Search for the Fractional Josephson Effect in Topological and Nontopological Materials

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Korea School on Mesoscopic Physics

May 2024 Christian Schönenberger
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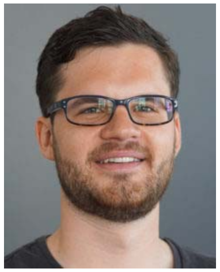
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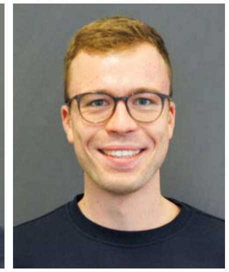
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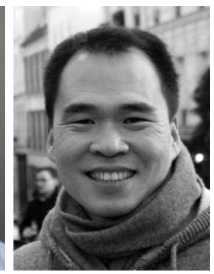
Christian Schönenberger


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QSIT Quantum Science and Technology
National Centre of Competence in Research

Swiss National Science Foundation

NCCR SPIN

SNI Swiss Nanoscience Institute
Eine Initiative der Universität Basel und des Kantons Aargau

AndQC

TOPSQUAD

QUANTERA
ERA-NET Cofund in Quantum Technologies

Georg H. Endress Postdoc Cluster

InAs nanowires:
Jesper Nygard et al.
University of Copenhagen, Denmark

WTe_2 growth:
David Mandrus' group
Materials Science and Engineering, The University of Tennessee

HgTe device:
provided by Dieter Weiss' group University of Regensburg, Germany

InAs heterostructure growth:
Mike Manfra's group
Purdue University and Microsoft Quantum@ Purdue

Cd3As2
Minkyung Jung et al.
DGIST, Daegu Gyeongbuk, Institute of Scienc & technology, Korea

hBN growth:
Kenji Watanabe, Takashi Taniguchi
Advanced Materials Laboratory, National Institute for Materials Science, Japan

Introduction to the Fractional Josephson Effect

Introduction to Topological SC

A Short Introduction to Topological Superconductors

--- A Glimpse of Topological Phases of Matter

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Dec. 09, 2015 @ Superconductivity Course, ETH 1

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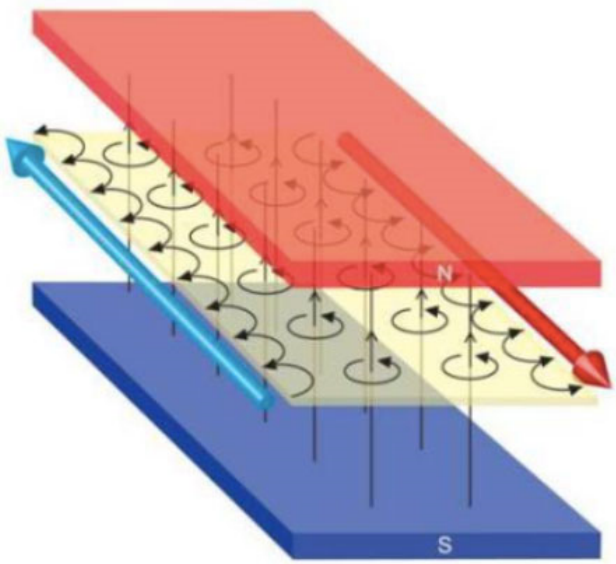
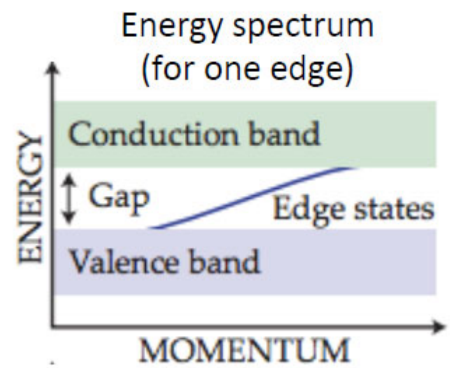
Quantum Hall Effect: chiral gapless edge states

Halperin, 1982

Chiral edge state
(skipping orbit picture)

Gapless excitations at the edges



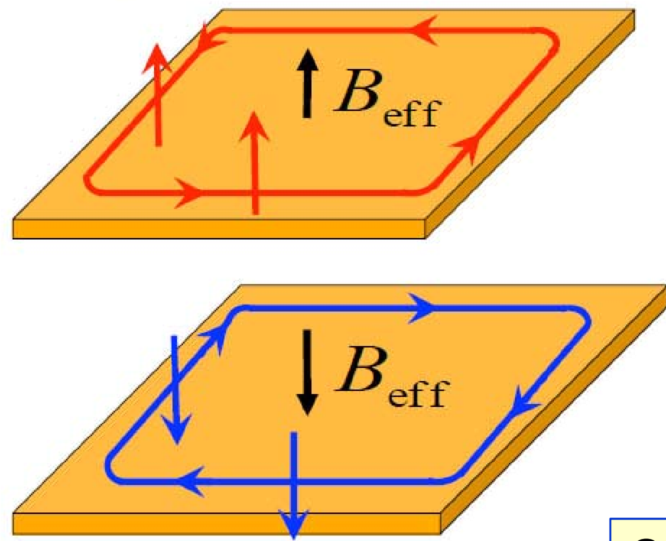


- **Quantum Hall** state is a **topological insulator (TI)**, where the bulk is gapped due to Landau quantization.
- Typical for TI's are compressible (conducting) **edge modes** (in this case, chiral modes). This is also known under the term **"bulk-boundary correspondence"**
- If time-reversal symmetry is maintained, there are further classes of TI, e.g. the **Quantum Spin Hall insulator**

2005: Quantum Spin Hall Effect/Z_2 topological insulator

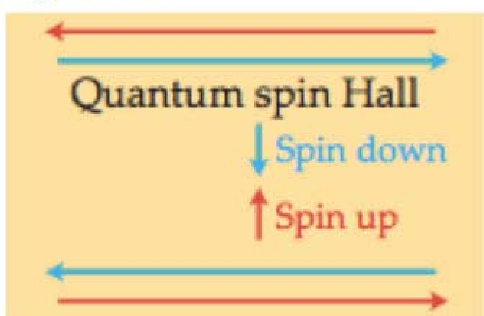
- QSH = two copies of QH states, one for each spin component, each seeing the opposite magnetic field.
- Time reversal symmetric, and can exist without any external magnetic field.
- Effective magnetic field: Spin-orbital coupling

$$H_{so} = \lambda_{so}\vec{\sigma}(\vec{p}\times\vec{E})$$

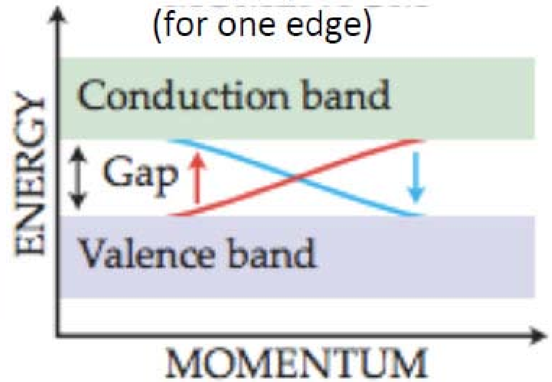


Bernevig and Zhang, 2006

helical edge states



Energy spectrum (for one edge)

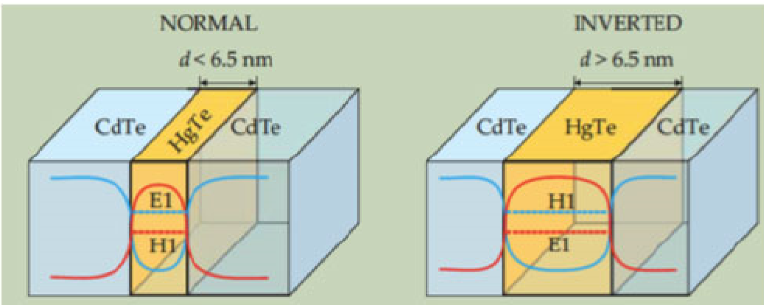


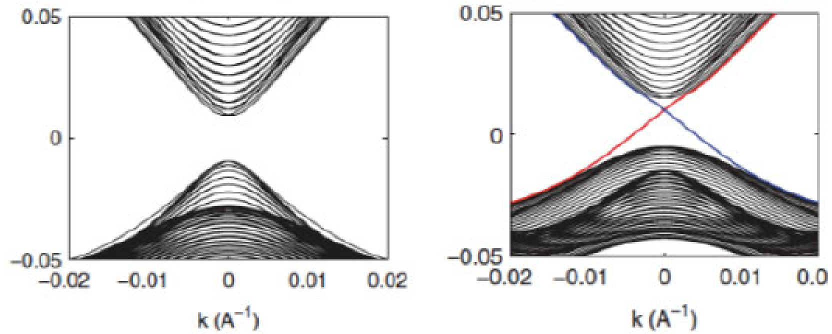
Quantum Spin Hall insulator maintain T-symmetry leading to helical edge states

Introduction to Topological SC

Experimental observation of HgTe TI

- **Theoretically predicted in 2006** Bernevig, Hughes, and Zhang, Science, 2006

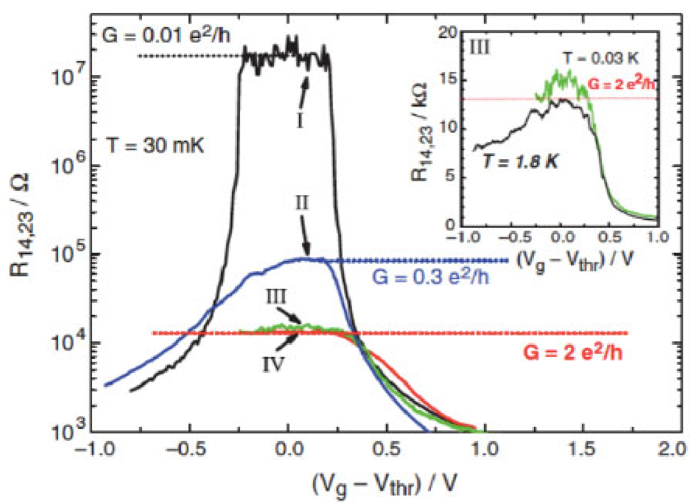


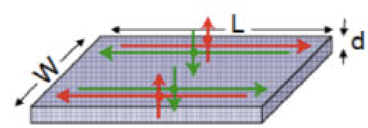


- **Experimentally found in Nov. 2007** Konig et al., Science, 2007

– Measure conductance while tuning E_F through the bulk energy gap

– edge state conductance $2e^2/h$ observed independent of W and L





I. d=5.5nm (normal) Insulating in gap

II-IV d=7.3nm (inverted) conducting in gap

II. L = 20 μm (> L_{in})

III. L = 1 μm W = 1 μm

IV. L = 1 μm W = .5 μm

Quantum Spin Hall insulator maintain T-symmetry leading to helical edge states

Introduction to Topological SC

New topological phases of matter

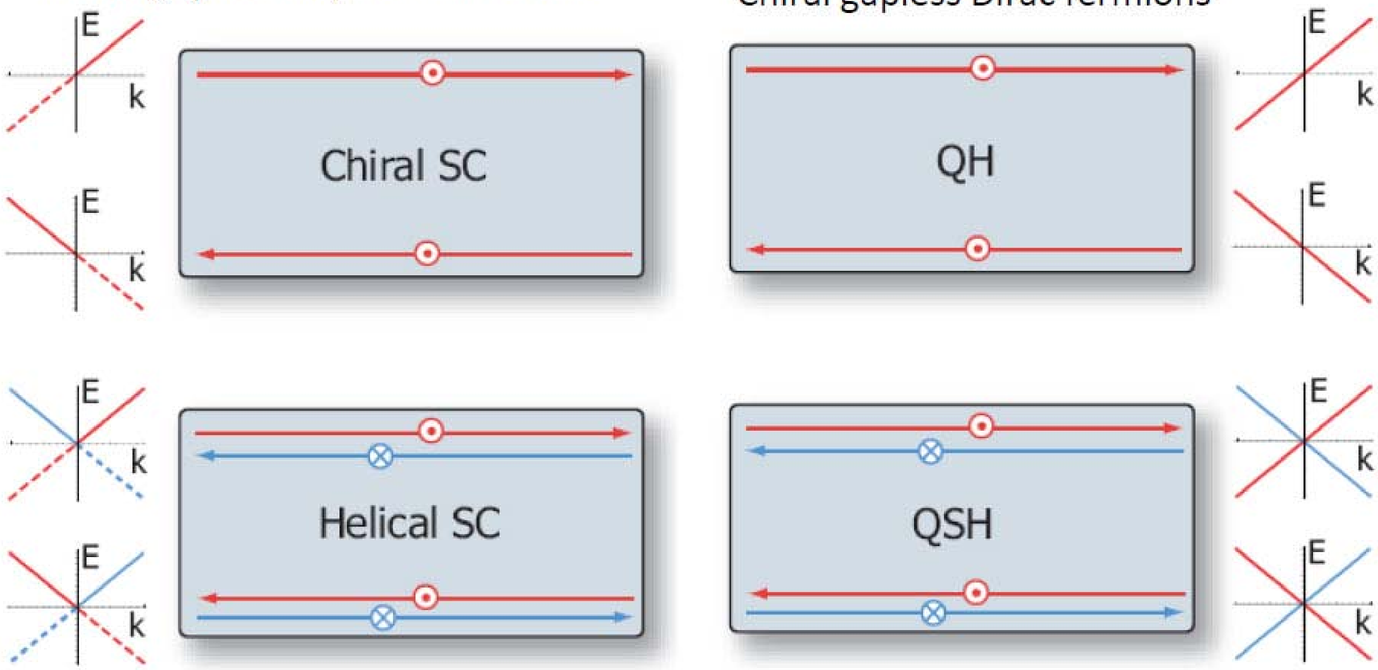
E. Majorana

chiral superconductor,
helical superconductor

quantum Hall insulator,
quantum spin Hall insulator

Chiral gapless Majorana fermions

Chiral gapless Dirac fermions



Helical gapless Majorana fermions

Helical gapless Dirac fermions

Majorana fermion:
particle = antiparticle

✧ Quasiparticle excitations in superconductors posses all the key attributes of Majorana fermions

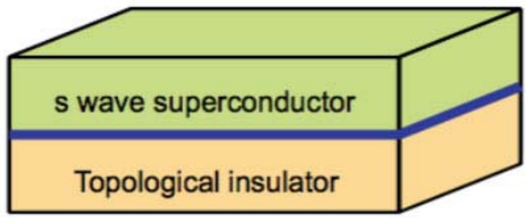
Introduction to Topological SC

Superconducting proximity effect

Minimal surface state model: $H_0 = \psi^\dagger(-iv\vec{\sigma}\cdot\vec{\nabla} - \mu)\psi$

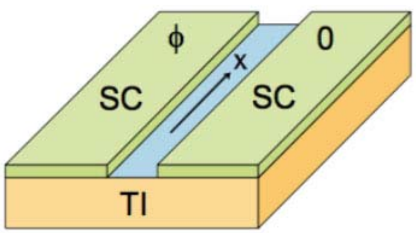
$$V_S = \Delta\psi_\uparrow^\dagger\psi_\downarrow^\dagger + \Delta^*\psi_\downarrow\psi_\uparrow$$

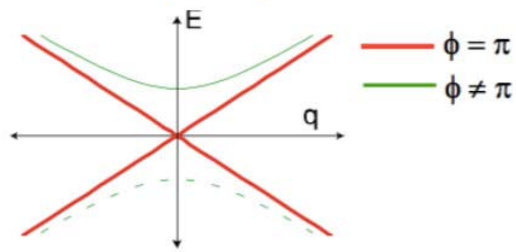
Fu & Kane, PRL, 08



localized **MBS** in e.g. cores of magnetic vortices

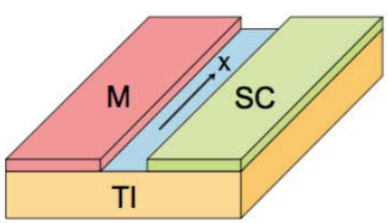
- 1D helical Majorana edge states at SC-TI-SC Josephson junction

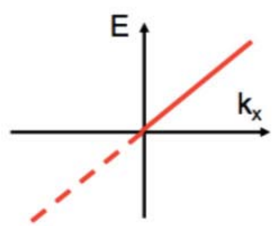


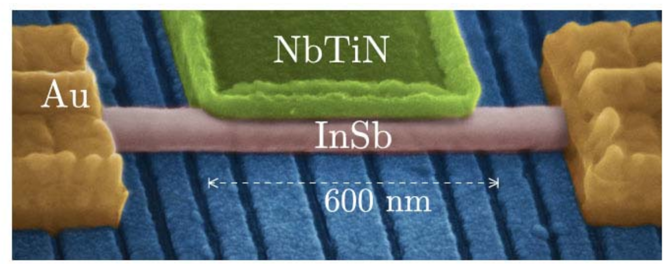


$$H = -i\hbar v_F\,(\gamma_L\partial_x\gamma_L - \gamma_R\partial_x\gamma_R) + i\Delta\cos(\phi/2)\gamma_L\gamma_R$$

- 1D chiral Majorana edge states at superconductor-magnet interfaces







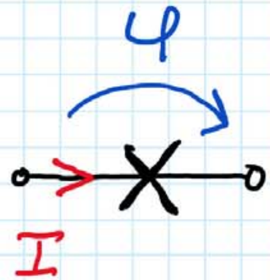
a device similar to Mourik et al. 2012 that started the “race” for Majorana fermions in 1d, topological qubits, and ...

What I will be focusing on

- We will discuss the physics (mostly experimental) of **Josephson junctions** (JJ) **realized with supposedly topological materials**
- The **fractional Josephson effect** could be a hint for the presence of MBS, and hence, topological superconductivity

Introduction (Josephson relations)

Symbol



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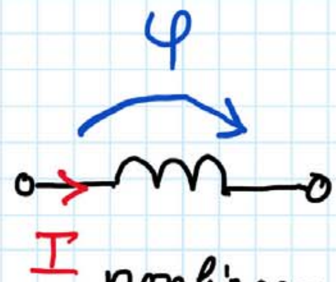


nonlinear inductor

φ = phase bias

I = supercurrent

} Current - Phase - Relation (CPR)

$$I = I(\varphi)$$

TRS : $I(-\varphi) = -I(\varphi)$ and $I(\varphi + 2\pi) = I(\varphi)$ implies

$$I(0) = 0 \quad \text{and} \quad I(\pi) = 0$$

1. Josephson relation : $\boxed{I(\varphi) = I_c \sin(\varphi)}$ sinusoidal CPR

2. Josephson relation : $\boxed{V(t) = \frac{\Phi_0}{2\pi} \frac{d\varphi}{dt}}$; $\Phi_0 = \frac{h}{2e}$

Introduction (Josephson relations)

work done to add current to inductor

$$W_{0\to 1} = \int_0^1 I(t)\, V(t)\, dt = \frac{\Phi_0}{2\pi} \int_0^{\varphi} I(\varphi)\, d\varphi \propto -\frac{\Phi_0}{2\pi} \cdot I_c \cos(\varphi)$$

$\to$ $E = E(\varphi)$ Energy-Phase Relation with

$$I(\varphi) = \frac{2\pi}{\Phi_0} \cdot \frac{\partial E(\varphi)}{\partial \varphi}$$

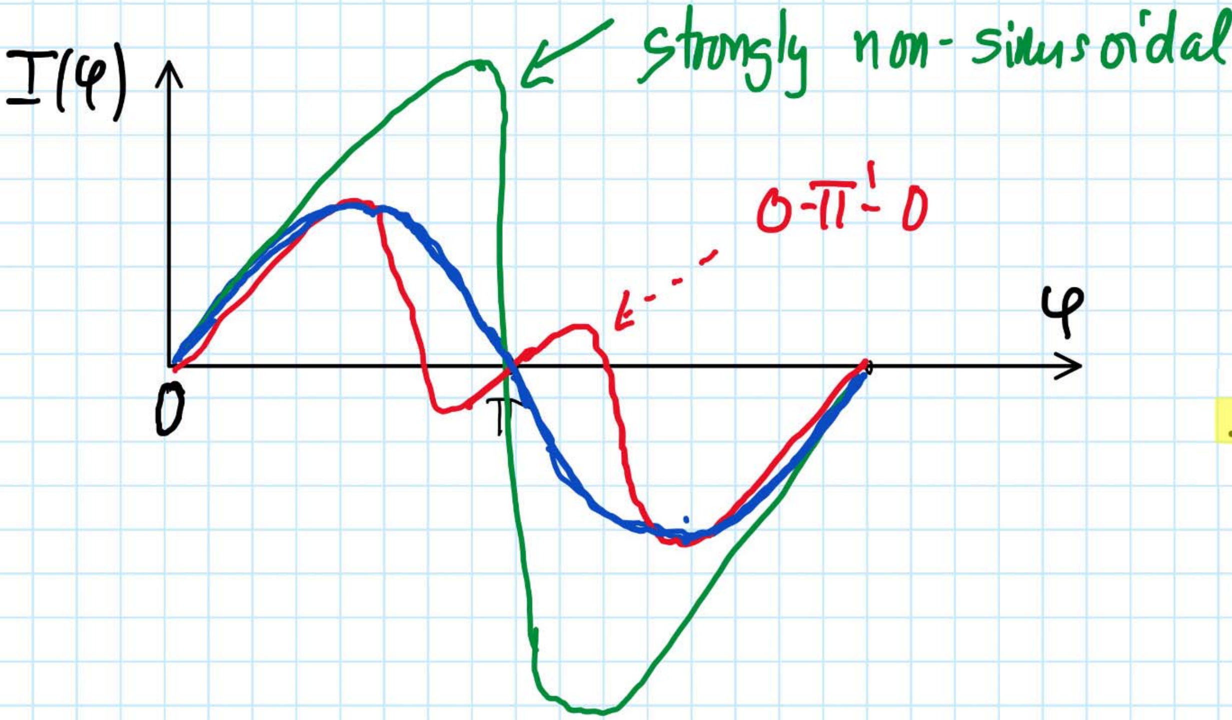
Today: Unconventional CPR's ; non-sinusoidal CPR

$$I(\varphi) = \sum_k I_k \sin(k\varphi)$$ has higher-order terms

realized in highly transmissive junctions (e.g. one channel)

Example of CPR's

Introduction (Josephson relations)



in general

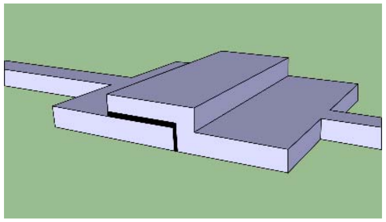
$$I_C = \max_{\varphi} \left(I(\varphi) \right)$$

→ "diode effect"

Introduction (Devices)

SIS junction

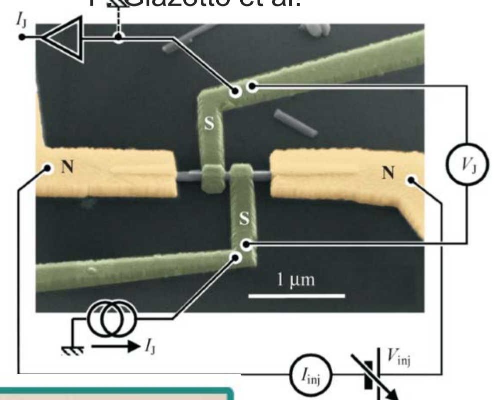
JJ by two-angle evaporation



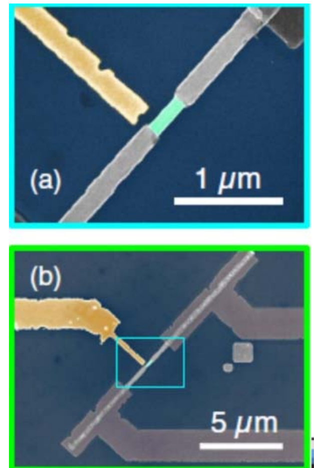
metal: Al, black part is Al-oxide
source: wikipedia

SNS “weak link” (superconductor-normal metal-superconductor)

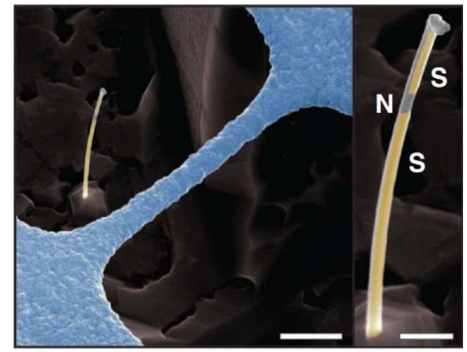
F. Giazotto et al.

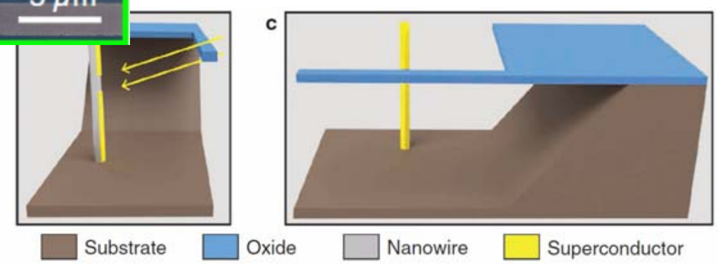


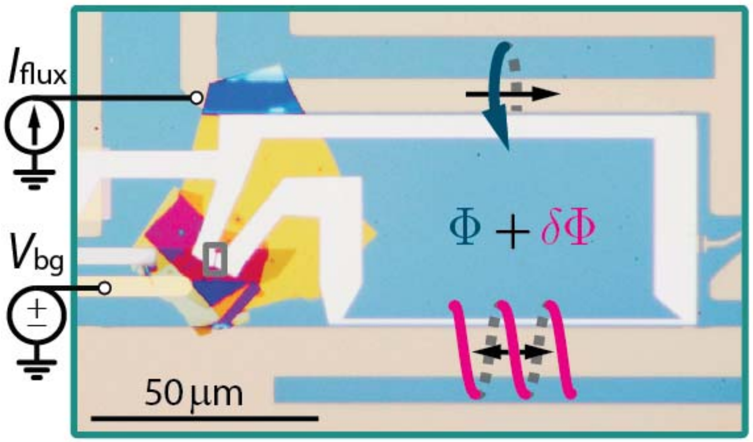
Quantronics group, CEA-Saclay



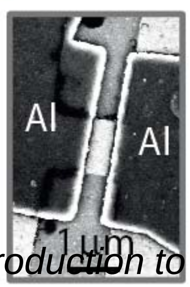
UCPH – Copenhagen, J. Nygard et al.

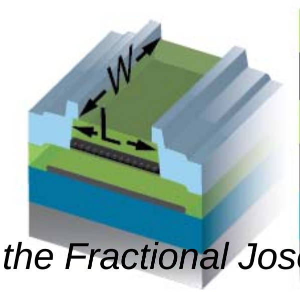


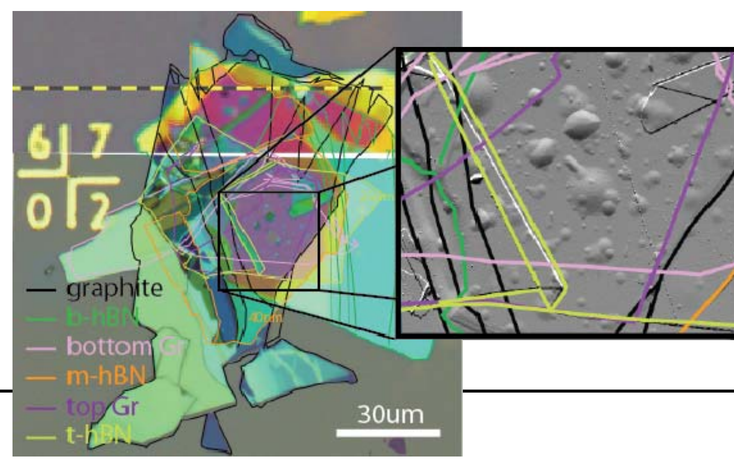


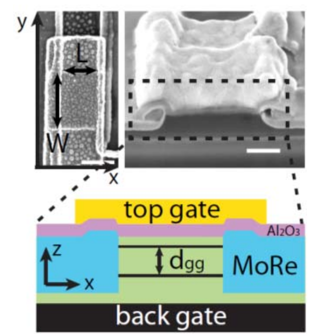


SNS with **2D materials**



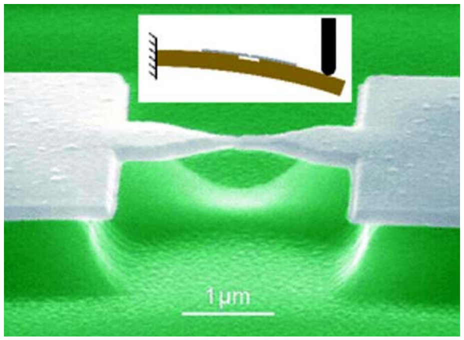






Introduction (Andreev level)

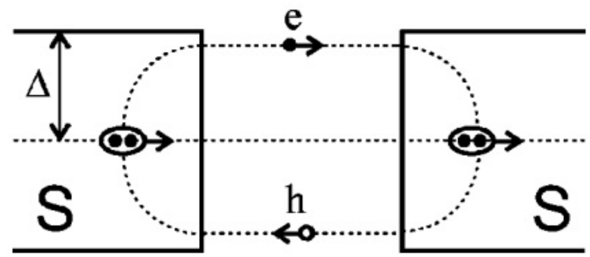
atomic contact = prototype single channel Josephson junction in the short-junction limit to demonstrate **Andreev Bound State(s)** (ABS)



for example:
M. F. Goffman et al. Supercurrent in atomic point contacts and Andreev states, Phys. Rev. Lett. 85, 170 (2000).

L. Bretheau et al. Exciting Andreev pairs in a superconducting atomic contact, Nature 499 (7458), 312-315 (2013).

formation of Andreev Bound State



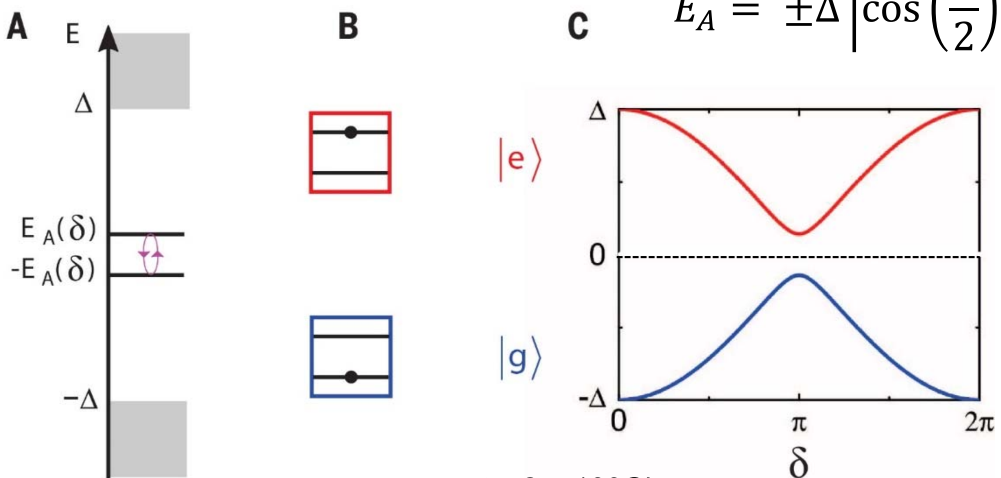
$$I(\varphi) = \frac{2e}{\hbar}\frac{\partial E(\varphi)}{\partial \varphi}$$

$$\pm E_A(\varphi) = \pm\,\Delta\sqrt{1 - \tau sin^2\left(\frac{\varphi}{2}\right)}$$

τ = transmission probability

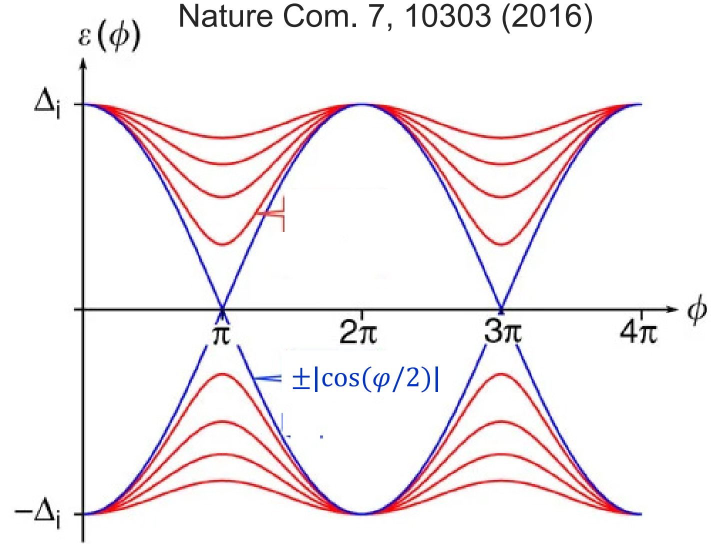
Note, limit for $\tau \to 1$:

$$E_A = \ \pm\Delta\left|\cos\left(\frac{\varphi}{2}\right)\right|$$



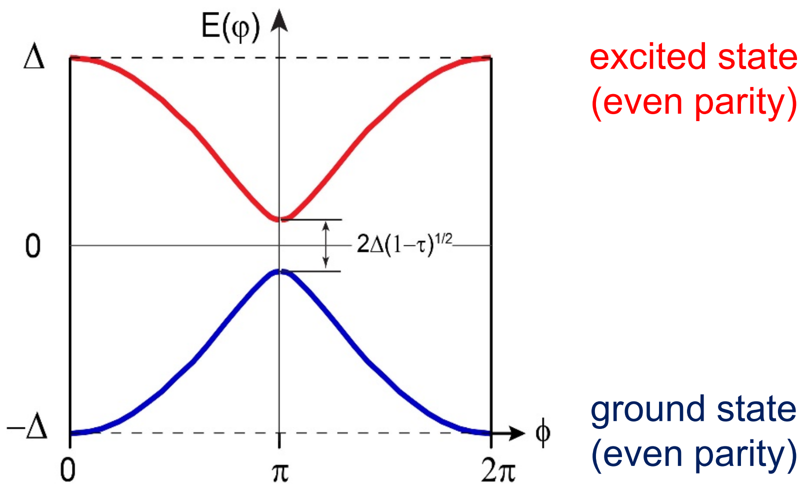
note: 2Δ~100Ghz

HgTe QSH system with Nb contacts
Nature Com. 7, 10303 (2016)

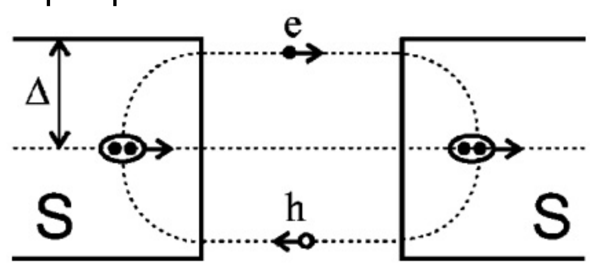


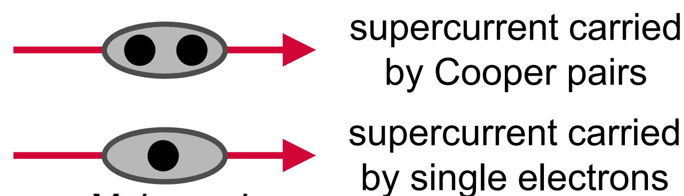
Introduction (CPR trivial vs topological)

"trivial" junction

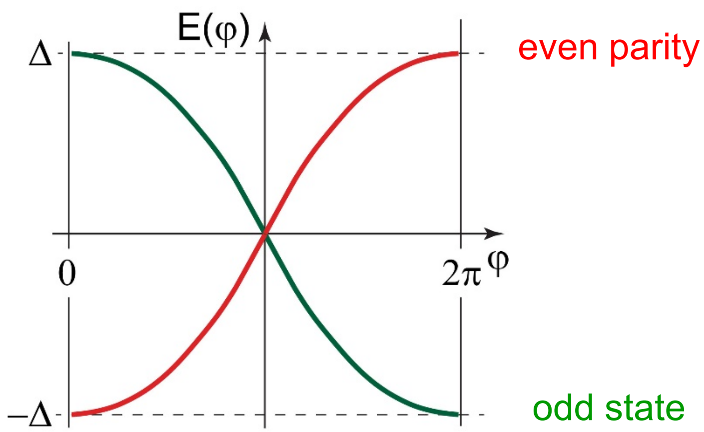


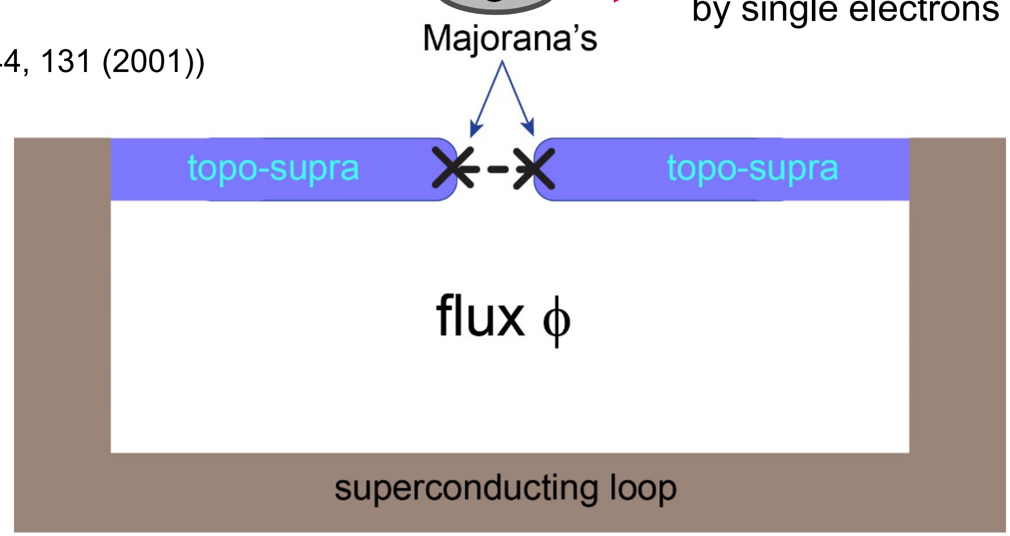
Andreev Josephson junction:
relatively open channel that transports
Cooper-pair from one side to the other



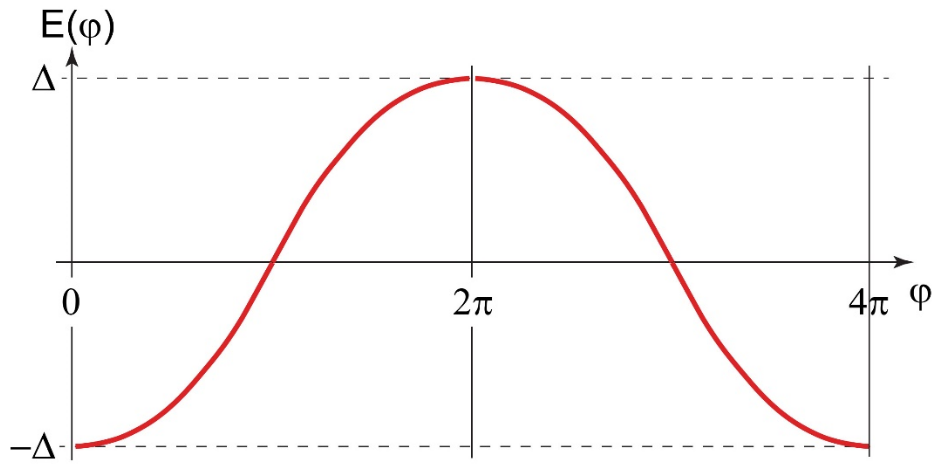


"topological" junction (A. Y. Kitaev, Phys. Usp. 44, 131 (2001))



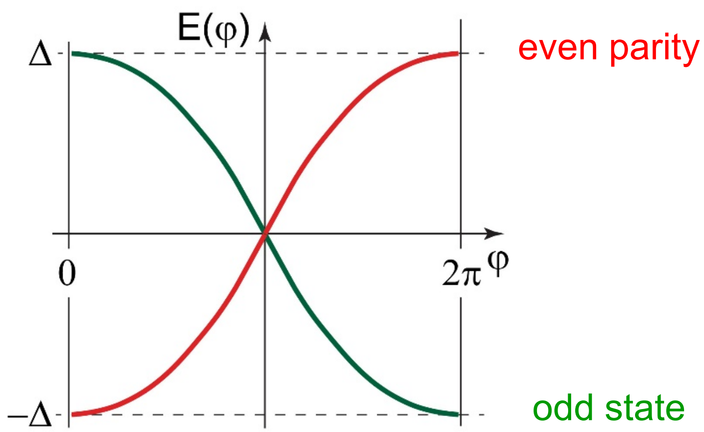


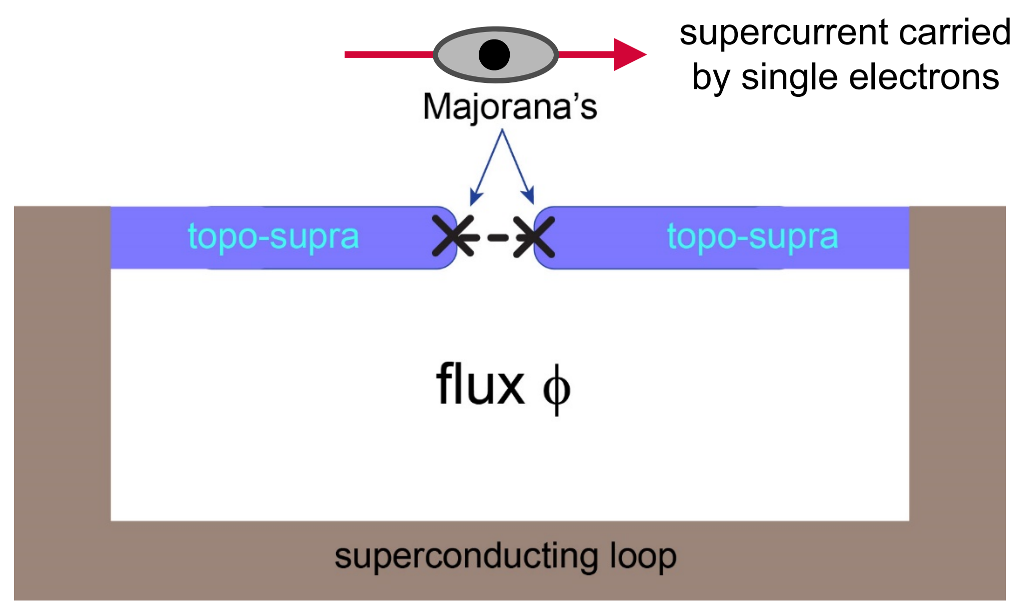
Introduction (CPR trivial vs topological)



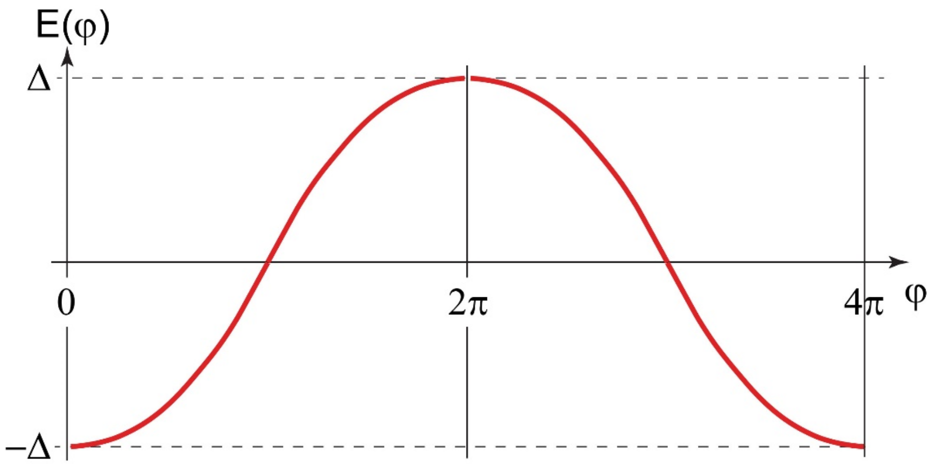
if parity is conserved, the CPR (current-phase relation) has a **doubled** periodicity of $\mathbf{4\pi}$ instead of 2π

"topological" junction





Introduction (CPR trivial vs topological)



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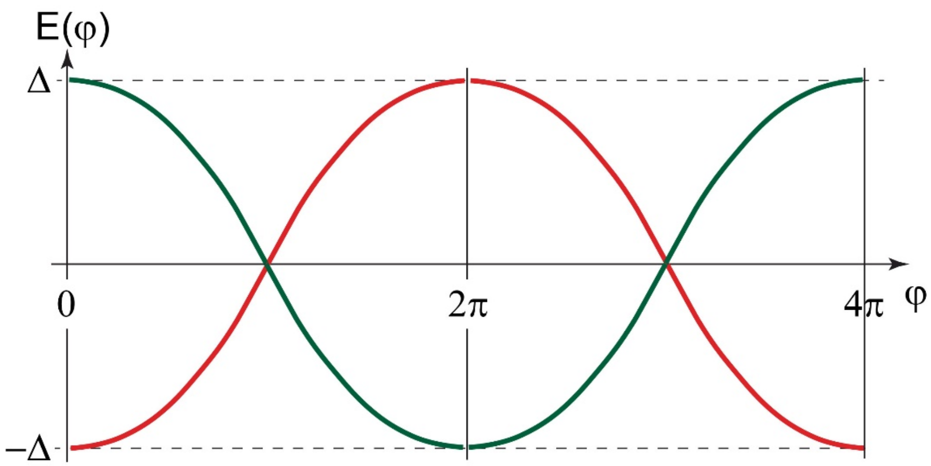
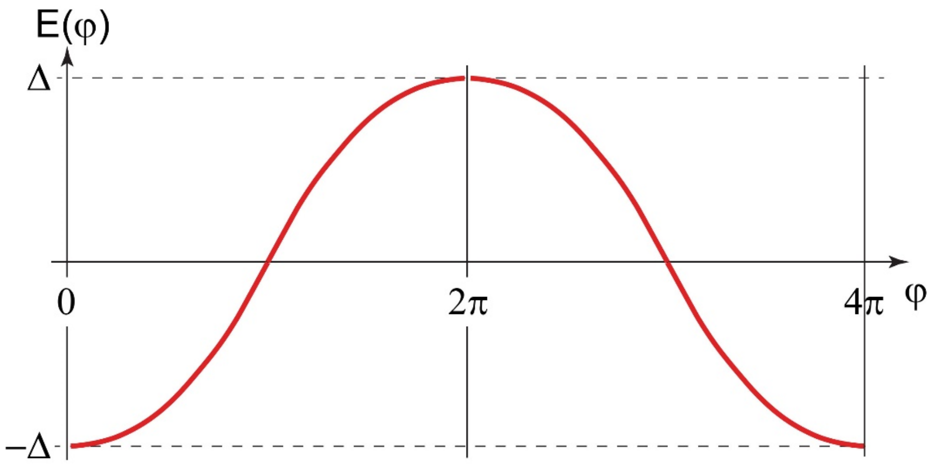


if parity is not conserved, the $\boldsymbol{2\pi}$**-periodicity** of the CPR is **restored**

Introduction (CPR trivial vs topological)



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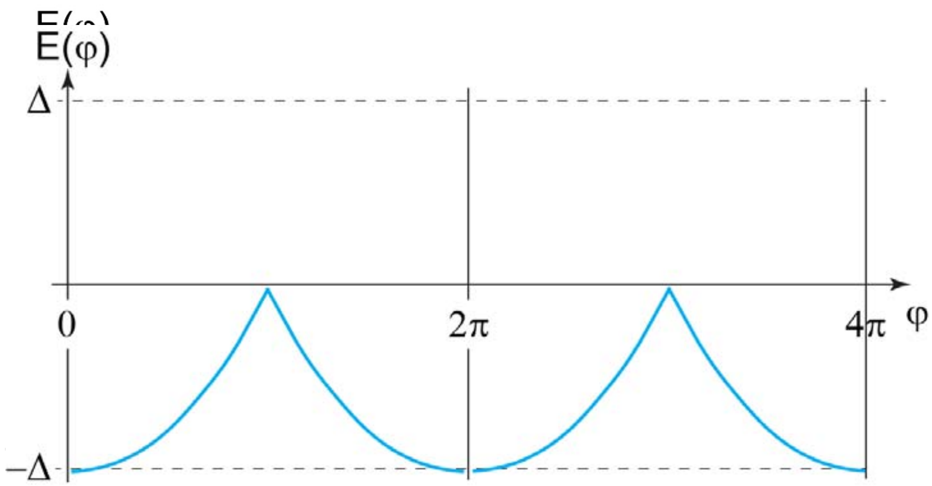
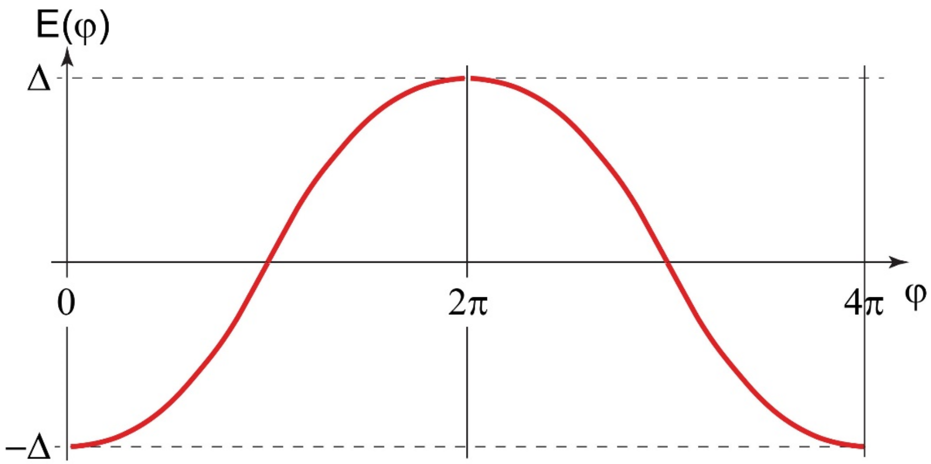
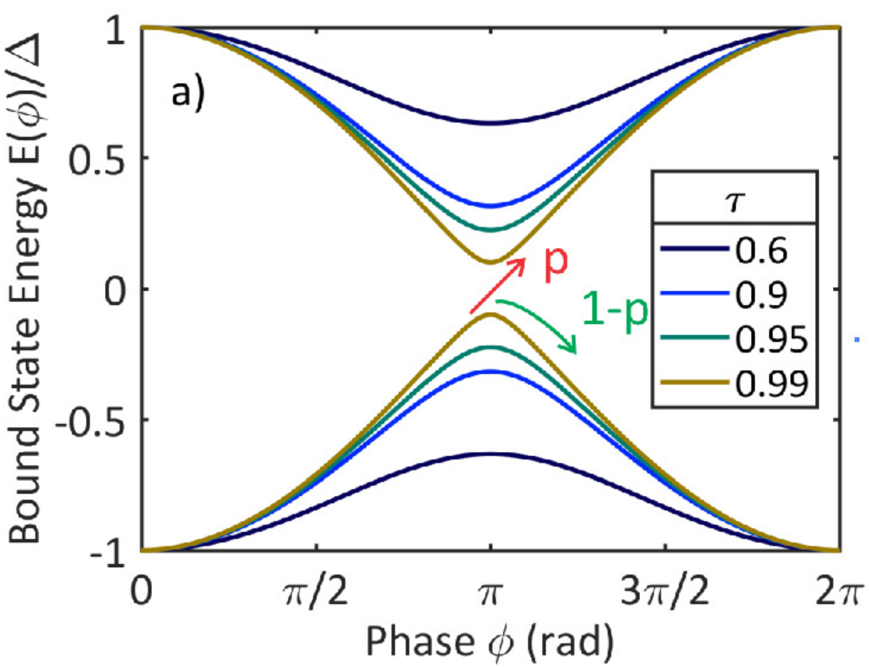


if parity is not conserved, the $\mathbf{2\pi}$**-periodicity** of the CPR is **restored**

Introduction (CPR trivial vs topological)



if phase evolution in a **dynamic process** is faster than the "poisoning" time, one expects to still see a contribution from the 4π-periodicity



but note, a trivial CPR can also assume a 4π-periodic contribution through Landau-Zener transitions

The idea is to **do "proper" dynamic experiments** in the search of a **"higher-order" periodicity**, also termed the **"fractional" Josephson effect**.

How to access the CPR in experiments

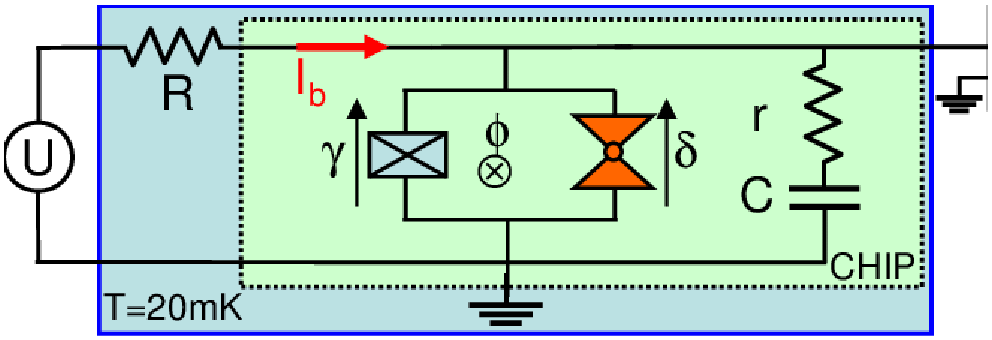
1. measure the **AC Josephson effect** while voltage biasing the junction
   a) measure the **emitted microwave radiation**
   b) explore the I-V characteristics while exposing the junction to an external microwave field → **Shapiro steps**

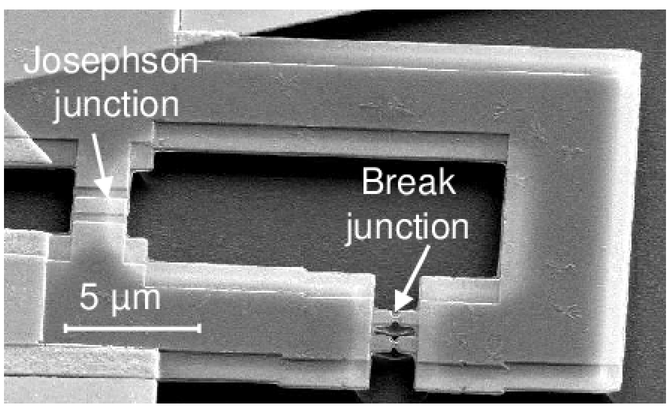
2. measure the **inductance of the junction** (susceptibility) as a function of flux bias

3. use an **asymmetric DC-SQUID** to measure the CPR

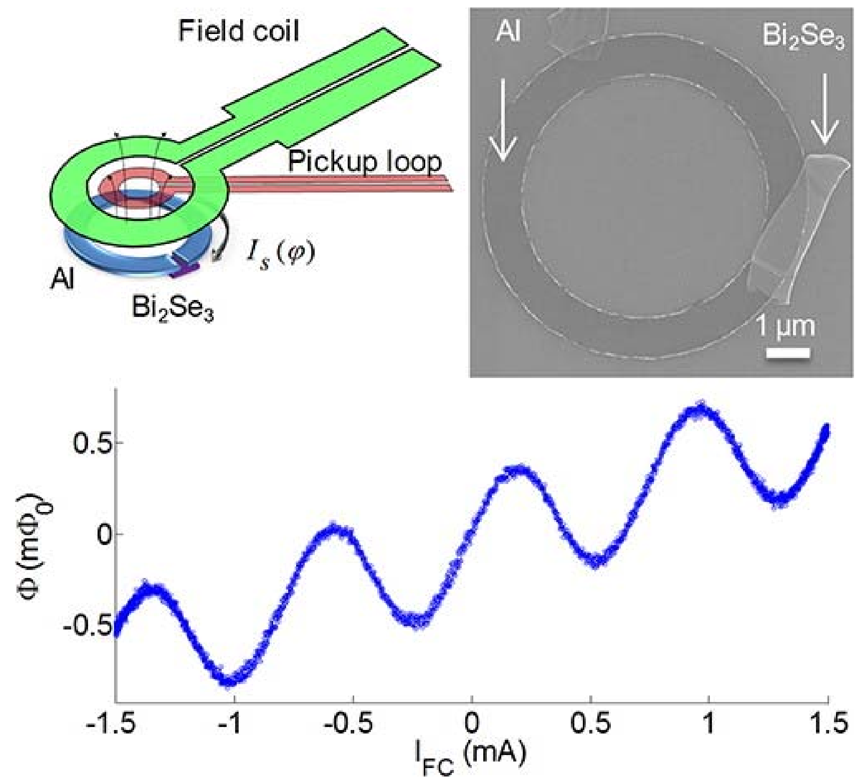
Asymmetric SQUID / RF-SQUID

asymmetric DC SQUID

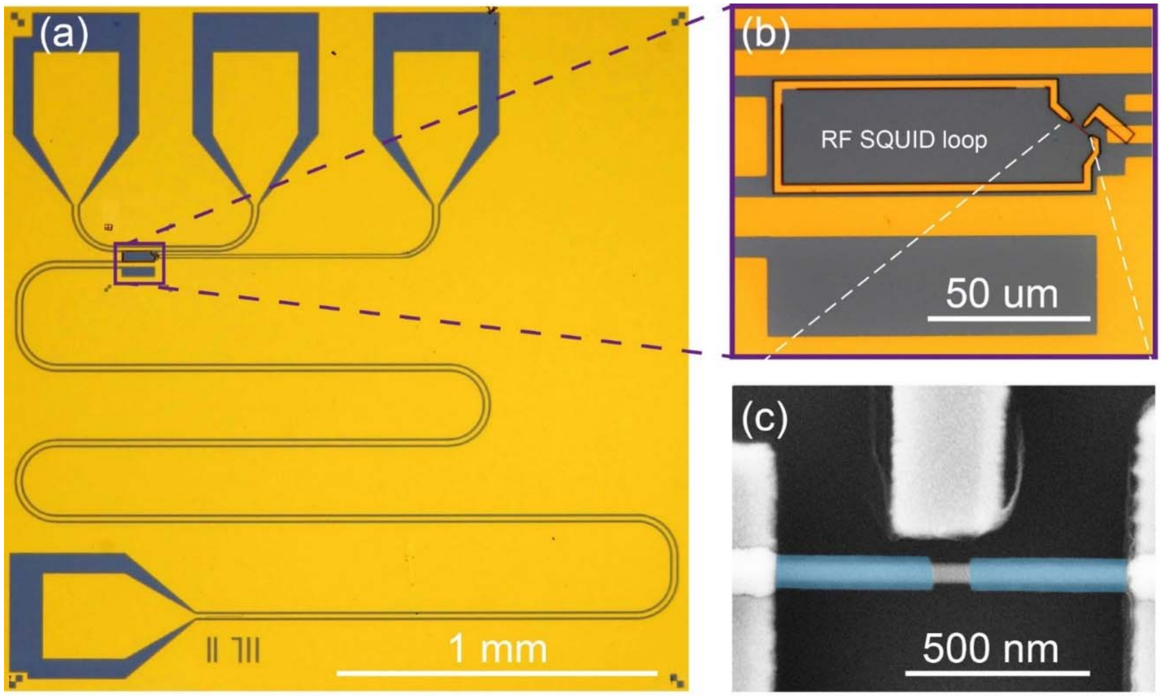


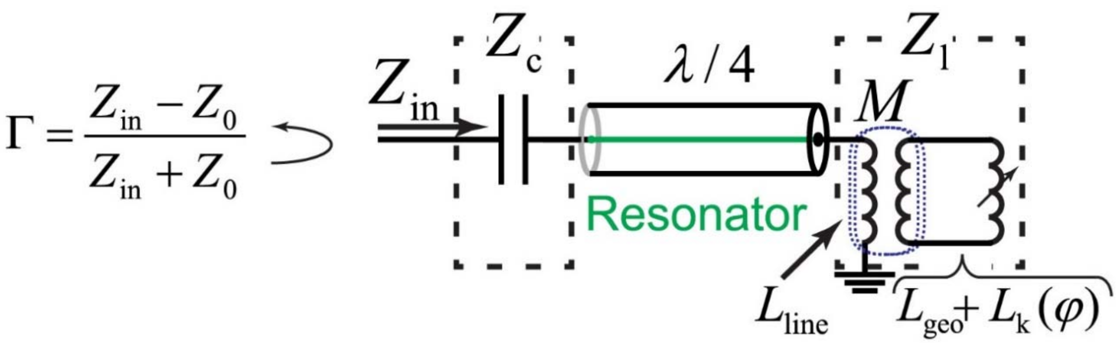


Rf-SQUID: *Nano Lett.* 2013, 13, 7, 3086-3092, Kathryn A. Moler's group

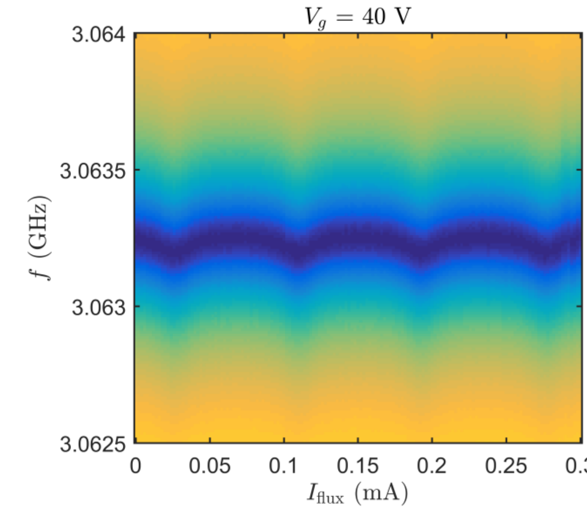


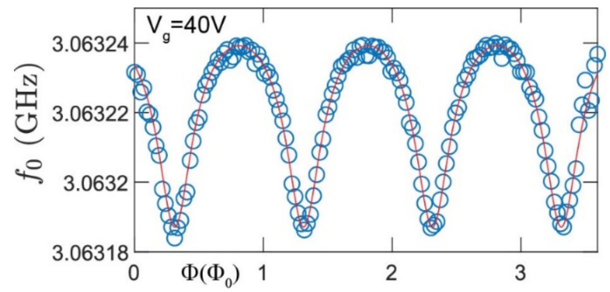
RF-SQUID with “qubit” readout





see for the concept: R. Haller et al. *Phase-dependent microwave response of a graphene Josephson junction,* Phys. Rev. Research **4**, 013198 (2022)

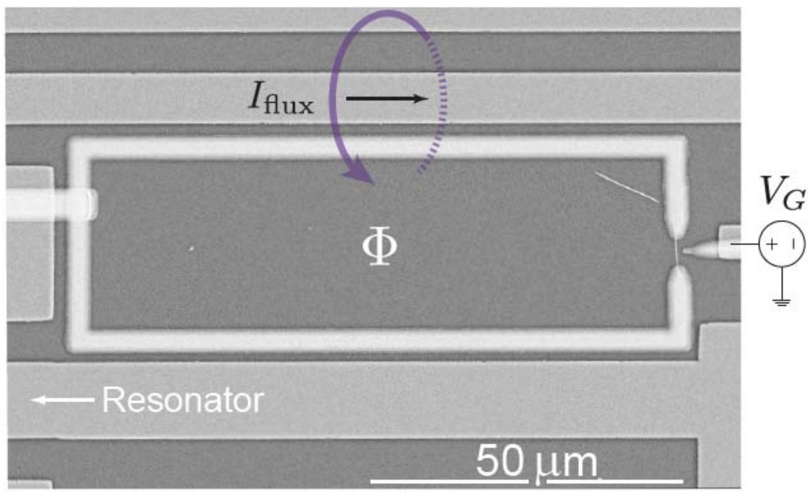


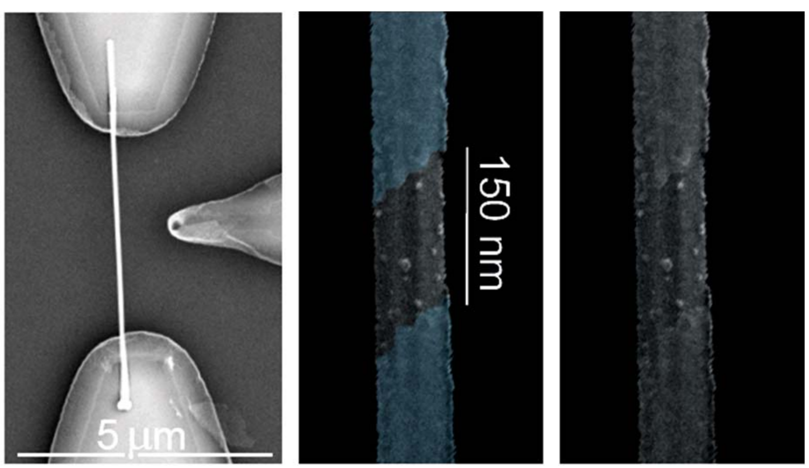


one obtains the $I_S = 25$nA and a $\bar{T} = 70\%$

here: **half-shell InAs NWs from UCPH** (J. Nygard et al.)

RF-SQUID with "qubit" readout





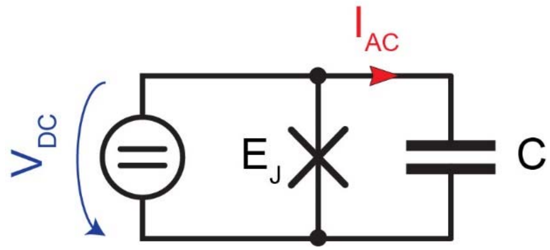
- **Superconducting loop**
  - Sputtered NbTiN (120 nm)
  - Loop 100 um x 30 um (1 uT)
  - PMMA/MA (large undercut)
  - Ar-plasma
- **MBE-grown wurtzite InAs NW** with **epitaxial aluminum half shell**
  - NW deposition with micromanipulator
  - Partially remove shell with wet etching process (MF321)
- **Phase biasing via flux line**
- Tuning transparency via **gate**
  - Ground reference needed
  - Side gate 900 nm apart

Introduction to the AC Josephson Effect in the Experiment, i.e.

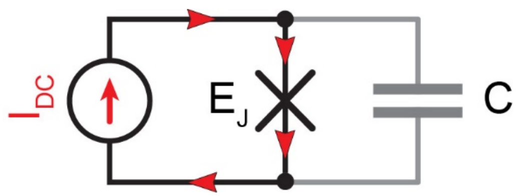
a) Josephson radiation

b) Shapiro steps

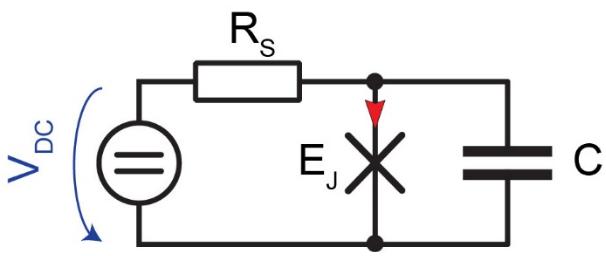
Introduction (how to drive the JJ)

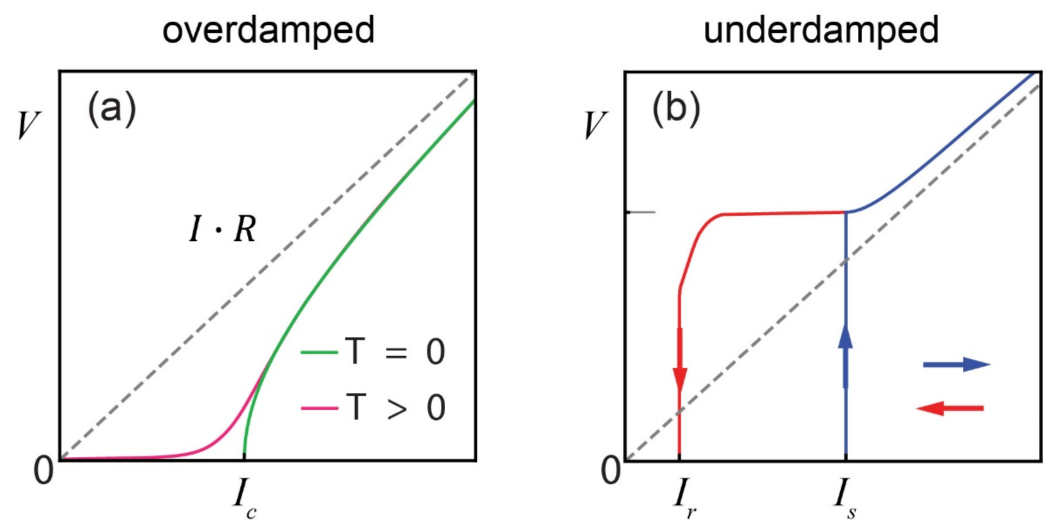


"truly" DC voltage biased → ideal AC Josephson effect
(not useful, need a "receiver")



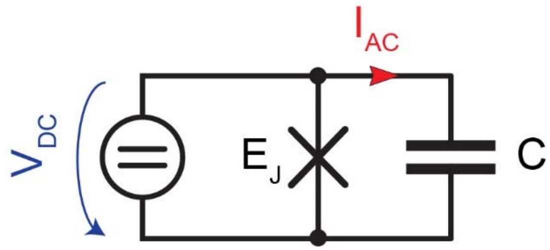
"truly" DC current biased → used to determine the critical current





current-biased V(I) curves

Introduction (how to drive the JJ)



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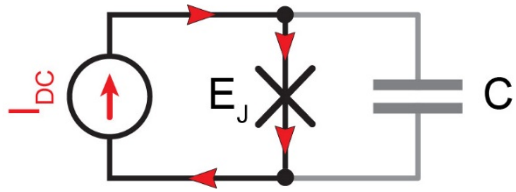

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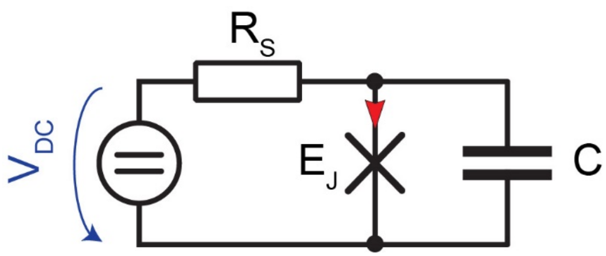
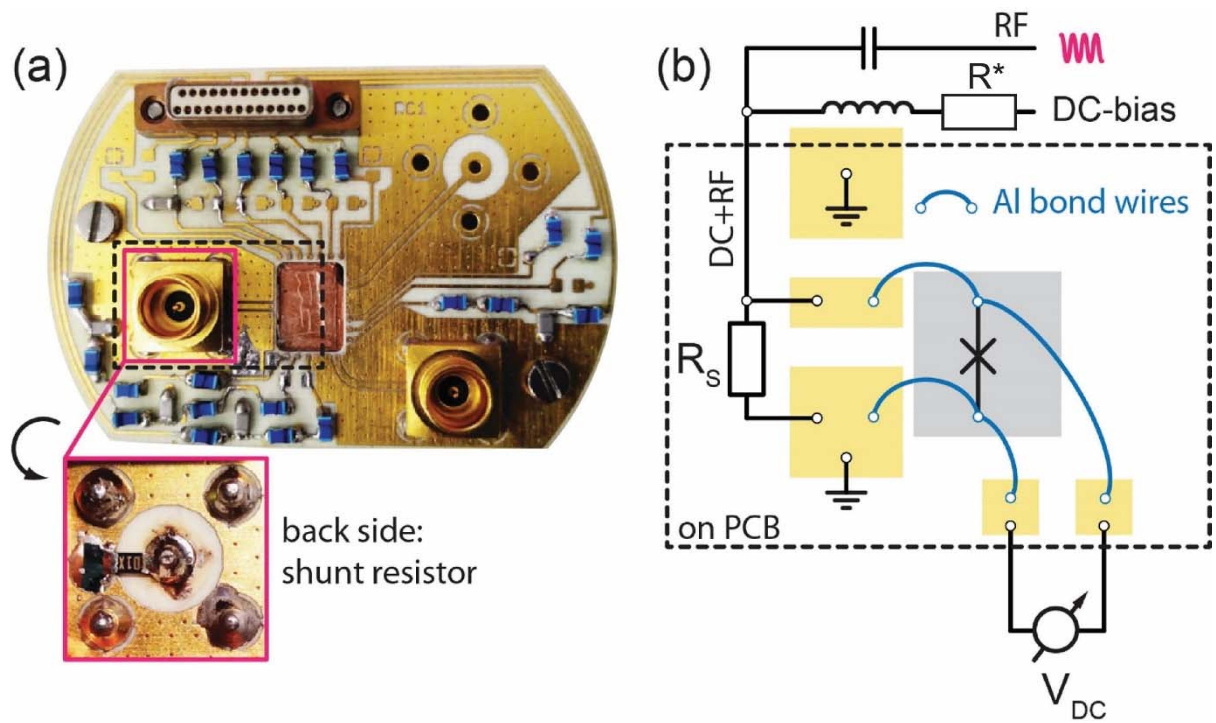
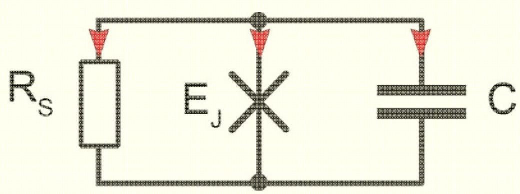


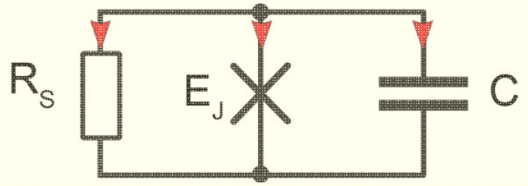


RCSJ model

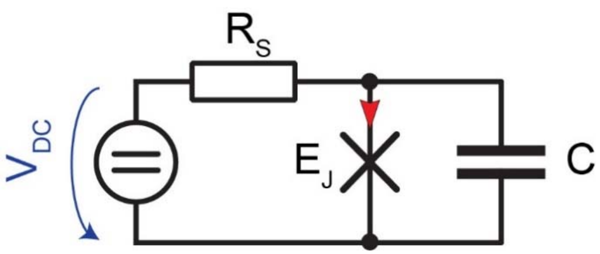


Introduction (how to drive the JJ)

RCSJ model



RSCJ model



$$\omega_p = \sqrt{\frac{2e}{\hbar}\frac{I_c}{C}}$$ Plasmafrequency

$$R_s C \frac{\hbar}{2e}\frac{\partial^2\varphi}{\partial t^2} + I_c R_s \sin(\varphi) + \frac{\hbar}{2e}\frac{\partial\varphi}{\partial t} = V_{DC}$$

in the “frictional-sliding” limit, one obtains as condition for an approximate $\varphi \doteq \omega t \approx \frac{2e}{\hbar} V_{DC} t$

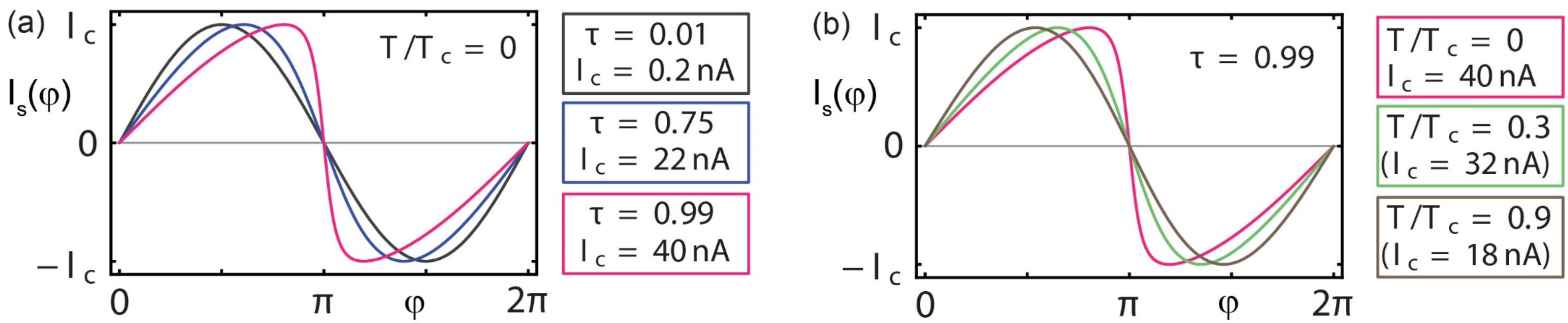
$$1/\tau_{RC} \gg \omega \gg R I_c \left({}^{2e}/_{\hbar}\right)$$

AC Josephson Effect with higher harmonics

In "general" we know that the CPR can be written as a **Fourier series**:

$$I_s(\varphi) = \sum_k (-1)^{k-1} A_k \sin(k\varphi),$$

An example is a junction with highly transmissive channels. Current-Phase Relation:



T = temperature and τ = transparency

Assume, we could **perfectly DC bias** the junction with **voltage** V. The **phase** would then evolve with a constant velocity. The **Fourier spectrum** of the AC current contains harmonics at frequencies that are integer multiples of the fundamental Josephson frequency $f_J = 2eV/h$:

$$I_s(t) = \sum_{k=1} (-1)^{k-1} A_k \sin\left(k \frac{2eV}{\hbar} t\right)$$

If the junctions emits AC radiation, the **power spectral density** of the harmonics with index k would correspond to $|A_k|^2$

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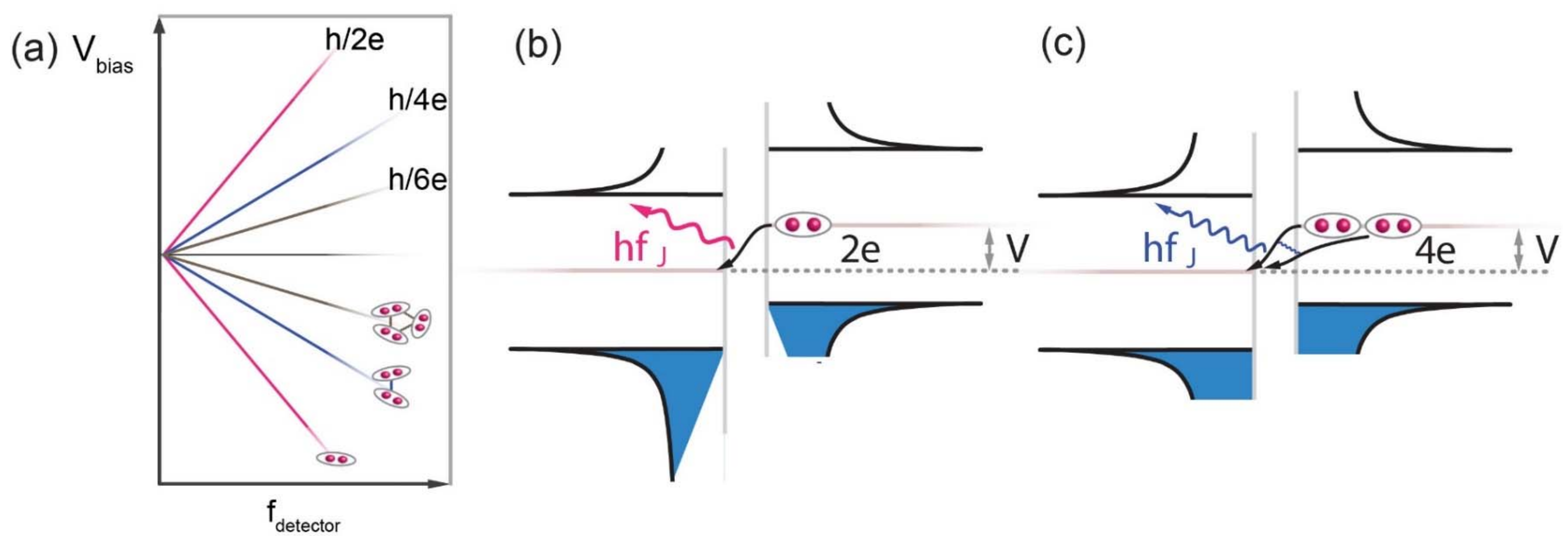
A different (more QM-like) description**: inelastic tunneling of Cooper-pairs (charge 2e)**



...and for Majorana's?

AC Josephson Effect with higher harmonics

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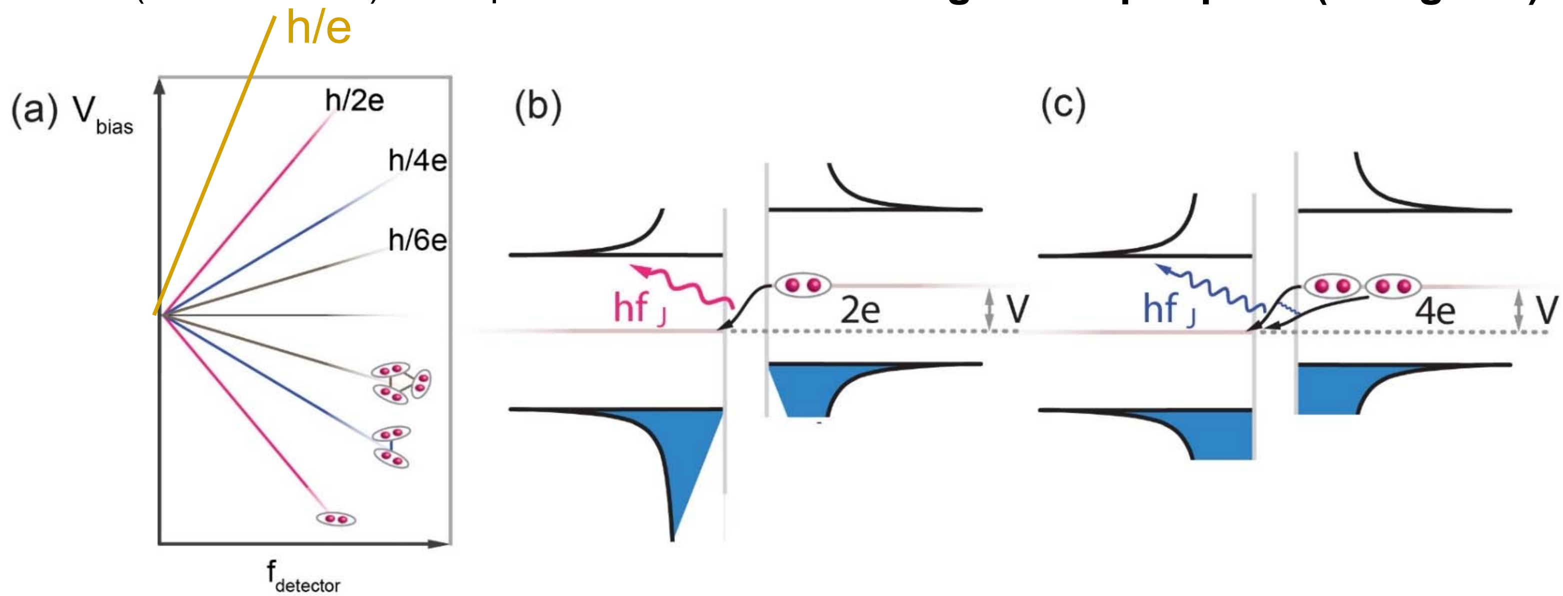
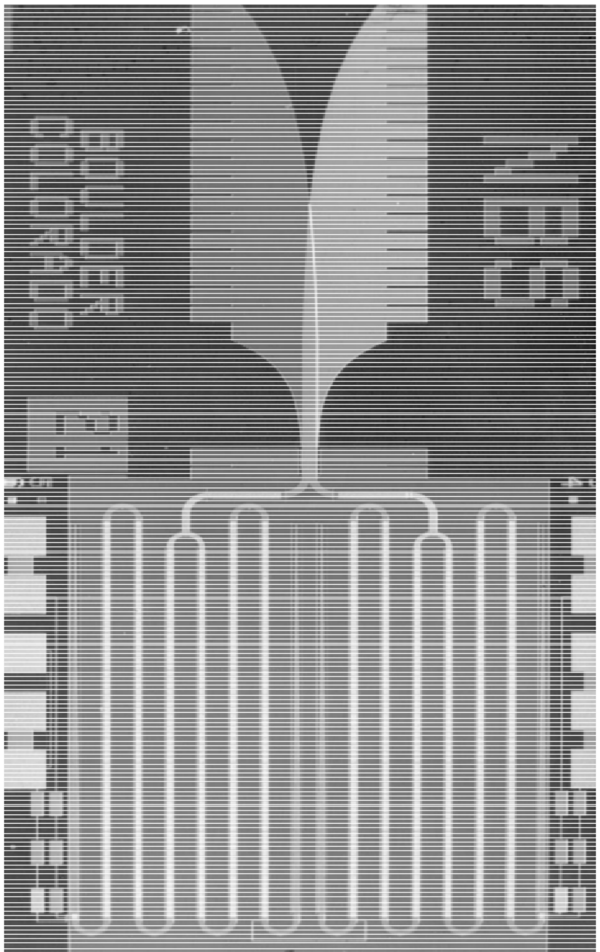


For Majorana's: **inelastic tunneling of electrons (charge e)** $f_M = eV/h = \frac{1}{2} f_J$

AC Josephson (relevance for metrology)

$$\frac{f_J}{V} = \frac{2e}{h} = \Phi_0^{-1} = 483.6\,\mathrm{MHz}\,\mu\mathrm{V}^{-1}$$



AC Quantum Voltmeter Cooler

Programmable Josephson Voltage Standard

supracon PTB esz TRUEAC

DESCRIPTION

The **cryocooled AC Quantum Voltmeter** is a turn-key programmable Josephson voltage standard system applicable for the highest level of precision voltage measurements from DC up to kHz frequencies. It was developed by Supracon in cooperation with the Physikalisch-Technische Bundesanstalt Braunschweig (PTB) and esz AG. It facilitates a variety of voltage calibrations and measuring functions:

- **Primary DC & AC Josephson voltage standard** up to kHz frequencies,
- Calibration of **calibrators,**
- Calibration of **secondary voltage standards,**
- Calibration of **voltmeter linearity,**
- Calibration of **thermal converters** (optional),
- **Voltage source** with ultimate precision and lowest noise level

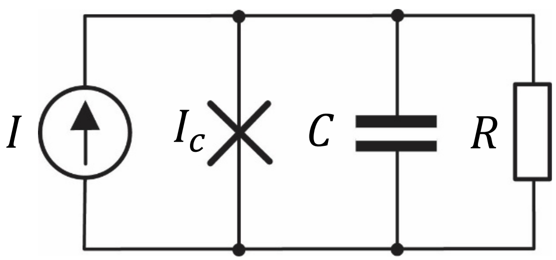
The cryocooled **AC Quantum Voltmeter** consists of the following components:

1. **10 V programmable JVS array** on thermal interface
2. Two-stage **Pulse Tube Cooler**
3. Air-cooled **Compressor**, 4 kW input power
4. Compact **70 GHz microwave source**
5. **Programmable 20 channel bias source**
6. **Control electronics** with optical isolation unit
7. Nanovoltmeter as **DC null detector**
8. **Sampler** for AC voltage measurements
9. **Waveform generator** with synchronisation unit
10. **Multiplexer** with polarity switch
11. Host computer with **control software**
12. **Sensors** for temperature, humidity, and pressure
13. **Optional:** Vacuum pump, GPS 10 MHz frequency reference

Shapiro Steps

a) we can try to **DC bias** a JJ and stud the **emission spectrum**

b) but we could also **radiate onto the JJ** with a fixed external Rf source at a drive frequency f_D → **Shapiro steps (spikes)** in the I-V characteristics at voltage values corresponding to $V = hf_D/2e$.

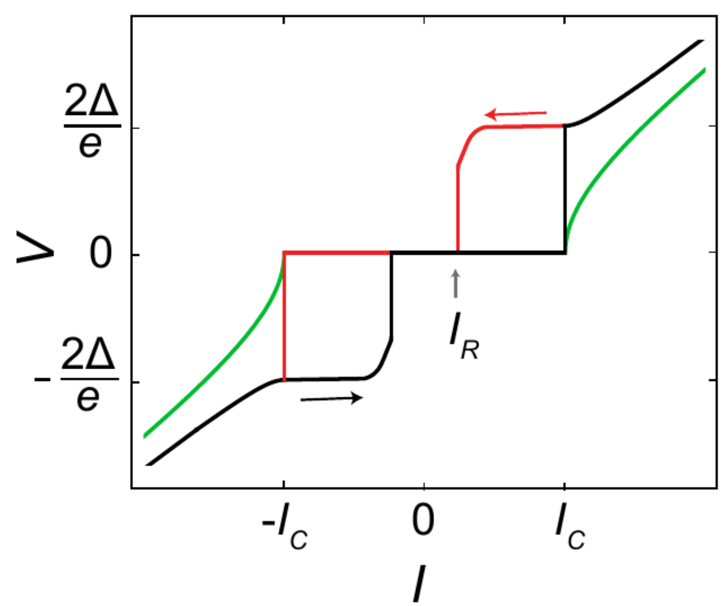


$$I_c \sin(\varphi) + C\frac{\hbar}{2e}\ddot{\varphi} + \frac{1}{R}\frac{\hbar}{2e}\dot{\varphi} = I$$

$$\ddot{\varphi} + \frac{1}{RC}\dot{\varphi} + \omega_p^2 \sin(\varphi) = \frac{I}{I_c}\omega_p^2$$

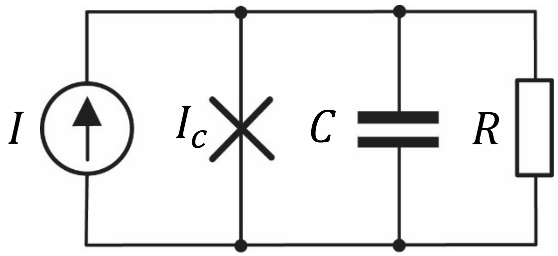
$\omega_p = \sqrt{2eI_c/\hbar C}$ Plasmafrequency

$Q = RC\omega_p$ quality factor



Green: overdamped ($Q < ½$)
Black and **red**: underdamped ($Q > ½$)

Shapiro Steps



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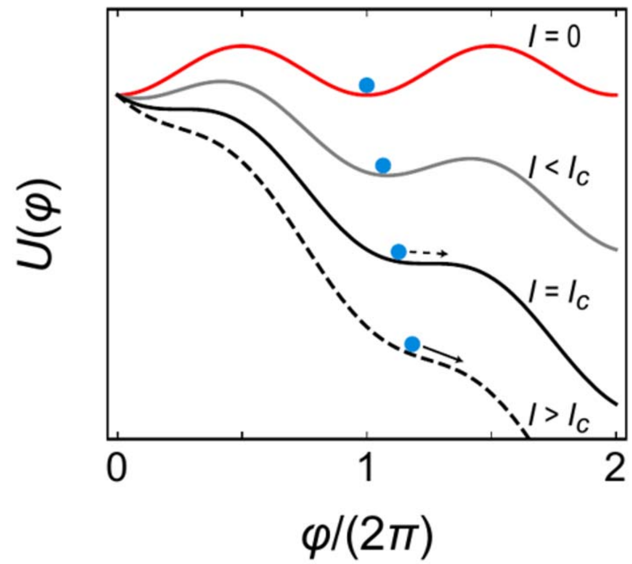
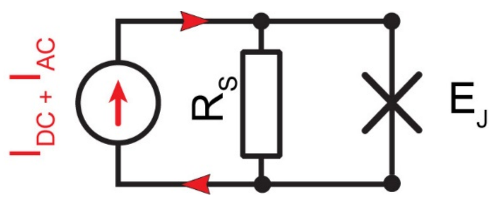
$$U(\phi) = -E_J\cos(\phi) - \frac{\hbar I_{tot}}{2e}\phi$$

$E_J = \frac{I_c \cdot \hbar}{2e}$

$I_{tot} = I_{DC} + I_{rf}$

Mechanical analog: phase particle moving in potential U

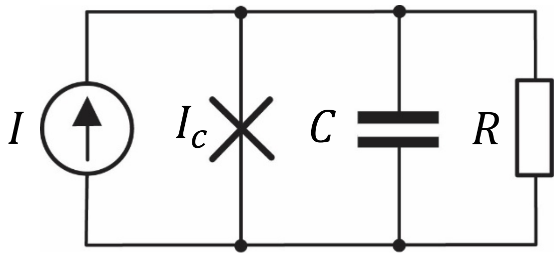




Let us add in addition an **AC source** driving at frequency f_d.

Due to the non-linearity of the Josephson circuit, the internal Josephson AC signal and the external can mix. This gives rise to **current spikes** (underdamped) or **Shapiro voltage steps** (overdamped and current biased JJ)

Shapiro Steps



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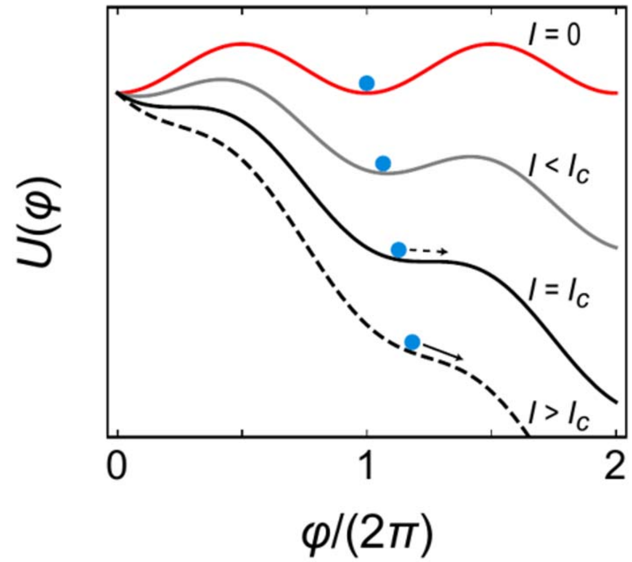

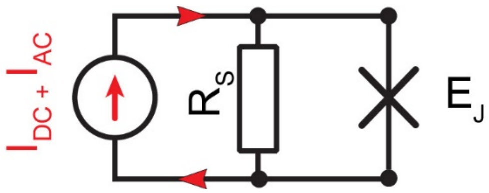

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Shapiro Steps

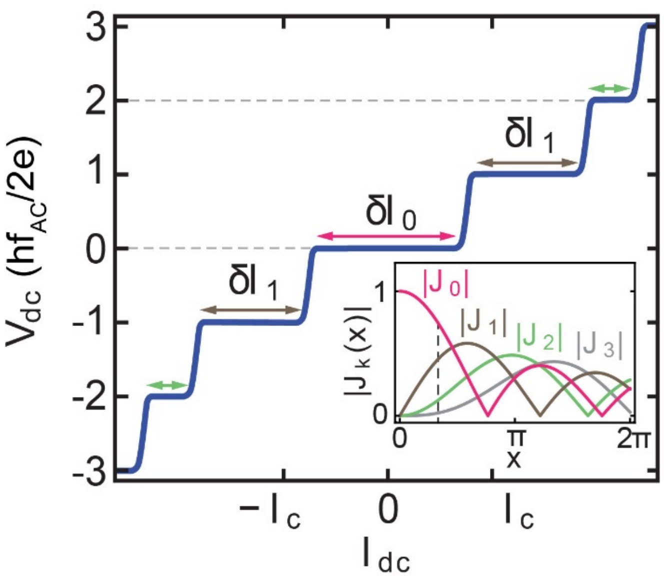
...the easiest way to see this is in the case of an applied AC voltage source:

AC voltage bias: $V(t) = V_{\mathrm{DC}} + V_{\mathrm{rf}} \cos(\omega t)$

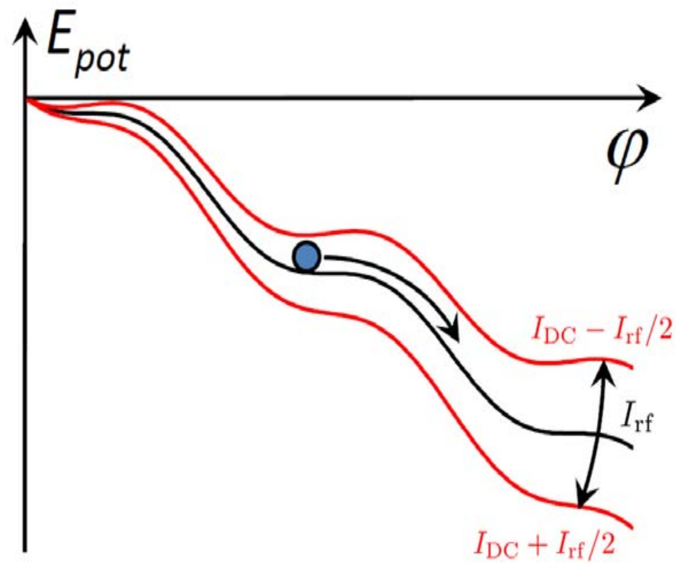
$$I(t) = I_c \cdot \sin[\tfrac{2e}{\hbar} V_{\mathrm{DC}} t + \tfrac{2e}{\hbar} \tfrac{V_{\mathrm{rf}}}{\omega} \cdot \sin(\omega t) + \phi_0]$$

$$I(t) = I_c \cdot \sum_{n=-\infty}^{+\infty} (-1)^n J_n(\tfrac{2eV_{\mathrm{rf}}}{\hbar\omega}) \sin[(\omega_{DC} - n\omega)t + \phi_0] + V_{DC}/R$$

here $\omega_{DC} = \omega_J = 2eV_{DC}/\hbar$

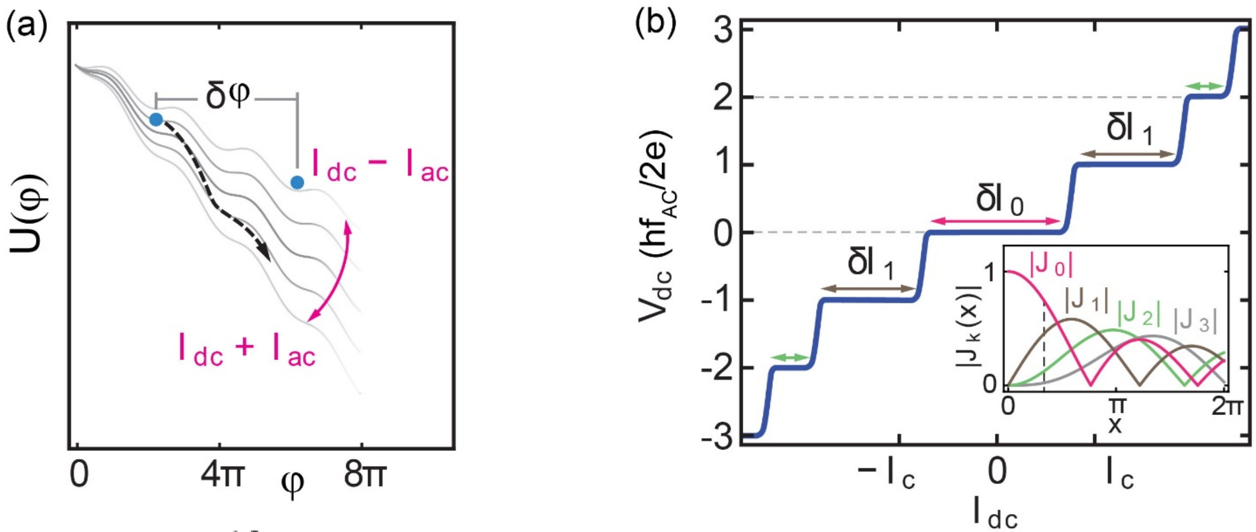


it is a synchronization effect taking place between the external drive and the AC Josephson effect. It relies on the non-linearity (mixing)



for step n the phase advances by $n2\pi$ per period of the drive leading to $V_n = \frac{\hbar}{2e} n\omega$

Shapiro Steps



emergence of Shapiro steps at voltages

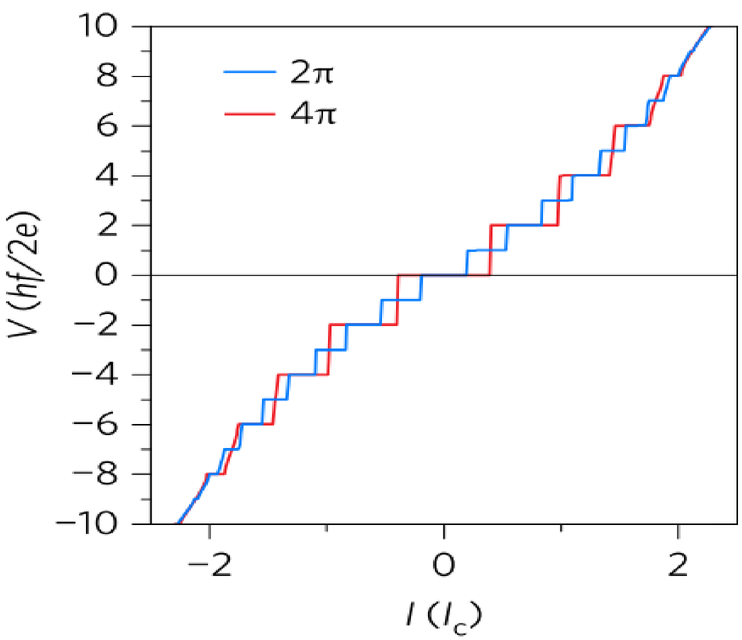
$$V_l = l \cdot hf_{in}/2e.$$

for a trivial JJ, or

$$V_p = p \cdot hf_{in}/e$$

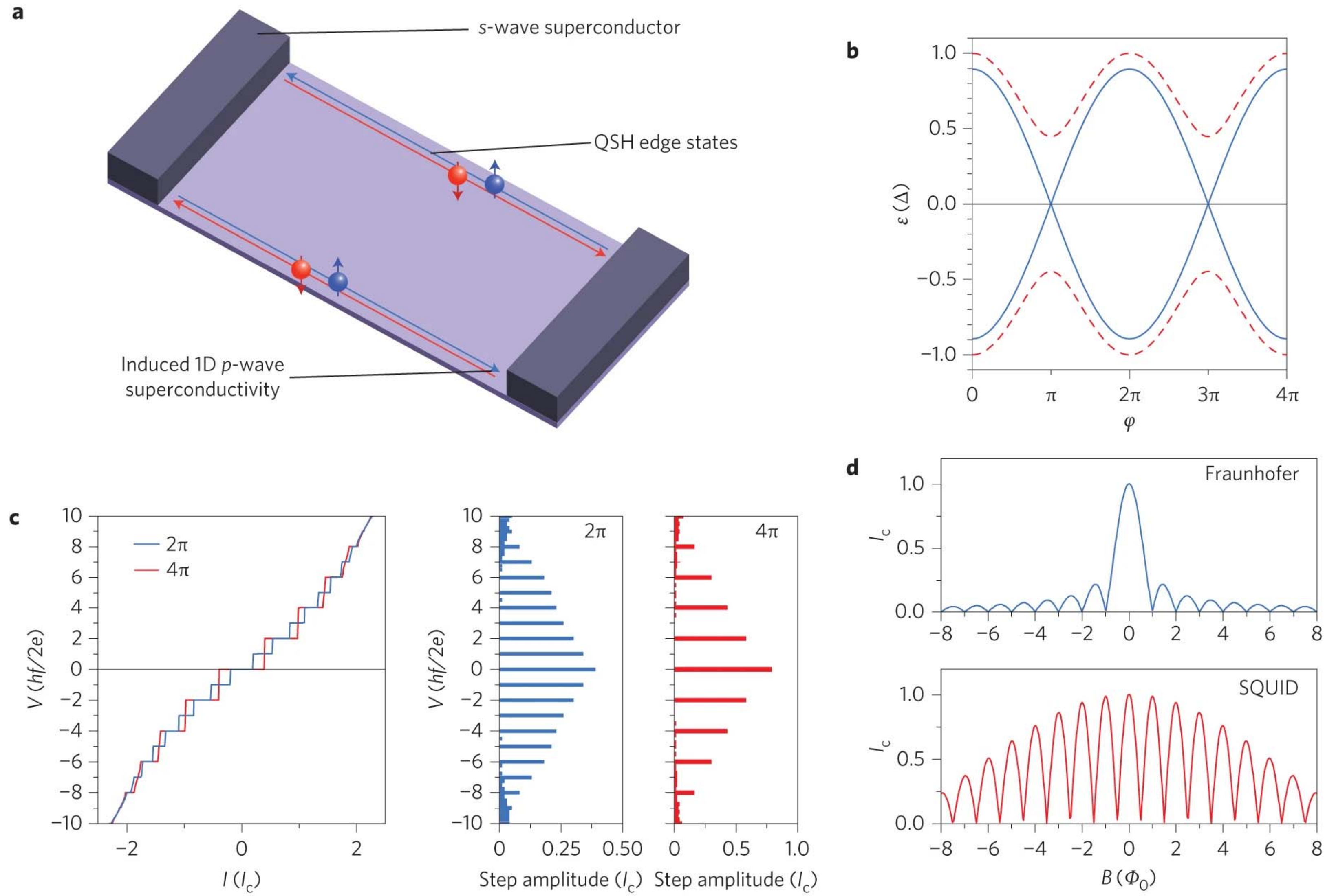
for a Majorana-type JJ;

$$l = 2p \text{ with } p \in \mathbb{Z}$$



E. Bocquillon et al., Nature Nanotechnology 12, 137 (2016)

Shapiro Steps



E. Bocquillon et al., Nature Nanotechnology 12, 137 (2016)

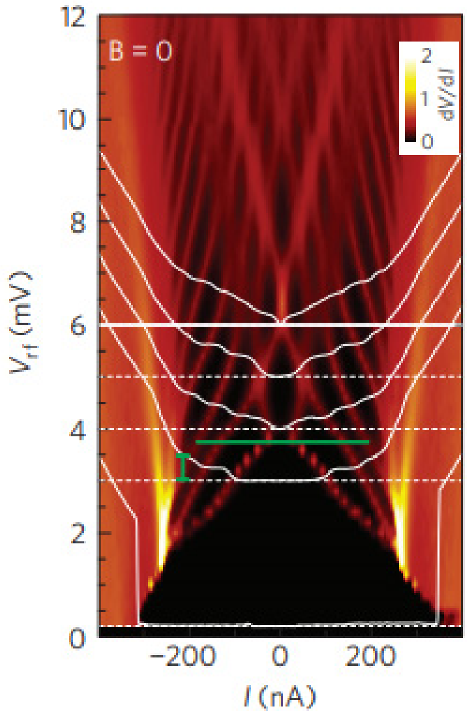
Selection of published Results

Search for $\omega_e = eV/\hbar$ (literature)

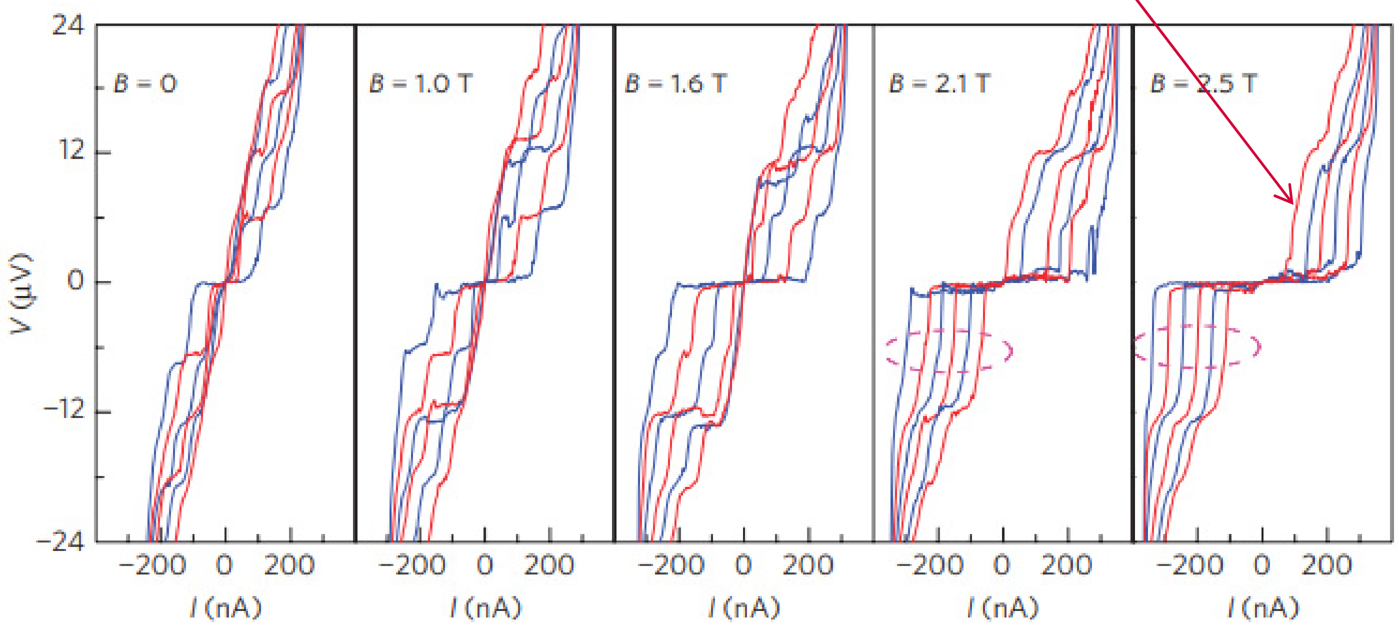
The fractional a.c. Josephson effect in a semiconductor–superconductor nanowire as a signature of Majorana particles

Leonid P. Rokhinson[1]*, Xinyu Liu[2] and Jacek K. Furdyna[2]

Nature Phys. 8, 795 (2012)



missing first odd Shapiro step



InSb nanowire at $f_{in} = 3GHz$

Search for $\omega_e = eV/\hbar$ (literature)

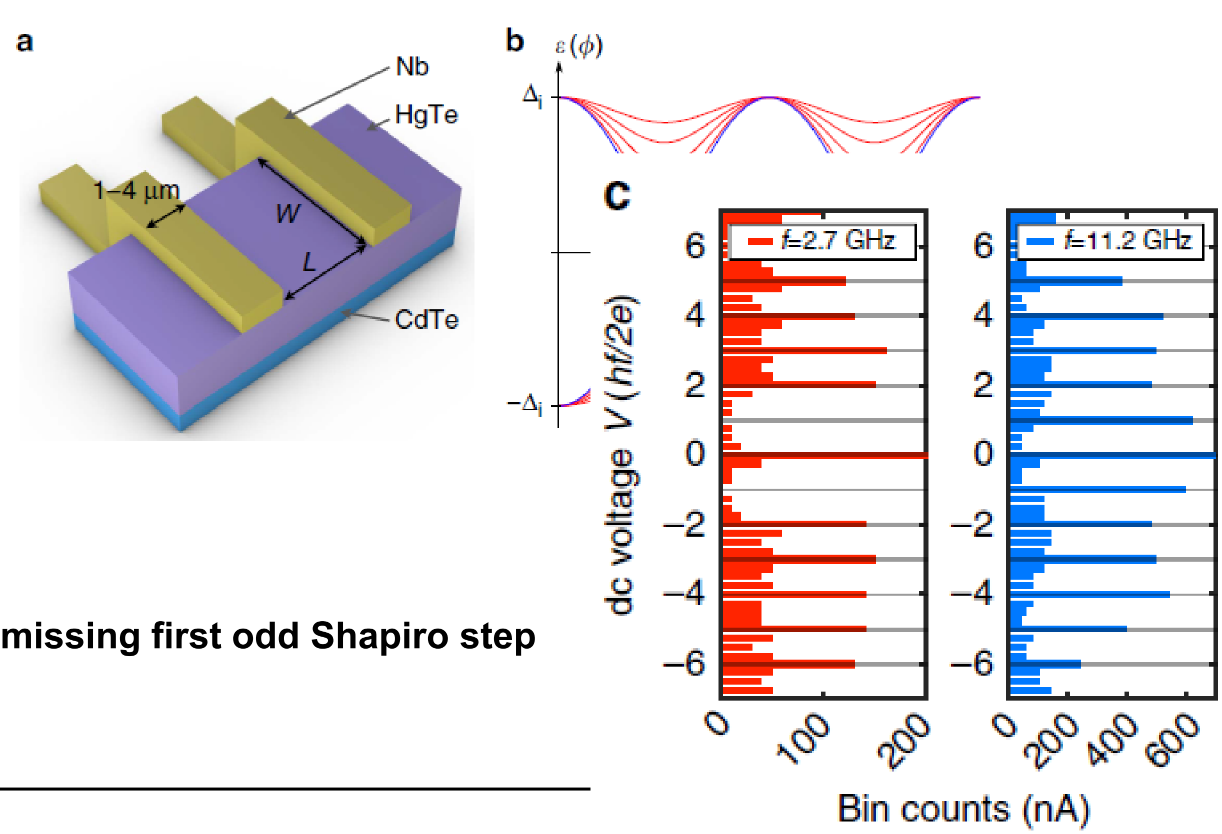
ARTICLE

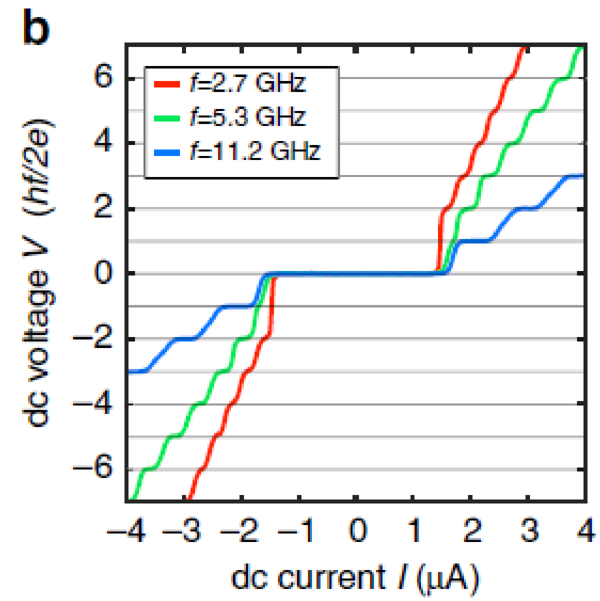
Received 15 Sep 2015 | Accepted 27 Nov 2015 | Published 21 Jan 2016
DOI: 10.1038/ncomms10303 OPEN

4π-periodic Josephson supercurrent in HgTe-based topological Josephson junctions

J. Wiedenmann[1,*], E. Bocquillon[1,*], R.S. Deacon[2,3,*], S. Hartinger[1], O. Herrmann[1], T.M. Klapwijk[4,5], L. Maier[1], C. Ames[1], C. Brüne[1], C. Gould[1], A. Oiwa[6], K. Ishibashi[2,3], S. Tarucha[3,7], H. Buhmann[1] & L.W. Molenkamp[1]

Shapiro steps





missing first odd Shapiro step

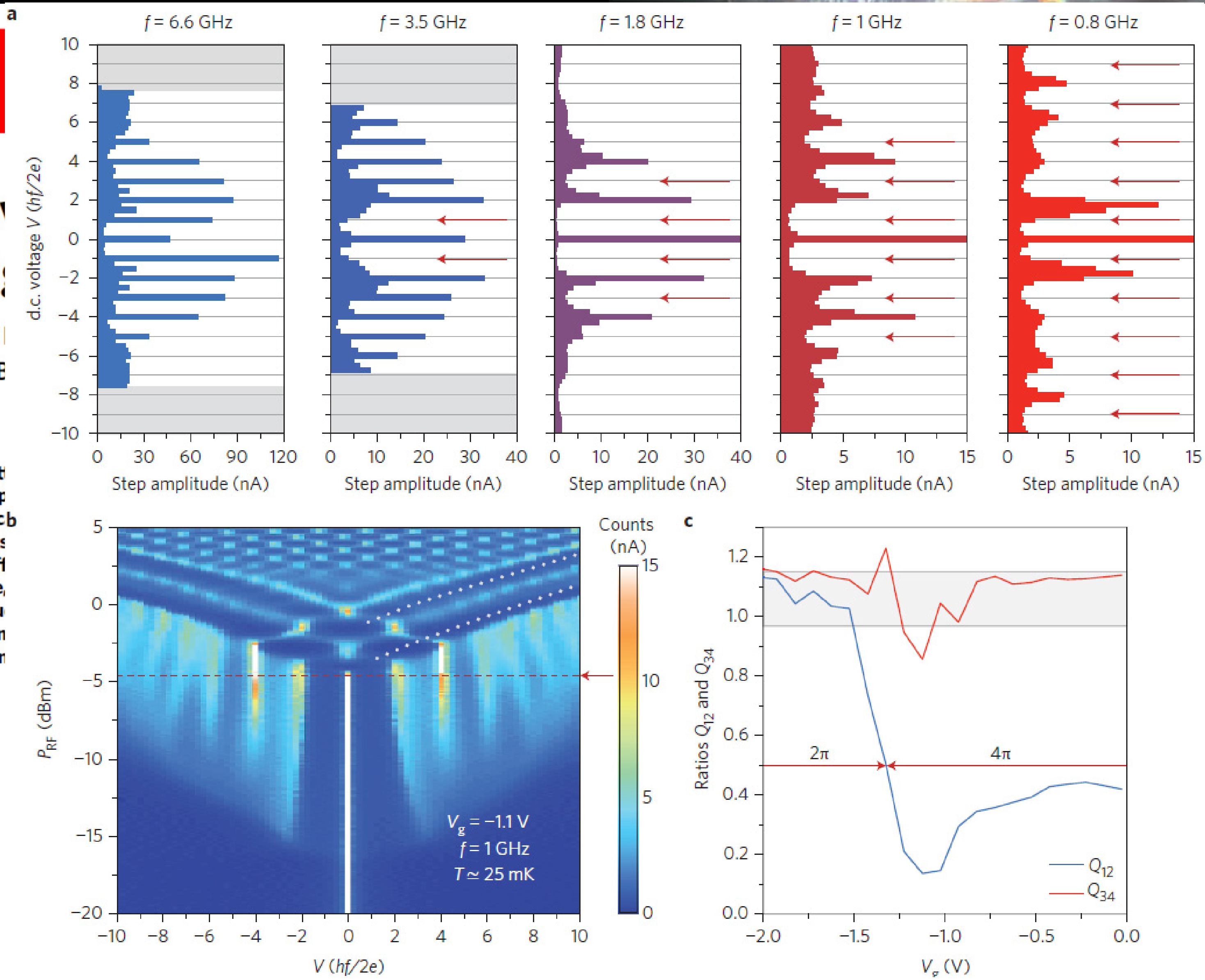
Search for $\omega_e = eV/\hbar$ (literature)

nature nanotechnology

Gapless Andree[...]
Hall insulator H[...]

Erwann Bocquillon[1*†], Russell S. [...]
Teunis M. Klapwijk[4], Christoph B[...]
and Laurens W. Molenkamp[1]

In recent years, Majorana physics has at[...] fault-tolerant topological quantum comp[...] and electronic properties in a topologic[...] experimental evidence for topological s[...] exhibits the quantum spin Hall (QSH) eff[...] in the superconducting phase difference, [...] this response like that of a supercondu[...] 4π-periodic supercurrent originates fro[...] the QSH regime, and thus provide evide[...]

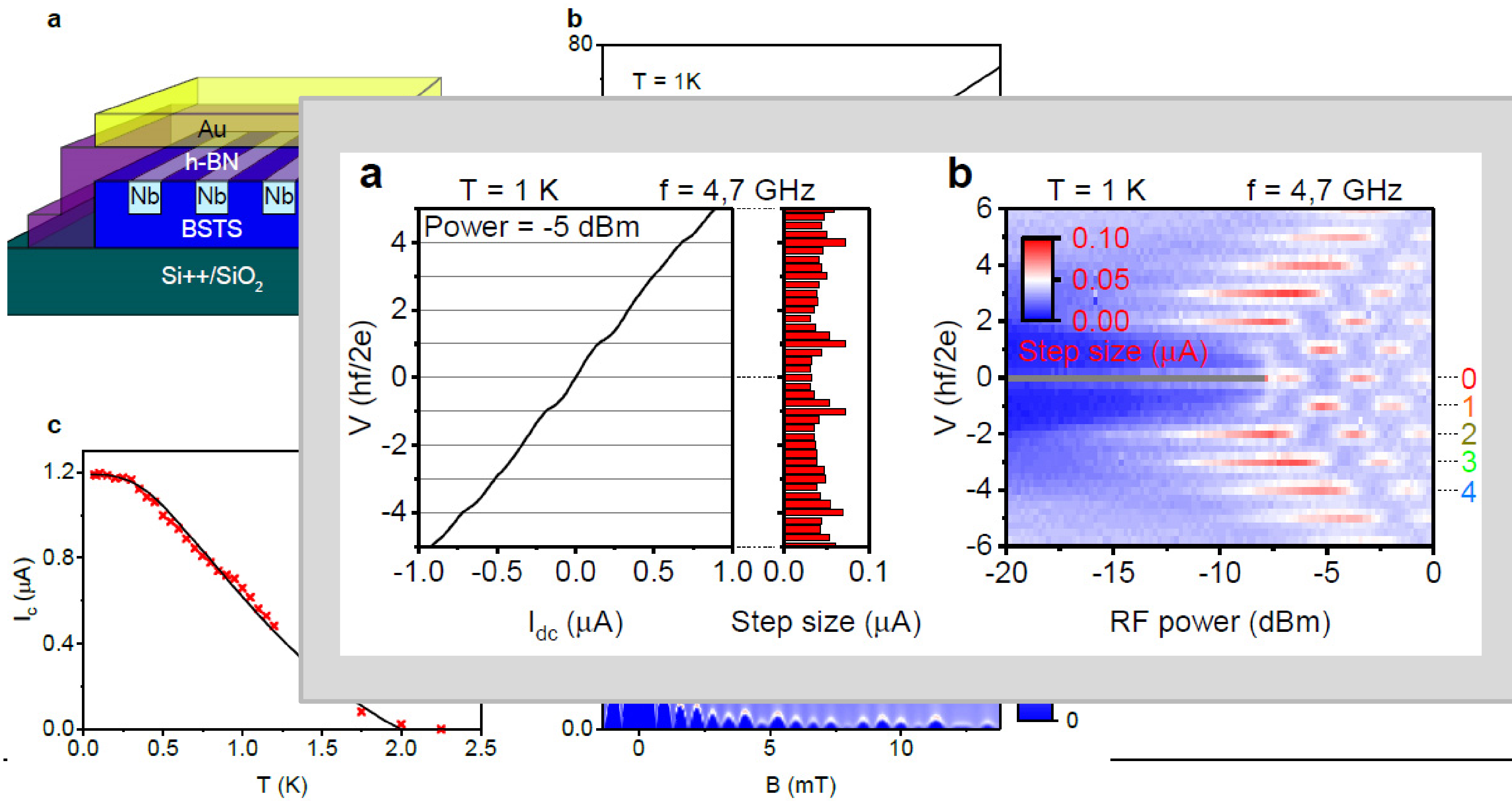


Search for $\omega_e = eV/\hbar$ (literature)

Article

Induced Topological Superconductivity in a $BiSbTeSe_2$-Based Josephson Junction

Bob de Ronde [1], Chuan Li [1], Yingkai Huang [2] and Alexander Brinkman [1,*]

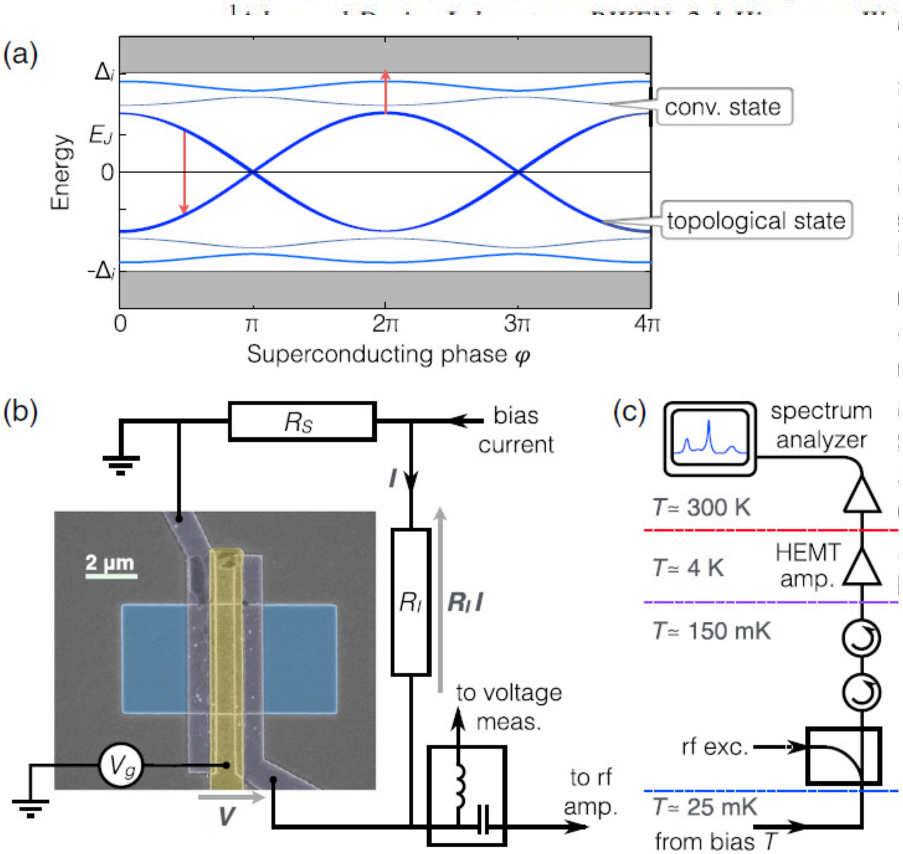


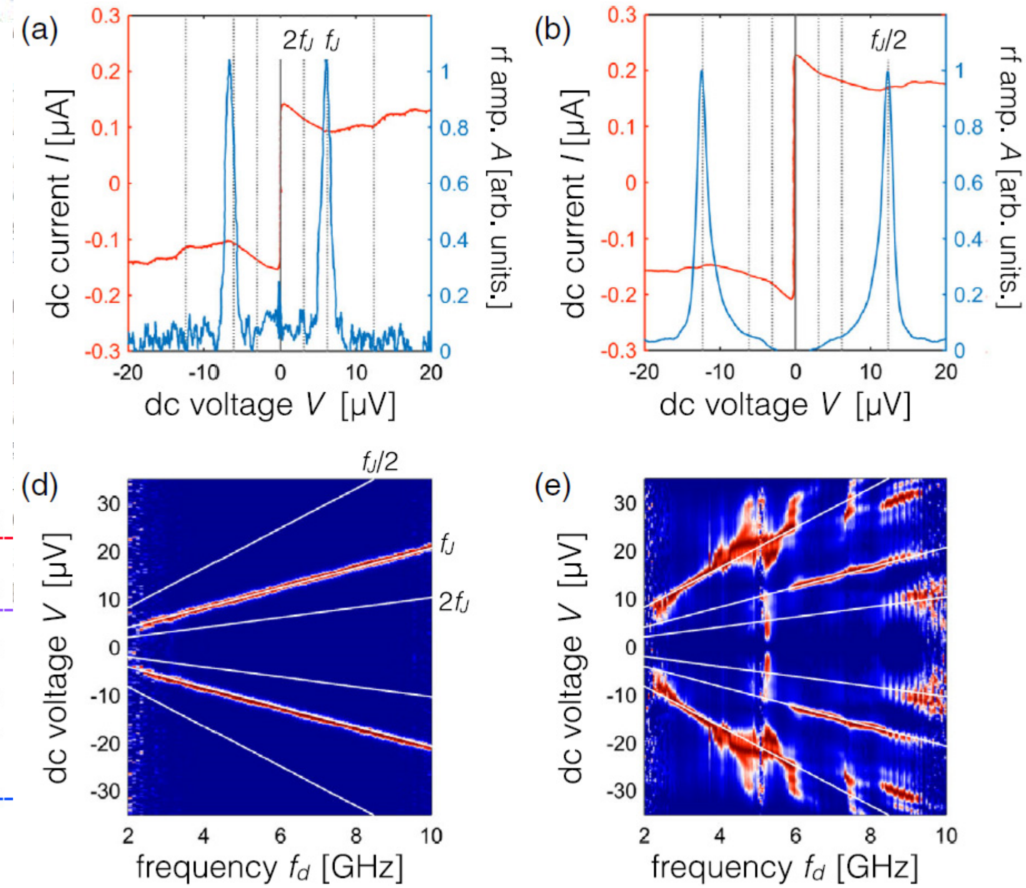
Search for $\omega_e = eV/\hbar$ (literature)

PHYSICAL REVIEW X 7, 021011 (2017)

Josephson Radiation from Gapless Andreev Bound States in HgTe-Based Topological Junctions

R. S. Deacon,[1,2] J. Wiedenmann,[3] E. Bocquillon,[3,*] F. Domínguez,[4] T. M. Klapwijk,[5] P. Leubner,[3] C. Brüne,[3]
E. M. Hankiewicz,[4] S. Tarucha,[2,6] K. Ishibashi,[1,2] H. Buhmann,[3] and L. W. Molenkamp[3]



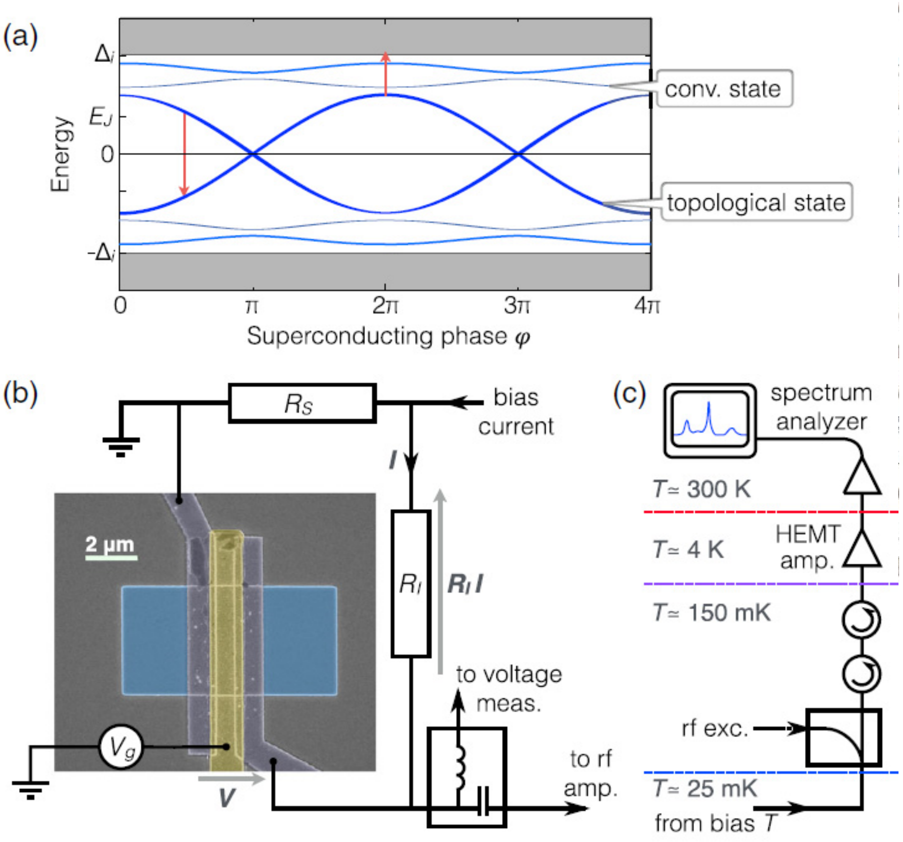


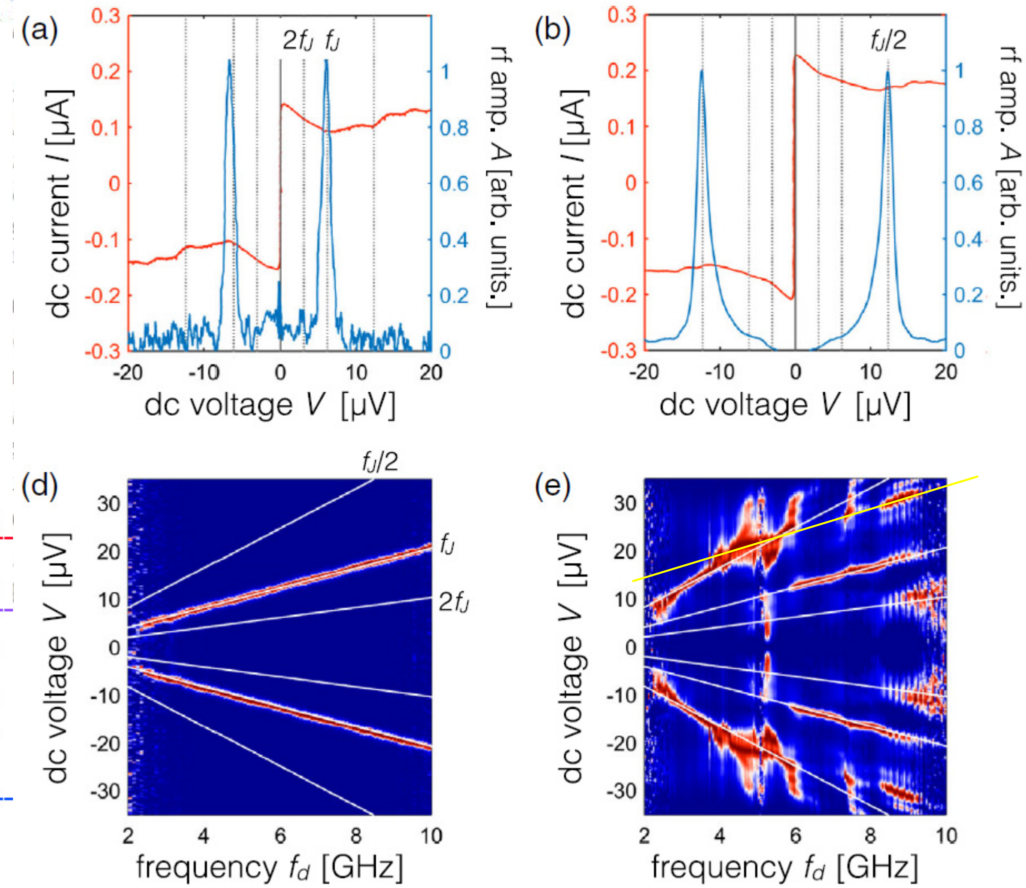
Search for $\omega_e = eV/\hbar$ (literature)

PHYSICAL REVIEW X 7, 021011 (2017)

Josephson Radiation from Gapless Andreev Bound States in HgTe-Based Topological Junctions

R. S. Deacon,[1,2] J. Wiedenmann,[3] E. Bocquillon,[3,*] F. Domínguez,[4] T. M. Klapwijk,[5] P. Leubner,[3] C. Brüne,[3] E. M. Hankiewicz,[4] S. Tarucha,[2,6] K. Ishibashi,[1,2] H. Buhmann,[3] and L. W. Molenkamp[3]





Search for $\omega_e = eV/\hbar$ (literature)

ARTICLE

Nature Comm. 10:245 (2019)

https://doi.org/10.1038/s41467-018-08161-2 OPEN

Observation of the 4π-periodic Josephson effect in indium arsenide nanowires

Dominique Laroche[1], Daniël Bouman[1], David J. van Woerkom[1], Alex Proutski[1], Chaitanya Murthy[2], Dmitry I. Pikulin[3], Chetan Nayak[2,3], Ruben J.J. van Gulik[1], Jesper Nygård[4], Peter Krogstrup[4], Leo P. Kouwenhoven[1,5] & Attila Geresdi[1]

Search for $\omega_e = eV/\hbar$ (literature)

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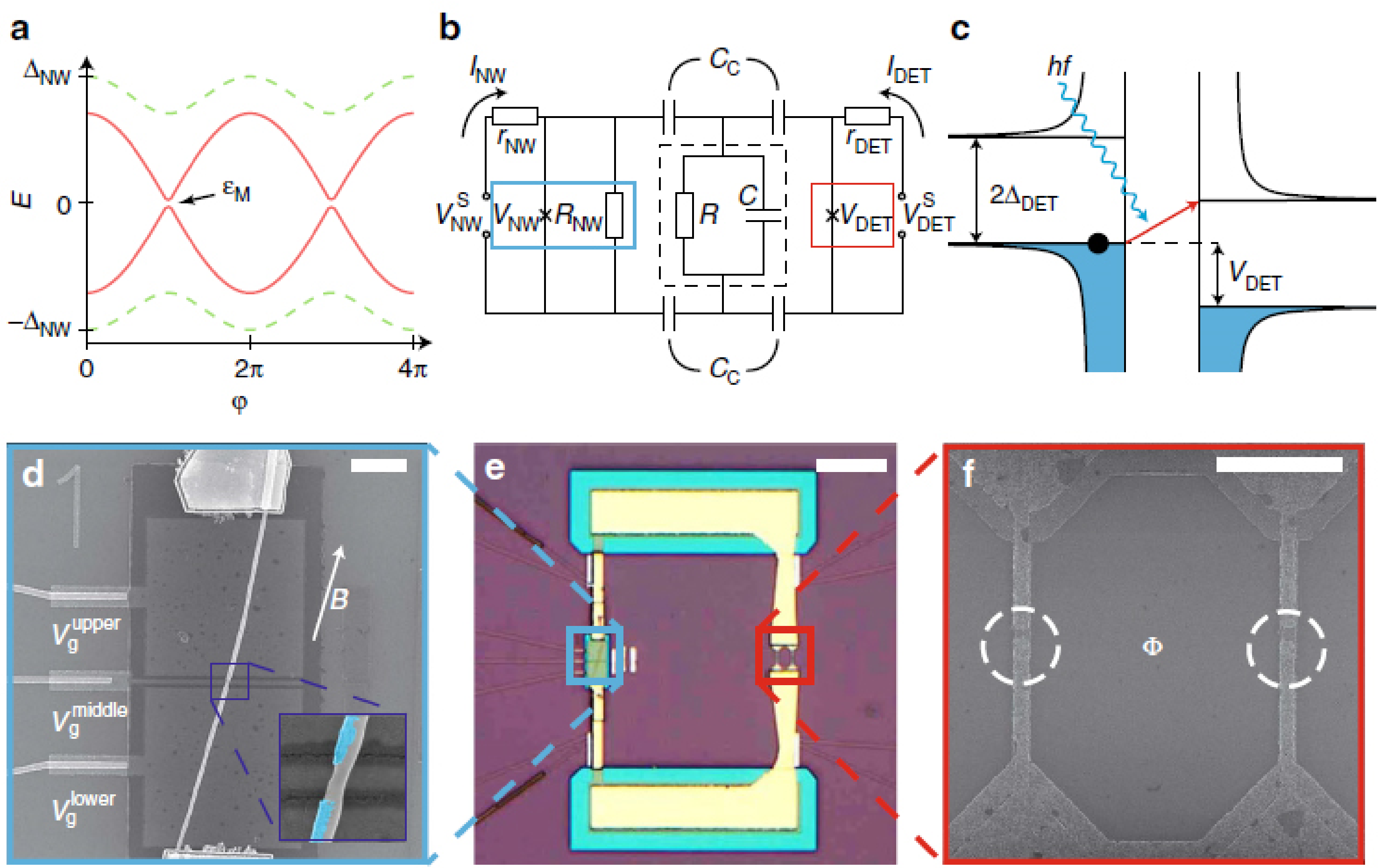
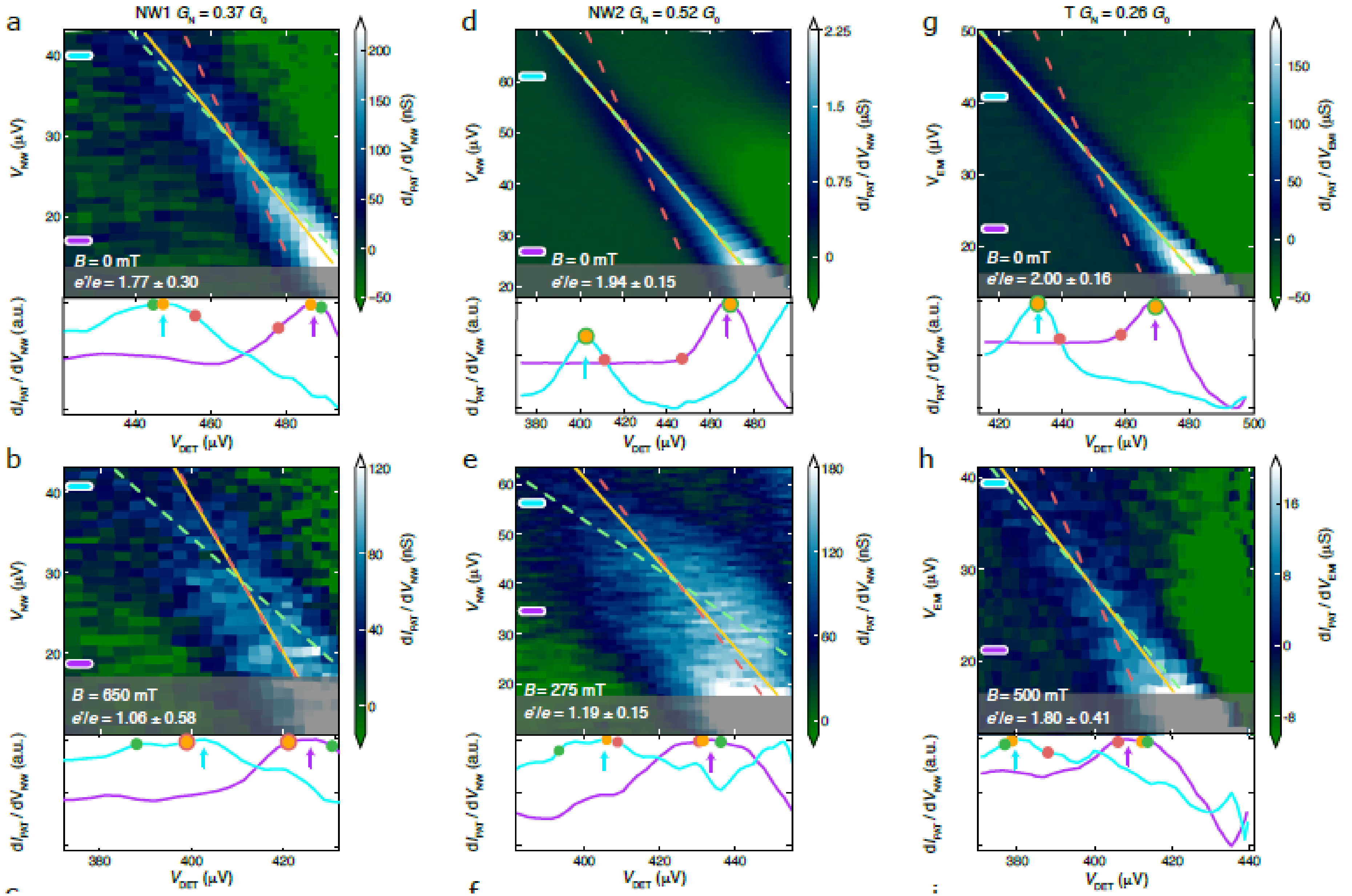


Search for $\omega_e = eV/\hbar$ (literature)

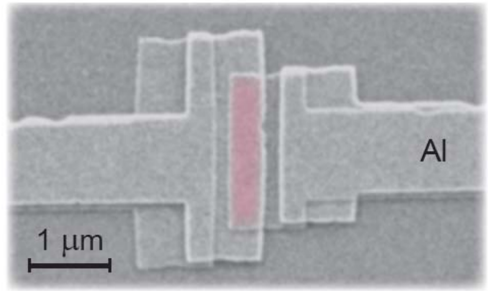


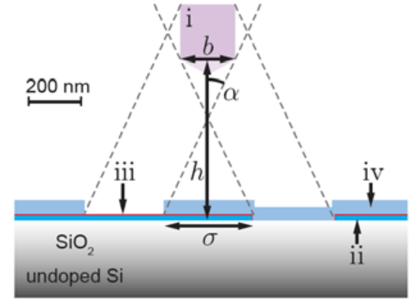
Our own Results

Device overview

Tunnel junction

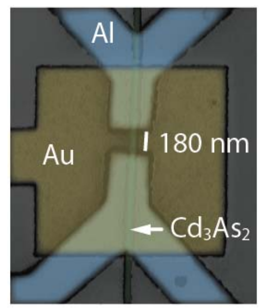
Double angle shadow evaporated **Al/AlO$_x$/Al**

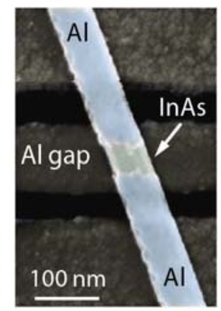




Nanowire junctions

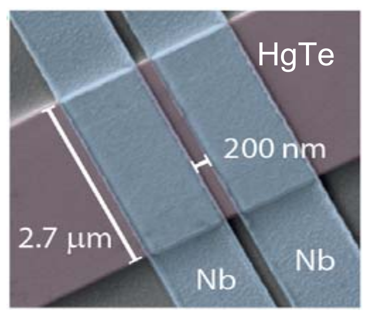
Dirac semimetal: **Cd$_3$As$_2$**
(collaboration with M. Jung)
Semiconductor: **InAs NW**

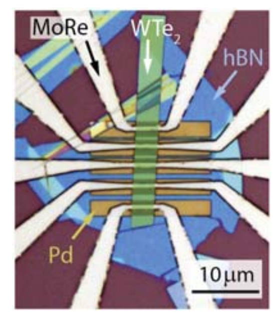




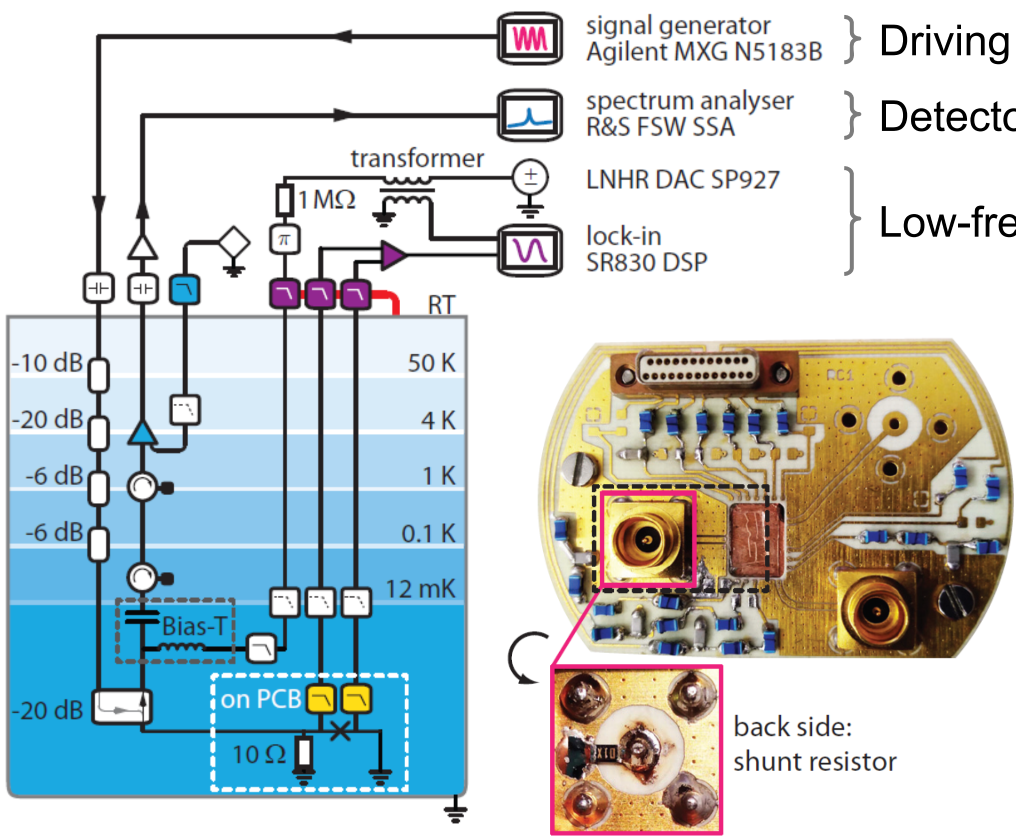
Multi-dimensional junctions

InAs 2DEG; Topological insulator**:**
HgTe (with D. Weiss' group)
Higher-order topological insulator:
WTe$_2$ with 1D hinge states





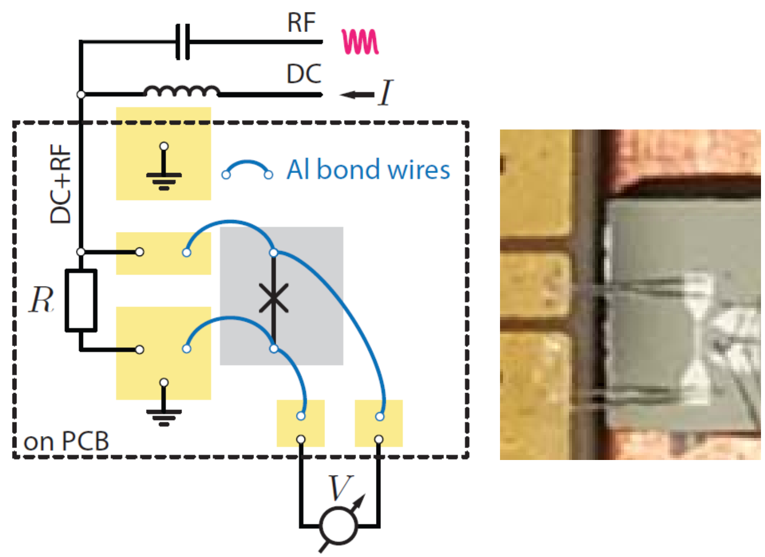
Measurement setup



} Driving source for Shapiro measurements

} Detector for the radiative power (2-8 GHz)

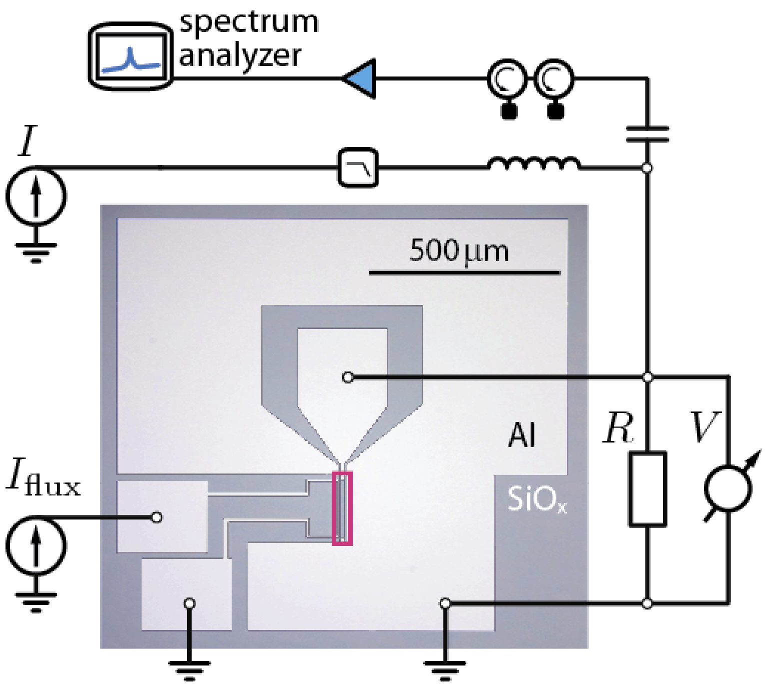
} Low-frequency biasing and probing controls

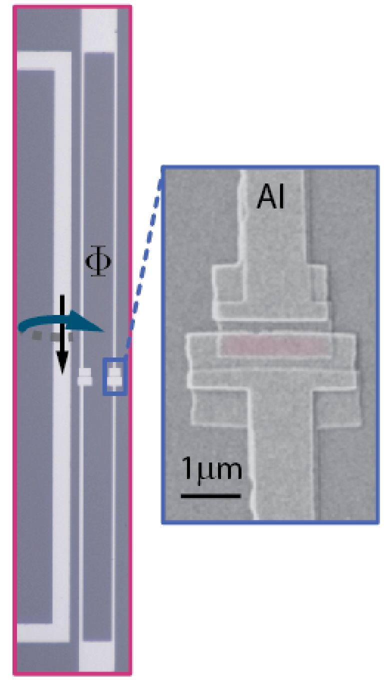


Low-ohmic metal film resistor in parallel to the junction to provide a stable voltage drop and to tune the junction into the overdamped regime.

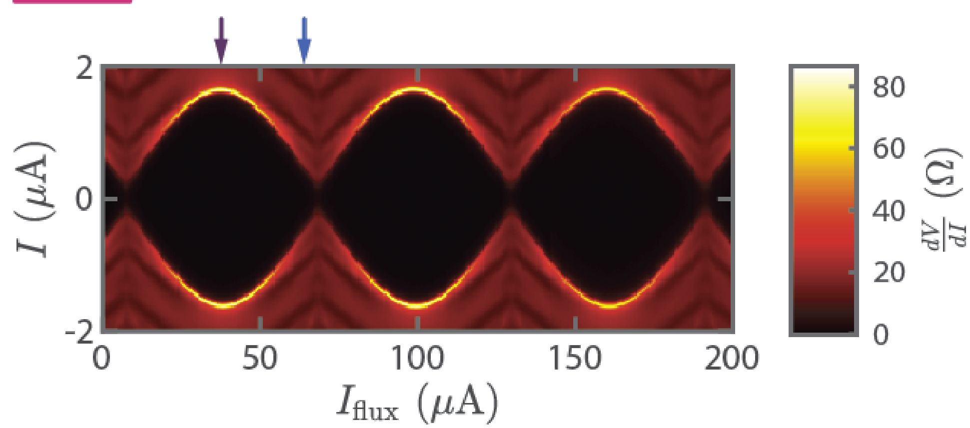
Inspired by Deacon *et al.*, PRX **7**, 021011 (2017)

Tunnel junction SQUID ($Al\text{-}Al_2O_3\text{-}Al$)



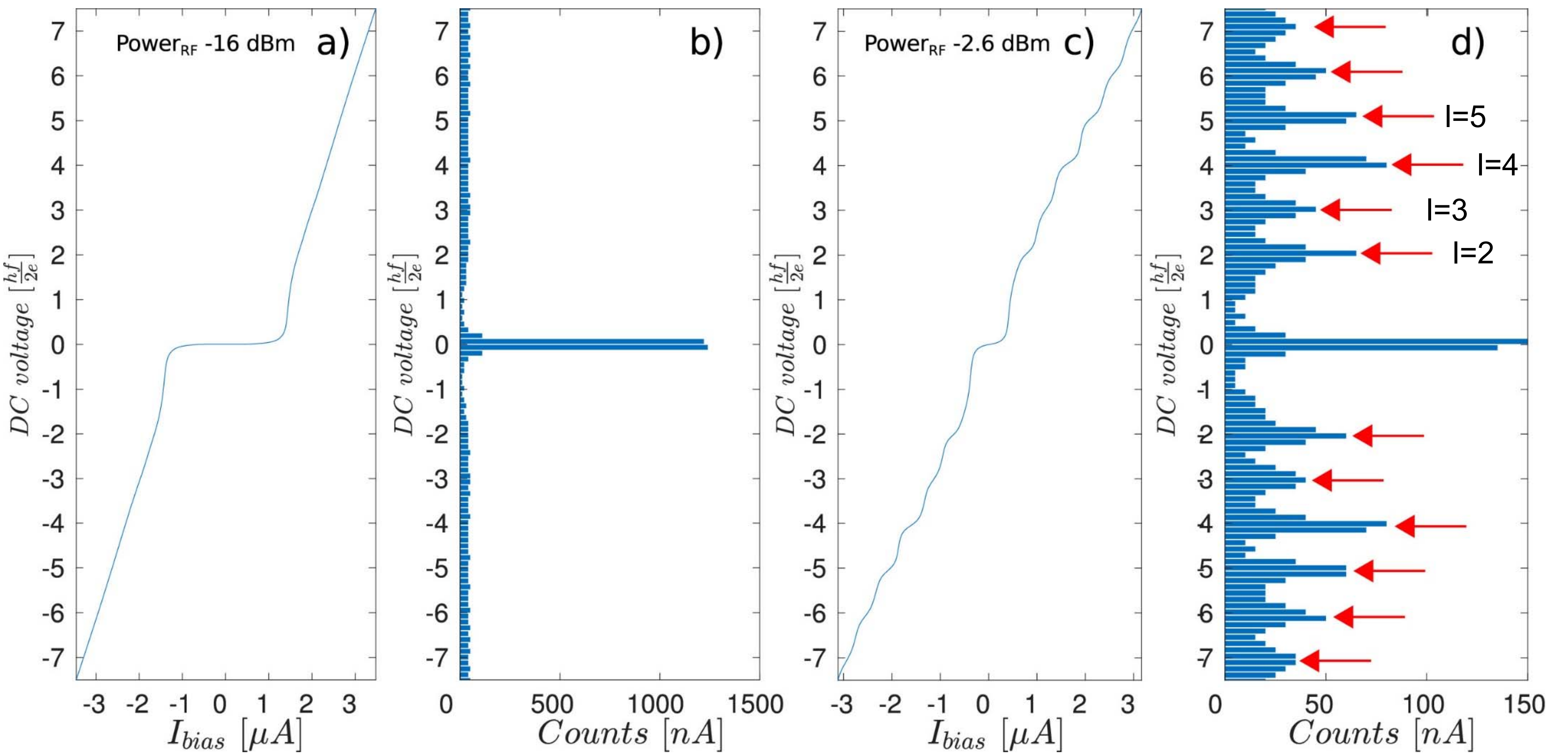


On-chip flux line allows tuning the supercurrent through the dc SQUID



PhD thesis of Roy Haller

Tunnel junction SIS: Shapiro steps

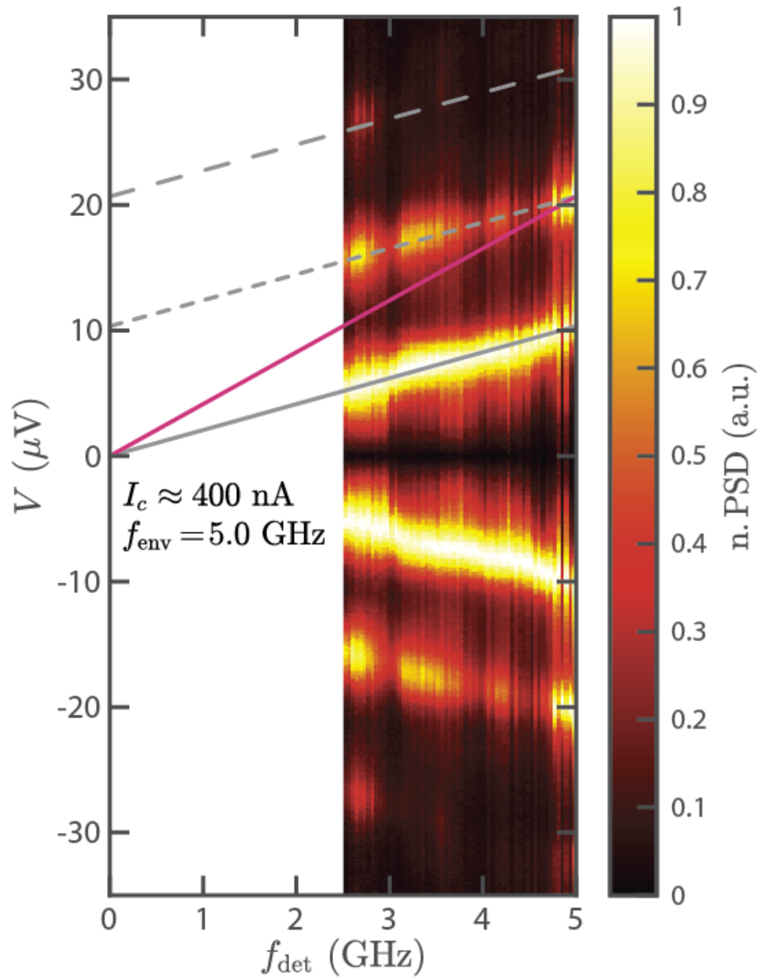


$f_{in} = 2.5\ GHz$. Note, the missing first odd step!
measurements by **Dario Sufra** et al. (master student **2018-19**)

$$V_l = l \cdot hf_{in}/2e$$

master thesis of Dario Sufra and PhD thesis of Roy Haller

Tunnel junction SIS: Josephson radiation

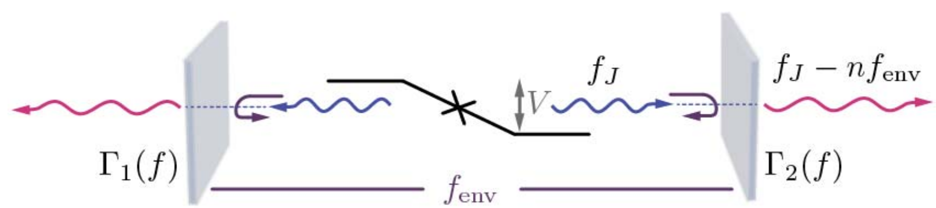


$V = \frac{h}{2e} f_{det}$ } expected 2e-peak position

$V = \frac{h}{2e}(f_{det} + f_{env})$
$V = \frac{h}{2e}(f_{det} + 2f_{env})$ } down-converted emission

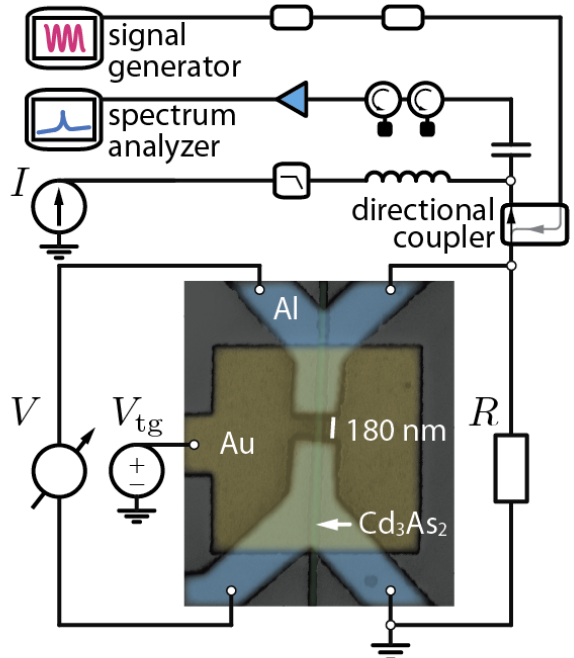
$V = \frac{h}{e} f_{det}$ } peak position of a 4π-signal

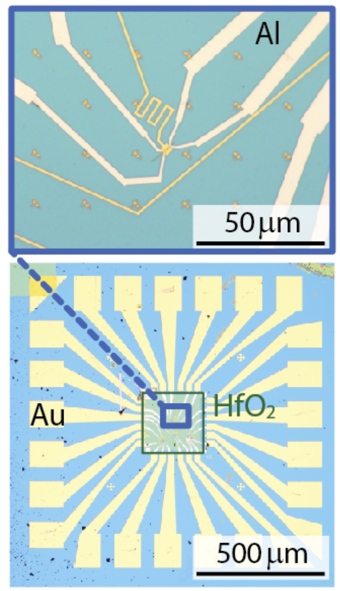
- No features of higher-order tunneling events due to low junction transparency
- No evidence of the 4π signal
- Down-conversion of the AC Josephson signal to lower energy



The energy 2eV is delivered to **two photons**, one that enters a cavity mode (environmental mode, which could be the plasma mode), the other the detector.

Nanowire JJ junction: Cd_3As_2 (Dirac SM)





- Evaporated Al leads define the junction
- Top gate structure isolated by a 20 nm thick HfO_2 layer

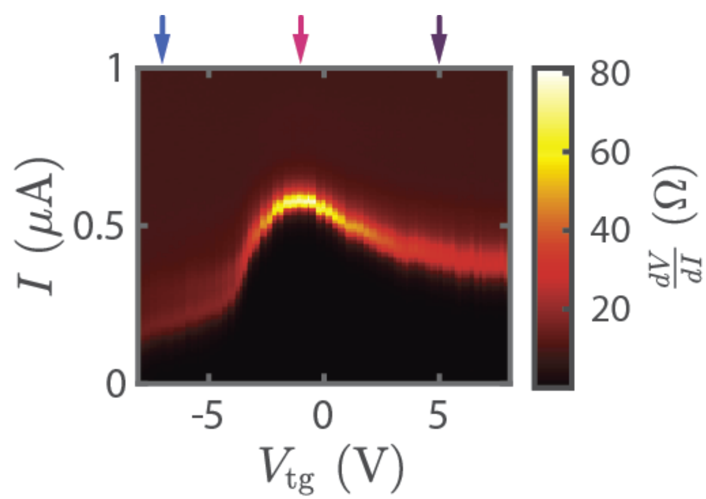
Anomalous evolution of the critical current as function of gate voltage could stem from surface scattering.

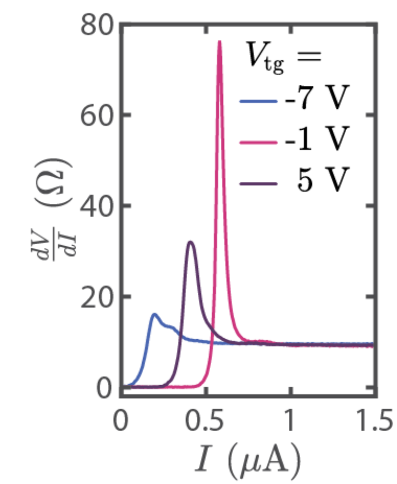
C.Z. Li *et al.*, PRB **97**, 115446 (2018)

Material platform:

- Dirac semimetal
- Ultrahigh carrier mobility
- Nontrivial surface states

A.Q. Wang *et al.*, PRL **121**, 237701 (2018)

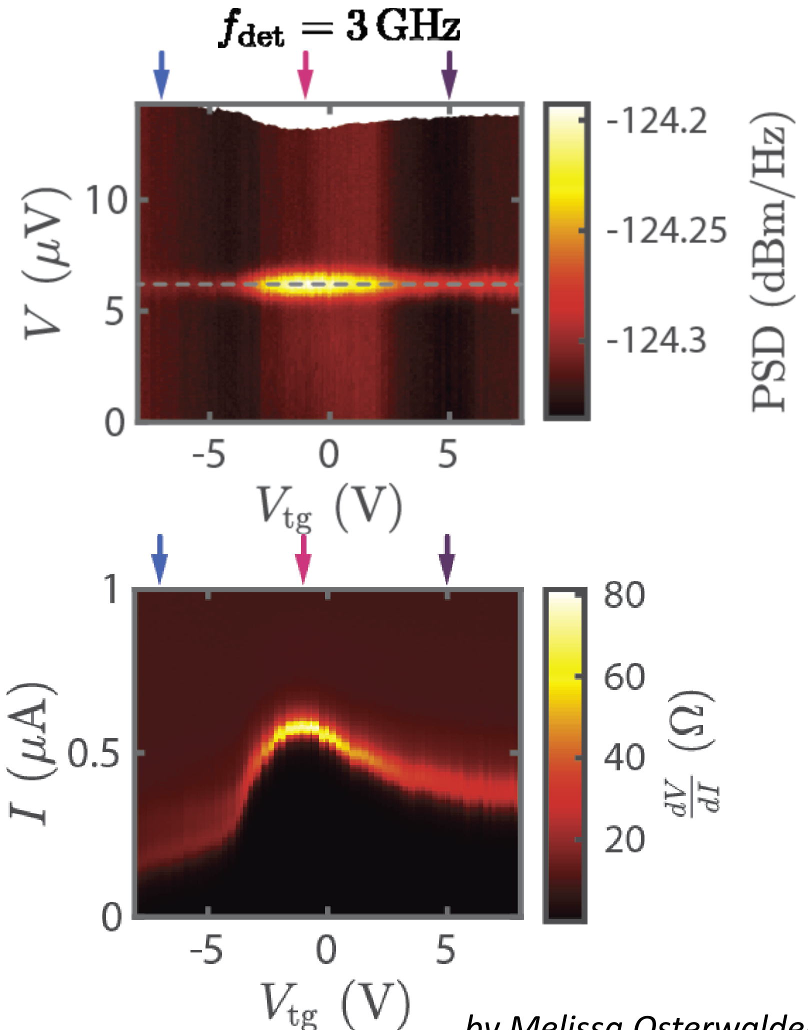




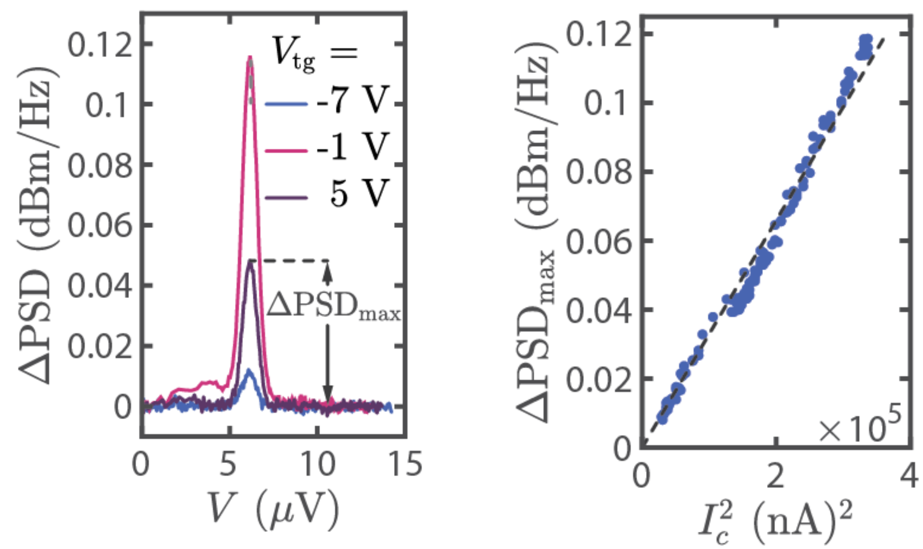
by Melissa Osterwalder ***(master student 2019)****, Roy Haller and in collab. with Minkyung Jung*

Nanowire JJ junction: Cd_3As_2 (Dirac SM)

Emission at constant detection frequency as function of top gate voltage



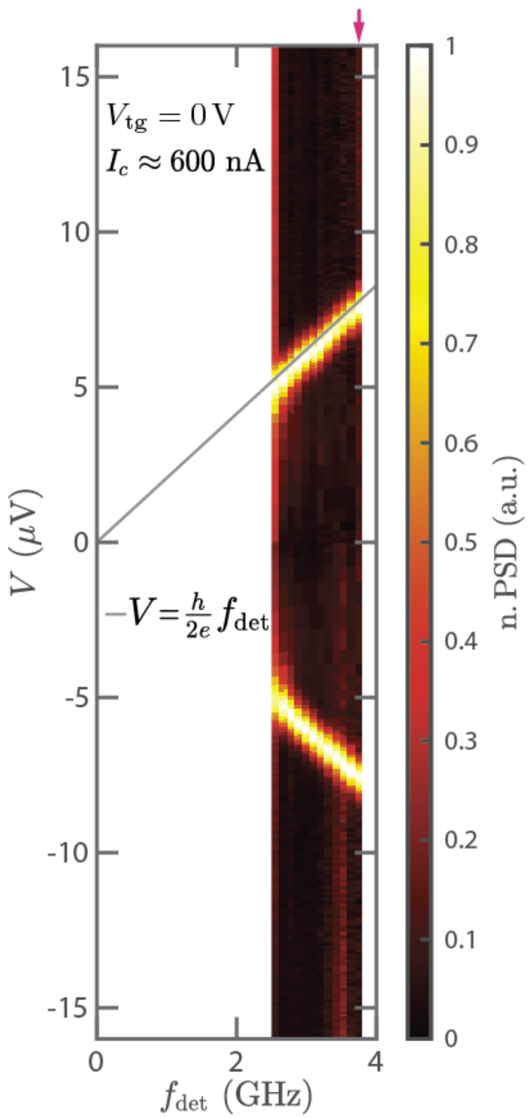
The background corrected peak height follows a quadratic power law as a function of critical current.



$$P \propto I_c^2$$

*by Melissa Osterwalder **(master student 2019)**, Roy Haller and in collab. with Minkyung Jung*

Nanowire junction: Cd_3As_2



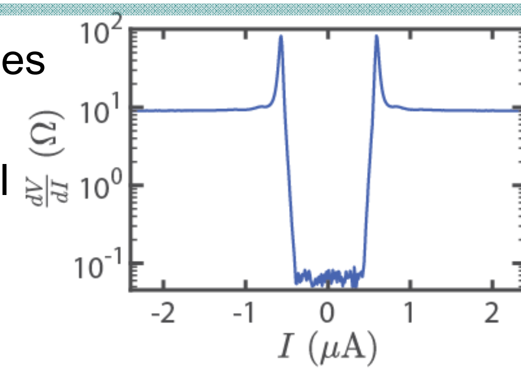
Optimized device architecture:

- Omit surrounding ground plane
- Short, continuously spreading supply lines

→ Suppression of environmental modes

No features of down-converted emission peaks

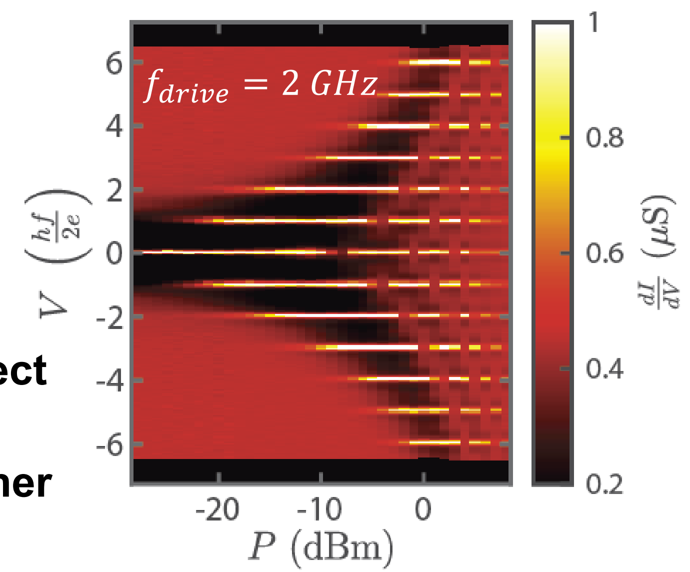
Stable differential resistance



- **No features of higher-order tunneling events**

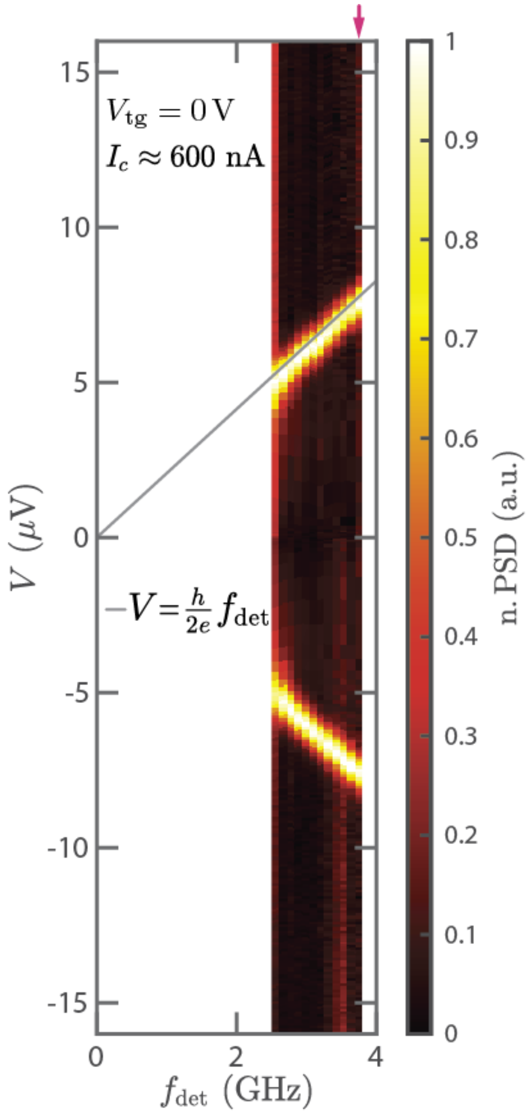
→ Sinusoidal CPR

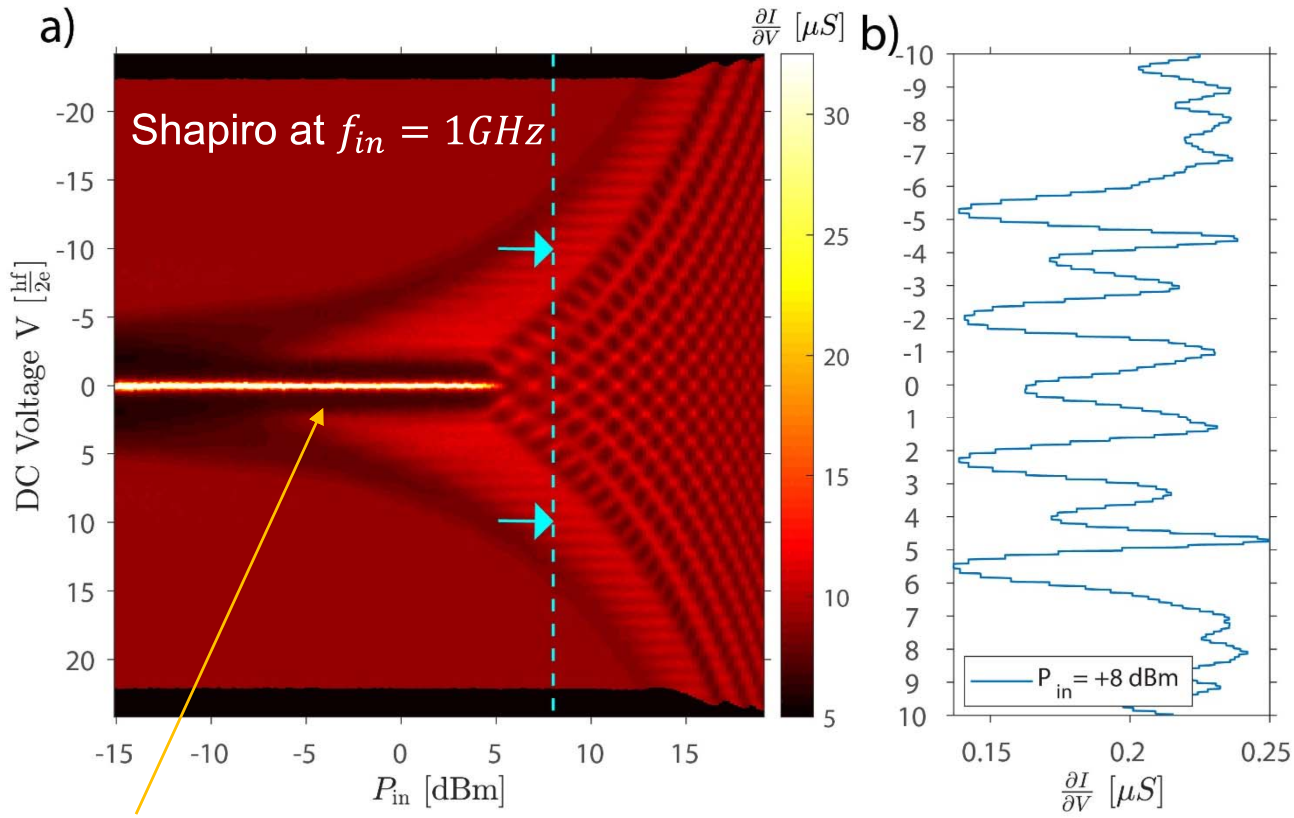
- **No fractional Josephson effect**
- **No missing Shapiro step either**



by Melissa Osterwalder ***(master student 2019)****, Roy Haller and in collab. with Minkyung Jung*

Nanowire junction: Cd_3As_2

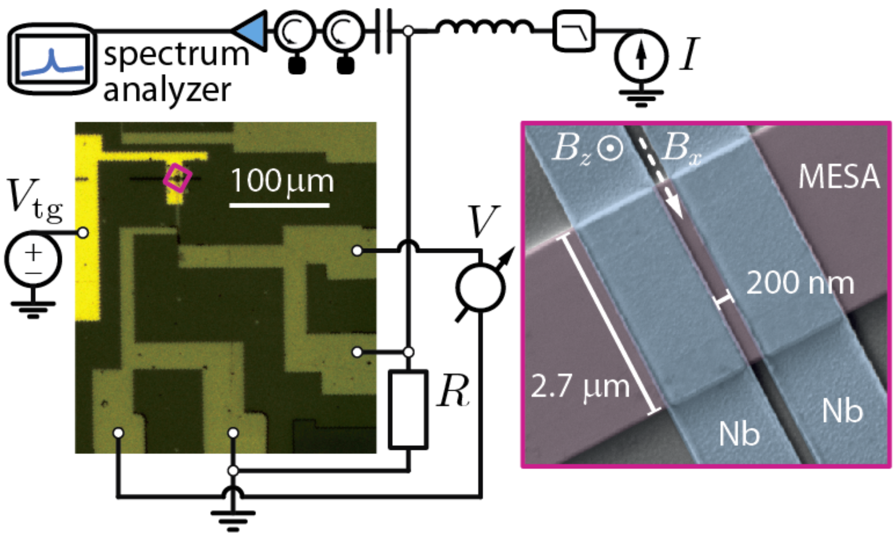


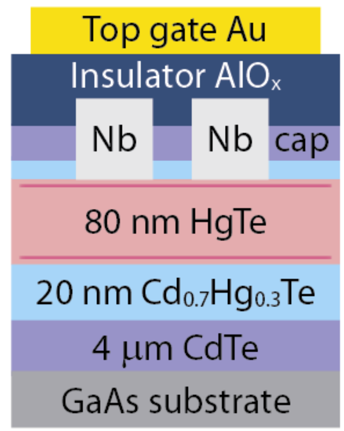


missing 1st step ?

*by Melissa Osterwalder **(master student 2019)**, Roy Haller and in collab. with Minkyung Jung*

3d HgTe TI – junction (with D. Weiss' group)





Device fabricated by Ralf Fischer from the Univ. of Regensburg, Dieter Weiss' group.

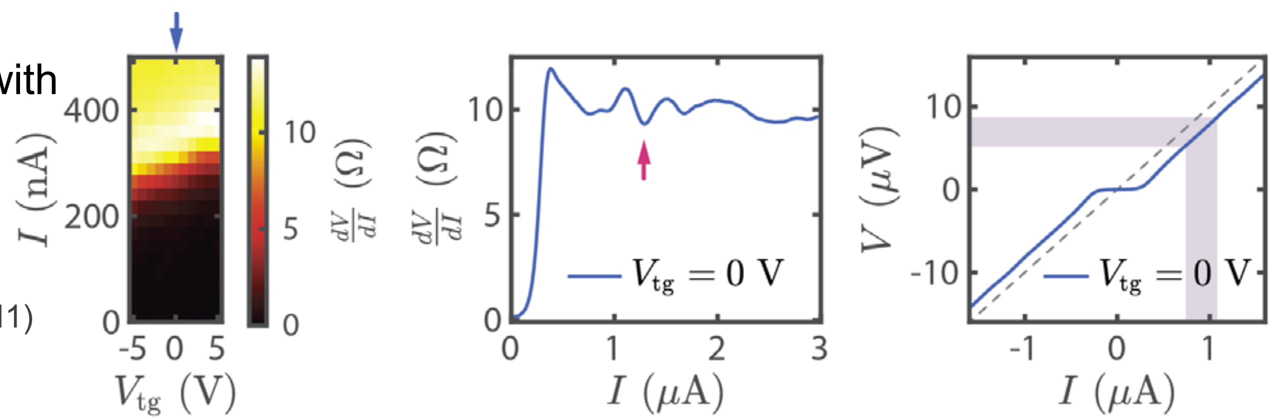
material, see:
D.A. Kozlov *et al.*, PRL **116**, 166802 (2016)

Material platform:

- **3D topological insulator**
- superconducting interacts with surface states
- possible formation of Majorana fermions

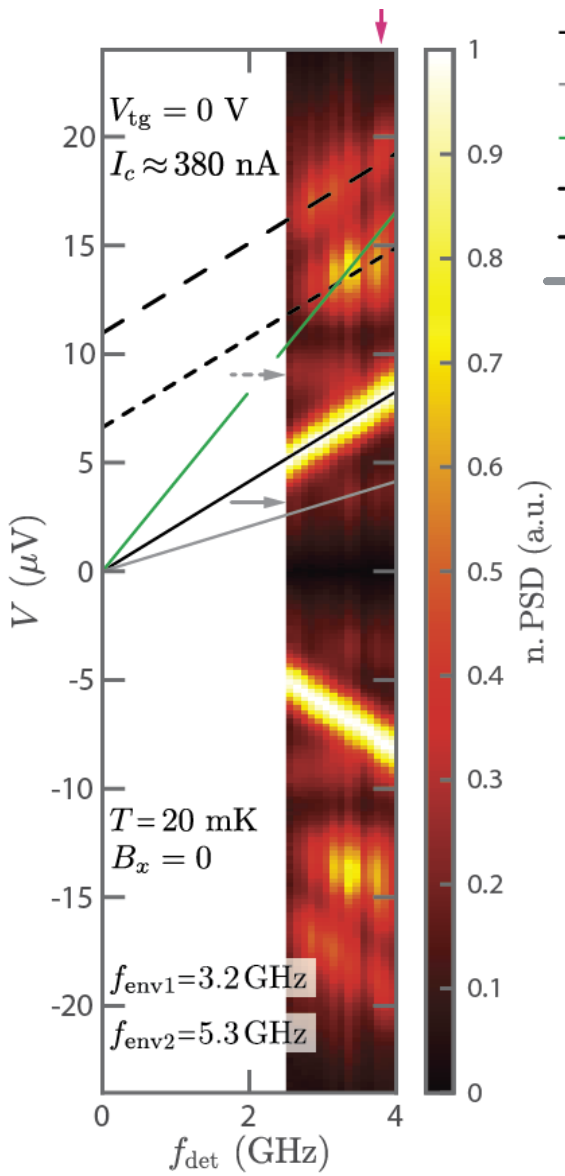
C. Brüne *et al.*, PRL **106**, 126803 (2011)

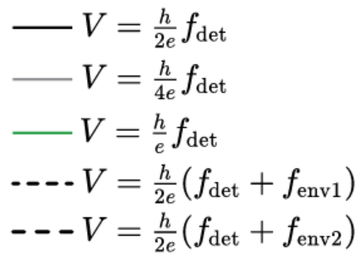
Weak gate tunability :



by Roy Haller et al. in collaboration with R. Fischer et al. (Regensburg)

3d TI junction: HgTe

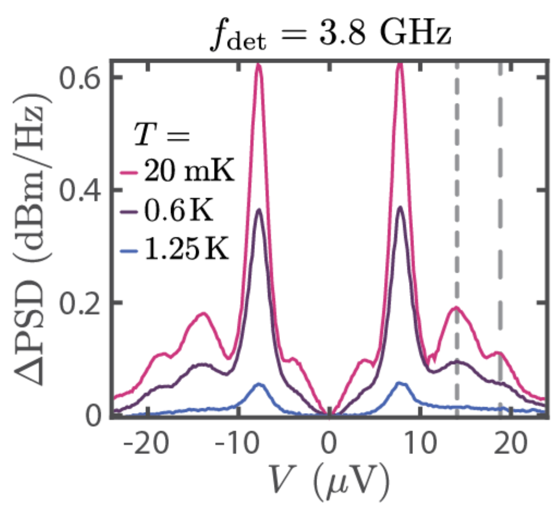


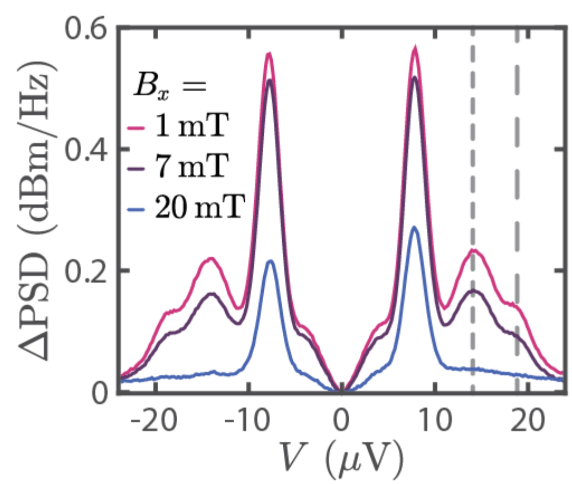


Topological 1e-emission **not** detected

- too high electronic temperature?
- bulk-contribution too large ?
- lack of sensitivity?

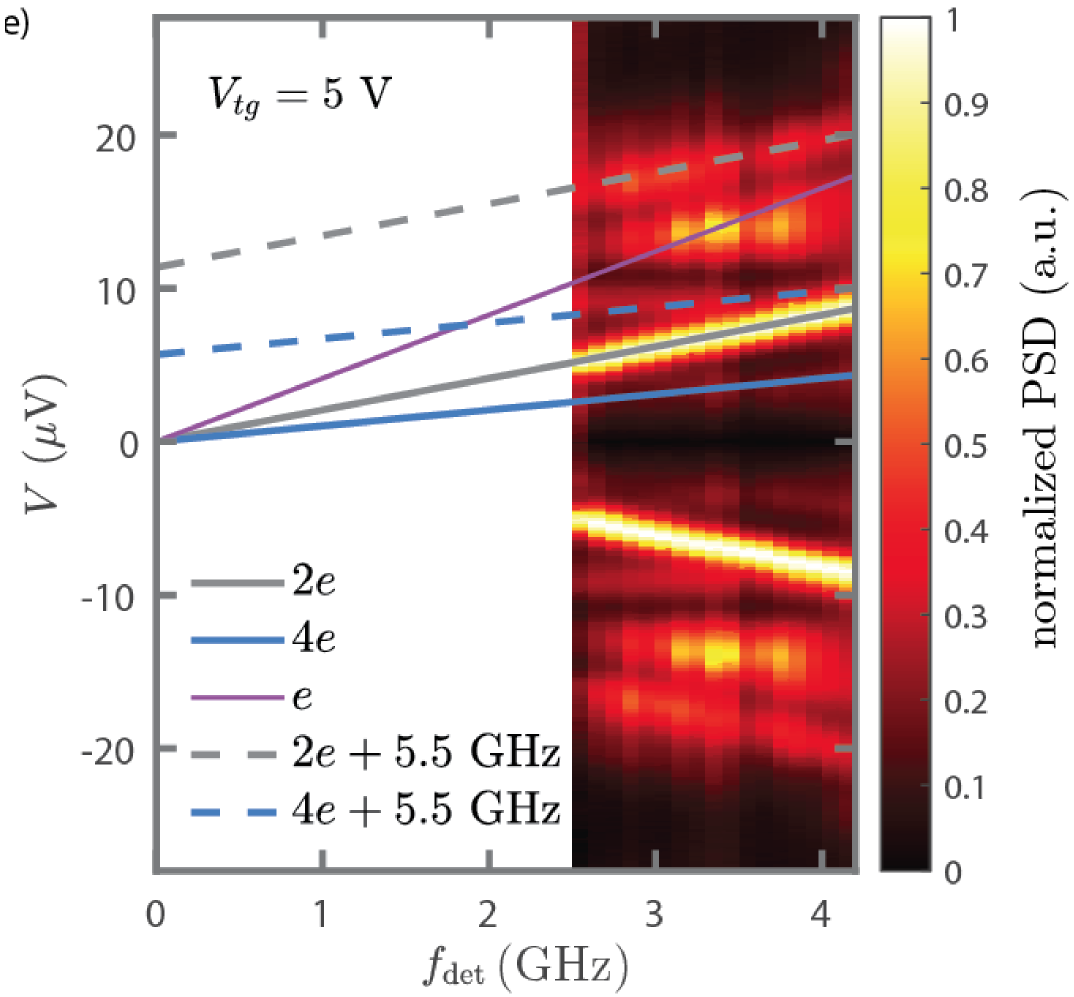
Environmental modes are suppressed at elevated temperatures and applied in-plane magnetic field

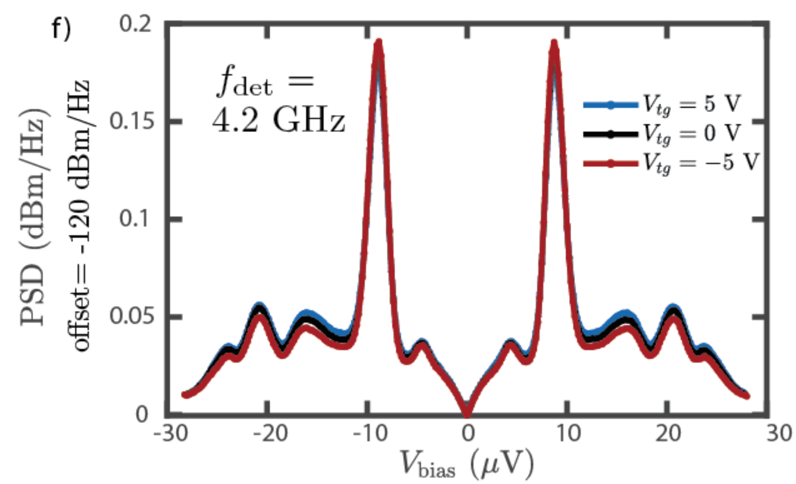




by Roy Haller et al. in collaboration with R. Fischer et al. (Regensburg)

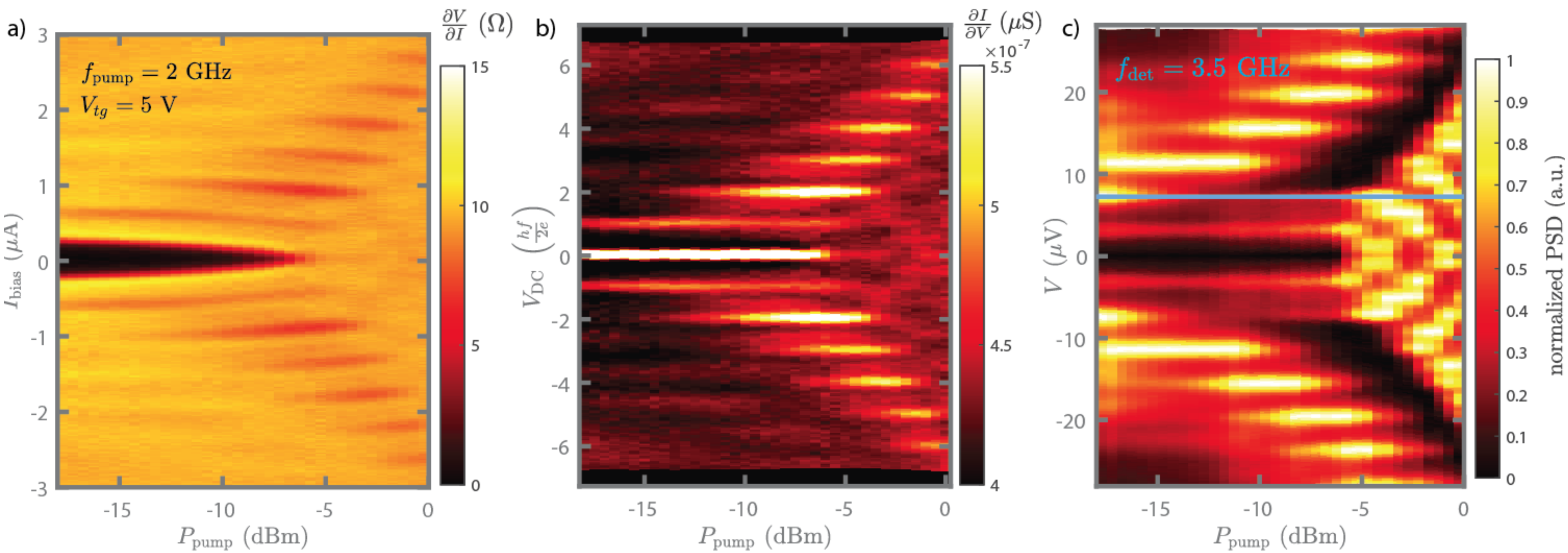
3d TI junction: HgTe





no fractional Josephson radiation !

3d TI junction: HgTe



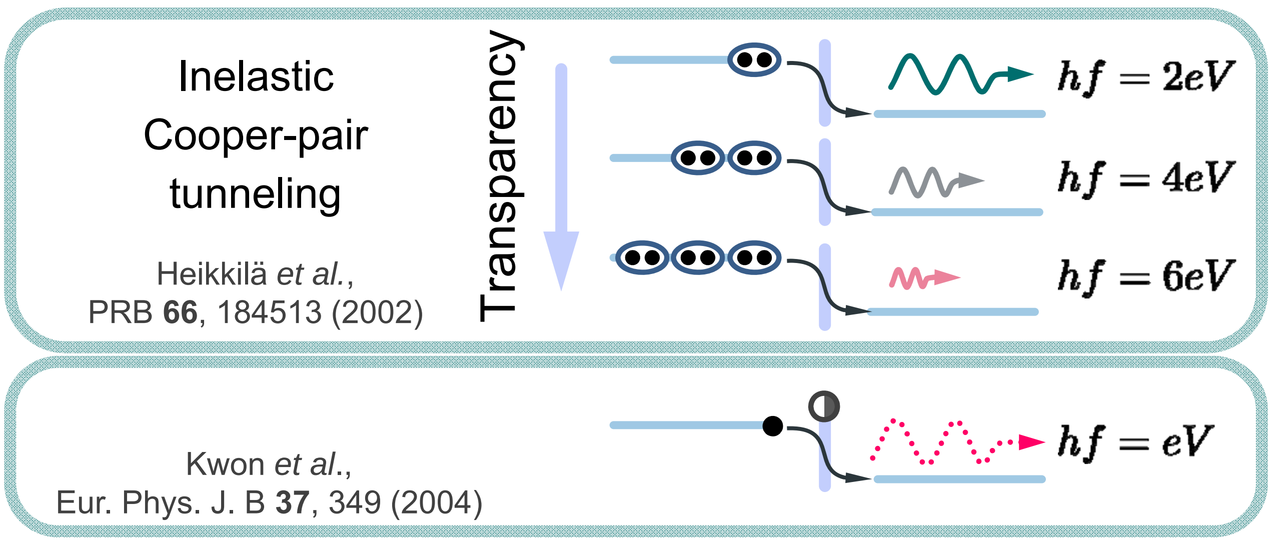
no missing steps either !

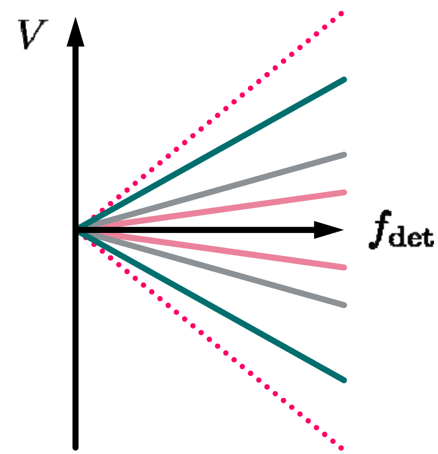
measure PSD at $f_{det} = 3.5\ GHz$ while a pump of $f_{pump} = 2\ GHz$ Is on!

by Roy Haller (unpublished)

Conclusion 1. Part

- We have studied both the **AC Josephson emission** and **Shapiro steps** mostly in the **overdamped limit of Josephson junctions** made from: Al-Al-oxide, InAs nanowires, a Dirac semimetal and HgTe 3d topological insulator a WTe_2 Weyl semimetal (or higher-order topological material) and InAs quantum well material..
- **While first odd Shapiro step can be missing** (also in trivial junctions), it reappears at high enough microwave input frequency!
- The **"fractional" AC emission at frequency $f_{topo} = eV/h$ has not been observed**, in none of the samples (until now)!
- **Reasons (?):** overheating leading to parity flipping; too large trivial "bulk" current and a not high enough sensitivity to detect the 4π signal
- What can we do? Design the RF part such that Josephson emission can be carried away "fully". Need a $10\ \Omega$ transmission line that smoothly evolves into a $50\ \Omega$





End Lecture I