# TOPOLOGICAL MATTER SCHOOL 2022

# BOOK OF ABSTRACTS

**Donostia-San Sebastian**
**22-26 August 2022**

Understanding and exploiting the robustness of topological superconductivity and the unique quantum mechanical properties of strongly entangled particles is a thriving avenue to develop new quantum technologies. The first ideas and platforms, notably Majorana zero modes at the edges of one-dimensional topological superconductors, have led to a richer landscape of systems that include unconventional superconductors, spin-liquids, fractional quantum Hall states, as well as the simulation of many-body ground states in quantum computers. A hands-on session on quantum matter and AI with emphasis on quantum computing will also be delivered. This new edition of TMS is devoted to pedagogically present the main recent developments in the field in order to prepare future generations to uncover the true potential of these developments.

## Organizers

- Maia G. Vergniory – Donostia International Physics Center, Donostia, Spain and Max Planck for Chemical Physics of Solids, Dresden, Germany.
- Reyes Calvo – Universidad de Alicante, Alicante, Spain
- Santiago Blanco-Canosa, Donostia International Physics Center and Ikerbasque, Donostia – San Sebastian, Spain
- Fernando de Juan, Donostia International Physics Center and Ikerbasque, Donostia – San Sebastian, Spain
- Adolfo Grushin, Institut NEEL – CNRS, France
- Alexander Altland – University of Cologne, Germany
- Frank Pollmann – Technical University of Munich, Germany

## Invited speakers

- Roser Valentí (Goethe-Universität Frankfurt am Main, Germany) : Conventional versus unconventional superconductivity, hands on unconventional superconductivity
- Pedram Roushan (Google Inc, Santa Barbara, USA): Quantum simulations with superconducting qubits
- Charles Marcus (Niels Bohr Institute, Denmark): First title: Phase-Controlled Topological Superconductivity: Experiment, Josephson Matter: Experiment.
- Vidya Madhavan (University of Illinois Urbana-Champaign, USA) : Measurements of topological boundary states in 1D and 2D, STM studies of Majorana modes
- Eliska Greplova (TU-Deflt, Netherlands): Engineered topological matter and machine learning for quantum applications
- Lucile Savary (CNRS, France) : Quantum Spin Liquids: an Introduction
- Adam Smith (University of Nottingham, UK): Non-abelian anyons: the basics of tooplogical quantum field theory.
- Jason Alicea (Caltech, USA) : Topological superconductivity and Majorana modes
- Charlie Kane (Univerity of Pennsylvania, USA): Topological Band Theory and Topological Superconductivity
- Bella Lake (Helmholtz Zentrum Berlin, Germany): Introduction to neutron scattering: neutron scattering as a tool to study quantum magnetism
- Claudia Felser (Max Planck Institute, Dresden, Germany): Chirality and topology, magnetism and topology
- Ady Stern (Weizmann Institute of Science, Israel): Platforms for realizing non abelian states of matter
- Andrei Bernevig (Princeton University, US): Topological flatbands

<u>Program</u>

Topological Matter School 2022
Donostia-San Sebastián, August 22-26

| | Monday 22.08.2022 | Tuesday 23.08.2022 | Wednesday 24.08.2021 | Thursday 25.08.2022 | Friday 26.08.2022 |
|---|---|---|---|---|---|
| 9:00-10:00 | Registration 8:15 Kane | Kane | Savary | Alicea | Stern |
| 10:00-11:00 | Felser | Roushan | Alicea | Madhavan | Madhavan |
| 11:30-12:30 | Felser | Valentí | Marcus | Alicea | Stern |

**LUNCH AT COSTA VASCA**

| | | | | | |
|---|---|---|---|---|---|
| 14:30-15:30 | Valentí | Smith | Marcus | Surf | Bernevig |
| 15:30-16:30 | Roushan | Roushan | Greplova | Surf | Bernevig |
| 17:00-18:00 | Smith | Savary | Greplova | Surf | |
| 18:00-19:00 | Lake | Lake | | | |

| Cocktail 19:00-21:00 | Poster 19:00-21:00 | Conf. Dinner 20:00 | Coffee Break (grey bar) |
|---|---|---|---|

# Posters

- Aya Abouelela '*Topology and DC quantum transport in Floquet-driven systems'.*
- Balaganchi A. Bhargava '*Quantum phase transitions and a disorder-based filter in a Floquet system'.*
- Eduardo Barredo '*Cherenkov radiation in an ideal Weyl semimetal'.*
- Rik Broekhoven *'Yu-Shiba-Rusinov band dispersion of infinite Mn chains'.*
- Chiara Devescovi *'3D Chern photonic insulators with orientable large Chern vectors'.*
- Pierre-Oliver Downey '*Mott transition, Widom line and pseudogap in the triangular lattice Hubbard model'.*
- Georgia Fragkopoulou '*Bond disorder in Heisenberg-Kitaev-Gamma models'*.
- Axel Fünfhaus '*Symmetry oriented identification of correlated topological phases'.*
- N. Heinsdorf '*Topological Superconductivity in the nodal-plane material RhGe'*.
- Mikel Iraola '*IrRep: Symmetry eigenvalues and irreducible representations of ab initio band structures'.*
- Ivaki Moein Najafi 'T*opological Random Fractals'.*
- Alicia Kawala '*Electronic Structure and Superconductivity of the High Entropy Alloy Sc-Zr-Nb-Rh-Pd'*.
- Parth Kummar '*On the partitioning of Energy and Entropy in Time-Dependent Open Quantum Systems'*.
- C. Lahaie '*An improved Two-Particle Self-Consistent Approach'.*
- Gal Lemut '*Deconfinement of Majorana vortex modes produces a superconducting Landau level'.*
- Raphael L. R. C. Teixeira *'Overlap of Parafermionic Zero Modes at a Finite Distance'.*
- Andrea Maiani '*Conductunce-Matrix Symmetries of Multiterminal Semiconductor-Ssuperconduuctor Devices'*.
- Antonio Lucas Manesco '*Can Caroli-de Gennes-Matricon and Majorana vortex states be distinguished in the presence of impurities?'*
- Leo Mangeolle '*Thermal Conductivity and Theory of Inelastic Scattering of Phonons by Collective Fluctuations'.*

- Mateo Moreno '*Effective field theory of critical surfaces in class AIII topological insulators'.*
- S. Patil '*Ising superconductors: The signatures of triplet pairings in the density of states and vanishing of the "mirage" gap'.*
- Miguel Oliveira '*Effects of spin dilution on a topological system of magnons'.*
- Lorenzo Pizzino '*Dimensional crossover in weakly-coupled chains'.*
- Iñigo Robredo '*Cubic Hall Viscosity in Three-Dimensional Topological Semimetals*'.
- Aleksander Sanjuan Ciepielewski '*Transport signatures of van Hove singularities in mesoscopic twisted bilayer graphene'.*
- Martina Solidini '*Building crystalline topological superconductors from Shiba lattices*'.
- Antonio David Subires Santana '*Electronic band structure of the Co-pnictide $CaCo_2As_2$ probed by ARPES'*
- Spenser Talkington '*Exceptional Surface Topology of Lindbladian Systems'.*
- Tereza Vakhtel '*Bloch oscillations in the magnetoconductance of twisted bilayer graphene'.*
- David van Driel '*Direct Measurement of the Andreev Bound State'.*
- Ksotas Vilkelis '*Bloch-Lorentz magnetoresistance oscillations in delafossites'.*
- C. Walsh '*Prediction of anomalies in the velocity of sound for the pseudogap of hole-doped cuprates*'.
- Zhen Wu 'Topological *Superconductivity in Ge-Si Nanowires'.*
- Evgenii Zheltonozhskii '*Competition of dissipative and Andreev processes in Abelian quantum Hall - superconductor junctions'.*

# Topology and DC quantum transport in Floquet-driven systems

December 2021

## 1 Abstract

Anomalous edge modes and DC quantum transport in Floquet topological systems

Aya Abouelela and Johann Kroha University of Bonn

Recently, several works have investigated the topological properties emerging in periodically driven systems, where a periodic drive is used to engineer the band structure such as to support topologically stabilized edge modes. The topological phases of periodically driven systems have been classified across all dimensions in the periodic table of Floquet topological insulators. The Floquet multiplicity of bands implies the emergence of anomalous edge states which cross bulk gaps that do not occur in static systems. Here, we present our studies on the non-interacting topological Qi-Wu-Zhang (QWZ) model under the influence of a periodic drive, and analyze its drive-induced edge modes, using the Floquet formalism. Investigating two regimes of the driving frequency , higher or lower than the static bandwidth, the latter is shown to support anomalous edge modes. For the experimental detection of edge states, we calculate the dI/dV spectra at non-zero DC bias voltage $V$, using the Keldysh-Floquet formalism. We predict quantized conductance plateaus when the transport voltage is within a normal gap ($V$ centered around $V = 0$, normal edge mode) or within an anomalous gap ($V$ centered around $V = \pm\Omega/2$, anomalous edge mode). We also perfom a spatially resolved computation of the chiral tranmission channels of the finite-size system with finite bias applied, showing that the transport is along an edge and that it is spatially modulated corresponding to the wave number $\pi$ of the (anomalous) edge mode.

# Quantum phase transitions and a disorder-based filter in a Floquet system

**Balaganchi A. Bhargava,** Sanjib Kumar Das and Ion Cosma Fulga

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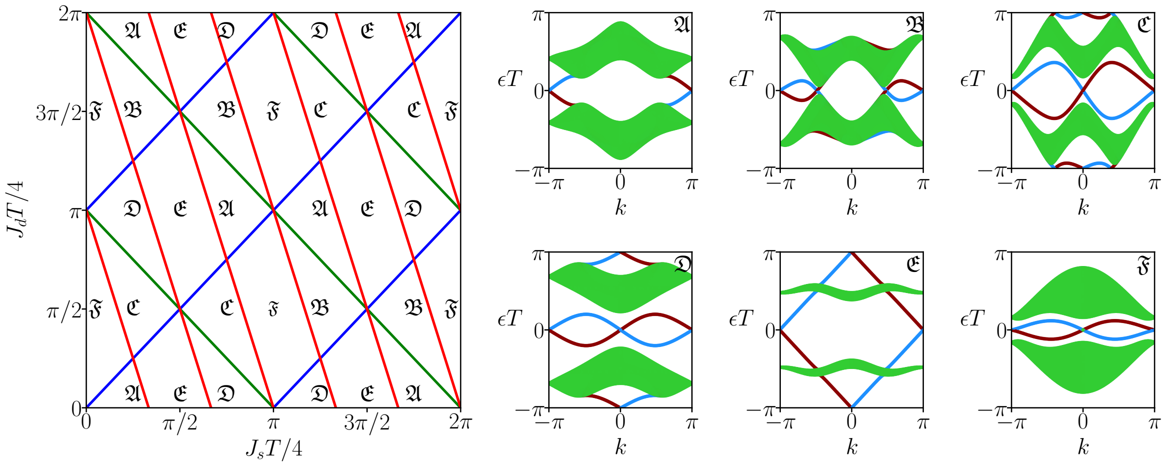
Abstract : Two-dimensional periodically-driven topological insulators have been shown to exhibit numerous topological phases, including ones which have no static analogue, such as anomalous Floquet topological phases. We study a two dimensional model of spinless fermions on a honeycomb lattice with periodic driving. We show that this model exhibits a rich mixture of weak and strong topological phases, which we identify by computing their scattering matrix invariants. Further, we do an in-depth analysis of these topological phases in the presence of spatial disorder and show the relative robustness of these phases against imperfections. Making use of this robustness against spatial disorder, we propose a filter which allows the passage of only edge states, and which can be realized using existing experimental techniques.

Figure : Phases in the system

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References: 1. B.A.Bhargava, S.K.Das, and I.C.Fulga, Quantum phase transitions and a disorder-based filter in a Floquet system, Phys. Rev. B 105, 054205 (2022).

2. T. Kitagawa, E. Berg, M. Rudner, and E. Demler, “Topological characterization of periodically driven quantum systems, Phys. Rev. B 82, 235114 (2010).

# Cherenkov radiation in an ideal Weyl semimetal

E. Barredo and L. F. Urrutia

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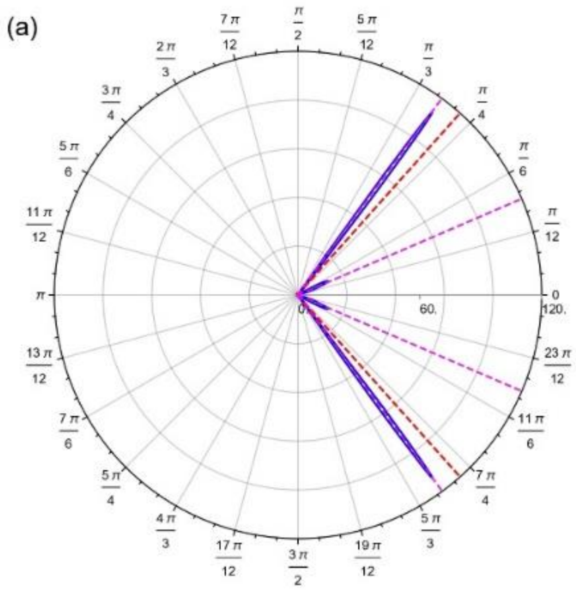
Abstract: We present the spectral distribution of the Cherenkov radiation in an ideal Weyl semimetal. The electromagnetic response of Weyl semimetals (chiral media) is described by a modified Maxwell theory developed by Carroll, Field and Jackiw (CFJ) [1], which is based on the addition of a Lorentz-violating Chern-Simons term to the electromagnetic Lagrangian density, $\mathcal{L}_{LV} = \frac{1}{8\pi}\, \tilde{b}^{\mu}\tilde{F}_{\mu\nu}A^{\nu}$ , where the LIV coefficient $\tilde{b}^{\mu} = (b_0, \vec{b})$ correspond to precise physical terms in chiral matter, with $b_0$ and $\vec{b}$ accounting for the separation of the corresponding Weyl nodes in energy and momentum space, respectively.

We implement the Green's function (GF) method, considering only the spatial components of the violating coefficient in the Chern-Simons Lagrangian. Using the GF in the far-field approximation we analyze the emitted radiation of a fast-moving charge travelling parallel to the vector $\vec{b}$. From the spectral distribution we find out that chiral media produces a splitting of the Cherenkov radiation with each cone corresponding to the two different phase velocities of the two polarizations of the light (birefringence).




The figure shows the polar plot of the spectral distribution for chiral Cherenkov radiation with a refraction index $n = 2$ and $c|\vec{b}|/(\omega n^2) = 0.5$ . The charge moves from left to right with a speed of 0.75 the speed of light. The red dashed line corresponds to the standard Cherenkov radiation with $\vec{b} = 0$ . We conclude that the Green's function approach using suitable approximations allows us to obtain analytical forms to study modifications to electromagnetic radiation in chiral matter.

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References: [1] S.M. Carroll, G. B. Field, and R. Jackiw, Phys. Rev. D 41, 1231 (1990)

Acknowledgments: The authors acknowledge support from the project CF/2019/428214.

# Yu-Shiba-Rusinov band dispersion of infinite Mn chains

Rik Broekhoven[1,*], Artem Pulkin[1], Antonio Manesco[1], Sander Otte[1], Anton Ahkmerov[1], Michael Wimmer[1]

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Chains of magnetic atoms on s-wave superconductors have been proposed to have a topological non-trivial phase, when the induced in-gap Yu-Shiba-Rusinov (YSR) bands are p-wave gapped by for example spin-orbit coupling. In order to determine the topological phase diagram, recent improvements in STM methodology have made it possible to probe the YSR band dispersion relation. It was found to be highly dependent on the chain spacing and orientation with respect to the superconductor lattice [1].
Motivated by this discovery, here we present a method to evaluate the in-gap dispersion relation of chains with different orientations and spacing. In contrast to previous works [2, 3], we work with infinite chains on a semi-infinite surface to make sure the system is larger than the superconductor coherence length. We focus on Mn atoms on top of superconducting Nb(110). First, we derive an effective tight-binding model from ab initio calculation, and subsequently we use the multidimensional Green's function formalism [4] to extend to a semi-infinite system and solve for the corresponding in-gap YSR bands

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References:

[1] Schneider, L., Beck, P., Posske, T. et al. Topological Shiba bands in artificial spin chains on superconductors. Nat. Phys. 17, 943–948 (2021).

[2] Nyári, B., Lászlóffy, A. ,Szunyogh L. et al. Relativistic first principles theory of Yu--Shiba--Rusinov states applied to an Mn adatom and Mn dimers on Nb(110), PRB, 104, 235426 (2021).

[3] Crawford, D. , Mascot, E., Shimizu et al., M.,Majorana modes with side features in magnet-superconductor hybrid systems. arXiv, 2109.06894 (2021)

[4] Istas, M. , Groth, C. and Waintal, X. Pushing the limit of quantum transport simulations. Phys. Rev. Research. 1, 3 33-188 (2019)

# 3D Chern photonic insulators with orientable large Chern vectors

Chiara Devescovi [1], Mikel García-Díez [1,2], Iñigo Robredo [1], María Blanco de Paz [1], Jon Lasa Alonso [1,3], Barry Bradlyn [4], Juan Luis Mañes [2], Maia G. Vergniory [1,5], Aitzol García-Etxarri [1,5]

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A 3D Chern insulator is a Time Reversal Symmetry (TRS) broken topological phase characterized by a vector of three first Chern invariants [1-3], associated with the planes supporting topologically protected surface states. In this work [4], we devise a general strategy to design 3D Chern Insulating (3D CI) cubic Photonic Crystals (PhCs) with orientable and arbitrarily large Chern vectors, in a reduced TRS broken environment. The strategy proceeds in two steps: formation of photonic Weyl points in a magnetic PhC, and their annihilation via geometric modulation on multifold supercells. The resulting crystals present the following novel characteristics: First, large Chern vectors can be obtained by design, making the PhC ideal for multi-modal operation. Second, full orientability of Chern vectors is achieved in the 3D space, opening up larger 3D CI/3D CI interfacing possibilities as compared to 2D. Finally, non-zero Chern vectors can be achieved at reduced magnetization conditions, interestingly for photonic applications in the frequency regime where the magnetic response is weak.

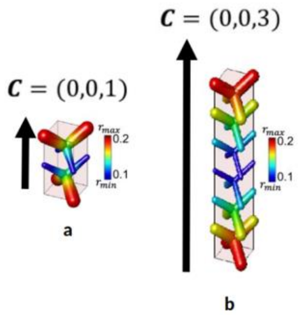


Figure. (a) Unit Chern number. (b) Large Chern number on a multi-fold supercell.

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## References:

[1] D. Vanderbilt, Berry Phases in Electronic Structure Theory, 1st. ed., (Cambridge University Press, Cambridge, 2018).
[2] Y. Xu, L. Elcoro, Z-D. Song, B. J. Wieder, M.G. Vergniory, N. Regnault, Y. Chen, C. Felser, B. A. Bernevig, "High-throughput calculations of magnetic topological materials", Nature, 586, 7831 (2020).
[3] L. Elcoro, B. J. Wieder, Z-D. Song, Y. Xu, B. Barry, B. A. Bernevig, "Magnetic topological quantum chemistry", arXiv preprint, arXiv:2010.00598 (2020).
[4] C. Devescovi, M. García-Díez, I. Robredo, M. Blanco de Paz, J. Lasa Alonso, B. Bradlyn, J. L. Mañes, M. G. Vergniory, and A. García-Etxarri. "Cubic 3D Chern photonic insulators with orientable large Chern vectors." Nature Communications, 12, 7330 (2021)

## Acknowledgments:

The authors dedicate this work to the memory of their beloved colleague and friend, Prof. Alexey A. Soluyanov. The work is supported by the Spanish Ministerio de Ciencia e Innovación (PID2019-109905GA-C2, PID2019-109905GB-C21, CEX2018-000867-S-19-1 and PGC2018-094626-BC21), Basque Government (IT979-16,IT1164-19, KK-2019/00101 and KK-2021/00082), Programa Red Guipuzcoana de Ciencia, Tecnología e Innovación (2021-CIEN-000070-01), Air Force Office of Scientific Research (FA9550-21-1-0131).

# Mott transition, Widom line and pseudogap in the triangular lattice Hubbard model

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Although the pseudogap in the weak coupling regime is mostly understood, in the strong coupling regime, it still poses an important challenge to the understanding of hole doped cuprates. It has been proposed that short-range antiferromagnetic fluctuations and Mott physics were involved in the formation of the strong coupling pseudogap~[1]. However, Mott physics might not be behind the formation of the pseudogap if the doubts raised in Ref.~[2] about the observability of the Mott transition are confirmed. Here, we use the dynamical cluster approximation on the 2D triangular Hubbard model to show that a) the Widom line that extends above the critical point of the first-order Mott transition exists in the thermodynamic limit; b) the presence of this line argues for the existence of the Mott transition in the thermodynamic limit; c) the loss of spectral weight in the metal to Mott insulator transition for strong interactions is momentum dependent, the hallmark of a pseudogap; d) the pseudogap at half filling is continuously connected to the hole doped and electron doped strong coupling pseudogaps; e) The antiferromagnetic Brillouin zone is not linked to the formation of the pseudogap. Most of this work appears in Ref. ~[3].

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[1]. G. Sordi, K. Haule, and A.-M. S. Tremblay. Phys. Rev. B, 84(7) :075161, 2011.

[2]. A. Wietek, R. Rossi, F. Simkovic, M. Klett, P. Hansmann, M. Ferrero, E. M. Stoudenmire, T. Schäfer, and A. Georges, Phys. Rev. X 11, 041013, 2021.

[3]. P.-O. Downey, O. Gingras, M. Charlebois, C.-D. Hébert, A.-M. S. Tremblay, arXiv.2207.08008

Acknowledgments:

We thank Giovanni Sordi for interesting and useful comments, discussions about Mott physics and suggestions on the calculations, Kostya Trachenko for references to the Frenkel line, Chloé-Aminata Gauvin-Ndiaye for interesting discussions about electron doped cuprates, David Sénéchal for his help understanding the basics of DCA, Claude Bourbonnais for his help understanding the physics of organic conductors and the current state of art, and finally Antoine Georges and Michel Ferrero for interesting discussions on the onset of the pseudogap. This work has been supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) under grants RGPIN-2019-05312, the Canada First Research Excellence Fund and by the Research Chair in the Theory of Quantum Materials. Simulations were performed on computers provided by the Canadian Foundation for Innovation, the Ministère de l'Éducation des Loisirs et du Sport (Québec), Calcul Québec, and Compute Canada. The Flatiron Institute is a division of the Simons Foundation.

# Bond disorder in Heisenberg-Kitaev-Gamma models

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As an extension to Kitaev's celebrated spin-liquid model on the honeycomb lattice [1], extended Heisenberg-Kitaev models that include further symmetry-allowed interaction terms have gained significant attention, as they are believed to describe Kitaev materials. Motivated by experiments on α-$RuCl_3$ [2,3], we investigate the role of quenched disorder in Heisenberg-Kitaev-Gamma models in applied magnetic fields. Using a combination of analytical and numerical tools, we find that bond disorder has significant consequences for the system's classical state as well as the magnon spectrum.

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References:

[1] A. Kitaev, Annals of Physics, 321, 2 (2006)

[2] R. Hentrich et al., Physical Review B, 102, 235155 (2020)

[3] S.-H. Baek et al., Physical Review B, 102, 094407 (2020)

# Symmetry oriented identification of correlated topological phases

*Axel Fünfhaus[1], *Mikel García-Díez[3,4], Maia García-Vergniory[3,5,6], Juan Luis Mañes[4], Roser Valentí[1], Stephen M. Winter[2]

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Abstract

**TQC in interacting phases: the Kitaev model** (Mikel García-Díez and Axel Fünfhaus):

The aim of this project is to extend the tools of Topological Quantum Chemistry (TQC) into the realm of correlated systems. TQC studies the topology of a band structure based on a real space picture in terms of localized Wannier functions representing the electronic states. We explore the topology of the Kitaev model in a honeycomb lattice by obtaining a similar band structure using the topological Hamiltonian technique. The bands of this non-interacting Hamiltonian correspond to excitations which are more complex than just electronic states, and that can be created by more than one operator. We study a subset of the excitations and try to localize them as "orbitals" with a certain symmetry which would generate the bands obtained. This lays the ground for applying TQC directly and trying to find meaningful conclusions about the topology without using much more complex and costly many-body methods.

**Topological indices in inversion symmetric correlated phases** (Axel Fünfhaus):

Momentum space topological invariants can be generalized to interacting phases by relating the shift of canonical momentum under flux insertion to twisted boundary conditions in real space. In the case of inversion symmetry, high symmetry points in the manifold of twisted boundary conditions can be used to identify topological phases and phase transitions. This is accomplished by analyzing sections with suitable gauge choices of fiber bundles for (fractional) Chern insulators and of Pfaffian line bundles for $Z_2$ invariants. Such an analysis promises to be beneficiary for exact diagonalization, as only high symmetry points have to be analyzed to determine the topological index.

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## Topological Superconductivity in the nodal-plane material RhGe

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We find a symmetry-enforced nodal plane in the noncentrosymmetric crystal RhGe that was reported to become superconducting below 4.5K in 2015 [1]. The degeneracy at the boundaries of the Brillouin zone is stabilized by the combined effect of a nonsymmorphic screw rotation and time-reversal symmetry.

Since the nodal plane is close to the Fermi level, we suspect it to play an important role in the emergence of superconductivity and potentially enhance interband pairing effects.

Density Functional Theory predicts this material to be a weak ferromagnet. Starting from our own ab-inito calculations, we construct an effective low-energy model and calculate the susceptibility within the Random Phase Approximation.

Lastly, we analyze the spin-fluctuation mediated paring symmetry as a function of filling and intra- and inter-band interactions.

We find a number of different superconducting phases with non-trivial toplogies, and discuss implications for experiments on RhGe.

**References**

[1]. A. B. Tsvyashchenko et al., Journal of Alloys and Compounds 686:431–437 (2016).

IrRep: Symmetry eigenvalues and irreducible representations of *ab initio* band structures

Mikel Iraola, Stepan S. Tsirkin and Maia G. Vergniory

Abstract: The symmetry analysis of band structures has regained importance with the discovery of topological insulators. Indeed, the formalisms of Topological Quantum Chemistry and symmetry-based indicators have unveiled the interplay between crystal symmetries and topology. According to them, the topology of a set of bands can be diagnosed and classified based on the irreducible representations (irreps) of its Bloch states. In spite of it, most Density Functional Theory codes lack the possibility of calculating irreps of bands or follow a personal notation for irreps. We present IrRep, a code to calculate the irreps and symmetry eigenvalues of *ab initio* band structures of solids.

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# Topological Random Fractals

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The search for novel topological quantum states has recently moved beyond naturally occurring crystalline materials to complex and engineered systems. In this work we generalize the notion of topological electronic states to random lattices in non-integer dimensions. By considering a class $D$ tight-binding model on critical clusters resulting from a two-dimensional site percolation process, we demonstrate that these topological random fractals exhibit the hallmarks of topological insulators. Specifically, our large-scale numerical studies reveal that topological random fractals display a robust mobility gap, support quantized conductance and represent a well-defined thermodynamic phase of matter. The finite-size scaling analysis further suggests that the critical properties are not consistent with the expectations of class $D$ systems in two dimensions, hinting to the nontrivial relationship between fractal and integer-dimensional topological states.

## References

[1] Noah P. Mitchell, et al. "Amorphous topological insulators constructed from random point sets," Nat. Phys. 14, 380-385 (2018).

[2] Adhip Agarwala and Vijay B. Shenoy, "Topological insulators in amorphous systems," Phys. Rev. Lett. 118, 236402 (2017).

[3] Kim Pöyhönenen, et al. "Amorphous topological superconductivity in a Shiba glass," Nat. Commun. 9, 2103 (2018).

[4] Marta Brzezińska, et al. "Topology in the Sierpiński-Hofstadter problem," Phys. Rev. B 98, 205116 (2018).

[5] Sander N. Kempkes, et al. "Design and characterization of electrons in a fractal geometry," Nat. Phys. 15, 127–131 (2019).

[6] Zhaou Yang, et al. "Photonic Floquet topological insulators in a fractal lattice," Light: Science & Applications 9, 128 (2020).

[7] Shriya Pai and Abhinav Prem, "Topological states on fractal lattices," Phys. Rev. B 100, 155135 (2019).

[8] Askar A. Iliasov, et al. "Hall conductivity of a Sierpiński carpet," Phys. Rev. B 101, 045413 (2020).

[9] Sourav Manna, et al. "Anyons and fractional quantum Hall effect in fractal dimensions," Phys. Rev. Research 2, 023401 (2020).

[10] Sonja Fischer, et al., "Robustness of chiral edge modes in fractal-like lattices below two dimensions: A case study," Phys. Rev. Research 3, 043103 (2021).

[11] Sourav Manna, et al. "Higher-order topological phases on fractal lattices" Phys. Rev. B 105, L201301 (2022).

[12] Tobias Biesenthal, et al. "Fractal photonic topological insulators." Science 376(6597), 1114-1119 (2022).

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# Electronic Structure and Superconductivity of the High Entropy Alloy Sc-Zr-Nb-Rh-Pd

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In 2014, the superconductivity was discovered in the new type of materials - High Entropy Alloys (HEA), the alloys that are formed by mixing relatively large proportions of five or more elements. Since then, the superconductivity was found experimentally in many HEAs. However, the theoretical research concerning the electronic structure and the mechanism behind forming of the superconducting state is scant. HEAs are of high interest from material science point of view due to their unique properties such as high fracture toughness, ductillity and yield strength in extreme temperatures as well as resistance to corrosion and oxidation. The superconductivity of Sc-Zr-Nb-Rh-Pd alloy was experimentally confirmed in 2018 and reported in [1]. This research investigates electronic structure of the Sc-Zr-Nb- Rh-Pd HEA by employing the Korringa-Kohn-Rostoker Coherent Potential Approximation method (KKR-CPA) and Density Functional Theory. The main purpose of this work was to analyze how well the KKR-CPA method can describe the electronic properties of HEAs. Similar computations were carried out in [2] for Ta-Nb-Hf-Zr-Ti HEA superconductor. The results obtained in this work concern the McMillan-Hopfield coefficients, the density of electronic states around Fermi Energy and dispersion relations for different concentrations of the components in Sc-Zr-Nb-Rh-Pd HEA for which the formation of the superconducting state was observed. The computations also showed that the CsCl structure should be observed in this type of alloy, and the experimental data in [1] shows that this is indeed the case. Additionally, strong smearing of the electronic bands show the significance of the chemical disorder in the properties of the alloy.

[1] K. Stolze, J. Tao, F. O. von Rohr, T. Kong, and R. J. Cava, Chemistry of Materials 2018 30 (3), 906-914
[2] Jasiewicz, K. and Wiendlocha, B. and Górnicka, K. and Gofryk, K. and Gazda, M. and Klimczuk, T. and Tobola, J., Phys. Rev. B, Vol. 100,iss. 18 (2019)

# On the partitioning of Energy and Entropy in Time-Dependent Open Quantum Systems

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An unambiguous operator is established for the internal energy of a multiply-connected, interacting, time-dependent open quantum system subject to an external topological field, shedding light on a long-standing debate about how exactly the First Law of Thermodynamics should be formulated for such systems [1–5]. We arrive at this using a key insight from Mesoscopics [6] about how to unambiguously define Heat in strongly driven quantum systems: Infinitely far away from the local driving and coupling of an open quantum system, reservoirs are only infinitesimally perturbed from equilibrium, allowing one to unambiguously define Heat in strongly driven systems. General expressions for the quantum-statistical averages of the heat current and the power delivered by various agents including the external topological fields, for an interacting Fermionic system are derived using Non-Equilibrium Green's Functions, establishing an experimentally meaningful and quantum mechanically consistent division of the energy of the system under consideration into Heat flowing from and Work done on the system [7]. Our thermodynamic analysis also readily incorporates phonons and electron-phonon interactions and their effect on the first law is investigated. We also analyze the spatial distribution of the internal energy [8], which is concentrated within the system and along the system-reservoir interface. We then proceed to discuss the connection of the First law thus formulated with the quantum operator for entropy. Discovering that a partitioning of the entropy consistent with that imposed by the First Law exists only for linear perturbations of the system from equilibrium owing to the fact that Heat and Entropy have an apriori connection only for linearly perturbed systems. Motivated by previous work [9], we apply our formalism to analyze the thermodynamic performance of a model quantum machine: a driven two-level quantum system strongly coupled to two metallic reservoirs, which can operate in several configurations as a chemical pump/engine and a heat pump/engine by leveraging Rabi Oscillations of the system. We present a detailed analysis of its operation as a chemical pump and a heat engine, the latter of which performs at 53% of Carnot efficiency for the parameters chosen. Finally, we consider multiply-connected geometries threaded by topological fields [10] capable of inducing the Aharonov-Bohm (for charged particles) and Aharonov-Casher (for neutral spin-1/2 particles) effects and the topological work [11] done by the fields in such systems is investigated.

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[1] P. Talkner and P. Hänggi, *Colloquium* : Statistical mechanics and thermodynamics at strong coupling: Quantum and classical, Rev. Mod. Phys. **92**, 041002 (2020).
[2] P. Strasberg and A. Winter, First and Second Law of Quantum Thermodynamics: A Consistent Derivation Based on a Microscopic Definition of Entropy, PRX Quantum **2**, 030202 (2021).
[3] M. F. Ludovico, J. S. Lim, M. Moskalets, L. Arrachea, and D. Sánchez, Dynamical energy transfer in ac-driven quantum systems, Phys. Rev. B **89**, 161306 (2014).
[4] A. Bruch, M. Thomas, S. Viola Kusminskiy, F. von Oppen, and A. Nitzan, Quantum thermodynamics of the driven resonant level model, Phys. Rev. B **93**, 115318 (2016).
[5] N. Bergmann and M. Galperin, A Green's function perspective on the nonequilibrium thermodynamics of open quantum systems strongly coupled to baths: Nonequilibrium quantum thermodynamics, Eur. Phys. J. Spec. Top. **230**, 859 (2021).
[6] J. U. Nöckel, A. D. Stone, and H. U. Baranger, Adiabatic turn-on and the asymptotic limit in linear-response theory for open systems, Phys. Rev. B **48**, 17569 (1993).
[7] P. Kumar and C. A. Stafford, On the first law of thermodynamics in time-dependent open quantum systems, in *APS March Meeting Abstracts*, APS Meeting Abstracts, Vol. 2022 (2022) p. K50.00002.
[8] C. A. Stafford, M. A. Jimenez Valencia, C. M. Webb, and F. Evers, Entropy density and flux in topological and nonequilibrium quantum systems, in *APS March Meeting Abstracts*, APS Meeting Abstracts, Vol. 2022 (2022) p. K50.00005.
[9] C. A. Stafford and N. S. Wingreen, Resonant Photon-Assisted Tunneling through a Double Quantum Dot: An Electron Pump from Spatial Rabi Oscillations, Phys. Rev. Lett. **76**, 1916 (1996).
[10] M. Büttiker and C. A. Stafford, Charge Transfer Induced Persistent Current and Capacitance Oscillations, Phys. Rev. Lett. **76**, 495 (1996).
[11] C. Stafford, Y. Xu, and F. Evers, Topological effects on the thermodynamics of open quantum systems, in *APS March Meeting Abstracts*, APS Meeting Abstracts, Vol. 2021 (2021) p. J34.010.

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# An improved Two-Particle Self-Consistent Approach

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Abstract

One of the important models for the study of electron interactions in strongly correlated materials is the Hubbard model. There is a handful of numerical approaches to find approximate solutions to this model. One of these methods is the Two-Particle Self-Consistent approach (TSPC) [1][2], which has been used, in particular, to study the electron-doped cuprates successfully. However, this method is not valid in regimes where the antiferromagnetic correlation length becomes large.

Thus, we propose an improvement of the method which is called TPSC+ [3]. We show that the method respects the Mermin-Wagner theorem, it is valid in the classical renormalized regime and recovers a renormalized antiferromagnetic ground state. The main hypothesis of TPSC+ is that the spin and charge susceptibilities are now dependent of the interacting green function. We show comparisons to benchmarks for the pseudogap in the 2D Hubbard model.

Figure

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References:

[1] Vilk, Y. M., and al. *Journal de Physique I* 7, no. 11 (November 1997): 1309–68

[2] K. Zantout, S. Backes, and R. Valent́ı, Two-particle self-consistent method for the multi-orbital hubbard model, Annalen der Physik 533, 2000399 (2021).

[3] Schäfer, et al. *Physical Review X* 11, no. 1 (March 23, 2021): 011058.

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# Deconfinement of Majorana vortex modes produces a superconducting Landau level

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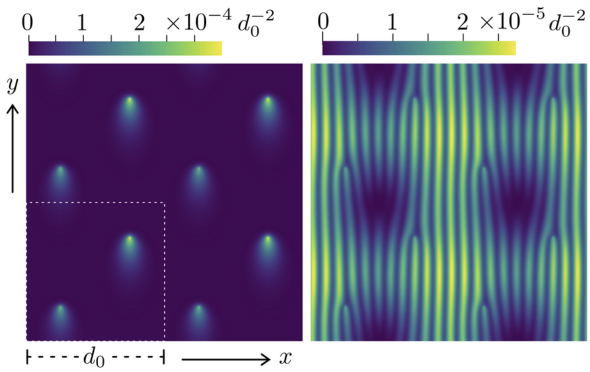
Abstract:

A spatially oscillating pair potential $\Delta(\mathbf{r}) = \Delta_0 e^{2i\mathbf{K}\cdot\mathbf{r}}$ with momentum $K > \Delta_0/\hbar v$ drives a deconfinement transition of the Majorana bound states in the vortex cores of a Fu-Kane heterostructure (a 3D topological insulator with Fermi velocity v, on a superconducting substrate with gap $\Delta_0$, in a perpendicular magnetic field). In the deconfined phase at zero chemical potential the Majorana fermions form a dispersionless Landau level, protected by chiral symmetry against broadening due to vortex scattering. The coherent superposition of electrons and holes in the Majorana Landau level is detectable as a local density of states oscillation with a characteristic wave vector. The striped pattern also provides a means to measure the chirality of the Majorana fermions.

Figure:

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References: Phys. Rev. Lett. **126**, 226801 – Published 2 June 2021

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# *OVERLAP OF PARAFERMIONIC ZERO MODES AT A FINITE DISTANCE*

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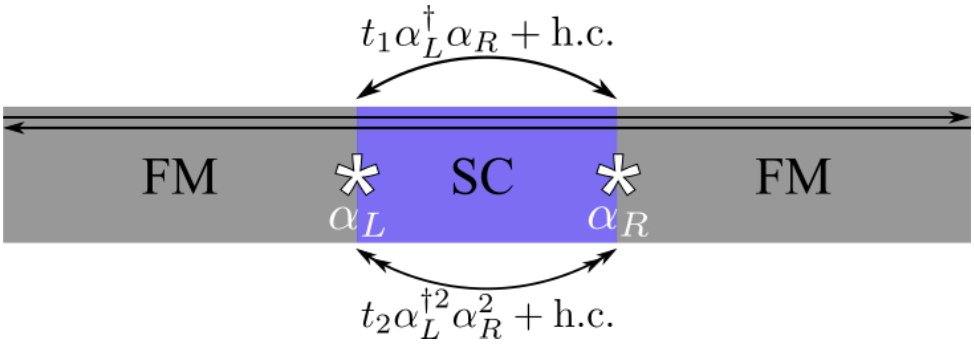
Abstract: Parafermion bound states (PBSs) are generalizations of Majorana bound states (MBSs) and have been predicted to exist as zero-energy eigenstates in proximitized fractional quantum Hall edge states. Similarly to MBSs, a finite distance between the PBS can split the ground state degeneracy. However, parafermionic modes have a richer exchange statistics than MBSs, so several interaction terms are allowed by the underlying $Z_{2n}$ symmetry, rendering the effective Hamiltonian governing a pair of PBSs at a finite distance nontrivial. Here, we use a combination of analytical techniques (semiclassical instanton approximation) and numerical techniques (quantum Monte Carlo simulations) to determine the effective coupling Hamiltonian. For this purpose, we go beyond the dilute one-instanton gas approximation and show how finite-size effects can give rise to higher-order parafermion interactions. We find excellent agreement between the analytical results and Monte Carlo simulations. We estimate that these finite-size corrections should be observable in some of the recently proposed experiments to observe PBSs in strongly correlated systems.

Figure:

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# CONDUCTANCE-MATRIX SYMMETRIES OF MULTITERMINAL SEMICONDUCTOR-SUPERCONDUCTOR DEVICES

Andrea Maiani*, Max Geier, Karsten Flensberg

Nonlocal tunneling spectroscopy of multiterminal semiconductor-superconductor hybrid devices is a powerful tool to investigate the Andreev bound states below the parent superconducting gap. We examine how to exploit both microscopic and geometrical symmetries of the system to extract information on the normal and Andreev transmission probabilities from the multiterminal electric or thermoelectric differential conductance matrix under the assumption of an electrostatic potential landscape independent of the bias voltages, as well as the absence of leakage currents. These assumptions lead to several symmetry relations on the conductance matrix. Next, by considering a numerical model of a proximitized semiconductor wire with spin-orbit coupling and two normal contacts at its ends, we show how such symmetries can be used to identify the direction and relative strength of Rashba versus Dresselhaus spin-orbit coupling. Finally, we study how a voltage-bias-dependent electrostatic potential as well as quasiparticle leakage break the derived symmetry relations and investigate characteristic signatures of these two contributions.

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References: arXiv: 2205.11193

# Can Caroli-de Gennes-Matricon and Majorana vortex states be distinguished in the presence of impurities?

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Abstract

Majorana zero modes states (MZMs) are predicted to appear as bound states in vortices of topological superconductors. MZMs are pinned at zero energy and have zero charge due to particle-hole symmetry. MZMs in vortices of topological superconductors tend to coexist with other subgap states, named Caroli-de Gennes-Matricon (CdGM) states. The distinction between MZMs and CdGM is limited since current experiments rely on zero-bias peak measurements obtained via scanning tunneling spectroscopy. In this work, we show that a local impurity potential can push CdGM states to zero energy. Furthermore, the finite charge in CdGM states can also drop to zero under the same mechanism. We establish, through exploration of the impurity parameter space, that these two phenomena generally happen in consonance. This means that energy and charge shifts in CdGM may be enough to imitate spectroscopic signatures of MZMs.

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References:

[1] de Mendonça, Bruna S., et al. "Can Caroli-de Gennes-Matricon and Majorana vortex states be distinguished in the presence of impurities?." *arXiv preprint arXiv:2204.05078* (2022).

[2] B. S. de Mendonça, A. L. R. Manesco, N. Sandler, and L. G. D. da Silva, “Can Caroli-de Gennes-Matricon and Majorana vortex states be distinguished in the presence of impurities?”, Zenodo repository 10.5281/zenodo.6444338 (2022).

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Portions of this work were completed at NBI (KU) and the Physics Department at DTU (Denmark) under support from Otto Monsteds and NORDEA foundations.

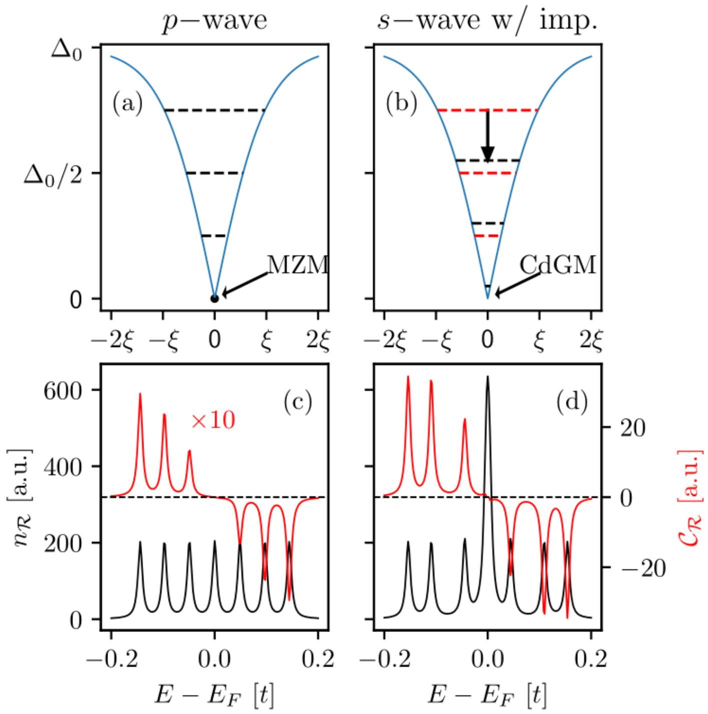


Figure: Sketch of the spectrum of states inside the vortex for a (a) clean p-wave system and (b) an s-wave system with and without a screen charge impurity. The blue line shows the position dependency of the superconducting order parameter, the dashed lines schematically show the energy of in-gap CdGM states, and the black arrow indicates the energy shift caused by the impurity potential. In panel (b), red dashed lines indicate the CdGM spectrum in the absence of a charge impurity, whereas the spectrum with an impurity is shown in black. Density of states (black) and BCS charge (red) for (c) p-wave system and (d) s-wave system with impurity.

# Thermal Conductivity and Theory of Inelastic Scattering of Phonons by Collective Fluctuations

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We study the coupling of phonons to any general operator field and its consequences on the thermal conductivity of phonons. Using a scattering approach, we find that the lowest-order diagonal scattering rate, which determines the longitudinal conductivity, is controlled by two-point correlation functions of the collective fluctuations the phonons couple to, while the off-diagonal scattering rates involve a minimum of four-point correlation functions. We take up the challenge of computing analytically these two- and four-point correlation functions in an ordered antiferromagnet and fermionic spinon spin liquid, hence providing expressions for the longitudinal and Hall conductivities in such systems. By explicit numerical computation of the phonon conductivity tensor from a given realistic interacting model of spins, we relate thermal conduction properties to features of the spin dynamics and the magnetoelastic coupling.

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**References:**

[**1**] L. Mangeolle, L. Balents, L. Savary. *Thermal Conductivity and Theory of Inelastic Scattering of Phonons by Collective Fluctuations.* (2022) arXiv:2202.10366

[**2**] L. Mangeolle, L. Balents, L. Savary. *Phonon thermal Hall conductivity from scattering with collective fluctuations.* (2022) arXiv:2206.06183

[**3**] L. Mangeolle, L. Balents, L. Savary. *Phonon Thermal Hall Conductivity from Electronic Systems and Fermionic Quantum Spin Liquids.* To appear (2022).

# Effective field theory of critical surfaces in class AIII topological insulators

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Abstract: In recent years there has been increasing numerical evidence of integer quantum Hall criticality at the surface of 3-dimensional topological insulators in class AIII at finite energies. We develop an effective field theory for the surfaces of our system starting from a microscopic description of the 3-dimensional bulk. The low energy field theory of the surfaces turns out to be a topological non-linear σ model with a topological angle π, signaling criticality at the surface for all finite energies.

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## Effects of spin dilution on a topological system of magnons

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# Abstract

Topological quantum matter has been intensively studied in recent years due to the robustness (topological protection) of its exotic properties to perturbations like small disorder. Interestingly, this property not only applies to electron systems, but also applies to magnon systems opening new application possibilities in spin-based electronic devices. In this work we discuss the effect of dilution disorder, where atoms are randomly removed from the lattice sites. Starting with electronic systems subjected to this disorder, we discuss the diluted Haldane model and characterize numerically the topological phase diagram (M,p), being M and p the Haldane mass and fraction of occupied sites respectively. Alongside the topological properties, we also explore the gapped-gappless phases of the system using Kernel Polynomial Methods (KPM). For all M values, the topological transition occurs long before the percolation transition for the honey-comb lattice with NN and NNN. Additionally we found that for larger M, the topological transition driven by disorder occurs for smaller values of dilution. Finally, we discuss a topological magnon model on the honeycomb lattice with Dzyaloshinkii-Moriya interaction subjected to dilution disorder and make the comparison of the results of this model with Haldane model.

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# Ising superconductors: The signatures of triplet pairings in the density of states and vanishing of the "mirage" gap

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The conventional two-dimensional superconductors are governed by the critical in-plane magnetic field above which the superconductivity is destroyed. Monolayer transition-metal dichalcogenides lack inversion symmetry and along with a strong spin-orbit coupling, lead to valley-dependent Zeeman-like spin splitting. This is the Ising spin-orbit coupling (ISOC) which then lifts the degeneracy of the two valleys and enhances the in-plane critical magnetic field. The finite energy pairings are thus obtained in such systems. The main superconducting gap-like feature shifted to finite energy is observed and termed a “mirage” gap.

The triplet pairings are introduced by the applied field, which then affects the critical field of the Ising superconductors. The equal-spin triplet pairing is always coupled to the singlet pairing thereby affecting the singlet order parameter greatly at higher fields. Importantly, we observe a peculiar feature of the mirage gaps in such systems. As the applied field increases from zero, the mirage gap appears, vanishes at some finite value of the field, and then appears back again as the applied field is increased. This finite value of the field at the mirage gap closing is exactly where the eigenvalues of the BdG Hamiltonian seem to cross each other. The concerned phenomenon can be observed within an interval of the critical temperature of the triplet pairing at a fixed ISOC and at a fixed temperature. This would further be explored by obtaining a phase diagram for the vanishing of the gap in the three-dimensional space of the applied field, temperature, and the critical triplet temperature, for a fixed ISOC. The role of topology in such a mirage gap closing would be our topic of study. We would also like to investigate if the vanishing of the mirage gap has any observable physical effects on the superconductivity.

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References: G. Tang et. al., Phys. Rev. Lett. 126, 237001 (2021).

M. Kuzmanović et. al., arXiv:2104.00328 (2021).

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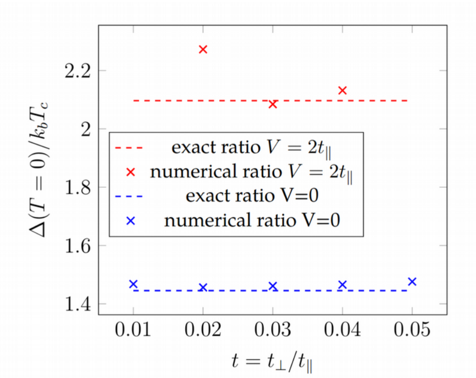
# Dimensional crossover in weakly-coupled chains

Lorenzo Pizzino and Thierry Giamarchi (University of Geneva)

Abstract

We study the dimensional crossover that occurs in weakly-coupled 1D chains. We combine a mean-field treatment with Bosonization technique to exploit our system made of interacting particles (hard-core bosons and negative U fermions). We show that the very small transverse coupling opens a gap (sine-Gordon Hamiltonian) which at zero temperature is known exactly [1]. The ratio between the gap and the mean-field critical temperature is controlled by the only Luttinger parameter K. We verify our findings with numerical simulations (DMRG + MF) [2]. For the case of fermions at large U<0, we directly link with the hard-core bosons via Schrieffer-Wolff transformation. Furthermore, we find the Luttinger parameter from Bethe Ansatz result. For finite U we attempt to use the Renormalization group apporach.

Figure




Comparison analytical and numerical ratio gap and critical temperature for hard-core bosons

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References

1. S. Lukyanov and A. Zamolodchikov. “Exact expectation values of local fields in the quantum sine-Gordon model”. In: Nuclear Physics B (1997);

2. G. Bollmark, T. Kohler, L. Pizzino, Y. Yang. H. Shi, J. S. Hofmann, H. Shi, S. Zhang, T. Giamarchi, A. Kantian. “Solving 2D and 3D lattice models of correlated fermions -- combining matrix product states with mean field theory”. In: arXiV:2207.03754 (2022).

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# Cubic Hall viscosity in three-dimensional topological semimetals

Iñigo Robredo, Pranav Rao, Fernando de Juan, Aitor Bergara, Juan L. Mañes, Alberto Cortijo, M. G. Vergniory, and Barry Bradlyn

Abstract

The nondissipative (Hall) viscosity is known to play an interesting role in two-dimensional (2D) topological states of matter, in the hydrodynamic regime of correlated materials, and in classical active fluids with broken time-reversal symmetry (TRS). However, generalizations of these effects to 3D have remained elusive. In this work, we address this question by studying the Hall viscoelastic response of 3D crystals. We show that for systems with tetrahedral symmetries, there exist new, intrinsically 3D Hall viscosity coefficients that cannot be obtained via a reduction to a quasi-2D system. To study these coefficients, we specialize to a theoretically and experimentally motivated tight-binding model for a chiral magnetic metal in (magnetic) space group [(M)SG] P213 (No. 198.9), a nonpolar group of recent experimental interest that hosts both chiral magnets and topological semimetals (TSMs). Using the Kubo formula for viscosity, we compute two forms of the Hall viscosity, phonon and “momentum” (conventional) and show that for the tight-binding model we consider, both forms realize the novel cubic Hall viscosity. We conclude by discussing the implication of our results for transport in 2D magnetic metals and discuss some candidate materials in which these effects may be observed.

Figure

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References: Phys. Rev. Research **3**, L032068

# Transport signatures of van Hove singularities in mesoscopic twisted bilayer graphene

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Abstract: Magic-angle twisted bilayer graphene is a fascinating strongly correlated electron system. It has exceptionally flat low-energy bands with van Hove singularities close to the Fermi level, and it is believed that the van Hove singularities play a prominent role in the exotic phenomena of magic-angle twisted bilayer graphene by amplifying the electron correlation effects. Most theoretical and experimental research of twisted bilayer graphene has so far focused on observables in the thermodynamic limit, and transport in large samples in the semiclassical regime where inelastic scattering is important. In this work, we instead concentrate on mesoscopic ballistic samples in the quantum transport regime, which allows us to probe the quantum states and band structure in an energy-resolved fashion. We calculate the four-terminal conductance of twisted bilayer graphene as a function of the twist angle, interlayer hopping amplitude and energy, and we identify signatures of different types of van Hove singularities.

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# Building crystalline topological superconductors from Shiba lattices

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Localized or propagating Majorana boundary modes are the key feature of topological superconductors. While being a rarity in natural compounds, the tailored manipulation of quantum matter offers novel opportunities for their realization. Specifically, lattices of Shiba bound states that arise when magnetic adatoms are placed on the surface of a conventional superconductor can be used to create topological minibands within the superconducting gap of the substrate. Here, we exploit the possibilities of scanning tunneling microscopy to create and probe adatom lattices with single atom precision to create topological crystalline superconductors. Their topological character and boundary modes are protected by the spatial symmetries of the adatom lattice. We combine scanning probe spectroscopy, spin-sensitive measurements, first principle calculations, and theoretical modeling to to reveal signatures consistent with the realization of two types of mirror-symmetry protected topological superconductors: (i) with full bulk gap and topological edge as well as higher-order corner states and (ii) with symmetry-protected bulk nodal points. Our results show the immense versatility of Shiba lattices to design the topology and sample geometry of 2D superconductors.

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# Electronic band structure of the Co-pnictide CaCo2As2 probed by ARPES

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Abstract

Topological quantum materials represent an ideal scenario where to study the interplay between different interactions that can manifest interesting micro and macroscopic properties. One of this type of materials are the Weyl semimetals whose low-energy excitations are Weyl fermions. By the bulk-surface correspondence, these materials have topological protected Fermi arcs surface states. The experimental observation of these surface states gives an unequivocal proof that a particular compound is a Weyl semimetal [1]. Here, we report the experimental band structure of the recently predicted magnetic Weyl semimetal [2] Co-pnictide ACo2X2 (A=Ca,Ce and X=P,As). We present the angle-resolved photoemission spectroscopy (ARPES) measurements and density functional theory calculations to describe the electronic band structure and the possible existence of Weyl fermions in CaCo2As2.

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References:

[1] Su-Yang Xu et al., Science, 349, 613-617 (2015).

[2] Yuanfeng et al., Nature, 586, 702-707 (2020).

# Exceptional Surface Topology of Lindbladian Systems

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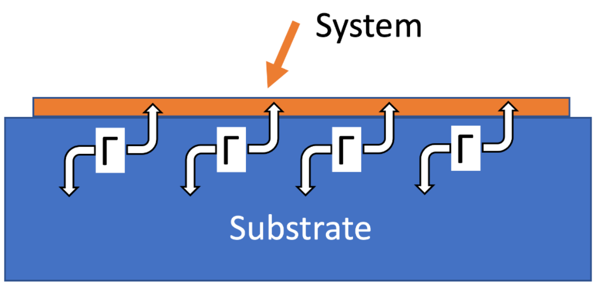
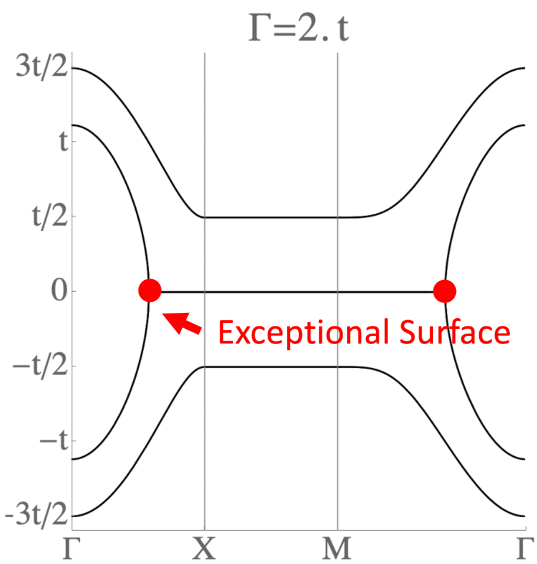
Exceptional points in parameter space where eigenvalues and eigenvectors coalesce are a key feature of non-Hermitian systems. Non-Hermiticity can originate with dissipation processes that lead to the gain or loss of energy and/or particles. In quantum systems, these processes can be represented via Lindbladian superoperators that determine the time evolution of the density matrix of a system subjected to continuous measurements by a memoryless bath. For quadratic Hamiltonians the Lindbladian can be reformulated in terms of right and left superfermions/superbosons with a low-dimension matrix representation. We showed (in arXiv:2203.07453) conditions under which symmetries of the dissipation (jump operators) ensure the formation of flat bands that are protected from dissipation. Here we review this work and discuss our more recent work on Bloch oscillations and the signatures of winding topology around exceptional points and surfaces in the Brillouin zone.




Subsystems of a full system exhibit non-Hermitian dynamics when particles are exchanged (at rate Γ) leading to the formation of exceptional surfaces and flattened bands in the Brillouin Zone.

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References:

- ST and MC, Dissipation Induced Flat Bands, arXiv:2203.07453 (2022)
- ST and MC, Bloch Oscillations in Open Fermionic Systems, (in preparation)

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# Bloch oscillations in the magnetoconductance of twisted bilayer graphene

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Abstract

We identify a mapping between two-dimensional (2D) electron transport in a minimally twisted graphene bilayer and a 1D quantum walk, where one spatial dimension plays the role of time. In this mapping a magnetic field B perpendicular to the bilayer maps onto an electric field. Bloch oscillations due to the periodic motion in a 1D Bloch band can then be observed in purely DC transport as magnetoconductance oscillations with periodicity set by the Bloch frequency.

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# Direct Measurement of the Andreev Bound State Spin During the Singlet-Doublet Transition

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Abstract: The past decade has seen many proposals to measure Majorana quasi-particles definitively. One such measurement involves probing the bulk spin polarization of a system undergoing a topological phase transition. An Andreev bound state (ABS) is expected to similarly show both charge and spin reversal at the singlet-doublet quantum phase transition. Here, we demonstrate a direct measurement of the spin and charge of an ABS. We measure the spin of the ABS by coupling it to a spin-polarized quantum dot and track its evolution as a function of magnetic field and chemical potential. We also measure the charge of the ABS by using non-local spectroscopy. Considering the ABS as a model for a topological system, we observe the expected signal at the quantum phase transition. We propose to extend these techniques as complementary measures for the occurrence of a topological phase transition.

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References:

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# Bloch-Lorentz magnetoresistance oscillations in delafossites

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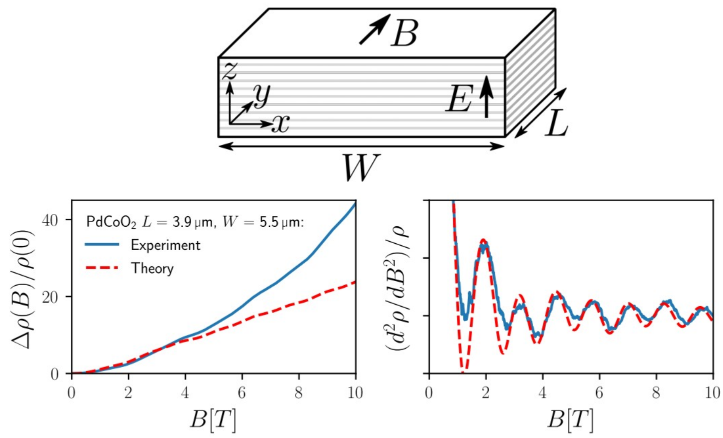
Abstract

Recent measurements [1] of the out-of-plane magnetoresistance of delafossites (PdCoO2 and PtCoO2) observed oscillations which closely resemble the Aharonov-Bohm effect. We develop a semiclassical theory of these oscillations and show that they are a consequence of the quasi-2D dispersion of delafossites. We observe that the Lorentz force created by an in-plane magnetic field makes the out-of-plane motion of electrons oscillatory, similarly to Bloch oscillations. The visibility of these Bloch-Lorentz oscillations is limited by sample wall scattering. Therefore, the aspect ratio of the sample controls the intensity of scattering. Our theory offers a way to design an experimental geometry that is better suited for probing the phenomenon and investigating the out-of-plane dynamics of ballistic quasi-two-dimensional materials.

Figure

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References: [1] C. Putzke, M. D. Bachmann, P. McGuinness, E. Zhakina, V. Sunko, M. Konczykowski, T. Oka, R. Moessner, A. Stern, M. K¨onig, S. Khim, A. P. Mackenzie et al., h/e oscillations in interlayer transport of delafossites (2019), 1902.07331.

# Prediction of anomalies in the velocity of sound for the pseudogap of hole-doped cuprates

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We predict sound anomalies at the doping δ* where the pseudogap ends in the normal state of hole-doped cuprates. Our prediction is based on the two-dimensional compressible Hubbard model using cluster dynamical mean-field theory. We find sharp anomalies (dips) in the velocity of sound as a function of doping and interaction. These dips are a signature of supercritical phenomena, stemming from an electronic transition without symmetry breaking below the superconducting dome. If experimentally verified, these signatures may help to solve the fundamental question of the nature of the pseudogap - pinpointing its origin as due to Mott physics and resulting short-range correlations.

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References: Arxiv 2207.00676v1

# Topological Superconductivity in Ge-Si Nanowires

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Abstract

Hybrid superconductor-semiconductor nanowire devices are promising candidate to achieve one-dimensional topological superconductivity. Recent theoretical studies[1] have drawn attention on an underestimated problem—the superconducting layer can significantly metalize the nanowire which could make the topological states unattainable. Here, we introduce Ge-Si core-shell nanowires and present the proximity induced superconductivity in such wires to prevent metallization. In addition, we studied the induced gap and its dependence on different Si shell thickness, providing a way to control the coupling strength between the superconductor and semiconductor. Lastly, we will discuss the prospect of realizing topological states in a double Ge-Si nanowire device[2].

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References:

1. Reeg, C., Loss, D., & Klinovaja, J. (2018). *Physical Review B*, 97(16), 165425.
2. Klinovaja, J., & Loss, D. (2014). *Physical Review B*, 90(4), 045118.

Acknowledgments:

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# Competition of dissipative and Andreev processes in Abelian quantum Hall - superconductor junctions

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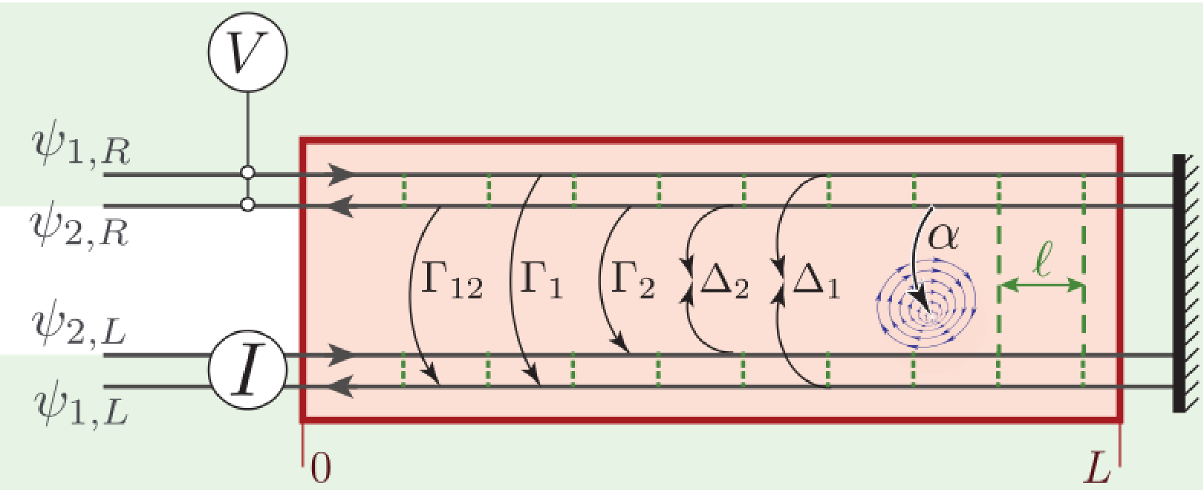
We investigate the interplay of disorder and proximity coupling to superconductors in quantum Hall edges coupled to superconductors. We show that this interplay can lead to new fixed points characterized by different conductance values. We investigate the magnitude of crossed Andreev reflection across different filling fractions and find the relation between the filling fraction and the behavior of the crossed Andreev reflection at low temperatures.

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