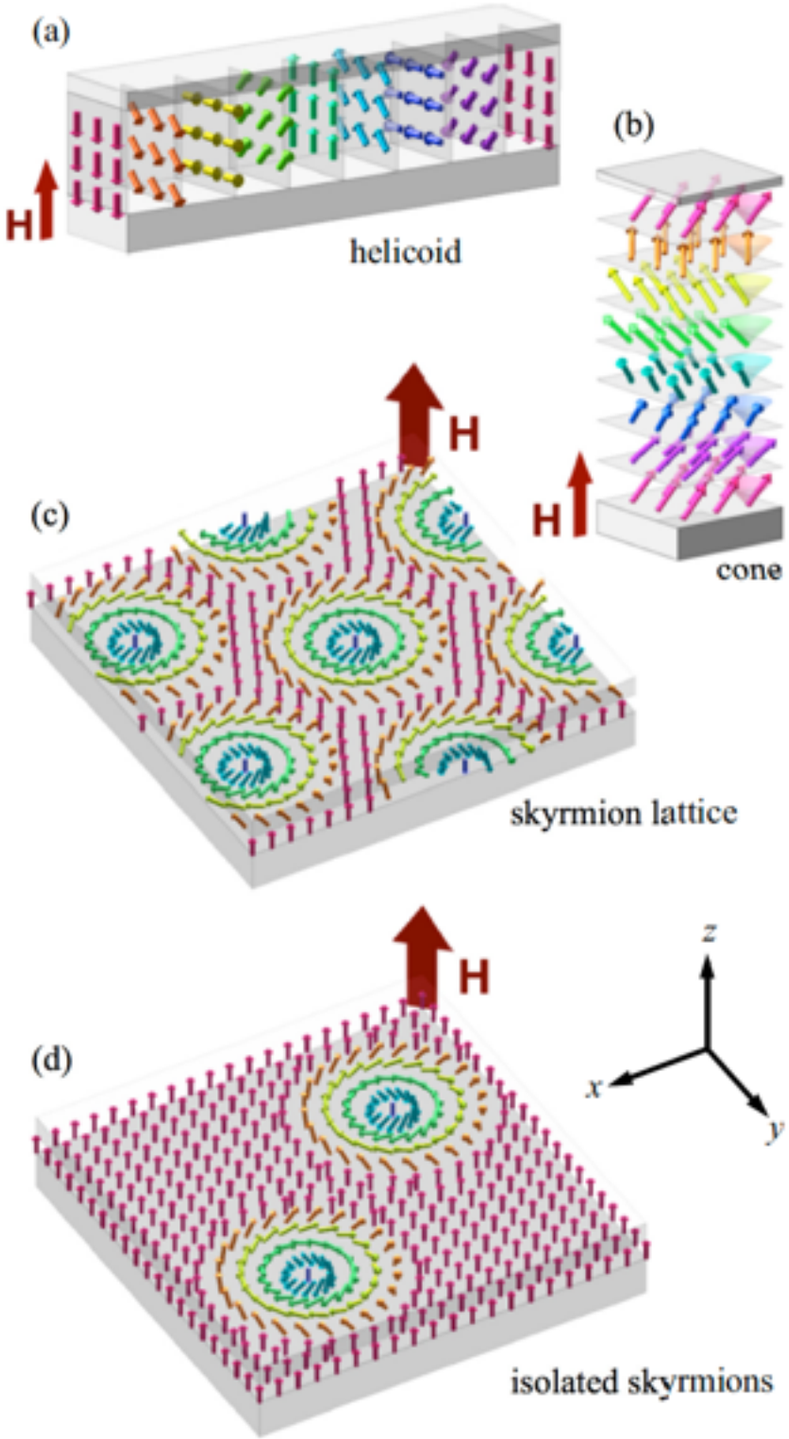
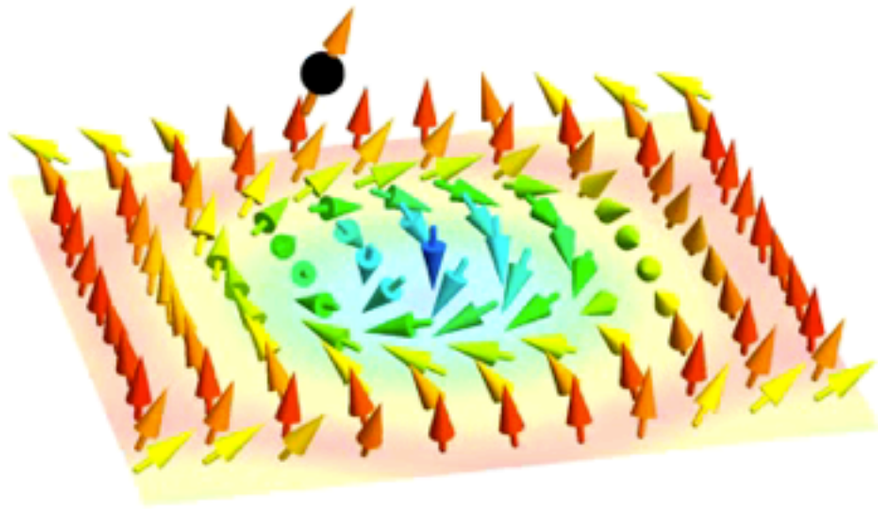
Skyrmionics

Topological Spin Phenomena
in Real-Space for Applications

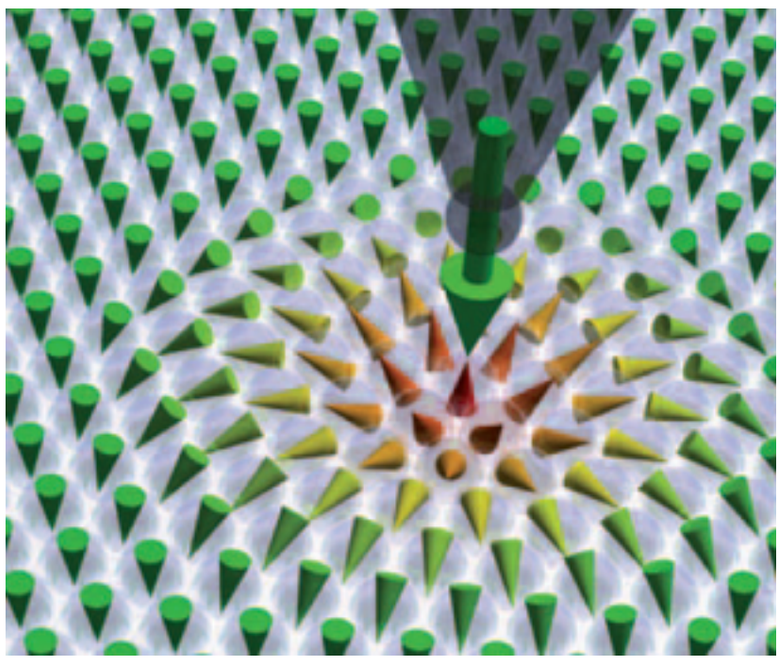
Starting Point & Motivation



Bogdanov & Yablonskii JETP **68** 101 (1989)
Wilson et al. PRB **89**, 094411 (2014)

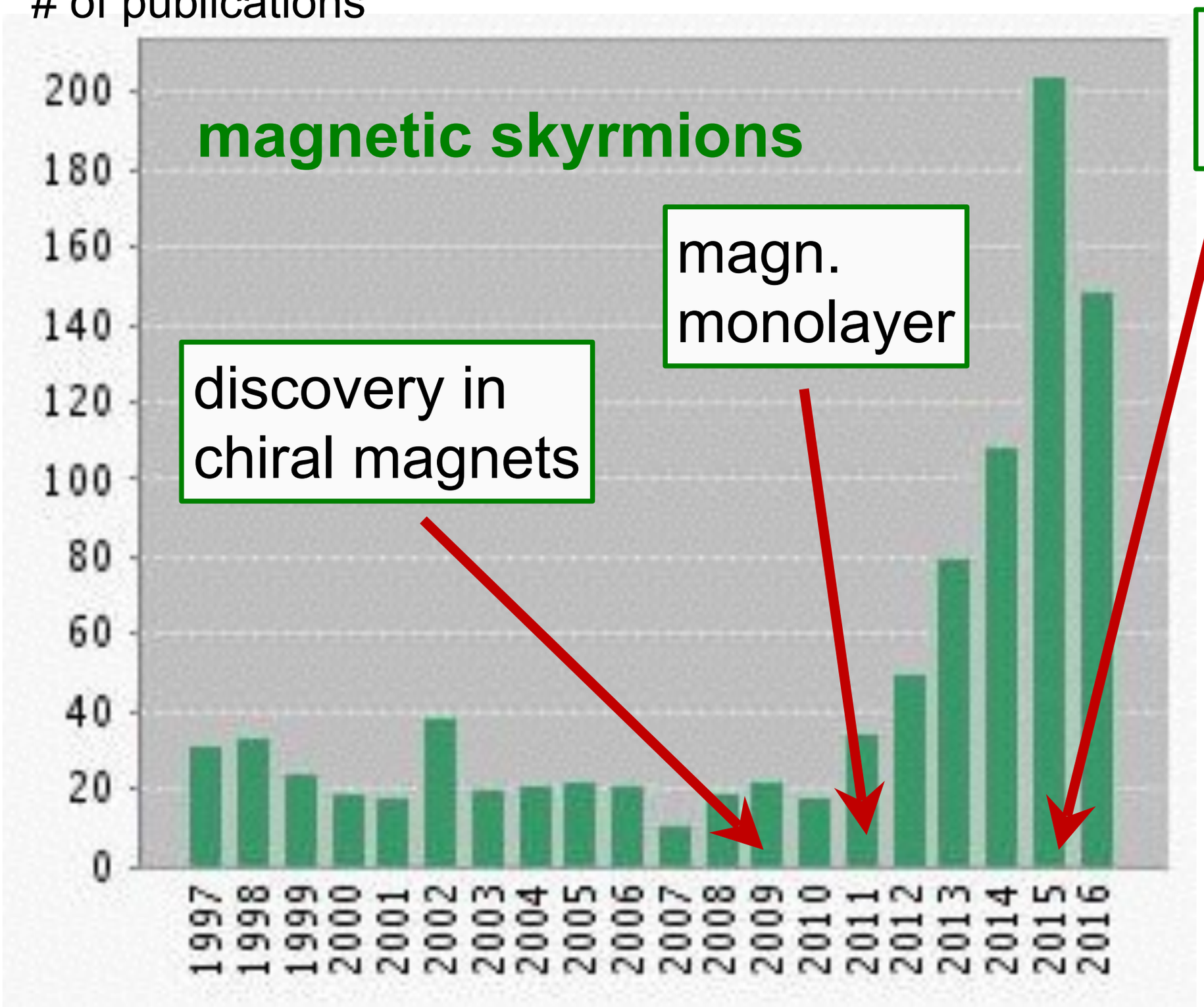


Mühlbauer, et al. Science **323**, 915 (2009)
Jonietz et al, Science **330**, 1648 (2010)
Yu et al., Nature Materials **10**, 106 (2010)



Heinze et al. Nature Physics **7**, 713 (2011)
Romming et al. Science **341**, 636 (2013)

Challenges & Opportunities



National & International Context

Germany	Hamburg	Köln	Stuttgart	Kaiserslautern	Braunschweig	Halle
	Dresden	München	Mainz	Konstanz	Bielefeld	Berlin
	Jülich	Augsburg	Regensburg	Münster	Duisburg	
	Kiel	Karlsruhe	Frankfurt	Würzburg	Aachen	

Japan	Tokyo	**Switzerland**	Lausanne	**France**	Paris	**Netherlands**	Delft
	...		Zürich		Grenoble		Groningen
			Villigen		Saclay		
			Bern				

USA	Los Alamos	**UK**	Oxford	**Sweden**	Uppsala	**China**	Beijing
	New York		Leeds				
	Berkeley		Southhampton				
	Argonne		Cambridge				
			Glasgow				

Russia Petersburg
Moscow

coordinated programs
UK: The Skyrmion Project
CH: sinergia-project (EPFL, ETH, UB,…)
NL: network (Groningen, Delft, …)
D+F+UK: ERC FET Open
USA: Los Alamos
several initiatives to establish ITN's & more

Assessments of 2014 & 2015 Proposals

- Das Feld der Skyrmionen ist hochaktuell.
- Führung deutscher Wissenschaftler in einem „emerging field“.
- Bestehende und sehr erfolgreiche Zusammenarbeit zwischen den Gruppen.
- Forschungsziele sind klar umrissen und gut aufeinander abgestimmt.
- Das Programm ist fokussiert auf drei klare Fragestellungen.
- Koordinatorenteam ist hervorragend ausgewiesen und international führend (Pioniere bei der Erforschung der Skyrmionen).
- Das Gebiet „Skyrmionen“ hat seinen klaren Kern in Deutschland und strahlt auf andere Länder aus.
- Kein anderer Forschungsverbund in D mit diesem Thema im Zentrum.

2014 Einziger Vorbehalt: die „kritische Masse“ an Wissenschaftlern auf diesem Forschungsfeld in D noch nicht erreicht ist.

2015 Einziger Vorbehalt: … zum Thema Gleichstellung wird (im Antrag) nur knapp Stellung genommen.

Organisation & Budget

steering committee

Christian Back*
Stefan Blügel
Karin Everschor-Sitte
Stuart Parkin
Christian Pfleiderer*
Achim Rosch

< 25 projects
+ international workshop
+ summer school
+ guest program

6 Mio€ for 1st funding period

Timeline

10. July 2017	sketch of proposals (non-committing)
11. July 2017	network-meeting @ Mainz
23. October 2017	deadline for submission of proposals
18. January 2018	review of proposals @ Bad Honnef arrival 17. January; decision 19. January

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May 2018	start of funding

Deutsche Forschungsgemeinschaft (German Research Foundation)

Information for Researchers

Call for Proposals

No. 29 **2 June 2017**

Priority Programme “Skyrmionics: Topological Spin Phenomena in Real-Space for Applications” (SPP 2137)

Call for Proposals: Step by Step

The main objective of SPP2137 will be fundamental research towards the development of devices and applications based on **topological spin solitons in real space**, alluding to skyrmions as most prominent examples. It is motivated by the recent discovery of skyrmion lattices and isolated skyrmions in magnetic materials exhibiting **bulk or interface inversion-asymmetry and associated Dzyaloshinskii-Moriya interactions**. Skyrmions can be found in **bulk compounds and tailored thin film and nano-systems**. Studies of the fundamental properties of skyrmion systems have revealed several remarkable features associated with non-trivial topological winding. As one prime example, electrons traversing this spin-texture accumulate geometrical phases - Berry phases – that may be described by **emerging electric and magnetic fields**, leading to **new transport phenomena**. Others are novel mechanisms of **creating and deleting magnetic configurations** and metastable states, new capabilities to **create and destroy magnetically encoded information** as well as exceptionally efficient coupling to spin currents generating **spin transfer torques** at dramatically reduced current densities.

Call for Proposals: Step by Step

The priority program SPP2137 will be organized in three research areas:

(1) **New materials** and **tailored design** of static and dynamic properties of topological spin solitons

(2) Topological spin solitons in **nanostructured systems**

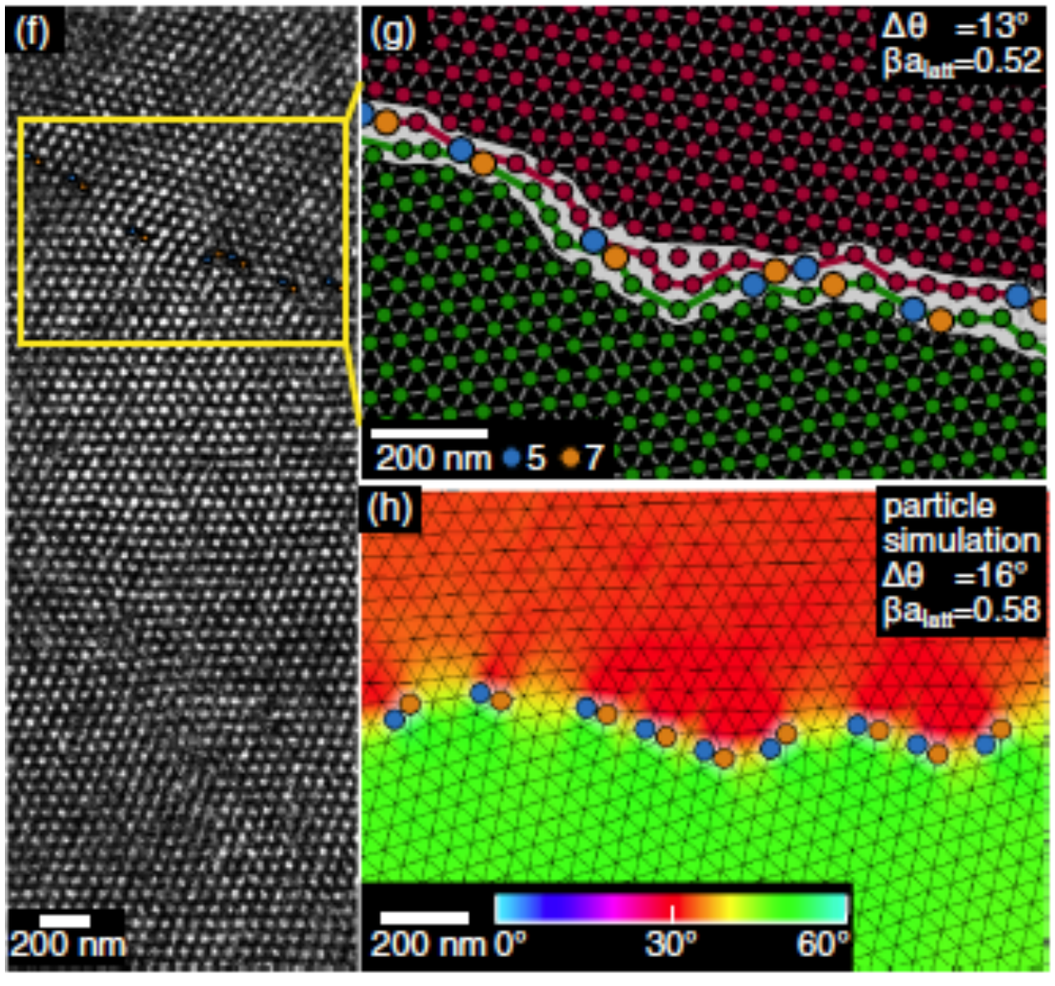
(3) Topological spin solitons in **artificial composite systems**

Call for Proposals: Step by Step

Pursuing the following milestones:

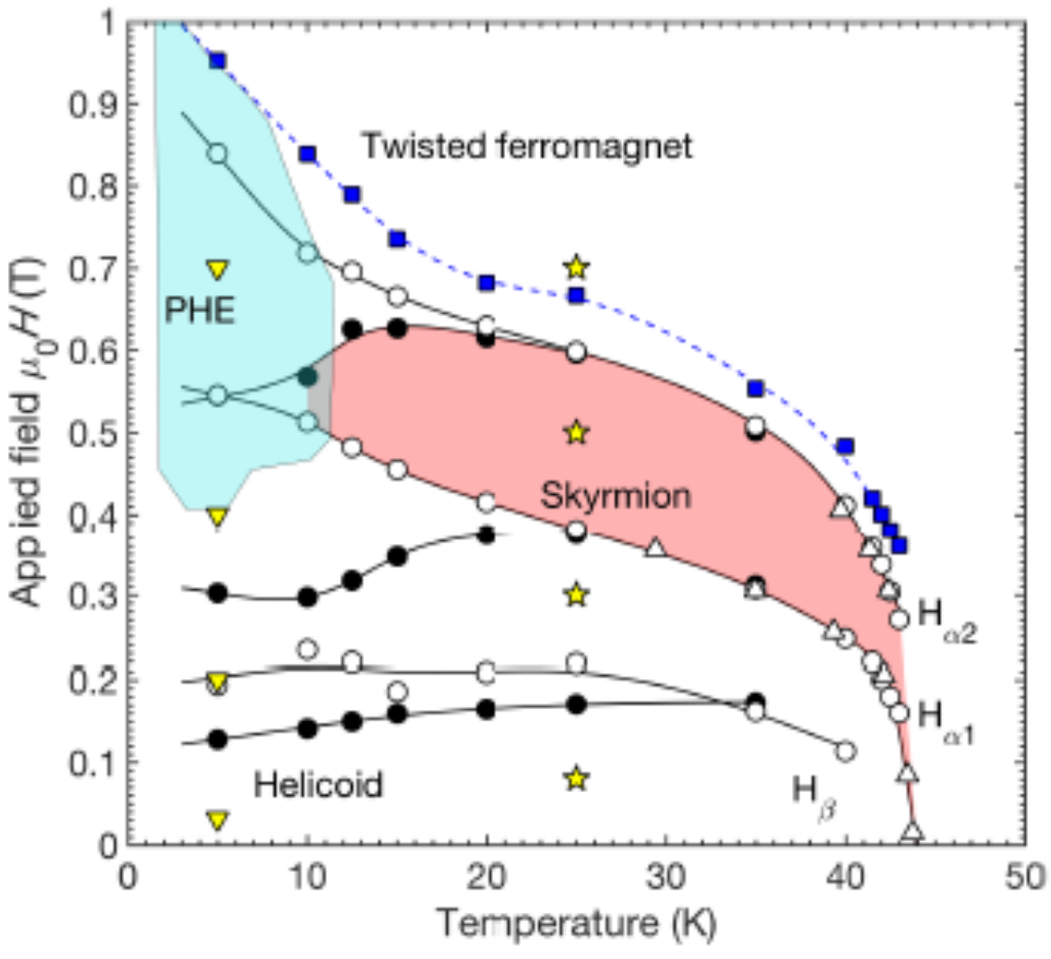
- Tailored design of topological spin phenomena in **thin films including bulk samples in the thin film limit**, focusing on non-centrosymmetric materials with a **vision of potential applications**.

Dynamical defects in Cu_2OSeO_3



Pöllath et al., PRL (2017)

MBE films of MnSi



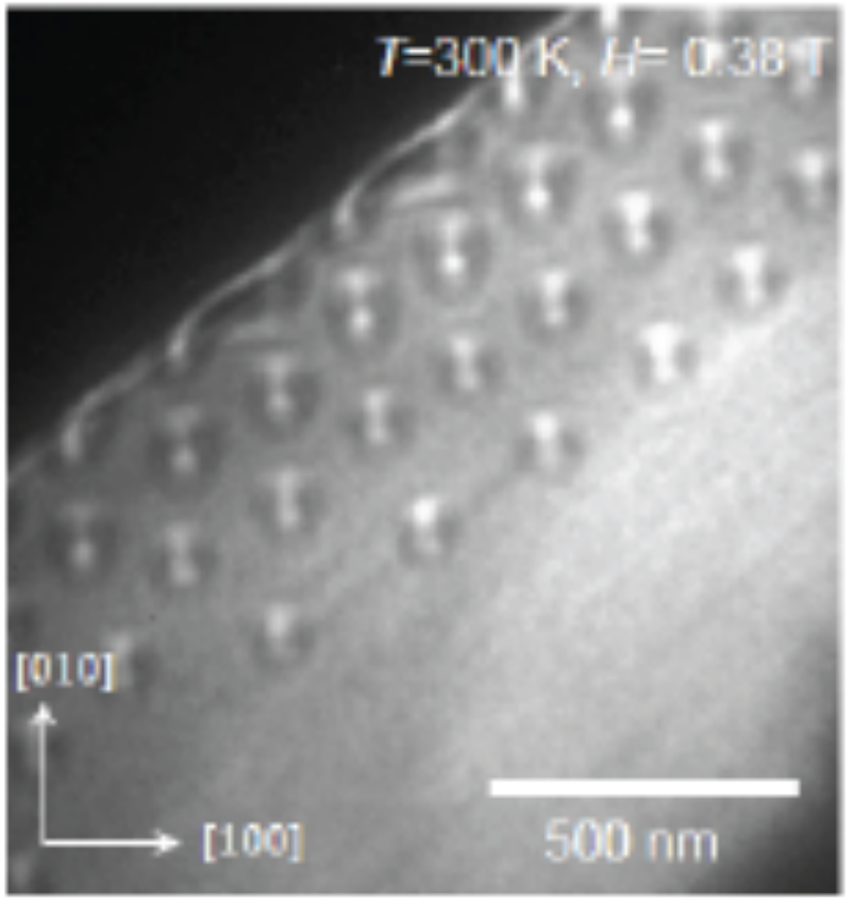
Meynell et al., arXiv/1706.01910

Call for Proposals: Step by Step

Pursuing the following milestones:

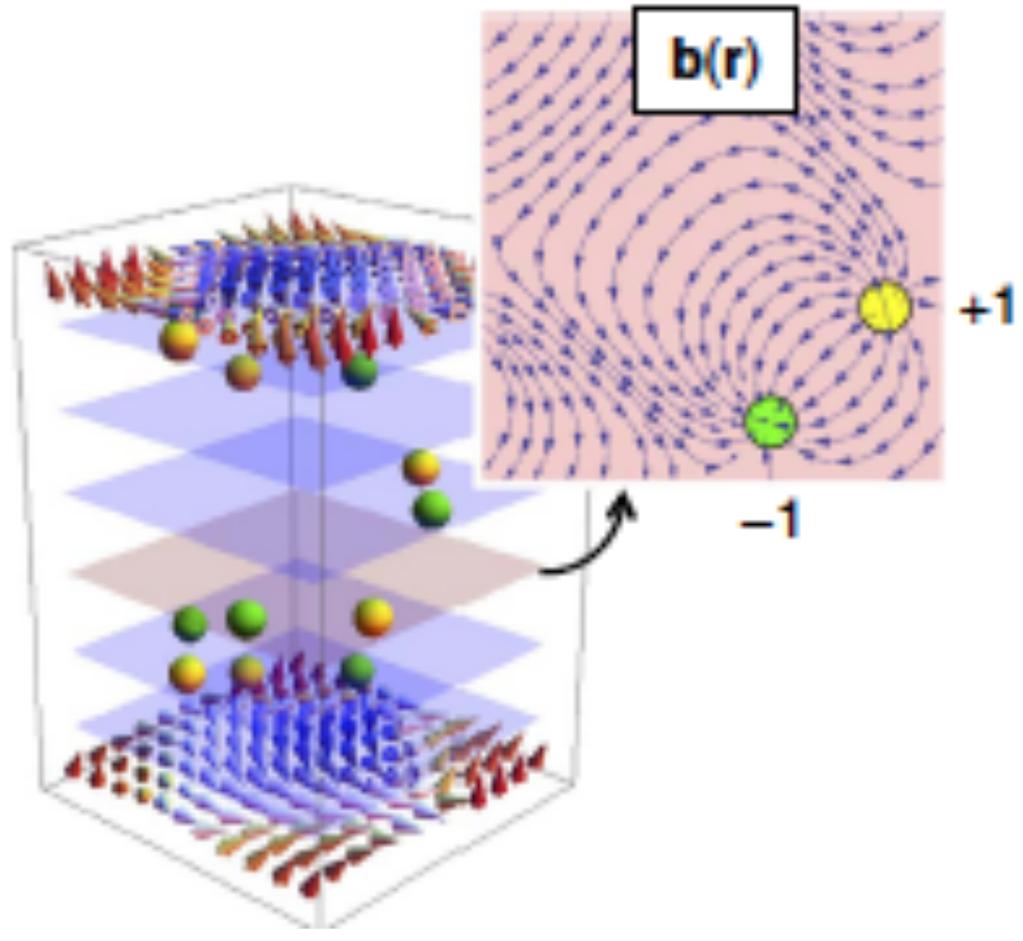
- Tailored design of topological spin phenomena in **thin films including bulk samples in the thin film limit**, focusing on non-centrosymmetric materials with a **vision of potential applications**.

Anti-Skyrmions in $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$



Nayak et al., Nature, in press (2017)

3D-Skyrmions in MnGe

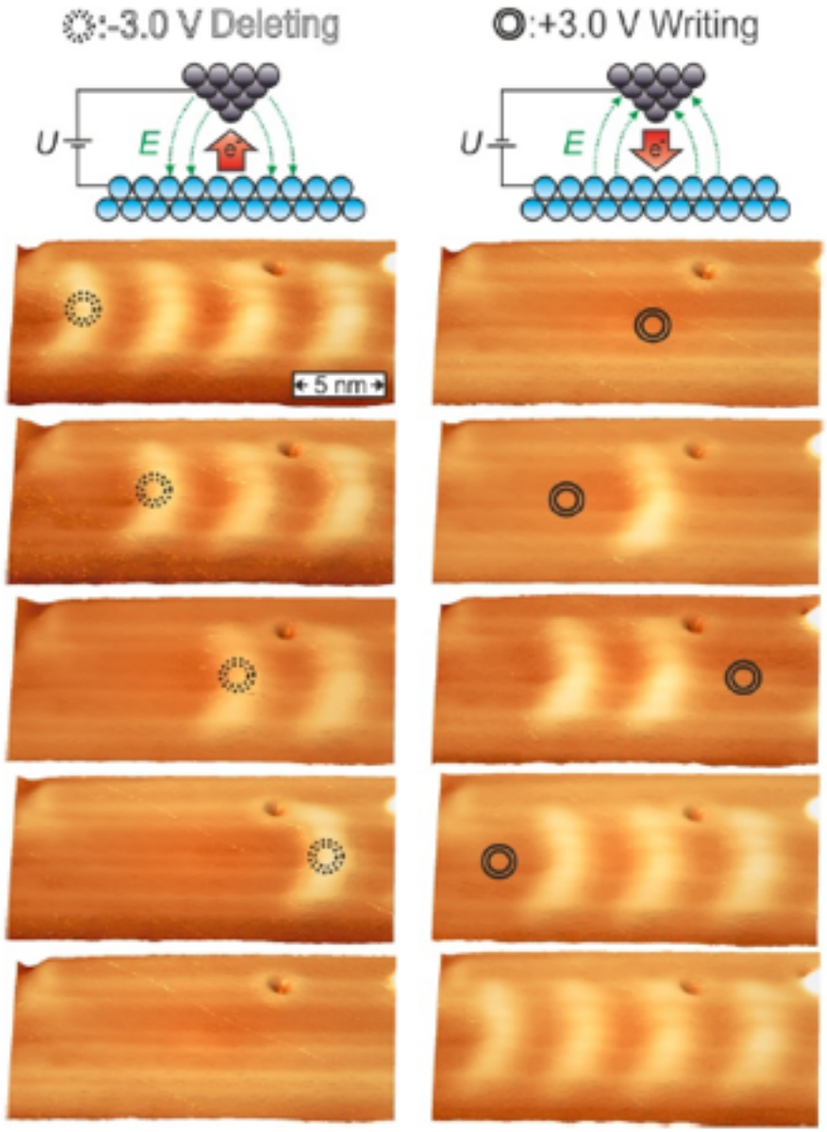


Kanazawa et al., Nat. Comm. (2016)

Call for Proposals: Step by Step

Pursuing the following milestones:

- The **creation, destruction and external manipulation** of skyrmions and related topological spin phenomena in **nano-structured systems** exploiting **interface asymmetry** driven spin interactions.



Writing and Deleting Single Magnetic Skyrmions

Niklas Romming, Christian Hanneken, Matthias Menzel, Jessica E. Bickel,* Boris Wolter, Kirsten von Bergmann,† André Kubetzka,† Roland Wiesendanger

Science 2013

Electric field driven switching of individual magnetic skyrmions

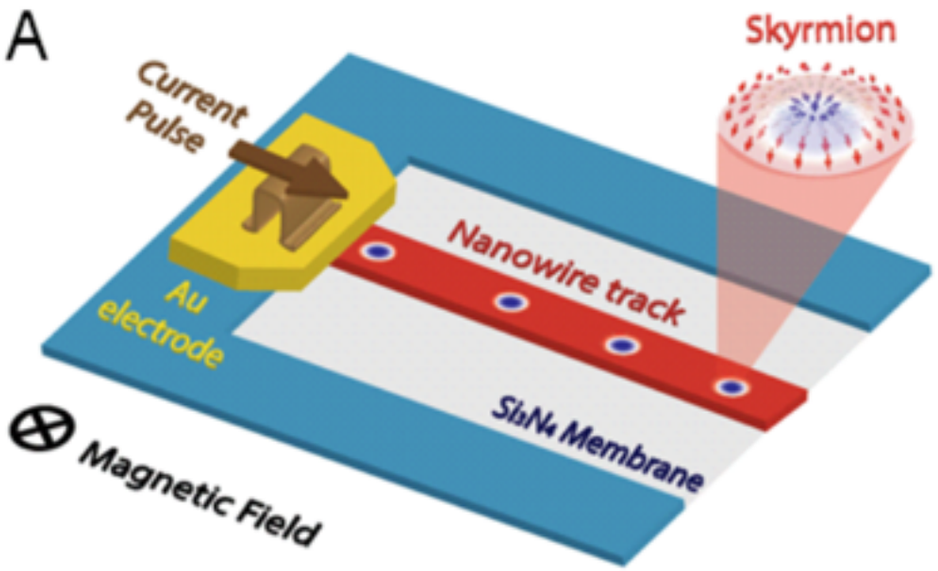
arXiv 2016

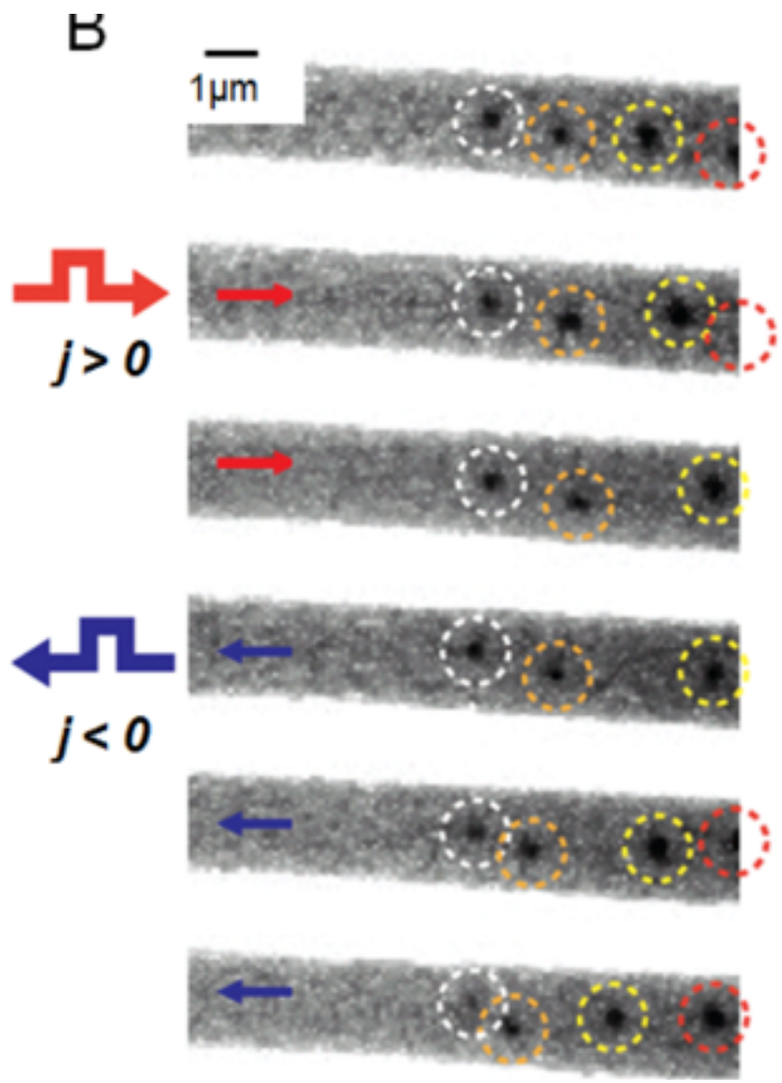
deformed skyrmions along dislocation lines in strained 3 layers of Fe on Ir

Call for Proposals: Step by Step

Pursuing the following milestones:

- The **creation, destruction and external manipulation** of skyrmions and related topological spin phenomena in **nano-structured systems** exploiting **interface asymmetry** driven spin interactions.





speed 100 m/s

S. Woo et. al, MIT, Mainz, Nature Materials 2016

also: Boulle et al. Nature Nanotechnogy 2016

Call for Proposals: Step by Step

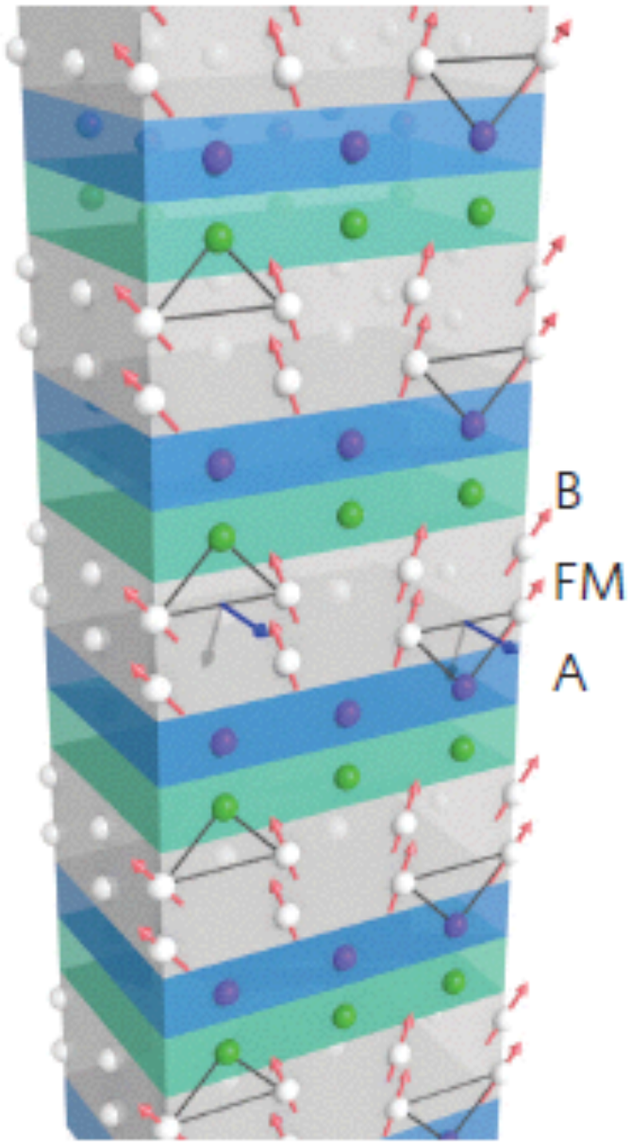
Pursuing the following milestones:

- Insights in **advanced hybrid architectures** revealing **new functionalities** of topological spin phenomena in real space such as fractional excitations.

promising for application:

magnetic multilayers with heavy elements
grown by sputter deposition
e.g. Pt/Co/Ta, Pt/CoFeB/MgO, Ir/Fe, Ir/Co/Pt

design of spin-orbit interaction at interfaces
Fert, Levy 1980, Heinze, Blügel 2011



Call for Proposals: Step by Step

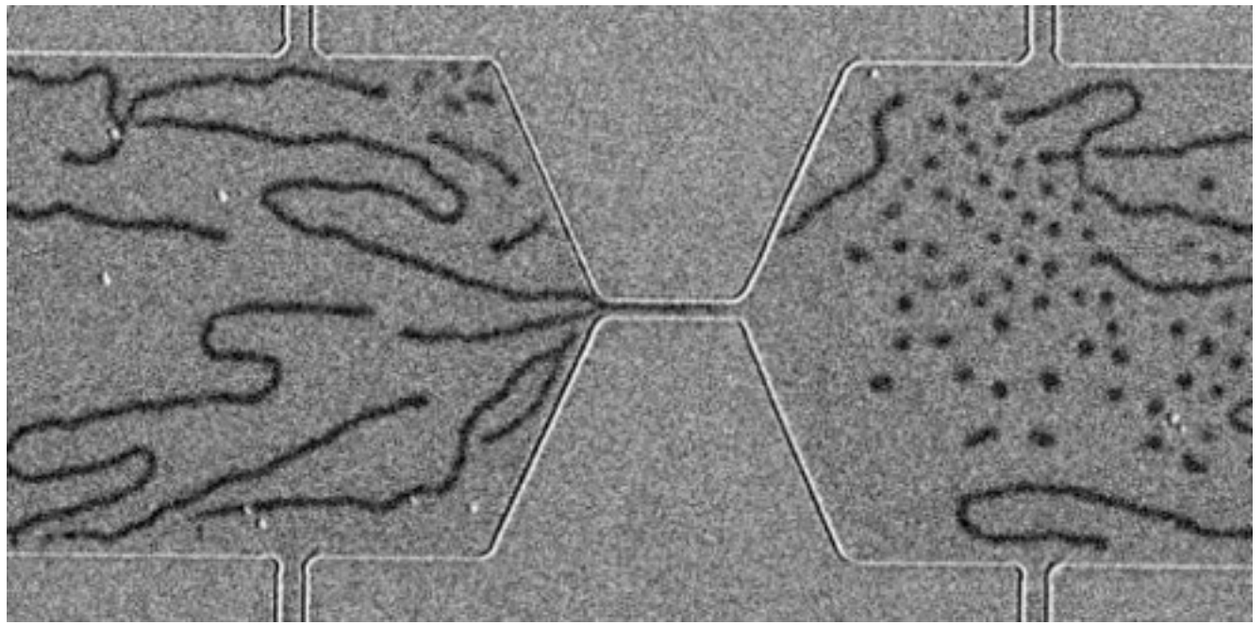
Pursuing the following milestones:

- Insights in **advanced hybrid architectures** revealing **new functionalities** of topological spin phenomena in real space such as fractional excitations.

Blowing magnetic skyrmion bubbles

Hoffmann et al., Argonne, UCLA, Science 2015
creation of skyrmion bubbles (μm size) at room temperature
imaging: magneto-optical Kerr effect (MOKE) microscope

current



current

$\mathrm{Ta(5\ nm)/Co_{20}Fe_{60}B_{20}(CoFeB)(1.1\ nm)/TaO_{\mathit{x}}(3\ nm)}$ $\quad j_e = +5 \times 10^5\ \mathrm{A/cm^2}$

Materials & Systems

Bulk Systems

non-centrosymmetric compounds

bubble materials

perovskites

new materials systems

superconductor

ferroelectrica

multi-ferroica

Thin Films & Heterostructures

Interfaces & Surfaces

Nanostructured

Methods & Expertise

Models & Theory

ab initio
phenomenology
micromagnetic simul.

Samples

sputter
PLD
CVD
MBE
Bridgman
Czochralsky
float-zoning
nano-patterning

Structure

x-rays
synchrotron
optical
neutrons
STM
AFM/MFM
TEM

Spectroscopy

FMR/ESR
Kerr spectrocopy
synchrotron
optical
neutrons
STM
AFM/MFM

Transport

electrical resistivity
thermal conductivity
Hall effect
thermopower

Thermodynamics

susceptibility
magnetisation
electrical polarisation
specific heat
thermal expansion

Proposed Scientific Objectives & Delineation

Topological Spin Solitons
non-zero topological winding
and/or solitonic character

fundamental

create/destroy
modify topology
modify solitonic character

move & manipulate:
- currents
- defects
- dimension

excitations
- collective
- non-linearities
- out-of-equilibrium

applied

established recording materials
read/write heads
nano-oscillators

developing magnonics
spin-caloritronics
all-oxide electronics
all-Heusler devices

‚novel‘ quantum science
really, really novel...

Delineation project must pursue questions related to
non-zero topological winding and/or (strong) solitonic character

Call for Proposals: Step by Step ctd.

The priority program has an **interdisciplinary** character. It aims to connect the **spintronics community** with fundamental research on **new materials**, as well as **engineering**, **mathematics** and **chemistry** related aspects. The progress on skyrmionics is gained through mathematical reasoning, micromagnetic and atomistic simulations, computational and theoretical condensed matter physics, cutting edge synthesis techniques, advanced and highly specialized imaging and characterization methods, supplemented with engineering strategies developed for the design of nano-electronic devices.

The priority program encourages a broader exchange of scientific ideas and concepts with areas such as **particle and nuclear physics**, **quantum Hall systems** and **soft matter** (polymers and liquid crystals). However, specific proposals from these communities are **not in the focus** of the priority program.

Questions?

Comments & Questions at End of Networking-Meeting

(1) List of Participants
- will be made available on the website
  (including city; no titles of projects or posters)

(2) Posters
- will not be made available on the website
- please get in touch with each other to set up collaborations

(3) Transparencies of C. Schuster & C. Pfleiderer
- will be made available on the website

(4) Research Areas
- there is no need to state a research area in your proposal
- the organisational structure might get adapted after the review

(5) Joint Proposals
- there are different ways how to define collaborations
- joint proposals of more than two to three PI's tend to have disadvantages
- collaboration with groups outside Germany is possible
- funding for collaborations might cover travel expenses (check details with DFG)
- it is recommended to state clearly plans for specific collaborations in your proposal

(5) Number of Letters of Interest
- roughly 50 projects have been suggested so far