Interaction-induced charge transfer in a mesoscopic electron spectrometer

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In collaboration with T. Krähenmann, M. Röösli, K. Ensslin, and T. Ihn
(ETH Zürich)

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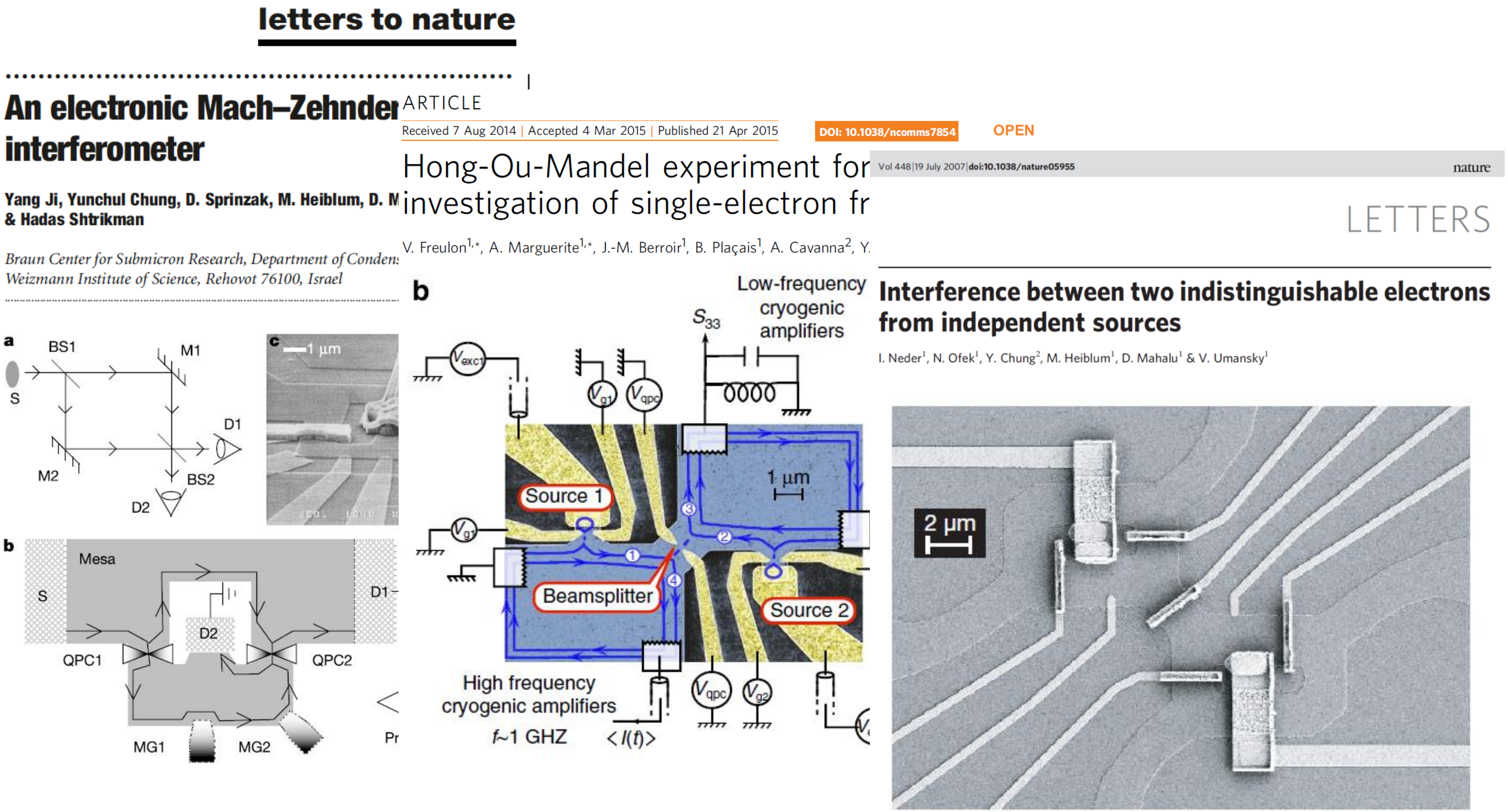
Ben-Gurion University of the Negev

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Interferometers in quantum Hall edge channels


letters to nature

An electronic Mach–Zehnder interferometer

Yang Ji, Yunchul Chung, D. Sprinzak, M. Heiblum, D. M
& Hadas Shtrikman

Braun Center for Submicron Research, Department of Conden
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ARTICLE

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Hong-Ou-Mandel experiment for
investigation of single-electron fr

V. Freulon[1,*], A. Marguerite[1,*], J.-M. Berroir[1], B. Plaçais[1], A. Cavanna[2], Y.

Vol 448 | 19 July 2007 | doi:10.1038/nature05955 nature

LETTERS

Interference between two indistinguishable electrons from independent sources

I. Neder[1], N. Ofek[1], Y. Chung[2], M. Heiblum[1], D. Mahalu[1] & V. Umansky[1]

Electrons interact: dissipation / loss of coherence

PRL **105**, 056803 (2010) PHYSICAL REVIEW LETTERS week ending 30 JULY 2010

Energy Relaxation in the Integer Quantum Hall Regime

H. le Sueur, C. Altimiras, U. Gennser, A. Cavanna, D. Mailly, and F. Pierre*

CNRS, Laboratoire de Photonique et de Nanostructures (LPN)—Phynano team, route d

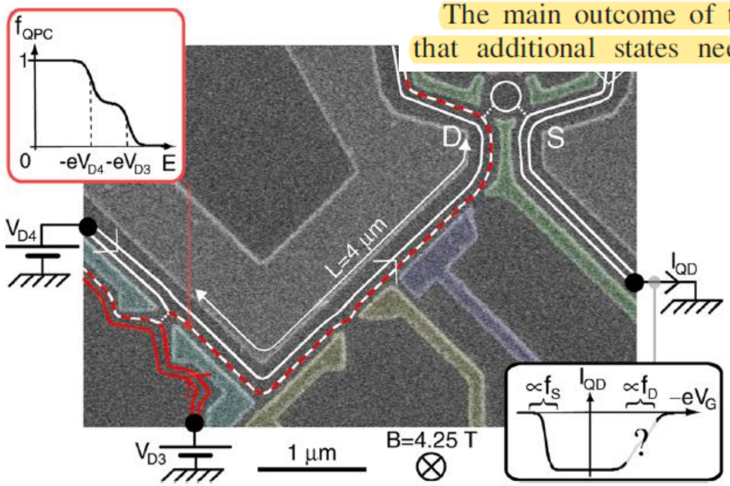
(Received 22 March 2010; published 27 July 2010)

We investigate the energy exchanges along an electronic quantum chan quantum Hall regime at a filling factor of $\nu_L = 2$. One of the two edge equilibrium and the resulting electronic energy distribution is measured in the propagation lengths $0.8\ \mu\text{m} \leq L \leq 30\ \mu\text{m}$. Whereas there are no discernib thermalized states, we find efficient energy redistribution between the two exchanges. At long distances $L \geq 10\ \mu\text{m}$, the measured energy distribution is temperature is lower than expected for two interacting channels, which sugges degrees of freedom. The observed short energy relaxation length challenge quantum Hall excitations as quasiparticles localized in one edge channel.

DOI: 10.1103/PhysRevLett.105.056803

spin propagate at the same speed. Motivated by the present experiment, T_{exc} was recently calculated in the bosonization framework [25]. Assuming strong interactions and a standard drift velocity 10^5 m/s, calculations are found to reproduce the measured nonlinear shape of $T_{\text{exc}}(\delta V_D)$ and also the energy relaxation length scale, without the need to introduce disorder [25]. However, the same lower bound $T_{\text{exc}}^{\text{qpc}}/\sqrt{2}$ was confirmed for arbitrary interaction strength between two 1DCF branches. In [25], the data are reproduced quantitatively by assuming *ad hoc* 25% of the energy leaks out toward other degrees of freedom.

The main outcome of the data-theory comparisons is that additional states need to be taken into account.



Transfer QPC → QD: not all of the injected energy reaches QD, unknown loss mechanism

Electrons interact: dissipation / loss of coherence

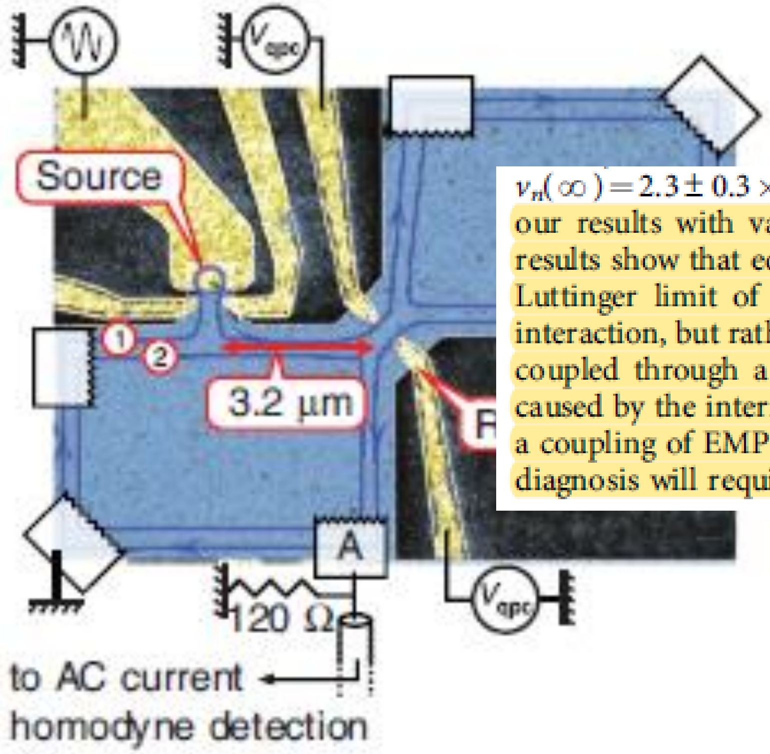
ARTICLE

Received 5 Jul 2012 | Accepted 22 Mar 2013 | Published 14 May 2013

DOI: 10.1038/ncomms2788

Separation of neutral and charge modes in one-dimensional chiral edge channels

E. Bocquillon[1], V. Freulon[1], J.-M. Berroir[1], P. Degiovanni[2], B. Plaçais[1], A. Cavanna[3], Y. Jin[3] & G. Fève[1]

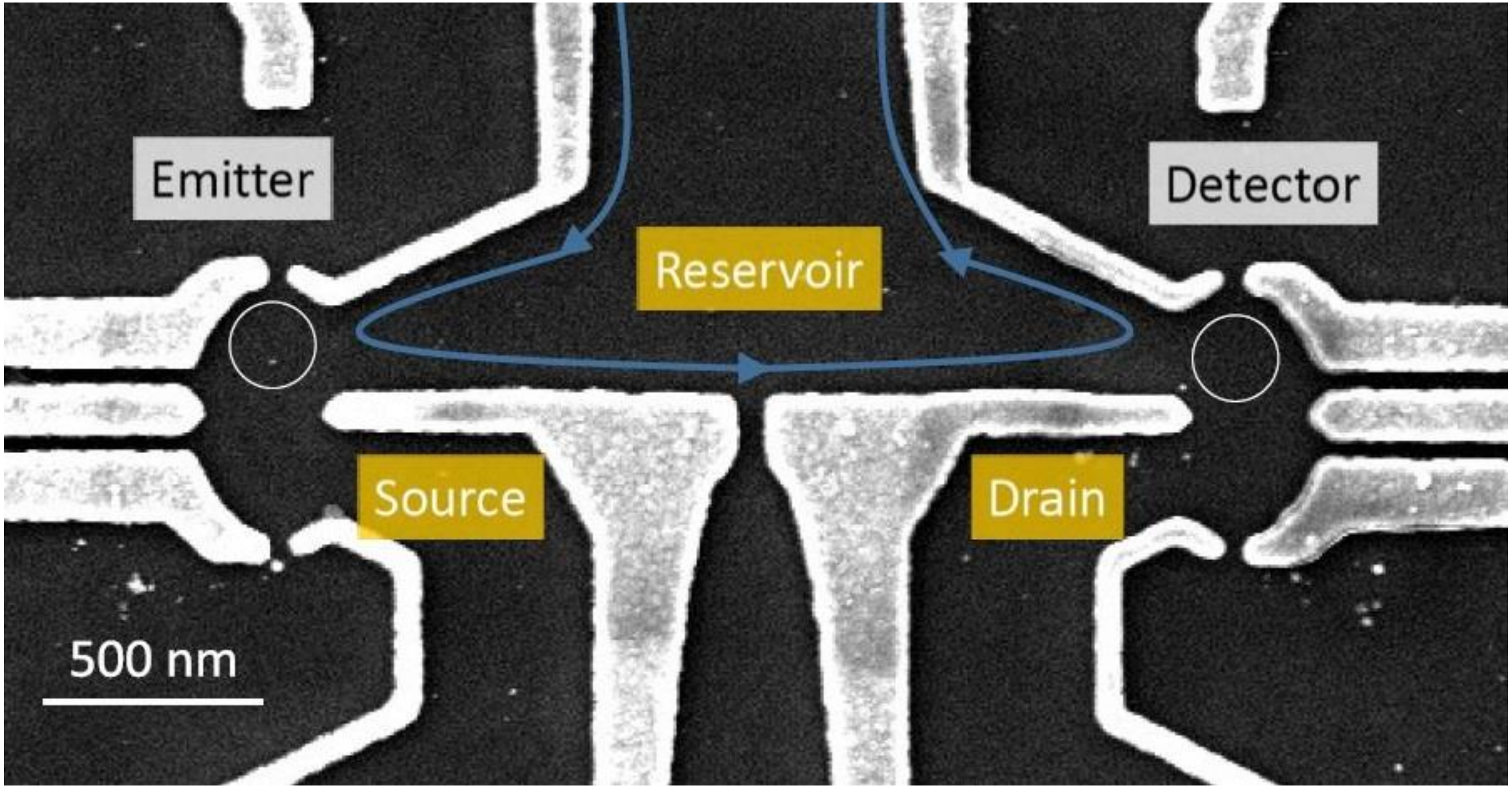


$v_n(\infty) = 2.3 \pm 0.3 \times 10^4\ \mathrm{m\,s^{-1}}$ at high frequency. Comparing our results with various models of inter-edge interactions, our results show that edge channel propagation differs from the ideal Luttinger limit of dissipationless propagation with short-range interaction, but rather agrees with a model of dissipative channels coupled through a long-range interaction. Dissipation could be caused by the internal structure of compressible edges, leading to a coupling of EMP to acoustic modes[37,38], but a non-ambiguous diagnosis will require further investigation.

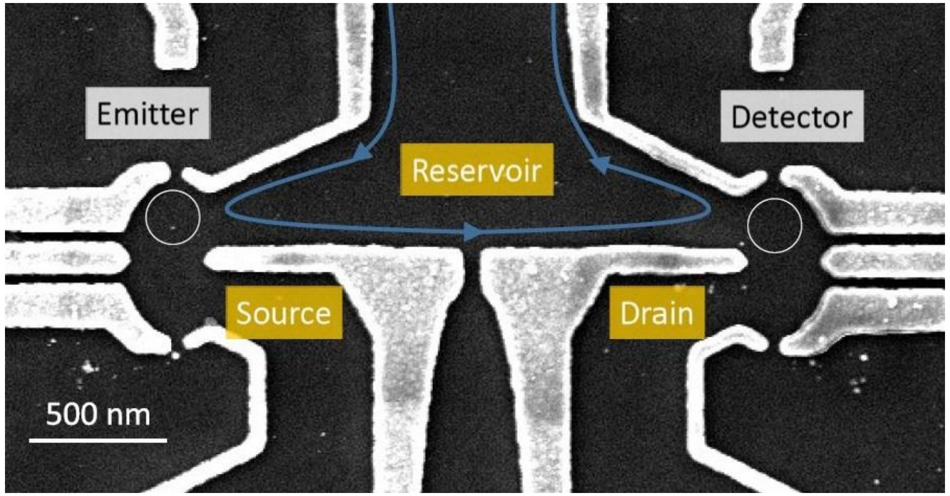
RF injection: channels are dissipative, unknown mechanism

Introduction

- Experiment: energy resolved transfer along quantum Hall edge
- Distinct transfer processes show distinct signatures in energy landscape
- Theory: relate signatures to underlying physical processes by diagrammatic approach to identify relaxation mechanisms



T. Krähenmann (Dissertation, ETH Zürich, 2017)



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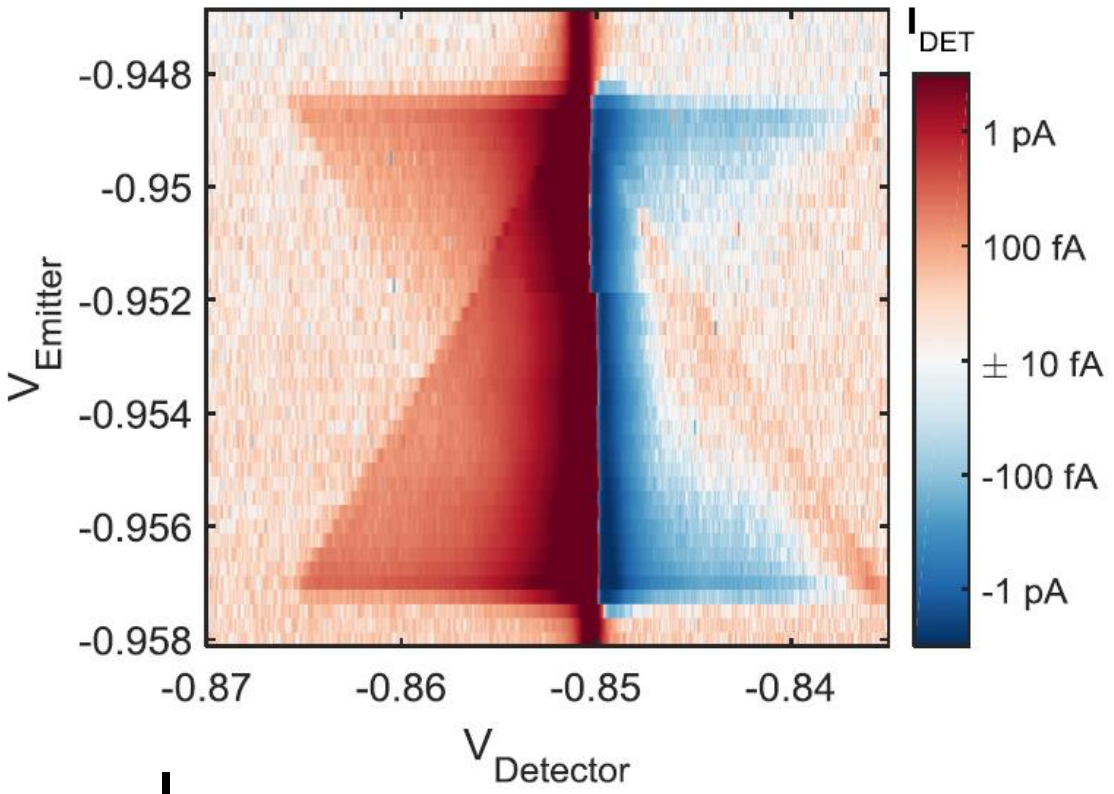

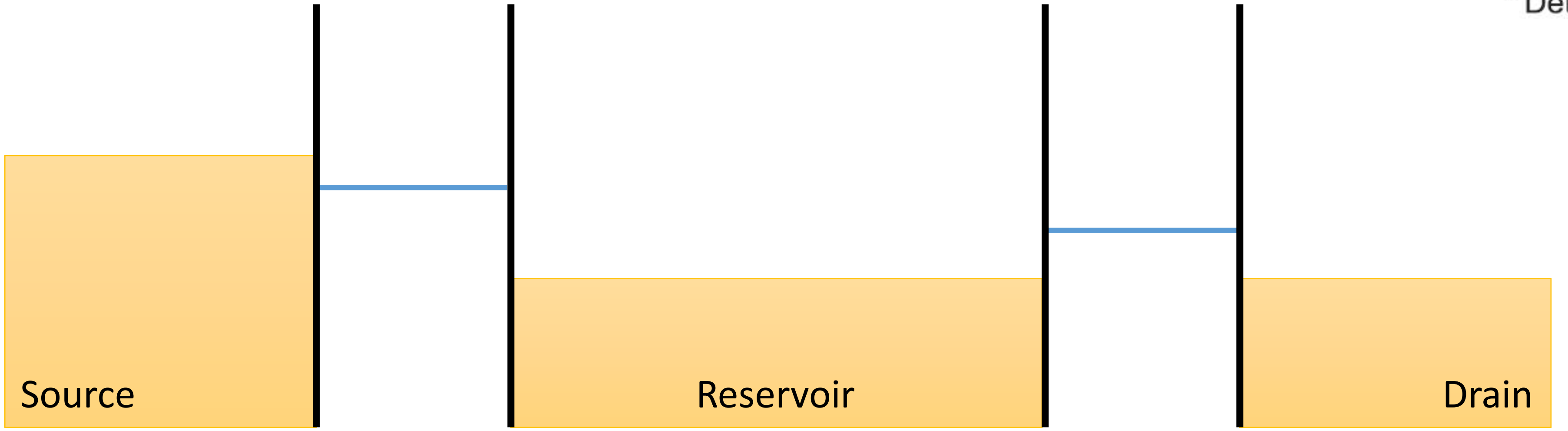

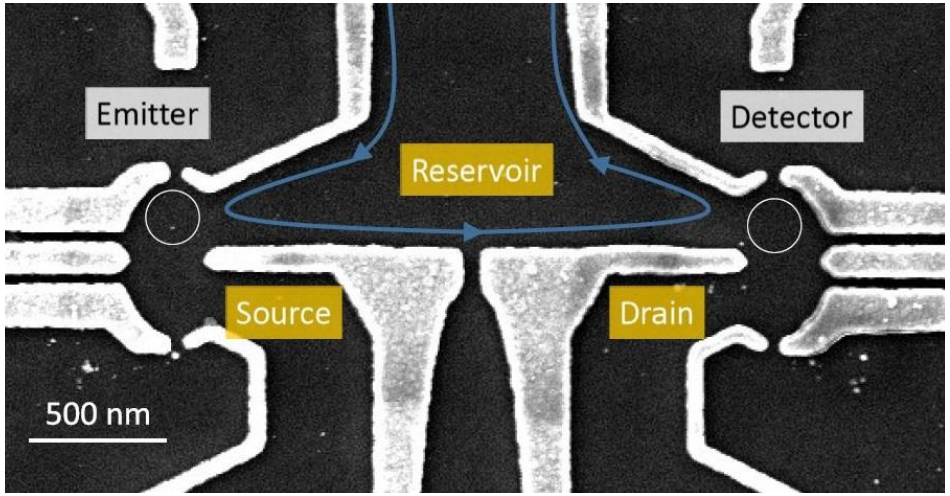

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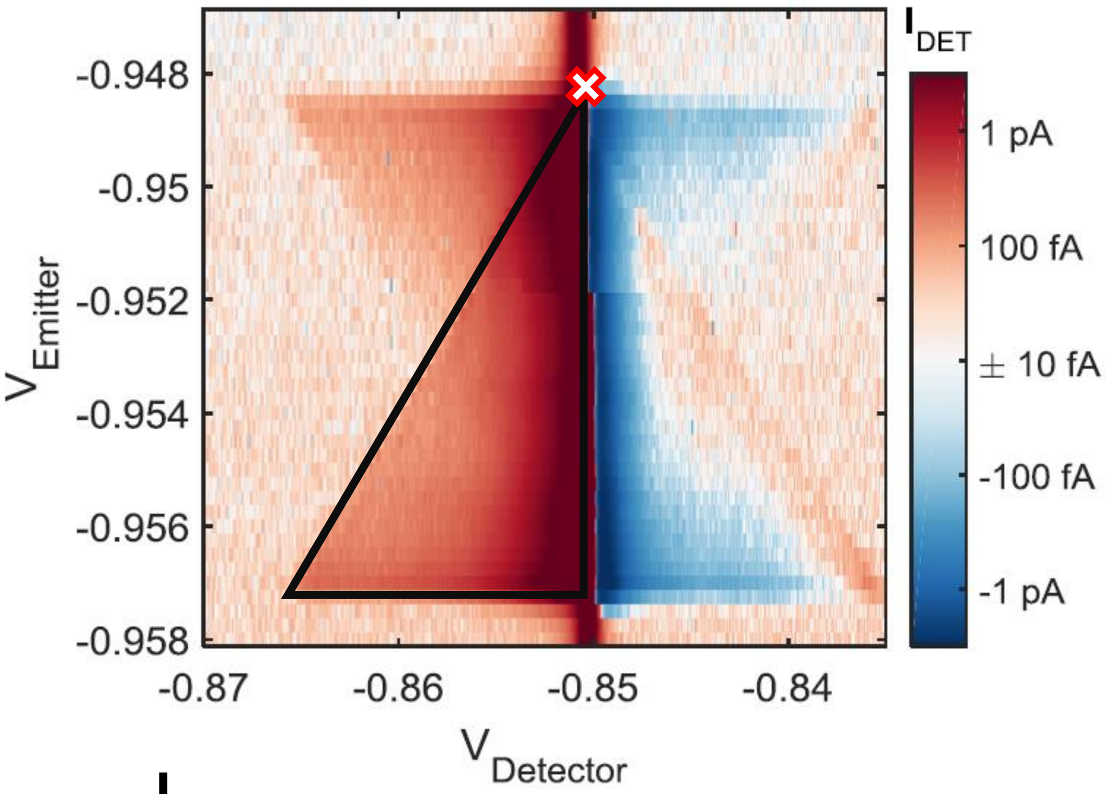

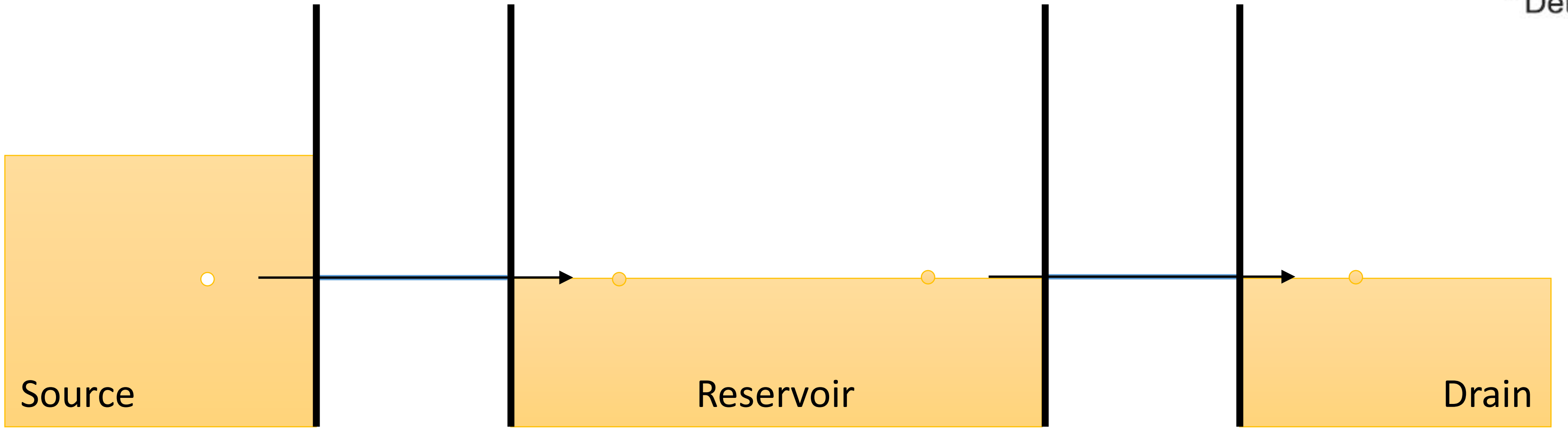

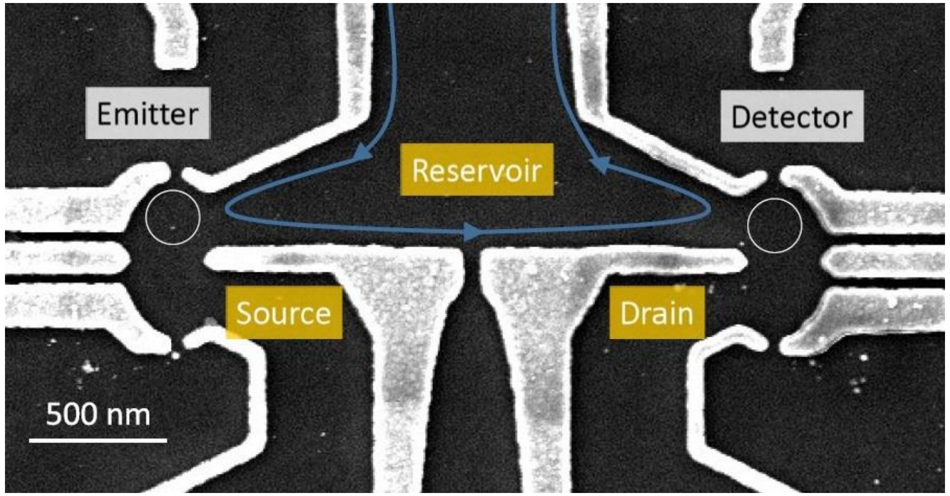

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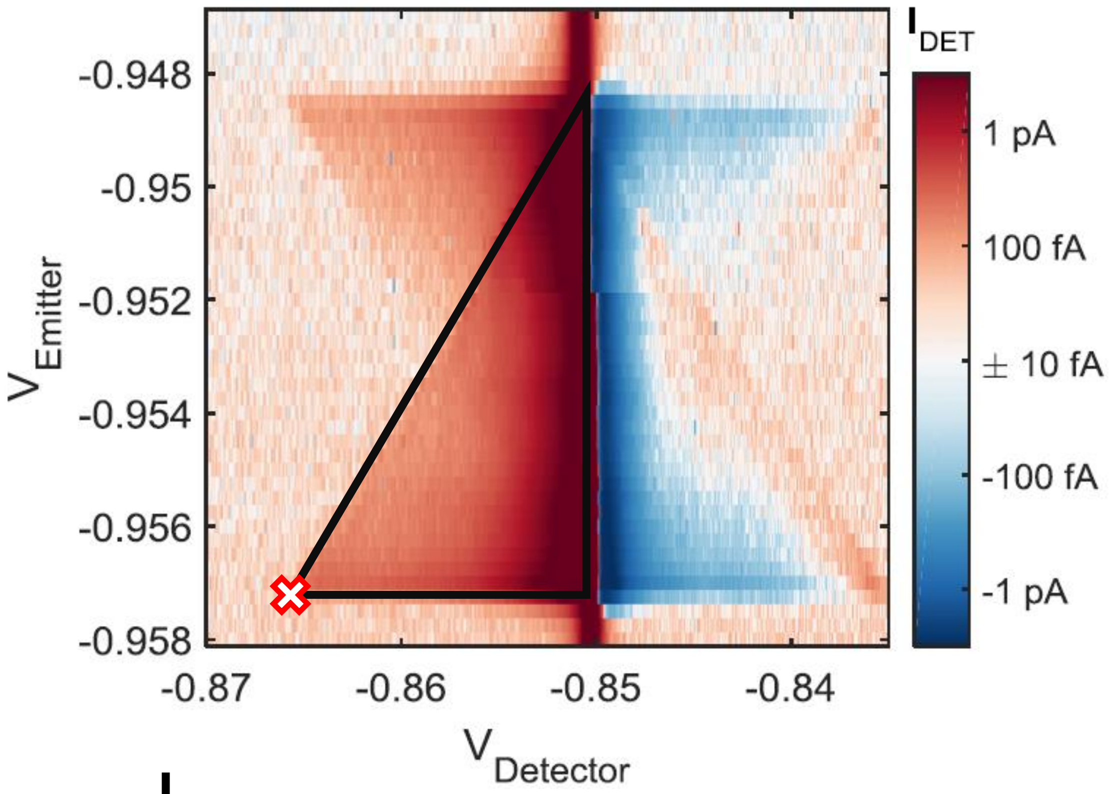

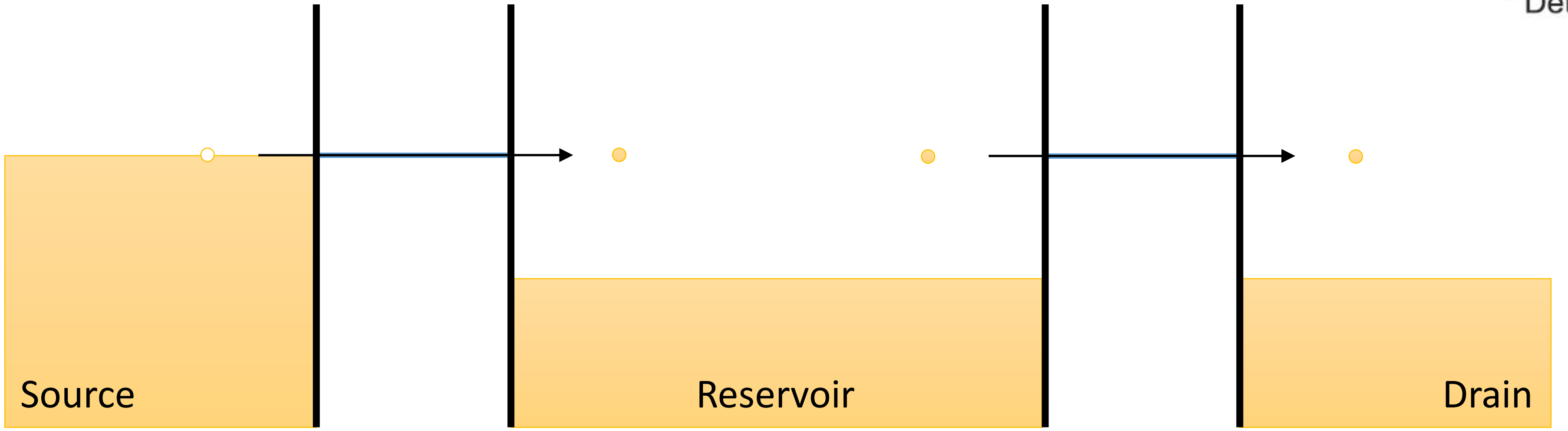

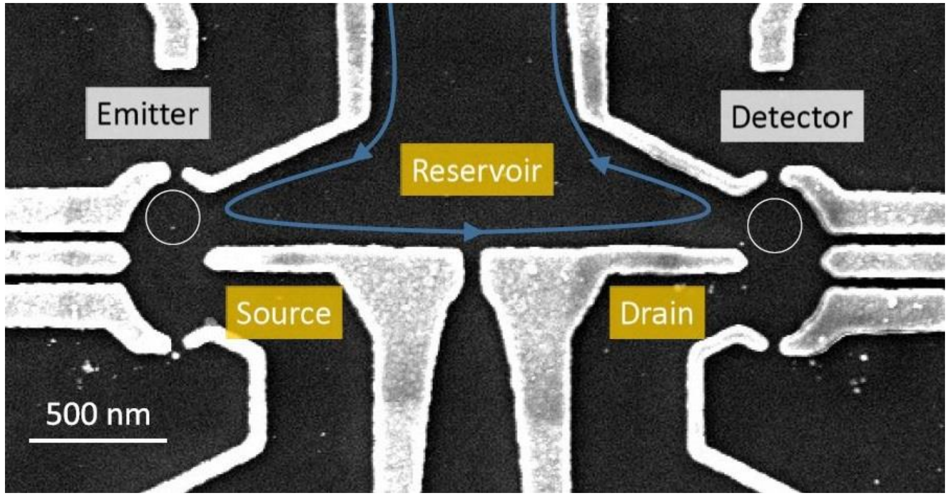

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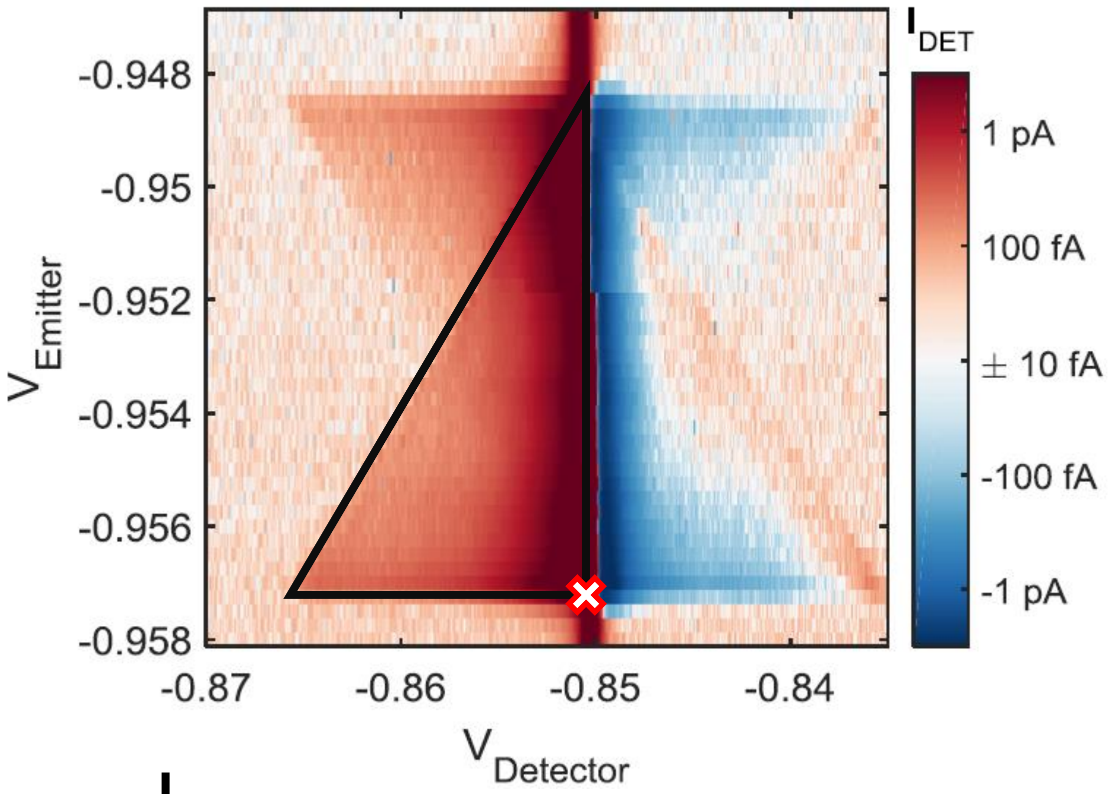

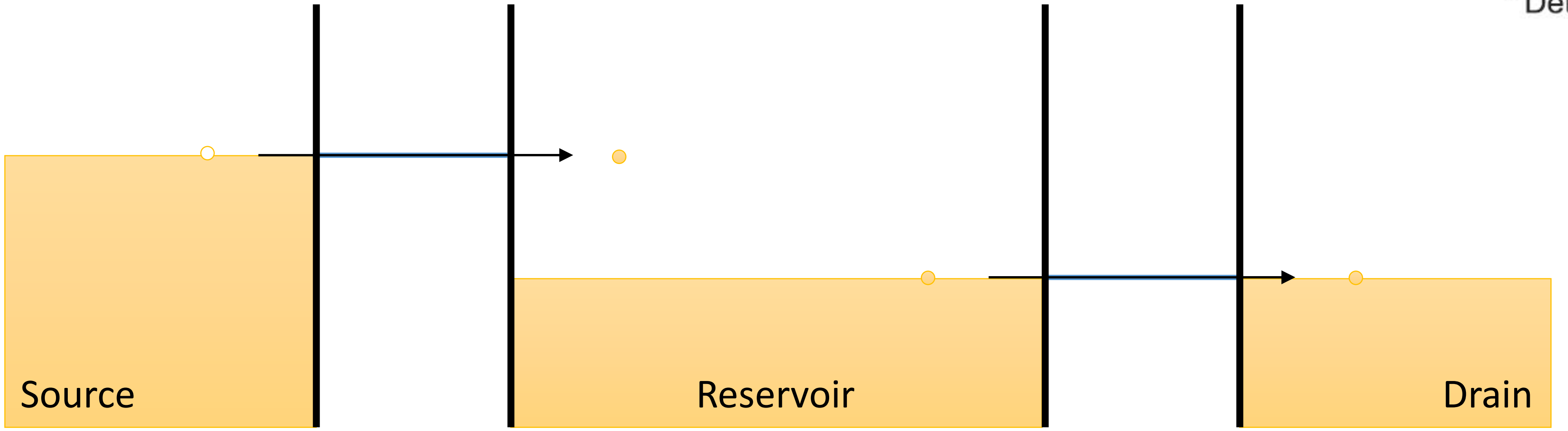

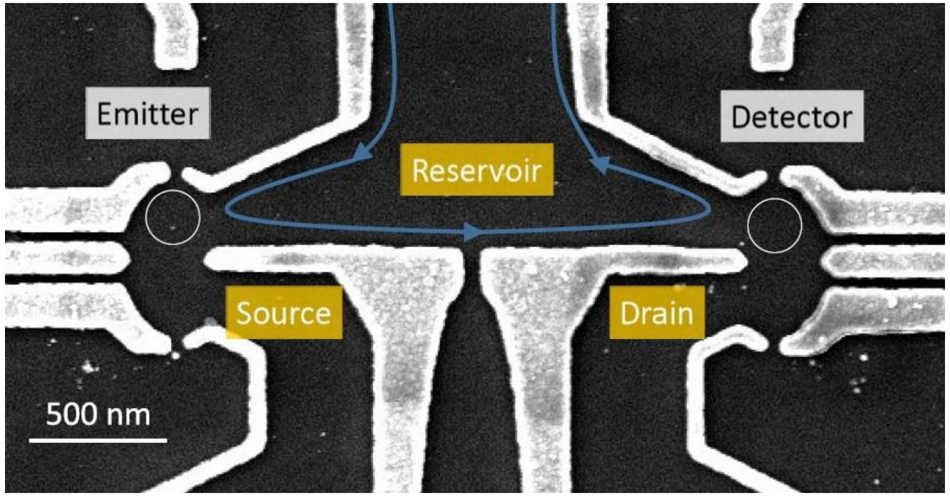

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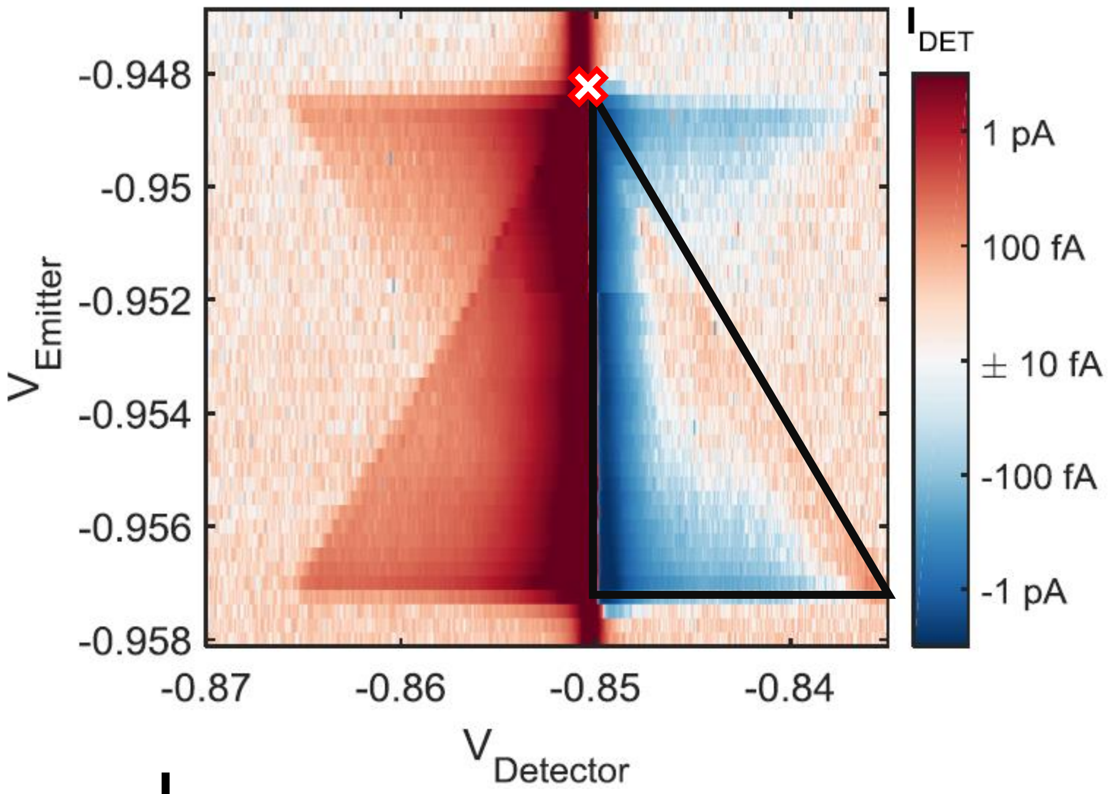

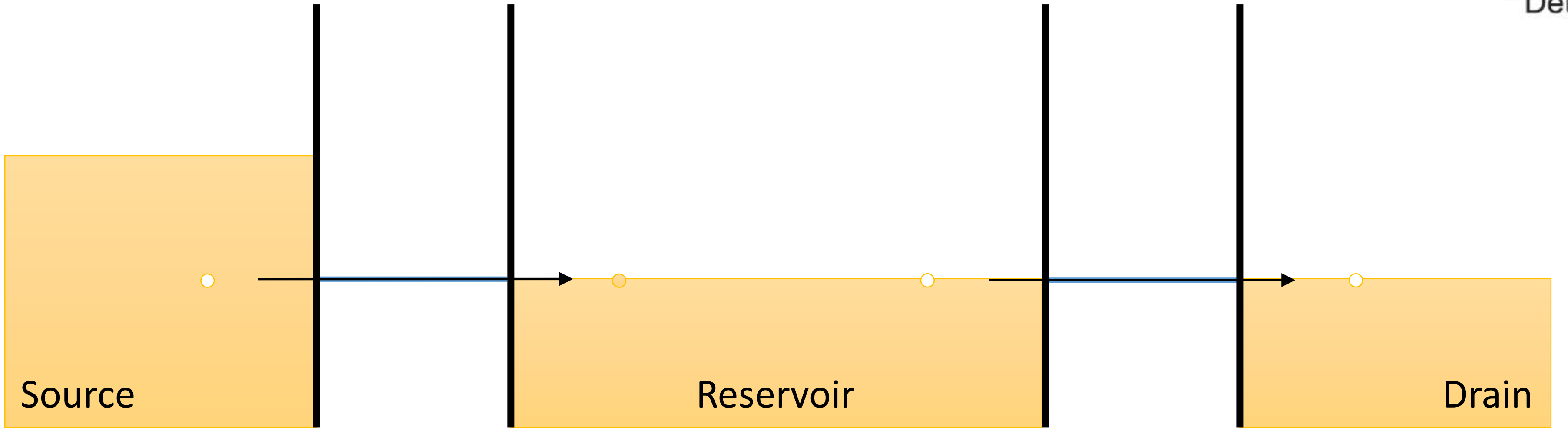

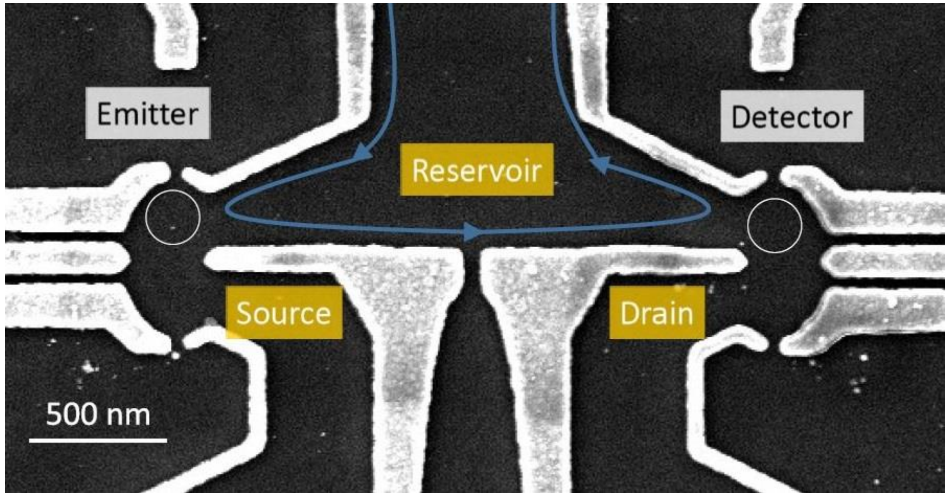

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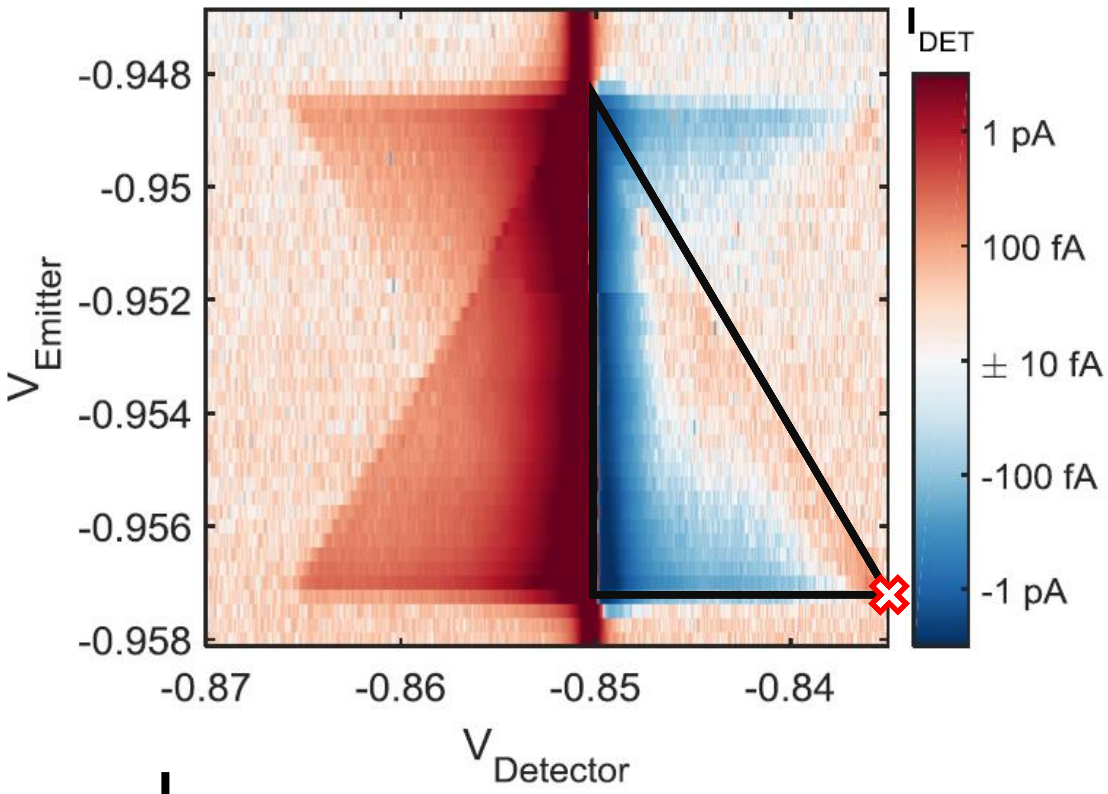

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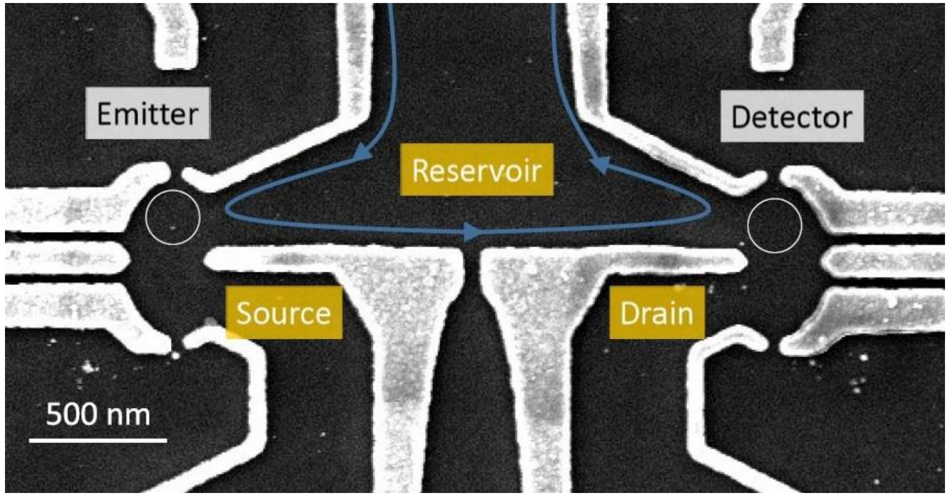

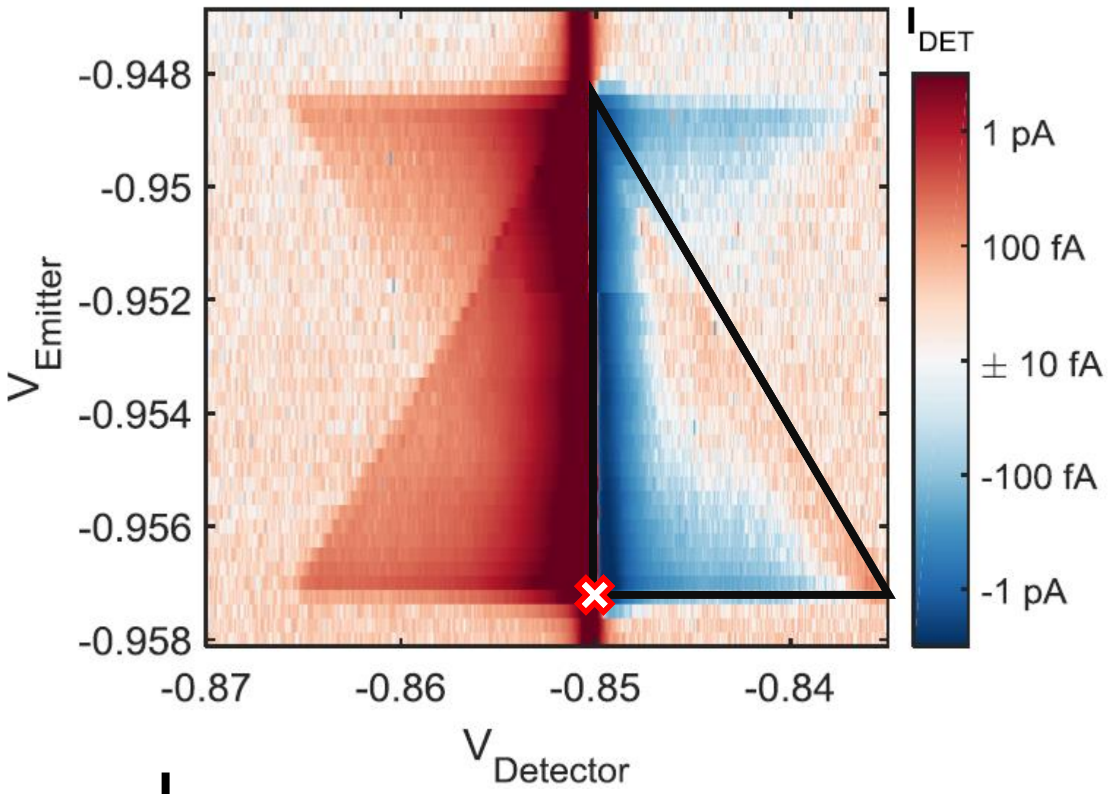

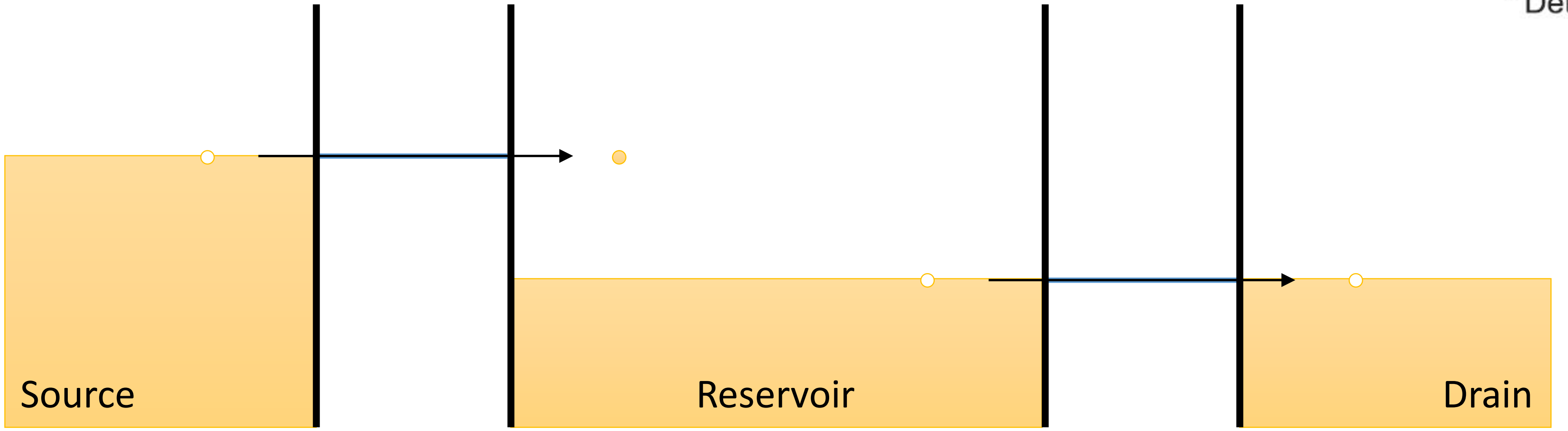

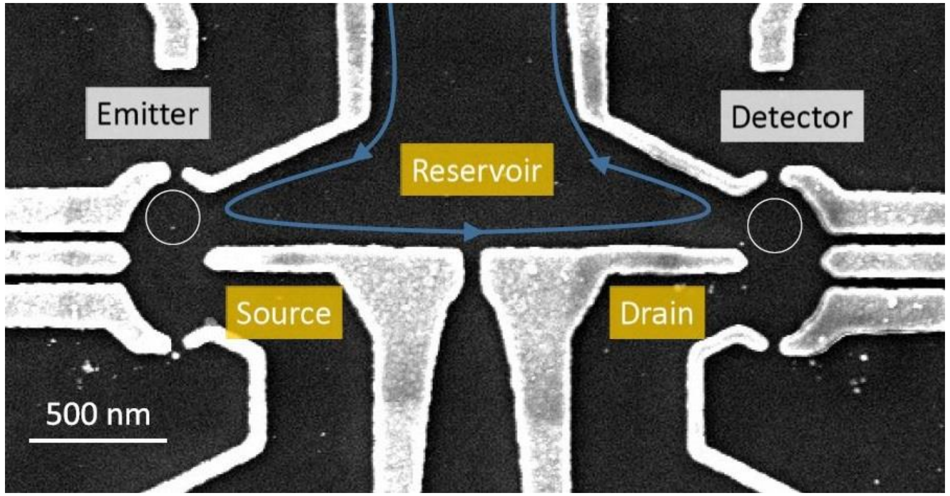

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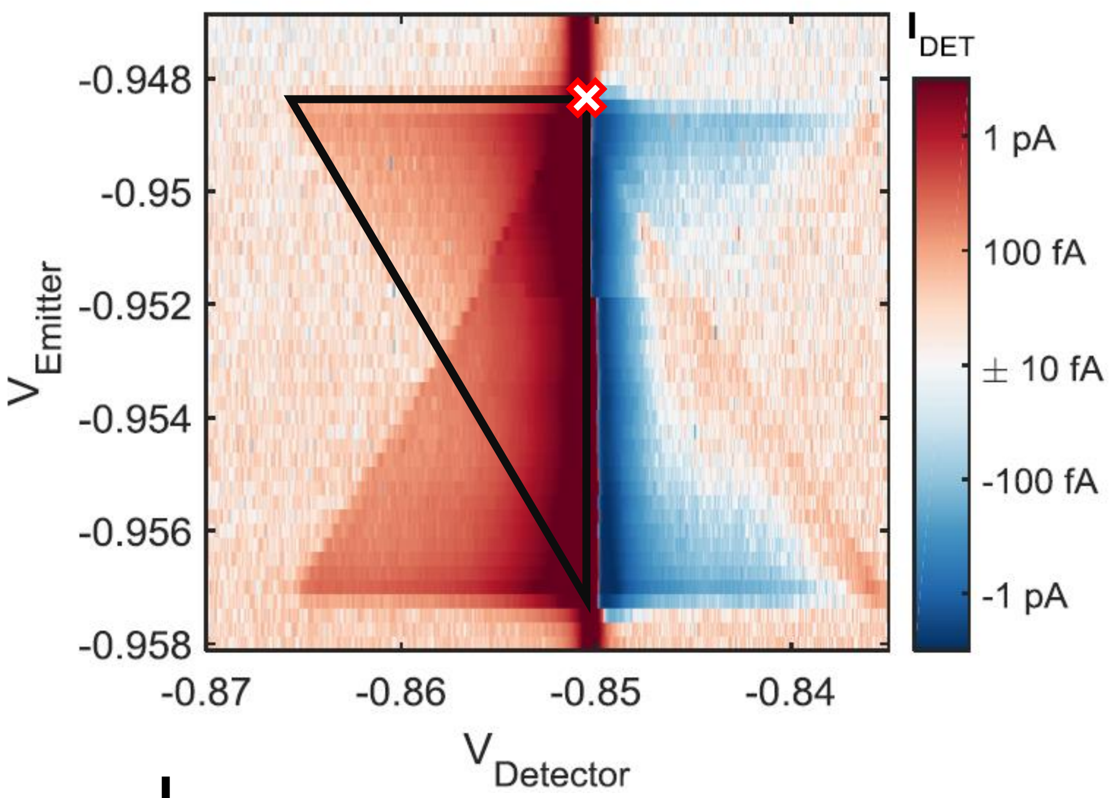

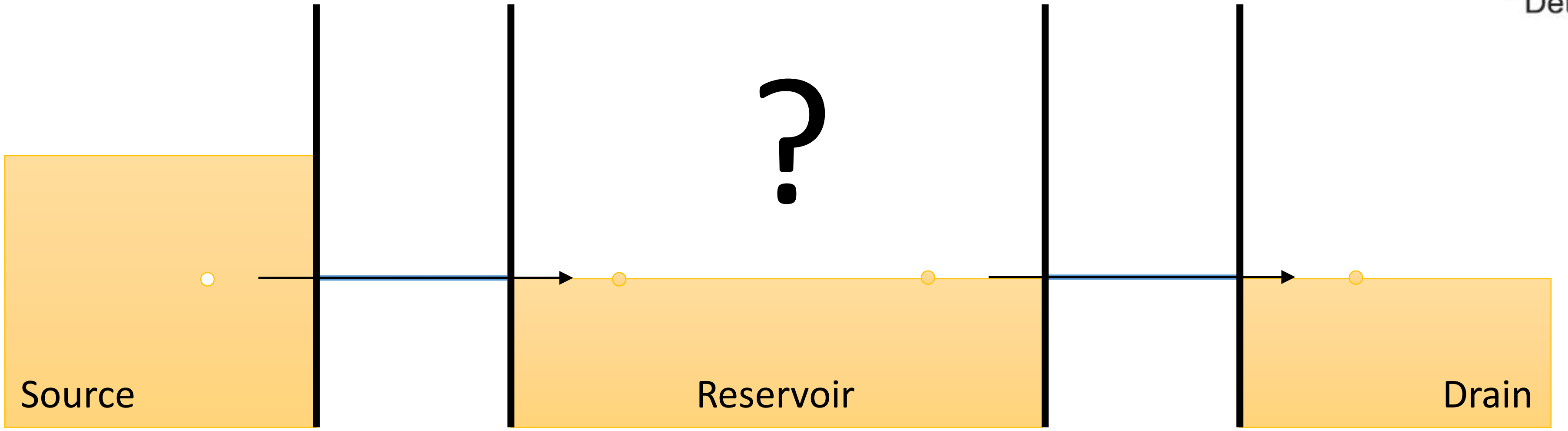

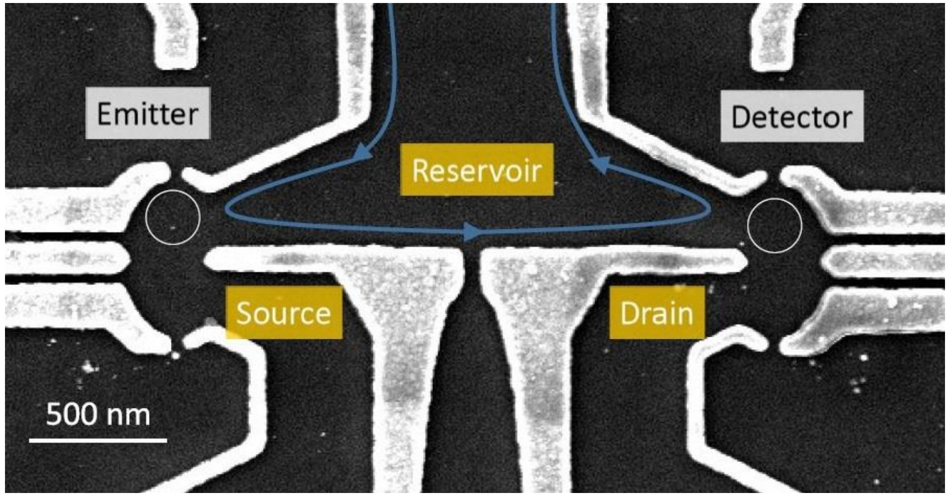

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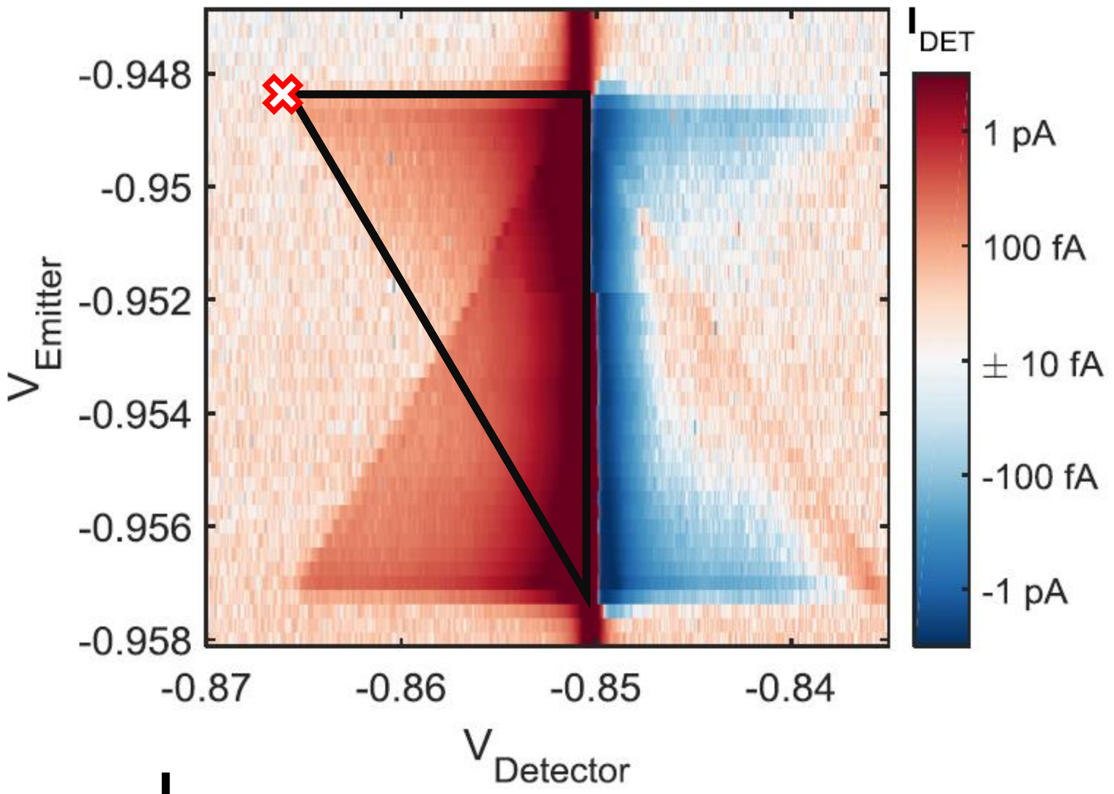

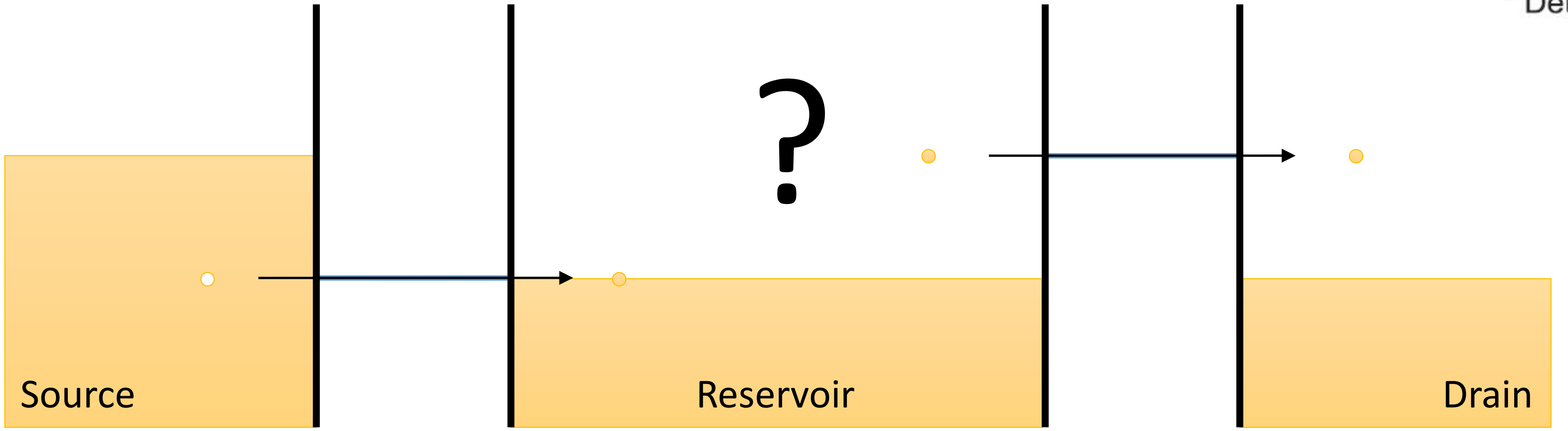

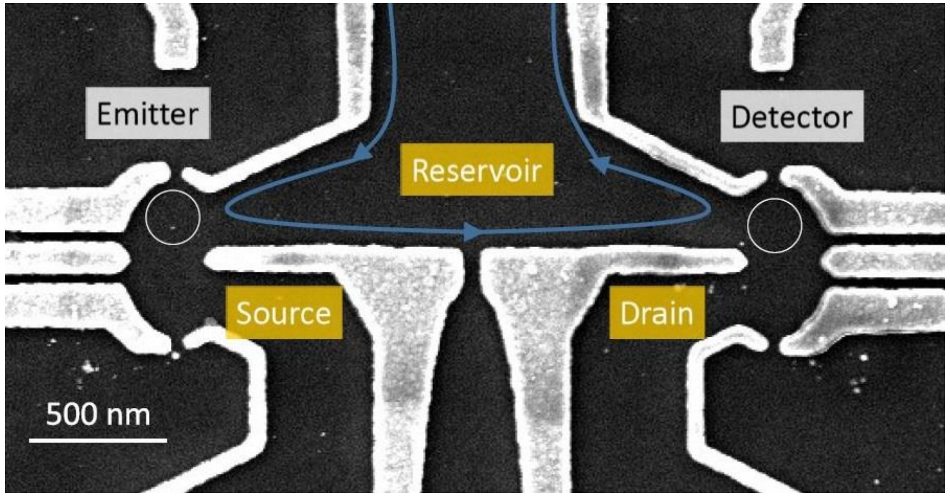

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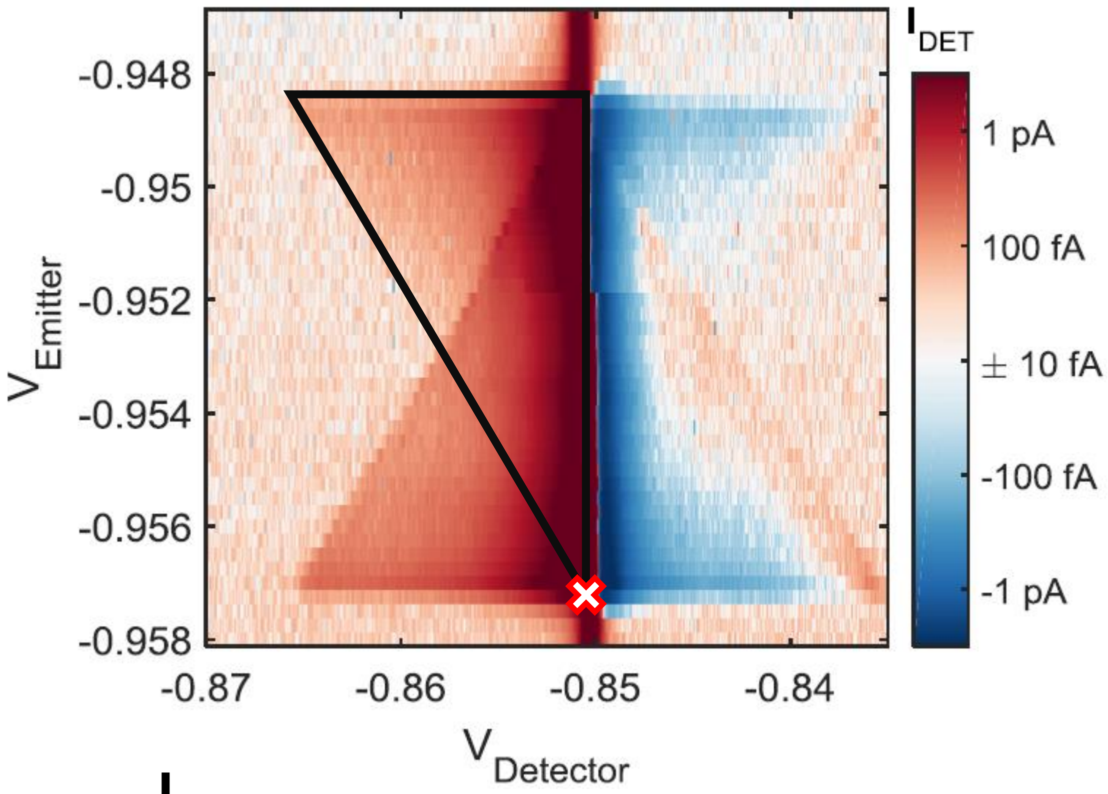

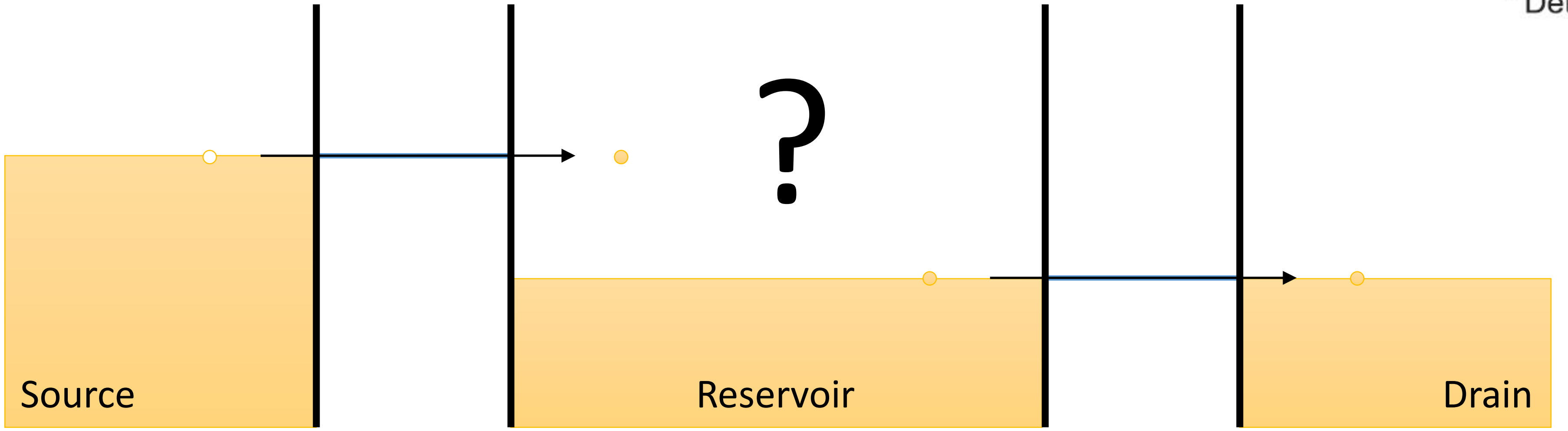

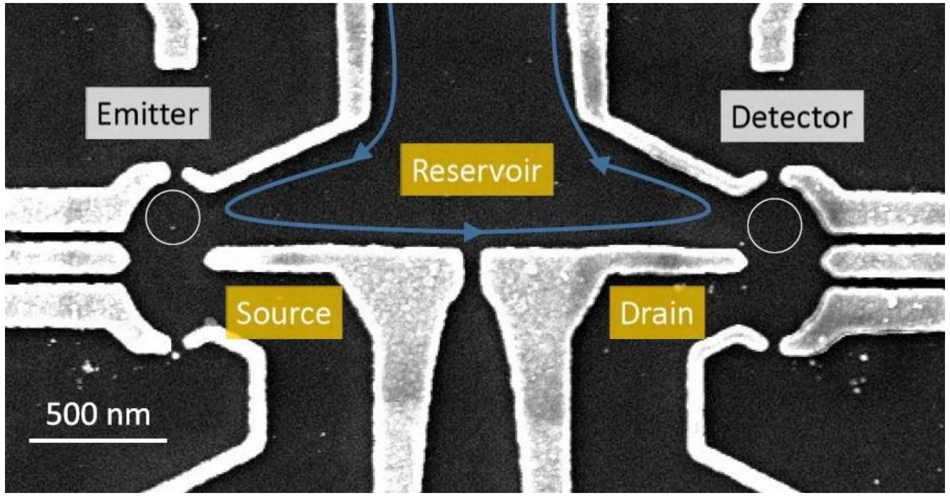
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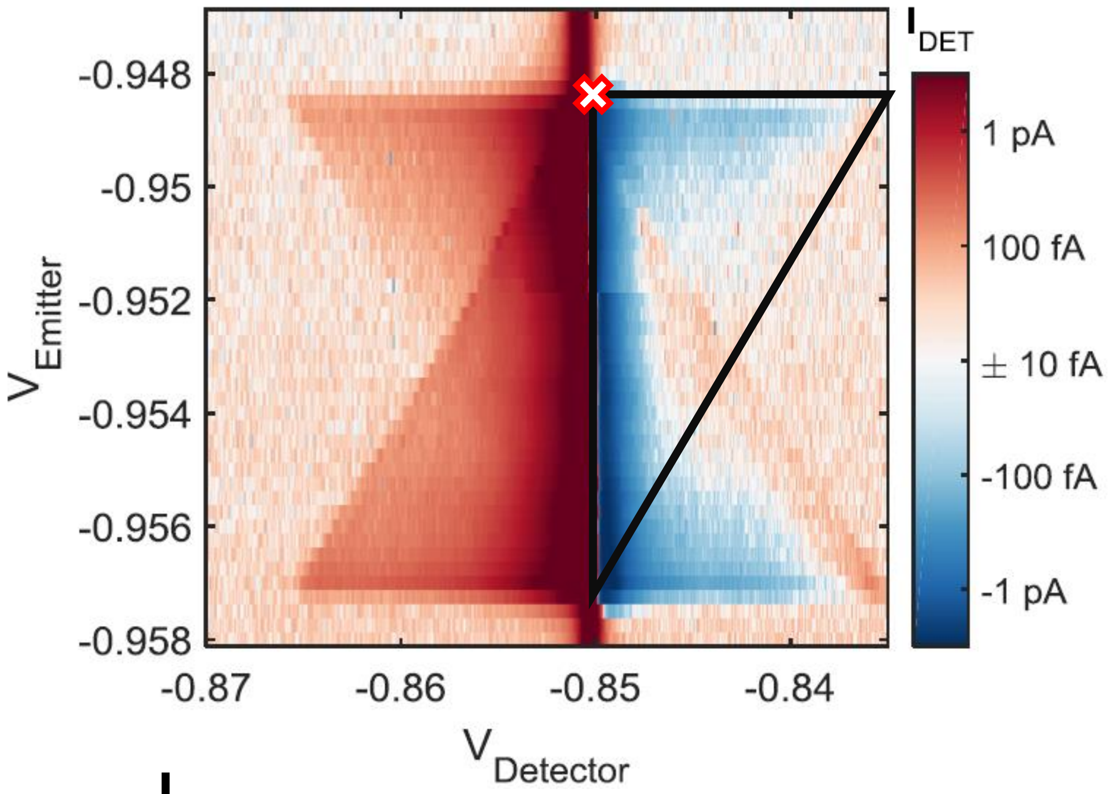
I_{DET}
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± 10 fA
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-1 pA
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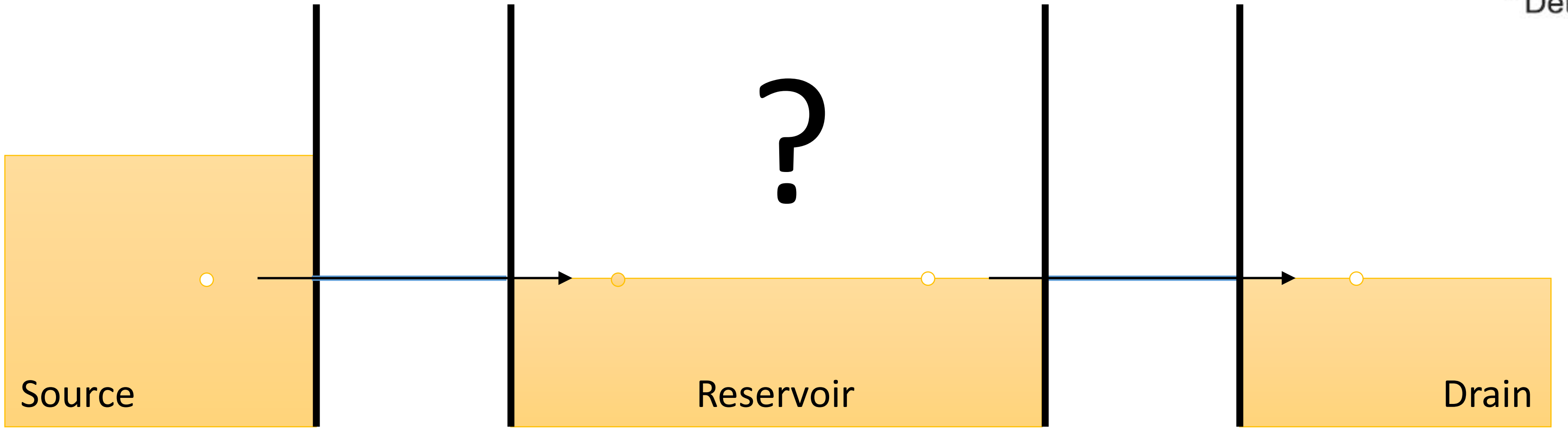
-0.95
-0.952
-0.954
-0.956
-0.958
$V_{Emitter}$
-0.87
-0.86
-0.85
-0.84
$V_{Detector}$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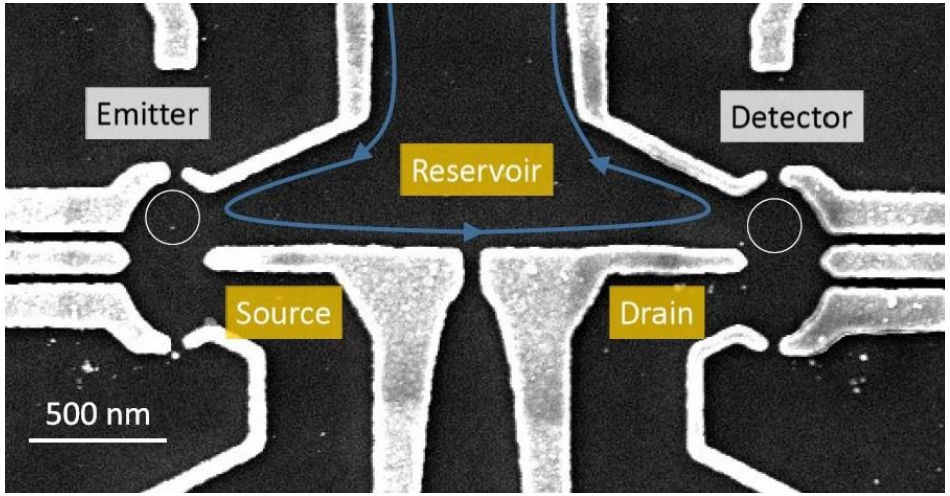
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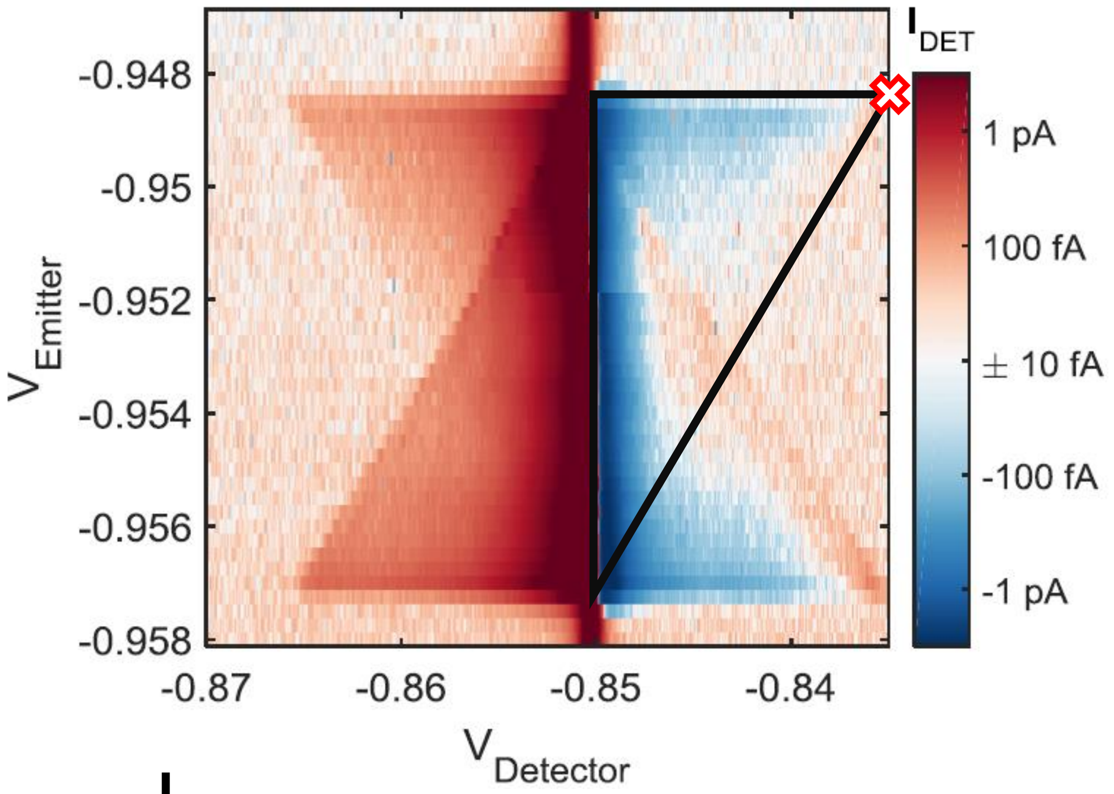
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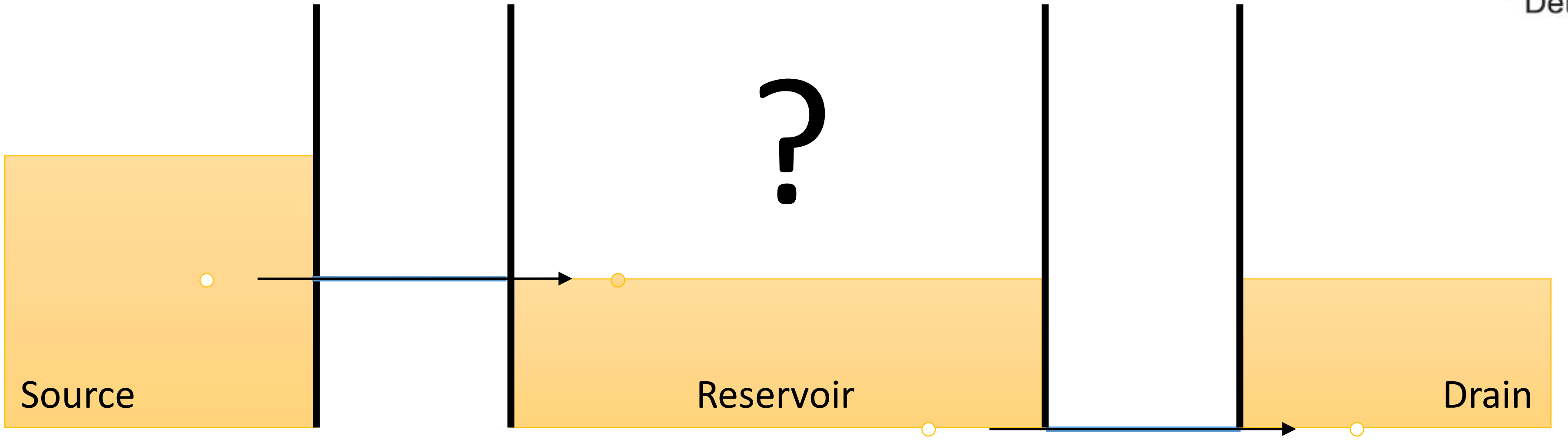
$V_{Detector}$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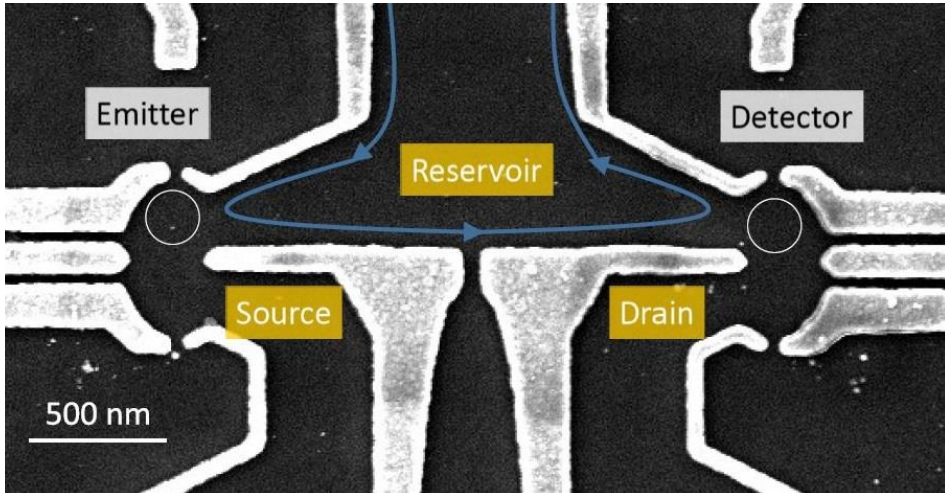
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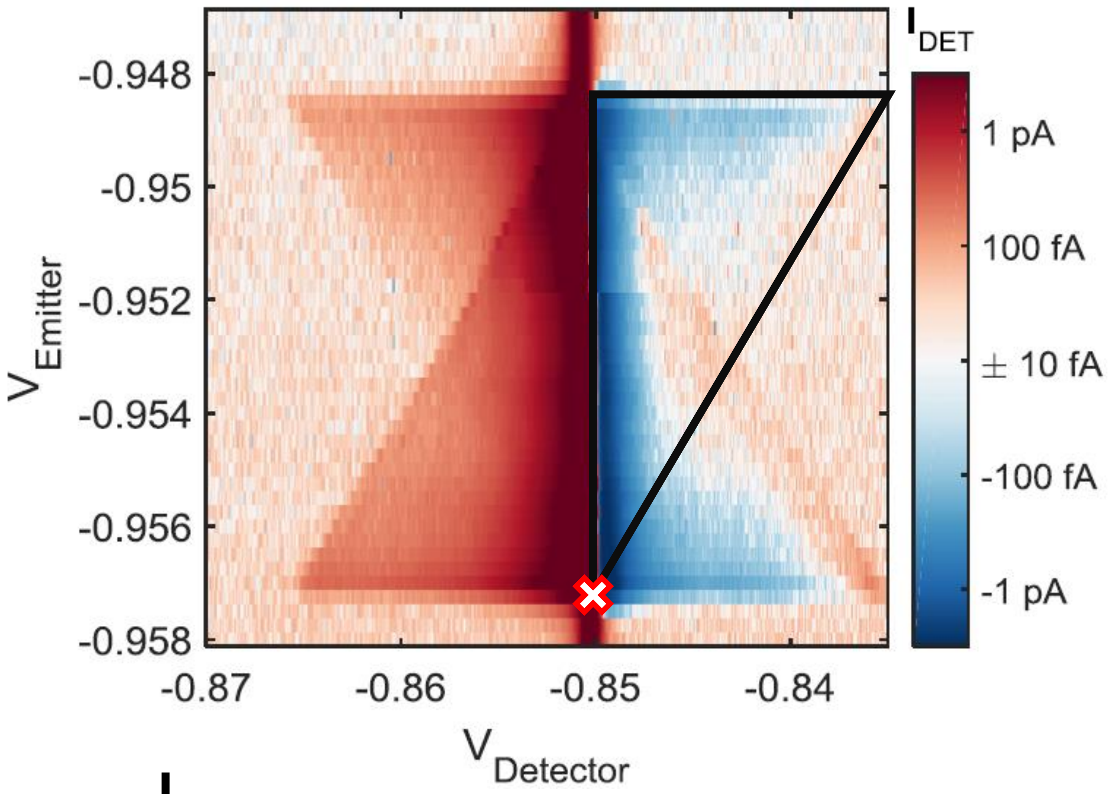
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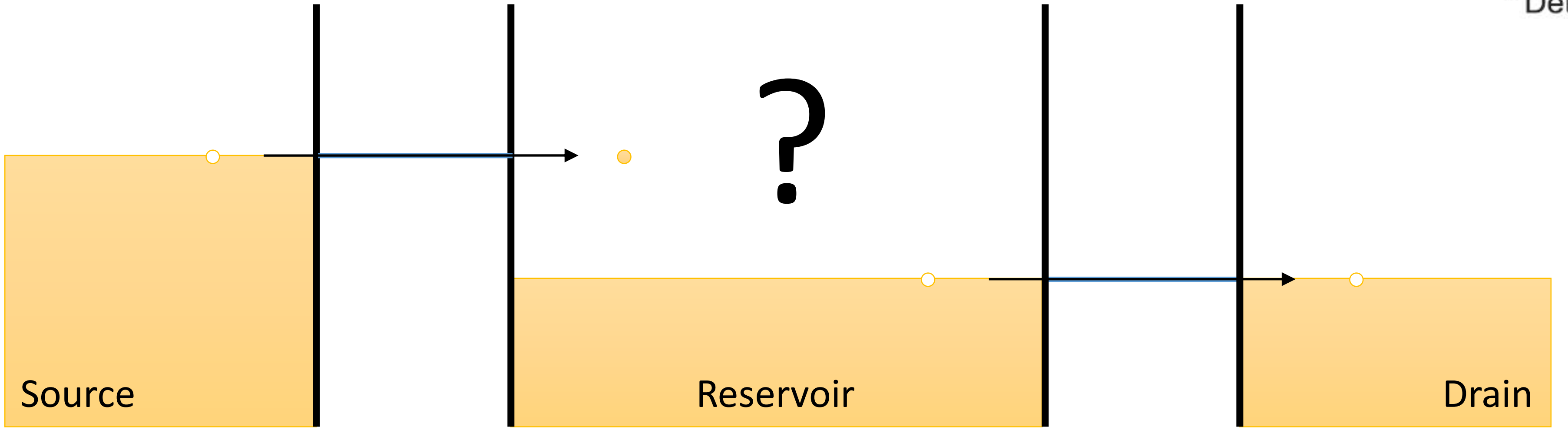
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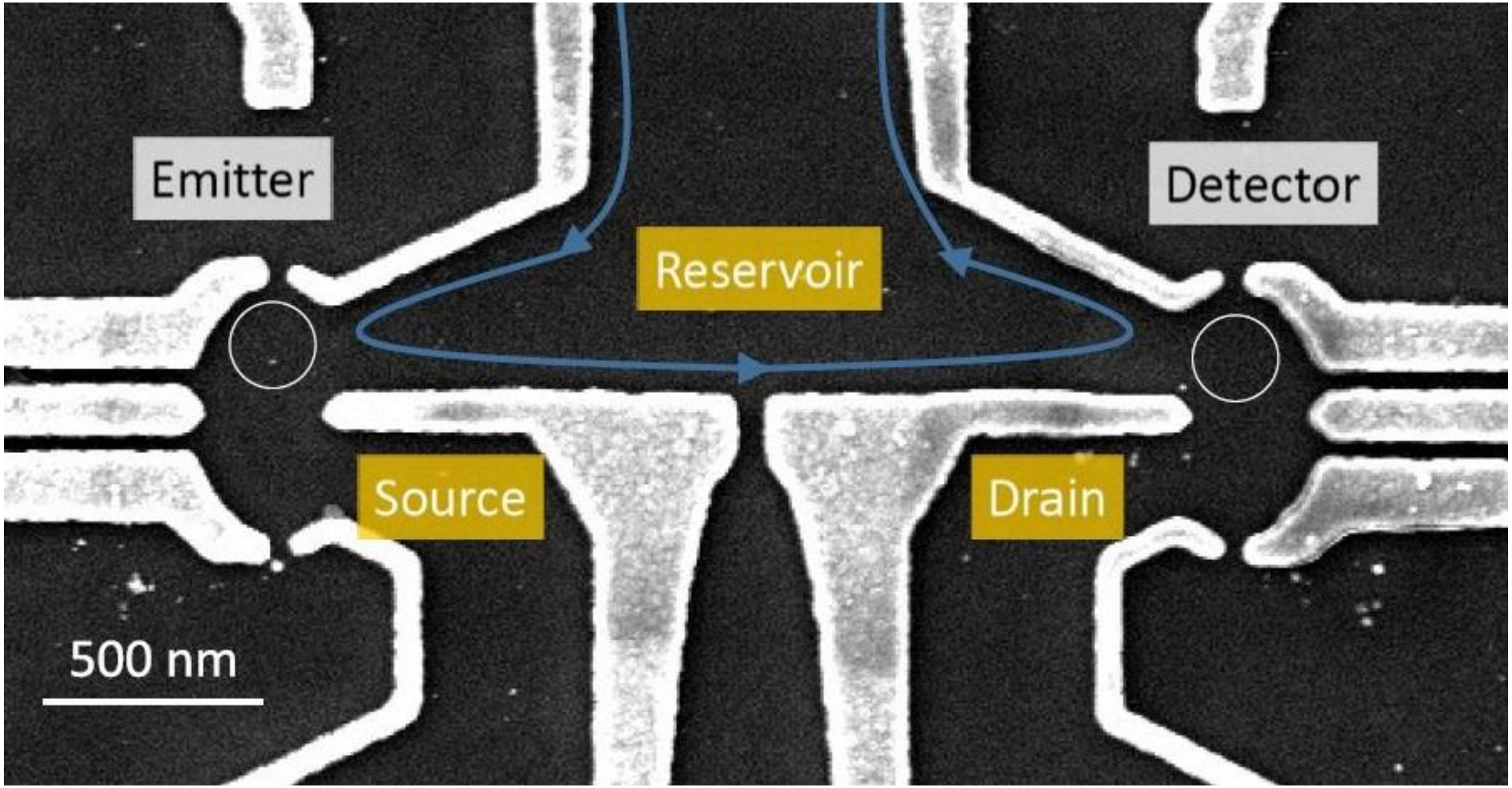
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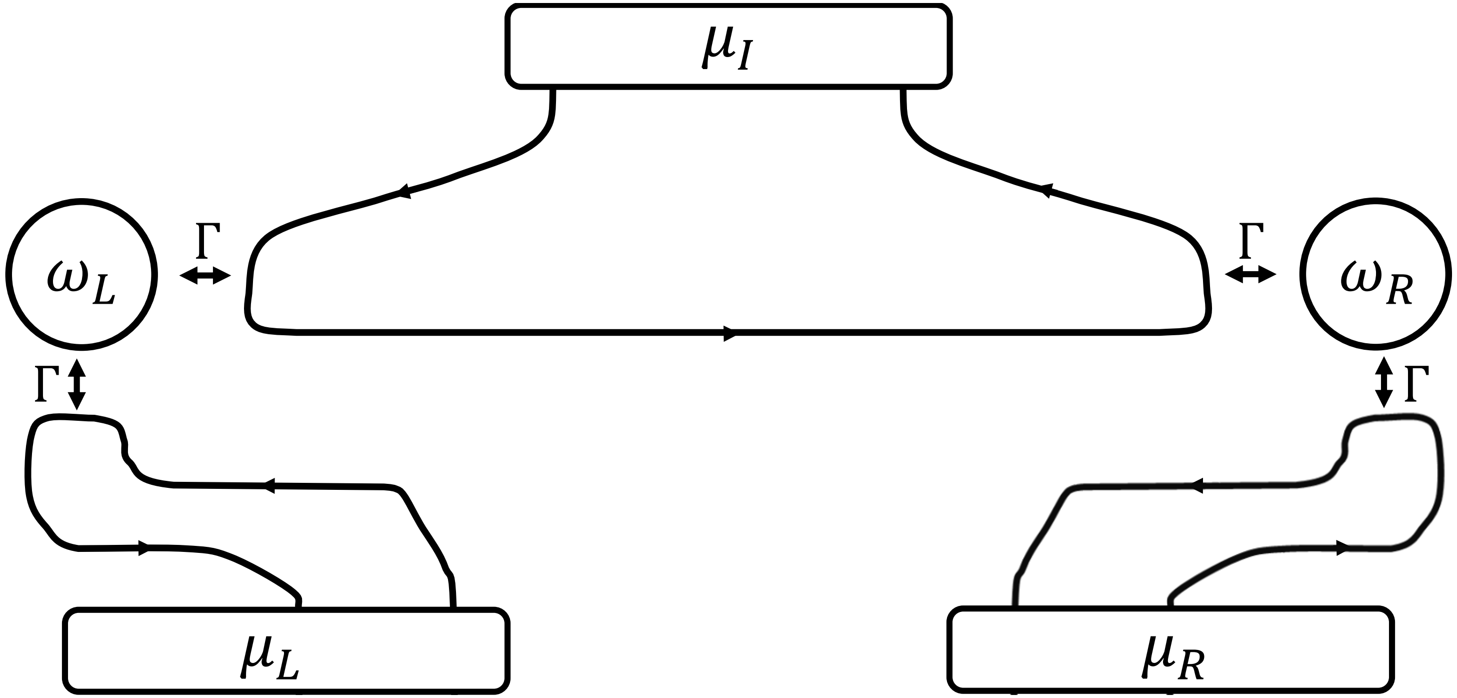

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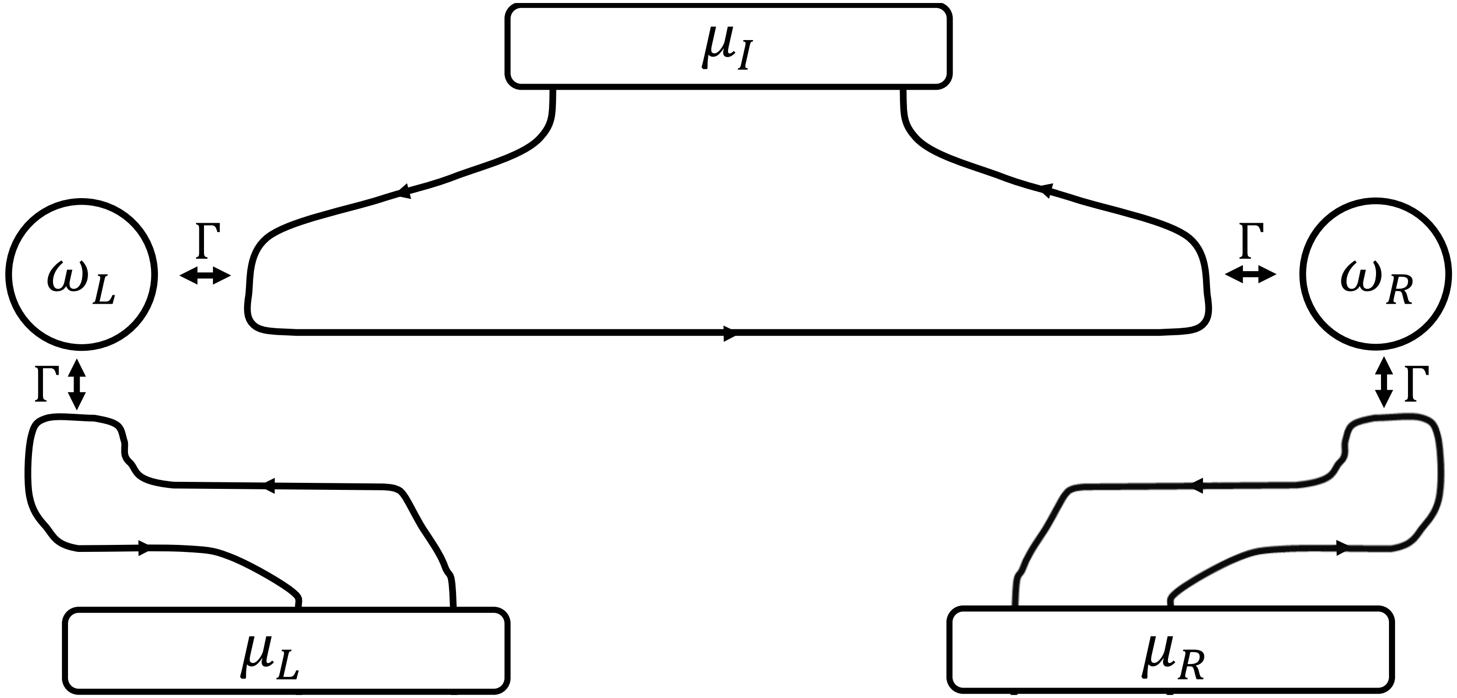
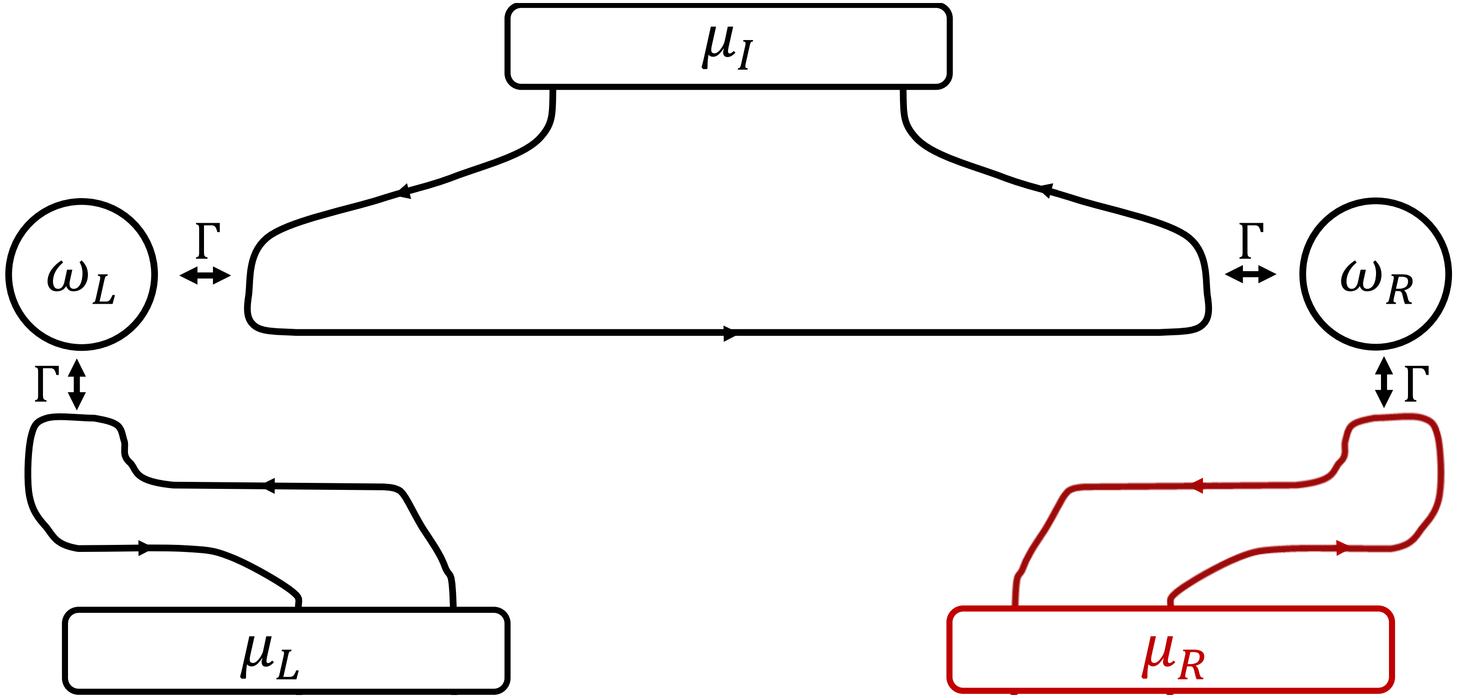
Γ
Γ
Γ
μ_L
μ_R



$$I_R = -\frac{e}{2\pi}\int_{-\infty}^{\infty} d\omega\,\mathrm{tr}\{\overline{g_{D_R}^{a}}t_{D_R L_R}g_{L_R}^{<}t_{L_R D_R}\overline{g_{D_R}^{r}}t_{D_R I}G_{II}^{>}t_{ID_R} - \overline{g_{D_R}^{a}}t_{D_R L_R}g_{L_R}^{>}t_{L_R D_R}\overline{g_{D_R}^{r}}t_{D_R I}G_{II}^{<}t_{ID_R}\}$$

Y. Meir and N. S. Wingreen, Phys. Rev. Lett. **68**, 2512 (1992).



$$I_R = -\frac{e}{2\pi}\int_{-\infty}^{\infty} d\omega\, \mathrm{tr}\{\overline{g_{D_R}^{a}}t_{D_RL_R}g_{L_R}^{<}t_{L_RD_R}\overline{g_{D_R}^{r}}t_{D_RI}G_{II}^{>}t_{ID_R} - \overline{g_{D_R}^{a}}t_{D_RL_R}g_{L_R}^{>}t_{L_RD_R}\overline{g_{D_R}^{r}}t_{D_RI}G_{II}^{<}t_{ID_R}\}$$

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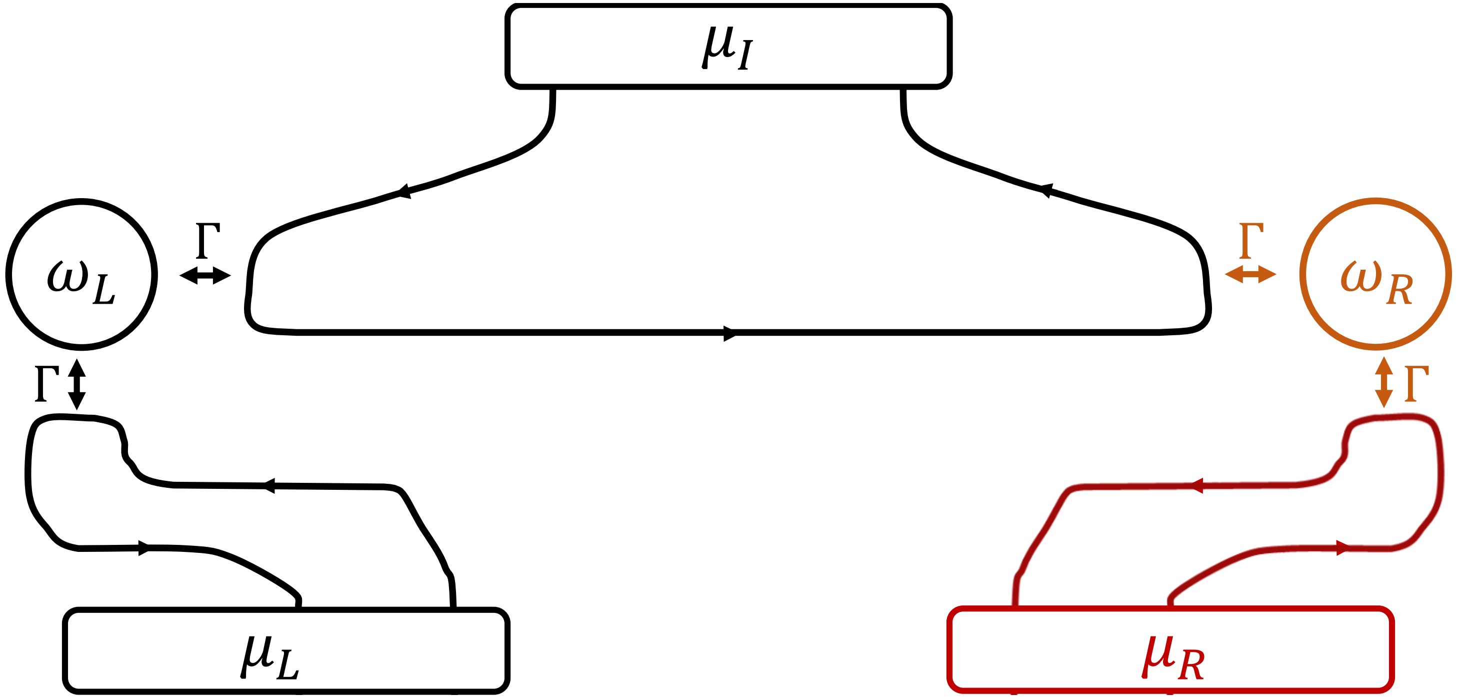

$$I_R = -\frac{e}{2\pi}\int_{-\infty}^{\infty} d\omega\, \mathrm{tr}\{\overline{g_{D_R}^{a}} t_{D_R L_R} g_{L_R}^{<} t_{L_R D_R} \overline{g_{D_R}^{r}} t_{D_R I} G_{II}^{>} t_{I D_R} - \overline{g_{D_R}^{a}} t_{D_R L_R} g_{L_R}^{>} t_{L_R D_R} \overline{g_{D_R}^{r}} t_{D_R I} G_{II}^{<} t_{I D_R}\}$$

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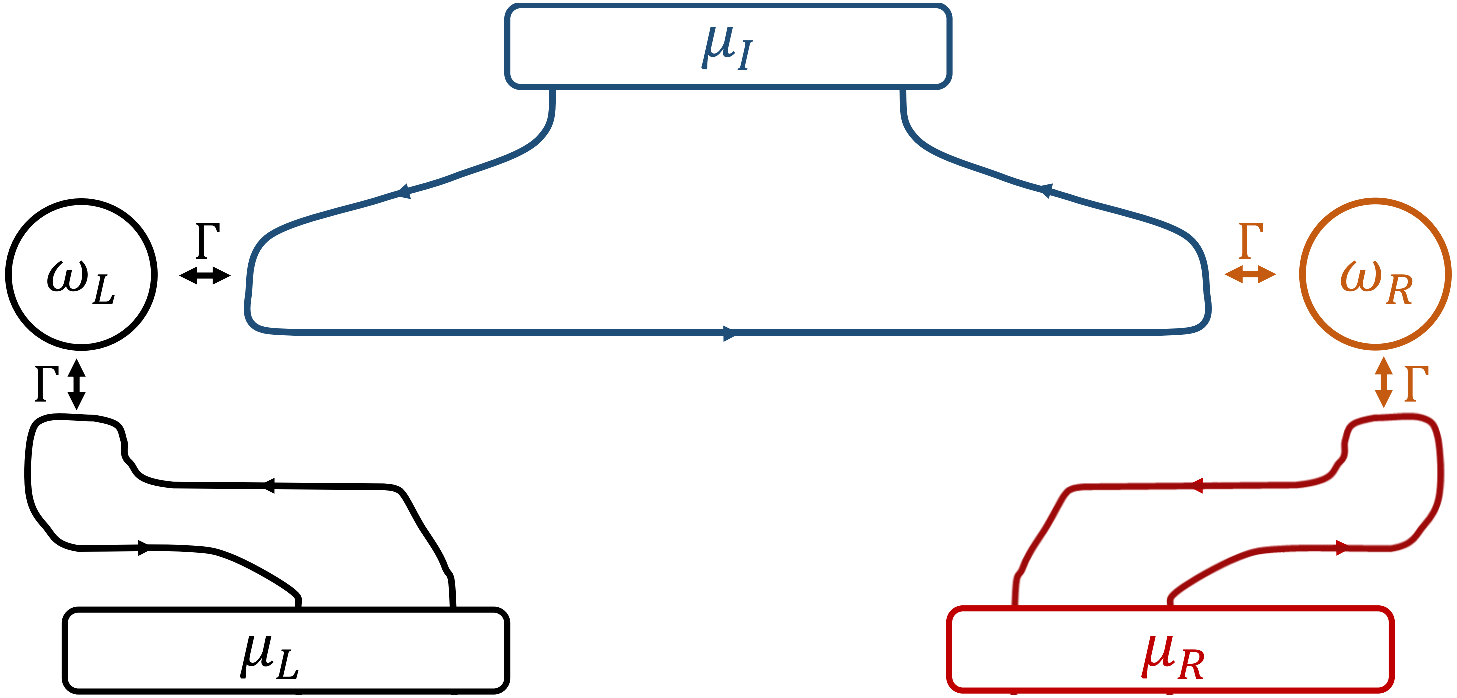

$$I_R = -\frac{e}{2\pi}\int_{-\infty}^{\infty} d\omega\, \mathrm{tr}\{\overline{g^a_{D_R}}\, t_{D_R L_R}\, g^<_{L_R}\, t_{L_R D_R}\, \overline{g^r_{D_R}}\, t_{D_R I}\, G^>_{II}\, t_{I D_R} - \overline{g^a_{D_R}}\, t_{D_R L_R}\, g^>_{L_R}\, t_{L_R D_R}\, \overline{g^r_{D_R}}\, t_{D_R I}\, G^<_{II}\, t_{I D_R}\}$$

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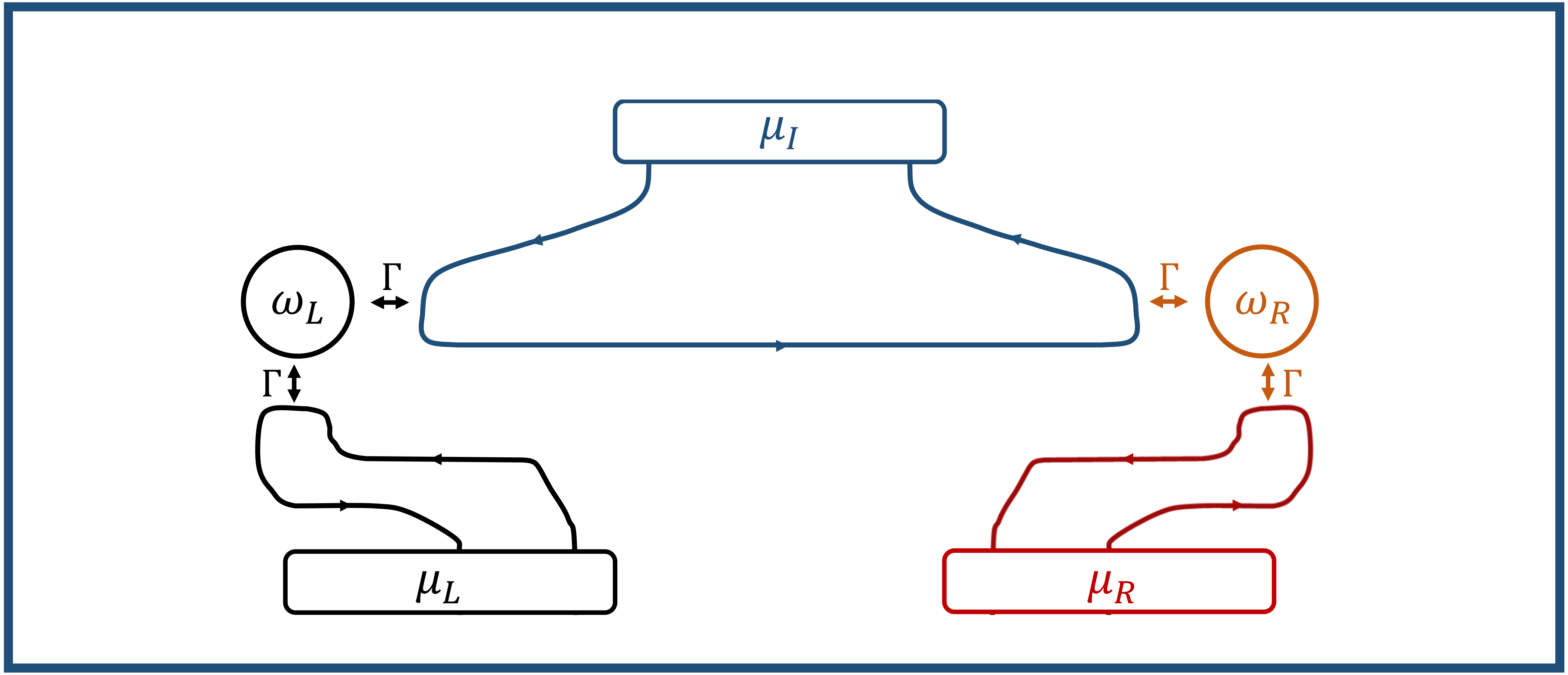
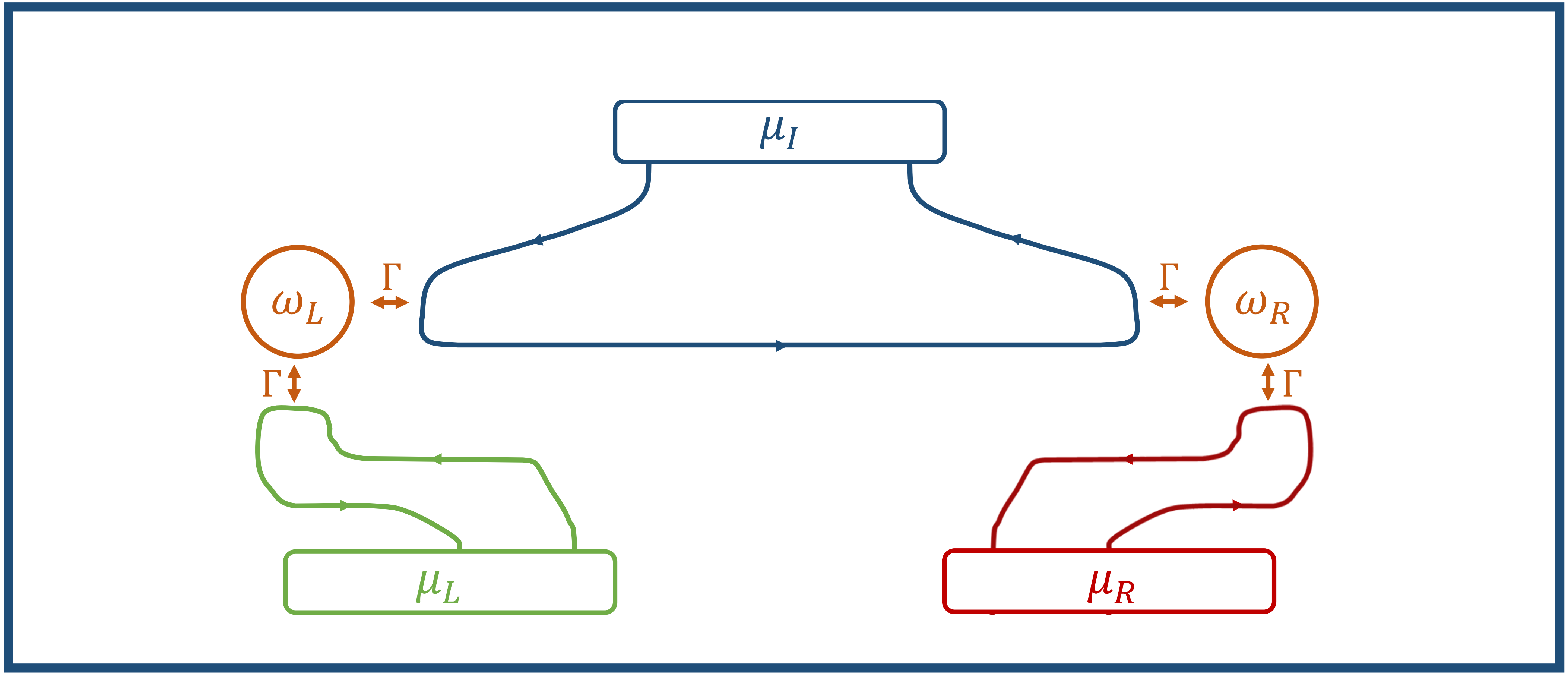


$$I_R = -\frac{e}{2\pi}\int_{-\infty}^{\infty} d\omega\, \mathrm{tr}\{\overline{g^a_{D_R}} t_{D_R L_R} g^<_{L_R} t_{L_R D_R} \overline{g^r_{D_R}} t_{D_R I} G^>_{II} t_{I D_R} - \overline{g^a_{D_R}} t_{D_R L_R} g^>_{L_R} t_{L_R D_R} \overline{g^r_{D_R}} t_{D_R I} G^<_{II} t_{I D_R}\}$$

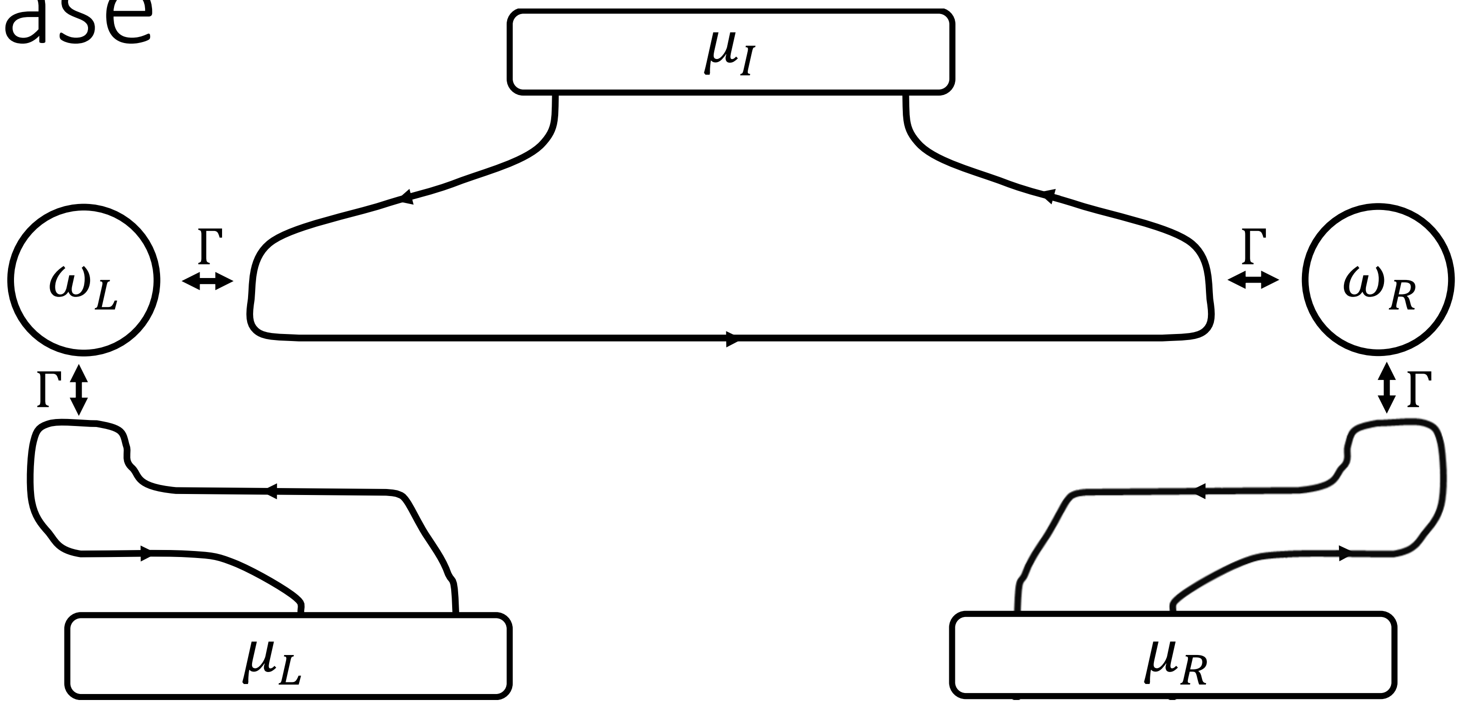
Y. Meir and N. S. Wingreen, Phys. Rev. Lett. **68**, 2512 (1992).



$$I_R = -\frac{e}{2\pi}\int_{-\infty}^{\infty} d\omega\, \mathrm{tr}\{\overline{g_{D_R}^{a}} t_{D_R L_R} g_{L_R}^{<} t_{L_R D_R} \overline{g_{D_R}^{r}} t_{D_R I} G_{II}^{>} t_{I D_R} - \overline{g_{D_R}^{a}} t_{D_R L_R} g_{L_R}^{>} t_{L_R D_R} \overline{g_{D_R}^{r}} t_{D_R I} G_{II}^{<} t_{I D_R}\}$$

Y. Meir and N. S. Wingreen, Phys. Rev. Lett. **68**, 2512 (1992).

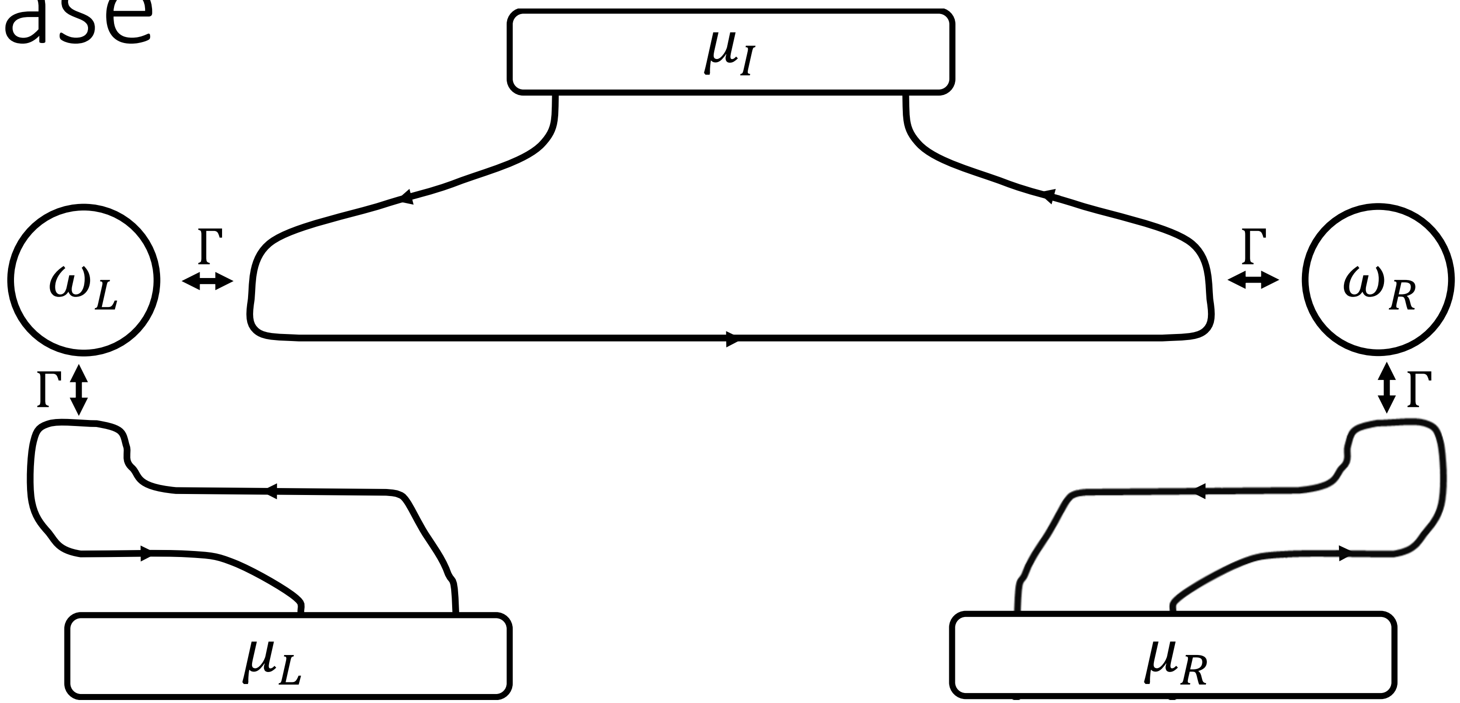
Non-interacting case



- Landauer-Büttiker result:

$$I_R = \int_{-\infty}^{\infty} d\omega[f_L(\omega) - f_R(\omega)]T_L(\omega)T_R(\omega) + \int_{-\infty}^{\infty} d\omega[f_I(\omega) - f_R(\omega)]R_L(\omega)T_R(\omega)$$

Non-interacting case



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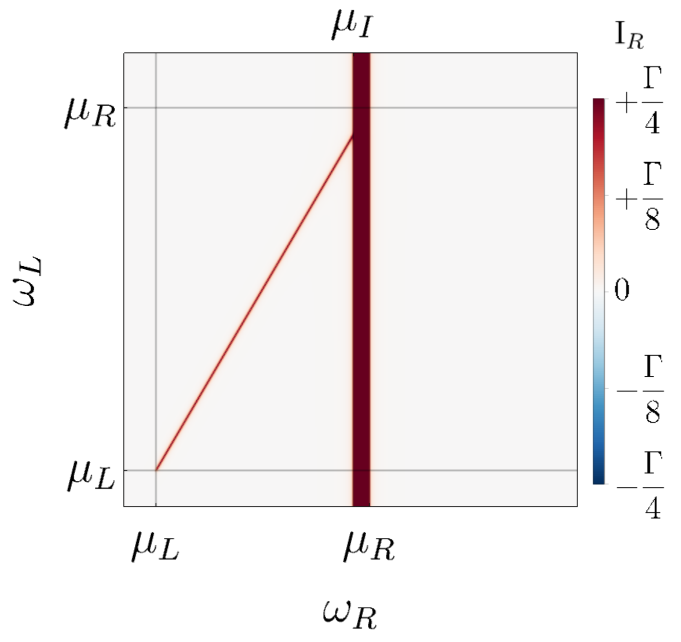
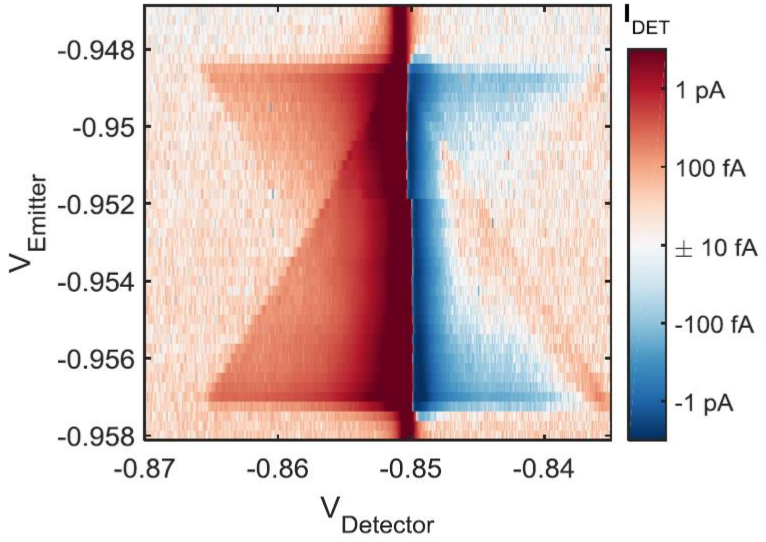
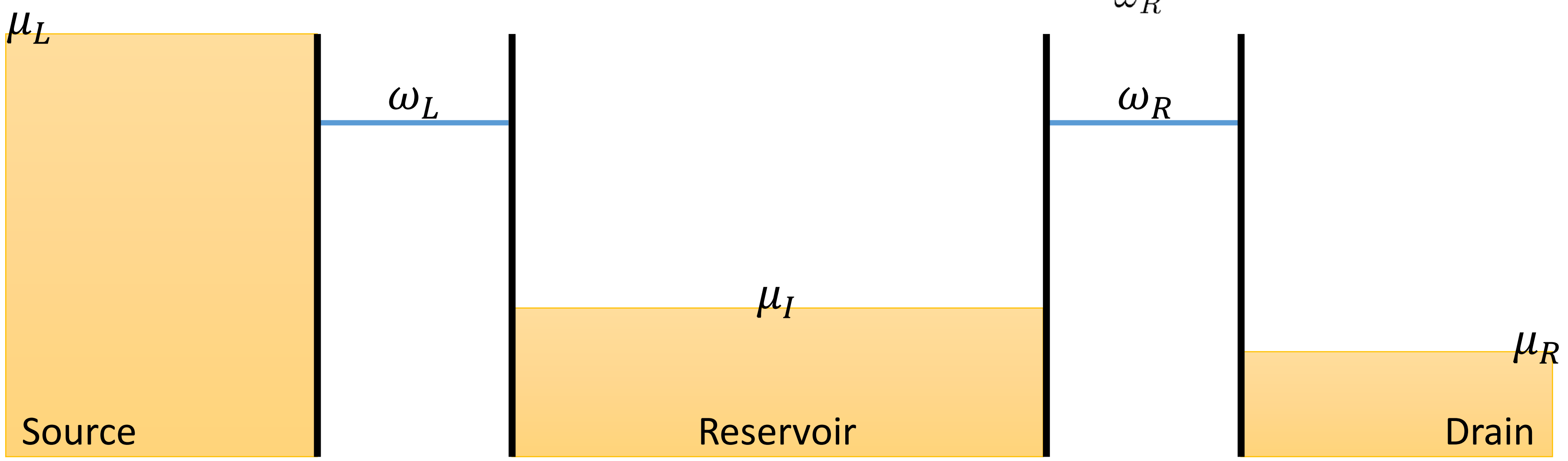
$$T_{L/R}(\omega) = \frac{\Gamma^2}{(\omega - \omega_{L/R})^2 + \Gamma^2} \qquad R_{L/R} = 1 - T_{L/R}$$

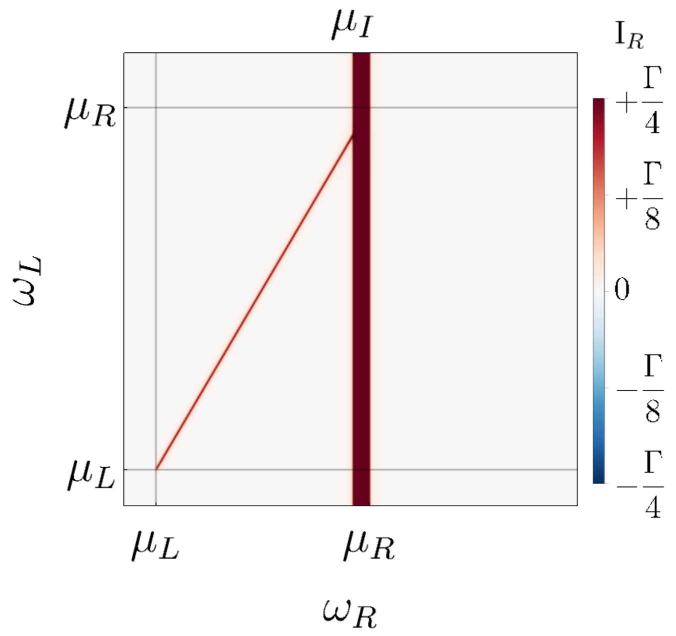
Non-interacting case

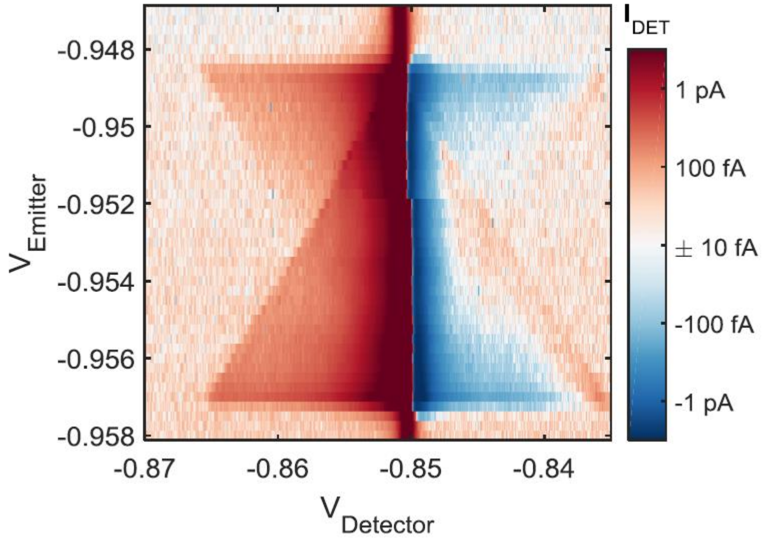


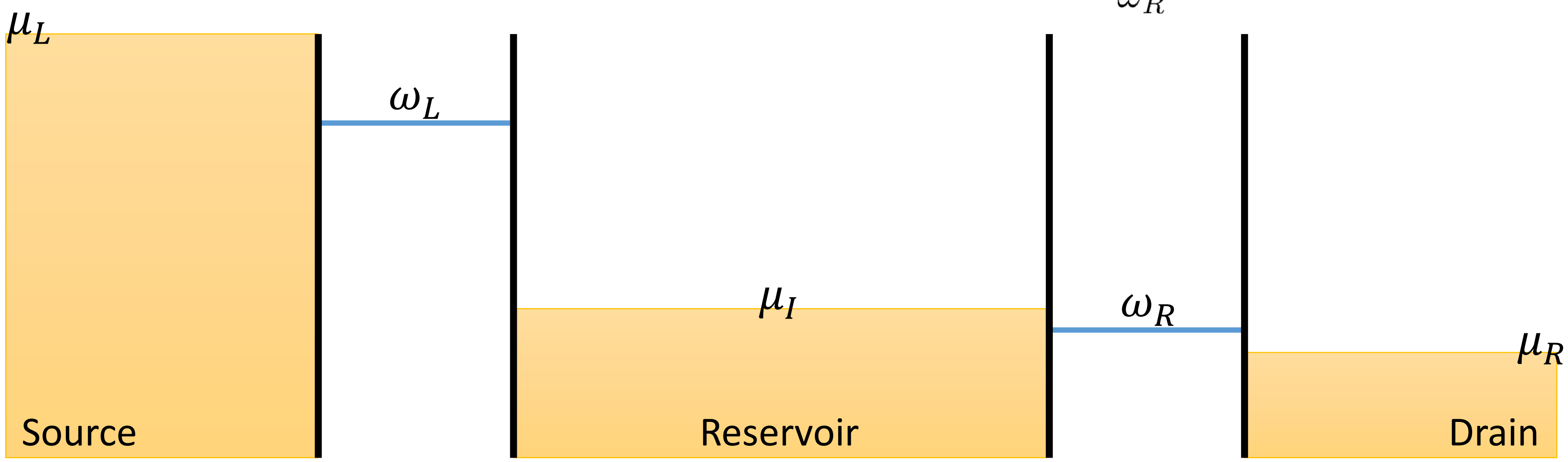




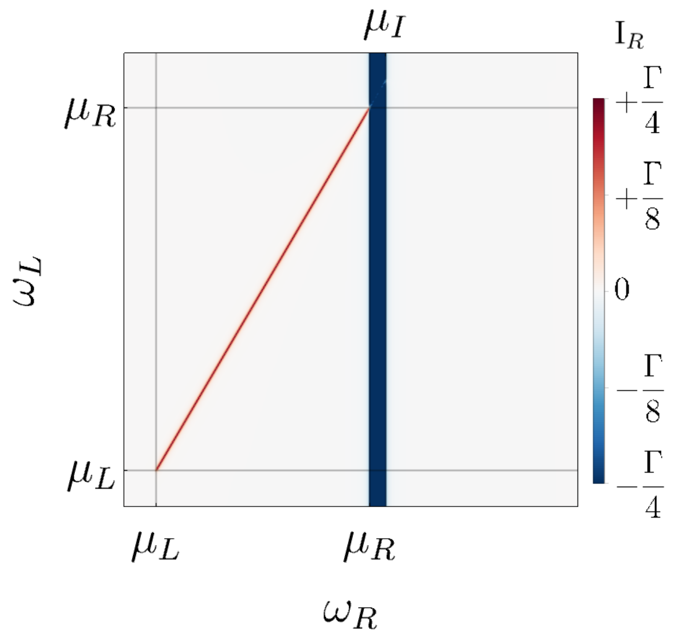
Non-interacting case

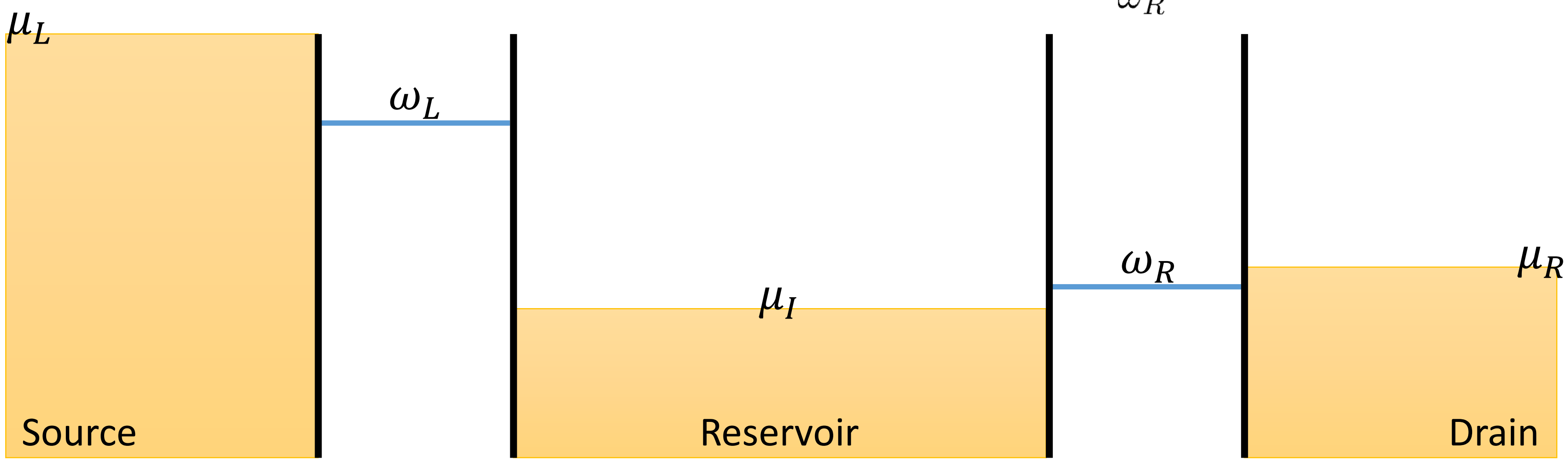




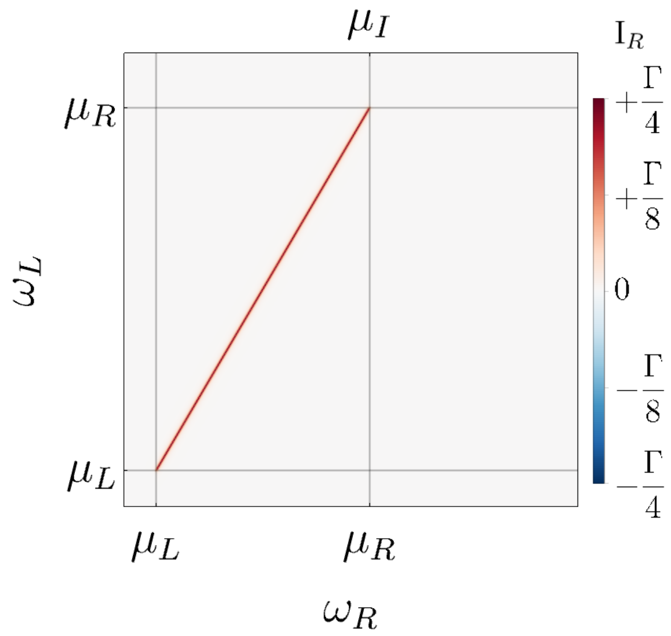


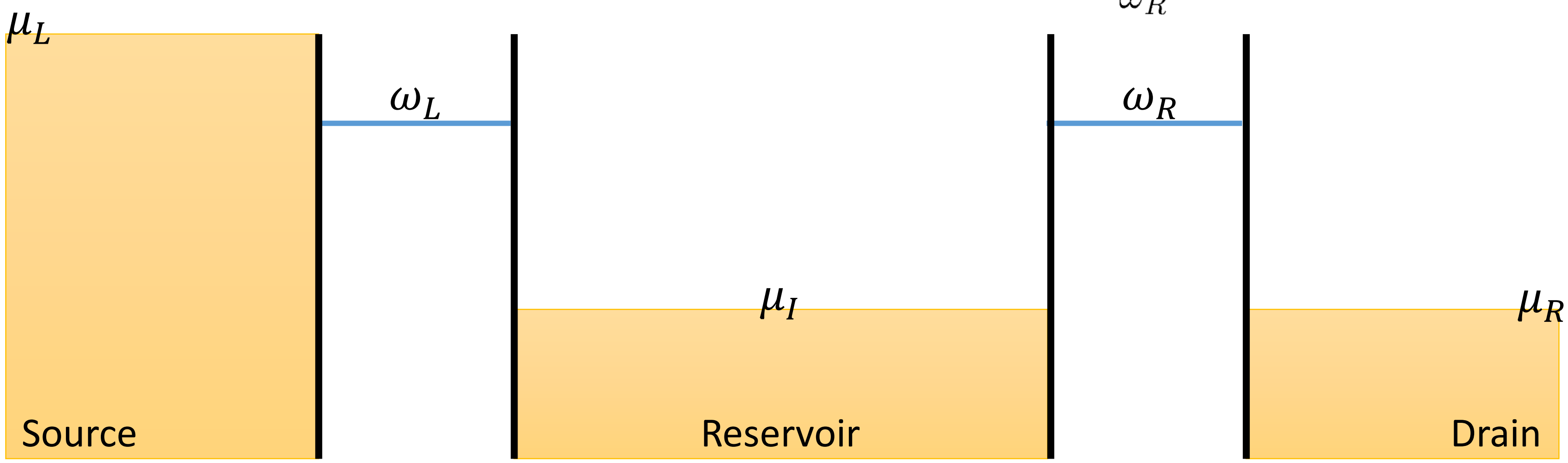
Non-interacting case



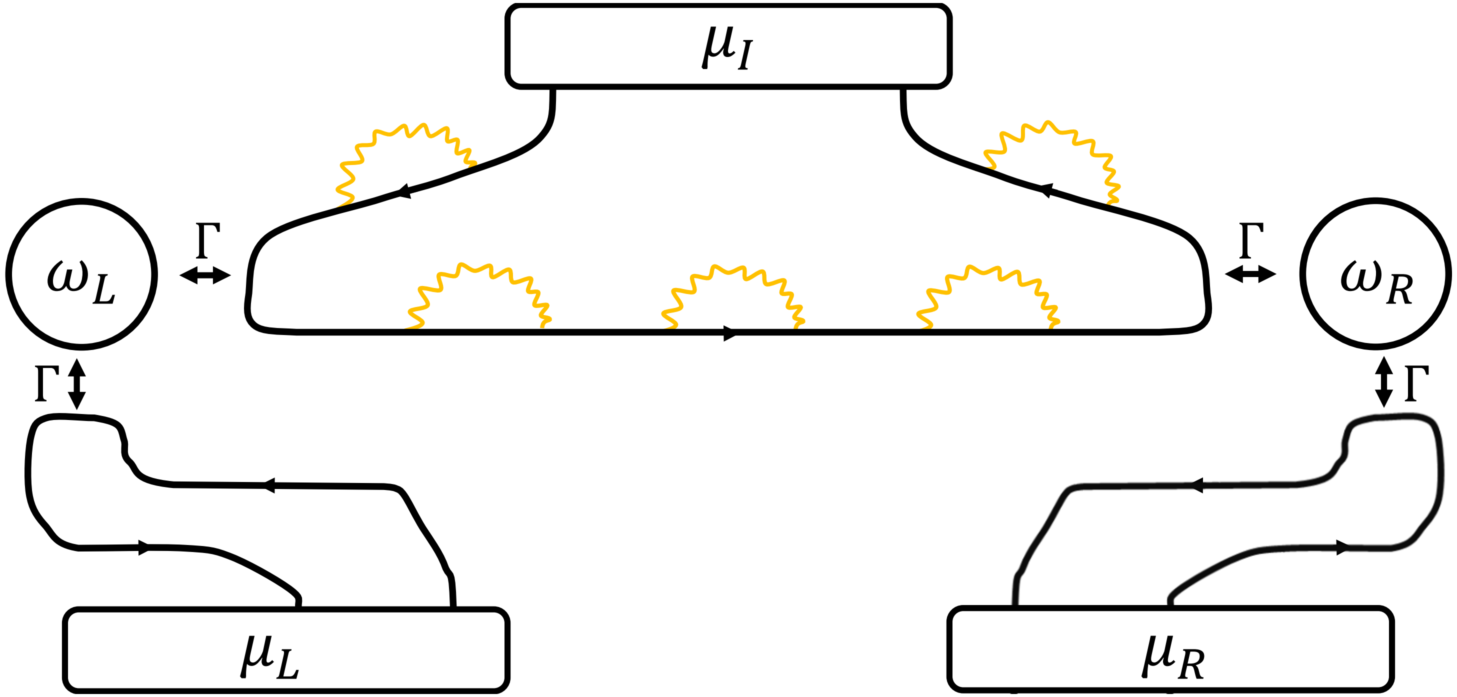


Non-interacting case





Interactions in the reservoir region



- 2nd order diagrams
- One transmission event per quantum dot (neglecting reflections)
- Finite-ranged model interaction

Decay of elastic current

$$I_{El} = I_0 \cdot (1 - \left[\frac{E \cdot x}{v}\right]^2 + \cdots)$$

Decay of elastic current

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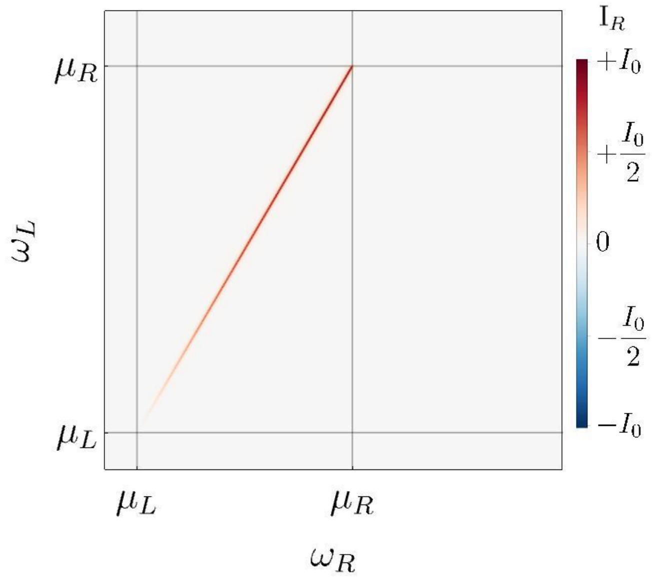

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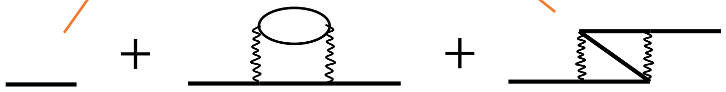

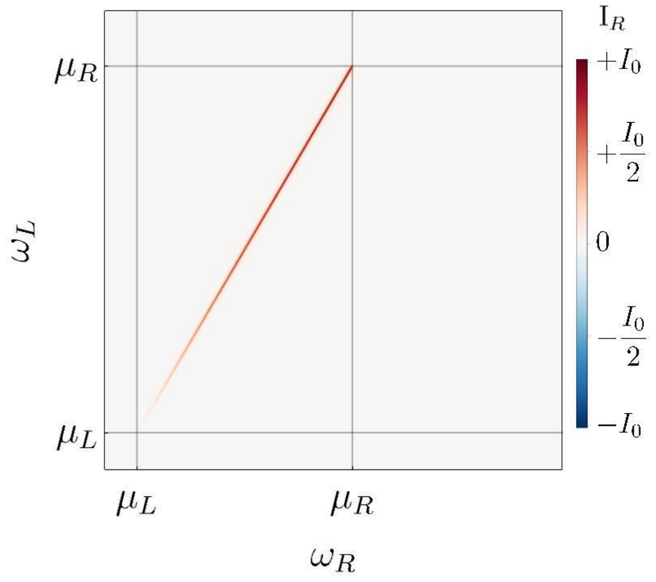

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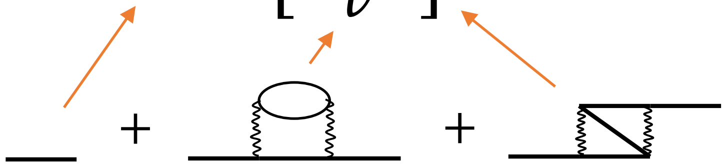
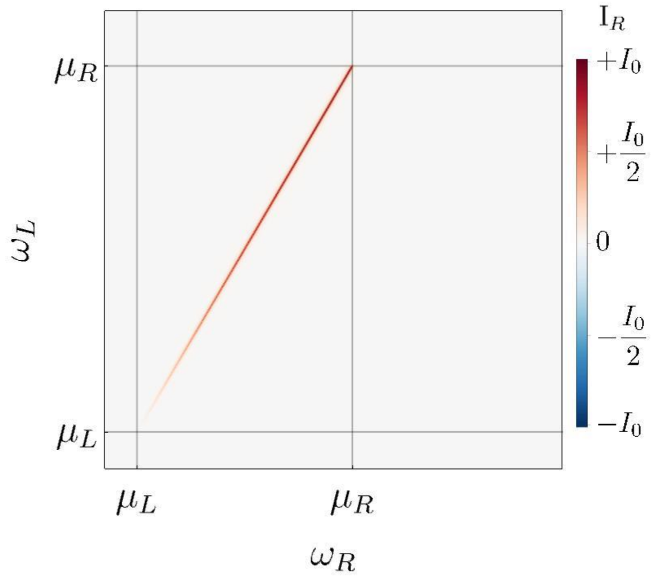
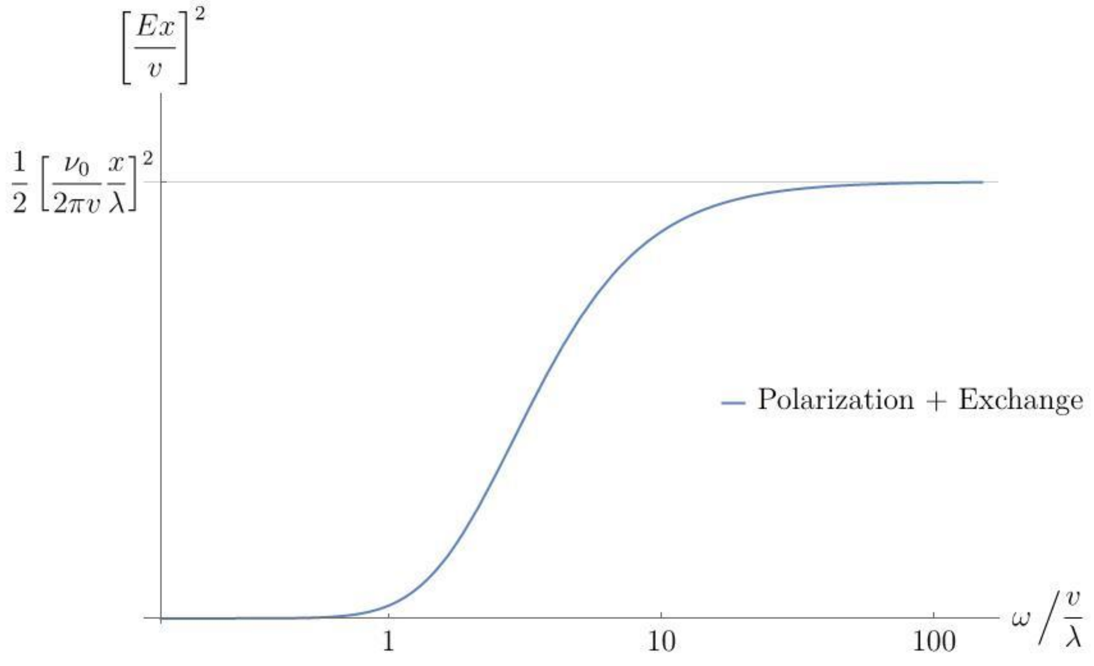
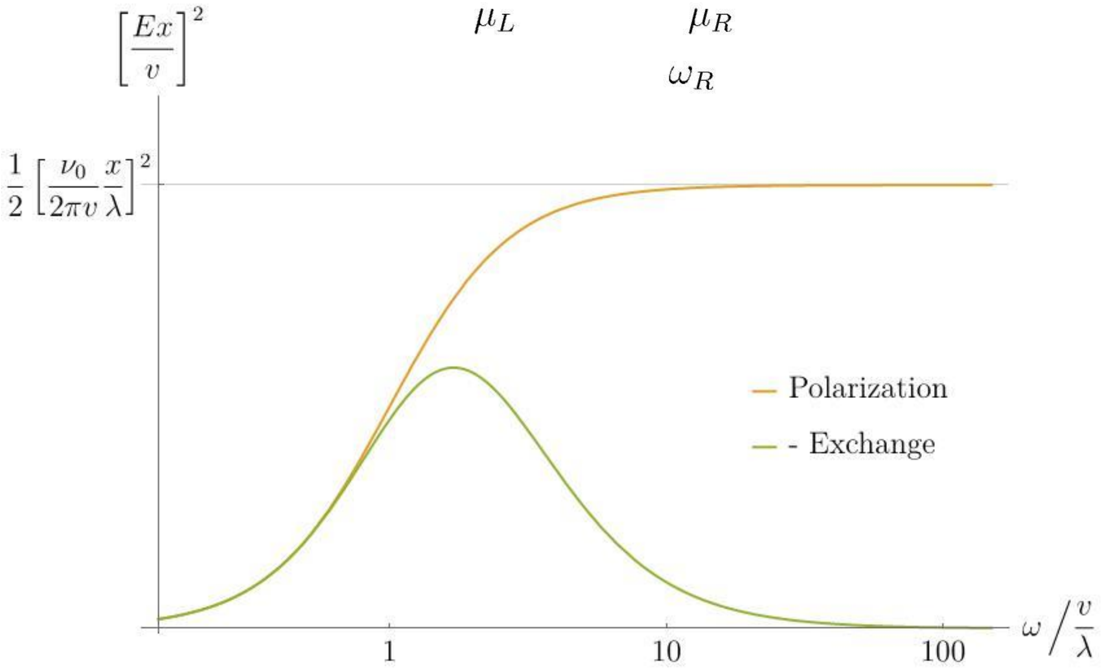




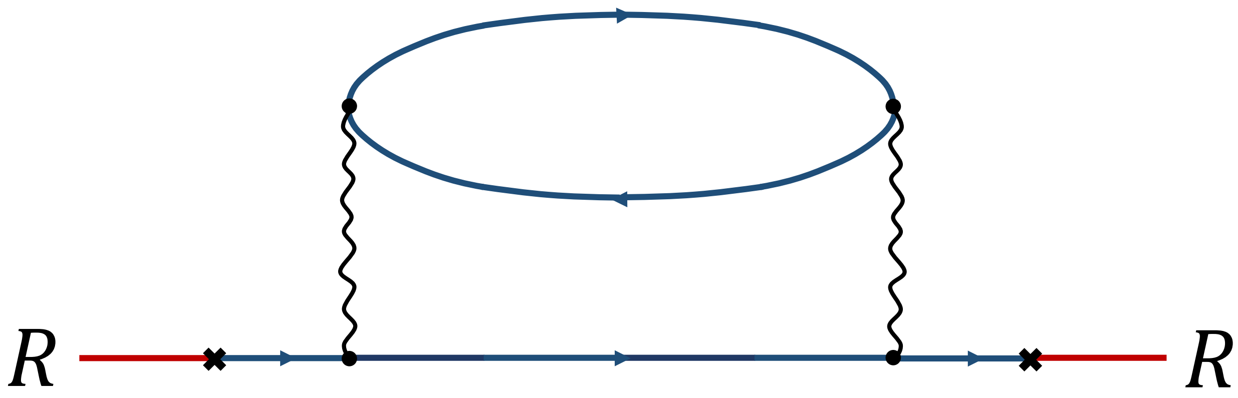


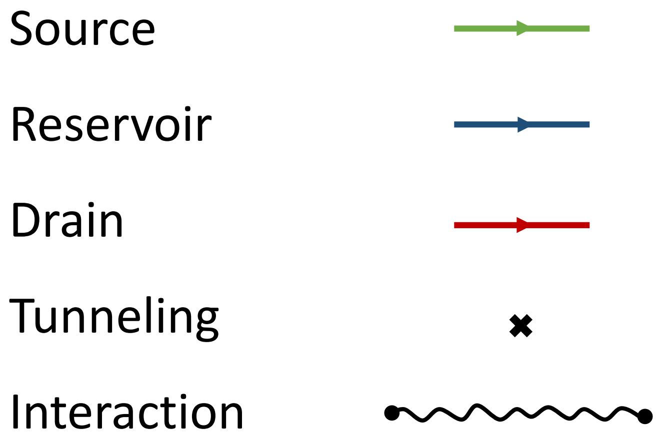


C. Neuenhahn and F. Marquardt, NJP **10**, 115018 (2008).

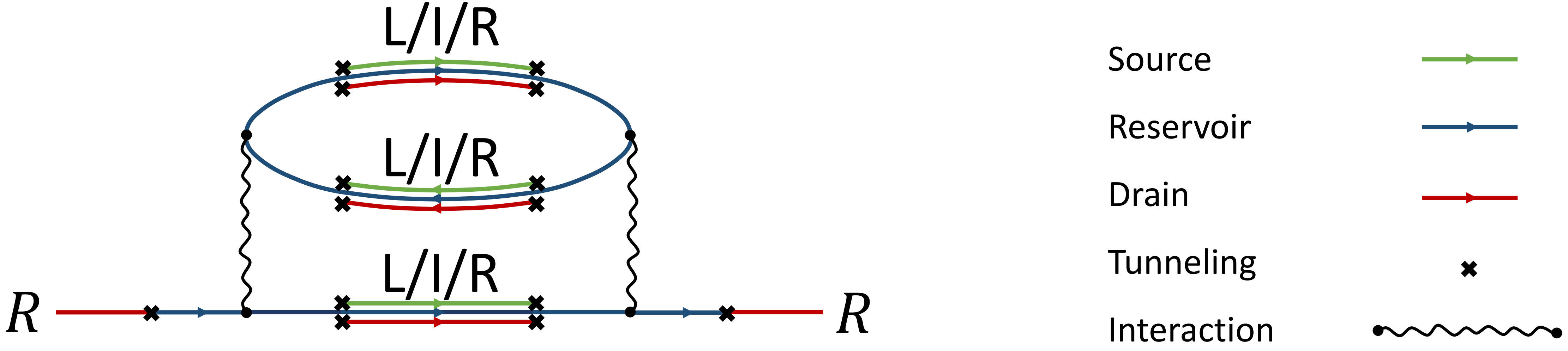
Inelastic current

Dressing interaction diagrams with tunneling

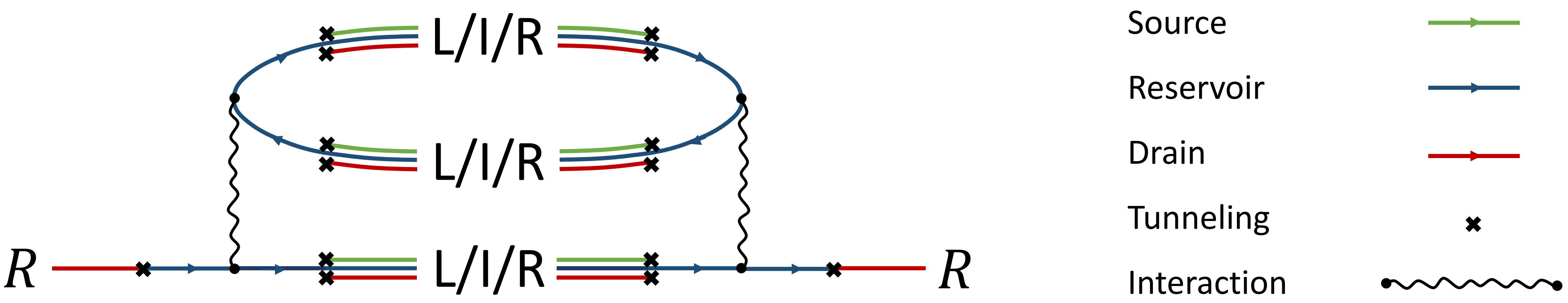




Dressing interaction diagrams with tunneling

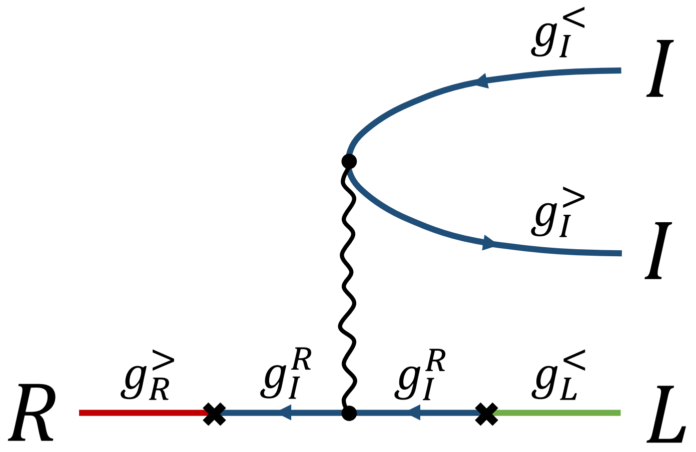


Dressing interaction diagrams with tunneling

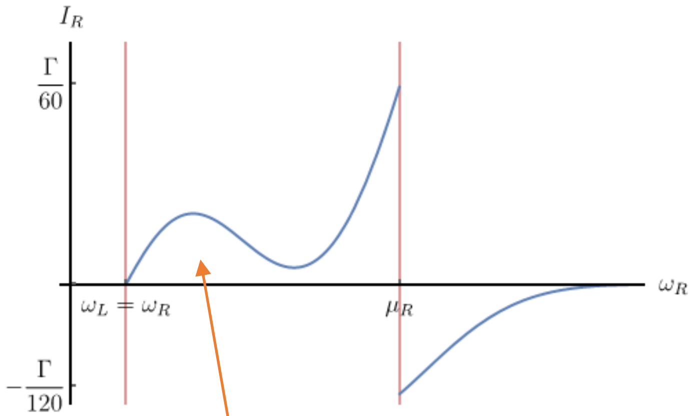


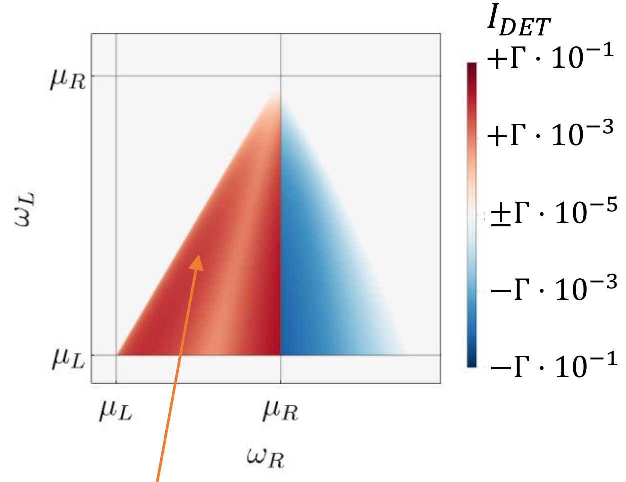
- 27 distinct relaxation processes
- For one transfer event per quantum dot, 3 processes contribute to triangles

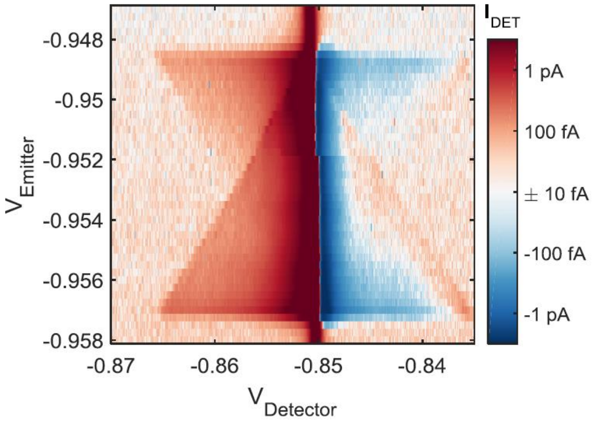
Keldysh component of Green’s functions

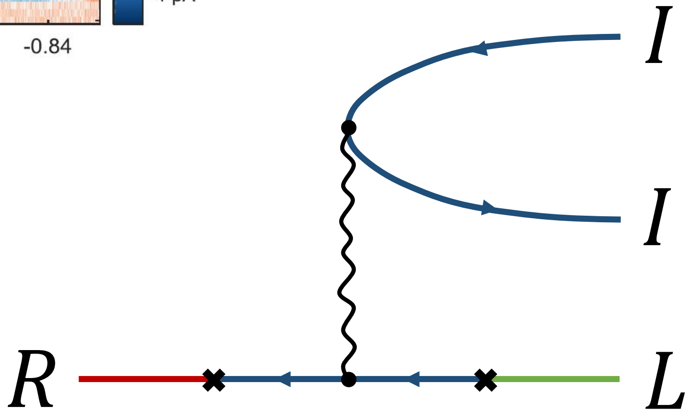


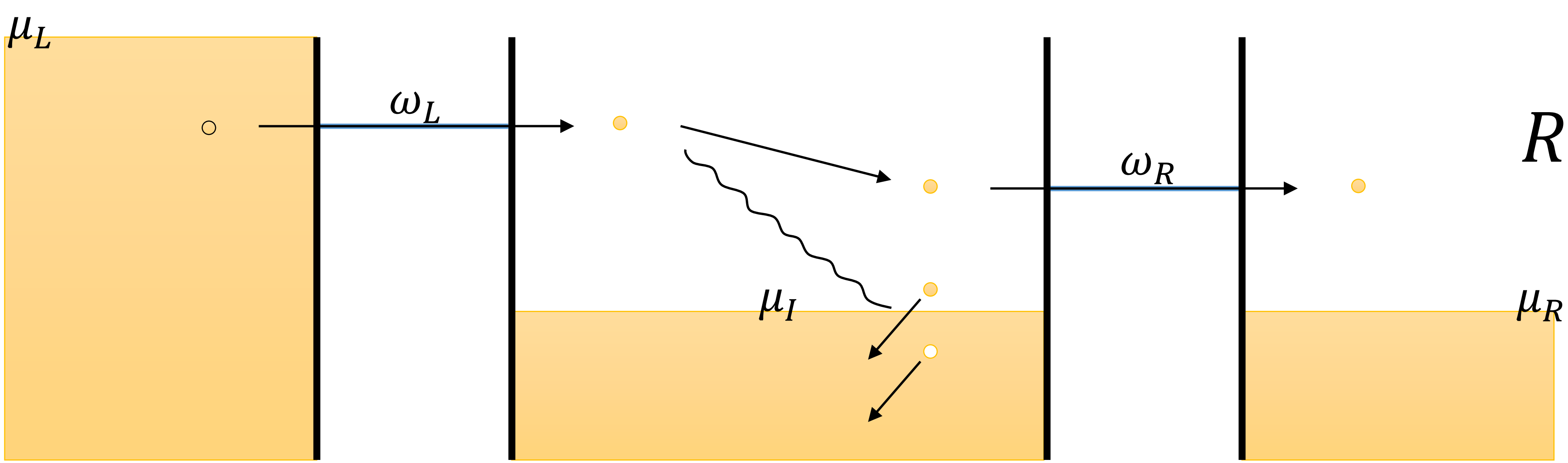
Direct electron current



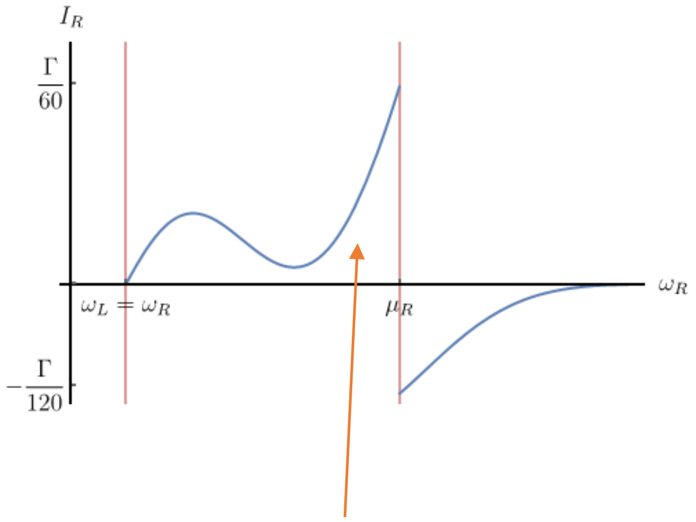


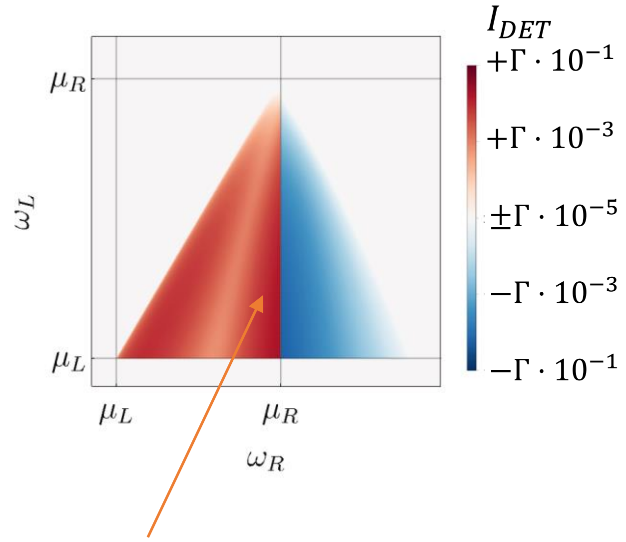


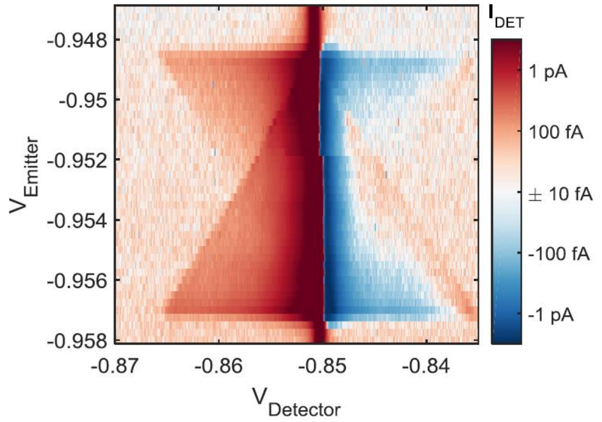


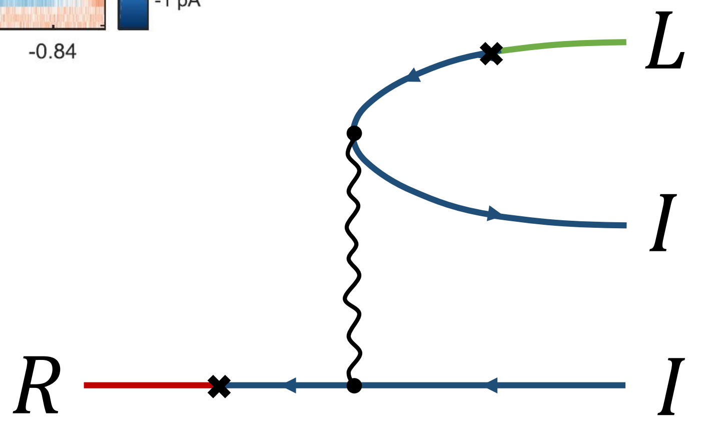


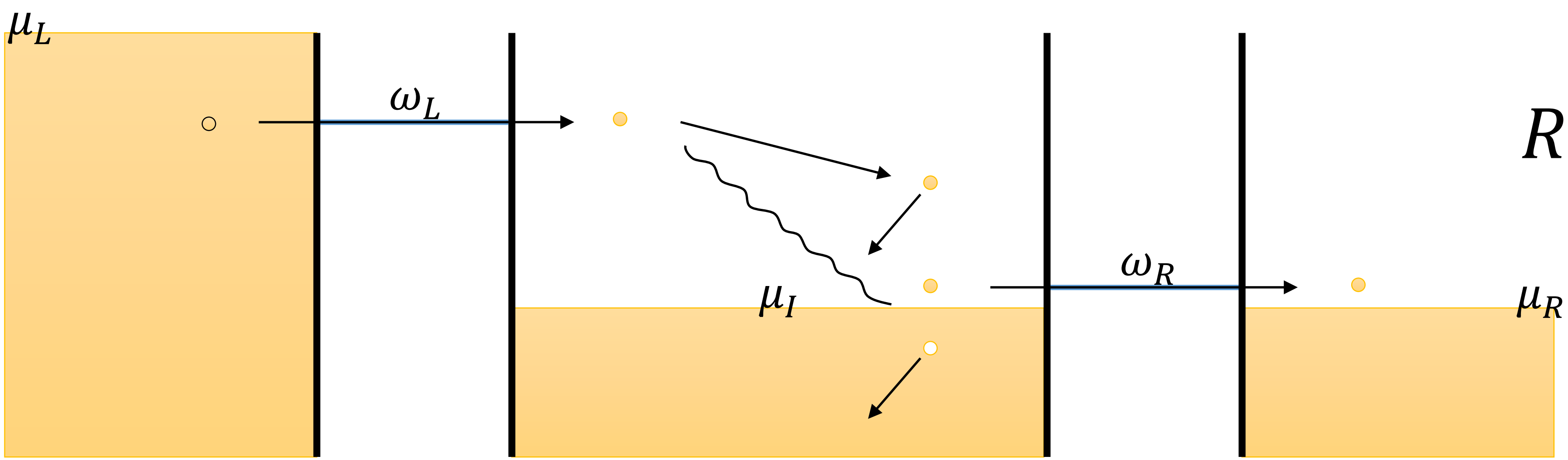
Electron swap current





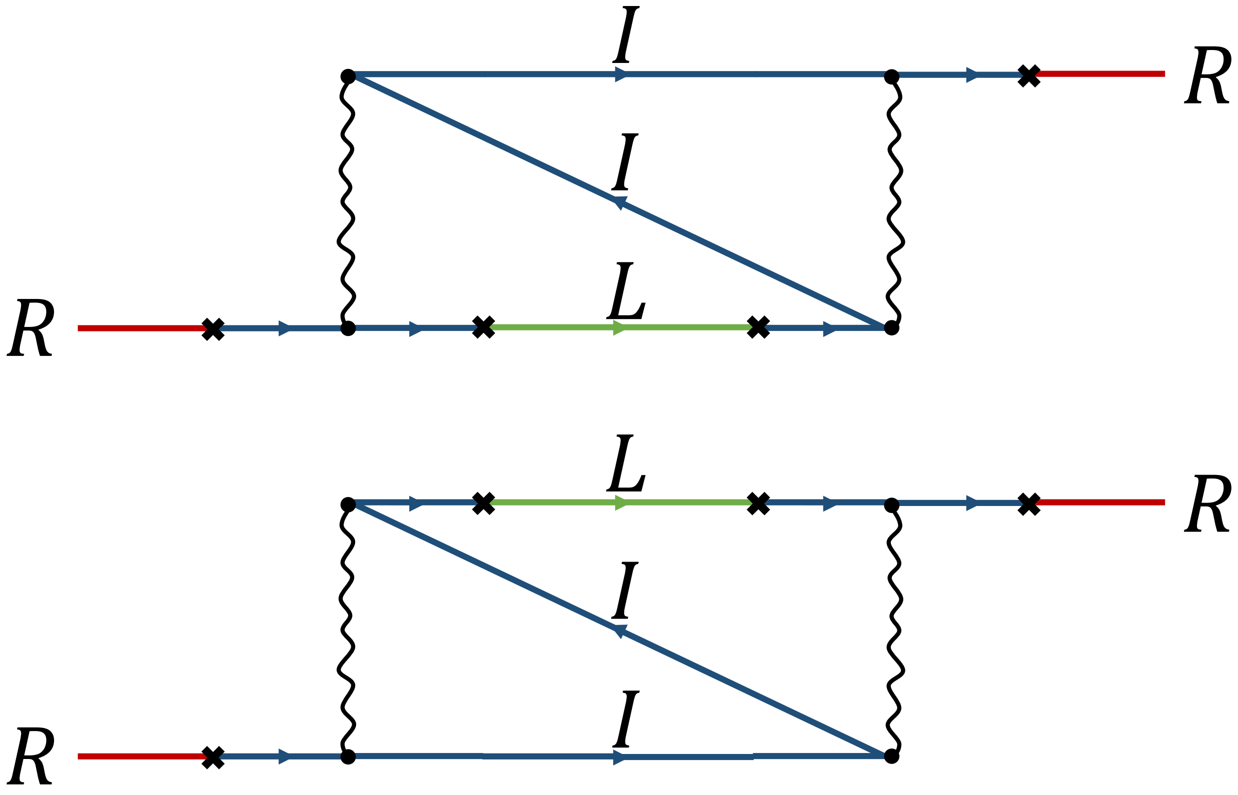




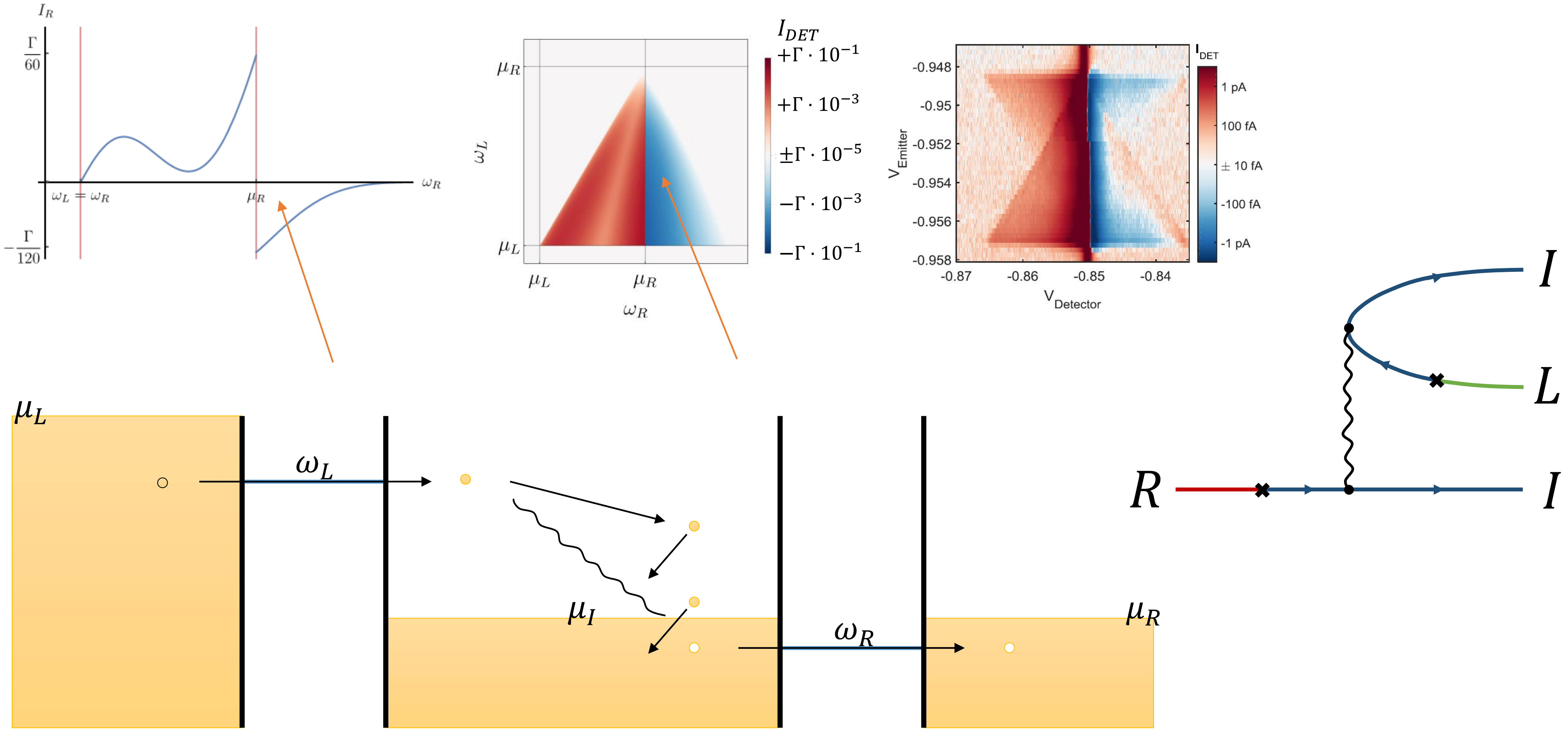


Exchange diagrams

- Interference between direct and swap process:

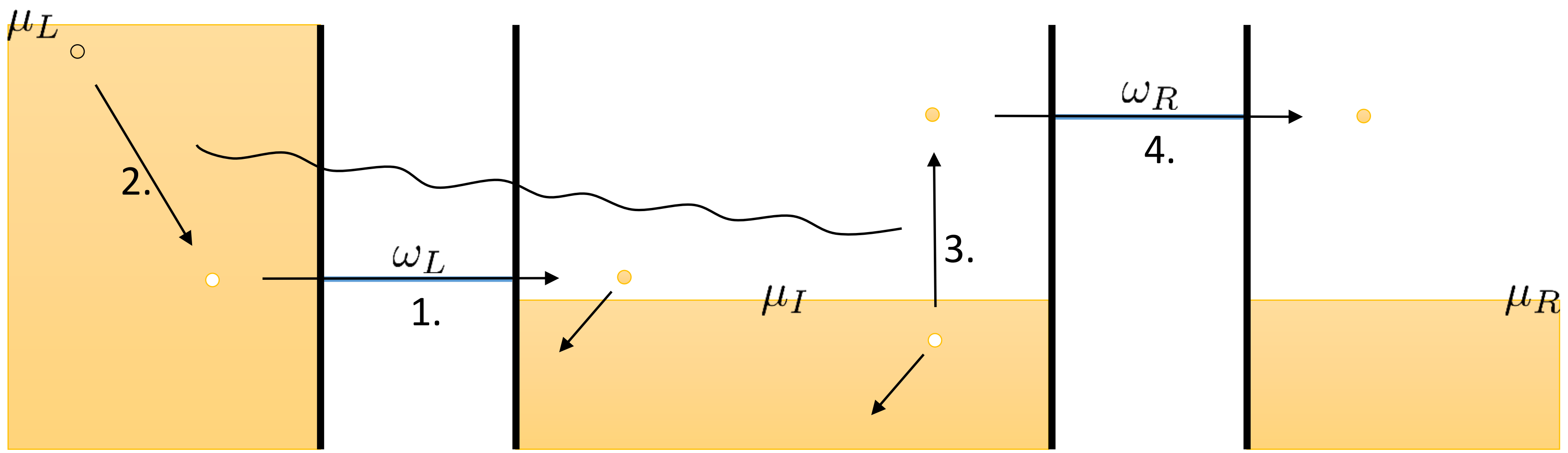


Hole current



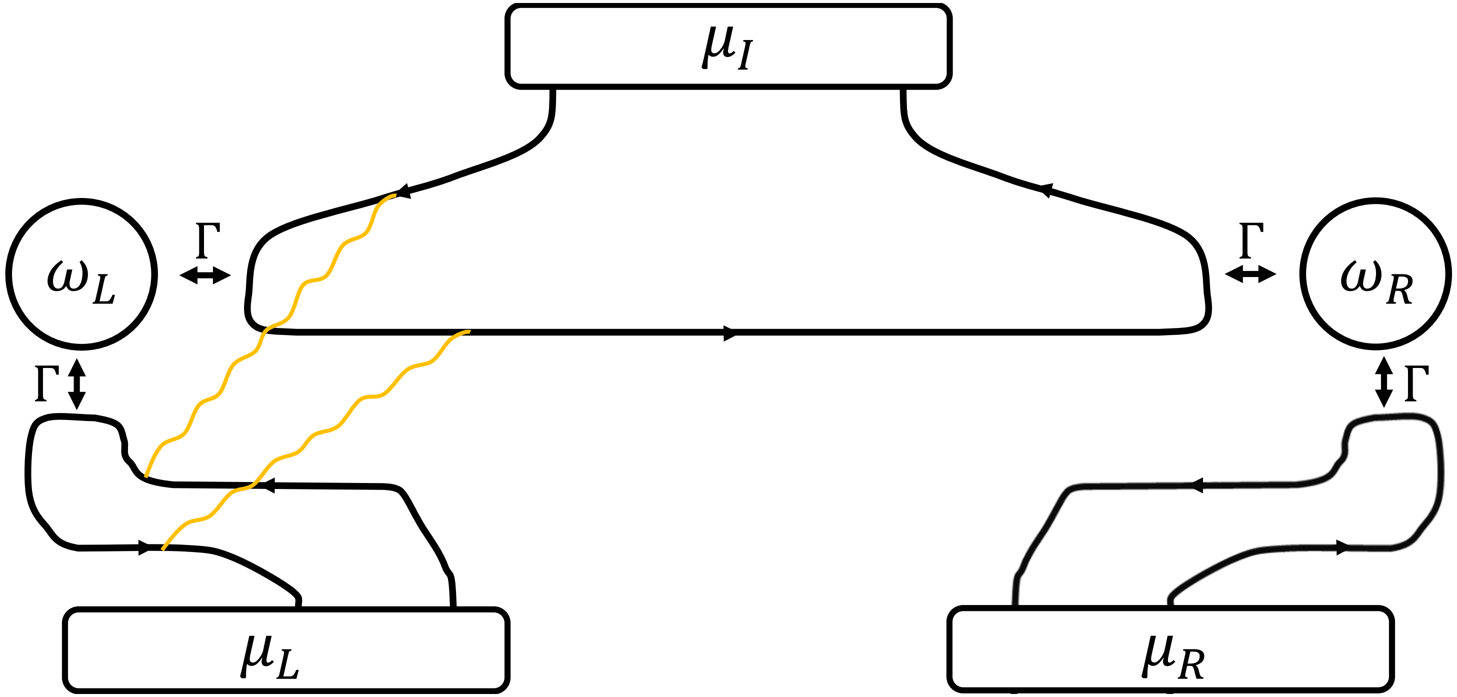
Inverted triangles

- Auger-like process?



adapted from T. Krähenmann, M. Röösli, T. Ihn, K. Ensslin, private communication

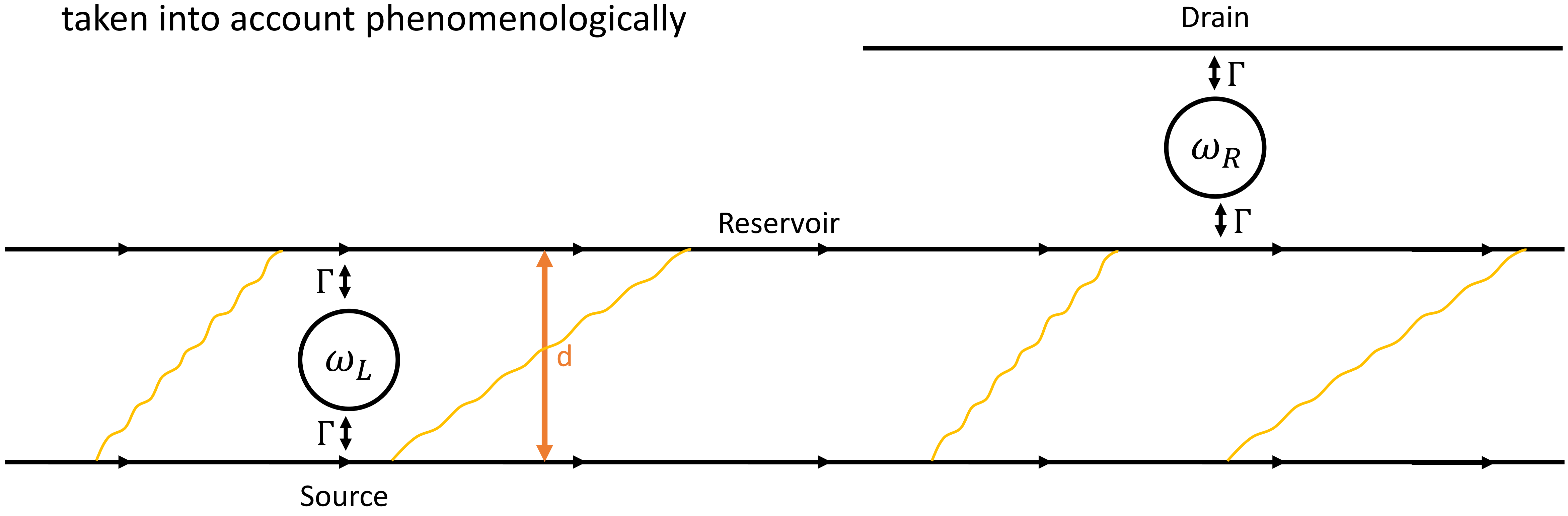
Interactions between reservoir and source



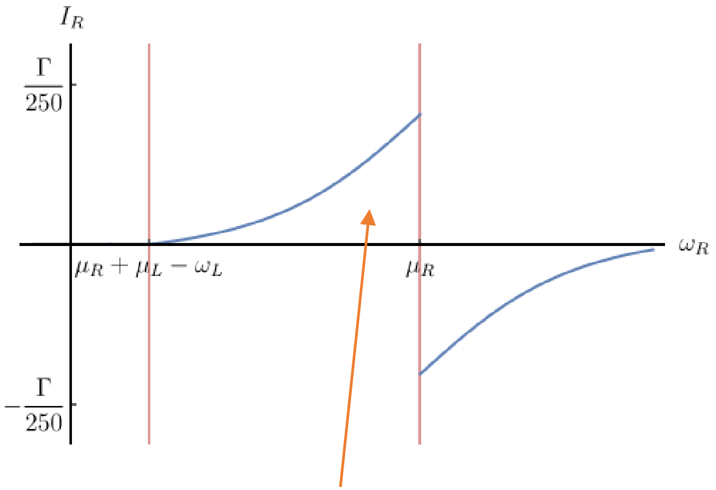
Interactions between reservoir and source

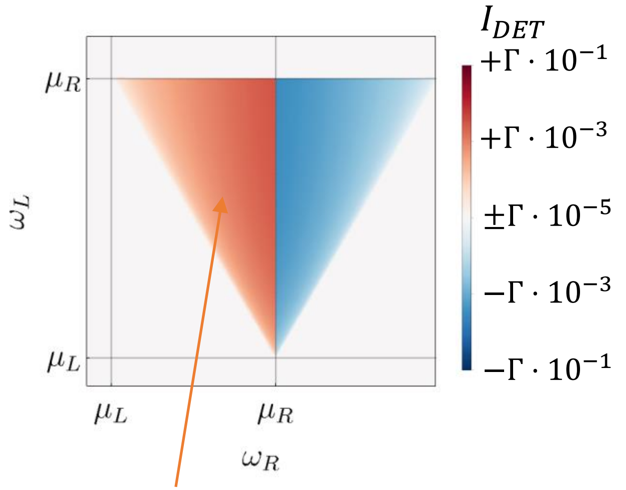
- Simplified model: parallel channels
- additional distance d for interactions,

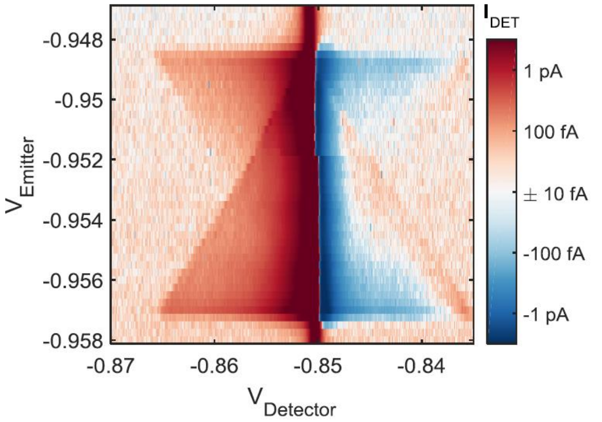
taken into account phenomenologically

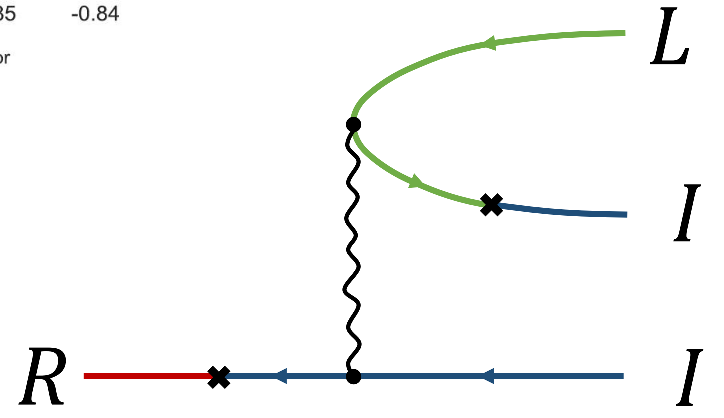


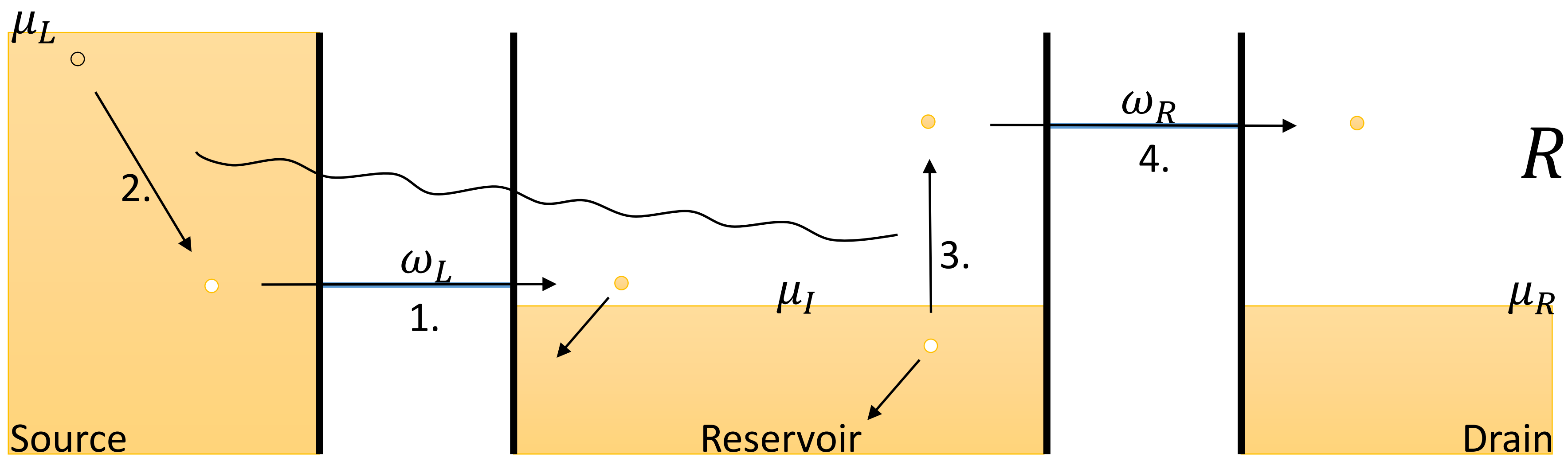
Inverted triangle electron current



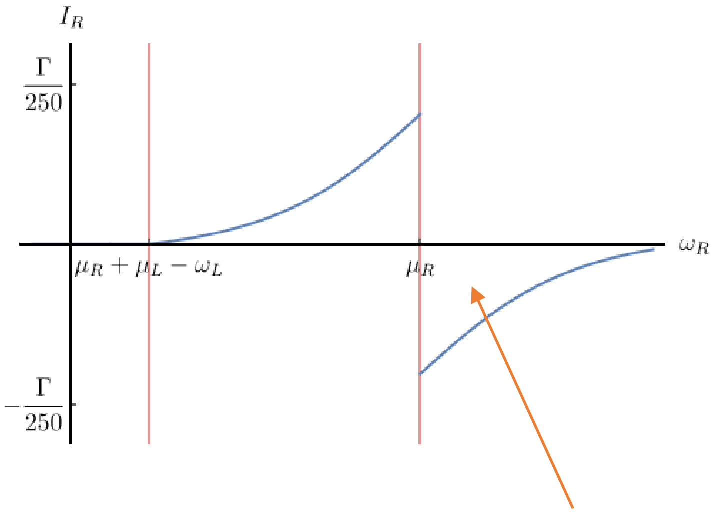


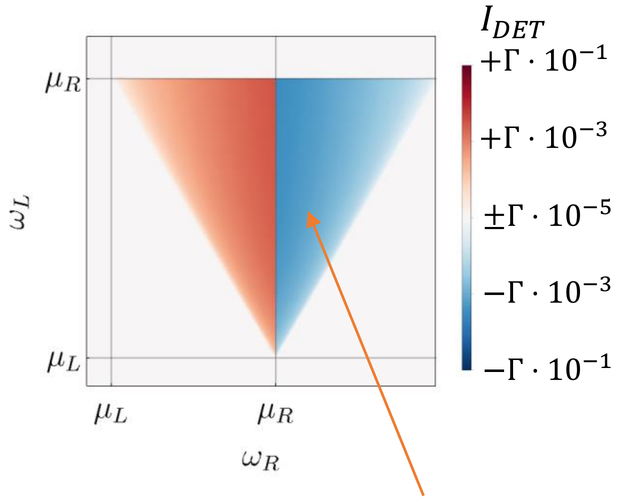


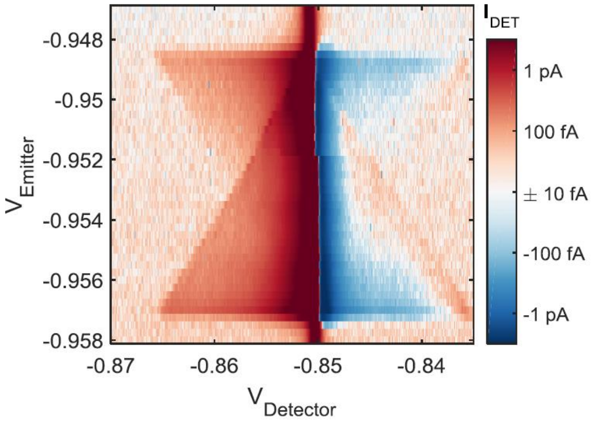


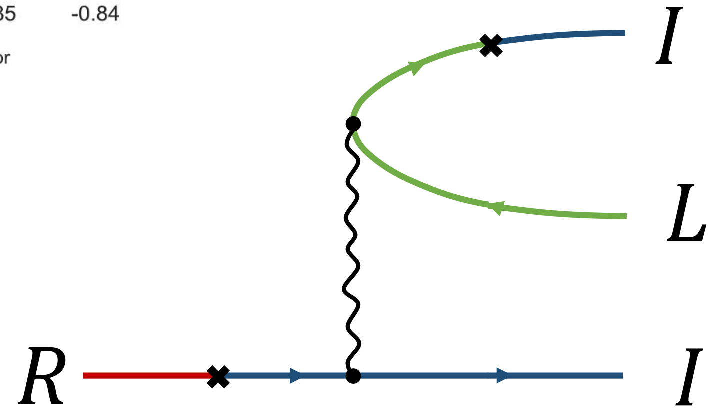


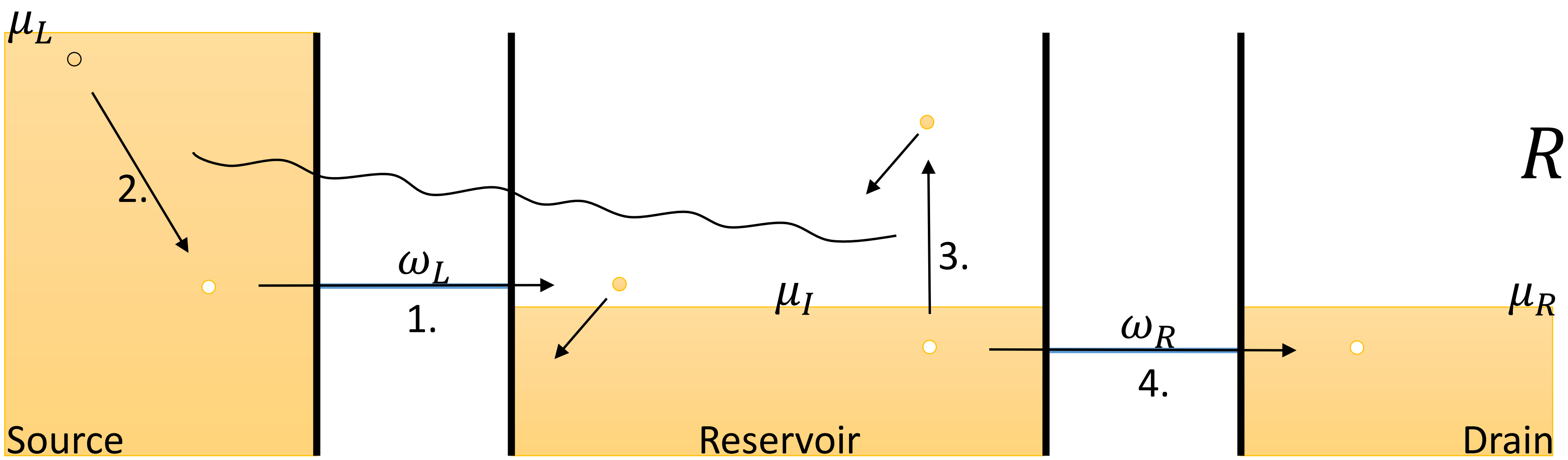
Inverted triangle hole current



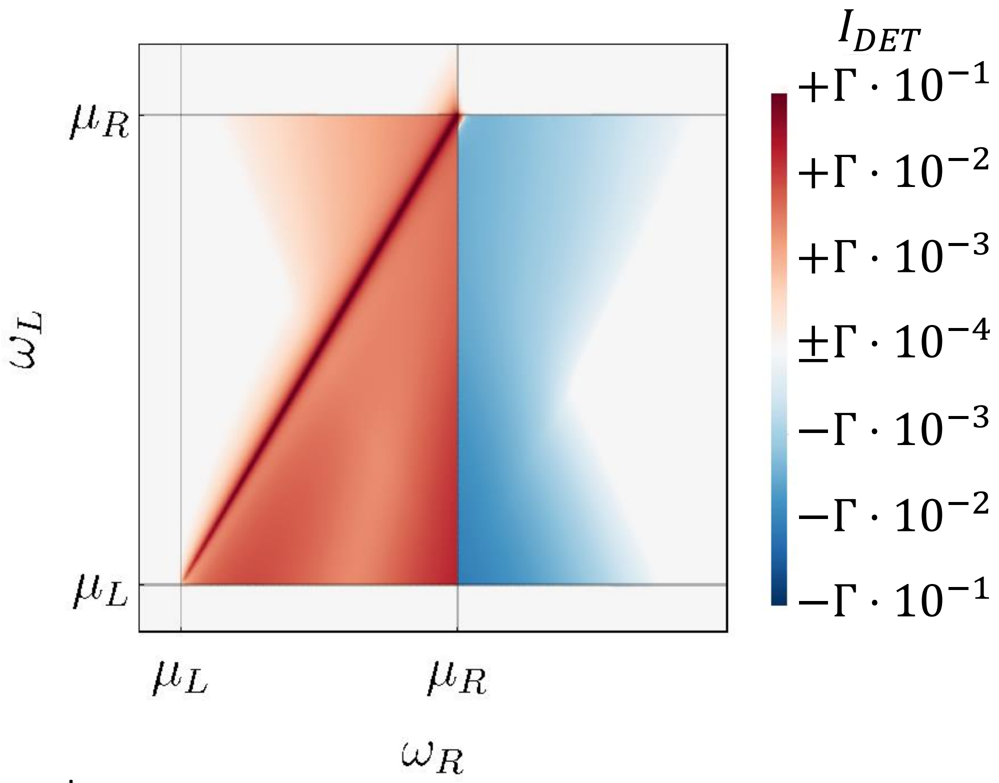


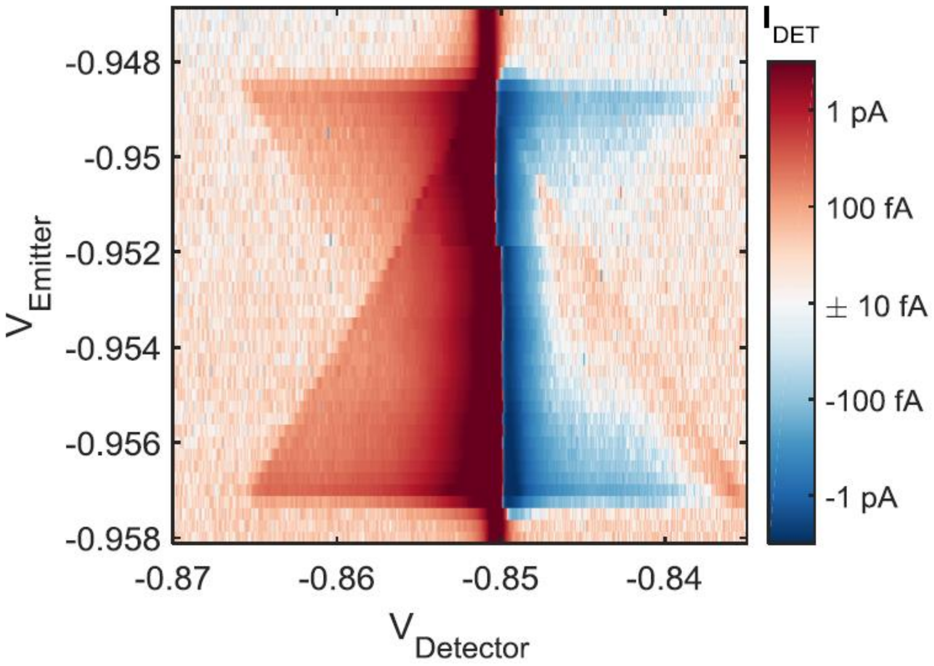






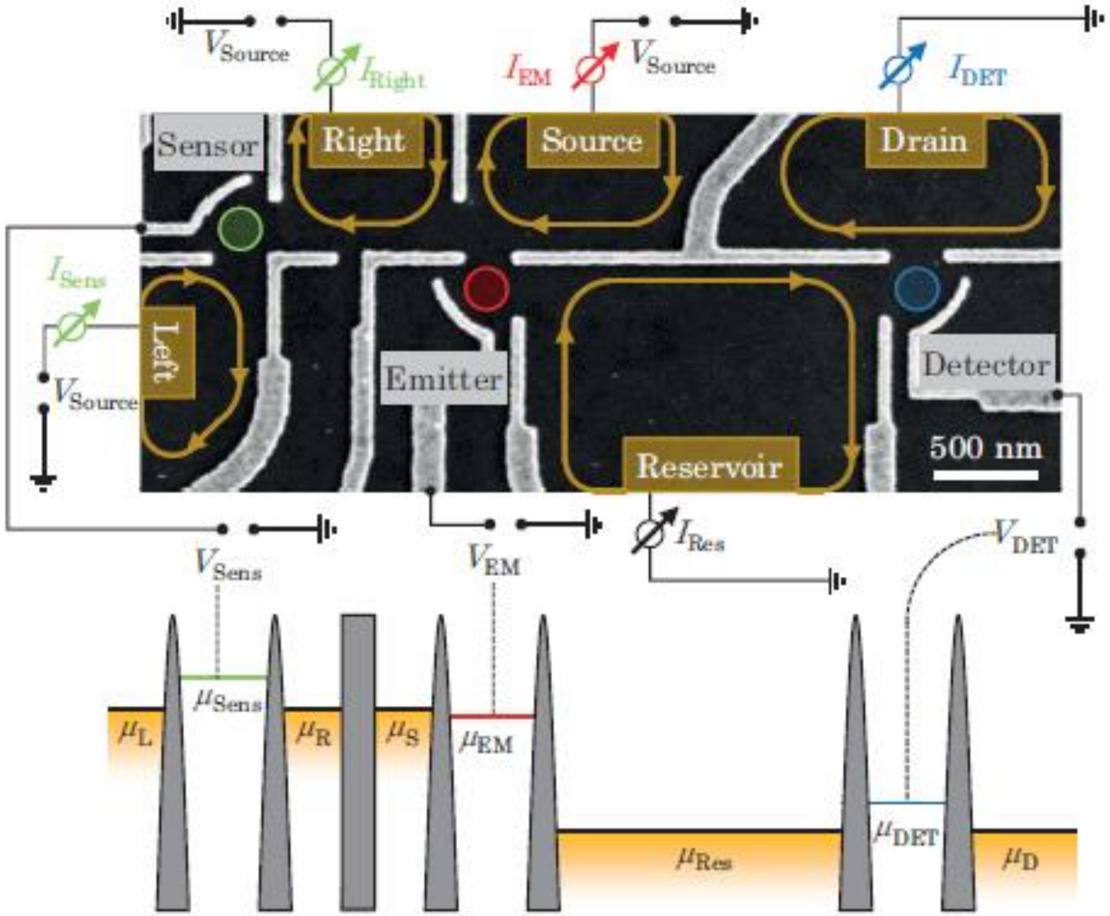
All contributions, including elastic current

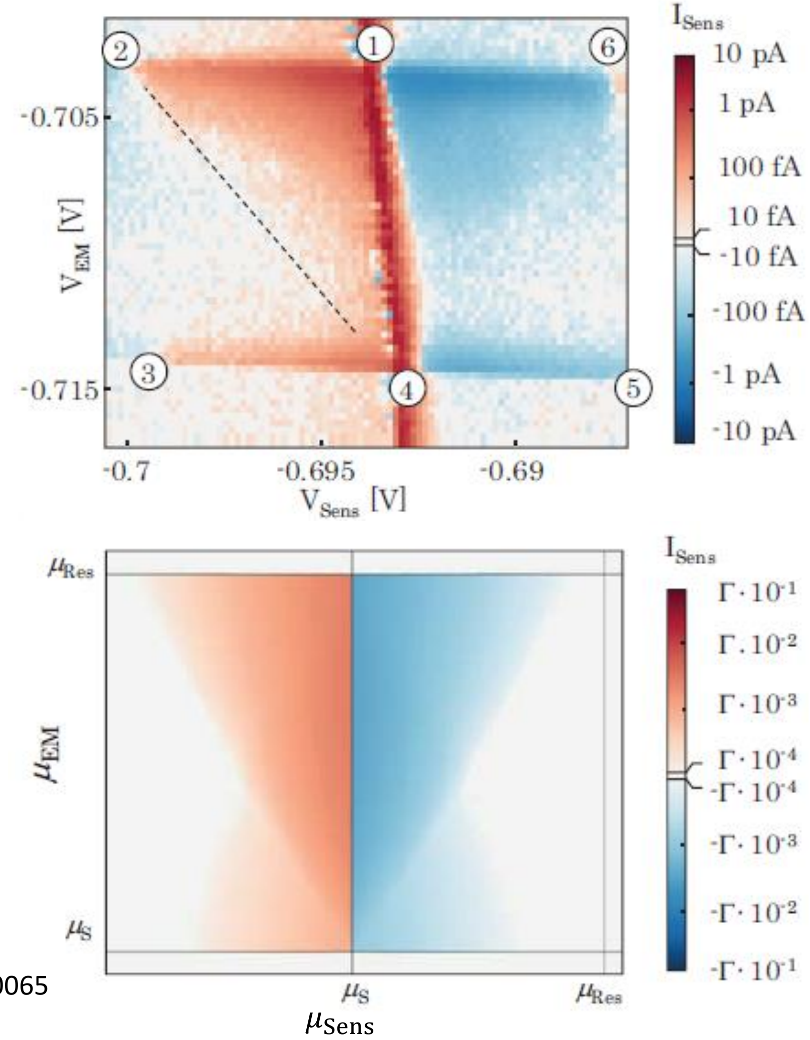




- 2^{nd} order interactions not sufficient to capture absence of elastic current
- Quantitative agreement requires taking into account: higher interaction orders, sample geometry, more channels, realistic interaction, non-zero temperature, interactions between channels and dots…

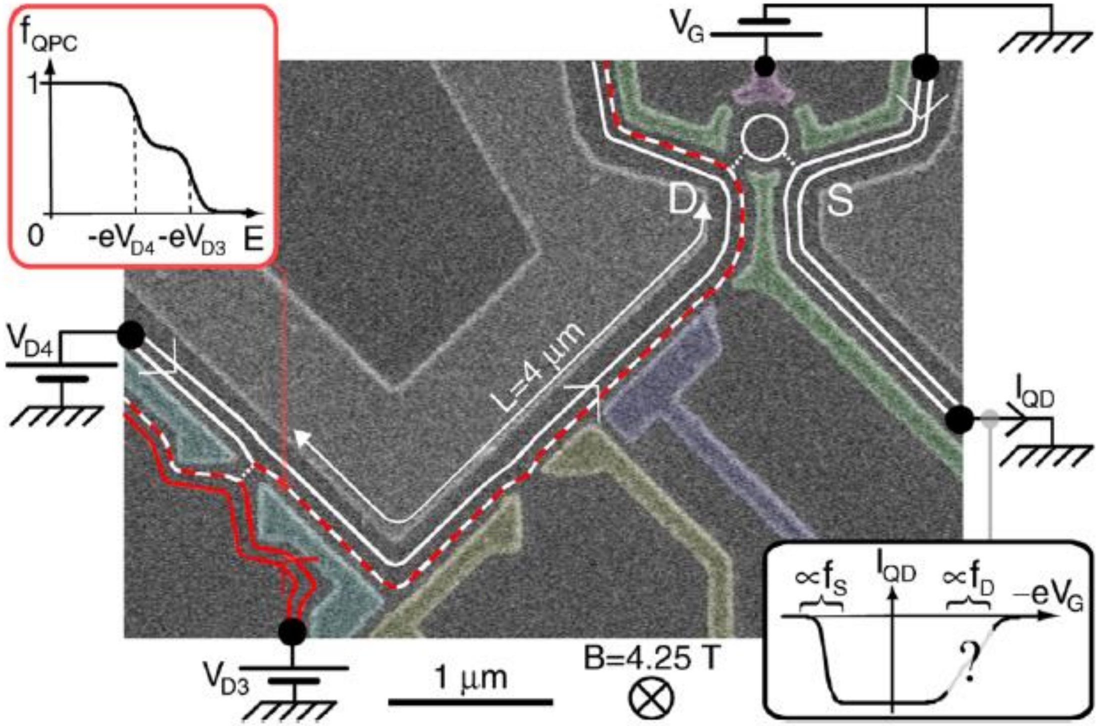
Direct evidence for Auger-like recombination



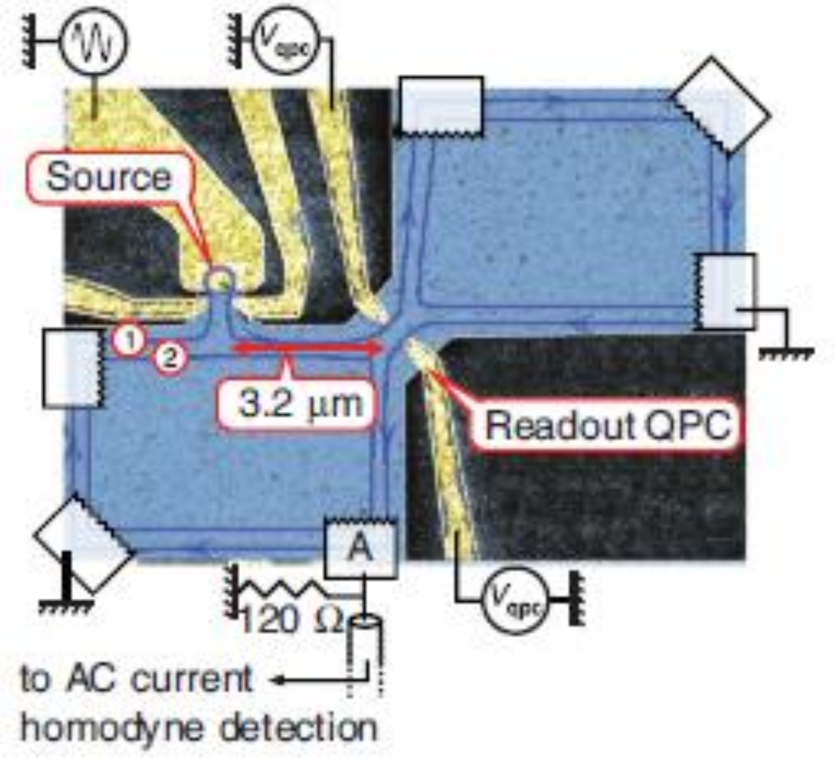


T. Krähenmann, SGF, M. Röösli, T. Ihn, C. Reichl, W. Wegscheider, K. Ensslin, Y. Gefen, Y. Meir, arXiv:1902.10065

Relevance for unexpected energy loss?



Le Sueur et al., PRL **105**, 056803 (2010)



Bocquillon et al., Nat Comm **4**, 1839 (2013)

Conclusions

- Distinct contributions to measured current are captured by diagrammatic approach

- Interactions between spatially separated parts of the sample confirmed as origin of inverted triangles

- 2nd order interactions not sufficient to qualitatively capture predominant absence of elastic current

  → bosonization

- Quantitative agreement (currently?) out of reach