_{\text{loc}}}, \qquad L_{\varphi} \sim L_{\text{loc}}^{1/3} L_{\text{T}}^{2/3},$

Crossover to Anderson localization at:

$$L_{\text{T}} \sim L_{\varphi} \sim L_{\text{loc}}$$

Intrinsic Decoherence in Mesoscopic Systems

P. Mohanty, E. M. Q. Jariwala, and R. A. Webb
Center for Superconductivity Research, Department of Physics, University of Maryland, College Park, Maryland 20742
(Received 17 December 1996)

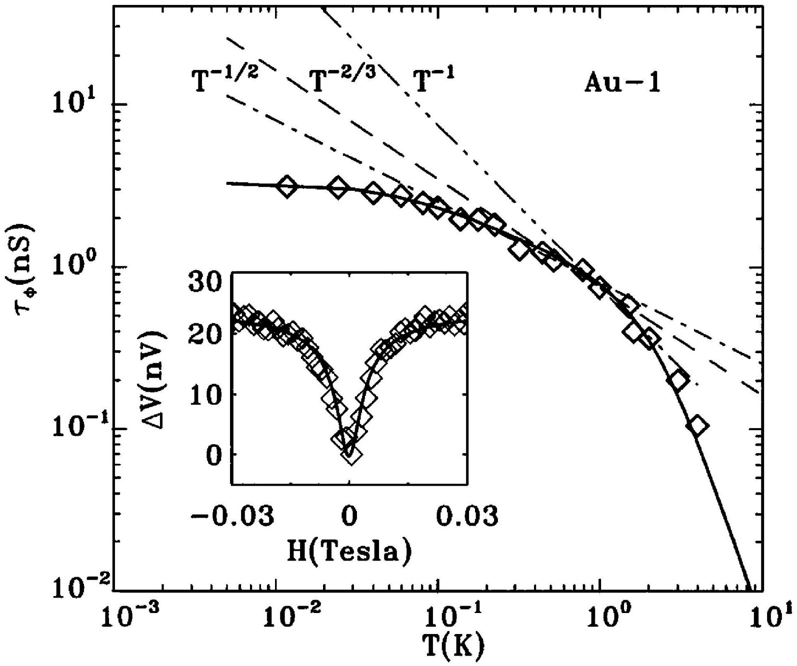


FIG. 1. Temperature dependence of τ_ϕ for sample Au-1. The broken lines are the functional forms expected from previous theories. The solid line is a fit to Eq. (1) with phonons. The inset shows the typical weak localization data taken with 2 nA at 11 mK with a fit to the standard 1D theory.

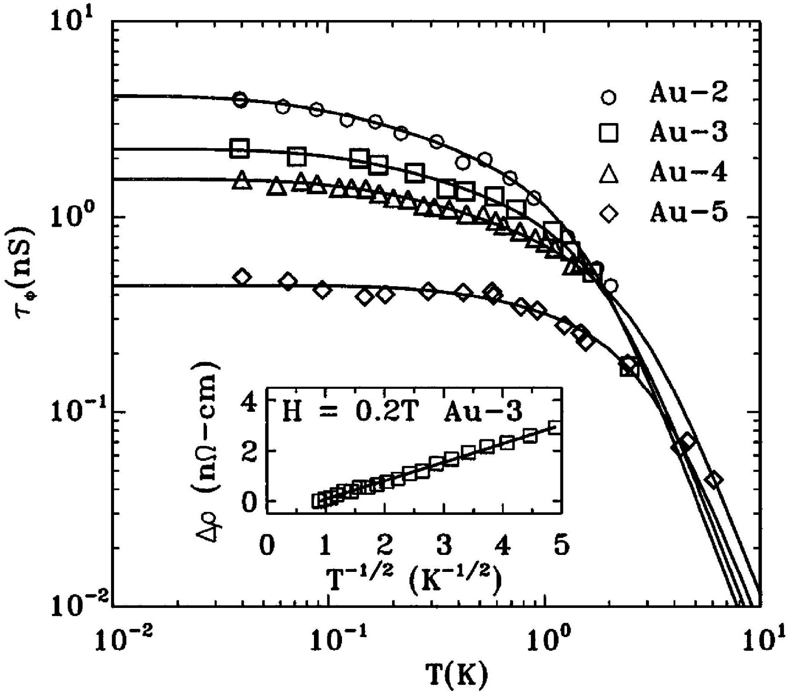


FIG. 2. Temperature dependence of τ_ϕ for four Au wires. Solid lines are fits to Eq. (1) with phonons. The inset is the EE contribution to $\Delta\rho$ with the theoretical prediction.

$$G(T) = G_{\text{Drude}} - \delta G_{\text{int}} - \delta G_{\text{WL}}$$

- $\frac{\delta G_{\text{int}}}{G_{\text{Drude}}} \sim \frac{L_{\text{T}}}{L_{\text{loc}}}, \qquad L_{\text{T}} \sim \sqrt{\frac{D}{T}}, \qquad L_{\text{loc}} \sim Nl$

No Anderson localization!

- **low** $T: \quad L_\varphi \sim \sqrt{N} l, \qquad \frac{\delta G_{\text{WL}}}{G_{\text{Drude}}} \sim \frac{1}{\sqrt{N}} \ll 1$

Disorder + Interactions:

Universal theory

Disorder + Interactions:

↓

Scattering matrix approach

Disorder + Interactions:

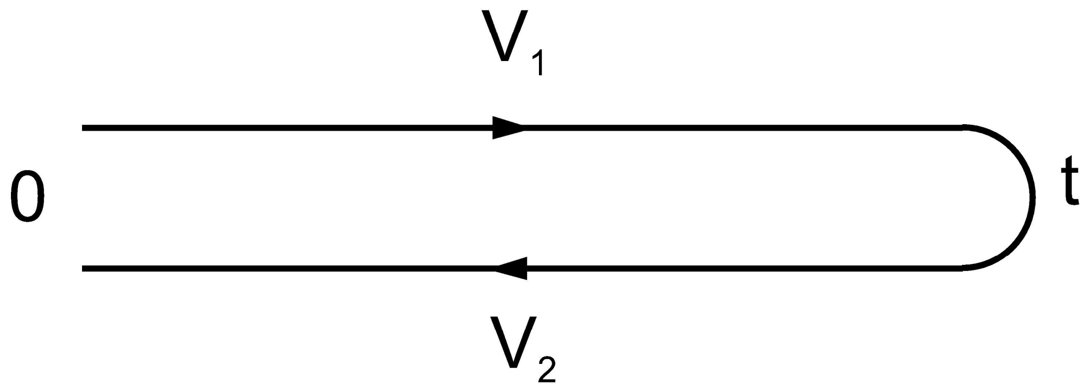
↓	↓
Scattering matrix approach	Hubbard-Stratonovich + Keldysh

Hamiltonian

$$\mathbf{H} = \int d\mathbf{r}\psi_\sigma^+(\mathbf{r})h(\mathbf{r})\psi_\sigma(\mathbf{r}) + \mathbf{H}_{int},$$

$$h(\mathbf{r}) = -\frac{\nabla^2}{2m} - \mu + U(\mathbf{r}),$$

$$\mathbf{H}_{int} = \frac{1}{2}\int d\mathbf{r}\int d\mathbf{r}'\psi_\sigma^+(\mathbf{r})\psi_{\sigma'}^+(\mathbf{r}')\frac{e^2}{|\mathbf{r}-\mathbf{r}'|}\psi_{\sigma'}(\mathbf{r}')\psi_\sigma(\mathbf{r})$$



$$\widehat{G} = \frac{\int \mathcal{D}V_1 \mathcal{D}V_2 G_V \exp(iS)}{\int \mathcal{D}V_1 \mathcal{D}V_2 \exp(iS)}$$

$$\begin{pmatrix} i\frac{\partial}{\partial t'} + h(\mathbf{r}') + eV_1(t', \mathbf{r}') & 0 \\ 0 & i\frac{\partial}{\partial t'} + h(\mathbf{r}') + eV_2(t', \mathbf{r}') \end{pmatrix} \widehat{G}_V(t't'', \mathbf{r}'\mathbf{r}'') = \sigma_z \delta(t' - t'')\delta(\mathbf{r}' - \mathbf{r}'').$$

Effective action

$$iS = 2 \mathrm{Tr} \ln \widehat{G}_V^{-1} + i \int_0^t dt' \int d\mathbf{r} \frac{(\nabla V_1)^2 - (\nabla V_2)^2}{8\pi}.$$

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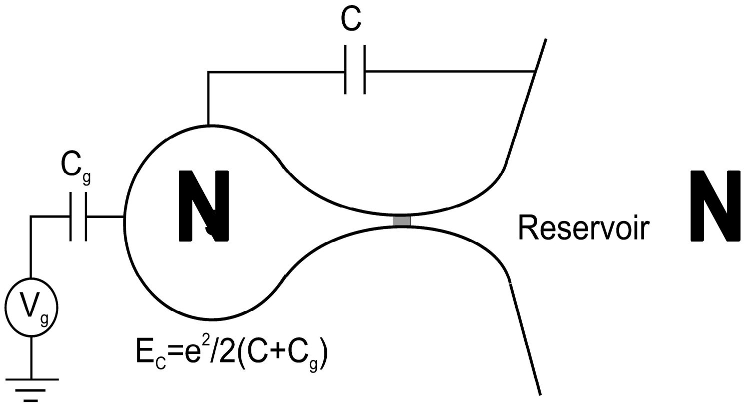
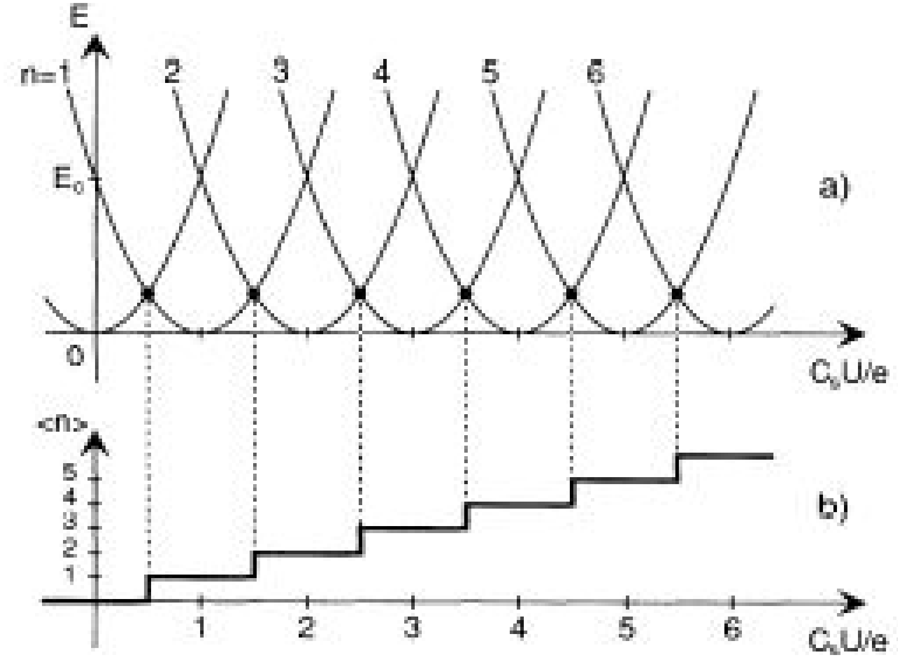


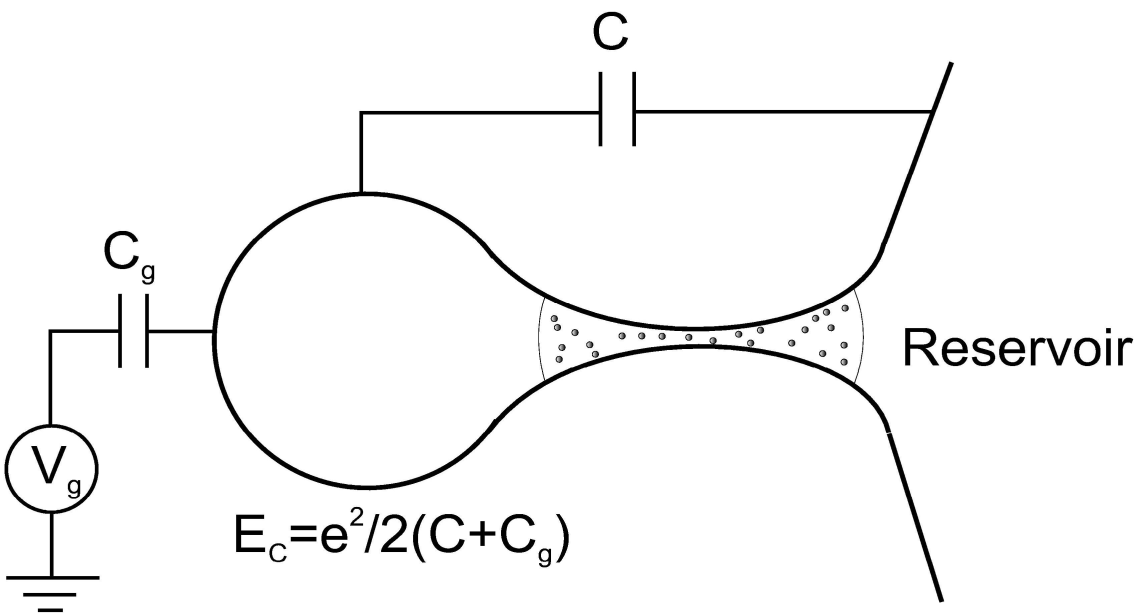
$$E=(Q_g-ne)^2/2(C+C_g)$$

$$Q_g=C_gV_g$$

$$n_g=Q_g/e$$



Coherent scatterer: basic model



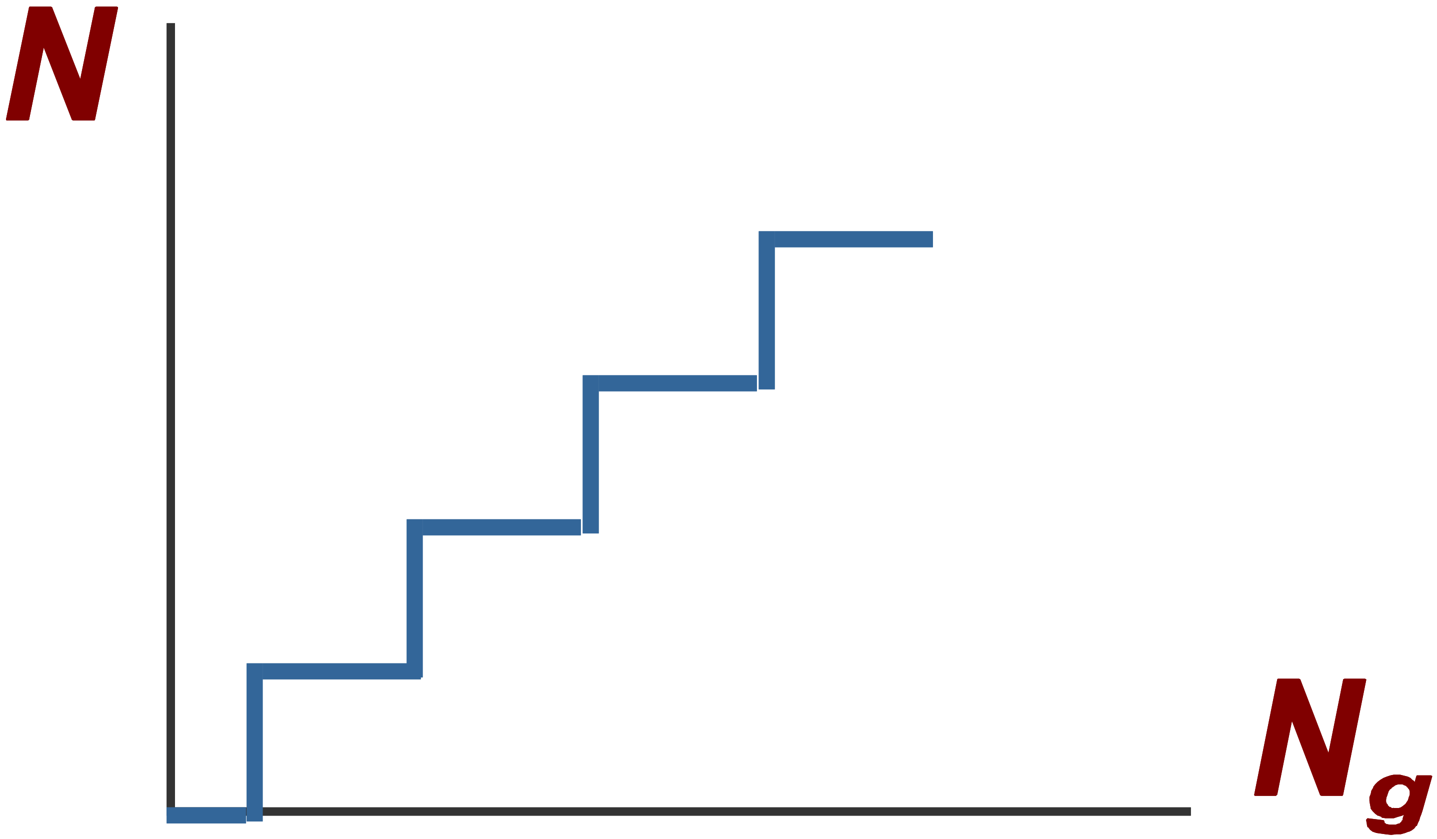
$$\frac{1}{R} = \frac{e^2}{\pi\hbar}\mathrm{tr}[\hat{t}^{+}\hat{t}] = \frac{e^2}{\pi\hbar}\sum_n T_n$$

$$g = \frac{2\pi\hbar}{e^2 R} = 2\sum_n T_n$$

Tunnel junction, weak tunneling

all $T_n \ll 1 \quad g \ll 1$

Averin-Likharev'86 ("Orthodox" theory)

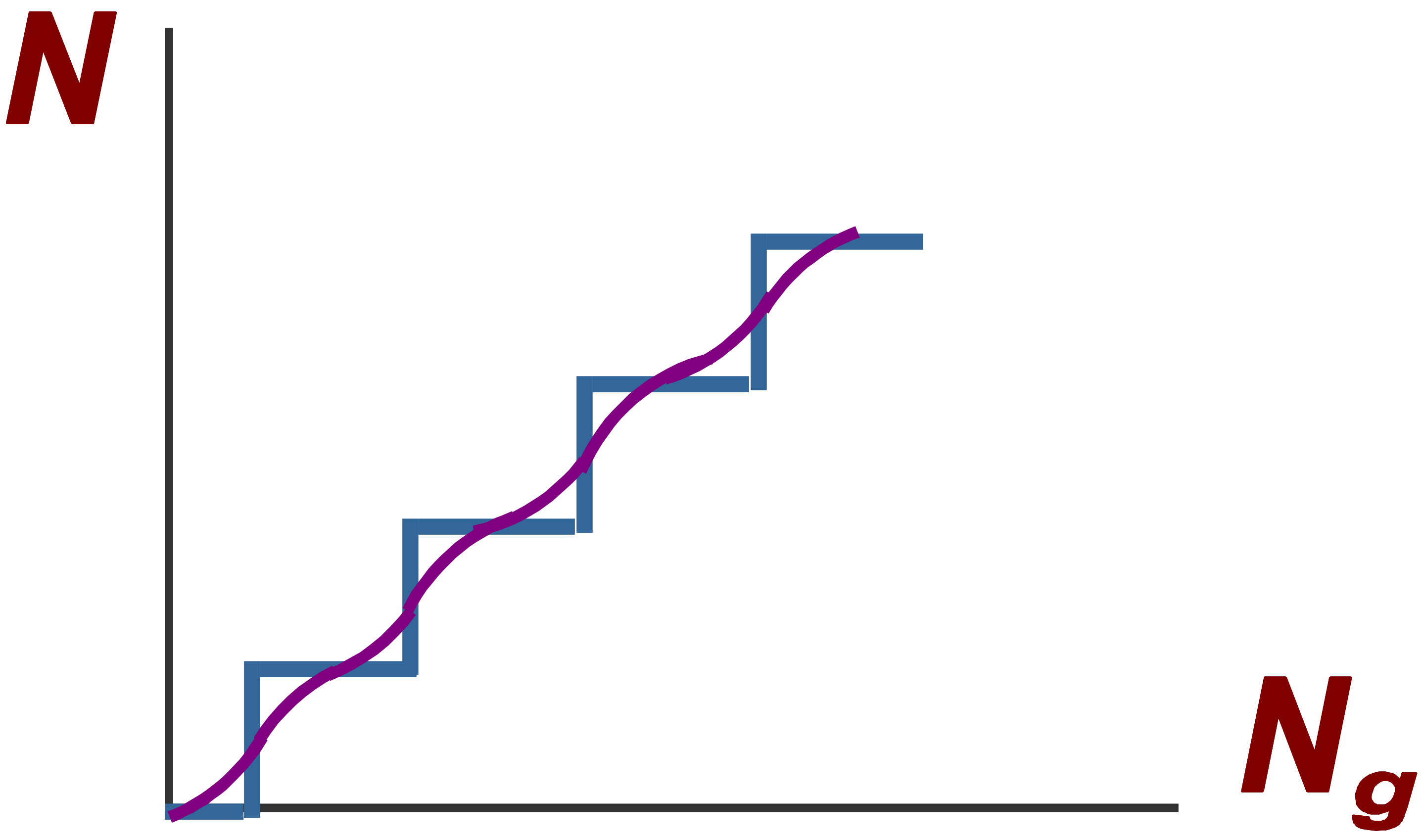


Tunnel junction, strong tunneling

all $T_n \ll 1$ but $g \gg 1$

Panyukov, A.D.Z.'88'91 **(Instanton technique)**

$$\tilde{E}_c \propto E_c \exp(-g/2)$$



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One channel, arbitrary T_1

Matveev'95 **(bosonization)**

$$\tilde{E}_c = 0 \quad \text{for} \quad T_1 = 1$$

Tunnel junction, strong tunneling

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One channel, arbitrary T_1

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$$\tilde{E}_c = 0 \quad \text{for} \quad T_1 = 1$$

Arbitrary scatterer, $g \gg 1$

Nazarov'99 **(effective action, instantons)**

$$\tilde{E}_c \propto E_c \prod_n [1 - T_n] = E_c \exp(-ag)$$

diffusive conductor: $a = \pi^2/8$

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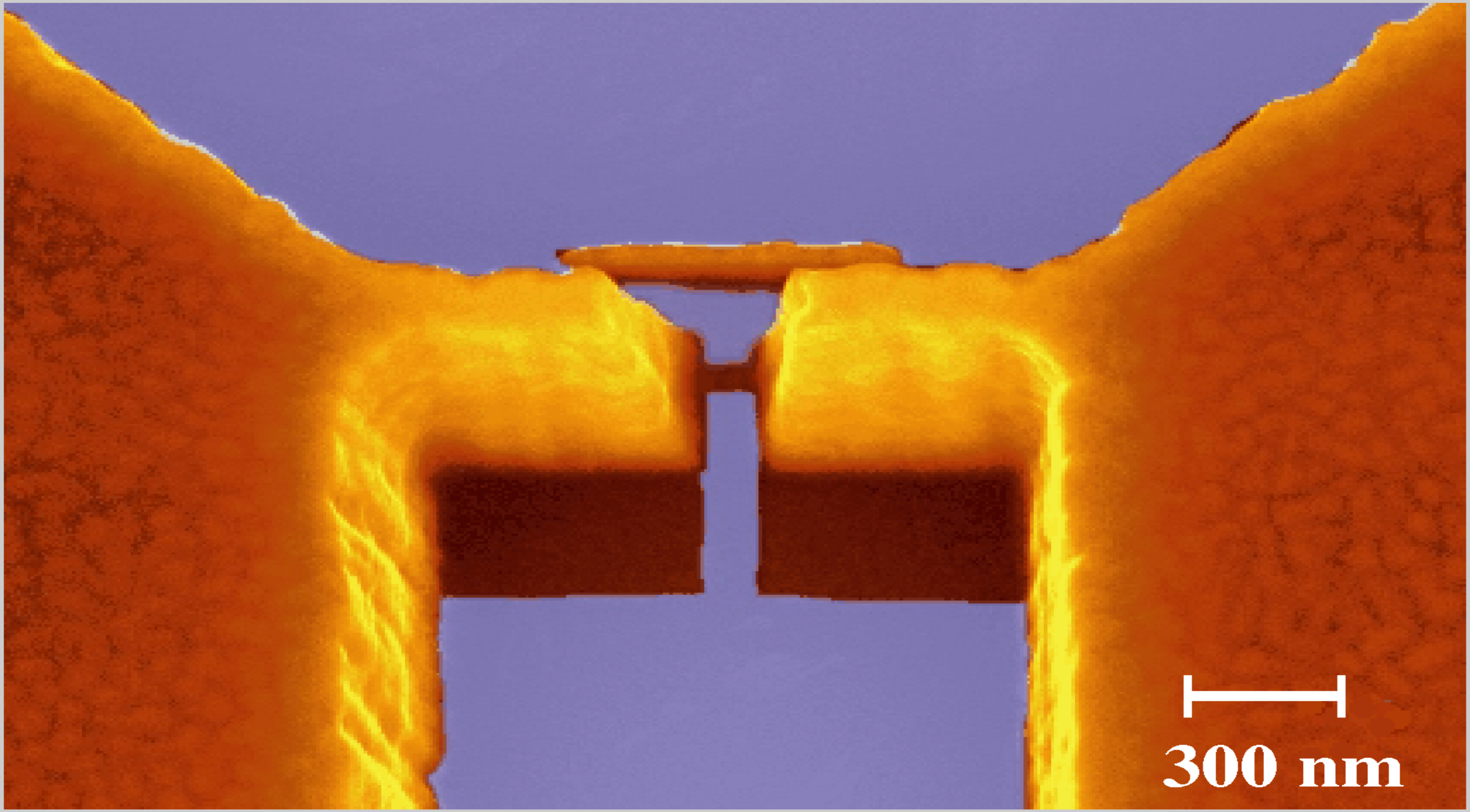
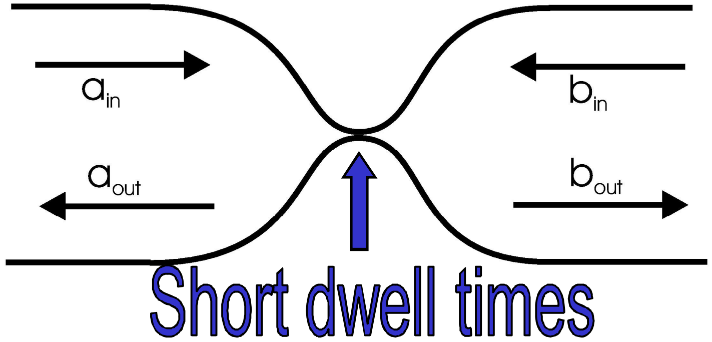
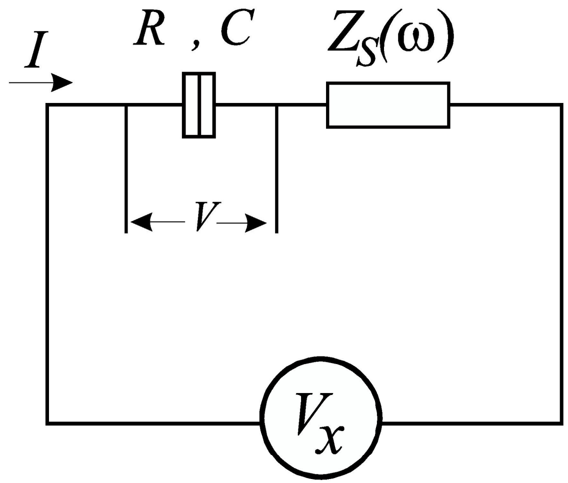
Diffusive metallic bridges

H. Weber et al., PRB´01



Scatterer+Environment



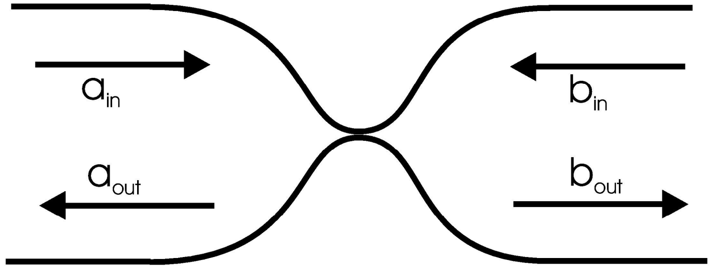


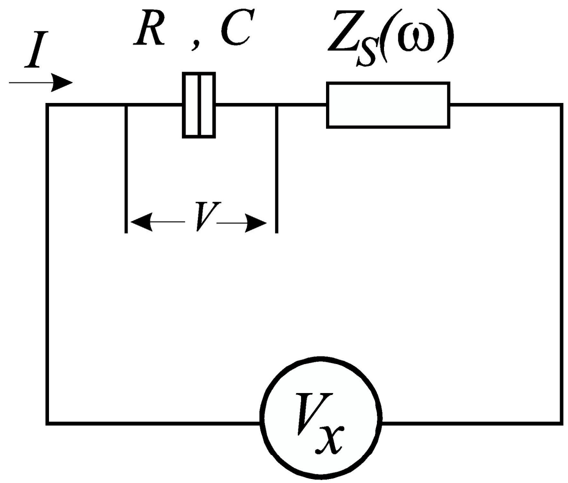
Golubev, A.D.Z.'01:

$$R\frac{dI}{dV} = 1 - \beta f(V,T)$$

$$\beta = \frac{\Sigma_n T_n(1 - T_n)}{\Sigma_n T_n}$$

Scatterer+Environment





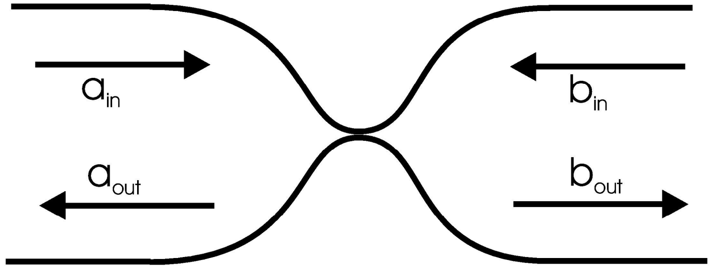
Golubev, A.D.Z.'01:

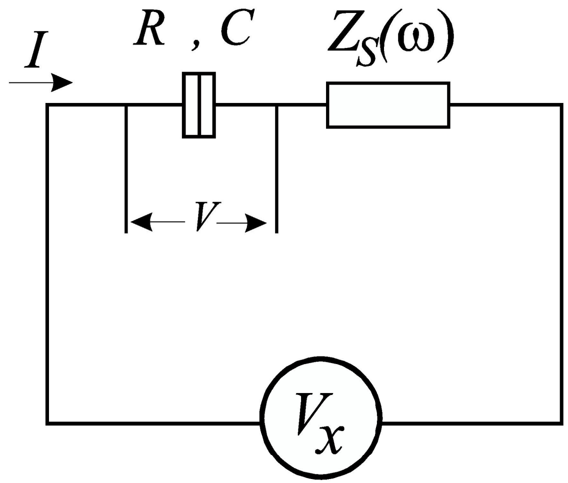
$$R\frac{dI}{dV} = 1 - \beta f(V,T)$$

→ Universal function

$$\beta = \frac{\sum_n T_n(1-T_n)}{\sum_n T_n}$$

Scatterer+Environment



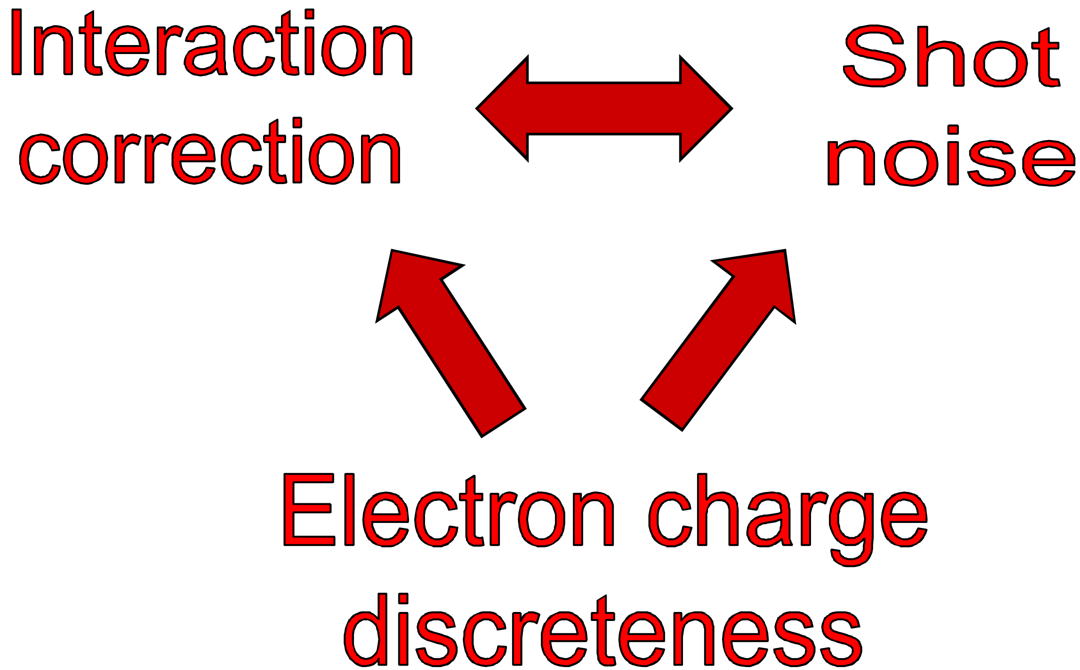


Golubev, A.D.Z.'01:

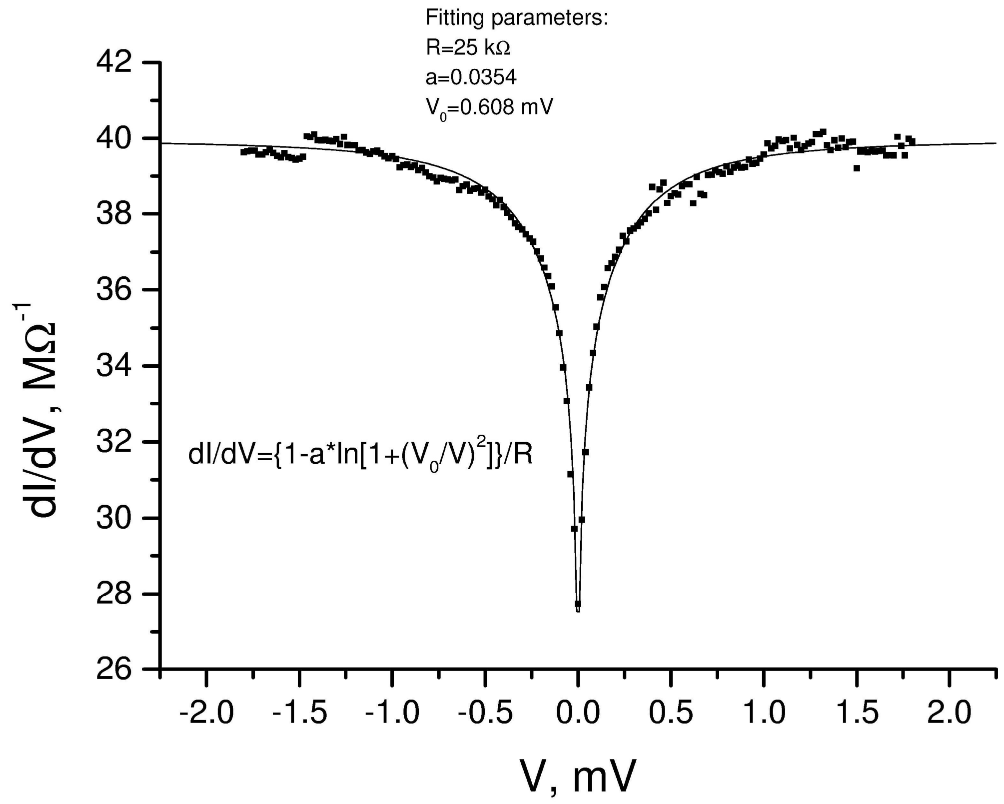
$$R\frac{dI}{dV} = 1 - \beta f(V,T)$$ → Universal function

$$\beta = \frac{\Sigma_n T_n(1-T_n)}{\Sigma_n T_n}$$ ↔ Shot noise

Interaction correction ⟷ Shot noise


Interaction correction
Shot noise
Electron charge discreteness

Experiment: Krupenin et al., APL'02 (Granular metals)

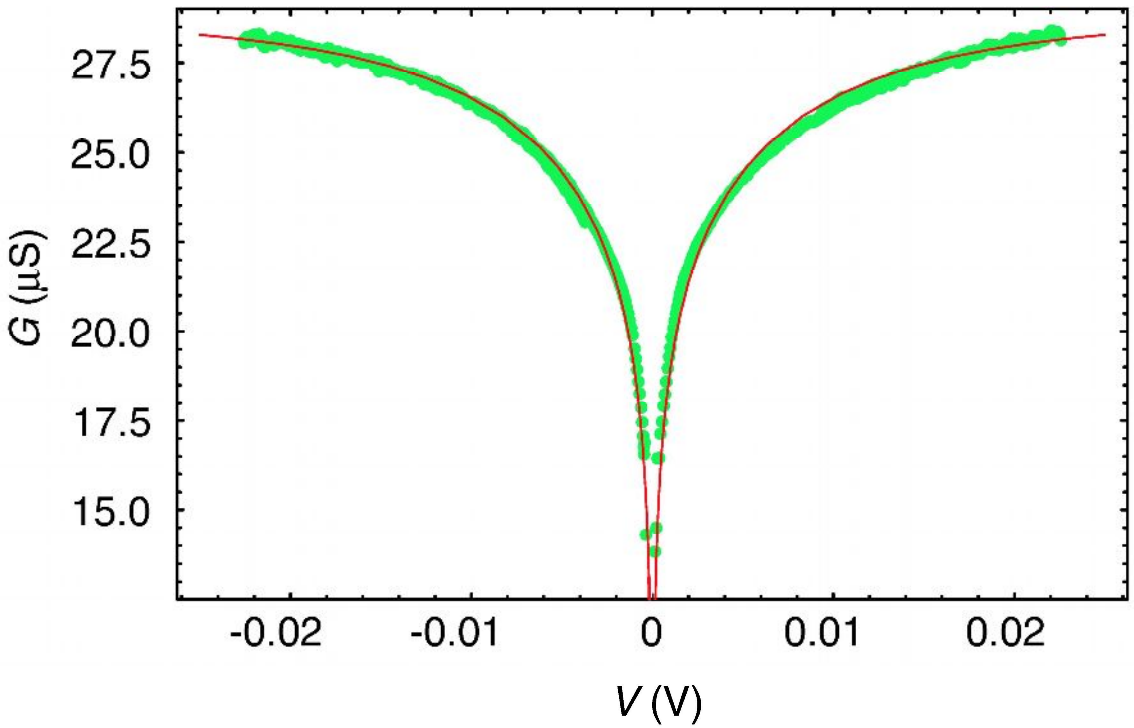


$I-V$ curve at low T:

$$R\frac{dI}{dV} = 1 - \frac{\beta}{g}\ln\left(1 + \frac{1}{(eVRC)^2}\right)$$

Multiwalled Carbon Nanotubes

Paalanen et al. (LTL, Helsinki)



Applied Physics A
Materials
Science & Processing

Appl. Phys. A 69, 283–295 (1999)

Interference and Interaction in multi-wall carbon nanotubes

C. Schönenberger[1], A. Bachtold[1], C. Strunk[1], J.-P. Salvetat[2], L. Forró[2]

[1] Institut für Physik, Universität Basel, Klingelbergstr. 82, CH-4056 Basel, Switzerland
[2] Institut de Génie Atomique, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Received: 17 May 1999/Accepted: 18 May 1999/Published online: 4 August 1999

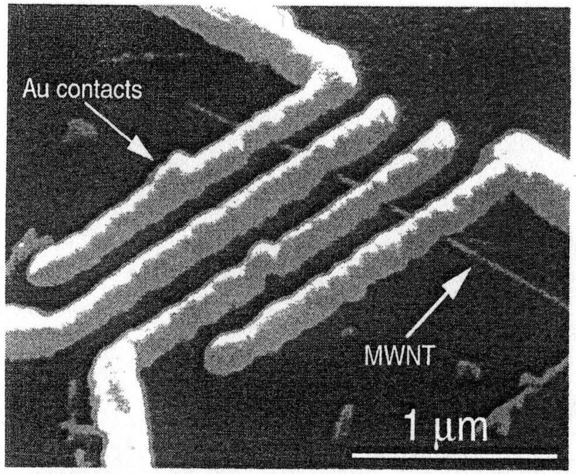


Fig. 1. Scanning electron microscopy image of a single multi-wall nanotube (MWNT) electrically contacted by four Au fingers from above. The separation between the contacts is 350 nm center to center

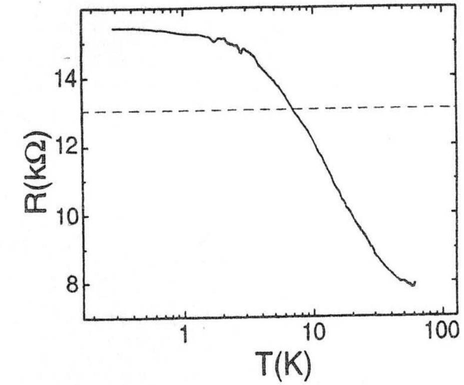


Fig. 2. Typical temperature-dependent electrical resistance $R(T)$ of a single MWNT measured in a four-probe configuration, i.e. the current is passed through the outer contacts and voltage is measured over the inner ones. The *dashed line* corresponds to the resistance quantum $h/2e^2$

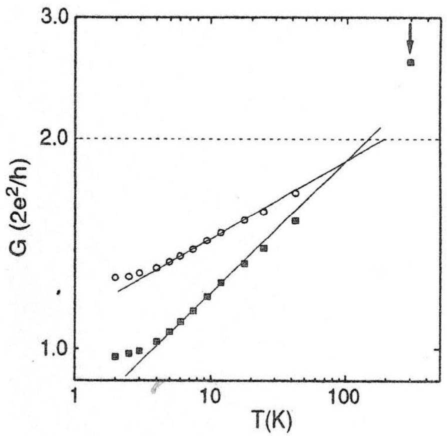
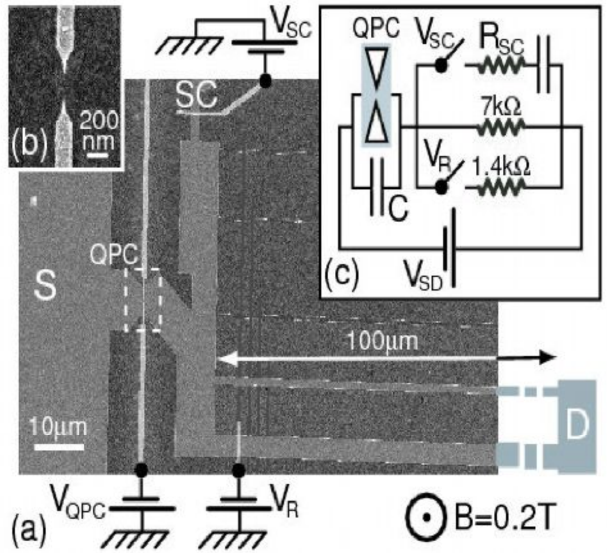
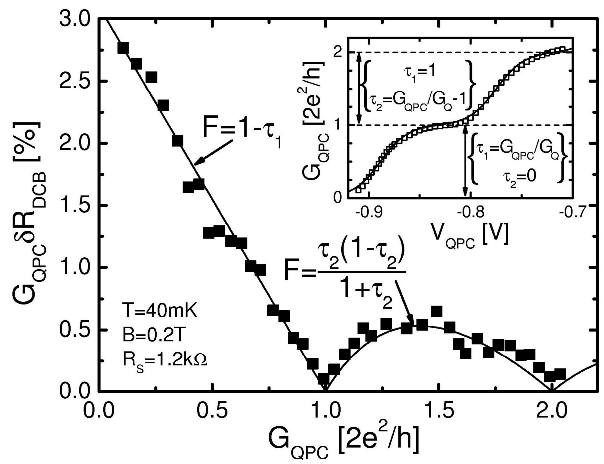


Fig. 6. Conductance G at zero magnetic field as a function of temperature T for the measurement shown in Fig. 5. *Filled squares* correspond to G at $B = 0$ and *open circles* to $G - \delta G_{WL}$ with δG_{WL} the contribution to the conductance from weak localization. The *dashed horizontal line* is the conductance expected for an ideal metallic carbon nanotube. The *arrow points* to the measured room temperature value

Interaction correction ⟷ Shot noise (Fano factor)

Experiments on break junctions: Altimiras et al. PRL'07



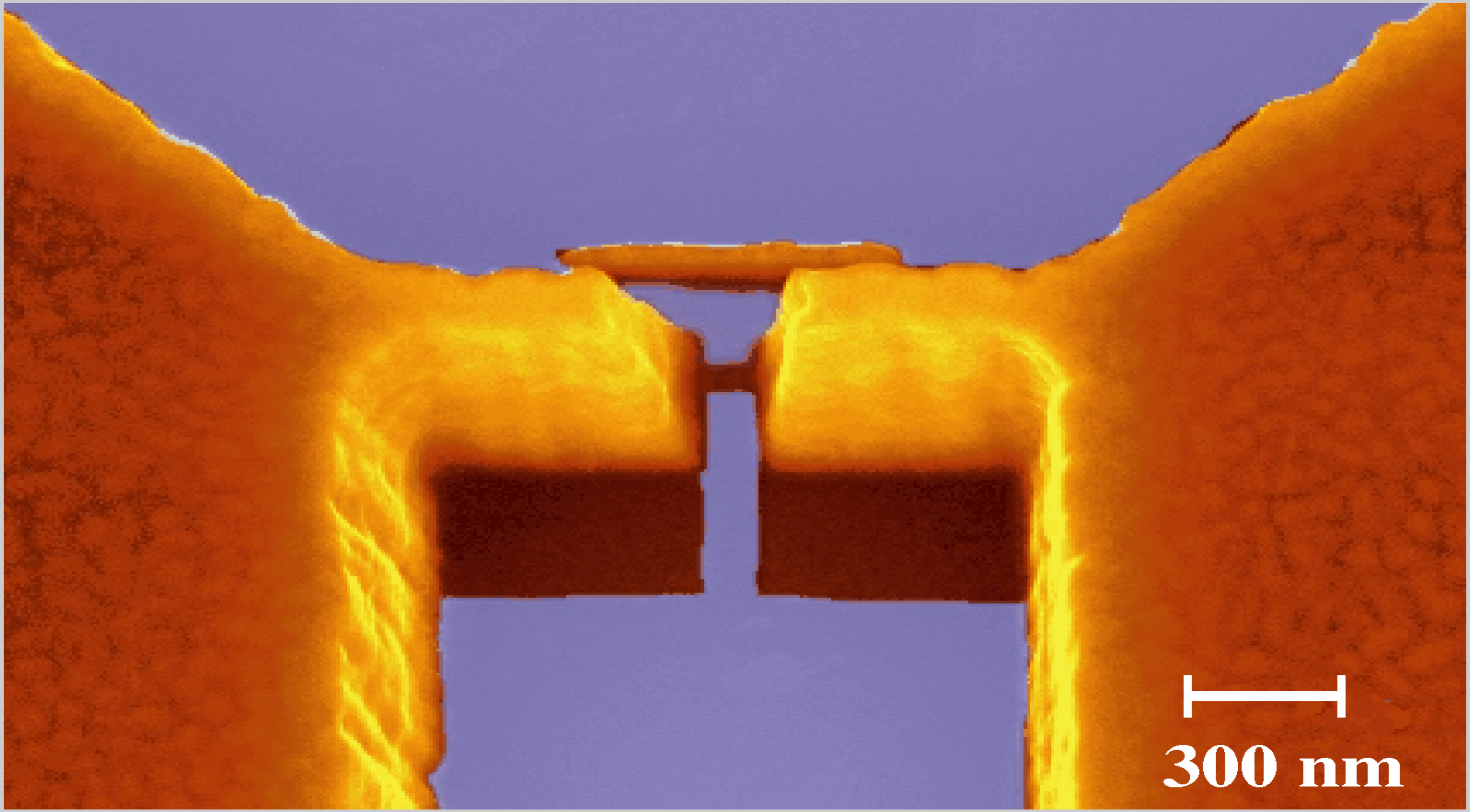


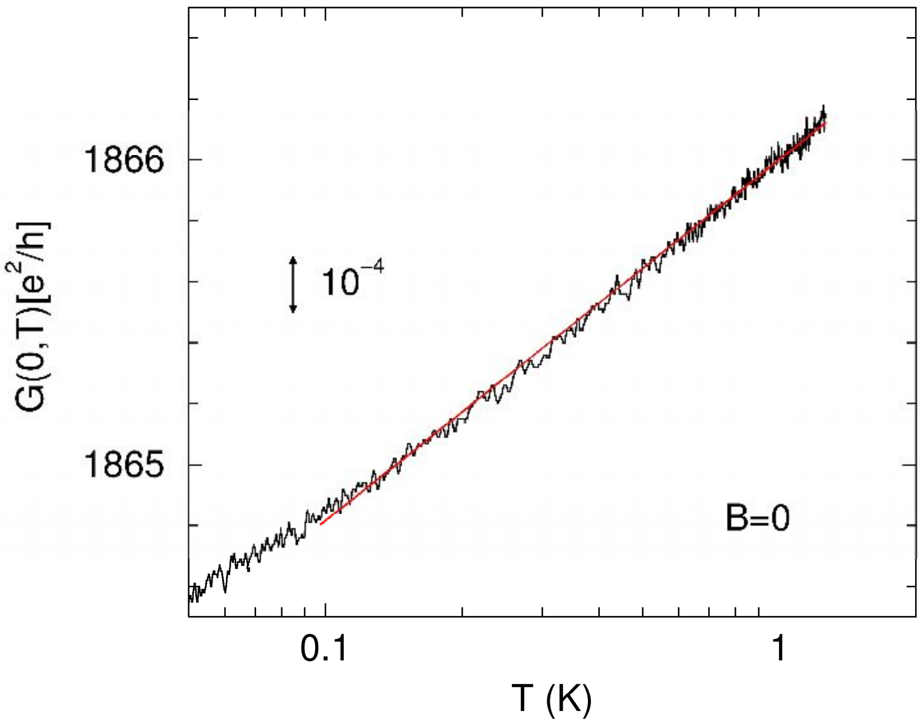
Zero bias conductance:

$$RG(T) \simeq 1 - \frac{2\beta}{g} \ln\left(\frac{gE_C}{T}\right)$$

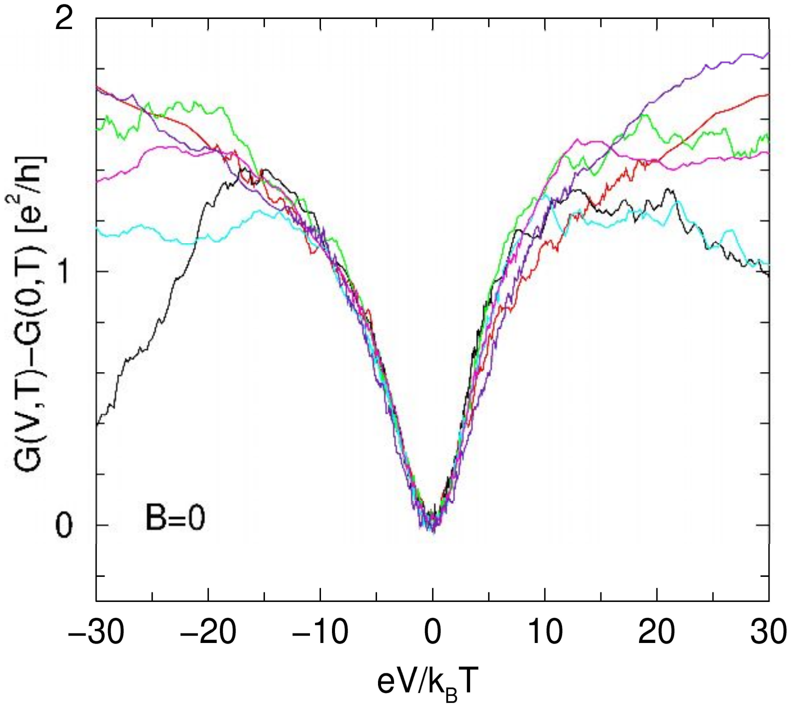
Diffusive metallic bridges

H. Weber et al., PRB´01

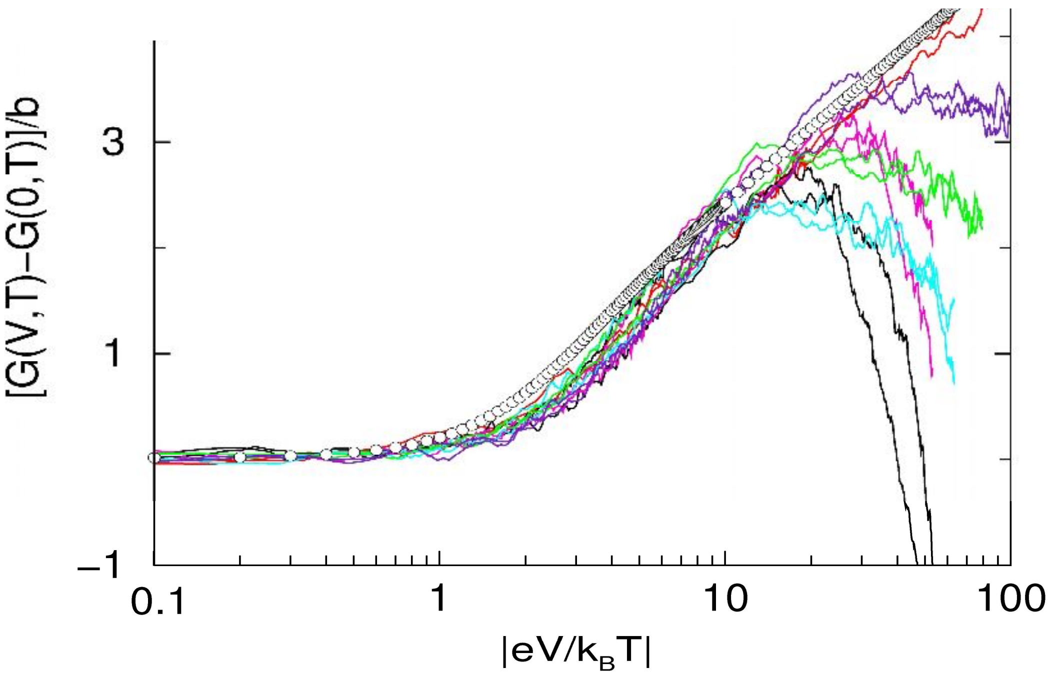




1866
1865
10^{-4}
B=0
G(0,T)[e^2/h]
0.1
1
T (K)



2
1
0
B=0
G(V,T)−G(0,T) [e^2/h]
−30
−20
−10
0
10
20
30
eV/k_BT



3
1
−1
[G(V,T)−G(0,T)]/b
0.1
1
10
100
|eV/k_BT|

Zero bias conductance:

$$RG(T) \simeq 1 - \frac{2\beta}{g} \ln\left(\frac{gE_C}{T}\right)$$

$$+\frac{4}{g^2} \ln^2\left(\frac{gE_C}{T}\right)\left[\frac{\beta(1-\beta)}{2} - \gamma\right] + \ldots$$

$$\gamma = \frac{\Sigma_n T_n^2 (1 - T_n)}{\Sigma_n T_n}$$

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Interaction correction to higher cumulants and full counting statistics

Shot noise: $S_2 = \langle I\, I \rangle_+$

Interaction correction to higher cumulants and full counting statistics

Shot noise: $S_2 = \langle I\ I \rangle_+$

$$\delta S_2^{int} \sim (2\gamma - \beta)/g$$

Interaction correction to higher cumulants and full counting statistics

Shot noise: $S_2 = \langle I\, I \rangle_+$

$$\delta S_2^{int} \sim (2\gamma - \beta)/g \;\sim\; S_3$$

Golubev, Galaktionov, A.D.Z.'03

$$\tilde{S}(t,t') = \tilde{S}^{\mathrm{ni}}(t,t') + \delta\tilde{S}(t,t')$$

Nyquist noise...

$$\delta\tilde{S}_\omega = -\frac{4\beta T}{R_q}\ln\frac{gE_C}{T}, \qquad \text{if } |\omega|, |eV| \ll T \ll gE_C,$$

$$\delta\tilde{S}_\omega = -\frac{2\beta|\omega|}{R_q}\ln\frac{gE_C}{|\omega|}, \quad \text{if } T, |eV| \ll |\omega| \ll gE_C$$

... always suppressed

$$\tilde{\mathcal{S}}(t,t') = \tilde{\mathcal{S}}^{\mathrm{ni}}(t,t') + \delta\tilde{\mathcal{S}}(t,t')$$

Shot noise...

$$\delta\tilde{\mathcal{S}}_\omega = -\frac{2(\beta - 2\gamma)|eV|}{R_q} \ln \frac{gE_C}{|eV|},$$

$$\text{if } T, |\omega| \ll |eV| \ll gE_C$$

... enhanced for $\beta<2\gamma$

Shot noise

Large voltages:

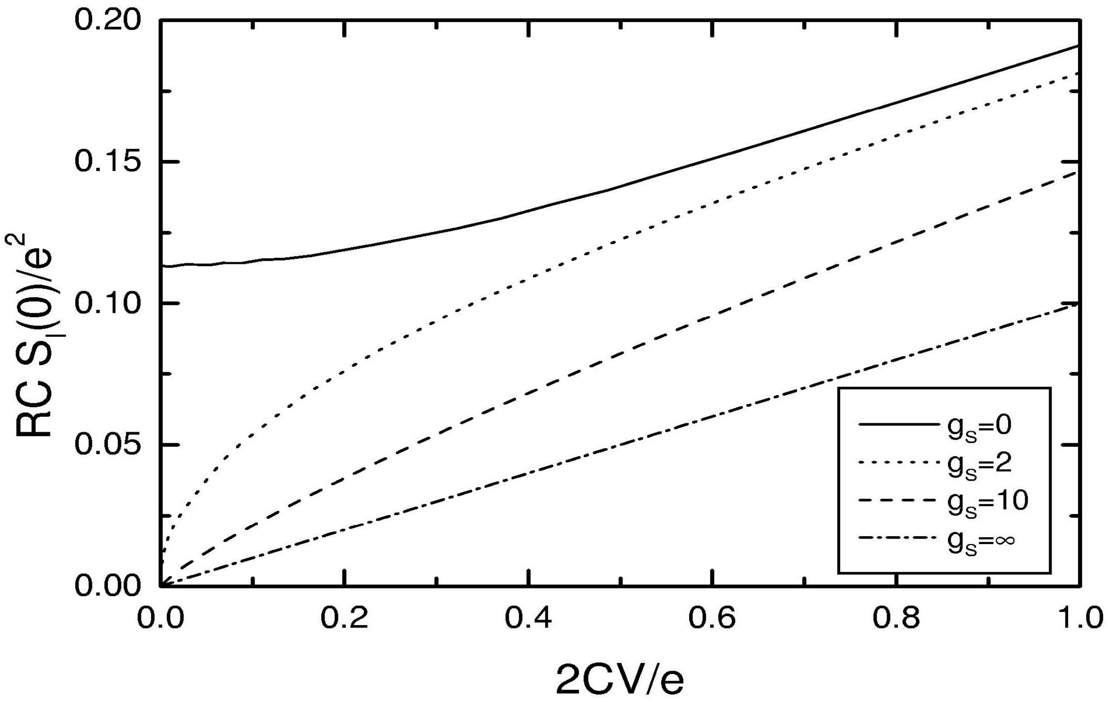
$$\mathcal{S}_I(0) = \frac{2e^3\mathcal{R}}{\pi}\left(V + \frac{e}{2C}\right),$$

Small voltages:

$$\mathcal{S}_I(0) = \frac{2e^2\mathcal{R}(R+R_S)\mathrm{e}^{\frac{2\gamma_0}{g+g_s}}}{\pi\Gamma\left(2-\frac{2}{g+g_s}\right)RR_SC}\left(\frac{e|V|RR_SC}{R+R_S}\right)^{1-\frac{2}{g+g_s}}$$

Shot noise

Golubev, Galaktionov, A.D.Z.'05



Interaction-induced excess noise

Renormalization group

Kinderman, Nazarov'03
Golubev, A.D.Z.'04
Bagrets, Nazarov'05

$$\frac{dTn}{d\ln V} = \frac{2Tn(1-Tn)}{g}$$

$$g \gg 1$$

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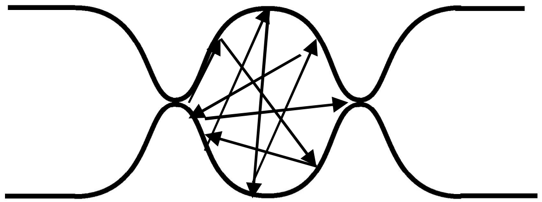
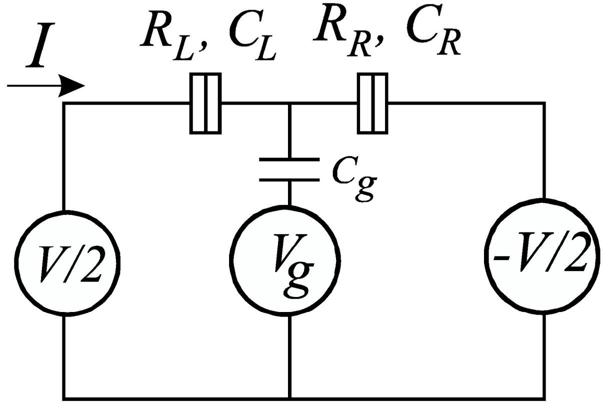
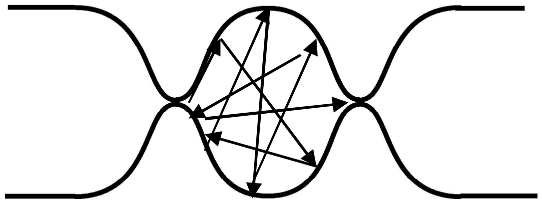
Long dwell times...

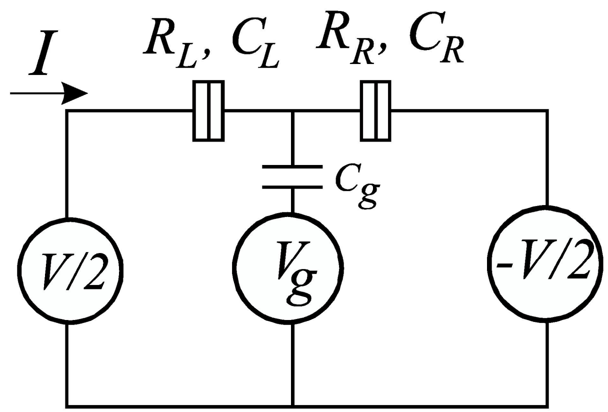




$$RG(T) \simeq 1 - \frac{2(\beta_L g_R + \beta_R g_L)}{(g_L + g_R)^2} \ln\left(\frac{g E_C}{T}\right)$$

Long dwell times...





$$RG(T) \simeq 1 - \frac{2(\beta_L g_R + \beta_R g_L)}{(g_L + g_R)^2} \ln\left(\frac{g E_C}{T}\right)$$

Finite τ_D ?

Non-zero external impedance

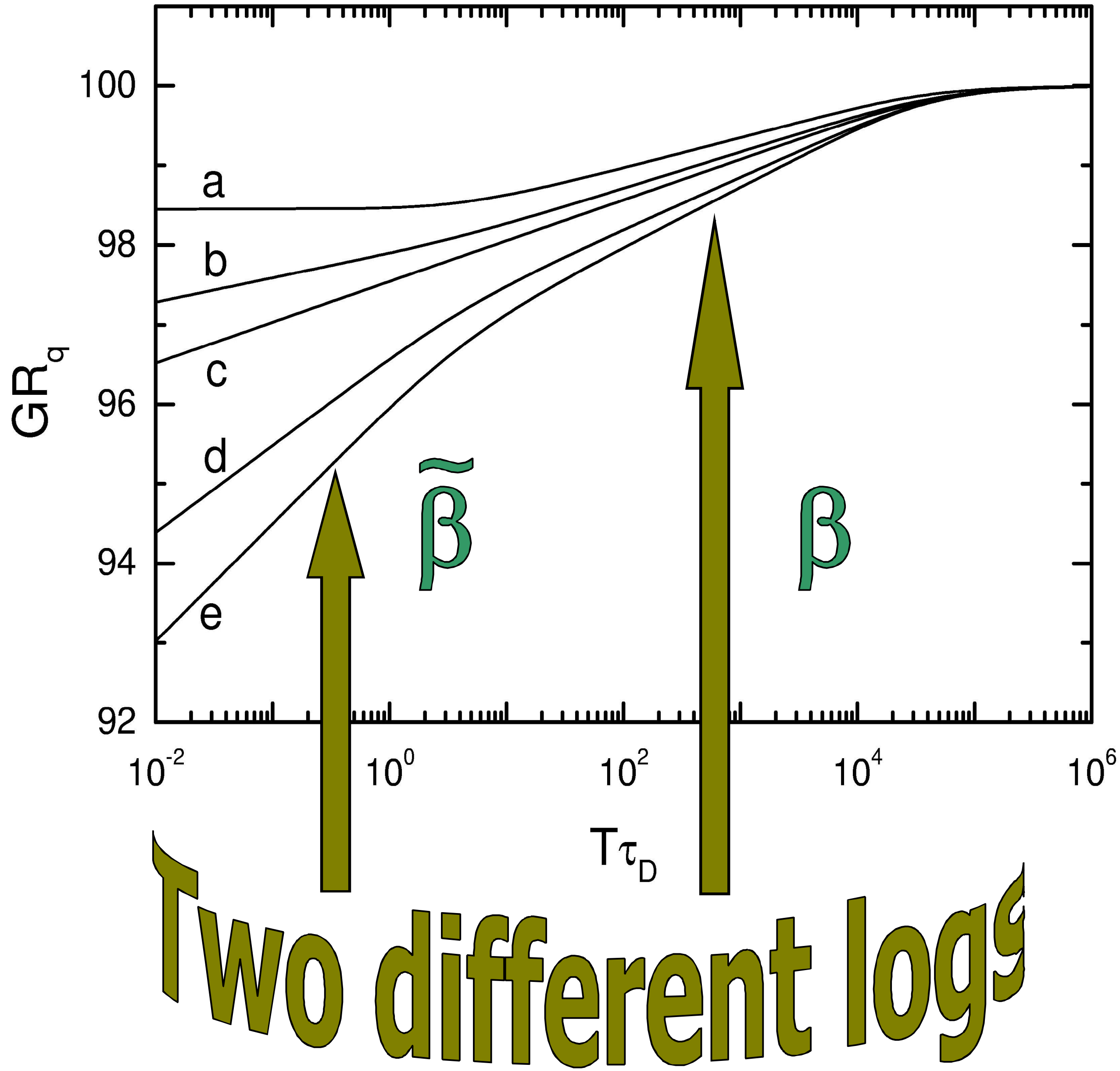
- $1/\tau_D \ll T \ll gE_C$:

$$G = G_0 + \frac{\beta\chi}{R_q} \ln\left(T/gE_C\right), \quad 1 \le \chi \le 2,$$

- $T \ll 1/\tau_D$:

$$G \simeq \tilde{G}_0 + \frac{2\tilde{\beta}}{R_q} \frac{1}{1 + 4R/R_S} \ln(T\tau_D),$$

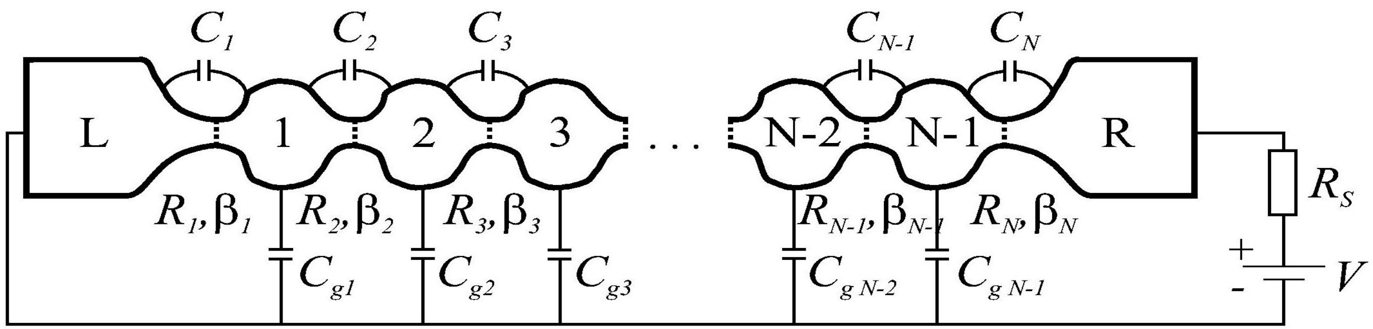
$$\tilde{G}_0 \simeq G_0 - \frac{\beta\chi}{2R_q} \ln \frac{\tau_D}{RC}$$

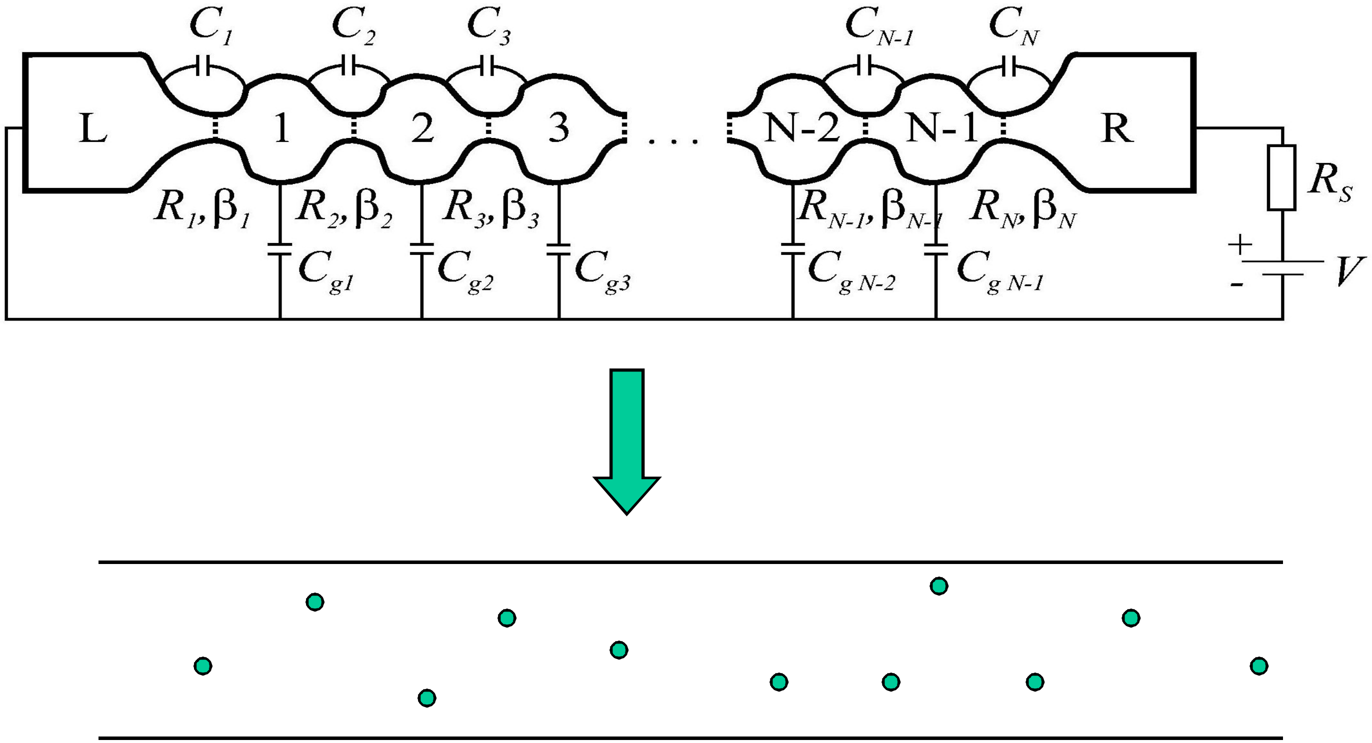

100
98
96
94
92
GR_q
a
b
c
d
e
$\tilde{\beta}$
β
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
$T\tau_D$
Two different logs

Experiments

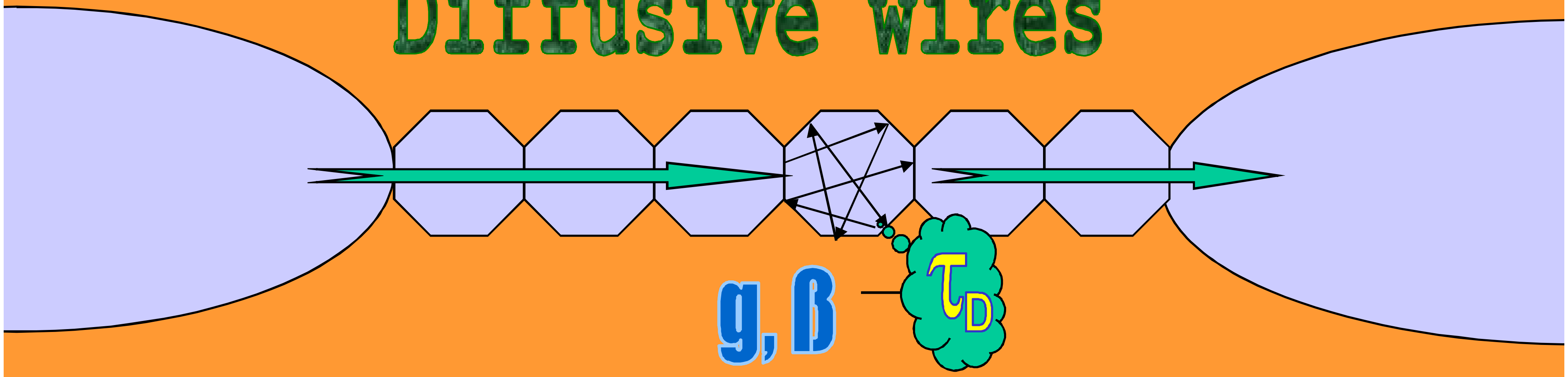
- Diffusive metallic nanobridges (Weber et al.)
- Break junctions (Saclay)
- Metallic constrictions (Natelson et al.)
- Carbon nanotubes (numerous)
- Single tunnel junctions and granular arrays (numerous)
- Diffusive metallic wires (Mohanty-Webb)

Both logs have been observed

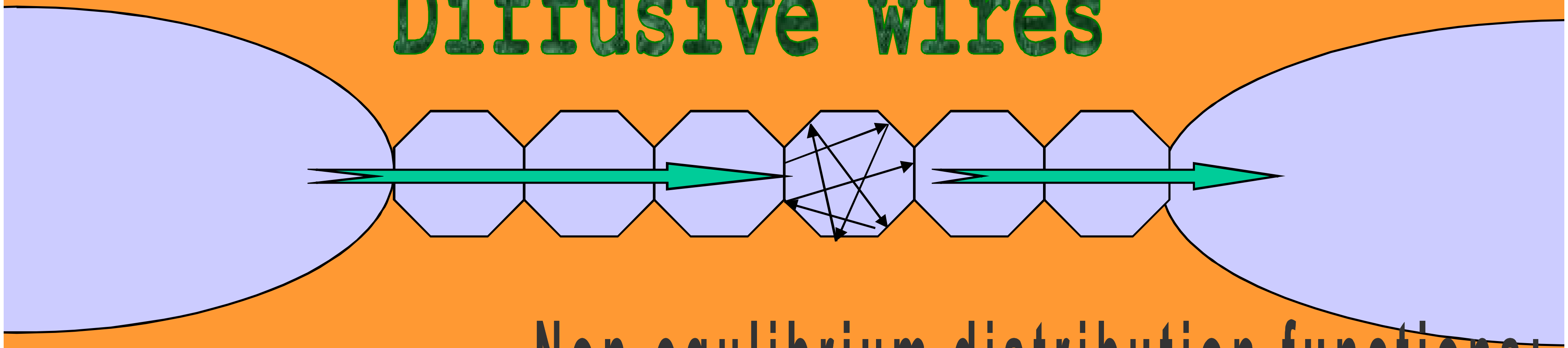

C_1
C_2
C_3
C_{N-1}
C_N
L
1
2
3
. . .
N-2
N-1
R
R_1, β_1
R_2, β_2
R_3, β_3
R_{N-1}, β_{N-1}
R_N, β_N
C_{g1}
C_{g2}
C_{g3}
$C_{g\,N-2}$
$C_{g\,N-1}$
R_S
+
-
V


C1
C2
C3
CN-1
CN
L
1
2
3
. . .
N-2
N-1
R
R1, β1
R2, β2
R3, β3
RN-1, βN-1
RN, βN
Cg1
Cg2
Cg3
Cg N-2
Cg N-1
RS
+
-
V

Diffusive wires



Diffusive wires



Non-equlibrium distribution functions:

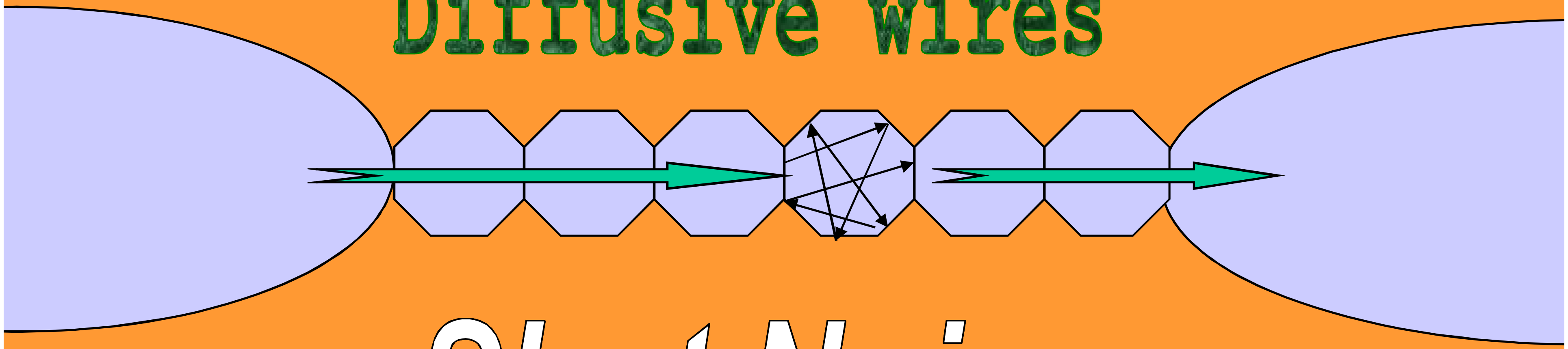
shot noise modified

General strategy:

Kinetic equation

Balance of charges and voltages

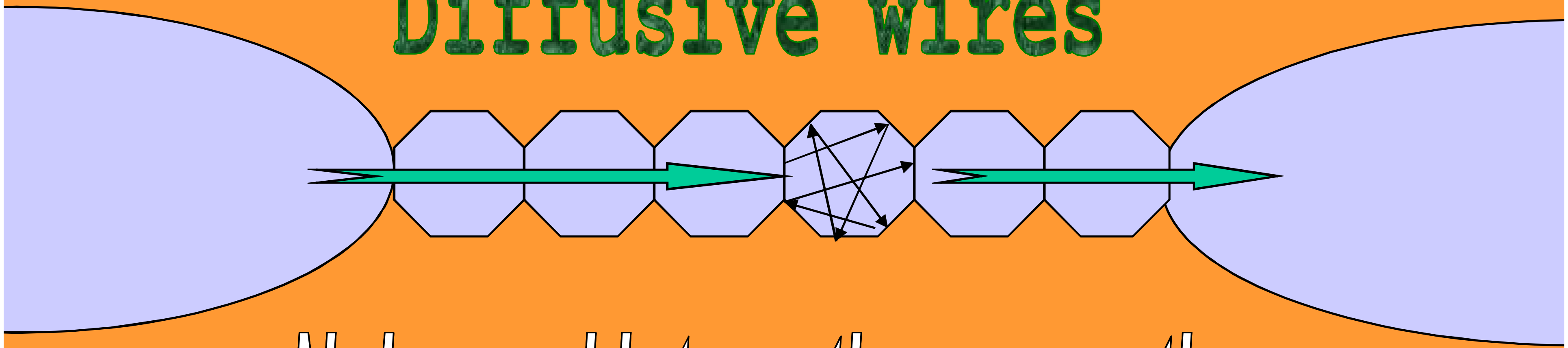
Diffusive wires



Shot Noise:

$$\tilde{\beta} = 1/3 + \frac{\sum_n (1/g_n^3)(\beta_n - 1/3)}{(\sum_n 1/g_n)^3}$$

Diffusive wires



Noise and interaction correction

$$I R_{\Sigma} = V + \sum_n R_n \langle \xi_n \rangle$$

Perturbation theory: complete expression

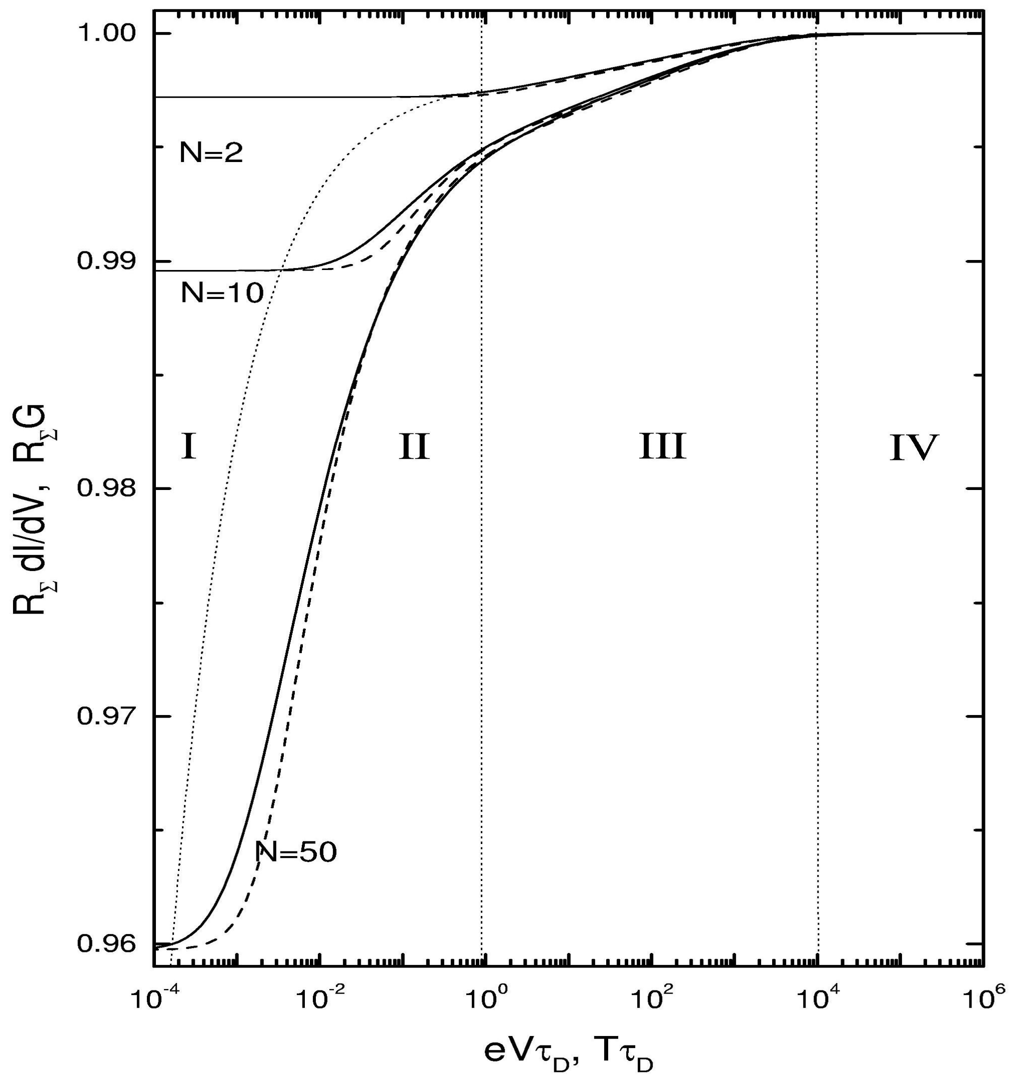
$$I = V/R_{\Sigma} + \delta I,$$

$$\delta I = -\frac{2Te}{N^2}\sum_{q=1}^{N-1}\left[\beta + \frac{\cos\frac{\pi q}{N}}{4\sin^2\frac{\pi q}{2N}}\right]\left[W\left(\frac{2\sin^2\frac{\pi q}{2N}}{\pi T R\left(4C\sin^2\frac{\pi q}{2N}+C_g\right)}+\frac{\sin^2\frac{\pi q}{2N}}{\pi T\tau_D}+\frac{ieV}{2\pi T}\right)-W\left(\frac{\sin^2\frac{\pi q}{2N}}{\pi T\tau_D}+\frac{ieV}{2\pi T}\right)\right]$$

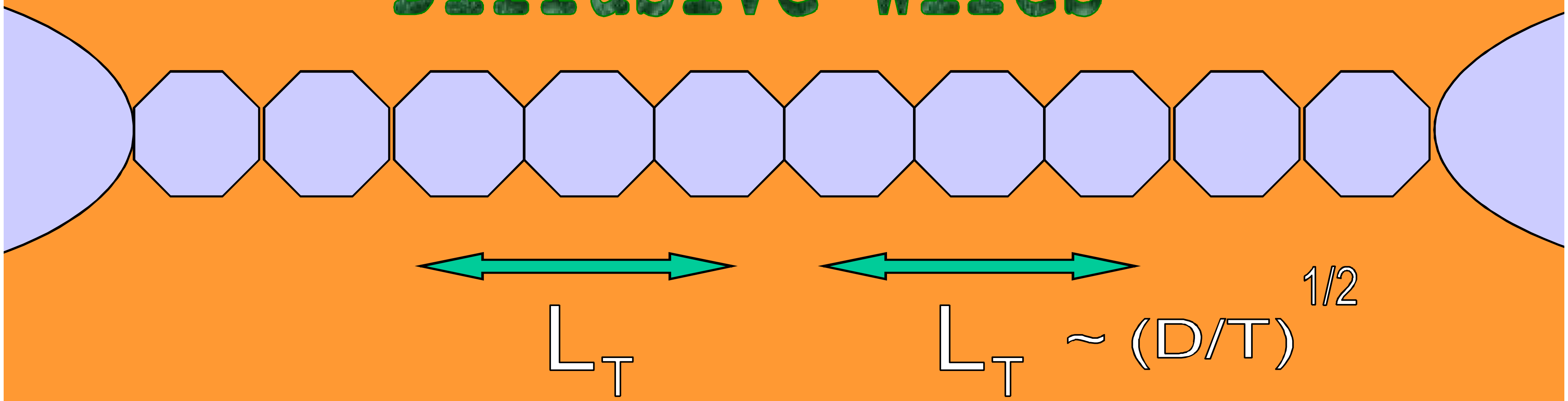
$$-\frac{4Te}{N^4}\sum_{p,q=1}^{N-1}\frac{\left(1-(-1)^{p+q}\right)\sin^2\frac{\pi q}{N}\sin^2\frac{\pi p}{N}}{\left(\cos\frac{\pi q}{N}-\cos\frac{\pi p}{N}\right)^3\left(2\sin^2\frac{\pi p}{2N}+\frac{R}{2\tau_D}\left(4C\sin^2\frac{\pi p}{2N}+C_g\right)\left(\cos\frac{\pi q}{N}-\cos\frac{\pi p}{N}\right)\right)}$$

$$\times\left[W\left(\frac{2\sin^2\frac{\pi p}{2N}}{\pi T R\left(4C\sin^2\frac{\pi p}{2N}+C_g\right)}+\frac{\sin^2\frac{\pi p}{2N}}{\pi T\tau_D}+\frac{ieV}{2\pi T}\right)-W\left(\frac{\sin^2\frac{\pi q}{2N}}{\pi T\tau_D}+\frac{ieV}{2\pi T}\right)\right].$$

$$W(x) = \mathrm{Im}[x\Psi(1+x)]$$


1.00
0.99
0.98
0.97
0.96
N=2
N=10
N=50
I
II
III
IV
R_Σ dI/dV, R_ΣG
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
$eV\tau_D$, $T\tau_D$

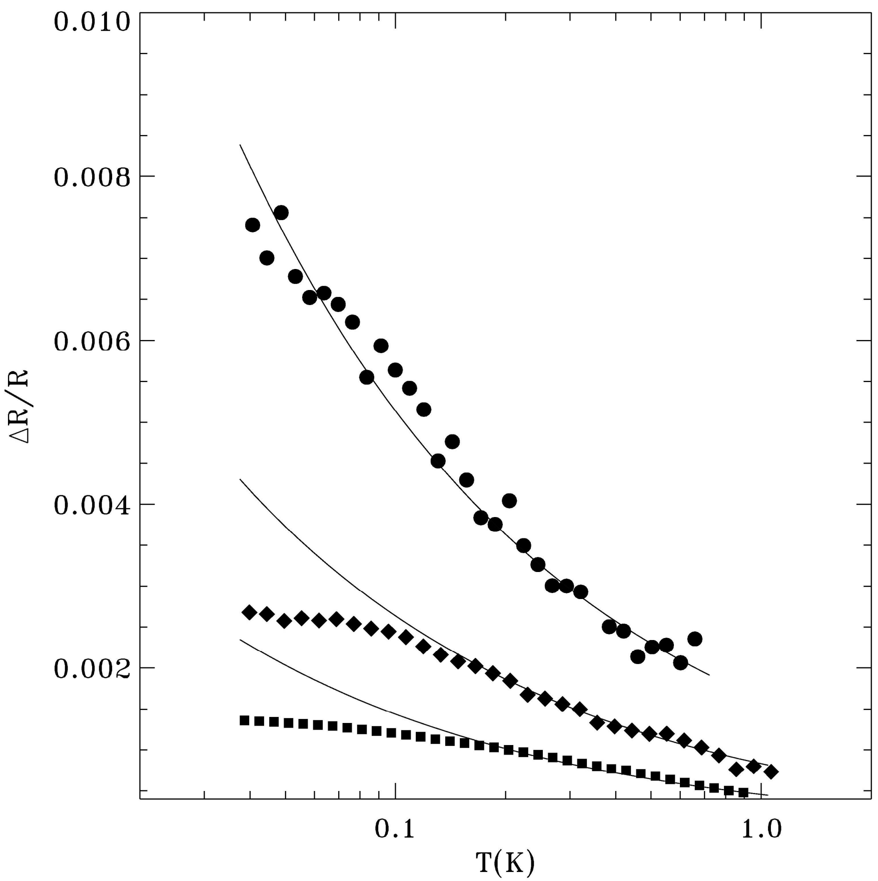
Diffusive wires



$$\delta G \sim \beta(L_T)/g(L_T) \sim T^{-1/2}$$

Quasi-1D Disordered Wires

Mohanty-Webb'98



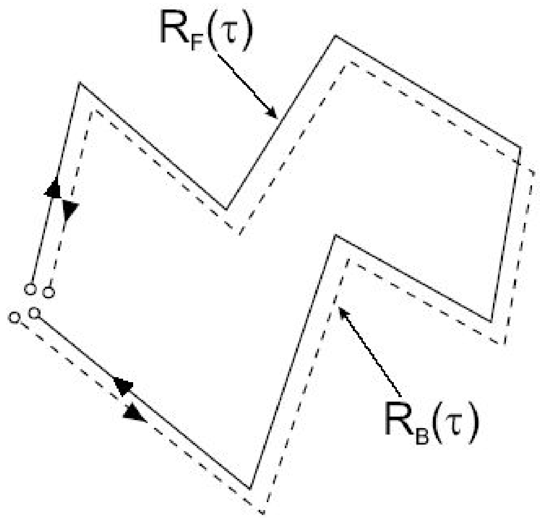
Outline

- Introduction and motivation
- Short coherent conductors: Weak Coulomb blockade
- Short coherent conductors: interaction correction and shot noise
- Interactions and higher current cumulants
- Transport and interactions in quantum dots and arrays: universal model for ANY diffusive conductor
- Weak localization and decoherence at T=0

Interference (weak localization) correction to conductance:

$$\sigma_{\alpha\beta}(r,r') = -\frac{e^2}{4\pi m^2}\int_{-\infty}^{t} dt_0 \int dt' (\nabla^{\alpha}_{r_1} - \nabla^{\alpha}_{r_2})_{r_1=r_2=r}(\nabla^{\beta}_{r'_1} - \nabla^{\beta}_{r'_2})_{r'_1=r'_2=r'} \langle G_R(t,t';r_1,r'_2)G_A(t_0,t;r'_1,r_2)\rangle_{\rm imp}$$

$$G_R(t,t';r_1,r'_2) \sim e^{iS_0[t,t';R_F(\tau)]},\quad G_A(t_0,t;r'_1,r_2) \sim e^{-iS_0[t,t_0;R_B(\tau)]}$$



time reversed paths

$$R_B(\tau) = R_F(t+t_0-\tau),\ t'=t_0 \Rightarrow$$
$$S_0[t,t';R_F(\tau)] = S_0[t,t_0;R_B(\tau)]$$

weak localization correction

$$\delta\sigma^{\rm WL}_{\alpha\beta}(r,r') = -\frac{2e^2 D(r)}{\pi}\delta_{\alpha\beta}\delta(r-r')\int_{-\infty}^{t} dt_0\ C(t,t_0;r,r)$$

Decoherence:

Electron-electron interaction ⟶ fluctuating field

$$G_R(t,t';r_1,r_2') \sim e^{iS_0[t,t';R_F(\tau)]} e^{-i\int_{t_0}^{t} d\tau\, eV(\tau,R_F(\tau))}, \quad G_A(t_0,t;r_1',r_2) \sim e^{-iS_0[t,t_0;R_B(\tau)]} e^{i\int_{t_0}^{t} d\tau\, eV(\tau,R_F(t+t_0-\tau))}$$

Hence

$$\delta\sigma_{\alpha\beta}^{\mathrm{WL}}(r,r') \approx -\frac{2e^2 D(r)}{\pi}\delta_{\alpha\beta}\delta(r-r')\int_{-\infty}^{t} dt_0\, C(t,t_0;r,r)\, e^{-F(t-t_0,r)}$$

where

$$e^{-F(t-t_0,r)} = \left\langle e^{-i\int_{t_0}^{t} d\tau \left[eV(\tau,R_F(\tau)) - eV(\tau,R_F(t+t_0-\tau))\right]} \right\rangle_{V,\,\mathrm{paths}} \approx e^{-(t-t_0)/\tau_\varphi}$$

Saturation of electron dephasing time is observed in:

- Quantum dots (0d)
- Quasi-1d metallic wires
- Quasi-1d semiconductors
- Carbon nanotubes
- 2d metallic films
- 2DEGs
- Graphene
- Bulk metals (3d)
- …

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Low-Temperature Saturation of the Dephasing Time and Effects of Microwave Radiation on Open Quantum Dots

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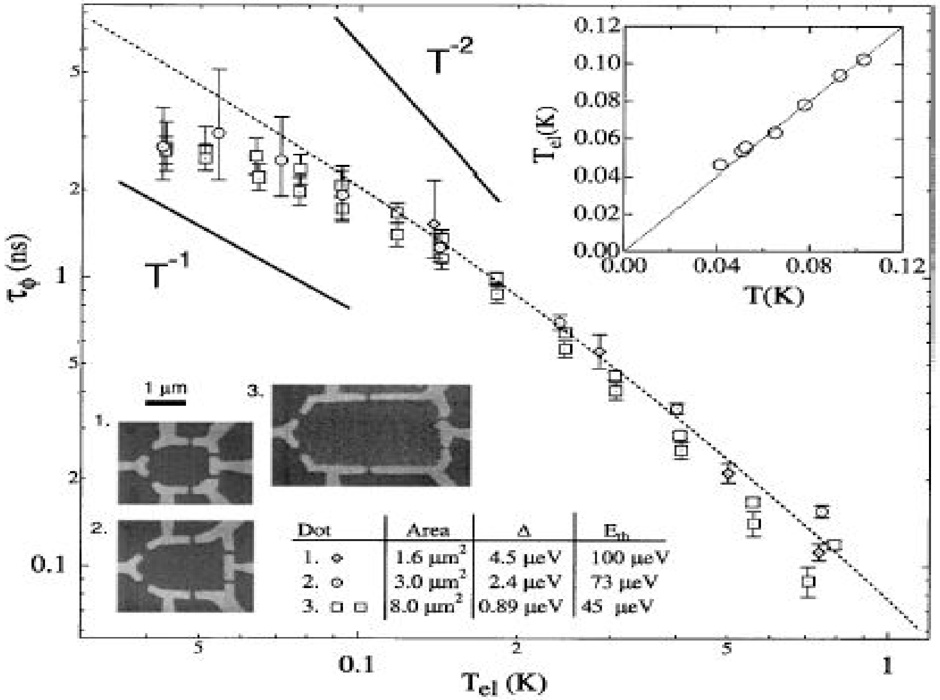
(Received 20 April 1999)



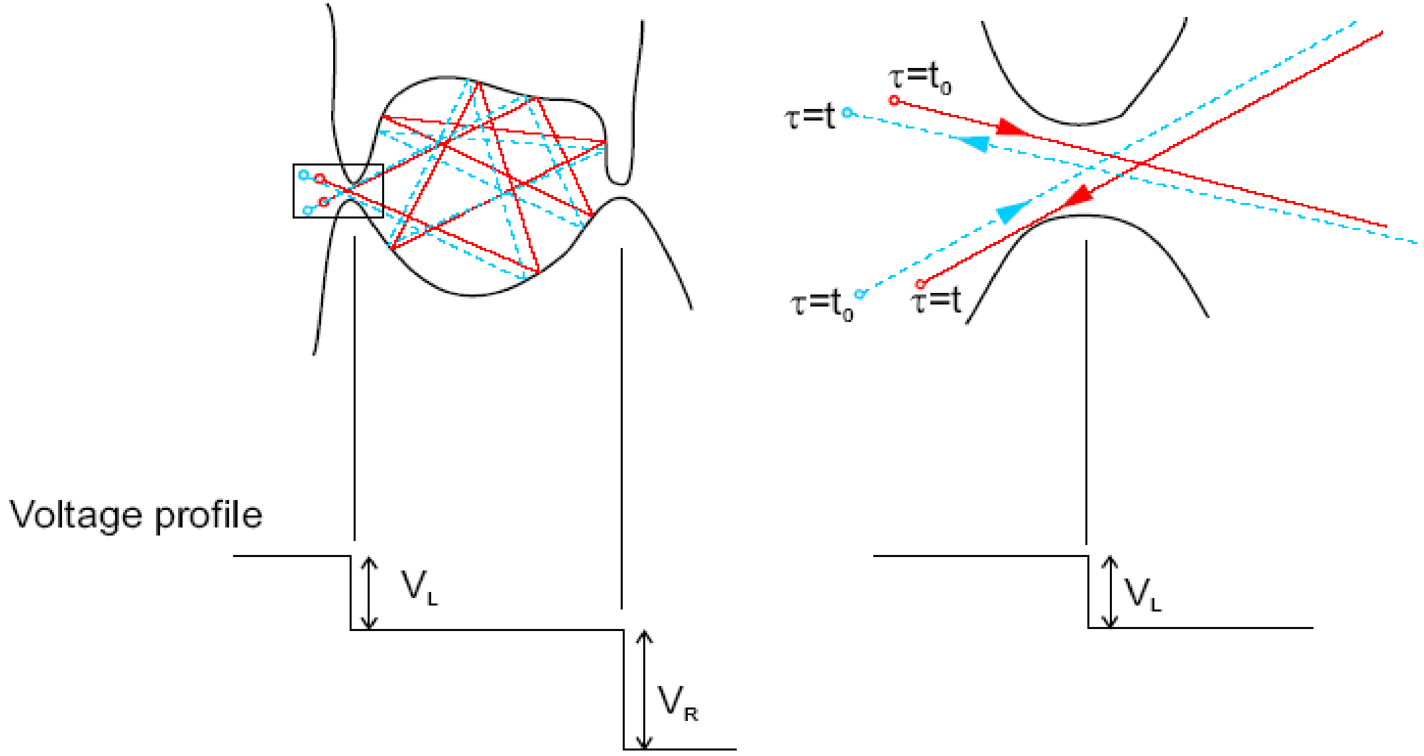
High T:

power law

Low T:

saturation

Two scatterers: no dephasing at ANY T



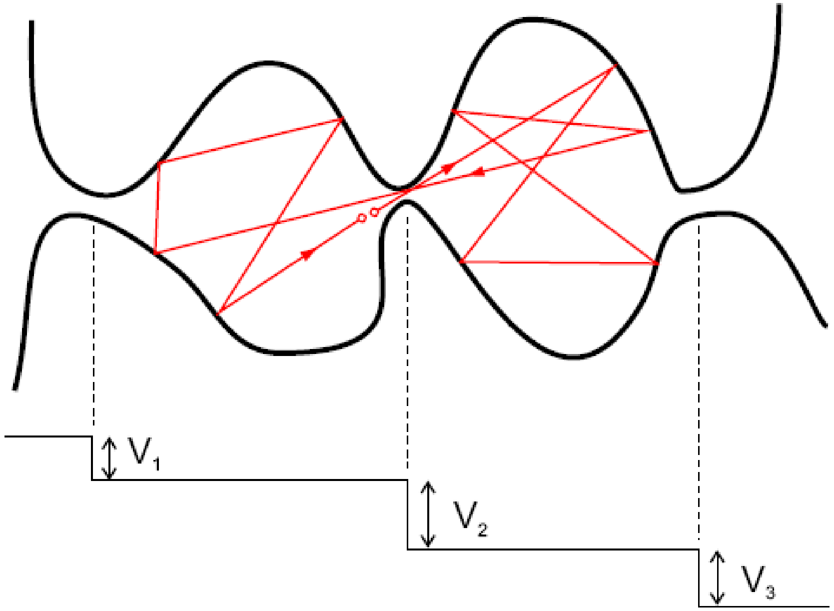
Since $R_F(\tau)$ and $R_B(\tau) = R_F(t + t_0 - \tau)$ cross the left barrier at the same time,

$$eV(\tau, R_F(\tau)) - eV(\tau, R_F(t + t_0 - \tau)) = 0$$

and

$$\left\langle e^{-i \int_{t_0}^{t} d\tau \left[eV(\tau, R_F(\tau)) - eV(\tau, R_F(t+t_0-\tau)) \right]} \right\rangle_{V,\ \text{paths}} = 1 \quad \Rightarrow \quad \underline{\text{no dephasing}}$$

Three barriers:



$$\varphi_2(\tau) = \int_{t_i}^{\tau} d\tau' \, eV_2(\tau')$$

Forward path crosses the central barrier twice: at $\tau = t_0$ and at $\tau = s$.

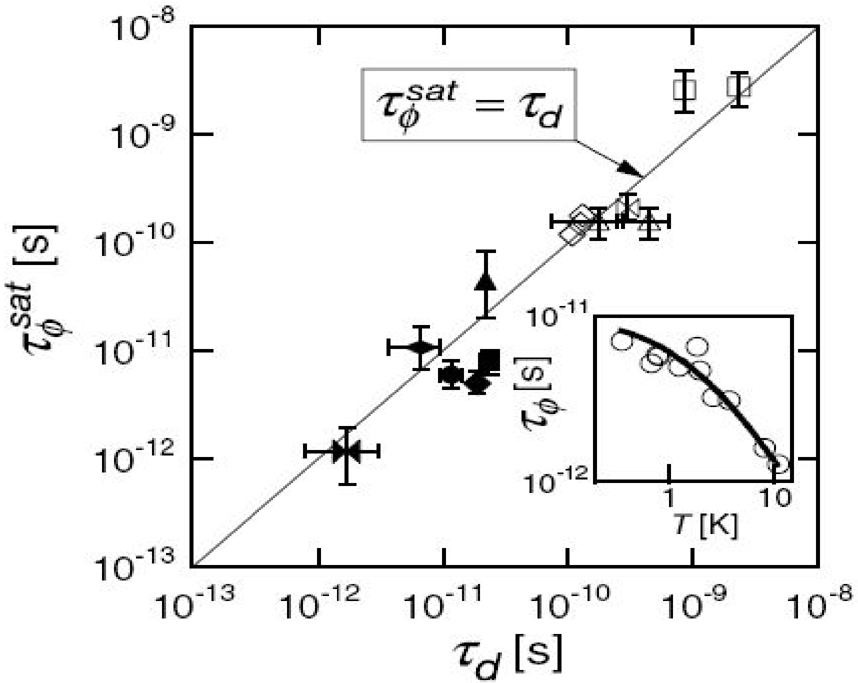
Then the backward, time reversed path, crosses it at $\tau = t + t_0 - s$ and at $\tau = t$

$$G_R \propto e^{iS_0[R_F]} e^{-i\varphi_2(t_0)+i\varphi_2(s)}, \quad G_A \propto e^{-iS_0[R_B]} e^{-i\varphi_2(t+t_0-s)+i\varphi_2(t)}$$

$$\left\langle e^{-i\varphi_2(t_0)+i\varphi_2(s)} e^{-i\varphi_2(t+t_0-s)+i\varphi_2(t)} \right\rangle < 1 \quad \Rightarrow \quad \text{finite dephasing}$$

QUANTUM DOTS

Experiment:



Theory:

$$\tau_{\varphi 0} = \frac{\tau_D}{(2E_C/\delta)^{4/g} - 1}$$

$$g \gg 1:$$

$$\tau_{\varphi 0} \simeq \frac{g\tau_D}{4\ln(2E_C/\delta)} = \frac{\pi}{\delta \ln(2E_C/\delta)}$$

- $$1/\tau_\phi = 1/\tau_{\phi 0}^{GZ} + 1/\tau_\phi^{AAK}(T)$$

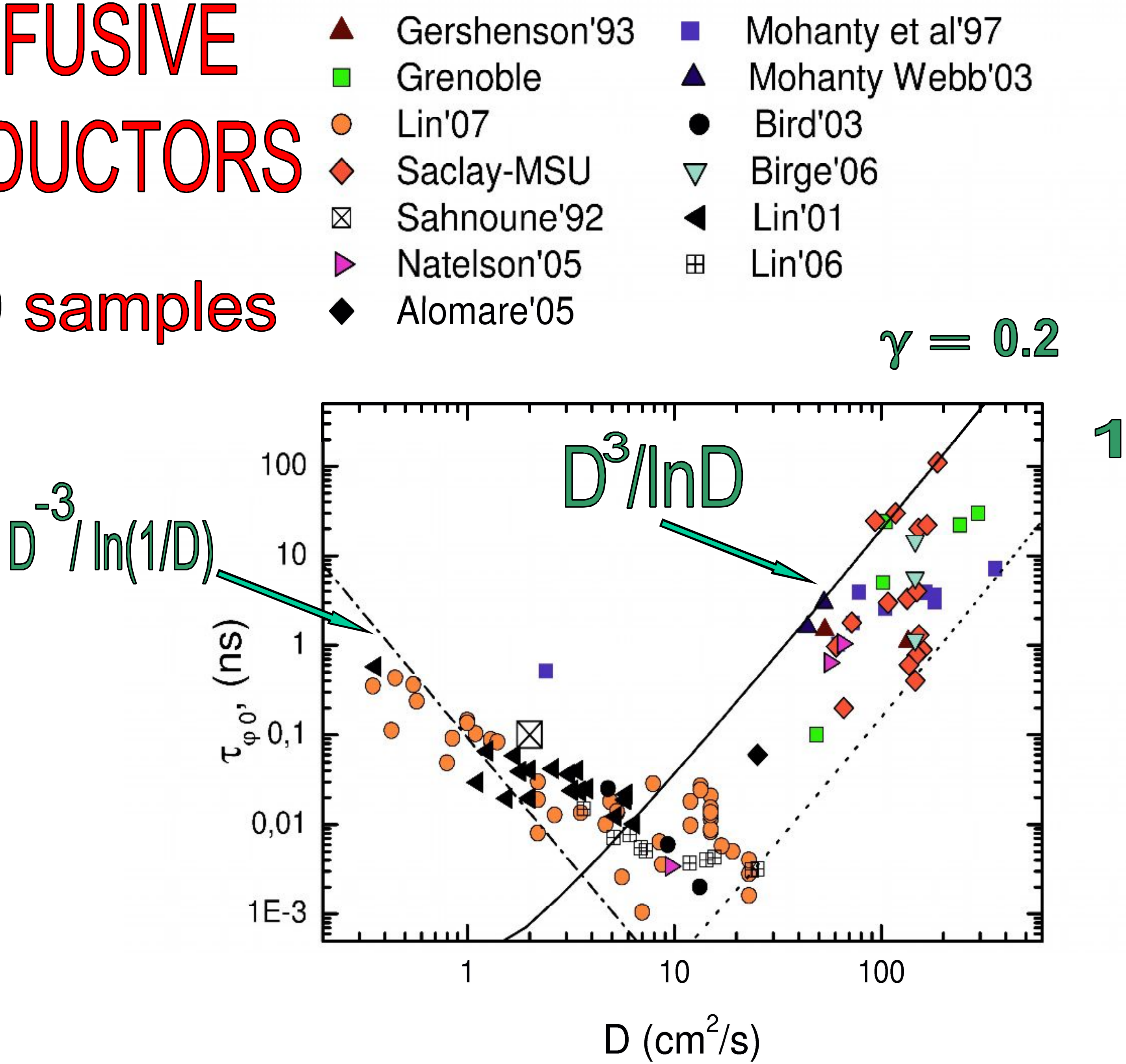
- $$\tau_{\phi 0}^{GZ} \sim D^3/\ln D, \quad l < t, w$$

- $$\tau_\phi^{AAK} \sim D^{1/3} T^{-2/3} (tw)^{1/3}$$

- $$T_q \sim (tw)^{1/2} D^{-4}$$

DIFFUSIVE CONDUCTORS

~ 130 samples



Thank you!


The End

$$\tilde{\mathcal{S}}(t,t') = \tilde{\mathcal{S}}^{\mathrm{ni}}(t,t') + \delta\tilde{\mathcal{S}}(t,t')$$

Shot noise...

$$\delta\tilde{\mathcal{S}}_\omega = -\frac{2(\beta - 2\gamma)|eV|}{R_q} \ln \frac{gE_C}{|eV|},$$

$$\text{if } T, |\omega| \ll |eV| \ll gE_C$$

Quantum Transport in a Multiwalled Carbon Nanotube

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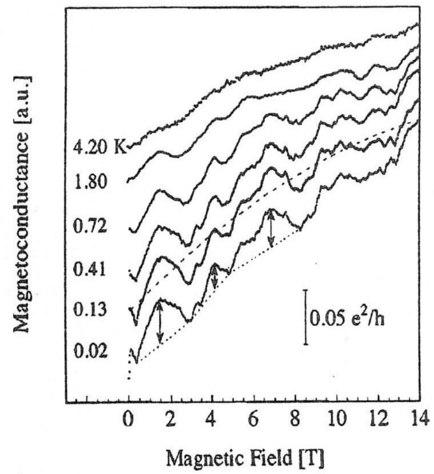
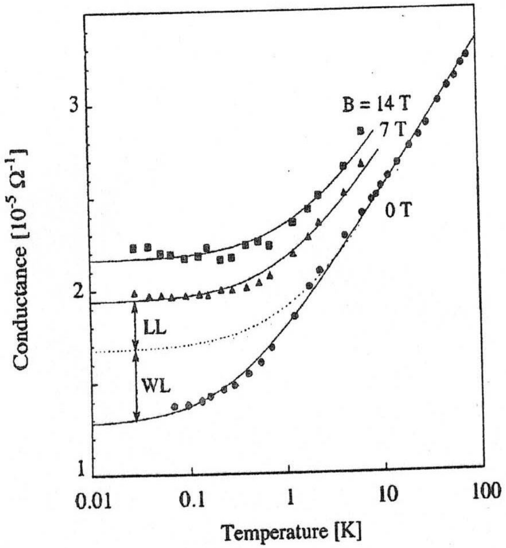
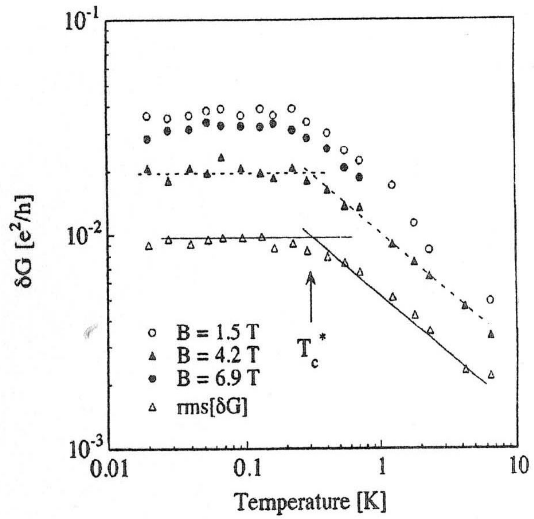
(Received 2 August 1995)





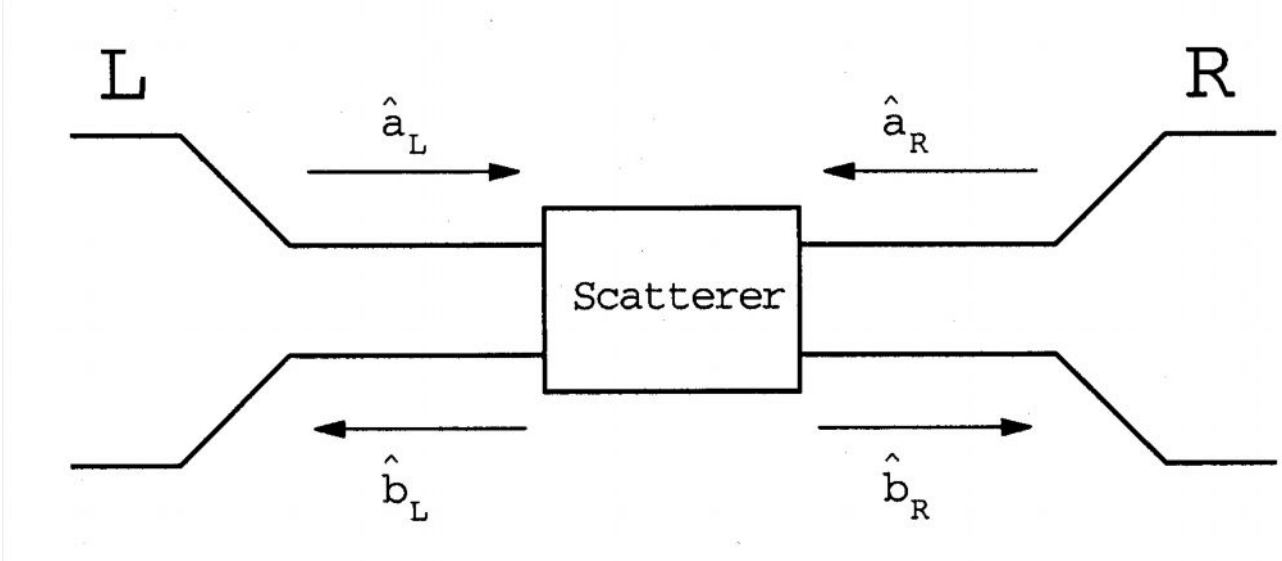


- $$1/\tau_{\phi} = 1/\tau_{\phi 0}^{GZ} + 1/\tau_{\phi}^{AAK}(T)$$

- $$1/\tau_{\phi} = 1/\tau_{\phi 0}^{GZ} + 1/\tau_{\phi}^{AAK}(T)$$

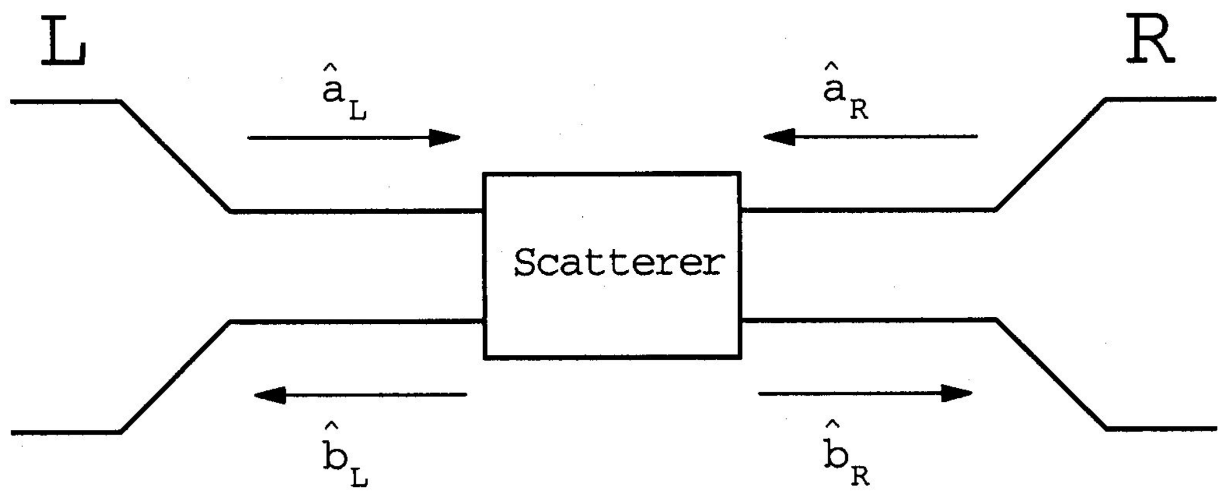
- $$\tau_{\phi 0}^{GZ} \sim D^{3}, \qquad l < t, w$$

- $$\tau_{\phi}^{AAK} \sim D^{1/3} T^{-2/3} (tw)^{1/3}$$



$$-\frac{\nabla^2}{2m}\psi(\boldsymbol{r}) + W(\boldsymbol{r})\psi(\boldsymbol{r}) = E\psi(\boldsymbol{r})$$

$$\psi(\boldsymbol{r}) = \sum_n c_n \Phi_n(\boldsymbol{r}_\perp)\chi_n(x).$$



$$-\frac{1}{2m}\frac{d^2}{dx^2}\chi_n(x) = (E - E_n)\chi_n(x).$$

$$-\frac{\nabla_\perp^2}{2m}\Phi_n(\boldsymbol{r}_\perp) + W(\boldsymbol{r}_\perp)\Phi_n(\boldsymbol{r}_\perp) = E_n\Phi(\boldsymbol{r}_\perp),$$

Scattering matrix:

$$\begin{pmatrix} b_{L1} \\ \cdots \\ b_{LN_L} \\ b_{R1} \\ \cdots \\ b_{RN_R} \end{pmatrix} = \hat{S}(\xi) \begin{pmatrix} a_{L1} \\ \cdots \\ a_{LN_L} \\ a_{R1} \\ \cdots \\ a_{RN_R} \end{pmatrix}$$

$$(N_L + N_R) \times (N_L + N_R)$$

$$\hat{S}(\xi) = \begin{pmatrix} \hat{r}(\xi) & \hat{t}'(\xi) \\ \hat{t}(\xi) & \hat{r}'(\xi) \end{pmatrix}$$

$$G(T) = G_{\mathsf{Drude}} - \delta G_{\mathsf{int}} - \delta G_{\mathsf{WL}}$$

- $\frac{\delta G_{\mathsf{int}}}{G_{\mathsf{Drude}}} \sim \frac{L_{\mathsf{T}}}{L_{\mathsf{loc}}}, \qquad L_{\mathsf{T}} \sim \sqrt{\frac{D}{T}}, \qquad L_{\mathsf{loc}} \sim Nl$