DEPHASING IN QUANTUM CHAOTIC TRANSPORT

A SEMICLASSICAL APPROACH

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Banff, February 2008

Collaborators :

- Philippe Jacquod (*University of Arizona*)
- Robert S. Whitney (*Institut Laue-Langevin*)

Universität Regensburg

Institut Laue-Langevin — NEUTRONS FOR SCIENCE

Alexander von Humboldt Stiftung/Foundation

Outline

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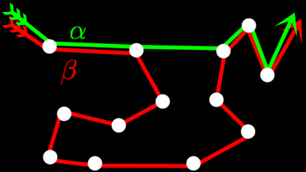
Quantum Transport and Chaos

"The conductance is proportional to the transmission probability through the sample"

Quantum Mechanics :

Probability is given by the square of an Amplitude.



$$\mathbf{G} \propto \sum_{\alpha} |\mathcal{A}_\alpha|^2 + \sum_{\alpha \neq \beta} \mathcal{A}_\alpha \mathcal{A}_\alpha^*$$

Classical Conductance

Quantum Interference

Anderson, Abrahams and Ramarkrishnan (1979)

Gorkov, Larkin and Khmelnitskii (1979)

Quantum Transport and Chaos

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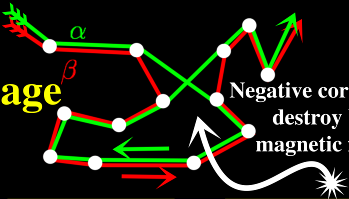


$$\overline{\mathrm{G}} \propto \overline{\sum_{\alpha} |\mathcal{A}_\alpha|^2} + \overline{\sum_{\alpha\neq\beta} \mathcal{A}_\alpha \mathcal{A}_\alpha^*}$$

Weak localization

Anderson, Abrahams and Ramarkrishnan (1979)

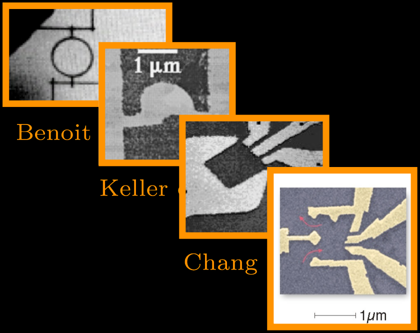
Gorkov, Larkin and Khmelnitskii (1979)

QUANTUM TRANSPORT AND CHAOS

EXPERIMENTS : OPEN BALISTIC QUANTUM DOT

BALLISTIC CAVITY :

- ✓ Clean sample, very few impurity
- ✓ Randomness / chaoticity ⇒ sample boundaries



Benoit

Keller

Chang

Marcus et al.

Quantum Transport and Chaos

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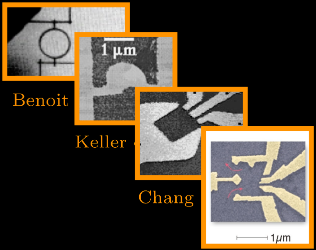

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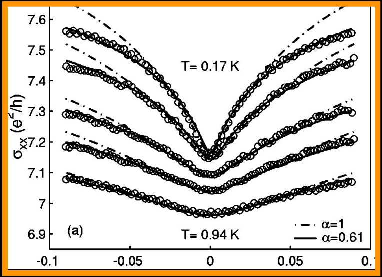
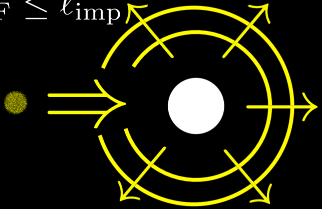


Senz et al. (2000)

Why ballistic transport is different ?

■ Quantum Disorder

$\lambda_F \leq \ell_{imp}$



- ✓ Huygens diffraction
- ✓ Universal average properties

■ Quantum Chaos

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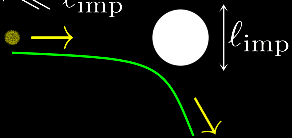

- ✓ Classical trajectories resolved
- ✓ Features of Classical dynamic
- ✓ (ergodicity + mixing)

WHY BALLISTIC TRANSPORT IS DIFFERENT ?

- Quantum Disorder

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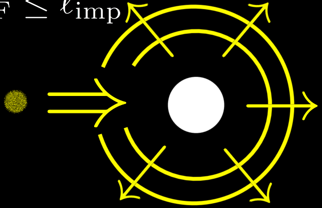

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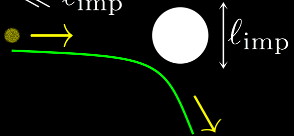


!! Classical Chaotic Dynamics !!

✓ New "Ehrenfest " time scale

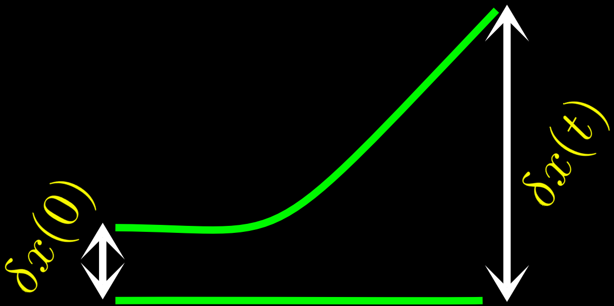
✓ Short time correction to the universality

THE EHRENFEST TIME SCALE

LARKIN AND OVCHINIKOV JETP 28, 1200(1969) & BERMAN AND ZASLAVSKY, PHYSICA A 91,450 (1978)

- Classical Chaos
  Local exponential divergence (Lyapunov exponent)
- Quantum Chaos

$$\delta x(t) = \delta x(0) \exp[\lambda t]$$



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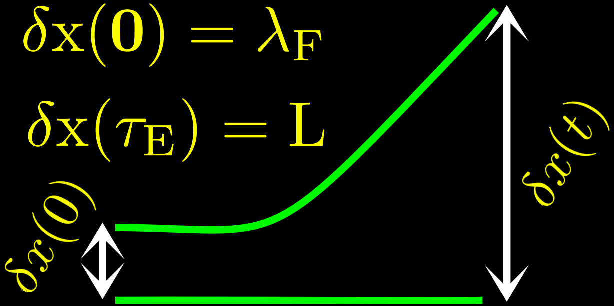
$$\delta x(0) = \lambda_F$$

$$\delta x(\tau_E) = L$$



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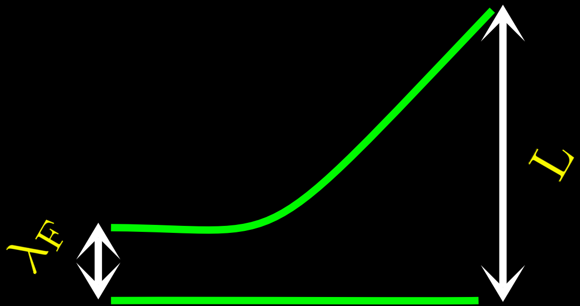
$$\tau_E \simeq \lambda^{-1} \ln[L/\lambda_F]$$



Scattering Approach and semiclassical formalism

Scattering matrix

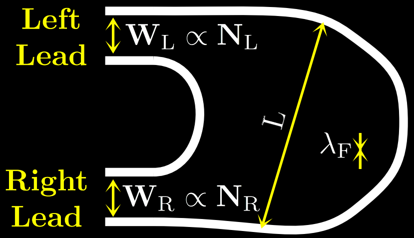
Büttiker, Phys. Rev. B **33**, 3020 (1986).

$$\hat{\mathbf{S}} = \begin{pmatrix} \mathbf{r} & \mathbf{t} \\ \mathbf{t}' & \mathbf{r}' \end{pmatrix}$$

Landauer- Büttiker Formula :

$$\mathbf{g} = \mathrm{Tr}[\mathbf{t}^{\dagger}\mathbf{t}]$$

Open Quantum dot



$$\lambda_F \ll \mathbf{W}_{L,R} \ll L$$

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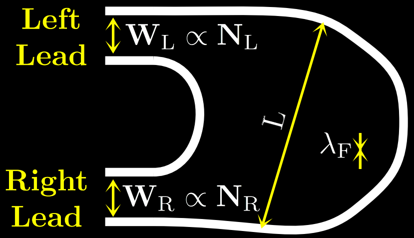

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Semiclassic : $\sum$ over classical paths from mode *m* to *n*

$$\mathbf{t}_{nm} = \sum_{\gamma} \mathcal{B}_{\mathbf{nm}} \mathbf{A}_{\gamma}^{\frac{1}{2}} \exp[i\mathbf{S}_{\gamma}/\hbar]$$

join lead-modes

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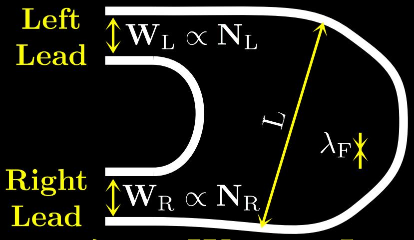

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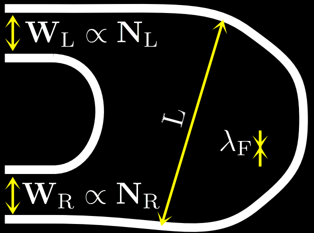

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- $\mathcal{B}_{nm}$: join lead-modes
- $A_{\gamma}^{\frac{1}{2}}$: classical stability
- S_{γ}: classical action

SCATTERING APPROACH AND SEMICLASSICAL FORMALISM

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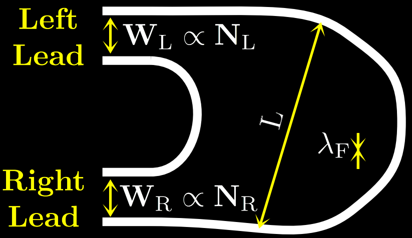

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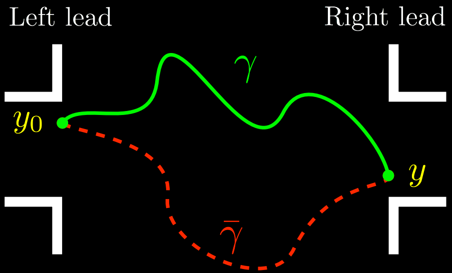

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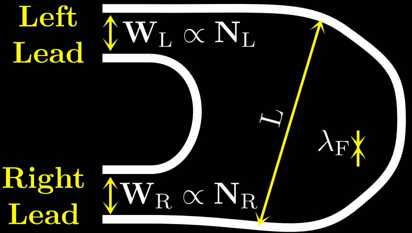

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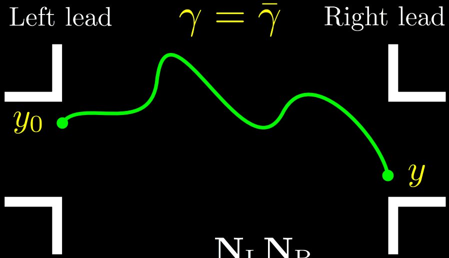

$$g_D = \frac{N_L N_R}{(N_L + N_R)}$$

Baranger et al., Phys. Rev. Lett. **70**, 3876 (1993)

Scattering Approach and Semiclassical Formalism

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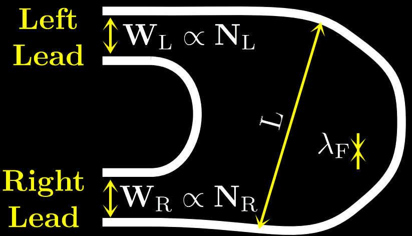

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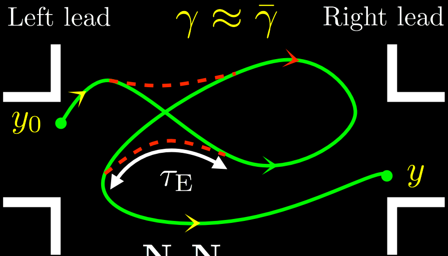

$$\delta g = \frac{N_L N_R}{(N_L + N_R)^2} \exp[-\tau_E/\tau_D]$$

Aleiner, Larkin, (1996)
Sieber, Richter, (2001)
Adagideli, (2003)
Rahav, Brouwer, (2005)
Jacquod, Whitney,(2006)

Quantum Transport and Dephasing

What is left out in the standard scattering approach ?

✓ All dissipative processes occur in the leads

✓ Apart from this lead connection System is isolated

Effects due to the coupling with an external environment cannot be described

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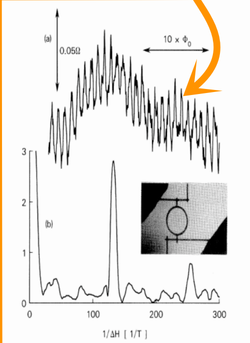
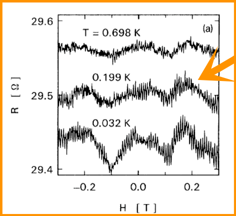
Magnetoresitance



Amplitude of oscilations decreases with increasing Temperature

~ Decoherence



Webb, Washburn, Umbach, and Laibowitz, Phys. Rev. Lett. **54**, 2696 (1985)

Quantum Transport and Dephasing

What is left out in the standard scattering approach ?

Treatement of Decoherence $\neq$ Ways :

Microscopic Model $\Rightarrow$ New scattering formalism

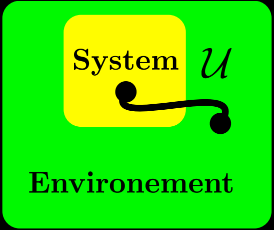
Phenomenological Model $\Rightarrow$ Dephasing Model

STANDARD TREATMENT OF DECOHERENCE

JOOS, ZEH, KIEFER, GIULINI, KUPSCH, AND STAMATESCU, SPRINGER, (2003).

ZUREK, REV. MOD. PHYS. **75**, 715 (2003).

"There is no fully isolated quantum system. When we measure one, we implicitely intergrate out its environement"



Reduced Density Matrix

$$\eta_{\mathrm{Sys}} = \mathrm{Tr}_{\mathrm{Env}}\left[\eta_{\mathrm{Tot}}\right]$$

Application to :

✓ Coupled chaotic system
- Jacquod, Phys. Rev. Lett. **92**, 150403 (2004)
- C.P., Jacquod, Phys. Rev. Lett. **97**, 194103 (2006)

✓ Fidelity (Boltzmann echo)
- C.P., Jacquod, Phys. Rev. Lett. **97**, 124103 (2006)

✓ Quantum Transport, $\cdots$ Now
- C.P., Jacquod, Whitney, JETP Lett. **86**, 736 (2007)
- Whitney, Jacquod, C.P., Phys. Rev. **B 77**, 045315 (2008)

SCATTERING FORMALISM IN PRESENCE OF AN ENVIRONMENT

C.P., JACQUOD, WHITNEY, JETP LETT. 86, 736 (2007)

WHITNEY, JACQUOD, C.P., PHYS. REV. B 77, 045315 (2008)

Coupled Dot Model

$$\mathcal{H} = \mathbf{H}_{\rm Sys} + \mathbf{H}_{\rm Env} + \mathcal{U}(\mathbf{U},\xi)$$

$$\mathbf{U} = \text{Strength}$$

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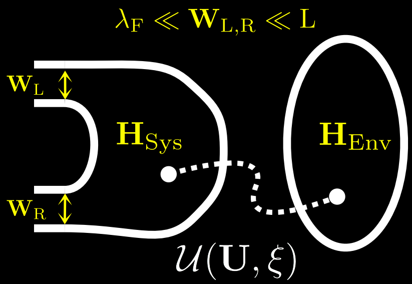

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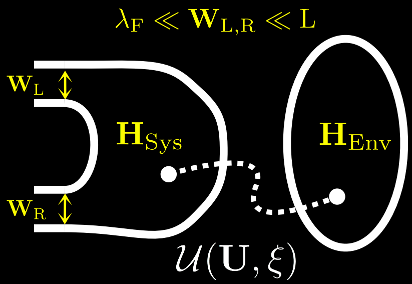

$\Rightarrow$ New Scattering matrix :

1. Include external non- current carrying degrees of freedom
2. in a Time-resolved manner .

Scattering formalism in presence of an environment

C.P., Jacquod, Whitney, JETP Lett. 86, 736 (2007)
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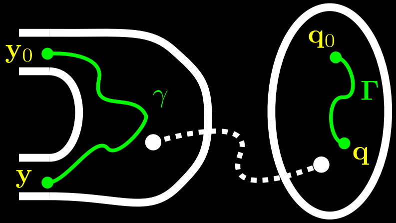

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Classical Paths determined by H_{Sys}, H_{Env}

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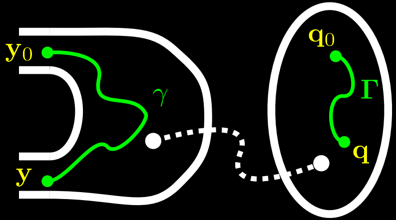

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join lead-modes

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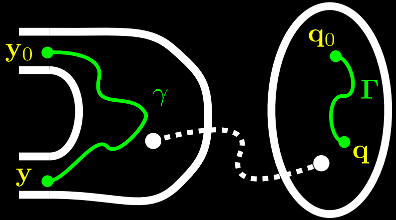

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join lead-modes

classical stability

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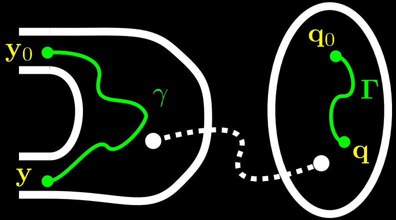

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Classical Paths determined by H_{Sys}, H_{Env}

join lead-modes

classical stability

One-particle actions

Two-particle action

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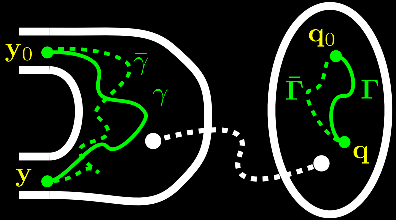

Conductance

$$\mathbf{g} = \sum_{\mathbf{nm}} \mathrm{Tr}_{\mathrm{Env}} \left[\mathbb{S}_{\mathbf{mn}} \left(\mathbb{I}_{\mathbf{n}} \otimes \eta_{\mathrm{Env}} \right) \mathbb{S}^{*}_{\mathbf{nm}} \right]$$

$$\mathbf{g} \propto \int_{\mathrm{time}} \int_{\mathrm{Env}} \int_{\mathrm{Lead}} \mathrm{d} \cdots \sum_{\mathrm{paths}} \mathbf{A}^{\frac{1}{2}}_{\gamma\bar{\gamma}\Gamma\bar{\Gamma}} \exp \left[i \frac{\mathbf{\Phi}_{\mathrm{Sys}} + \mathbf{\Phi}_{\mathrm{Env}}}{\hbar} + i \frac{\mathbf{\Phi}_{\mathcal{U}}}{\hbar} \right]$$

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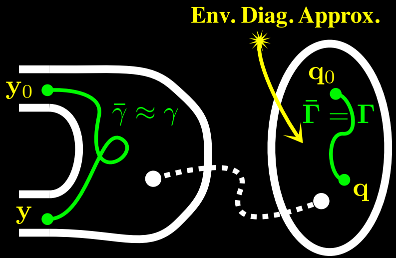
Whitney, Jacquod, C.P., Phys. Rev. B 77, 045315 (200

Coupled Dot Model

$$\mathcal{H} = \mathbf{H}_{\text{Sys}} + \mathbf{H}_{\text{Env}} + \mathcal{U}(\mathbf{U},\xi)$$

$$\mathbf{U} = \text{Strength}$$

$$\xi = \text{Correlation length}$$



Conductance

$$\mathbf{g} = \sum_{\mathbf{nm}} \text{Tr}_{\text{Env}} \left[\mathbb{S}_{\mathbf{mn}} \left(\mathbb{I}_{\mathbf{n}} \otimes \eta_{\text{Env}} \right) \mathbb{S}^*_{\mathbf{nm}} \right]$$

$$\mathbf{g} \propto \int_{\text{time}} \int_{\text{Lead}} \mathrm{d} \cdots \sum_{\text{paths}} \mathbf{A}_{\gamma\Gamma} \exp\left[i \frac{\boldsymbol{\Delta\Phi}_{\text{Sys}}}{\hbar} + i \frac{\boldsymbol{\Delta\Phi}_{\mathcal{U}}}{\hbar} \right]$$

Scattering formalism in presence of an environment

C.P., Jacquod, Whitney, JETP Lett. 86, 736 (2007)

Whitney, Jacquod, C.P., Phys. Rev. B 77, 045315 (200

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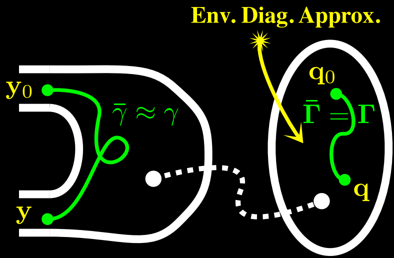

Conductance

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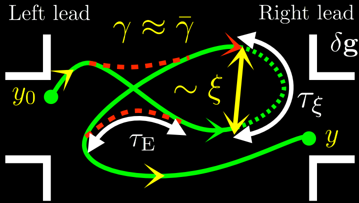

$$\delta g = \frac{N_L N_R \exp[-\tau_E/\tau_D]}{(N_L + N_R)^2} \frac{\exp[-\tau_\xi/\tau_\phi]}{1 + \tau_D/\tau_\phi}$$

$$\tau_\xi = \lambda^{-1} \ln\left[(L/\xi)^2 \right] \neq \tau_E$$

Scattering formalism in presence of an environment

C.P., Jacquod, Whitney, JETP Lett. 86, 736 (2007)

Whitney, Jacquod, C.P., Phys. Rev. B 77, 045315 (200

Coupled Dot Model

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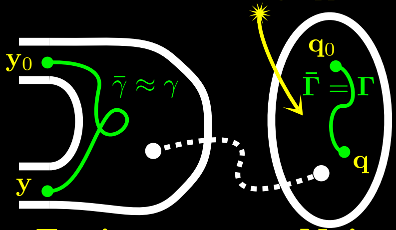
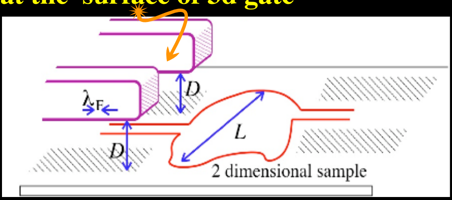


Diagonal Approximation for Environment $\simeq$ Noise

$$\Delta\Phi_{\mathcal{U}} \Rightarrow \Delta\Phi_{\rm Noise}$$

Noise generated by the fluctuations at the surface of 3d gate

$$\delta g = \frac{N_L N_R \exp[-\tau_E/\tau_D]}{(N_L + N_R)^2} \; \frac{\exp[-\tau_\xi/\tau_\Phi]}{1 + \tau_\xi/\tau_\Phi}$$



Natural cutoff provide by D

$$\xi \propto \sqrt{D}$$

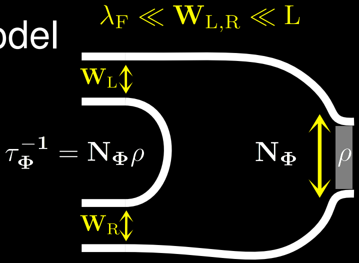
Scattering formalism in presence of an environment

C.P., Jacquod, Whitney, JETP Lett. **86**, 736 (2007)

Whitney, Jacquod, C.P., Phys. Rev. **B 77**, 045315 (2008)

Voltage[1]-Dephasing[2] Model

- Add Fictitious probe
- Net current is Null



1. Büttiker, Phys. Rev. B **33**, 3020 (1986)
2. De Jong, Beenakker, Physica A **230**, 219 (1996)

Scattering formalism in presence of an environment

C.P., Jacquod, Whitney, JETP Lett. **86**, 736 (2007)

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Dephasing
&
Quantum
Transport

Cyril Petitjean

Voltage[1]-Dephasing[2] Model

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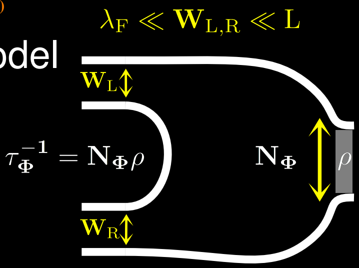

1. Büttiker, Phys. Rev. B **33**, 3020 (1986)
2. De Jong, Beenakker, Physica A **230**, 219 (1996)

Two terminal conductance : Büttiker, Phys. Rev. B **33**, 3020 (1986)

$$g = T_{RL} + \frac{T_{R\Phi} T_{\Phi L}}{T_{R\Phi} + T_{\Phi L}}$$

$$\text{with, } T_{ij} = T^{D}_{ij} + \delta T_{ij}$$

Scattering formalism in presence of an environment

C.P., Jacquod, Whitney, JETP Lett. **86**, 736 (2007)

Whitney, Jacquod, C.P., Phys. Rev. B **77**, 045315 (2008)

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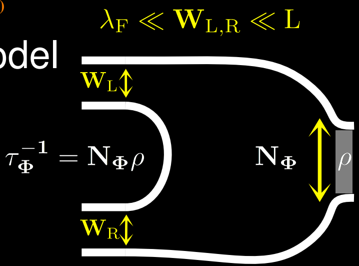


1. Büttiker, Phys. Rev. B **33**, 3020 (1986)
2. De Jong, Beenakker, Physica A **230**, 219 (1996)

Tunnel barriere semiclassic : Whitney, Phys. Rev. B **75**, 235404 (2007)

$$\delta T_{ij} = \frac{N_i N_j}{N_T^2} \exp[-\tau_E/\tau_D^*]$$

$$\tau_D^* = \tau_D (1 + \tau_D/\tau_\phi)^{-1}$$

Scattering formalism in presence of an environment

C.P., Jacquod, Whitney, JETP Lett. **86**, 736 (2007)

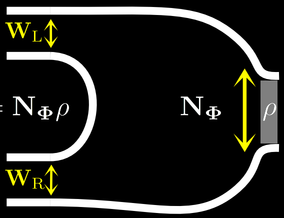
Whitney, Jacquod, C.P., Phys. Rev. B **77**, 045315 (2008)

Voltage[1]-Dephasing[2] Model

- Add Fictitious probe
- Net current is Null

$$\lambda_F \ll W_{L,R} \ll L$$

$$\tau_\Phi^{-1} = N_\Phi \rho$$



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$$\delta g = \frac{N_L N_R \exp[-\tau_E/\tau_D]}{(N_L+N_R)^2} \frac{\exp[-2\tau_E/\tau_\phi]}{1+\tau_D/\tau_\phi}$$

Dephasing Model versus Microscopic Model

C.P., Jacquod, Whitney, JETP Lett. 86, 736 (2007)

Whitney, Jacquod, C.P., Phys. Rev. B 77, 045315 (2008)

$$\delta \mathbf{g} = \frac{\mathrm{N_L N_R} \exp[-\tau_\mathrm{E}/\tau_\mathrm{D}]}{(\mathrm{N_L}+\mathrm{N_R})^2} \frac{\exp[-\tau^*/\tau_\phi]}{1+\tau_\mathrm{D}/\tau_\phi}$$

- Microscopic Model
  ✓ Dephasing is model-dependent

$$\tau^* \propto \lambda^{-1} \ln\left[L/\xi\right]$$

- Dephasing Model
  ✓ No independent parameter ξ

$$\tau^* \propto \lambda^{-1} \ln\left[L/\lambda_\mathrm{F}\right]$$

✓ ξ is replaced by λ_F

Dephasing Model versus Microscopic Model

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$$\delta g = \frac{N_L N_R \exp[-\tau_E/\tau_D]}{(N_L + N_R)^2} \frac{\exp[-\tau^*/\tau_\phi]}{1 + \tau_D/\tau_\phi}$$

- Microscopic Model
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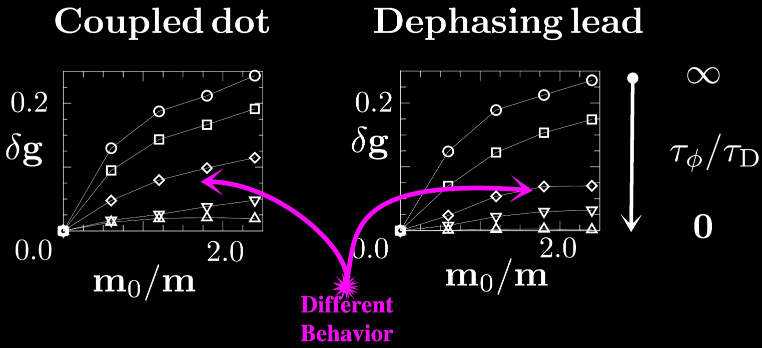
- Dephasing Model
  - ✓ No independent parameter ξ

$$\tau^* \propto \lambda^{-1} \ln [L/\lambda_F]$$

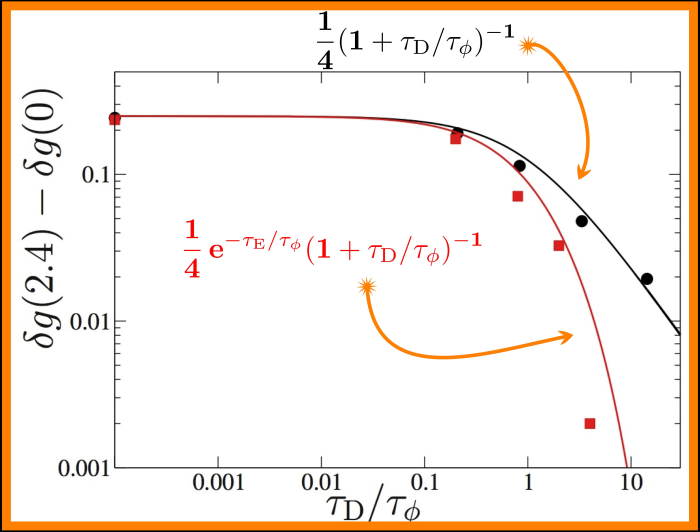
  - ✓ ξ is replaced by λ_F

Dephasing Model cannot mimic a system-environment model with $\xi \sim L$

Numerical simulations



NUMERICAL SIMULATIONS



SUMMARY

Dephasing First trajectory based treatment of an

✓ environment ("New scattering formalism")

✓ of the dephasing model.

Dephasing is model-dependent $\tau^* = \{\tau_\xi, \ \tau_E\}$

For more see (Shot noise, UCF, ...):

Whitney, Jacquod, C.P.,

Phys. Rev. **B 77**, 045315 (2008)

See also

Altland, Brouwer, Tian,

Phys. Rev. Lett. **99**, 036804 (2007)

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- Markus Büttiker
- Philippe Jacquod
- Mikhail Polianski
- Robert S. Whitney

Universität Regensburg

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Thank for your attention