polytopo | Topological Textures in Condensed Matter

International Workshop

Physics and Mathematics of Topological Textures

14-16 May 2025 | Budapest, Hungary

Workshop Program
&
Book of Abstracts

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- **Martin Speight**, University of Leeds, United Kingdom

Program Overview

Time	Tuesday May 13	Wednesday May 14	Thursday May 15	Friday May 16
09:00-09:30	Arrival	Opening S. Komineas	R. Ignat	S. Kumar
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10:00-10:30		M. Krawczyk	M. Ruggeri	F. Franchini
10:30-11:00		Coffee break		
11:00-11:30		F. Rybakov	B. Stroffolini	S. Franke-Arnold
11:30-12:00		B. Barton-Singer	T. Ioannidou	R. Khomeriki
12:00-14:00		Lunch break		
14:00-14:30		D. Sheka	W. Lang	M. Speight
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16:00-16:30		Ž. Kos	Management Committee Meeting	Working Group Meetings
16:30-17:00		P. Leask		
17:00-17:30		Working Groups Meetings		
17:30-18:00				
18:00-20:00	Poster session Training school	Poster session	Core Group Meeting	

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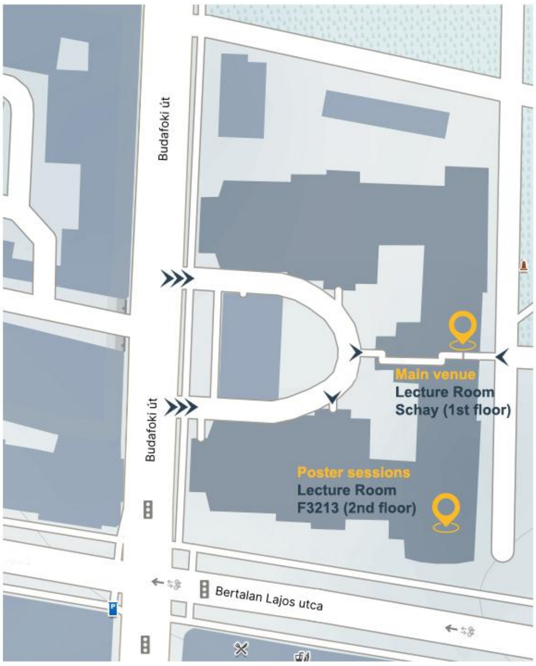
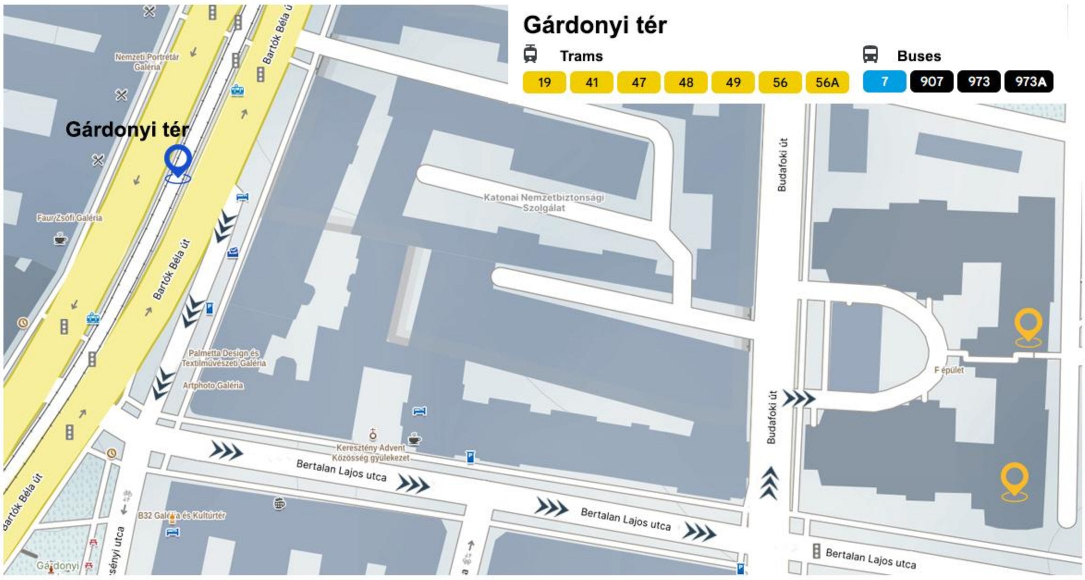
The Venue Map

Training School & Workshop venue: Budafoki út 8., BME, Building F





Workshop Program

Tuesday, May 13

18:00-20:00		**Poster session of the Training School**

You are invited to join the poster session of the Training School "Physics and Mathematics of Topological Textures". Meet the training school and workshop participants in an informal atmosphere!

Wednesday, May 14

09:00-09:30	Scientific Organizers	**Opening and Welcome**
	Stavros Komineas	**Overview on the COST Action POLYTOPO**
09:30-10:00	Markus Garst	**Topological dipoles of quantum skyrmions**
10:00-10:30	Maciej Krawczyk	**Multifunctional spin-wave platform based on hybrid magnonic crystal with confined skyrmions and soft ferromagnetic film**
10:30-11:00	Coffee break	
11:00-11:30	Filipp Rybakov	**Merons in magnets revisited: no need for fractional topological charges**
11:30-12:00	Bruno Barton-Singer	**Inter-skyrmion forces**
12:00-14:00	Lunch break	
14:00-14:30	Denis Sheka	**Curvilinear Magnetism: Fundamentals, Applications and Perspectives**
14:30-15:00	Claire Donnelly	TBA
15:00-15:30	Mehmet Cengiz Onbaşlı	**Ultralow power and ultra-wideband spintronics near thermodynamic limits**
15:30-16:00	Coffee break	

16:00-16:30	Žiga Kos	**Dynamics of topological defects in active and driven soft matter**
16:30-17:00	Paul Leask	**Flexoelectric polarization effect on skyrmions in chiral liquid crystals**
17:00-18:00	Working Group Meetings	
18:00-20:00	**Poster Session**	

Thursday, May 15

09:00-09:30	Radu Ignat	**Boundary vortices in ferromagnetic thin films**
09:30-10:00	Annika Bach	**Discrete-to-continuum variational analysis for Ising and Spin models**
10:00-10:30	Michele Ruggeri	**Time-stepping methods for projection-free approximations of evolutionary geometrically constrained partial differential equations**
10:30-11:00	Coffee break	
11:00-11:30	Bianca Stroffolini	**Mathematical analysis of a model for ferronematics in two dimensions**
11:30-12:00	Theodora Ioannidou	**Novel Lie-Poisson Algebras**
12:00-14:00	Lunch break	
14:00-14:30	Wolfgang Lang	**Topological effects of Abrikosov vortices in superconductors**
14:30-15:00	Mauro António Pereira Gonçalves	**Highway to electrifying skyrmions**
15:00-15:30	Dániel Varjas	**Stability of Weyl node merging processes under symmetry constraints**

15:30-16:00	Coffee break	
16:00-18:00	Management Committee Meeting	
18:00-19:00	Core Group Meeting	

Friday, May 16

09:00-09:30	Susmit Kumar	**Quantum anomalous Hall effect materials and devices for metrology (QuAHMET): An European Partnership on Metrology project**
09:30-10:00	András Pályi	**The geometry of the Hermitian matrix space and the Schrieffer-Wolff transformation**
10:00-10:30	Fabio Franchini	**The Frustration of Being Odd**
10:30-11:00	Coffee break	
11:00-11:30	Sonja Franke-Arnold	**Polarisation textures of light and atomic gasses**
11:30-12:00	Ramaz Khomeriki	**Photonic ferroelectric vortex lattice**
12:00-14:00	Lunch break	
14:00-14:30	Martin Speight	**Dipole interactions in chiral ferromagnets**
14:30-15:00	Thomas Winyard	**Skyrmion lattices for generic DMI**
15:00-15:30	Lucija Nora Farkaš	**Capturing instantons within the Functional Renormalization Group**
15:30-16:00	Closing remarks and Coffee break	
16:00-18:00	Working Groups	

List of Poster Presentations

1. János Asbóth	**Topological delocalization in two-dimensional quantum walks**
2. Ricardo Barbosa*	**Velocity operator renormalization in a s-3/2 Weyl Hamiltonian framework**
3. Domantas Burba	**Strong long-range interactions and geometrical frustration in subwavelength Raman lattices**
4. Dalibor Chevizovich	**Topology of biomolecular chains and self-trapping of an excitation**
5. Anirban Das	**Theory of Excitonic condensate in monolayer 1T′-WTe**
6. Sudipto Das	**Anomalous Reentrant Fractional Quantum Hall Effect at 5/2 in GaAs at Moderate Landau Level Mixing**
7. Shilpa Dutta	**Stray field effect in ferronematic thin films**
8. Mateusz Gołębiewski	**Three-dimensional gyroid and scaffold-like networks: Unveiling a new surface localization mechanism of ferromagnetic resonance modes in complex nanoarchitectures**
9. Jiri Hlinka	**Raman scattering of light with angular orbital moment**
10. Adarsh Hullahalli	**Magnon Spectrum around Skyrmions in Frustrated Magnets**
11. Baksa Kolok	**Protocols to measure the non-Abelian Berry phase by pumping a spin qubit through a quantum-dot loop**
12. Michail Lianeris	**Devices based on spin-torque diode for energy harvesters and sensors: A theoretical analysis**

13. David Miguélez-Caballero — **Unveiling the Internal Structure of Topological Vortices in the Abelian-Higgs model**

14. Emma Minarelli — **Topological inverse Faraday effect: Optical Hopfion interacting with matter**

15. Sergio Navarro — **Exploring the Moduli Space Metric of Excited Abelian-Higgs Vortices**

16. Hywel Normington — **A decoupled, convergent and fully linear algorithm for the Landau-Lifshitz-Gilbert equation with magnetoelastic effects**

17. Mario Pérez Diego — **Bloch-ball type representation of two-party composite systems with different local dimensions**

18. Edoardo Piccolo — **High order finite difference method for exchange field computation**

19. Gergő Pintér — **Upper bound on the number of Weyl points born from a multifold degeneracy point**

20. Ralph Rajamathi* — **Fascinating mesoscale magnetic textures in the topological Kagome system $TbMn_6Sn_6$**

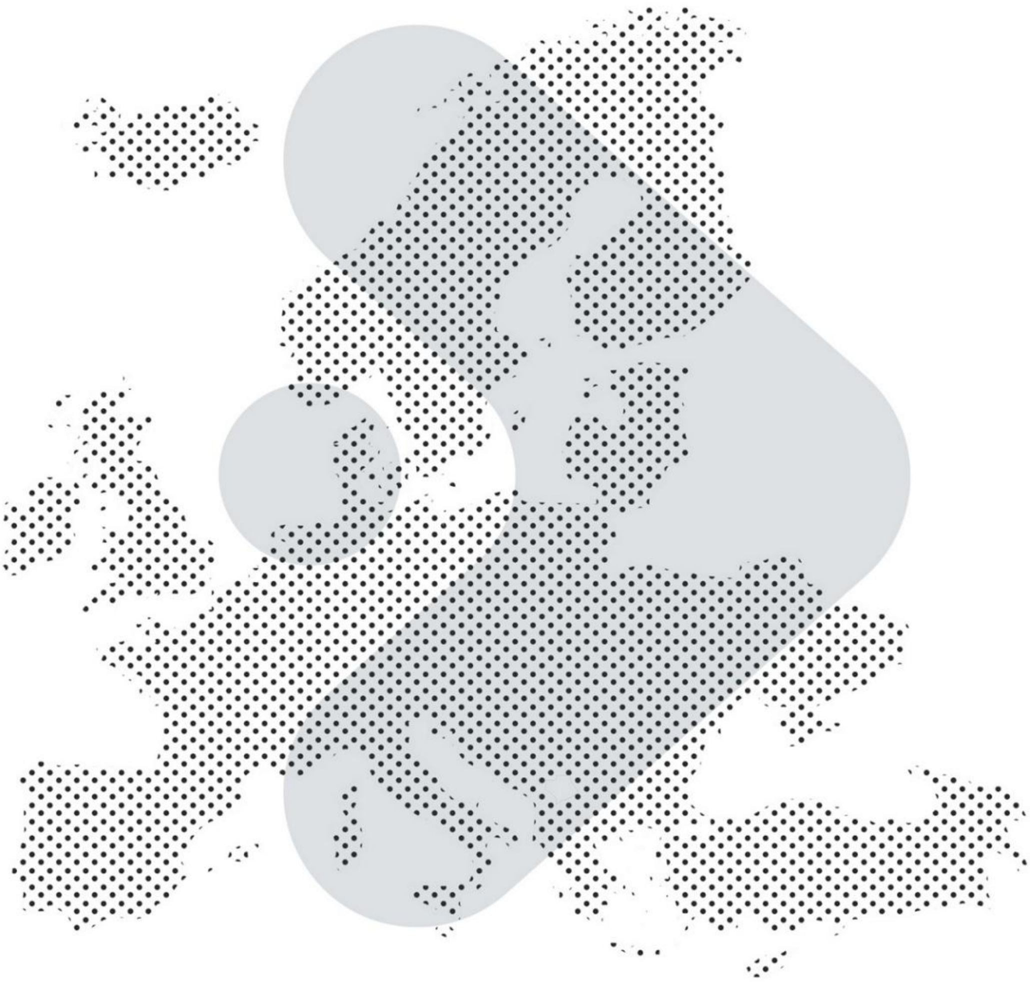
21. George Theodorou — **Interaction and collision of skyrmions in chiral antiferromagnets**

22. Gianpaolo Torre — **Interplay between local and non-local frustration in the 1D ANNNI chain**

23. Boglárka Tóth — **Terahertz spin-wave excitations in the transverse conical phase of $BiFeO_3$**

** Training school poster session only*

Book of Abstracts



Workshop Talks

Topological dipoles of quantum skyrmions

Sopheak Sorn[1], Jörg Schmalian[1], Markus Garst[1]

[1] *Karlsruhe Instiute of Technology, Karlsruhe, Germany*

Magnetic skyrmions are spatially localized whirls of spin moments in two dimension, featuring a nontrivial topological charge and a well-defined topological charge density. We demonstrate that the quantum dynamics of magnetic skyrmions is governed by a dipole conservation law associated with the topological charge, akin to that in fracton theories of excitations with constrained mobility. The dipole conservation law enables a natural definition of the collective coordinate to specify the skymion's position, which ultimately leads to a greatly simplified equation of motion in the form of the Thiele equation. In this formulation, the skyrmion mass, whose existence is often debated, actually vanishes. As a result, an isolated skyrmion is intrinsically pinned to be immobile and cannot move at a constant velocity. In a spin-wave theory, we show that such dynamics corresponds to a precise cancellation between a highly nontrivial motion of the quasi-classical skyrmion spin texture and a cloud of quantum fluctuations in the form of spin waves. Given this quenched kinetic energy of quantum skyrmions, we identify close analogies to the bosonic quantum Hall problem. In particular, the topological charge density is shown to obey the Girvin-MacDonald-Platzman algebra that describes neutral modes of the lowest Landau level in the fractional quantum Hall problem. Consequently, the conservation of the topological dipole suggests that magnetic skyrmion materials offer a promising platform for exploring fractonic phenomena with close analogies to fractional quantum Hall states.

Multifunctional spin-wave platform based on hybrid magnonic crystal with confined skyrmions and soft ferromagnetic film

Maciej Krawczyk[1], Krzysztof Szulc[1], Mateusz Zelent[1]

[1] *Institute of Spintronics and Quantum Information, Faculty of Physics and Astronomy, Adam Mickiewicz University, Poznan, Poland*

Materials with perpendicular magnetic anisotropy and antisymmetric exchange interactions are widely explored in spintronics, but have so far been of limited use in magnonics due to high damping. We propose a hybrid structure that exploits the rich dynamic properties of skyrmions in high-damping materials to control spin-wave propagation in a low-damping ferromagnetic strip [1]. The proposed hybrid magnonic crystal consists of a chain of skyrmions confined in circular multilayer nanodots located above a permalloy strip. Numerical results show complex spin-wave spectra with several key features for magnonics: dispersive bands with Bragg band gaps, anti-crossing gaps related to a coupling between two magnon modes of different origin; the flat bands and bound states related to the skyrmion azimuthal modes with frequencies below and above the ferromagnetic resonance frequency of the permalloy strip, respectively. In addition, the system offers reprogrammability due to two stable magnetisation states in the nanodots, a single domain state and a skyrmion state. With these properties, the proposed hybrid structure has multiple functionalities useful for magnonics that overcome the damping limitations of materials with perpendicular magnetic anisotropy and antisymmetric exchange interactions, opening up potential applications in spin-wave filtering, spin-wave generation and analog computing, in particular in the realisation of magnonic neural networks.

We acknowledge the financial support from National Science Centre, Poland, grants no. UMO-2020/39/I/ST3/02413 and UMO-2021/41/N/ST3/04478.

[1] K. Szulc, M. Zelent, M. Krawczyk, https://arxiv.org/abs/2404.10493

Merons in magnets revisited: no need for fractional topological charges

Filipp N. Rybakov[1]

[1] *Uppsala University, Sweden*

I will present a unified topological classification based on homotopy theory for vortices, merons and skyrmions in magnets. It will be shown how to solve the puzzling conclusion on a fractional topological charge for merons, which has become standard practice over the past decades.

F.N. Rybakov, O. Eriksson and N.S. Kiselev, arXiv:2412.17641 (2024)

Inter-skyrmion forces

Bruno Barton-Singer[1], Bernd Schroers[2]

[1] *Foundation of Research and Technology – Hellas, Greece*

[2] *University of Edinburgh, United Kingdom*

One of the first questions that arises when considering emergent particles such as the skyrmion is the influence of one on another: do they repel or attract, and can we show this mathematically. This question was asked about baby skyrmions by Schroers, Piette and Zakrzewski in 1995, and the methods developed were applied to magnetic skyrmions in 2019: they repel, with an exponentially decaying force set by the material anisotropy and external field (and independent of the DMI). In this talk I discuss generalising this method for more exotic textures such as the chiral drop, or more general situations such as applying a tilted magnetic field. The resulting structure of interactions becomes very rich, with the DMI playing an important role.

Curvilinear Magnetism: Fundamentals, Applications and Perspectives

Denis D. Sheka[1]

[1] *Department of Nanophysics of Condensed Media, Educational Scientific Institute of High Technologies, Taras Shevchenko National University of Kyiv, 64/13 Volodymyrska str., 01601 Kyiv, Ukraine*

The onrush of nanotechnologies extended conventional flat architectures to curved space, showcasing the fundamental importance of the mutual interplay between geometry, topology and the order parameter. In the case of magnetism a mutual interplay of magnetization texture (material properties), curvature, and topology (geometrical properties) becomes a playground for curvilinear magnetism [1]. By tailoring curvature and topology of the conventional magnetic materials there appears a possibility to control material response leading to modification or even launching new functionalities [2]. This is granted by complementary expertise and advances of fundamental researched, materials sciences and technologies.

This talk focuses on the peculiarities emerging from geometrically curved magnetic objects, including 3D bent and twisted curved wires and films. The curvilinear geometry manifests itself in emergent interactions. These geometry-governed interactions can be local driven by exchange and stemming from local curvature and torsion or stemming from the varying cross-section, but also can be nonlocal driven by magnetostatics and supported by topology [3]. As a consequence, family of novel geometry-governed effects emerge, which include magnetochiral effects and topological patterning, resulting in theoretically predicted domain wall automotion, unlimited domain wall velocities, chirality symmetry breaking, mesoscale DMI etc. Current and future challenges of the curvilinear magnetism will be discussed [4].

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[1] Makarov D and Sheka D, Curvilinear Micromagnetism: From Fundamentals to Applications (2022), Springer (doi: 10.1007/978-3-031-09086-8)

[2] Sheka D D, Curvilinear magnetism, Encyclopedia of Materials, 2023 (doi: 10.1016/B978-0-12-819728-8.00069-3)

[3] Sheka D D et al, Comm.Phys., 2020 (doi: 10.1038/s42005-020-0387-2); Yershov K V and Sheka D D, PRB, 2023 (doi: 10.1103/PhysRevB.107.L100415); Volkov O M et al, Nature Commun, 2023 (doi: 10.1038/s41467-023-37081-z)

[4] Sheka D D, APL, 2021 (doi: 10.1063/5.0048891); Gubbiotti G et al, JAP, 2025 (doi : 10.1088/1361-648X/ad9655)

Ultralow power and ultra-wideband spintronics near thermodynamic limits

Mehmet Cengiz Onbaşlı [1]

[1] *Department of Electrical-Electronics Engineering, Department of Physics, Koç University Rumelifeneri Yolu Sariyer 34450 Istanbul Türkiye*

Skyrmions are swirling quasi-particles that look and behave like particles. They could revolutionise the fields of data storage, information processing and artificial intelligence. For example, their size, speed and stability could mean smaller and faster memory devices. Their nanoscale spin structures allow for room temperature computation and memory functions near thermodynamic limits while being robust against fabrication imperfections and stray magnetic fields. The EU-funded SKYNOLIMIT project plans to experimentally demonstrate ultra-wideband, ultralow-power and non-volatile logic circuit architectures that are based on magnetic skyrmions. The project's activities will focus on modelling and testing novel functional nanomaterials with giant spin–orbit coupling, skyrmion processors and skyrmion-based neural network hardware.

Dynamics of topological defects in active and driven soft matter

Žiga Kos [1]

[1] *University of Ljubljana, Faculty of Mathematics and Physics, Slovenia*

Fluids with nematic orientational order emerge in various soft matter materials, from nematic liquid crystals to biological and synthesised active matter. Topological defects in the orientational order are called disclinations and genereally appear in the form of point defects, lines, and loops. I will present disclination dynamics for self-propagating active nematics [1,2] as well as driven nematic fluids in microchannels [3] and colloidal systems [4]. I will mainly focus on three-dimensional properties, where I will present the dynamic modes of single disclination loops, as well as topological reconfiguration dynamics of multiple loops and disclination networks. This work aims to provide insight into non-equilibrium soft matter from the perspective of the topology and dynamics of the emergent defects.

[1] N. Kralj, M. Ravnik, Ž. Kos, Defect line coarsening and refinement in active nematics, Phys. Rev. Lett. 130, 128101 (2023).

[2] N. Kralj, M. Ravnik, Ž. Kos, Chirality, anisotropic viscosity and elastic anisotropy in three-dimensional active nematic turbulence, Comm. Phys. 7, 222 (2024).

[3] S. Čopar, Ž. Kos, T. Emeršič, U. Tkalec, Microfluidic control over topological states in channel-confined nematic flows, Nat. Comm. 11, 59 (2020).

[4] T. Yao, Ž. Kos, Q.X. Zhang, Y. Luo, F. Serra, E.B. Steager, M. Ravnik, K.J. Stebe, Nematic Colloidal Micro-Robots as Physically Intelligent Systems, Adv. Func. Mat. 32 , 2205546 (2022).

Flexoelectric polarization effect on skyrmions in chiral liquid crystals

Paul Leask [1], Martin Speight[2]

[1] *Department of Physics, KTH Royal Institute of Technology, 10691 Stockholm, Sweden*

[2] *School of Mathematics, University of Leeds, Leeds, LS2 9JT, England, UK*

The presence of topological defects in liquid crystals cause orientational distortions, leading to non-uniform strain. This non-uniform strain generates an electric polarization response due to the flexoelectric effect, which induces an internal (flexo-)electric field. Associated to this flexoelectric field is an electrostatic self-energy, which has a back-reaction on the director field. Calculation of this internal flexoelectric field and its resulting back-reaction on the director field is complicated.

We propose a method to do such, adapting a method recently developed to study the magnetostatic self-interaction effect on skyrmions in chiral ferromagnets. Bloch skyrmions in chiral magnets are solenoidal and are unaffected by the magnetostatic self-interaction. However, Bloch skyrmions in liquid crystals yield non-solenoidal flexoelectric polarization and, thus, are affected by the electrostatic self-interaction. I will explore the main differences between the effect of electrostatic self-interactions on skyrmions in chiral magnets and chiral liquid crystals.

Boundary vortices in ferromagnetic thin films

Radu Ignat[1], Matthias Kurzke[2], François L'Official[1]

[1] *Institut de Mathématiques de Toulouse, France*

[2] *School of Mathematical Sciences. University of Nottingham, UK*

We consider a three-dimensional ferromagnetic model with Dzyaloshinskii-Moriya interaction in a thin-film regime for boundary vortices. In this regime, we prove a dimension reduction result: the nonlocal three-dimensional model reduces to a local two-dimensional Ginzburg-Landau type model in terms of the averaged magnetization in the thickness of the film. This reduced model captures the interaction between boundary vortices (so-called renormalised energy), that we determine by a Γ-convergence result at the second order and then we analyse its minimisers. They nucleate two boundary vortices whose position depends on the Dzyaloshinskii-Moriya interaction.

Discrete-to-continuum variational analysis for Ising and Spin models

Annika Bach[1], Marco Cicalese[2], Leonard Kreutz[2], Gianluca Orlando[3]

[1] *Eindhoven University of Technology, Netherlands*

[2] *Technical University of Munich, Germany*

[3] *Politecnico di Bari, Italy*

This talk is meant as an introductory talk to discrete-to-continuum variational analysis. Here the general objective is to characterise the macroscopic behaviour of energy-driven atomistic systems while keeping the scale-dependent relevant microscopic information. This is done via Gamma-convergence, which allows to coarse-grain discrete functionals to their continuum counterparts as the discretisation parameter vanishes. In this talk we will focus on some models with a particularly rich energy landscape, namely Ising and spin models such as the classical XY-model. In the first part I will give a short introduction to the topic and review some of the classical results in this context. In the second part I will present some recent results obtained in collaboration with Marco Cicalese, Leonard Kreutz, and Gianluca Orlando on the antiferromagnetic XY-model on the triangular lattice.

Time-stepping methods for projection-free approximations of evolutionary geometrically constrained partial differential equations

Michele Ruggeri[1]

[1] *University of Bologna, Italy*

We consider the numerical approximation of time-dependent geometrically constrained partial differential equations. Prototypical examples are problems with sphere-valued solutions, arising, e.g., in continuum models of ferromagnetic materials (micromagnetics) or nematic liquid crystals, or problems with solutions satisfying an isometry constraint, which arise in nonlinear bending theory. For the time discretization of this class of problems, we propose a projection-free linearly implicit theta-method, which is unconditionally energy stable and, for certain choices of the parameters of the method and under a sharp discrete regularity condition, achieves second-order accuracy in the constraint violation. Furthermore, the method accommodates variable step sizes. This feature, combined with appropriate step size control strategies, allows to speed up the convergence to stationary states and to improve the accuracy of the approximations near singularities. Numerical experiments illustrate the theoretical findings and compare the proposed approach with strategies based on the linearly implicit Euler method and the two-step BDF method. This is joint work together with G. Akrivis (U Ioannina), S. Bartels (U Freiburg), and J. Wang (Harbin Institute of Technology).

Mathematical analysis of a model for ferronematics in two dimensions

Bianca Stroffolini[1], Giacomo Canevari[2], Federico Dipasquale[3] , Apala Majumdar[4], Yiwei Wang[5]

[1] *University of Naples Federico II, Italy*

[2] *University of Verona, Italy*

[3] *SSM, University of Naples, Italy*

[4] *University of Strathclyde, UK*

[5] *University of California, Riverside, CA, USA*

Ferronematics are composite materials characterised by the coupling between magnetic particles and nematic liquid crystals. In this talk, I will present some results on a two-dimensional model for ferronematics in confined geometries. The model is based on the coupling between a polar order parameter – the magnetisation vector, which describes the magnetic inclusions - and a nonpolar one - the Landau-de Gennes Q-tensor, which describes the liquid crystal matrix. We will discuss the qualitative behaviour of free-energy minimisers in some asymptotic regimes of parameters, where both point and line singularities appear. The talk is based on joint work with Giacomo Canevari, Federico Dipasquale, Apala Majumdar and Yiwei Wang.

Novel Lie-Poisson Algebras

Theodora Ioannidou[1]

[1] *Civil Engineering, Aristotle University of Thessaloniki, Greece*

The starting point of our derivation is the discrete Frenet frame assigned at each vertex of the string. Then the link vector that connects the neighboring vertices is assigned the SU(2) Lie-Poisson bracket. Moreover, the same bracket defines the transfer matrices of the discrete Frenet equation which relates two neighboring frames along the string. The procedure extends in a self-similar manner to an infinite hierarchy of Poisson structures. As an example, the first descendant of the SU(2) Lie-Poisson structure is presented in detail.

Topological effects of Abrikosov vortices in superconductors

Wolfgang Lang[1]

[1] *Faculty of Physics, University of Vienna, Austria*

The study of various topological effects on the static location and the dynamics of Abrikosov vortices is an exciting field combining experimental research with theoretical concepts, ultimately touching the development of practical applications. After a short introduction into the underlying physics of vortices in superconductors, I will discuss several topological concepts, leading to regular and quasi-periodic arrangement of vortices, non-reciprocal transport properties caused by vortex motion, vortex ratchets and superconducting diodes. Cellular automata based on vortices could be an avenue for realizing ultrafast data processing with minimal dissipation. Recently, neuromorphic computing has been discussed in relation to topological vortex ensembles.

One of the essential prerequisites for most experimental studies is the magnetic coupling of these vortices, ensuring their separation does not exceed the London penetration depth at the target operating temperature. Achieving the necessary nanoscale precision is particularly challenging in copper-oxide superconductors, the so-called high-temperature superconductors, due to their intricate atomic structure and sensitivity to environmental factors. Traditional lithographic methods face significant limitations in this context, but these can now be circumvented by employing the focused beam of a helium ion microscope. Some examples of this technique will be presented.

Highway to electrifying skyrmions

Mauro António Pereira Gonçalves[1]

[1] *Institute of Physics of the Czech Academy of Sciences Na Slovance 1999/2, 182 00 Prague 8, Czech Republic*

Researchers have long sought to determine whether ferroelectric materials, known for their spontaneous and switchable electric polarization, can exhibit topological textures similar to magnetic skyrmions and chiral bubbles. The experimental discoveries of dipole vortices in $PbTiO_3/SrTiO_3$ superlattices [1,2], alongside earlier theoretical predictions of Bloch-like structures in ferroelectric domain walls [3], have catalyzed the search for electric Skyrmions.

In this work, I demonstrate that a simple multidomain configuration in $PbTiO_3$ or $BaTiO_3$ – specifically, a columnar nanodomain with polarization opposite to that of its surrounding matrix – is sufficient to stabilize, using atomistic simulations, a variety of dipole textures with the topology of a skyrmion [4] or antiskyrmion [5]. The combination of theoretical and experimental efforts has led to the first observation of electric skyrmions in $PbTiO_3/SrTiO_3$ superlattices [6] at room temperature. These electric skyrmions were observed in the $PbTiO_3$ ferroelectric layers, which are confined by paraelectric $SrTiO_3$ layers.

[1] Yadav, A.K., Nelson, C.T. et al., Observation of polar vortices in oxide superlattices. Nature 530, 198-201 (2016).

[2] Damodaran, A. R. et al., Phase coexistence and electric-field control of toroidal order in oxide superlattices. Nature Materials 16, 1003 (2017).

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[5] M. A. P. Gonçalves, et al, Antiskyrmions in Ferroelectric Barium Titanate. Phys. Rev. Lett. 133, 066802 (2024)

[6] S. Das et al., Observation of room temperature polar skyrmions. Nature 568, 368-372 (2019).

Stability of Weyl node merging processes under symmetry constraints

Dániel Varjas[1,2], Gabriele Naselli[2], György Frank[1], Ion Cosma Fulga[2], Gergő Pintér[1], András Pályi[1], Viktor Könye[3]

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Changes in the number of Weyl nodes in Weyl semimetals occur through merging processes, usually involving a pair of oppositely charged nodes. More complicated processes involving multiple Weyl nodes are also possible, but they typically require fine tuning and are thus less stable. In this work, we study how symmetries affect the allowed merging processes and their stability, focusing on the combination of a two-fold rotation and time-reversal (C2T) symmetry. We find that, counter-intuitively, processes involving a merging of three nodes are more generic than processes involving only two nodes. Our work suggests that multi-Weyl-merging may be observed in a large variety of quantum materials, and we discuss SrSi2 and bilayer graphene as potential candidates

Quantum anomalous Hall effect materials and devices for metrology (QuAHMET): An European Partnership on Metrology project

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The Quantum Hall effect (QHE) is the foundation for the realisation of the primary resistance standard (PRS), representing the "gold standard" in electrical metrology. QHE devices currently require low temperatures and high magnetic fields, impeding their adoption beyond national metrology institutes. The Quantum Anomalous Hall effect (QAHE) provides an opportunity to overcome these limitations while maintaining the unsurpassed accuracy expected of PRS. Greater knowledge of QAHE devices is essential to accelerate the development of a 'quantum electrical metrology toolbox' for the universal adoption of quantum electrical SI standards. QuAHMET project will grow, characterise, and evaluate thin films for QAHE and devices fabricated from them, leading to a detailed metrological assessment from sub-K to above 1 K, currents from below 100 nA to above 1 μA and over a wide range of external magnetic fields up to several Tesla.

Quantum anomalous Hall effect materials and devices for metrology (QuAHMET) is a Joint research Project of the European Partnership on Metrology. The project will focus on the traceable measurement and characterisation of quantum anomalous Hall effect (QAHE) materials as devices and primary resistance standard candidates.

The QuAHMET project consortium consists of 14 partners and gathers 7 leading European national metrology institutes (NMIs), a Japanese NMI for metrology, complemented by 6 globally recognized institutes from academia and applied research.

The geometry of the Hermitian matrix space and the Schrieffer-Wolff transformation

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In quantum mechanics, the Schrieffer--Wolff (SW) transformation (also called quasi-degenerate perturbation theory) is known as an approximative method to reduce the dimension of the Hamiltonian. We present a geometric interpretation of the SW transformation: We prove that it induces a local coordinate chart in the space of Hermitian matrices near a k-fold degeneracy submanifold. Inspired by this result, we establish a `distance theorem': we show that the standard deviation of k neighboring eigenvalues of a Hamiltonian equals the distance of this Hamiltonian from the corresponding k-fold degeneracy submanifold, divided by √k. We show how these relations unify the phenomenology of protected spectral degeneracies in various subfields of physics, including Weyl semimetals, topological insulators and superconductors, and quantum error correction codes.

Reference: G. Pinter, Gy. Frank, D. Varjas, A. Palyi, https://arxiv.org/abs/2407.10478

The Frustration of Being Odd

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We consider the effects of combining periodic boundary conditions inducing geometrical frustration with quantum interaction, a setting we call "topological frustration" (TF). The ground states with TF cannot be characterized as a vacuum, but they rather host single fractionalized, delocalized, topological excitations, which confer them unique properties, reminescent of systems with massive amount of frustration.

In this seminar I will introduce these concepts, show how to exploit TF for quantum technologies and discuss the possibilities for experimental realizations.

Polarisation textures of light and atomic gasses

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Polarisation - while invisible to the eye - has been recognized as an important feature of light since the days of Ptolemy. Over the last decades we have gained unprecedented control over light, allowing us to generate polarisation structures in 2D and 3D, explore its topologies and its interaction with matter. In this talk I will present how we generate and analyse arbitrary polarization textures and introduce you to some of its curious properties, including new insights into knife-edge diffraction, and optical skyrmions. I will explain how we can transfer optical polarisation textures to polariton structures in atomic gasses. Unlike optical polarizations, atomic spin alignments react to external fields and forces, promising applications in magnetometry and inertial sensing - and vice versa allowing us insights into optical properties that can not be detected directly with photodiodes or cameras.

Photonic ferroelectric vortex lattice

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The recent discovery of polar vortex textures revealed a new fascinating facet of nanoscale ferroelectric materials with prospects for new interaction pathways with chiral, topological, and photonic materials. Here, we demonstrate how the subterahertz collective response of the ferroelectric vortex lattice enables a coupling to electric and magnetic fields resulting in a novel type of photonic vortex lattice with particular dispersion that we analyze for a wide class of ferroelectric/paraelectric layered heterostructures. General arguments supported by full, material-specific numerics evidence the appearance of polarization-dependent optoelectronic modes and band gaps. The ferroelectric-photonic vorticity coupling renders photonic elements amenable to elastic, electric, and magnetic probes with far-reaching implications for new multifunctional optoelectronics.

Dipole interactions in chiral ferromagnets

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It is known that the magnetization in a ferromagnet induces an internal demagnetizing magnetic field. This, in turn, generates a magnetostatic self-energy, coming from dipole-dipole interactions. In general, this energy is singular and intrinsically non-local, making its study a hard numerical challenge. We show how recent advances in constrained Newton flow, introduced to study Skyrmions in variants of the nuclear Skyrme model with extra meson fields, can reduce this to a computationally tractable problem. The effect of dipole interactions on skyrmions turns out to depend crucially on the form of the DM interaction, and is particularly striking in Heusler magnets.

Skyrmion lattices for generic DMI

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In chiral magnets with DMI interactions, lattices of skyrmions are formed when the repulsive forces between skyrmions are balanced by the lowering of the energy through creation of skyrmions. Mathematically, these lattices can be determined by minimising the energy per unit cell, and minimising over all possible unit cells. In this talk , we'll discuss the nature and stability of such lattices for general DMI interactions and direction of applied magnetic fields.

Capturing instantons within the Functional Renormalization Group

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We investigate localized excitations (instantons) in the scalar ϕ^4 theory (Ising universality class) using Renormalization Group, RG. We do so in the regime of high interest for phase transitions, the vicinity of the lower critical dimension (d_{lc}) at which finite-temperature ordering becomes impossible due to such excitaions. Instantons are inherently nonperturbative, so we use Non-Perturbative Functional RG (NPFRG) allowing for nonperturbative Ansätze.

The 1+ε regime of the Ising model has been studied in depth by Bruce and Wallace [1-3]. They consider "droplets", i.e., closed domain walls, to be the extension of the instantons to d=1+ ε (instantons being the excitations which prohibit ordering in d_{lc}=1). However, this is a very specialized method, and they had to introduce these excitations "by hand".

We do not aim to "re-solve" te Ising model. In reality, we investigate whether FRG, a tried and versatile method when it comes to phase transitions [4], can quantitatively capture the long-wave effects of localized excitations. This is challenging, as any RG method uses coarse-graining to build an effective action describing long-wave physics. The relevance comes from the potential for generalization to problems where the nature of the excitations is unknown. This is why we chose FRG, as its Ansätze are built from minimal information, such as the symmetry of the system and the nature of the order parameter. For instance, we calculate the value of d_{lc} - it does not have to be known a priori.

Even in the lowest approximations of the NPFRG we find strong evidence that it captures instantons in the vicinity of d_{lc}. The hallmark of the approach to the lower critical dimension is nonuniform (in field) convergence of the fixed point potential. This is due to a a boundary layer forming near the minimum of the effective potential, the width of which shrinks to 0 as d_{lc} is approached. The emergence and shape of this shrinking boundary layer allows us to recover the T_c and gives strong evidence that the critical exponent 1/ν goes to 0 in the limit of d_{lc} regardless of approximation [5, 6].

Some systems dominated by localized, nonuniform excitations, that we hope to generalize our findings to, are hysteresis in the Random Field Ising model [7, 8] or even to tunneling problems that occur at the d_{lc}, like Josephson junctions [9].

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Poster Presentations

Topological delocalization in two-dimensional quantum walks

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Quantum walks, the quantum mechanical generalization of random walks, are interesting for quantum information processing, but also as simple dynamical systems that have topological features. One such feature is a delocalization of quantum walks under maximal disorder, which we study here. Disorder that does not fluctuate in time, generically induces in 1 and 2 dimensional coherent dynamical systems (such as quantum walks) Anderson localization. Thus, an initially localized wavepacket does not spread off to infinity, but its extent remains bounded by the localization length. Increasing the amount of disorder makes the localization stronger, localization length shorter. However, for quantum walks we find [1] that increasing the amount of disorder to the maximum value leads to first an increase of the localization length, and then a change in the dynamics from localized to diffusive. The reason is that maximal disorder tunes the quantum walk to a critical point between phases with different topological invariants.

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Velocity operator renormalization in a s-3/2 Weyl Hamiltonian framework

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We investigate nonlinear transport [1,2] in three-dimensional materials hosting Weyl nodes—linear band touchings that act as point-like sources and sinks of Berry curvature in momentum space, often referred to as "Weyl-Berry monopoles" [3,4]. These nodes feature higher-than-two-fold band degeneracies and carry nonzero Chern numbers, leading to unconventional electronic properties. Using a semiclassical approach with perturbative corrections [5,6], we achieve a renormalized velocity operator that incorporates higher-order contributions determined by the quantum geometric tensor, enabling a detailed analysis of nonlinear charge conductivity.

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Strong long-range interactions and geometrical frustration in subwavelength Raman lattices

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Non-local interactions are the key building block to allow for a spontaneous breaking of the translational symmetry. The latter represents one of the most fundamental symmetries in physics as it reflects the formation of periodic structures of mass and electric charge. Quantum matter with such a feature falls in the class of spontaneously symmetry broken (SSB) many-body phases with broken translational invariance. Their ubiquity in nature has made the investigation and creation of such states of matter of central importance. In this respect, quantum simulators made of ultracold magnetic atoms with large magnetic dipolar momentum (e.g., erbium) represent a promising and powerful resource. However, current setups only explore frustrated regimes with weak local interactions or regimes where quantum fluctuations are suppressed. To the best of our knowledge, there are no experimental schemes able to simultaneously realize long-range interactions and geometrical frustration.

Here we consider a possible alternative to current setups - a recently realized subwavelength lattice formed by a pair of counter-propagating lasers driving two photon Raman transitions in an ensemble of ultracold atoms. It was shown that one may precisely control the tunneling amplitude, range, and phase by tuning the detunings. One also achieves significantly stronger interactions in the proposed scheme due to its subwavelength nature. Thus, one may realize intriguing phases of matter, such as density waves and chiral superfluids. Our results show several possible scenarios may occur, depending on the lattice depth and detunings. For deep optical lattices, we find quasi long-range order of the single particle Green's function, thus signalling the presence of a normal superfluid. For lower lattice depths, a superfluid with spontaneously generated chiral currents appears. Finally, density waves of period two or three were observed for a large range of detuning values.

Topology of biomolecular chains and self-trapping of an excitation

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To the problem of the excitation self-trapping in the quasi one dimensional biomolecular structures was devoted numerous investigations. But in these investigations, macromolecules were regarded mainly as linear structures, neglecting the influence of the topology of the macromolecule on the process of the exciton self-trapping. It is clear that the taking into consideration of the curved shape with interlaced points of the macromolecule by itself, significantly complicates the considerations of physical phenomena occurring in such systems. On the other hand, twisted forms of macromolecular chains in which the particular structural elements become spatially very close to each other, become a source of additional local interactions of the macromolecular structure elements. Such interactions can significantly alter the process of the excitation self-trapping. We intend to analyze the influence of the regularly distributed interlaced points of the twisted single chain macromolecule to the effective mass of the self-trapped excitation. We taking into account the influence of the temperature, considering that vibron excitation is in thermal equilibrium with the surrounding thermal bath.

Theory of Excitonic condensate in monolayer 1T′-WTe_2

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Monolayer 1T′-WTe_2 is known for exhibiting a topological quantum spin Hall insulating (QSHI) state, characterized by band inversion and strong spin-orbit coupling (SOC), which results in a bulk insulating gap and spin-momentum-locked conducting edges. However, recent studies question the microscopic origin of this bulk insulating gap—whether it arises purely from SOC or from electron correlations, which could lead to the formation of an excitonic condensate, which has been named as a topological excitonic insulator. In systems with an indirect band gap, the real-space ground state associated with excitonic bound states can manifest as a charge density wave, spin density wave, or spin spiral wave, with a wave vector given by valence and conduction band extrema. In this work, we show that a realistic tight-binding Hamiltonian for the semi-metallic phase of 1T′-WTe_2, including Coulomb interactions, can describe the low energy properties of this monolayer system. Our results demonstrate the nature of a charge density wave at the conducting edge. We also show how a gate voltage applied to a substrate layer can be utilized to tune the topological gap and compare our results with recent scanning tunneling microscopy (STM) experiments on 1T′-WTe_2.

Anomalous Reentrant Fractional Quantum Hall Effect at 5/2 in GaAs at Moderate Landau Level Mixing

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The fractional quantum Hall effect at 5/2 state has been experimentally found to host non-Abelian quasi-particles, which could be devised as qubits for topological quantum computation. In recent years, thermal Hall conductivity measurements at 5/2 have confirmed the particle-hole symmetric Pfaffian (PH-Pf) topological order, which is in contrast to the theoretical predictions of anti-Pfaffian orders. While earlier theoretical studies were mostly performed at Coulomb or small Landau level mixing regimes, in experimental systems the Landau level mixing strength is relatively high. At a moderate range of Landau level mixing strength, in accordance with the GaAs systems, we found a reentrant Anomalous phase (A-phase), which is quantized and well gapped in the thermodynamic limit and topologically distinct from the phase near pure Coulomb interaction. We further propose a wave function for this A-phase, that possesses high overlap and good matching of low-lying entanglement spectra. This work finds a possible resolution to the discrepancies between the theoretical predictions and experimental observations, and we believe our predicted wave function at the A-phase should possibly corroborate the experimentally found topological order.

Stray field effect in ferronematic thin films

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This work deals with the solution landscape of ferronematic materials confined on a thin film (2D domain) in the presence of an external magnetic field. Ferronematics are complex materials that consist of magnetic nanoparticles dispersed within a nematic liquid crystal medium. The ferronematic energy comprises the Landau-de Gennes energy for Q-tensor order parameter, the micromagnetics energy for magnetisation M and a bulk potential for the interaction between nematic director and magnetisation.

In the energy, we explicitly incorporate the contribution of the stray field effect by including the stray field energy and the energy due to the coupling between the nematic director and the stray field. This work discusses the existence and uniqueness of energy minimizers for the proposed ferronematic energy using techniques from the calculus of variations. Moreover, it illustrates the numerical solutions of the corresponding gradient flow system obtained by employing the Crank-Nicolson finite difference scheme. The numerical results reveal the influence of the stray field on nematic and magnetic configurations: the stray field pushes the nematic defects and magnetic vortices toward the boundary of the domain and changes the shape of the core of localized defects.

Three-dimensional gyroid and scaffold-like networks: Unveiling a new surface localization mechanism of ferromagnetic resonance modes in complex nanoarchitectures

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We present a comprehensive study on the localization of ferromagnetic resonance (FMR) modes in three-dimensional nanoarchitectures, focusing on scaffold-like nanorods and gyroids – periodic chiral structures defined by their distinctive triple-junctions. These architectures extend the landscape of magnonics beyond conventional planar geometries, offering unique features such as intricate connectivity, large surface-area-to-volume ratios, and inherent curvature. By exploring how FMR modes manifest under different external magnetic field orientations, our work bridges multiple scientific disciplines interested in topological textures, from condensed-matter physics and materials science to applied mathematics and engineering.

At the core of this investigation is a set of advanced micromagnetic simulations that capture both dipolar and exchange interactions within these complex 3D systems. Although demagnetizing fields are recognized as crucial for determining the overall resonance response, they alone do not account for the subtle displacement and specific surface localization of the observed FMR modes. Instead, our results indicate that exchange coupling plays a decisive role. More precisely, field-aligned nanorods enhance the magnetic energy in neighboring rods via the “pinning” exchange coupling, leading to preferential localization in rods adjacent to a single field-aligned counterpart, typically near the surface. This mechanism leads to a characteristic dependence of mode concentration on the external field orientation, resulting in a noticeable mode switch or shift as the applied field is rotated.

Our analysis suggests that the interplay between curvature, connectivity, and exchange interactions underpins a robust, broadly applicable phenomenon: tuning surface-localized modes in three-dimensional nanolattices. This has significant implications for next-generation magnonic devices, including the possibility of designing tailored spin-wave pathways in 3D networks, as well as optimizing FMR-based sensors and filters that exploit these localized excitations for enhanced performance.

The detailed results and theoretical interpretations of this study are published in Ref. [1]. The research leading to these findings has been supported by the National Science Centre of Poland through Projects No. UMO-2020/39/I/ST3/02413 and

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Raman scattering of light with angular orbital moment

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Polarized Raman spectra of piezoelectric bismuth germanate single crystal were recorded using vortex light in order to verify the predicted symmetry selection rules for Raman scattering of photons with nonzero orbital angular momentum. I would like to discuss interpretation of our experiments recently reported at arXiv:2410.20983.

Magnon Spectrum around Skyrmions in Frustrated Magnets

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Magnetic skyrmions are topologically nontrivial spin textures typically studied in chiral magnets. We consider isolated skyrmions and skyrmion lattices in frustrated magnets, investigating their dynamics via their magnon spectra. The 'helicity' zero mode in these systems hybridizes with magnon modes, and gives rise to a new band in lattices. Magnetic fluctuations around skyrmions introduce new helicity-based modes around interacting skyrmions, and strongly affect magnon propagation in lattices.

Protocols to measure the non-Abelian Berry phase by pumping a spin qubit through a quantum-dot loop

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A quantum system constrained to a degenerate energy eigenspace can undergo a nontrivial time evolution upon adiabatic driving, described by a non-Abelian Berry phase. This type of dynamics may provide logical gates in quantum computing that are robust against timing errors. A strong candidate to realize such holonomic quantum gates is an electron or hole spin qubit trapped in a spin-orbit-coupled semiconductor, whose twofold Kramers degeneracy is protected by time-reversal symmetry.

In this work, we propose and quantitatively analyze a protocol to experimentally characterize the holonomic single-qubit gates induced by the non-Abelian Berry phase when a spin qubit is shuttled around a loop of quantum dots. The device, shown in the figure, includes an on-chip wire and a reservoir besides the loop. These ingredients are used for initialization and read out.

In semiconductor spin-qubit devices with strong spin-orbit interaction, e.g. planar SiGe/Ge quantum dot arrays, every loop induces a unitary transformation upon shuttling a spin qubit through it. This technique is suitable for realizing a universal single qubit holonomic gate set on a device with multiple quantum dot loops.

We also present extensions of the original protocol: a) a version characterizing the local internal Zeeman field directions in the dots, b) a simplified protocol offering the near-term measurement of the non-Abelian Berry phase.

We expect the protocols to be realized in the near future, as all key elements have been already demonstrated in spin-qubit experiments. The strong spin-orbit interaction and weak hyperfine interaction of holes in Si or Ge quantum wells make these materials strong candidates to observe these effects; the recently realized 3-4-3 Ge quantum dot array is especially promising due to its high material quality and the two-dimensional layout that enables shuttling a qubit through a loop.

Devices based on spin-torque diode for energy harvesters and sensors: A theoretical analysis

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We investigate novel spintronic devices for energy harvesting and thermal sensing by integrating spin-torque diodes (STD) with materials exhibiting phase transitions and magnetic skyrmions. One such material is FeRh, which undergoes a first-order magnetic phase transition between FM and AFM states at T∼350K [1,2]. Herein, we will demonstrate the STD broadband devices able to convert the electromagnetic waves from kHz up to THz to the electrical energy with phase transitions driven by an AC input, which was predicted by theoretical models and macrospin simulations. Further, we introduce a spintronic temperature sensor based on topologically protected and stable magnetic skyrmions interfaced with magnetic tunnel junctions (MTJ) [3]. This sensor relies on the temperature-dependent resonant frequency and amplitude of skyrmions, enabling high thermal sensitivity and a linear response for nanoelectronics. Simulations confirm superior thermal stability in multilayer systems compared with single-layer ones and thus solve issues related to conventional sensors. FeRh-based STDs combined with skyrmion-based thermal sensors may open new horizons for next-generation energy harvesting, spintronics, thermal management, and nanoelectronics.

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Unveiling the Internal Structure of Topological Vortices in the Abelian-Higgs model

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Vortices are among the most versatile topological textures. They play a key role in diverse areas such as superconductivity, condensed matter physics, and cosmology. The most well-known model in which these solutions can be found is the Abelian-Higgs model.

Due to the relevance of this theory, it is important to understand in detail the dynamics of these objects. For example, one of the most well-known properties of these textures is the 90° scattering that occurs when two vortices collide with the same impact velocity. It has recently been discovered that the internal mode structure associated with these solutions plays a key role in vortex dynamics, leading to fractal pattern scattering when at least one of its internal modes is initially excited.

The main goal of this talk is to study in detail the internal mode structure associated with these objects. We will show how the eigenvalue problem can be simplified by correctly choosing the angular dependence of the corresponding eigenfunctions. By doing so, the problem reduces to solving a coupled system of three second-order ordinary differential equations that can be numerically solved almost instantly.

Furthermore, we will also study the analytic properties of the eigenfunctions that solve this problem, including the behavior of these functions near the vortex center. Finally, we will analyze in detail the modes responsible for the instabilities of vortices with a topological charge greater than n = 1.

Topological inverse Faraday effect: Optical Hopfion interacting with matter

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Control and manipulation of quantum materials is of paramount significance, both for fundamental characterization and for quantum technologies. Among others, light-matter interaction has recently gained traction because both optical counterpart of solid-state phenomena and emergent effects can be investigated.

We extend this paradigm to 3D topological optical quasiparticle i.e. optical Hopfion (oHop) - a knotted structure presenting robust topological protection, resolution on ultrafast time-scales, localization on nanometer-scale - as novel source to probe and regulate properties and phases of matter.

We show a first instance of OHop-matter coupling: an oHop traveling through a non-magnetic material induces a net effective magnetization, that is now promoted to be topologically quantized in virtue of the linking number (Hopf index) classifying the oHop source. By relating the induced magnetization to the Hopf index, we identify the topologically quantum inverse Faraday effect (IFE). This optical response is obtained without constraints on the material but only by introducing topological light.

We conclude with a demonstration of the topologically quantized IFE compared to the standard IFE for a typical magneto-optical material like TGG.

Exploring the Moduli Space Metric of Excited Abelian-Higgs Vortices

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In this poster presentation, we explore how the excitation of a vortex's radially symmetric shape mode modifies the standard moduli space of a single vortex. Our findings show that, when the vortex moves at constant velocity, the shape mode acquires a nonzero contribution. However, the radial symmetry of both the vortex and its shape mode limits the effective model's ability to fully reproduce Lorentz contraction. To overcome this limitation, we introduce the Derrick mode into the collective coordinate framework. This work offers new insights into vortex dynamics and the structure of their moduli space in relativistic settings.

A decoupled, convergent and fully linear algorithm for the Landau--Lifshitz--Gilbert equation with magnetoelastic effects

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We consider the coupled system of the Landau--Lifshitz--Gilbert equation and the conservation of linear momentum law to describe magnetic processes in ferromagnetic materials including magnetoelastic effects in the small-strain regime. For this nonlinear system of time-dependent partial differential equations, we present a decoupled integrator based on first-order finite elements in space and an implicit one-step method in time. We prove unconditional convergence of the sequence of discrete approximations towards a weak solution of the system as the mesh size and the time-step size go to zero. Compared to previous numerical works on this problem, for our method, we prove a discrete energy law that mimics that of the continuous problem and, passing to the limit, yields an energy inequality satisfied by weak solutions. Moreover, our method does not employ a nodal projection to impose the unit length constraint on the discrete magnetisation, so that the stability of the method does not require weakly acute meshes. Furthermore, our integrator and its analysis hold for a more general setting, including body forces and traction, as well as a more general representation of the magnetostrain. Numerical experiments underpin the theory and showcase the applicability of the scheme for the simulation of the dynamical processes involving magnetoelastic materials at submicrometer length scales.

Bloch-ball type representation of two-party composite systems with different local dimensions

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The Bloch representation is a mathematical description of quantum-mechanical density operators in terms of a matrix basis and is a powerful but far from fully developed tool to solve quantum mechanics problems. Its meaning is deeply connected with geometry, and therefore, its concepts are sensitive to geometric intuition. In only a few years, new methods have

been presented to adequately visualize higher-dimensional state spaces, such as the Bloch-sphere analog of a three-level system (qutrit) or a four-level system (ququart), and that of bipartite systems. There is a lot of potential for further research; in particular, these investigations of bipartite systems are fundamental to the understanding of which quantum correlations are possible and which are not. The central theme of this project is to study two-party systems of different local dimensions. While we kind of know the complete solution for equal local dimensions, it is logical that this case will have different geometrical properties, so it requires a precise analysis. The results of the project will open the possibility to, in the future, study multi-party systems, which are of tremendous importance, and extend this research to a variety of physics applications.

High order finite difference method for exchange field computation

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Many micromagnetic simulation codes employ a nearest neighbour approach with the central finite difference method to compute magnetization derivatives for the exchange field and DMI. While effective for obtaining results, this method requires a finer mesh to achieve a specific accuracy as compared to higher order finite difference approaches. In addition, for time integration this approach needs smaller time steps for accurate time domain ù evaluation.

The Petaspin [https://www.petaspin.com] [A. Giordano et al., J. Appl. Phys. 111, 07D112 (2012)] solver has been already used to describe several experiments and predict new phenomena in spintronics and micromagnetics. It's aimed at simulating the spin dynamic of ferromagnetic materials by numerically solving the Landau-Lifshitz-Gilbert (LLG) equation. It incorporates various energy terms influencing the material's effective magnetic field, such as exchange interaction, material anisotropy, the applied external fields, the demagnetizing field and magnetoelastic interactions. The user can also choose between different time integrators, like the 5th-order Runge-Kutta method method, the Heun method and the Adams2-Bashforth3 method.

In our latest development , Petaspin now supports high order (4th) neighbour central finite difference method for derivative computation in order to consider high order exchange and DMI interactions allowing the study of frustration and stabilization of three-dimensional solitons such as hopfions. From a numerical point of view, this advancement allows us to use fewer discretization cells and larger time steps while. All computations are natively optimized with NVIDIA's CUDA platform to fully harness GPU parallel computing capabilities, offering superior performance compared to CPU-based solvers.

Here we will show results achieved in the study of the static properties of spin textures, like bubbles, skyrmions, hopfions and vortices, and on new dynamical properties exploiting high order effects.

Upper bound on the number of Weyl points born from a multifold degeneracy point

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Two-fold energy degeneracies with linear dispersion relation, often referred to as Weyl points, arise generically in the spectrum of a Hamiltonian that depends on three parameters.

Isolated multifold degeneracy points are less generic, but arise often, e.g., in band structures of three-dimensional crystalline materials, and in models of spin systems subject to a magnetic field. A generic perturbation dissolves such a multifold degeneracy point into an ensemble of Weyl points. We show that the number of Weyl points born from the *k*-fold degeneracy point has an upper bound given by the *k*th four-dimensional pyramidal number $dm(k) = k^2(k^2-1)/12$. We refer to this upper bound as the `birth quota' of the *k*-fold degeneracy point. Our results yield a strong result for the perturbation theory of multifold degeneracies in general, and in particular, provide clear predictions for the perturbation-induced dissolution of multifold degeneracies in band structures.

Fascinating mesoscale magnetic textures in the topological Kagome system $TbMn_6Sn_6$

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In recent years, the Kagome ferrimagnet $TbMn_6Sn_6$ has garnered significant interest due to its unconventional band topology, which realizes exotic quantum states like a Chern insulating phase [1]. It exhibits a spin-reorientation transition (SRT) from easy-axis to easy-plane above 310K, where skyrmion bubbles have been observed in lamellae [2]. Less, however, is known about the bulk magnetic textures in this system. Here, we used magnetic force microscopy (MFM) to image the magnetic structure of $TbMn_6Sn_6$, and magnetometry to study the role of second order magnetic anisotropy. Two types of textures were observed, namely long-ranged stripes that invert contrast on reversing the tip's magnetization, and smaller star-shaped struc- tures that do not invert, possibly indicating two different magnetization mechanisms. The effect of an external magnetic field was also studied, showing that the textures were indeed affected by the same. Analyzing the in-plane magnetometry data, a metastable magnetization state was observed for curves below the SRT temperature, indicating the possibility of an intermediate canted state. This was confirmed via temperature-dependent MFM, where three distinct con- trasts were observed.

[1] J. Yin, W. Ma, Nature 583, 533-536 **2023**.

[2] Z. Li, Q. Yin, Adv. Mater. 35, 2211164 **2020**.

Interaction and collision of skyrmions in chiral antiferromagnets

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Skyrmions in an antiferromagnet can travel as solitary waves in stark contrast to the situation in ferromagnets. Traveling skyrmion solutions have been found numerically in chiral antiferromagnets. We study head-on collision events between two skyrmions. We find that the result of the collision depends on the initial velocity of the skyrmions. For small velocities, the skyrmions shrink as they approach, then bounce back and eventually acquire almost their initial speed. For larger velocities, the skyrmions approach each other and shrink until they become singular points at some finite separation and are eventually annihilated. Considering skyrmion energetics, we can determine the regimes of the different dynamical behaviors. Using a collective co-ordinate approach, we reproduce the dynamics of the collisions including the variation of the size of the skyrmions and collapse above a critical velocity.

Interplay between local and non-local frustration in the 1D ANNNI chain

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We explore the interplay between topological frustration (TF), a form of frustration induced by boundary conditions, and a local source of frustration arising from competing interactions within the system, using the 1D ANNNI model. We focus on entanglement entropy (EE) as a measure of quantum correlations. Near the classical point, we observe a violation of the entanglement entropy (EE) area law, with the measure decomposing into two contributions: one independent of TF and another size-dependent contribution arising from TF, suggesting that the ground state hosts two excitations. This is confirmed by considering two fermionic excitations over the vacuum of a quadratic theory. Furthermore, the same behavior is found throughout the entire phase, where we numerically observe that the local and topological contributions to EE decouple.

Terahertz spin-wave excitations in the transverse conical phase of $BiFeO_3$

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Among multiferroics, materials with coexisting ferroelectric and magnetic orders, $BiFeO_3$ is the most studied compound due to its unique combination of ordering temperatures above room temperature and high electric polarization which is a prerequisite for applications. Furthermore, the broken inversion symmetry allows antisymmetric exchange coupling leading to modulated magnetic structures. The bulk magnetic ground state is cycloidally modulated, but thin films may even host antiferromagnetic skyrmions. Despite the multitude of research over the years on this material, recent magnetization and neutron scattering studies have revealed a new magnetic phase: the transverse conical phase. To study the collective spin excitations of this phase, we performed terahertz spectroscopy in magnetic fields up to 17 T at and above room temperature. We observed five spin-wave branches in the magnetic phase with conical modulation. Our numerical spin dynamics calculations allowed us to distinguish two kinds of excitations: magnetic moments oscillating either along or perpendicular to the static fields. Remarkably, we detected strong directional dichroism, an optical manifestation of the magnetoelectric effect, for one spin-wave mode of the conical phase. According to our experiments, the conical state can become (meta)stable at or close to zero magnetic field after field treatment, which may allow exploiting its magnetoelectric properties at room temperature.

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