University of Basel

One-dimensional states residing on edges and steps in few-layer WTe_2

at workshop on *“Topological Superconductivity in Quantum Materials”*, organized by SPICE (Spin Phenomena Interdisciplinary Center) at the Johannes Gutenberg Universität in Mainz

online from Oct. 19th – 22nd

by Christian Schönenberger
Quantum- and Nanoelectronics group

www.nanoelectronics.ch

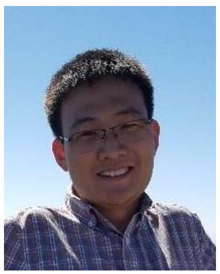
Director of the Swiss Nanoscience Institute
and faculty at the Physics Department of the University of Basel:
https://physik.unibas.ch

Team

WTe_2 growth:

K. Qu, J.Yan, D. G. Mandrus

Materials Science and Engineering,
The University of Tennessee



hBN growth:

Kenji Watanabe, Takashi Taniguchi
Advanced Materials Laboratory,
National Institute for Materials Science

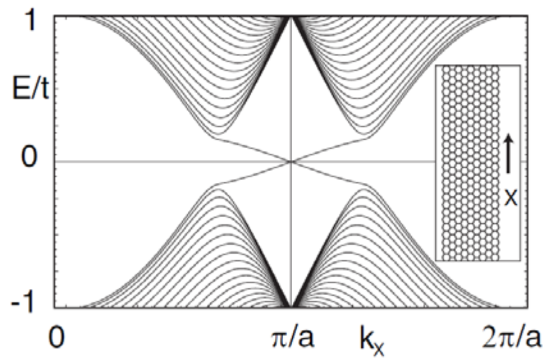

Samples and measurements:

Artem Kononov, Gulibusitan Abulizi, Martin Enders, Melissa Osterwalder and Christian Schönenberger

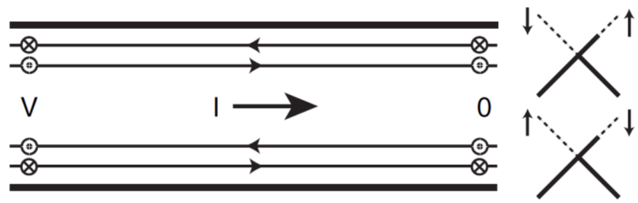
Department of Physics, University of Basel
and Swiss Nanoscience Institute

Funding: Georg H. Endress Postdoc Cluster

Motivation

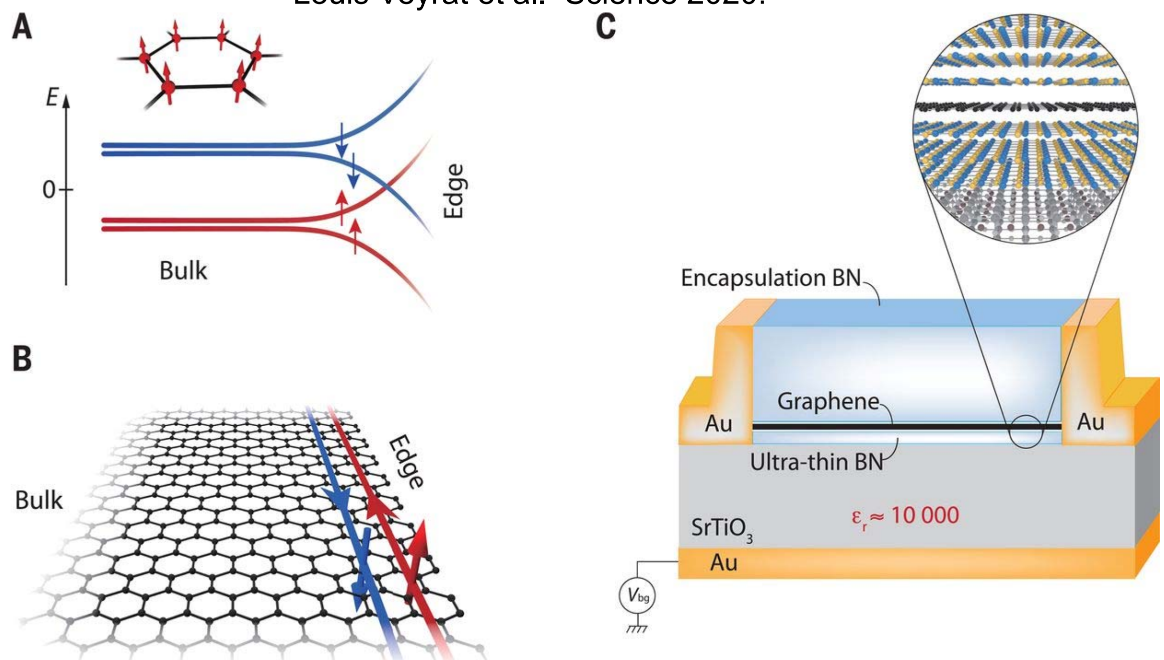


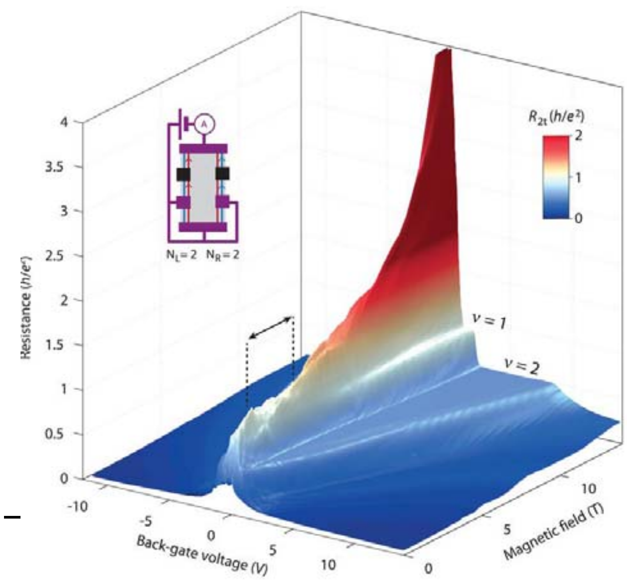
Goal: **Engineer topological superconductors** using 2d van der Waals materials, e.g. graphene, or a topological insulators with **helical edge states** and induce **superconductivity through proximity**.



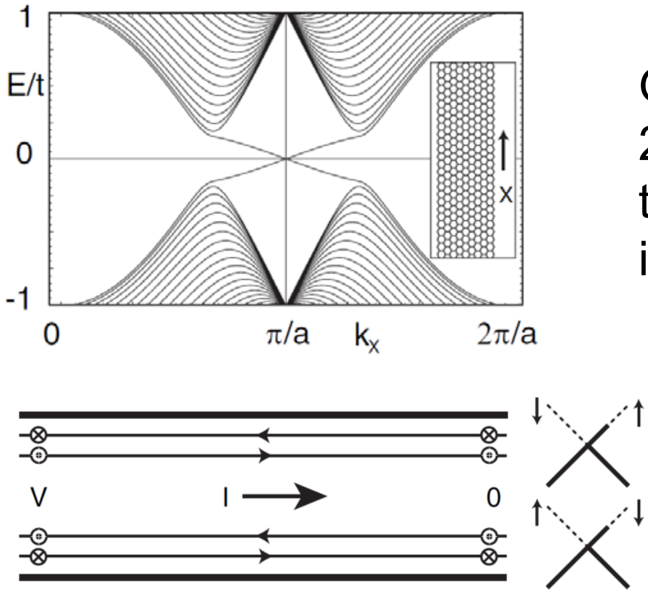
Kane & Mele, Phys. Rev. Lett. **95**, 226801 (2005)

Helical quantum Hall phase in graphene on SrTiO3
Louis Veyrat et al. Science 2020:





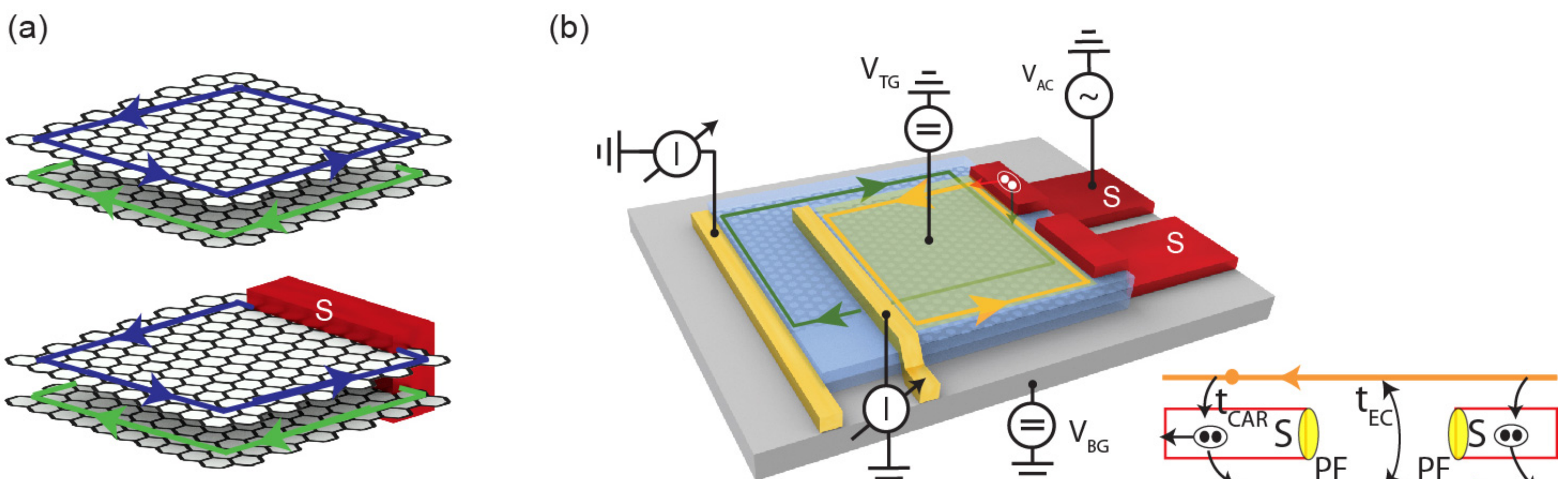
Motivation



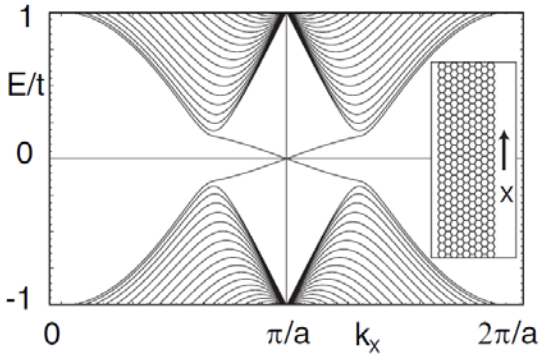
Goal: **Engineer topological superconductors** using 2d van der Waals materials, e.g. graphene, or a topological insulators with **helical edge states** and induce superconductivity through proximity.

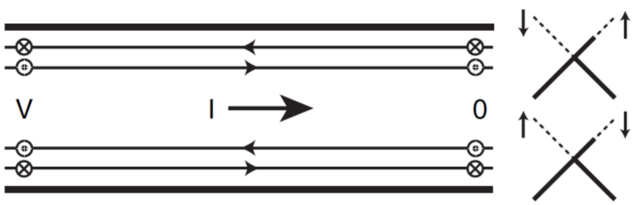
Kane & Mele, Phys. Rev. Lett. **95**, 226801 (2005)

D. Indolese et al., Nano Lett. 2020, 20, 7129



Motivation

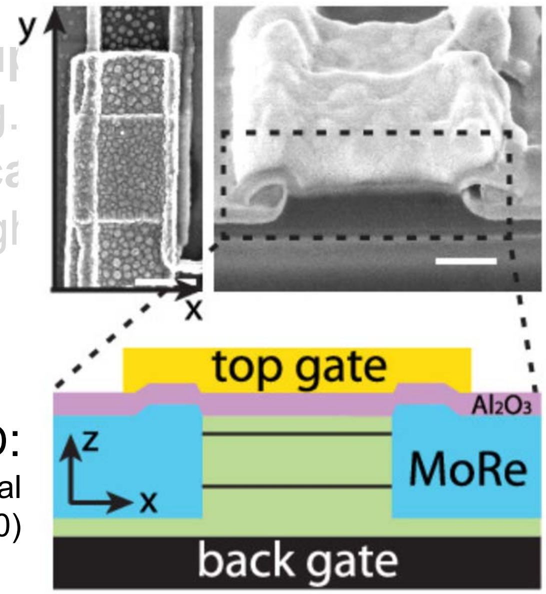




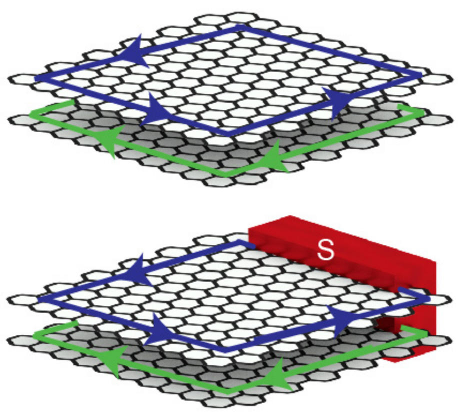
Kane & Mele, Phys. Rev. Lett. **95**, 226801 (2005)

Goal: **Engineer topological su**
2d van der Waals materials, e.g.
topological insulators with **helica**
induce superconductivity through

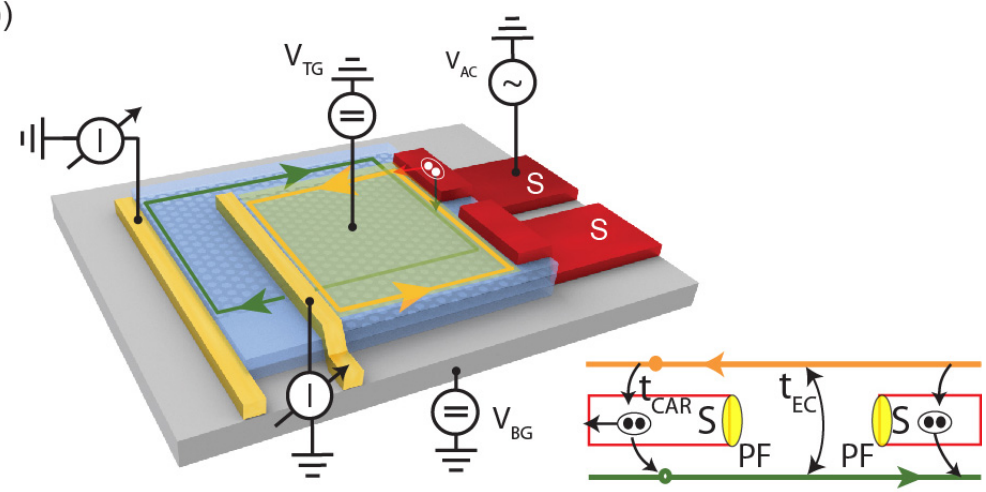
actual device: 2layer SQUID:
D. Indolese et al
Nano Lett. 20, 7129 (2020)



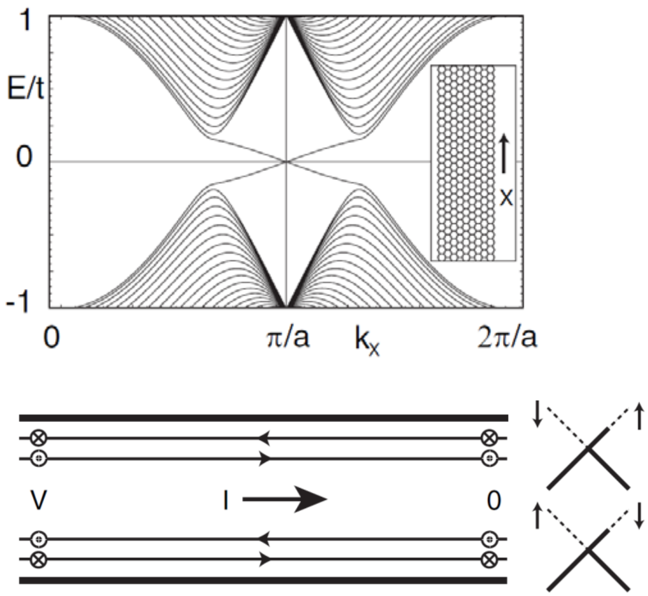
(a)



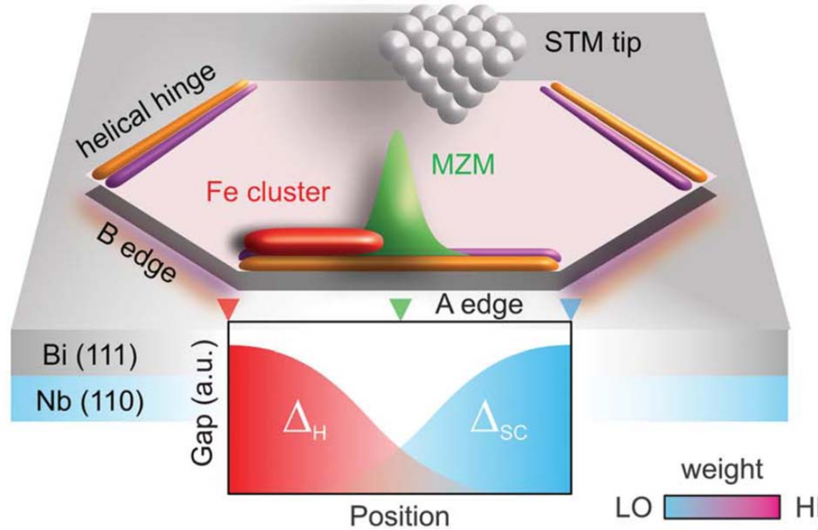
(b)



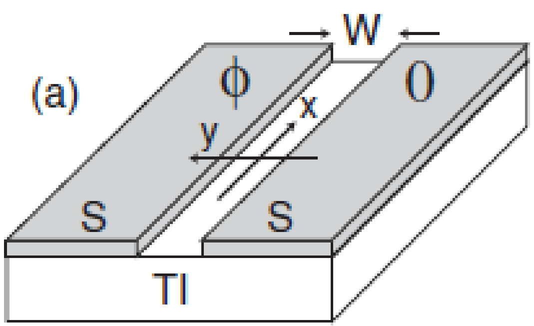
Motivation



Kane & Mele, Phys. Rev. Lett. **95**, 226801 (2005)



Jäck et al., Science 364, 1255–1259 (2019)



Superconducting Proximity Effect and Majorana Fermions at the Surface of a Topological Insulator

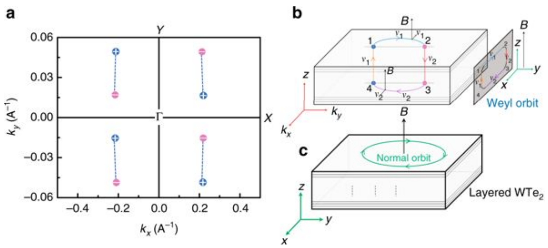
L. Fu, C. L. Kane, Phys. Rev. Lett. **100**, 096407 (2008)

WTe$_2$ with intrinsic edge-states ?

Nontrivial topology

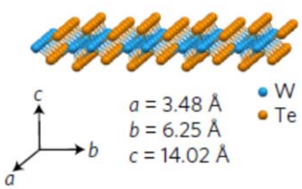
✓ Bulk crystal is type II Weyl semimetal

P. Li, Y. Wen, X. He, Nature Comm. 8, 2150 (2017)



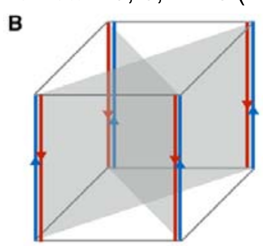
✓ Monolayer is 2D topological Insulator

Z. Fei, T. Palomaki, S. Wu et al., Nature Physics 13, 677 (2017)



❑ Higher-Order Topological insulator

Z. Wang, B.J. Wieder, J. Li, B. Yan, B.A. Bernevig, arXiv:1806.11116
A. Kononov et al., *Nano Lett.* **20**, 6, 4228 (2020)



Superconductivity

✓ Under high pressure is superconducting

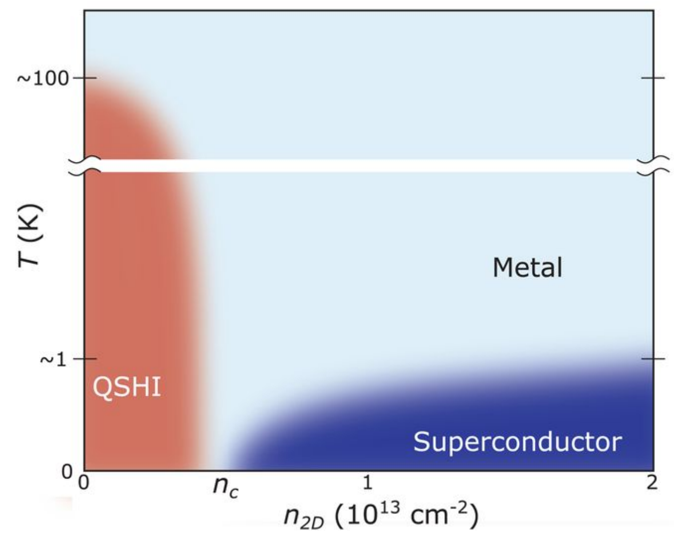
X.-Ch. Pan, X. Chen, H. Liu, Nature Comm. 6, 7805 (2015)

✓ Superconducting when doped

T. Asaba, Y. Wang, G. Li et al., Scientific Rep. 8, 6520 (2018)

✓ Monolayer is tunable with gate into superconducting state

E. Sajadi, T. Palomaki, Z. Fei et al., Science 362, p. 922 (2018)
V. Fatemi, S. Wu, Y. Cao et al., Science 362, p. 926 (2018)



Current distribution in a 2D JJ

Current phase relation (CPR): $I_S(\varphi)$

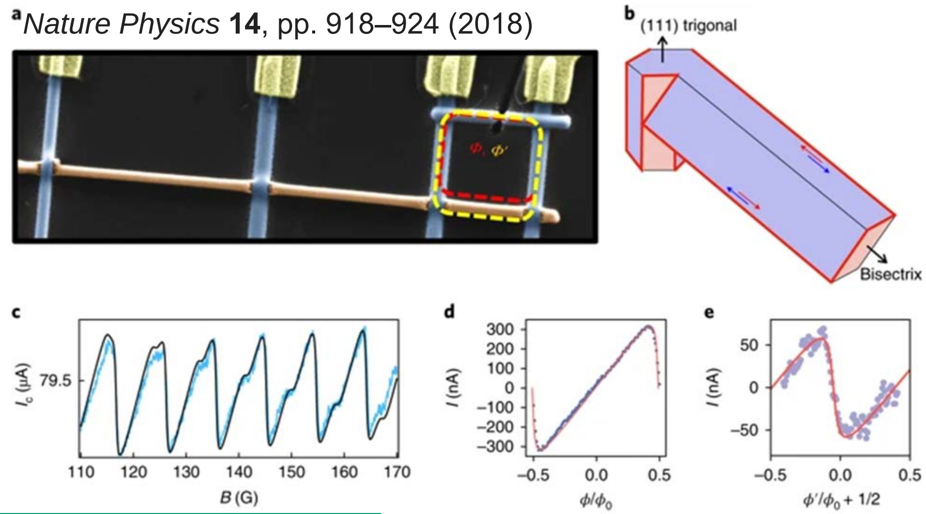
e.g. a tunnel junction: $I_s = I_c \sin\varphi$

can also look more complex, **non-sinusoidal CPR.** E.g. for a diffusive coherent SNS device in the short junction limit: $E_{Th} \gg \Delta$

$$\boxed{I(\phi) = \frac{e\Delta_0}{\hbar}\frac{2W}{\pi L}\cos(\phi/2)\operatorname{arctanh}[\sin(\phi/2)]}$$

H. Bouchiat's group

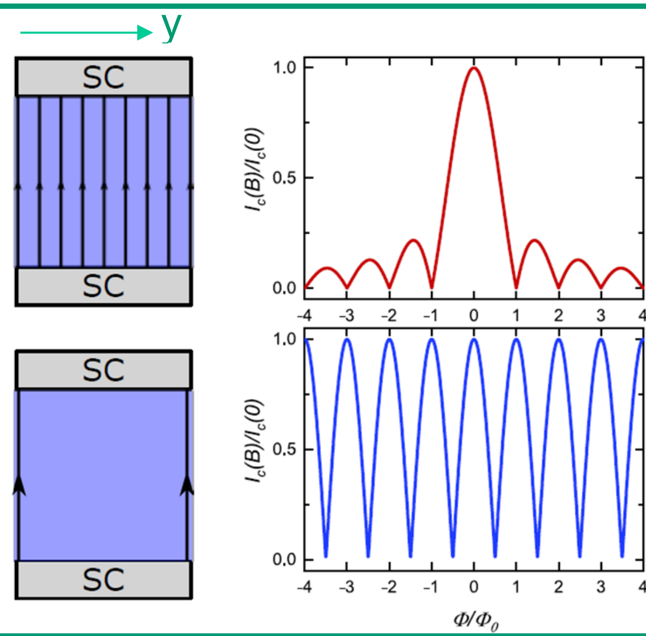
Nature Physics **14**, pp. 918–924 (2018)



for a JJ made from a Bi NW, dominant SQUID signal and a non-sinusoidal CPR

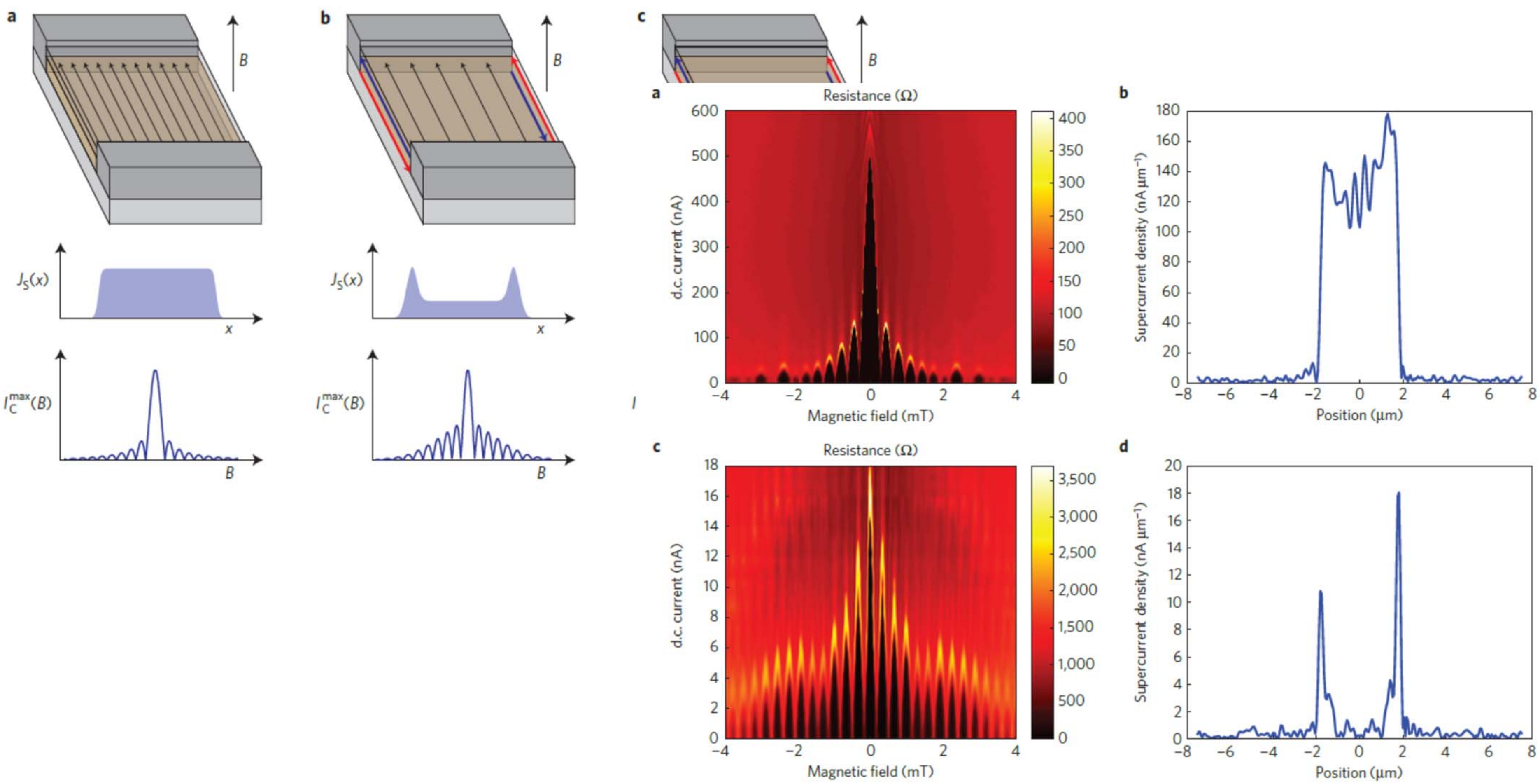
To measure the **current distribution** in plane one makes use of quantum interference induced by the electromagnetic gauge field, related to the mag. field B.

The acquired phase is given by the **flux $\boldsymbol{\Phi}(\boldsymbol{y})$** divided by the flux quantum for a Cooper pair.



Example from the literature

Induced superconductivity in the quantum spin Hall edge Yacoby and Molenkamp groups: Nature Physics 10, 238 (2014)

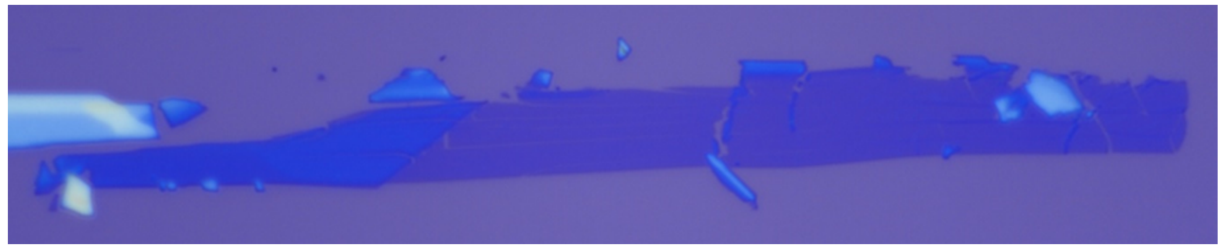


Our results on WTe_2 thin crystals

20 µm

- exfoliation with X4 PDMS

15 µm

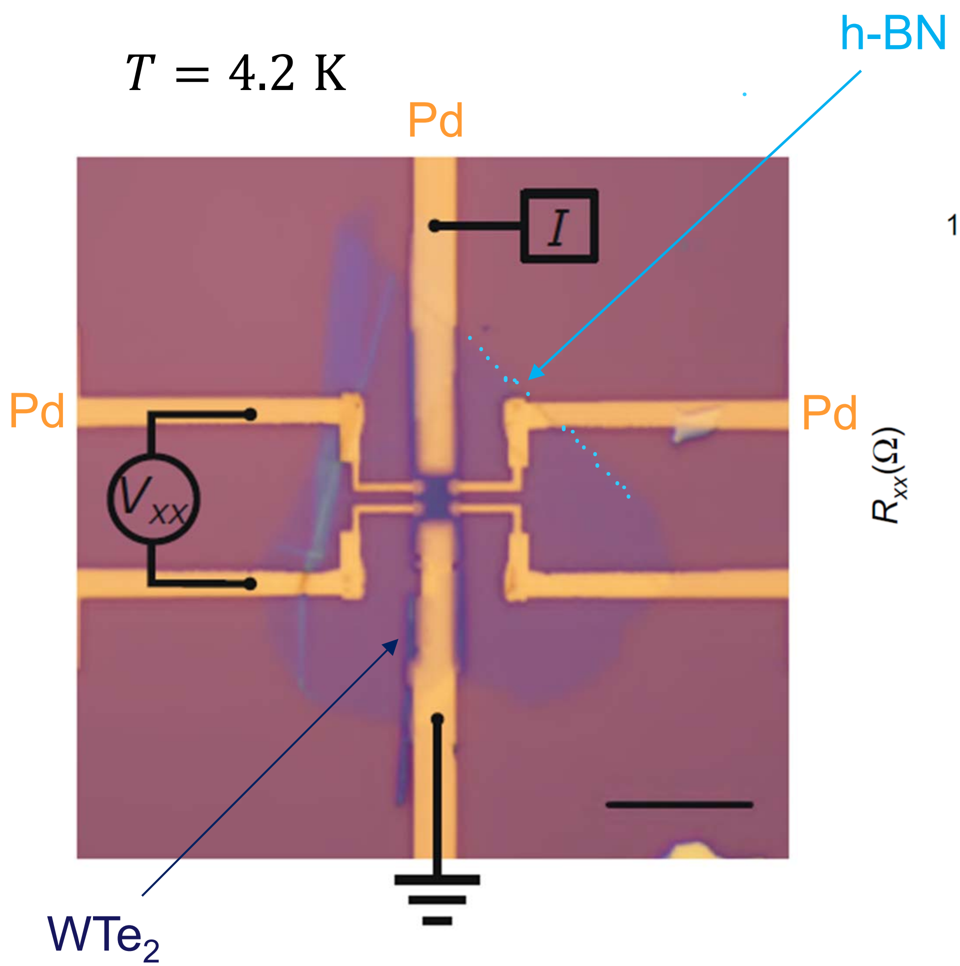


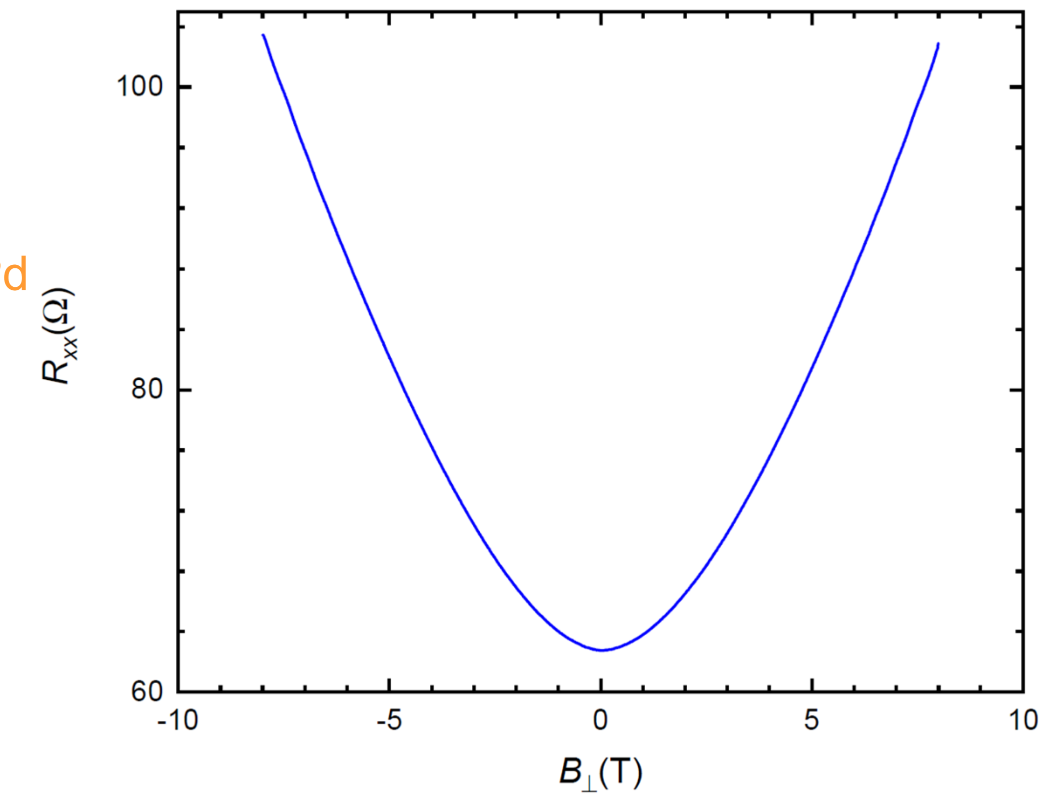
- pickup with hBN and depositing over prepatterned contacts, in our case made from Pd

Non-saturating MR WTe_2

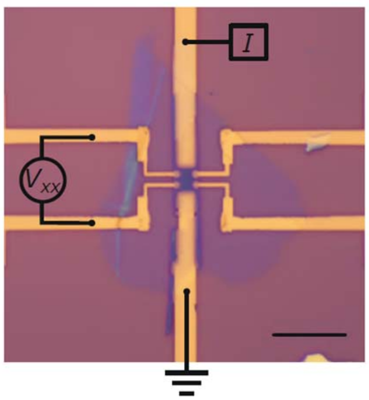
see Nature 514, 205 (2014)

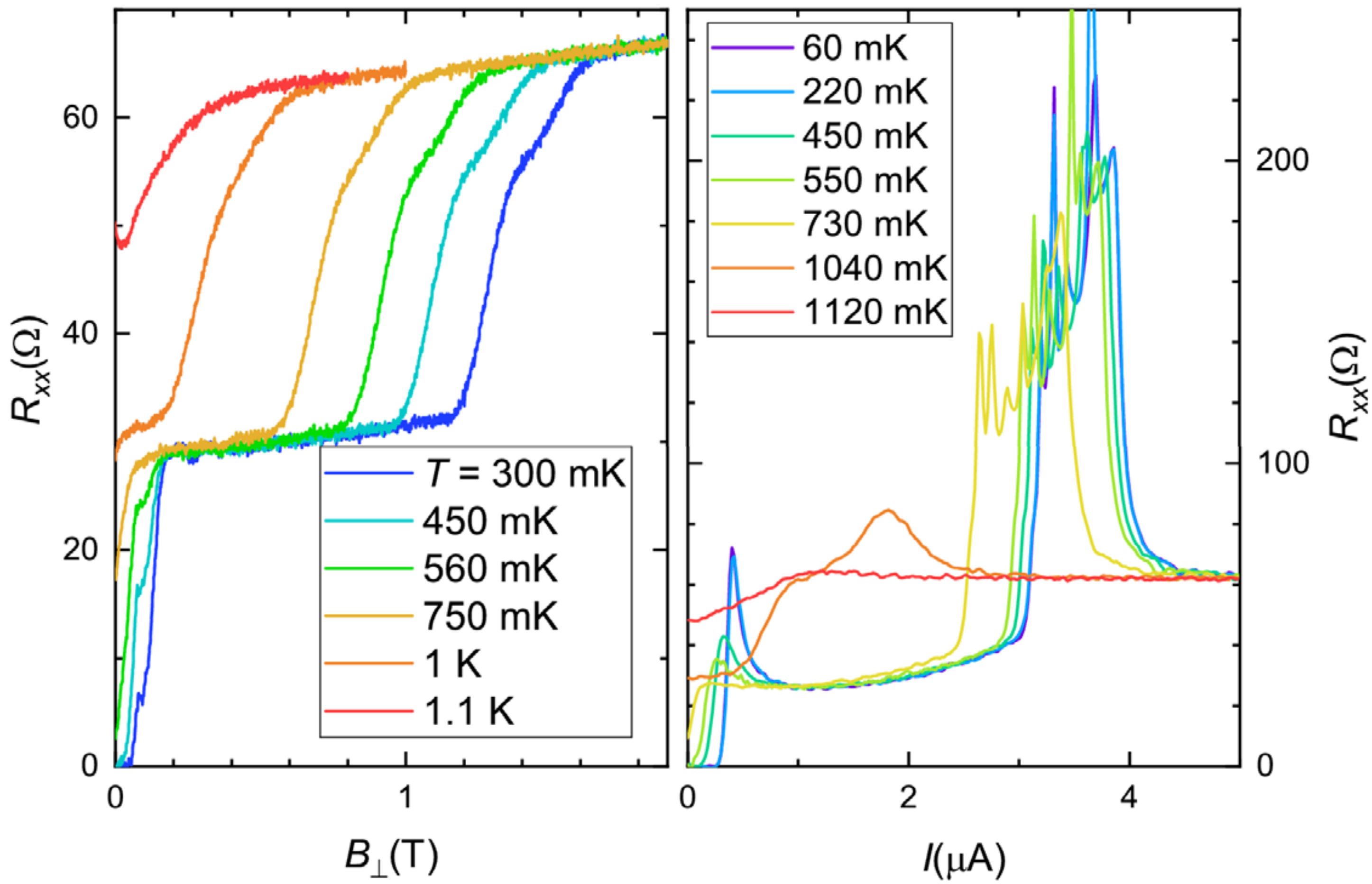
$T = 4.2$ K





Superconductivity in WTe^2

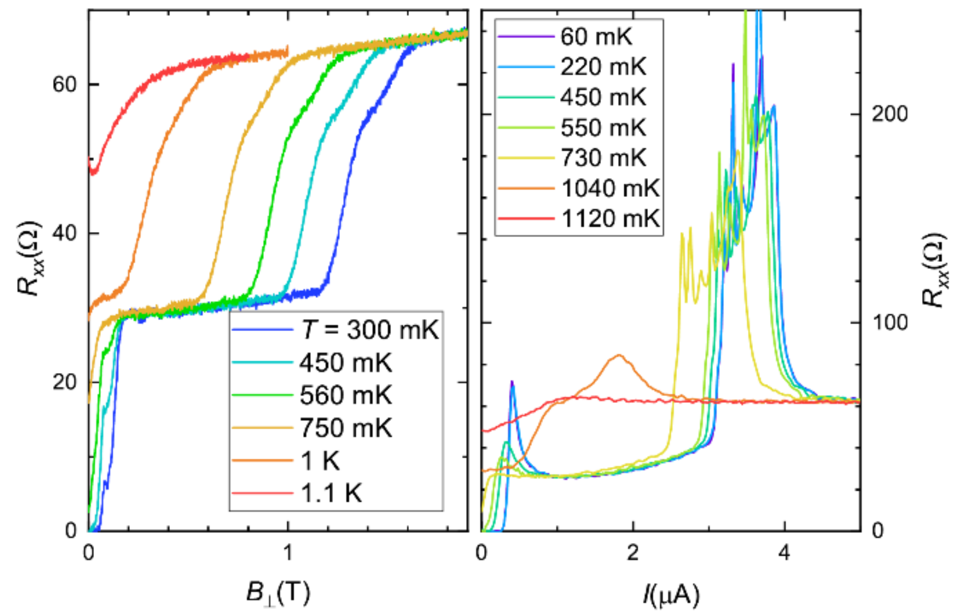




Lead induced SC in WTe_2

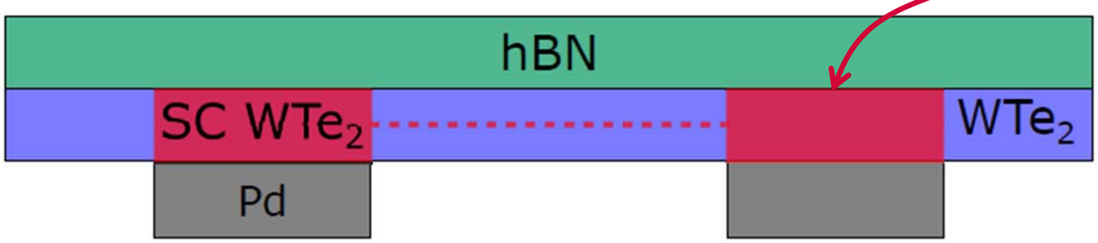
SC in WTe_2 above contacts due to electron doping

Pseudodoping of a metallic two-dimensional material by the supporting substrate.
Shao, B. et al. Nat. Commun. 10, 180 (2019).



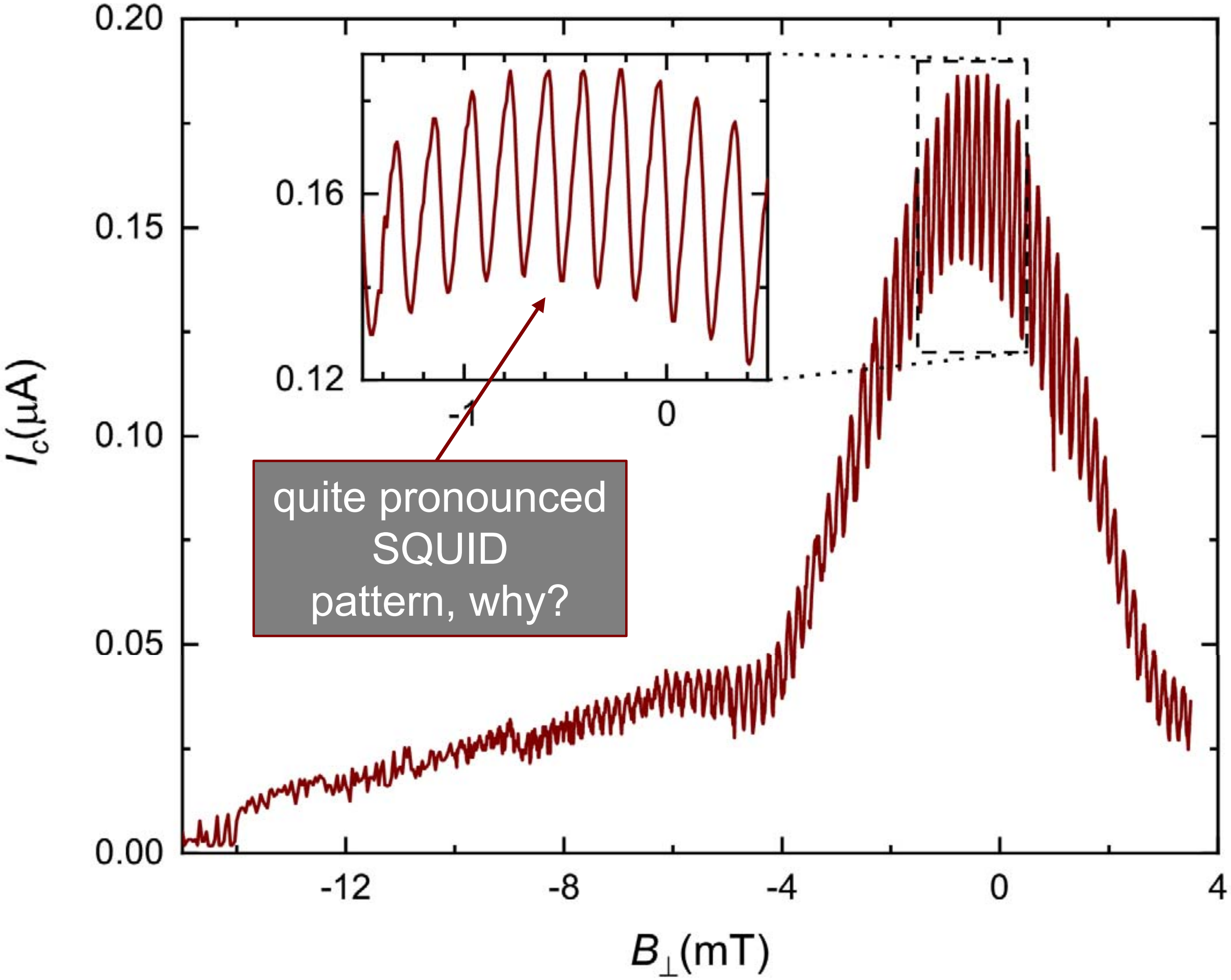
Inter-diffusion of W/Te and Pd, with the formation of $PdTe_x$

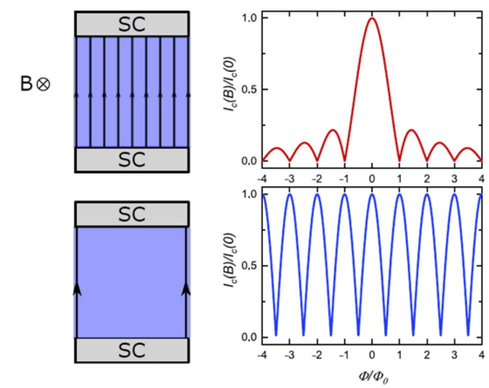
$PdTe$: Supercond. Sci. Technol. 28, 055008 (2015).
$PdTe_2$: Phys. Rev. B 98, 024508 (2018).

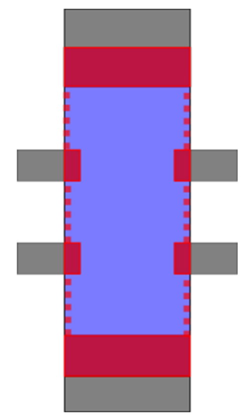


$T_C \approx 1$ K

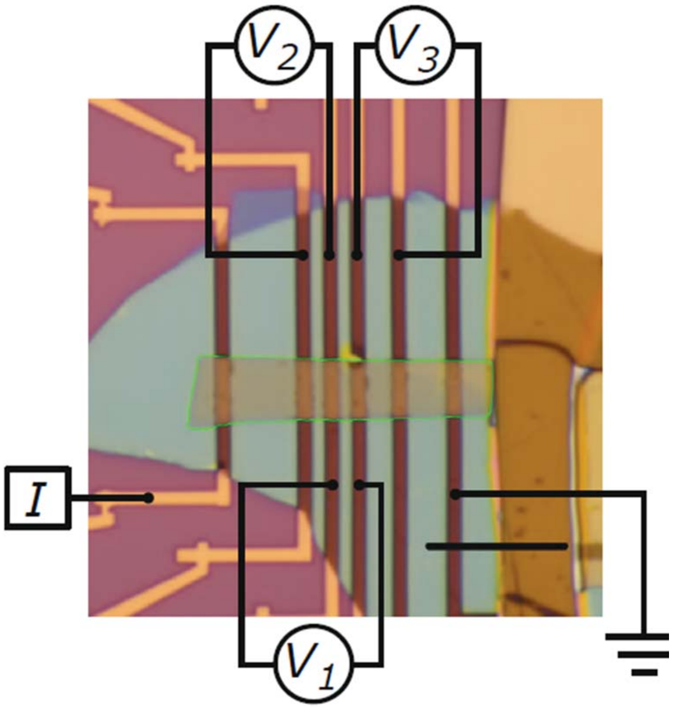
Josephson current spectroscopy

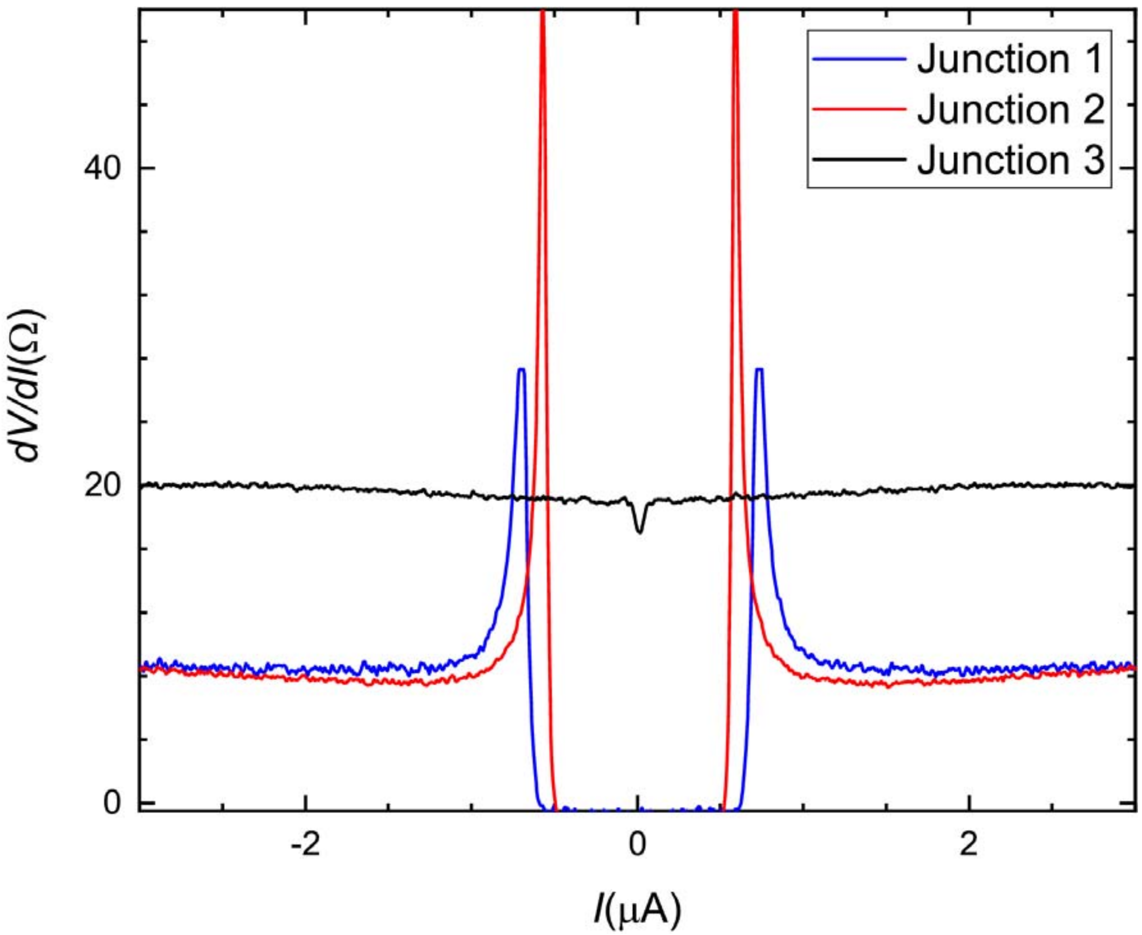






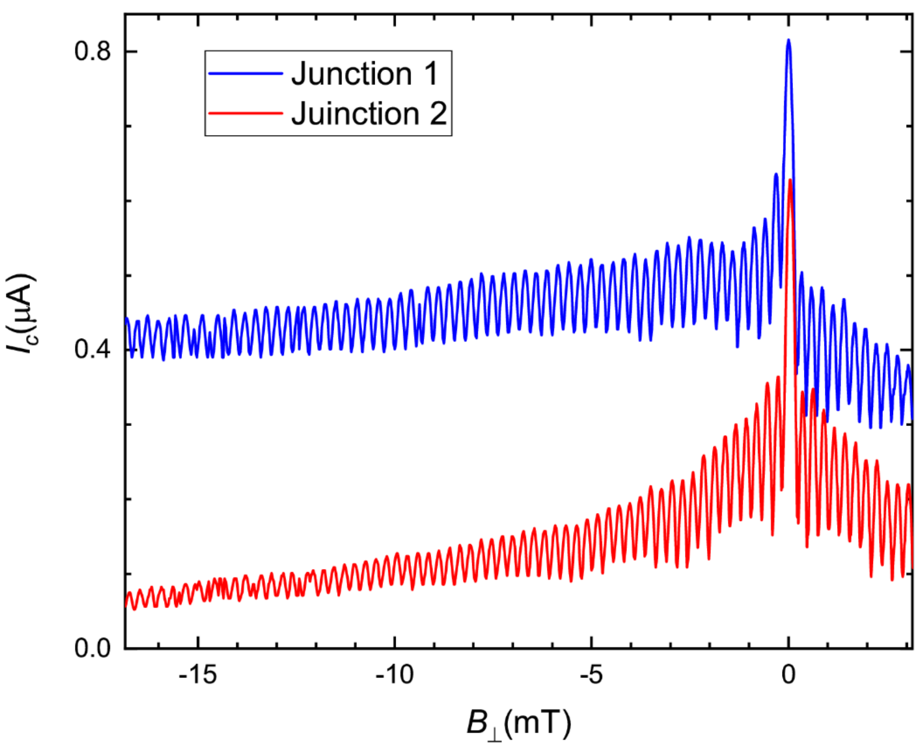
Current distribution on a new sample

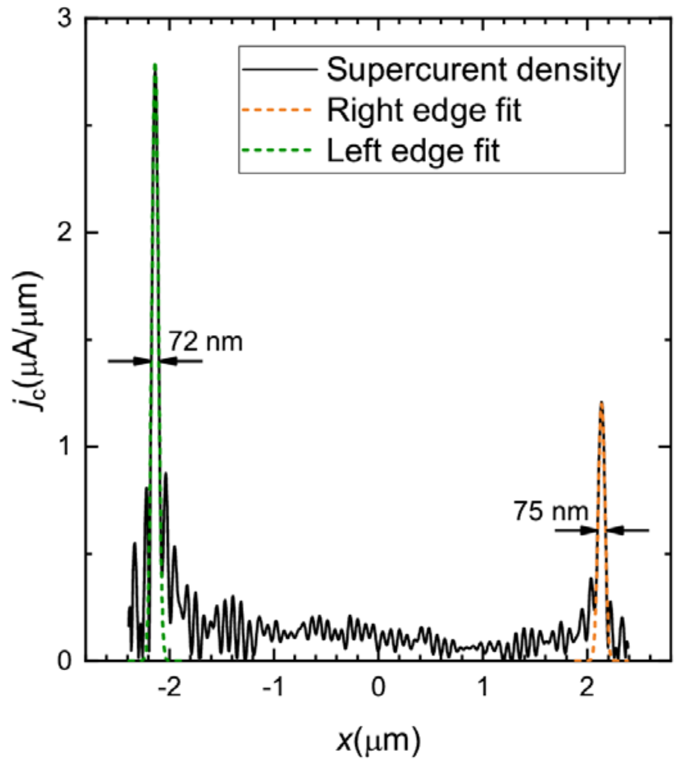




junction 1 & 2: $L = 1\ \mu m$
junction 3 $L = 2\ \mu m$

Current distribution on a new sample





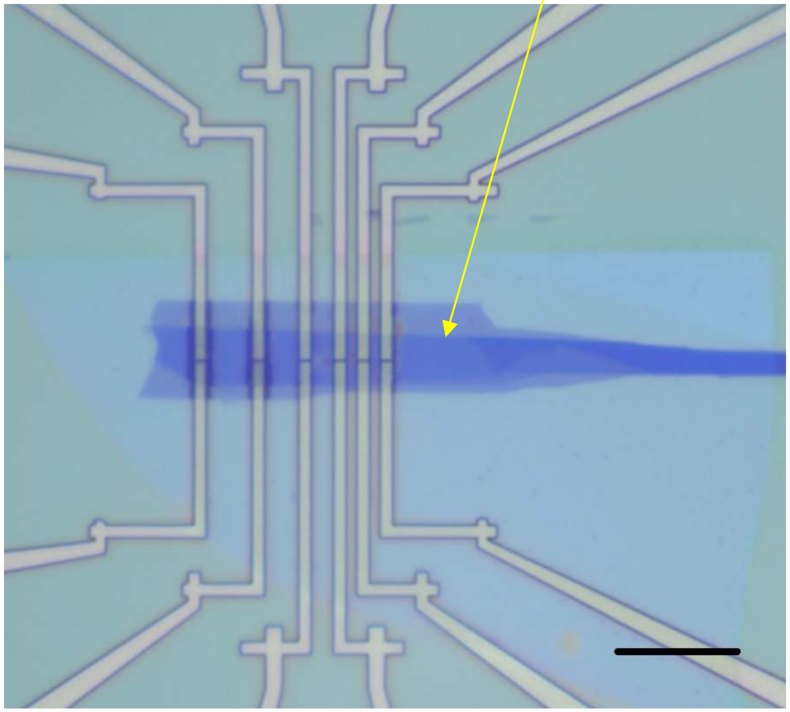
$$I_c(B) = \left| \max_{\varphi} \int j(x) \cdot \sin\left(\varphi + \frac{2\pi x L B}{\Phi_0}\right) dx \right|$$

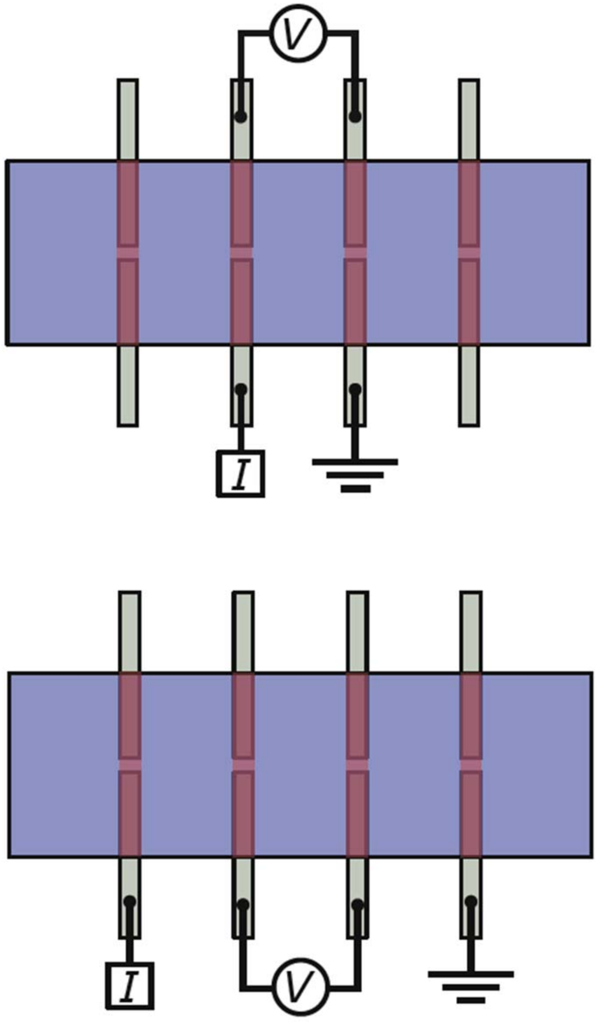
note: it assumes a sinusoidal CPR

Dynes, R.C., Fulton, T.A., Supercurrent density distribution in Josephson Junctions.
Phys. Rev. B 3, 3015 (1971).

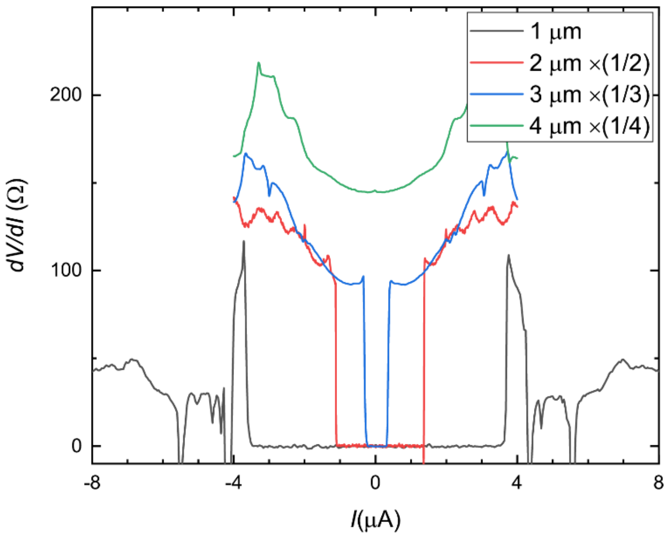
A different WTe_2 sample

step in WTe_2





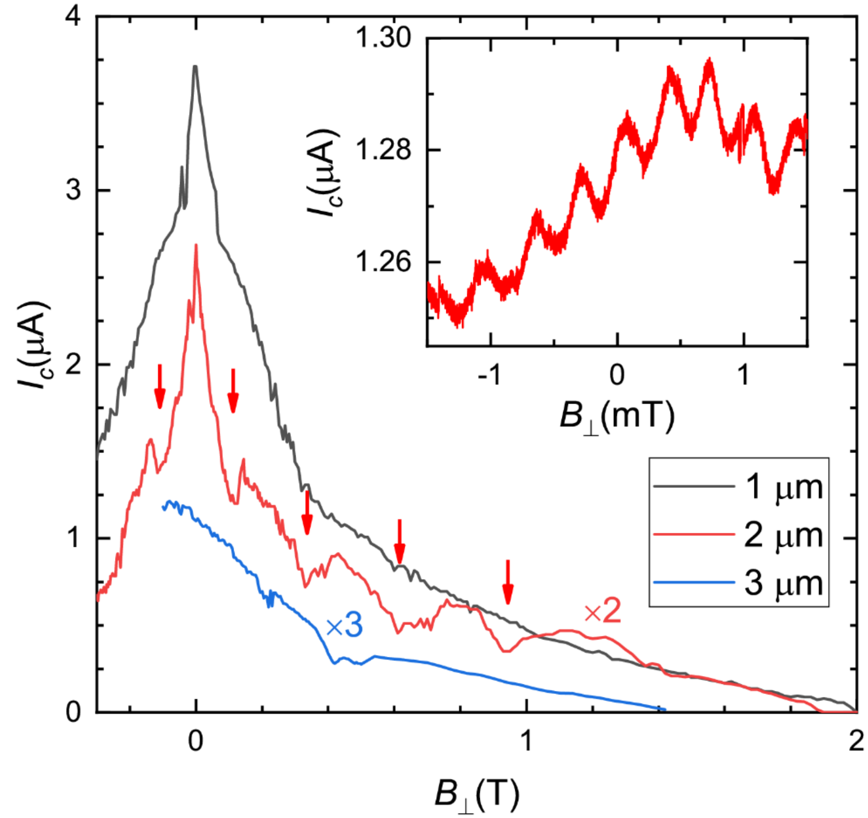
Steps in WTe_2



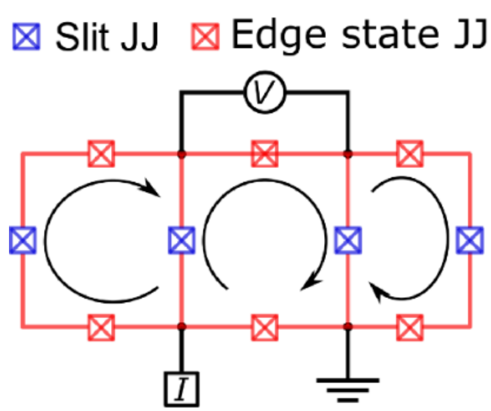
$I_c R_N \sim 150 - 380\ \mu V$

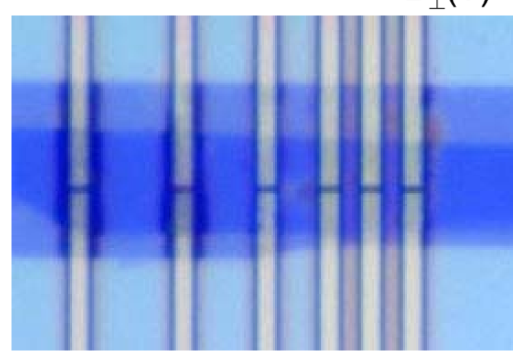
Close to short ballistic limit:

$I_c R_N = \pi\Delta/e \sim 540\ \mu V$

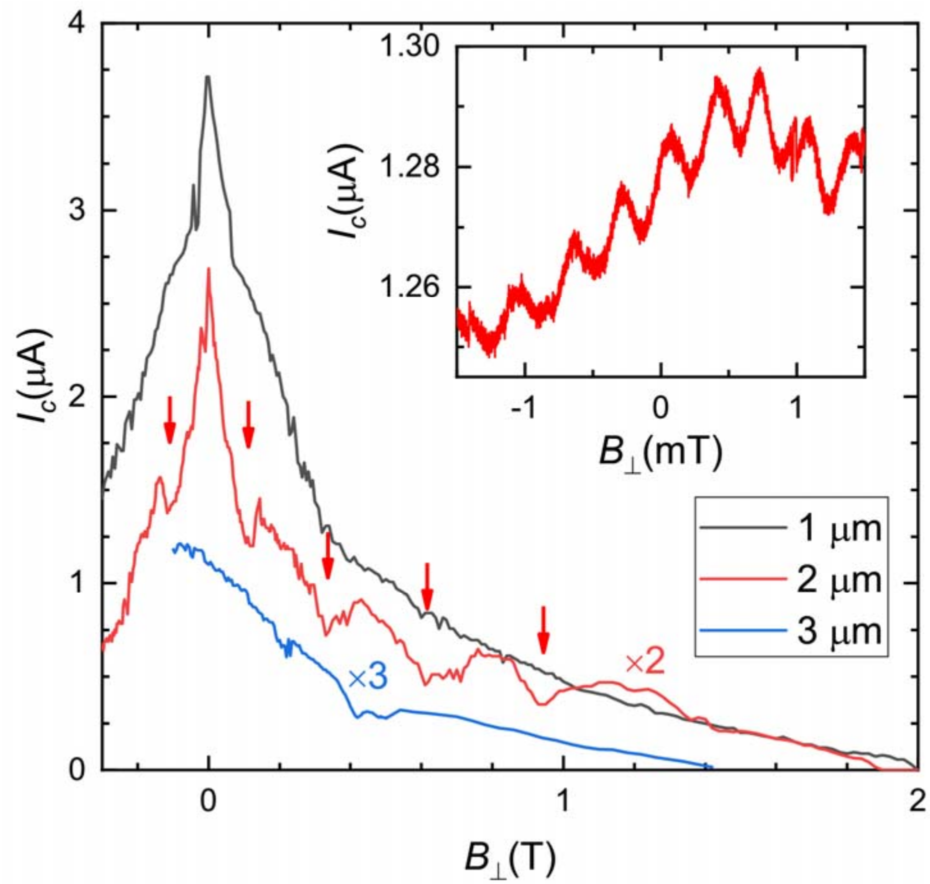


to explain the fast oscillations need a larger aera

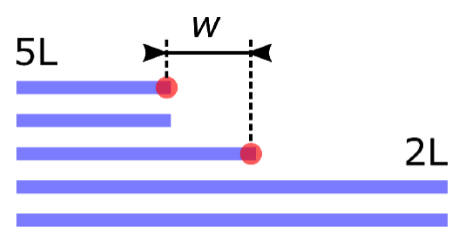




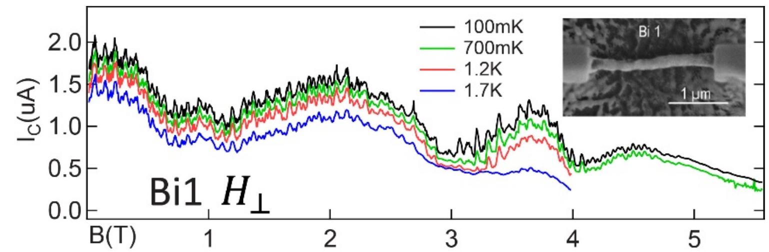
and slow modulation ??

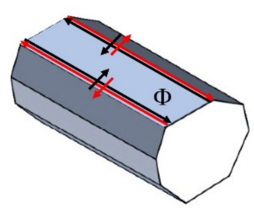


More than one state on the step



$$w \sim W\delta B/\Delta B \sim 5 \text{ nm}$$





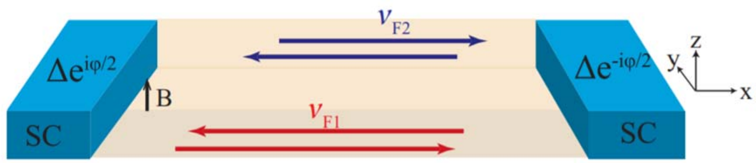
H. Bouchiat's group
LPS, Paris-Sud

Interference of electron-hole part due to spin-Zeeman term
Can only be seen, if there is a single or very few channels only!

$$\delta B \sim 2\pi\hbar v_F/g_{eff}\mu_B L \sim 0.15-0.7 \text{ T}$$

Li, C. et al. Magnetic field resistant quantum interferences in Josephson junctions based on bismuth nanowires. Phys. Rev. B 90, 245427 (2014).

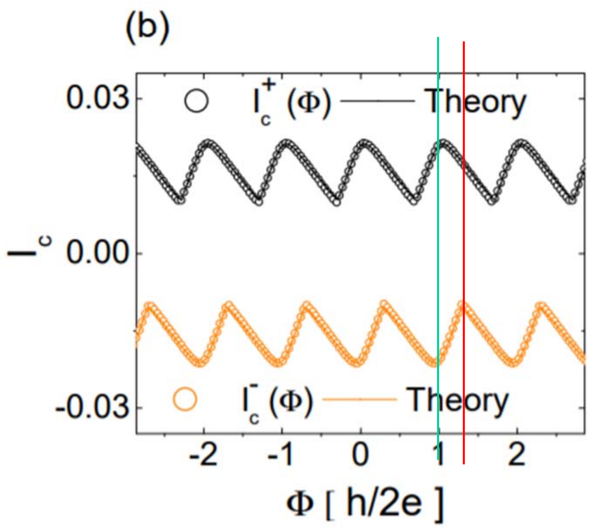
Asymmetric Josephson effect

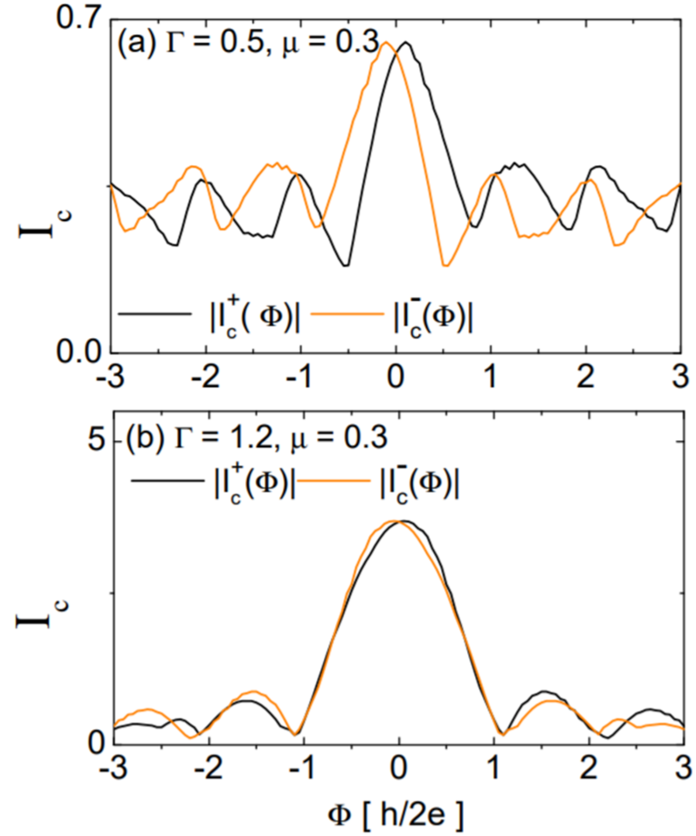


must always hold $|I_c^+(B)| = |I_c^-(-B)|$

due to inversion symmetry breaking in a topological material it is possible that:

$$|I_c^+(B)| \neq |I_c^-(B)| \quad |I_c(B)| \neq |I_c(-B)|$$

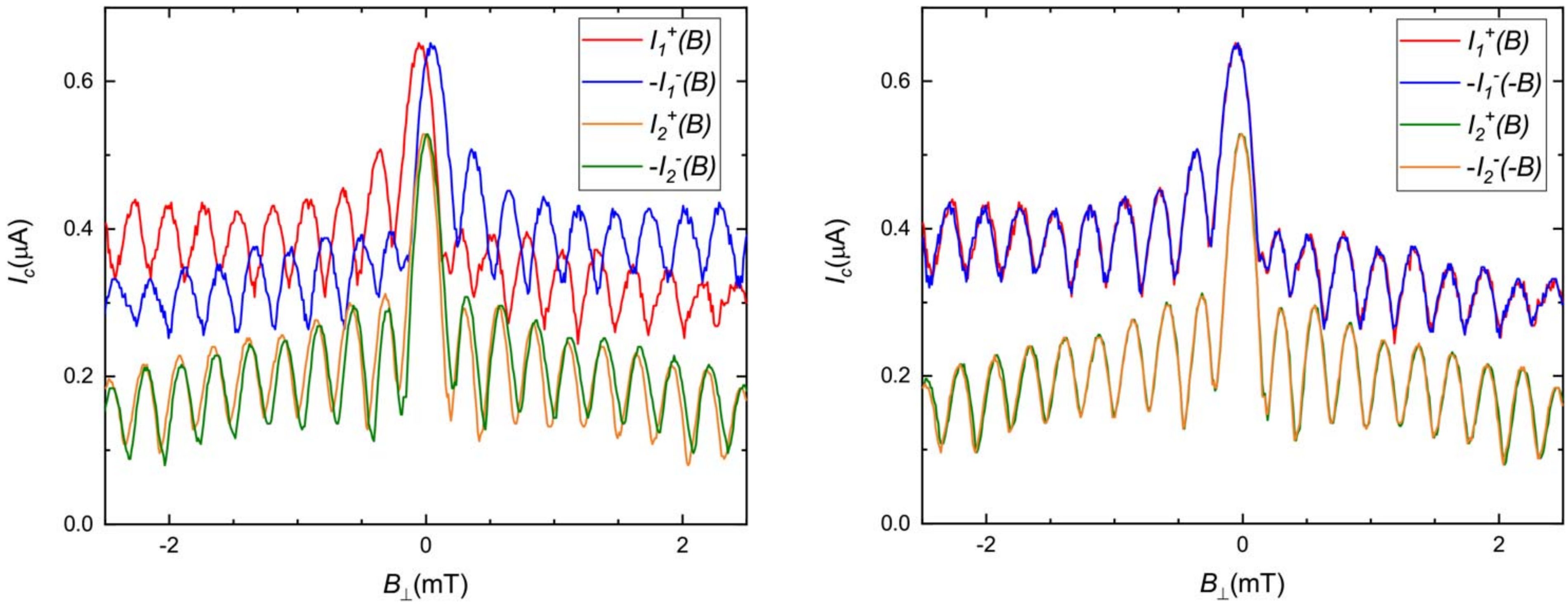




Γ is the symmetry-breaking parameter. (a) / (b) correspond to type I and type II Weyl. SC due to Fermi arcs and Weyl node in the bulk.

C.-Z. Chen, J.J. He, M.N. Ali, G.-H. Lee, K.C. Fong, and K.T. Law; Phys. Rev. B 98, 075430 (2018) **Asymmetric Josephson effect in inversion symmetry breaking topological materials**; Phys. Rev. B **98**, 075430 (2018)

Asymmetric Josephson effect



Note: The ASJ is not a proof, since any non-sinusoidal CPR will also yield a similar asymmetry

What can we learn from the SC

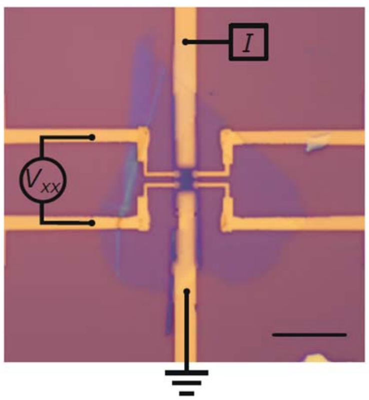
1. What is carrying Josephson current over such long distances?

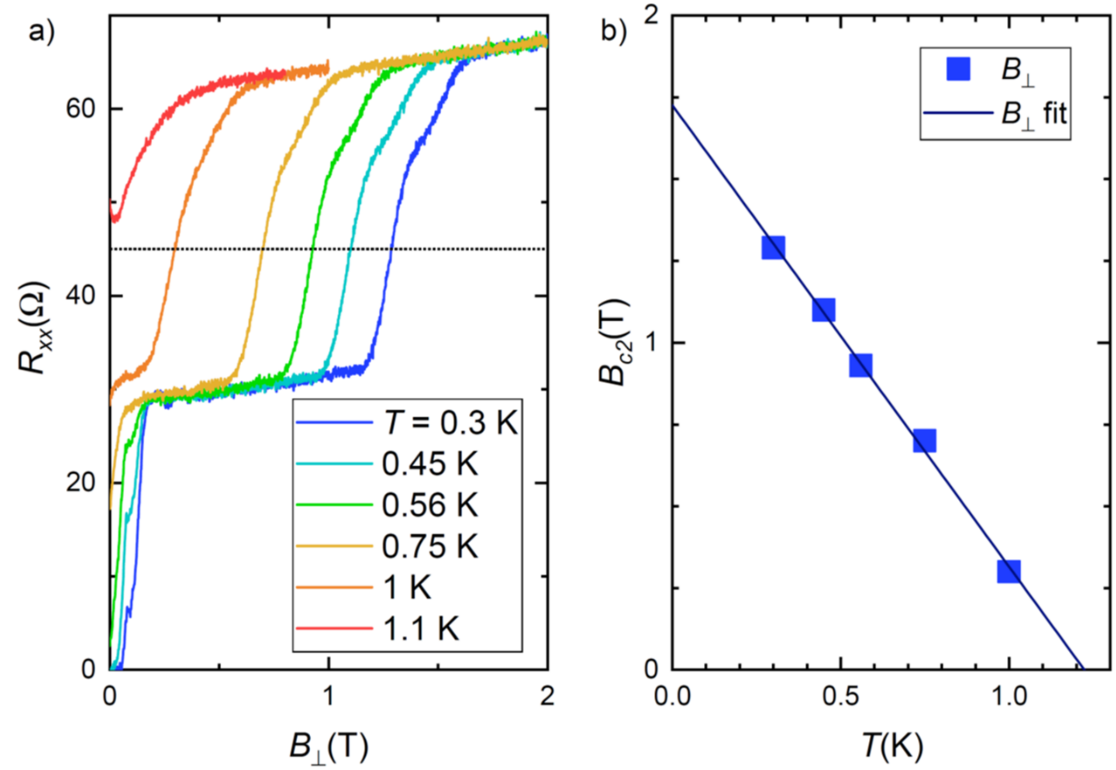
   A. Kononov, G. Abulizi, K. Qu, J. Yan, D. Mandrus, K. Watanabe, T. Taniguchi, and C. Schönenberger, One-Dimensional Edge Transport in Few-Layer WTe2, *Nano Lett.* **20**, 6, 4228 (2020)

2. What can we find out about the superconducting state?

   A. Kononov, M. Endres, G. Abulizi, K. Qu, J. Yan, D. Mandrus, K. Watanabe, T. Taniguchi, and CS Flat band superconductivity in type-II Weyl-semimetal WTe2 induced by a normal metal contact, arXiv:2007.04752 (2020)

Coherence length





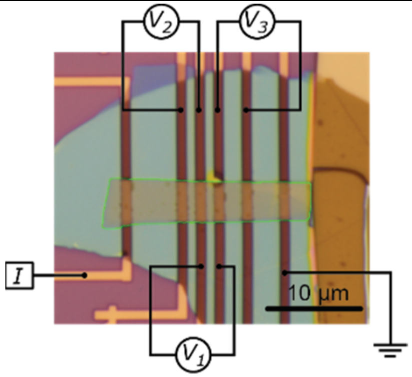
$l_{mfp} \sim 40\ nm$

2D GL equation:

$$B_{c2}(T) = \frac{\Phi_0}{2\pi\xi_{GL}^2}\left(1 - \frac{T}{T_c}\right) \qquad \xi_{GL} \sim 14\ \text{nm} \qquad v_F = \xi\pi\Delta/\hbar \qquad v_F \sim 4\sqrt{\xi l_{mfp}}\Delta/\hbar$$

small Fermi velocity: $v_F \sim 1.2 \cdot 10^4\ \text{m}\,\text{s}^{-1}$

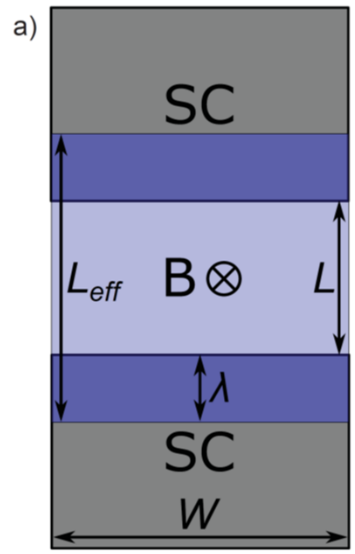
London penetration depth

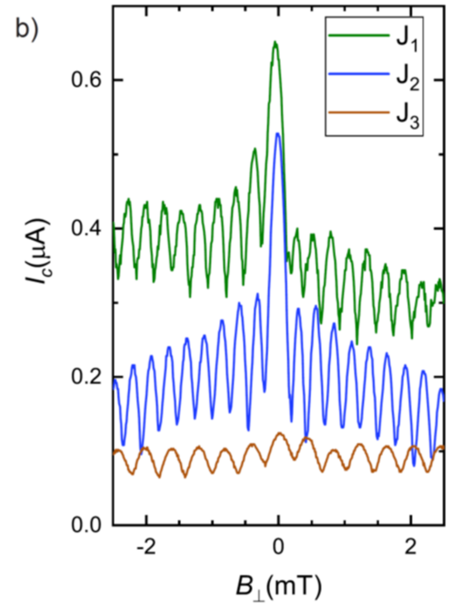


$$S_{eff} = WL_{eff} = W(L + 2\lambda)$$

$$\lambda = 380 \text{ nm}$$

$$\lambda = \lambda_P = \lambda_L^2 / d$$





$$\lambda_L \sim 50 \text{ nm}$$

$\lambda_L/\xi \sim 3 > 1/\sqrt{2}$ type II superconductivity

$$n_s = m/\mu_0 \lambda_L^2 e^2 \sim 3 \cdot 10^{21} \text{ cm}^{-3}$$

$$g(E_F) \sim n_s / 2\Delta \sim 8 \cdot 10^{24} \text{ cm}^{-3}\,\text{eV}^{-1}$$

High density of states at the Fermi level

⇩

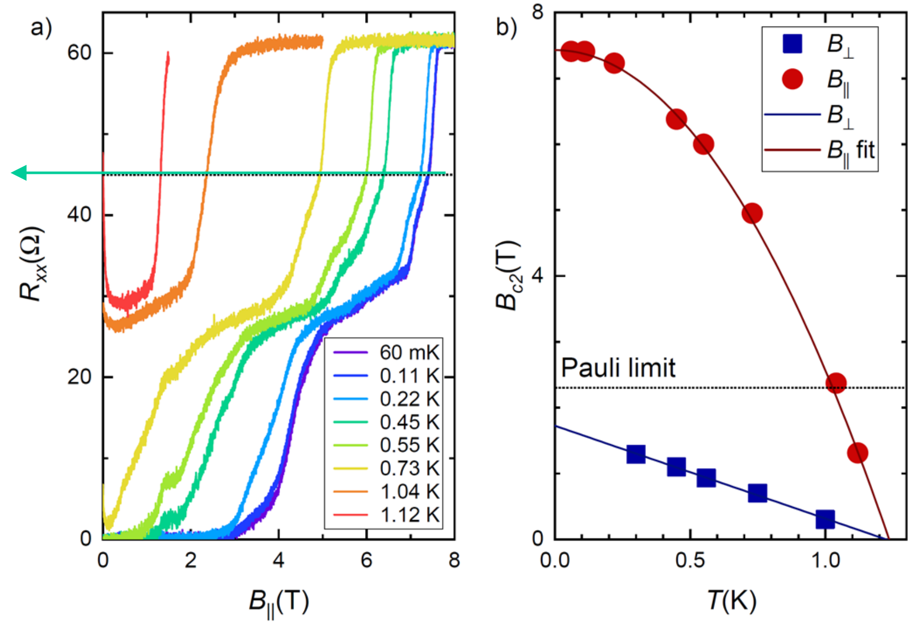
Flat band superconductivity ?

Origin of superconductivity

- Strain at the interface with Pd

- Doping from Pd

transition for proximity induced SC



Exceeding of Pauli limit in the previous experiments:

o Superconductivity under pressure
X.-Ch. Pan, X. Chen, H. Liu, Nature Comm. 6, 7805 (2015)

✓ Superconducting when doped
T. Asaba, Y. Wang, G. Li et al., Scientific Rep. 8, 6520 (2018)

✓ Monolayer is tunable with gate into superconducting state
E. Sajadi et al., Science 362, p. 922 (2018)
V. Fatemi et al., Science 362, p. 926 (2018)

Doping is probably dominating factor

Conclusion

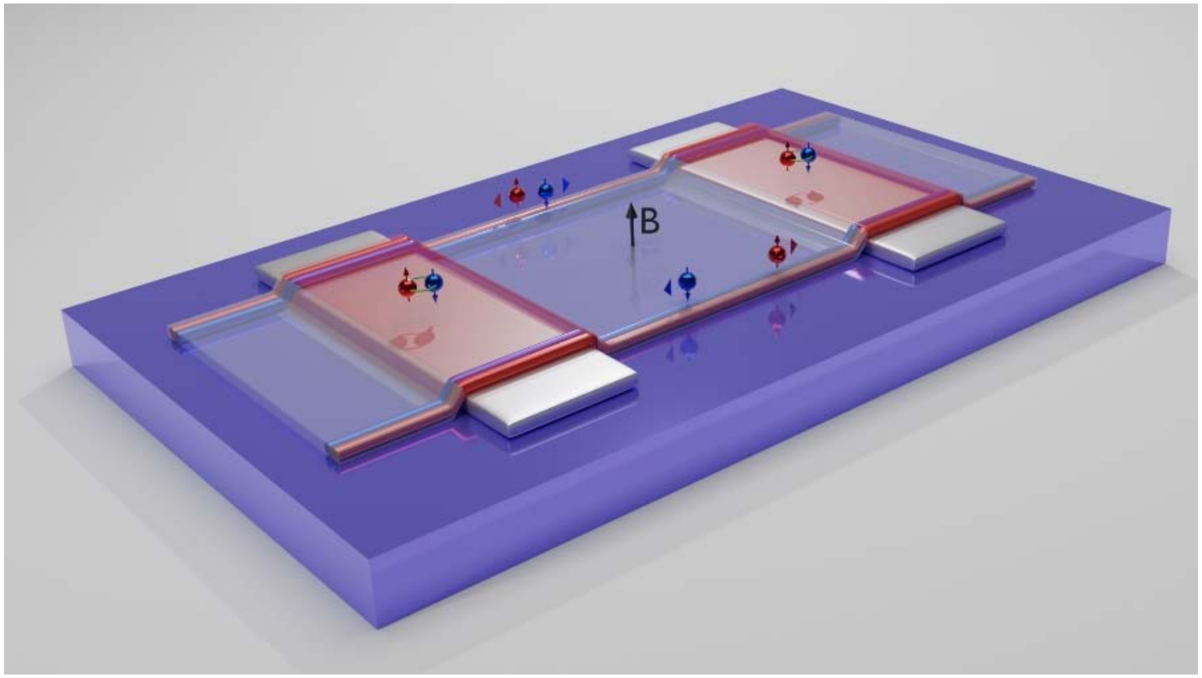
- We studied Josephson effect in few-layers WTe_2
- Supercurrent is hosted by 1D states with width below 80 nm
- Josephson current is present up to 3 μm and 2 T
- 1D states resides on edges *and* steps of the flakes
- Josephson effect shows symmetries predicted for AJE
- Supercurrent exceeds Pauli limit and corresponds to a situation of very high density-of-states *(flat-band superconductivity ?)*

University of Basel

Thank you

for your attention!

Christian Schönenberger, 19th of Oct. 2020



A. Kononov et al. *One-dimensional edge transport in few-layer WTe2,* Nano Letters 20, 4228–4233 (2020)