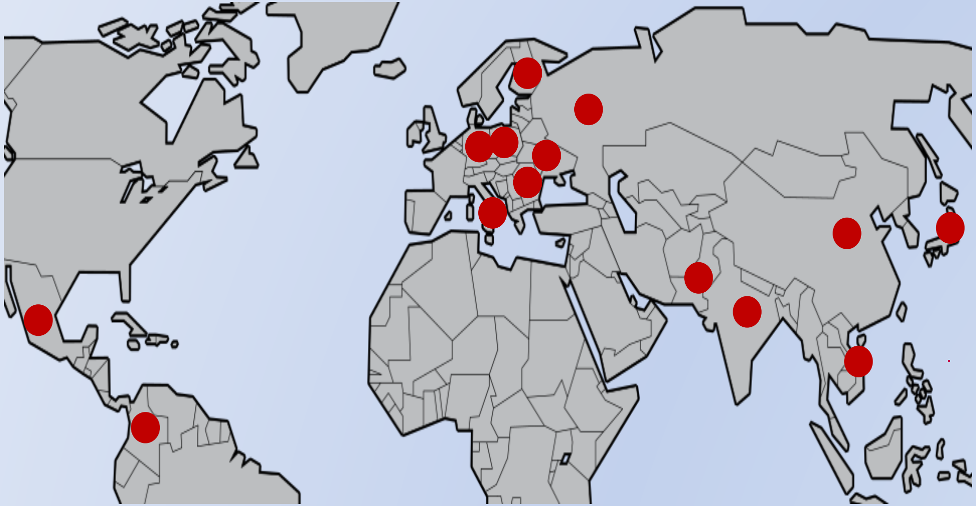
International Research Centre for Interfacing Magnetism and Superconductivity with Topological Matter MagTop at the Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

managerial success

- vibrant and friendly institution
- combines materials development, experimental and theoretical research
- extensive international collaboration with academia and industrial partners

European Funds
Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union
European Regional Development Fund

we are from 14 countries



organized in six teams

Theory

1 postdoc, 3 PhDs

Tomasz Dietl [theory + experiment]
MSc UW; PhD– Prof. at IFPAN
Ecole Polytechnique, Paris; TU Munich,
MIT, Uni Linz, Grenoble, Tohoku,
Regensburg, Orsay

MBE

1 postdoc, 2 PhDs, 1 MSc

Tomasz Wojtowicz [MBE + experiment]
MSc UW; PhD– Prof. at IFPAN
Uni Purdue, Notre Dame,
Tohoku, Regensburg

Characterization

1 postdoc, 3 PhDs

Vinayak Bhat [exper.+processing]
MSc Uni Mumbai, India
PhD Uni Kentucky
TUM, Munich,
EPFL, Lausanne

Dirac

3 postdocs, 2 PhDs

Mircea Trif [theory]
MSc Babes-Bolyai Uni, Romania
PhD Uni Basel
UCLA, Orsay, Saclay,
Tsinghua Uni, China

Weyl

1 postdocs, 2 PhDs

Marcin Matusiak [experiment]
MSc Uni Wrocław
PhD, hab. PAS Wrocław
Uni of Florida
Uni Cambridge, UK
Uni de Sherbrooke

Majorana

2 postdocs, 2 PhDs

Carmine Autieri
[computational materials science]
MSc PhD Salerno U, Italy
Jülich, Seagate (Derry), Uppsala,
SPIN-CNR (L'Aquila)

all team leaders employed only by MagTop

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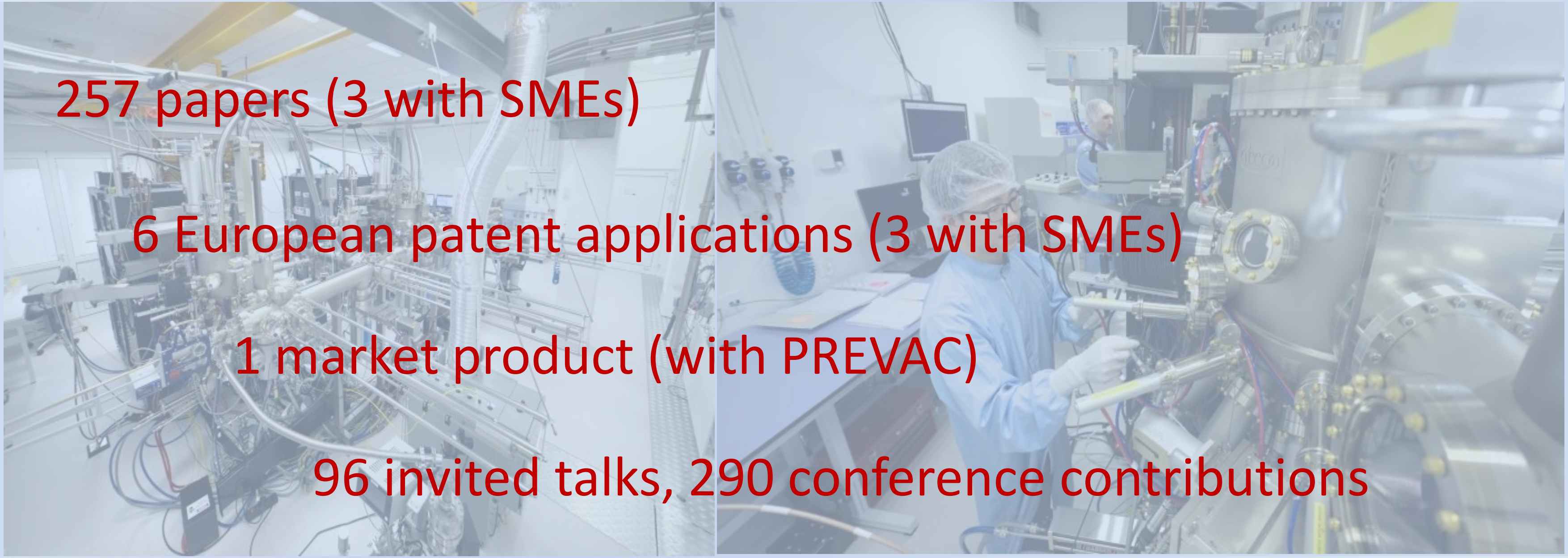
Laurens Molenkamp
THE CHAIRPERSON
Faculty of Physics and Astronomy,
Julius-Maximilians-Universität Würzburg,
Würzburg, Germany

ISC chaired by

Laurens Molenkamp
director of Institute for Topological Insulators
Würzburg

since 2017 we co-authored



257 papers (3 with SMEs)

6 European patent applications (3 with SMEs)

1 market product (with PREVAC)

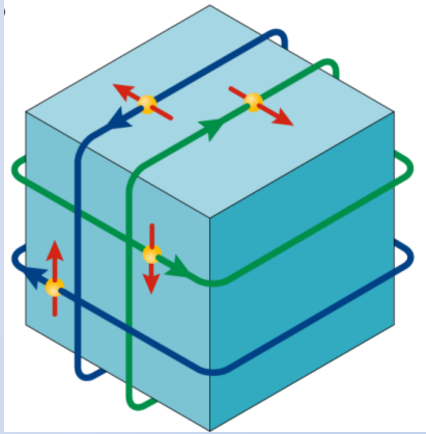
96 invited talks, 290 conference contributions

23 R & 4 D highlights, recent exemplified in **six posters**

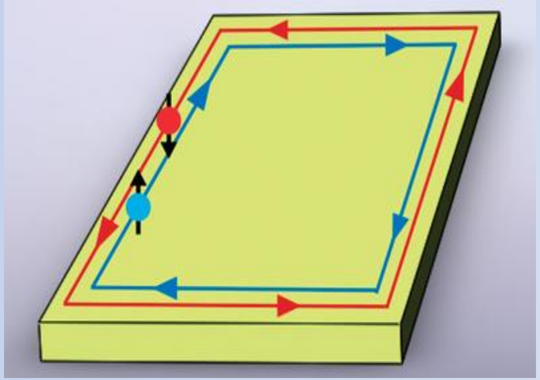
three outlined in the talk

what are we doing?

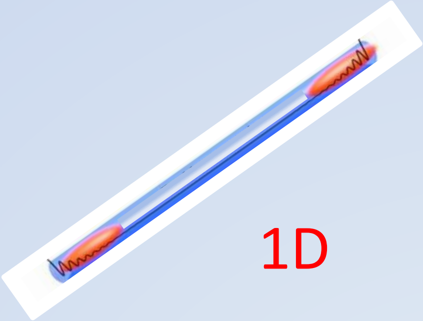
explore, interface, and functionalize Dirac, Weyl, and Majorana fermions
In materials with robust boundary states



3D

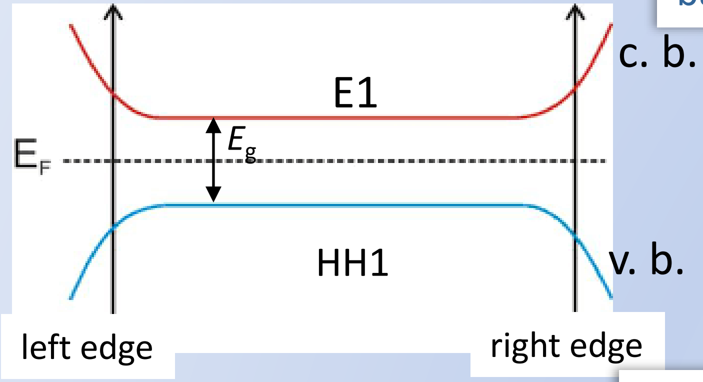


2D

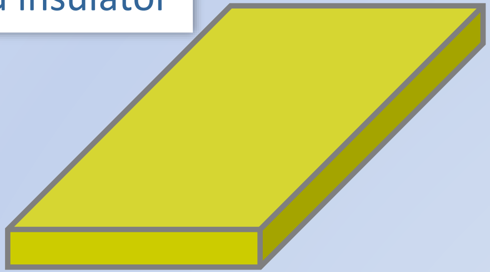


1D

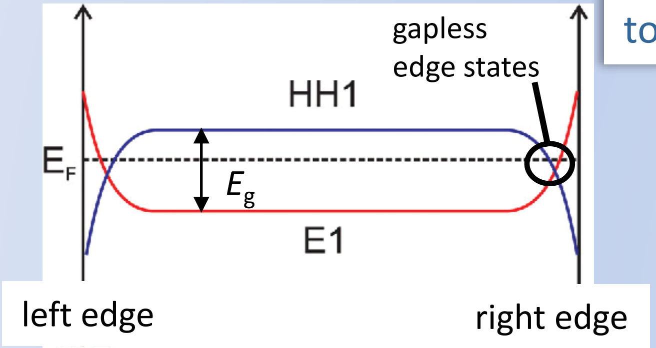
origin of edge states in topological QW

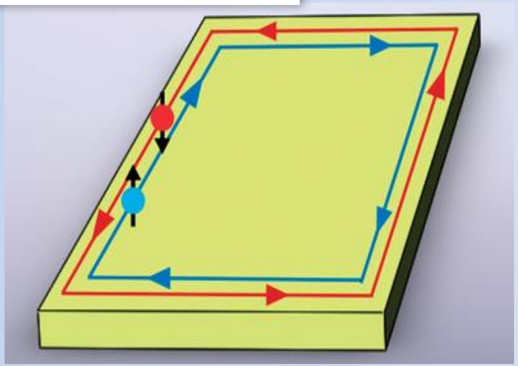


normal QW
band insulator

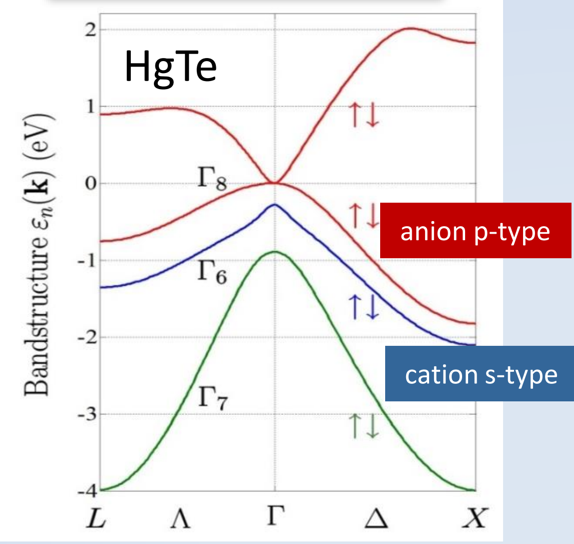


topological QW
topological insulator





inverted band order

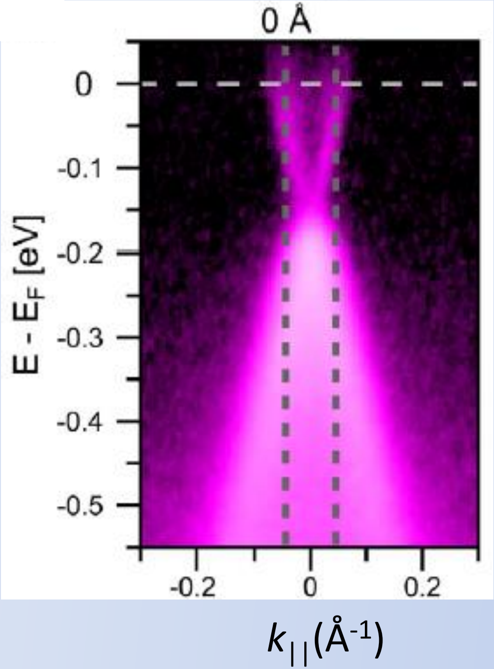


B. A. Bernevig et al. Science'2006

interfacing with magnetic and superconducting metals Valentine Volobuev poster

MBE grown n-$Pb_{0.7}Sn_{0.3}Se$

surface Dirac cone *P. Dircac (1928)*



B. Turowski *et al., Appl. Surf. Sci.* **610**, 155434 (2023)

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interfacing with magnetic and superconducting metals Valentine Volobuev poster

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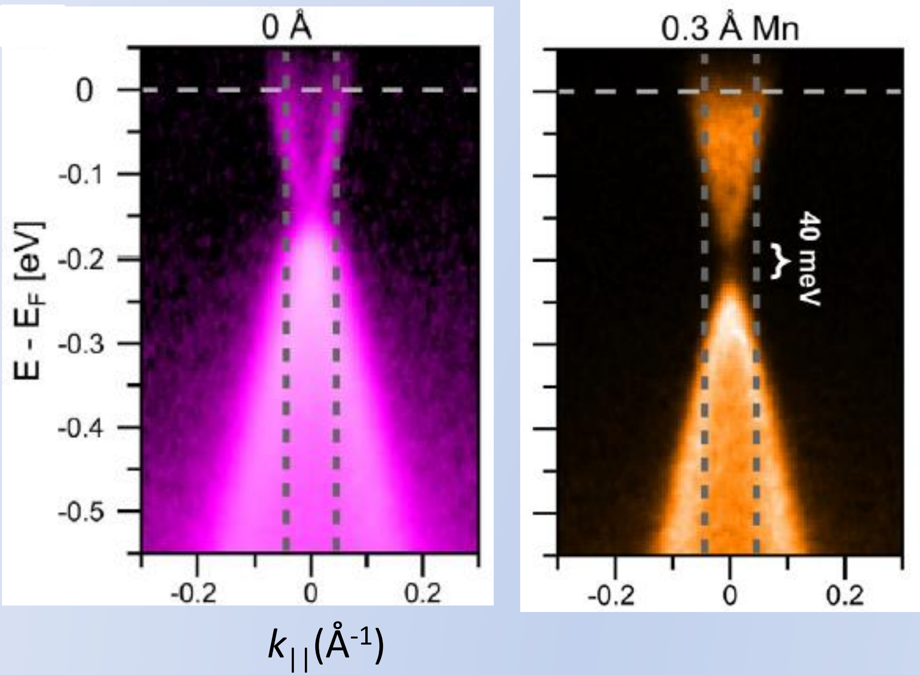

B. Turowski *et al., Appl. Surf. Sci.* **610**, 155434 (2023)

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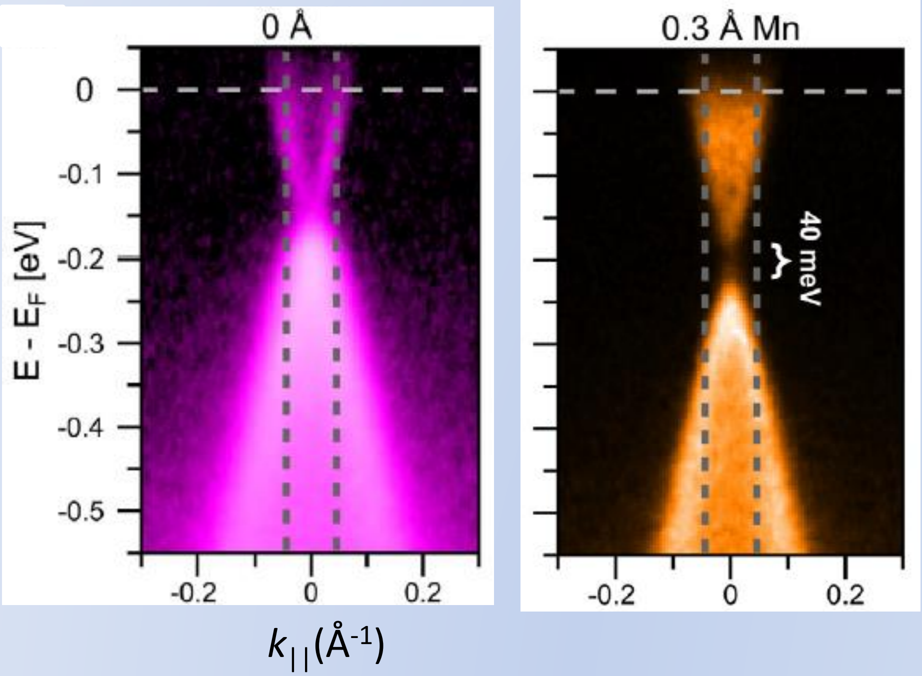
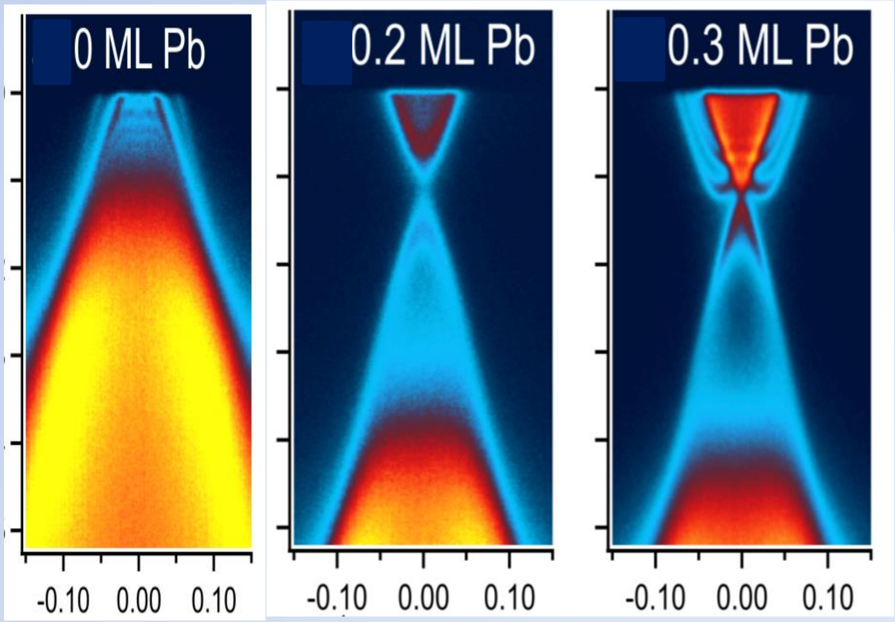


p-$Pb_{0.7}Sn_{0.3}Se$



B. Turowski *et al., Appl. Surf. Sci.* **610**, 155434 (2023)

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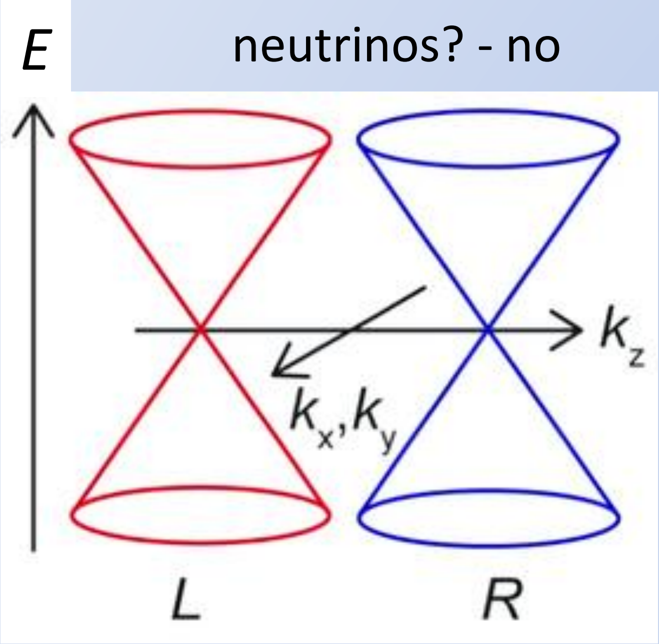
RADIATION CENTRE

Weyl fermions

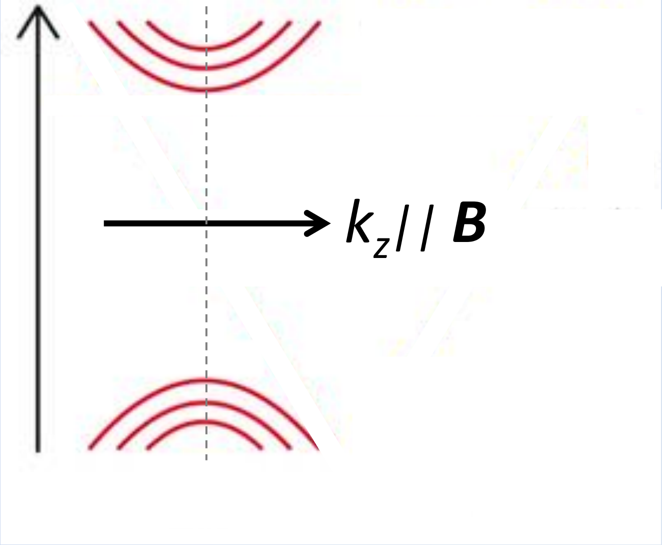
neutrinos? - no



H. Weyl (1929)

$m_{\mathrm{rest}} = 0$

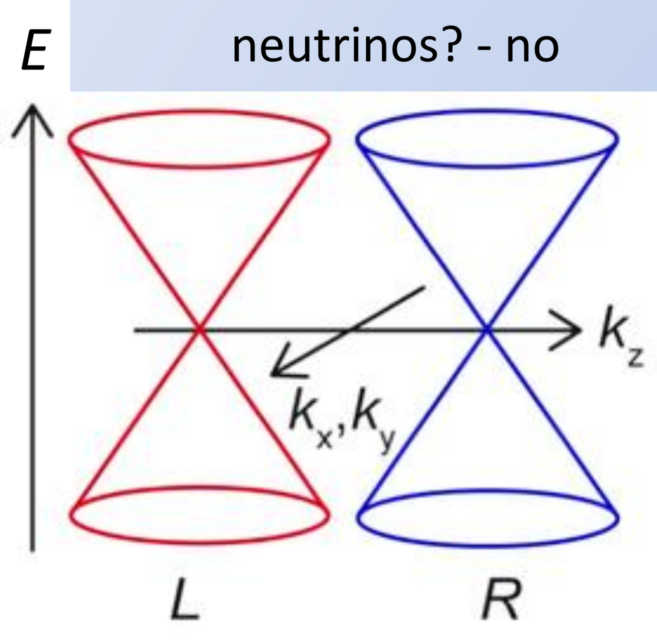
Landau levels in magnetic field



electrons and positrons

Weyl fermions in a magnetic field

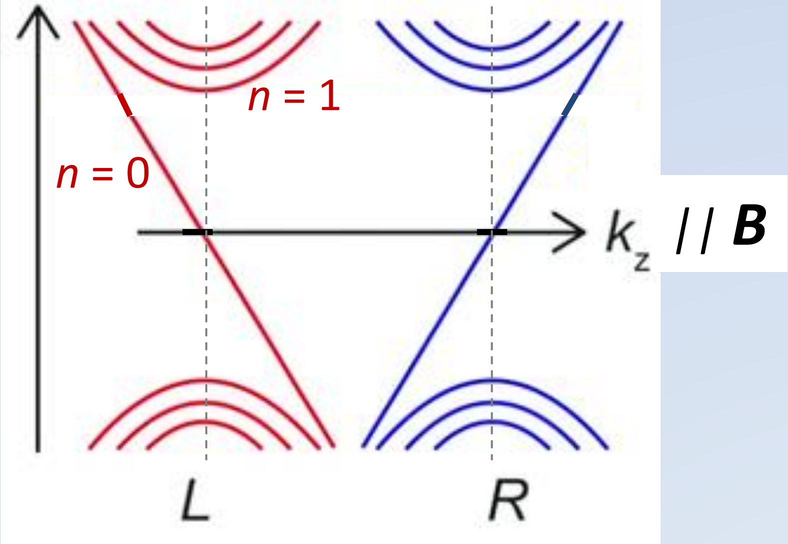
neutrinos? - no



H. Weyl (1929)

$m = 0$

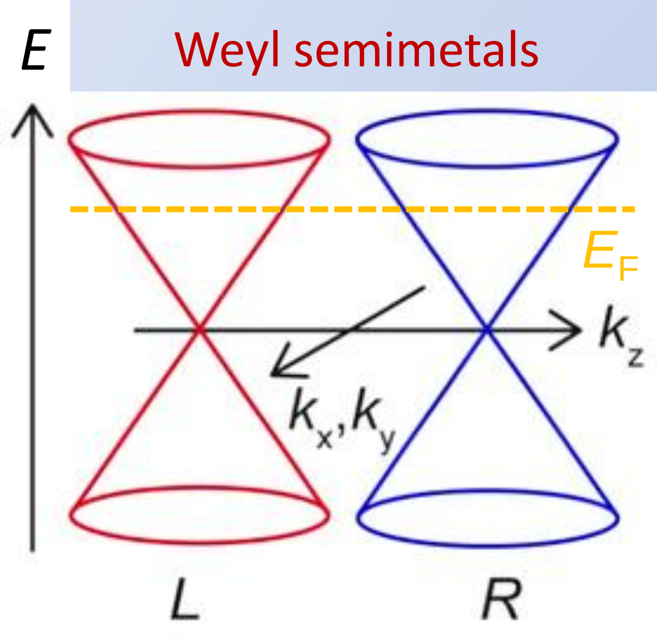
chiral anomaly



H.B. Nielsen and M. Ninomiya (1983)

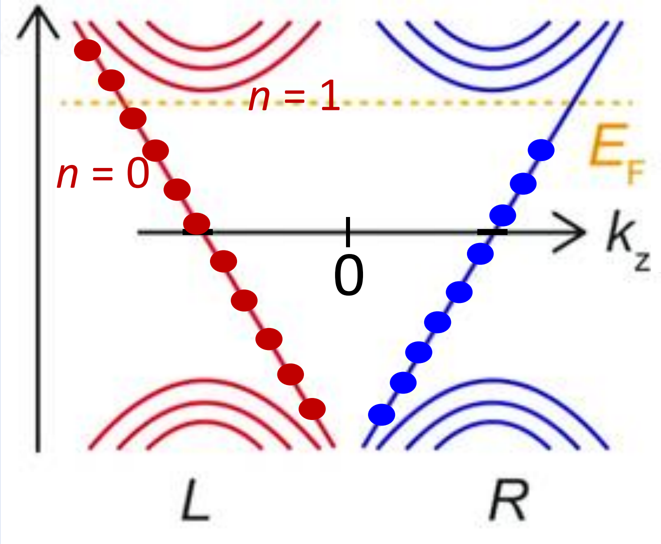
Weyl fermions Marcin Matusiak poster

Weyl semimetals



X. Wan et al. PRB'2011

thermal chiral anomaly



NdAlSi

$|| \boldsymbol{B} || \nabla T$

P. K. Tanwar *et al. Phys. Rev. B Lett.*, accepted

hunting for the God particle: Majorana

$\Psi = \Psi^{\dagger}$ *A. Majorana (1937)*

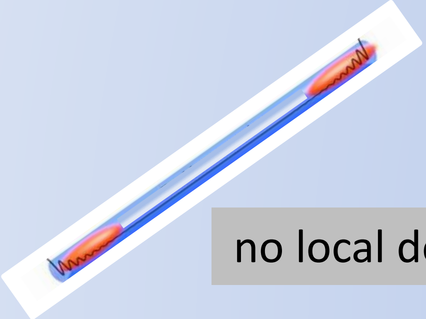
real – no dephasing

hunting for the God particle: Majorana

$\Psi = \Psi^{\dagger}$ *A. Majorana (1937)*

real – no dephasing

A. Y. Kitaev, Phys. Usp.'2001



no local decoherence

hunting for the God particle: Majorana

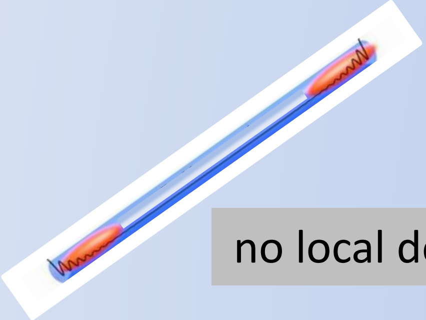
$\Psi = \Psi^{\dagger}$ *A. Majorana (1937)*

real – no dephasing

A. Y. Kitaev, Phys. Usp.'2001

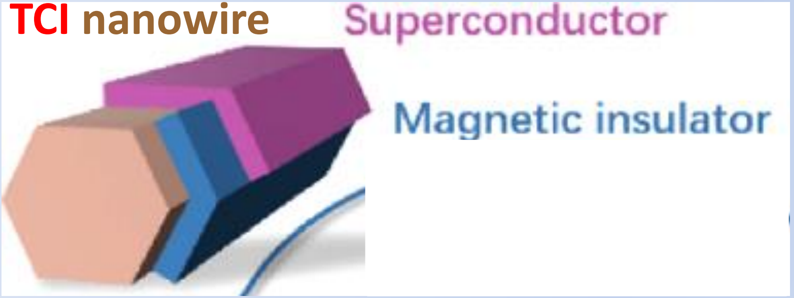
D. Castelvechi, Nature'2021

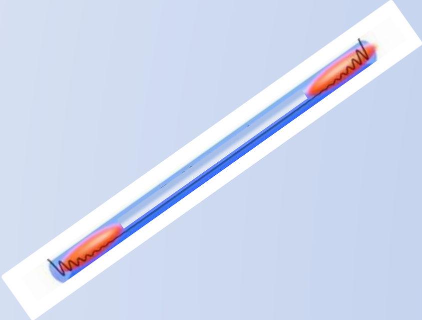
Evidence of elusive Majorana particle dies — but computing hope lives on

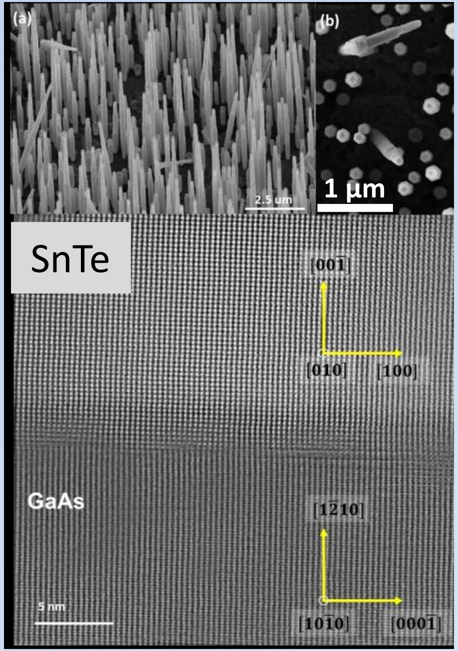


no local decoherence

hunting Majorana particles in TCI nanowires







S. Dad et al., arXiv:2211.08154

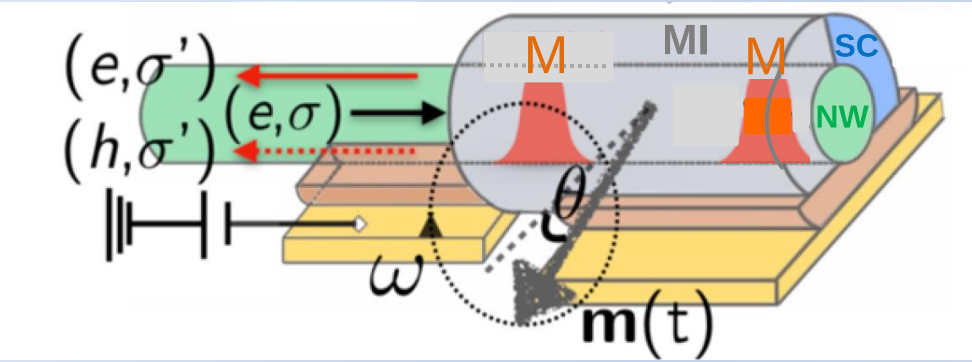
theory

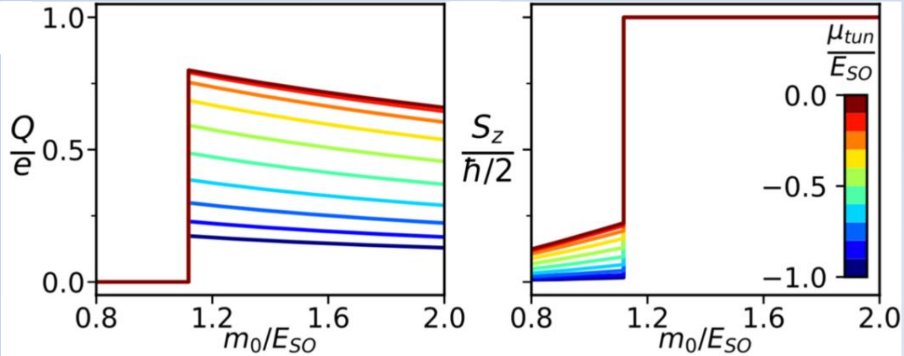
N. M. Nguyen *et al.*, Phys. Rev. B 105, 075310 (2022)

G. Hussain *et al.*, arXiv:2308.15358

quantized spin pumping Mircea Trif poster

nanowire proximitized by superconductor and magnetic insulator

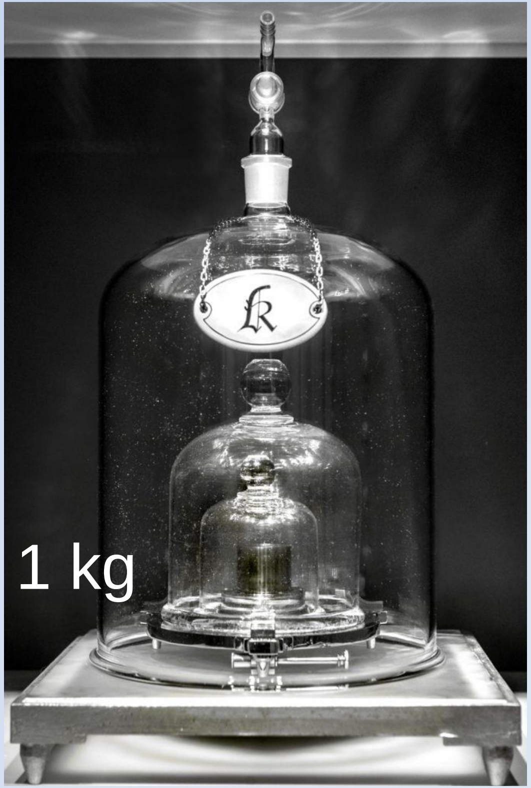




V. Fernández Becerra *et al.*, *Phys. Rev. Lett*. **130**, 237002 (2023)

How do quantum resistance standards operate, why do we need them?

then



since 2019

$$\Delta\nu_{\mathrm{Cs}} = \Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}} = 9192631770\ \mathrm{s}^{-1}$$

$$c = 299792458\ \mathrm{m{\cdot}s}^{-1}$$

$$h = 6.62607015{\times}10^{-34}\ \mathrm{kg{\cdot}m^{2}{\cdot}s}^{-1}$$

$$e = 1.602176634{\times}10^{-19}\ \mathrm{A{\cdot}s}$$

Josephson effect (h/e) and quantum Hall effects (h/e^2)

kilogram, ampere

since 2019

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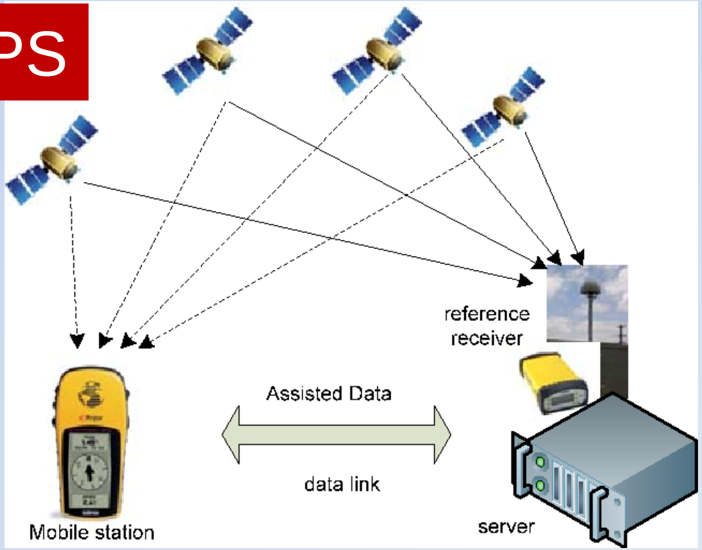
Josephson effect (h/e) and quantum Hall effects (h/e^2)

kilogram, ampere

GPS

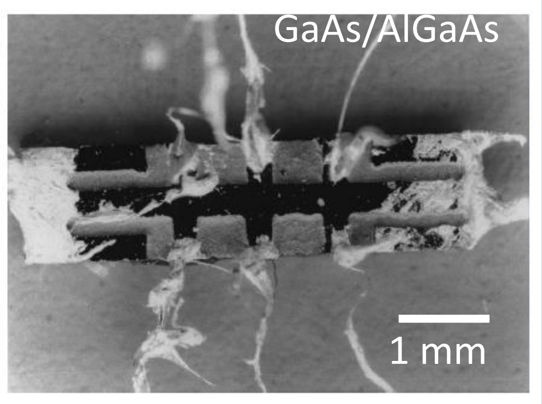


$\Delta t = 10^{-8}\ \mathrm{s} \rightarrow \Delta r = 5\ \mathrm{m}$

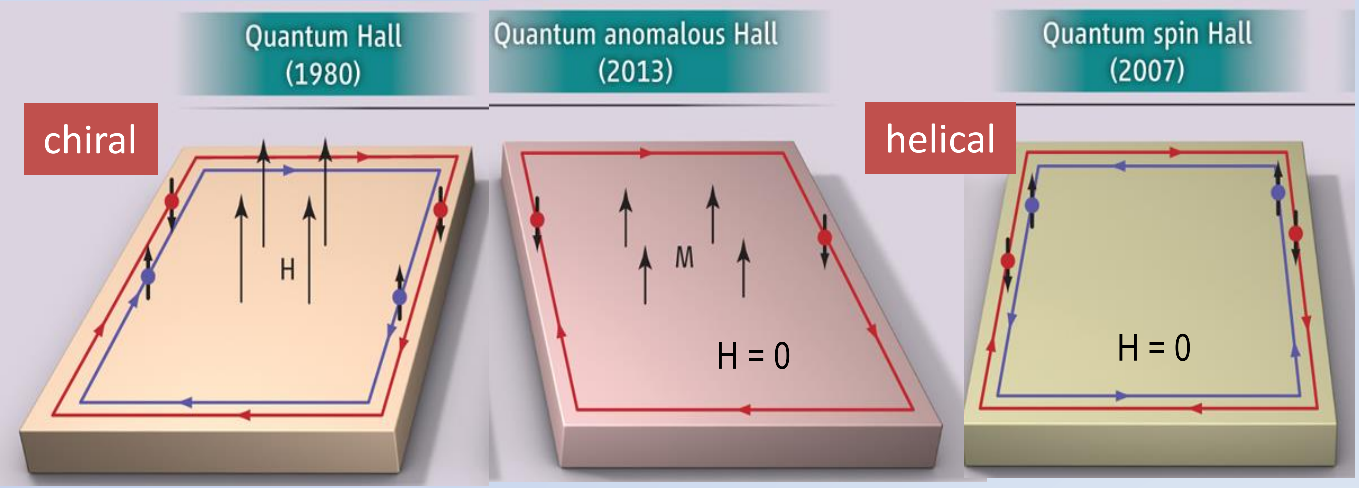
quantum Hall effects – 2D topological phenomena

- edge transport
- $R_{xy} = U_H / I = h/ne^2$

n – topological invariants



H.L. Stormer, RMP'1999

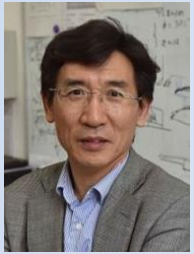


$R = h/ne^2$

Klaus von Klitzing

$R = h/e^2$

Qi-Kun Xue

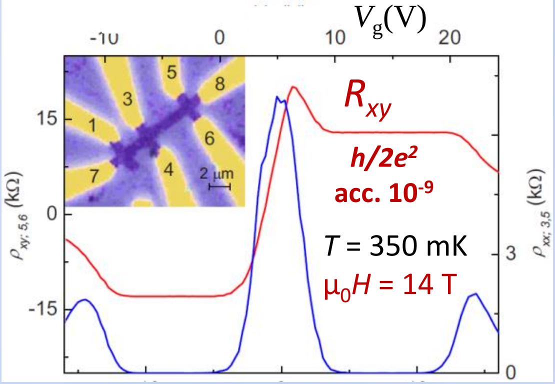


$R = h/2e^2$

Laurens Molenkamp

quantum chiral Hall effects – resistance quantization

graphene



R_{xy}

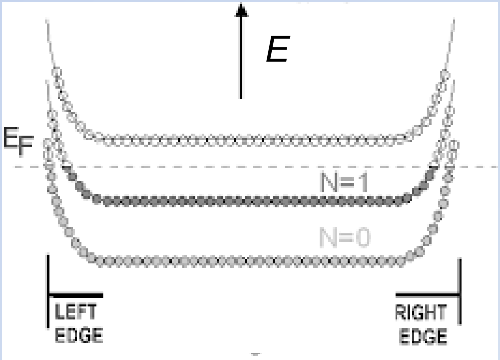
$h/2e^2$

acc. 10^{-9}

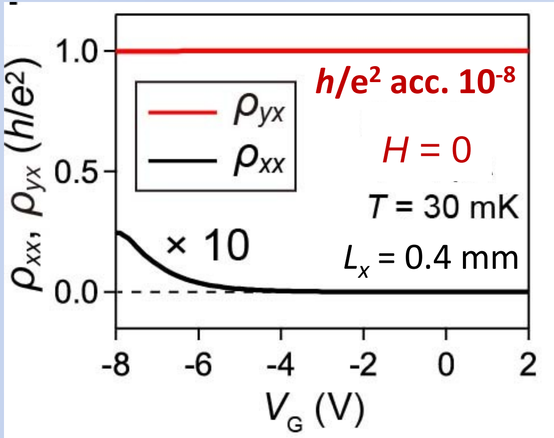
T = 350 mK

$\mu_0 H$ = 14 T

A.J.M. Giesbers et al., Appl. Phys. Lett.'2008



ferromagnetic (Bi,Sb,Cr)$_2$Te$_3$



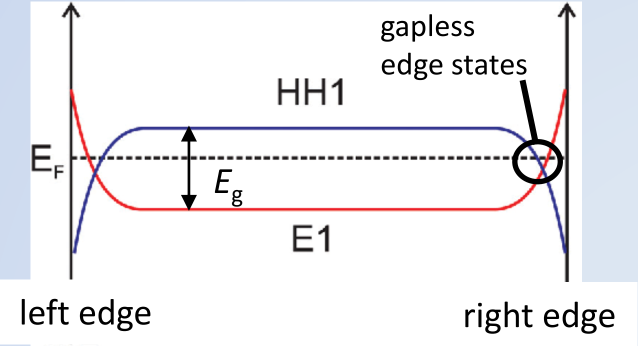
h/e^2 acc. 10^{-8}

$H = 0$

T = 30 mK

L_x = 0.4 mm

Y. Okazaki et al., Nat. Phys.'2022



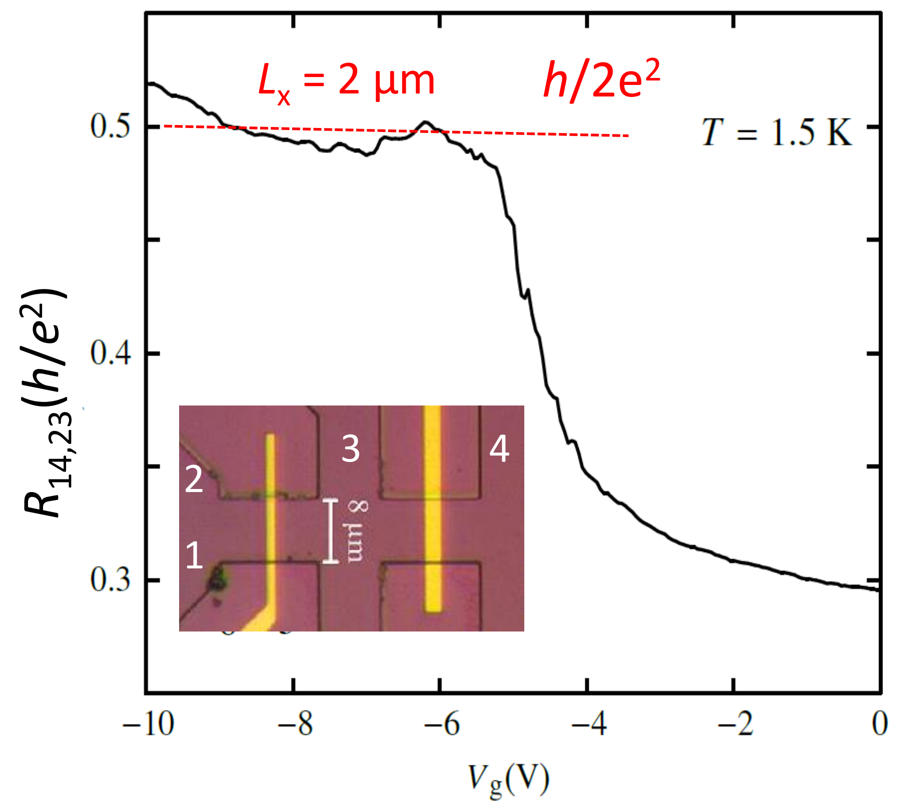
gapless edge states

left edge

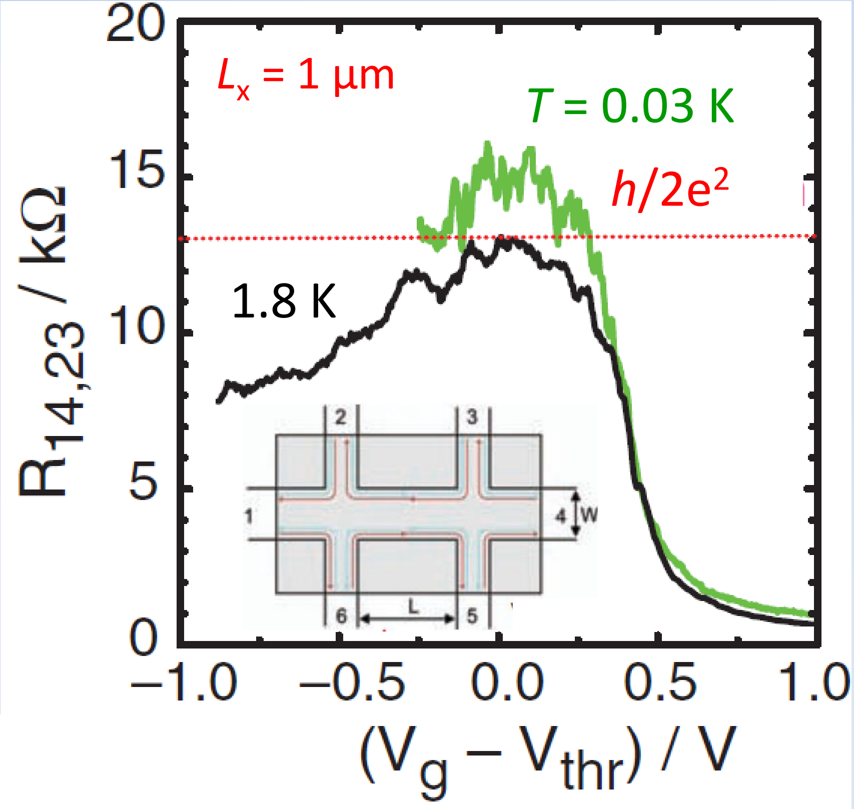
right edge

$$\Delta N = C\Delta V_g/e$$

quantum spin Hall effect – quantization not perfect and only in small samples



M. Majewicz, Ph.D. Thesis (2017)

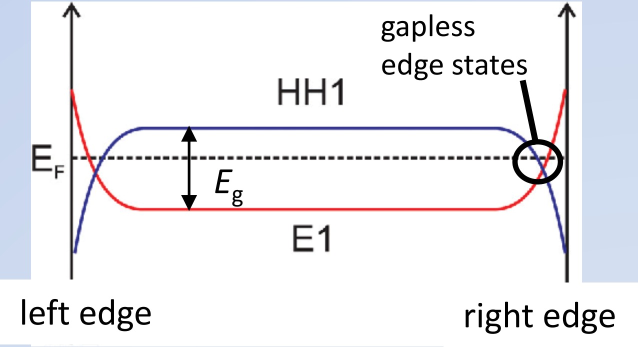


M. Koening et al. Science'2007

understanding the quantum spin Hall effect

key role of in-gap acceptor states

- pin E_F in gap leading to non-zero pleateau width $\Delta V_g = eN_a/C$



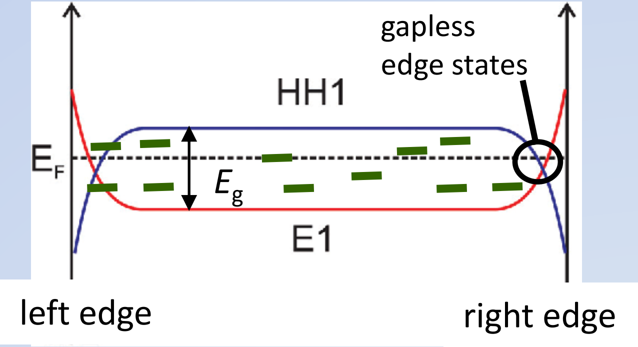
T. Dietl, *Phys. Rev. Lett.* **130**, 086202 (2023); *Phys. Rev. B* **107**, 085421 (2023)

understanding the quantum spin Hall effect

key role of in-gap acceptor states

- pin E_F in gap leading to non-zero pleateau width

$$\Delta V_g = eN_a/C$$ ☺

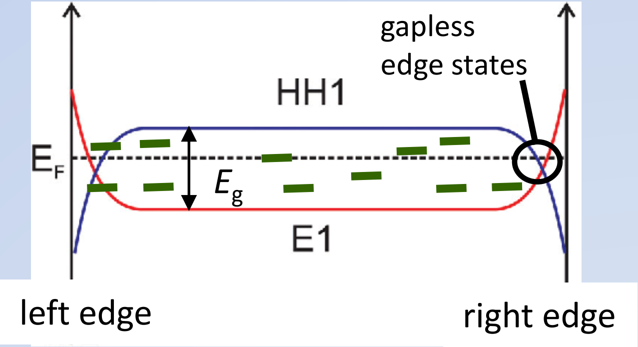


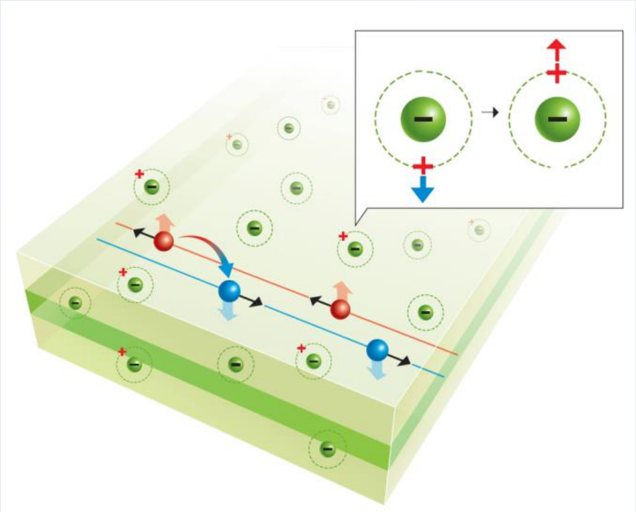
T. Dietl, *Phys. Rev. Lett.* **130**, 086202 (2023); *Phys. Rev. B* **107**, 085421 (2023)

understanding the quantum spin Hall effect

key role of in-gap acceptor states

- pin E_F in gap leading to non-zero pleateau width
  $\Delta V_g = eN_a/C$ 🙂
- allow for backscattering between helical states
  leading to $R > h/e^2$ 😟





<u>theoretical steps:</u>

Luttinger-Kohn, Kondo, Luttinger liquid, magnetic polarons,…

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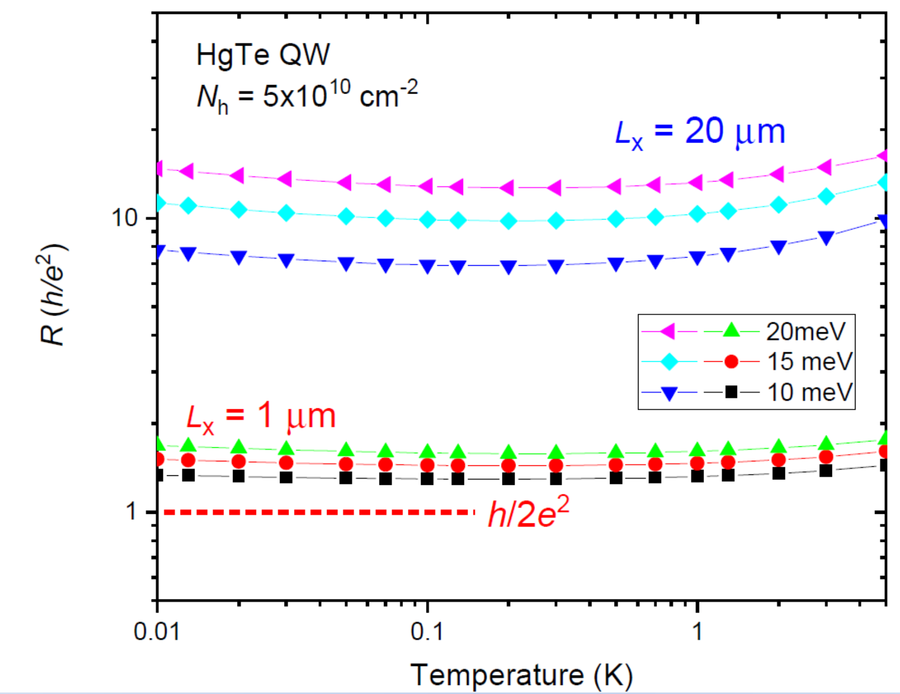
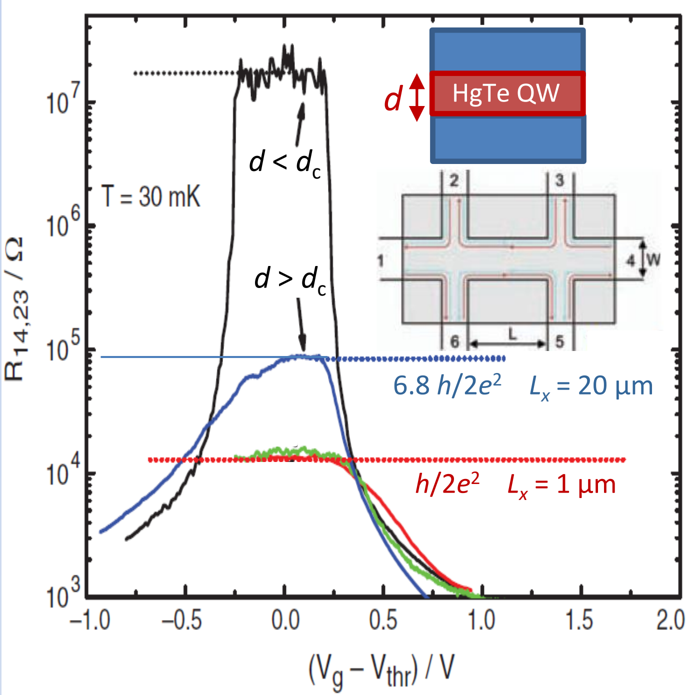
T. Dietl, *Phys. Rev. Lett.* **130**, 086202 (2023); *Phys. Rev. B* **107**, 085421 (2023)

channels' resistance vs. T and L_x





no adjustable parameters

M. Koening et al. Science'2007

T. Dietl, *Phys. Rev. Lett.* **130**, 086202 (2023); *Phys. Rev. B* **107**, 085421 (2023)

message from talk/posters

MagTop research relevant to:

- **spintronics** – dissipation less spin currents by edge states
- **quantum computing** – prospects for Majoranas in TCI
- **metrology** – understanding quantum Hall effects

new developments

- chiral anomaly in heat transport of Weyl fermions
- surprising topological states in open systems

European Funds
Smart Growth
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European Regional Development Fund
MagTop

a lot ahead

message from talk/posters

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European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund
MagTop

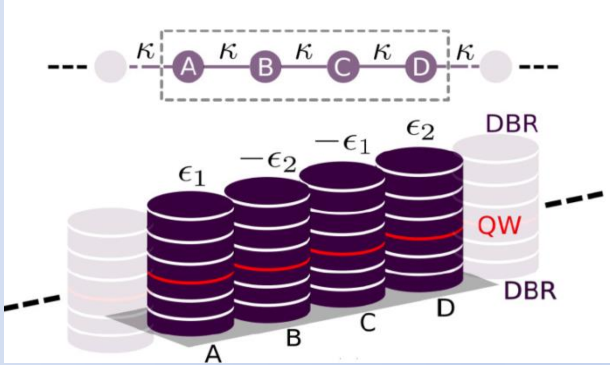
non-Hermitian topology Wojtek Brzezicki

How to make coupling to environment working for you?

New topological end-states in 1D systems with dissipation

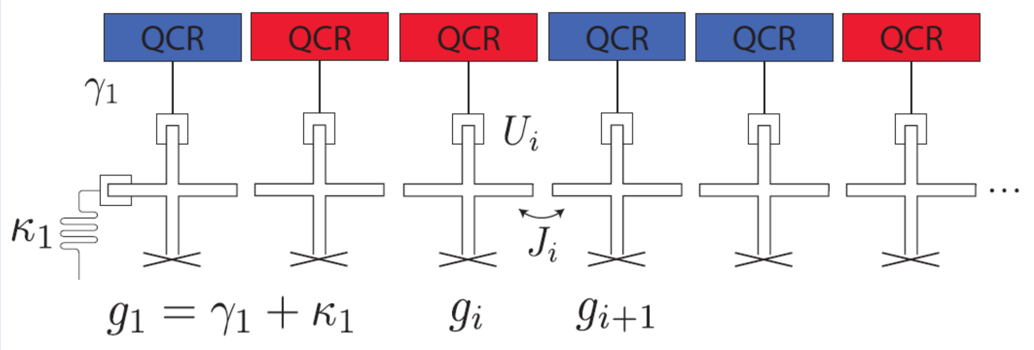
W. Brzezicki, T. Hyart, PRB (R) (2019)

Proposed 1D chains:



polariton microcatities
- end-states – lasing?

P. Comaron, …, W. Brzezicki, T. Hyart, ….PRResearch (R) (2019)



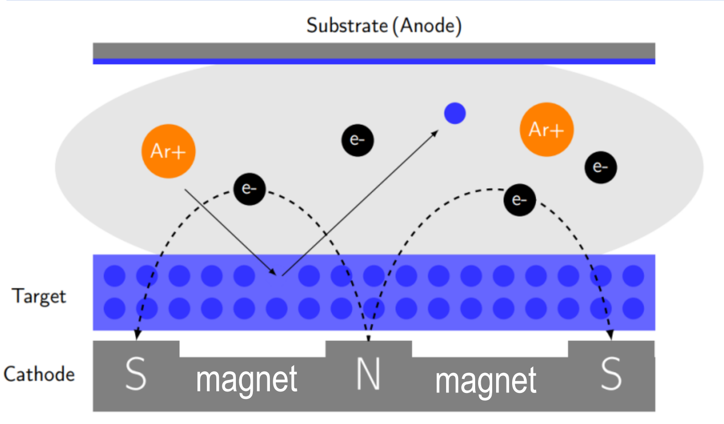
transmon qubits
- end-states – long-range entangled?

W. Brzezicki, …., T. Hyart, …. PRB (2023)

MagTop

MagTop product developed with PREVAC

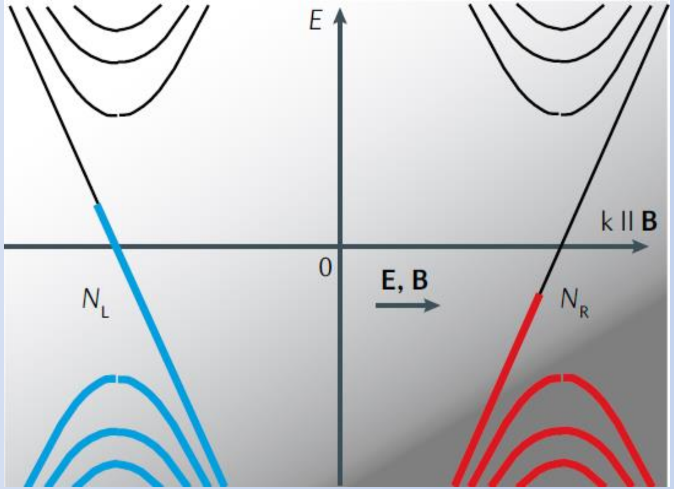
film deposition:
magnetron sputtering

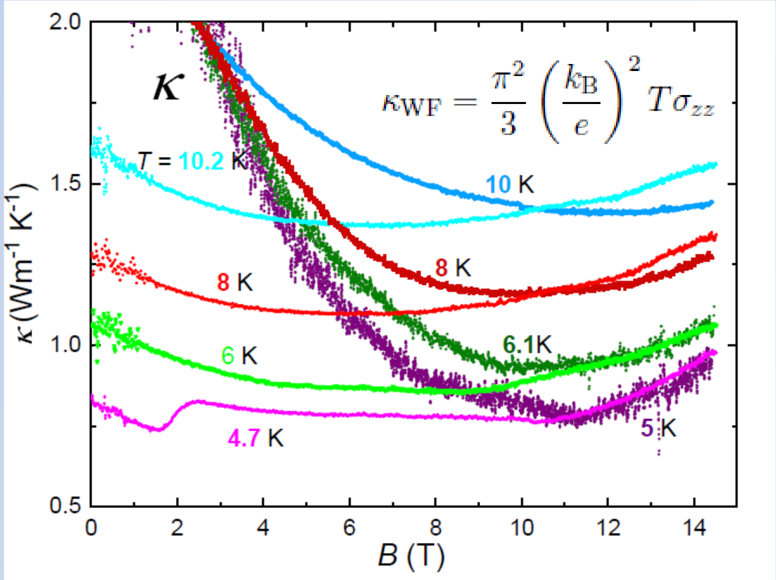


MagTop's **Krzysztof Fronc** designed deposition of magnetic metals by magnetron sputtering

chiral anomaly in Weyl systems Marcin Matusiak

NdAlSi

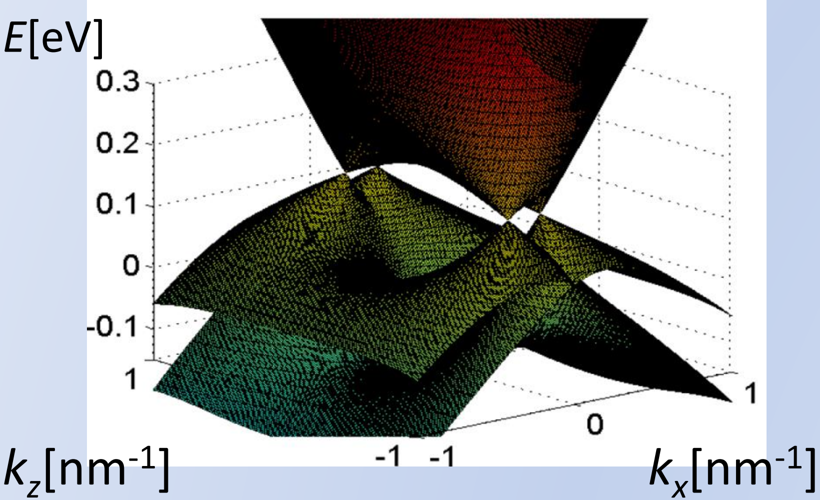




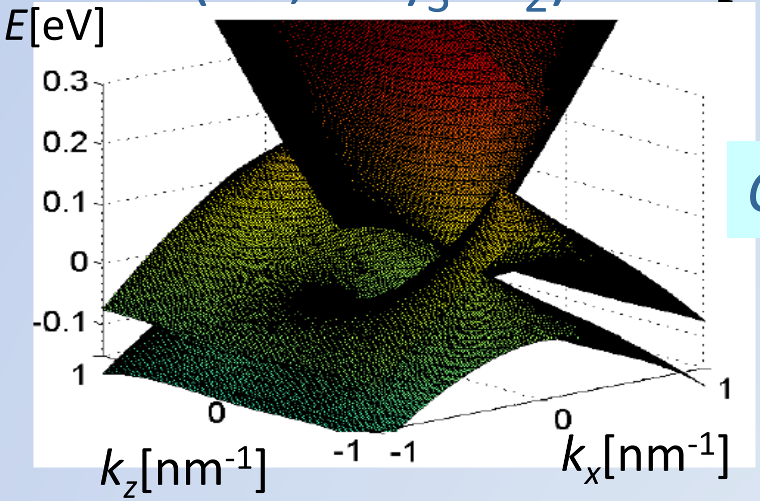
P. K. Tanwar *et al.* arXiv:2305.04650

Chern number in Weyl semimetals

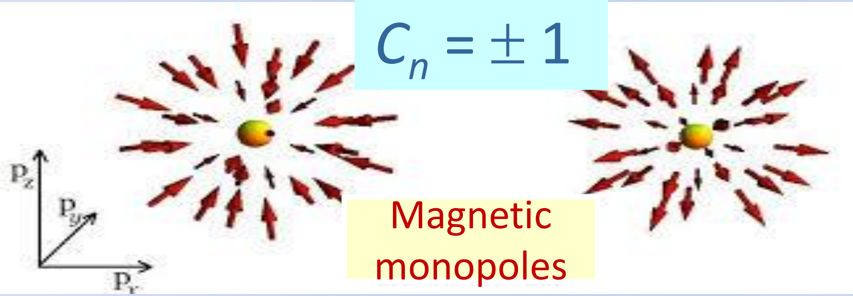
(Cd,TM)$_3$As$_2$ ***M*** // [100]



(Cd,TM)$_3$As$_2$) ***M*** // [001]



$C_n = \pm 2$



$C_n = \pm 1$

Magnetic monopoles

$$C_n = -\frac{1}{2\pi}\int_{S\vec{k}} \mathrm{d}\vec{S}_{\vec{k}}\vec{\Omega}^{(n)}(\vec{k})$$

integer

$$\vec{\Omega}^{(n)}(\vec{k}) = i\vec{\nabla}_{\vec{k}} \times \langle u^{(n)}_{\vec{k}}|\vec{\nabla}_{\vec{k}} u^{(n)}_{\vec{k}}\rangle$$

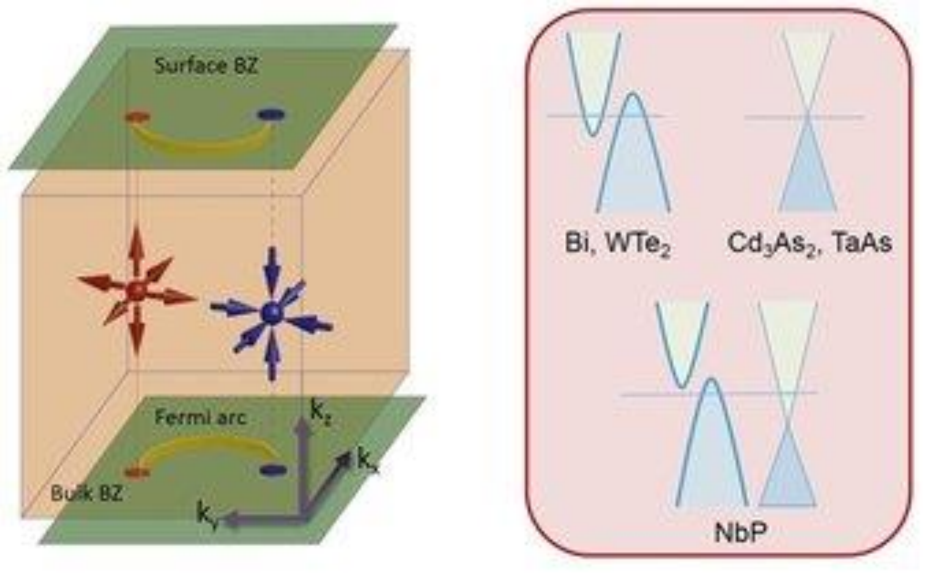
„magnetic field”

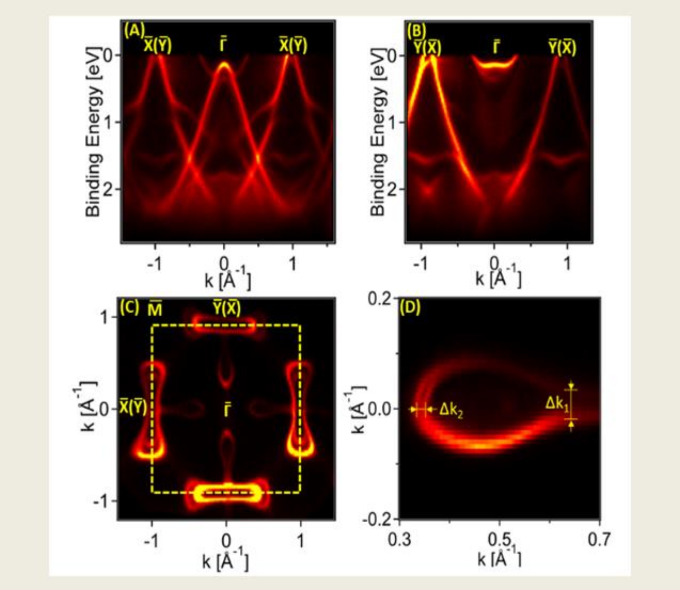
Berry curvature

T. D., C. Sliwa, 8x8 modelling

Weyl semimetals

NbP





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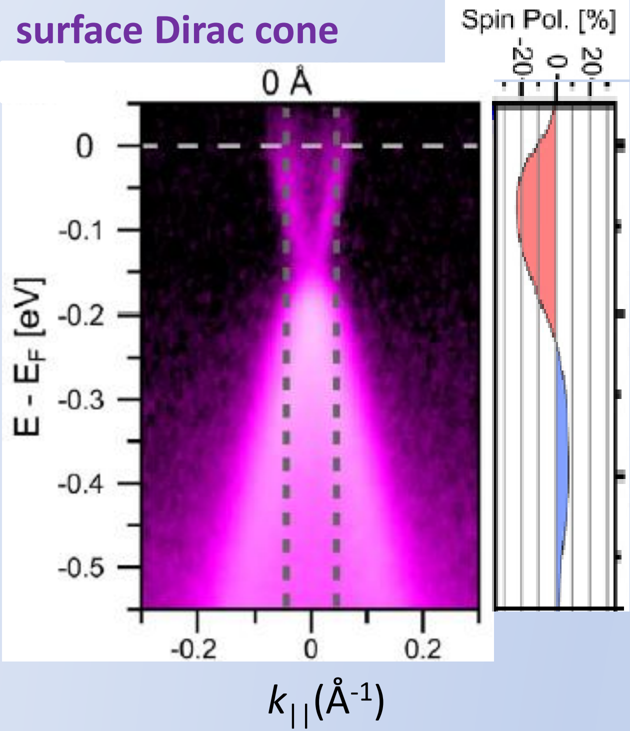
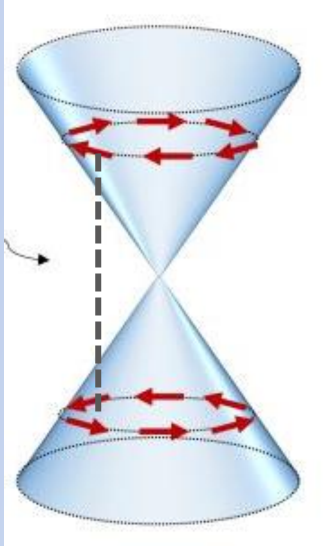
NATIONAL SYNCHROTRON
RADIATION CENTRE

spin-momentum locking Valentine Volobuev

n-$Pb_{0.7}Sn_{0.3}Se$

surface Dirac cone





B. Turowski *et al., Appl. Surf. Sci.* **610**, 155434 (2023)

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theoretical steps [see: T.D. PRB’2023]

- **electron states in quantum wells and topological edges (eight bands’ Luttinger –Kohn theory)**
- **acceptor states (*Z* = -1) in quantum wells (eight bands’ Luttinger–Kohn theory)**
- **tensor of exchange interaction electron- acceptor hoe (à la Bir-Pikus)**
- **Kondo temperature for that exchange**
- **unitary limit of spin relaxation (RGE) in 1D**

cf. T. Micklitz et al. [Cologne] PRL’2006

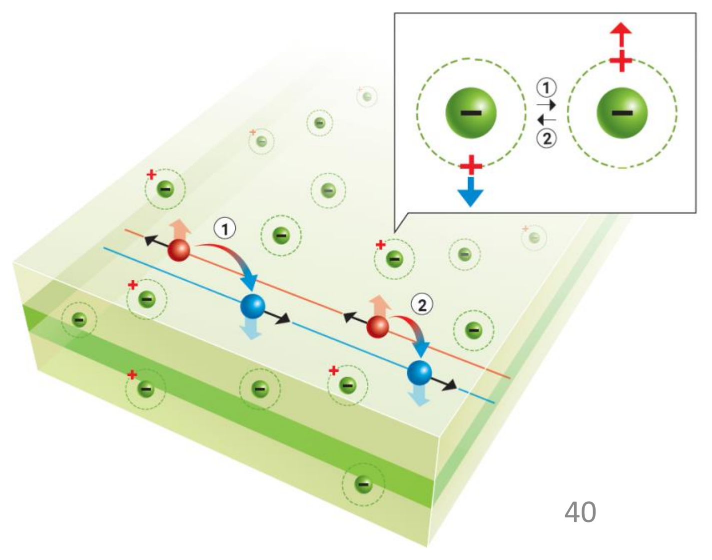
- **backscattering rate γ_b – role of spin non-conserving transitions**

cf. Y. Tanaka et al. [Riken, Argonne] PRL’2011

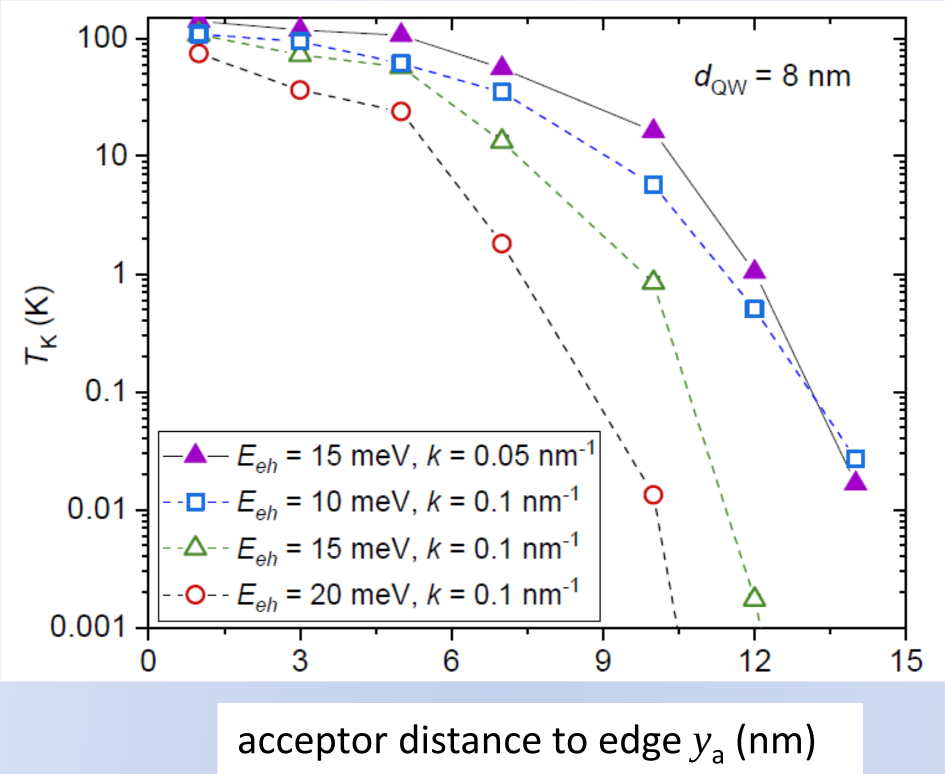
- **bound magnetic polaron in (Hg,Mn)Te**
- **edge resistance (QSHE):** $R(L_x) = (h/2e^2)(1 + \gamma_b L_x/v_F)$

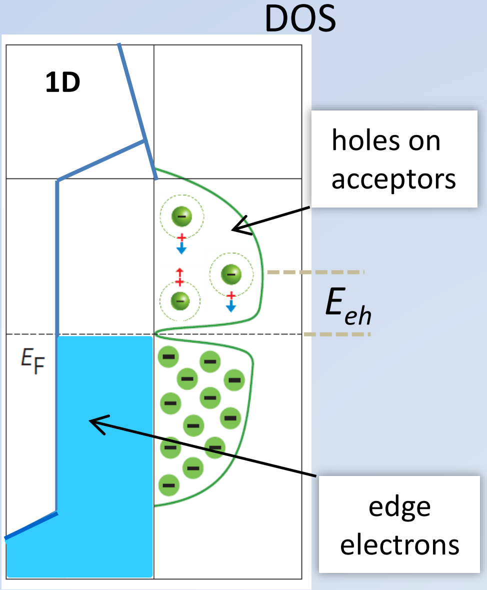
no fitting parameters

T. Dietl, *Phys. Rev. Lett.* (2023); *Phys. Rev. B* (2023)

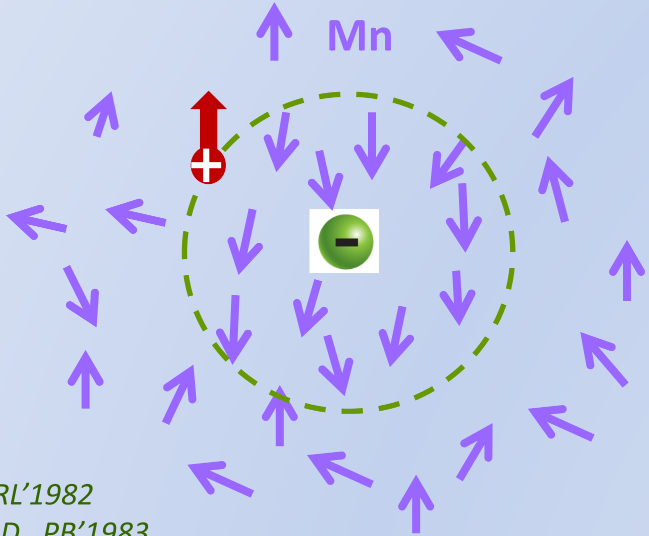


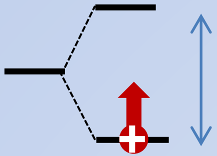
Computed Kondo temperatures for edge electron-acceptor hole exchange





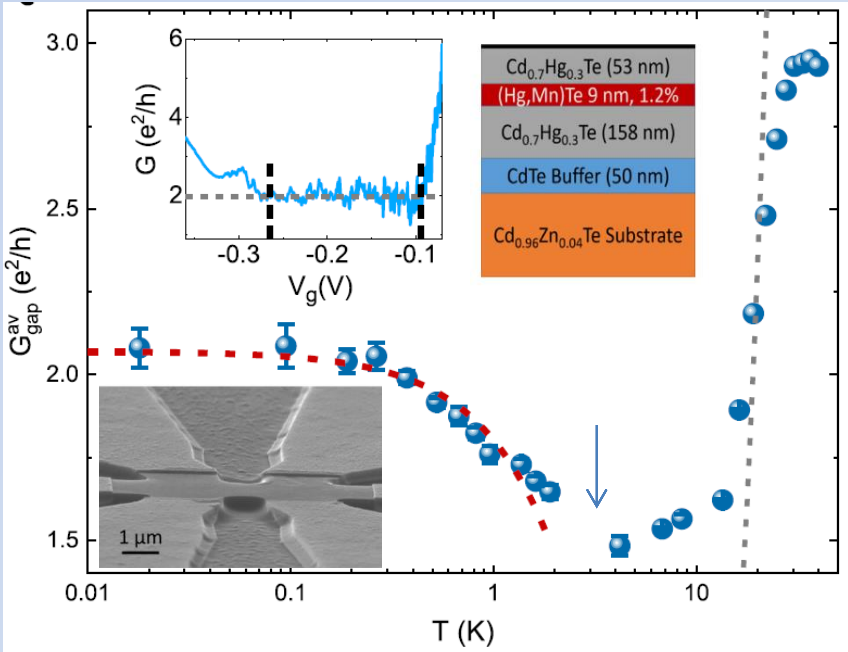
Killing of Kondo effect by BMP formation in DMS QW





ω_s increases with lowering T
diminishing Kondo effect

T.D, J. Spałek, PRL'1982
J. Jaroszyński, T.D., PB'1983



for $Hg_{0.988}Mn_{0.012}Te$ QW, $\omega_s > k_BT$ at $T < 3.5$ K

S. Shamim et al. [Wuerzburg] Nat. Commun.'2021

since 2019

$$\Delta\nu_{\mathrm{Cs}} = \Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}} = 9192631770\ \mathrm{s}^{-1}$$

$$c = 299792458\ \mathrm{m{\cdot}s}^{-1}$$

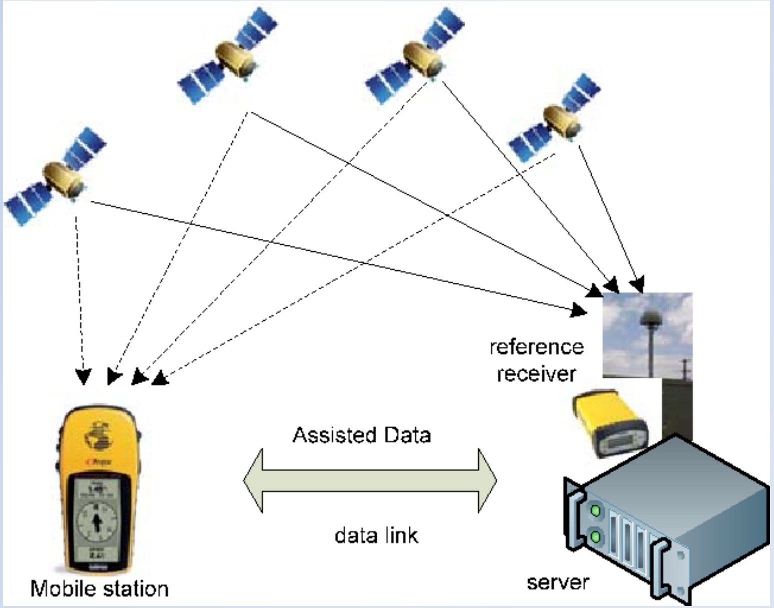
$$h = 6.62607015{\times}10^{-34}\ \mathrm{kg{\cdot}m^{2}{\cdot}s^{-1}}$$

$$e = 1.602176634{\times}10^{-19}\ \mathrm{A{\cdot}s}$$

$$k = 1.380649{\times}10^{-23}\ \mathrm{kg{\cdot}m^{2}{\cdot}K^{-1}{\cdot}s^{-2}}$$

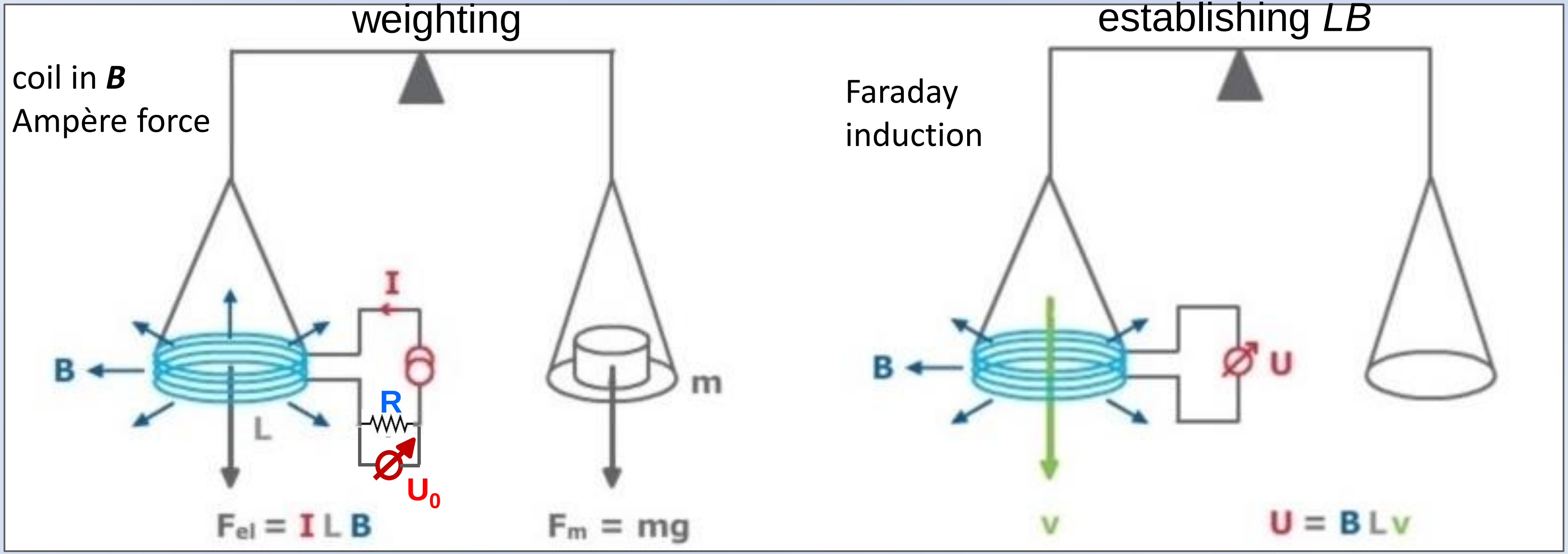
$$N_{\mathrm{A}} = 6.02214076{\times}10^{23}\ \mathrm{mol}^{-1}$$

$$K_{\mathrm{cd}} = 683\ \mathrm{cd{\cdot}sr{\cdot}s^{3}{\cdot}kg^{-1}{\cdot}m^{-2}}$$



$\Delta t = 10^{-8}\ \mathrm{s} \rightarrow \Delta r = 5\ \mathrm{m}$

example: kilogram standard - Kimbble’s balance



weighting

coil in ***B***

Ampère force

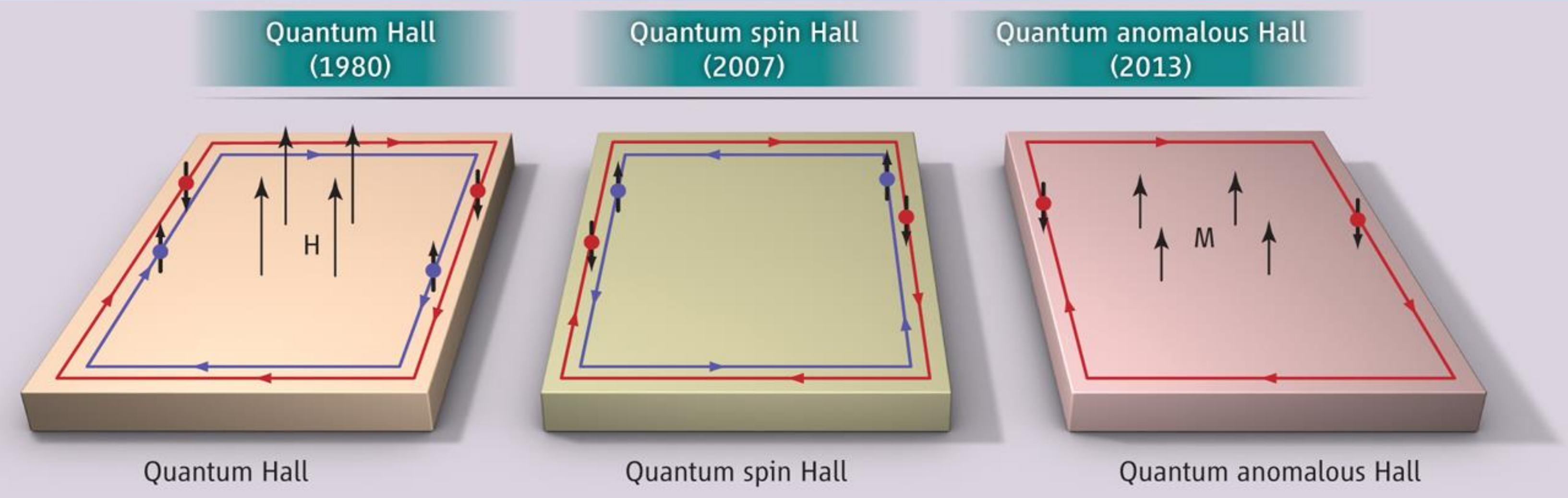
establishing *LB*

Faraday

induction

$$m = UU_0/Rvg$$ (accuracy $2\cdot10^{-8}$)

quantum Hall effects: resistance quantization h/ne^2

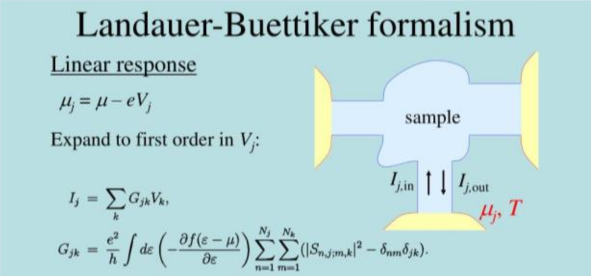


DOI: 10.1126/science.1237215

two-terminal resistance

(contact resistance)

- bulk insulating
- 1D edge conducting channels (number *N*)
- group velocity $\upsilon_g = \hbar^{-1} d\varepsilon/dk$
- in 1D, DOS $\nu(\varepsilon) = (2\pi d\varepsilon/dk)^{-1}$
- if *no* backscattering $I = Ne\upsilon_g \nu eU$
  $\rightarrow R = h/Ne^2$



Landauer-Buettiker formalism

<u>Linear response</u>

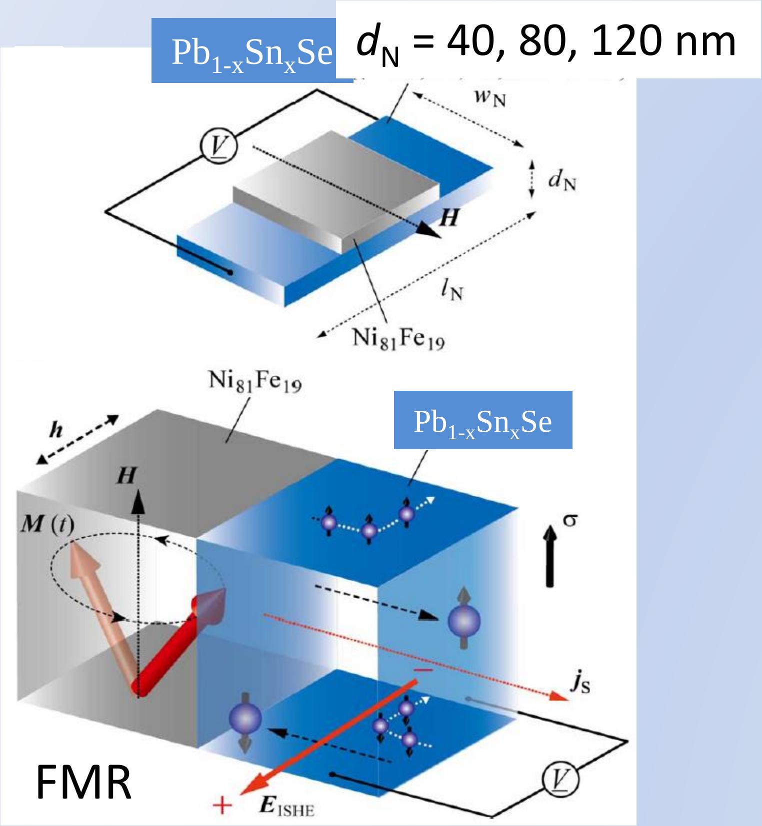
$\mu_j = \mu - eV_j$

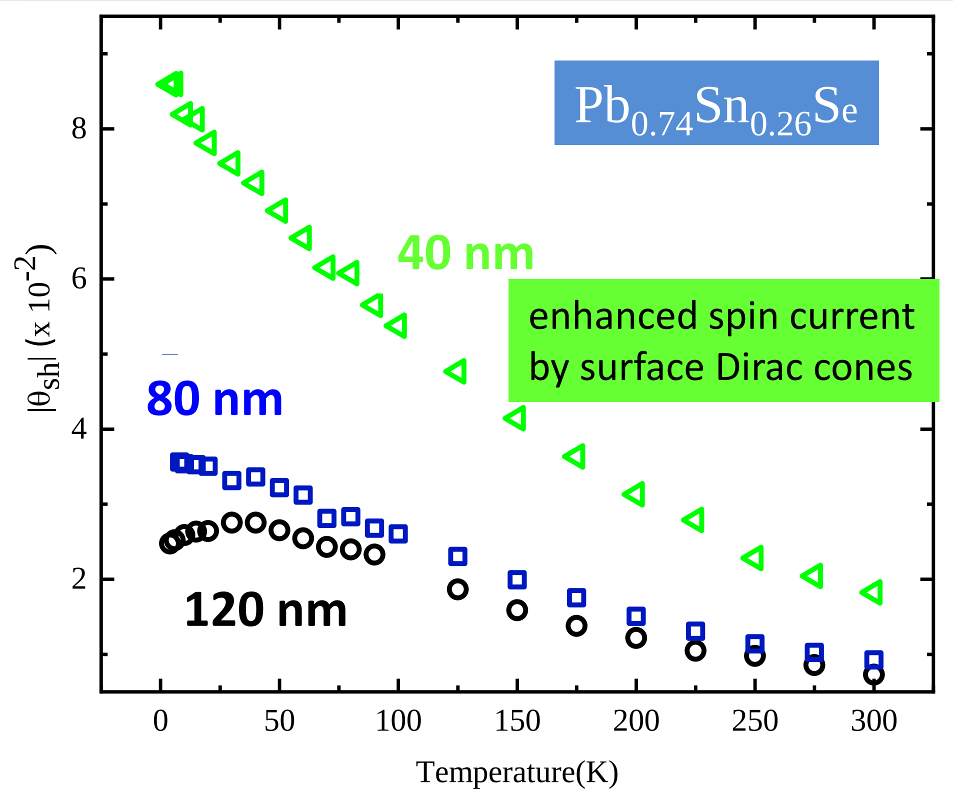
Expand to first order in V_j:

$$I_j = \sum_k G_{jk} V_k,$$

$$G_{jk} = \frac{e^2}{h} \int d\varepsilon \left(-\frac{\partial f(\varepsilon-\mu)}{\partial \varepsilon}\right) \sum_{n=1}^{N_j} \sum_{m=1}^{N_k} (|S_{n,j;m,k}|^2 - \delta_{nm}\delta_{jk}).$$

spin pumping in ferro/topological heterostructure Arathi Das Moosarikandy

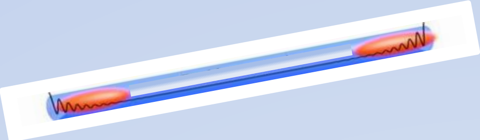

d_N = 40, 80, 120 nm



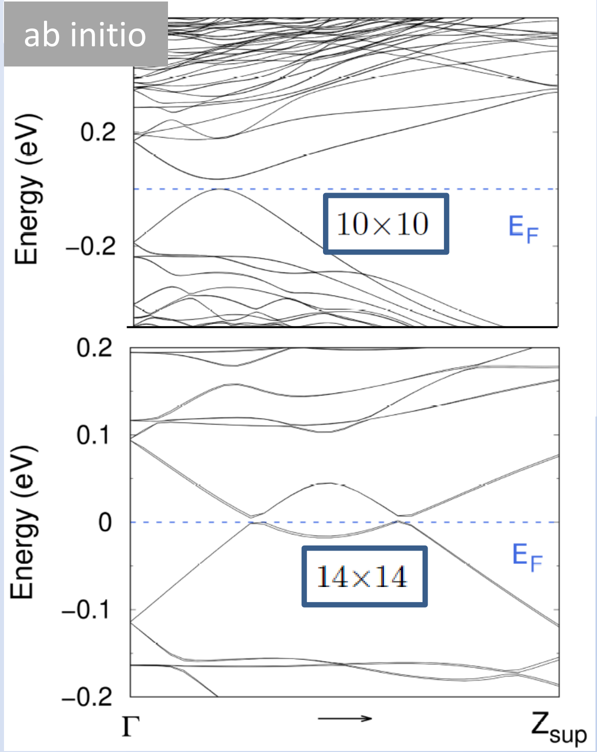
enhanced spin current by surface Dirac cones

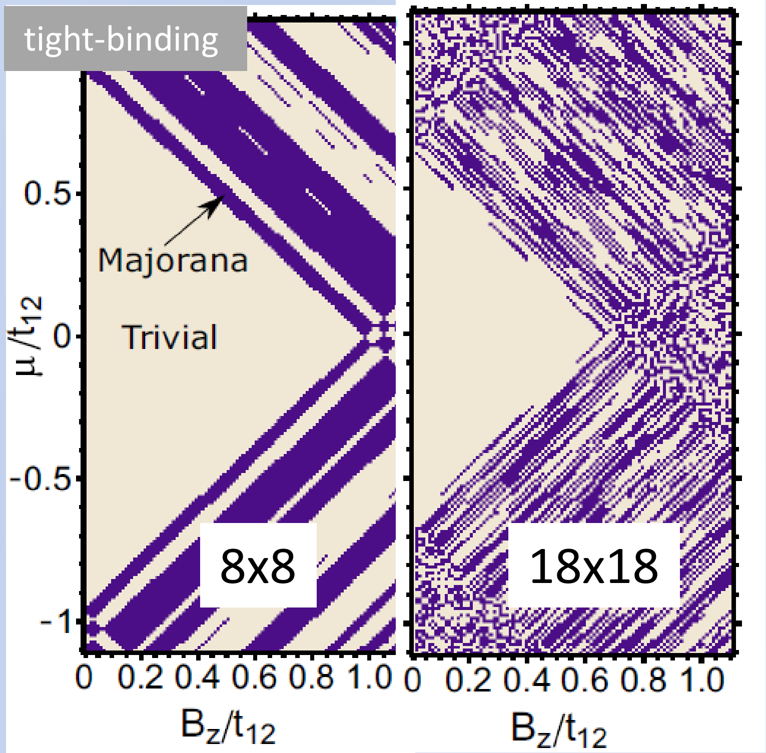
A. Das Moosarikandy *et al.* (2023)

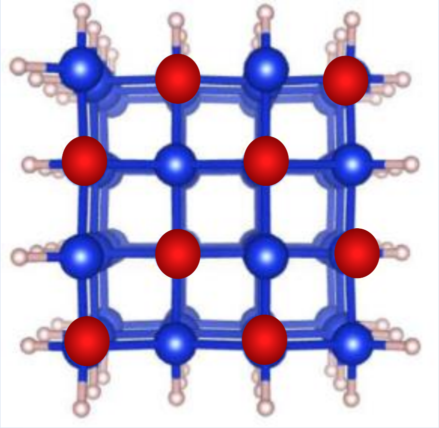
topological nanowires Giuseppe Cuono



hunting for the God particle: Majorana (MZM) – SnTe nanowires







4x4

G. Hussain *et al.*, arXiv:2308.15358

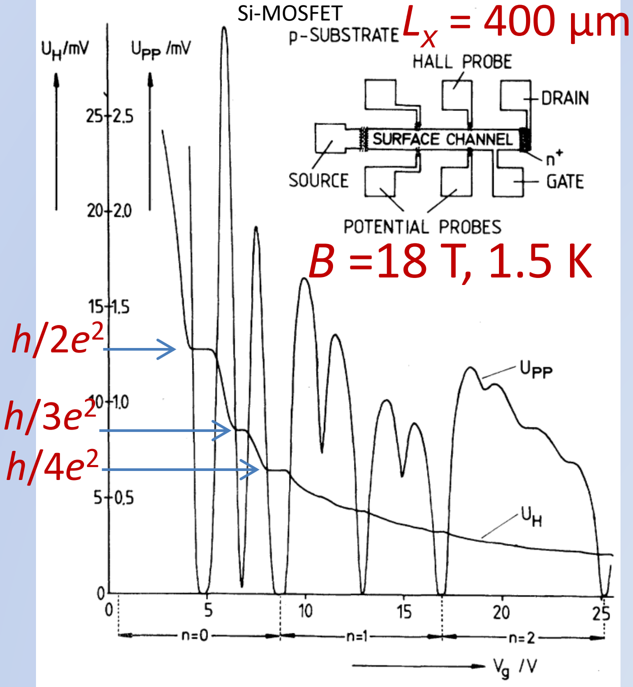
N. M. Nguyen *et al.*, Phys. Rev. B (2022)

macroscopic quantum phenomena: Josephson and quantum Hall effects

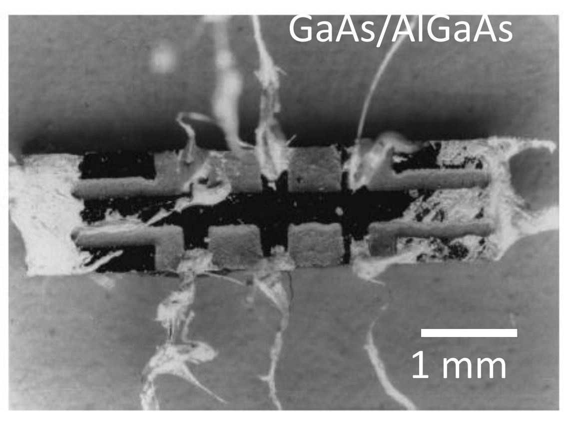
QHE in 2D systems

$K_J = h/2e$ [V/s]

$R_K = h/e^2$ [Ω]



K. v. Klitzing et al. [Wuerzburg, Grenoble] PRL'1980
Nobel Prize 1985



H.L. Stormer, RMP'1999

$R_{xy} = U_H/I = h/ne^2$

n = 1, 2, 3, 4

accuracy 10^{-9}

physics: quantum Hall effect as topological phenomenon

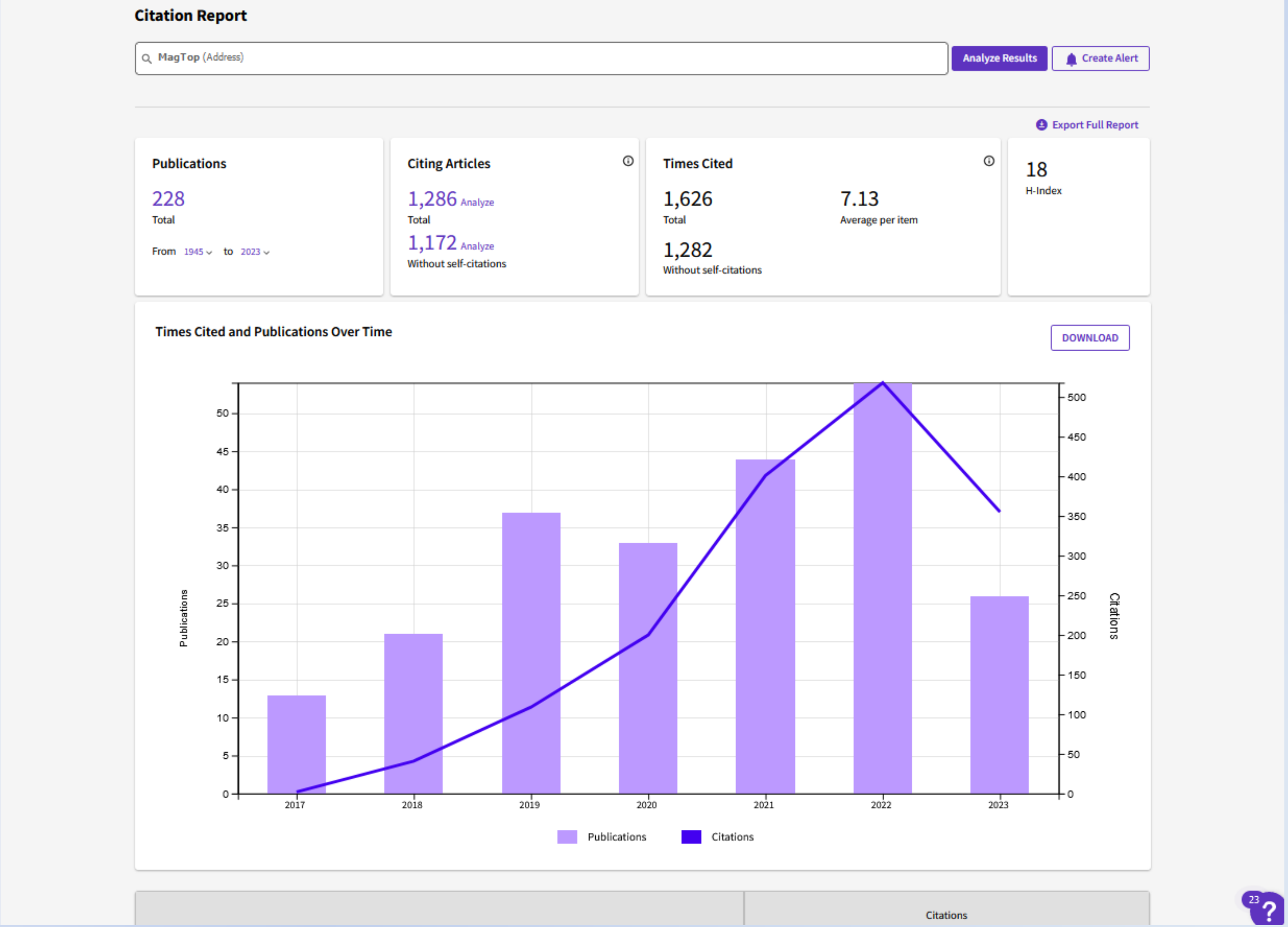
- edge transport
- $R_{xy} = h/ne^2$

  n – topological invariants
- possible without Landau levels

Nobel Prize 2016

David Thouless

Duncan Haldane



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