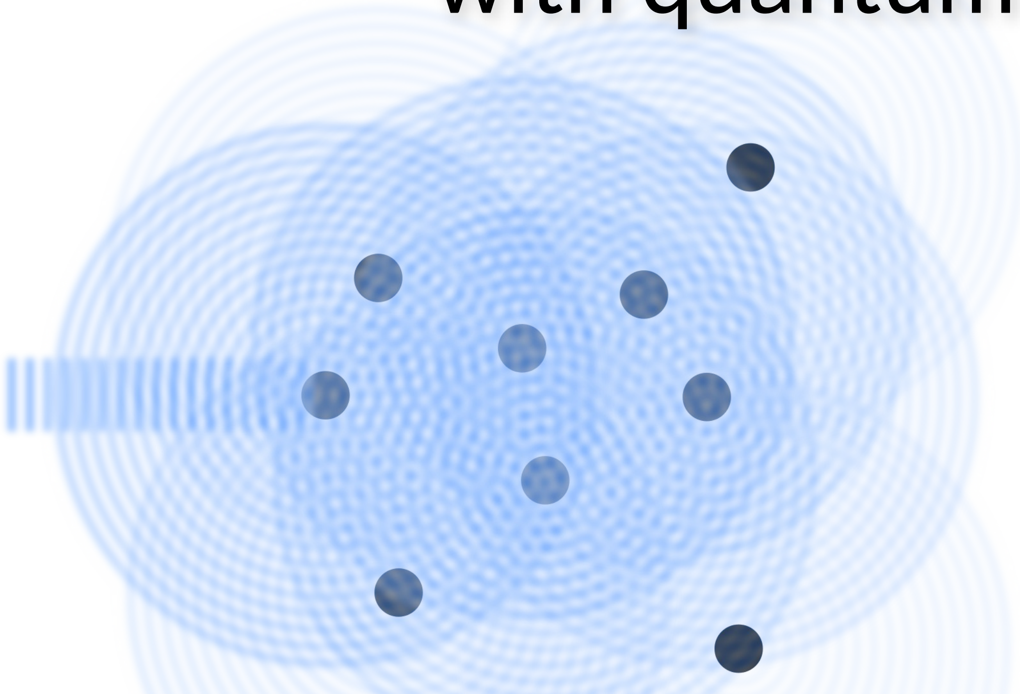
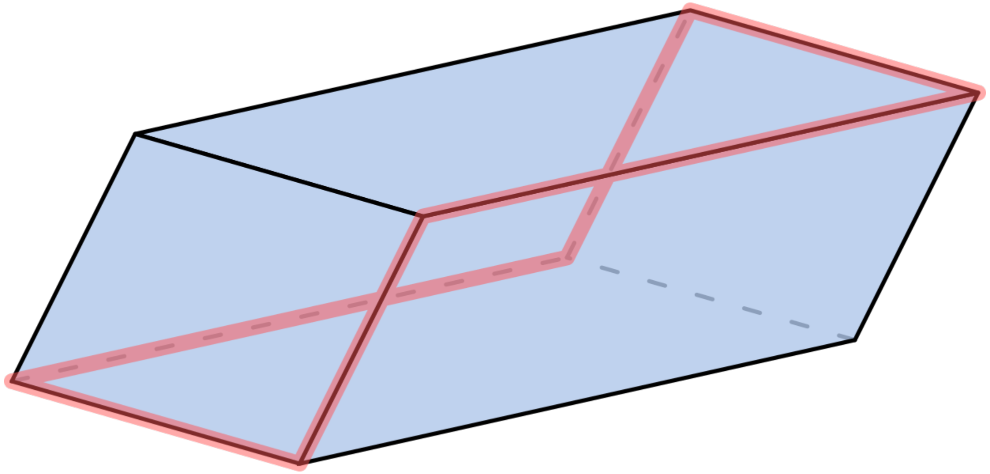
Unveiling topological hinge states in Bi_4Br_4 with quantum interferences





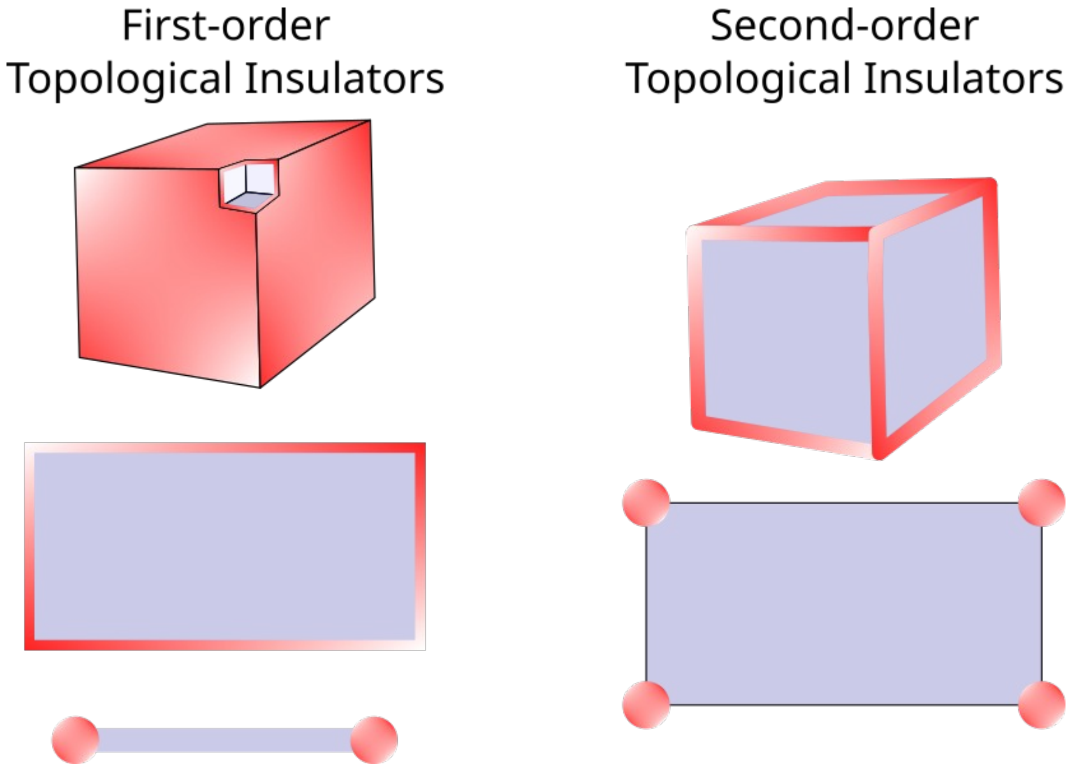
Jules Lefeuvre – LPS (UP-Saclay) – MESO group

Supervised by R. Deblock, S. Guéron and H. Bouchiat
Bi_4Br_4 crystals from M. Kobayashi and T. Sasagawa, *Tokyo Institute of Technology*

I) Topological Insulators (TIs)

Topological insulator :

Insulating bulk, conducting boundaries



I) Topological Insulators (TIs)

Topological insulator :

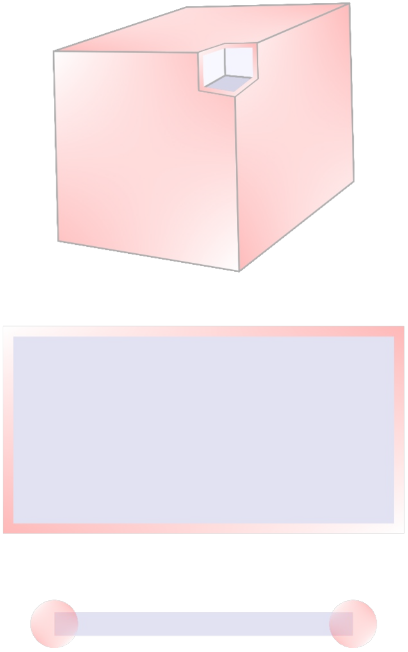
Insulating bulk, conducting boundaries

2nd order topological insulator :

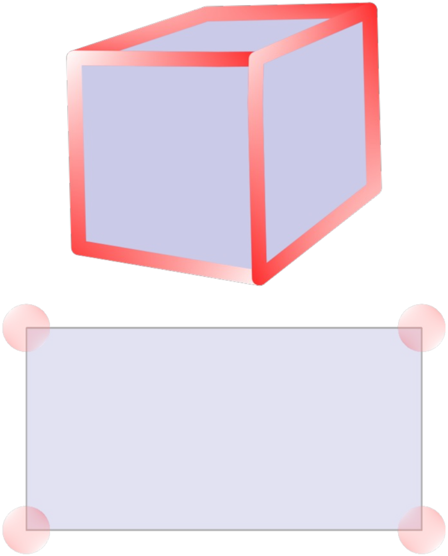
- Recent extension of the classification

→ **Predicted in Bi_4Br_4**

First-order Topological Insulators

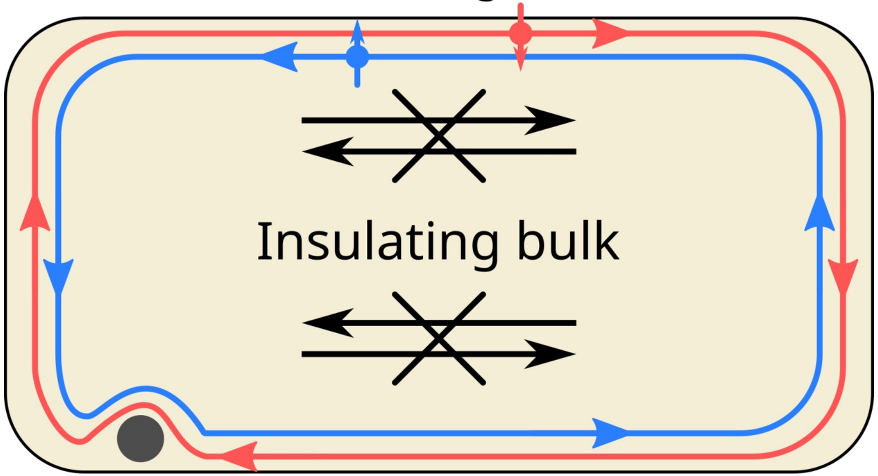


Second-order Topological Insulators



I) Topological protection

1D helical edge states



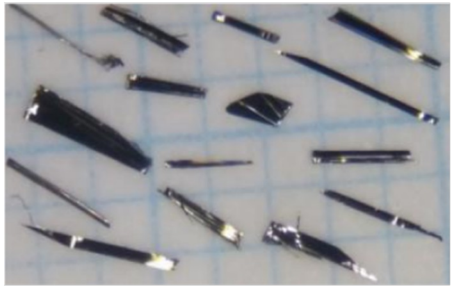
Spin-momentum locking :

Opposite directions of propagation have opposite spins

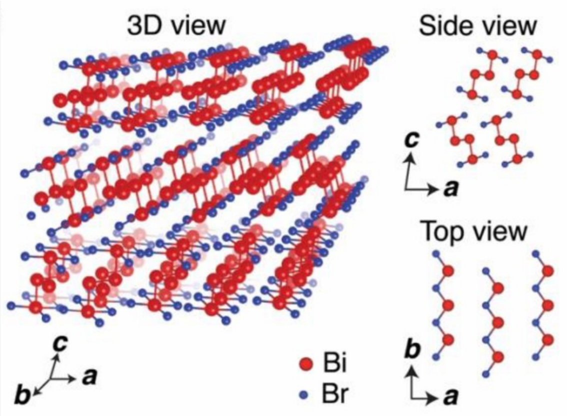
Topological protection
(against non-magnetic disorder)

→ **Ballistic transport**

I) Bi_4Br_4 – A truly insulating TI ?



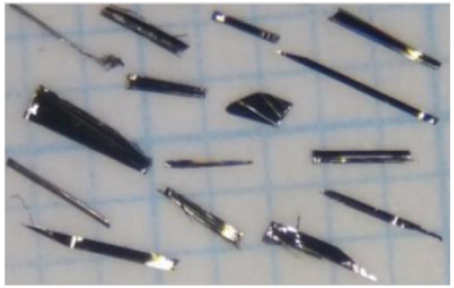
Noguchi, R. et al. (2021), Nature Materials, 20(4)

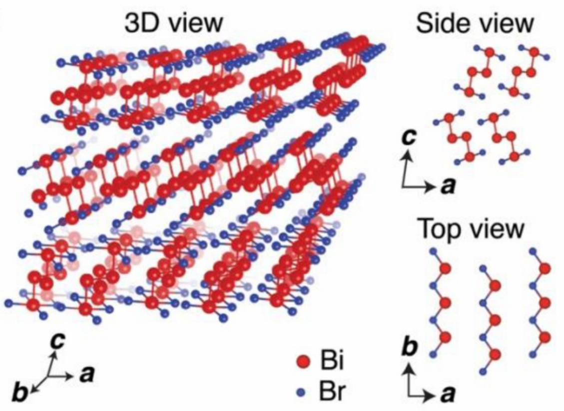


Quasi-1D :

- Strong covalent bonds along one direction
- Weak (Van der Waals) bonds along the other two

I) Bi_4Br_4 – A truly insulating TI ?



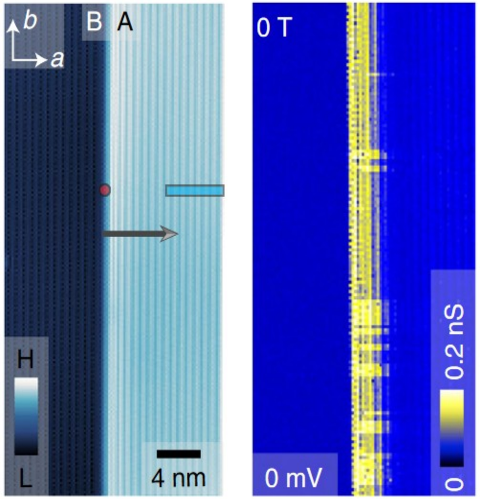


Noguchi, R. et al. (2021), Nature Materials, 20(4)

Quasi-1D :

- Strong covalent bonds along one direction
- Weak (Van der Waals) bonds along the other two

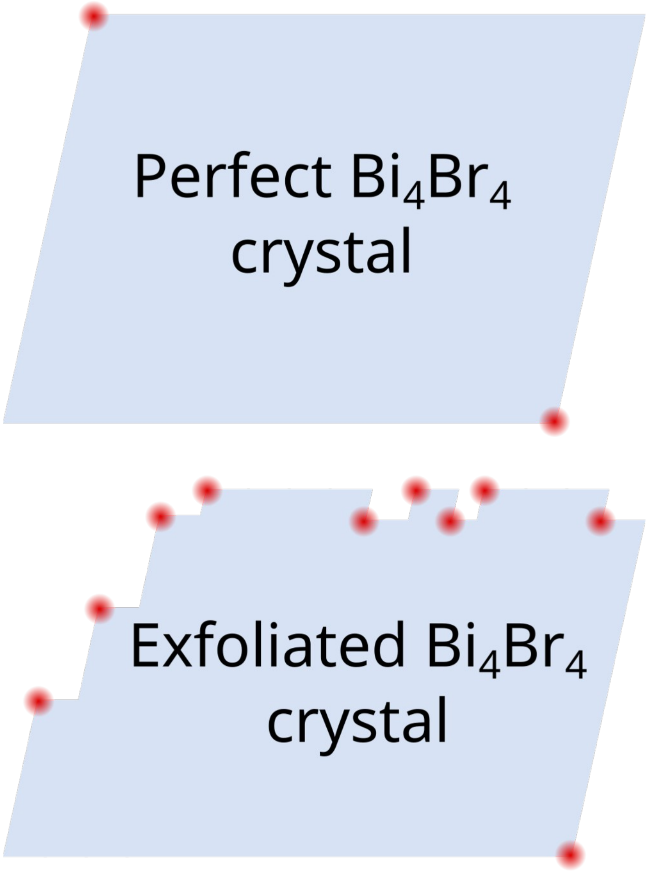
Topography Density of states



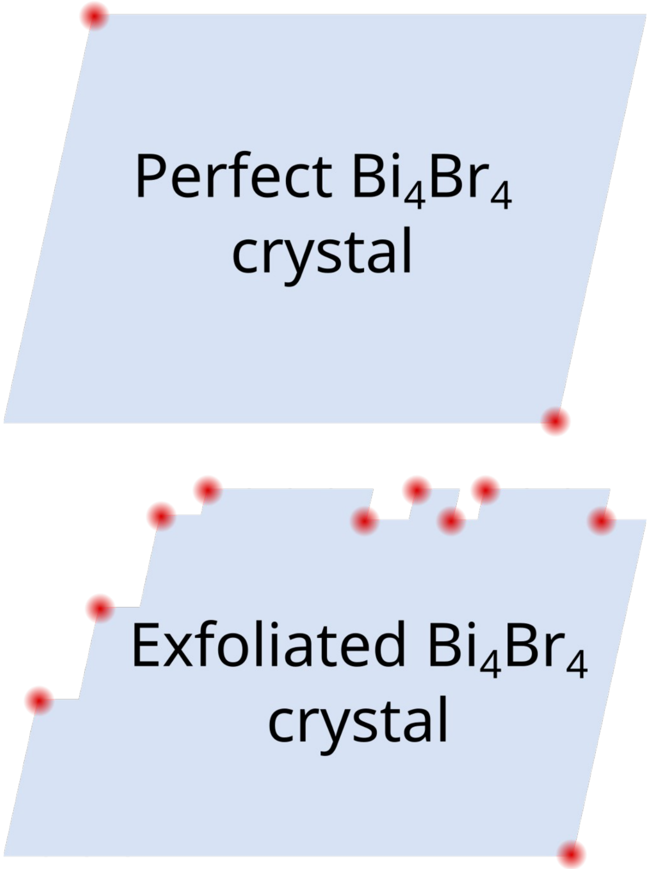
Shumiya, N. et al., 2022, Nat. Mater.

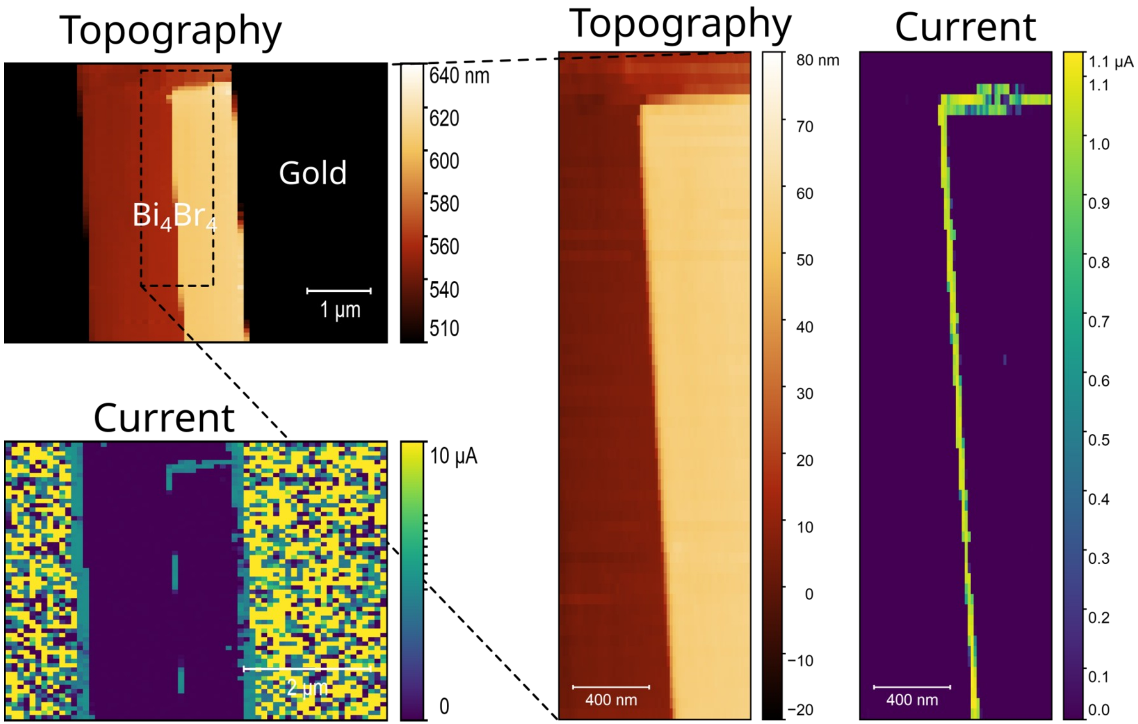
- Large spin-orbit gap (230 meV)
- Evidence of the topological states in ARPES and STM
- Topological states can survive up to **room temperature**

I) Conducting hinges



I) Conducting hinges

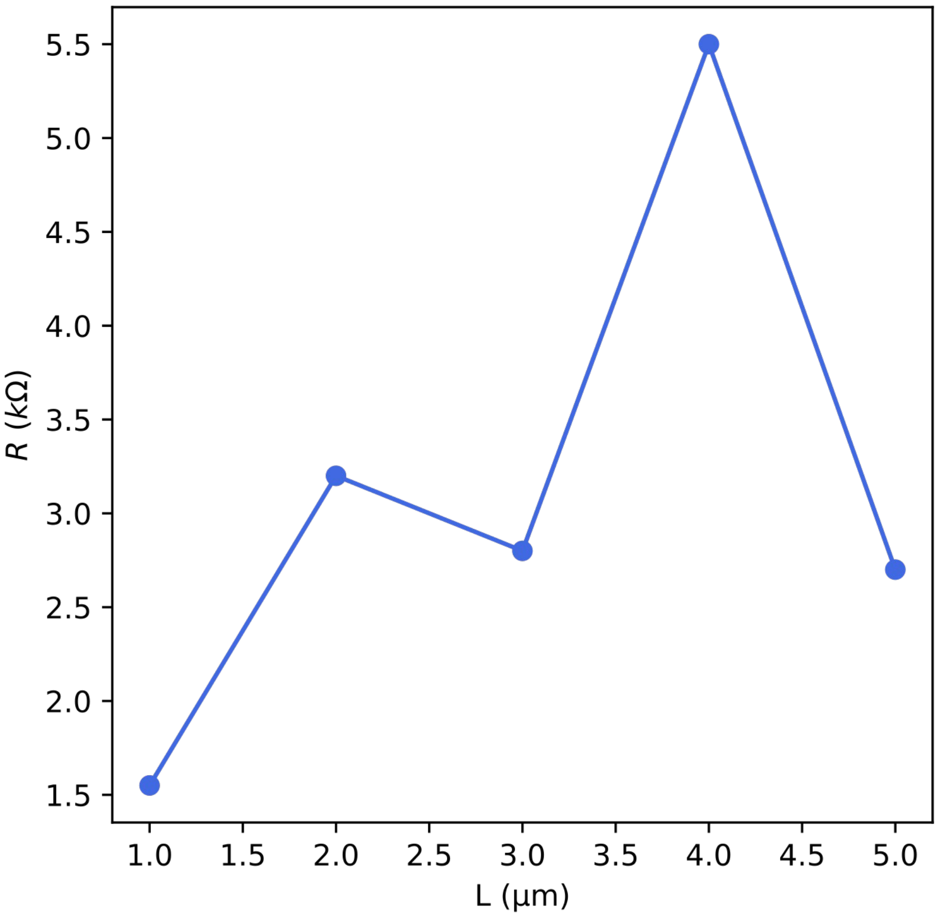




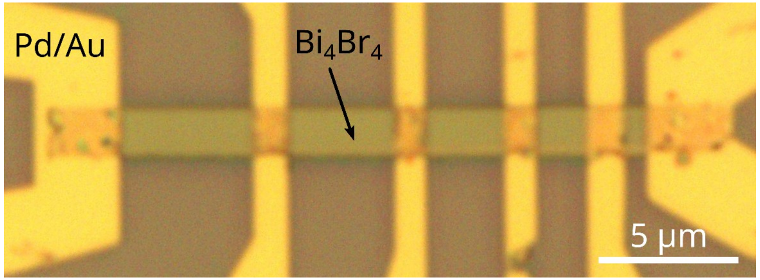
Edge conduction revealed by our conducting AFM measurements at 300 K

What about its transport properties ?

II) Scaling of the resistance



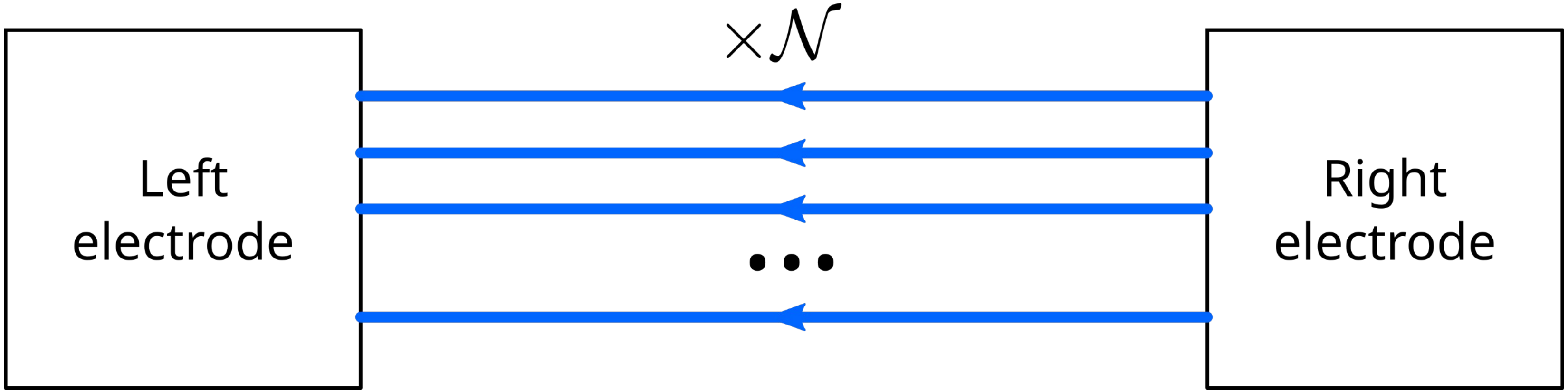
5 µm - 4 µm - 3 µm - 2 µm - 1 µm



$$R = \frac{\rho L}{S}$$

Diffusive conductors

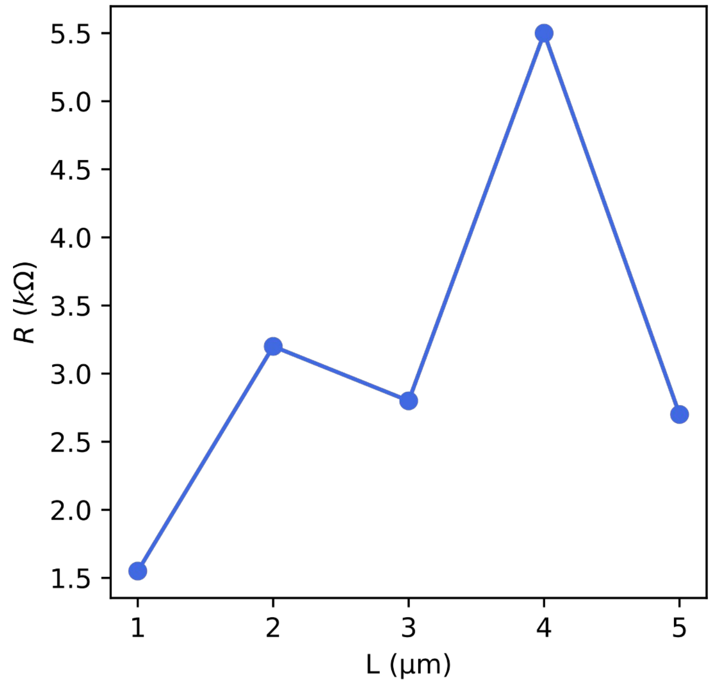
Hints at **ballistic transport**

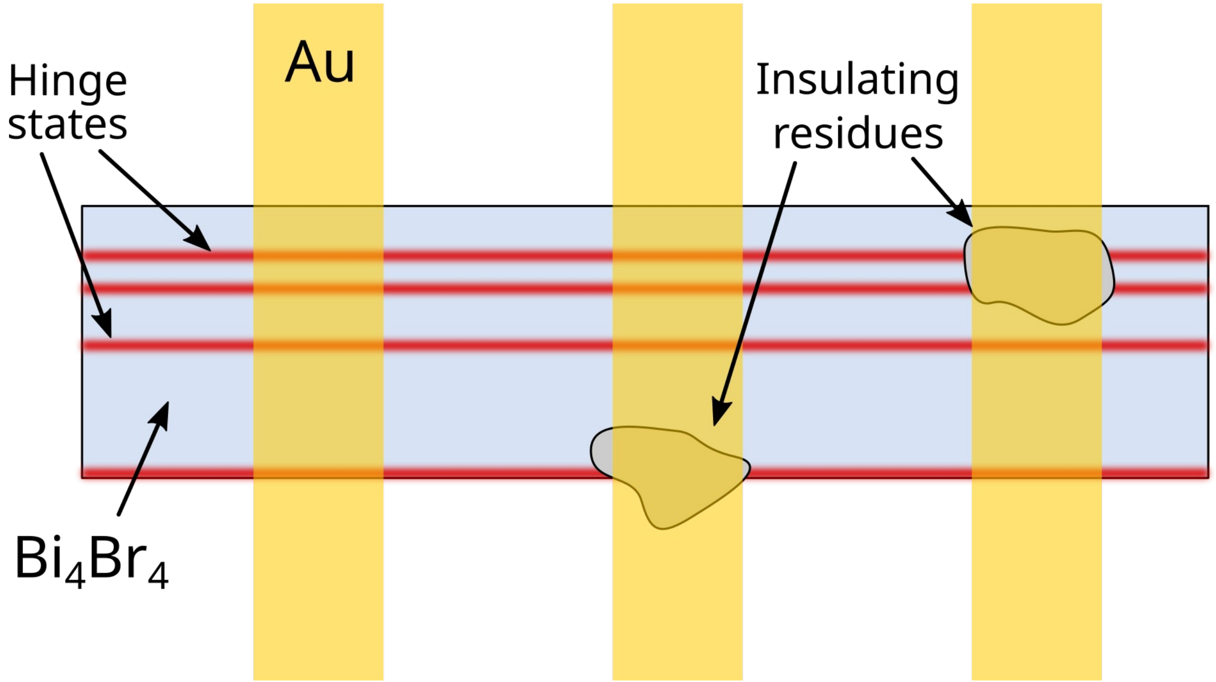


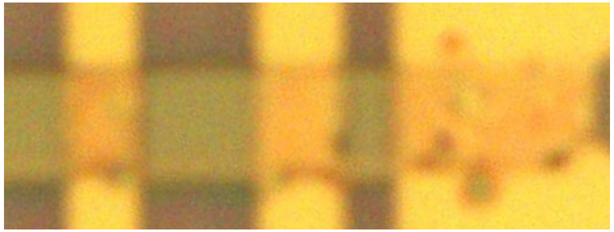
Landauer-Büttiker formula :

$$R = \frac{1}{\mathcal{N}} \times \frac{h}{e^2} \approx \frac{1}{\mathcal{N}} \times 26\ k\Omega$$

This is a **contact resistance**

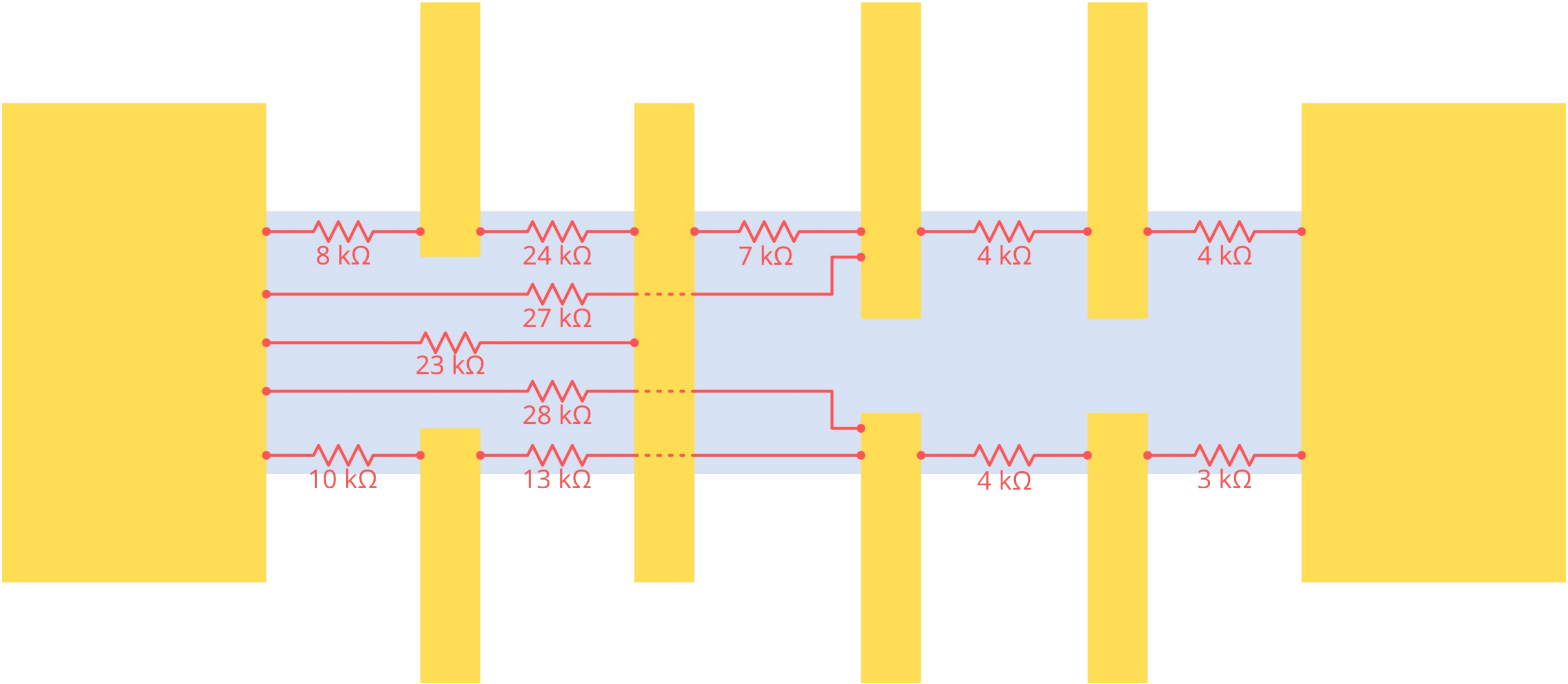


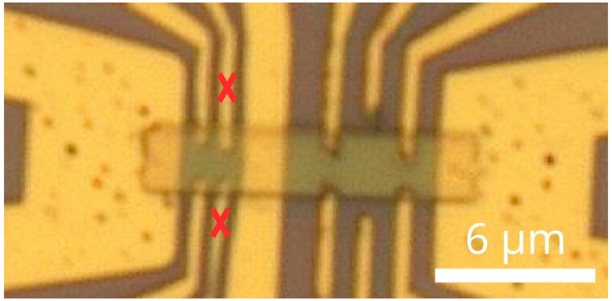




Number of contacted edge states can vary between contact pairs

II) Resistance network

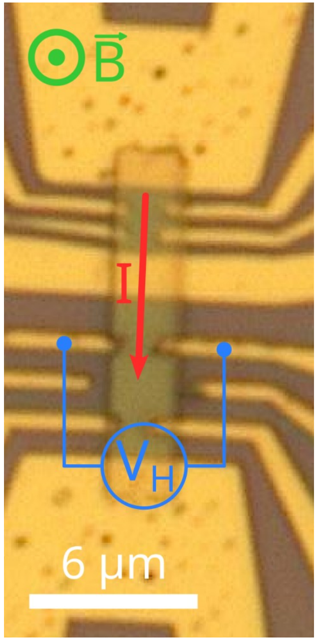


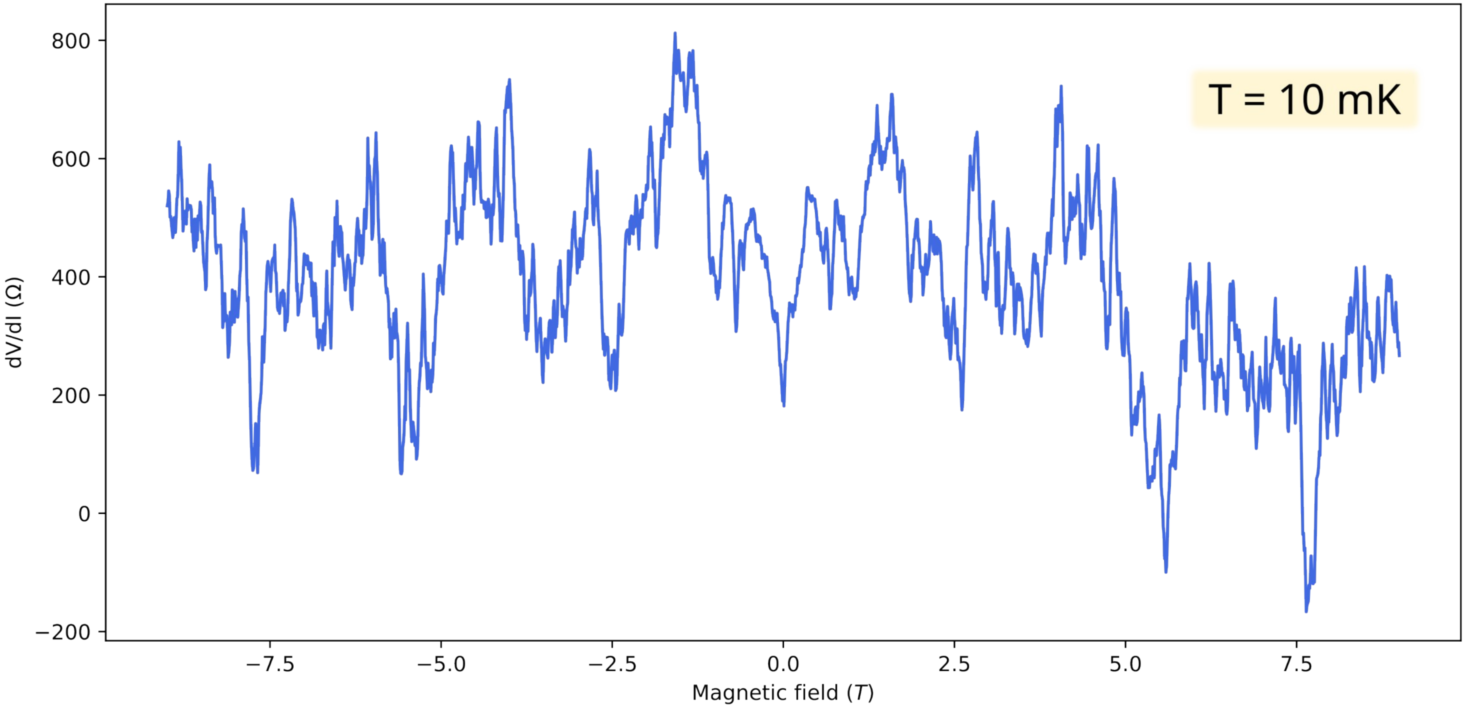


Highly anisotropic transport

Supports the 1D nature of transport along hinge states

II) Hall effect





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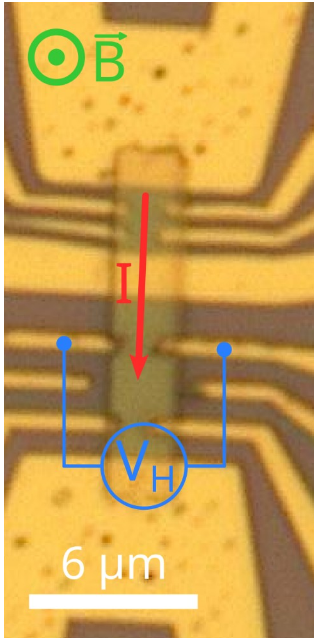
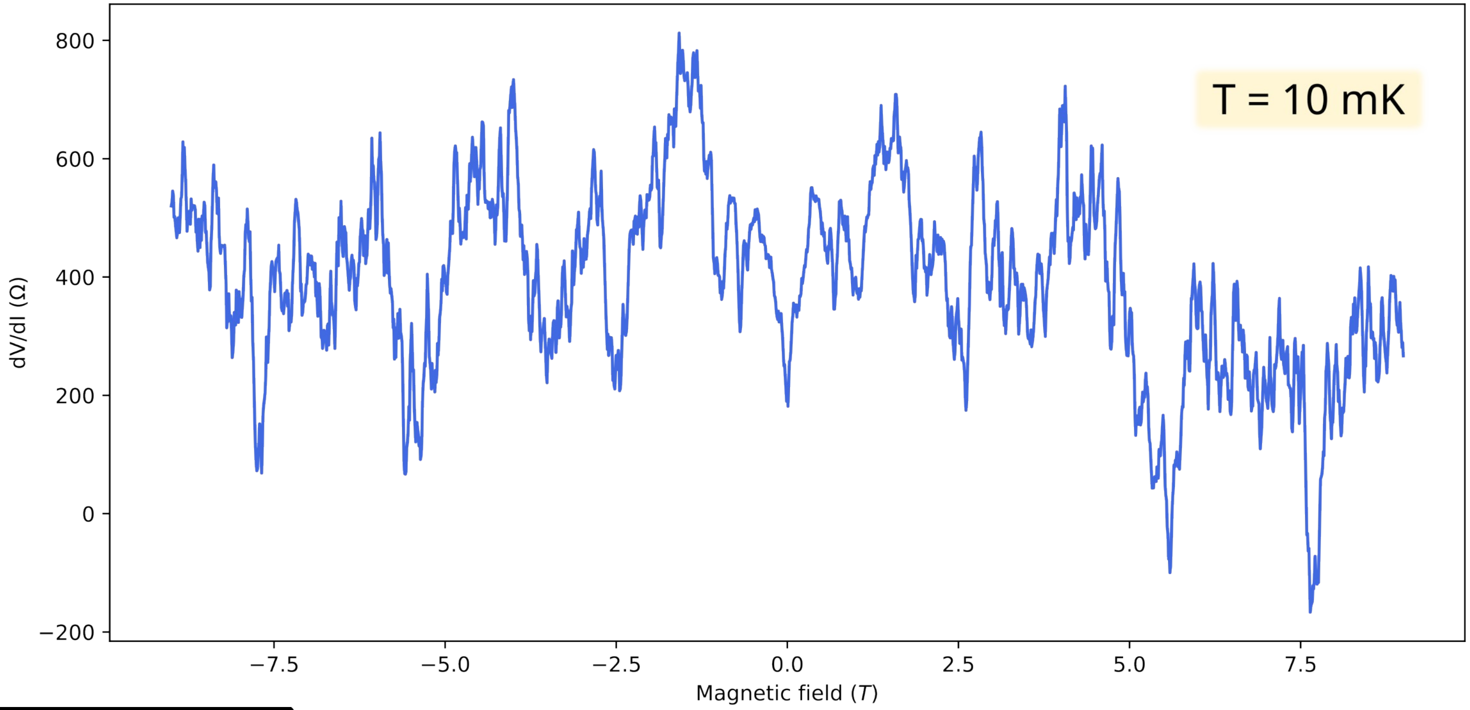
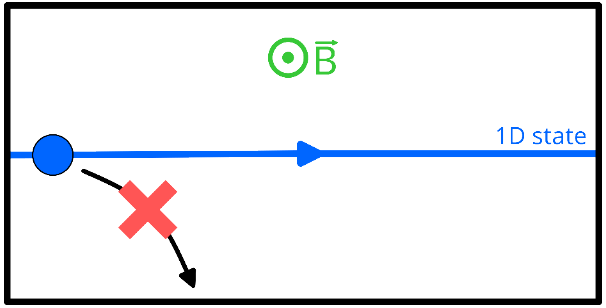


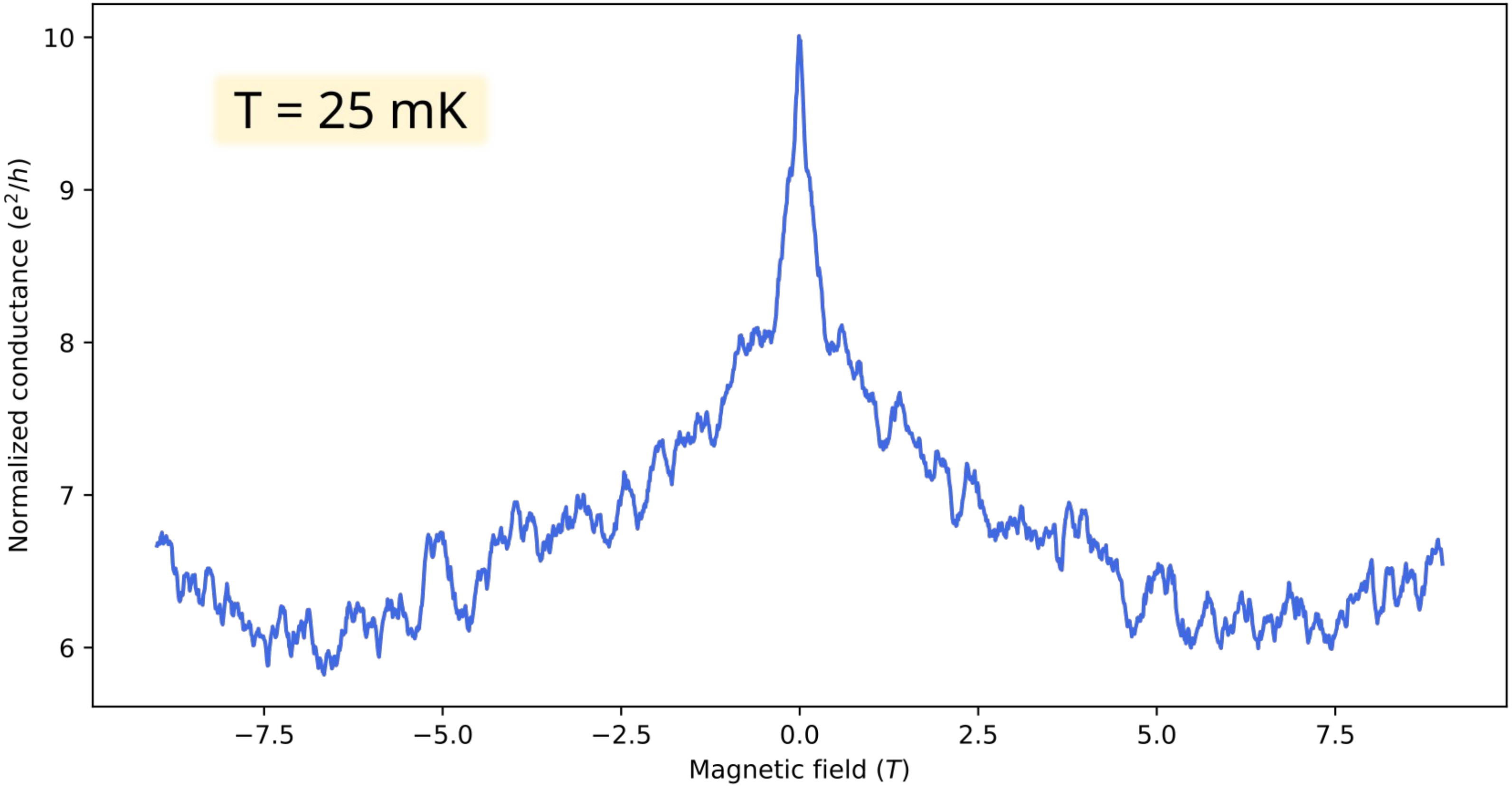




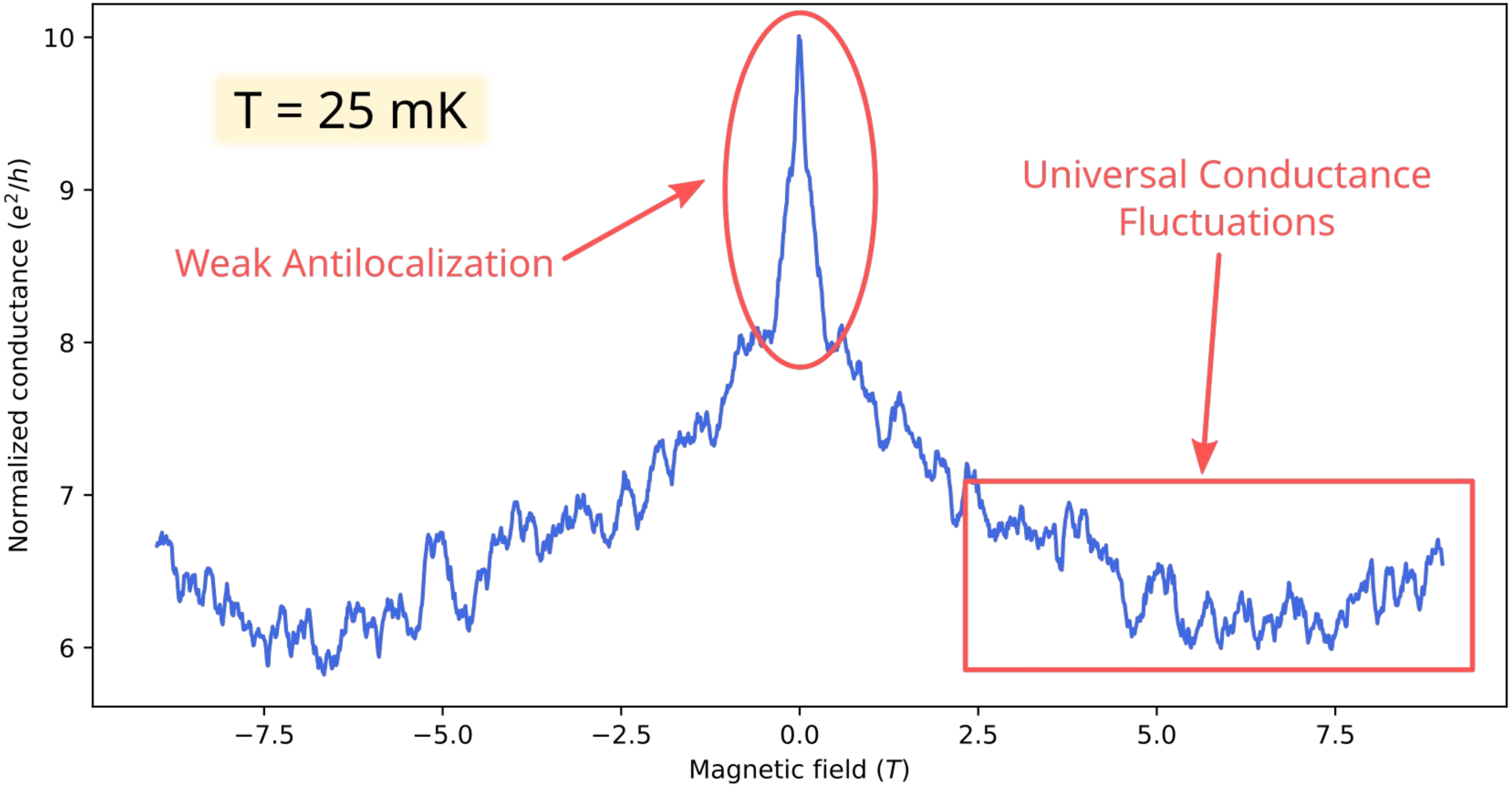
No Hall effect

Further evidence of conduction by 1D hinge states

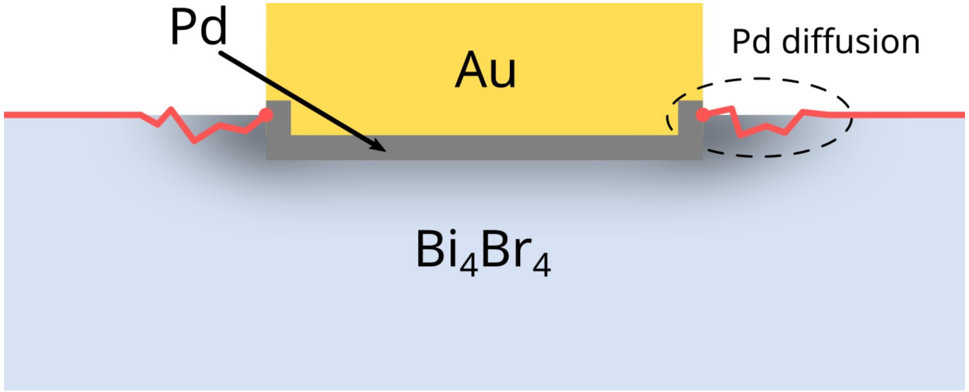
III) Quantum interferences



III) Quantum interferences

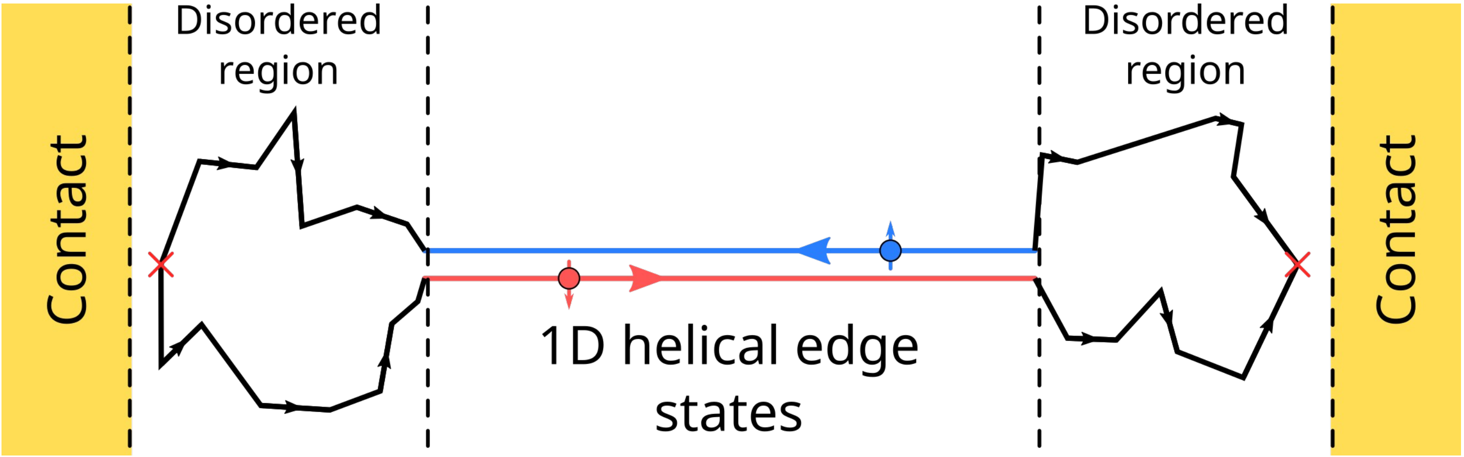


III) Refined model for the contacts

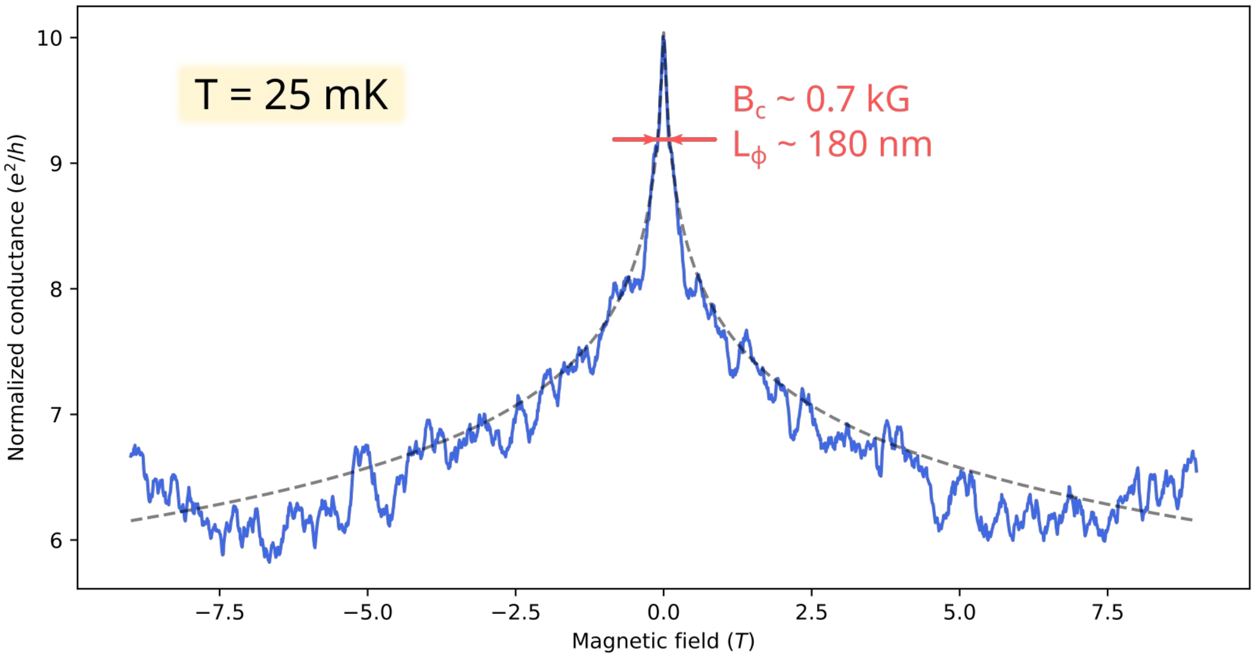


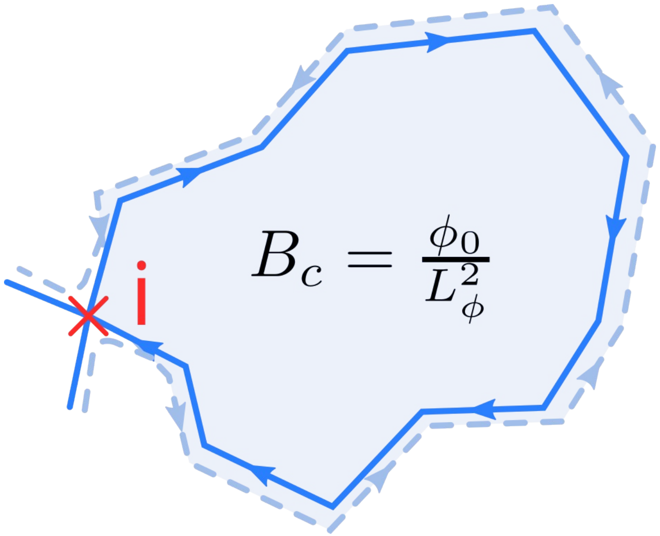
Interdiffusion of Pd inside Bi_4Br_4 creates a small disordered region near the contacts

→ **Quantum interferences at low T**



III) Weak Antilocalization

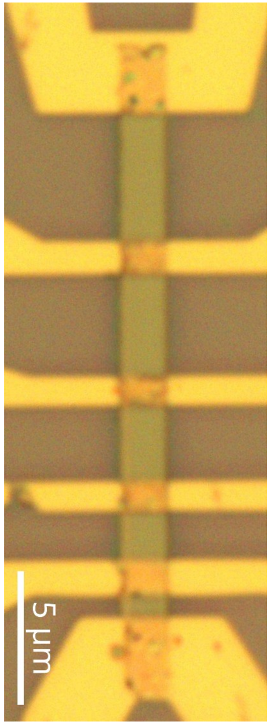


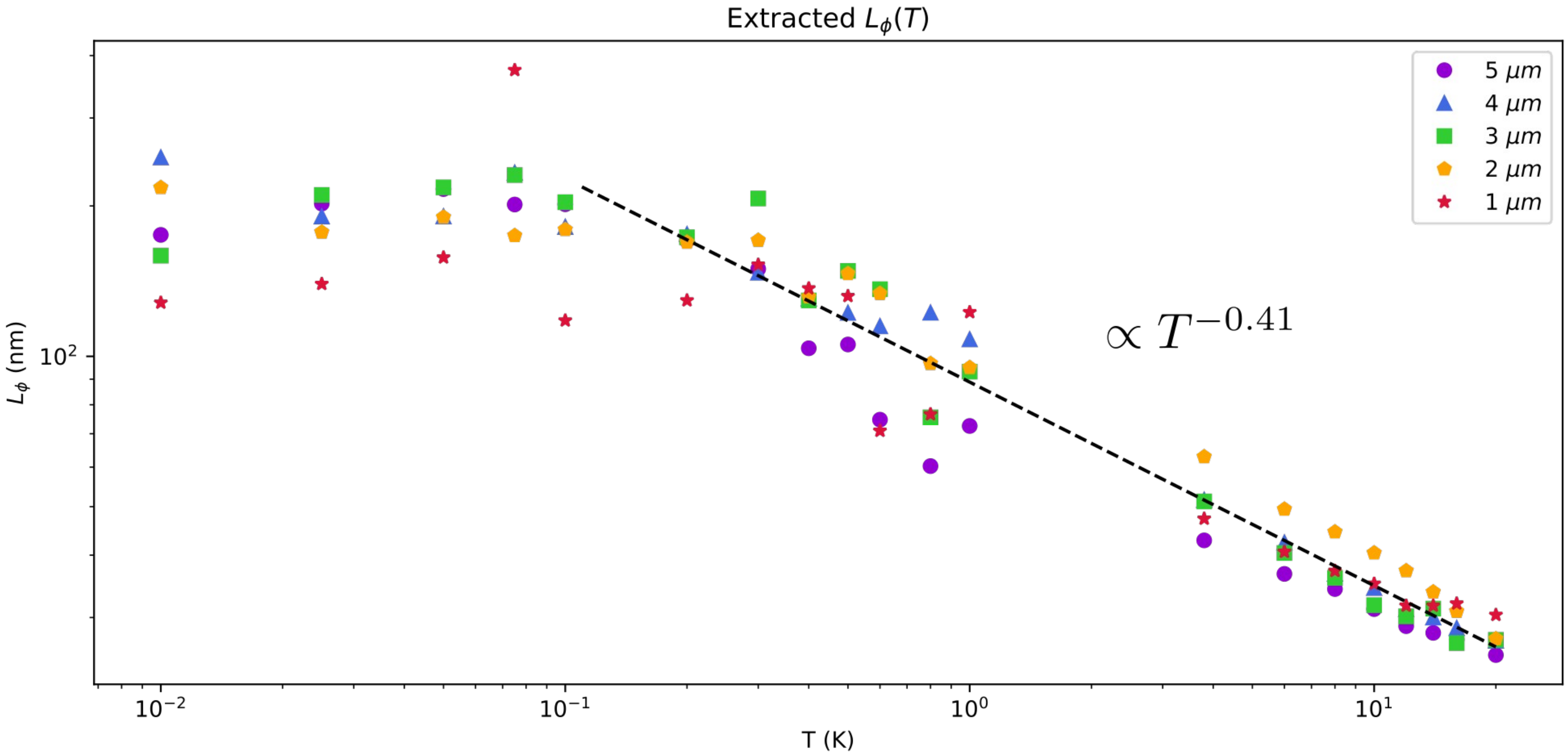


Conductance peak → **Weak Antilocalization**
Indicates strong spin-orbit coupling

Small Lφ
Reasonable considering interdiffusion hypothesis

III) Weak Antilocalization

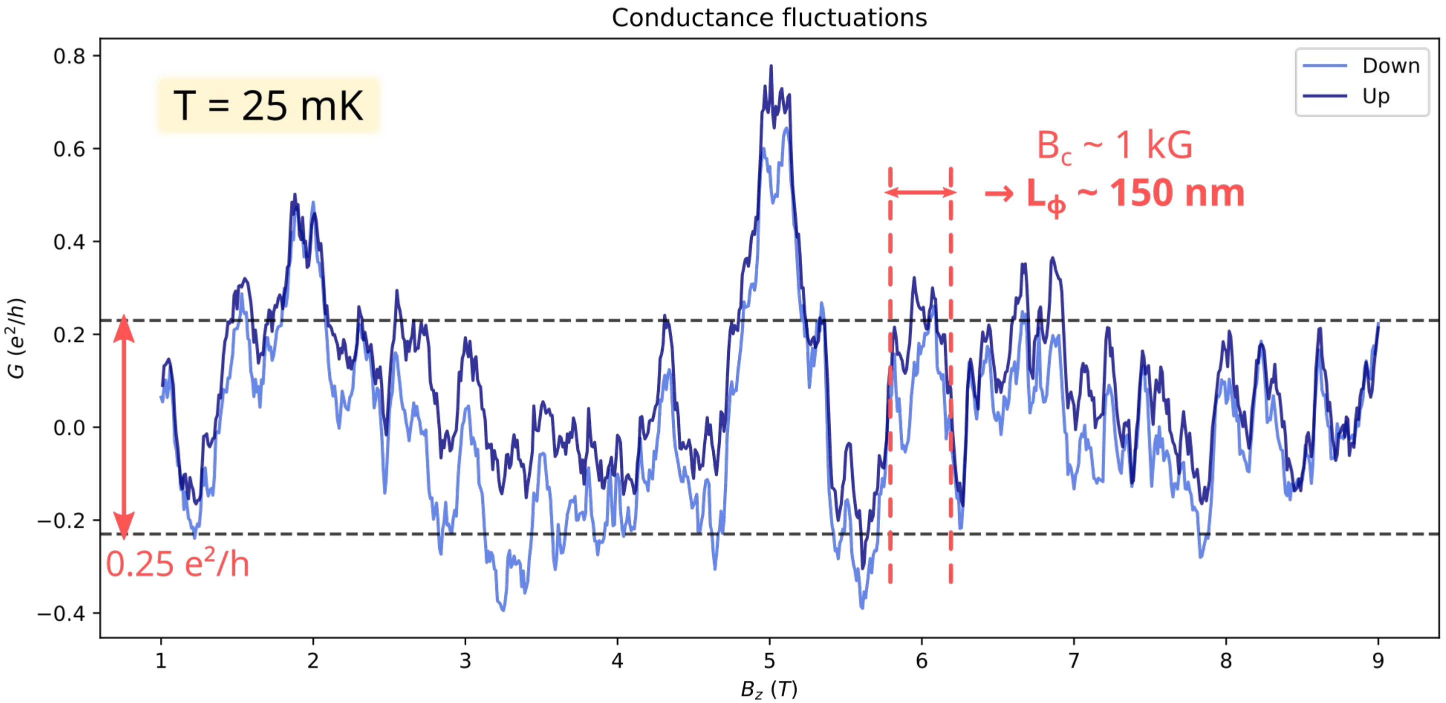




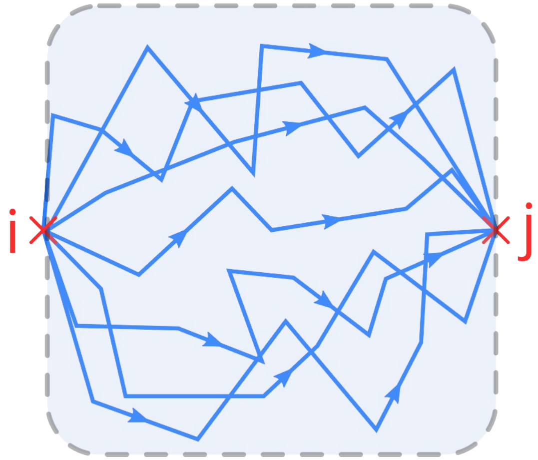
All sections exhibit very similar behavior in L_φ

~ $T^{-1/2}$ power law
Dephasing by e^- - e^- interactions

III) Universal Conductance Fluctuations



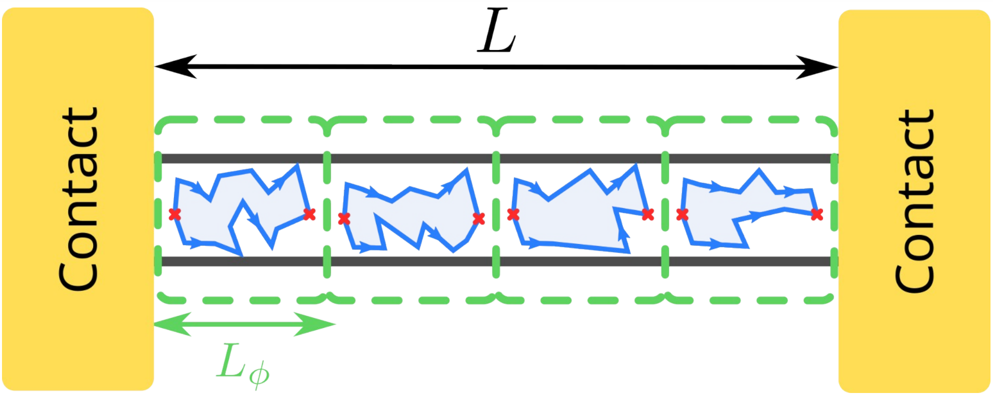
$$B_c = \frac{\phi_0}{L_\phi^2}$$



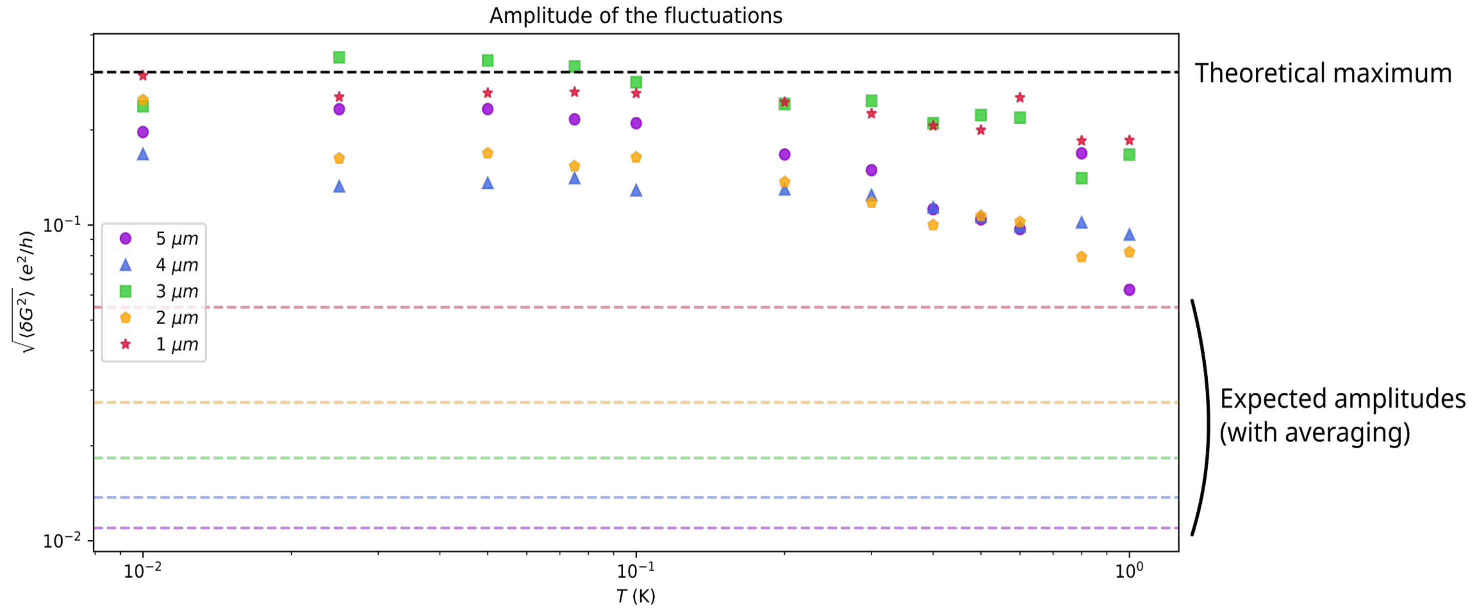
Confirms the Lφ extracted from Weak Antilocalization

Strong fluctuations

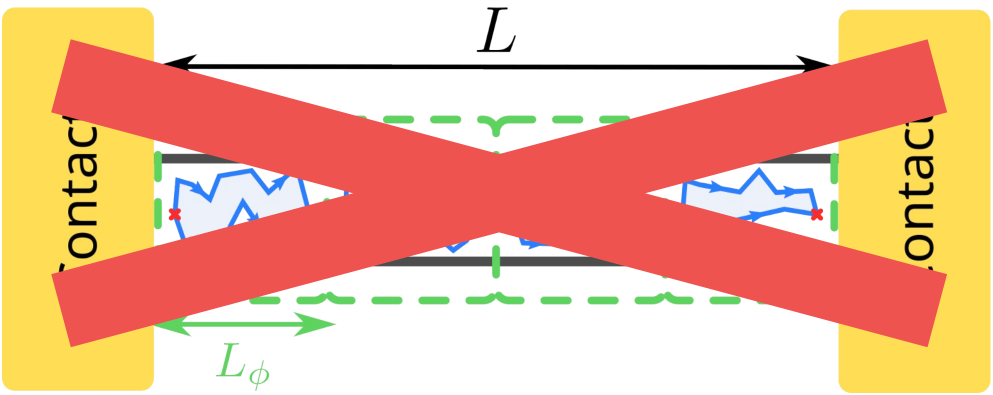
III) Self-averaging ?



$$\sqrt{\langle \delta G^2 \rangle} \propto \left(\frac{L_\phi}{L} \right)^{2-\frac{d}{2}}$$



III) No self-averaging



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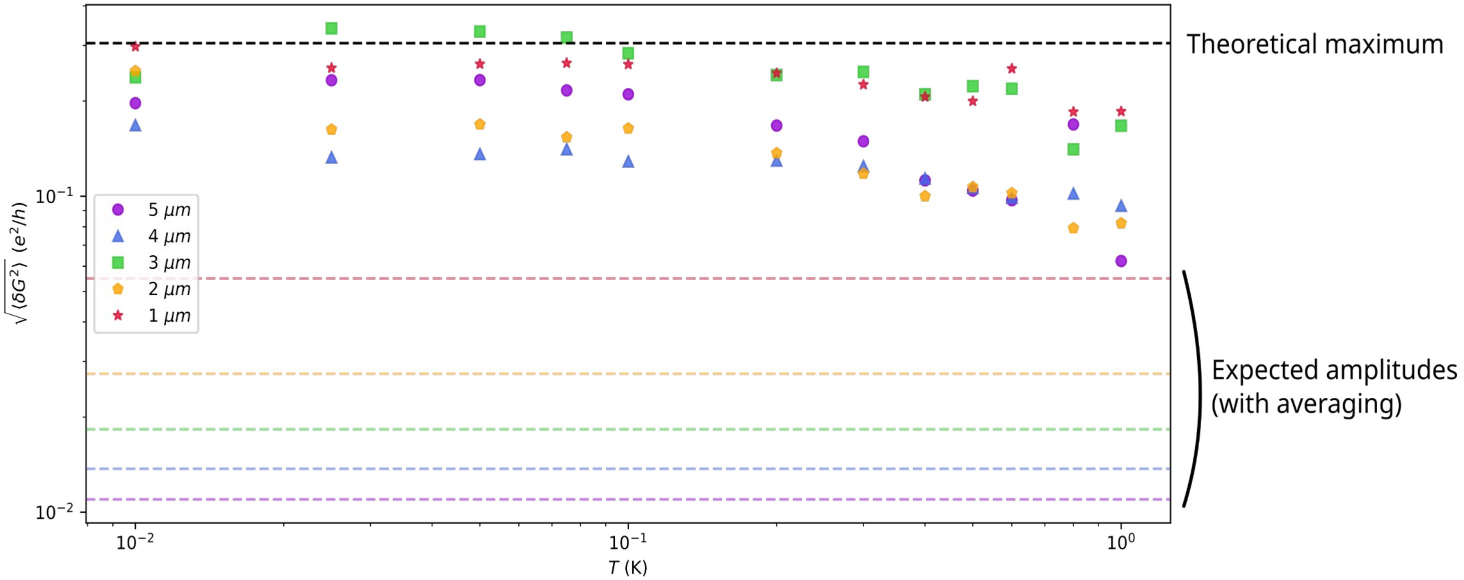
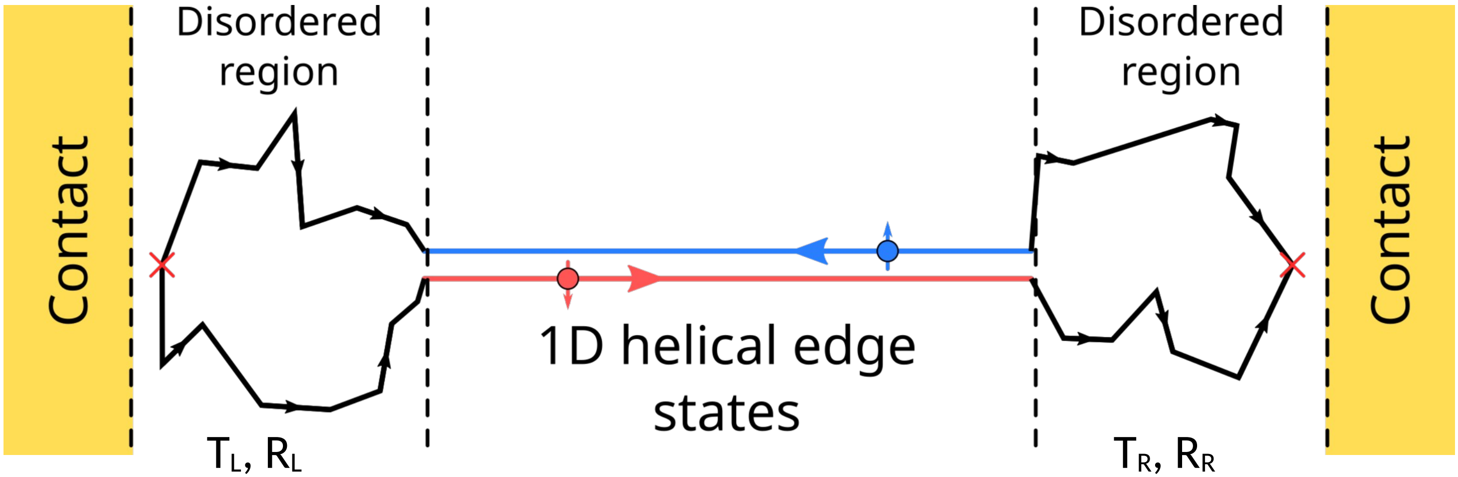


Fluctuations are **much larger** than expected

→ **No self-averaging**

III) Transmission modulated by interferences



$T_{R,L}$, $R_{R,L}$: Transmission / reflection coefficient of the left / right disordered region

Small disordered region ($L_{Pd/BiBr} \sim L_\varphi$) produces fluctuations of the global conductance of **1D hinge states**

Depend on B !

$$G_{1D} = \frac{e^2}{h} \frac{T_L T_R}{1 - R_L R_R}$$

Conclusion

- Strongly anisotropic transport suggests the existence of **1D channels**

- General lack of length dependence provide good evidence for the **ballisticity** of the 1D hinge states

Conclusion

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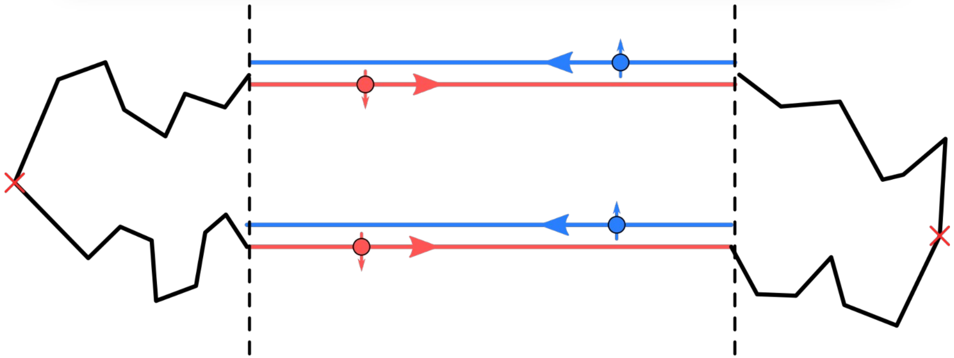
→ Bi_4Br_4 appears as an excellent material for the fundamental study of 1D topological states

Conclusion

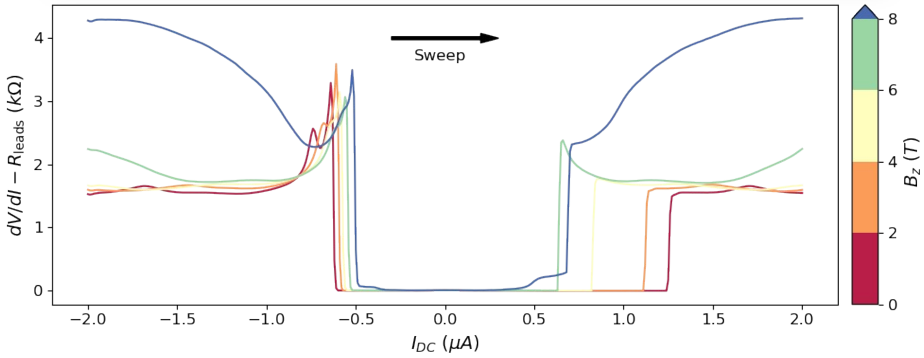
- Strongly anisotropic transport suggests the existence of **1D channels**
- General lack of length dependence provide good evidence for the **ballisticity** of the 1D hinge states

→ Bi_4Br_4 appears as an excellent material for the fundamental study of 1D topological states

Aharonov-Bohm oscillations ?

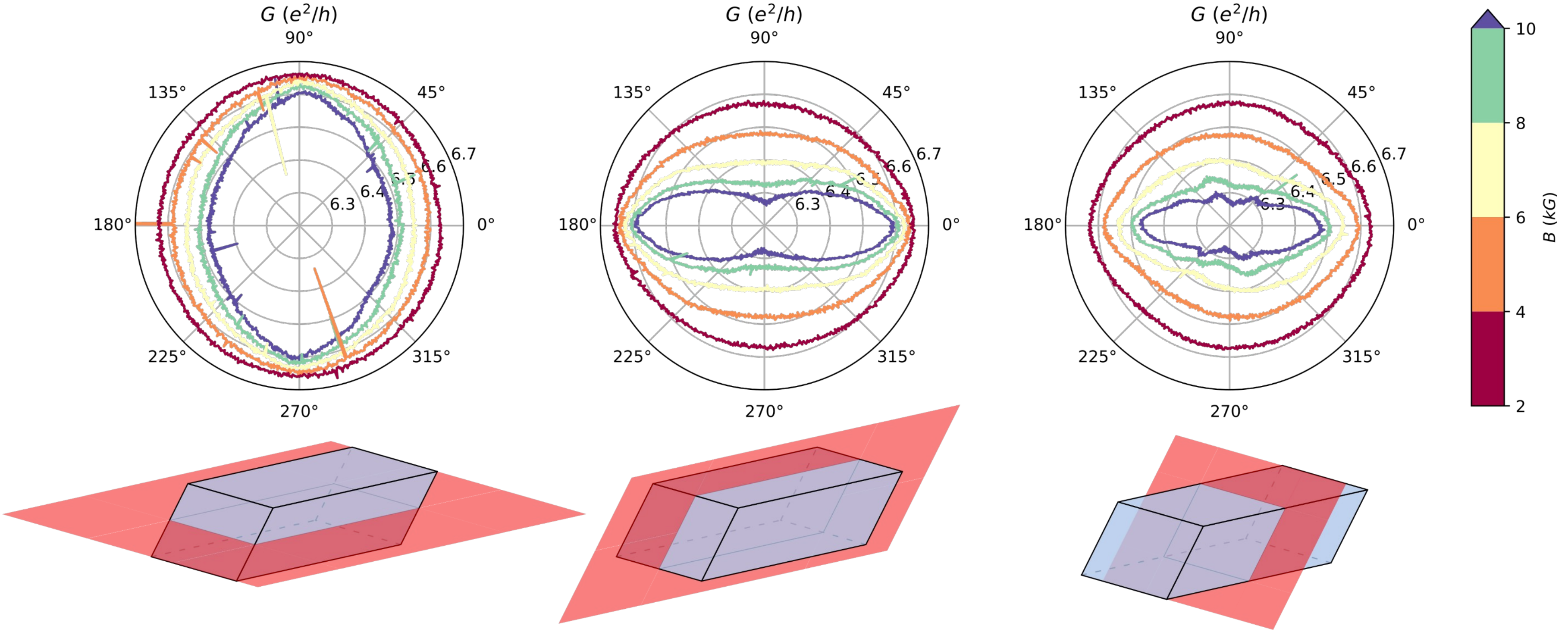


Interplay with superconductivity ?



Thank you !

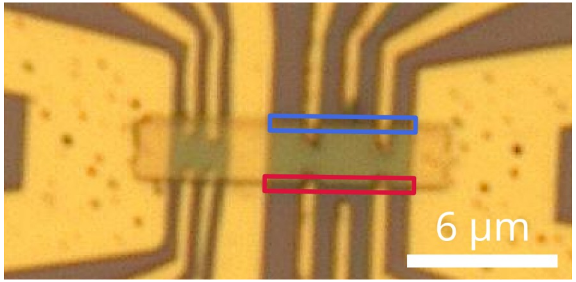
A1) Field anisotropy

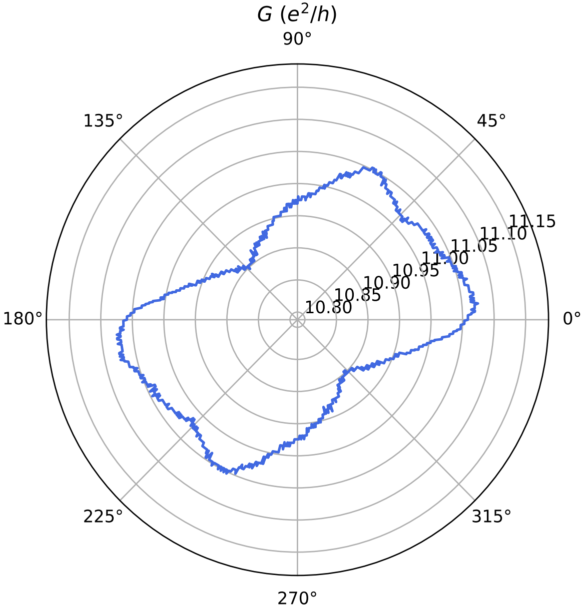


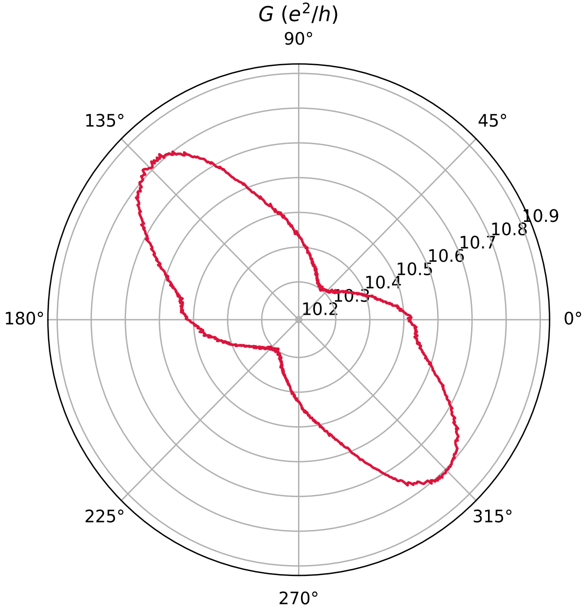
Diffusion paths do not explore the thickness of the flake → **2D diffusion**

Two smaller lobes in different directions…

A1) Field anisotropy

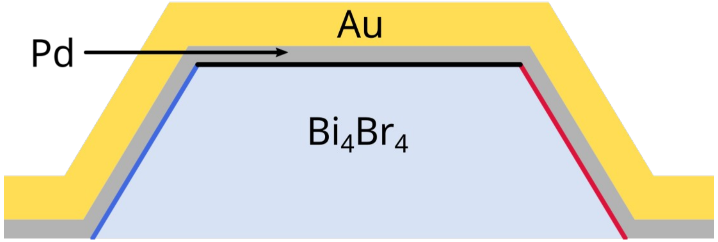




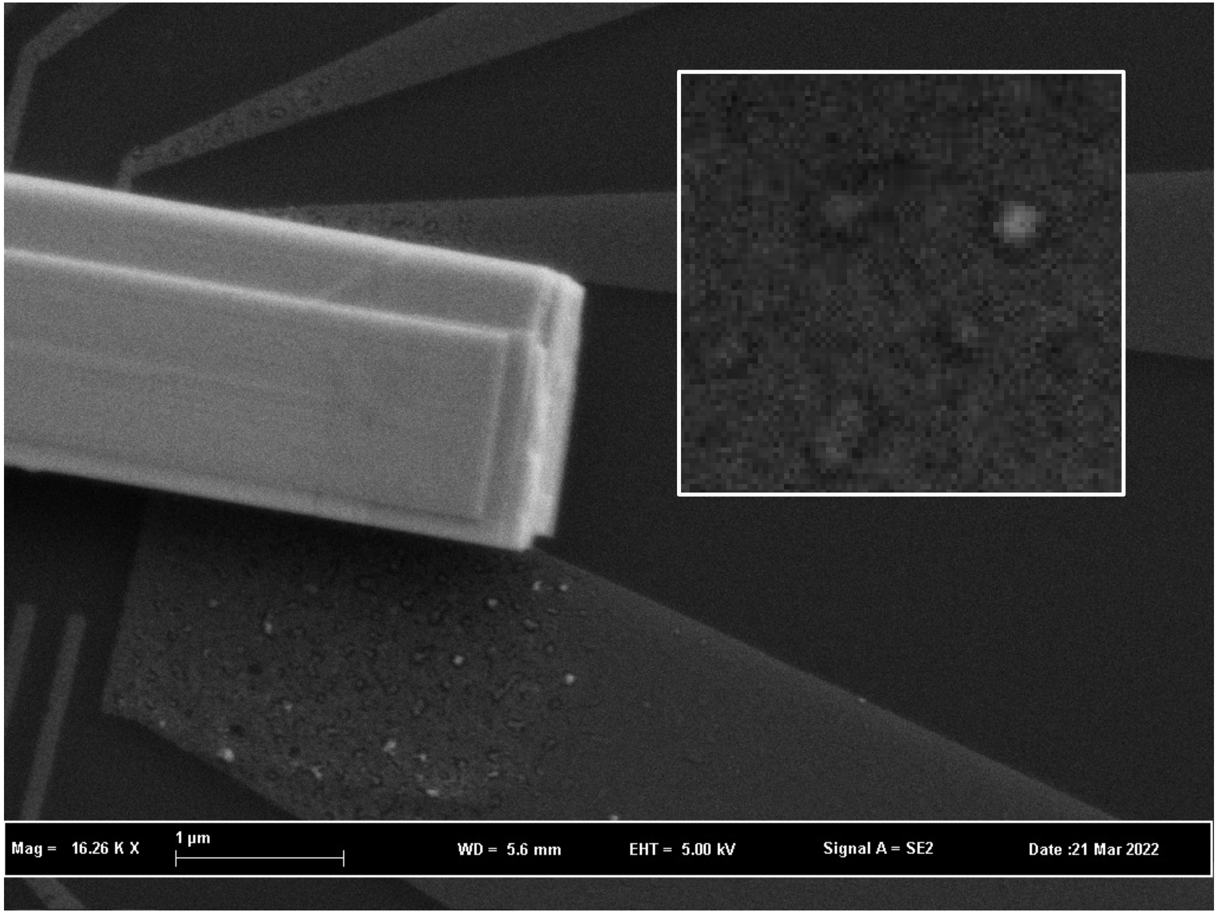


Direction of the lobes = slope of the side contacts

→ Confirms that the disordered region originates from the contacts

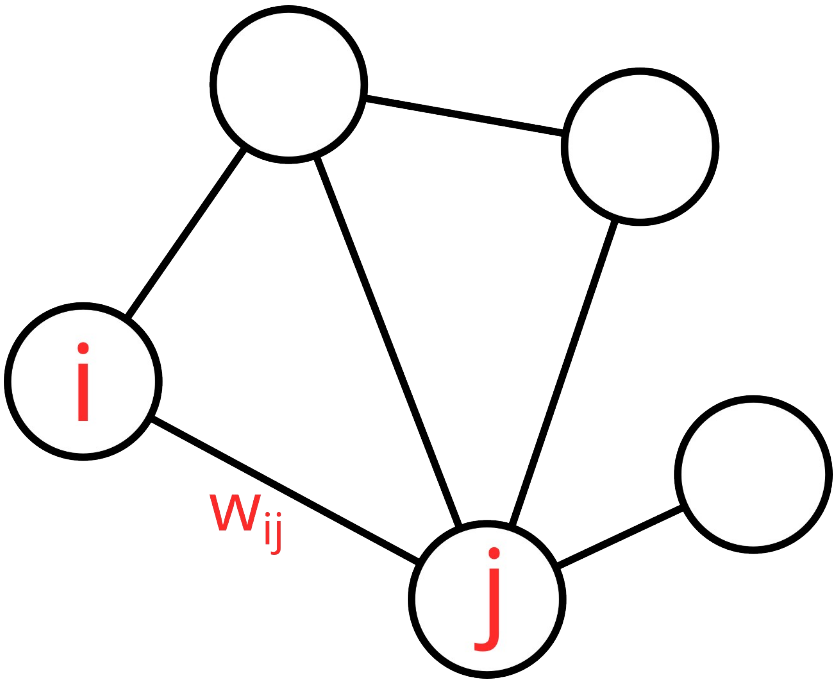


A2) Pd/Bi_4Br_4 interdiffusion



EDX measurement of the spots show **Bi** and **Pd** in their composition

Measuring the set of all 2-wire resistances (= the resistance distances) allow to recover the resistance network of the sample



Resistance distance matrix : $\mathcal{R}_{ij}$

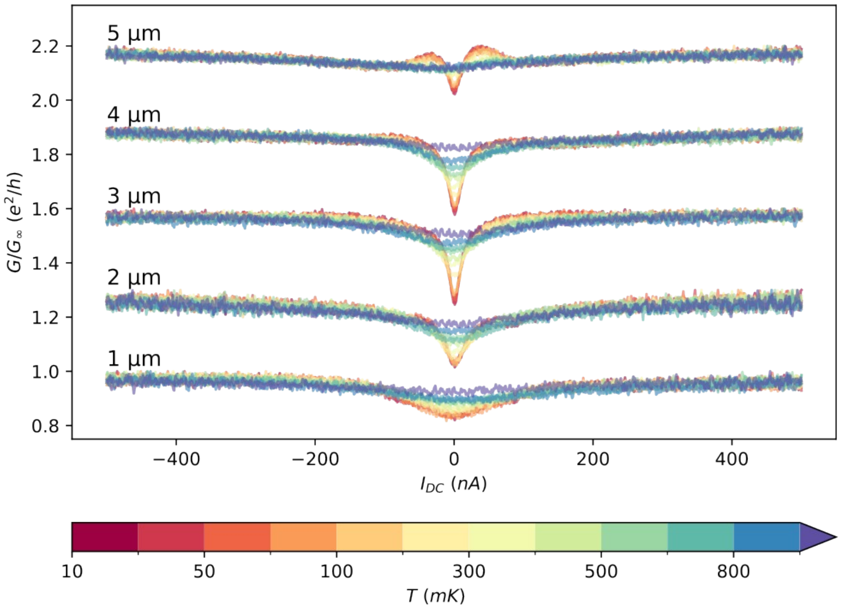
Laplacian matrix : $\mathcal{L}_{ij} = \frac{-1}{w_{ij}} \quad \text{if } i \neq j$

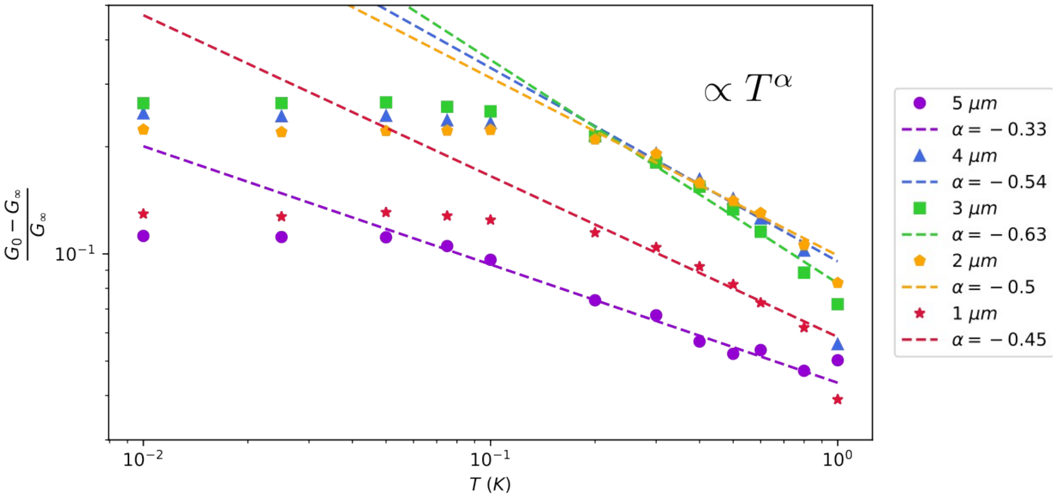
$$\mathcal{L} = 2\mathcal{R}^{-1} + \frac{2}{\mu^T \mathcal{R} \mu} \mu \mu^T$$

with $\mu_i = 2 - \sum_{j=\mathcal{N}(i)} \frac{R_{ij}}{w_{ij}}$

Bapat, R.B. (2004), Communications in Mathematical and in Computer Chemistry

A4) Dynamical Coulomb Blockade vs. Luttinger Liquid





$$E_{\mathrm{Th}} \in [3.8; 20]\ \mathrm{K}$$

For LL power law, $k_B T > E_{th}$

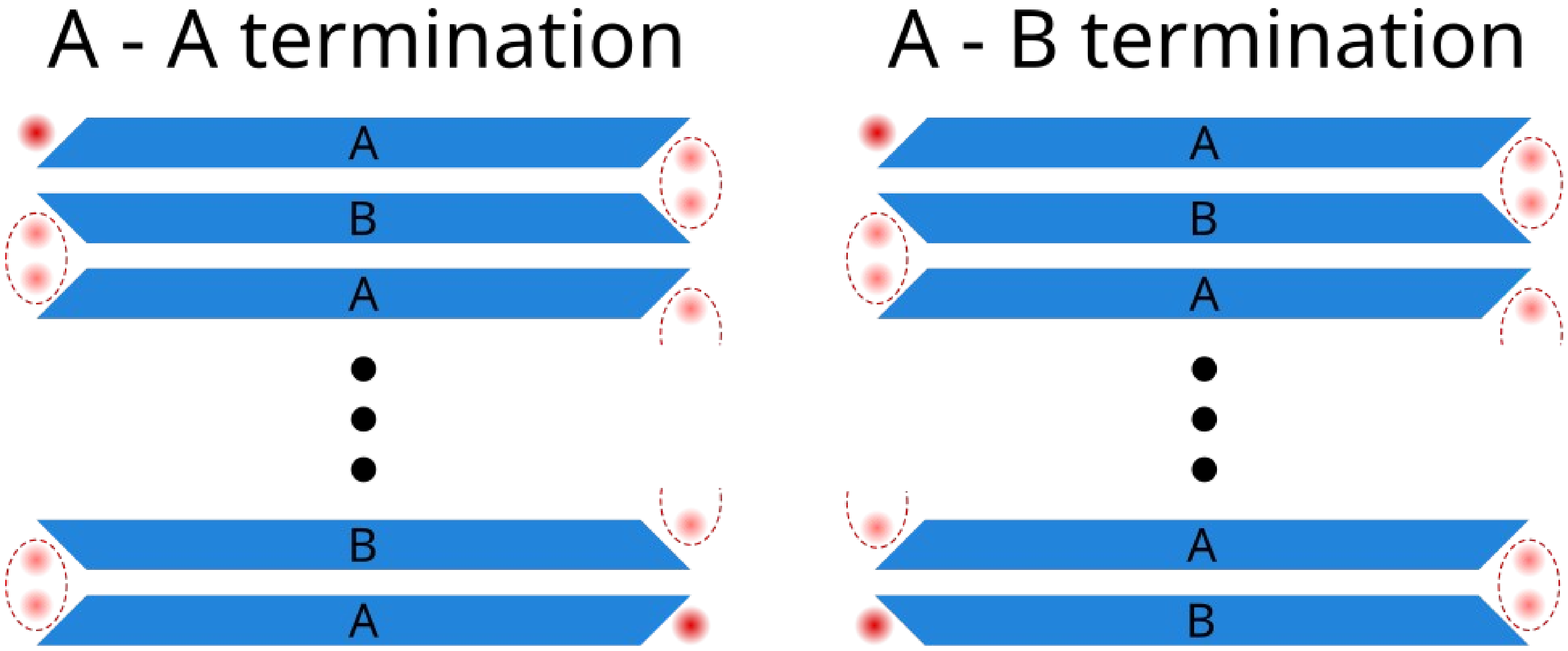
→ Incompatible with LL

For DCB :

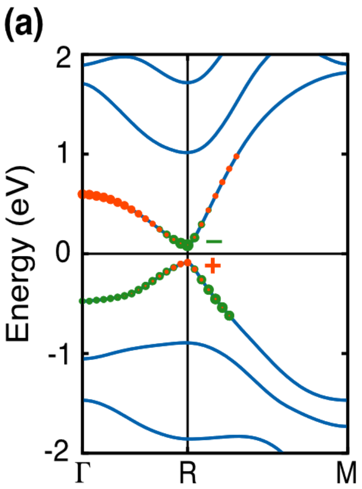
$$\alpha = -2\frac{R_{\mathrm{env}}}{R_{\mathrm{Q}}}$$

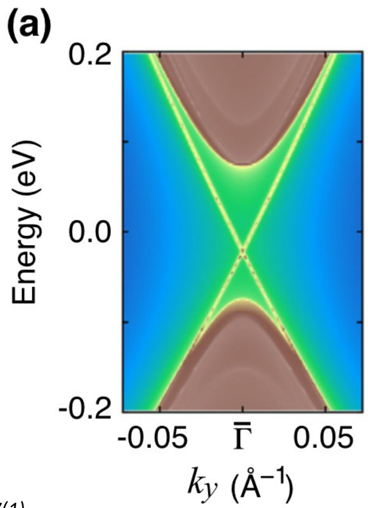
→ $R_{env} \sim R_Q/6 - R_Q/3$

A5) Hybridization of Bi_4Br_4 edges



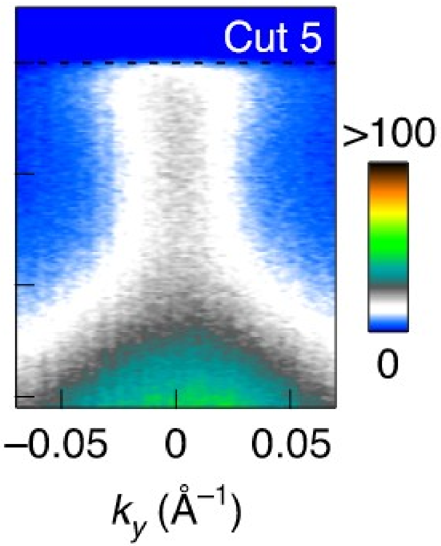
Theory :

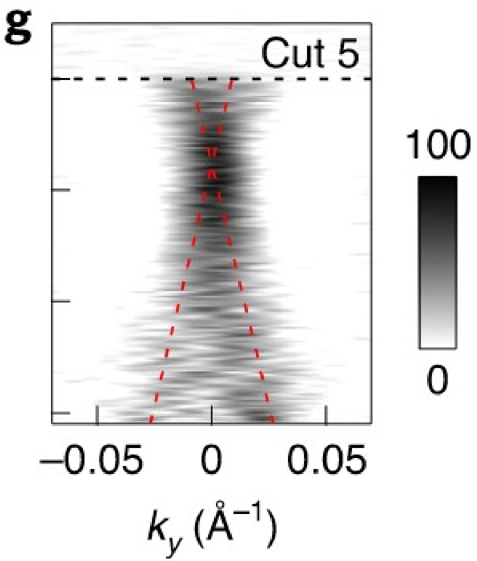




Zhou, J.-J. et al. (2015), New Journal of Physics, 17(1).

ARPES :





Noguchi, R. et al. (2021), Nature Materials, 20(4)