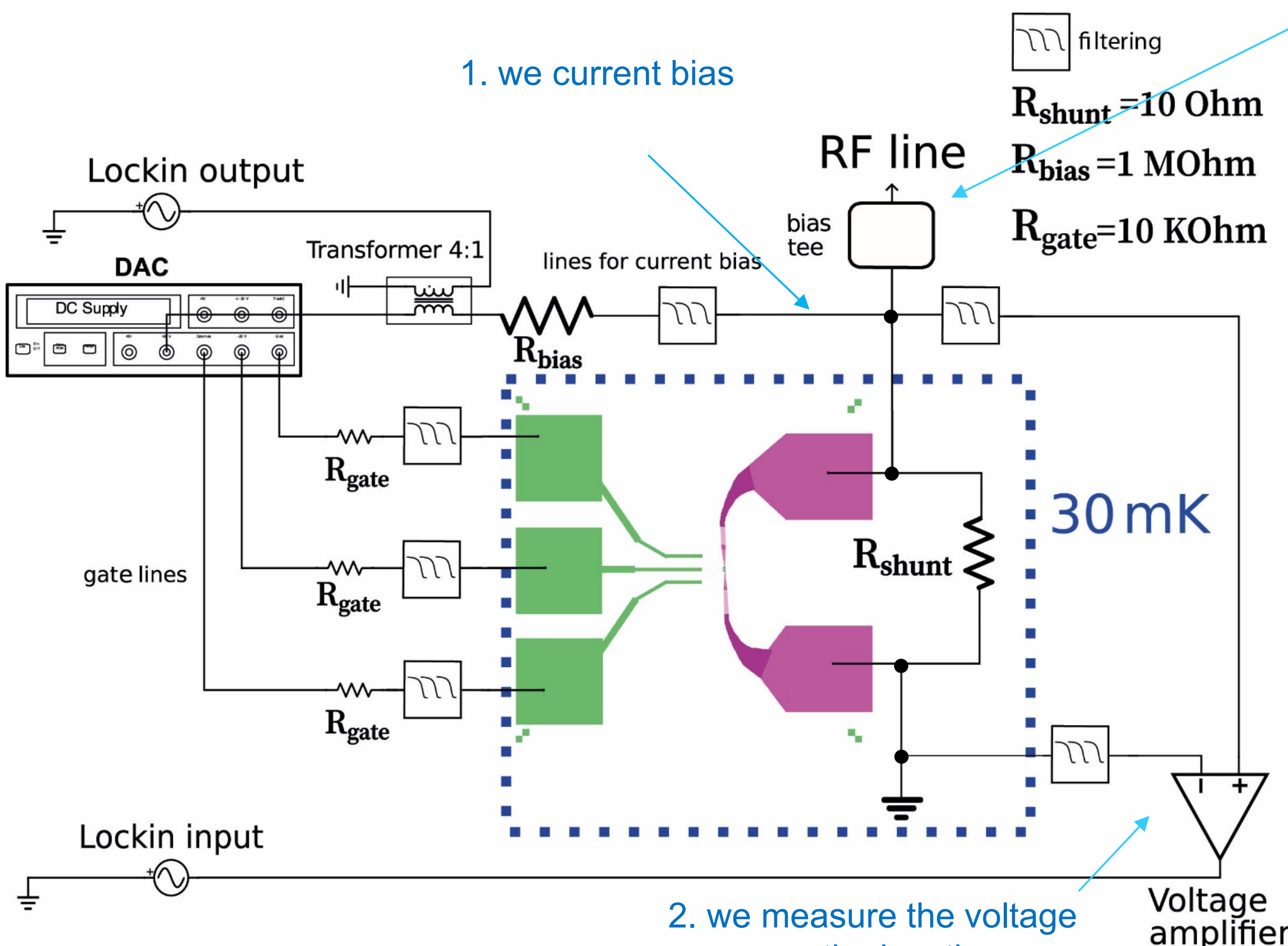
Lecture II
1^{st} reminder from last lecture

Bias circuitry

To wrap-up

For Josephson radiation we use a circuit similar to a Shapiro measurement. It consists of a JJ with a **proper shunt resistor** allowing to apply a DC bias over the junction:

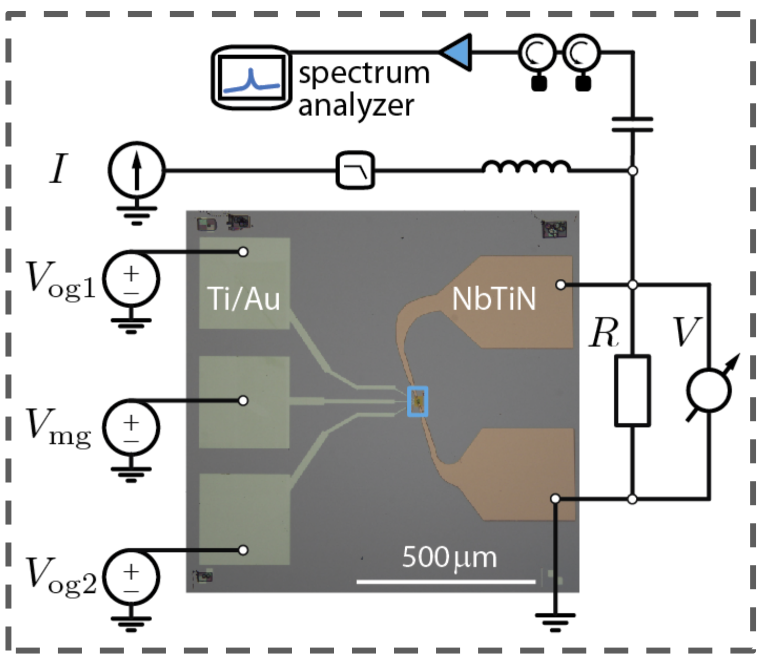


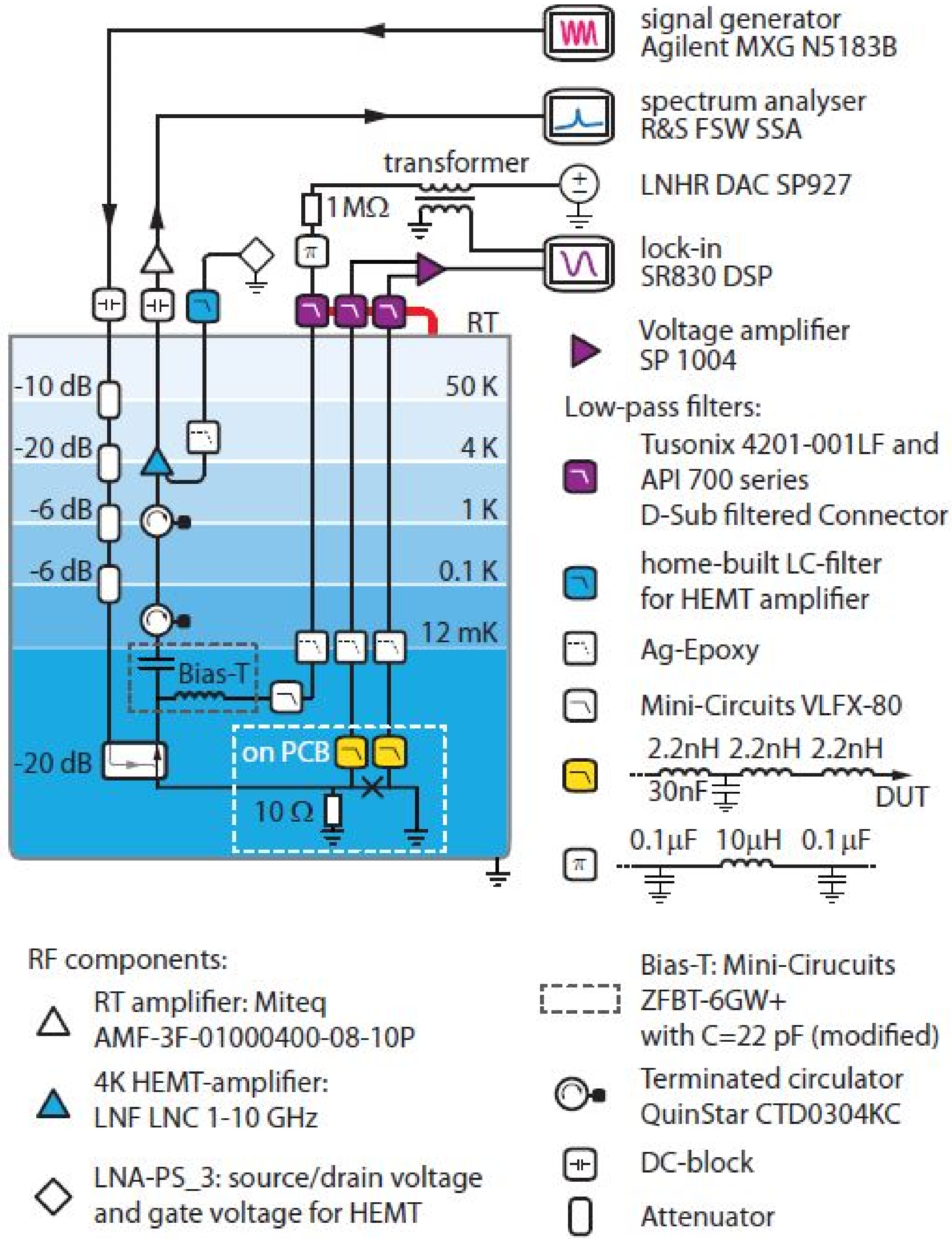
1. we current bias

2. we measure the voltage over the junction

and 3. we also measure the RF radiation using cryogenic low noise wide bandwidth amplifiers → **Josephson rad**.

Cryogenic setup



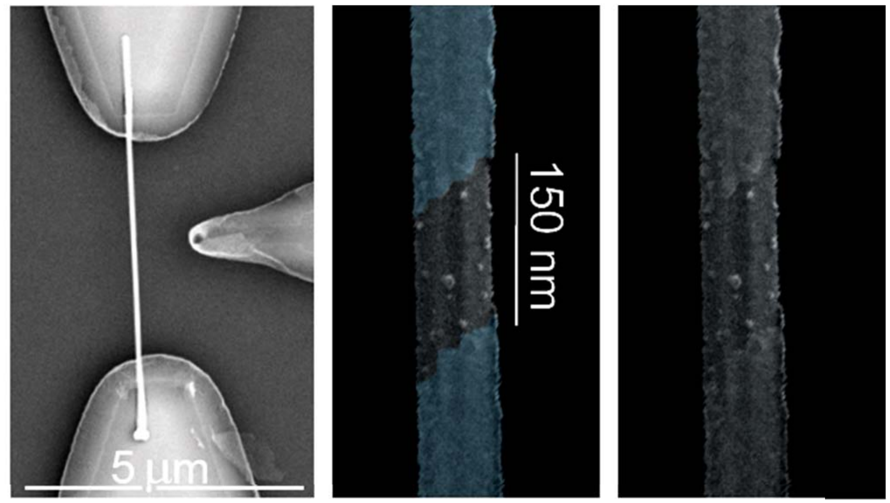


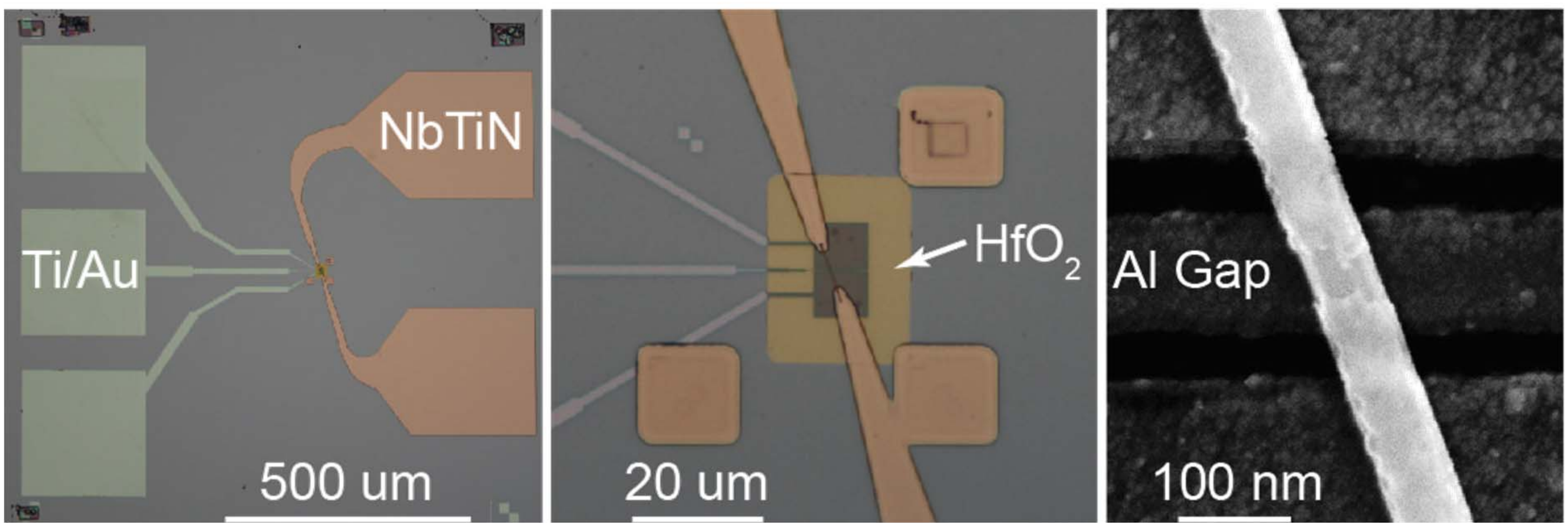
Al-InAs-NW-Al as reference

We have tested our setup sensitivity also for **InAs nanowires** with few modes and show that we can still detect the **Josephson radiation for a supercurrent that is due to a single conducting channel**.

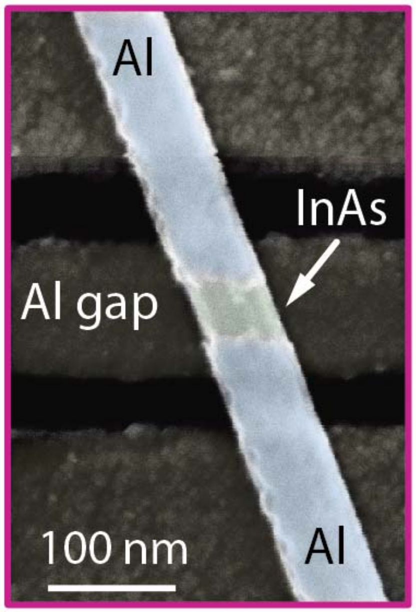
This slide first shows the nanowires we use. They are from Copenhagen, so called "half-shell-coated" InAs NWs with Al as shell.

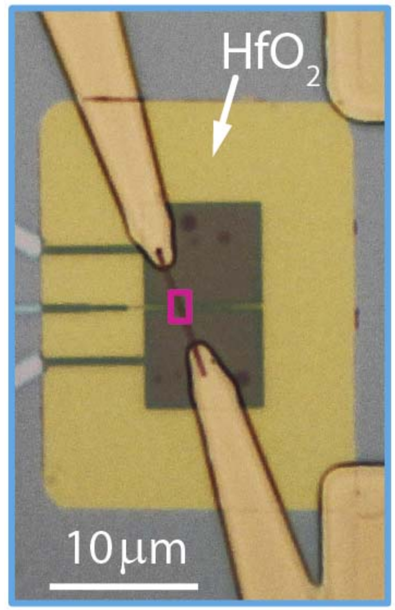
The figures on the right show a typical device where the Al shell is indicated with a weak blue touch. Here there is one gate from the right. In the device in which we have measured Josephson radiation, there are three gates

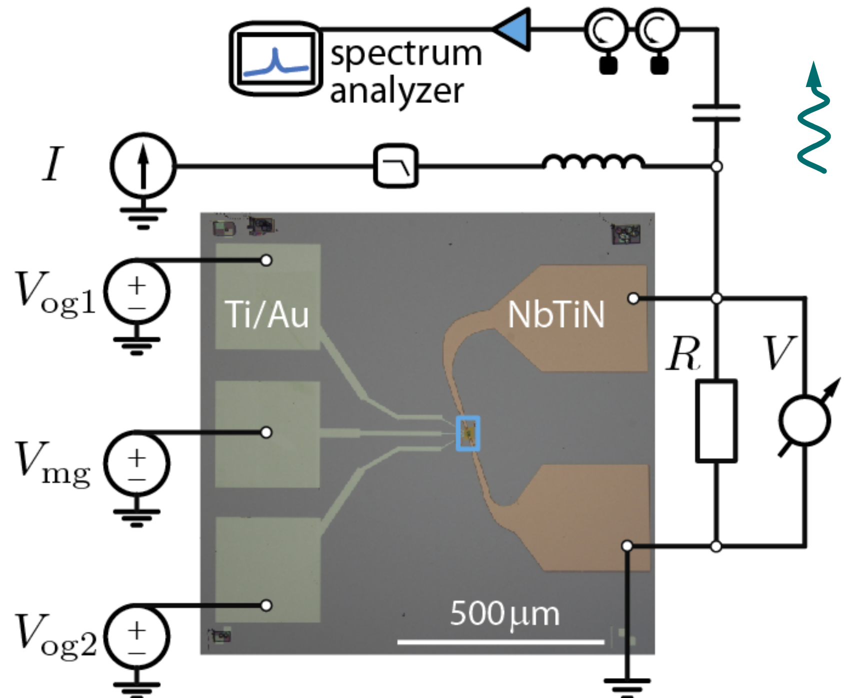


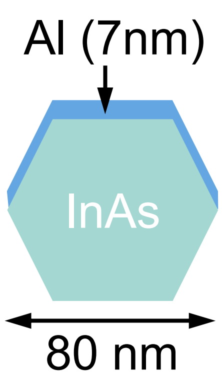


Al-InAs-NW-Al as reference









InAs nanowire with epitaxial Al half-shell

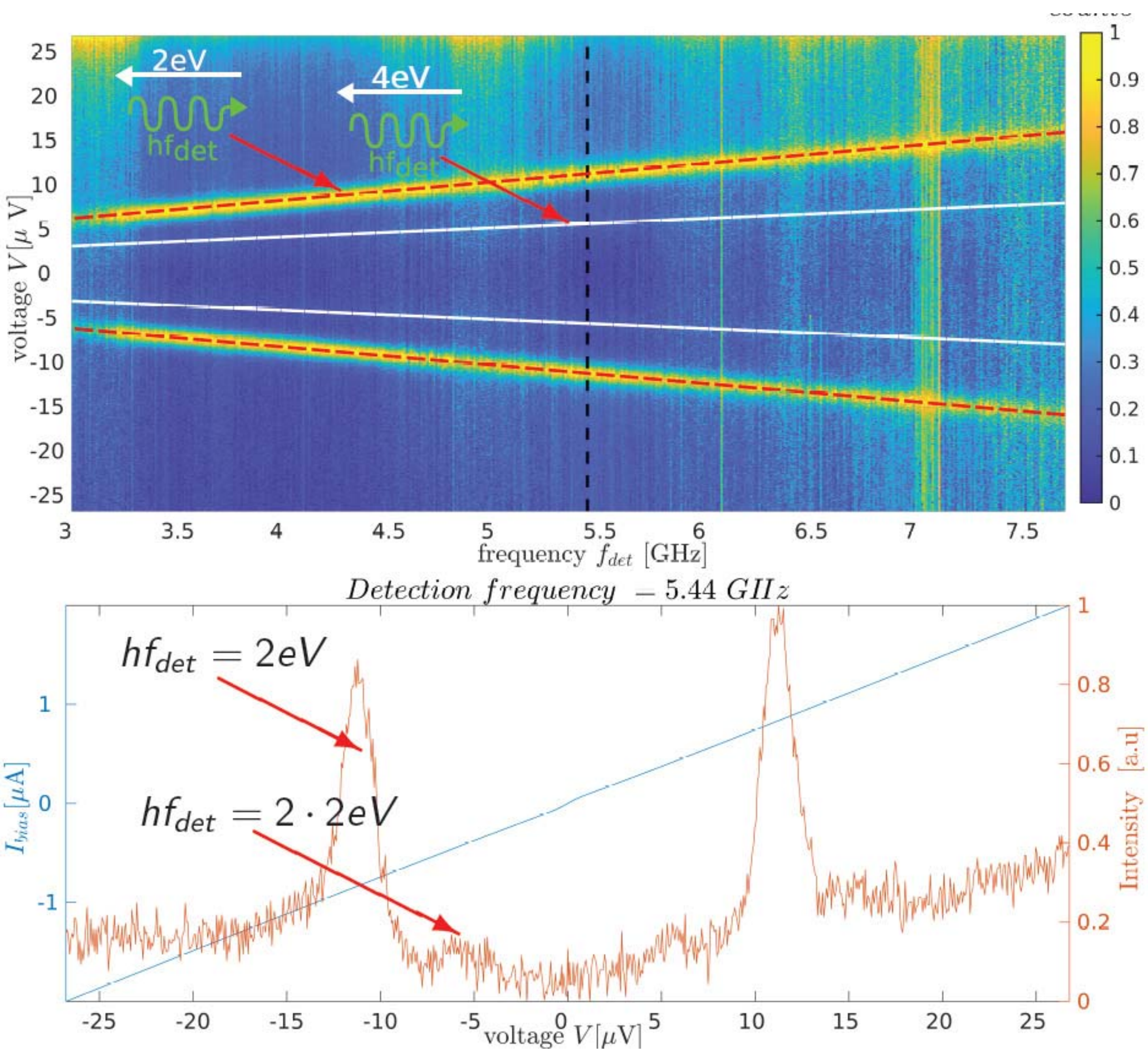
P. Krogstrup et al., Nature Materials **14**, 400 (2015)

- Deposit on bottom gate structure
- Partially remove Al by wet-etching
- Sputtered NbTiN contacts

by Roy Haller et al. (PhD thesis) in collaboration with J. Nygard et al (Copenhagen)

Al-InAs-NW-Al as reference

… and here the measurement



The **main peak** corresponds to the usual **2πJosephson** radiation, the normal AC Josephson effect: i.e.$\boldsymbol{hf = 2eV}$.

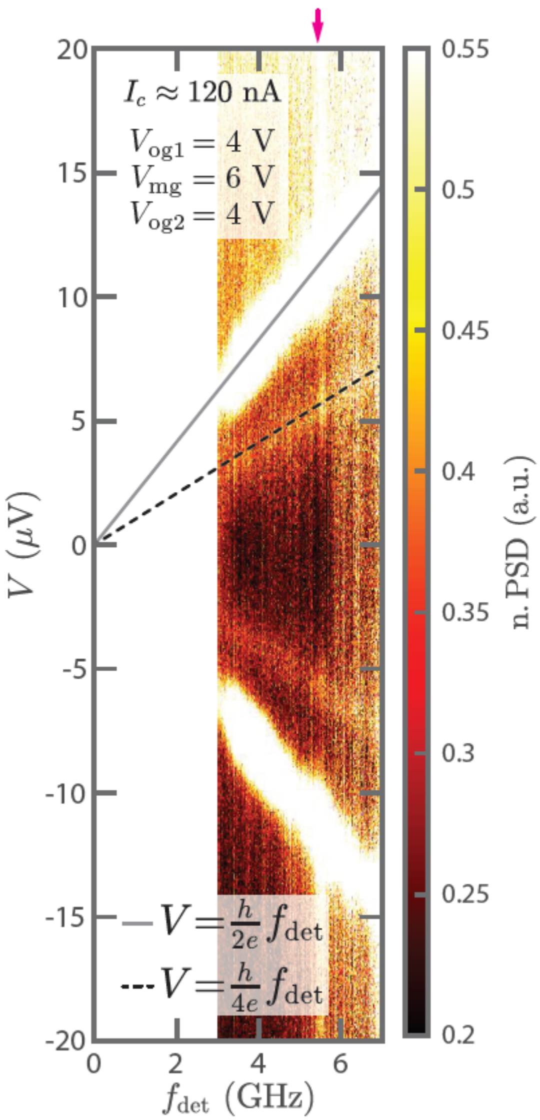
The much weaker peak for the same frequency at half the voltage is a second order process. Here, the inelastic tunneling is accomplished by the transfer of **two Cooper-pairs per photon**.

A 4π signal would show up with twice the slope as compared to the conventional 2πJosephson radiation

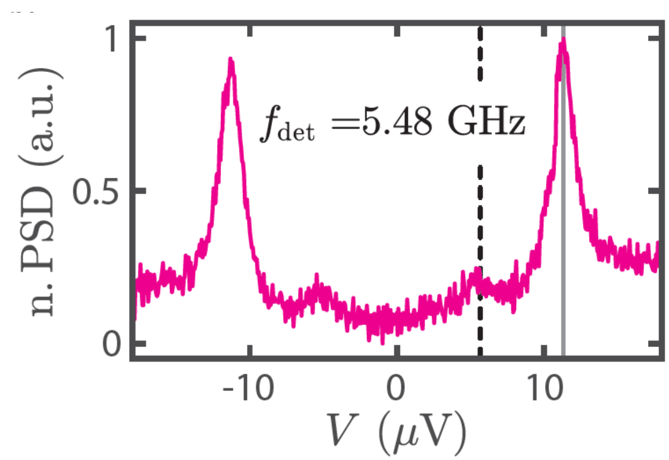
master work of Dario Sufra

Al-InAs-NW-Al as reference

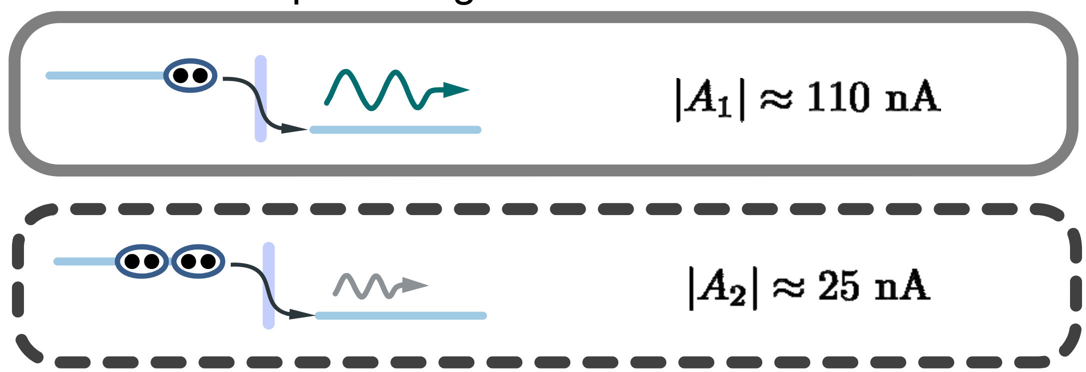
… and here the measurement



Fixed detection frequency



From the peak height ratio:

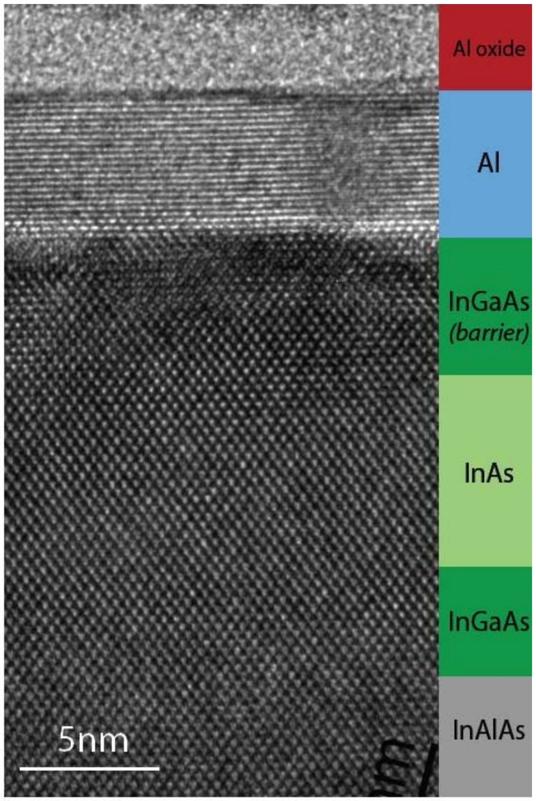


Non-sinusoidal current-phase relation

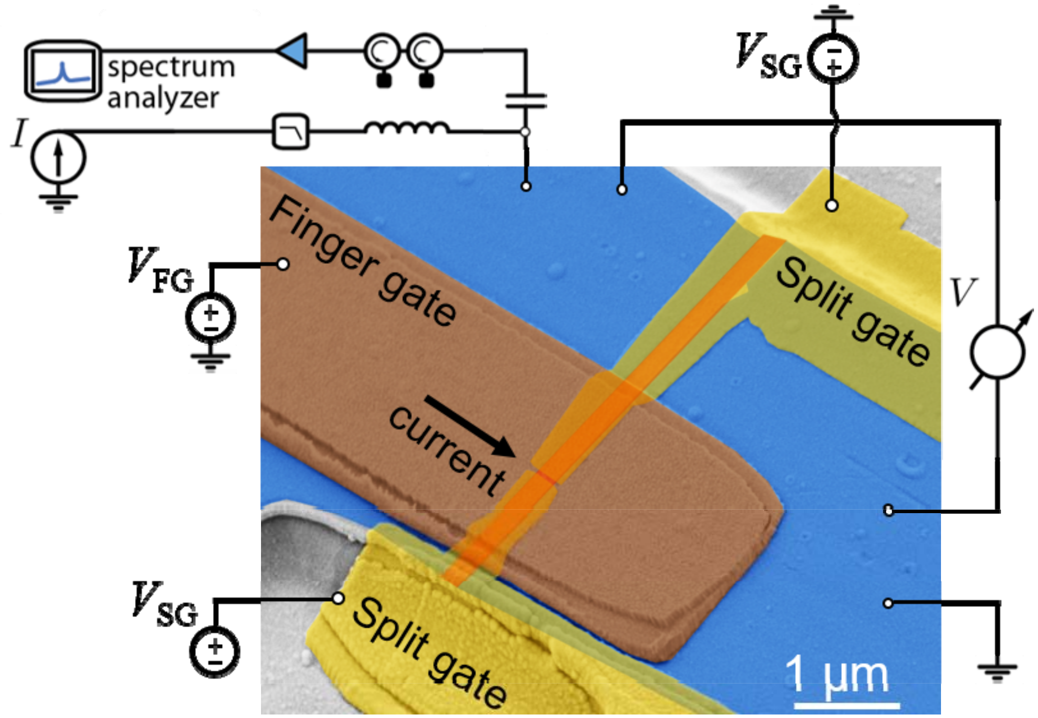
$$|A_2/A_1| \approx 0.22$$

by Roy Haller et al. (PhD thesis) in collaboration with J. Nygard et al (Copenhagen)

Further material platform: InAs QW



J. Shabani *et al*., Phys. Rev. B **93**, 155402 (2016)

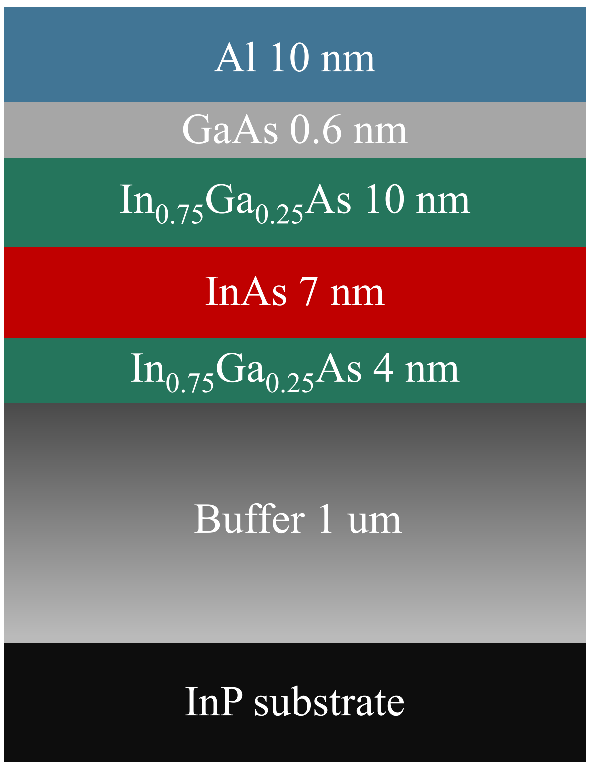


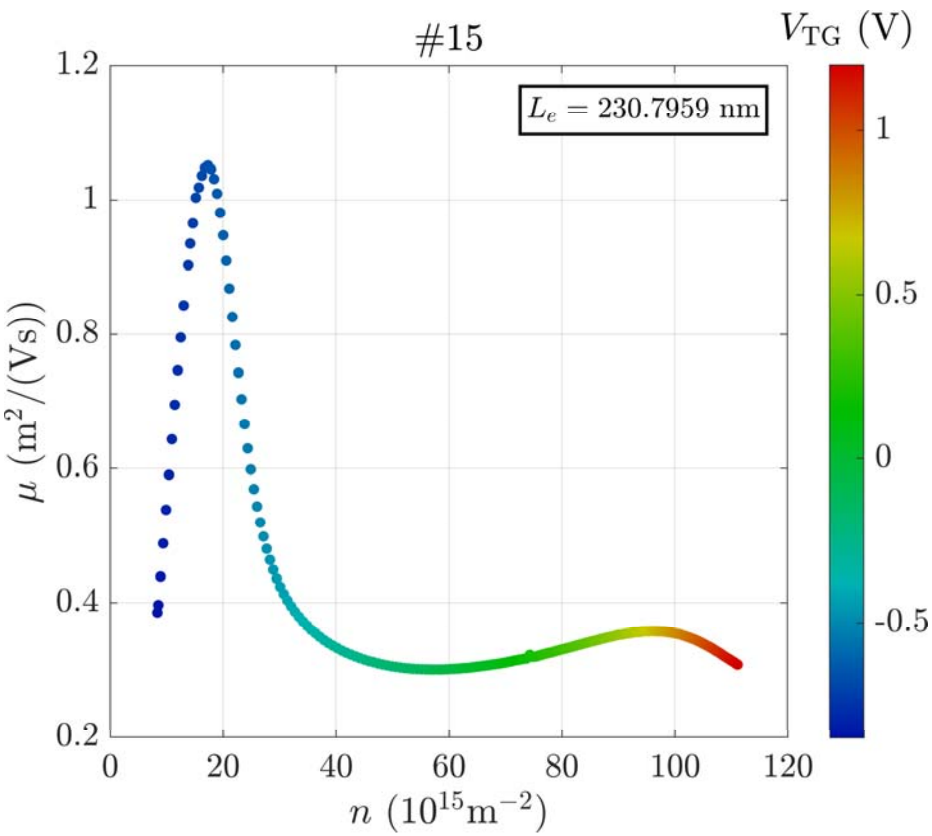
- Epi-Al on InAs 2DEG
- S-QPC is defined and tuned by two split gates and on finger gate

by Carlo Ciaccia & Libin Wang in collaboration with M. Manfra group (Purdue)& C. Marcus group (Copenhagen)

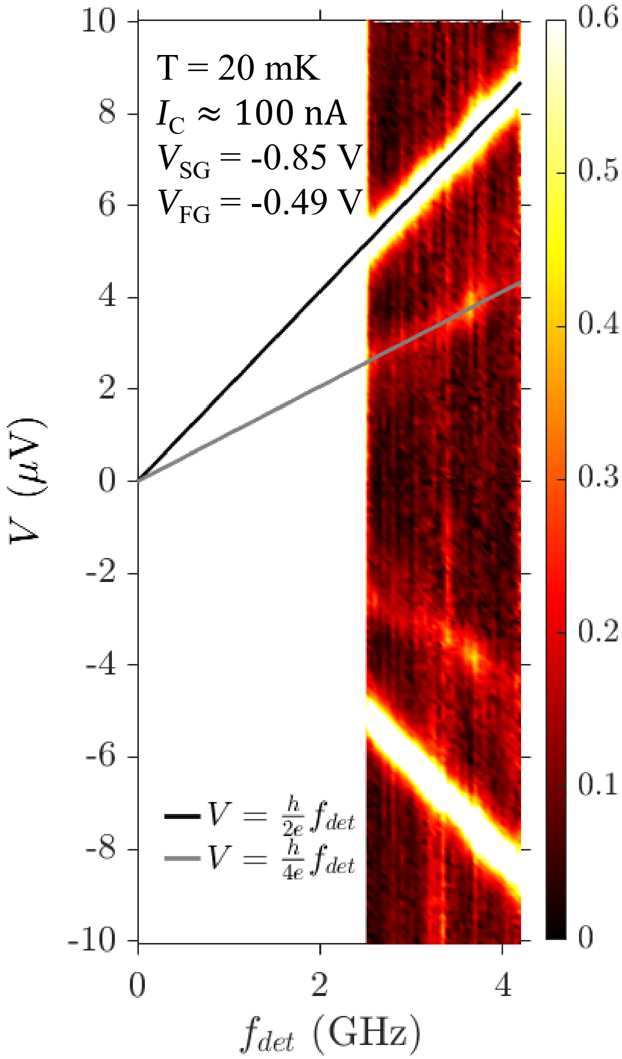
Further material platform: InAs QW

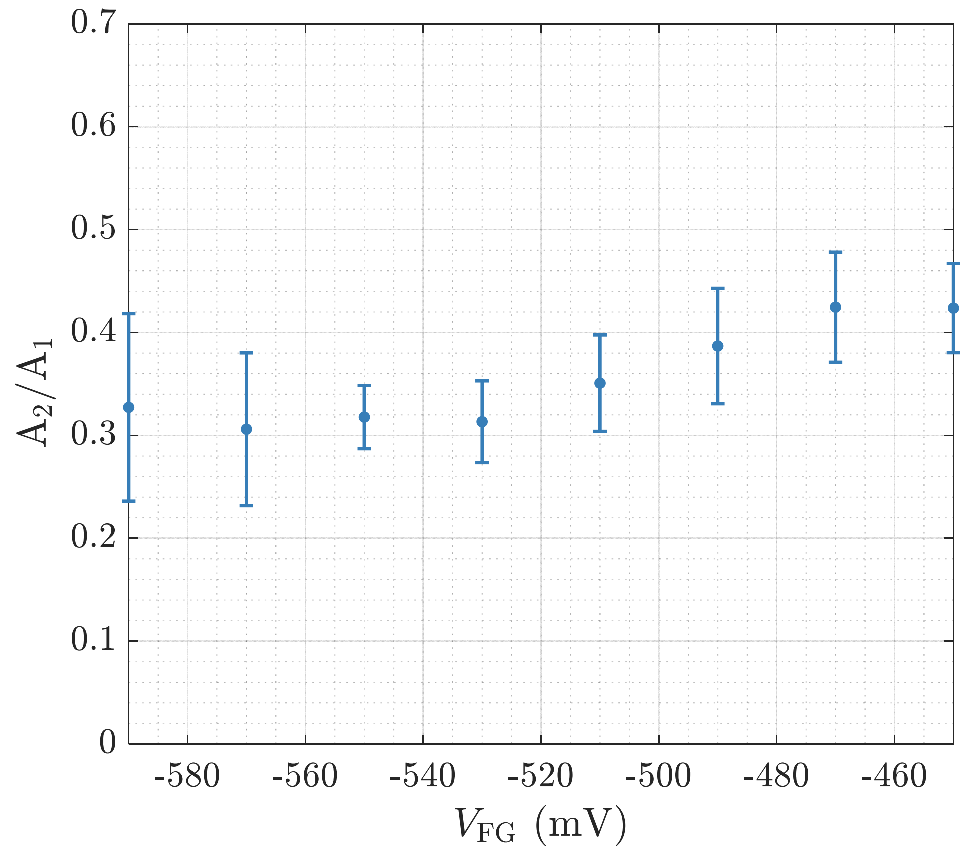
- Wafer no. M-11-11-16
- Sample: C3
- Measurements: Triton, Roy's PCB with 10 Ohm shunt resistor, → 15.7.2021





Further material platform: InAs QW





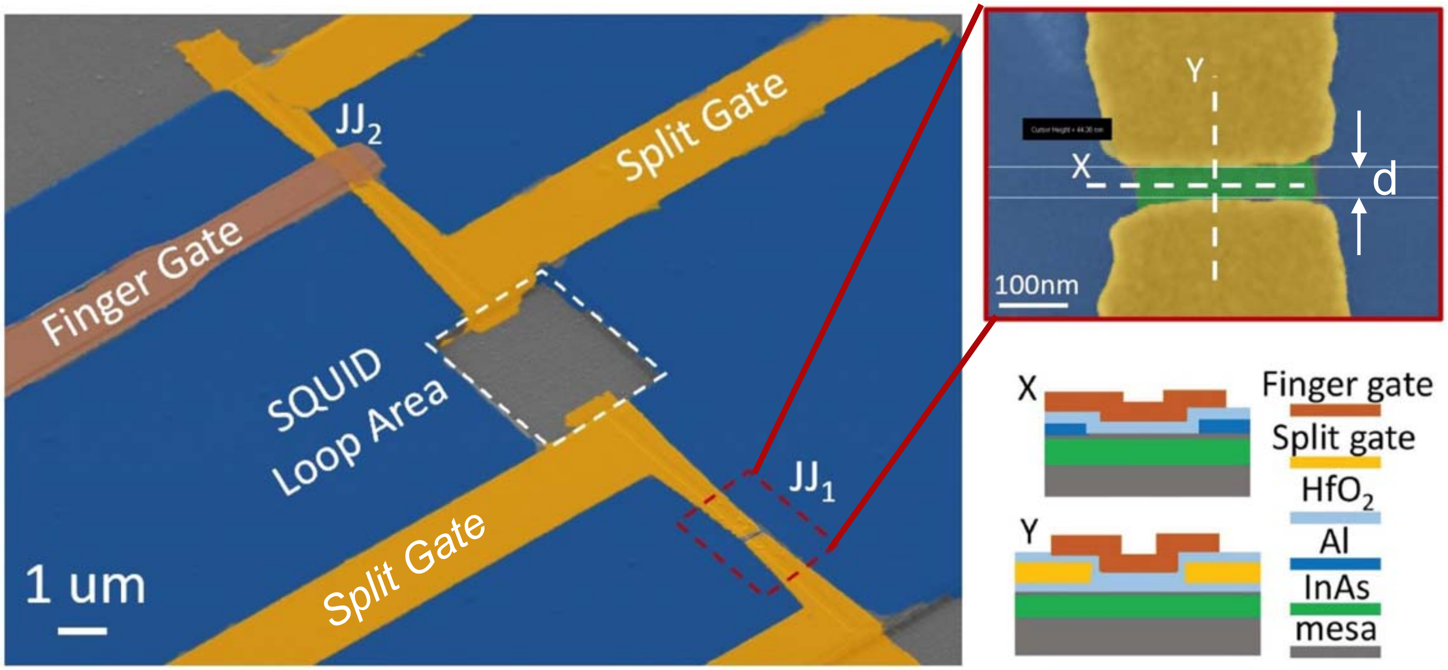
Strongly non-sinusoidal current-phase relation

$|A_2/A_1| \approx 0.4$

by Carlo Ciaccia & Libin Wang in collaboration with M. Manfra group (Purdue)& C. Marcus group (Copenhagen)

Further material platform: InAs QW

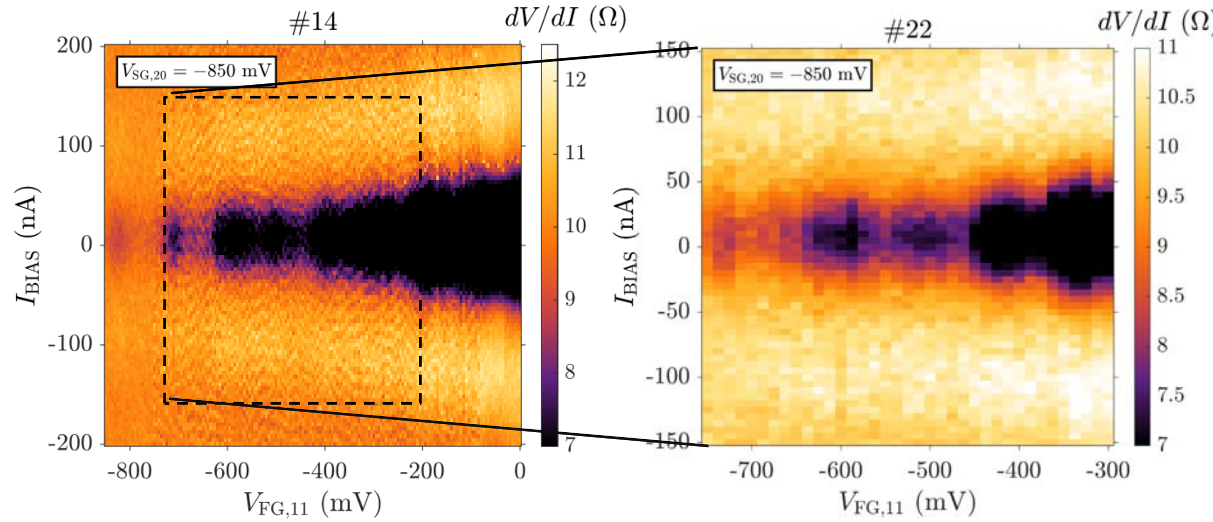
actually, we have fabricated DC-SQUIDs

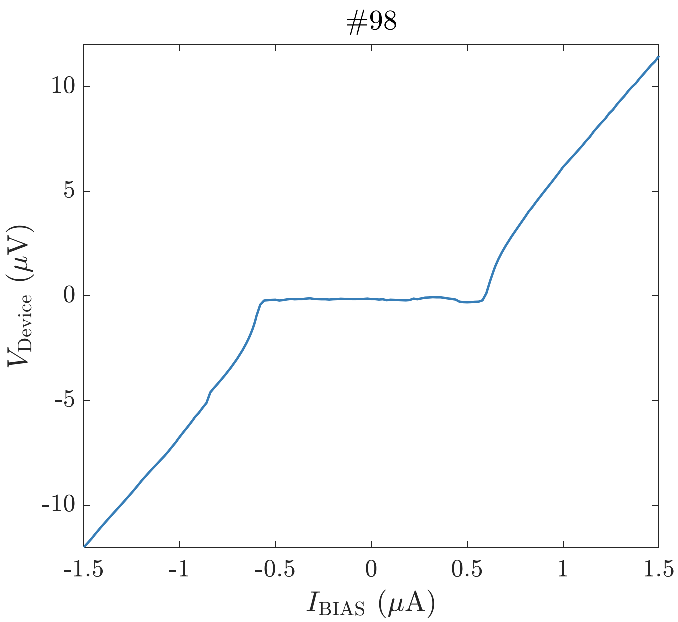


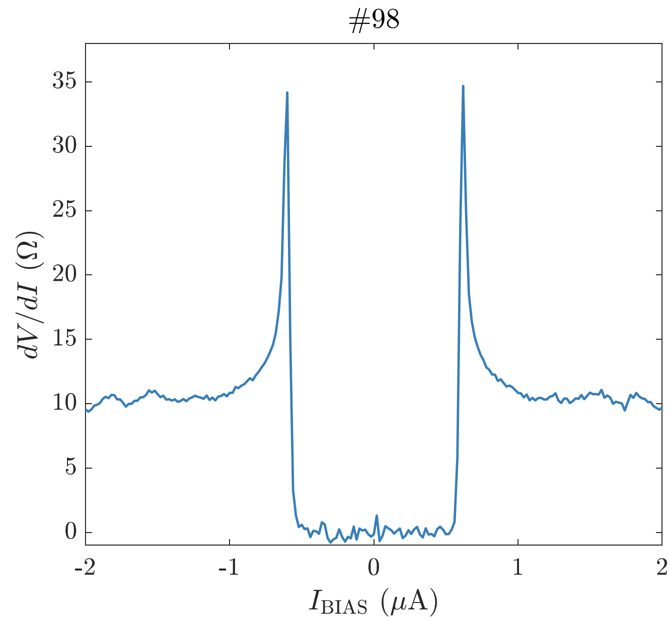
- Junction length ~145 nm, width 4 µm
- SQUID loop area: 8.9 µm x 8.9 µm
- Split gate separation: d = 40 nm (JJ1), 80 nm (JJ2)
- ALD thickness:
  - ✓ First layer: 15 nm
  - ✓ Second layer: 25 nm

Further material platform: InAs QW

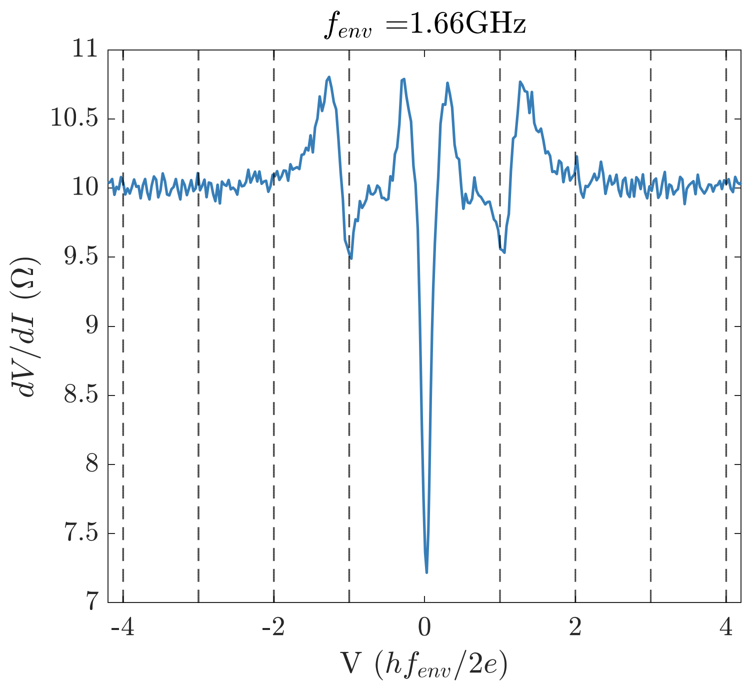
- 24 mK
- JJ1 depleted, V_{sg}^{1} = -1.5V
- JJ2: V_{sg}^{2} = V_{fg}^{2} = 0V
- No hysteresis
- Two JJs have comparable I_c (JJ1 not shown here)

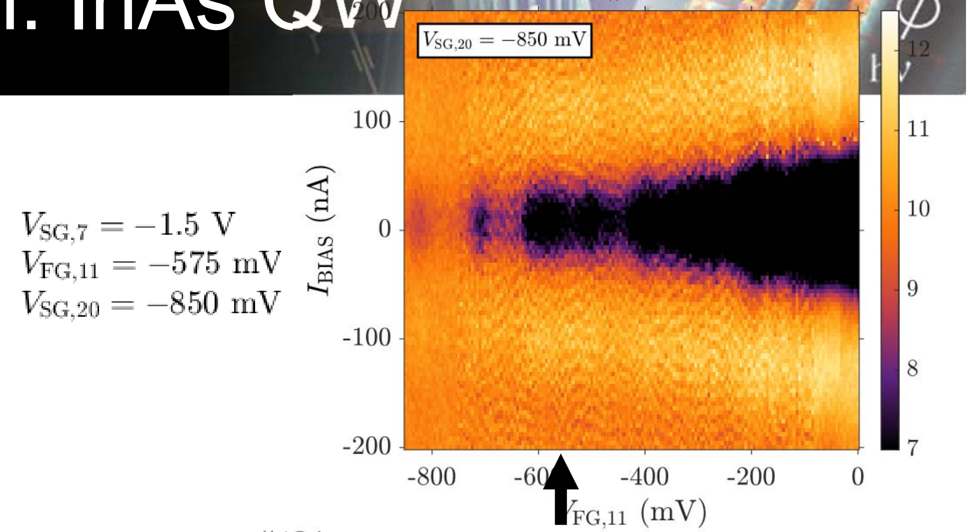


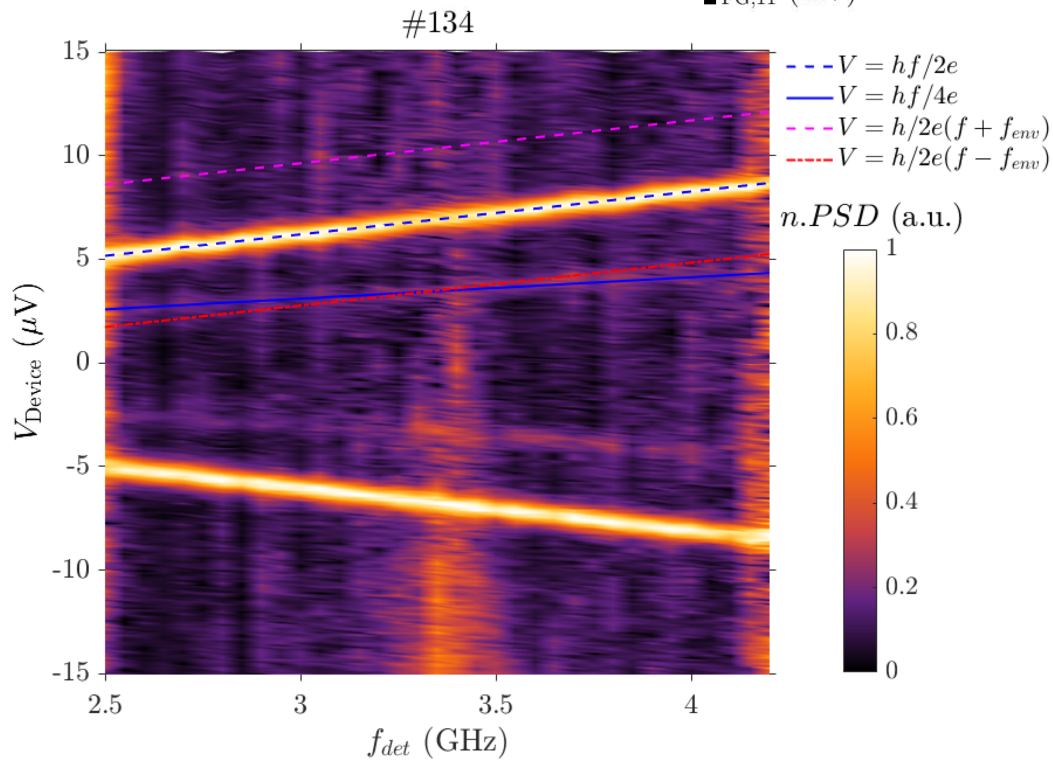




Further material platform: InAs QW

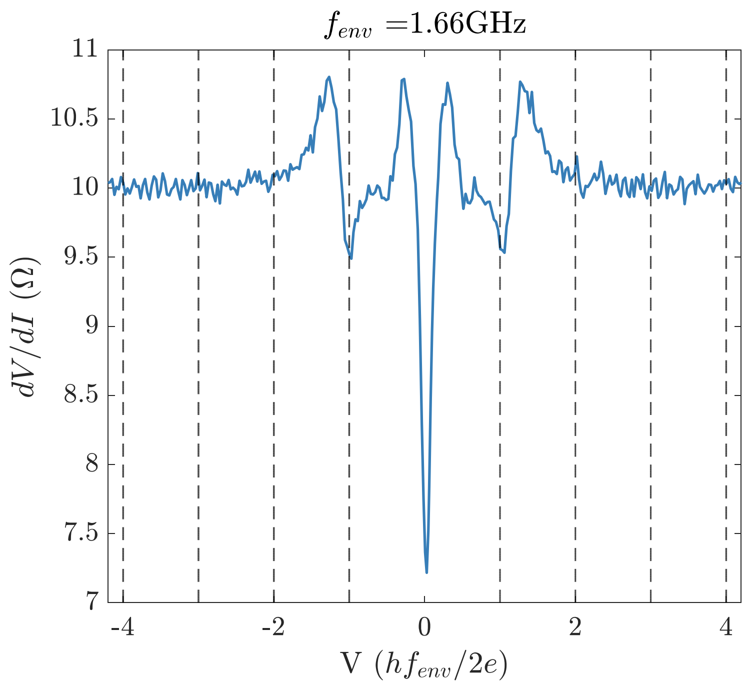




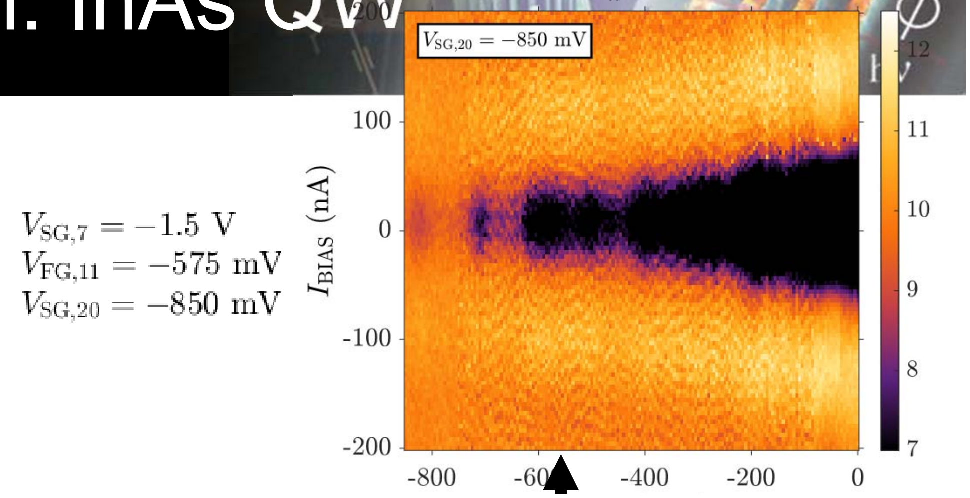


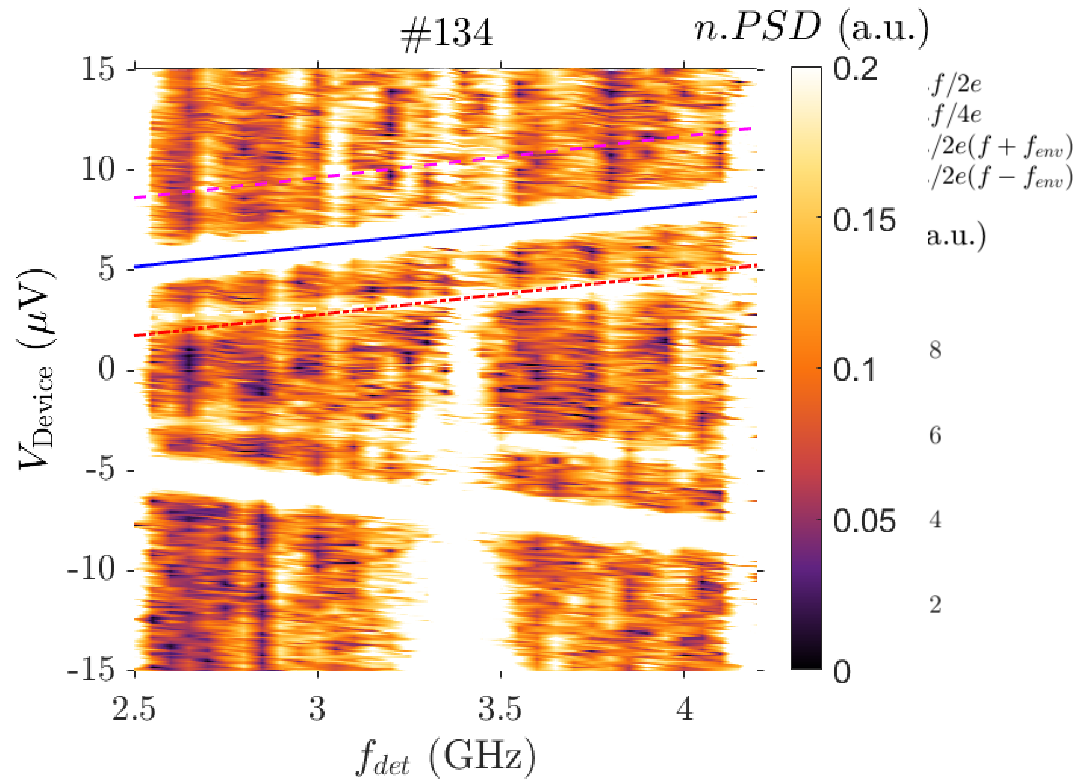
Not very obvious signature of environment coupling

Further material platform: InAs QW

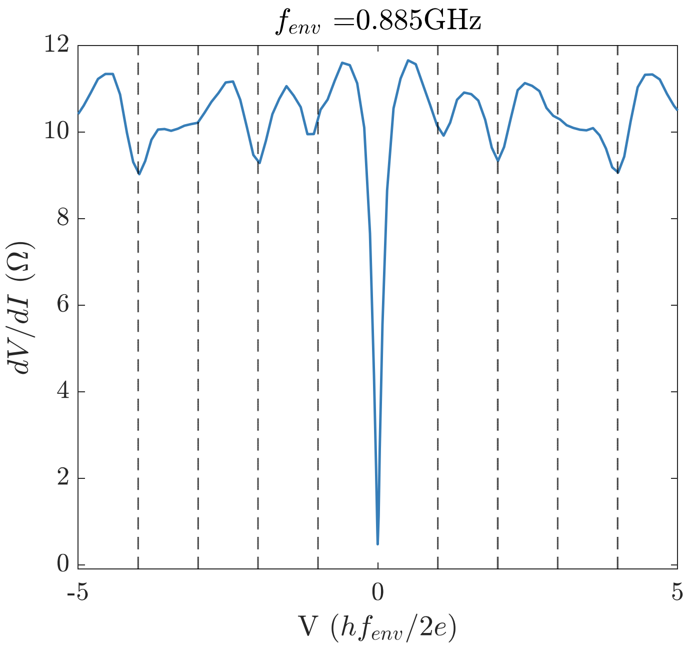


Not very obvious signature of environment coupling

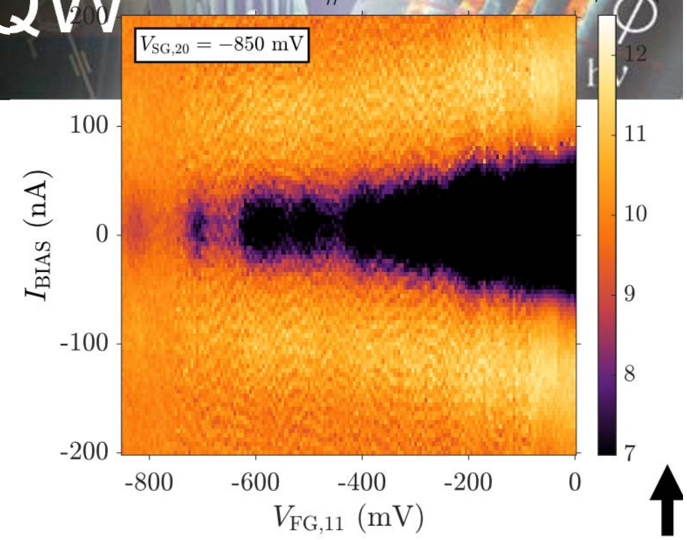


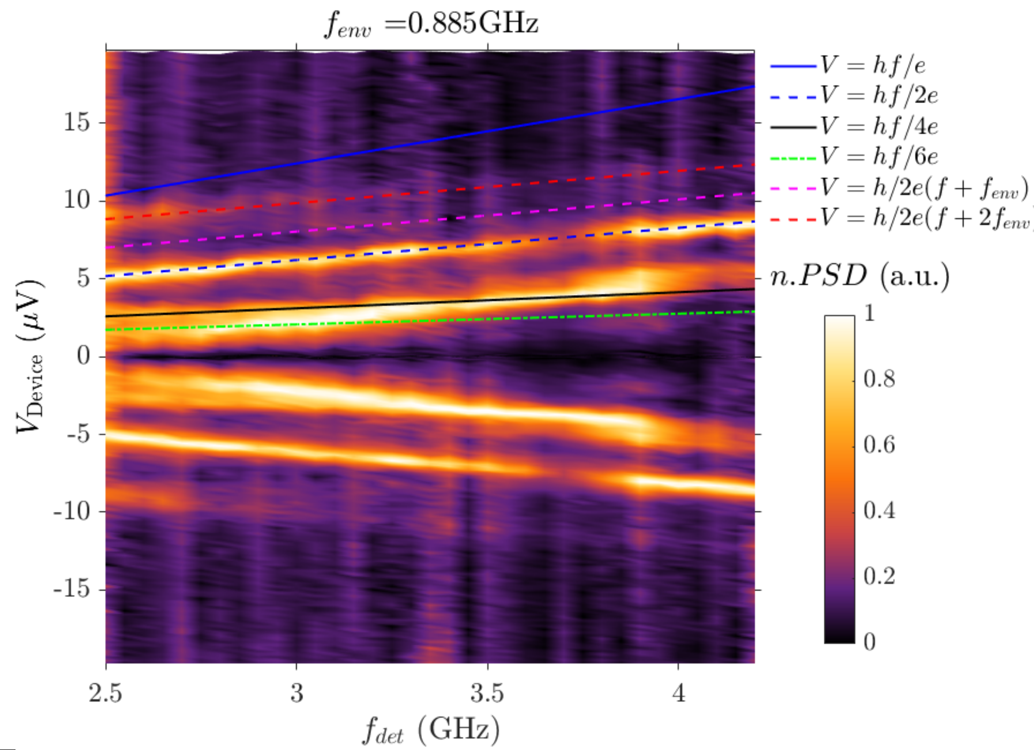


Further material platform: InAs QW

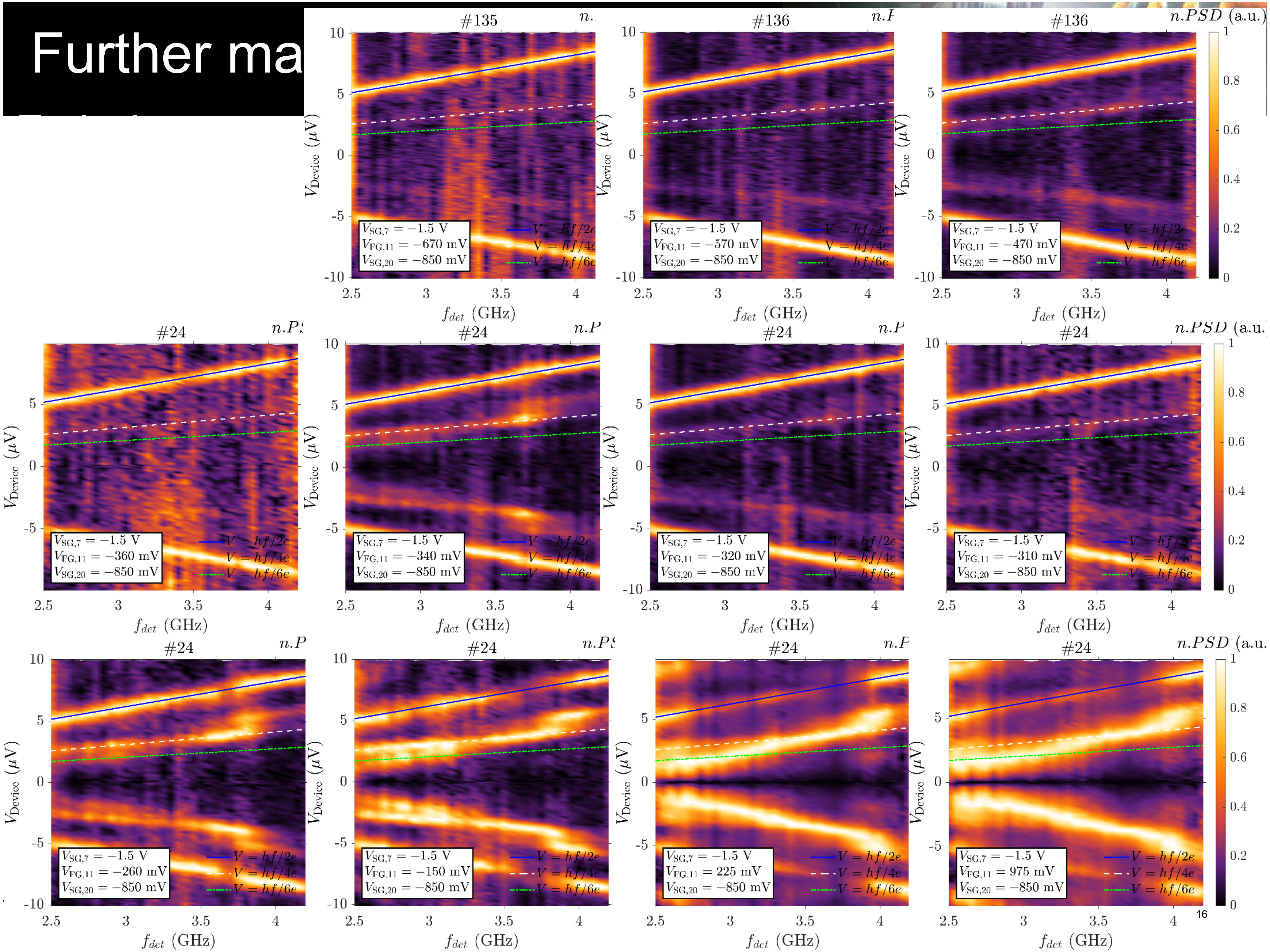


$V_{\mathrm{SG},7} = -1.5$ V
$V_{\mathrm{FG},11} = 200$ mV
$V_{\mathrm{SG},20} = -850$ mV



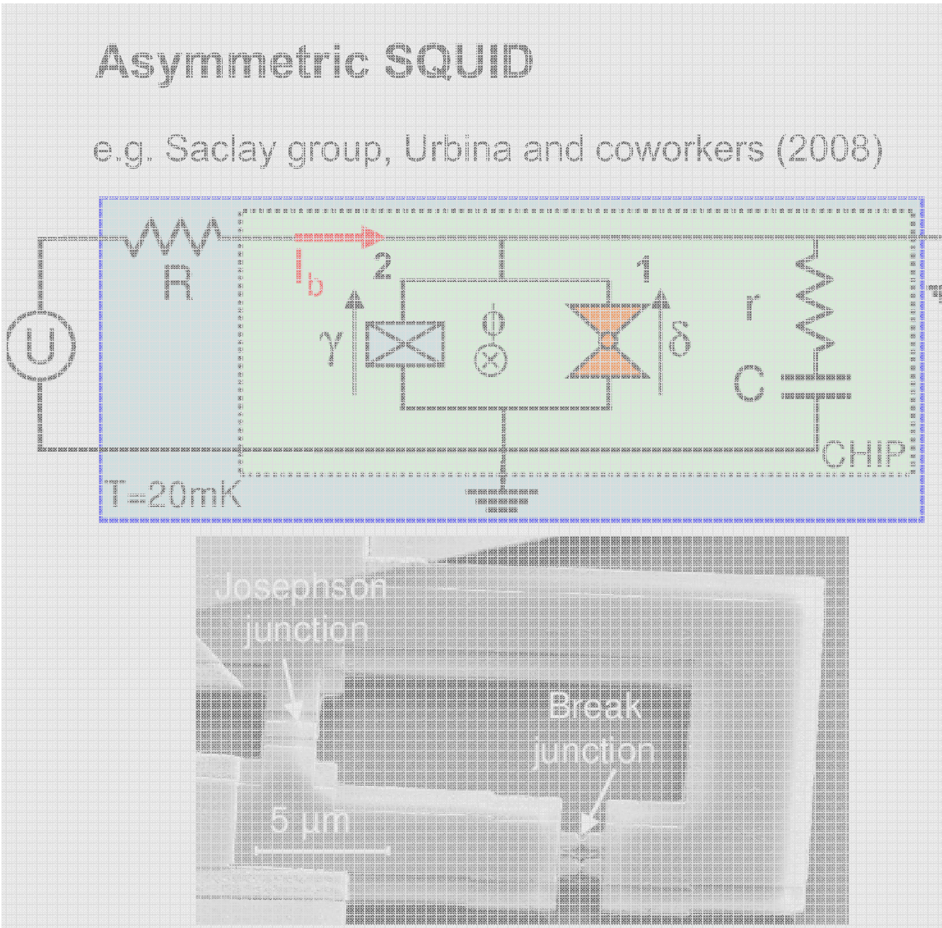


Further ma


#135
#136
#136
#24
$n.PSD$ (a.u.)
V_{Device} (μV)
f_{det} (GHz)
$V_{\mathrm{SG},7} = -1.5$ V
$V_{\mathrm{FG},11} = -670$ mV
$V_{\mathrm{SG},20} = -850$ mV
$V_{\mathrm{FG},11} = -570$ mV
$V_{\mathrm{FG},11} = -470$ mV
$V_{\mathrm{FG},11} = -360$ mV
$V_{\mathrm{FG},11} = -340$ mV
$V_{\mathrm{FG},11} = -320$ mV
$V_{\mathrm{FG},11} = -310$ mV
$V_{\mathrm{FG},11} = -260$ mV
$V_{\mathrm{FG},11} = -150$ mV
$V_{\mathrm{FG},11} = 225$ mV
$V_{\mathrm{FG},11} = 975$ mV
$V = hf/2e$
$V = hf/4e$
$V = hf/6e$

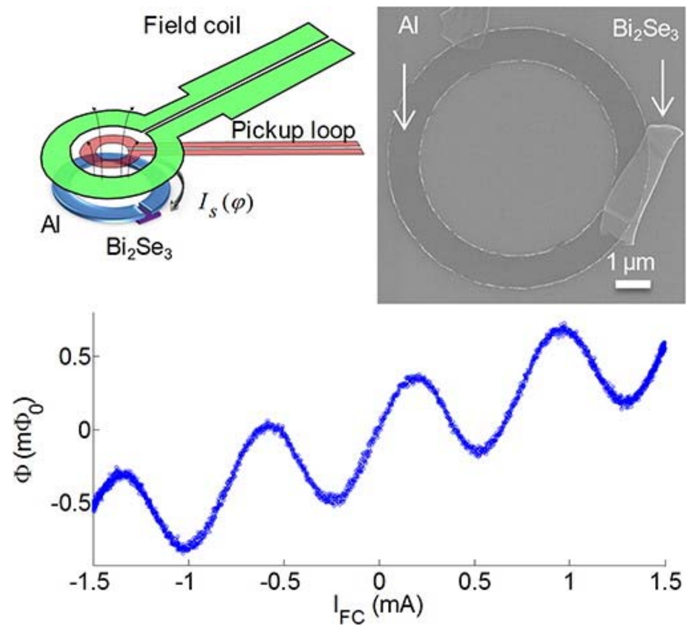
Lecture II
Introduction to CPR by DC-SQUID measurements

Measure the Current-Phase Relation



Rf susceptibility

Rf-SQUID: *Nano Lett.* 2013, 13, 3086-3092

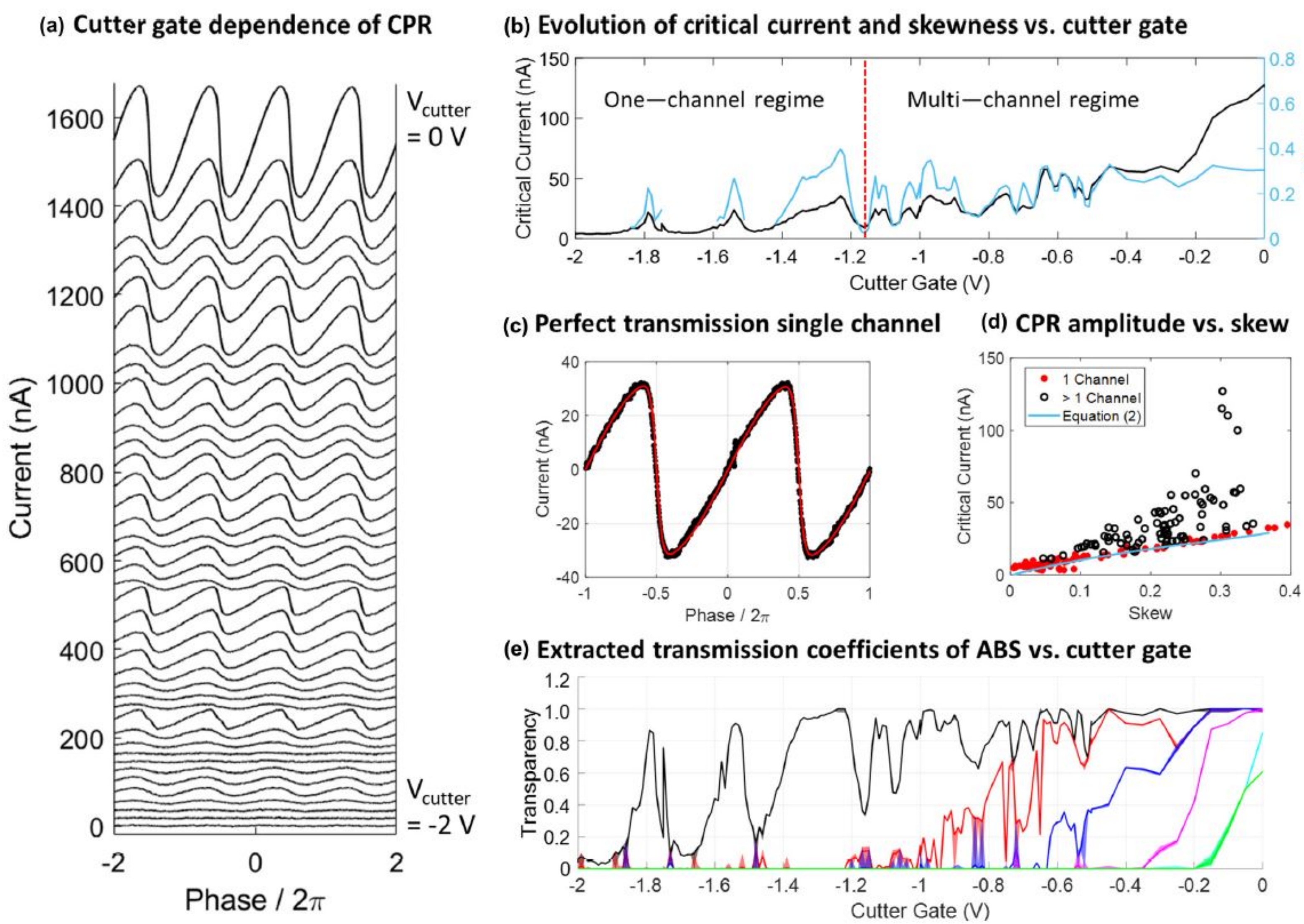


Kathryen A. Moler et al.

Current-phase relations of InAs nanowire Josephson junctions: From interacting to multimode regimes

PHYSICAL REVIEW B **100**, 064523 (2019)

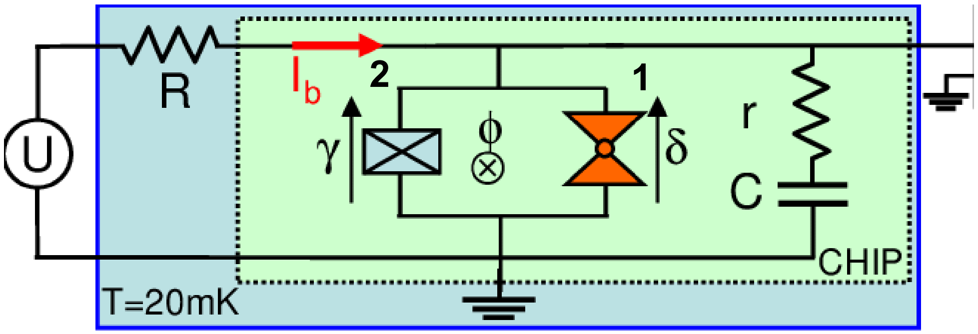
Sean Hart,[1,2,*] Zheng Cui,[1,2,3,*] Gerbold Ménard,[4] Mingtang Deng,[4] Andrey E. Antipov,[5] Roman M. Lutchyn,[5] Peter Krogstrup,[4,6] Charles M. Marcus,[4] and Kathryn A. Moler[1,2,3]

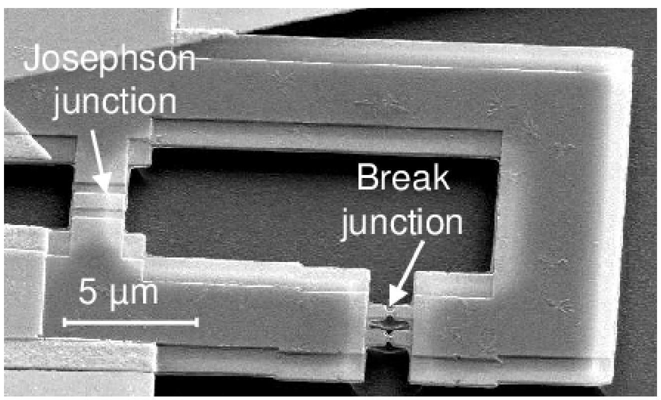


Measure the Current-Phase Relation

Asymmetric SQUID

e.g. Saclay group, Urbina and coworkers (2008)





$$I_s = I_1(\delta) + I_2(\gamma)$$

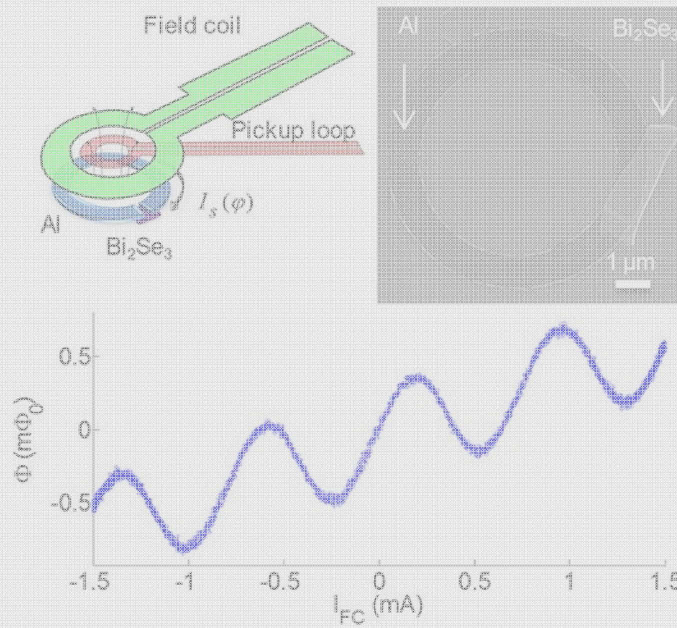
$$\delta - \gamma = 2\pi\phi/\phi_0$$ fluxoid relation

$$I_c(\phi) = max_{\delta,\gamma}|I_1(\delta) + I_2(\gamma)|$$ → $$I_c(\phi) = I_{c2} + I_1(2\pi\,\phi/\phi_0 + \gamma_{2c})$$

$$I_{c2} = I_2(\gamma_{2c})$$

Rf susceptibility

Rf-SQUID: *Nano Lett.* 2013, 13, 3086-3092



CPR by asymmetric SQUID

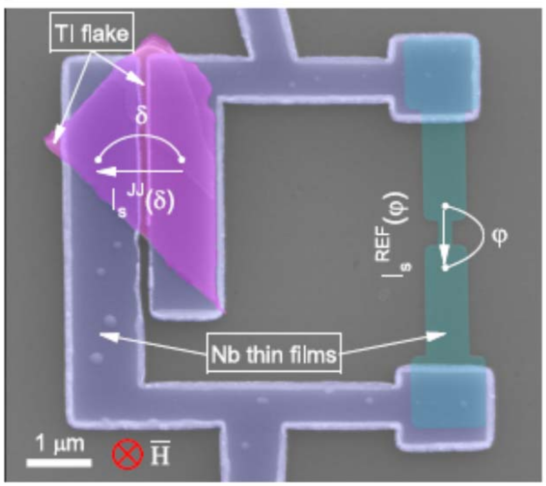
Limitations of the Current–Phase Relation Measurements by an Asymmetric dc-SQUID

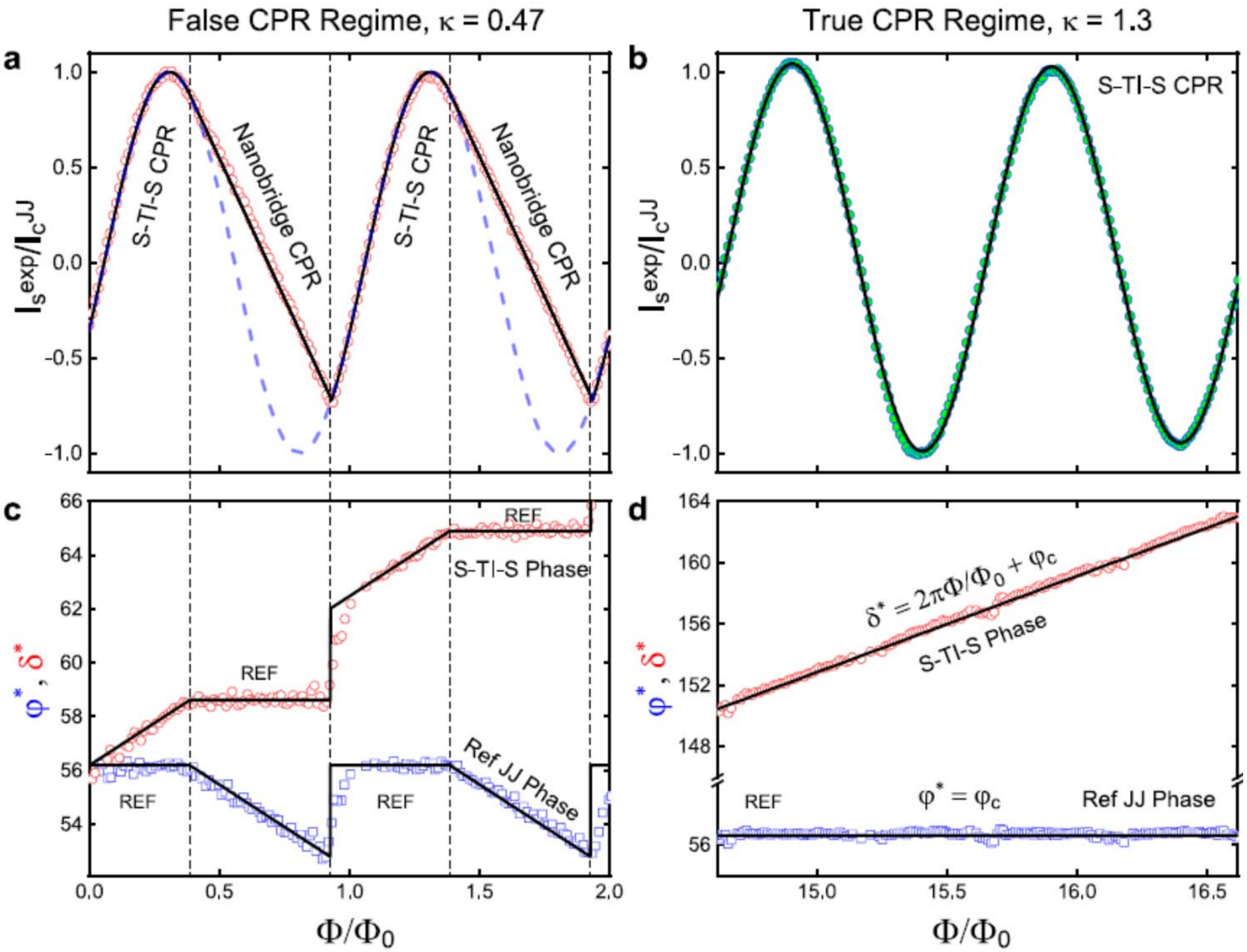
Ian Babich,* Andrei Kudriashov, Denis Baranov, and Vasily S. Stolyarov

Cite This: *Nano Lett.* 2023, 23, 6713–6719

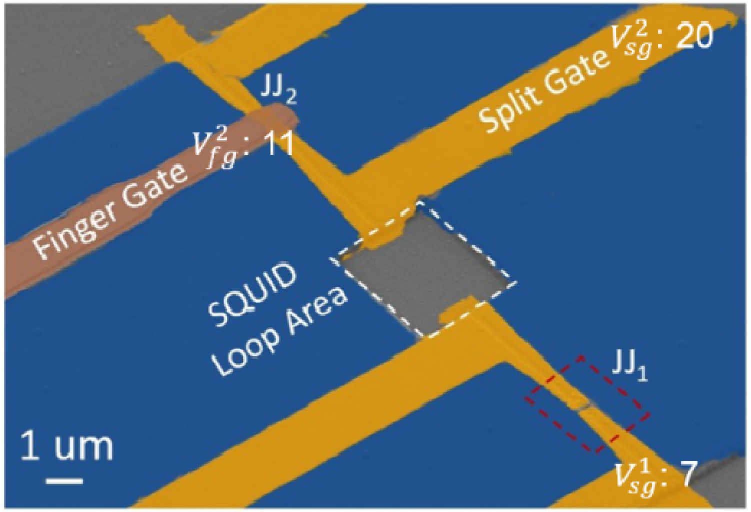
study JJ from 3D TI Bi_2Te_2Se

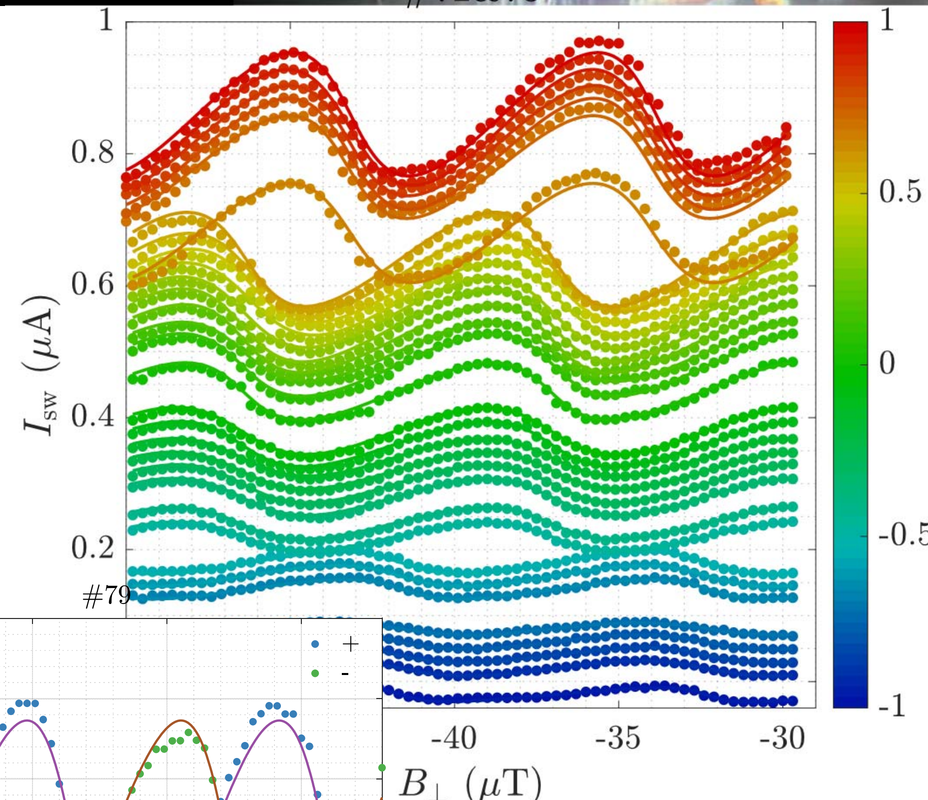
a

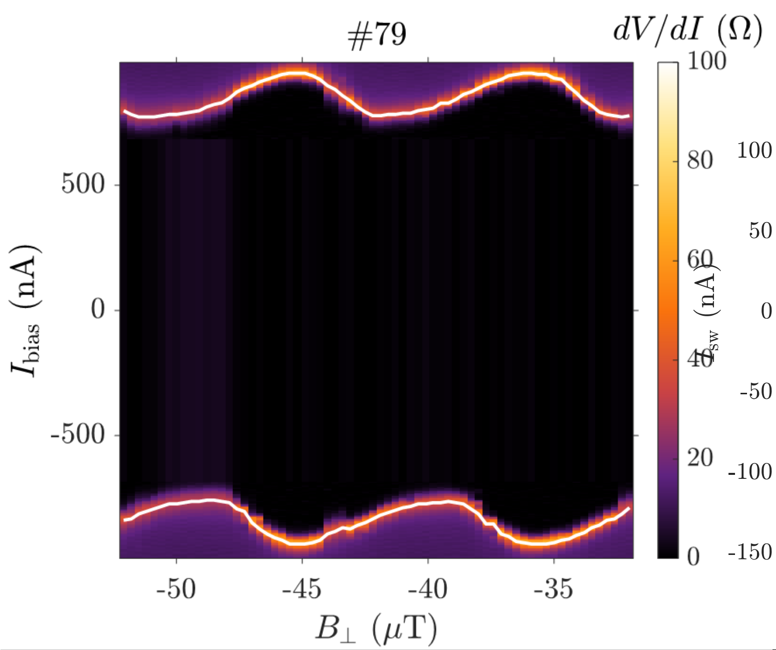


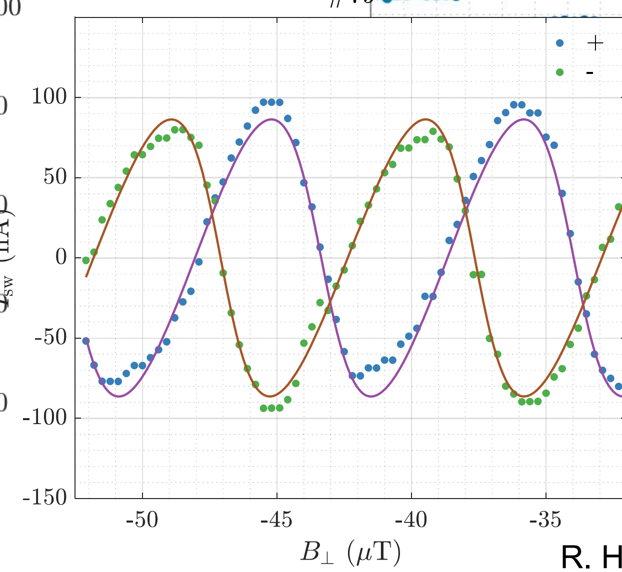


CPR by asymmetric SQUID









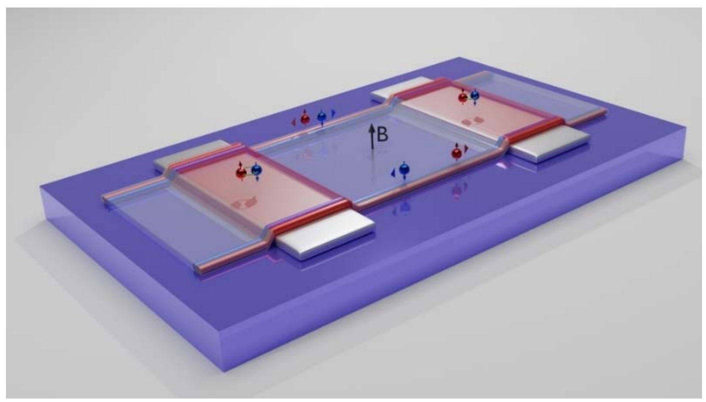
Yes, there is some **skewness** and hence, we have to expect **higher harmonics in AC radiation** (which we did).
But, it is **not** straightforward to extract the skewness from the relative intensities of the harmonics, see:

R. Haller, M. Osterwalder, G. Fülöp, J. Ridderbos, M. Jung, and C. Schönenberger. *Phys. Rev. B* **108**, 094514 (2023)

Lecture II
A study with the material WTe_2

An experimental search for topology in WTe_2

Lecture II: Focus more on CPR using the asymmetric SQUID approach



Martin Endres, Artem Kononov, Christian Schönenberger
Quantum- and Nanoelectronics group

Team

Samples and measurements:

A. Kononov, M. Endres, G. Abulizi and C. Schonenberger

Department of Physics, University of Basel




TEM-STEM EDX studies:

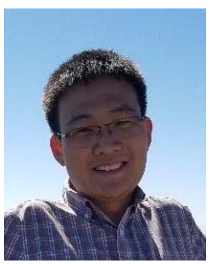
Marcus Wyss

NanoImaging Lab @ Swiss Nanoscience Institute, Univ. of Basel

WTe_2 growth:

H.S. Arachchige, 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


Funding:

erc

QSIT Quantum Science and Technology

National Centre of Competence in Research

Swiss National Science Foundation

ghe GEORG H. ENDRESS STIFTUNG

SNI Swiss Nanoscience Institute

Exzellenzzentrum

der Universität Basel und

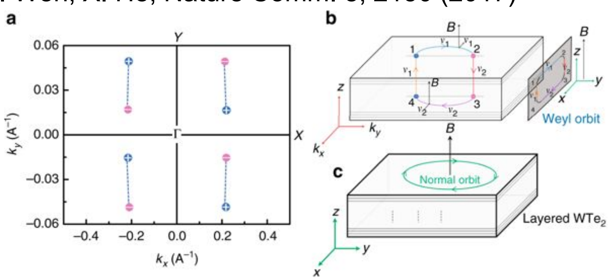
des Kantons Aargau

WTe_2 intriguing properties

Nontrivial topology

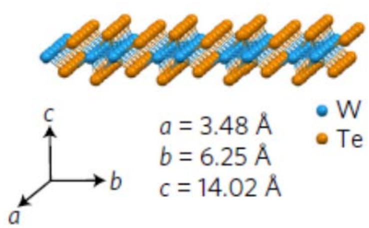
✓ Bulk crystal is type II Weyl semimetal

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)

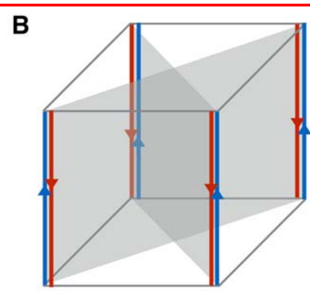


Image: F. Schindler et al., Science Advances 4, no. 6, eaat0346 (2018)

Superconductivity

✓ Under high pressure is superconducting

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

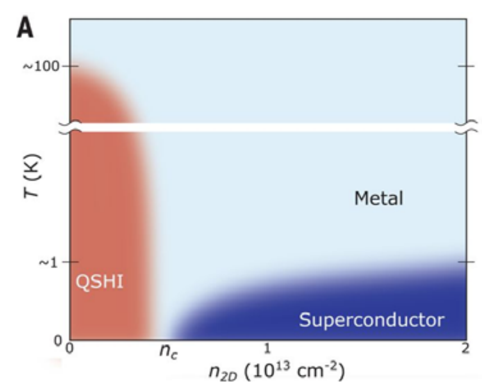
✓ Superconducting when doped

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

✓ Monolayer is tunable with gate into superconducting state

E. Sajadi et al., Science 362, p. 922 (2018)

V. Fatemi et al., Science 362, p. 926 (2018)



❑ Superconductivity at the interface with Pd

A. Kononov, M. Endres et al., *Journal of Applied Physics* **129**, 113903 (2021)

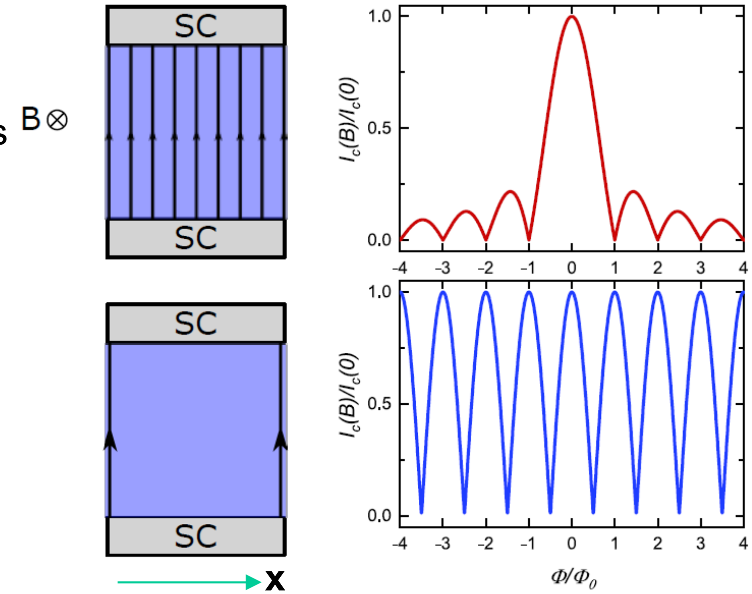
<u>Goal:</u> search for **edge currents** in transport or edge DOS in STM

Josephosn junctions in TI materials

Use superconducting interference in wide Josephson junctions to probe the current distribution

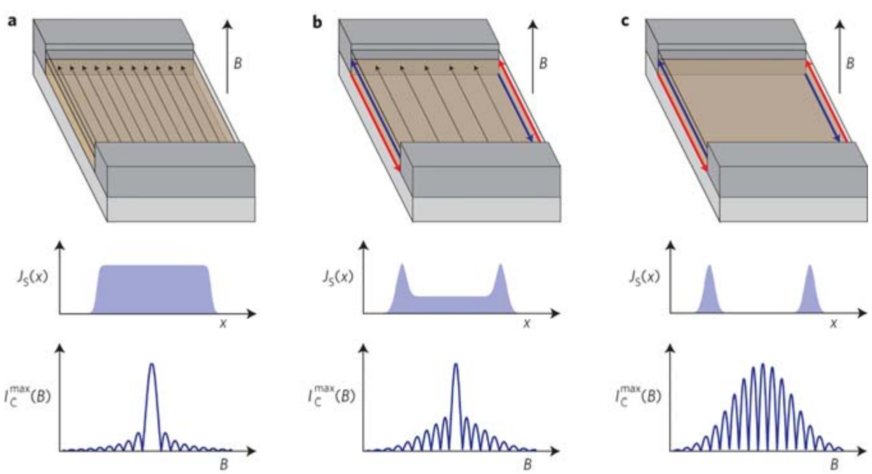
To measure the **current distribution** in plane one makes use of quantum interference induced by the electromagnetic gauge field, related to the mag. field B.

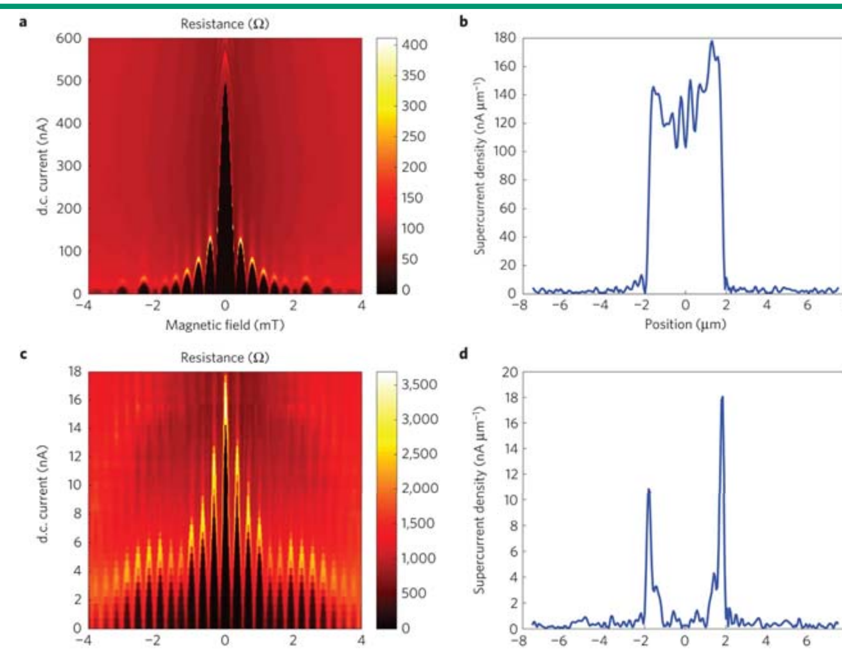
The acquired phase is given by the **flux Φ(x)** divided by the flux quantum for a Cooper pair.



Example:

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

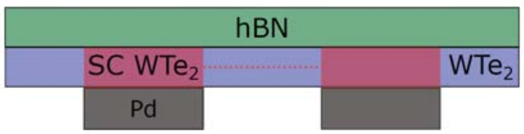


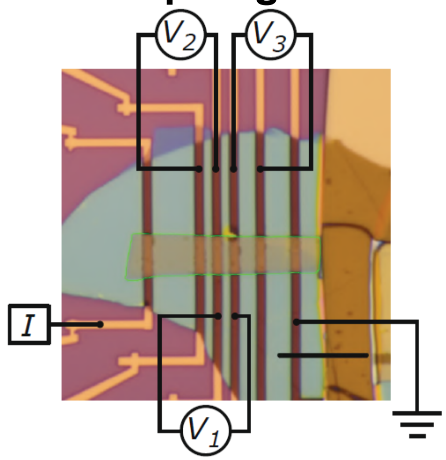


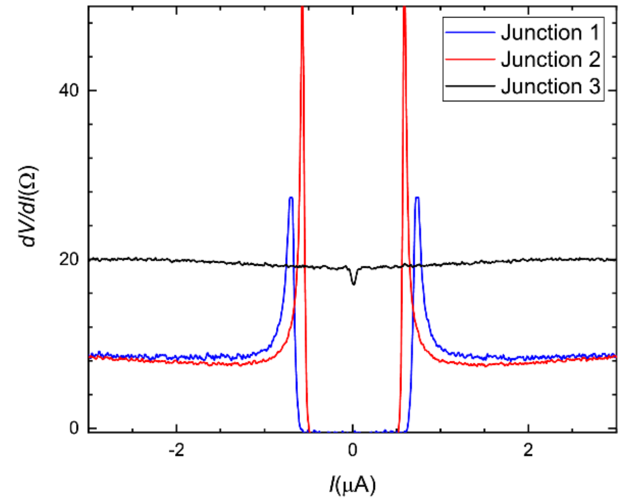
Weyl SM junction: WTe_2

WTe_2 predicted to be higher-order topological insulator

Pd induced superconductivity

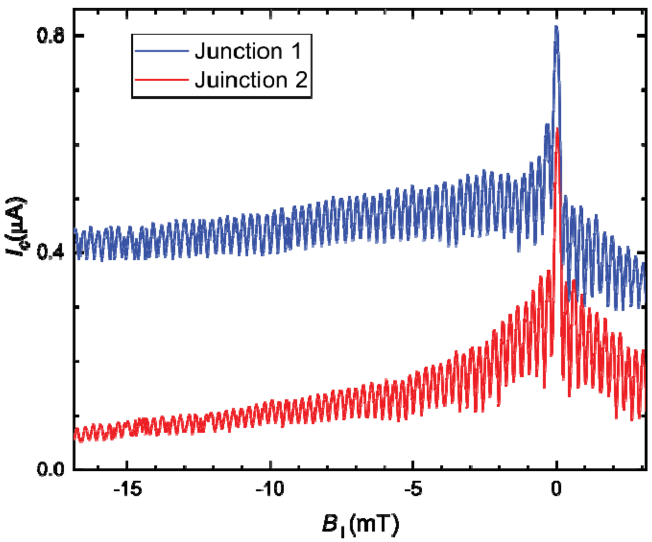


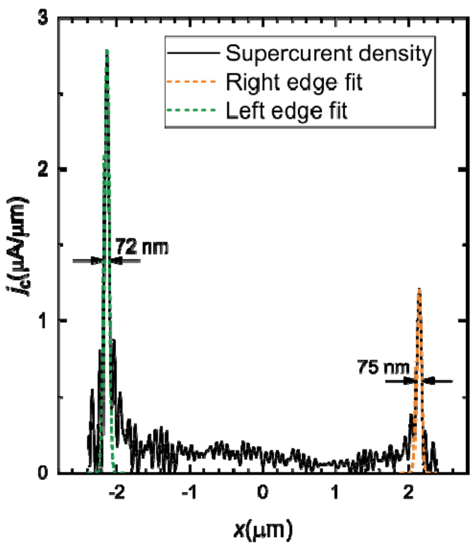




Junctions 1 & 2: $L = 1\ \mu m$
Junction 3: $L = 2\ \mu m$

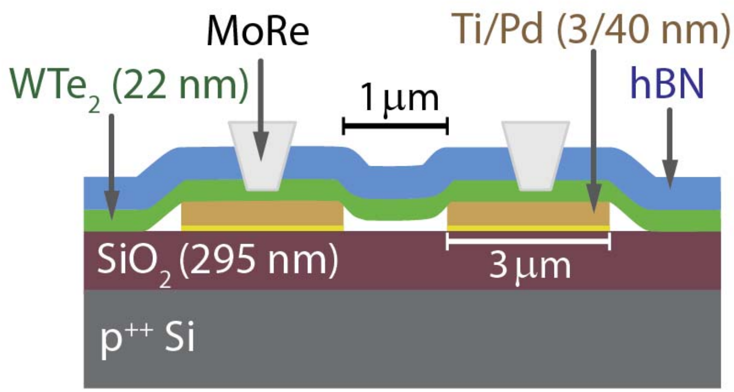
Robust **SQUID-like oscillations** of $I_c(B_\perp)$ highlight presence of extremely narrow edge states

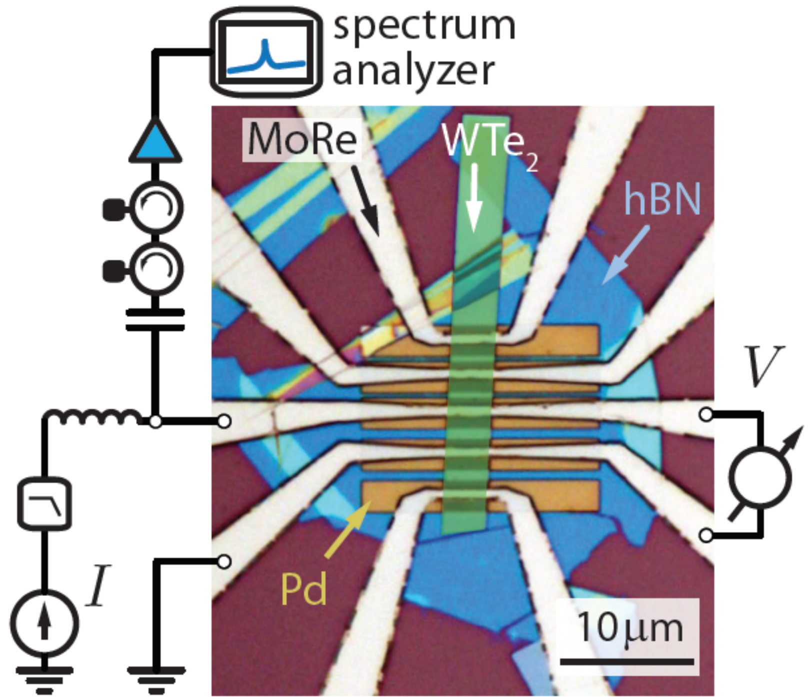




experiments:
Kononov *et al*., Nano Letters **20**, 4228 (2020)
Y.-B. Choi et al., *Nat. Mater.* **19**, 974 (2020)
C. Huang et al., *Nat. Sc. Rev.* **7**, 1468 (2020)

Weyl SM junction: WTe_2

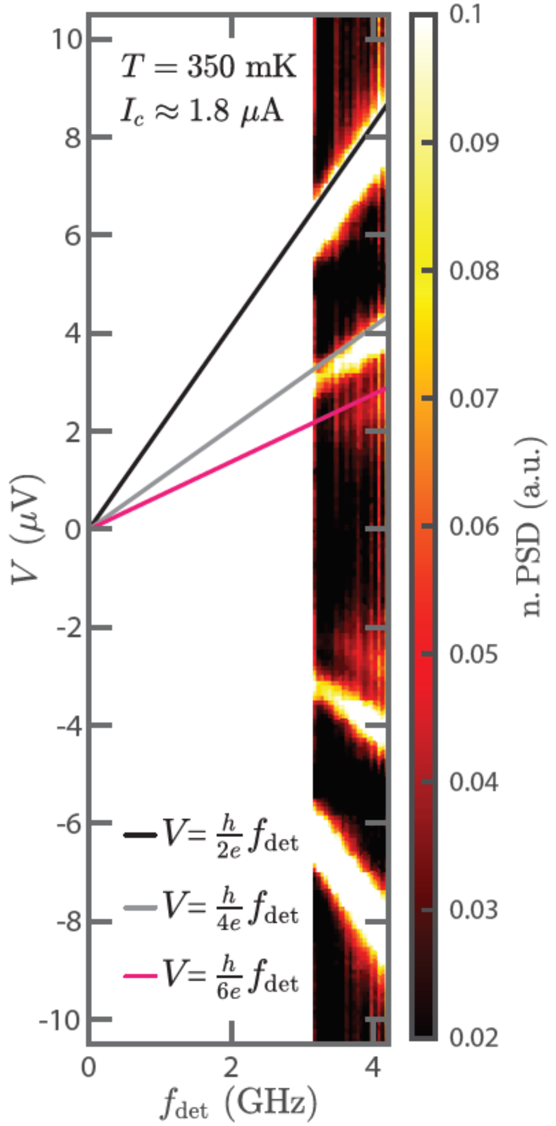


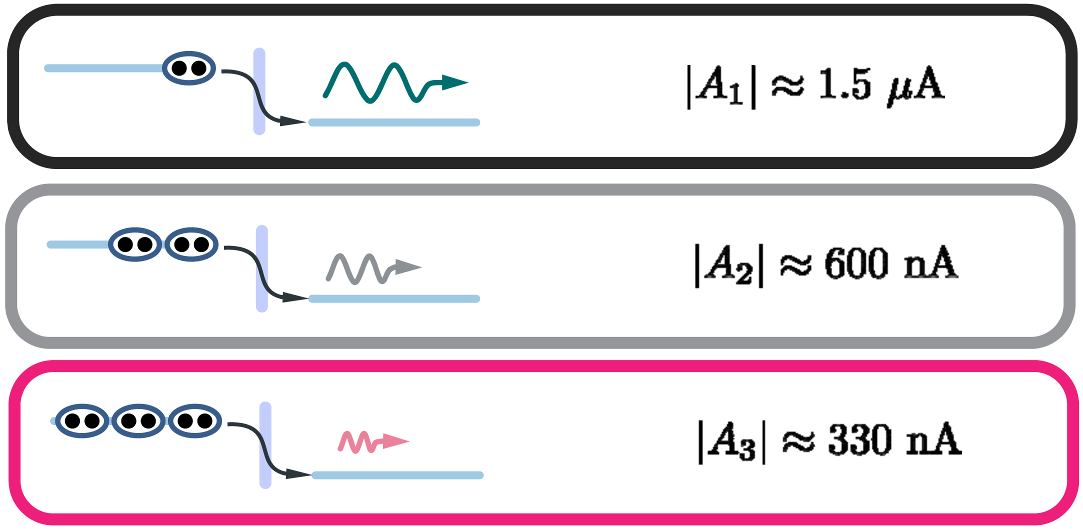


- Pd induced superconductivity   Kononov *et al*., Nano letters **20**, 4228 (2020)
- hBN protection layer
- MoRe side contacts   Indolese *et al*., Nano letters **20**, 7129 (2020)

by Artem Kononov et al. in collaboration with D. Mandrus group (Univ. of Tennessee)

Weyl SM junction: WTe_2





Strongly non-sinusoidal current-phase relation

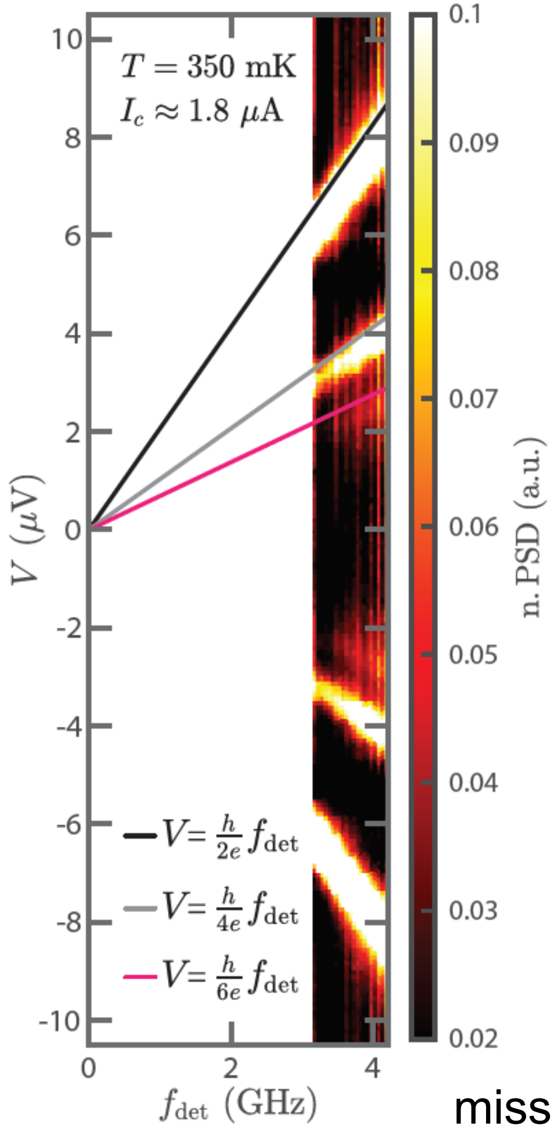
$$|A_2/A_1| \approx 0.4 \quad |A_3/A_1| \approx 0.22$$

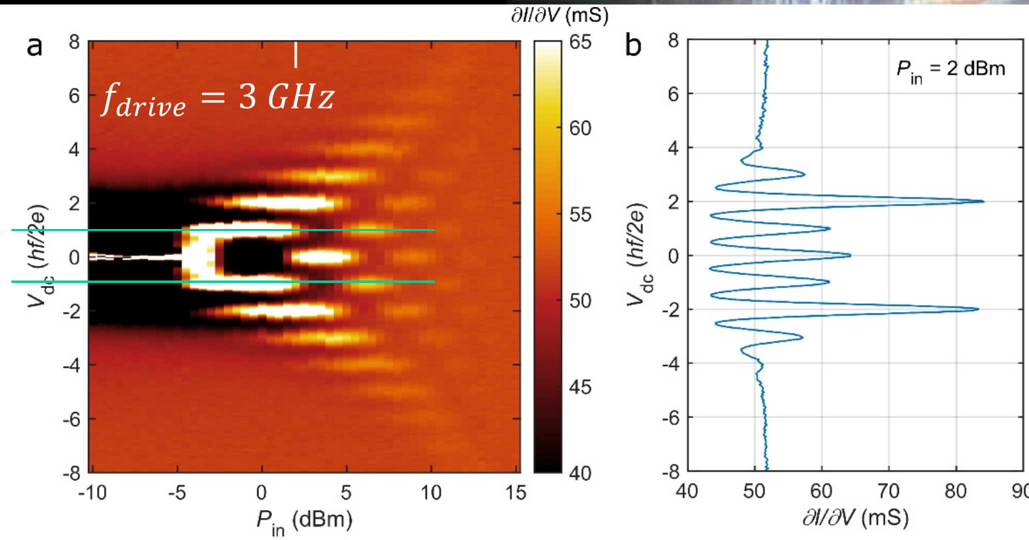
(close to the ballistic limit)

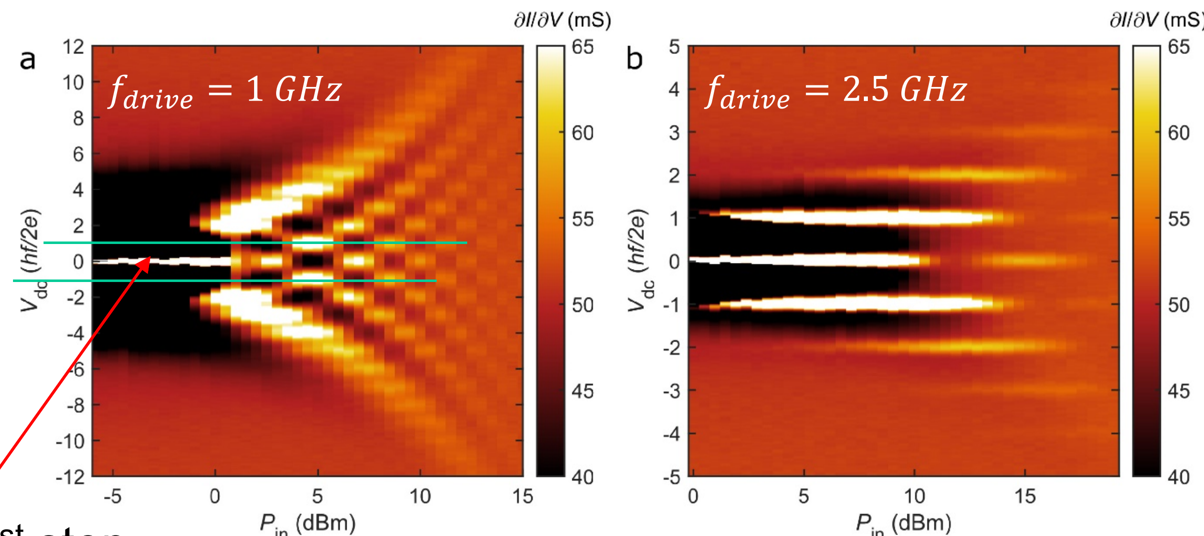
No signatures of topological superconductivity…

by ***Fabian Oppliger*** *(master student 2020) & Artem Kononov et al.*

Weyl SM junction: WTe_2







missing 1st step

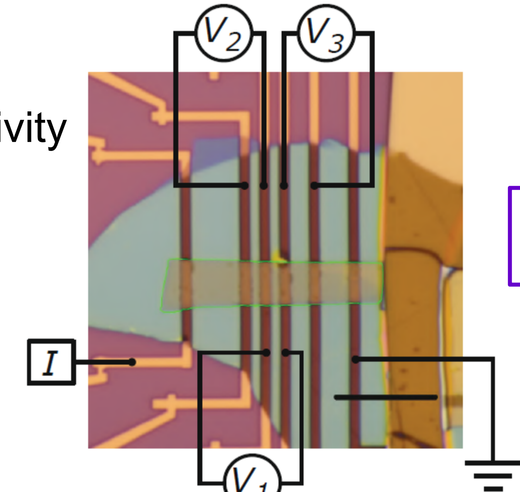
*by **Fabian Oppliger** (master student 2020) & Artem Kononov et al.*

WTe_2 “Fraunhofer effect”

theory: Z. Wang *et al.*, PRL **123**, 186401 (2019)

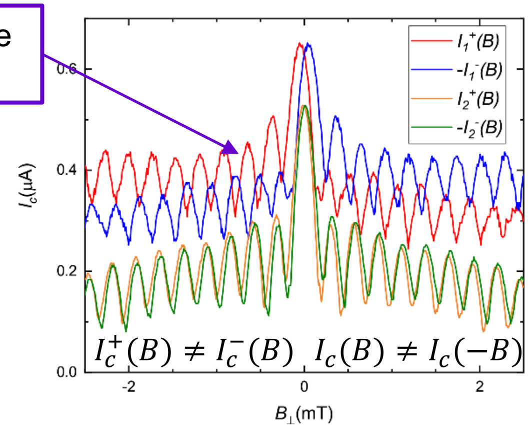
Pd induced superconductivity

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

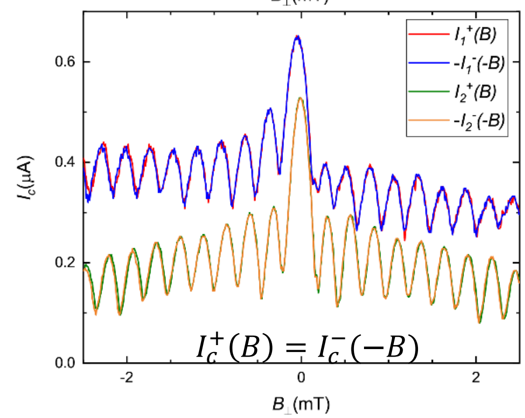


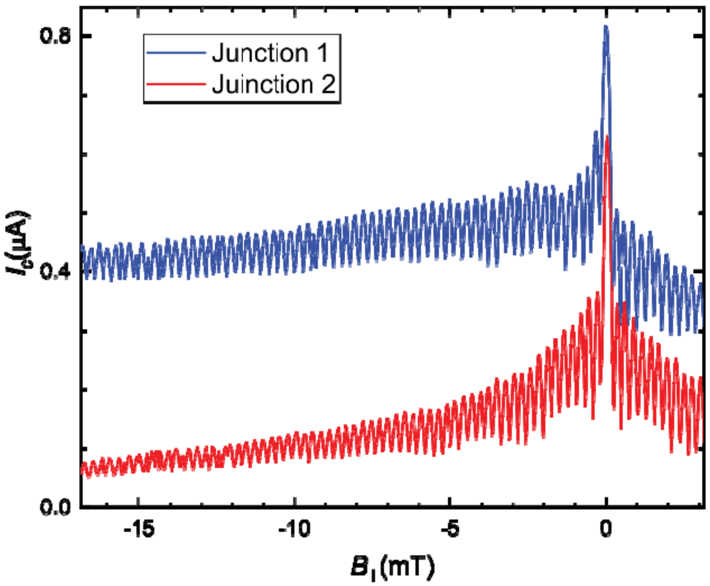
Asymmetric Josephson effect suggests non-sinusoidal CPR

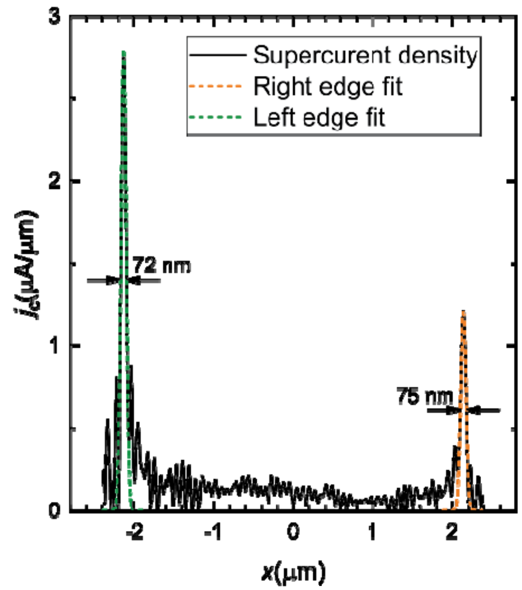
~50% “diode effect”



Robust **SQUID-like oscillations** of $I_c(B_\perp)$ highlight presence of extremely narrow edge states







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Y.-B. Choi et al., *Nat. Mater.* **19**, 974 (2020)
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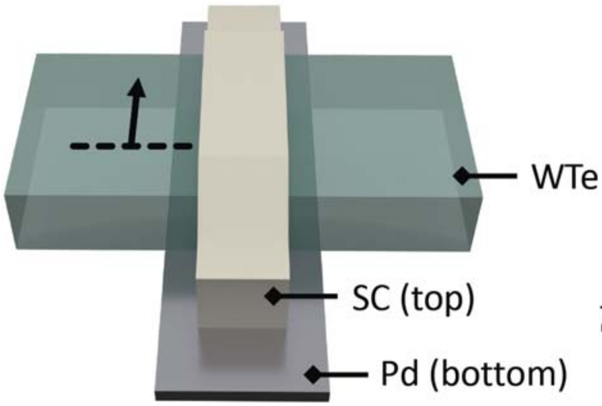
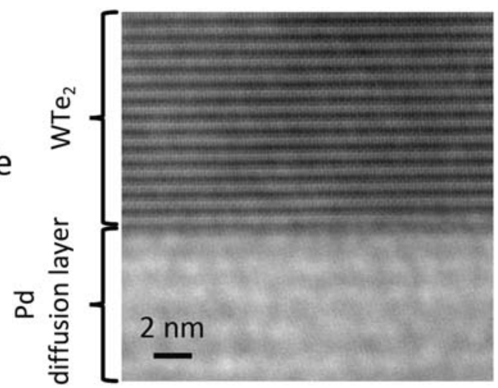
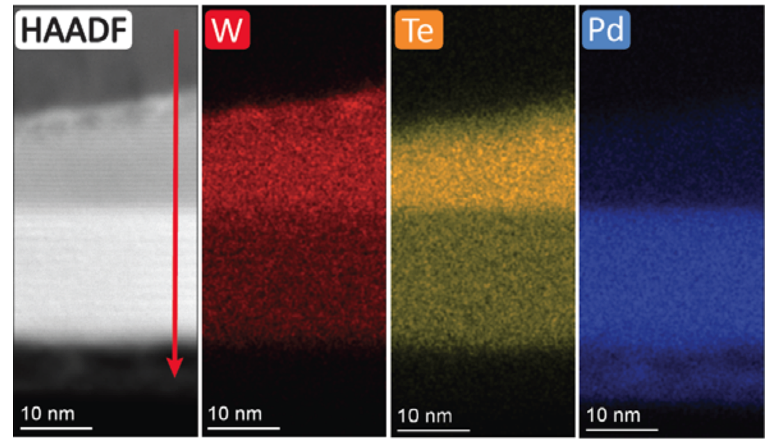
Origing of induced superconductivity

We investigated atomic structure with STEM/EDX

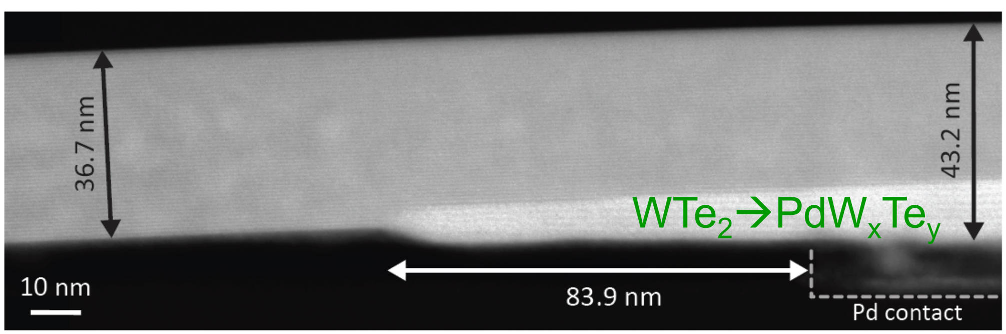


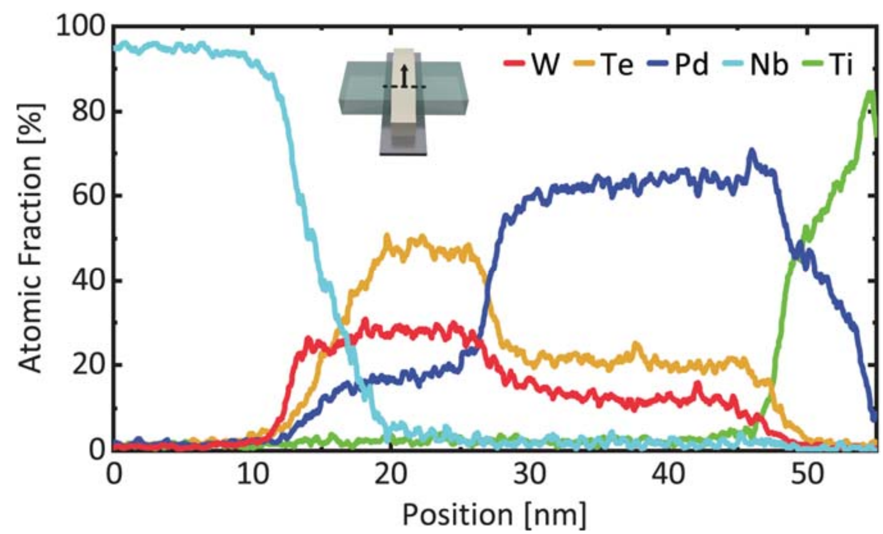
Sharp interface with WTe_2





New crystal structure formed near Pd contacts



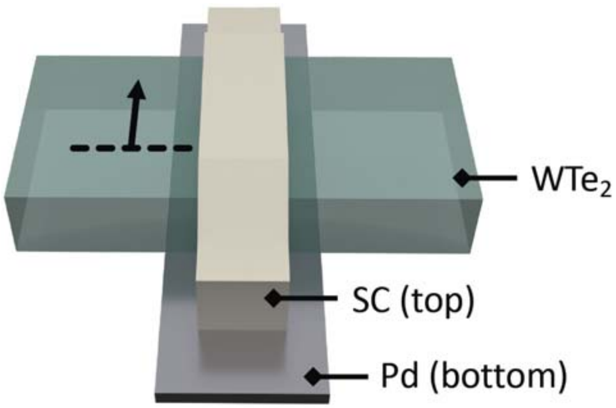


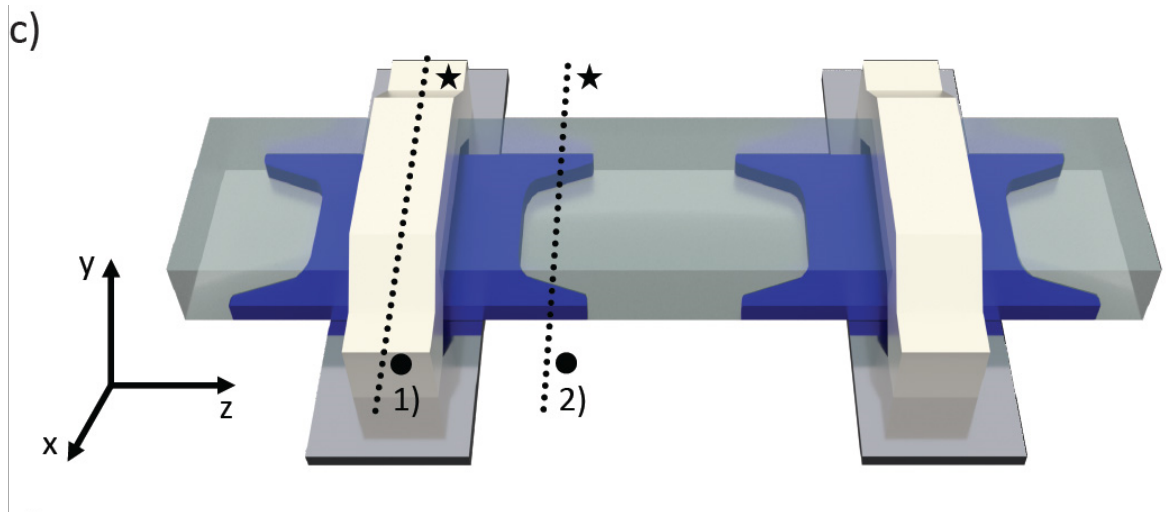
M. Endres et al., Transparent JJs in Higher-Order Topological Insulator WTe_2 via Pd Diffusion, Phys. Rev. Mat. **13**, L081201 (2022)

Origing of induced superconductivity

We investigated atomic structure with STEM/EDX

diffusion profile !





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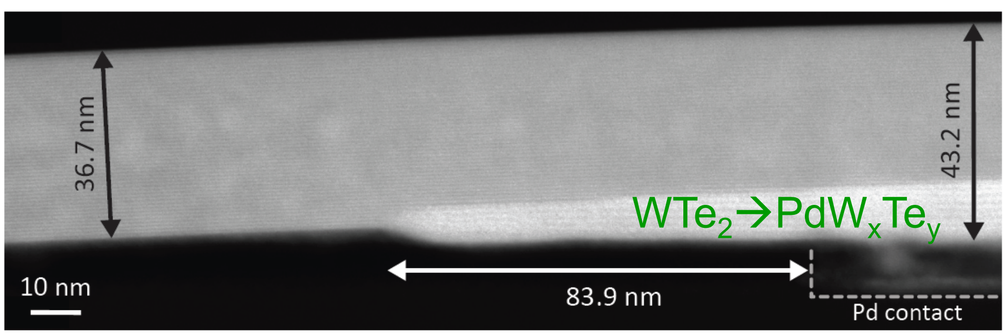
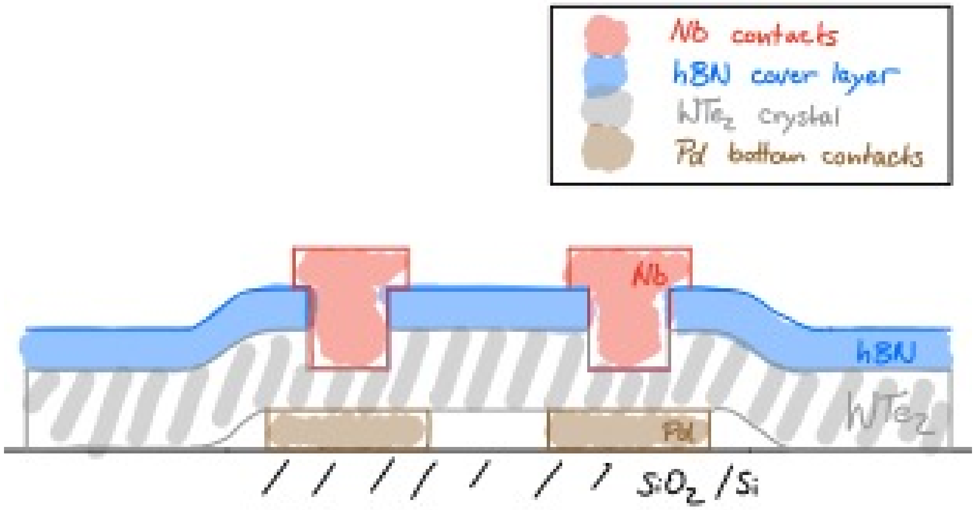
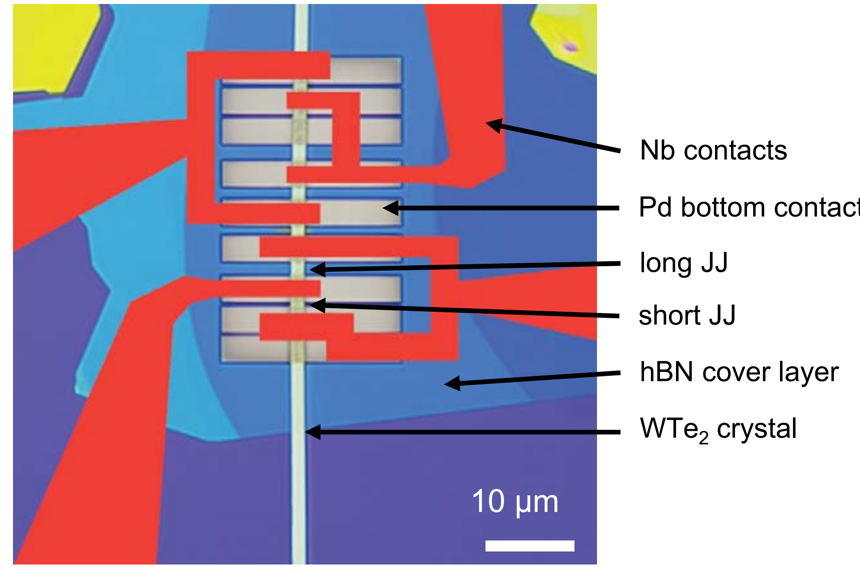


M. Endres et al., Transparent JJs in Higher-Order Topological Insulator WTe_2 via Pd Diffusion, Phys. Rev. Mat. **13**, L081201 (2022)

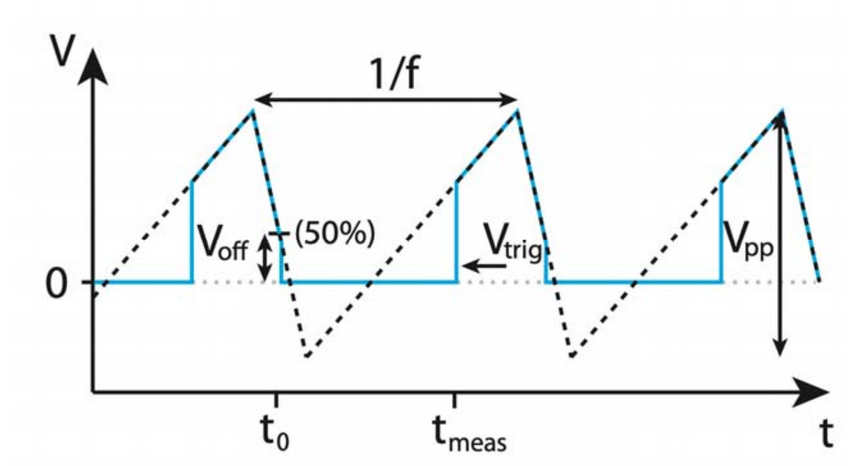
Asymmetric SQUID devices in WTe_2





Measurement of I_c with a counter

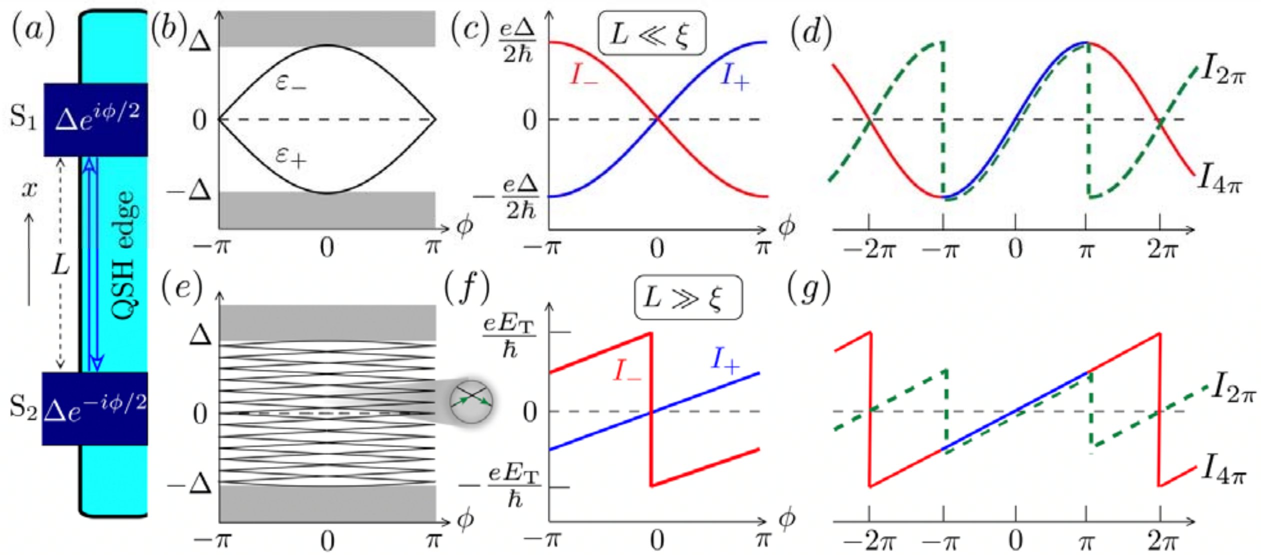
apply a current ramp and measure time when junction switches to the normal state, then repeat “over and over”



CPR of topological junctionn

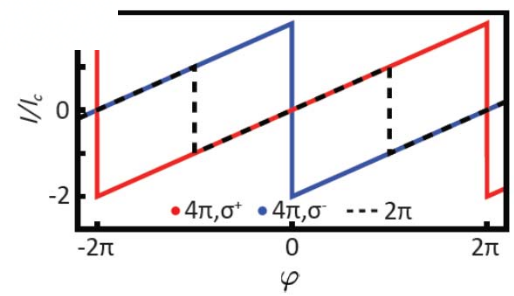
4π periodic SC in topological ballistic junction (with a helical edge)

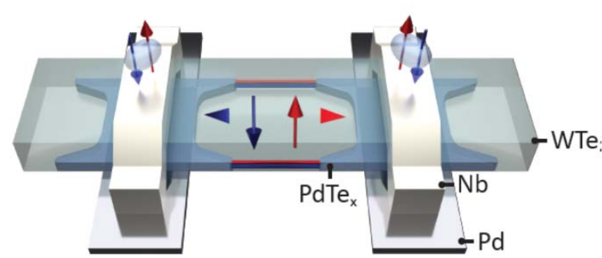
PRL **110,** 017003 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013



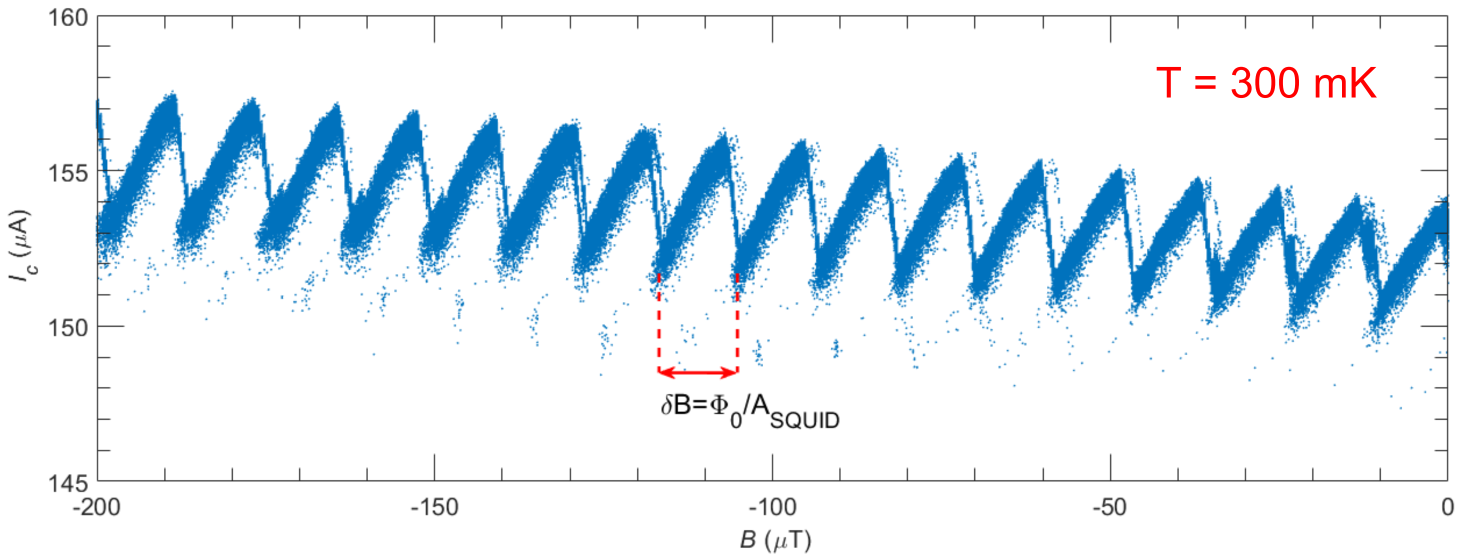
Beenakker et al., PRL 110 (2013)

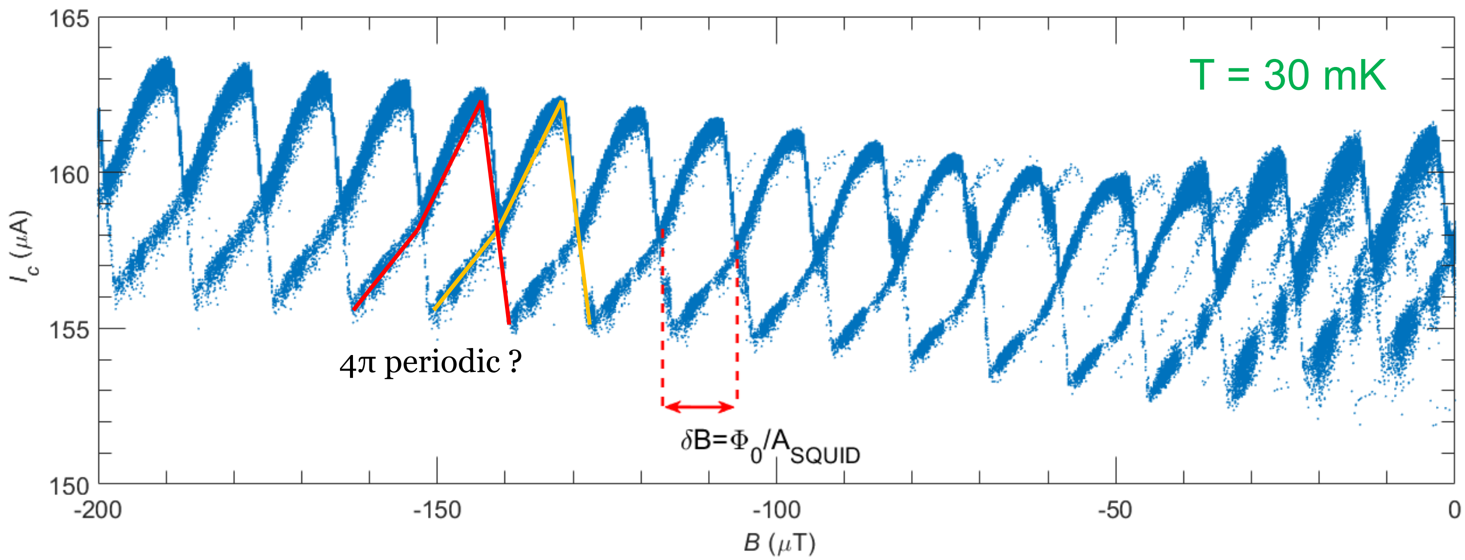
Fermion-Parity Anomaly of the Critical Supercurrent in the Quantum Spin-Hall Effect



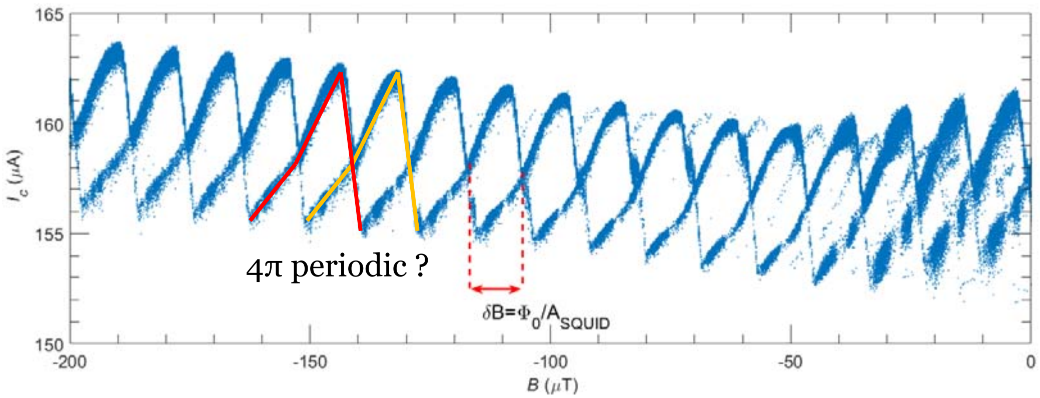


Interesting SQUID signals



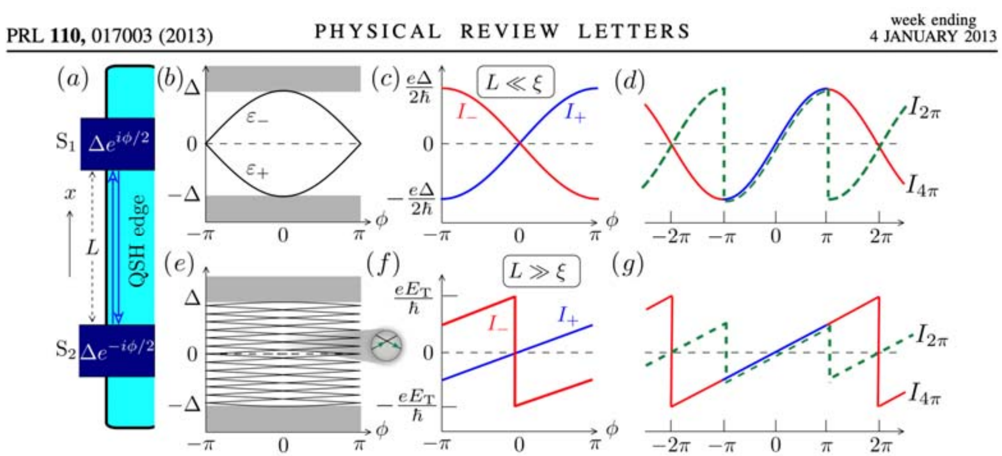


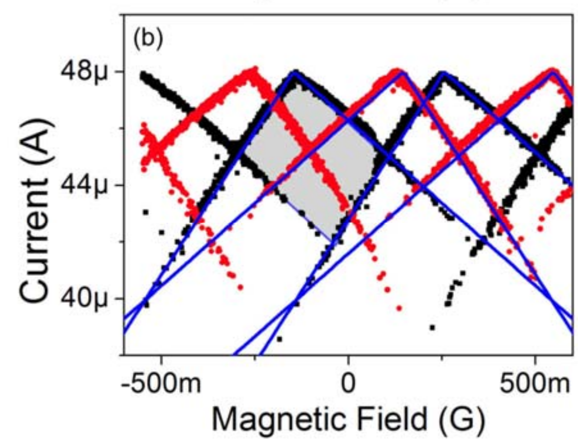
Interesting SQUID signals



Multivalued CPR, Little Parks diamonds

4π periodic SC in topological ballistic junction



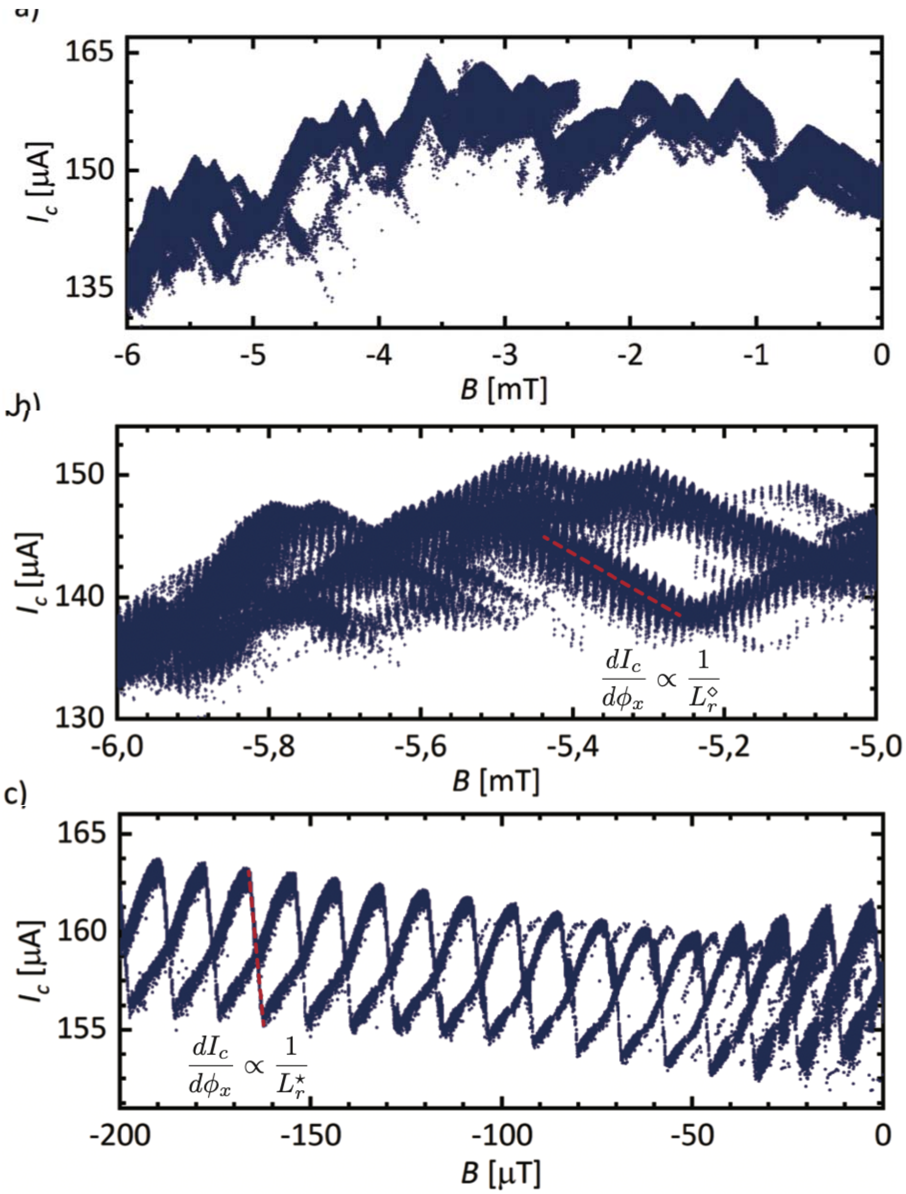


1) Doubled Amplitude
2) 4π periodicity

Murphy et al. , PRB 96, 2017

Beenakker et al., PRL 110 (2013)

Much larger flux range: multivalued !



Increasing magnetic field resolution

Long range behavior attributed to reference junction

Multivalued I_c resembling **inductance** dominated SQUID

Matching periodicity of SQUID oscillations:

$$\delta B = 11.6\ \mu\text{T}$$
$$\delta B = \Phi_0 / A_\circ = 11.1\ \mu\text{T}$$

Murphy et al., PRB 96 (2017)

Lefevre-Seguin et al., PRB 46 (1992)

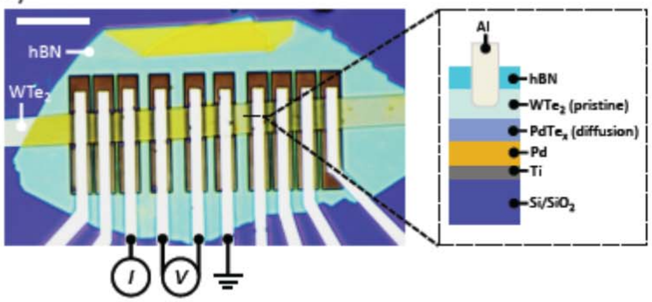
Friedrich et al., Appl. Phys. Lett. 104 (2014)

Hazra et al., Appl. Phys. Lett. 16 (2021)

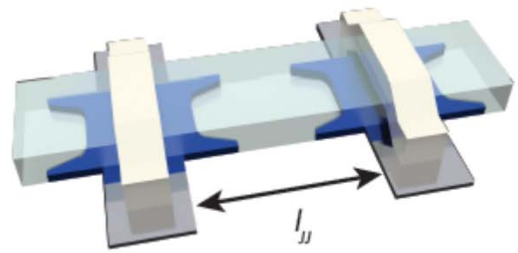
Dausy et al., Phys. Rev. Appl. (2021)

Single junction

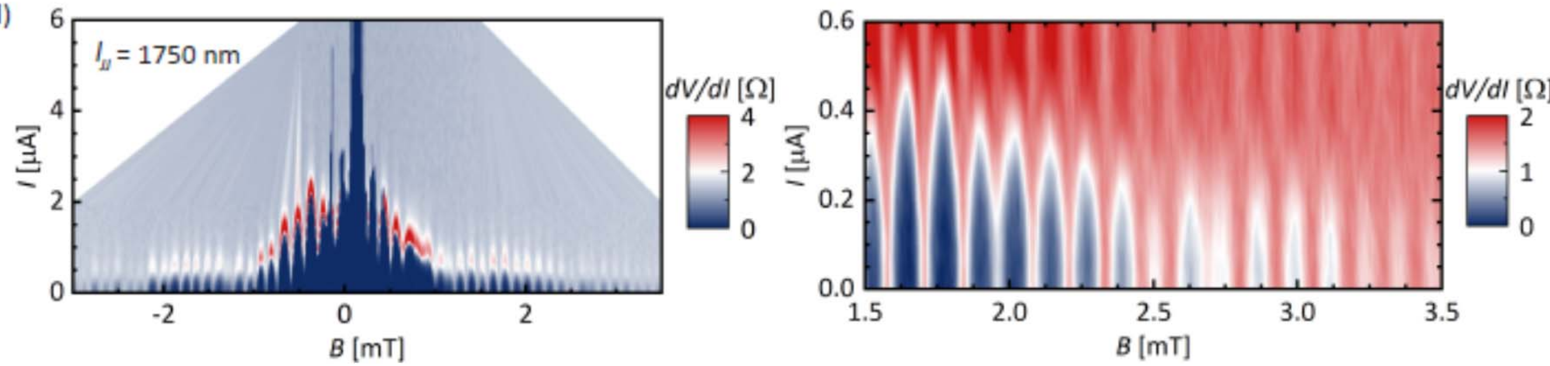
a)



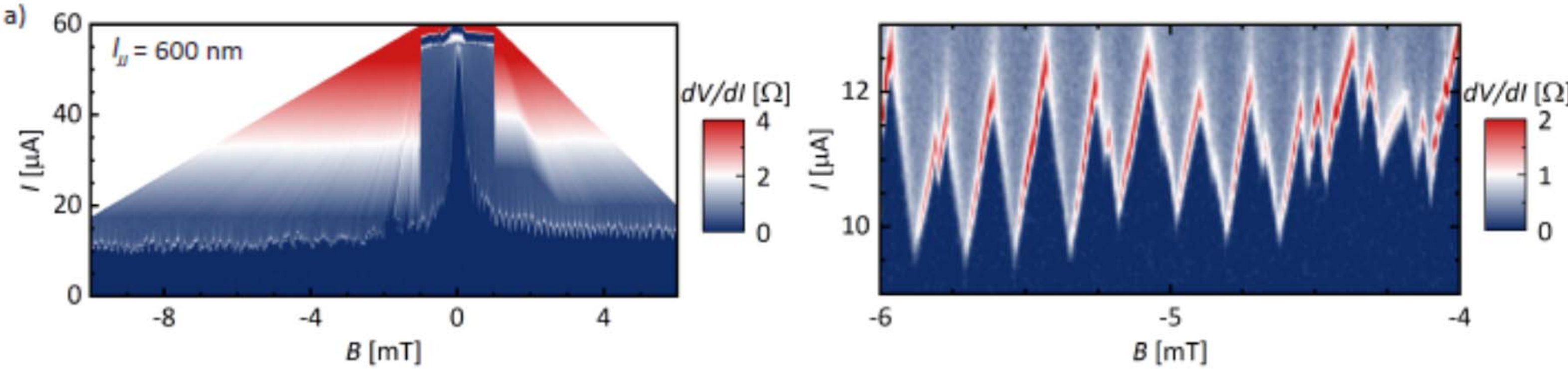
b)



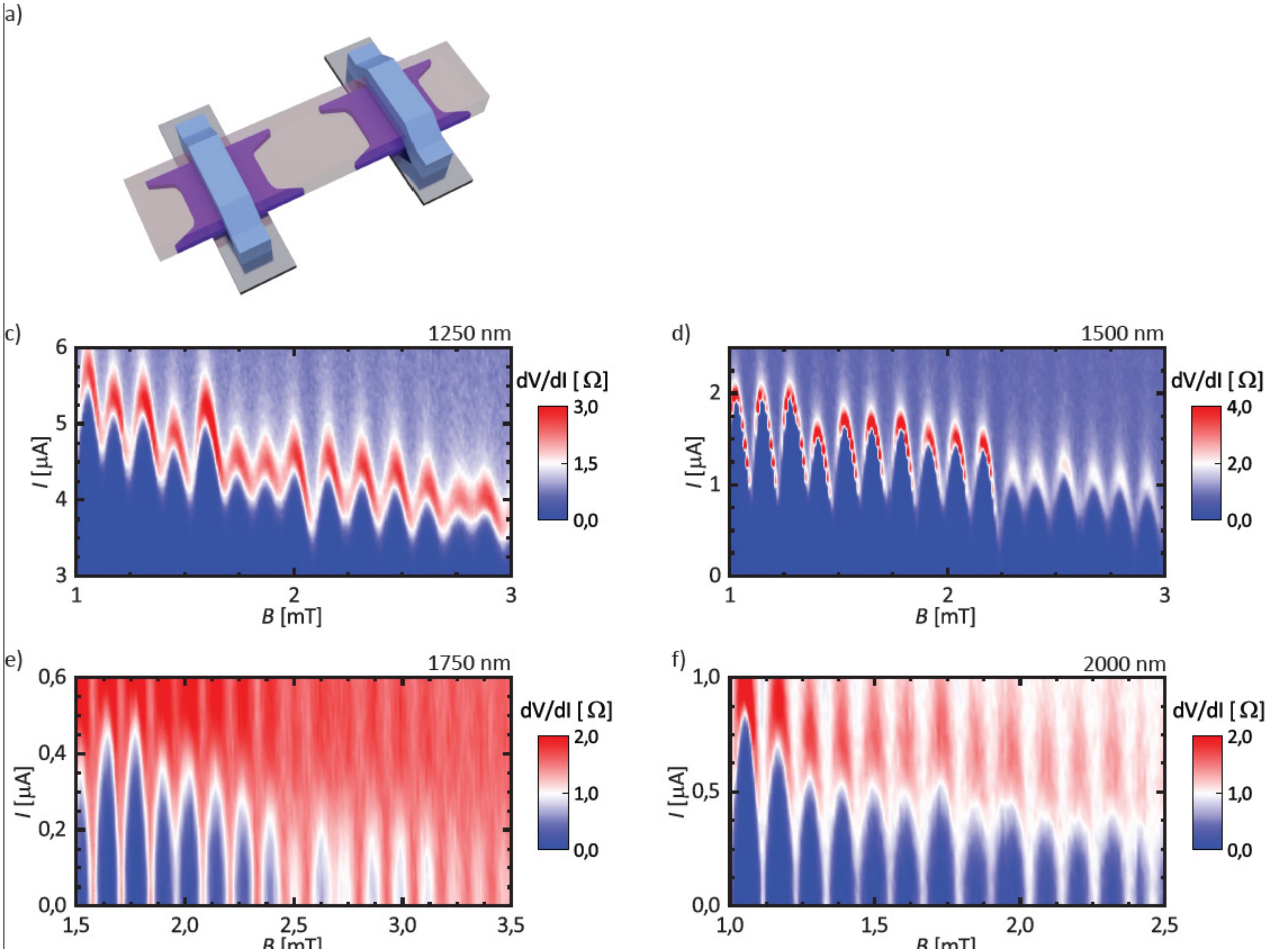
d)



a)



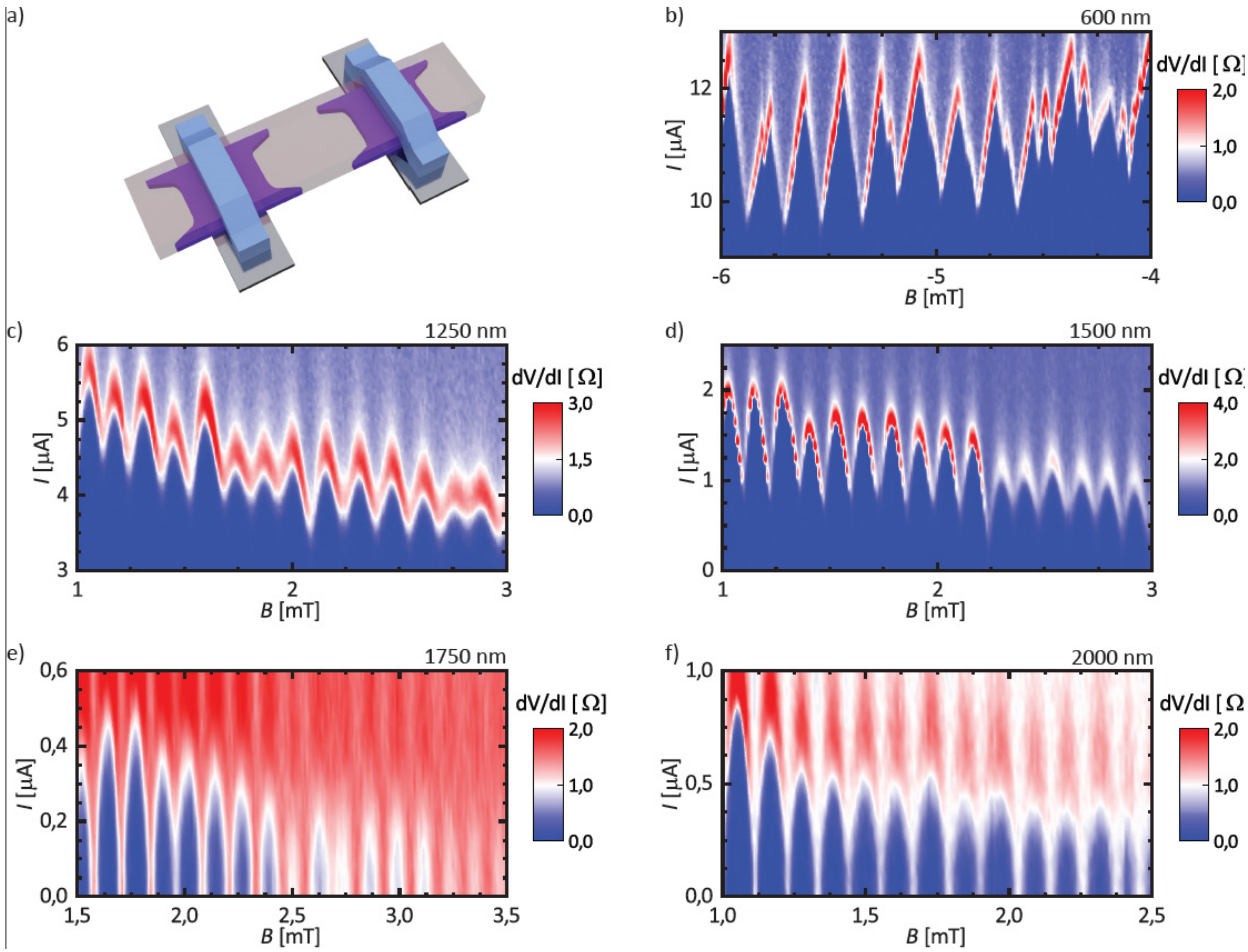
Single junction (also a sort of SQUID)



there is still a large super-current even for separations as large as $2\mu m$

M. Endres et al., Transparent JJs in Higher-Order Topological Insulator WTe_2 via Pd Diffusion, arXiv:2205.06542 (2022)

Single junction (also a sort of SQUID)



suggest a
S-**S**'-S weak link

there is still a large super-current even for separations as large as $2\mu m$

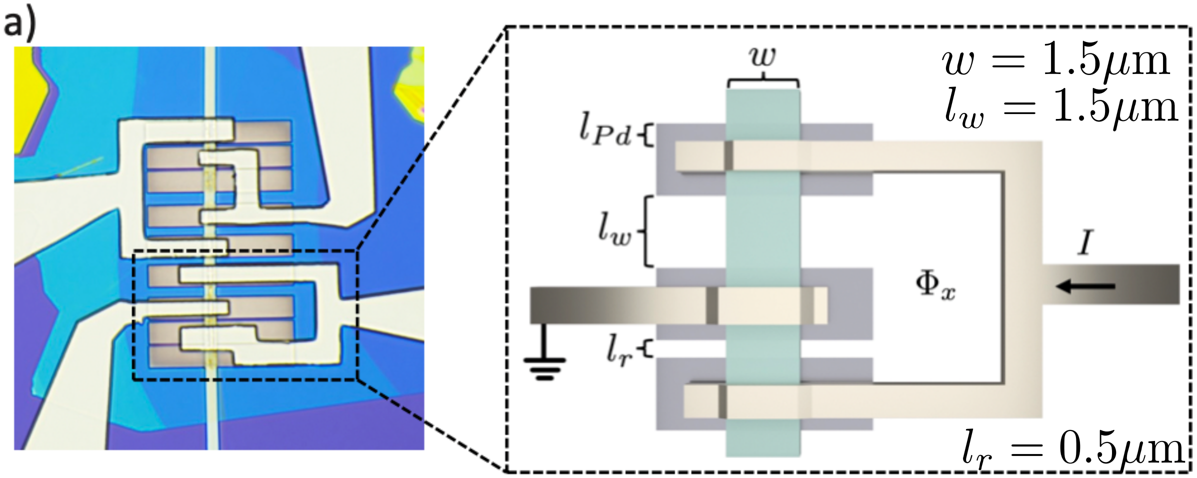
M. Endres et al., Transparent JJs in Higher-Order Topological Insulator WTe_2 via Pd Diffusion, arXiv:2205.06542 (2022)

CPR without loop inductance

Suggests that there is **inductance** likely produced by the PdTe alloy.

For large loop inductance, relation between applied **flux and phase** over the weak junction is **no longer single-valued**. Moreover, phase at reference junctions is not fixed at $\pi/2$!

a)



assumptions:

strong asymmetry:

$$I_c^r \gg I_c^w \longrightarrow \varphi_r = \varphi_r^{max}$$

no loop self inductance:

$$\varphi_w - \varphi_r = \phi_{tot} = 2\pi \frac{\Phi_{tot}}{\Phi_0}$$

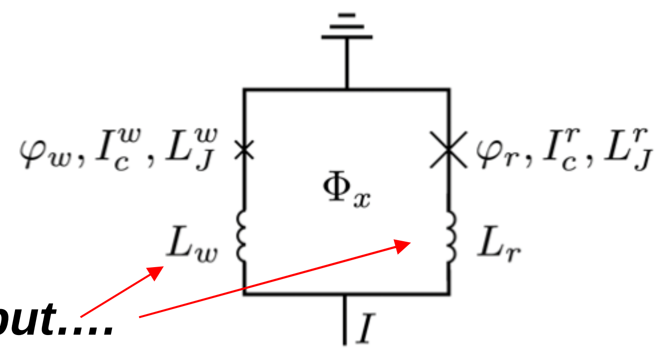
$$I_c = \underbrace{I_c^w f_w(\varphi_w)}_{I_w} + \underbrace{I_c^r f_r(\varphi_r)}_{I_r}$$

I_c^i critical current f_i normalized CPR

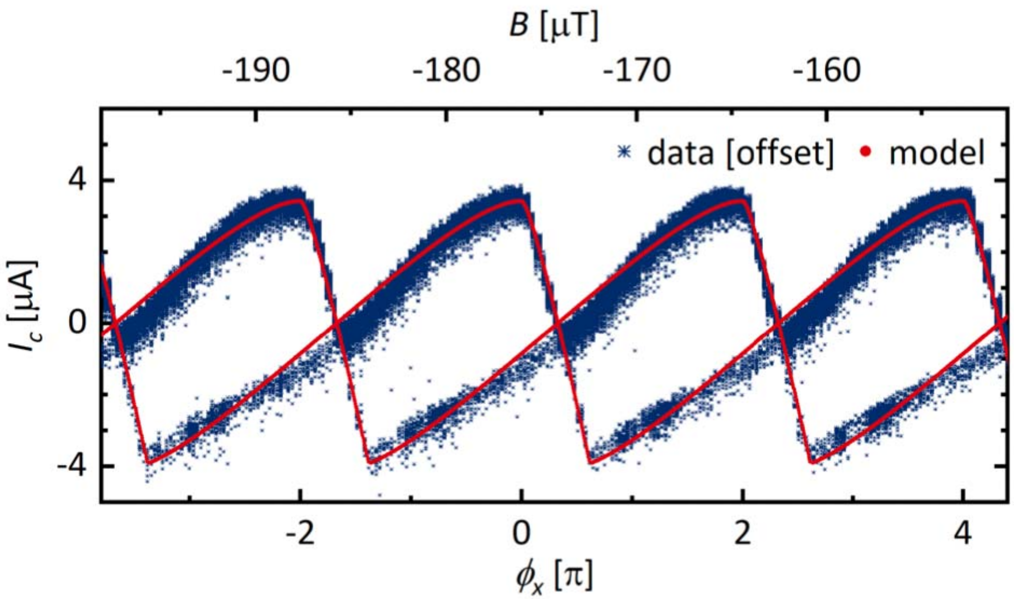
➡ CPR of the weak junction:

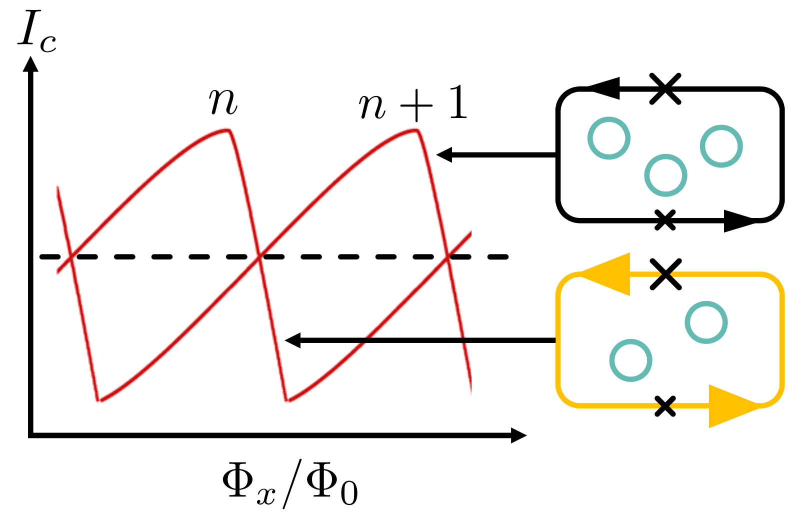
$$I_c(\phi_{tot}) \sim I_c^w f_w(\varphi_r^{max} + \phi_{tot}) + I_c^r f_r(\varphi_r^{max})$$

but….



CPR with loop inductance





Problem: inductance effects

Approch: CPR asumption

$$\phi_{tot} = \phi_x + \frac{2\pi(L_r I_r - L_w I_w)}{\Phi_0}$$

1) non-linearity in rising slope
2) Self-crossings

$$I_w(\varphi_w) = I_c^w \frac{sin(\varphi_w)}{\sqrt{1 - sin^2(\varphi_w/2)}}$$

one can show that a crossing in $I_c(\phi_x)$ implies that the reference phase jumps

CPR with loop inductance

1) Maximize $I_c(\phi_{tot}) = I_r(\varphi_r(\phi_{tot})) + I_w(\varphi_r(\phi_{tot}) + \phi_{tot})$ with respect to $\varphi_r(\phi_{tot})$

2) Extract the inductance effects $\phi_x = \phi_{tot} - 2\pi(L_r I_r - L_w I_w)/\Phi_0$

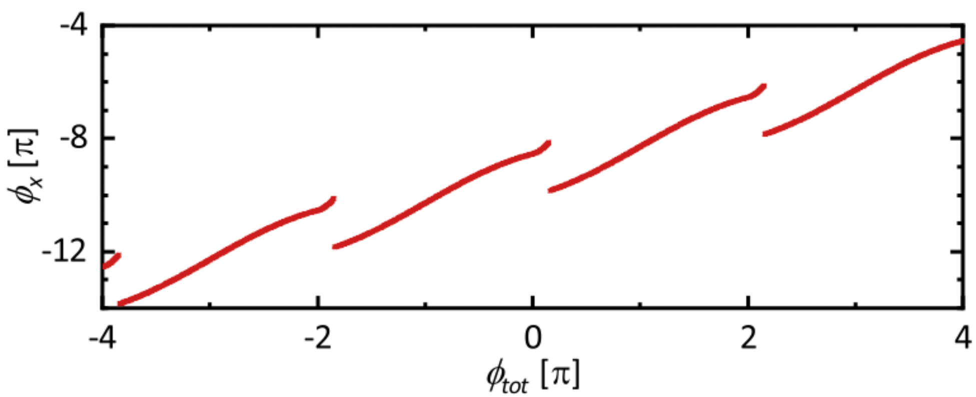
3) Plot $I_c(\phi_x)$

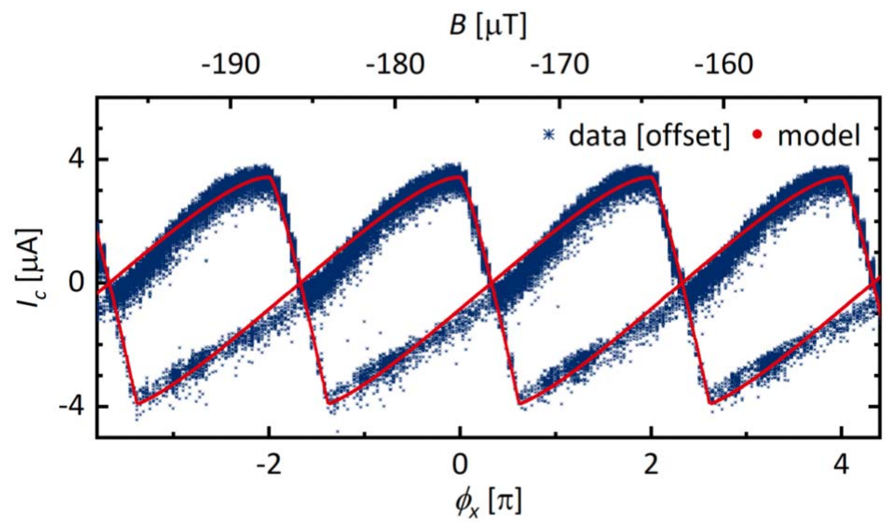
From the fit:

$L_r = 60\,pH$

$L_w = 220\,pH$

Exceeds $L_{geo} \approx 27\mathrm{pH}$ and $L_{kin} \approx 5.5\mathrm{pH}$

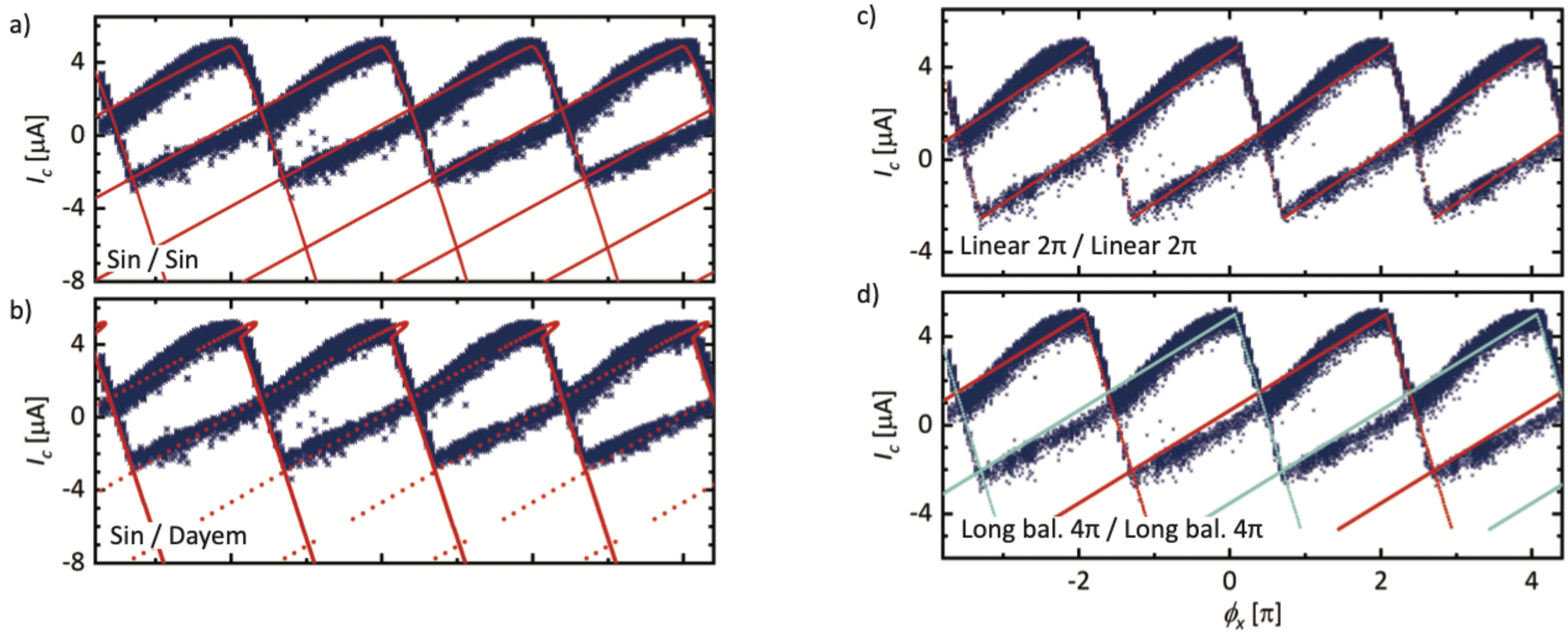




Shatz et al., PloS one 9 (2014)
Annunziata et al., Nanotechnology 21 (2010)

Inductance of the reference junction

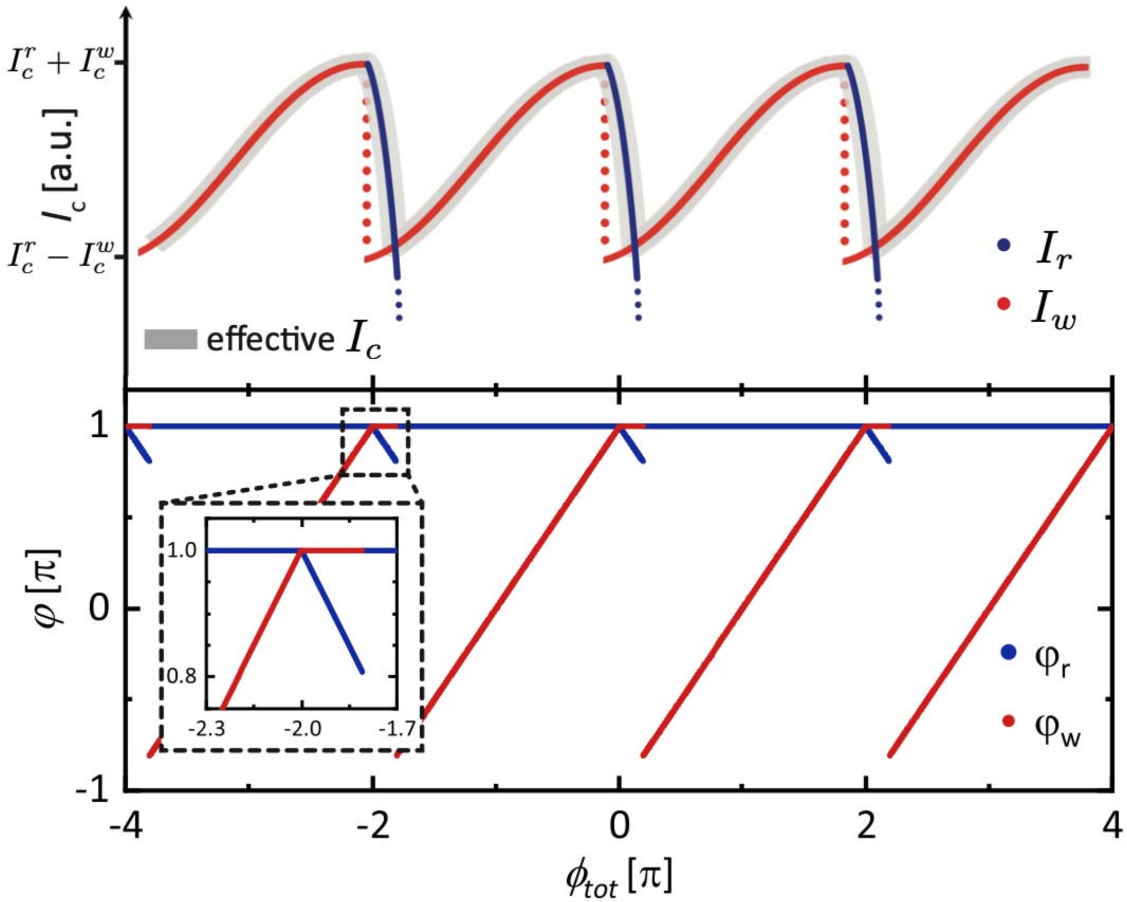
Comparison of fit models



f_w f_r	Sin(φ) Sin(φ)	Sin(φ) Dayem	Linear 2π Linear 2π	Long bal. 4π Long bal. 4π
I_c^w [µA]	60	10	3.8	5
L_w [pH]	450	400	200	80
I_c^r [µA]	104	154	160	160
L_r [pH]	270	-	80	80

graphical illustration

Visual apporach to maximize I_c



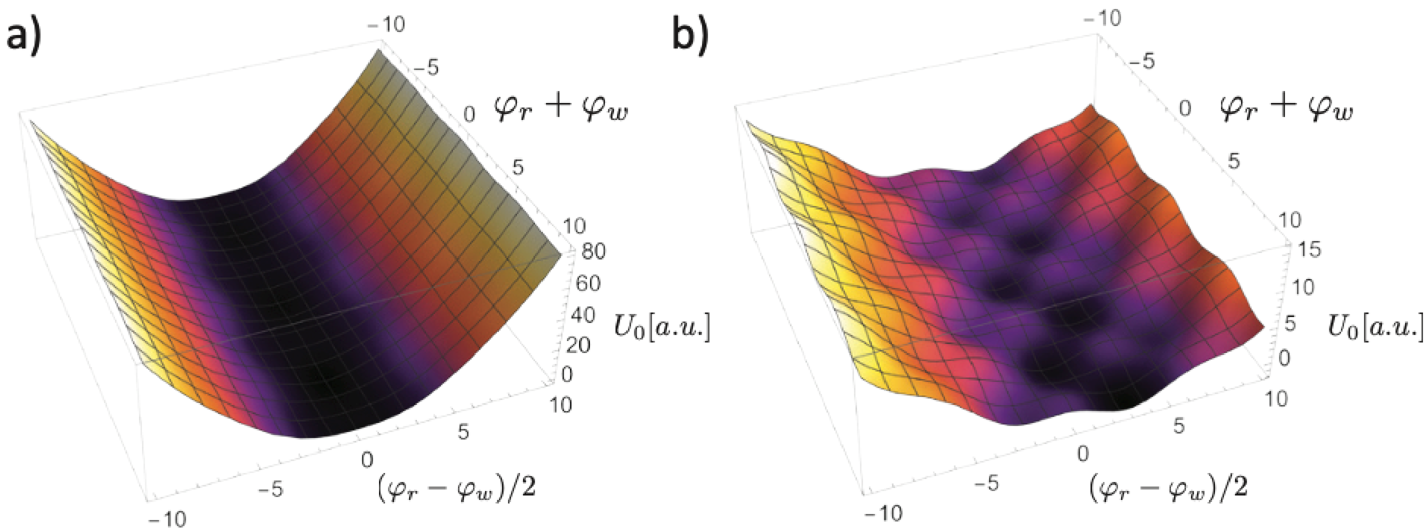
Goal: maximize I_c

$$\varphi_r - \varphi_w = \phi_{tot}$$

Both junction phases evolve in total flux

I_c is composed out of I_w and I_r

Another approach to multivalued SQUID



$$U(x,y) = U_0\left[-\frac{I}{2I_0}x - cos(x)cos(y) - \alpha sin(x)sin(y) - \eta\frac{I}{2I_0}y + \beta(y - \frac{1}{2}\phi_x)^2\right]$$

$$x = \varphi_r + \varphi_w$$

$$y = (\varphi_r - \varphi_w)/2$$

$$\beta = \frac{\Phi_0}{2\pi L I_0}$$

$$I = \frac{V_{bias}}{R_{bias}}$$

$$\alpha = \frac{a-1}{a+1}$$

$$a = I_c^r / I_c^w$$

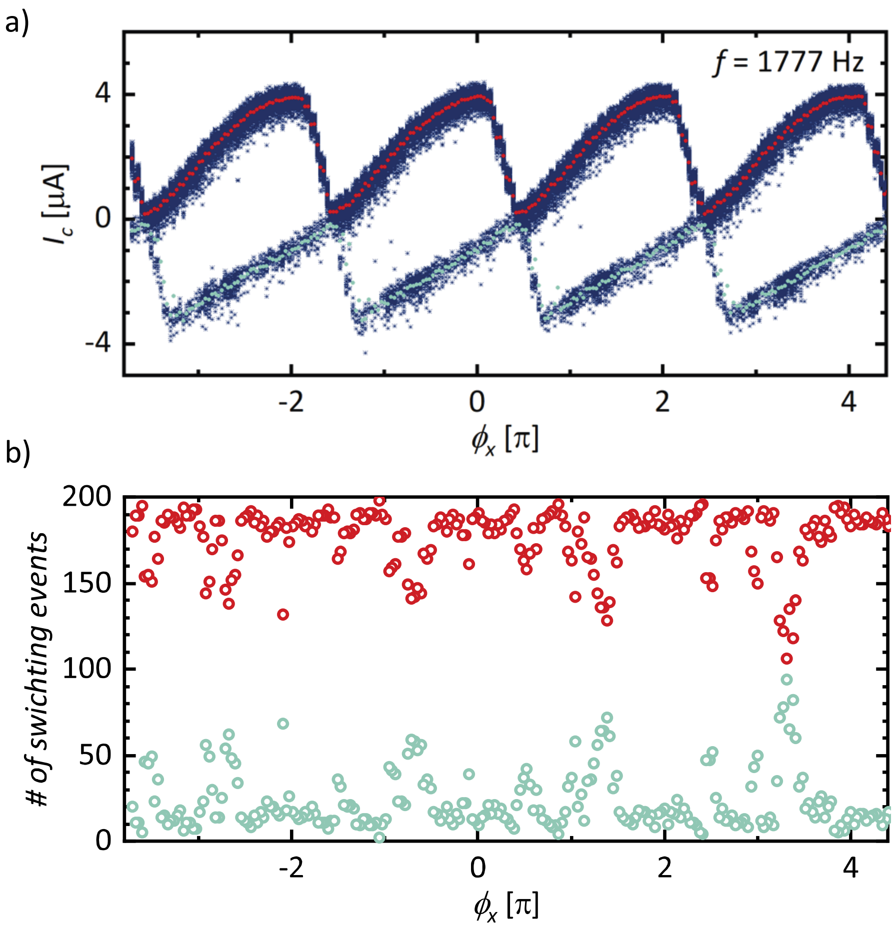
$$I_c^r = I_0(1+\alpha)$$

$$I_c^w = I_0(1-\alpha)$$

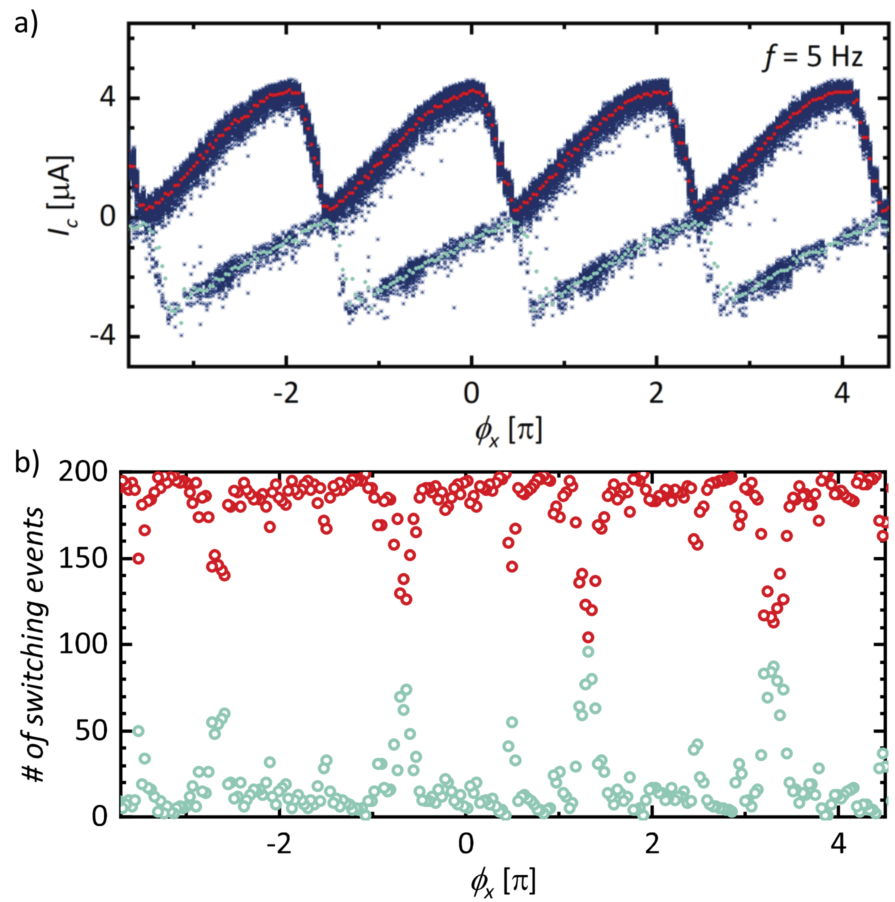
Lefevre-Seguin et al., PRB 46 (1992)

Another approach to multivalued SQUID

Occupation of vorticity states



$r \sim 0.128$



$r \sim 0.107$

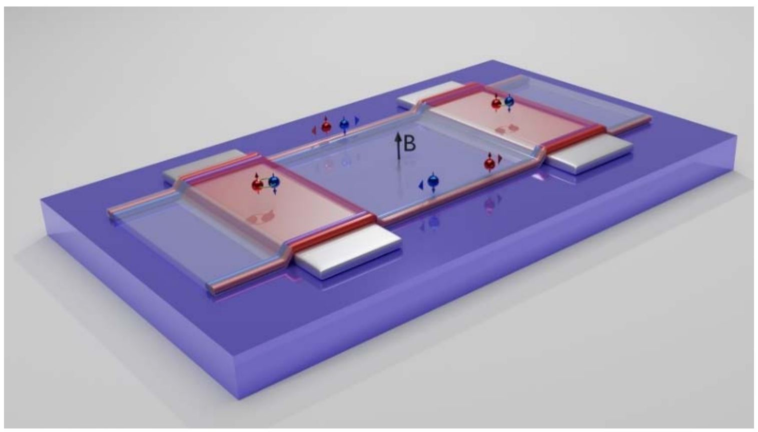
Conclusions

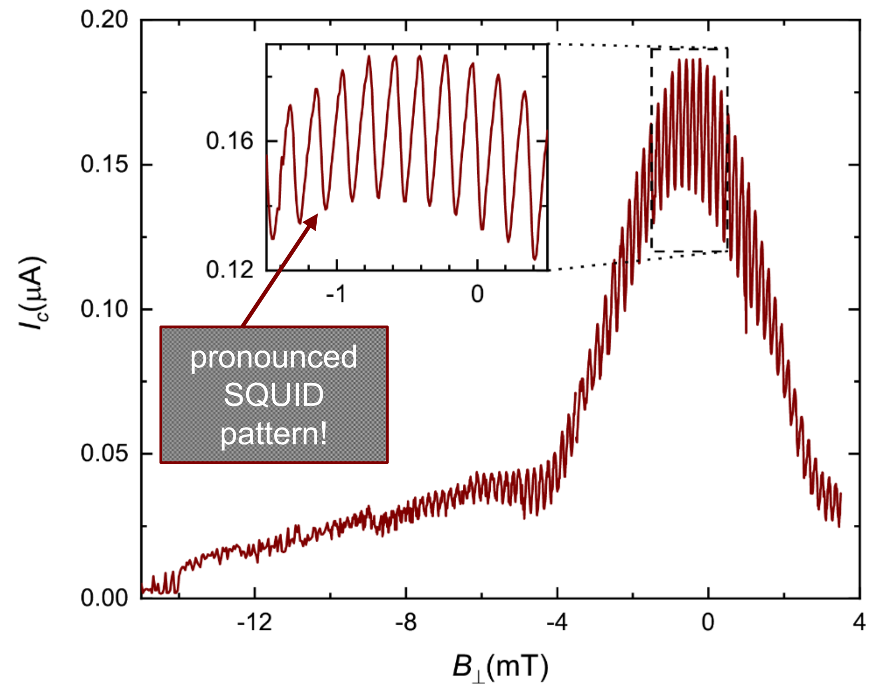
- **no sign** of 4π-periodic current-phase relation
- **no sign** of the fractional Josephson effect (AC Josephson current mediated by single electrons, not Cooper pairs)
- **supercurrent over 1.5μm** is still quite impressive

WTe_2 D. Mandrus et al. Univ. of Tennessee

Thank you
for your attention!

Christian Schönenberger, 14th Oct. 2022





A. Kononov et al. *One-dimensional edge transport in few-layer WTe_2,* Nano Letters 20, 4228–4233 (2020)
M. Endres et al. Transparent Josephson Junctions in Higher-Order Topological Insulator WTe2 via Pd Diffusion, Phys. Rev. Mat. 6, L081201 (2022)(2022)

End of Lecture II
(maybe add results from Orsay – Bouchiat's group)