PAUL SCHERRER INSTITUT

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:: **Paul Scherrer Institute (PSI), Switzerland**

Skyrmions in magnetic materials

Download slides from: **https://www.psi.ch/lns/jonathan-white**

Dresden17
Deutsche Physikalische Gesellschaft e.V.

19th March, 2017

I. What is a Skyrmion?

What is a Skyrmion?

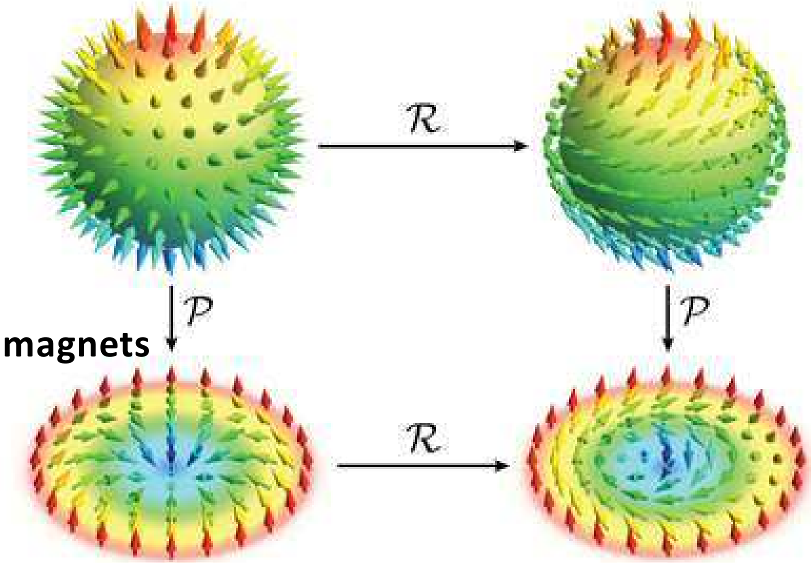
Tony Skyrme

Nucl. Phys. **31** 556 (1962)

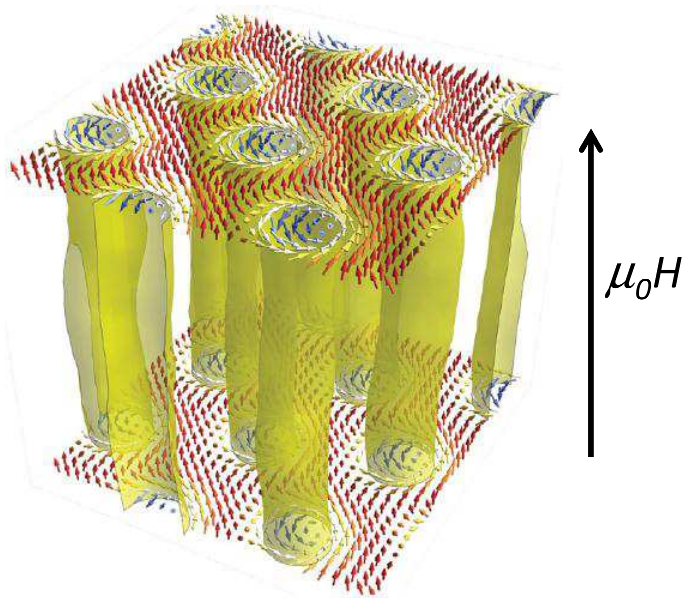
- A Skyrmion is a local, stable, soliton-like solution of a nonlinear field theory
- Interpreted as particle-like objects (baryons in a spinless pion medium)
- These particles persist due to topological-protection, which is characterised by a topological integer (winding number).
- Skyrmion excitation in CM: Liquid crystals, QHE, BEC, non-centrosymmetric magnets

In the original sense

In real magnets



http://www.christophschuette.com/physics/skyrmions.php



P. Milde *et al.*, Science **340**, 1076 (2013)

Classifying a magnetic skyrmion

Homotopy theory: allows a classification of magnetic structures according to topology.

→ Examine the mapping of magnetic spin vectors in a physical space S^n to its order parameter space S^m.

→ The order is considered 'topological' when the mapping cannot be shrunk to a single point:

$$\pi_n(S^m) > 0$$

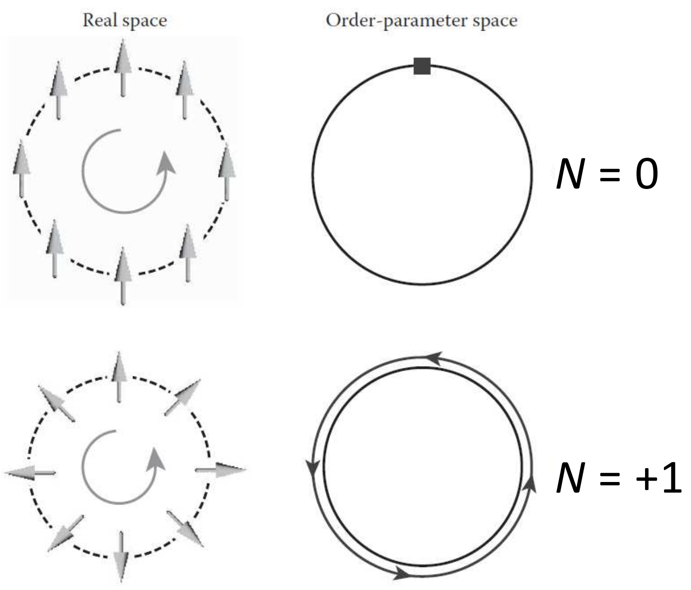
→ A topological structure can be characterised according to a winding integer *N*, which counts the number of times the physical space fully covers the order parameter space.

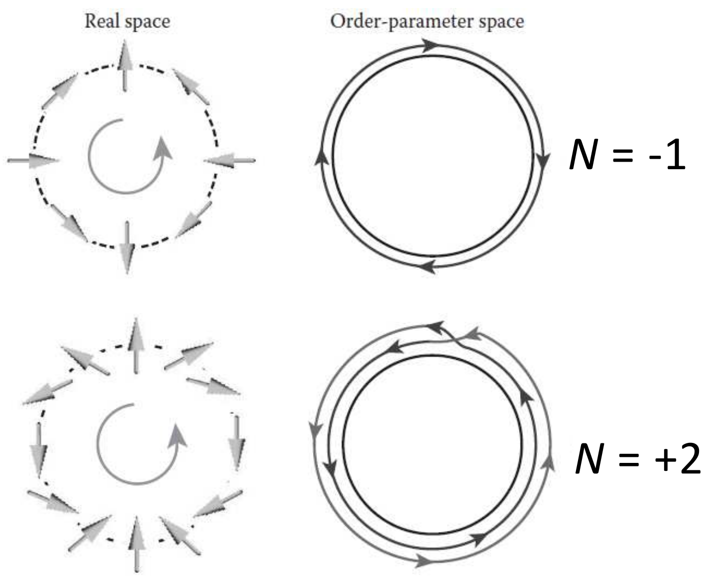
Example: Spins with fixed length on a circle (1-sphere).

Order parameter is a 2D magnetization vector: **m**

Order parameter space = circle (one angle) = S^1

Homotopy group: $\pi_1(S^1) = \mathbb{Z}$
e.g. magnetic vortex





Classifying a magnetic skyrmion

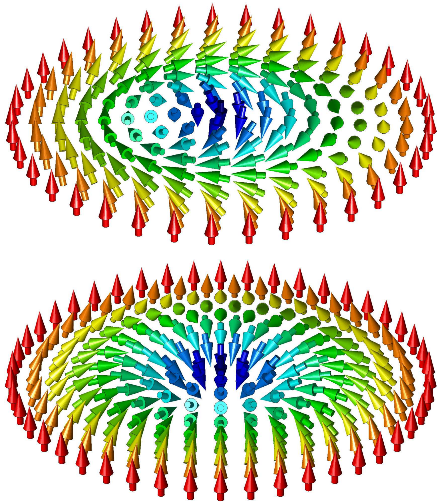
Magnetic Skyrmions belong the homotopy group: $\pi_2(S^2) = \mathbb{Z}$

Spins with fixed length on a 2-dimensional plane

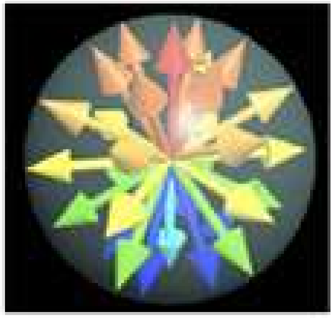
Order parameter is a 3D magnetization vector: **m**

Order parameter space = surface of a sphere (two angles) $=S^2$

Real Space



Depiction of mapping to order parameter space



Characterised by winding number - $|N| = 1$.

$$N = \frac{1}{4\pi}\int\left(\frac{\partial \mathbf{m}}{\partial x}\times\frac{\partial \mathbf{m}}{\partial y}\right)\cdot \mathbf{m}\,\mathrm{d}x\,\mathrm{d}y$$

- **Closed particle-like state (closed surface in order parameter space with physical stability)**
- **Topologically non-trivial (Skyrmions are countable objects)**
- **Topological protection (a continuous change of homotopy is forbidden → introduces an energy barrier between different topological states in a real physical system)**

II. Where are they found?

PAUL SCHERRER INSTITUT

Thermodynamically stable magnetic vortex states in magnetic crystals

A. Bogdanov *, A. Hubert

Institut für Werkstoffwissenschaften VI der Universität Erlangen-Nürnberg, Martensstr. 7, D 91058 Erlangen, Germany

Received 14 February 1994

A. Bogdanov and A. Hubert, JMMM **138**, 255 (1994).
A.N. Bogdanov and D.A. Yablonsky, Sov. Phys. JETP **95**, 178 (1989).
A.N. Bogdanov, U.K. Rößler and C. Pfleiderer, Physica B **359,** 1162 (2006).
U.K. Rößler, A.A. Leonov and A.N. Bogdanov, J. Phys: Conf. Series (2010)

"spin vortices" as solutions of a continuum model → **condensed hcp skyrmion phases**

$$W = A\sum_i \left(\frac{\partial \boldsymbol{m}}{\partial x_i}\right)^2 - Km_z^2 - \boldsymbol{J}\cdot\boldsymbol{H}_{\text{ext}} - \tfrac{1}{2}\boldsymbol{J}\cdot\boldsymbol{H}_{\text{d}} + w_{\text{D}}$$

Exchange

Anisotropy

Zeeman

DMI energy

- **DMI couplings included as Lifshitz-type invariants**
- **They generally exist in non-centrosymmetric magnets**
- **The pattern of allowed DMIs determines the Skyrmion type**

$$w_{\text{D}} = D_1 w_1 + D_2 w_2$$

$$= D_1\left(m_z\frac{\partial m_x}{\partial x} - m_x\frac{\partial m_z}{\partial x} + m_z\frac{\partial m_y}{\partial y} - m_y\frac{\partial m_z}{\partial y}\right)$$

$$+ D_2\left(m_y\frac{\partial m_x}{\partial z} - m_x\frac{\partial m_y}{\partial z} + m_x\frac{\partial m_z}{\partial y} - m_z\frac{\partial m_x}{\partial y} + m_z\frac{\partial m_y}{\partial x} - m_y\frac{\partial m_z}{\partial x}\right)$$

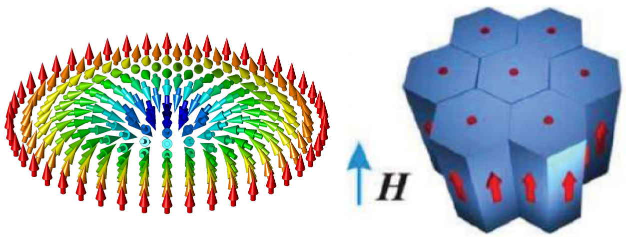
C_{nv} with *n=2,3,4,6*

cycloidal groundstate

q

DM

Néel-type skyrmion



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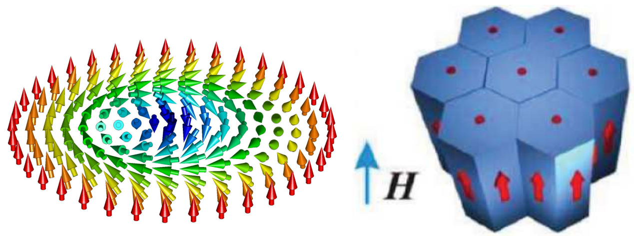
$$+ D_2\left(m_y\frac{\partial m_x}{\partial z} - m_x\frac{\partial m_y}{\partial z} + m_x\frac{\partial m_z}{\partial y} - m_z\frac{\partial m_x}{\partial y} + m_z\frac{\partial m_y}{\partial x} - m_y\frac{\partial m_z}{\partial x}\right)$$

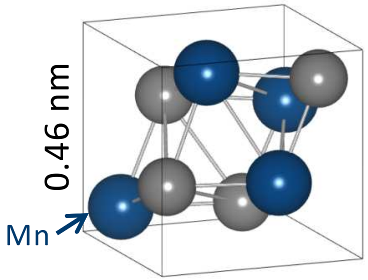
T, O crystal classes

helical groundstate *DM* || ***q***

Bloch-type chiral skyrmion



Chiral magnet MnSi



Crystal class *T*
Cubic ($P2_13$)
No inversion → DMI

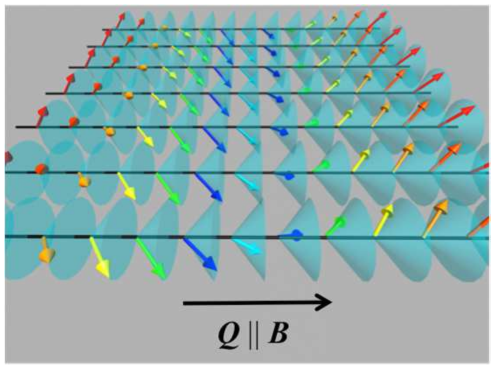
Simple Hamiltonian with a monochiral helix groundstate

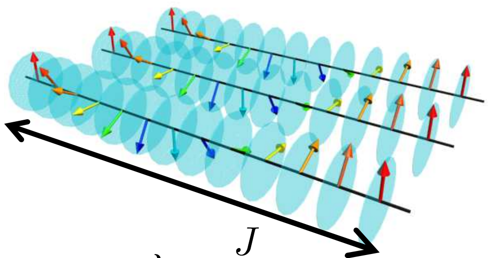
$$\mathcal{H} = J(\nabla \mathbf{S})^2 + D\mathbf{S}\cdot(\nabla\times\mathbf{S}) - hS_z$$

Ratio of *J/D* determines helical pitch = 18 nm.

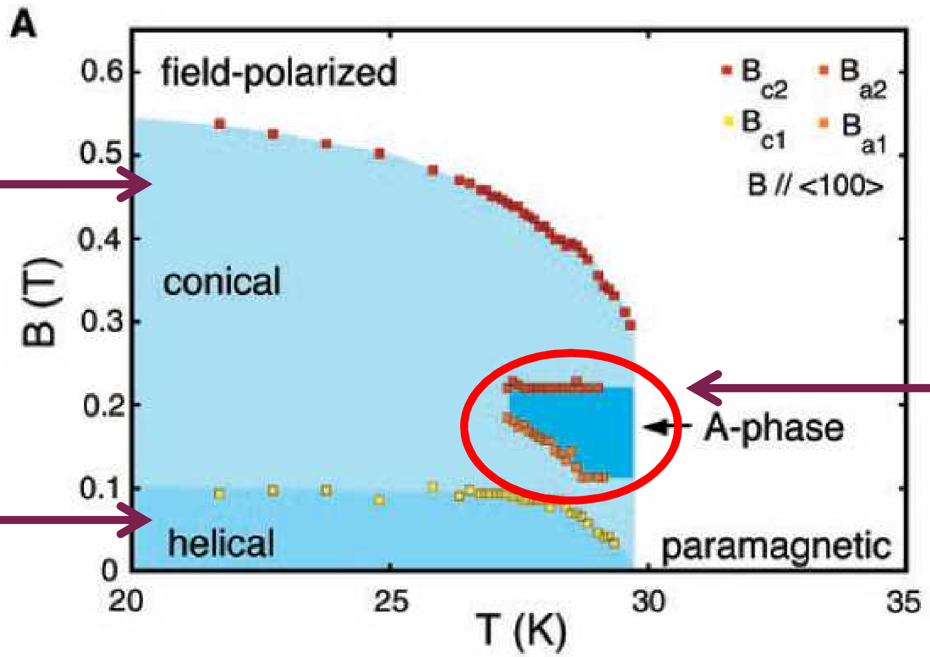
H-O anisotropy terms align helices with <111>.

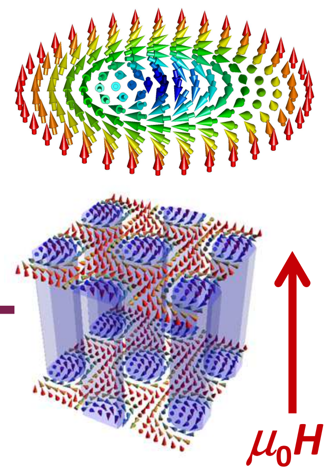
Phase diagram





$$\lambda = \frac{J}{D}$$





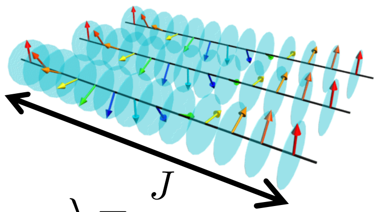
S. Mühlbauer *et al.*, Science **323**, 915 (2009)

Observing chiral magnetic order by SANS

Incommensurate chiral magnetic order → Bragg satellites around commensurate positions

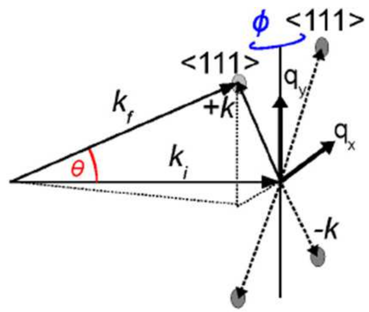
$$\left.\frac{d\sigma}{d\Omega}\right|_{mag,el} = N(\gamma r_0)^2 \frac{(2\pi)^3}{v_0} \sum_{\mathbf{G}} \sum_{\mathbf{k}} \sum_{\alpha,\beta} (\delta_{\alpha\beta} - \hat{q}_\alpha \hat{q}_\beta) F_M^{\mathbf{k}\alpha\dagger} F_M^{\mathbf{k}\beta} \delta(\mathbf{q} - \mathbf{k} - \mathbf{G})$$

In real space

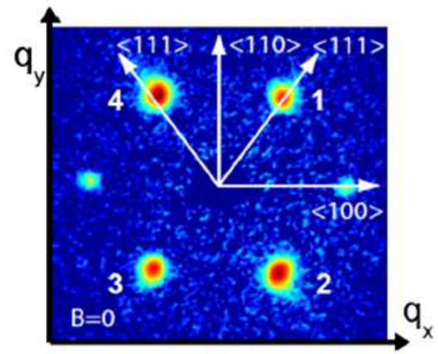


$$\lambda = \frac{J}{D}$$

In reciprocal space

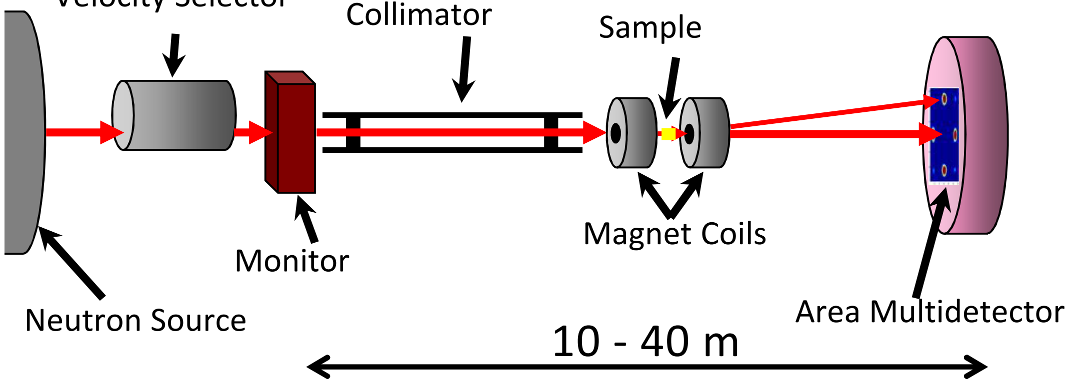


SANS pattern



S. Mühlbauer, PhD Thesis 2009

Large period magnetic structures (~30 to 5000 Å) → low *q* → SANS



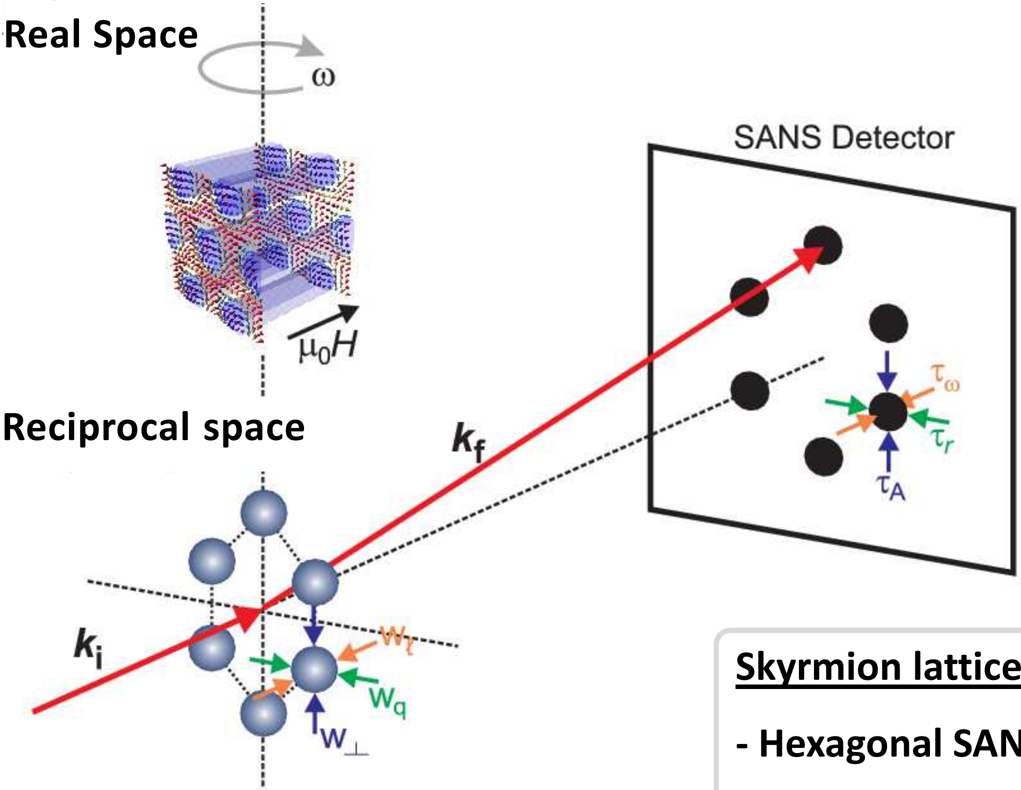
$$\lambda = 2d\sin\theta$$

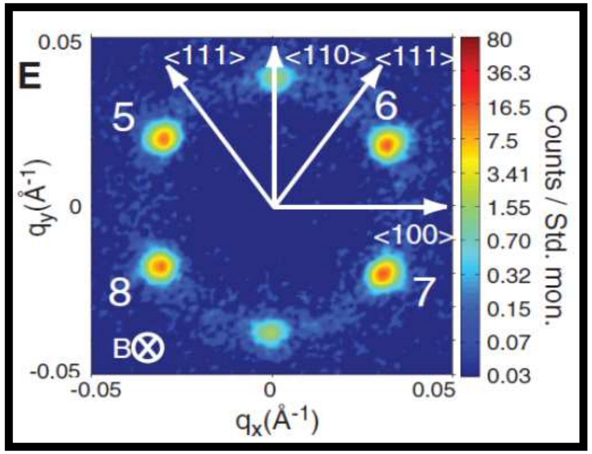
- Length of instrument: 10-40 m
- Scattering angle: ~1° (length-scales from ~30 to 5000 Å)
- Non-destructive bulk probe

Observing the Skyrmion lattice by SANS

Skyrmion Lattice

Real Space





S. Mühlbauer *et al.*, Science **323**, 915 (2009)

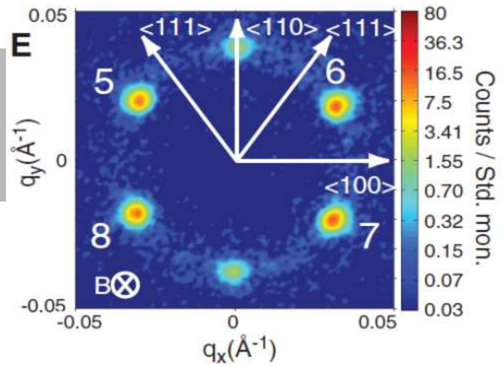
Skyrmion lattice in MnSi (and others)

- **Hexagonal SANS scattering pattern**
- **Propagation vectors perpendicular to B**
- **Weak pinning (alignment) with crystal directions**
- **First order phase boundary with conical + PM phases**

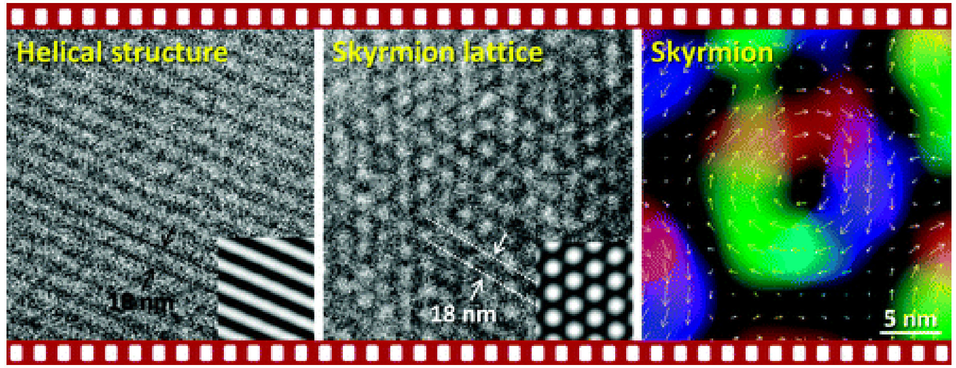
SANS does not directly 'see' the particle-like skyrmion property

Real-space imaging of the Skyrmion particle

SANS - bulk MnSi



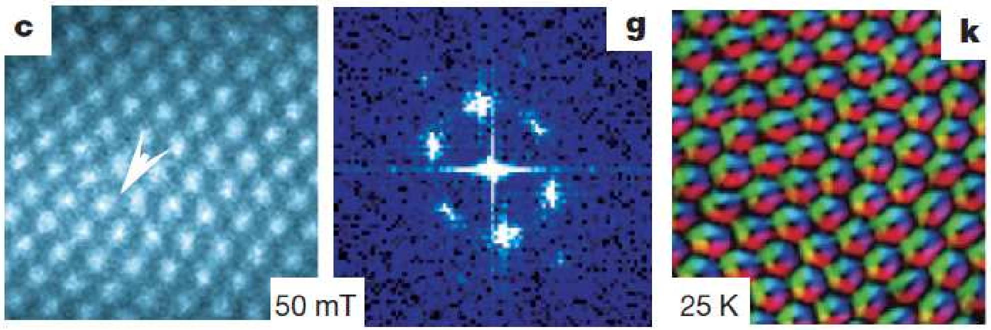
Spin-polarised TEM – thin samples MnSi



A. Tonomura et al., Nano Lett., **12**, 1673 (2012)

Lorentz force TEM – thin samples

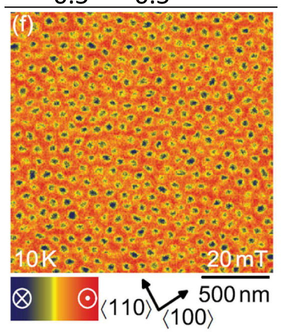
$Fe_{0.5}Co_{0.5}Si$ and FeGe



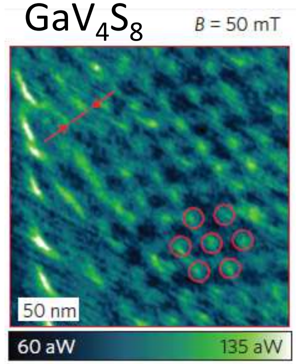
Z.X. Yu *et al.*, Nature **465**, 901 (2010), Nat. Mater. **10**, 106 (2011)

Magnetic tip AFM (MFM) – surfaces

$Fe_{0.5}Co_{0.5}Si$



GaV_4S_8



P. Milde *et al.*, Science **340**, 1076 (2013)

I. Kézsmárki *et al.*, Nat. Mater. **14**, 116 (2015)

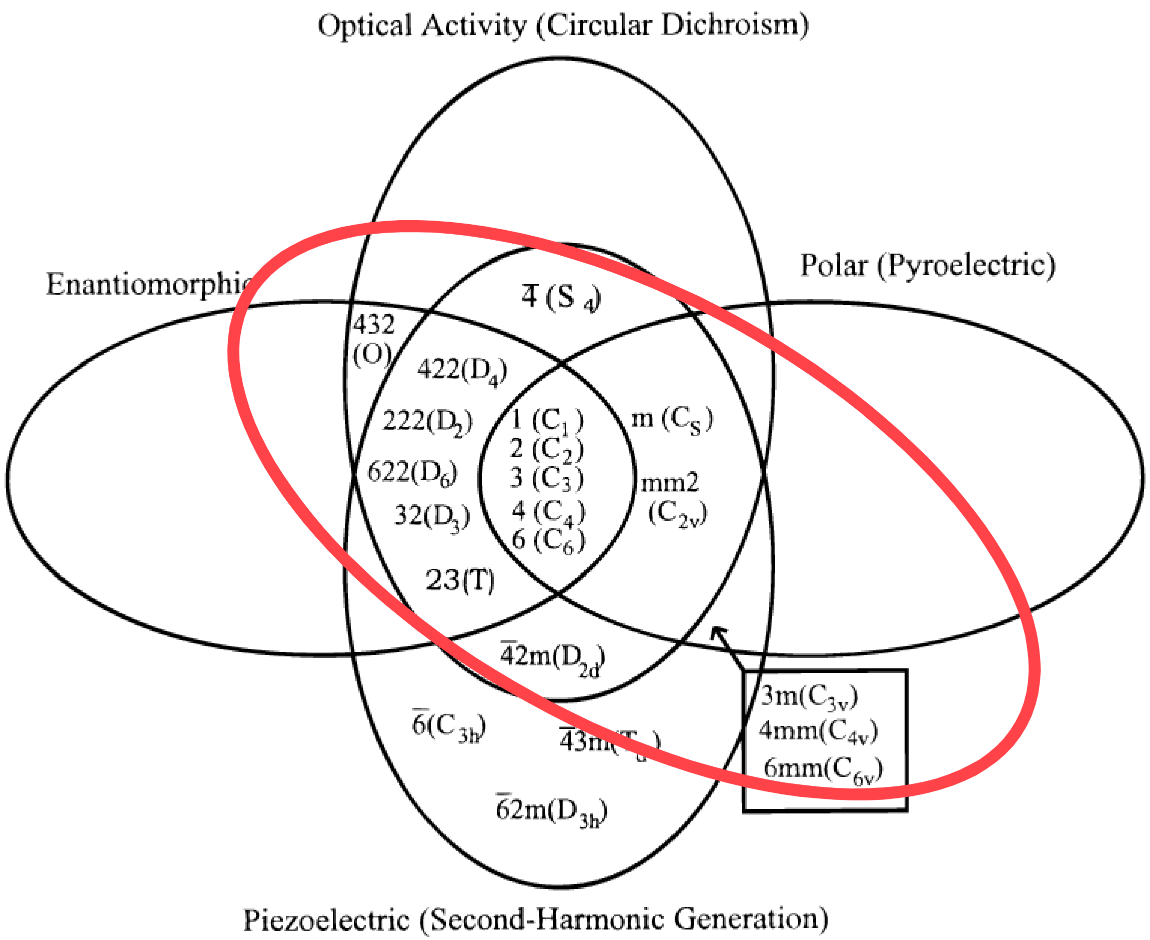
- Spin-polarised STM
- Ultrasonic measurements
- Microwave spectroscopy
- Muon spin rotation
- Resonant soft x-ray scattering
- PEEM
- Classical measurements, $M(H)$, χ_{ac}
- Transport (Hall effect)

Table of DMI Skyrmion host materials

Material	Crys. Class	SG	Skyrm. Type	T_c	λ (nm)	Trans.	References
MnSi	*T*	$P2_13$	Bloch	30 K	18	Metal	S. Mühlbauer *et al.*, Science **323**, 915 (2009)
FeGe	*T*	$P2_13$	Bloch	279 K	70	Metal	X.Z. Yu *et al.*, Nat. Mater. **10**, 106 (2010)
$\mathbf{Fe_{1-x}Co_x}$Si	*T*	$P2_13$	Bloch	< 36 K	40-230	Semi-cond.	W. Münzer *et al.*, PRB **81**, 041203(R) (2010) X.Z. Yu *et al.*, Nature **465**, 901 (2010)
$\mathbf{Mn_{1-x}Fe_x}$Si	*T*	$P2_13$	Bloch	< 17 K	10-12	Metal	S.V. Grigoriev *et al.*, PRB **79**, 144417 (2009)
$\mathbf{Mn_{1-x}Fe_x}$Ge	*T*	$P2_13$	Bloch	< 220 K	5–220	Metal	K. Shibata *et al.*, Nat. Nanotech. **8**, 723–728 (2013)
$\mathbf{Cu_2}OSeO_3$	*T*	$P2_13$	Bloch	58 K	60	**Insulator**	S. Seki *et al.*, Science **336**, 198 (2012) T. Adams *et al.*, PRL **108**, 237204 (2012)
$\mathbf{Co_x}Zn_y\mathbf{Mn_z}$	O	$P4_132$ / $P4_332$	Bloch	**150 K – 500 K**	120 – 200	Metal	Y. Tokunaga *et al.*, Nat. Commun. **6**, 7638 (2015)
$(\mathbf{Fe,Co})_2Mo_3N$	O	$P4_132$ / $P4_332$	Bloch	< 36 K	110	Metal	W. Li *et al.*, Phys. Rev. B **93**, 060409(R) (2016)
Ga$\mathbf{V_4}S_8$	C_{3v}	*R*3m	**Néel**	13 K	17	Semicond/ Insulator	I. Kézsmárki *et al.*, Nat. Mater. **14**, 1116 (2015)
Ga$\mathbf{V_4}Se_8$	C_{3v}	*R*3m	**Néel**	18 K	24	Semicond/ Insulator	Previous talk!

Nature is generous!

Non-centrosymmetric crystal classes



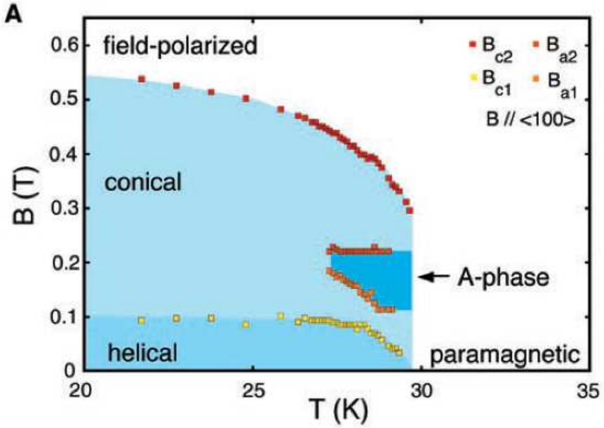
More Skyrmion host systems with novel functionalities are waiting to be discovered!

P. S. Halasyamani and K. R. Poeppelmeier, Chem. Mater. **10**, 2753 (1998)

III. Getting out of a tight spot
Understanding Skyrmion phase stability

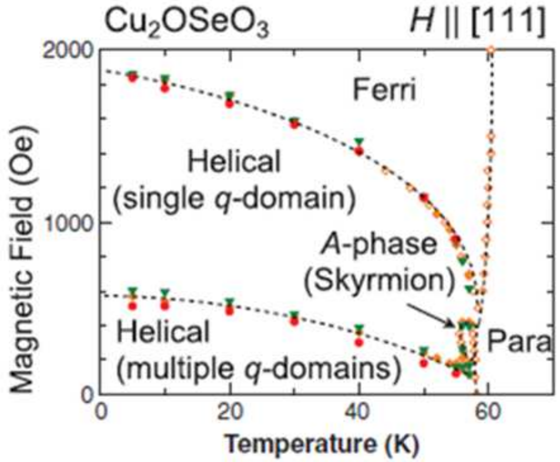
Important factors beyond DMI

MnSi



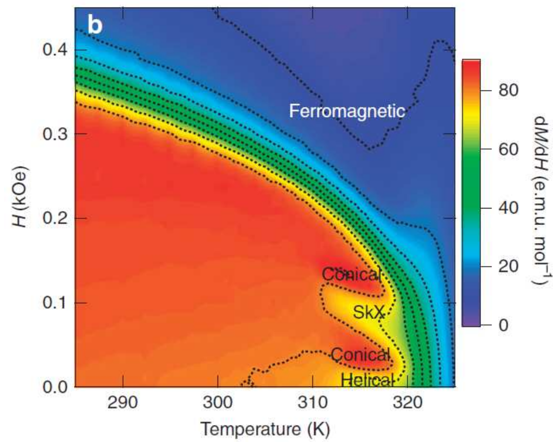
S. Mühlbauer *et al.*, Science (2009)

Cu_2OSeO_3



S. Seki *et al.*, Science (2012)

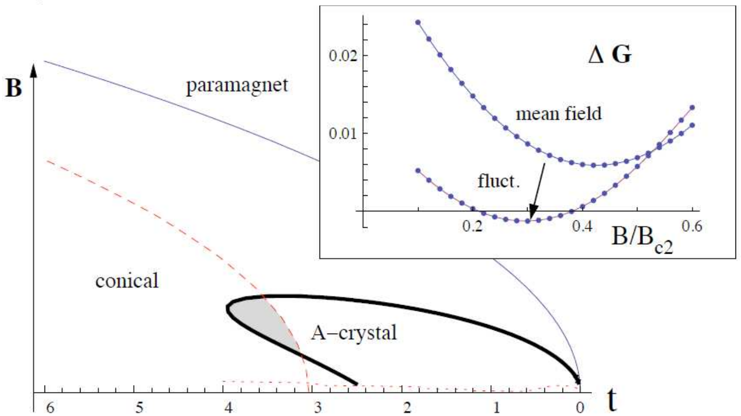
Co-Zn-Mn alloys



Y. Tokunaga *et al.*, Nat. Commun. (2015)

Skyrmion state stabilised by Gaussian fluctuations?

$$F[\mathbf{M}] = \int d^3r \left(r_0 \mathbf{M}^2 + J(\nabla \mathbf{M})^2 + 2D\,\mathbf{M}\cdot(\nabla \times \mathbf{M}) + U\mathbf{M}^4 - \mathbf{B}\cdot\mathbf{M} \right)$$

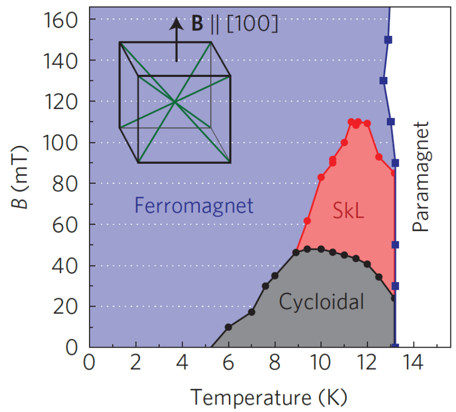


S. Mühlbauer *et al.*, Science **323**, 915 (2009)

Longitudinal magnetisation fluctuations

U.K. Rössler et al., Nature **442**, 797 (2006).

A.N. Bogdanov and D.A. Yablonskii, Sov. Phys. JETP **68**, 101 (1989).



Uniaxial anisotropy (with no conical phase)

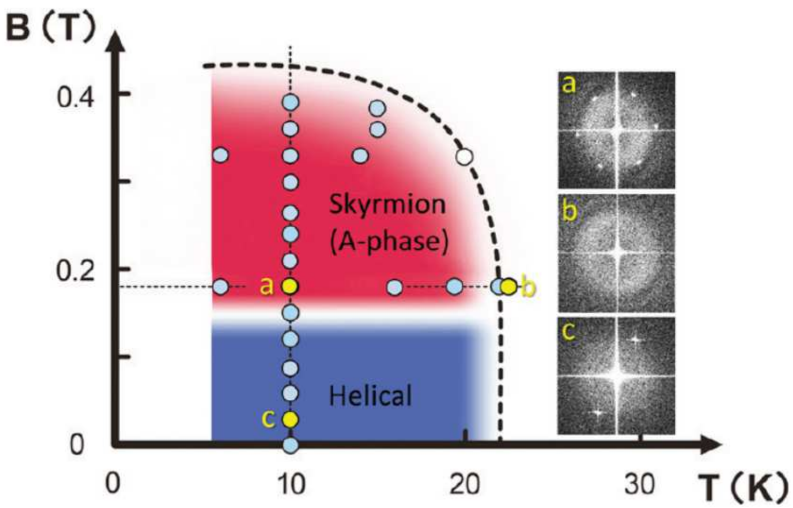
GaV_4S_8

I. Kézsmárki *et al.*, Nat. Mater. **14**, 116 (2015)

Thin samples of chiral magnets

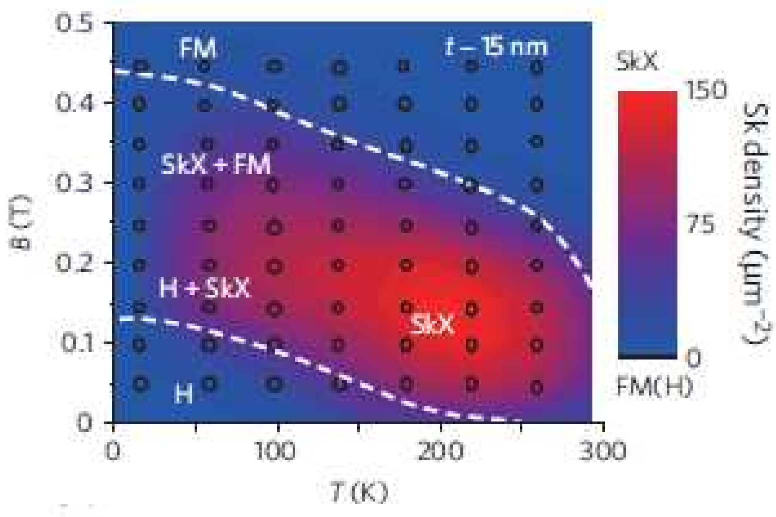
Fabrication of thin films (bottom-up) / thin plates (top-down)

MnSi (50nm thick)



A. Tonomura *et al.*, Nano Lett., **12**, 1673 (2012)

FeGe (15nm thick)



X.Z. Yu *et al.*, Nat. Mater. **10**, 106 (2010)

Uniaxial anisotropy is enhanced by reducing the sample thickness, *d*
→ competing conical phase suppressed when *d* ~ λ

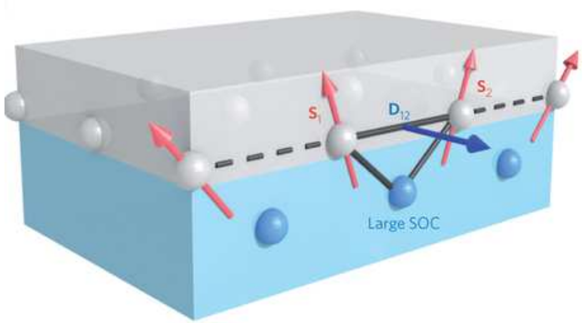
A.B. Butenko et al., PRB **82**, 052403 (2010)

S.D. Yi et al., Phys. Rev. B **80**, 054416 (2009)

Going even thinner..

Ultrathin metallic films

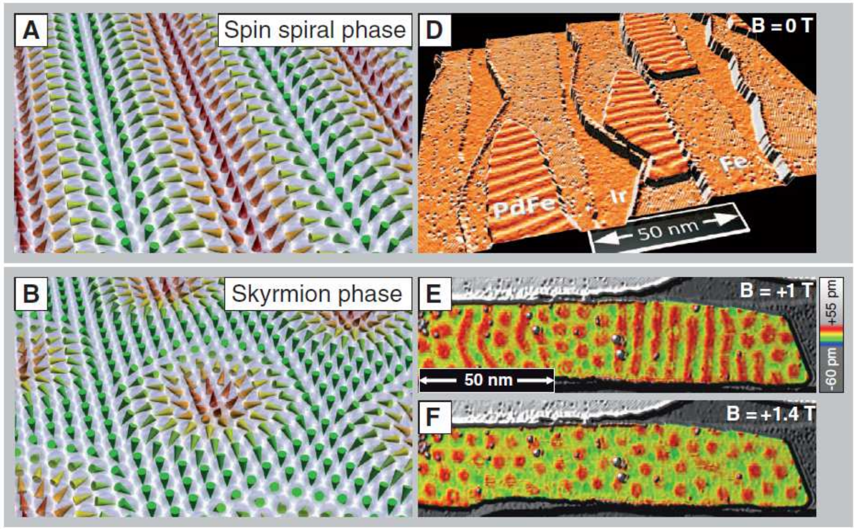
Interfaces break inversion symmetry!



Ingredients to induce a DMI (spin twisting):

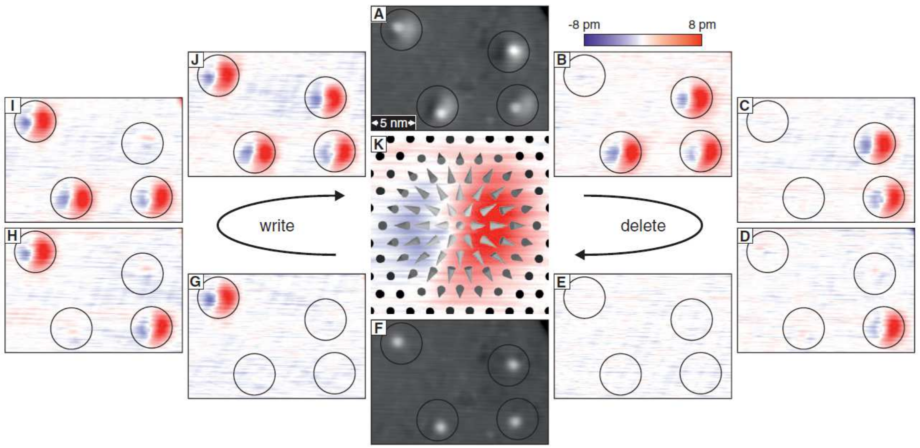
- **An interface!**
- **Ultrathin magnetic bi- or monolayer, e.g. PdFe or Fe**
- **Bottom layer of heavy metal with SOC, e.g. Ir**

PdFe bilayer on Ir(111) – 3 nm diameter Skyrmions



Writing and erasing of individual Skyrmions

SP-STM imaging



$$
\begin{aligned}
H &= -\sum_{ij} J_{ij}(\mathbf{M}_i\mathbf{M}_j) \\
&- \sum_{ij} \mathbf{D}_{ij}(\mathbf{M}_i \times \mathbf{M}_j) \\
&- \sum_{ijkl} K_{ijkl}[(\mathbf{M}_i\mathbf{M}_j)(\mathbf{M}_k\mathbf{M}_l) + (\mathbf{M}_i\mathbf{M}_l)(\mathbf{M}_j\mathbf{M}_k) \\
&- (\mathbf{M}_i\mathbf{M}_k)(\mathbf{M}_j\mathbf{M}_l)
\end{aligned}
$$

four-spin interaction

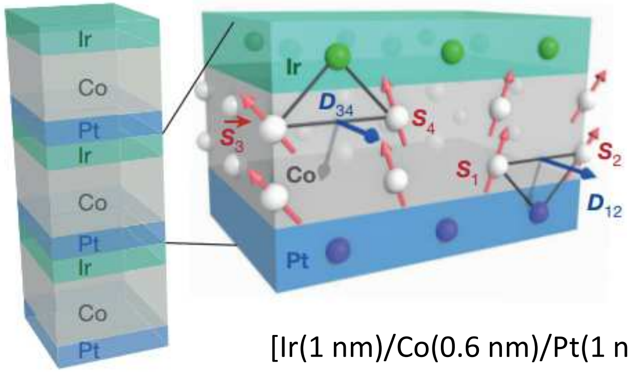
But at < 10 K ..

N. Romming *et al.*, Science **341**, 636 (2013)
S. Heinze *et al.*, Nat. Phys., **7**, 713 (2011)

Multilayers and room temperature Skyrmions

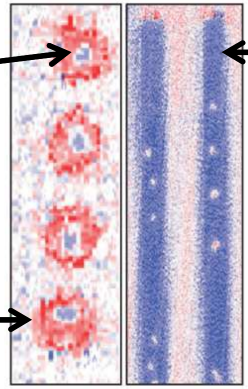
Ir/Co/Pt multilayer with additive interfacial chiral interactions → strong DMI at RT

C. Moreau-Luchaire *et al.*, Nat. Nanotech. **11**, 444 (2016)



[Ir(1 nm)/Co(0.6 nm)/Pt(1 nm)]$_{10}$

Scanning X-ray transmission microscopy



Small **< 100** nm diameter Néel-type Skyrmions

200 nm wide tracks

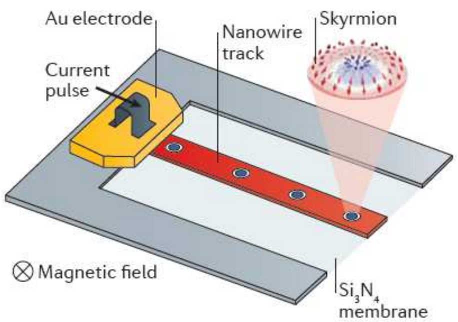
300 nm diameter disks

T = 300 K

$\mu_0 H_\perp$ = 8 - 50 mT

Room temperature, current pulse-driven motion of skyrmions at high speeds

S. Woo *et al.*, Nat. Mater. **15**, 501 (2016)



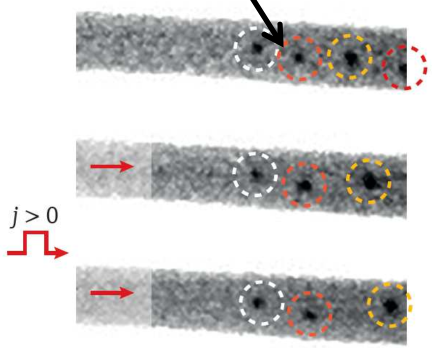
[Pt(3 nm)/Co(0.9 nm)/Ta(4 nm)]$_{15}$

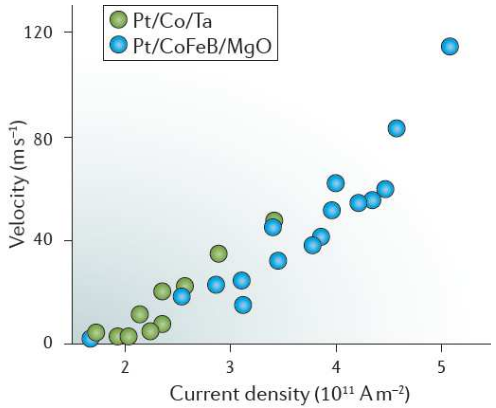
[Pt(4.5 nm)/CoFeB(0.7 nm)/MgO(1.4nm)]$_{15}$

400 nm diameter Néel-type Skyrmions

T = 300 K

$\mu_0 H_\perp$ < 2 mT





Multilayers seem very promising for skyrmionics: see

A. Soumyanarayanan *et al.*, Nature **539**, 509 (2016)

R. Wiesendanger, Nat. Rev. Mater. **1**, 16044 (2016)

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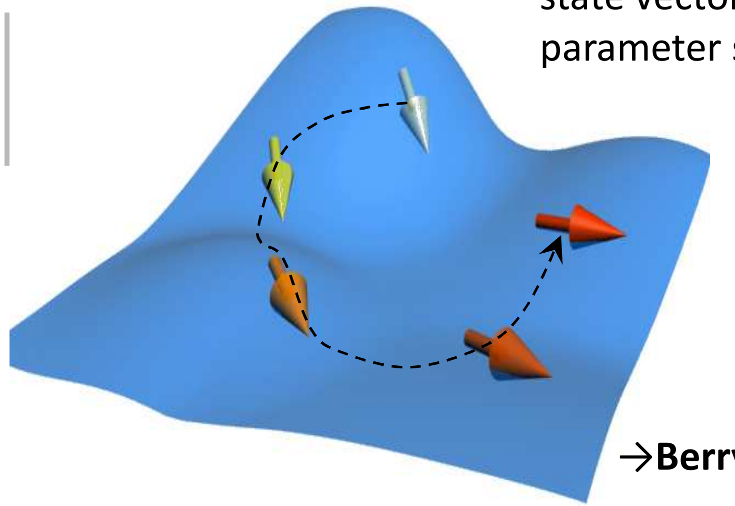
IV. Back to chiral magnets:
Consequences of the topology

Spin textures and emergent fields

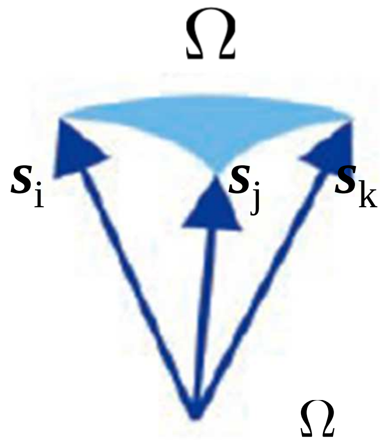
In general…

Development of an electron state vector in a **distorted** parameter space



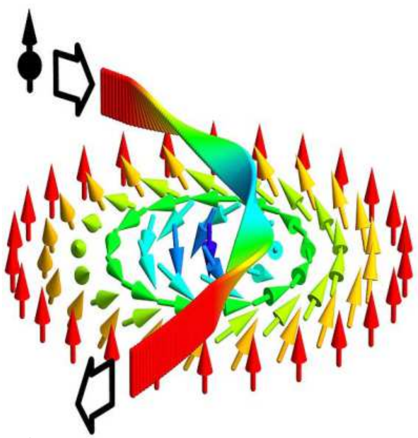
→**Berry phase, gauge fields**

Non-coplanar spin structure



Berry phase: $\frac{\Omega}{2}$

Topological spin texture



A. Rosch

-Electrons adiabatically traversing the Skyrmion spin texture adapt to the local **M** and acquire a quantum-mechanical Berry phase.

-The Berry phase physics is associated with **emergent EM fields**:

$$\mathbf{B}_i^e = \frac{\hbar}{2}\epsilon_{ijk}\hat{n}\cdot(\partial_j\hat{n}\times\partial_k\hat{n})$$

$$\hat{n}(\mathbf{r},t) = \mathbf{M}/|\mathbf{M}|$$

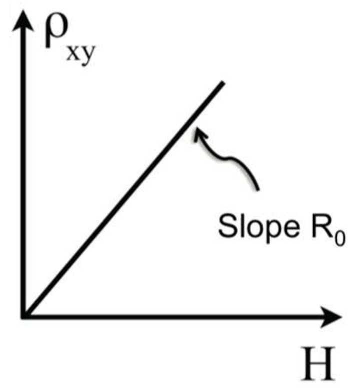
$$\mathbf{E}_i^e = \hbar\hat{n}\cdot(\partial_i\hat{n}\times\partial_t\hat{n})$$

T. Schulz *et al.*, Nat. Phys. **8**, 301 (2012)

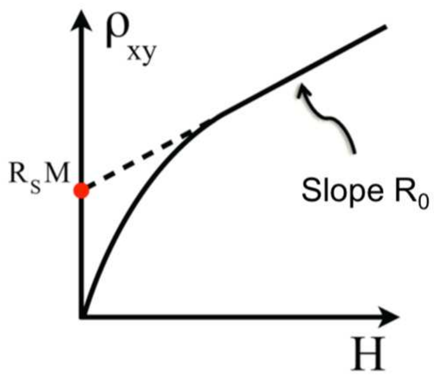
'Emergent flux' *B* is topologically quantised!

Experimental detection by Hall effect

Normal Hall effect

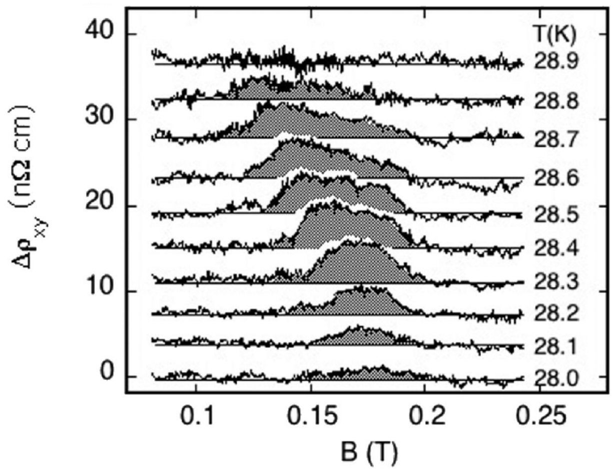


Anomalous Hall effect



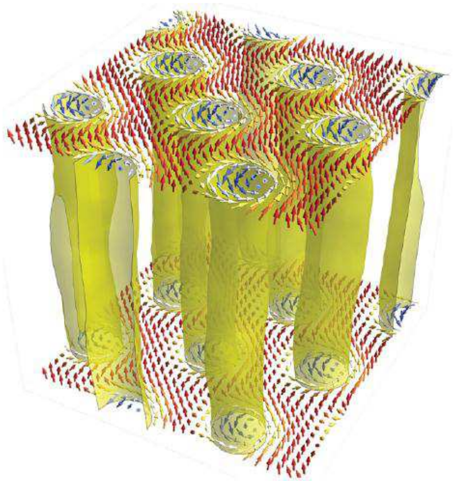
$$\rho_H = \rho_H^N + \rho_H^A + \rho_H^T = R_0 B + S_A \rho^2_{xx} M + \rho_H^T$$

Topological Hall effect **MnSi**



A. Neubauer *et al.*, PRL **102,** 186602 (2009)

$$\Delta\rho_{xy}^B \propto B_z^e$$



Size of the topological Hall response is proportional to B_i^e → gives a direct measure of the flux quantum!

Quantised emergent flux: $\int \mathbf{B}^e \mathrm{d}\sigma = -4\pi\hbar$

Average B_i^e in Skyrmion phase of MnSi ≈ 11 T!

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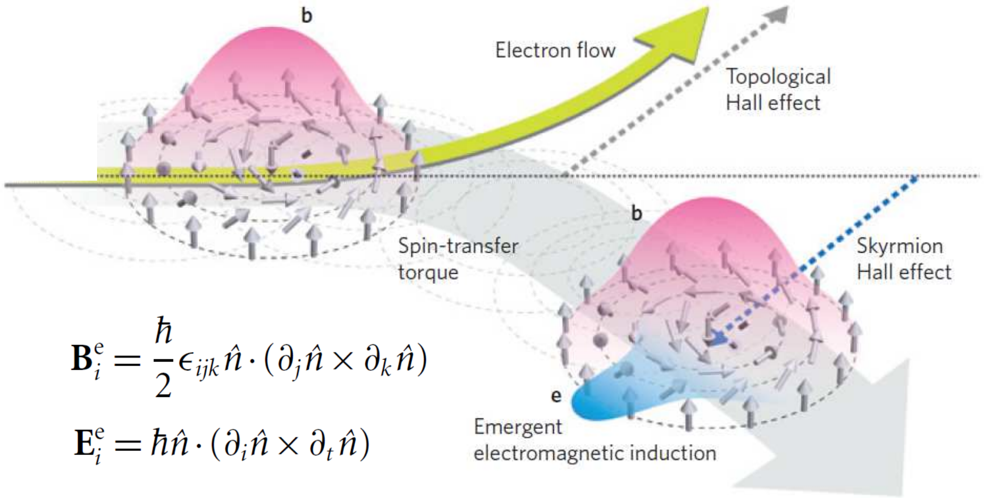
Detecting and driving skyrmion motion

Skyrmion motion is detectable by the THE

N. Nagaosa and Y. Tokura, Nat. Nanotech. **8**, 899 (2013)



$$\mathbf{B}_i^e = \frac{\hbar}{2}\epsilon_{ijk}\hat{n}\cdot(\partial_j\hat{n}\times\partial_k\hat{n})$$

$$\mathbf{E}_i^e = \hbar\hat{n}\cdot(\partial_i\hat{n}\times\partial_t\hat{n})$$

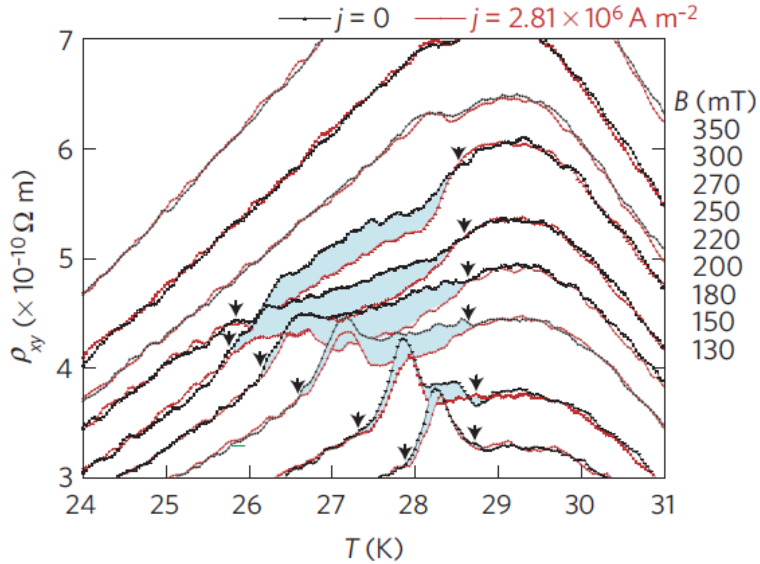
The topological Hall effect in MnSi is more pronounced above j_c due to E_i^e

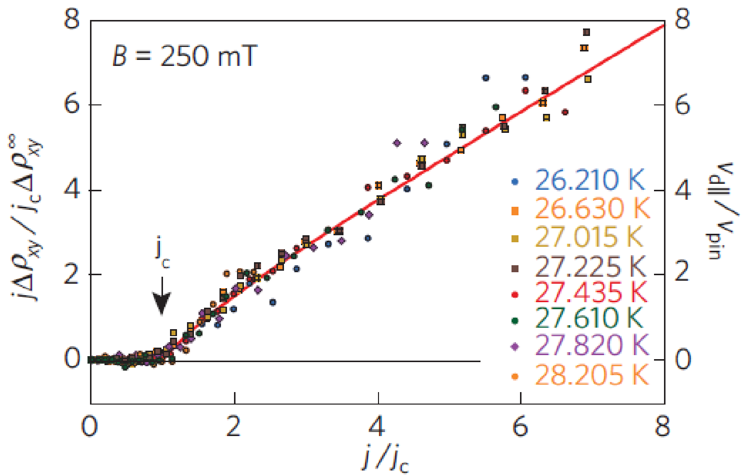
$$j \sim j_c \sim 10^6\ \mathrm{A\,m^{-2}}$$

Current-driven Skyrmion motion is an example of spin-transfer torques → Magnus force (Berry phase)

MnSi

T. Schulz *et al.*, Nat. Phys. **8**, 301 (2012)

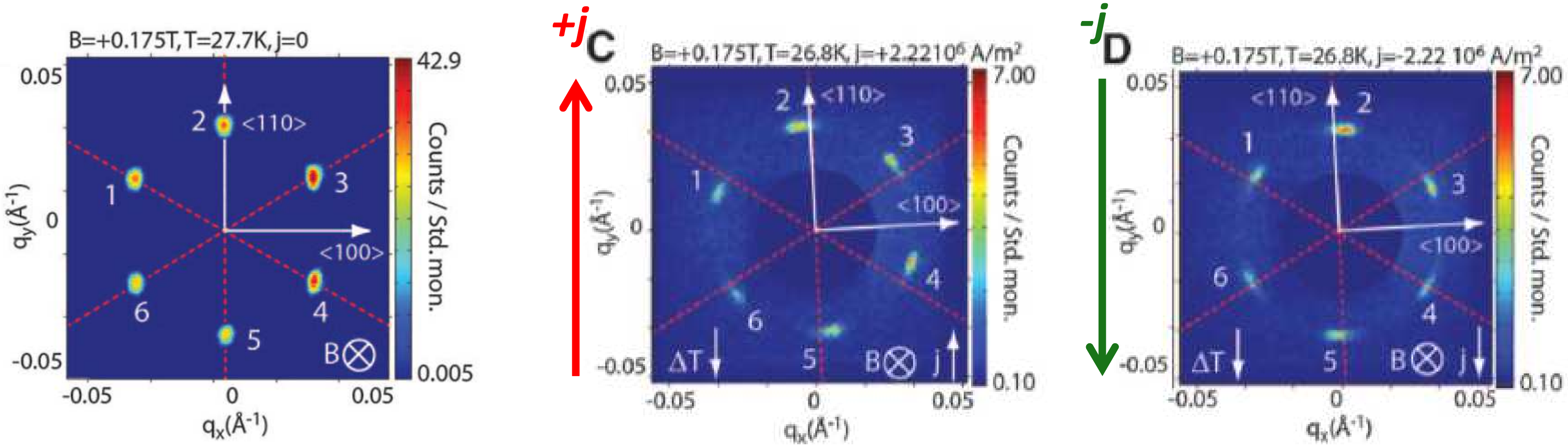




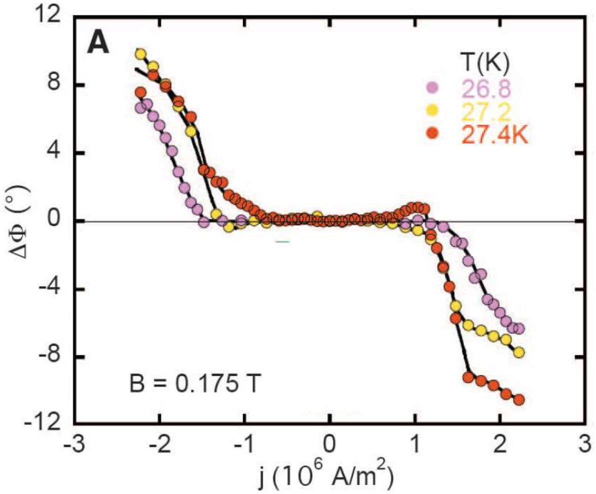
Spin transfer torques and SANS

Further indications of Skyrmion motion in MnSi

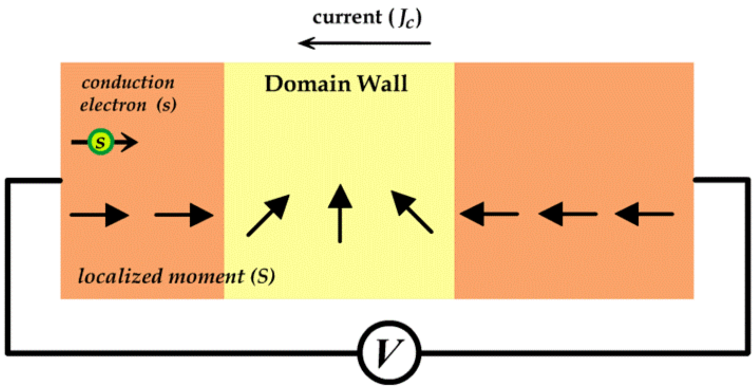
F. Jonietz *et al.*, Science **330**, 1648 (2010)



$$j \sim j_c \sim 10^6 \text{ A m}^{-2}$$



Compare: Current pulses drive the movement of FM domain walls by STTs: $j \sim j_c \sim 10^{11} \text{A m}^{-2}$



Why are very small current densities needed to drive skyrmions compared with FM domains?

Results from theory

- **Efficient coupling between the conduction electrons and emergent *B*-field (Berry phase) that generates Magnus forces**

  F. Jonietz *et al.*, Science 330, 1648 (2010)

  K. Everschor *et al.*, PRB **84**, 064401 (2011), PRB **86**, 054432 (2012)

- **No Magnus forces in helical (trivial) phase** → current–velocity relations similar to those of a FM domain wall

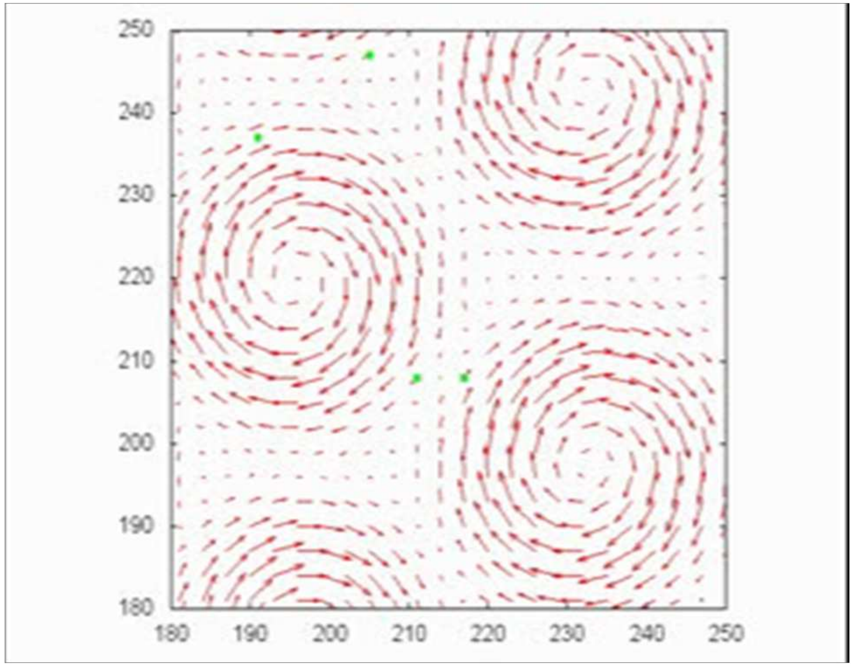
- **Weak pinning/alignment effects** due to the large length-scale of the Skyrmion lattice: $\lambda_{SkL} \gg a$

- **Skyrmions in motion are flexible:** can deform their shape and twist their trajectory to avoid pinning to defects/disorder.

↳ STTs also generated by **magnon currents** deflected by emergent *B*-field of Skyrmions

M. Mochizuki *et al.*, Nat. Mater. **13**, 241 (2014)

Numerical study using the LLG equation



←

Current density

t=0 → t = 65 ns

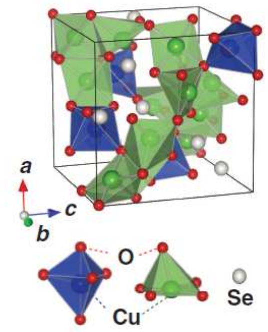
See: J. Iwasaki *et al.*, Nat. Commun. **4**, 1463 (2013)

Motion driven by currents of electrons or magnons relies on the emergent fields of the topological skyrmion spin structure

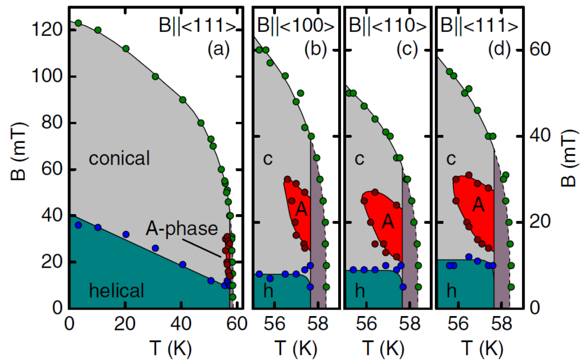
Electric field manipulation

Magnetoelectric <u>insulator</u> Cu_2OSeO_3

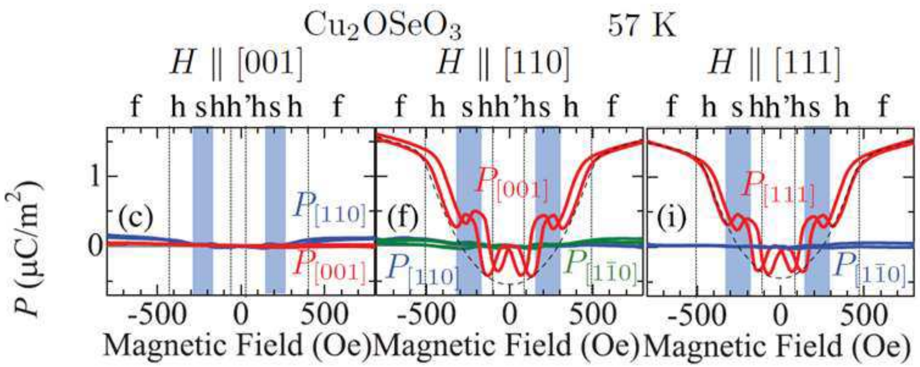
S. Seki, *et al.*, Science **336**, 198, (2012)
T. Adams *et al.*, Phys. Rev. Lett. **108**, 237204 (2012)



Class *T* ($P2_13$)



Magnetoelectric coupling in Skyrmion phase

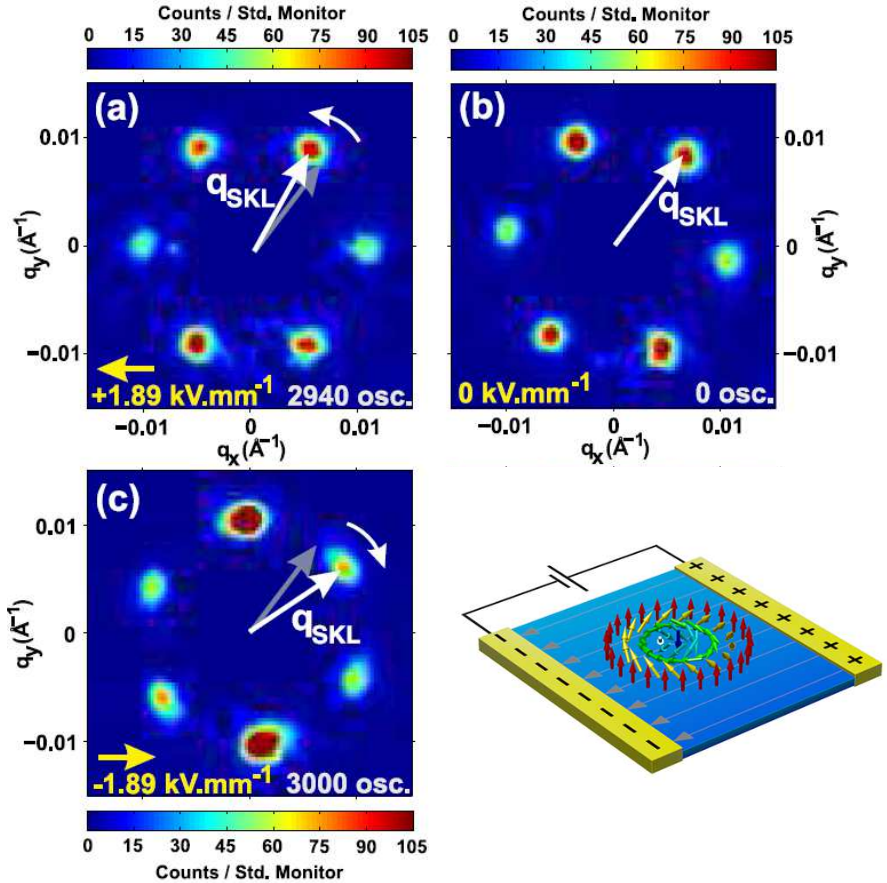


Symmetry of ME coupling: *d-p* hybridization model

For more on the ME coupling, see also:
E. Ruff *et al.,* Sci. Rep. **5**, 15025 (2015)
P. Milde *et al.*, Nano Lett. **16**, 5612 (2016)

Electric field control of the Skyrmion lattice

JSW *et al.*, Phys. Rev. Lett. **113**, 107203 (2014)



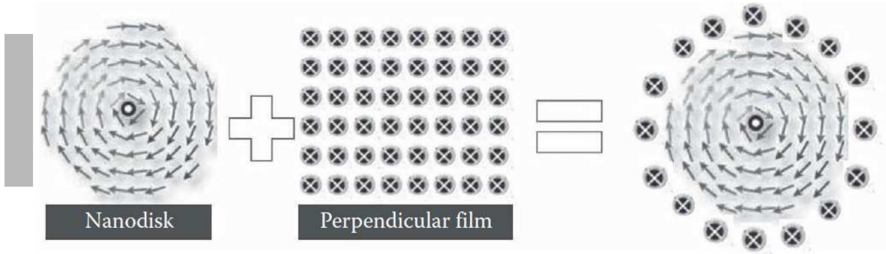
Skyrmion lattice rotations achieved with no STTs – i.e. no current or magnon flows

Microscopic explanation for rotation still missing!

V. Some interesting topics

But certainly not limited to ..

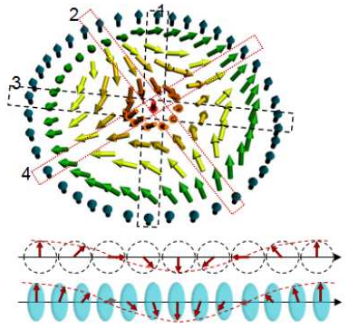
Artificial Skyrmions



Implant a magnetic vortex into a film with PMA

Skyrmions by design

Diverse topological spin textures



$Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ - LTEM

A. K. Nayak *et al.*, arXiv: 1703.01017

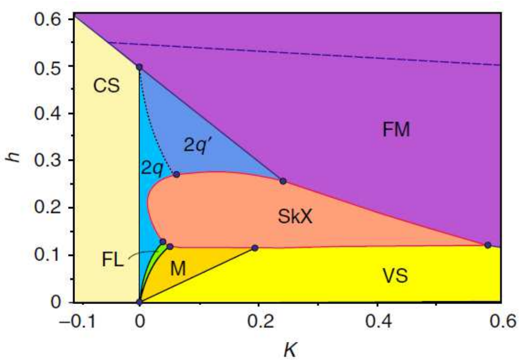
D_{2d} symmetry

$$\left(m_z \frac{\partial m_x}{\partial y} - m_x \frac{\partial m_z}{\partial y} - m_z \frac{\partial m_y}{\partial x} + m_y \frac{\partial m_z}{\partial x}\right)$$

'Antiskyrmions' spotted?

Skyrmions by magnetic frustration?

A.O. Leonov and M. Mostovoy, Nat. Commun. **6**, 8275 (2015)

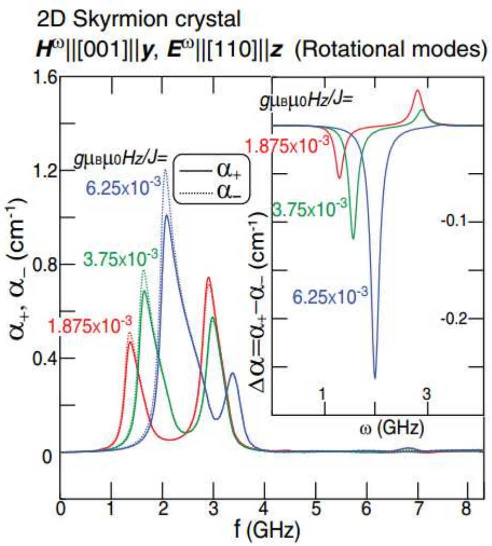


$$E = -J_1 \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + J_2 \sum_{\langle\langle i,j \rangle\rangle} \mathbf{S}_i \cdot \mathbf{S}_j - h \sum_i S_i^z - \frac{K}{2} \sum_i (S_i^z)^2.$$

Stability mechanism without DMIs

Gigahertz oscillators + optical dichroism

Cu_2OSeO_3

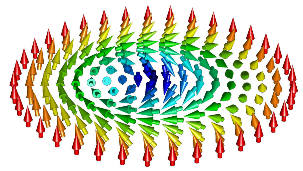


Novel microwave functionalities

Summary

Slides: **https://www.psi.ch/lns/jonathan-white**

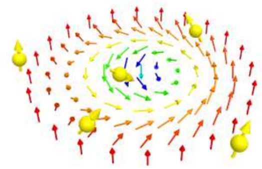
- **Skyrmions are topologically non-trivial particle-like objects composed of magnetic spins.**



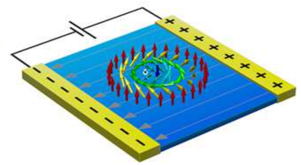
- **Identifiable using a variety of experimental techniques.**
  - **SANS, LTEM, Hall effect, MFM, STM ..**

- **Skyrmions are well-established to be stabilised by Dzyaloshinskii-Moriya interactions in a few bulk non-centrosymmetric materials like MnSi, GaV_4S_8.**
  - **Other stability mechanisms I did not discuss in detail: dipolar fields, frustration, four-spin interactions**

- **Skyrmions host quantised emergent electromagnetic fields in the presence of a flow of conduction electrons.**
  - **The conduction electrons exert forces via STTs on skyrmions driving their motion.**



- **Electric fields can drive skyrmion motion in insulators.**
  - **Open questions still to be addressed**



- **Ultrathin metallic films and multilayers host Néel-type skyrmions at room temperature that can be controlled by electric currents.**
  - **Most promising for Skyrmionics!**

There are many talks on Skyrmions at this meeting!

Advertisement

SWISS NATIONAL SCIENCE FOUNDATION

SNF Sinergia project:

"Discovery and Nanoengineering of Novel Skyrmion-hosting Materials"

Start: Oct. 2017 for 4 years **2 post-docs and 6 PhDs**

Dr. J.S. White
jonathan.white@psi.ch

1 PhD

1 post-doc (2yr +)

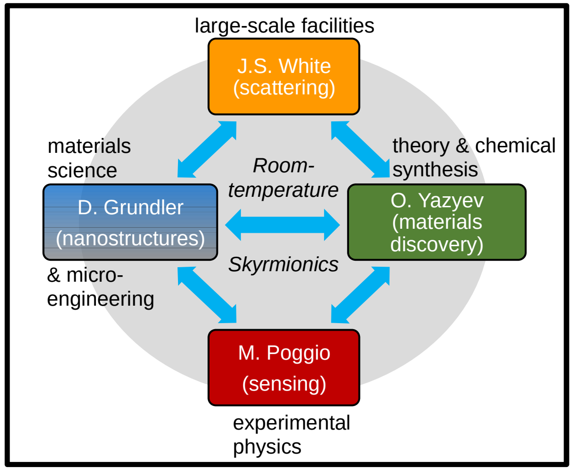
- **Application of large-scale facility techniques at PSI (SINQ + SLS)**
- **Real-space imaging at EPFL/PSI - LTEM, PEEM**

Prof. D. Grundler
dirk.grundler@epfl.ch

- **New approaches to nanofabrication of Skyrmion materials**
- **Device fabrication**

School of Engineering (STI)

2 PhDs



Prof. O. Yazyev
oleg.yazyev@epfl.ch

- **First-principles-driven materials discovery**
- **Synthesis**

School of Basic Sciences (SB)

1 PhD

1 post-doc (theory)

Prof. M. Poggio
martino.poggio@unibas.ch
University of Basel

2 PhDs

- **New techniques in nanosensing applied to Skyrmion-hosting nanostructures**

Start date: Summer/Fall 2017

Contact us if interested!