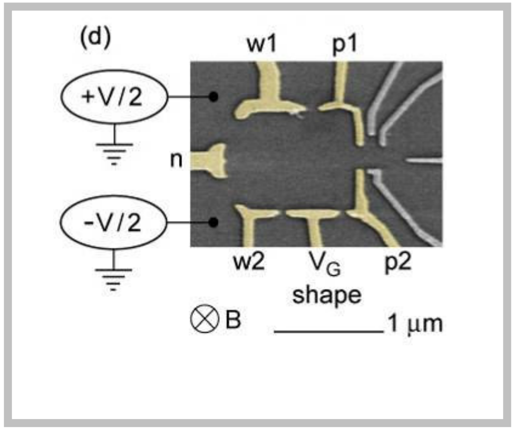
Rectification and nonlinear transport in chaotic dots and rings

Mikhail Polianski[1,2] and Markus Büttiker[2]

1. Niels Bohr Institute, Denmark

2. Université de Genève, Switzerland

Thanks for discussions:
Hélène Bouchiat
Renaud Leturcq
Dominik Zumbühl



Zumbühl et al'06

La Thuile, 2008

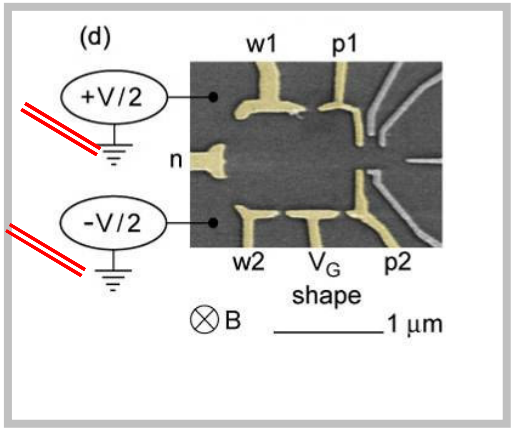
Outline

- Th./ exp. motivation

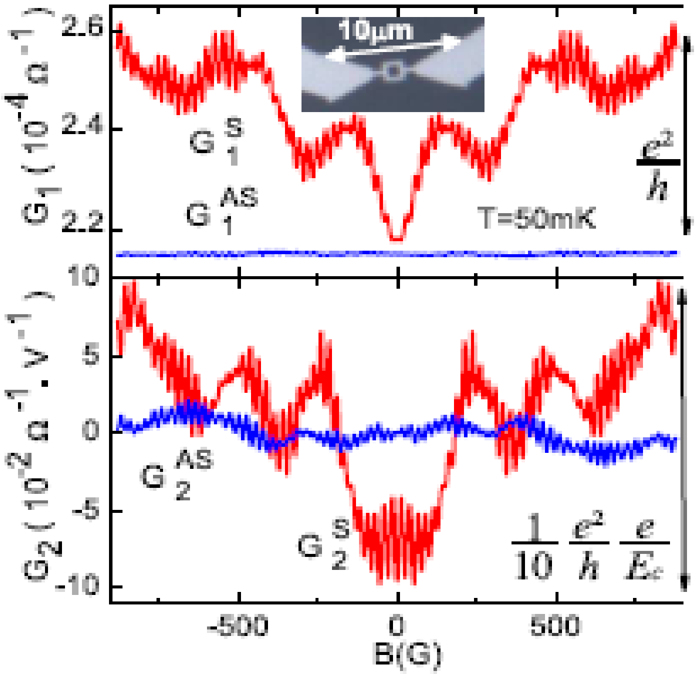
✓ Non-linear transport: DC⟶DC

✓ Rectification: AC⟶DC

- Importance of bias mode
- Rectification
- Aharonov-Bohm phase



Zumbühl et al'06



Angers et al'07

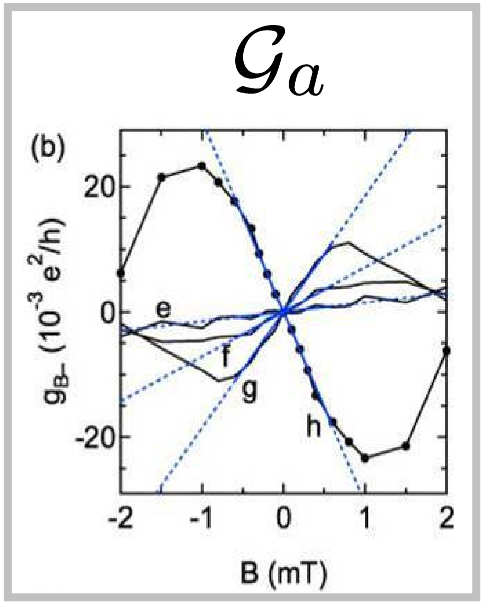
Motivation: Theory

Out-of-equilibrium: "Onsager" is invalid

$$G = I/V \Rightarrow G_{\alpha\beta}(\Phi) \neq G_{\beta\alpha}(-\Phi)$$

$$I \approx GV + V^2\mathcal{G}$$

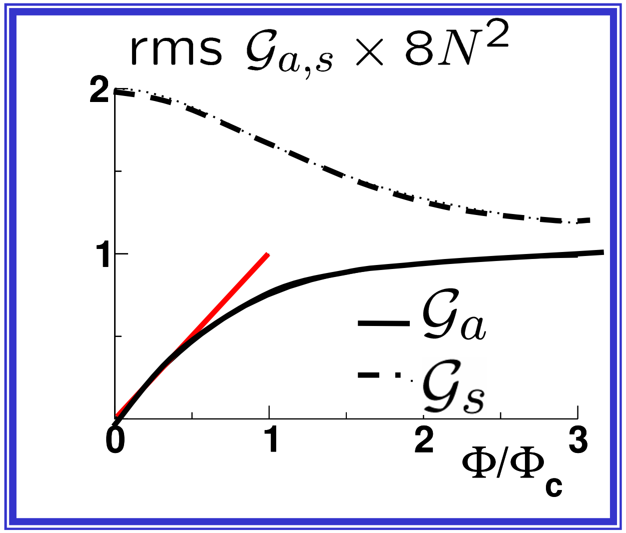
Random and asymmetric, $I(\Phi) \neq I(-\Phi)$



$$\begin{pmatrix}\mathcal{G}_s\\ \mathcal{G}_a\end{pmatrix} = \frac{\mathcal{G}(\Phi) \pm \mathcal{G}(-\Phi)}{2}$$

$$\langle \mathcal{G}_a \rangle = \langle \mathcal{G}_s \rangle = 0$$

Symmetric dot, strong int.



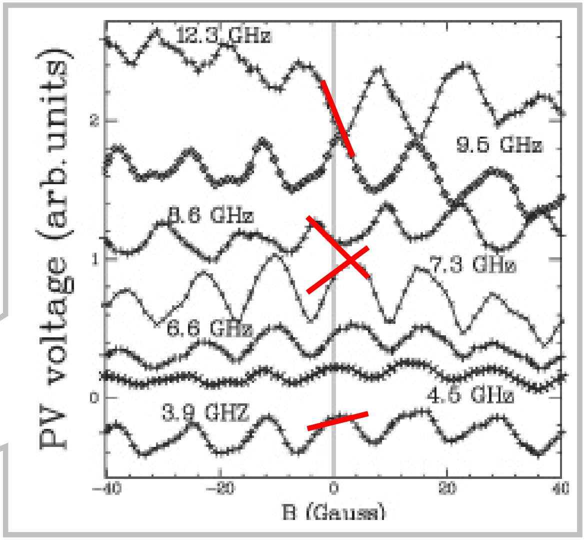
Non-eq. dot charge is flux-asymmetric

Electronic interference + interactions

Motivation: Experiments

Non-linear DC *I-V*

- Zumbühl et al ’06 (dot) $\mathcal{G}_a$
- Leturcq et al ’06 (AB ring) $\mathcal{G}_{a,s}$
- Angers et al ’07 (AB ring) $\mathcal{G}_{a,s}$



Phase of AB oscillations?

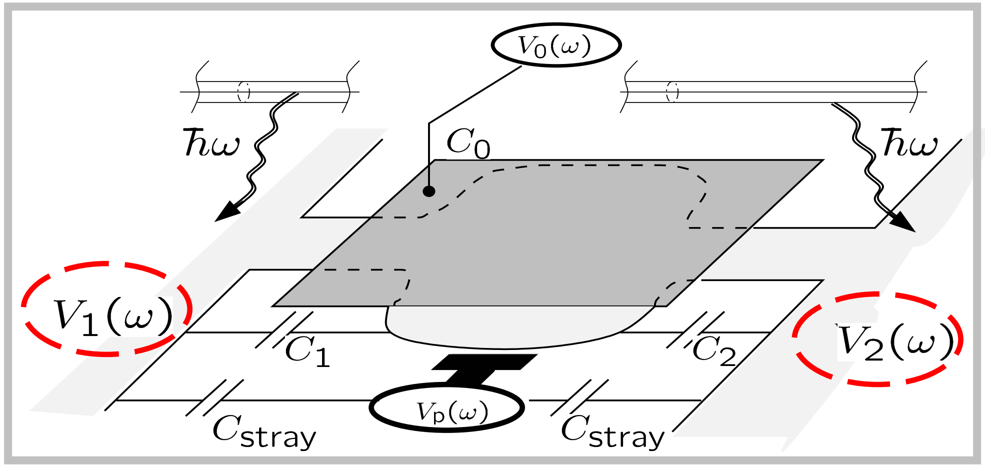
Photovoltaic effect, AC⟶DC

pumping or **rectification?**

- Switkes et al ’99
- DiCarlo et al ’05
- Angers et al ’07

$$I \propto V^2\overline{\cos^2 \omega t} \times \mathcal{G}(\omega)$$

Fluctuations of $\mathcal{G}_{a,s}(\omega)$ for arbitrary ω ?

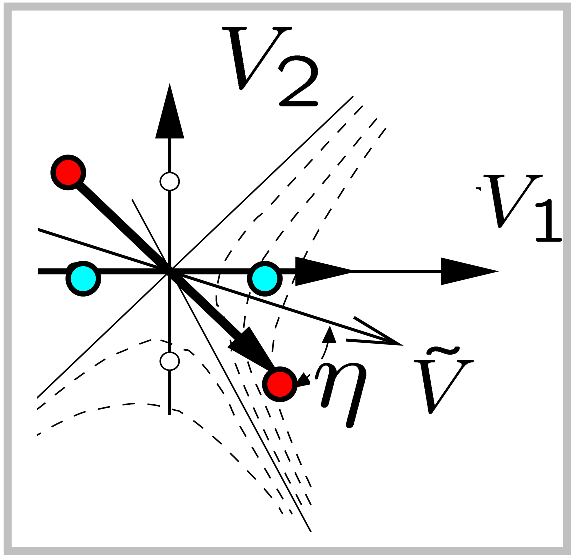


Bias mode

Bias mode= how voltages are shifted

$$I = XV_1^2 + YV_2^2 + ZV_1V_2$$

X, Y, Z randomly fluctuate



$\tilde{V}$ is the voltage varied $\Rightarrow \mathcal{G}(\eta) = \frac{\partial^2 I}{\partial \tilde{V}^2}$

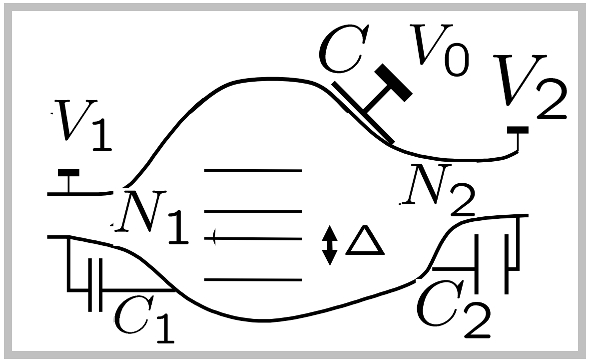
- Shift asymmetrically — Zumbühl, Leturcq

  $\eta = 0 \Rightarrow \tilde{V} = V_1 - V_2$

- Shift one voltage — Angers, Marlow, Löfgren

  $\eta = \pi/4 \Rightarrow \tilde{V} = V_1$

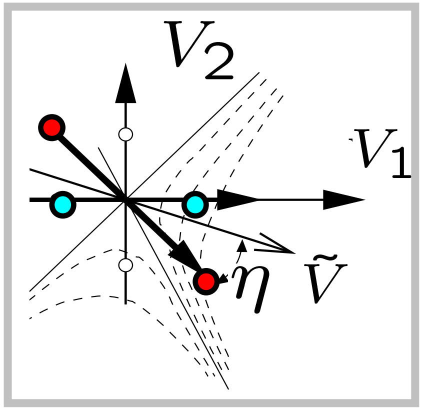
When is the bias mode η important?



Questions and Approach

- Choose bias mode to maximize $\mathcal{G}_a/\mathcal{G}_s$
- Consider rectification $\mathcal{G}_a(\omega), \mathcal{G}_s(\omega)$
- Find phase of AB-oscillations in rings, $\langle \mathrm{cotan}^2 \phi_{\mathrm{AB}} \rangle$

- RMT in open system, $N \gg 1$, no CB
- Self-consistent potential, $U(\{V_i\})$ (leads to displacement currents)
- Energy-dependent scattering

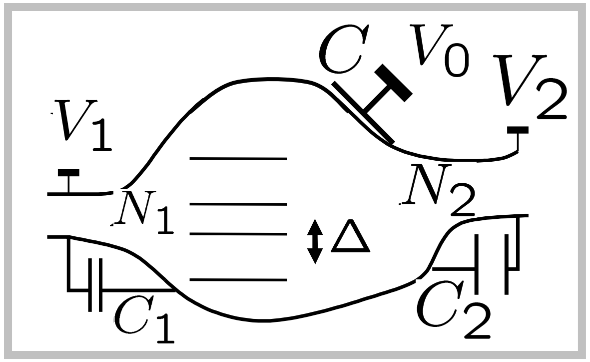


$$\mathcal{G} = \frac{\partial^2 I}{\partial \tilde{V}^2} \propto \int d\epsilon f'(\epsilon) g'(\epsilon) \left[\frac{\partial U}{\partial V_0} \tan \eta + \frac{\partial U}{\partial V_2} - \frac{\partial U}{\partial V_1} \right]$$

random$_{\mathrm{sym}}$ × [classical$_{\mathrm{sym}}$ + random$_{\mathrm{sym+asym}}$]

(B → -B)

Bias mode



$$\begin{Bmatrix} \mathcal{G}_a^2 \\ \mathcal{G}_s^2 \end{Bmatrix} \propto \left(\frac{C_\mu}{C_\Sigma}\right)^2 \frac{N_1^3 N_2^3}{N^{10}} \begin{Bmatrix} 1 \\ 1+X \end{Bmatrix}, \quad (T=0)$$

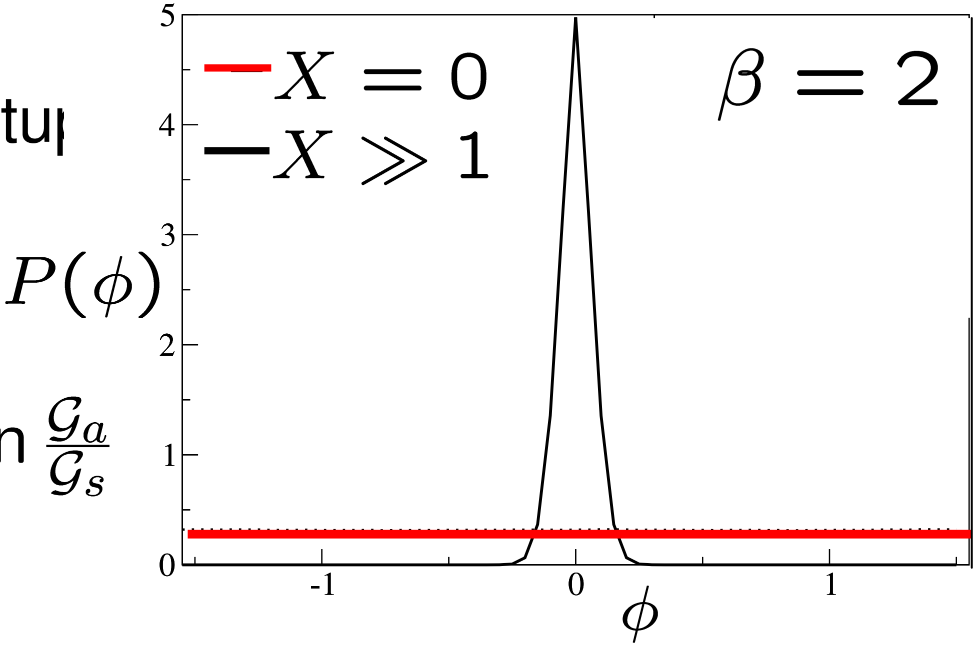
$$X(\eta) = \frac{N^4}{2N_1N_2}\left(\frac{C_0 \tan\eta + C_2 - C_1}{2e^2/\Delta} + \frac{N_2 - N_1}{N}\right)^2$$

To diminish $\mathcal{G}_s^2$ minimize X (fluctuations of $g'(\epsilon) \times \frac{\partial \langle U \rangle}{\partial V_0}$)

- $\eta \to 0 \Rightarrow X \to 0$
  only for symmetric setup
- $\eta \neq 0$ compensates setup asymmetry

- Distribution of $\phi = \arctan \frac{\mathcal{G}_a}{\mathcal{G}_s}$ depends on bias mode

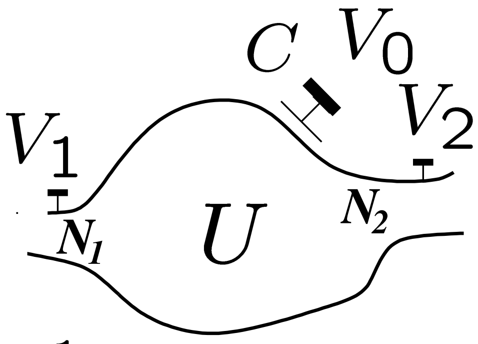
  …like AB-phase?



Rectification (strong interactions)

$$\partial U/\partial V_0 \to 0, \omega \to 0$$

$$\partial U/\partial V_0 \to 1, \omega\tau_{RC} \gg 1$$



Displacement current is finite, but at large ω capacitor is short-cut $\Rightarrow$ potential U follows V_0, not $V_{1,2}$

$$Z = \frac{1}{i\omega C_\mu} \to 0, \omega \to \infty$$

- $\eta \neq 0 \quad \mathcal{G}_s \gg \mathcal{G}_a, \omega\tau_{RC} \gg 1$

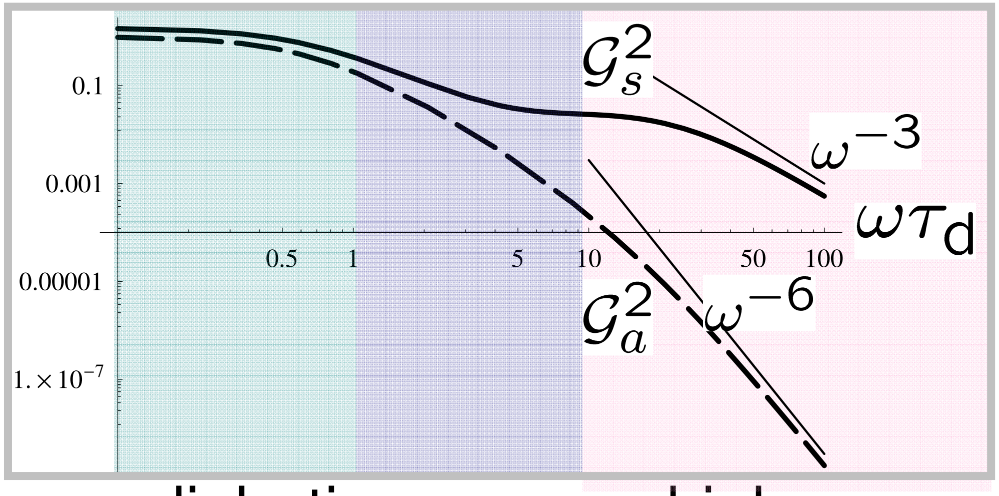
Asymmetry vanishes

Bias mode is more important in AC/DC

- $\eta = 0 \quad \mathcal{G}_a \approx \mathcal{G}_s$

Asymmetry is present

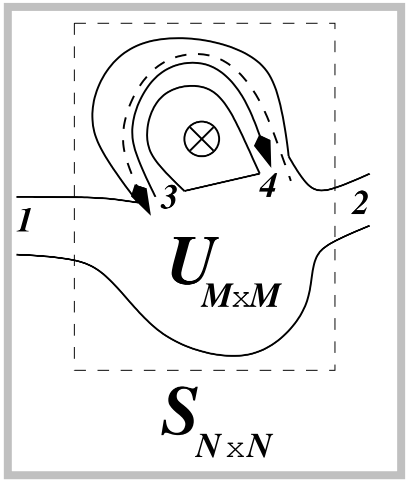
log-log



adiabatic high

Toy model of AB-ring

$$\mathcal{G} \approx \mathcal{G}_0 + \mathcal{G}_{\rm AB}\cos(2\pi\frac{\Phi}{\Phi_0} + \phi_{\rm AB}) \qquad \text{cotan}\ \phi_{\rm AB} = \frac{\mathcal{G}_{s,\rm AB}}{\mathcal{G}_{a,\rm AB}}$$



Model: chaos+ AB-effect

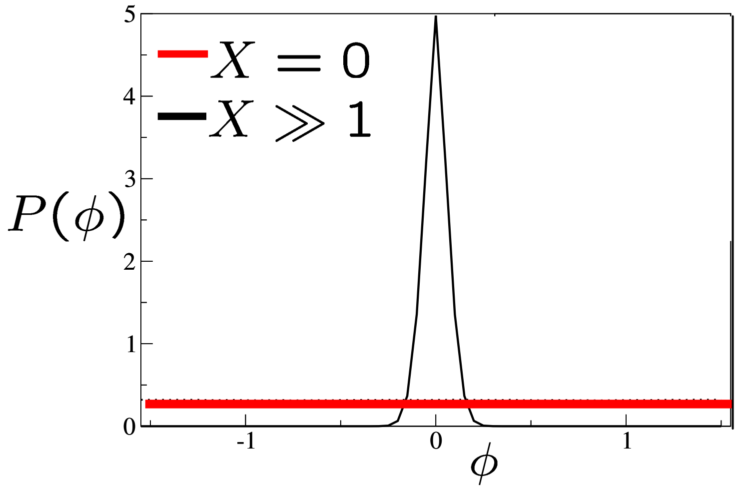
Chaotic dot + narrow ballistic arm

$$\Phi_{\rm arm} \ll \Phi_{\rm dot} \ll \Phi_{\rm hole}$$

$$\langle \text{cotan}^2\phi \rangle = 1 + 8X(\eta)\begin{cases} 1/5, & T \ll N\Delta/2\pi, \\ 3T/N\Delta, & T \gg N\Delta/2\pi \end{cases}$$

$$X(\eta) = \frac{1}{2}\left(\frac{N\Delta}{e^2/C}\tan\eta\right)^2$$

Qualitatively distribution of AB-phase is sensitive to bias mode



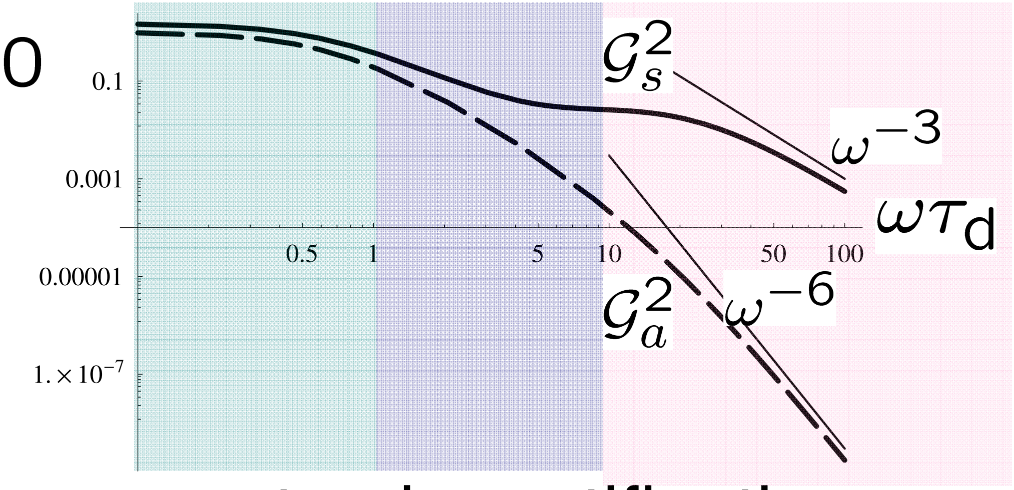
Conclusions

- Bias mode strongly affects measurement of $\mathcal{G}_s$

1) AC-bias with $\omega \neq 0$

2) asymmetric setup

3) $\frac{e^2/C}{\Delta} \neq \infty$



- Found magnetic (a) symmetry in rectification
- In rings found AB-phase, $\langle \mathrm{cotan}^2\phi \rangle \sim 1$

??? *Frequency mixing, Coulomb in FCS* $(\tau \neq \infty)$

M.L. Polianski and M. Büttiker, *Phys. Rev. B* **76**, 205308 (2007)

Physica E **40**, 67 (2007)