Low energy physics of the integer quantum Hall regime

φ Nano Team

(CNRS - LPN, Marcoussis)

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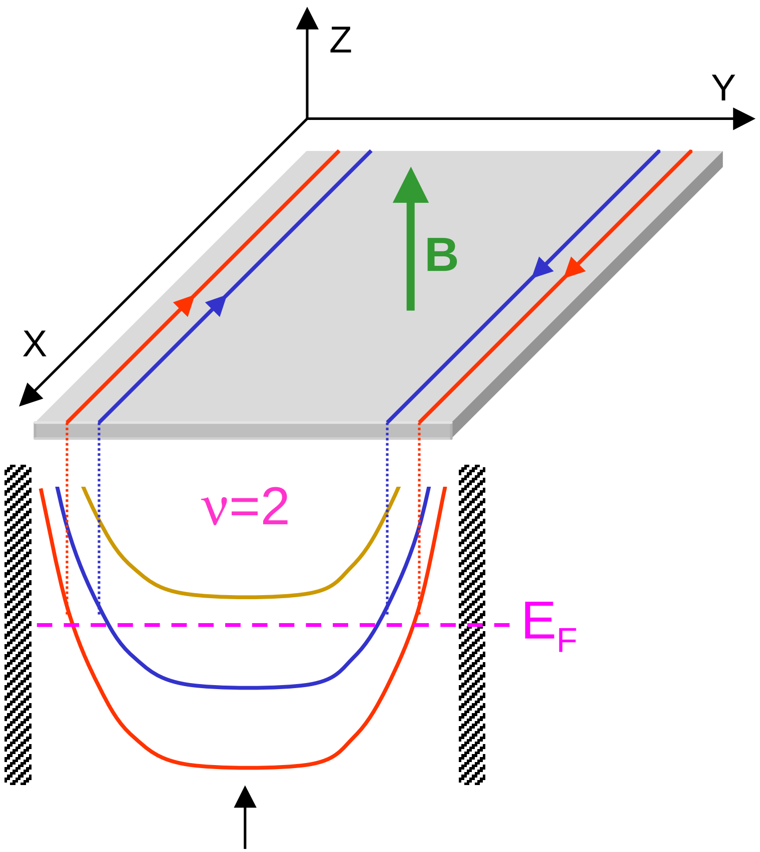
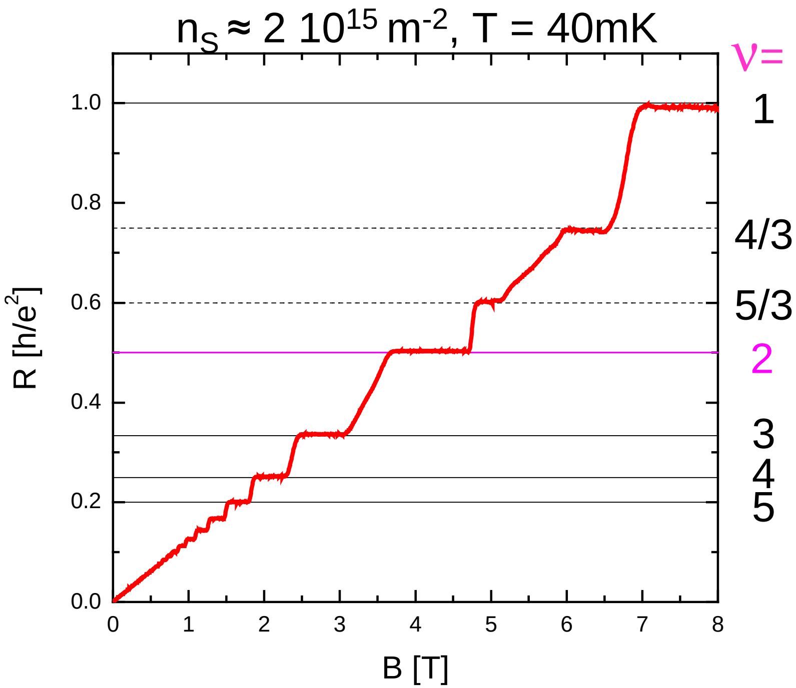
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

The quantum Hall effect regime

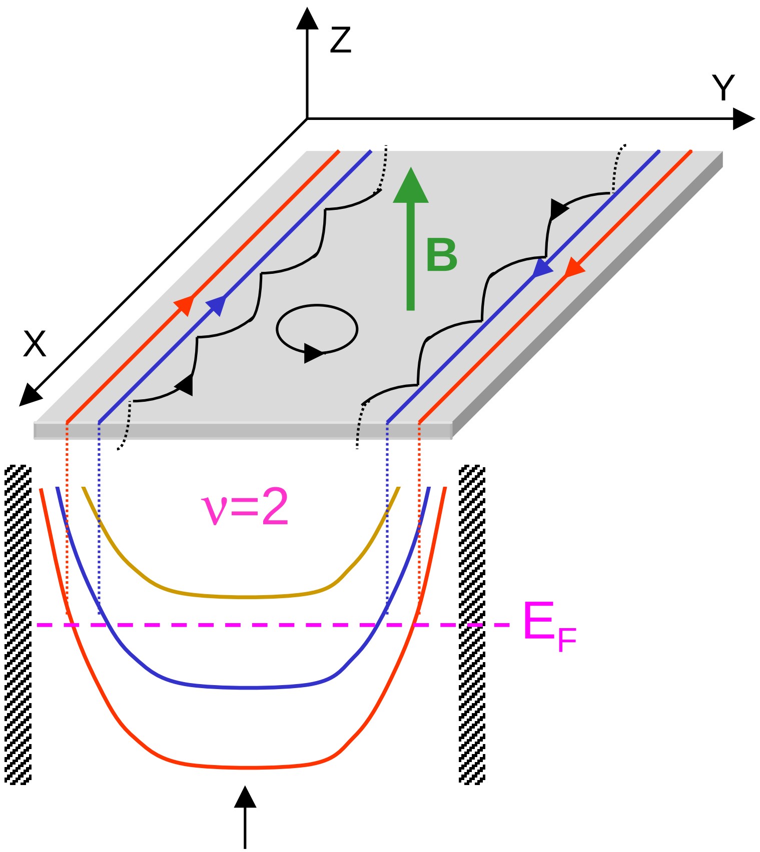


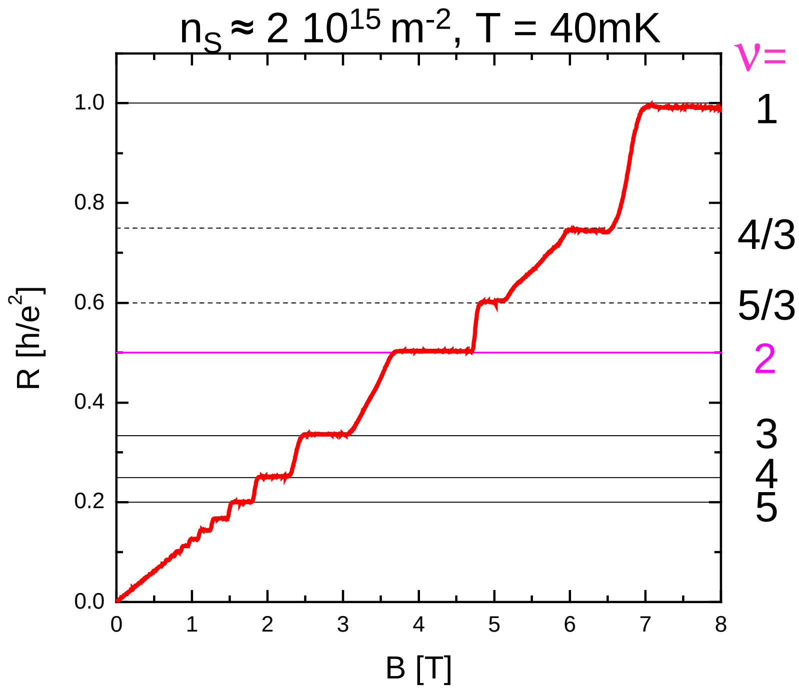


Landau levels: $E_n(k) \approx (n+1/2)\hbar\frac{eB}{m} + V_{conf}(y_k = -k\frac{\hbar}{eB})$
(spinless)

Non interacting electrons ⟹ edge excitations = chiral 1D fermions

The quantum Hall effect regime





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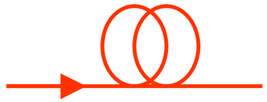
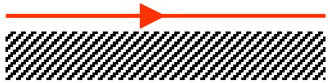
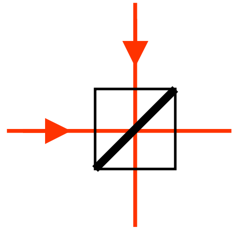
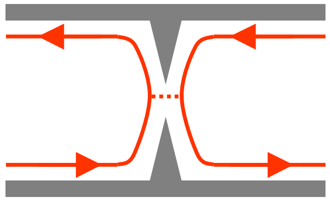
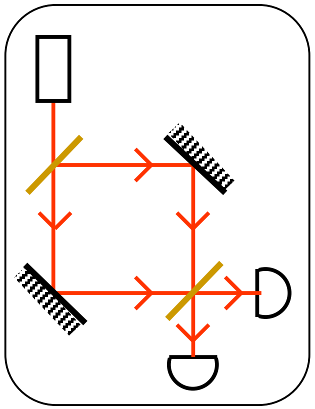
Non interacting electrons ➡ edge excitations = chiral 1D fermions

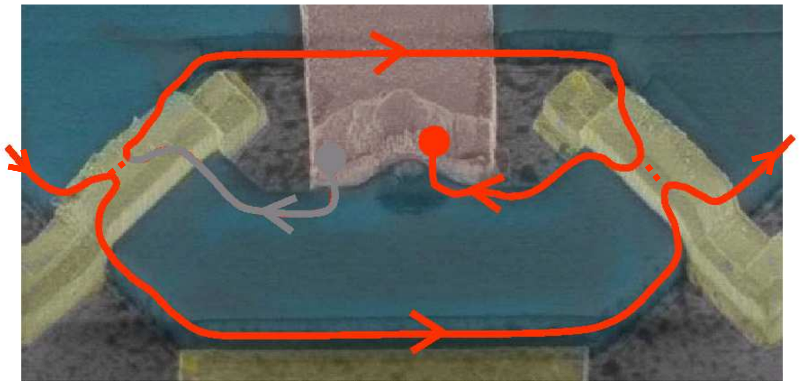
Electrical analog of optical devices

optic fiber  ⟷  sample edge

beam spliter   quantum point contact

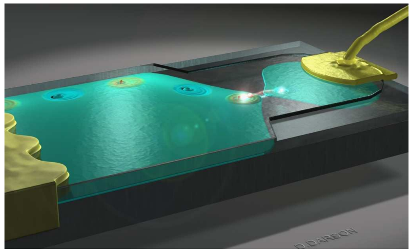
Mach-Zehnder interferometer

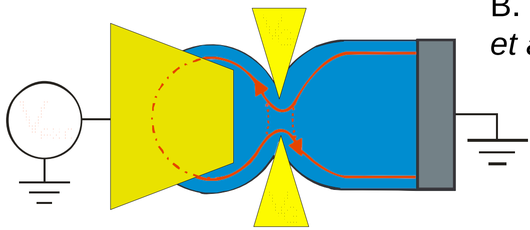




Courtesy P. Roche *et al.* (SPEC)

Single e^- source for Q information





Courtesy B. Plaçais *et al.* (LPA)

QHR: large potential to investigate new quantum physics

Coulomb interaction in the QHR

Cb interaction ignored in most cases

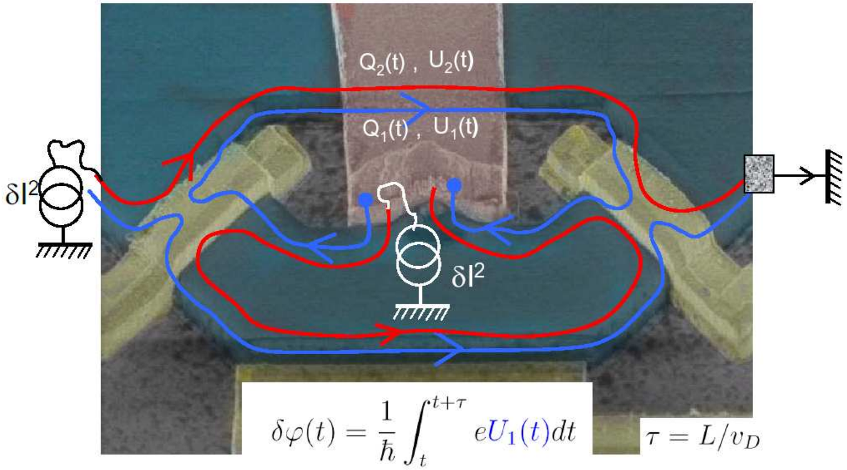
➡ Hall currents robust to µscopic details of EC

Recently: revealed by electronic MZI experiments

- Zoology of phenomenon not compatible with free chiral e^-
- Theoretical controversy: No single model explains all observations

Ex: ϕ fluctuations from low freq. noise

Seeling & Buttiker (PRB 2001);
Roulleau *et al.* (PRL 2008)



Courtesy P. Roche *et al.* (SPEC)

Electronic excitations are edge magnetoplasmons

Wen (PRL 1990); Aleiner & Glazman (PRL 1994);
Levkivskyi & Sukhorukov (PRB 2008)

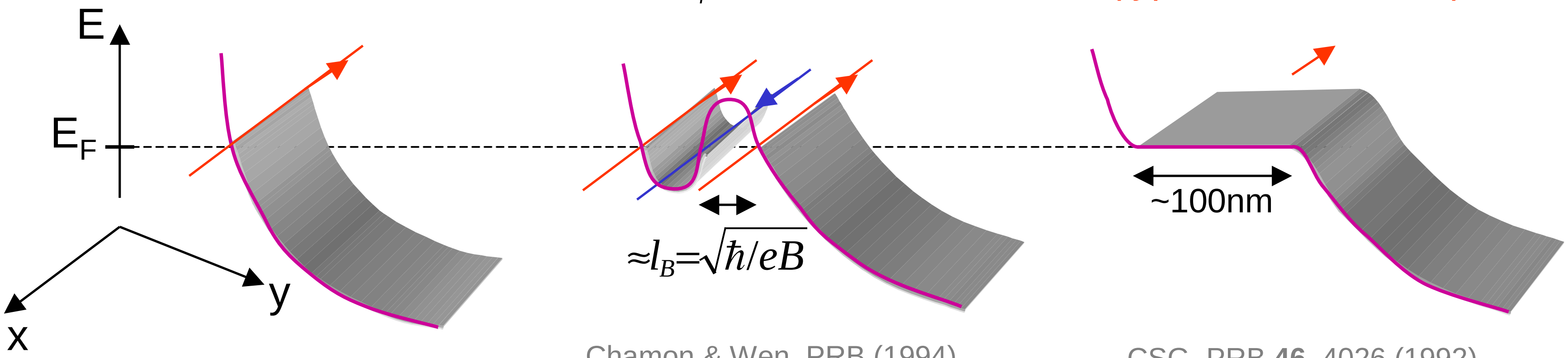
Turning on interactions

Competition confinement - Coulomb interaction

Sharp confinement → Smooth confinement

∃ edge instability
$\partial_y V_{conf} < \hbar\omega_C / 10 l_B$

wide compressible EC
(typical confinement)



Chamon & Wen, PRB (1994)

CSG, PRB **46**, 4026 (1992)

Not 1D fermions: ∃ new excitations branches

Counter propagating modes

Transverse density oscillations

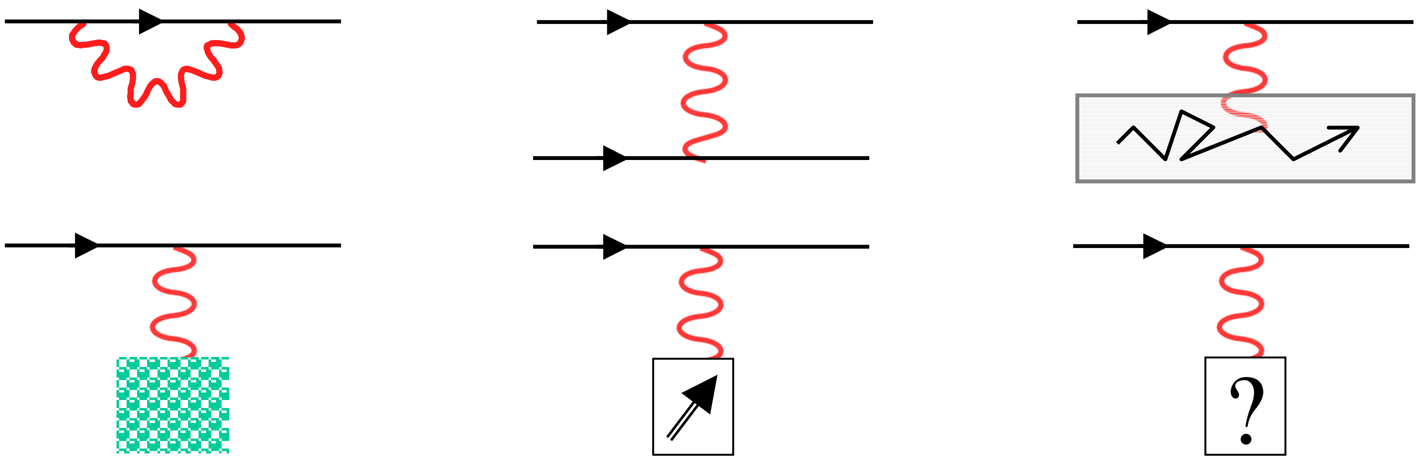
Aleiner & Glazman, PRL (1994)

New acoustic excitations predicted in realistic smooth edges

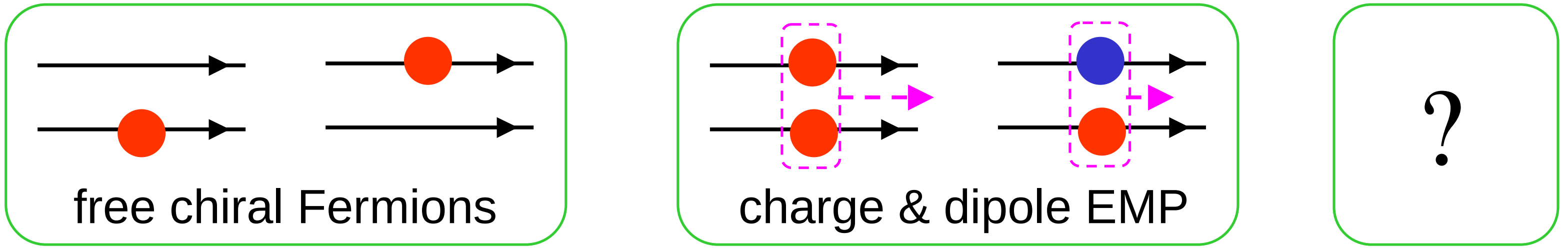
Problematic:

Nature of edge excitations & inelastic mechanisms

- Mechanism limiting Quantum coherence?
- Inelastic mechanism for energy exchanges?



- Electronic excitations in QHR?



Novel experimental approach to IQHR:

Non equilibrium edge channel spectroscopy

Key ingredients

- New tool to probe f(E)

  Using a *quantum dot* as an *energy filter*

- Generate a tunable non-equilibrium situation

  With a voltage biased *QPC*

→

- Test the analogy QPC-beam splitter

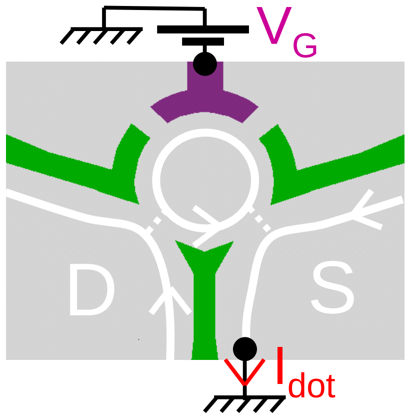
  Does it excite internal EC modes?

- Measurement of energy exchanges

  Viewpoint ≠ from dephasing: no contribution of low freq. noise

Energy distribution spectroscopy

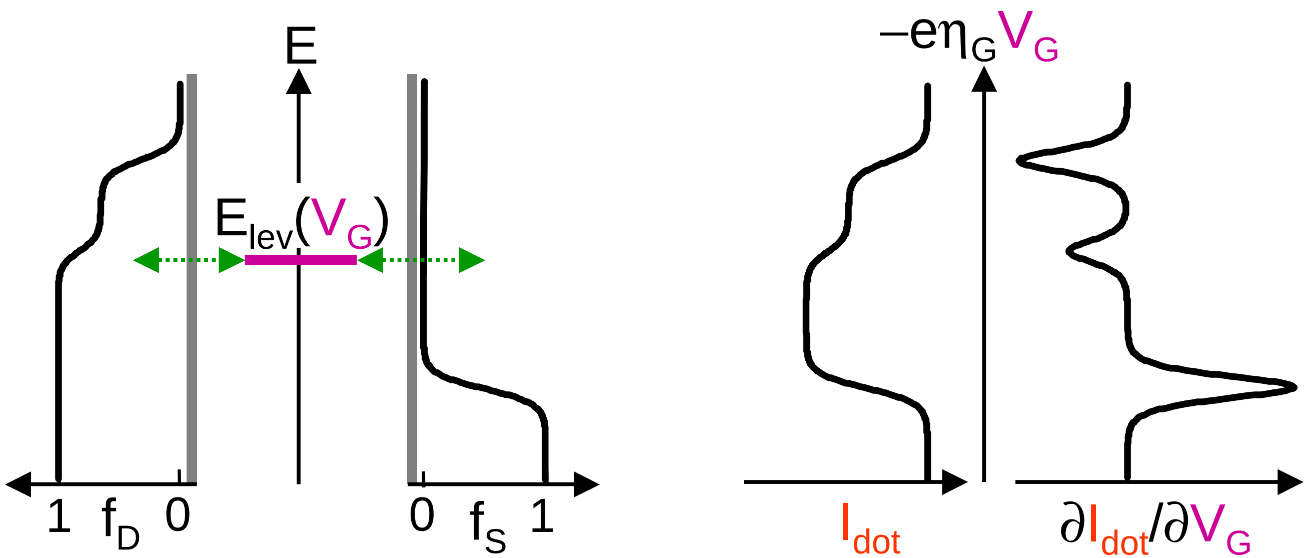
Single active level in QD



Sequential tunneling:

$$I_{dot}(V_G) = I_{max}\{f_S(E_{lev}(V_G)) - f_D(E_{lev}(V_G))\}$$

with $E_{lev}(V_G) = E_0 - e\eta_G V_G$

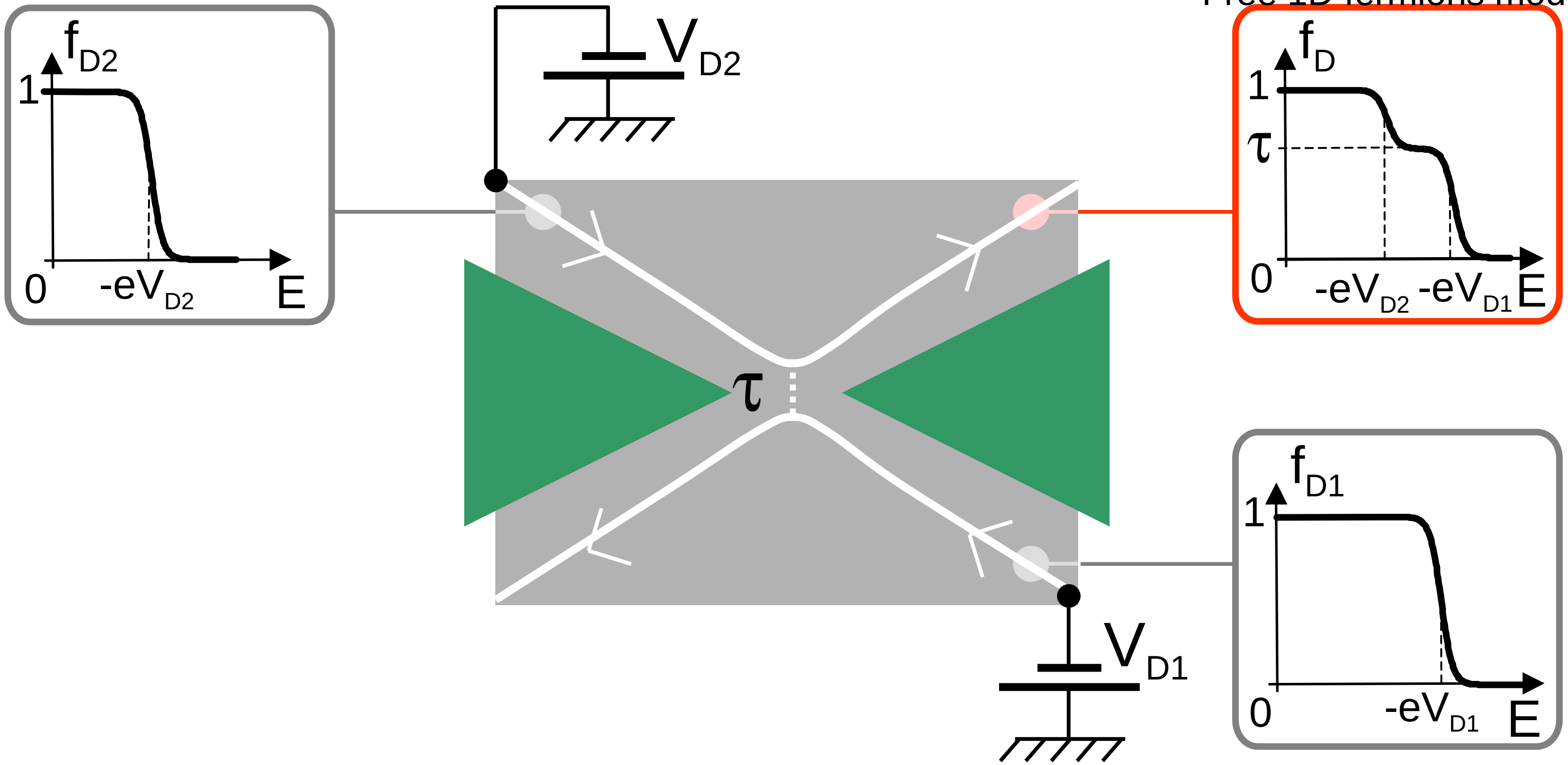


Quantum dot ⟷ Energy filter

Tunable non equilibrium situation

In the quantum Hall regime

Free 1D fermions model



Free chiral 1D fermions model: $f_D = \tau f_{D1} + (1-\tau) f_{D2}$

Step 1:

Demonstrate experiment principle & Test QPC-beam splitter analogy

- Short distance QPC-QD

➡ Reduces impact of propagation

- Test QPC-beam splitter analogy out-of-equilibrium

Hyp.: QD tunnel spectro insensitive to internal EC excitations

(Shown by linear I-V characteristics of QPCs in tunnel regime)

➡ Probed excitations are chiral 1D fermions

➡ Excited internal EC modes would appear as an energy loss

Experimental implementation

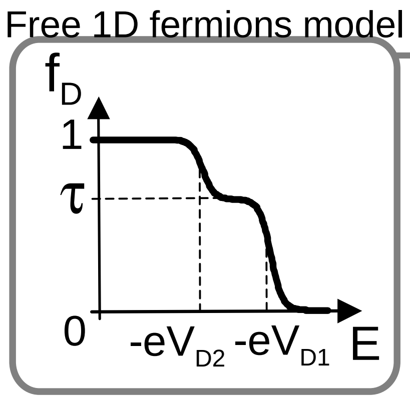
Propagation length: 0.8µm

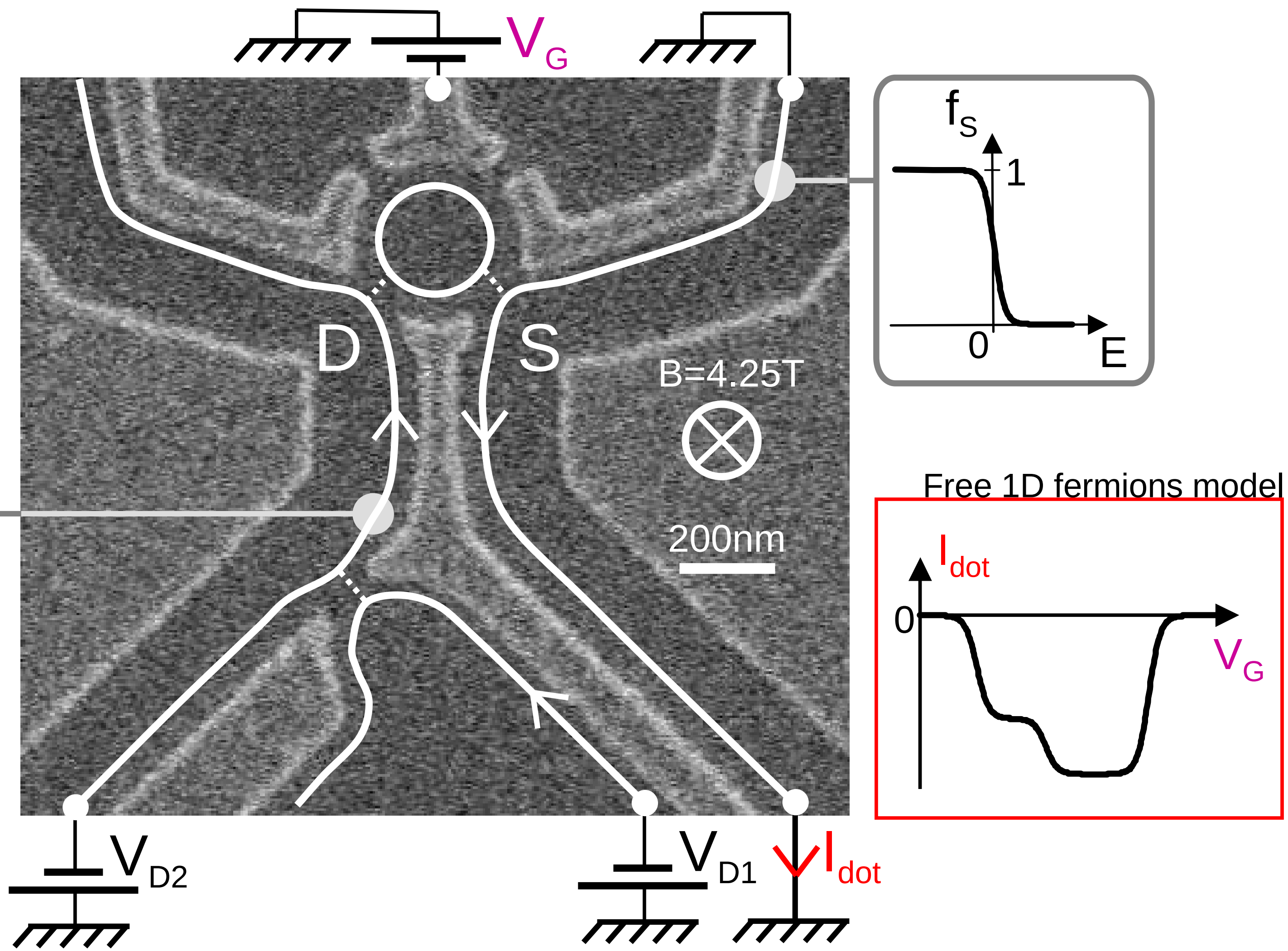
$n_S \approx 2\ 10^{15} m^{-2}$

$T \approx 30mK$

$\nu = 2$

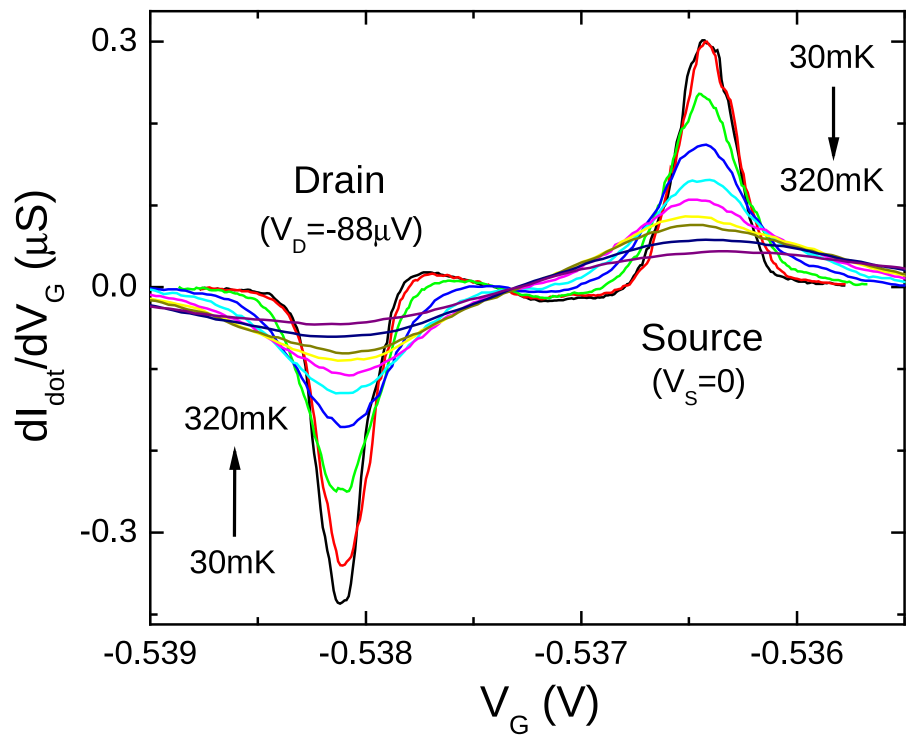
Inner EC (not shown) reflected

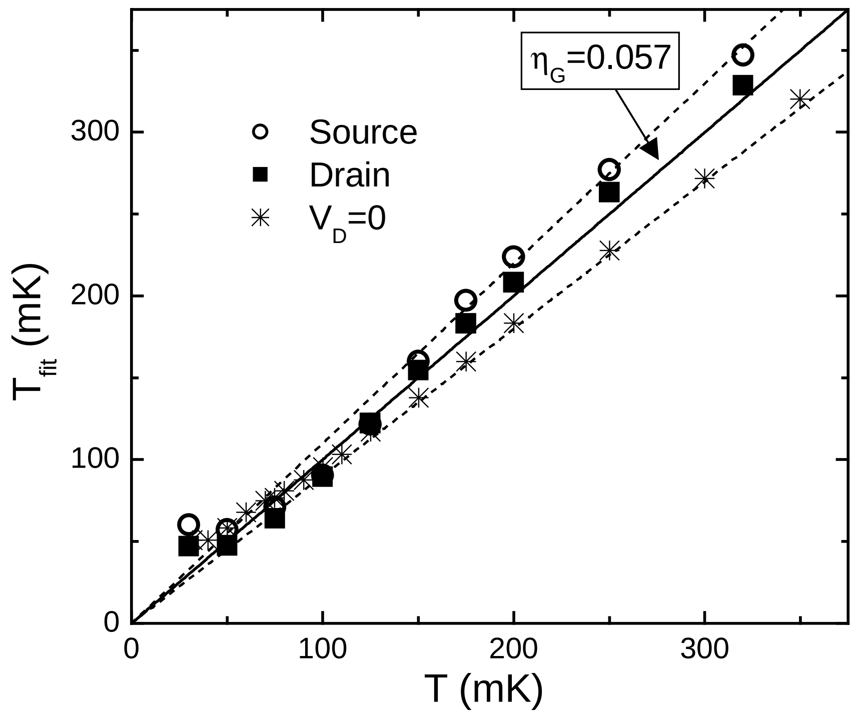




Equilibrium spectroscopy

QD gate voltage-to-energy calibration



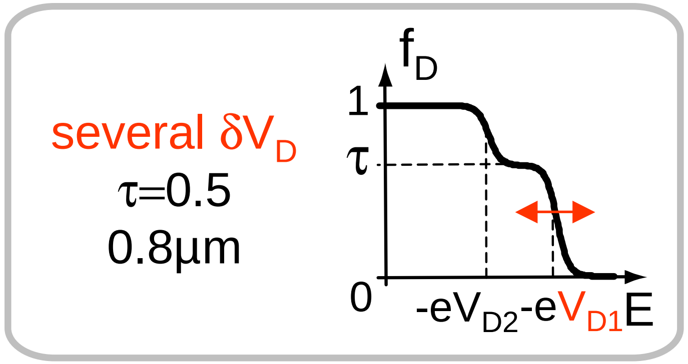


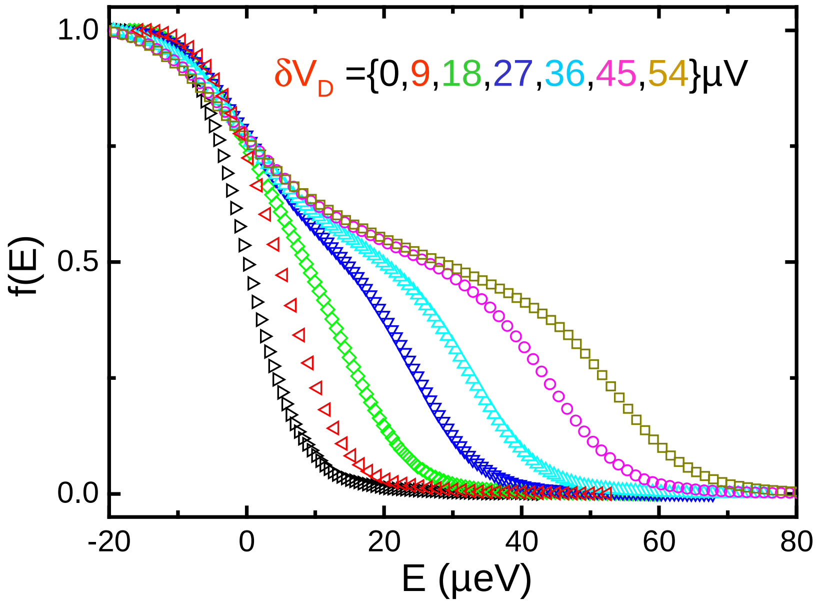
$T_{fit}=T$ ⇒ $\eta_G=0.057$ ±10%

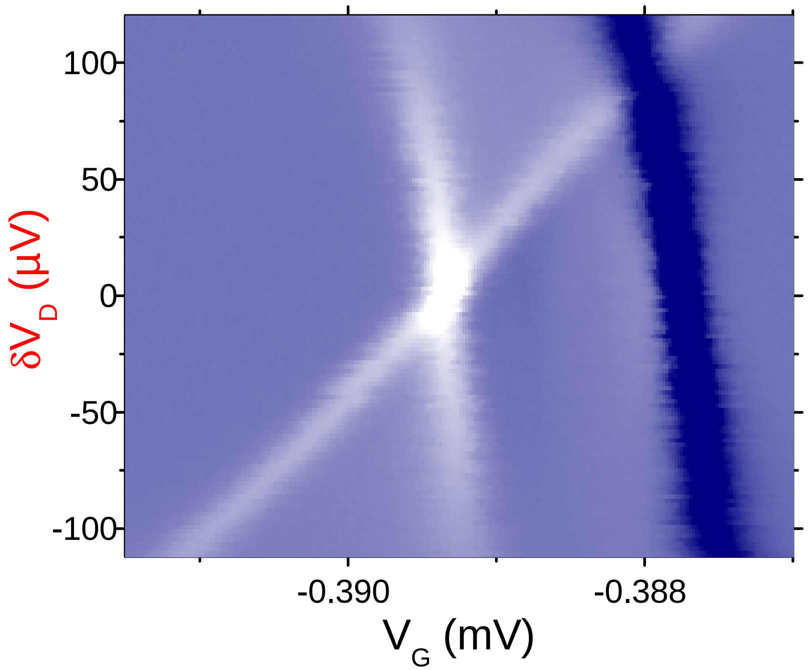
Consistent with Coulomb diamonds

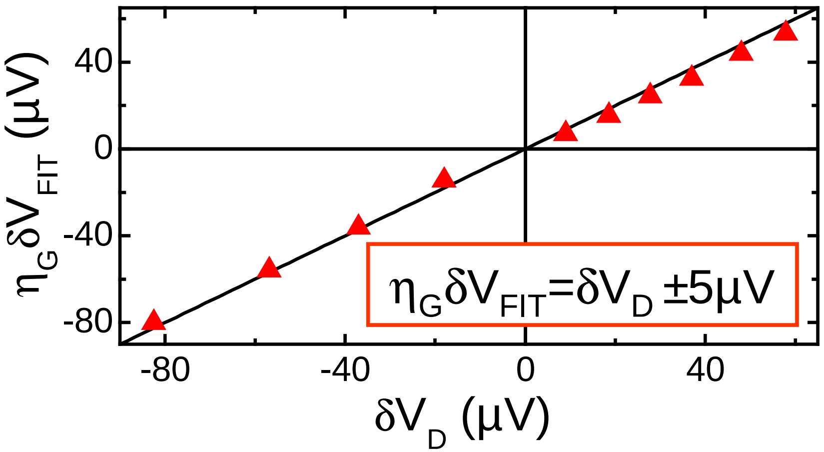
Non-equilibrium spectroscopy

Of an EC tuned out-of-equ. with the QPC bias voltage δV_D



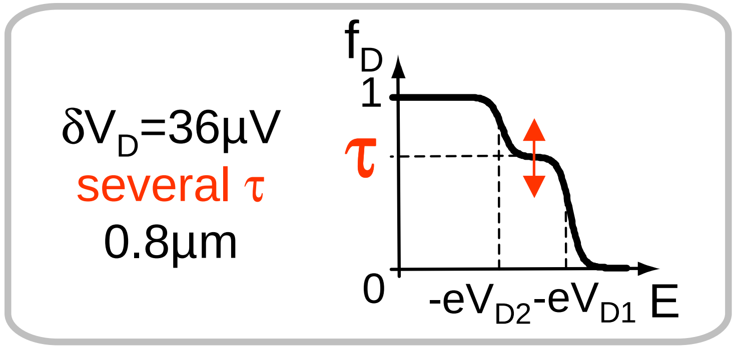


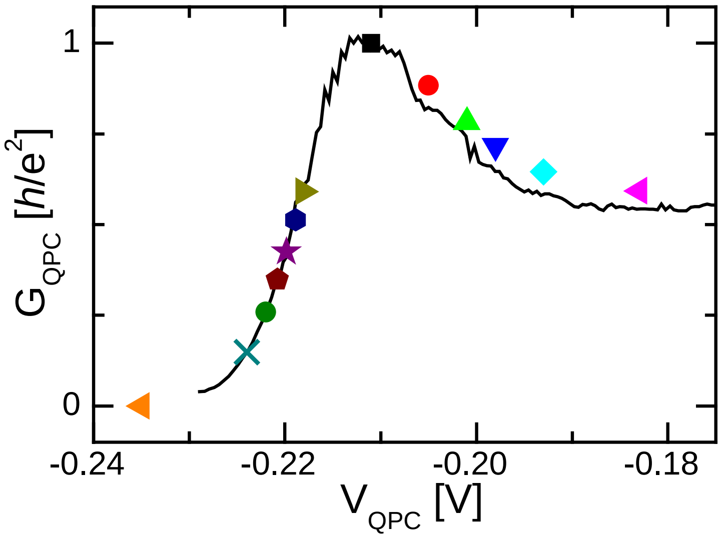


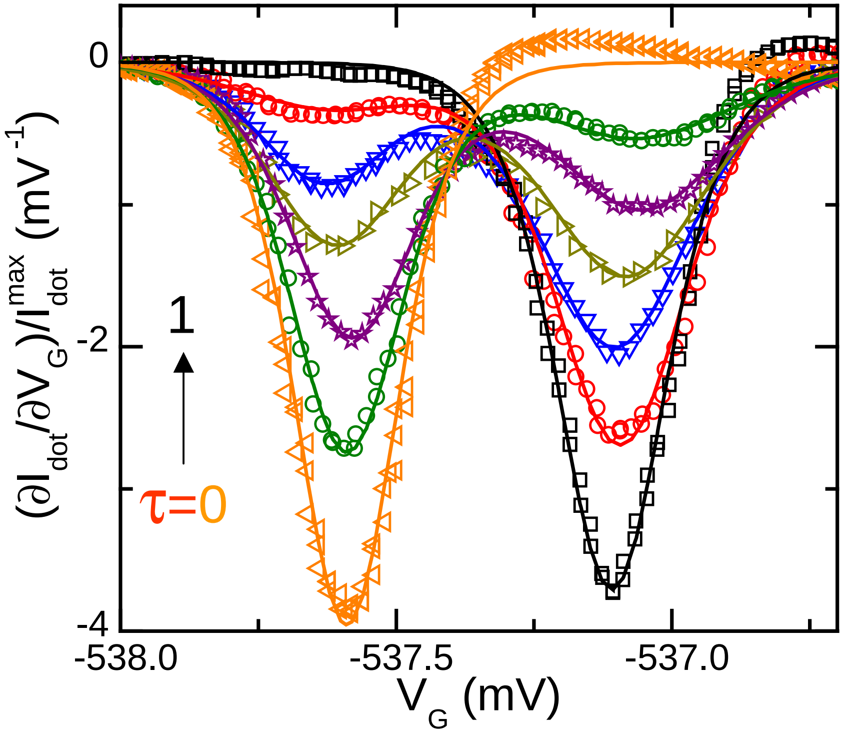


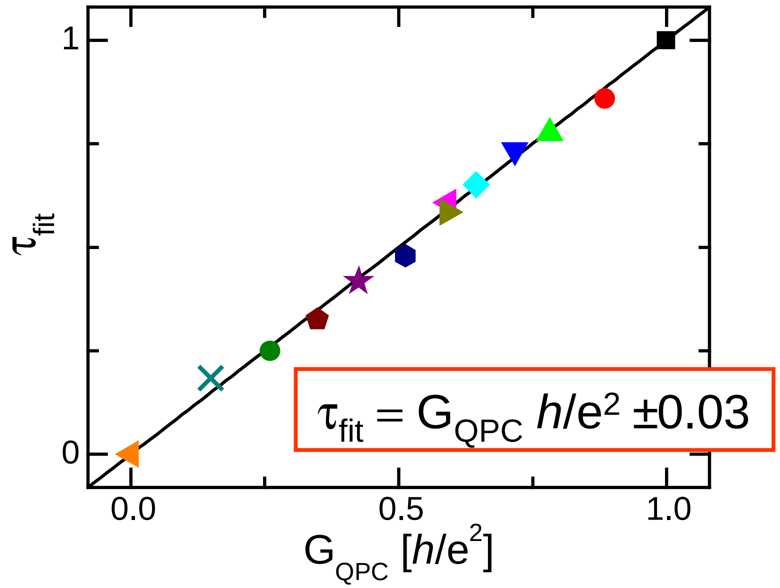
Non-equilibrium spectroscopy

Of an EC tuned out-of-equ. with the QPC transmission τ









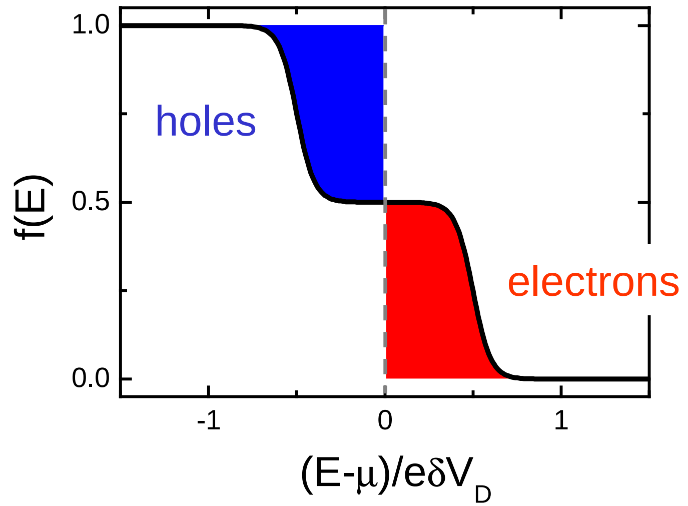
Total energy of probed excitations

Extracting E_{qp} from f(E)

$$\frac{E_{qp}}{\nu_F} = \int_{-\infty}^{\infty} (E-\mu)\,\delta f(E)\,dE$$

$$T_{qp} \equiv \sqrt{\frac{E_{qp}}{\nu_F}\frac{6}{\pi^2 k_B^2}}$$

$$J_Q = \underbrace{\mathrm{v}\nu_F}_{1/h}\frac{E_{qp}}{\nu_F} = \frac{\pi^2}{6h}(k_B T_{qp})^2$$



Power balance considerations

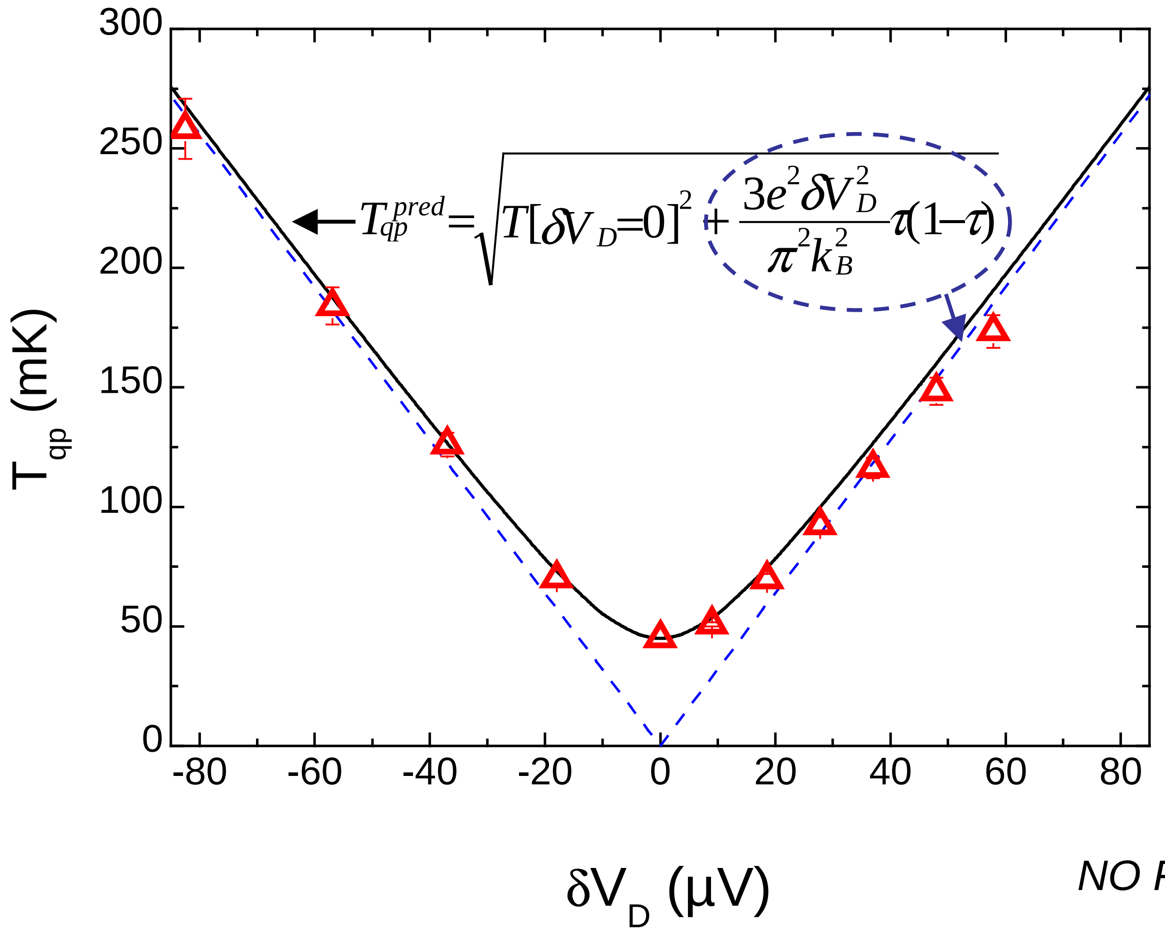
$$\Rightarrow \quad J_Q^{edge\ excitations}(T=0) = \frac{(e\,\delta V_D)^2}{2h}\,\tau(1-\tau)$$

∃ energy transported by internal modes ⟺

$$J_Q^{edge\ excitations} > J_Q^{meas.} \iff T_{qp}^{meas.} < \sqrt{T^2 + \frac{3e^2\delta V_D^2}{\pi^2 k_B^2}\,\tau\,(1-\tau)}$$

Total energy of probed excitations

L=0.8µm, τ=0.5, T=30mK



NO FIT PARAMETERS!

QPC ⟷ beam splitter

Check-point summary

➡ QD : tool to measure f(E)

Beyond QHR, opens new windows for
- *energy transport experiments*
- *out-of-equ physics*

➡ Voltage biased QPC in QHR: tunable non-eq. source

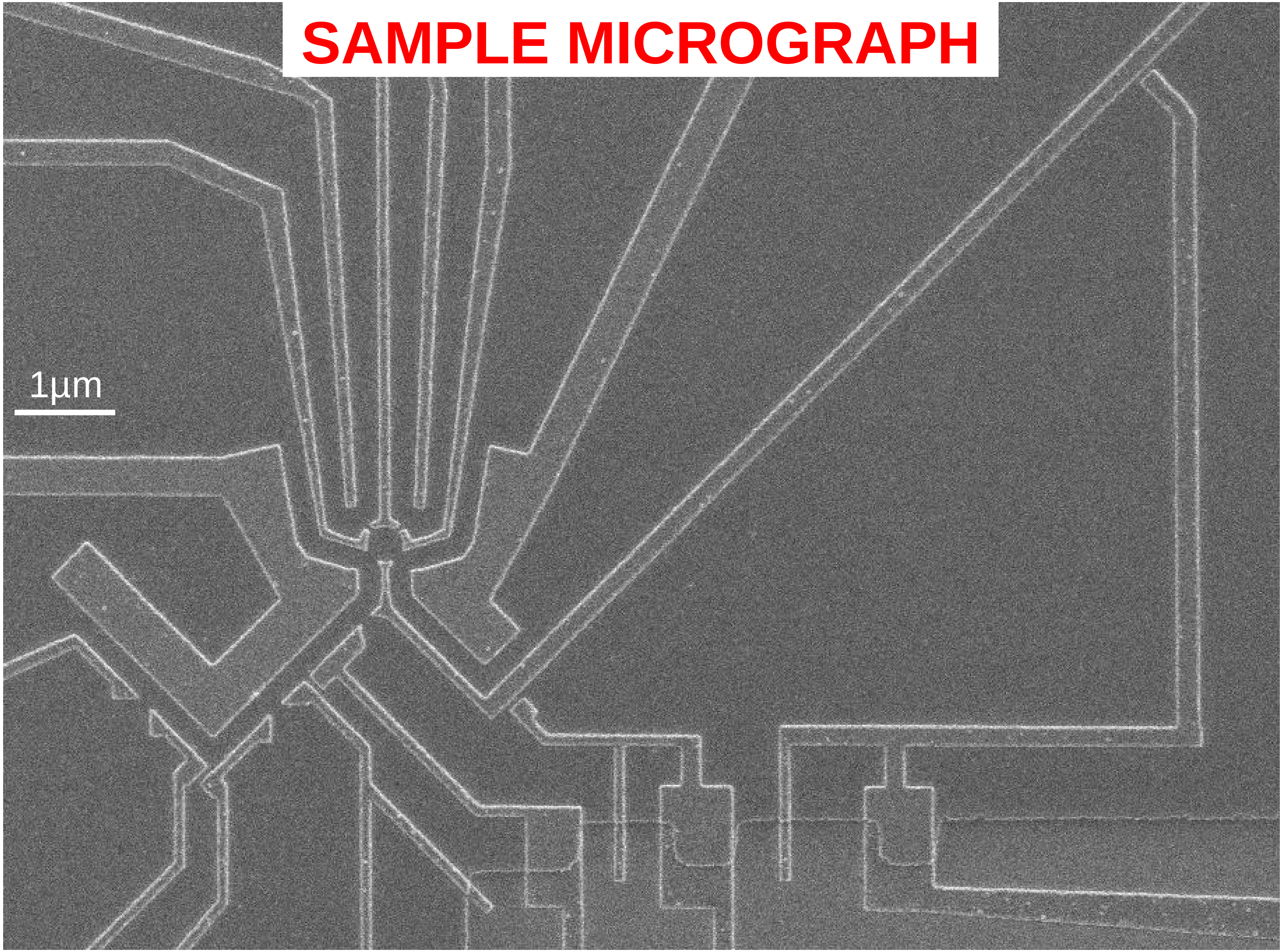
QPC analogue to optic beam splitter for 1D chiral fermions

Internal EC modes harmless to electronic analogue of quantum optics devices

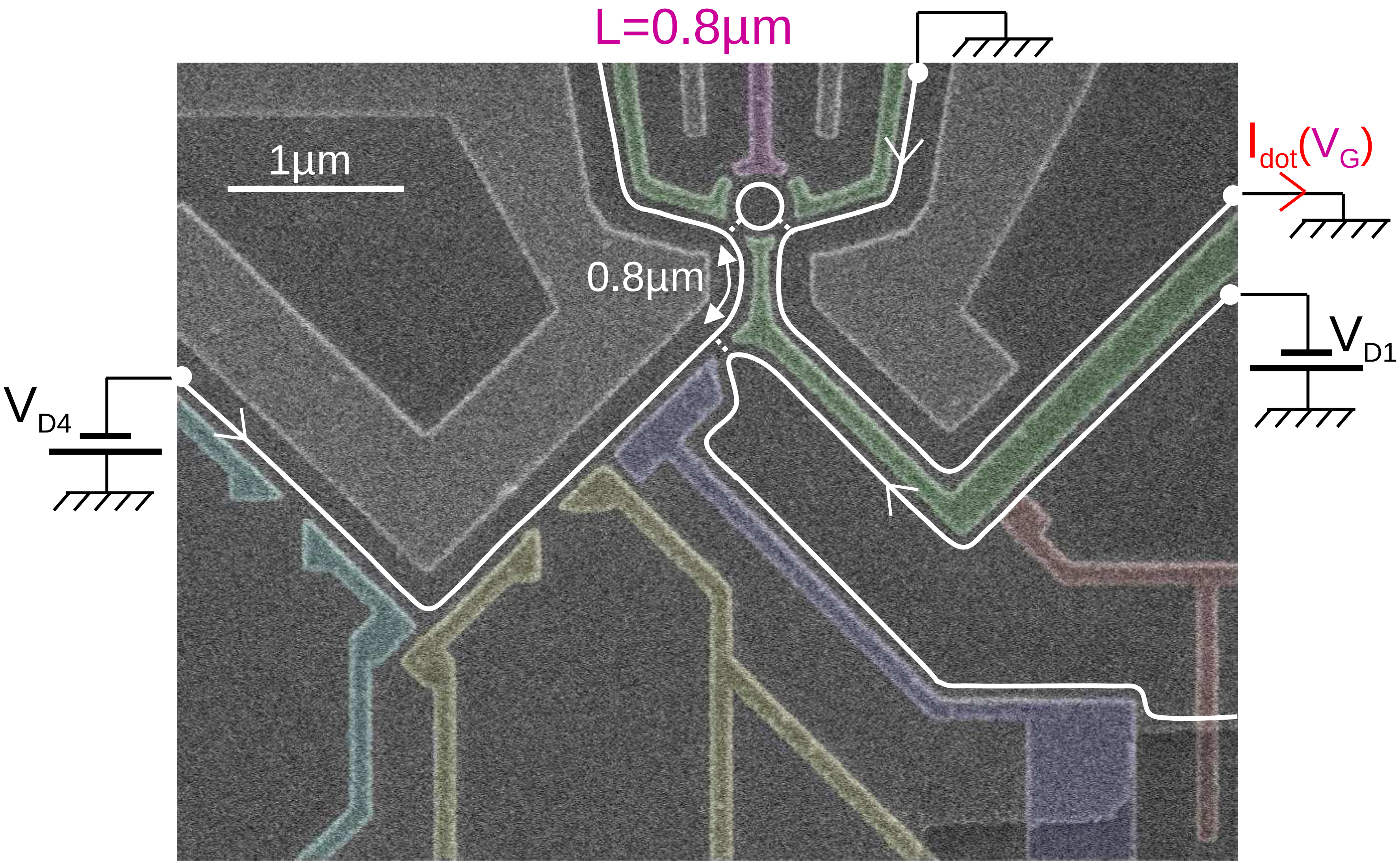
Now ready for
Step 2:

Energy exchanges in the QHR

Probed from f(E) vs propagation length

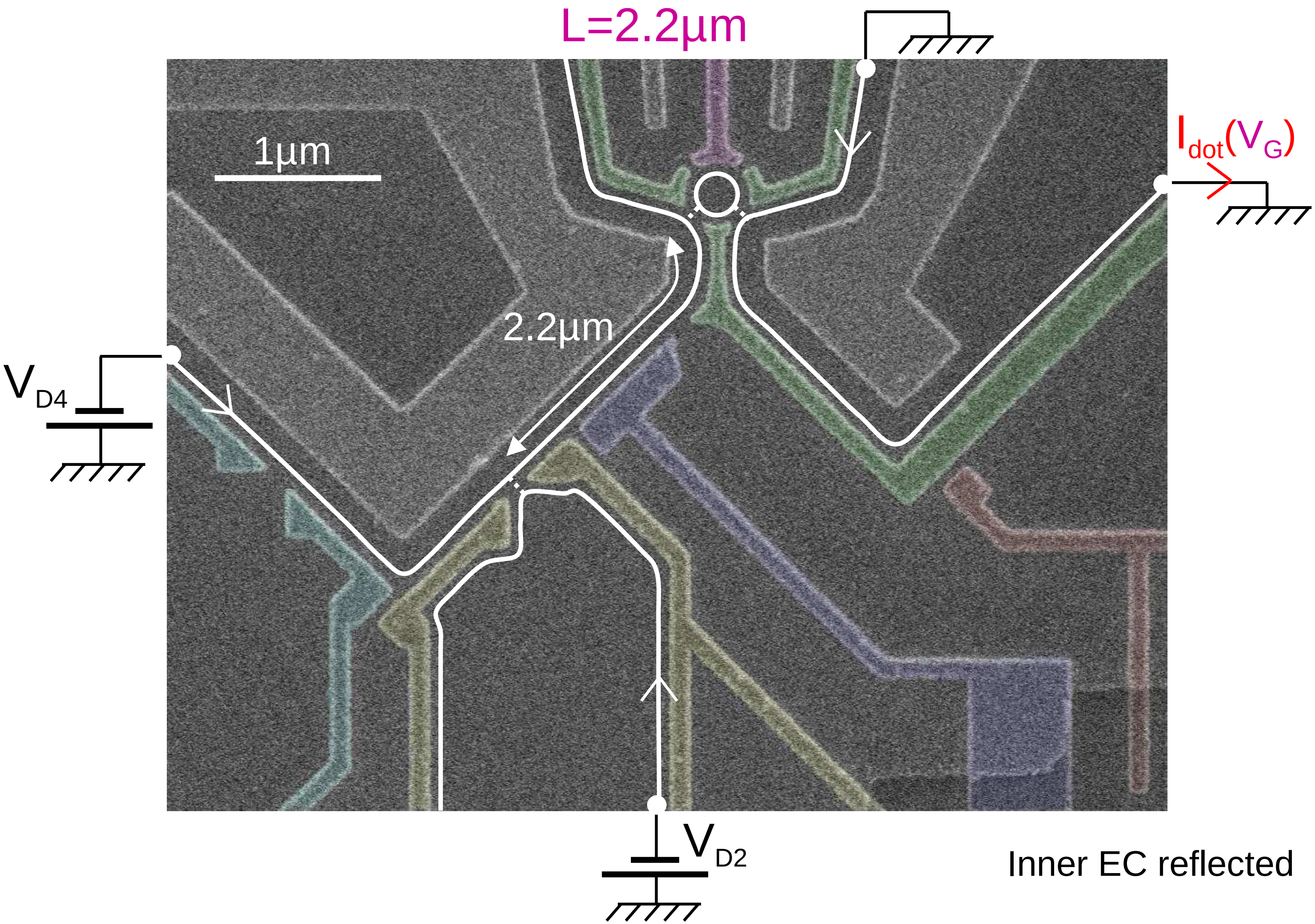

SAMPLE MICROGRAPH
1μm

Changing the propagation length



Inner EC reflected

Changing the propagation length



Inner EC reflected

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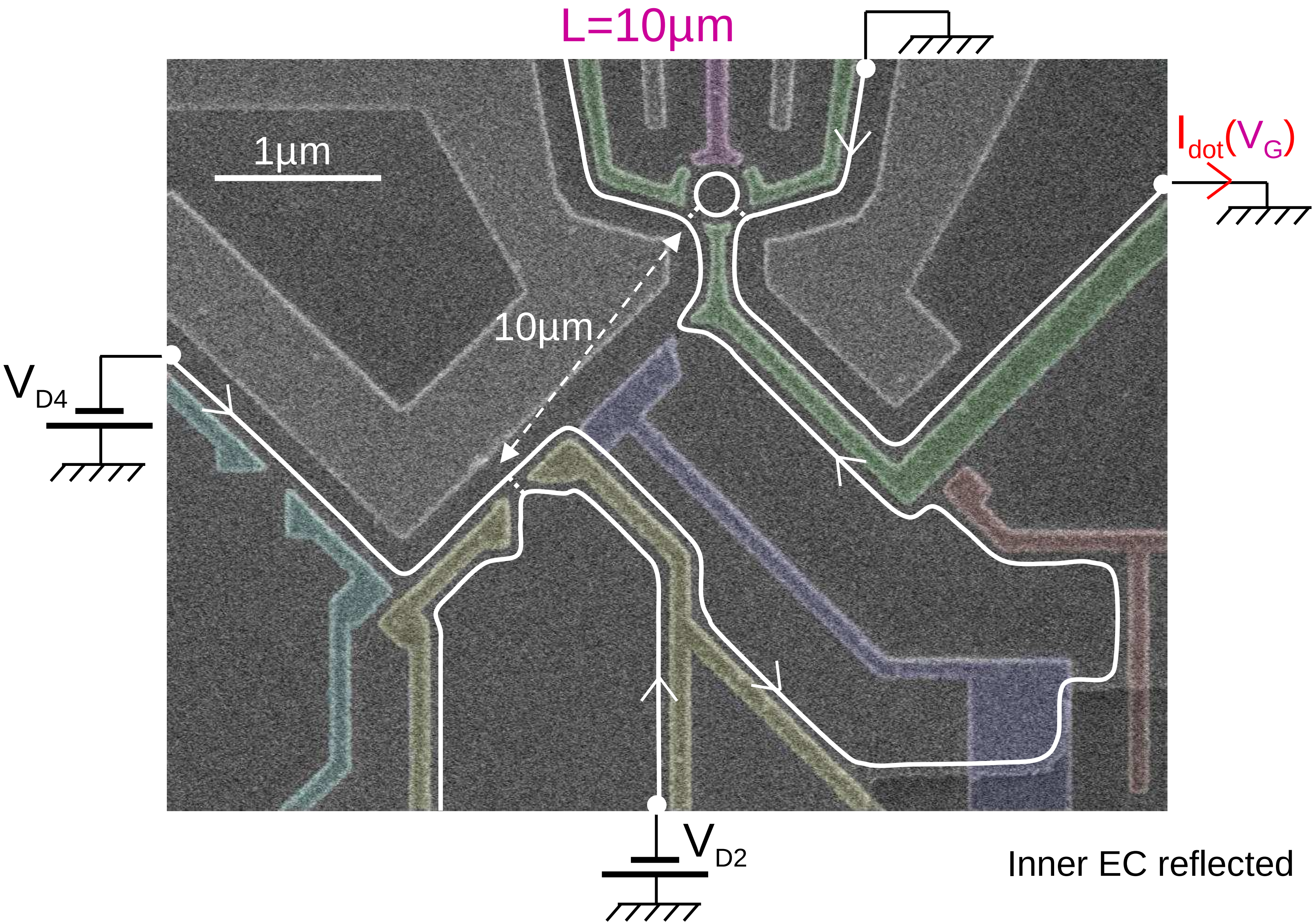
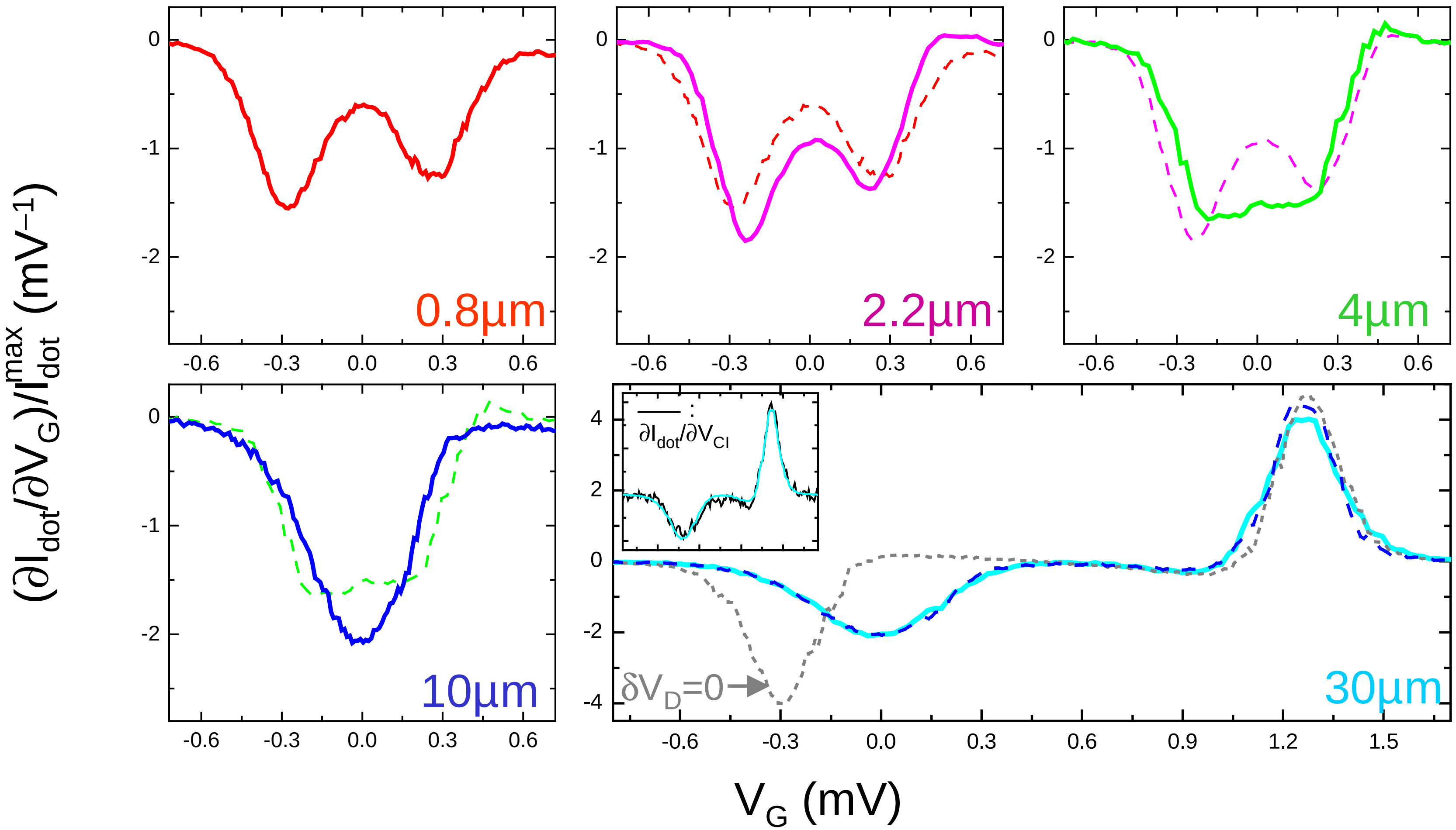


Inner EC reflected

f(E) vs propagation length

δV_D=36µV, τ~0.5, several L

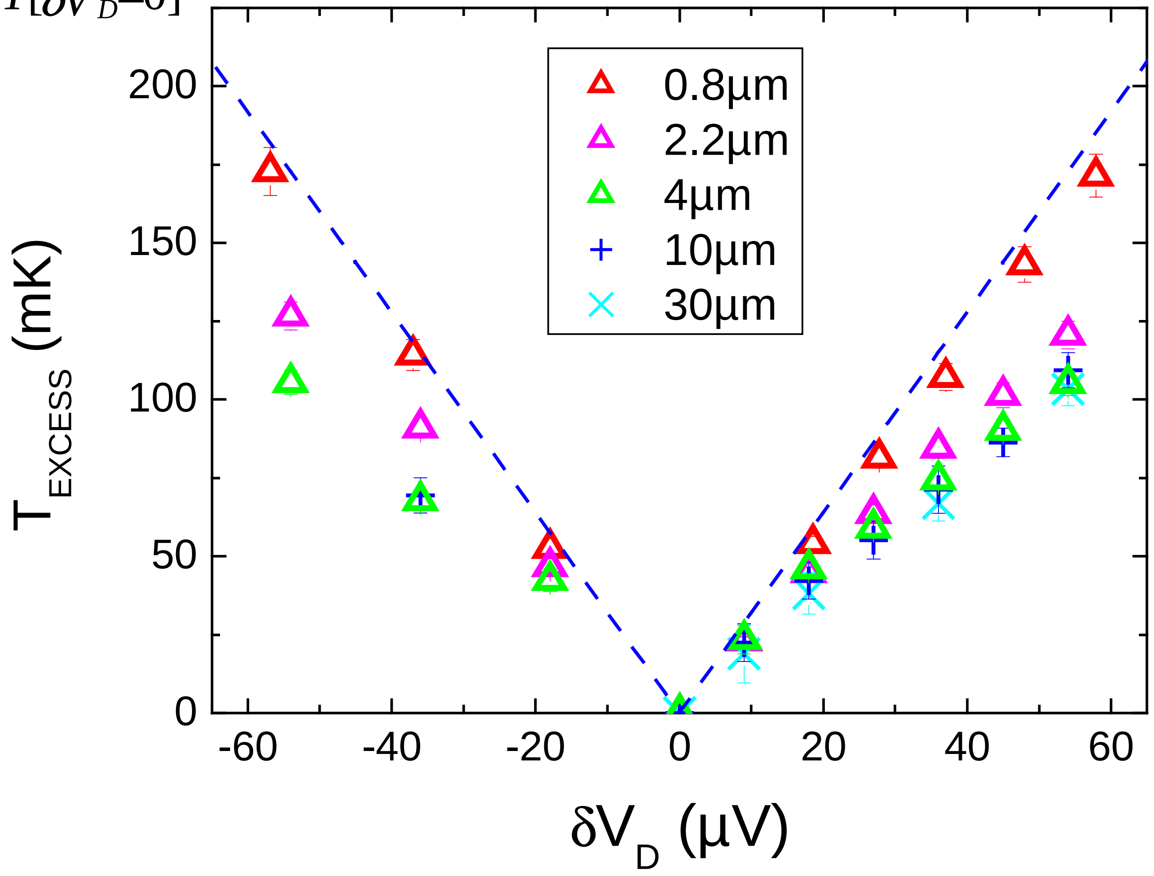


- f(E) relaxation!
- $L_{inelastic}$ ~ 3µm (δV_D=36µV, τ~0.5)
- f(E) saturates to a "hot" Fermi function: inner EC?

Total energy within probed outer edge channel

L={0.8,2.2,4,10,30}µm, τ=0.5, T=30mK

$$T_{EXCESS} \equiv \sqrt{T_{qp}^2 - T[\delta V_D\!=\!0]^2}$$

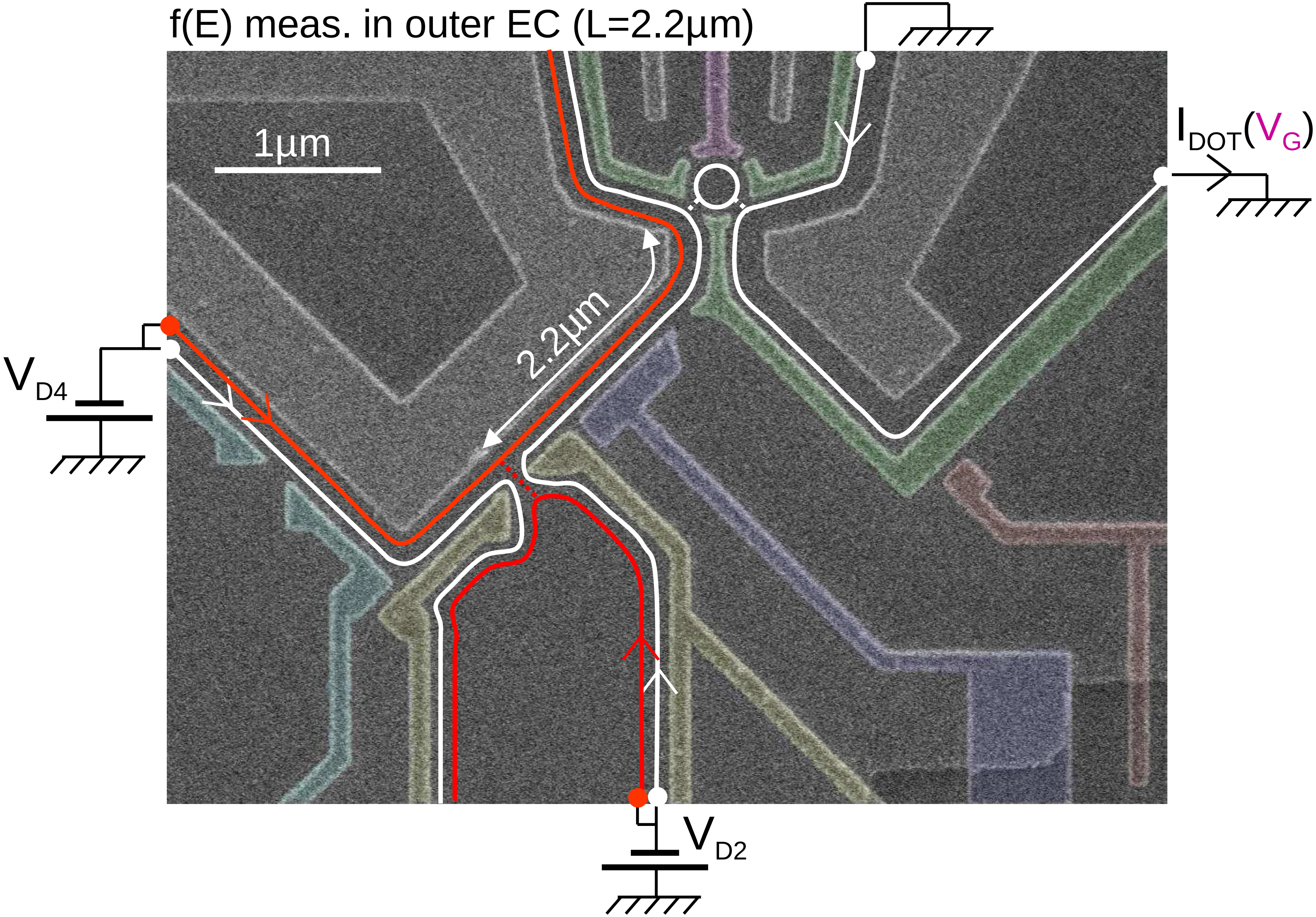


Injected energy redistributed with a co-propagating excitation branch:
Inner EC? Internal EC modes?

Test of energy exchanges between ECs

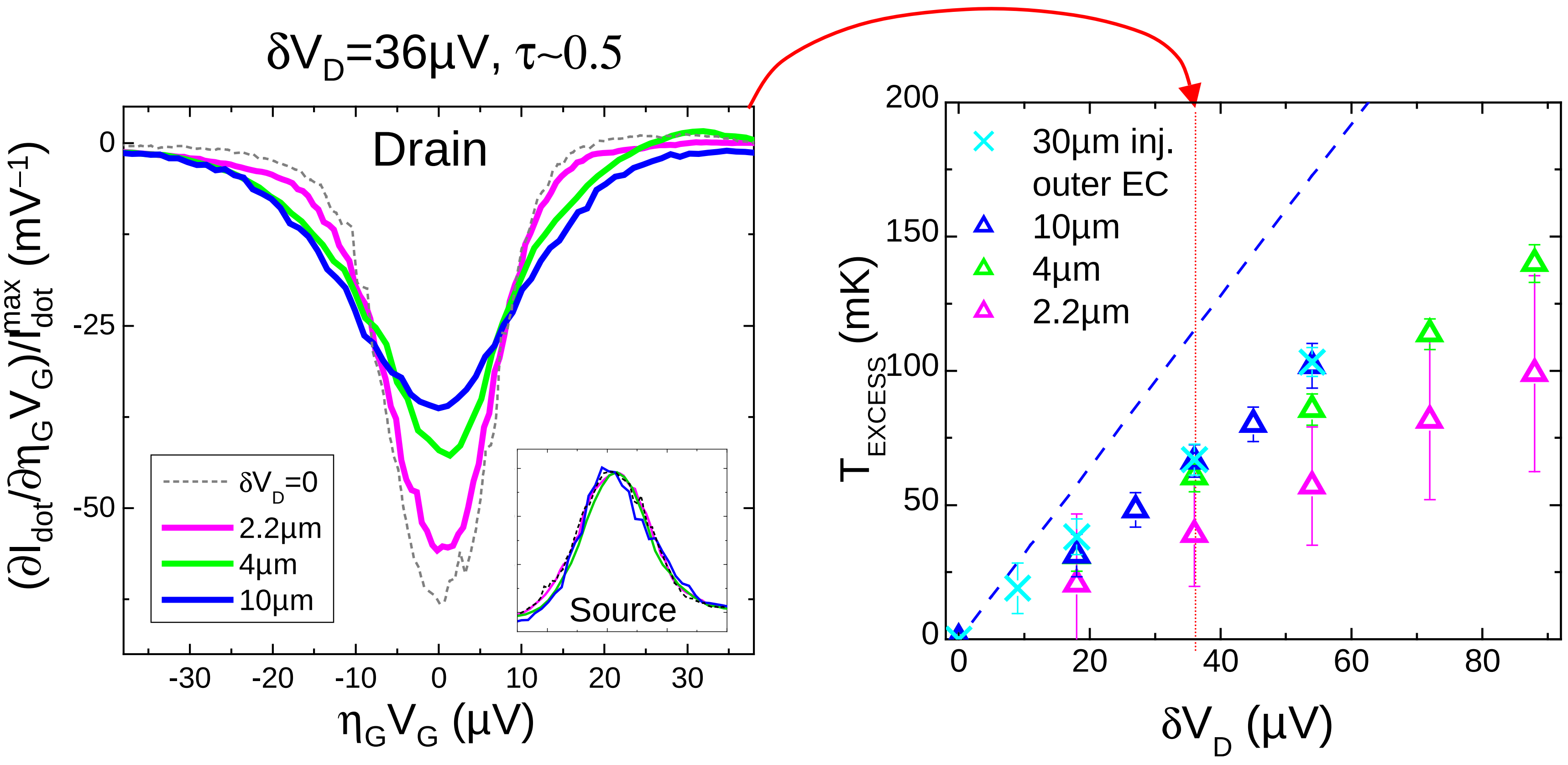
Energy injection in inner EC

f(E) meas. in outer EC (L=2.2µm)



Test of energy exchanges between ECs

Energy injected in inner EC, f(E) measured in outer EC

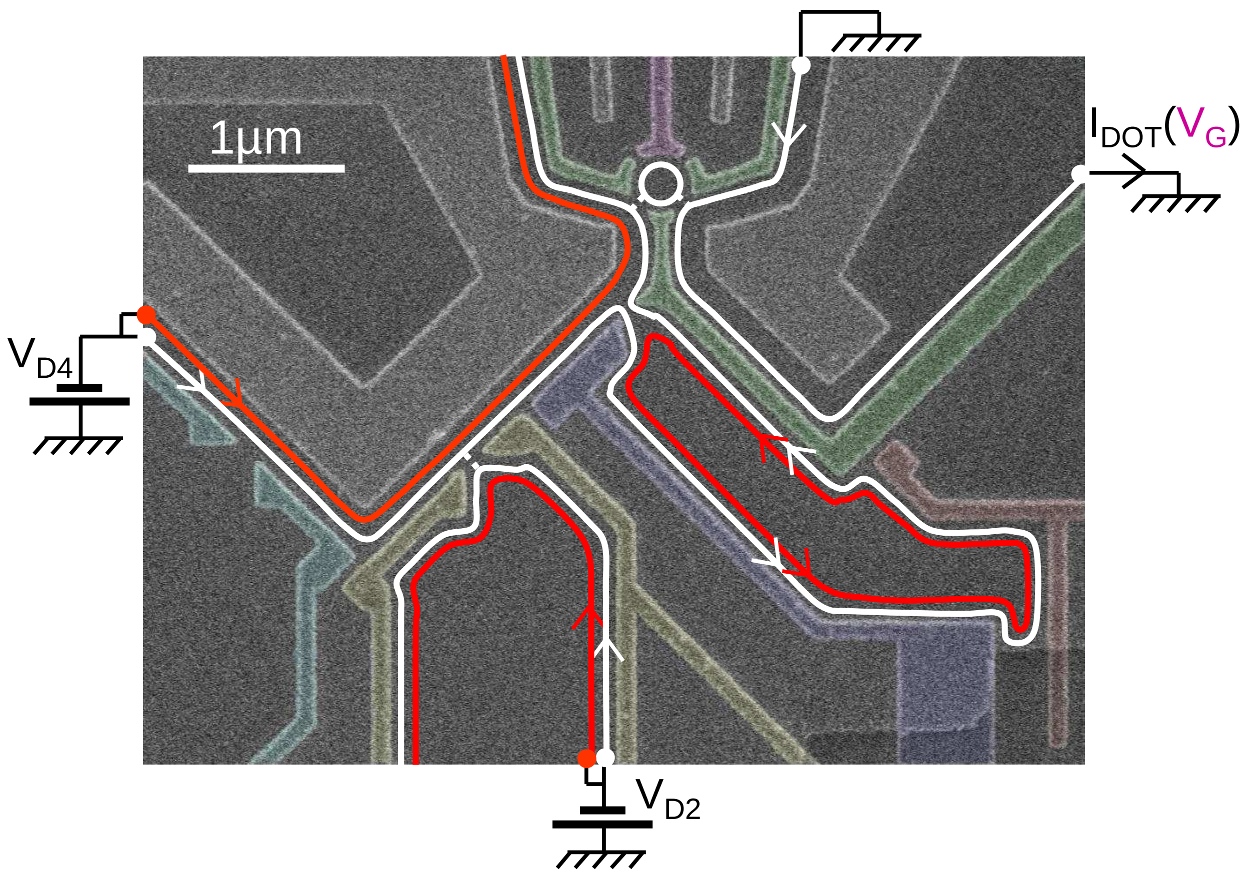


∃ energy exchanges between ECs!

Test energy exchanges with "rest of the world"

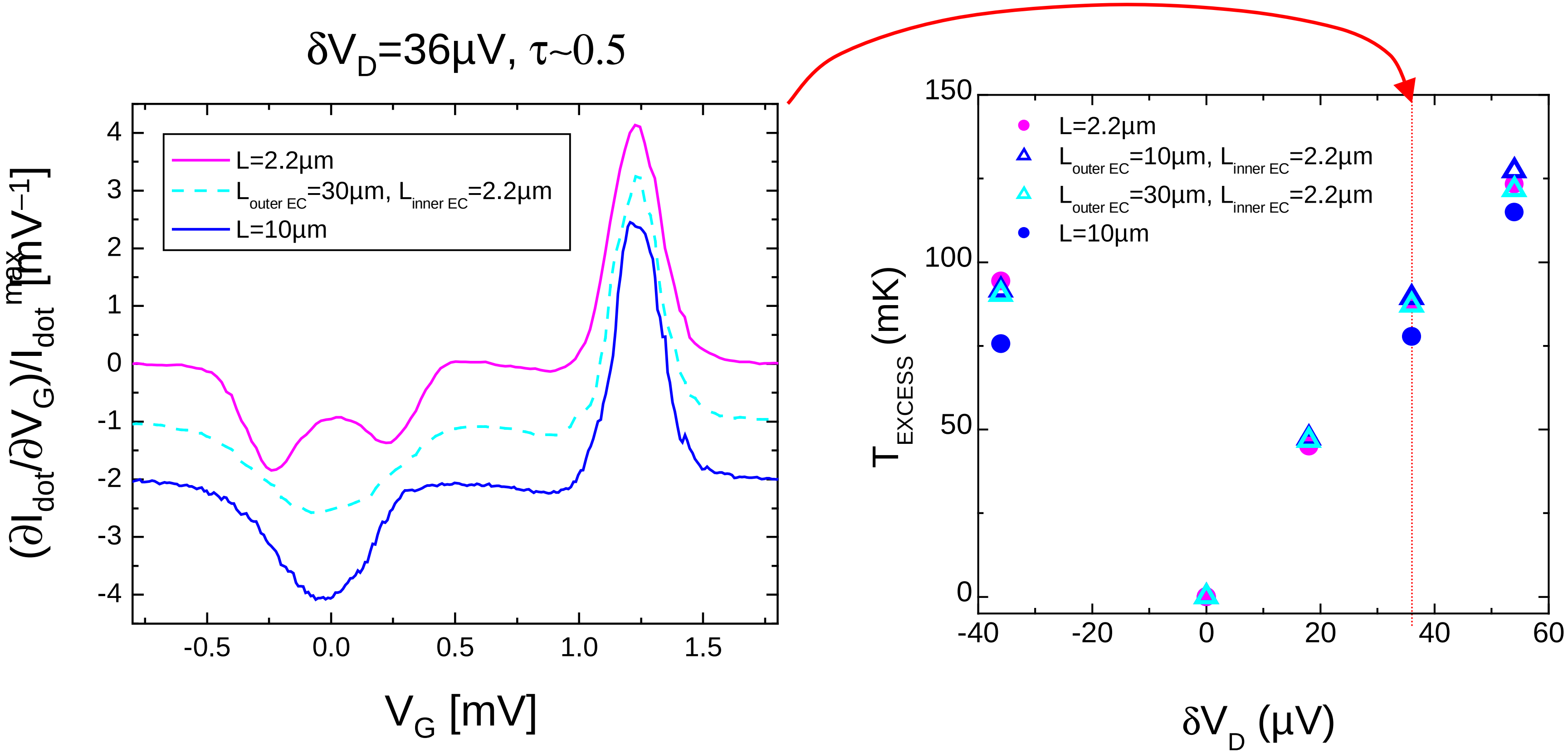
Closed loop inner EC

no loss of energy in outer EC resulting from coupling with inner EC



Test energy exchanges with "rest of the world"

Closed loop inner EC



Energy in outer EC is conserved

➡ No energy exchanges with "rest of the world"!

Check-point summary

- Main experimental observations:

> - ECs are exchanging energy
> - No energy exchange with rest of the world

⇒ No significant energy exchanges with:
internal outer EC modes, phonons, top metal gates, other deg of freedom

⇒ Most likely mechanism: *strong inter ECs Coulomb interactions* (as in MZI)

- Observed typical inelastic length:

> $L_{in}[T_{qp}=125\text{mK}] \sim 2.5\mu\text{m}$

⇒ *Similar to MZI dephasing:* $L_\phi \sim 20\mu\text{m}/(T/20\text{mK}) \Rightarrow L_\phi[125\text{mK}] \sim 3\mu\text{m}$

⇒ *1D chiral Fermions in EC not well defined excitations:*

Heisenberg time-energy uncertainty ⇒

$\Delta E[125\text{mK}] > h/4\pi\tau_{in} \approx 150\text{mK}$ $\quad (v_D \approx 10^5\text{m/s})$

Turning on interactions

Beyond perturbation

Non-perturbative *inter* EC ρ-ρ interactions (ν=2)

$$H = \pi\hbar \mathrm{v}_{\mathrm{inner}} \int dx\, \rho_{inner}^2(x) + H_{\mathrm{outer}} + \pi\hbar \mathrm{v}_{\mathrm{int}} \int dx\, \rho_{inner}(x) \rho_{outer}(x)$$

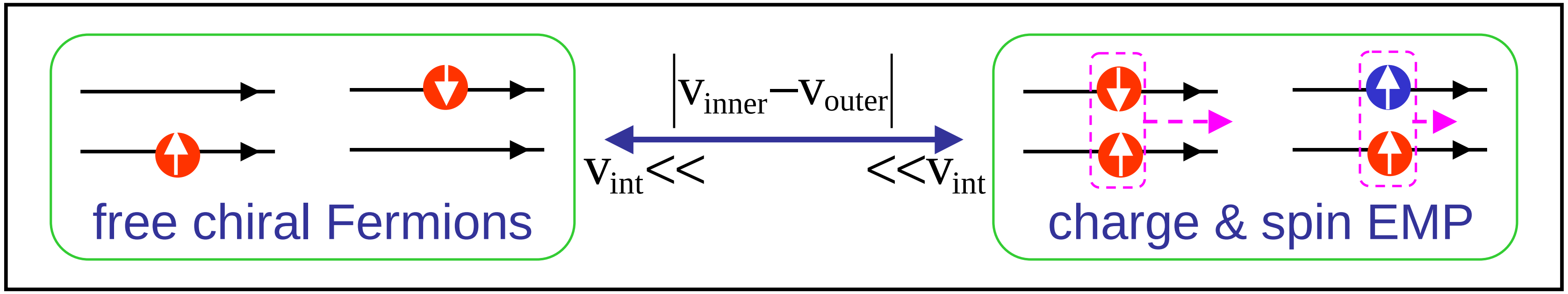
$$\Rightarrow \quad H = \pi\hbar \mathrm{v}_{\mathrm{C}} \int dx\, \rho_C^2(x) + \pi\hbar \mathrm{v}_{\mathrm{S}} \int dx\, \rho_S^2(x)$$

Free bosons delocalized on both ECs ≠ quasiparticles

Simple limit: $\mathrm{v}_{\mathrm{inner}} = \mathrm{v}_{\mathrm{outer}}$

$$\begin{cases} \rho_C = \frac{1}{\sqrt{2}}(\rho_{inner} + \rho_{outer}) \\ \rho_S = \frac{1}{\sqrt{2}}(\rho_{inner} - \rho_{outer}) \end{cases} \Rightarrow \text{spin-charge separation}$$

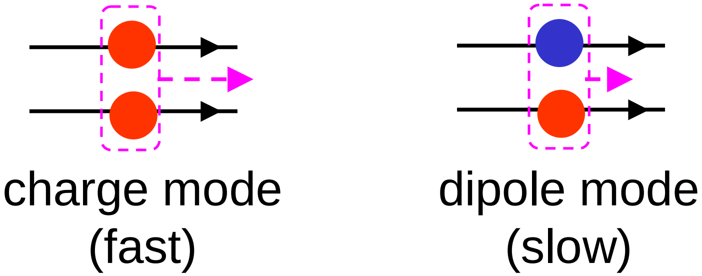
Wen (PRL 1990); Levkivskyi & Sukhorukov (PRB 2008)



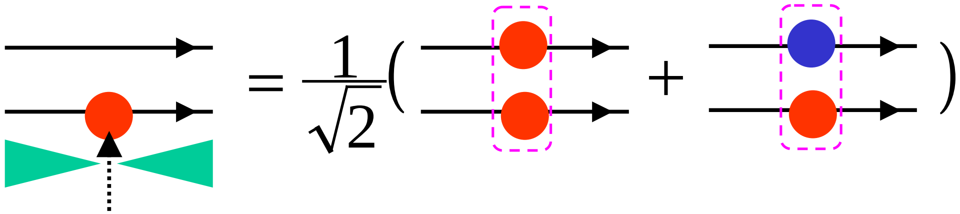
Energy exchanges within the edge magnetoplasmons model

- ν=2, strong ECs interaction

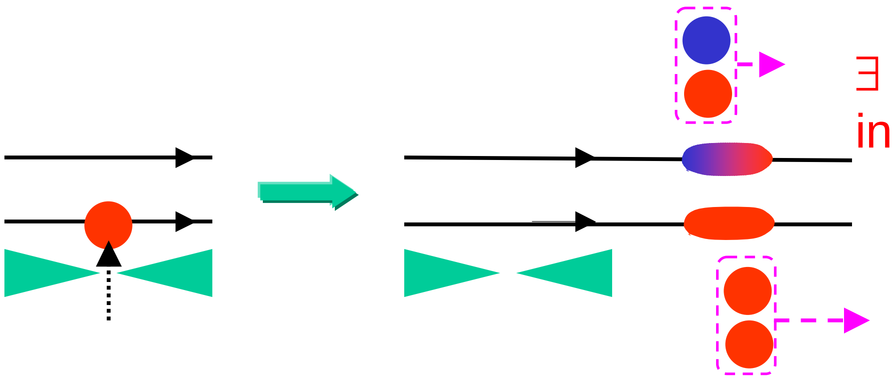
  Levkivskyi & Sukhorukov (PRB 2008)



- QPC excites 1 EC



- Time evolution:

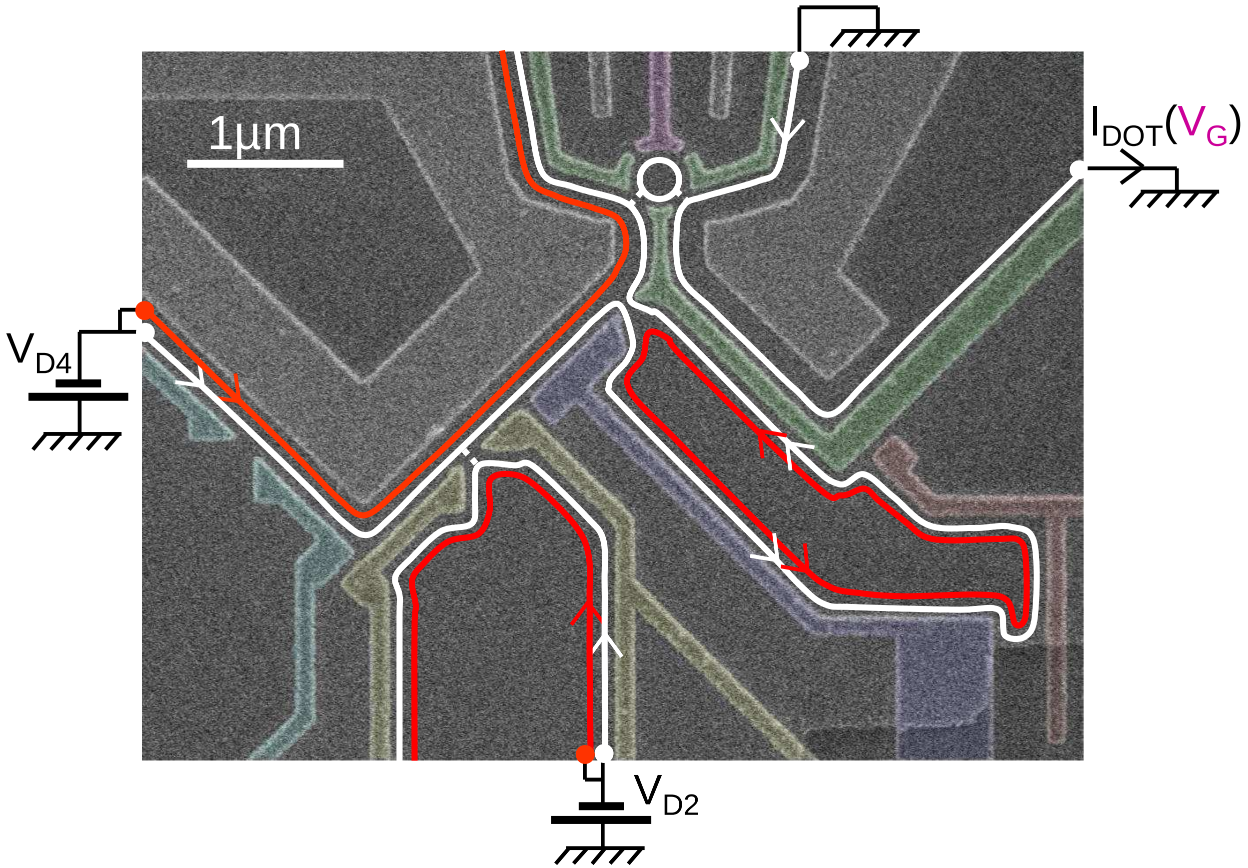


Tuning down interactions

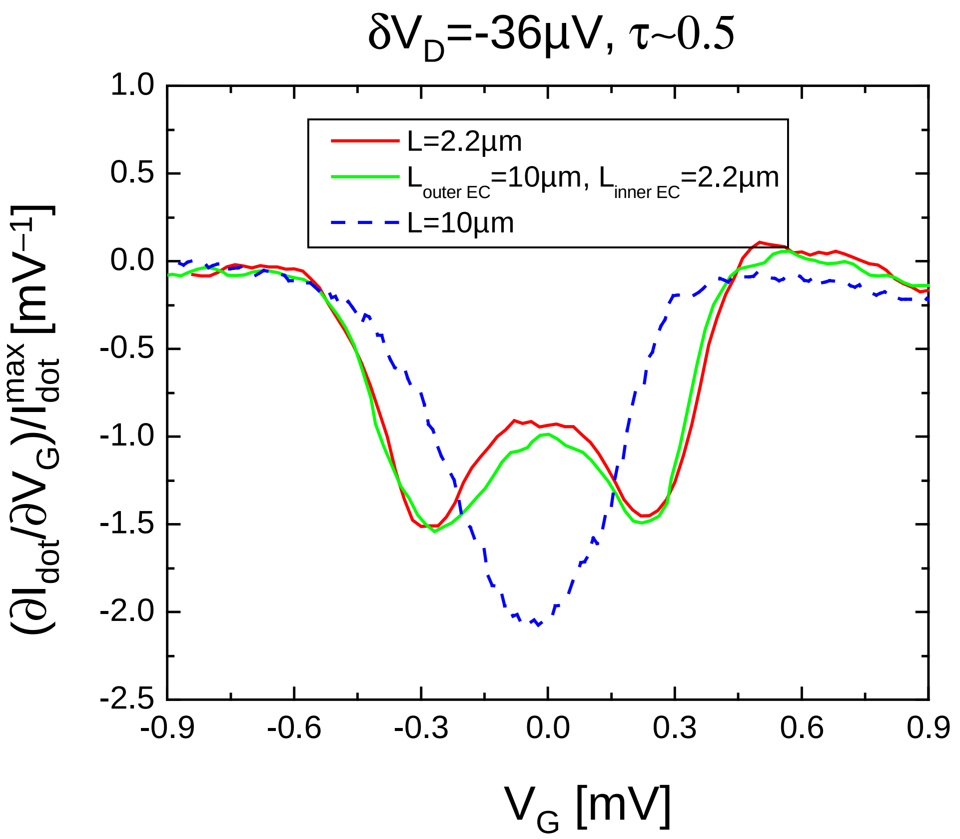
By closing the inner EC on a smaller loop (7.5µm)

Level quantization in closed inner EC

L_{loop}=7.5µm, V_{drift}=10^5m/s ⇒ ΔE=55µeV

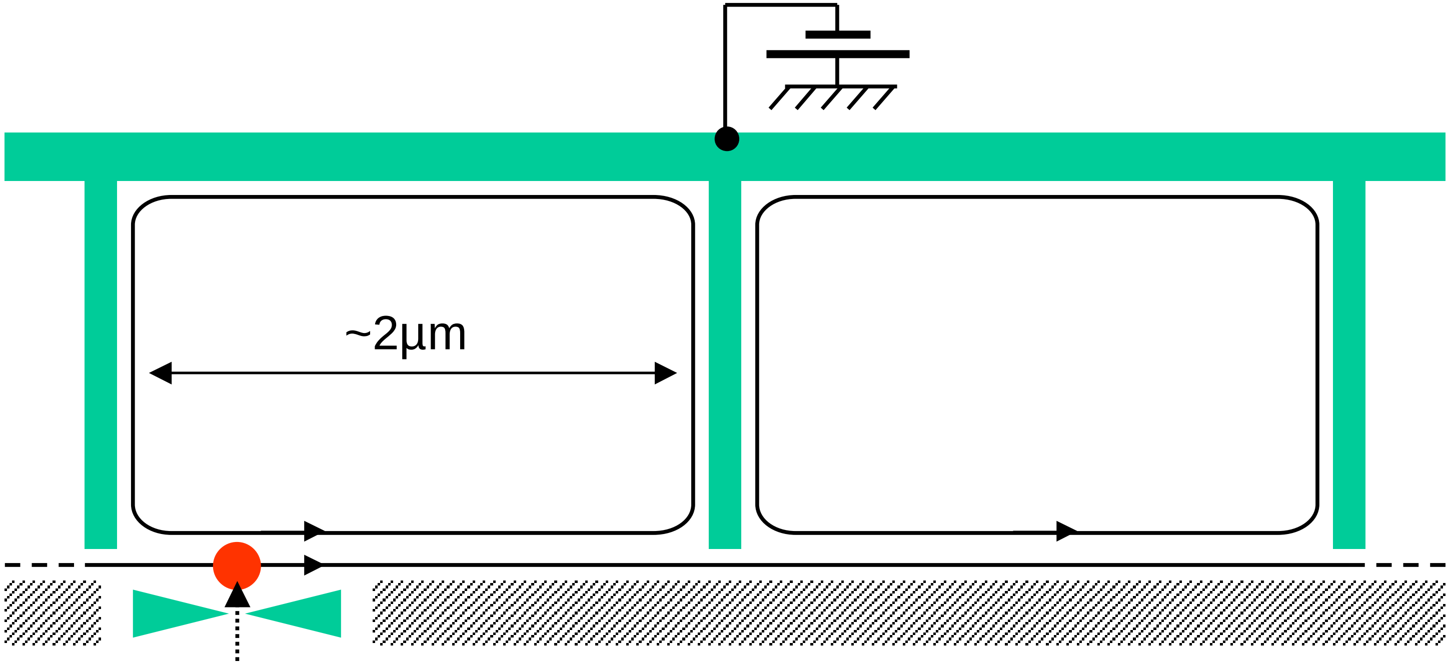


Tuning down interactions



Strongly reduced energy redistribution!

Practical implementation



Experimental implementation on MZI in progress…

(coll. P. Roche *et al.*)

Carles Altimiras

Hélène le Sueur

Ulf Gennser

Antonella Cavanna

Dominique Mailly

Thanks:

Giancarlo Faini, Romain Giraud, Yong Jin

Christian Glattli, Fabien Portier, Patrice Roche, Preden Roulleau

Daniel Estève, Philipe Joyez, Hugues Pothier, Cristiàn Urbina

Founding agency: ANR