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Observing separate spin and charge Fermi seas in a strongly correlated one-dimensional conductor

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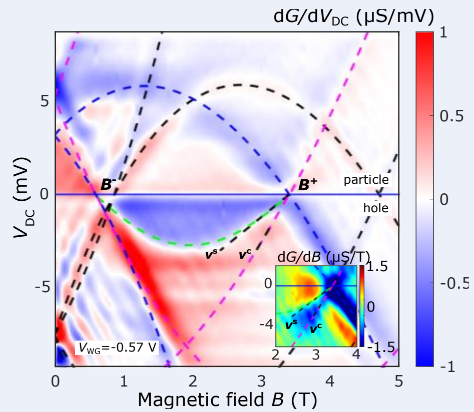
Vianez *et al.*, *Science Advances* **8**, eabm2781 (2022)
Vianez *et al.*, arXiv: 2110.14539
Jin, Vianez *et al.*, *Appl. Phys. Lett*. **118**, 162108 (2021)

Semiconductor Physics Group, Cavendish Laboratory

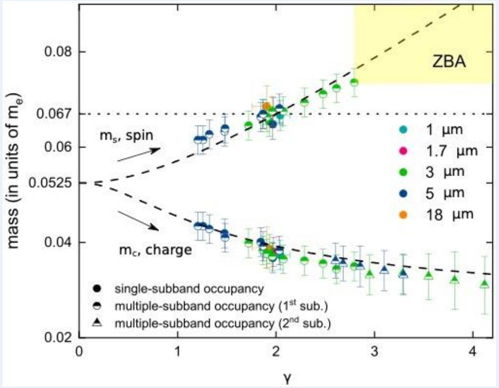
EPSRC Engineering and Physical Sciences Research Council

Outline

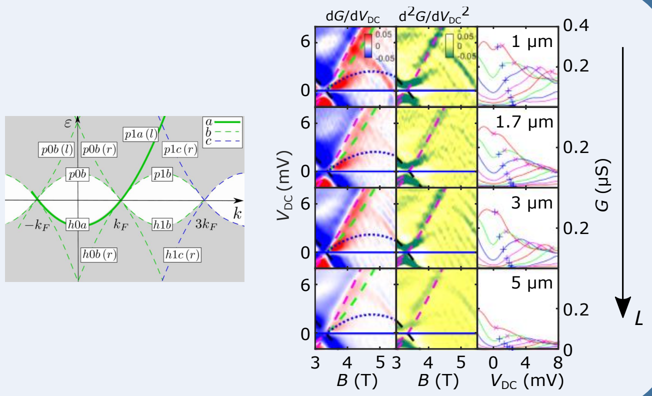
Two Fermi Seas



Electron mass in 1D GaAs



A Hierarchy of Modes



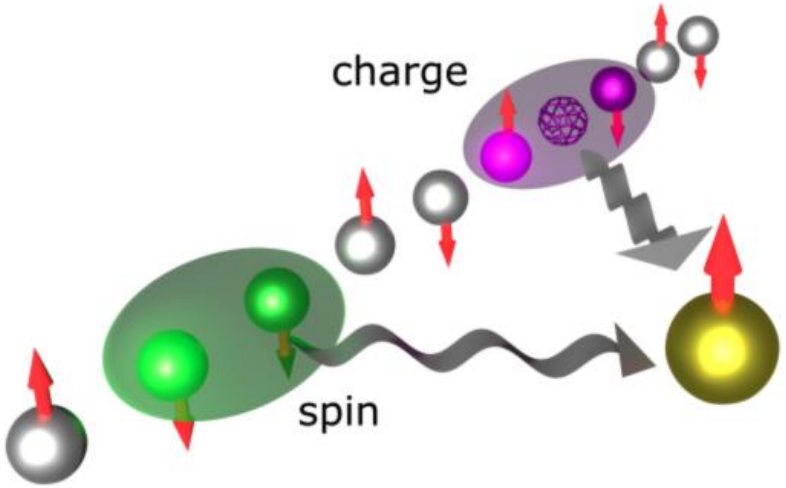
Acknowledgements

Experiment

- University of Cambridge, UK
  - Yodchay Jompol, Yiqing Jin, María Moreno, Wooi Kiat Tan, Ankita Anirban, Jonathan Griffiths, David Ritchie
- Université Paris Diderot, France
  - Anne Anthore

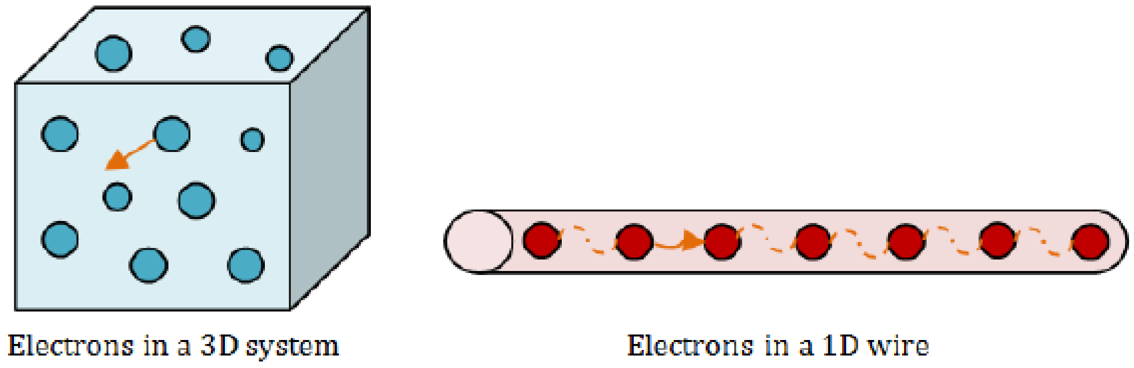
Theory

- Universität Frankfurt, Germany
  - Oleksander Tsyplyatyev
- Lancaster University, UK
  - Andrew Schofield



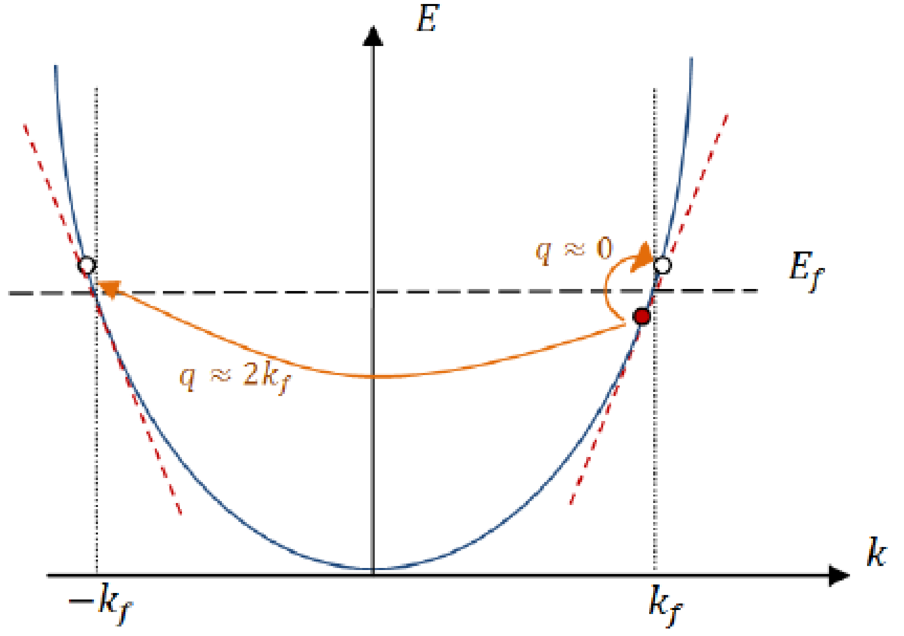
Can we observe interacting electrons?

- One-dimensional (1D) systems are of interest because they give rise to phenomena not detectable in their higher-dimensional counterparts;
    - High correlations + strong Coulomb interactions



Tomonaga-Luttinger Liquid (TLL) model

- Consider a 1D system of interacting electrons
  - Electrons **cannot** pass each other;
  - Due to the confinement, the motion of one electron cannot be modelled as a quasiparticle behaving freely (i.e. Fermi liquid is unstable);
  - Exciting one electron will perturb the entire system (i.e. all modes of excitation are **collective**);



- Tomonaga-Luttinger Liquid (TLL) model:
  - Assumes dispersion relation near the Fermi points is **linear**;
  - Only applicable in the **low-energy regime** and for **infinite-length** systems.

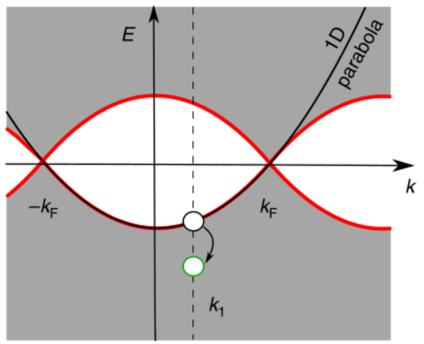
- **Can we measure the dispersion of a finite 1D system away from the Fermi points?**

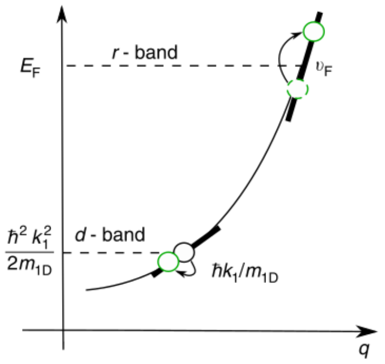
Excitations beyond the linear approximation

- Recent theoretical techniques to cope with **curved dispersion**

Mobile-Impurity Model

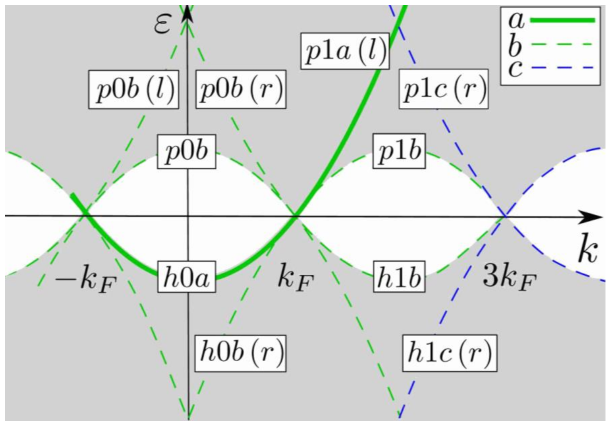
  - Power-law onset as for TLL (Imambekov & Glazman, Science (2009); Schmidt, Imambekov & Glazman, PRB (2010));
  - Recently, we reported the observation of a momentum-dependent power law in an interacting nonlinear TLL (Jin *et al.*, *Nat. Commun.* **10**, 2821 (2019)).





Hierarchy of Modes Model

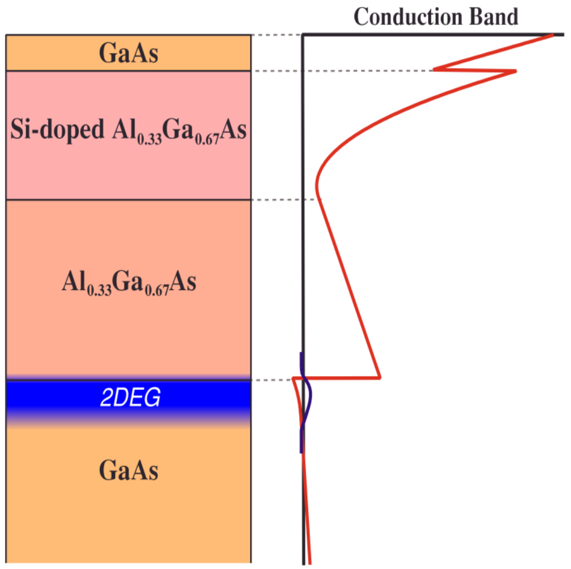
  - Length-controlled emergence of higher-order modes away from the Fermi points (Tsyplatyev *et al.* PRL **114**, 196401 2015; PRB **93**, 075147 2016);
  - “Replicas” should be much weaker, by $(\mathfrak{R}^2/L^2)^n$, where $\mathfrak{R}$ is an interaction factor and L the length of the system;

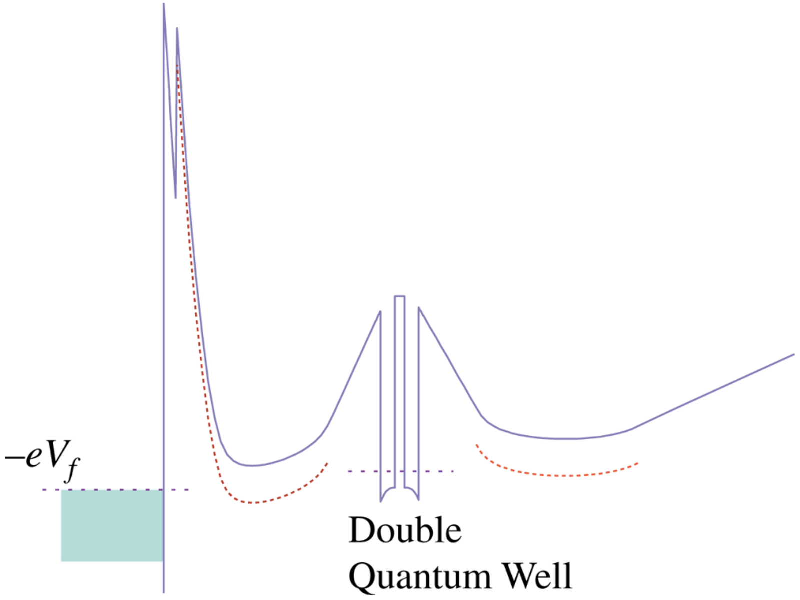


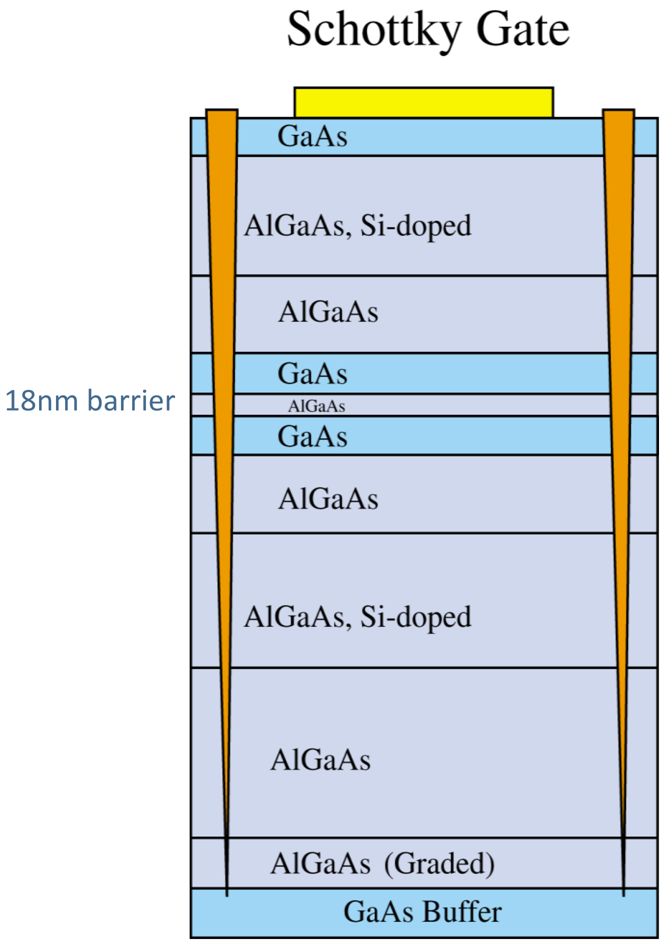
- **Can we measure these effects?**

Mapping out the spectral function of the 1D system

- Bi-layer **GaAs-AlGaAs** heterostructure:
  - Band offsets leads to 2D potential wells;
  - Doping offset from wells to reduce scattering.
- Tunnelling is measured from one layer to the other.







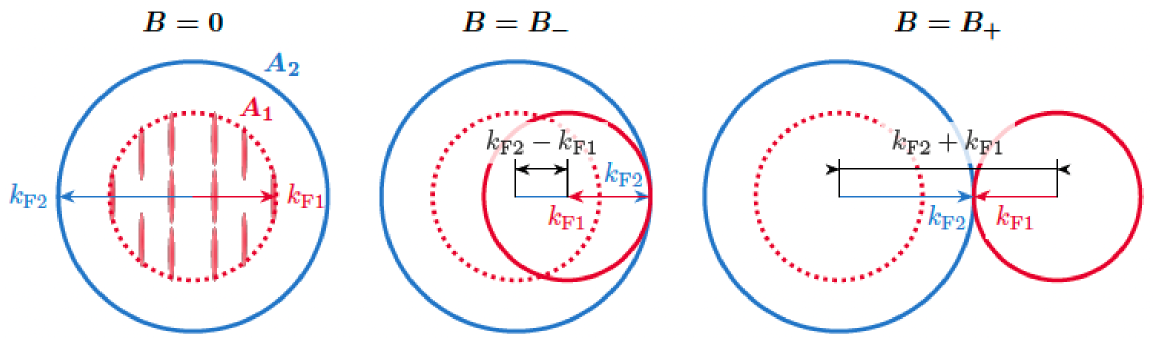
Magnetotunnelling Spectroscopy

- **Tunnelling spectroscopy** allows us to probe systems by analysing their dispersion relations
  - Typically done by measuring the tunnelling current between two systems while varying the **energy** and the **momentum** of the electrons;

$$I \propto \int d\boldsymbol{k} dE [f_T(E - E_{F1D} - eV_{DC}) - f_T(E - E_{F2D})] \times A_1(\boldsymbol{k}, E) A_2(\boldsymbol{k} + ed(\boldsymbol{n} \times \boldsymbol{B})/\hbar, E - eV_{DC})$$

- **In-plane magnetic field** adds momentum $\boldsymbol{\Delta k} = \boldsymbol{eBd}/\hbar$;

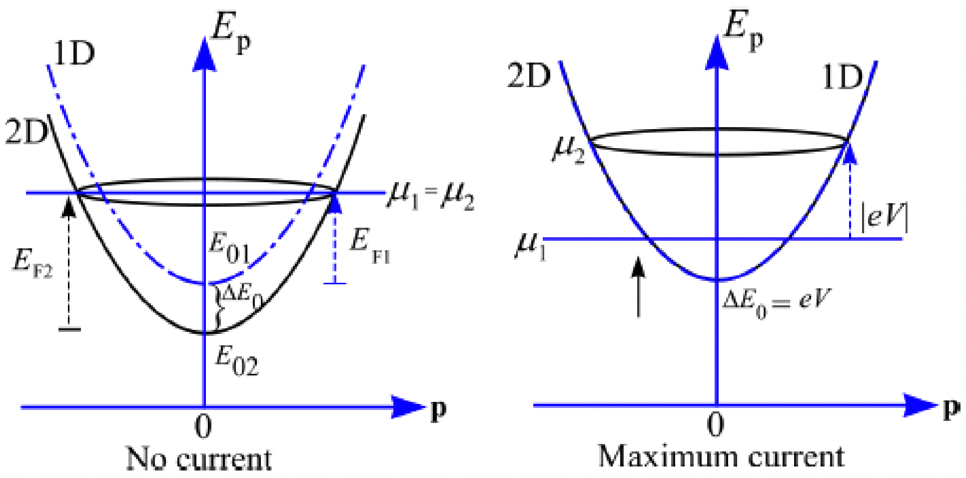
$$k_{F1} = \frac{ed}{2\hbar}(B_+ - B_-) \qquad k_{F2} = \frac{ed}{2\hbar}(B_+ + B_-)$$

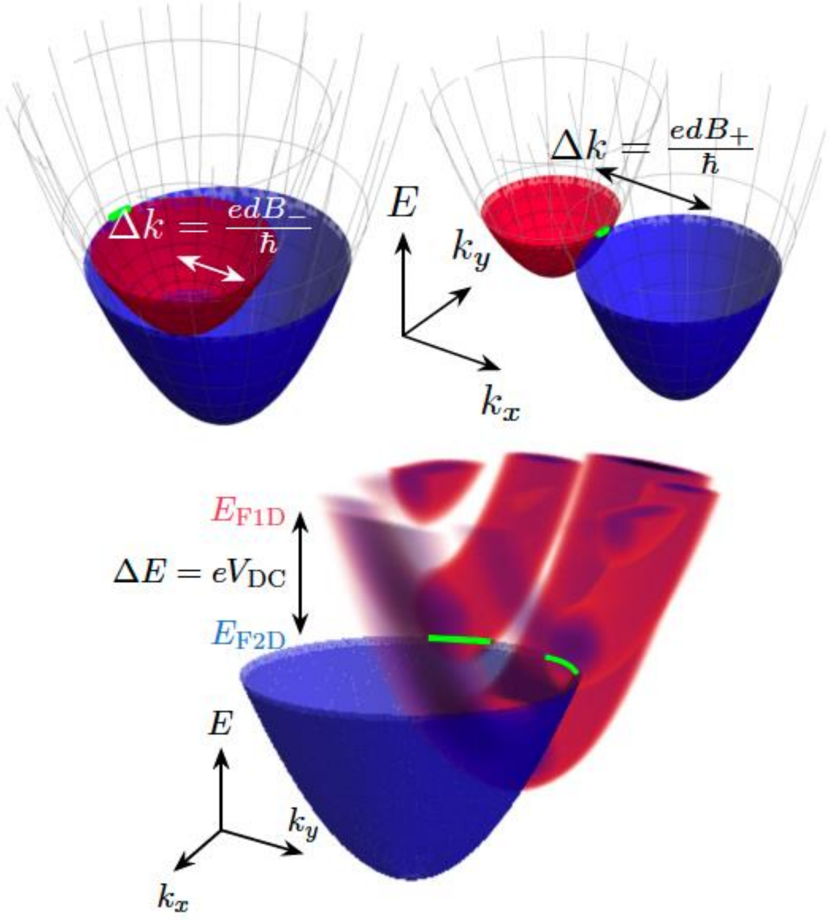


Magnetotunnelling Spectroscopy

- **DC bias** between the wells boosts in **energy**;

  $\Longrightarrow$ tunnelling current when Fermi surfaces overlap.





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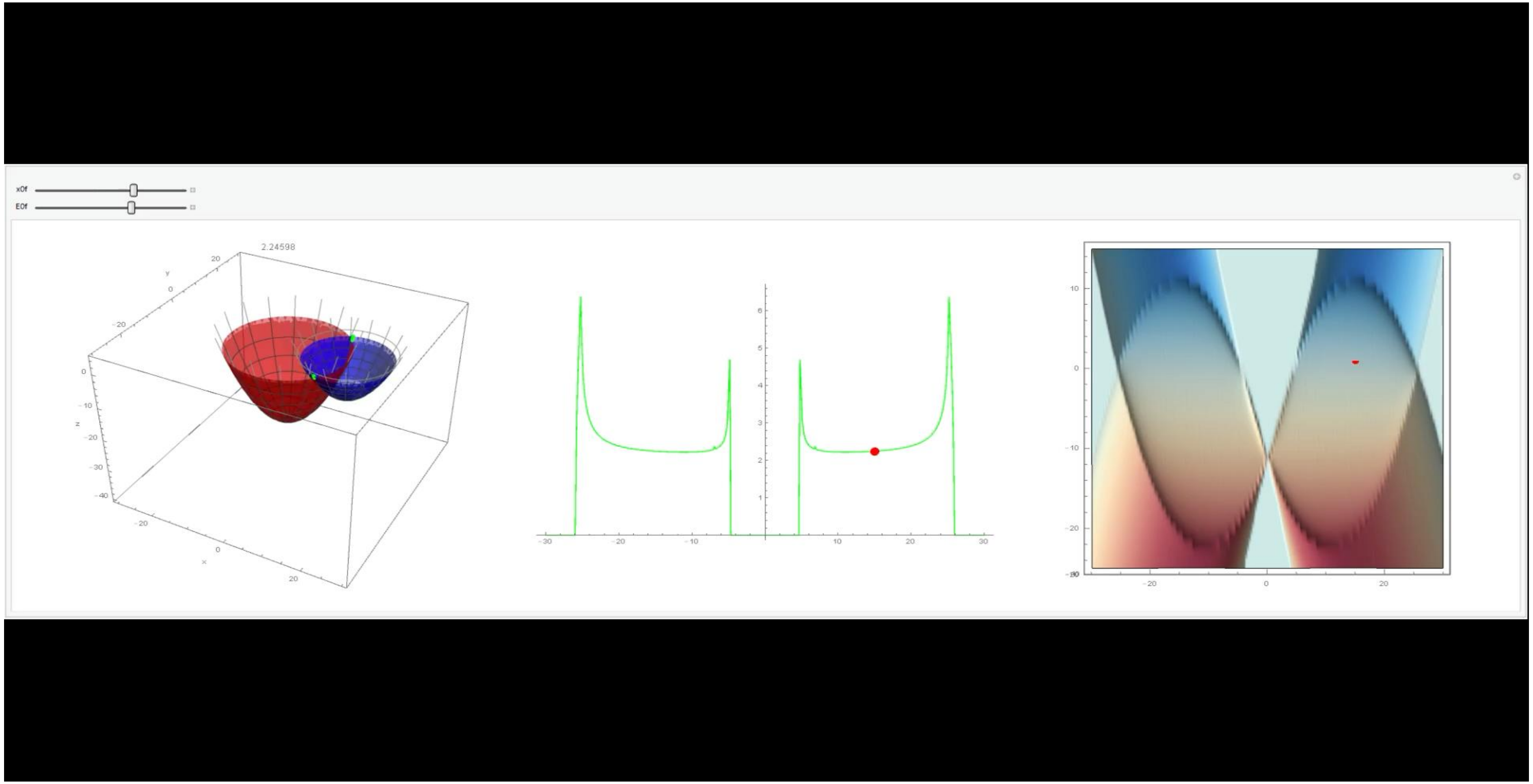
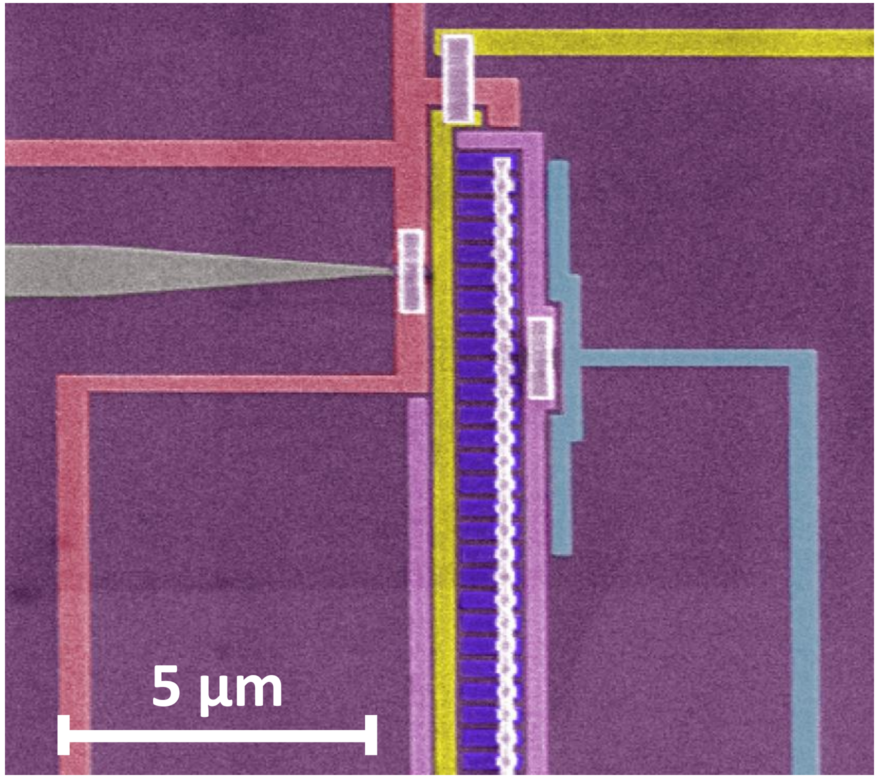
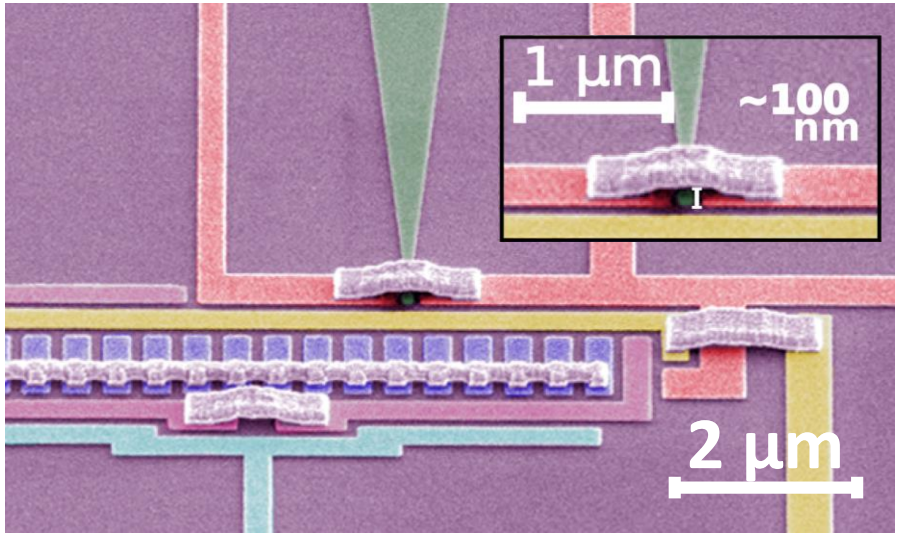


Vertical Tunnelling Device

- Double QWs **GaAs-AlGaAs** heterostructure:





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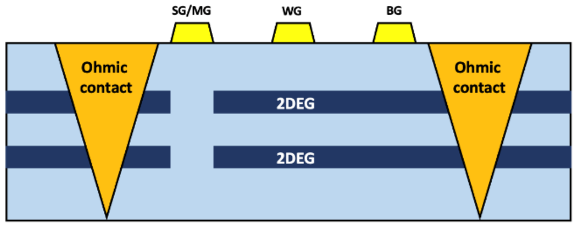
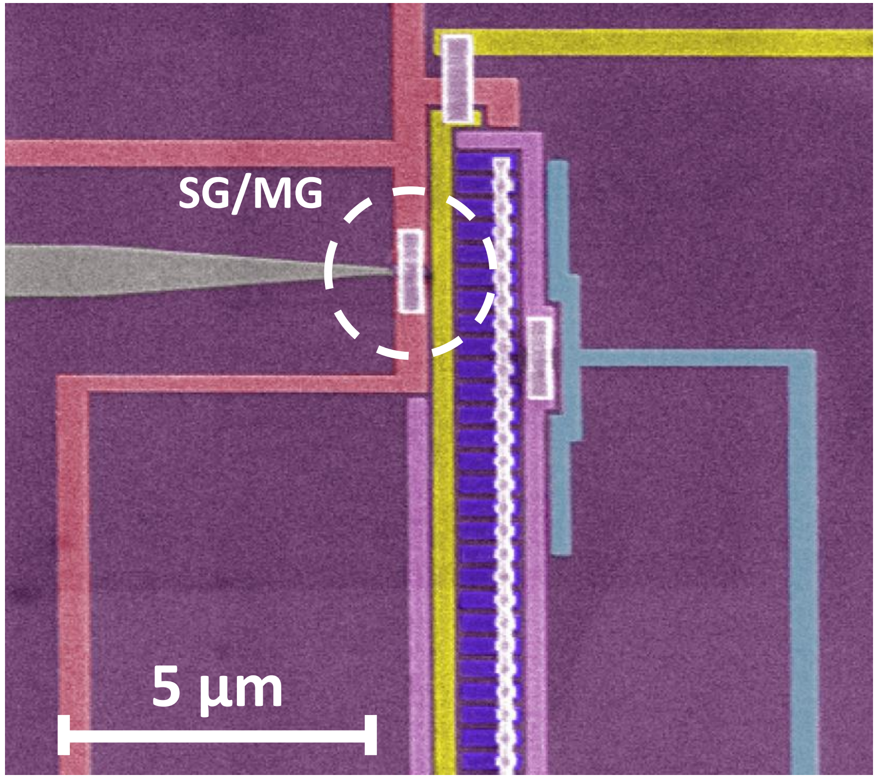
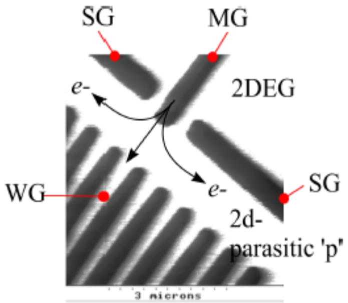
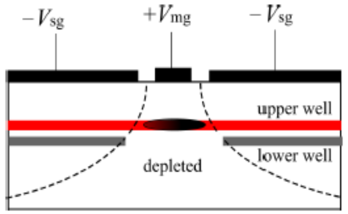
Device design

- "Split gate-mid gate" scheme
  - Ohmics contact both layers
  - Deplete lower 2DEG with V_{SG}
  - Induce upper wire with V_{MG}









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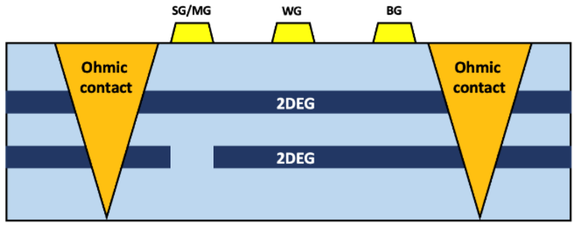
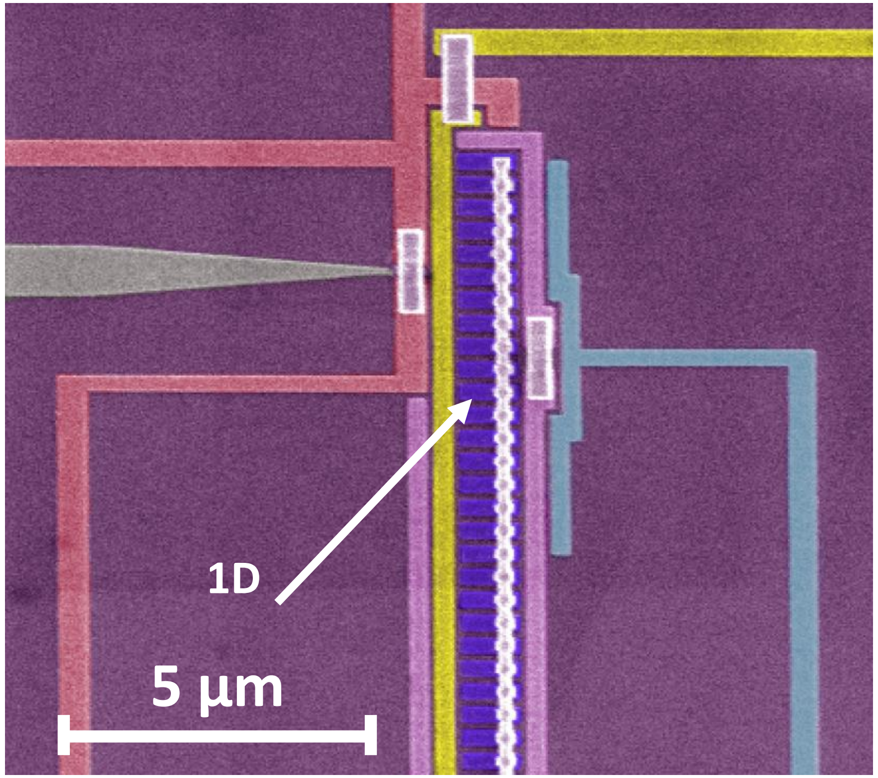


- 400x 1,1.7,3,5, 10 or 18-µm long gates
  - Produces array of 1D wires in the upper layer when V_{WG}<0



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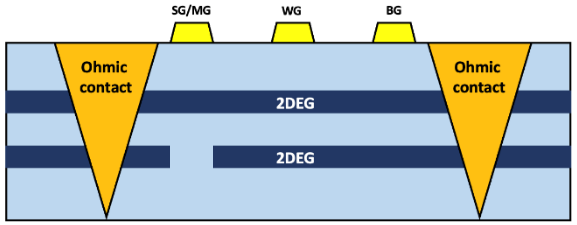

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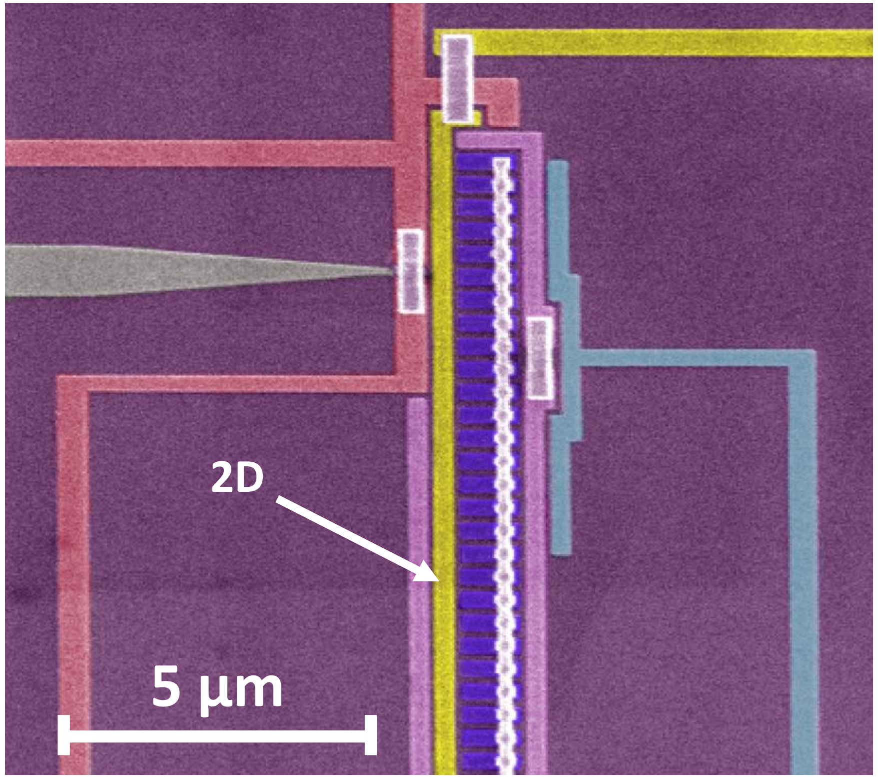
  - Small 'parasitic' region 'p', separate (2D) behaviour



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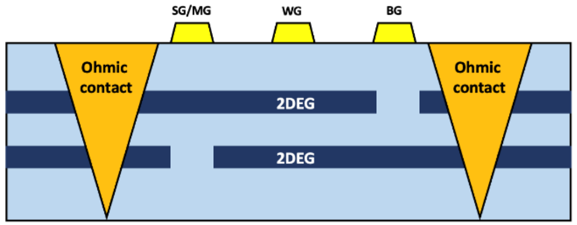

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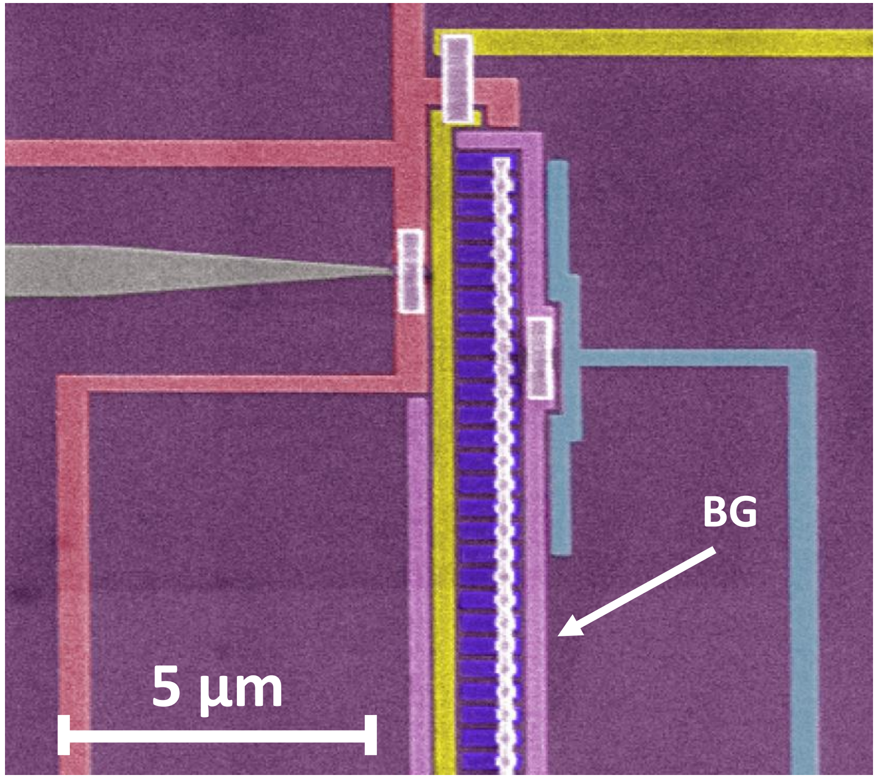

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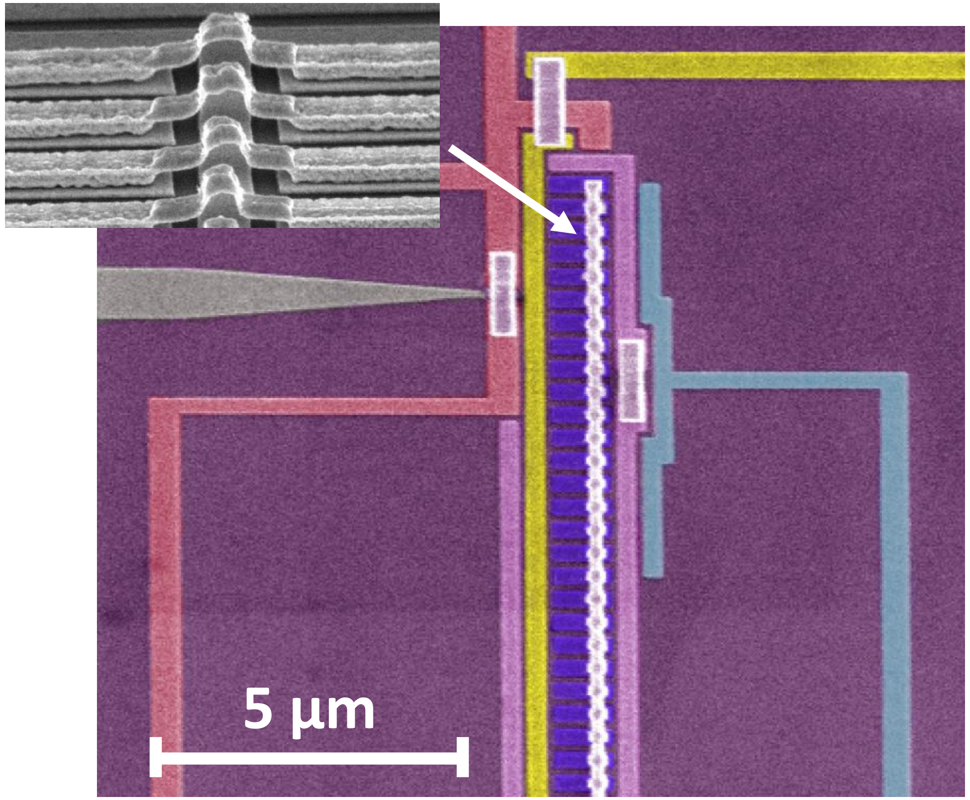
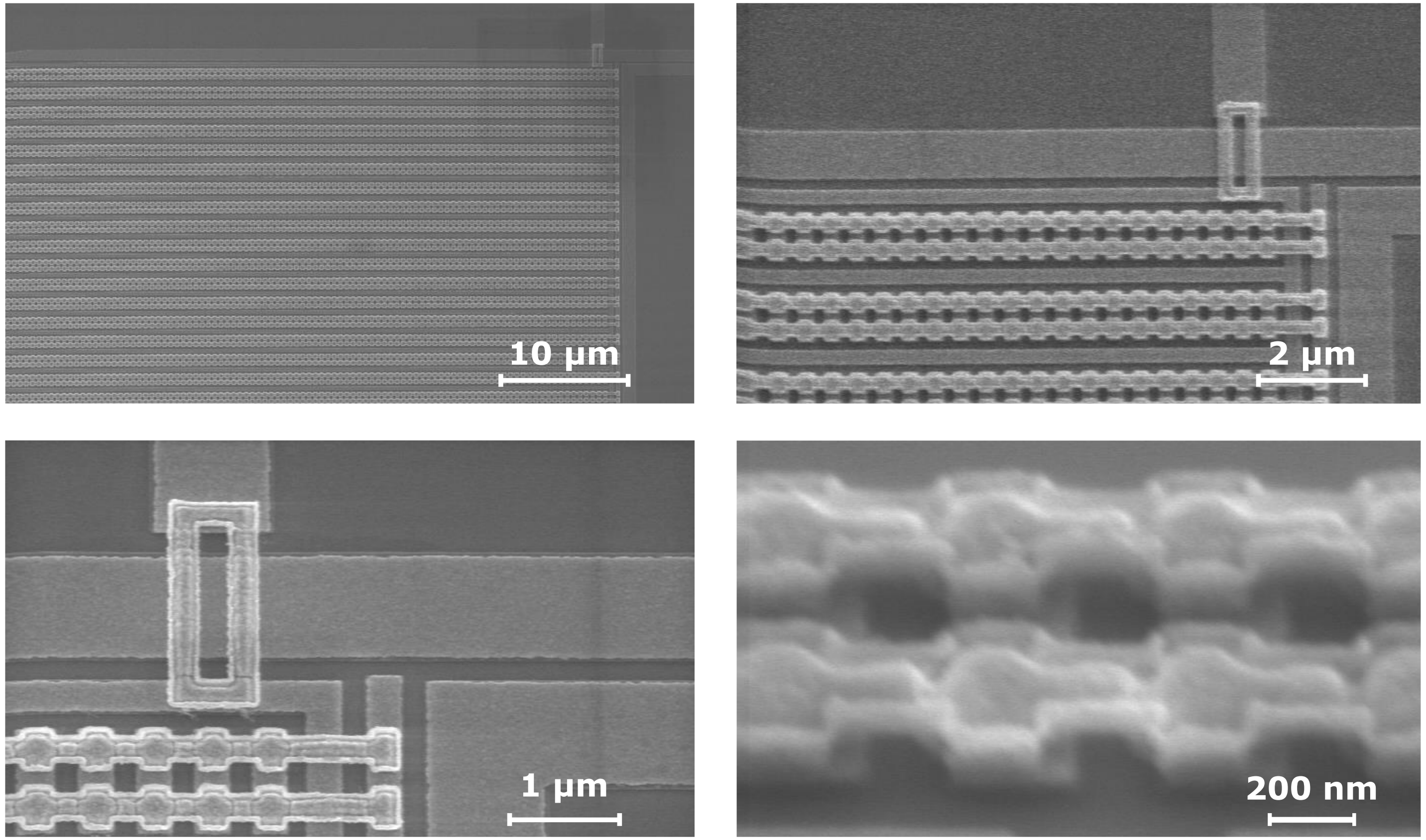
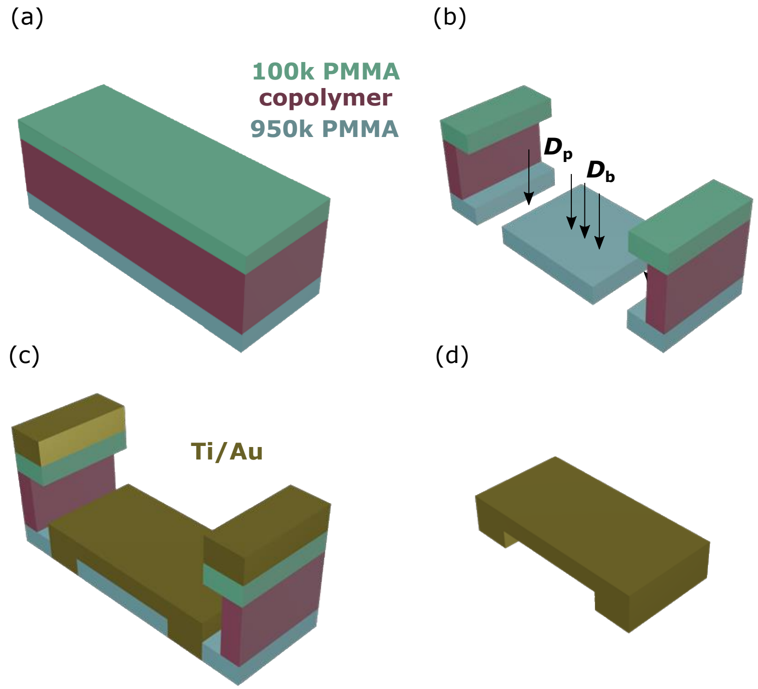
- Bar gate ensures no current reaches drain contact without tunnelling to lower layer
- For short wires (<3µm), avoid join at ends to get high uniformity
  - Connect gates via air bridges



Microscopic air-bridge structures for connecting nanodevices



Jin, Vianez *et al., Appl. Phys. Lett.* **118**, 162108 (2021) [Featured and Scilight]



- Over 6000 bridges on-chip
- Up to 10 μm in length

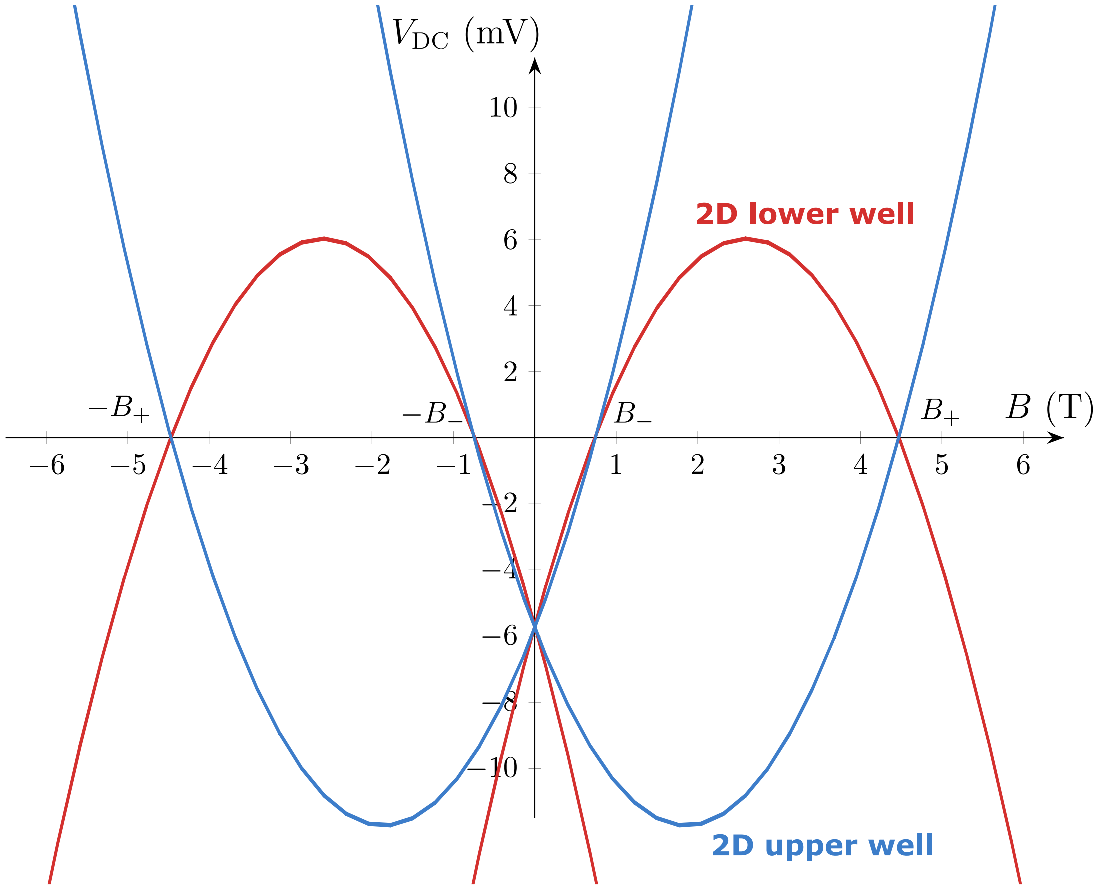
Example: 2D-2D tunnelling

$$eV_{DC} = \frac{\hbar^2}{2m_{2D}^*}\left[k_{F1}^2 - \left(k_{F2} \pm \frac{eBd}{\hbar}\right)^2\right]$$

$$eV_{DC} = \frac{\hbar^2}{2m_{2D}^*}\left[\left(k_{F1} \pm \frac{eBd}{\hbar}\right)^2 - k_{F2}^2\right]$$

$$k_{F1} = \frac{ed}{2\hbar}(B_+ - B_-) \qquad k_{F2} = \frac{ed}{2\hbar}(B_+ + B_-)$$

- *d* is known from MBE
- missing correction for capacitance- COMSOL simulation
  $\Longrightarrow$ extract m_{2D}^*



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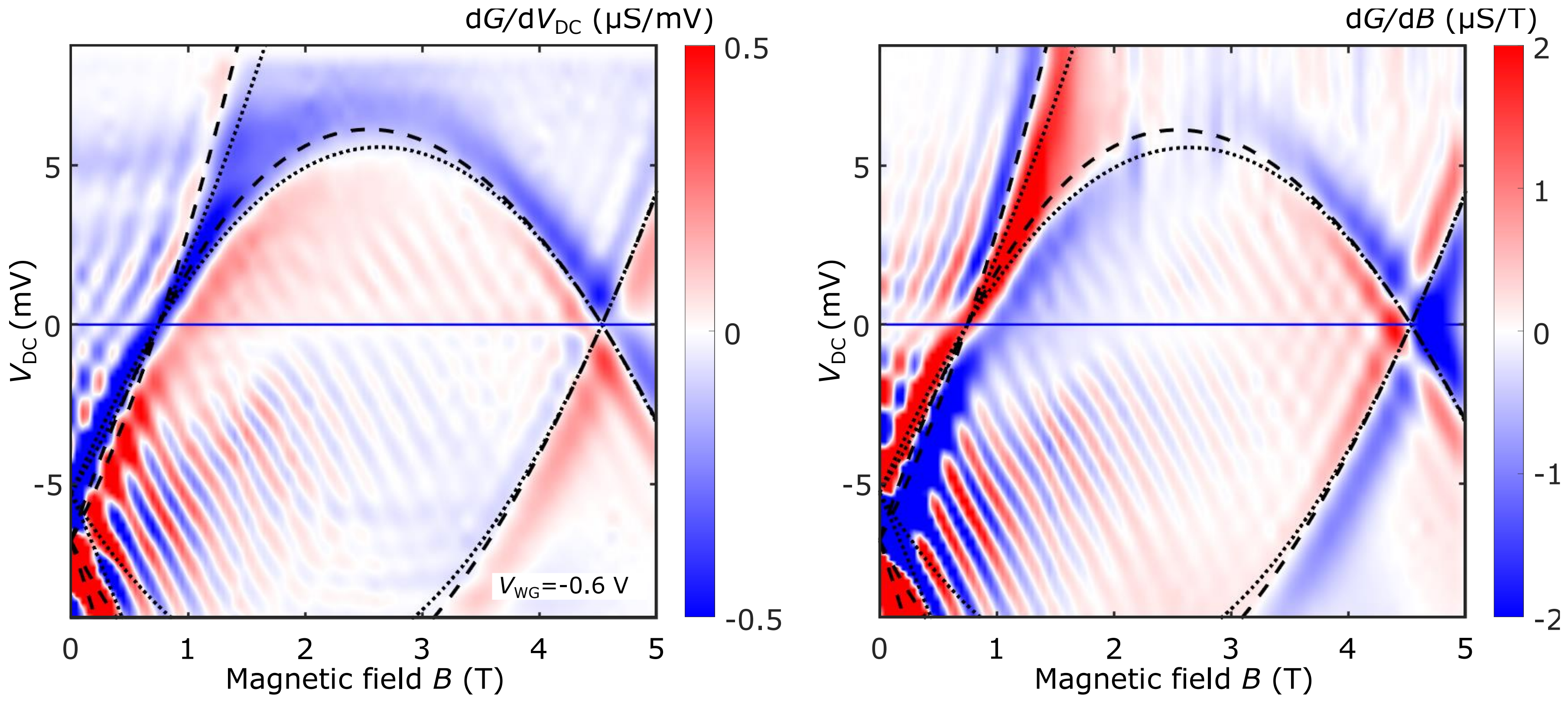

- MBE value: d=32 nm
- C_{COMSOL} = 0.047 Fm^{-2}

Fitting parameters:

- d = 31 nm
- C_{UW}^{2D} = 0.047 Fm^{-2}
- C_{LW}^{2D} = 0.033 Fm^{-2}
- $m_{2D}^{*} = (0.062 \pm 0.002)m_e$

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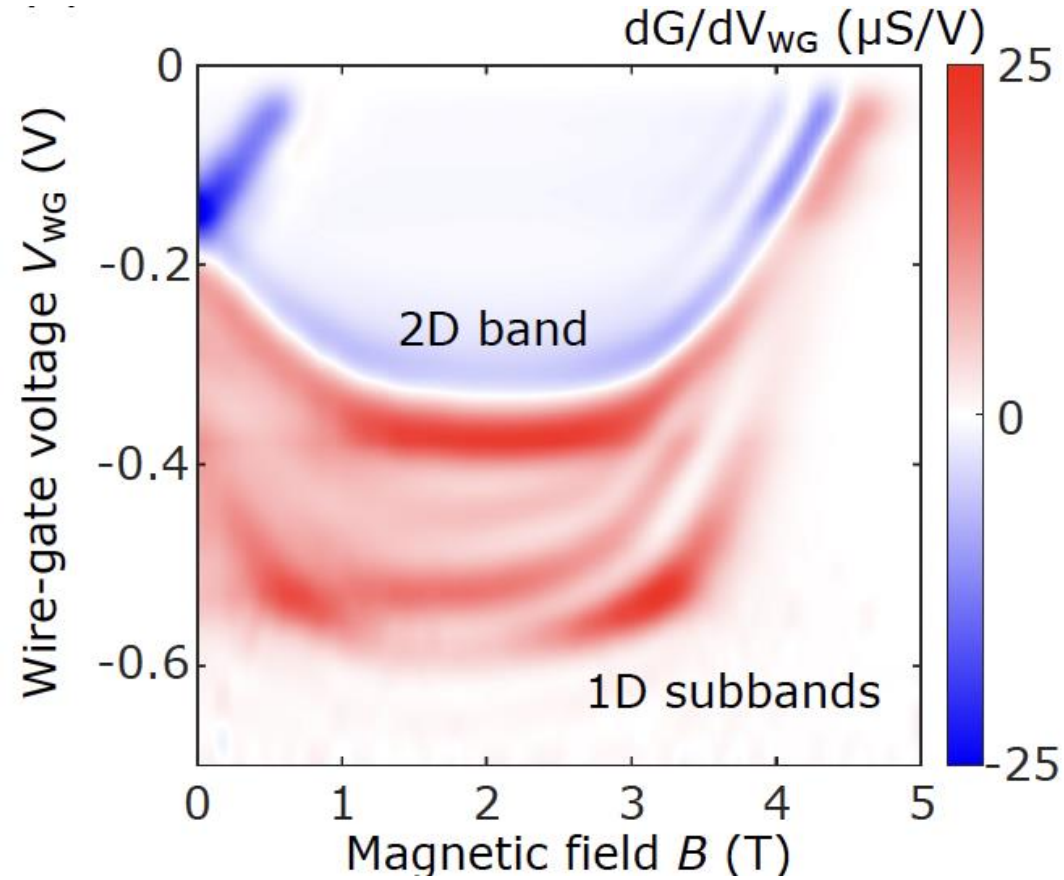
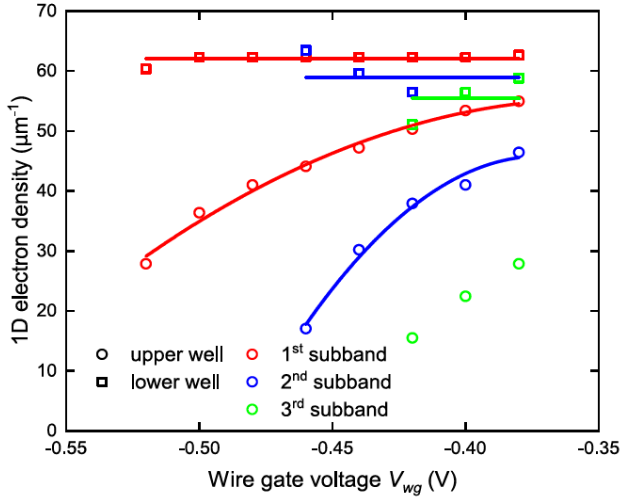
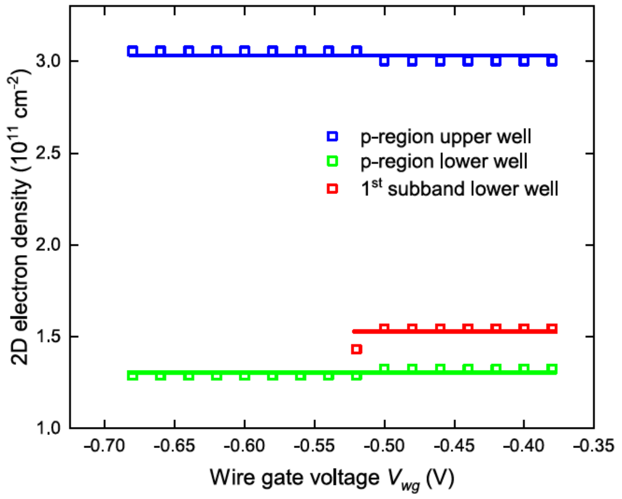
1D Wires



Top QW- 1D



Bottom QW-2D



- n_{1D}~18-55 μm^{-1} → $r_s \propto E_C/E_K \sim 0.7\text{-}4$

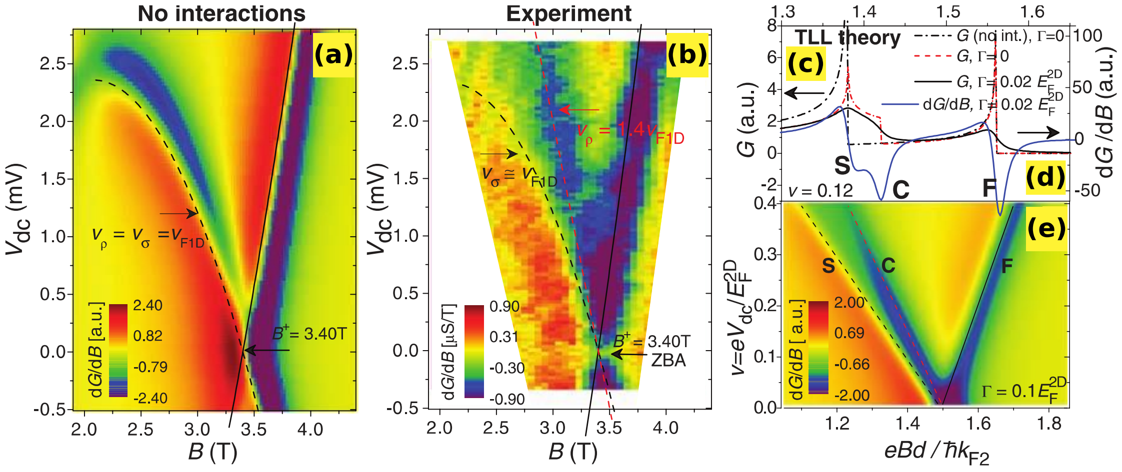
1. Two Fermi Seas for spin and charge

Spin-charge separation at high energies?

Probing Spin-Charge Separation in a Tomonaga-Luttinger Liquid

Y. Jompol,[1]* C. J. B. Ford,[1] J. P. Griffiths,[1] I. Farrer,[1] G. A. C. Jones,[1] D. Anderson,[1] D. A. Ritchie,[1] T. W. Silk,[2] A. J. Schofield[2]

In a one-dimensional (1D) system of interacting electrons, excitations of spin and charge travel at different speeds, according to the theory of a Tomonaga-Luttinger liquid (TLL) at low energies. However, the clear observation of this spin-charge separation is an ongoing challenge experimentally. We have fabricated an electrostatically gated 1D system in which we observe spin-charge separation and also the predicted power-law suppression of tunneling into the 1D system. The spin-charge separation persists even beyond the low-energy regime where the TLL approximation should hold. TLL effects should therefore also be important in similar, but shorter, electrostatically gated wires, where interaction effects are being studied extensively worldwide.



Jompol *et al., Science* **325**, 597-602 (2009)

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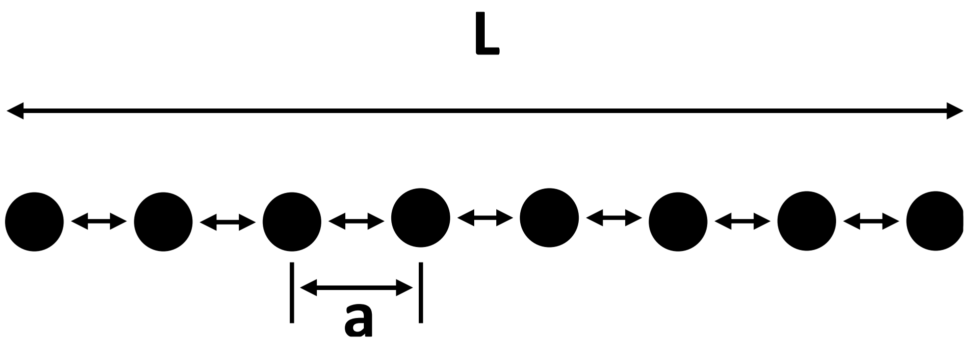
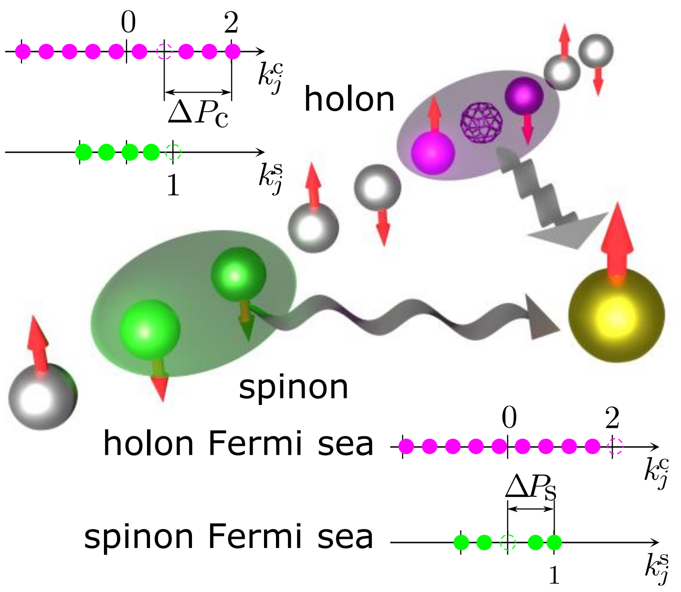
1D Fermi-Hubbard model

$$H = -t \sum_{j=1,\alpha=\uparrow,\downarrow}^{L/a} \left(c_{j\alpha}^{\dagger} c_{j+1,\alpha} + c_{j\alpha}^{\dagger} c_{j-1,\alpha}\right) + U \sum_{j=1}^{L/a} n_{j\uparrow} n_{j\downarrow}$$

$c_{j\alpha}$- Fermi ladder operators
$\alpha = \uparrow, \downarrow$- spin index
$n_{j\alpha} = c_{j\alpha}^{\dagger} c_{j\alpha}$- density operator
t- hopping amplitude
U- interaction strength
L- wire length
a- lattice parameter



1D Fermi-Hubbard model



Momentum states:

k_j- charge d.o.f.

λ_m- spin d.o.f.

The many-body spectra of this model are found from the Lieb-Wu equations:

$$k_j L - \sum_{l=1}^{M} \varphi(\lambda_m - k_j a) = 2\pi I_j$$

$$\sum_{j=1}^{N} \varphi(\lambda_m - k_j a) - \sum_{l=1}^{M} \varphi(\lambda_m/2 - \lambda_l/2) = 2\pi J_m$$

$\varphi(x) = -2\arctan(4tx/U)$- two-body scattering phase

- N non-equal integers I_j and M non-equal integers J_m define the solution for the orbital k_j and the spin λ_m momenta of an N-electron state for a given value of the microscopic parameter U/t

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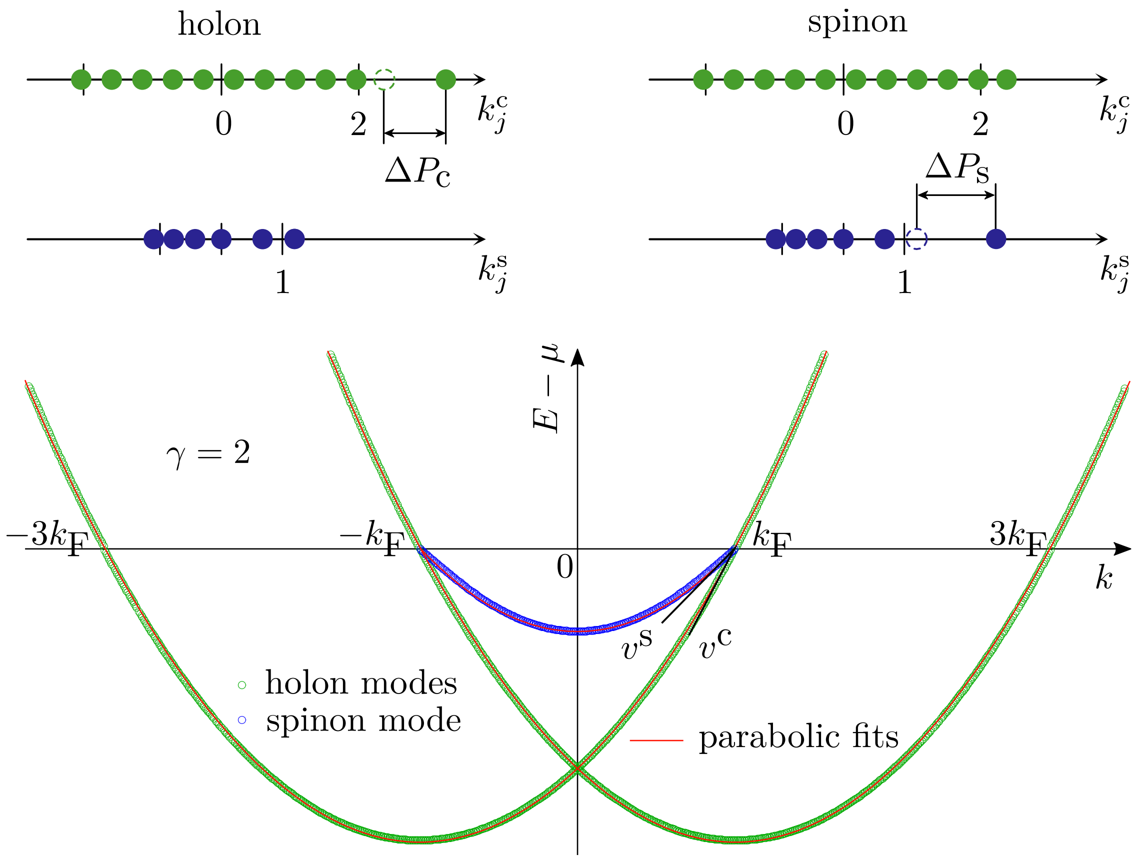
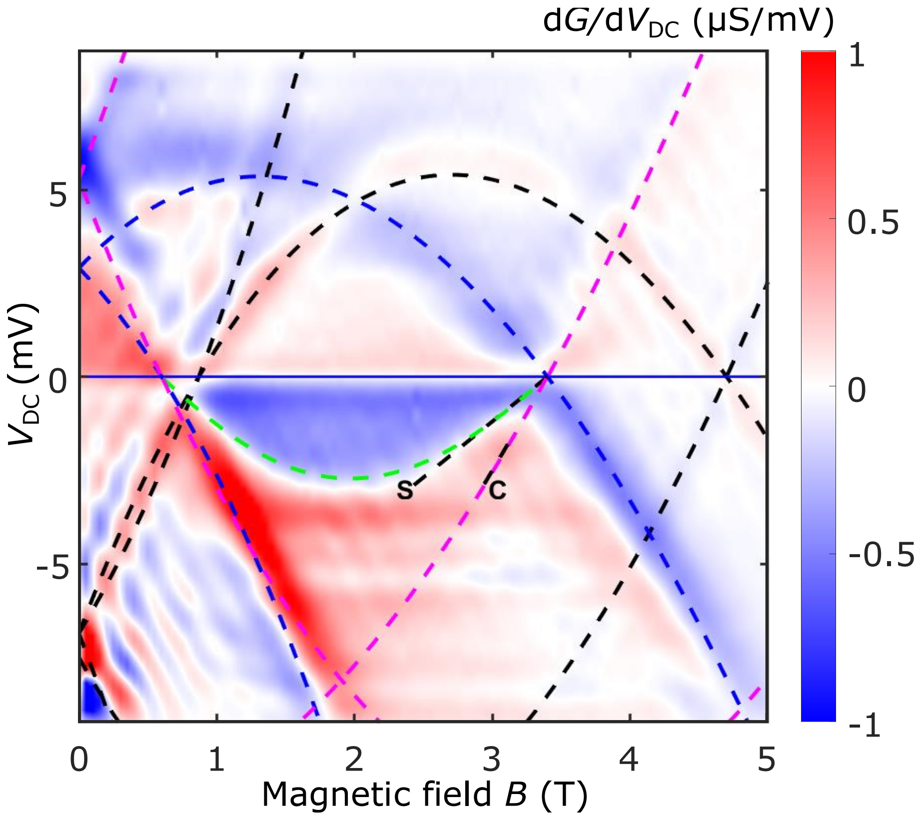


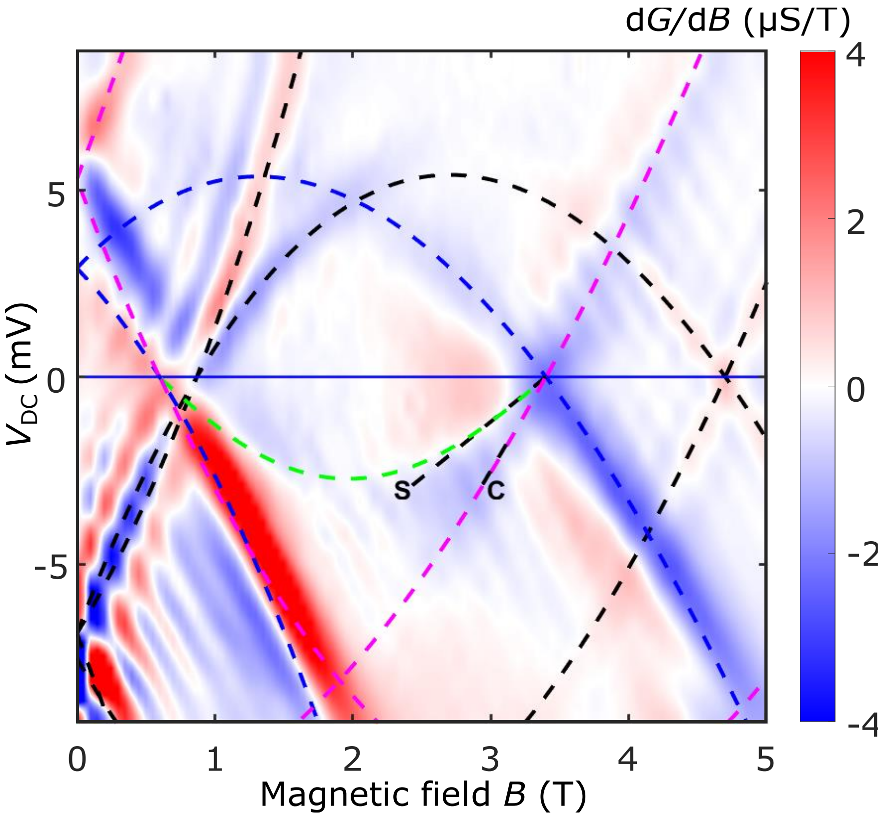
- Instead of U, there is a more natural dimensionless interaction parameter which emerges from the Hubbard model itself microscopically:

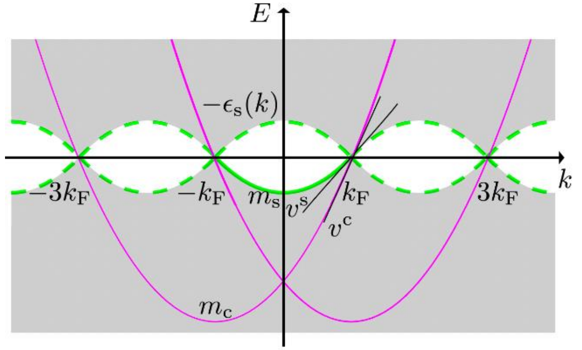
$$\gamma = \frac{\lambda_F}{16a}\frac{U}{t}\frac{1}{1-\frac{1}{N}\sum_{l=1}^{N/2}\frac{\lambda_l^2(\infty)-\left(\frac{U}{4t}\right)^2}{\lambda_l^2(\infty)+\left(\frac{U}{4t}\right)^2}}$$

$\lambda_F = 4L/N$ - Fermi wavelength of the free-electron gas

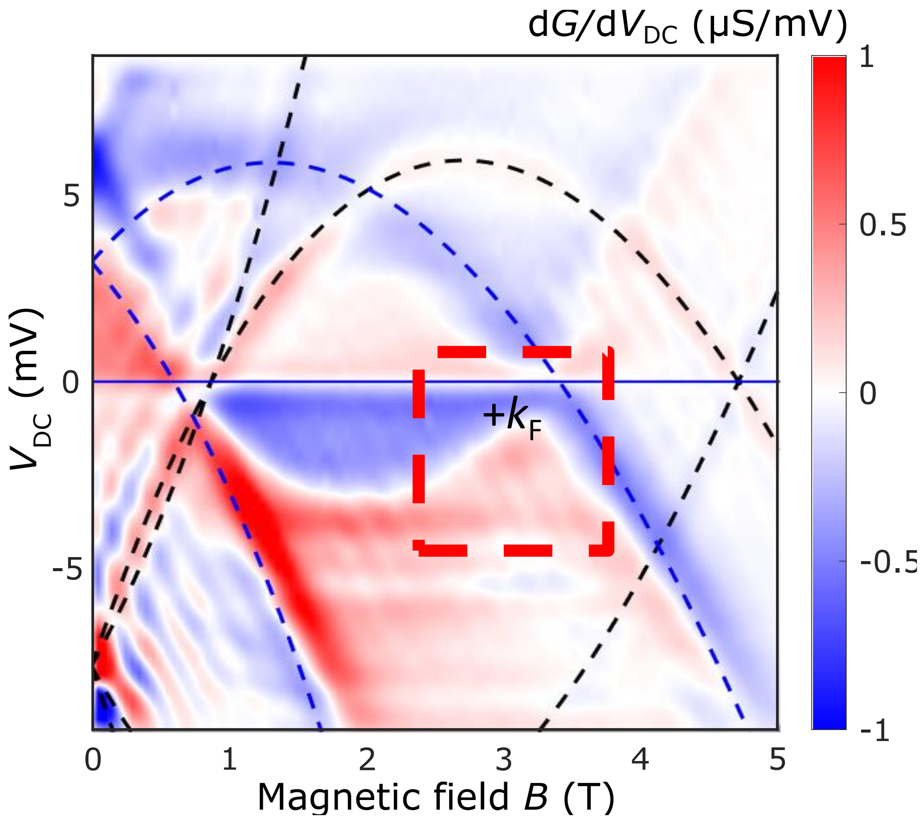
Two Fermi seas



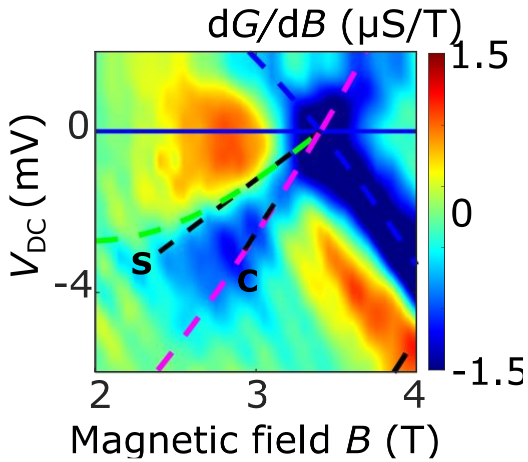




Tunnelling Dispersion Maps



- **Spin-charge separation:**



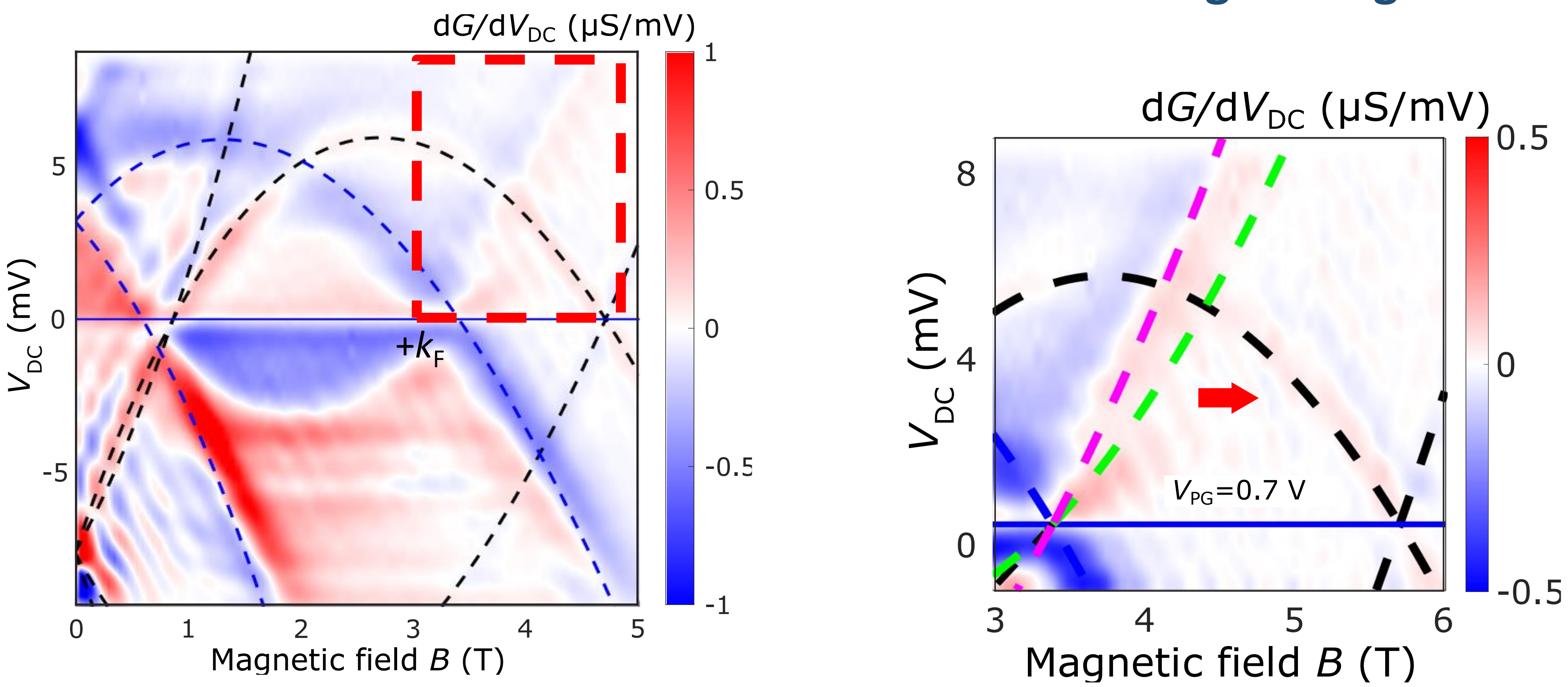
Spin charge separation at low energies

- $E_F \sim 2.5\ \mathrm{meV}$
- Charge mode visible up to $\sim 4-5\ \mathrm{meV}$

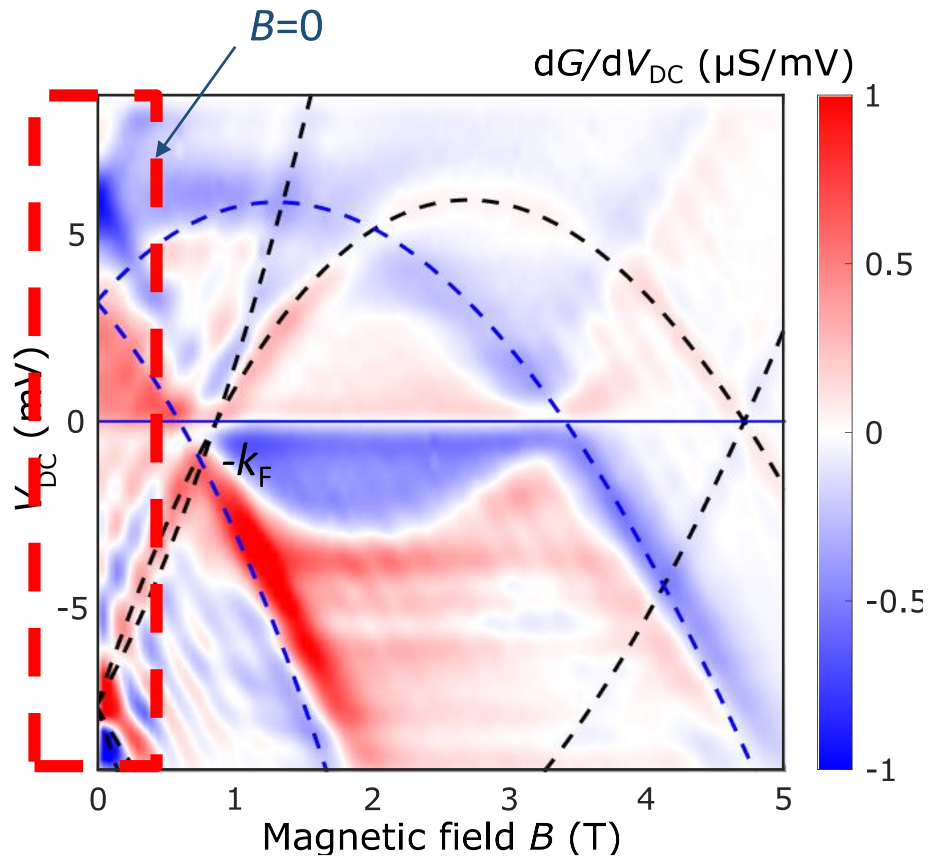
- Two different slopes ⇒ v_s and v_c
  - parameters of the spinful (linear) TLL

Tunnelling Dispersion Maps

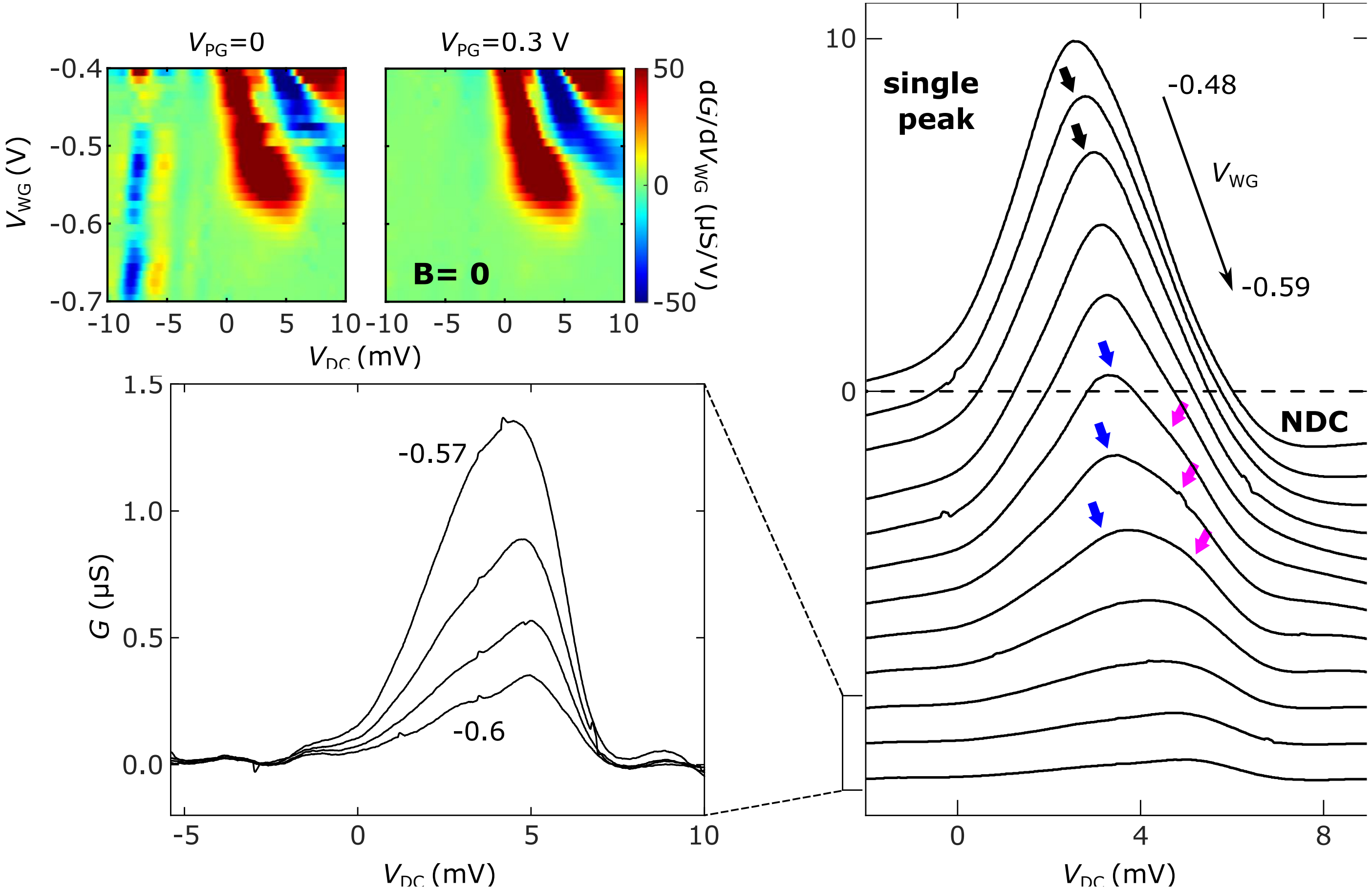
- **Holon mode at high-energies:**



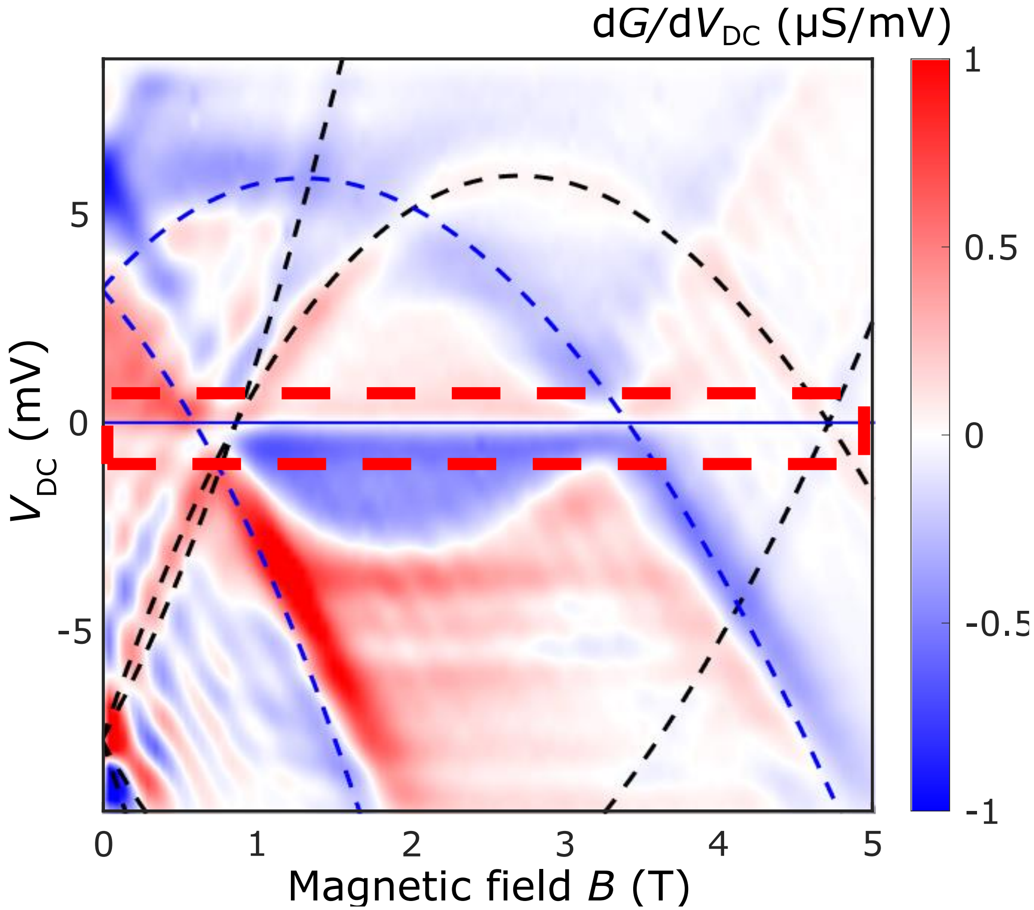
Tunnelling Dispersion Maps



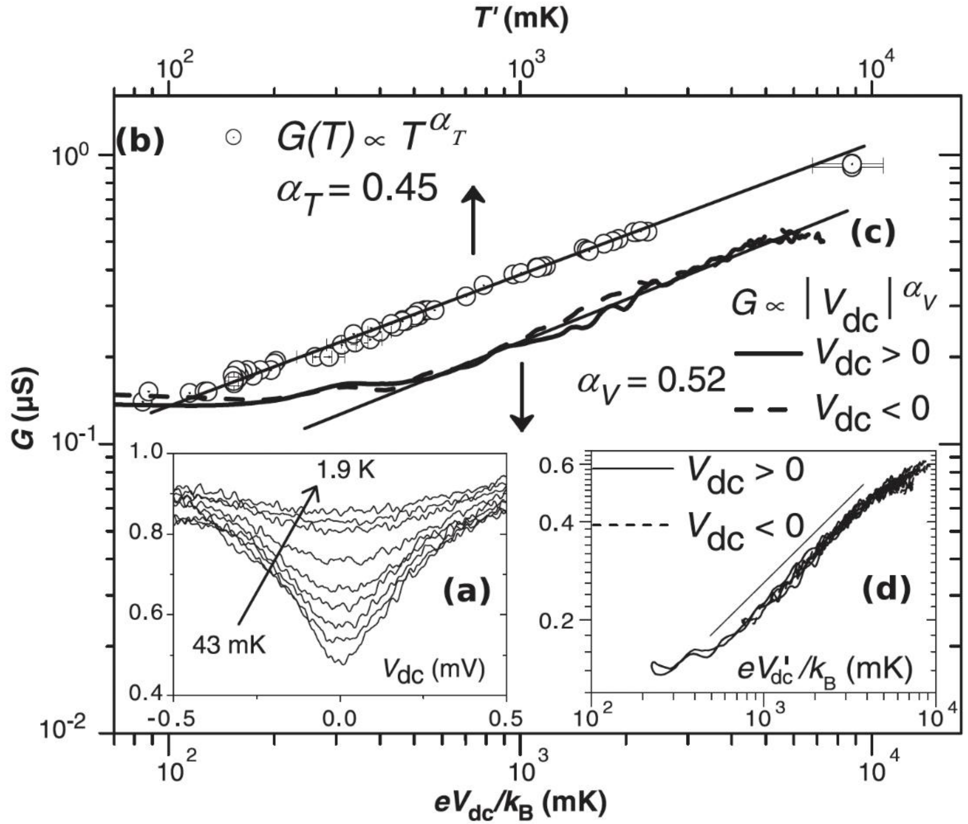
- **Holon mode at zero-field :**



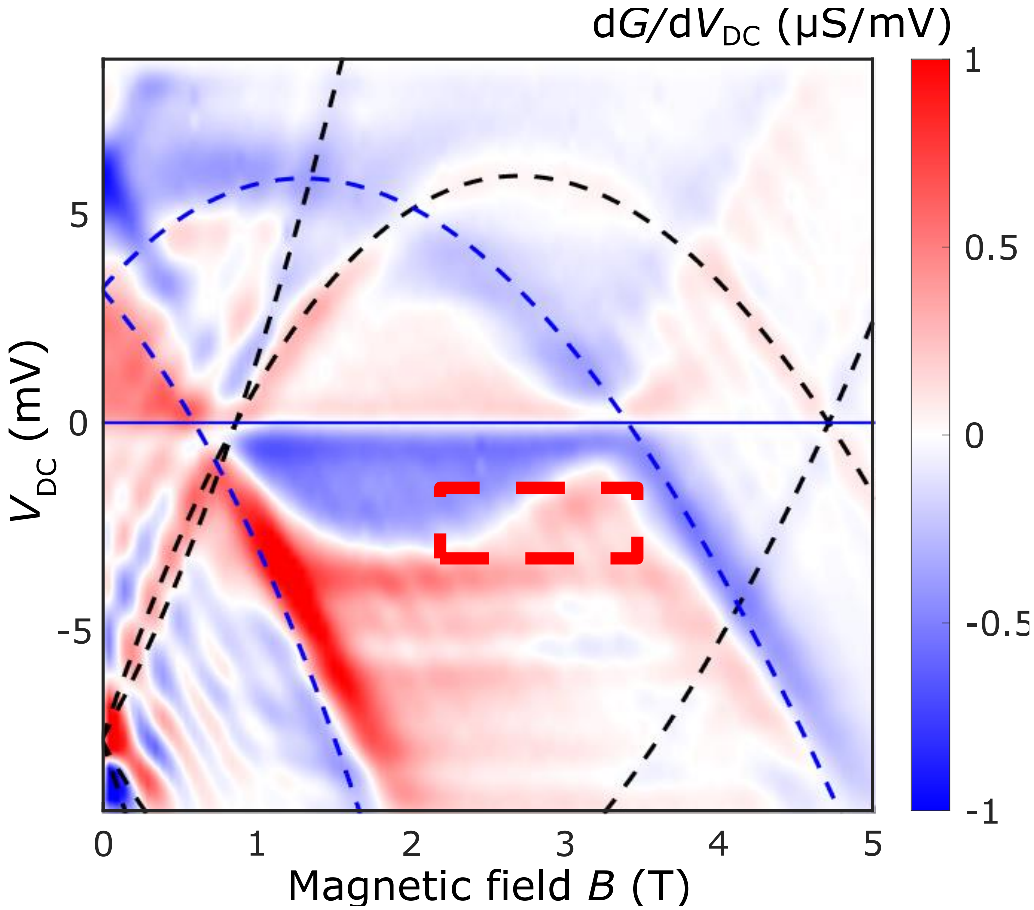
Tunnelling Dispersion Maps



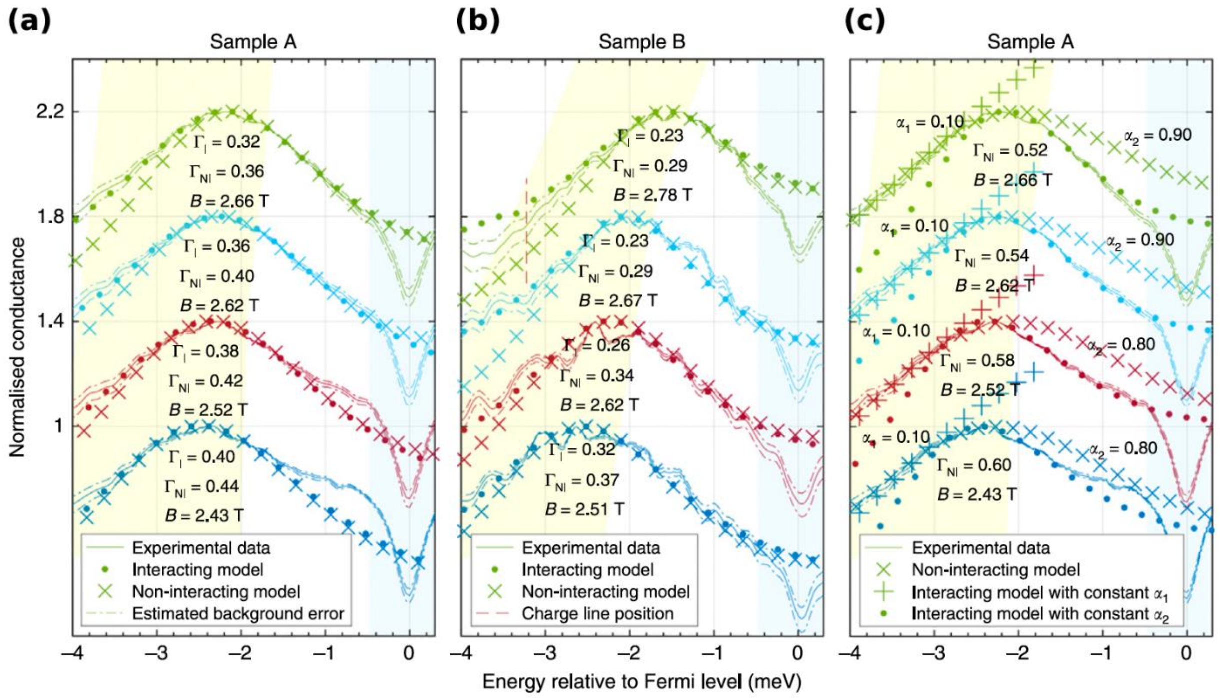
- **Zero-bias anomaly:**



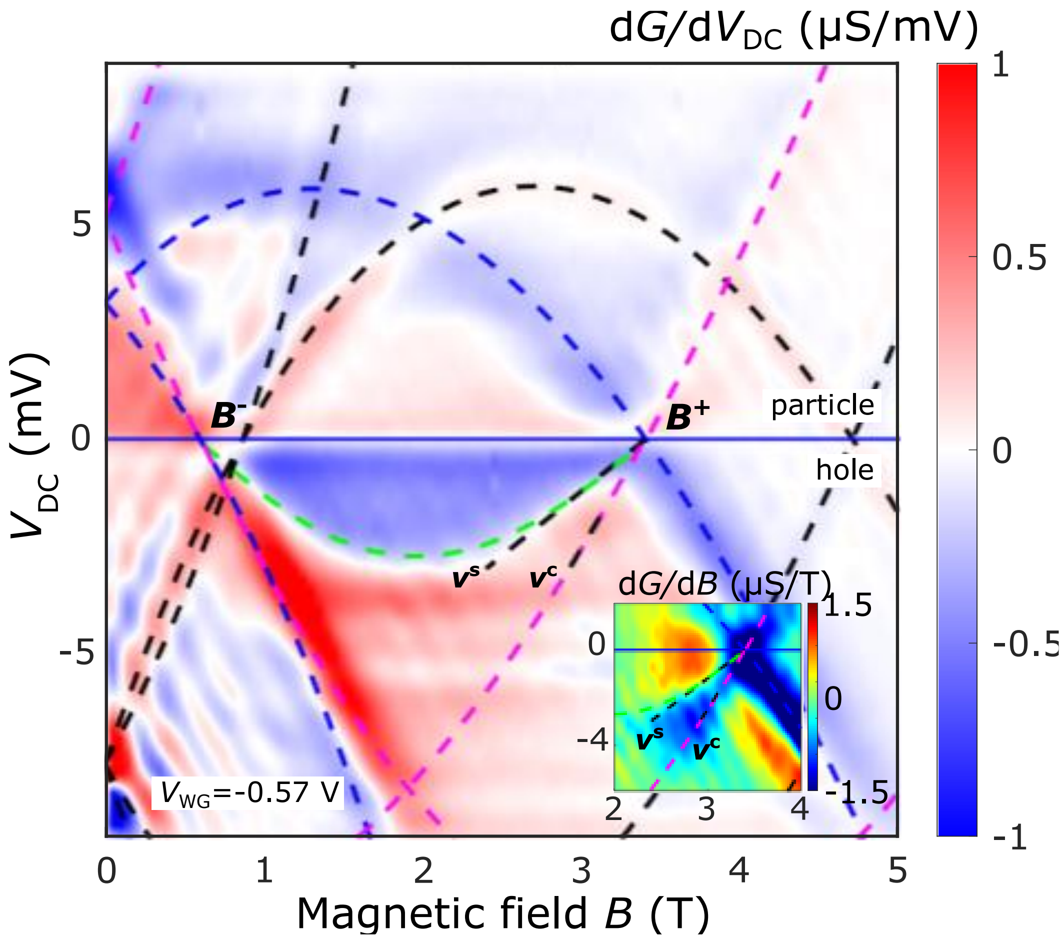
Tunnelling Dispersion Maps



- **Momentum-dependent power law:**



Jin *et al.*, *Nat. Commun.* **10**, 2821 (2019)



- We express the **holon and spinon effective masses** as $m_{c,s} = K_{c,s} m^*_{2D}$
  - $K_{c,s}$ account for the renormalisation of the effective mass due to 1D confinement

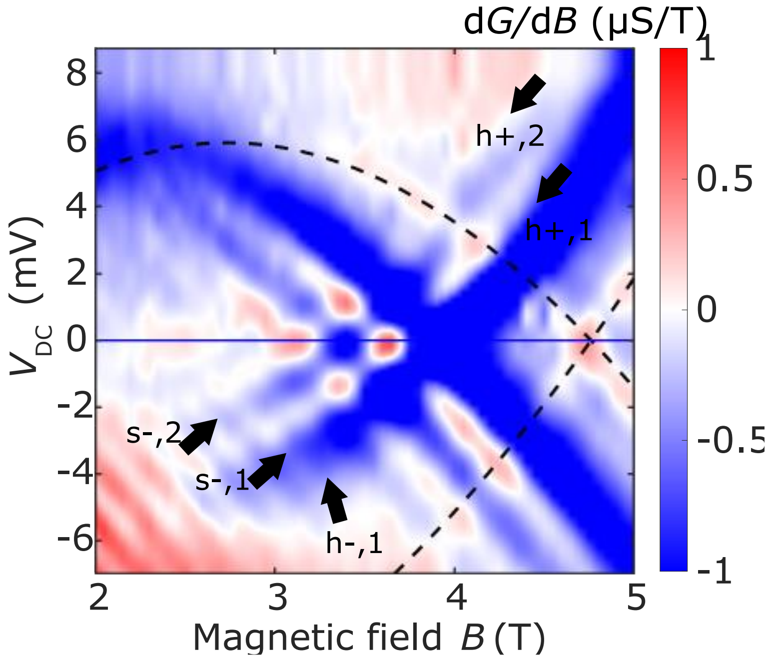
- Simultaneously, we can extract the **spinon and holon velocities** $v_{s,c} \propto 1/m_{c,s}$ close to zero-bias at the $+k_F$ point

- The ratio K_c/K_s is a good estimate of the **interaction strength**

$$\frac{K_c}{K_s} = \frac{m_c}{2m_s} = \frac{v_s}{v_c}$$

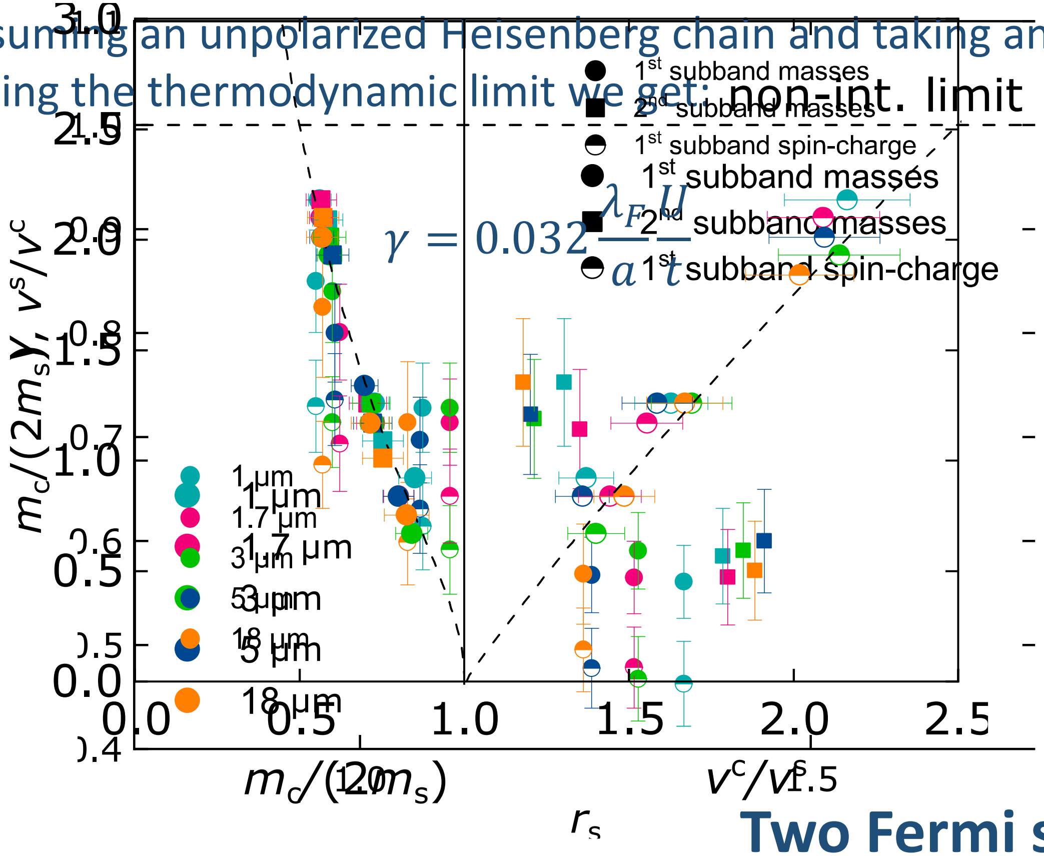
Estimating the interaction strength

- So far, we have only analysed dispersion maps in the single-subband regime
- We can also vary the number of occupied subbands up to 3-4, by tuning V_{WG}



- Assuming an unpolarized Heisenberg chain and taking the thermodynamic limit we get:

$$\gamma = 0.032 \frac{\lambda_F U}{a t}$$

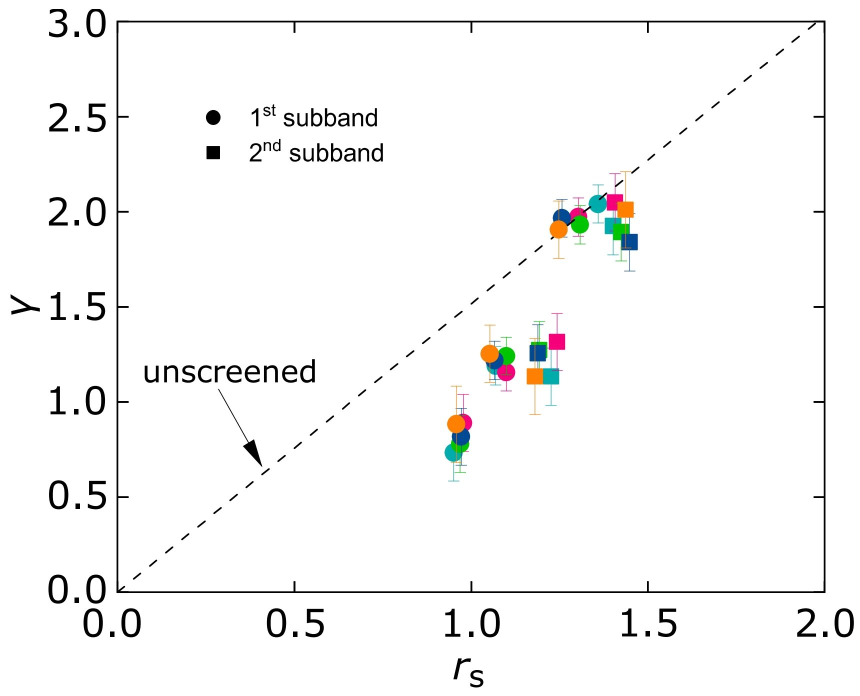


Two Fermi seas!

1D-1D screening

$$\gamma = 0.032 \frac{\lambda_F}{a} \frac{U}{t}$$

$$r_s = \frac{\lambda_F}{8a_B} = \frac{1}{2a_B n_{1D}}$$



2. Electron mass in 1D GaAs wires

Electron mass in bulk (3D) GaAs

- Band mass of electrons in GaAs
  $$m_{3D}^* = 0.067 m_e \text{ (at low densities)}$$
- It is well-established that in a crystal, the effective mass can often differ from its free-space counterpart by up-to several orders of magnitude
  - Direct result of the electron wave function interfering with the ionic lattice
  - Additional d.o.f.: phonons, spin waves, plasmons + SOC/impurity scattering
- Raymond et al: electron effective masses in the range of carrier concentration 10^{16}-10^{19} cm^{-3}

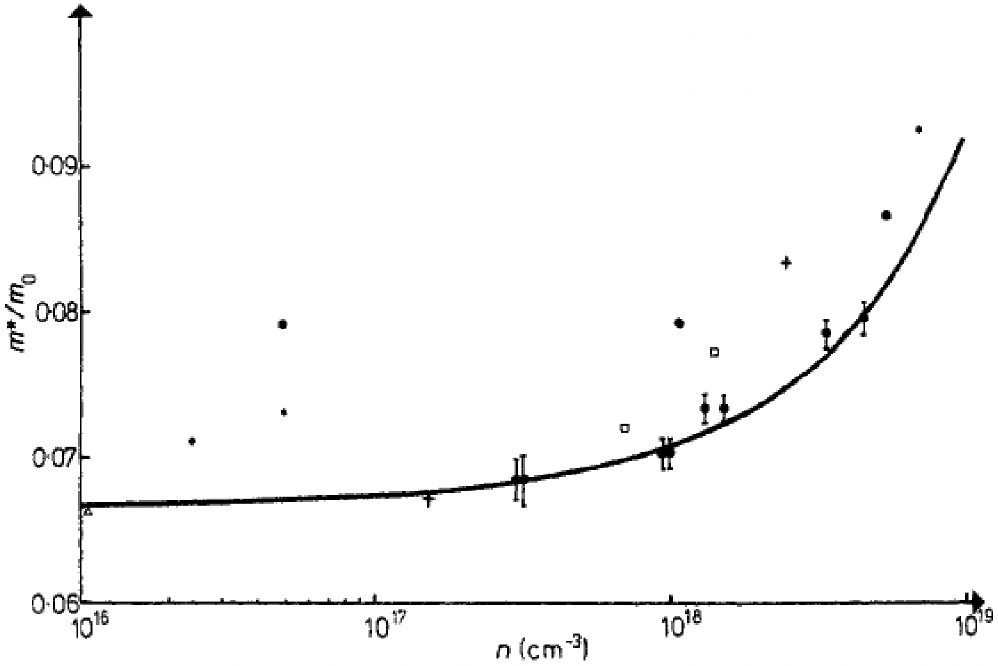


Figure 1. m^*/m_0 as a function of carrier density, n. Full curve calculated from equation (5); error bars, experimental results (Shubnikov–de Haas effect); triangles, experimental results (Stillman *et al* 1969, Chamberlain *et al* 1972, Hess *et al* 1976) and theoretical one (Lawaetz 1971) at the bottom of the band; full circles, Spitzer and Whelan (1959); crosses, Cardona (1961); star, Pillar (1966), open squares, Julienne *et al* (1976).

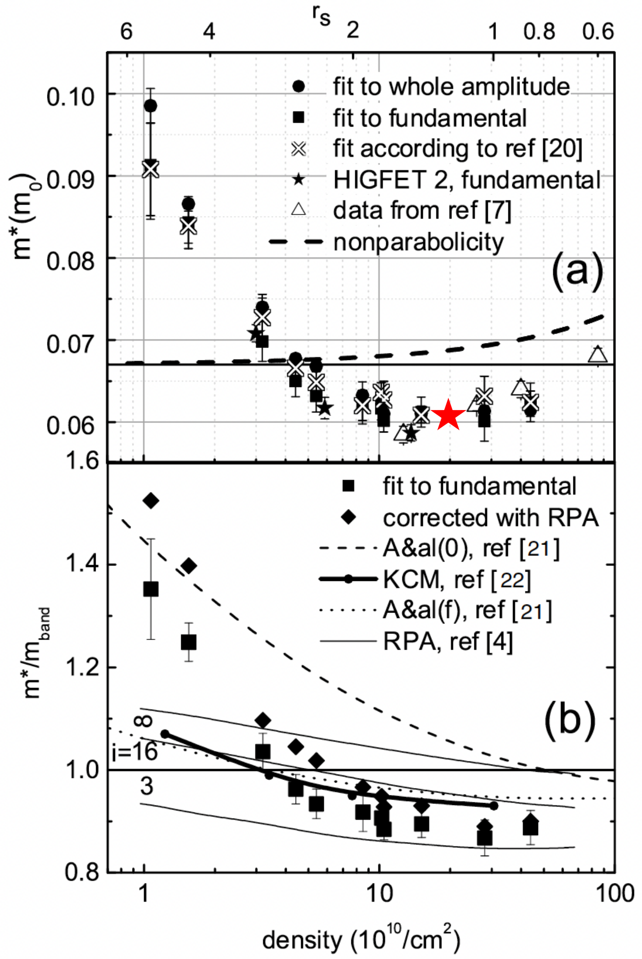
A Raymond *et al.*, J. Phys. C: Solid State Phys. **12** 2289 (1979)

Electron mass in 2D GaAs

- At a deeper level, one may wonder how strong the effect of the unavoidable electron-electron (e-e) interactions may be on their mass
- The effect of e-e interactions on the carrier mass can be controlled by altering the coordination number of the electrons
  - low-dimensional systems

- GaAs/AlGaAs QWs (2D):
  - Hatke *et al.*, PRB **87**, 161307 (2013) **MIROs/MPR**
  - Tan *et al.*, PRL **94**, 016405 (2005) **SdHs**
  - Coleridge *et al.*, Surf. Sci. **361-362**, 560 (1996) **SdHs**
  - Hayne *et al.*, PRB **46**, 9515 (1992) **SdHs**

  - **Our value:** $m_{2D}^{*} = (0.062 \pm 0.002)m_e$ @ r_s~1



- 1D changes the effect of interactions drastically

Fermi sea of electrons

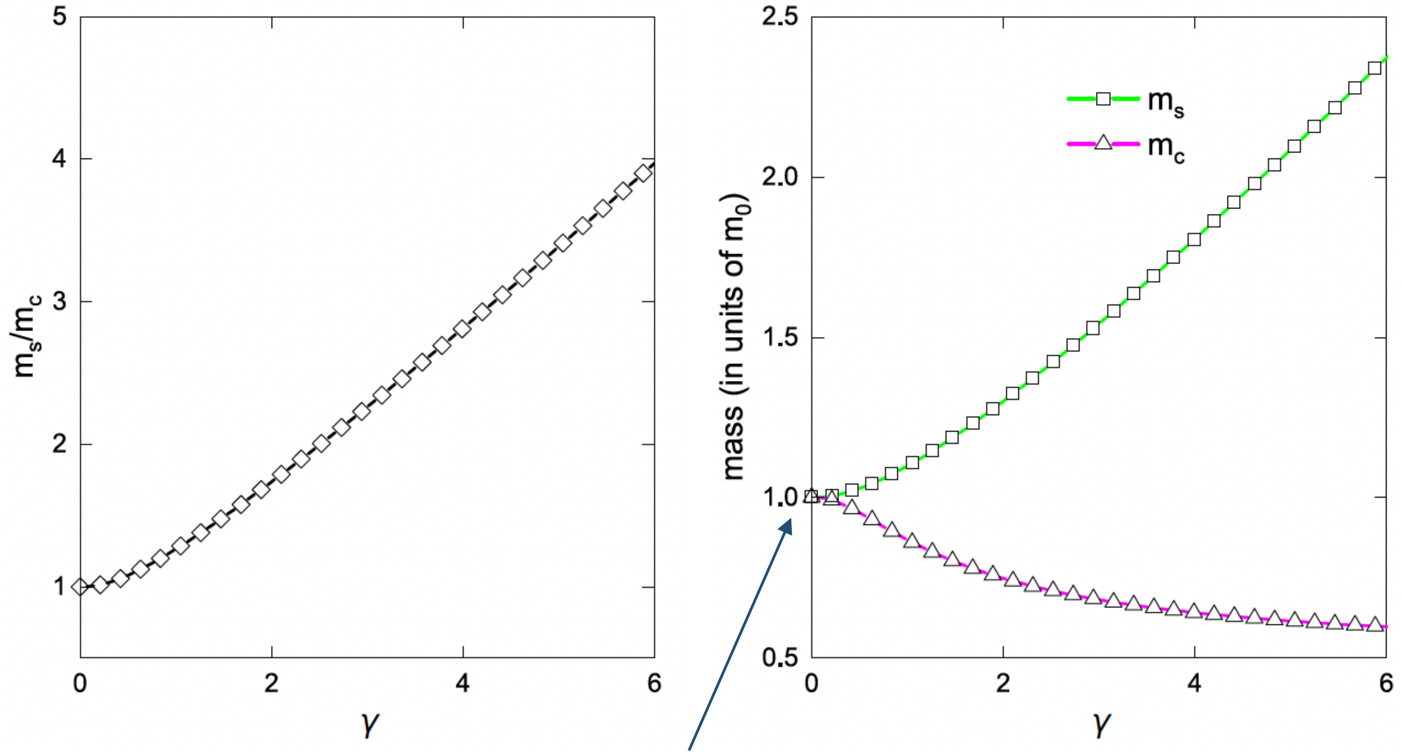
described by only one mass

$m^*_{3D}/\, m^*_{2D}$

Two Fermi seas

for spin and charge

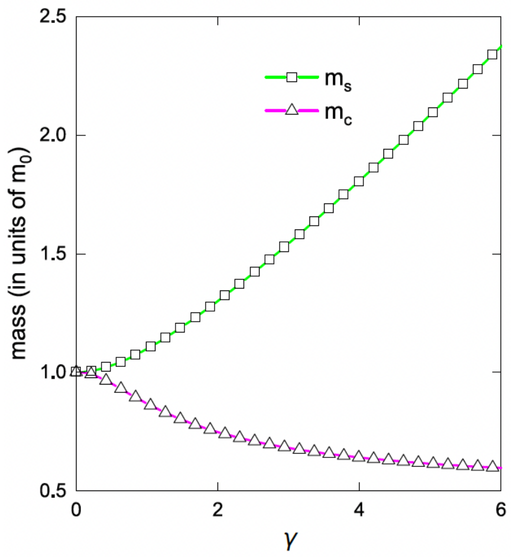
m_s/m_c

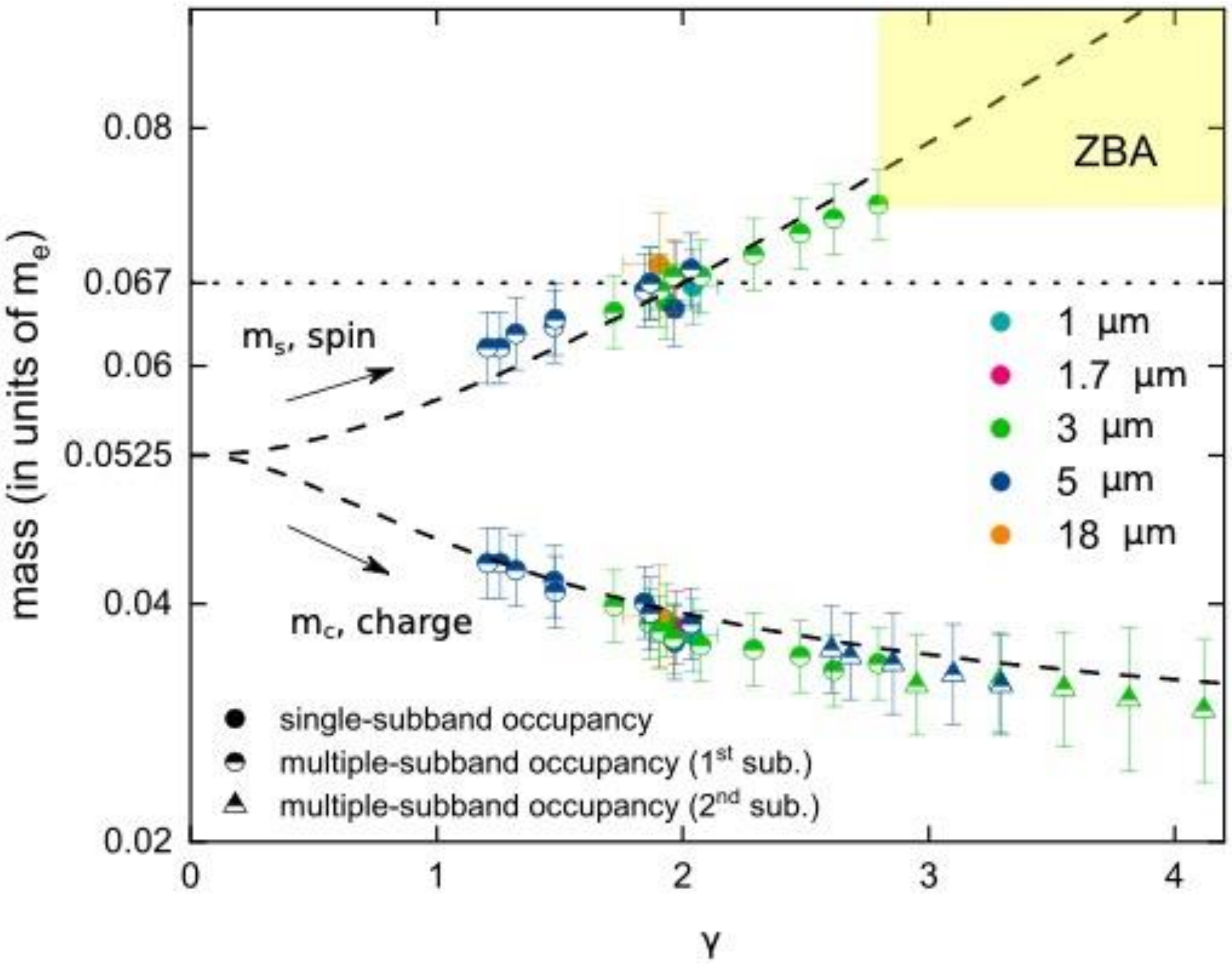


The bare electron mass, m_0, given by the point where m_s and m_c converge at $\gamma = 0$ (non-interacting limit)

- Taking the best fit to the data as given by the 1D Fermi-Hubbard model

$$m_0 = (0.0525 \pm 0.0015)m_e$$

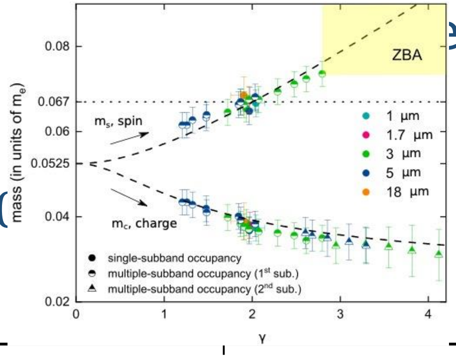


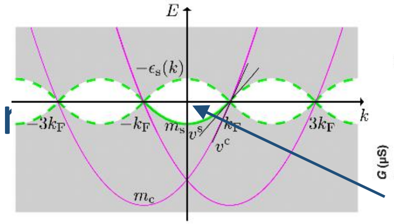


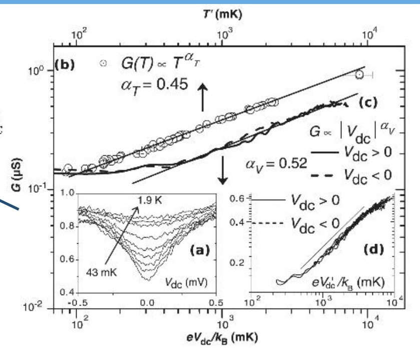
Alternatively, we can extract both m_0 and γ for each

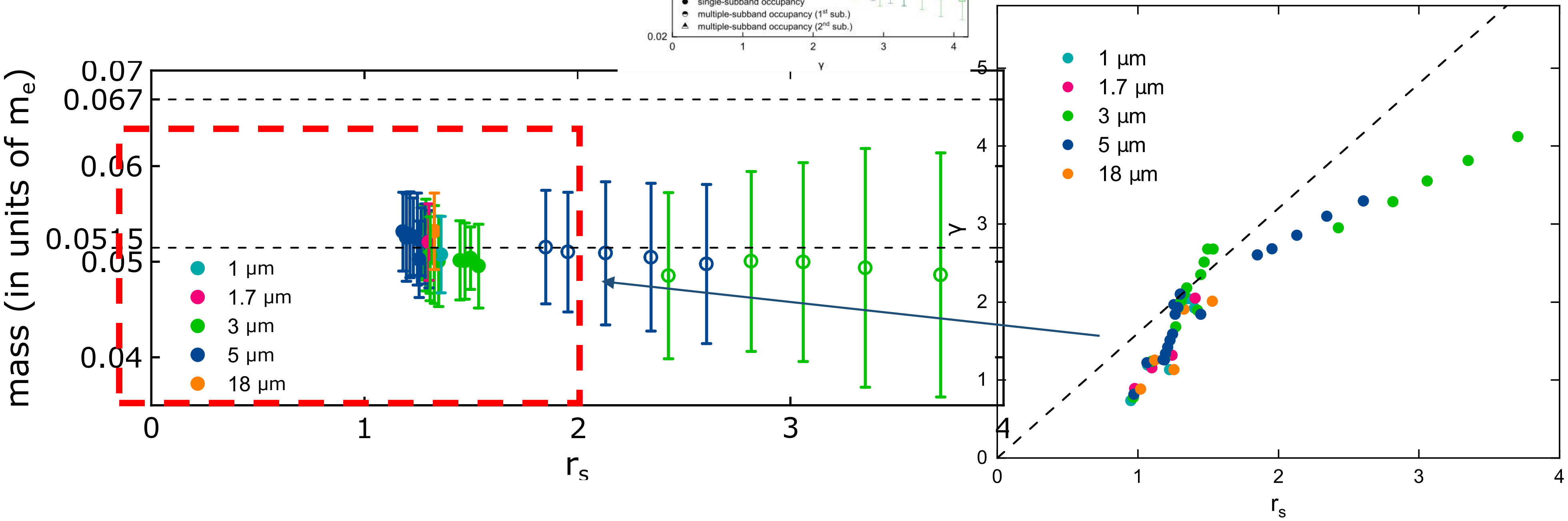
- m_s cannot be accurately extracted at higher γ (and higher r_s) due to the ZBA
- We assume a scenario of minimal screening in order to estimate m_0^{max}

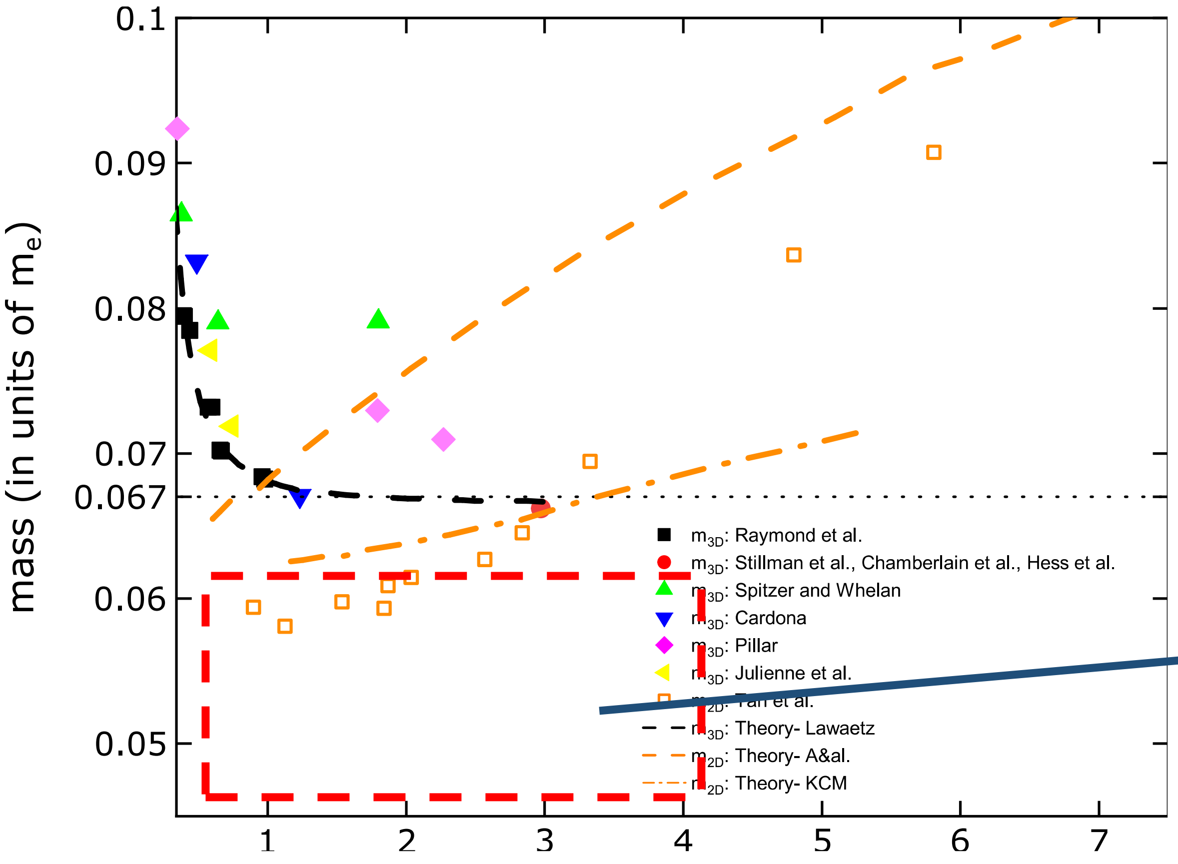
$$m_0 = (0.0515 \pm 0.0$$



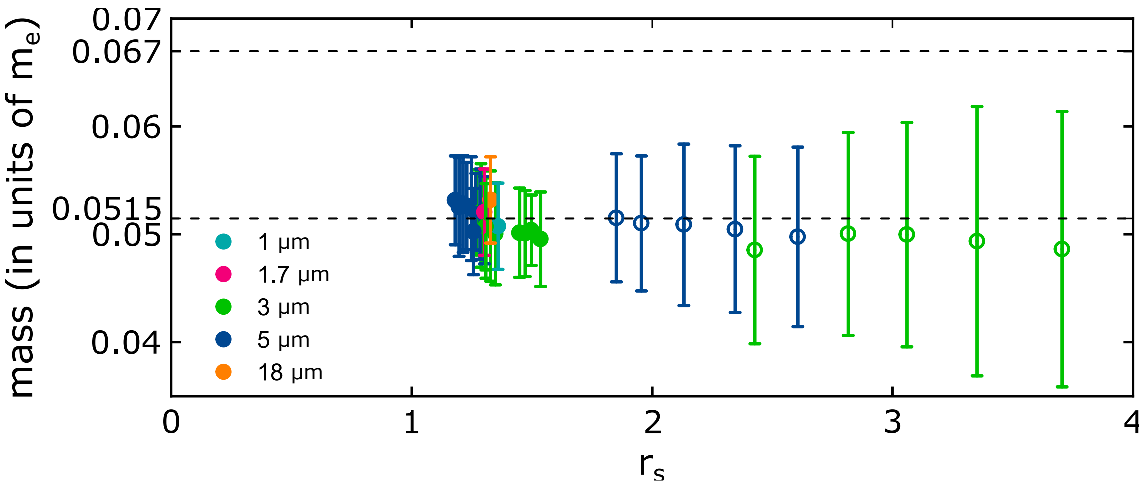








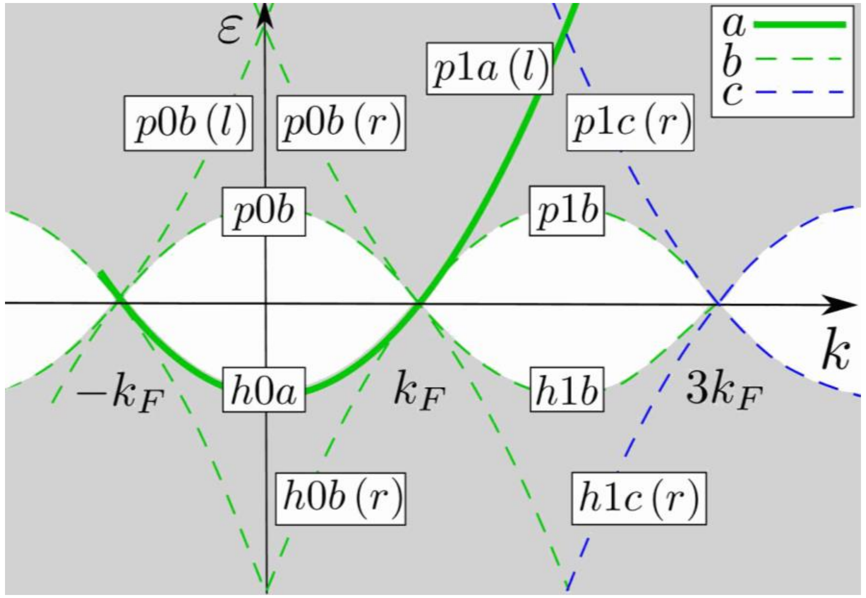
$$
r_s = \begin{cases} \left(\dfrac{1}{\pi a_B^2 n_{2D}} \right)^{1/2} & 2D \\ \left(\dfrac{3}{4\pi a_B^3 n_{3D}} \right)^{1/3} & 3D \end{cases}
$$



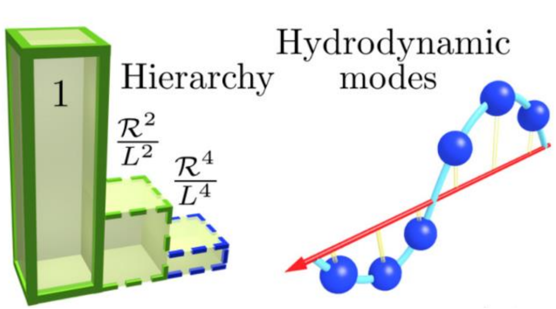
3. A Hierarchy of Modes

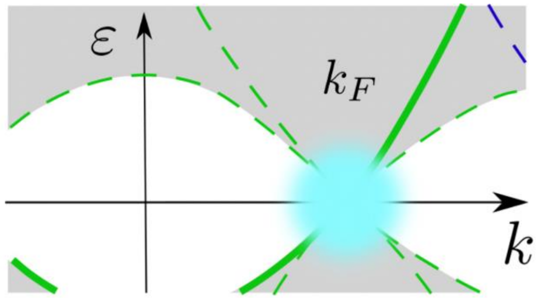
Hierarchy of modes model

- Microscopic analysis of the nonlinear excitations via the Bethe ansatz
- Length-controlled emergence of higher-order modes away from the Fermi points (Tsyplatyev *et al.* PRL 114, 196401 (2015); PRB 93, 075147 (2016));
- "replicas" should be much weaker, by $(\mathfrak{R}^2/L^2)^n$, where $\mathfrak{R}$ is an interaction factor and L the length of the system;

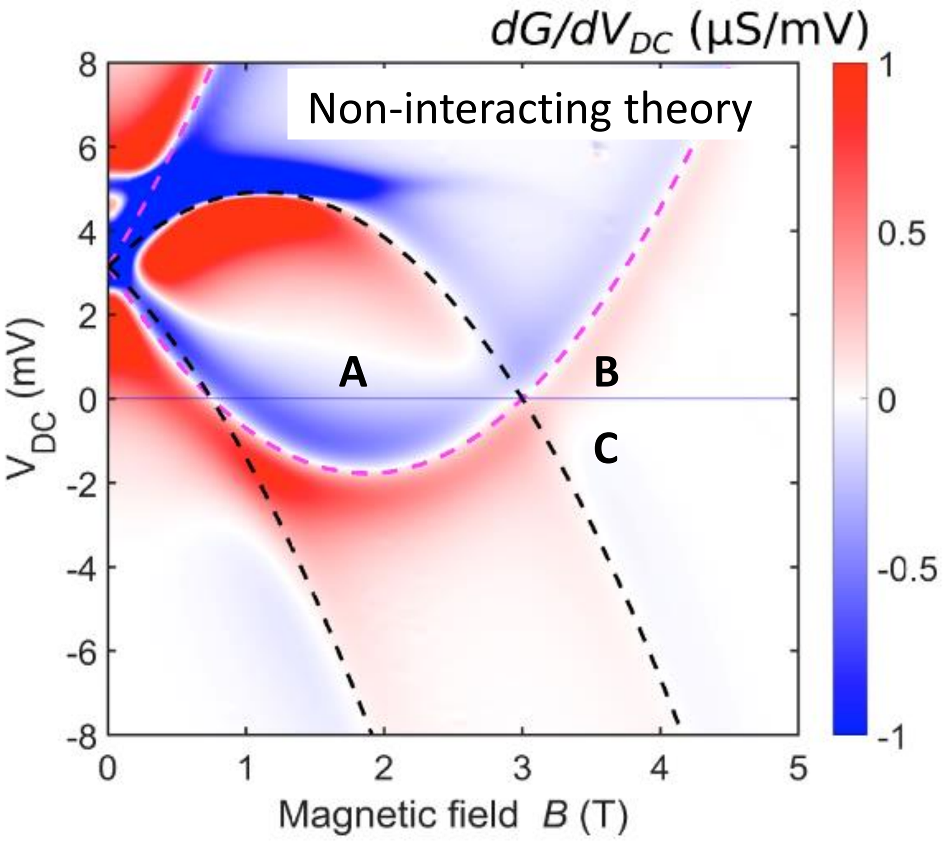


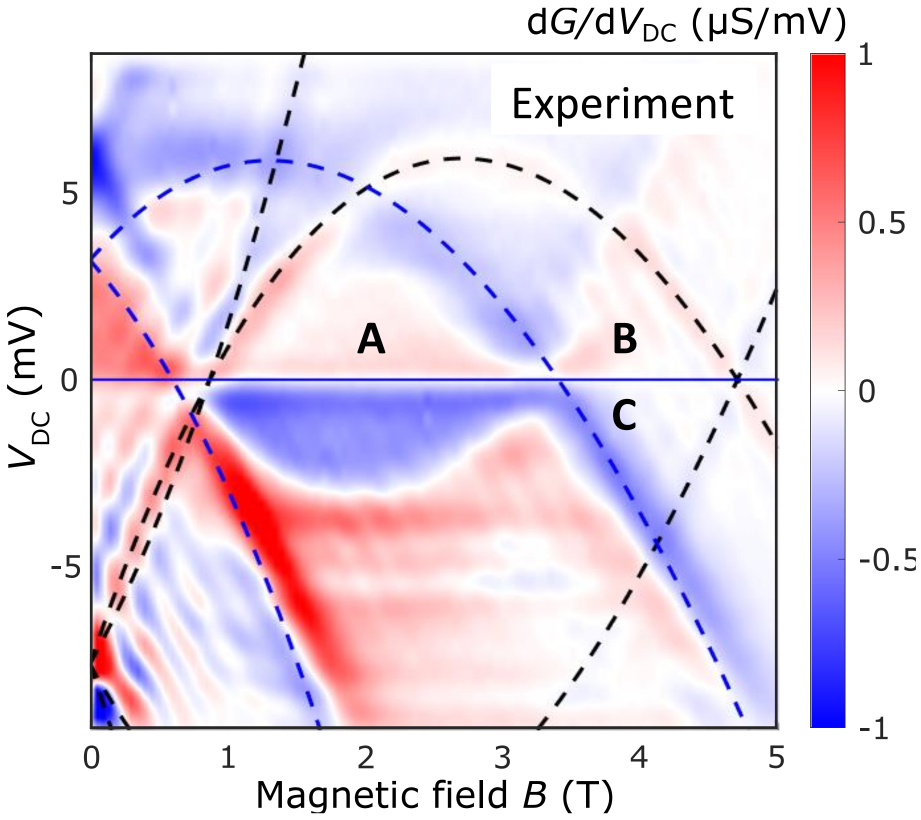
$$A_1(k_x, E) \propto \frac{R^2}{L^2} \frac{k_F^2 k_x^2}{(k^2 - k_F^2)} \delta(E - \mu + \xi_1)$$

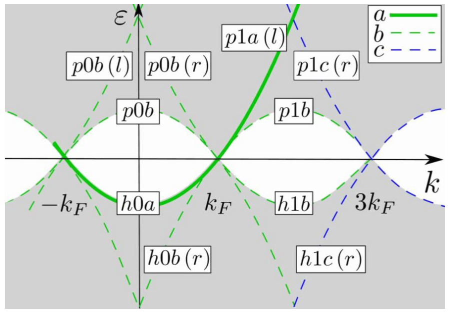




Higher-order modes



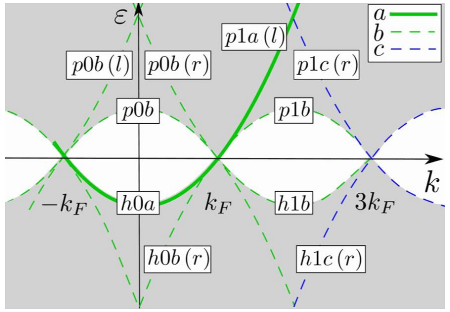


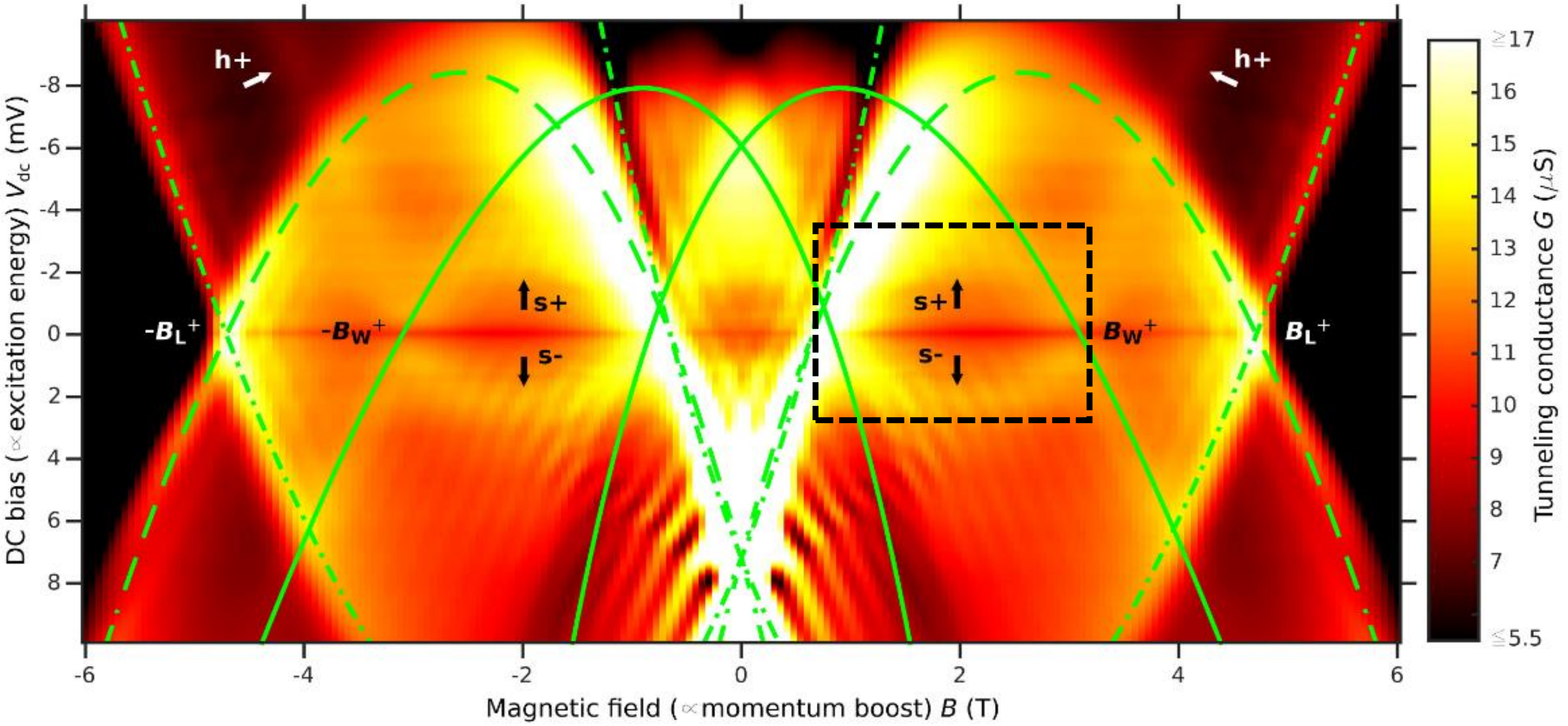


- Simulated map of the differential conductance dG/dV_{DC} vs V_{DC} and B, between a 1D non-interacting system and a 2DEG

Higher-order modes- *p0b*

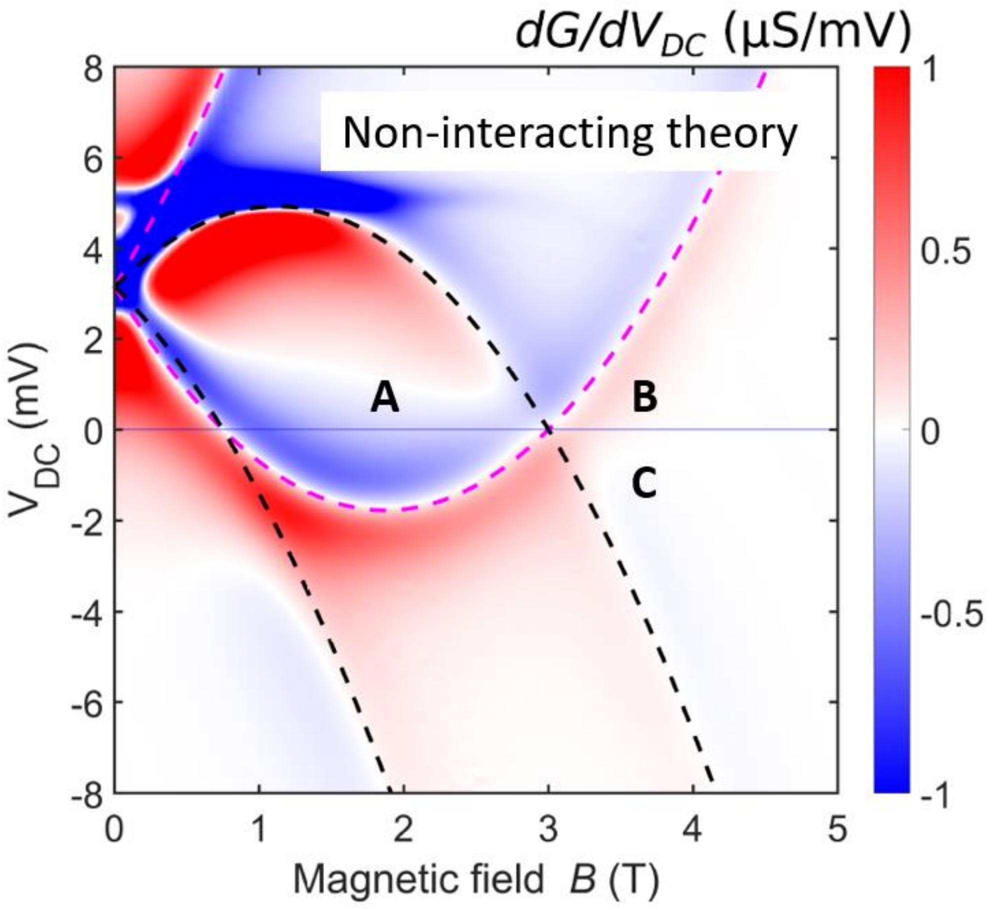
- We found evidence for the existence of an **inverted spinon shadow band** in the main region of the particle sector;

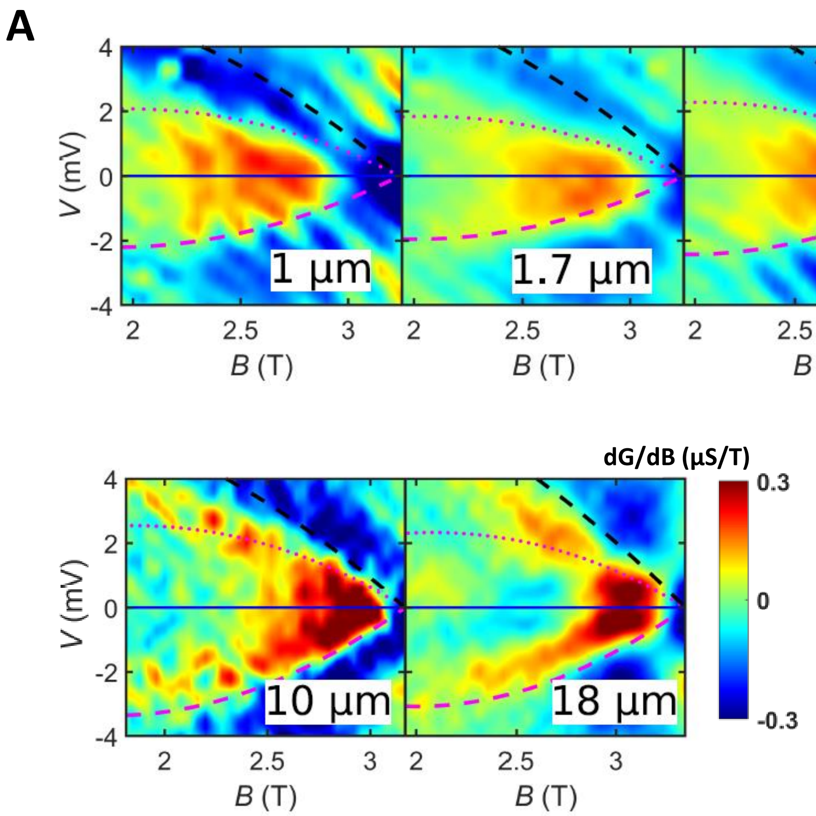


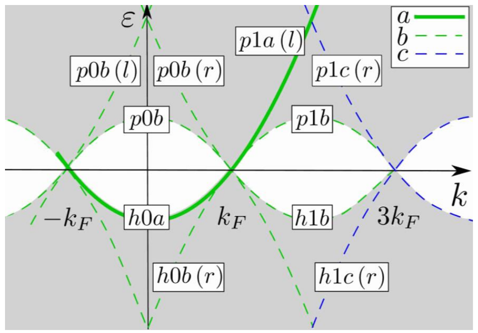


Moreno *et al.*, *Nat. Commun.* **7**, 12784 (2016)

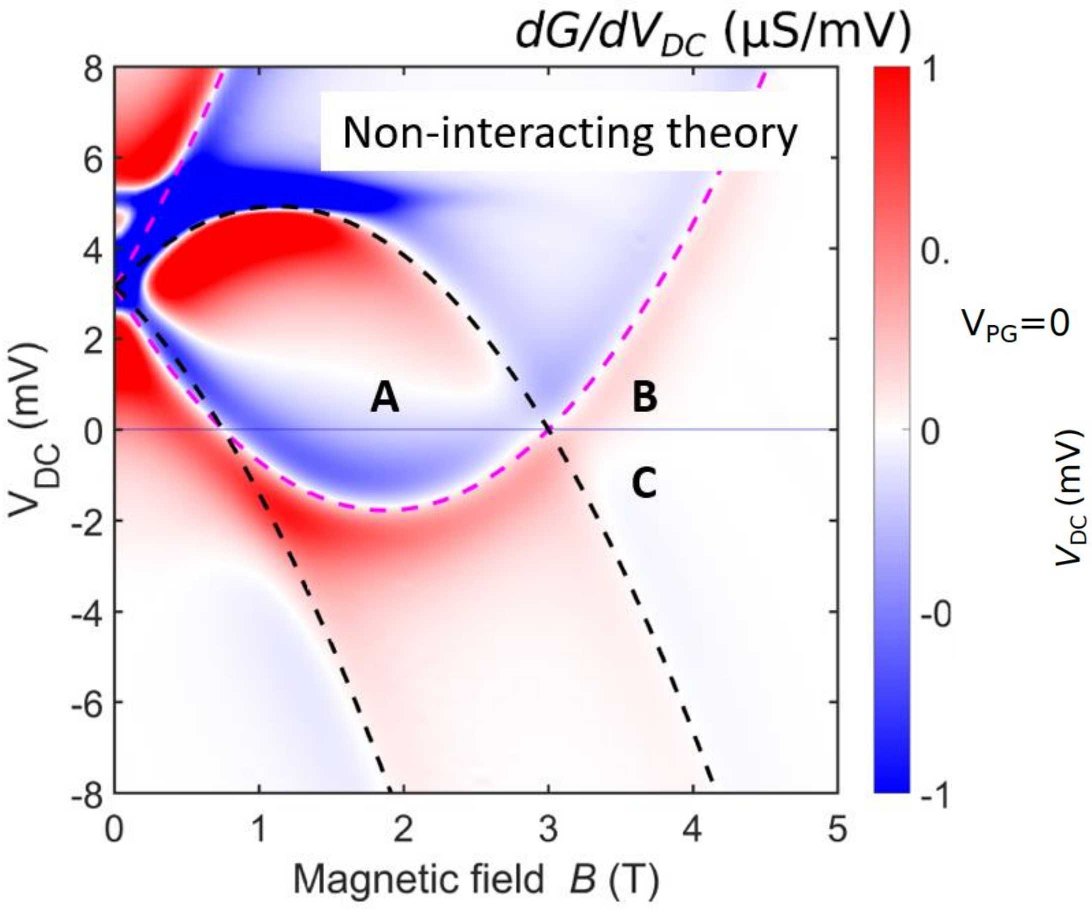
Higher-order modes- *p0b*

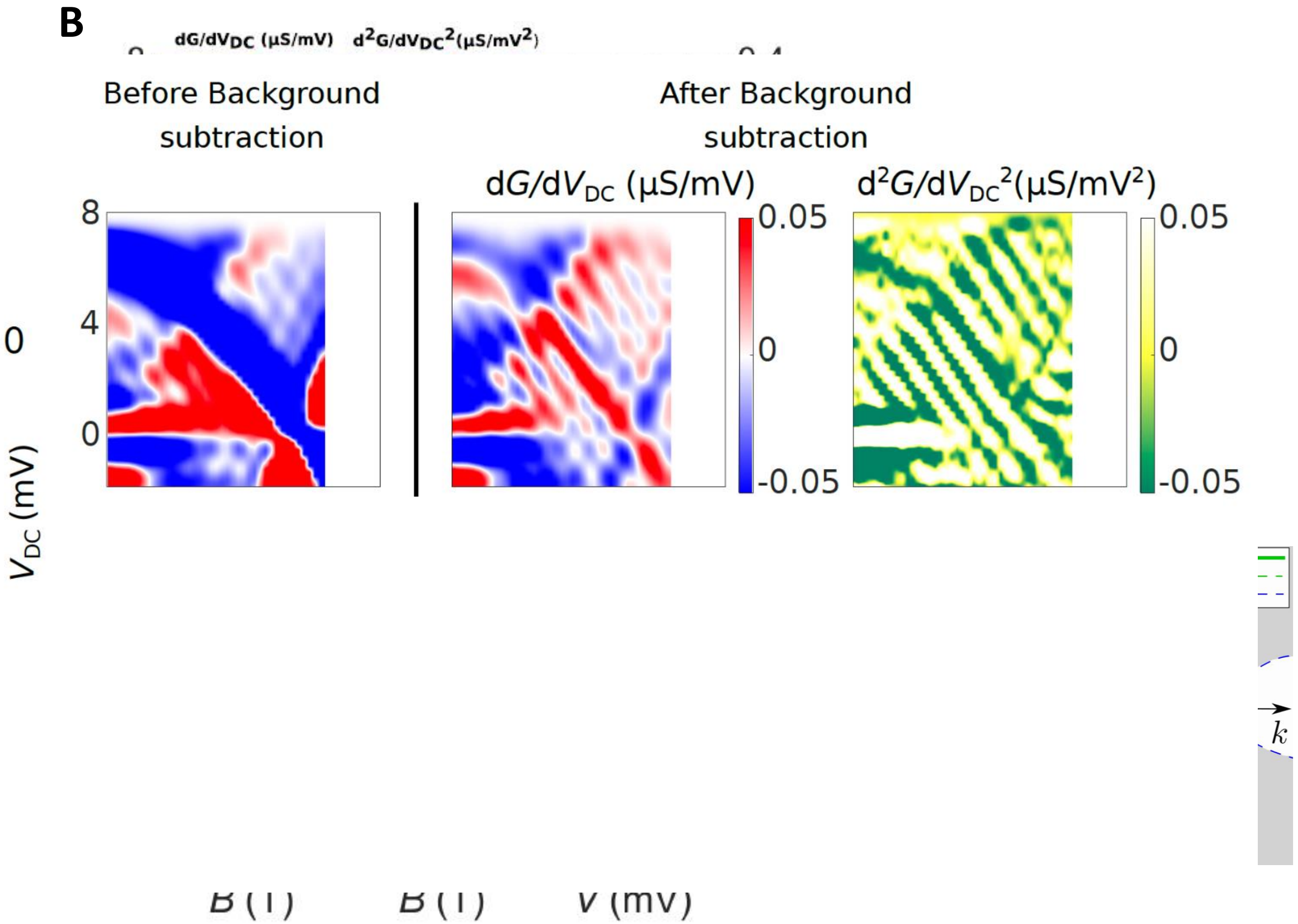






Higher-order modes- *p1b*

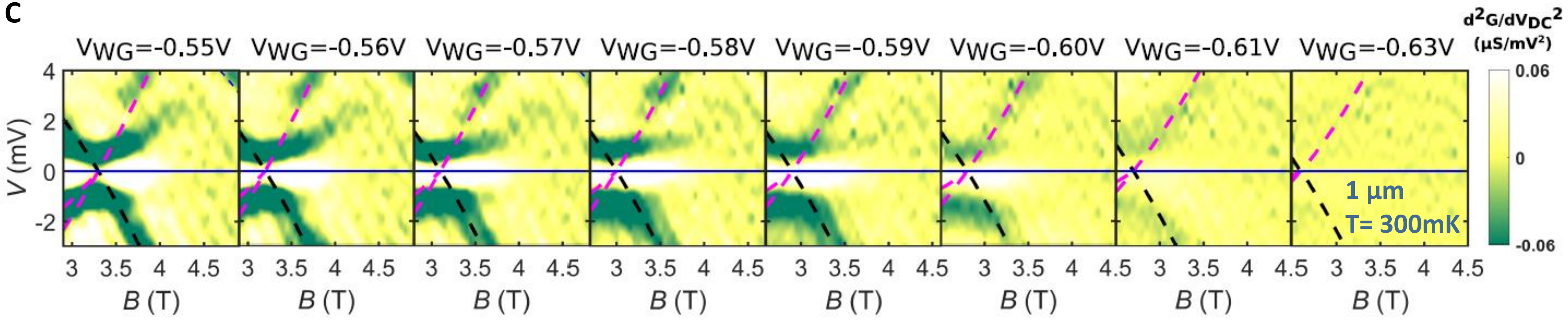




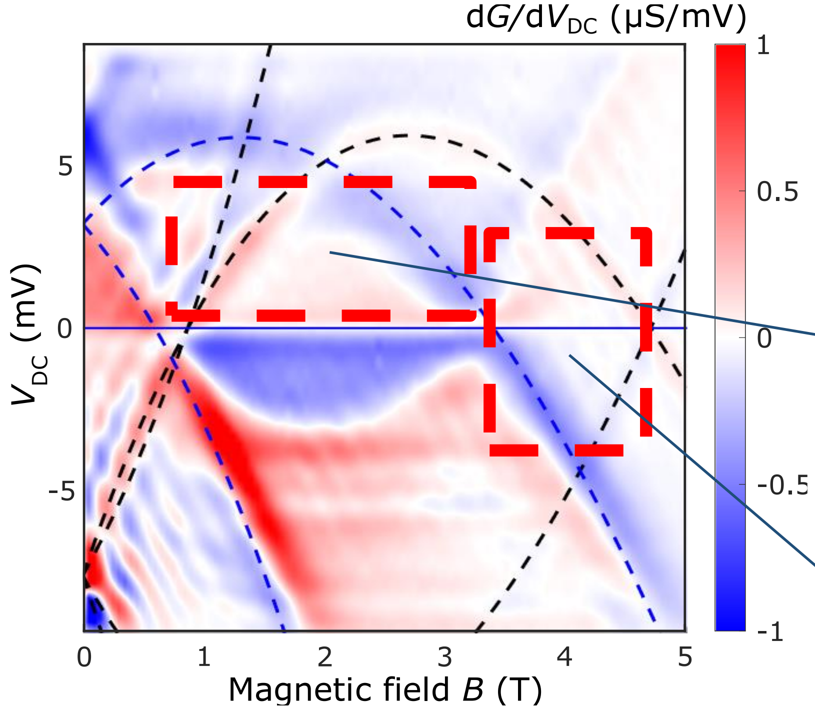
Higher-order modes- *p1b*

- We find structure resembling the **second-level excitations**, which dies away quite rapidly at high momentum;
- The amplitude of the signal from the second-order excitations is predicted to be smaller by a factor of about $\boldsymbol{\lambda_F^2/L^2}$**=2x10^{-4}**, which is higher than the noise level of our experiment.

C



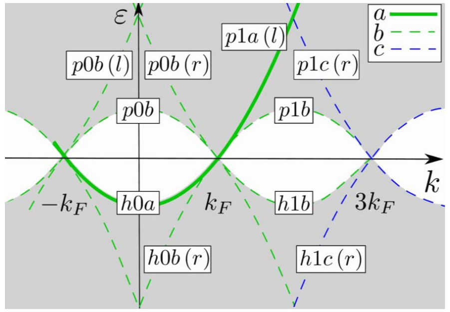
Tunnelling Dispersion Maps

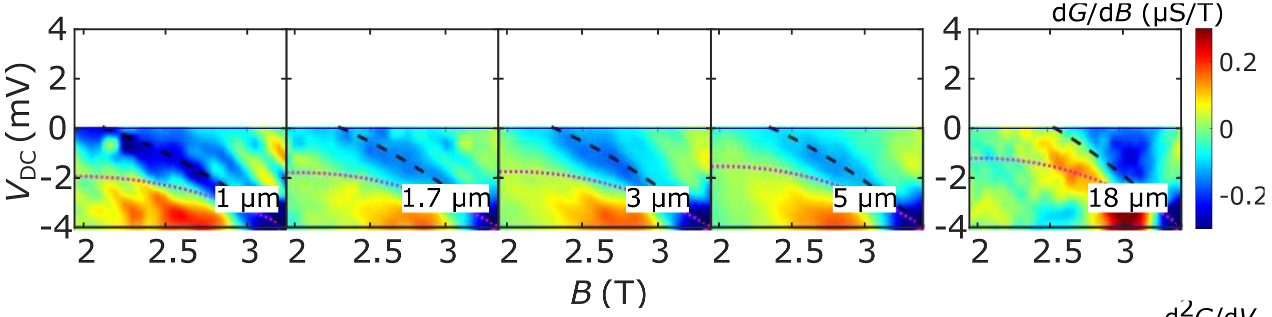


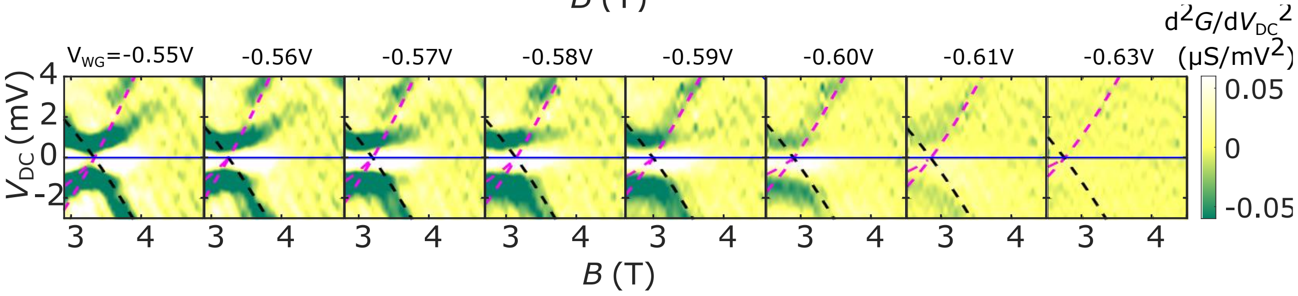
- **Higher-order 1D modes:**

Nonlinear TLLs:

Imambekov & Glazman, Science 2009
Schmidt, Imambekov & Glazman, PRB 2010
Tsyplatyev *et al.* PRL 2015
Tsyplyatyev *et al.*, PRB 2016

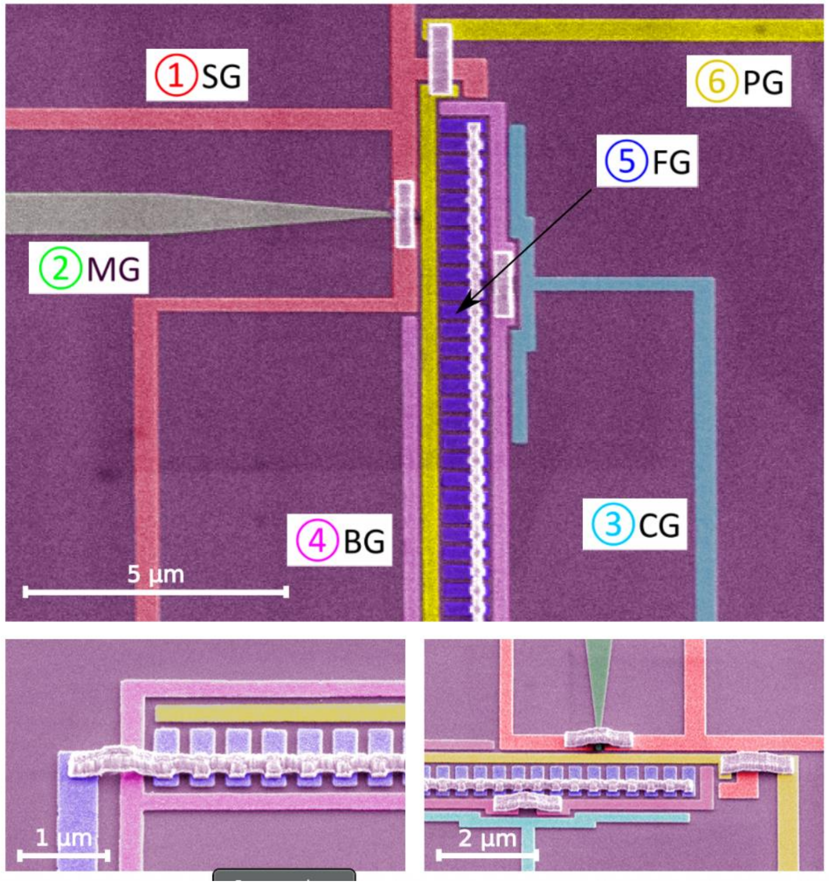


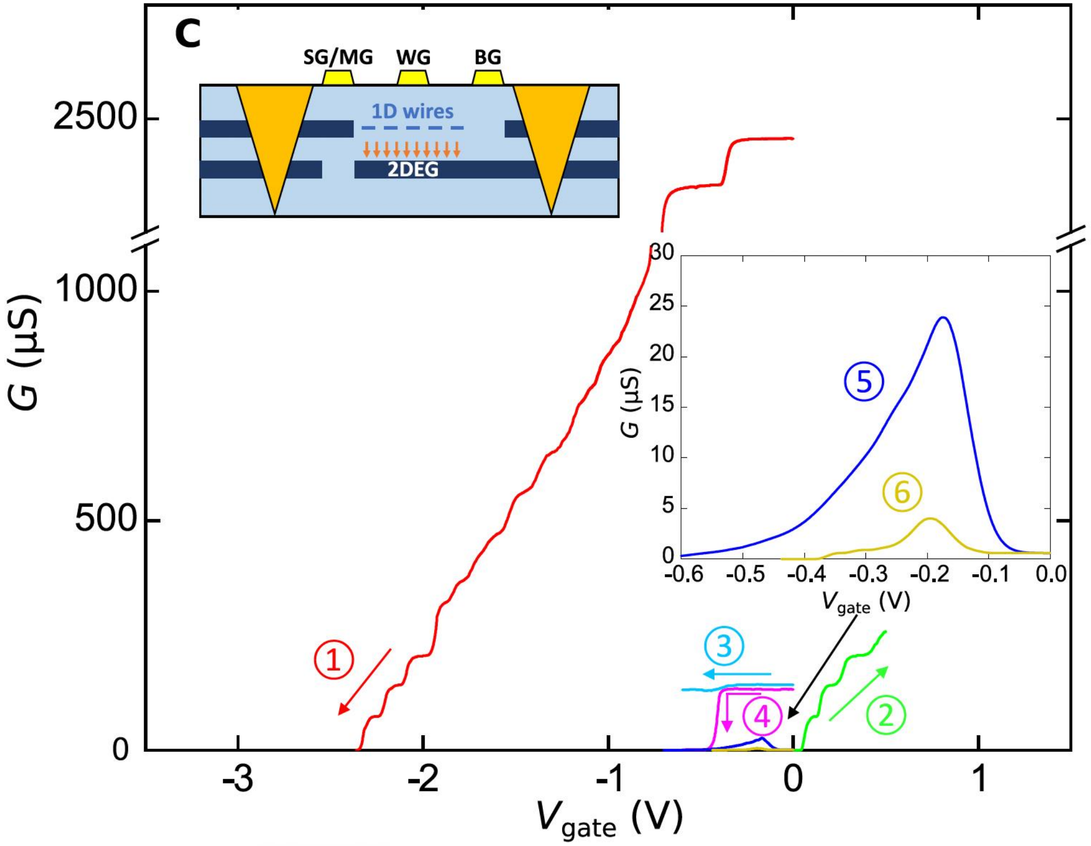




Gate Operation

A



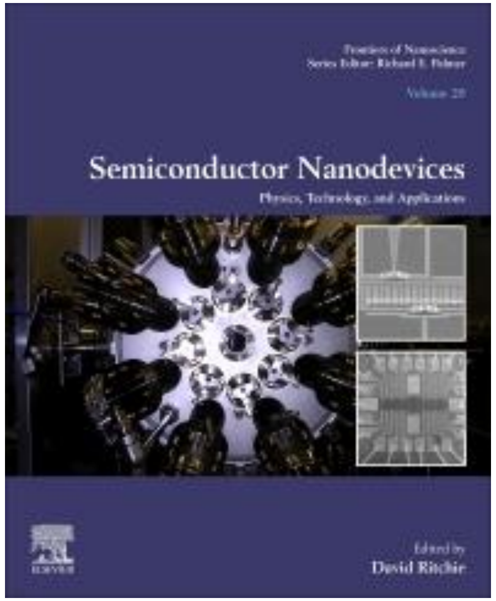


Conclusions

- We have shown that spin-charge separation is more robust than previously thought, extending past the low-energy regime of the TLL model.

- By tuning the degree of screening of the Coulomb interaction and changing the confinement in our wires, we saw how both masses and velocities associated with the spinon and holon Fermi seas evolve as a function of the interaction strength.

- We used this result to extract the bare mass of electrons in 1D GaAs wires, a result about 22% smaller than the commonly reported band value.



Vianez, Tsyplyatyev, and Ford, Semiconductor nanodevices as a probe of strong electron correlations, Elsevier (2021) [arXiv: 2105.12063]

Thank you for your time.
Any questions?