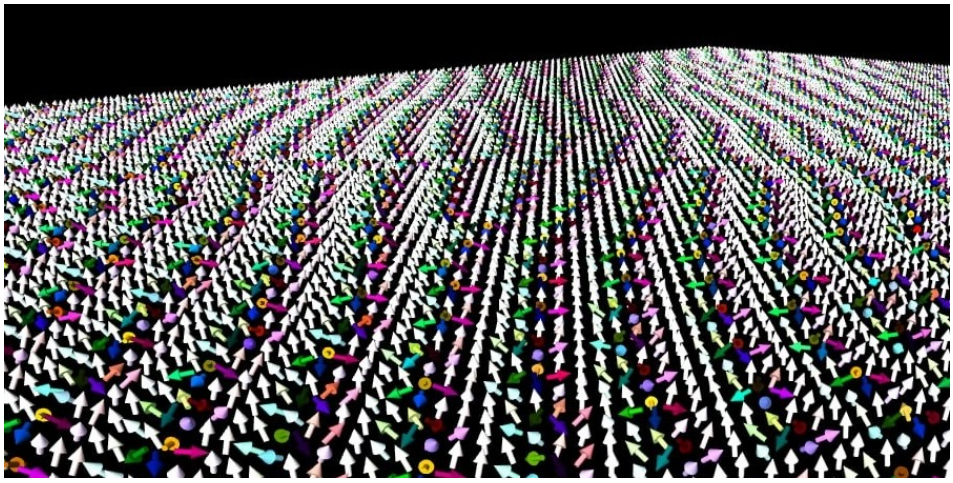
Progress in modeling and analysis for nanomagnetism and related topics



Report of Contributions

https://indico.sns.it/e/118

Contribution ID: **1** Type: **not specified**

Electrical manipulation of magnetic skyrmion in synthetic antiferromagnets and magnetic tunnel junctions for logic and memory applications

Tuesday, 14 October 2025 15:15 (45 minutes)

Skyrmions are topological spin textures which hold great promise as nanoscale bits of information in memory and logic devices [1].
Although room-temperature ferromagnetic skyrmions and their current-induced manipulation have been demonstrated [2,3], their velocity has been limited to about 100 meters per second [3,4]. In addition, their dynamics are perturbed by the skyrmion Hall effect, a motion transverse to the current direction caused by the skyrmion topological charge.
Antiferromagnetic skyrmions allow these limitations to be lifted owing to their vanishing magnetization and net zero topological charge, promising fast dynamics without skyrmion Hall effect. In this talk, I will address the stabilization and current induced manipulation of skyrmions in compensated synthetic antiferromagnetic (SAF). I will first show that skyrmions can be stabilized at room temperature in Pt/Co/Ru based compensated SAFs and nucleated using local current injection and ultrafast laser pulses [5]. I will then show that SAF skyrmions can be moved by current at velocities over 900 m/s without skyrmion Hall effect [6]. Micromagnetic simulations and analytical models using experimental parameters show that this enhanced skyrmion velocity can be explained by the compensation of the gyrotropic force in the synthetic antiferromagnet. I will conclude the talk with recent results on the electrical nucleation and detection of a skyrmion in magnetic tunnel junctions, which is another important milestone for skyrmion based devices [7]. Our results open important paths toward the realization of logic and memory devices based on the fast manipulation of skyrmions.

References:
[1] A. Fert, V. Cros, and J. Sampaio, Nat. Nano. 8, 152 (2013).
[2] O. Boulle et al., Nature Nano., 11, 449 (2016)
[3] A. Fert, N. Reyren and V. Cros, Nat Rev Mater 2, 17031 (2017).
[4] R. Juge, S-G. Je et al., Phys. Rev. Appl. 12, 044007 (2019)
[5] R. Juge, N. Sisodia et al. , Nature Comm., 13, 4807 (2022)
[6] V.T Pham, N. Sisodia, I. Di Manici, J. Urrestarazu Larranaga et al. , Science, 384, 6693 (2024)
[7] J. Urrestarazu Larranaga, N. Sisodia, R. Guedas, Nano Letters, 24, 3557 (2024)

Primary author: BOULLE, Olivier (CEA-CNRS, Granoble)

Presenter: BOULLE, Olivier (CEA-CNRS, Granoble)

Contribution ID: **2** Type: **not specified**

Consistency for the surface diffusion flow in three dimensions

Thursday, 16 October 2025 14:30 (45 minutes)

We will discuss the flat flow solution for the surface diffusion equation via a discrete minimizing movements scheme proposed in1994 in a celebrated paper by J.W. Cahn and J.E. Taylor. We will show that in dimension three the scheme converges to the unique smooth solution of the equation, provided the initial set is sufficiently regular.

Primary author: Prof. FUSCO, Nicola (Università degli Studi di Napoli)

Presenter: Prof. FUSCO, Nicola (Università degli Studi di Napoli)

Contribution ID: **3** Type: **not specified**

Topological defects and higher-order moiré patterns in a 2D van der Waals magnetic insulator.

Wednesday, 15 October 2025 17:15 (45 minutes)

Primary author: Prof. CREN, Tristan (CNRS-Sorbonne Université, Paris)

Presenter: Prof. CREN, Tristan (CNRS-Sorbonne Université, Paris)

Contribution ID: **4** Type: **not specified**

Global perturbation of isolated equivariant skyrmions from the Bogomol'nyi case

Wednesday, 15 October 2025 11:30 (45 minutes)

It has been discovered that the Landau-Lifshitz energy with certain interaction terms can accurately describe the formation of stable vortex-like magnetization configurations,known as chiral magnetic skyrmions.
Accordingly, mathematical communities have been paying increasing attention to give rigorous proofs to support and deepen this understanding.
In this talk, we consider the variational problem for the Landau-Lifshitz energy under the equivariant symmetry.
After reviewing preceding studies, I will introduce the recent perturbative analysis from the Bomogol'nyi case, showing the existence of solutions and some qualitative properties. This is joint work with Slim Ibrahim (Univ. of Victoria).

Primary author: Prof. SHIMIZU, Ikkei (Kyoto University)

Presenter: Prof. SHIMIZU, Ikkei (Kyoto University)

Contribution ID: **5** Type: **not specified**

Travelling waves in ferromagnetic nanotrips

Friday, 17 October 2025 09:30 (45 minutes)

We study the existence, uniqueness, and symmetry of variational domain-wall traveling waves for the LLG equation. The model is based on an energy functional obtained in a suitable asymptotic regime of the micromagnetics for infinitely long thin film ferromagnetic strips in which the magnetization is forced to lie in the film plane.

Primary author: MORINI, Massimiliano (Università di Parma)

Presenter: MORINI, Massimiliano (Università di Parma)

Contribution ID: **6** Type: **not specified**

Emulating spin liquid physics with 2D lattices of interacting nanomagnets

Thursday, 16 October 2025 09:30 (45 minutes)

When brought to sufficiently low temperature, matter generally orders, as in the case of a crystalline solid. Some systems remain disordered, though, in the manner of a liquid, even at the lowest temperatures achievable experimentally. Entropy, a thermodynamic quantity that characterizes the degree of disorder, is then very useful to describe the low-temperature properties of matter. While most materials have their entropy approaching a constant value as temperature tends to absolute zero, others instead preserve much of the gas-like entropy they had at high temperature. Nevertheless, these two disordered phases at high and low temperatures are not equivalent: a liquid and a gas have distinct properties. In liquids, the disorder is said to be correlated as correlations between degrees of freedom can be strong, at least at short distances, even though the system strongly fluctuates. This is not the case in an ideal gas, for which these correlations are zero on average, at all distances.

The aim of this presentation is to illustrate that one can fabricate, artificially, a meta-material exhibiting all the properties of a spin liquid, and which is advantageously amenable to direct imaging of its correlated disorder in space and time, at the scale of the elementary constituent. More specifically, we will show why lithographically-patterned arrays of interacting magnetic nanostructures proved to be a powerful platform in which to visualize intriguing and fascinating behaviors of matter that are difficult to access otherwise.

Primary author: ROUGEMAILLE, Nicolas (CNRS - Institut Néel)

Presenter: ROUGEMAILLE, Nicolas (CNRS - Institut Néel)

Contribution ID: **7** Type: **not specified**

Energy concentration in a two-dimensional magnetic skyrmion model

Thursday, 16 October 2025 11:30 (45 minutes)

In this talk, I present the formation of singularities in a chiral Skyrme-type energy model, which describes magnetic solitons in two-dimensional ferromagnetic systems. In the presence of a diverging anisotropy term, which enforces a preferred background state of the magnetization, I show how to establish a weak compactness result for the topological charge density and prove that it converges to an atomic measure with quantized weights. I characterize the Γ-limit of the energies as the total variation of this measure.
Then, I consider the case of lattice-type energies and prove a corresponding compactness and Γ-convergence result. To this end, I will first carefully define a notion of discrete topological charge for S2 -valued maps.
This is a joint work with Marco Cicalese and Leonard Kreutz.

Primary author: BRIANI, Luca (TUM, Munich)

Presenter: BRIANI, Luca (TUM, Munich)

Contribution ID: **8** Type: **not specified**

Regularized Micromagnetic Model

Friday, 17 October 2025 11:30 (45 minutes)

Magnetic singularities known as Bloch points (BPs) present a fundamental challenge for micromagnetic theory due to the divergence of the effective field. To overcome this problem, we propose a regularized micromagnetic model in which the magnetization vector is defined on the S3-sphere, while, similar to quantum systems, only three of the four vector components correspond to measurable quantities. Within this framework, we derive a regularized Landau–Lifshitz–Gilbert equation and an analogue of the Thiele equation describing the steady motion of spin textures under external stimuli. The applicability of the theory is demonstrated by modeling the dynamics of several magnetic textures containing BPs. Further details are provided in our preprint [https://doi.org/10.48550/arXiv.2508.19784].

Primary author: KISELEV, Nikolai (Forschungszentrum Jülich)

Presenter: KISELEV, Nikolai (Forschungszentrum Jülich)

Contribution ID: **9** Type: **not specified**

Minimizing entire solutions to vector Allen-Cahn equations

Thursday, 16 October 2025 16:30 (45 minutes)

I will report on a joint work with Peter Sternberg and a very recent joint work with Lia Bronsard and Peter Sternberg, where we try to describe minimizing entire solutions to the vector Allen-Cahn equation with three wells in two space dimensions. It is known that the Gamma-limit by blow-down of this problem is a minimal partition problem with weights for which minimal cones are easily described. We will see that, depending on the weights, each minimal cone may, or may not, correspond to a minimizing entire solution.

Primary author: SANDIER, Etienne (Université Paris-Est, Créteil)

Presenter: SANDIER, Etienne (Université Paris-Est, Créteil)

Contribution ID: **10** Type: **not specified**

Optimal control in ferromagnetism: minimal time of magnetization switching

Wednesday, 15 October 2025 15:15 (45 minutes)

In this talk, we consider an ellipsoidal ferromagnetic material exposed to an external magnetic field. The magnetization of the material is modeled by the Landau-Lifshitz equation. We are interested in the following question: can we reverse the magnetization of the material in minimal time by using the external magnetic field as our control variable? We prove that, depending on the material's ellipsoidal geometry, there is a threshold value for the magnetic field that allows reversal or not. This is a joint work with Raphaël Côte, Guillaume Ferrière and Yannick Privat.

Primary author: COURTES, Clémentine

Presenter: COURTES, Clémentine

Contribution ID: **11** Type: **not specified**

Rectifiability of entropy productions for weak solutions of the 2D eikonal equation with supercritical regularity

Thursday, 16 October 2025 17:15 (45 minutes)

Weak solutions of the 2D eikonal equation correspond to unit vector fields m with zero divergence in the sense of distributions. They arise naturally as sharp interface limits of bounded energy configurations in micromagnetics, elasticity or liquid crystal models (e.g. Aviles-Giga). For a given weak solution m, entropy productions are distributions which carry information about singularities and energy cost. If they are signed measures, it is conjectured that they must be concentrated on the 1-rectifiable jump set of m, as they do if m has bounded variation (BV). In a joint work with Elio Marconi, we prove this concentration property under an additional mild regularity assumption, going well beyond the BV setting, and leaving only a borderline case open.

Primary author: LAMY, Xavier (Université de Toulouse)

Presenter: LAMY, Xavier (Université de Toulouse)

Contribution ID: **12** Type: **not specified**

Skyrmion lifetime optimization in ultrathin ferromagnetic films and multilayers

Wednesday, 15 October 2025 10:15 (45 minutes)

The quest for predicting optimally stable and compact isolated magnetic skyrmions suitable for information technology applications relies on solving the micromagnetic equation. Numerical techniques have been successfully applied to find these solutions. The fundamental nature of these topological defects makes the development of skyrmion theory a very exciting topic from the point of view of both physics and mathematics. In the past few years we have successfully used the tools of calculus of variations to develop an analytical skyrmion theory that enables a systematical prediction of skyrmions characteristics. This theory exploits the fundamental properties of the exchange energy which posses exact solutions called Belavin-Polyakov solutions [1]. Using a modified Belavin-Polyakov solution we carry out an asymptotic analysis study and obtain explicit analytical expressions for the skyrmion size, rotation angle and energy, valid in the ultrathin film limit in the regime when the exchange energy dominates. This includes results on, the role of long range dipolar interaction in the stabilization of compact skyrmions as a function of the film effective thickness [2-3], the stability of skyrmions under a magnetic field applied parallel to their core [4] and the derivation of an explicit Arrhenius law for skyrmion lifetime [5]. Finally we will present our latest work where we extended our model to multilayers [6]. We show that in addition to the usual local shape anisotropy term and the non-local dipolar interaction term, that are already present in the case of single ultrathin ferromagnetic layers, the expansion of the stray field energy for multilayers leads to the appearance of a new local dipolar energy term corresponding to interlayer volume-surface interactions. This term cancels out in the case of identical magnetizations in the adjacent layers, but becomes equivalent to a stabilizing layer-dependent interfacial DMI when the in-plane magnetization components in two consecutive layers are opposite to one another.

[1] A. Belavin and A. Polyakov JETP Lett. 22 245 (1975)
[2] A. Bernand-Mantel, C. Muratov and T. Simon PRB 101 045416 (2020)
[3] A. Bernand-Mantel, C. Muratov and T. Simon ARMA 239 219 (2021)
[4] A. Bernand-Mantel, C. Muratov and T. Simon PRB 108 L161405 (2023)
[5] A. Bernand-Mantel, C. Muratov and V. Slastikov PNAS 119 e2122237119 (2022)
[6] N. Dubicki, V. Slastikov, A. Bernand-Mantel, C. Muratov arXiv:2505.14649 (2025)

Primary author: BERNAND- MANTEL, Anne (CEMES-CNRS, Toulouse)

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Contribution ID: **13** Type: **not specified**

Dynamics of domain walls on nanowire

Wednesday, 15 October 2025 12:15 (45 minutes)

Domain walls are natural topological structures which can be observed for the spin configuration on a ferromagnet.
I will present some stability and interaction results for domain walls on a nanowire. They evolve under the Landau-Lifschitz-Gilbert flow related to an energy which takes into account the Dzialochinski-Morya interaction. I will also discuss the effect of inhomogeneity in the nanowire, which is relevant when considering notches.

Primary author: COTE, Raphael (IRMA-CNRS, Strasbourg)

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Contribution ID: **14** Type: **not specified**

Crystalline symmetry breaking: a bridge from discrete to continuum

Thursday, 16 October 2025 15:15 (45 minutes)

In this talk I will present striped pattern formation results in presence of competing short-range/long-range interactions with crystalline symmetries. This result represents an intermediate step in passing from discrete symmetry breaking to continuous symmetry breaking (i.e. for isotropic interactions). This is a joint work in collaboration with Eris Runa and Francesco Paolo Maiale (GSSI).

Primary author: DANERI, Sara (GSSI, L'Aquila)

Presenter: DANERI, Sara (GSSI, L'Aquila)

Contribution ID: **15** Type: **not specified**

Variational analysis for the nonlinear elastic energy induced by edge dislocations: the dilute regime.

Thursday, 16 October 2025 12:15 (45 minutes)

We introduce nonlinear semi-discrete and discrete models for the elastic energy induced by a finite system of edge dislocations in two dimensions.
We analyze the asymptotic behavior of the nonlinear elastic energy, as the lattice spacing (in the purely discrete model) and the core-radius (in the semi-discrete framework) vanish. We work within the dilute regime, corresponding to a finite number of effective singularities.
Joint work with R. Alicandro, G. Lazzaroni, M. Palombaro, M. Ponsiglione.

Primary author: DE LUCA, Lucia (IAC-CNR, Roma)

Presenter: DE LUCA, Lucia (IAC-CNR, Roma)

Contribution ID: **16** Type: **not specified**

Gamma-convergence of two-dimensional lattice models of magnetic skyrmions.

Thursday, 16 October 2025 10:15 (45 minutes)

We consider energies defined on maps from a 2-dimensional lattice to the unit sphere in R^3, consisting of a (discrete) exchange energy term competing with a (discrete) Dzylashinksii- Moriya interaction term, and assuming suitable boundary conditions outside a regular set Ω.
Under additional constraints we prove the asymptotics of these energies to a confined model of magnetic skirmions in the continuum for ultrathin ferromagnetic films. More in details, we treat the two cases in which we assume bounds on a 'relaxed' discrete degree of the maps or on their oscillations.

Primary author: GELLI, Maria Stella (Università di Pisa)

Presenter: GELLI, Maria Stella (Università di Pisa)

Contribution ID: **17** Type: **not specified**

Liquid drop with capillarity

Friday, 17 October 2025 10:15 (45 minutes)

I will present recent results on the free boundary problem for an incompressible, irrotational liquid drop of nearly spherical shape with capillarity. Some results are of technical nature, such as reduction to a problem on the boundary, the Hamiltonian structure and a linearization formula for the Dirichlet-Neumann operator. The main result is the existence of travelling waves, which are nontrivial fixed profiles rotating with constant angular velocity. I will also discuss the case of charged liquid drop, a classical model dating back to Lord Rayleigh.
This is a joint work with Pietro Baldi and Domenico La Manna (Naples).

Primary author: JULIN, Vesa (University of Jyväskylä)

Presenter: JULIN, Vesa (University of Jyväskylä)

Contribution ID: **18** Type: **not specified**

THE ANTIFERROMAGNETIC XY -MODEL ON THE TRIANGULAR LATTICE: GEOMETRIC FRUSTRATION, CHIRALITY TRANSITIONS & TOPOLOGICAL SINGULARITIES

Wednesday, 15 October 2025 16:30 (45 minutes)

Antiferromagnetic spin systems are magnetic lattice models in which the exchange in-teraction between two spins favors anti-alignment. A system is said to be geometrically frustrated if, due to the lattice geometry, no spin configuration can simultaneously minimize all pairwise interactions. This frustration can lead to ground states with nontrivial patterns and unconventional magnetic order. A classical example is the antiferromagnetic XY model on the triangular lattice.
In this talk, we study the discrete-to-continuum variational analysis of this model for low-energy states. We show that, depending on the energy scaling, the continuum limit may exhibit both chirality transitions (a parameter describing the local sense of orientation) and topological singularities. This is joint work with Annika Bach (TU Eindhoven), Marco Cicalese (TU Munich), and Gianluca Orlando (Politecnico di Bari).

Primary author: KREUTZ, Leonard (TUM, Munich)

Presenter: KREUTZ, Leonard (TUM, Munich)

Contribution ID: **19** Type: **not specified**

Magnetic domains in ultrathin ferromagnetic films

Tuesday, 14 October 2025 16:30 (45 minutes)

We present an asymptotic analysis of the micromagnetic energy in a ultrathin ferromagnetic material with strong uniaxial anisotropy and easy axis perpendicular to the film plane. For subcritical dipolar strenghts, we show that, in the limit, the energy renormalizes the perimeter. Moreover, for critical dipolar strenghts we identify the next order Γ-limit. Lastly, we will focus on establishing a similar result in the case of ultrathin ferromagnetic materials of finite spatial extent, where a specific regularization is needed in order to account for possible jump-discontinuities at the sample boundary, which would make the nonlocal part of the energy inifinite. This is based on a joint project in collaboration with C. B. Muratov and M. Novaga.

Primary author: PICCININI, Mirco (Università di Pisa)

Presenter: PICCININI, Mirco (Università di Pisa)

Contribution ID: **20** Type: **not specified**

Theory of magnetic merons revisited: no need for fractional topological charges

Wednesday, 15 October 2025 14:30 (45 minutes)

Magnetic vortices and skyrmions are typically characterized by distinct topological invariants corresponding to elements of homotopy groups of different spaces. At the same time, intermediate forms of these states - merons - exist and are well studied. This term was introduced in the 1970s, and today an elementary magnetic meron is typically understood to be a planar vortex where the core is non-singular due to out-of-plane spins. In this talk, we show how to resolve the puzzling fractional topological charge postulate for merons, which has become standard practice in recent decades. Namely, we present a unified topological classification bringing together vortices, skyrmions, and merons [1]. In this classification, merons, as well as any combinations of them, correspond to elements of the homotopy group isomorphic to the free abelian group $\mathbb{Z}\times\mathbb{Z}$. Additionally, we briefly discuss generalizations to cases where the homotopy group is no longer abelian and has exponential growth [1,2].

[1] F.N. Rybakov, O. Eriksson and N.S. Kiselev, Phys. Rev. B 111, 134417 (2025).
[2] F.N. Rybakov and O. Eriksson, arXiv:2205.15264 (2022).

Primary author: RYBAKOV, Filipp (Uppsala University)

Presenter: RYBAKOV, Filipp (Uppsala University)

Contribution ID: **21** Type: **not specified**

Multiple skyrmions in bounded domains

Tuesday, 14 October 2025 17:15 (45 minutes)

In extremely thin ferromagnetic films, an additional interaction, the so-called Dzyaloshinskii-Moriya interaction (DMI), arises in the micromagnetic energy. In such materials, topoligically nontrivial, point-like configurations of the magnetization called magnetic skyrmions are observed, which are of great interest in the physics community due to possible applications in high-density data storage.
We will discuss our results regarding existence of higher degree minimizers on bounded domains. By inserting tiny skyrmions in carefully chosen locations, we prove that on sufficiently large domains doing so increases the energy by strictly less than the energy of an infinitesimal bubble. In turn, this will imply continuity of the degree along minimizing sequences.

Primary author: SIMON, Theresa (University of Münster)

Presenter: SIMON, Theresa (University of Münster)

Contribution ID: **22** Type: **not specified**

Skyrmion stacking in stray field-coupled ultrathin ferromagnetic multilayers

Wednesday, 15 October 2025 09:30 (45 minutes)

We explore the energy landscape of ferromagnetic multilayer heterostructures that feature magnetic skyrmions in each magnetic layer. Such magnetic heterostructures have been recently pursued as possible hosts of room temperature stable magnetic skyrmions suitable for the next generation of low power information technologies and unconventional computing. The presence of stacked skyrmions in the adjacent layers gives rise to a strongly coupled nonlinear system, whereby the induced magnetic field plays a crucial stabilizing role. Starting with the micromagnetic modeling framework, we derive a general reduced energy functional for a fixed number of ultrathin ferromagnetic layers with perpendicular magnetocrystalline anisotropy. We next investigate this energy functional in the regime in which the energy is dominated by the intralayer exchange interaction and formally obtain a finite-dimensional description governed by the energy of a system of one skyrmion per layer as a function of the position, radius and the rotation angle of each of theses skyrmions. For the latter, we prove that energy minimizers exist for all fixed skyrmion locations. We then focus on the simplest case of stray field-coupled ferromagnetic bilayers and completely characterize the energy minimizers. We show that the global energy minimizers exist and consist of two stray field-stabilized N\'eel skyrmions with antiparallel in-plane magnetization components.

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