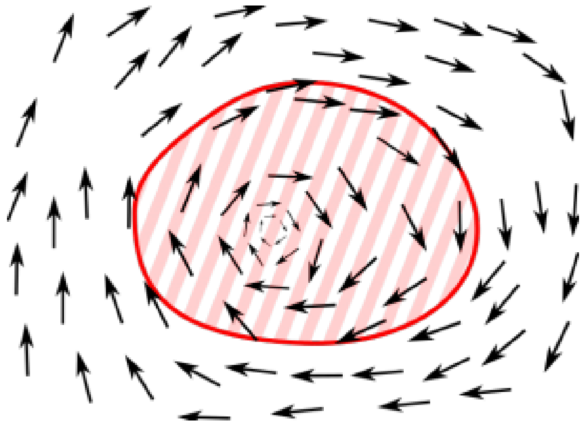
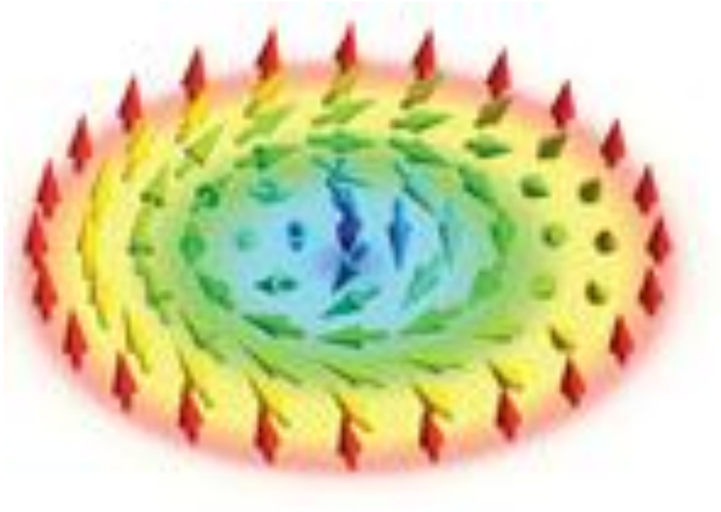
Topology in Magnetism
– a phenomenological account



Wednesday: vortices
Friday: skyrmions



Henrik Moodysson Rønnow

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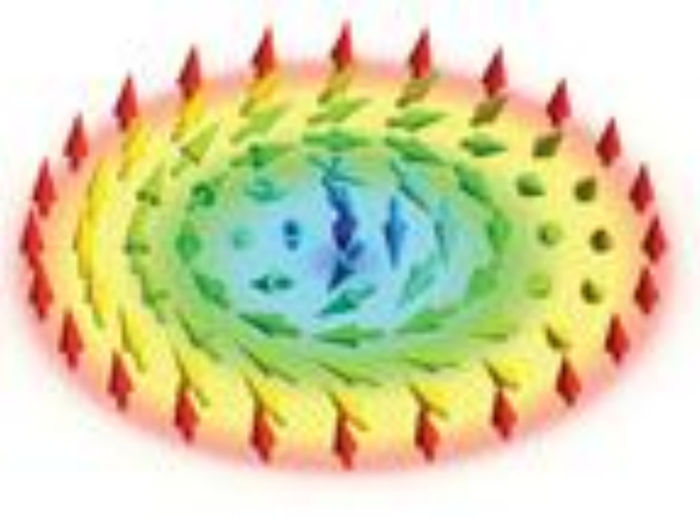
Thanks to Jiadong Zang and Shinichiro Seki for slides, many figures copied from internet

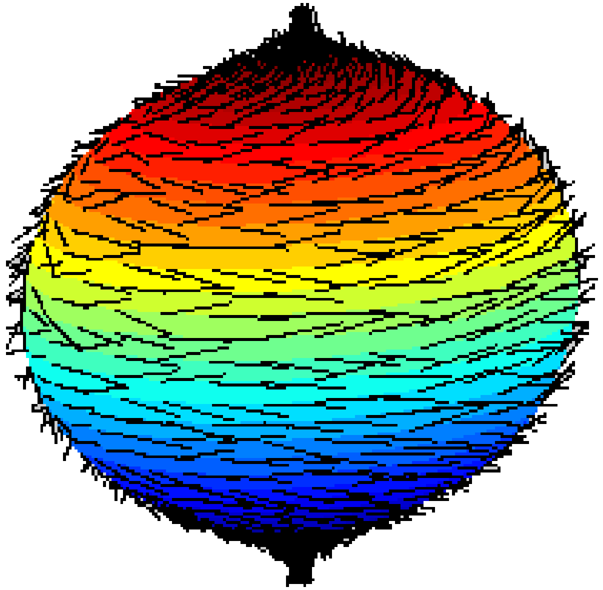
Skyrmions in Magnetism

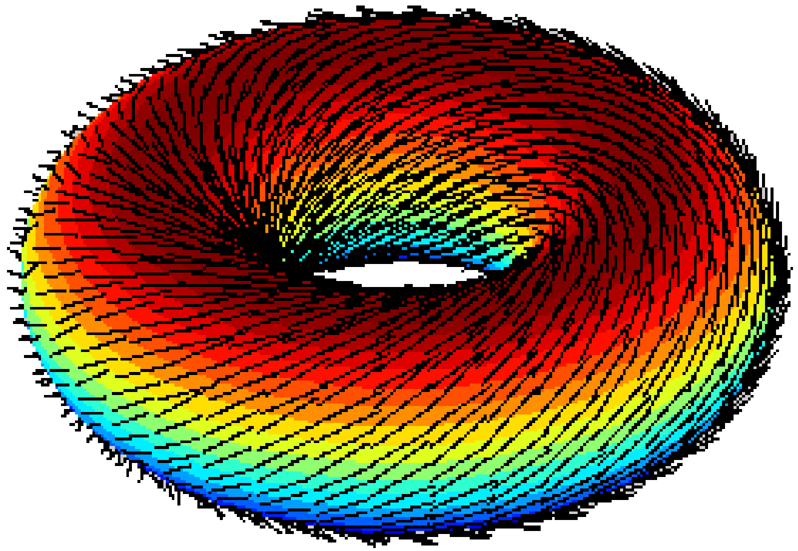


- Skyrmions
  - Topological solitons
  - 3-Q magnetic structure
  - Models
- Skyrmion measurements
  - SANS, LTEM, STXM, MFM, SPSTM
- Skyrmion materials
  - Bulk materials: Chiral, Polar, Frustrated
  - Interface systems
- Skyrmion fundamentals
  - Skyrmion types, Lattice effects, dynamics, …
- Skyrmion control

The hairy ball theorem

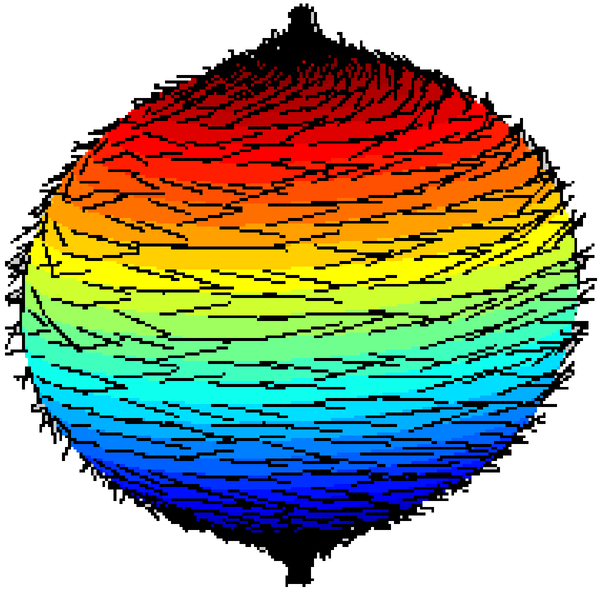
- "you can't comb a hairy ball flat without creating a cowlick“

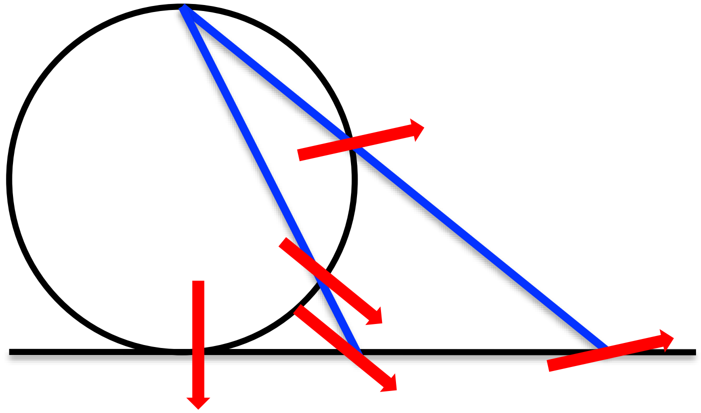


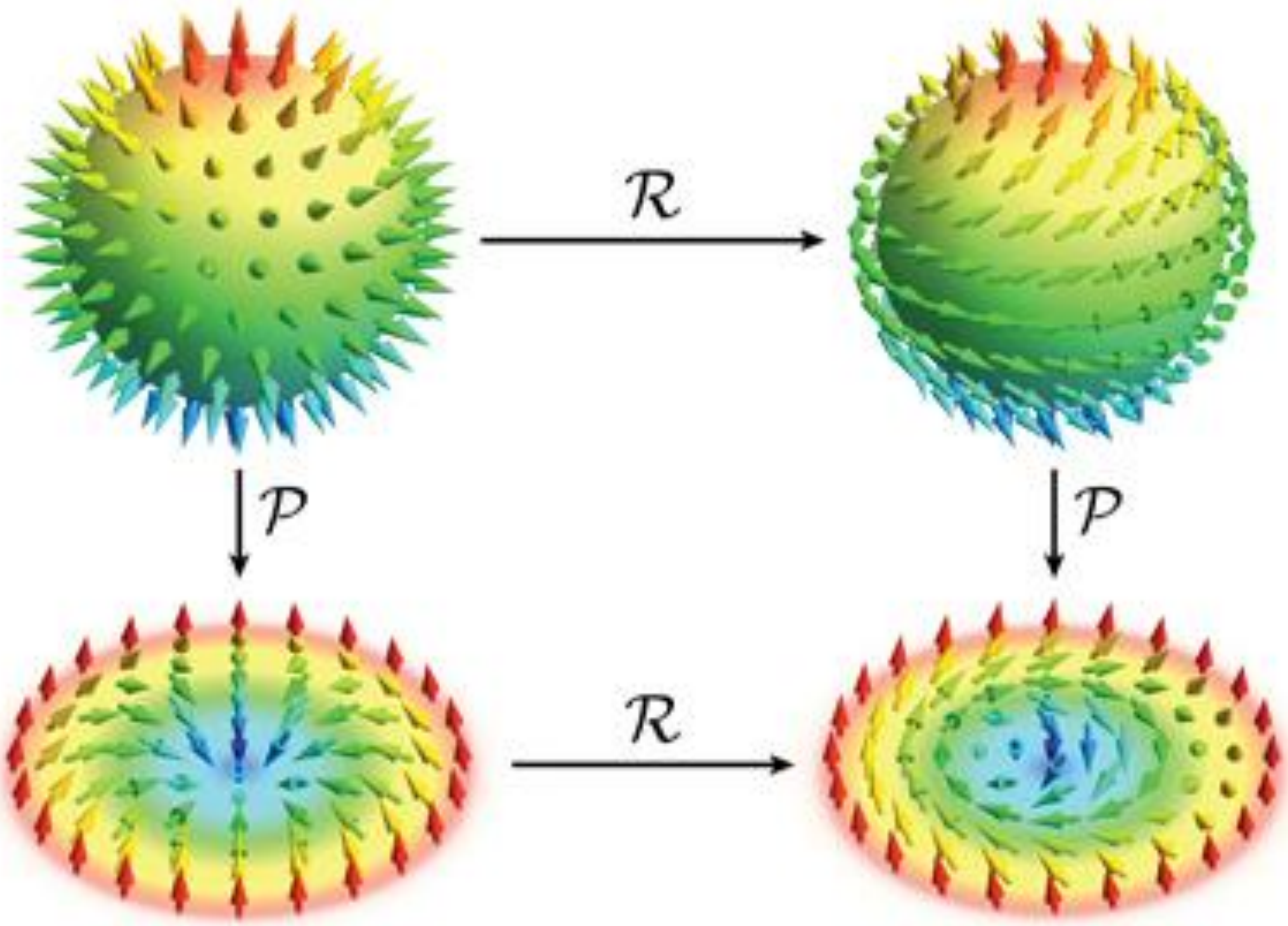


- Topology concern non-local properties !

Stereographic projection

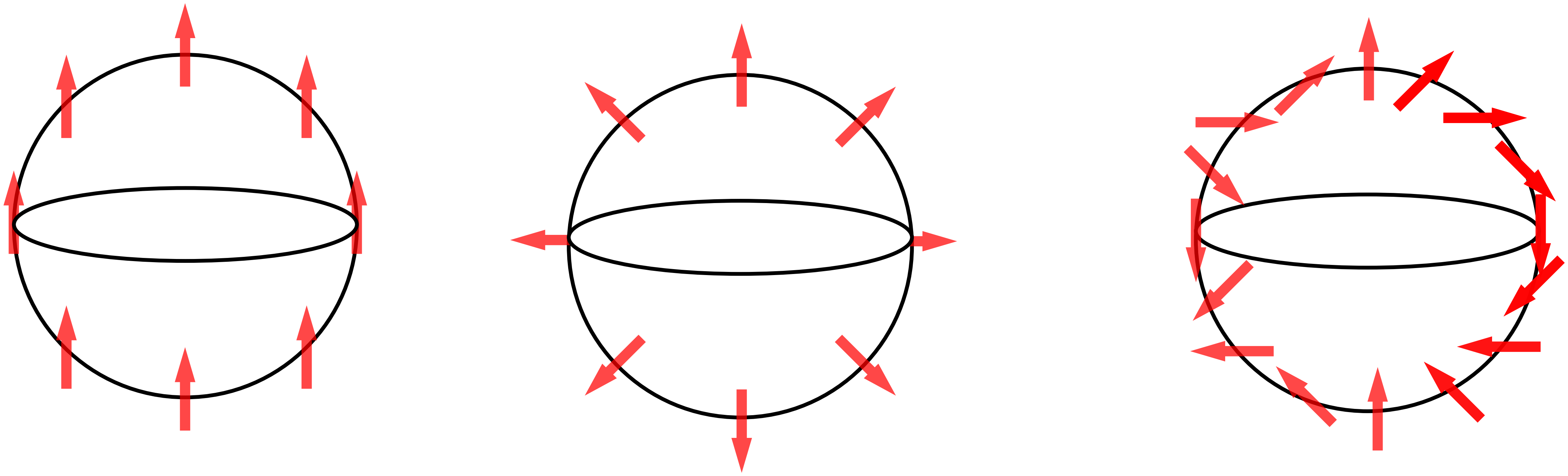






Topological charge

$$Q = \frac{1}{4\pi}\int dxdy\ \mathbf{m}\cdot\left(\frac{\partial \mathbf{m}}{\partial x}\times\frac{\partial \mathbf{m}}{\partial y}\right)$$



Q=0 Q=1 Q=2

Magnetic order - Against all odds

- Bohr – van Leeuwen theorem: (cf Kenzelmann yesterday)
  - No FM from classical electrons

- <M>=0 in equilibrium (cf Canals yesterday)

- Mermin – Wagner theorem:
  - No order at T>0 from continuous symmetry in D≤2

- No order even at T=0 in 1D

Derrick's Scaling Argument: No stable local texture

$$E[\mathbf{m}] = \int [(\nabla \mathbf{m})^2 + f(\mathbf{m})]\, d^3r \equiv I_1 + I_2$$

Assume existence of stable Local Texture $\mathbf{m_0}(\mathbf{r})$ Scale size of texture $\mathbf{m_0}(\lambda \mathbf{r})$

$E[\mathbf{m}_0(\lambda \mathbf{r})]$ is minimized at $\lambda = 1$ $\tilde{r} = \lambda r$

$$E[\mathbf{m}_0(\lambda \mathbf{r})] = \int \left[\frac{1}{\lambda} \left(\tilde{\nabla}\, \mathbf{m} \right)^2 + \frac{1}{\lambda^3} f(\mathbf{m}) \right] d^3\tilde{r} \quad = I_1/\lambda + I_2/\lambda^3$$

$$\left. \frac{dE}{d\lambda} \right|_{\lambda=1} = 0$$

$$\left. \frac{d^2E}{d\lambda^2} \right|_{\lambda=1} > 0$$

$\longrightarrow$ $I_1 = \int (\nabla \mathbf{m})^2 < 0$

Ways out:

Dzyaloshinskii-Moriya Interaction

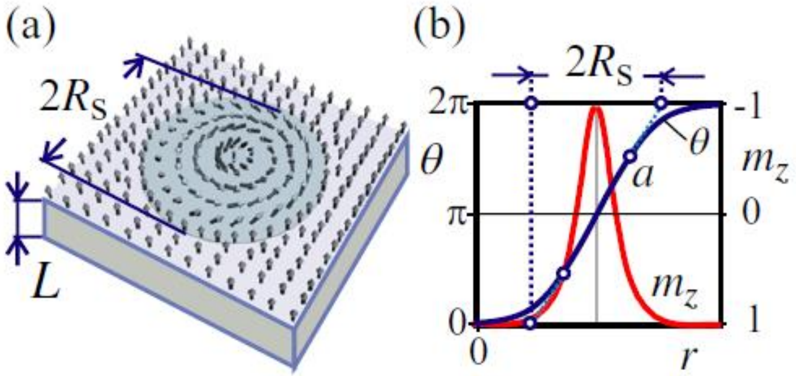
Finite Size

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



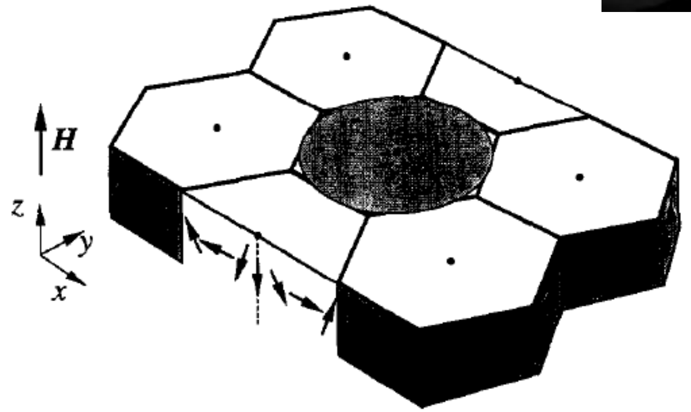


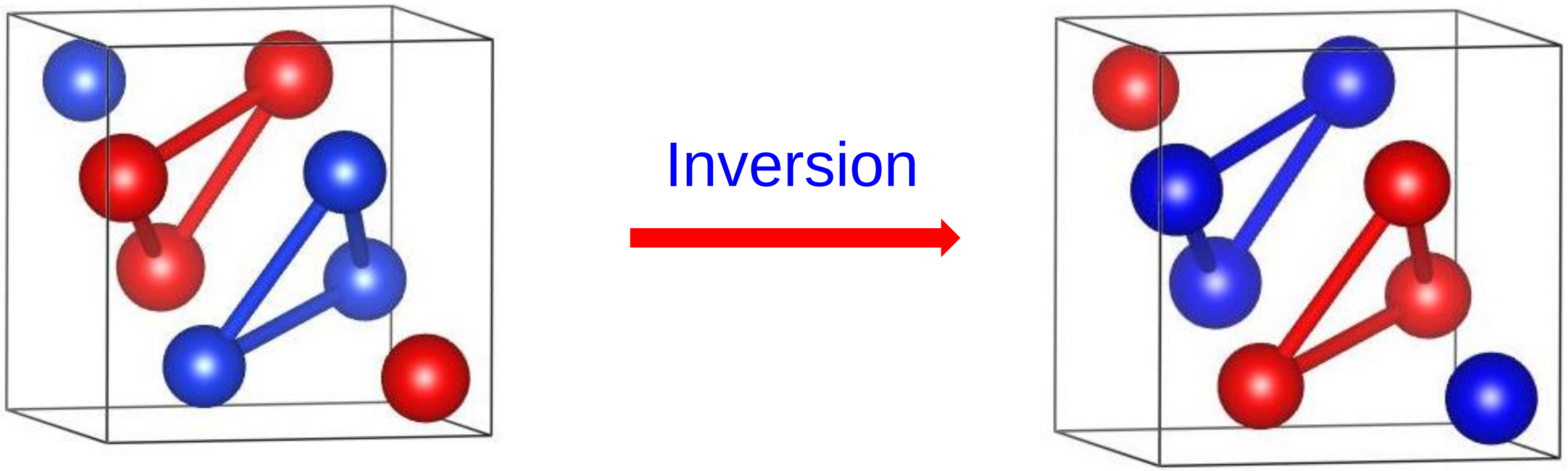
Fig. 1. Schematic view of a sample with a vortex lattice. In the cross-section a Néel-like rotation is indicated (see Section 2.5).

"spin vortices" as local solitonic solution to continuum model

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

Skyrmion lattice of individual skyrmions $\Longleftrightarrow$ 3-Q magnetic structure

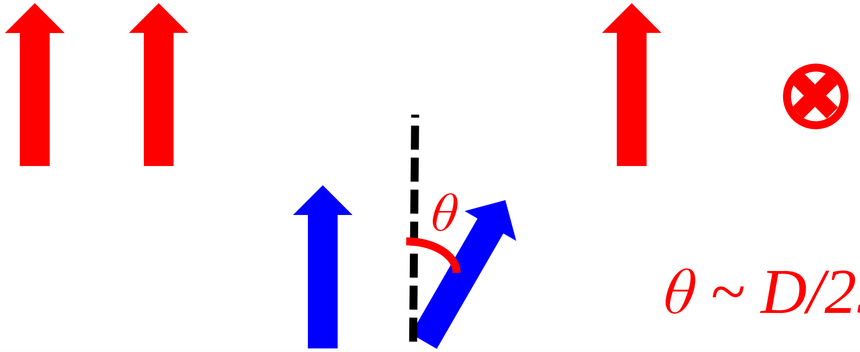
Broken Inversion Symmetry



Physical Consequence:

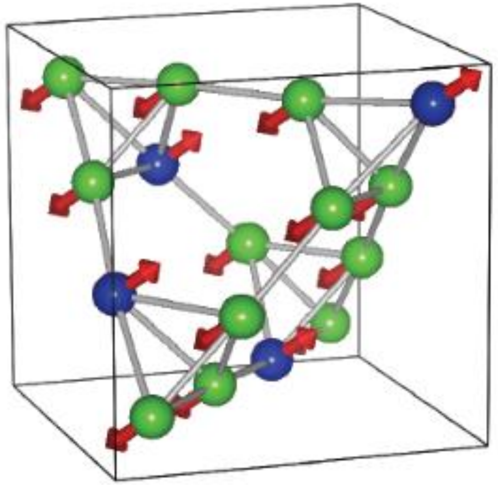
$$H = \sum_{<ij>} -J\mathbf{S}_i \cdot \mathbf{S}_j + \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

Dzyaloshinskii-Moriya Interaction (DMI)



$\theta \sim D/2J$

Model



- Microscopic $$H=\sum_{<ij>} -J\mathbf{S}_i\cdot\mathbf{S}_j+\mathbf{D}_{ij}\cdot(\mathbf{S}_i\times\mathbf{S}_j)$$
  Sum over all bonds
- Coarse grained simple cube $$H=\sum_{<ij>} -J\mathbf{S}_i\cdot\mathbf{S}_j+\mathbf{D}_{ij}\cdot(\mathbf{S}_i\times\mathbf{S}_j)$$
  Sum over neighboring unit cells
- Continuum version

$$\mathcal{H}=\mathcal{H}_{JDh}+\mathcal{H}_A$$

$$\mathcal{H}_{JDh}=J(\nabla\mathbf{S})^2+D\mathbf{S}\cdot(\nabla\times\mathbf{S})-\mathbf{h}\cdot\mathbf{S} \qquad \mathcal{H}_A=A(S_x^4+S_y^4+S_z^4)+U\mathbf{S}^4.$$

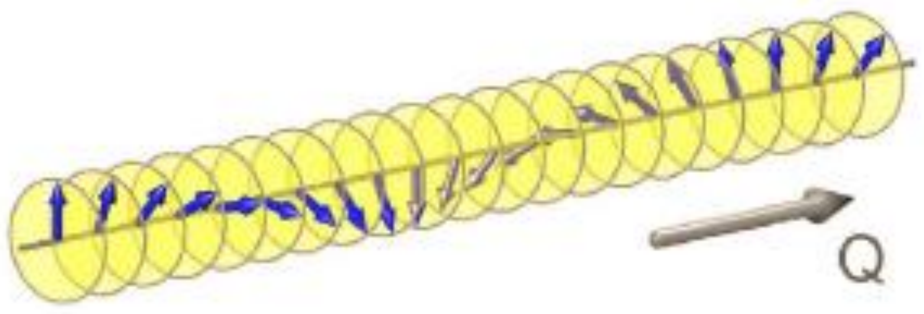
Dzyaloshinskii-Moriya helices

$$H = -\Sigma\, J_{ij} S_i \cdot S_j + D_{ij} \cdot (S_i \times S_j)$$

J favors parallel spins

J>0 Ferromagnet

J<0 Antiferromagnet



D favor perpendicular spins

J & D: twist spins by angle $\tan\Theta = D/J$

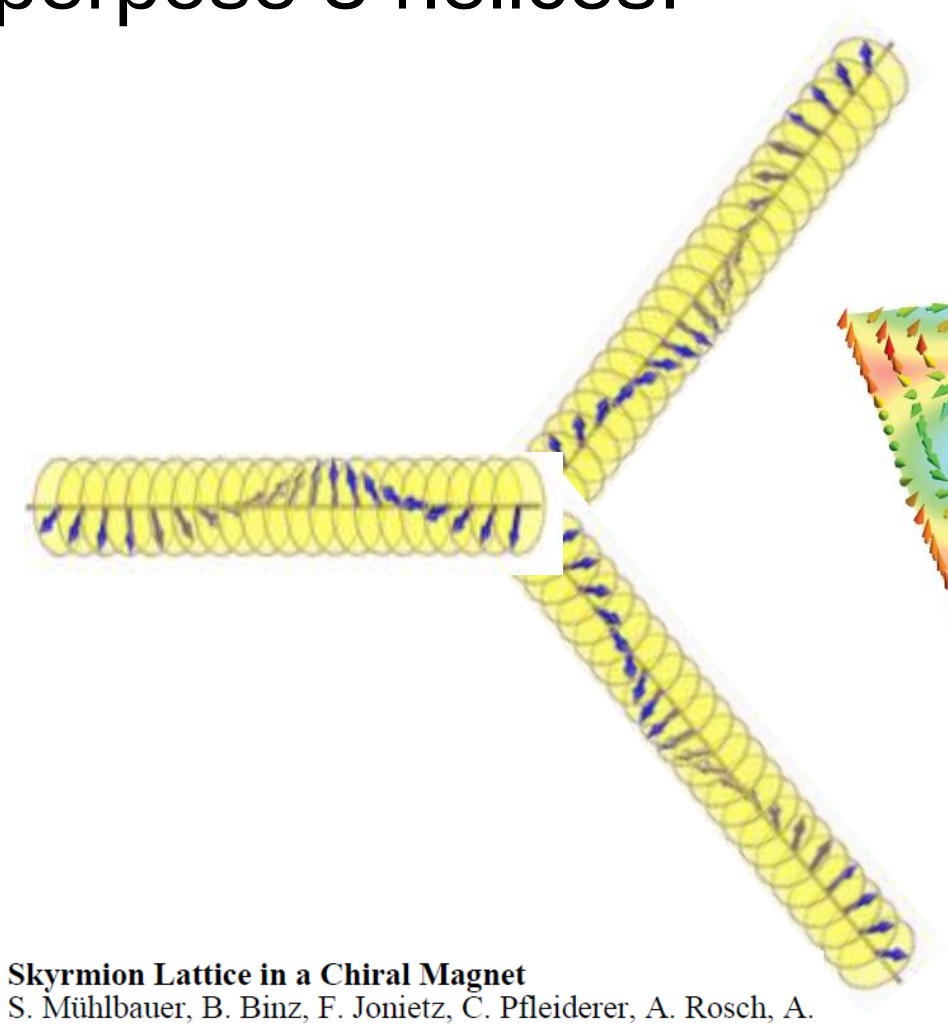
Helix with period $Q = 2\pi a\, J/D$

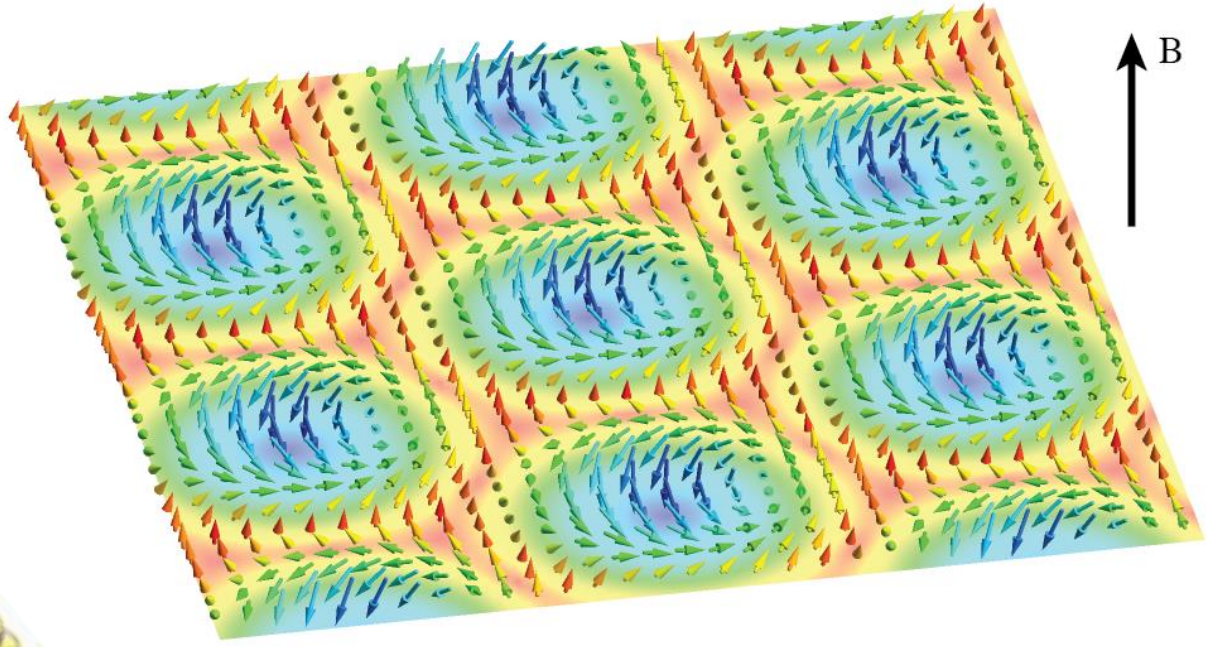
3Q structure

- Superpose 3 helices:

$$\mathbf{M}(r) \approx \mathbf{M}_f + \sum_{i=1}^{3} \mathbf{M}^h_{\mathbf{Q}_i}(\mathbf{r} + \Delta\mathbf{r}_i) \qquad (3)$$

where $\mathbf{M}^h_{\mathbf{Q}_i}(\mathbf{r}) = A[\mathbf{n}_{i1}\cos(\mathbf{Q}_i\mathbf{r}) + \mathbf{n}_{i2}\sin(\mathbf{Q}_i)\mathbf{r}]$





Skyrmion Lattice in a Chiral Magnet
S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii and P. Böni (February 13, 2009)
Science **323** (5916), 915-919. [doi: 10.1126/science.1166767]

Looks like “spin vortices”

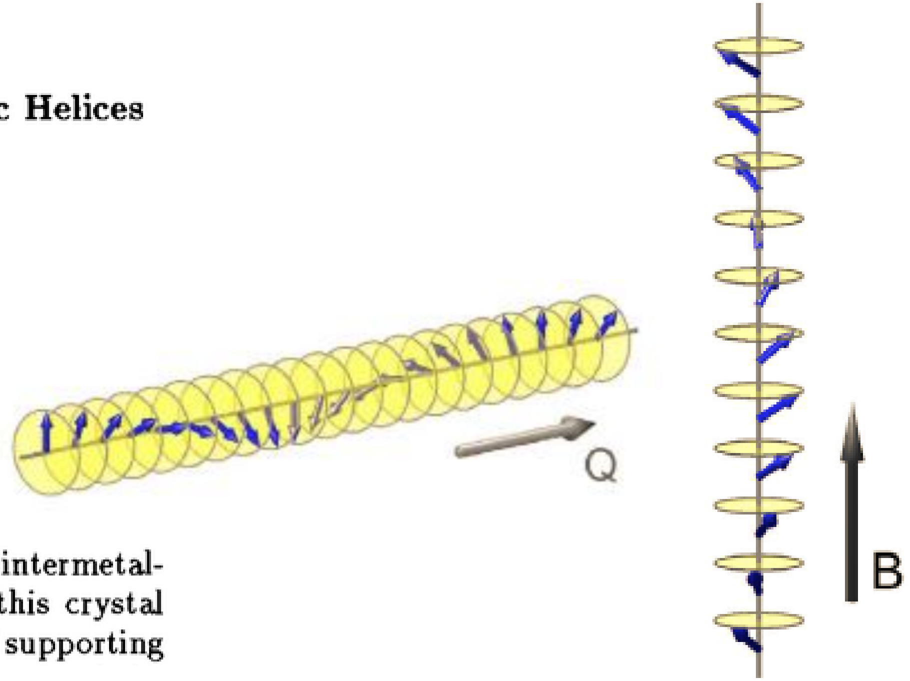
Helical, conical and "A-phase"

Magnetic Ordering in Nearly Ferromagnetic Antiferromagnetic Helices

1993

Bente LEBECH

Department of Solid State Physics, Risø National Laboratory, DK-4000 Roskilde, Denmark

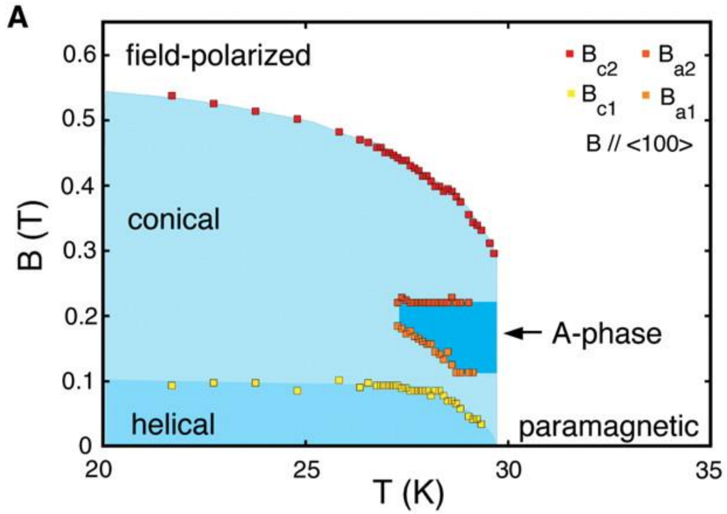


Abstract

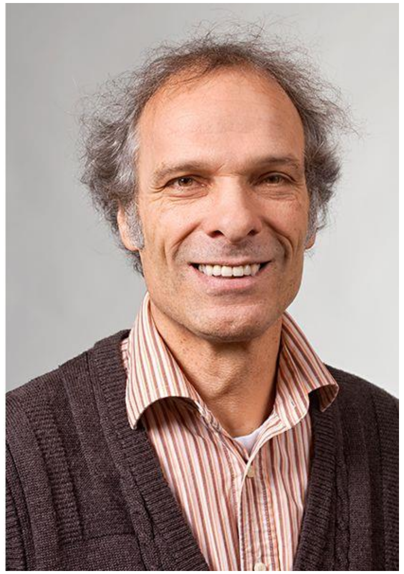
The cubic polymorph of FeGe and MnSi belong to a class of magnetic intermetallic compounds with the B20 crystal structure ($P2_13$). Materials with this crystal structure lack inversion symmetry; they have chirality and are capable of supporting

5. Conclusion

The present paper has considered various aspects of the magnetic phase diagram of cubic FeGe and MnSi and correlated the results of neutron small-angle scattering data to the existing theoretical treatments of Dzyaloshinskii-Moriya helices. The neutron scattering data agree reasonably well with the predictions of the present day theories. However, in the neutron diffraction data for both FeGe and MnSi there are indications that the magnetically ordered structure could be a single domain multi-q structure rather than a multi-q single domain structure. If the ordered structure is a multi-q structure, it may be necessary to revise the theoretical description outlined above.



"for the theoretical prediction, the experimental discovery and the theoretical analysis of a magnetic skyrmion phase in MnSi, a new state of matter."

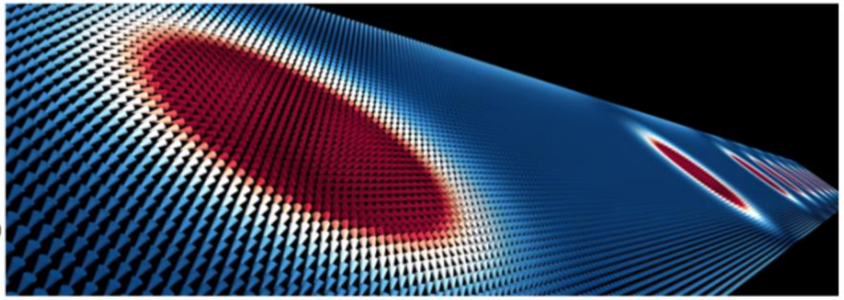



Many networks developing:

RIKEN
CEMS
Center for Emergent Matter Science

MAGic Sky

Funded by the Horizon2020 Framework Programme of the European Union



New UK consortium to explore use of magnetic skyrmions in data storage

2 Aug 2016
Durham - *The use of nanoscale magnetic whirlpools, known as magnetic skyrmions, to create novel and efficient ways to store data will be explored in a new GBP 7 million research programme led by Durham University.*

Interdisciplinary network with 12 project partners from EPFL, University of Basel and Paul Scherrer Institut (PSI)
Funded by SNSF via grant CRSII5_171003

SPP2137 Skyrmionics
Topological Spin Phenomena in Real-Space for Applications

Home Projects Members Publications About

DFG Establishes Skyrmionics Priority Programme

The Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) is establishing 17 new Priority Programmes for 2018. One of them is the SPP2137 - Skyrmionics: Topological Spin Phenomena in Real-Space for Applications

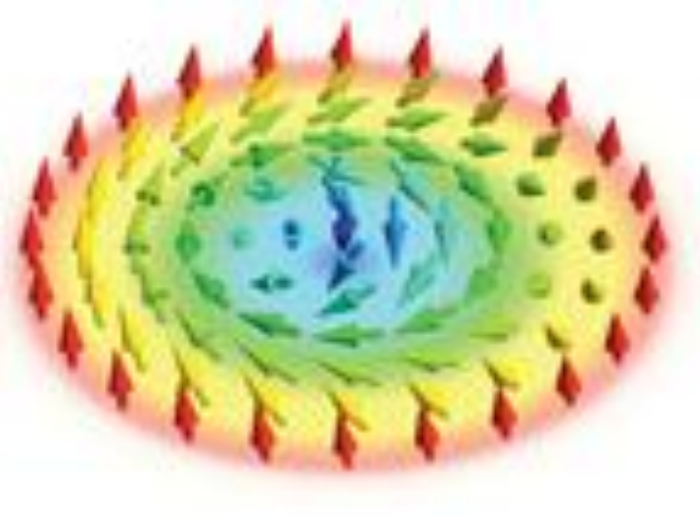
DARPA DEFENSE ADVANCED RESEARCH PROJECTS AGENCY ABOUT US / OUR RESEARCH

Defense Advanced Research Projects Agency › Program Information

Topological Excitations in Electronics (TEE)

Dr. Rosa Alejandra Lukaszew

Skyrmions in Magnetism



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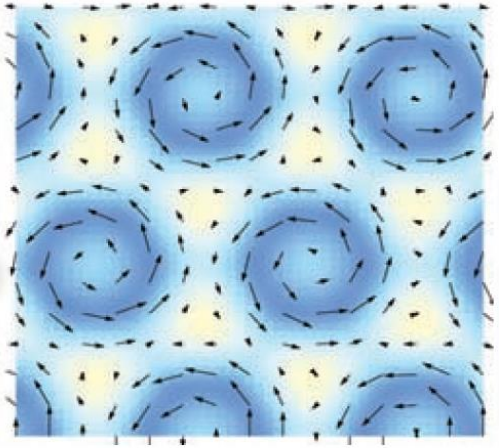
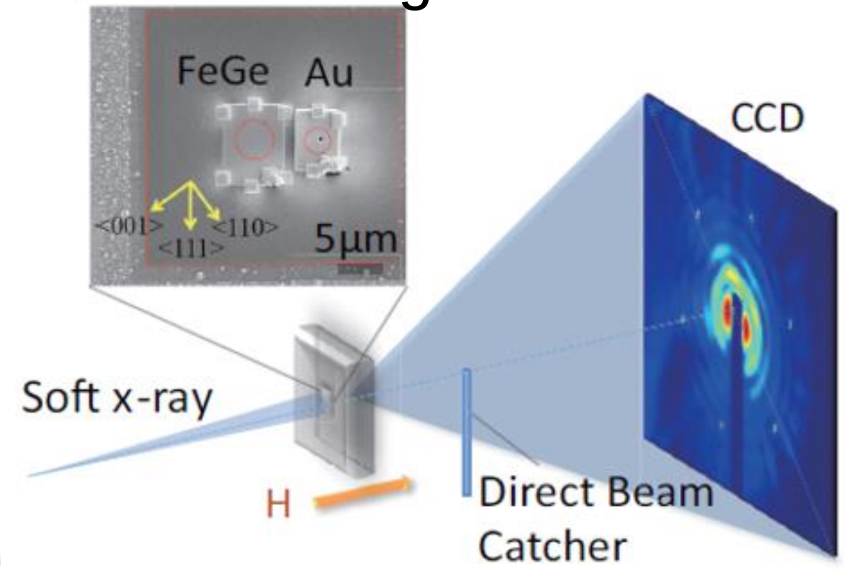
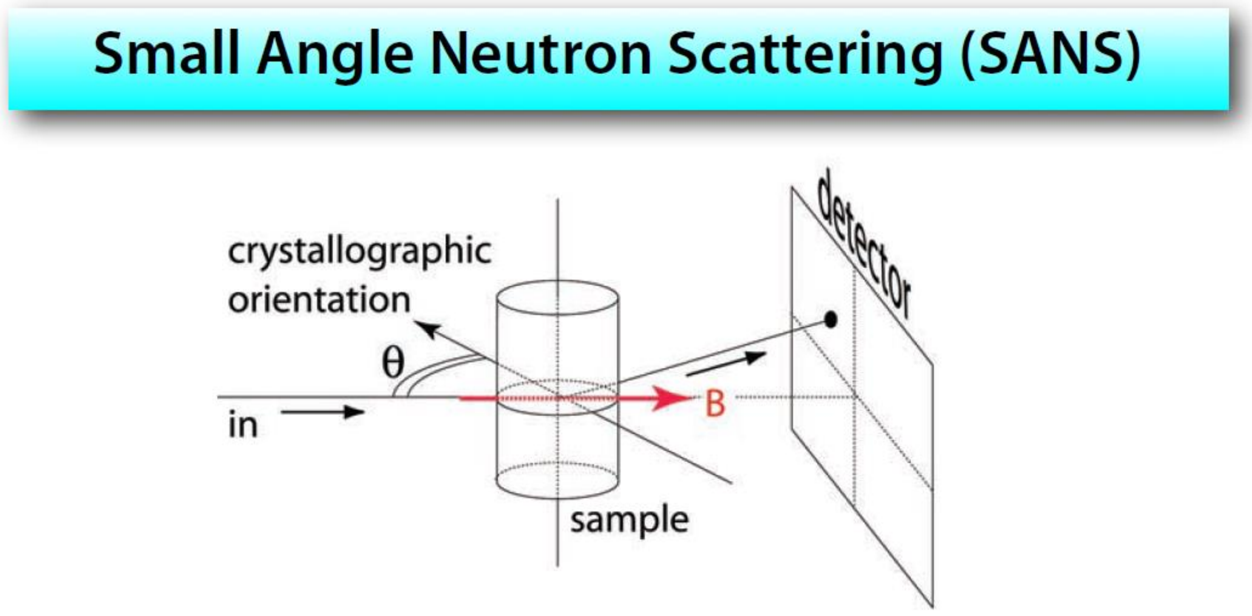
Skyrmion measurements

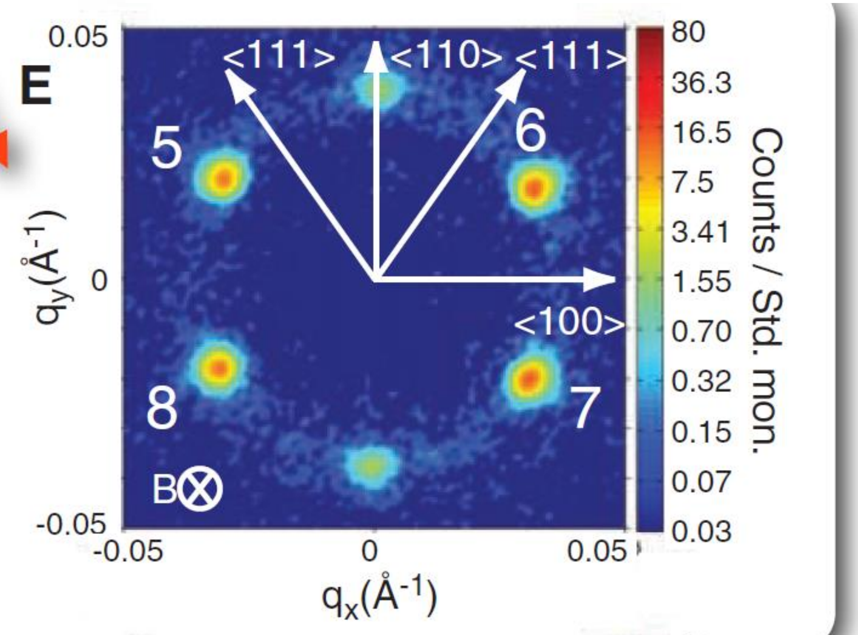
SASXRS Small angle Soft X-ray Resonant Scattering

- SANS Small Angle Neutron Scattering



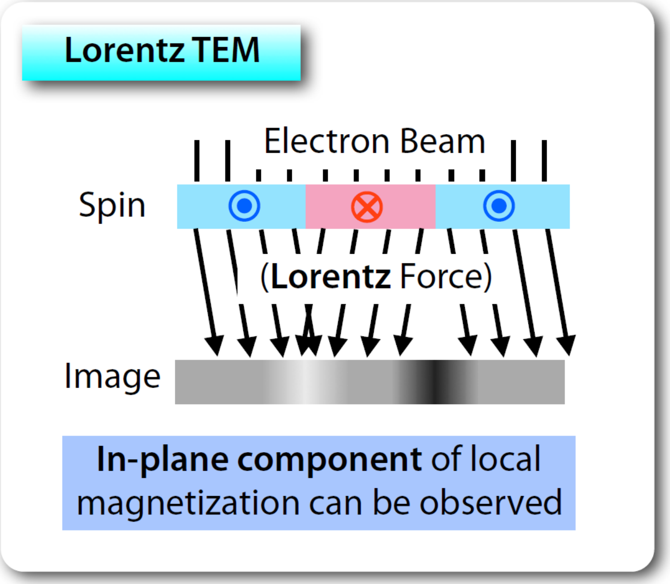


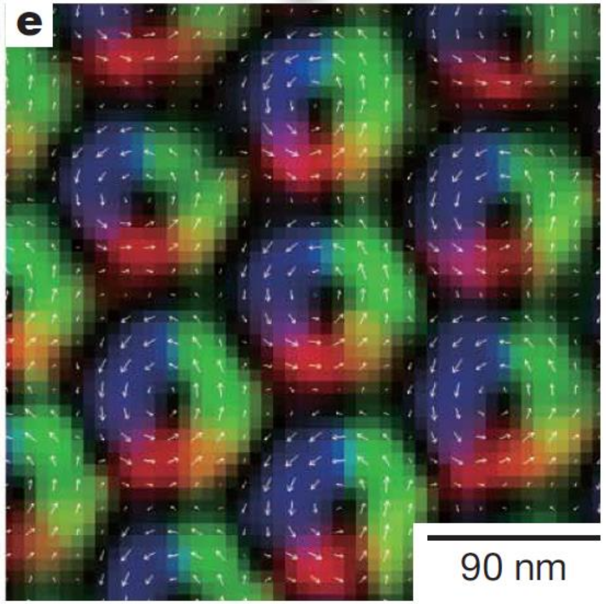




Skyrmion measurements

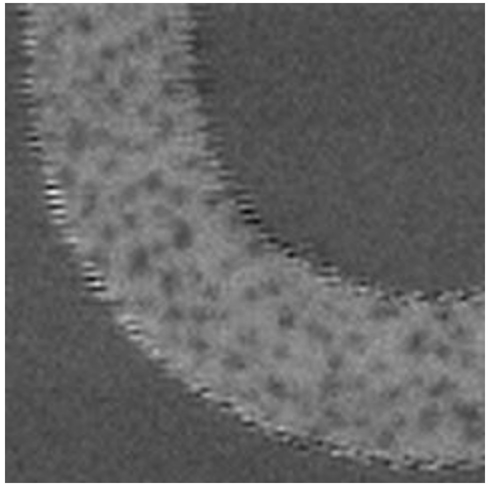
- Magnetic contrast transmission electron microscopy (LTEM)
- Sensitive to in-plane magnetization components
- TIE Transfer of intensity: recover phase
- Electron holography: towards 3D imaging of magnetic textures

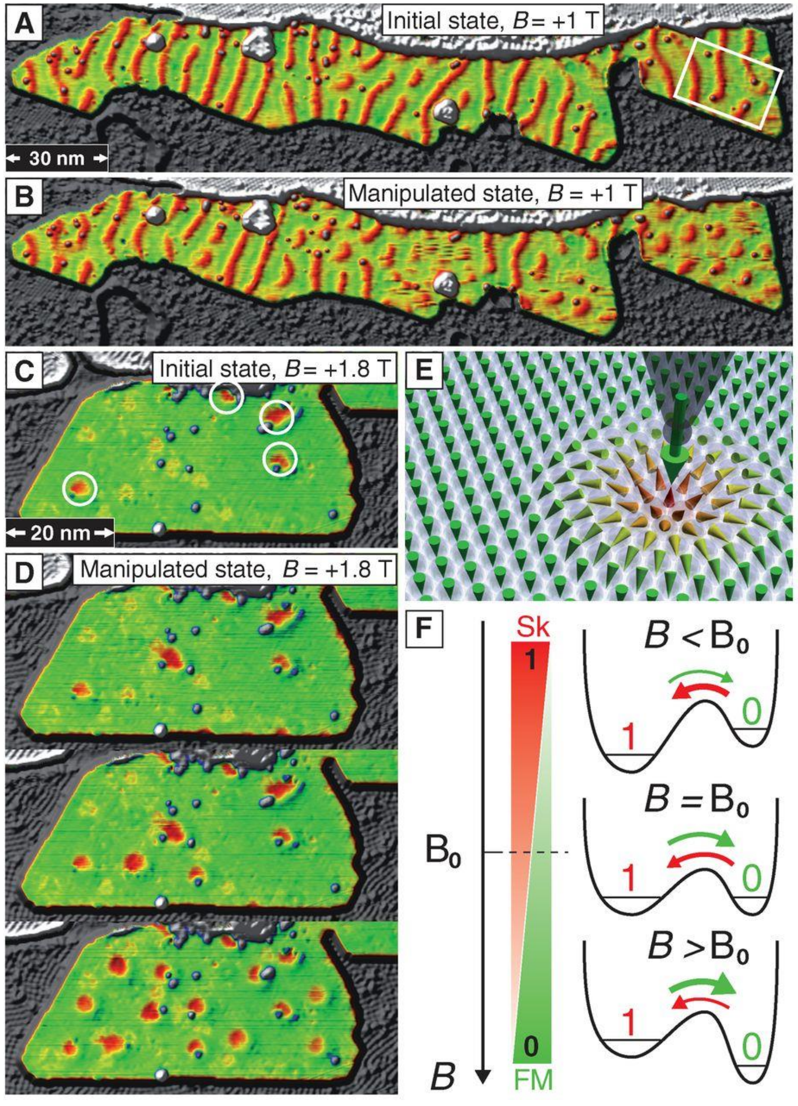


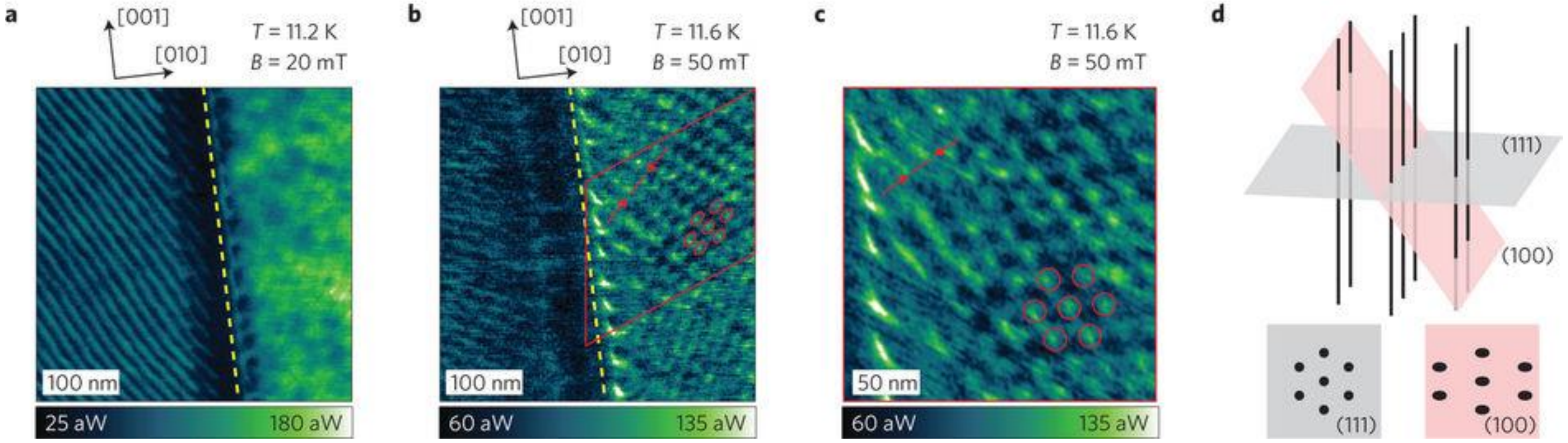


Skyrmion measurements

- Scanning Tunneling X-ray Microscopy
- Magnetic Force Microscopy
- Spin Polarized STM





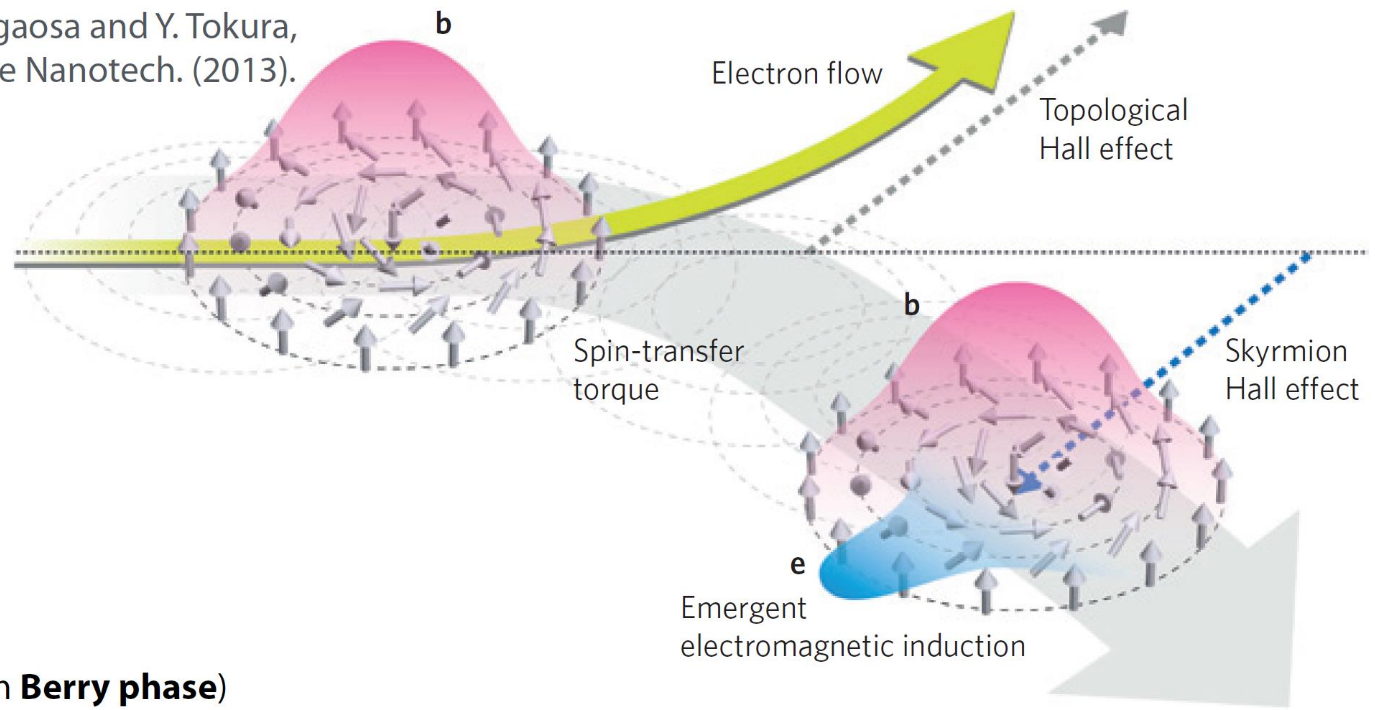


Skyrmion measurements Transport effects

Hall effect ∝ B
Anomalous Hall ∝ M
Topological Hall ∝ Q

Conduction Electrons and Skyrmions

N. Nagaosa and Y. Tokura, Nature Nanotech. (2013).

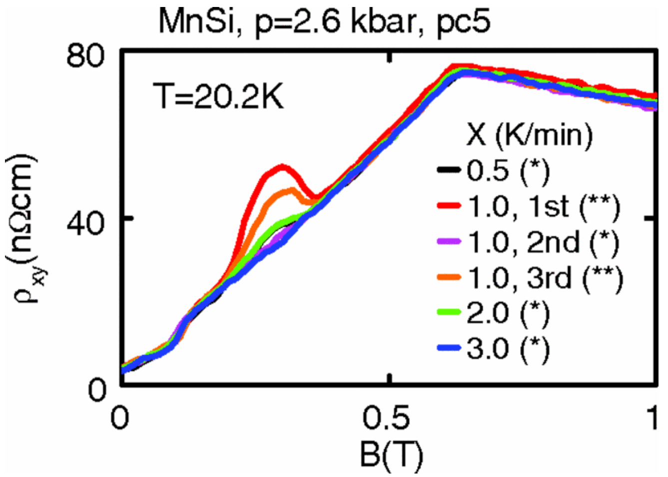


(from **Berry phase**)

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

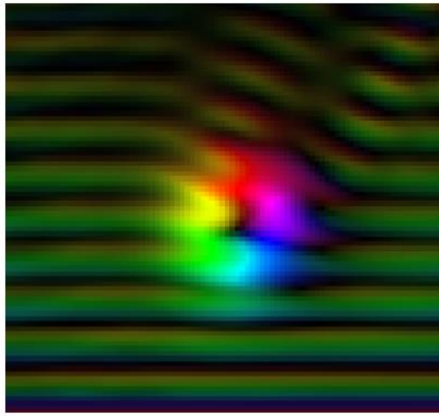
Emergent electric field $\mathbf{E}_i^e = \hbar\hat{n}\cdot(\partial_i\hat{n}\times\partial_t\hat{n})$

Skyrmion density $\phi = \frac{1}{4\pi}\vec{n}\cdot\frac{\partial\vec{n}}{\partial x}\times\frac{\partial\vec{n}}{\partial y}$



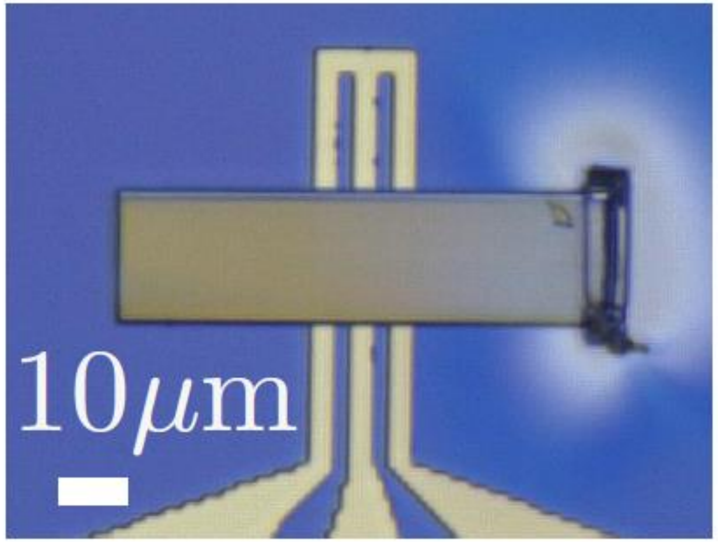
A. Neubauer *et al.*, Phys. Rev. Lett.(2009).
F. Jonietz *et al.*, Science (2010).
T. Schulz *et al.*, Nature Physics (2012).
X. Z. Yu *et al.*, Nature Comm. (2012).

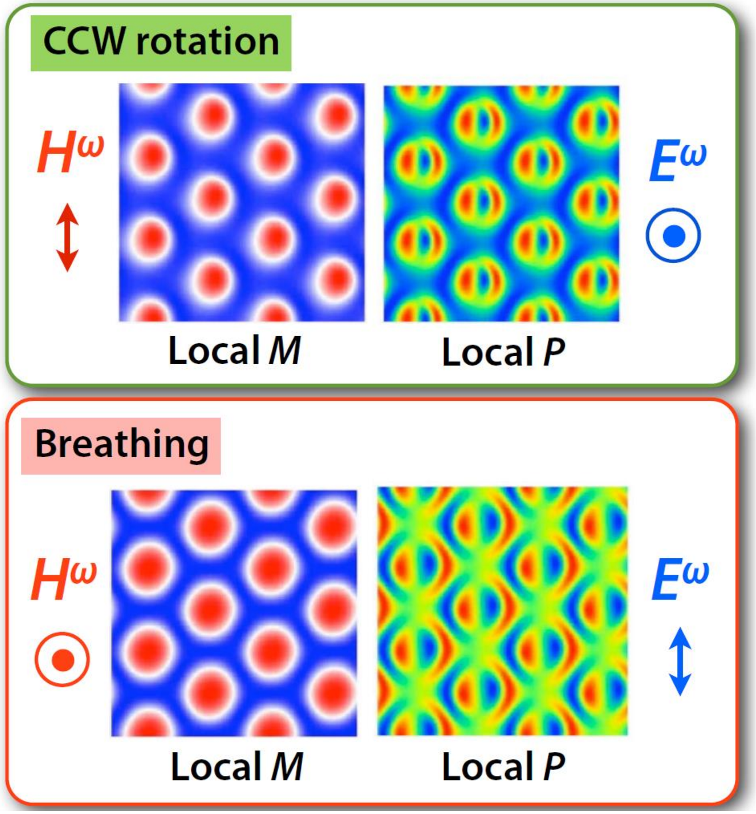
Mochizuki, Seki *et al.*, Nature Mater. (2014).

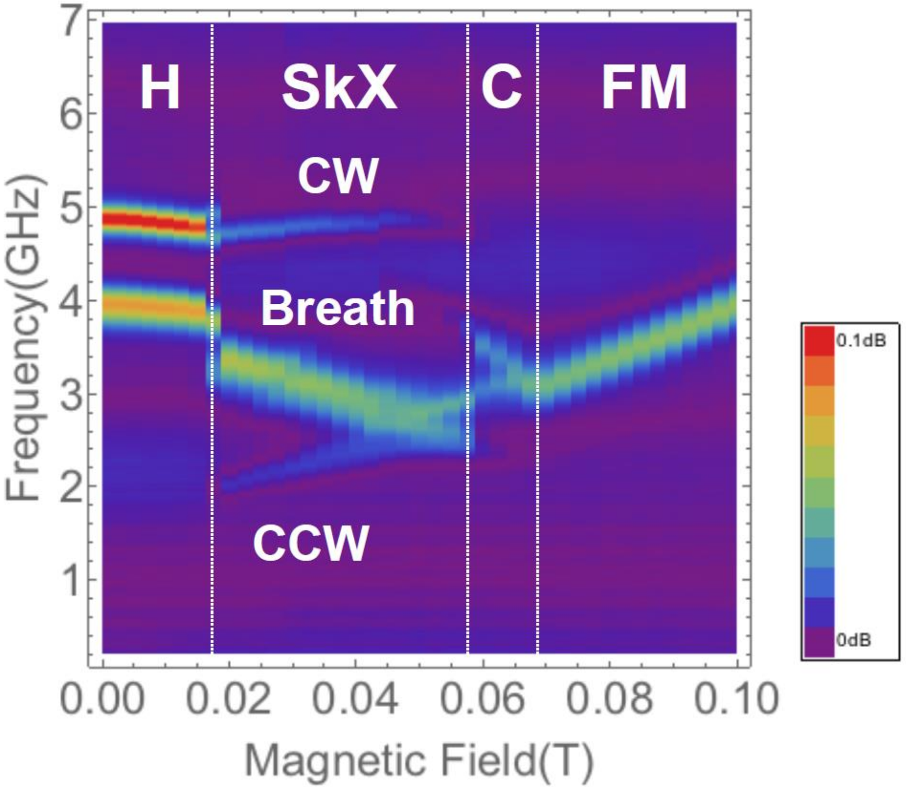


Skyrmion spectroscopy

- Seki et al.

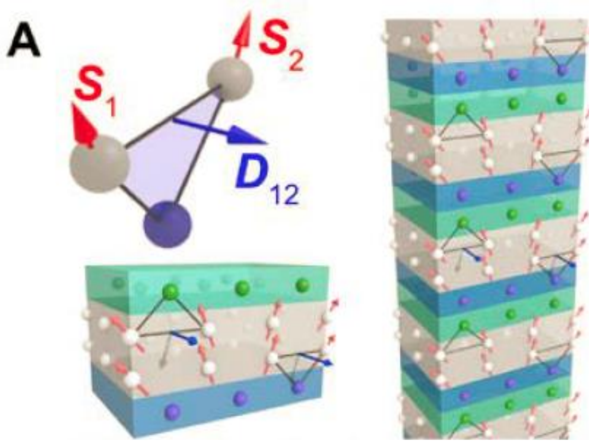






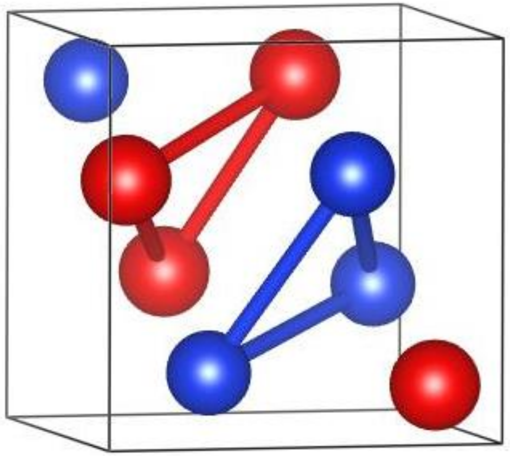
Skyrmion hosts

- Interface or “ABCABC” multilayer of FM and high-Z compounds



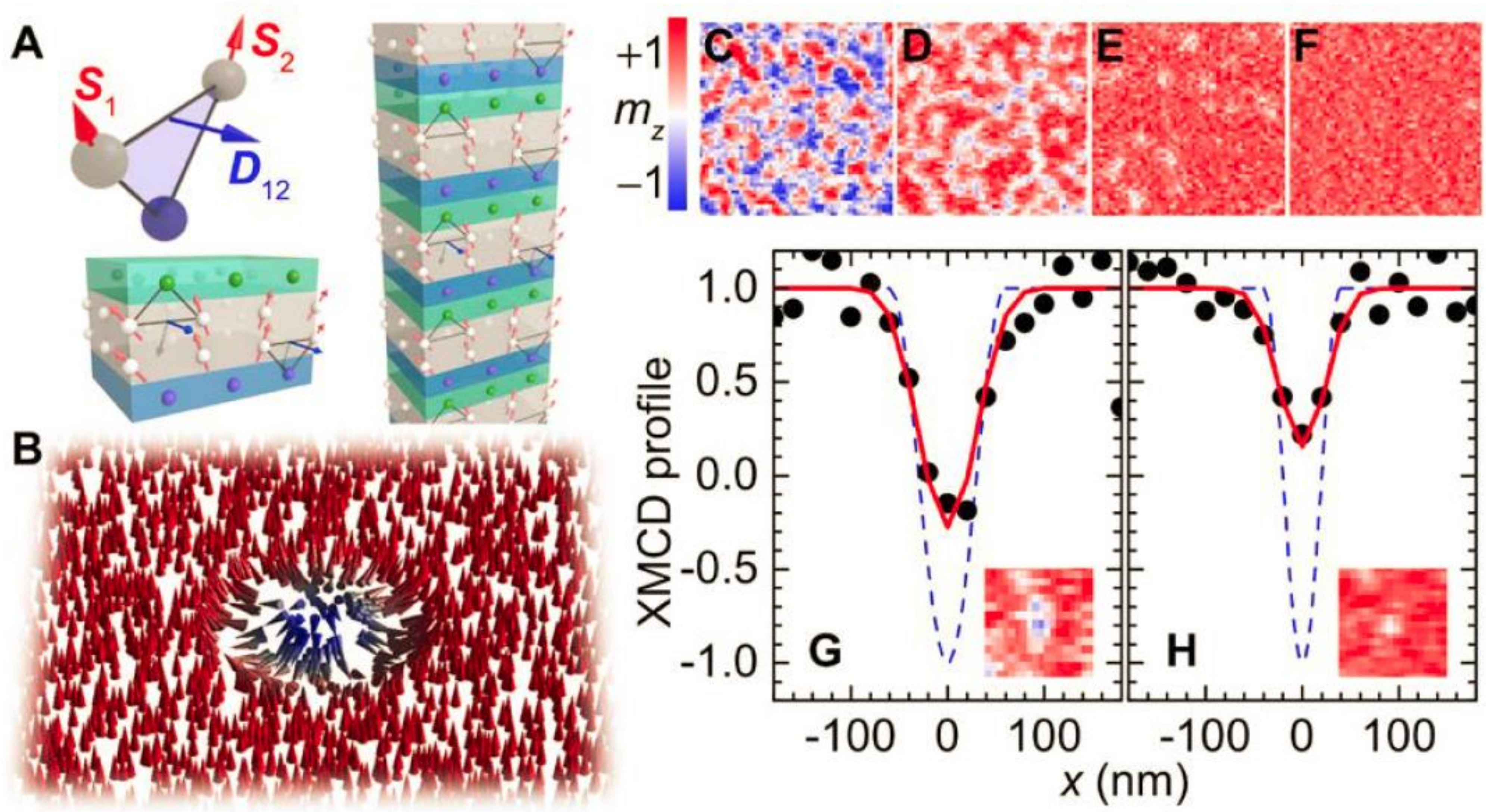
- Albert Fert
- Stuart S Parkin
- Manny others…

- Chiral and Polar bulk materials



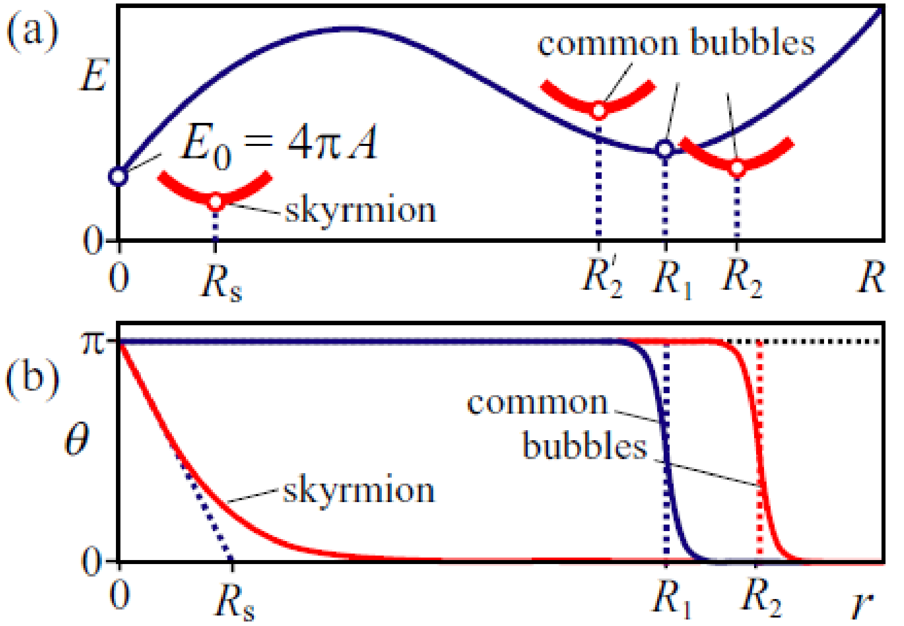
- Pfleiderer
- Tokura, Seki
- Keszmarki
- Many others…

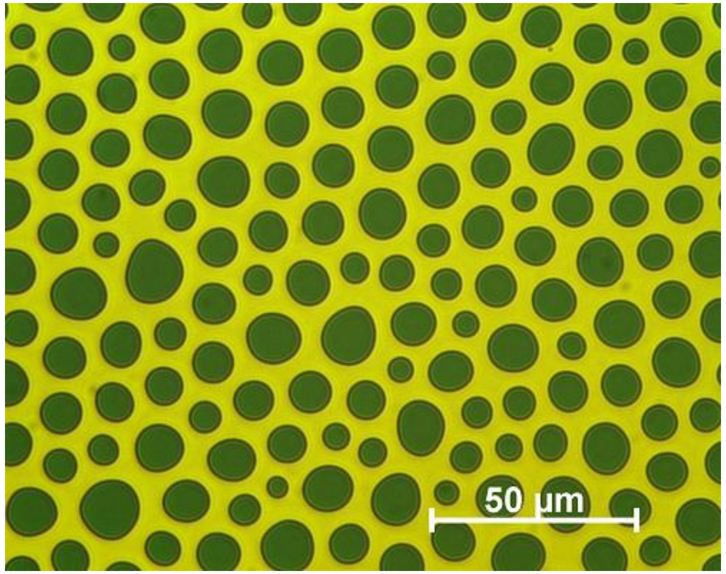
Skyrmions in fabricated interfaces/multilayers

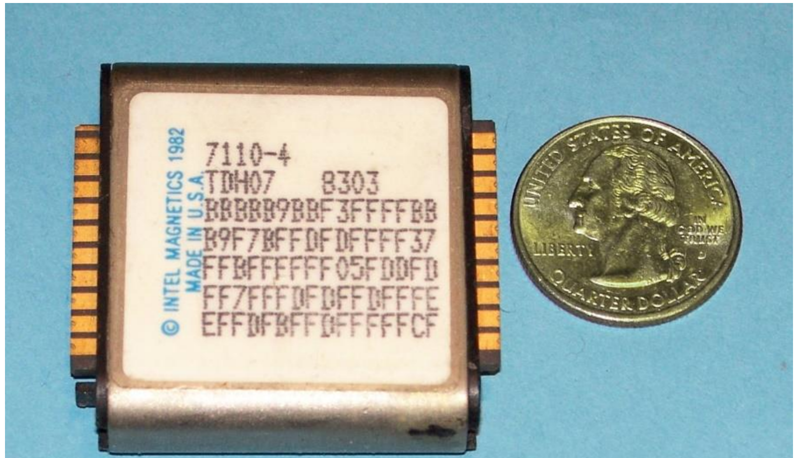


Skyrmions and magnetic bubbles

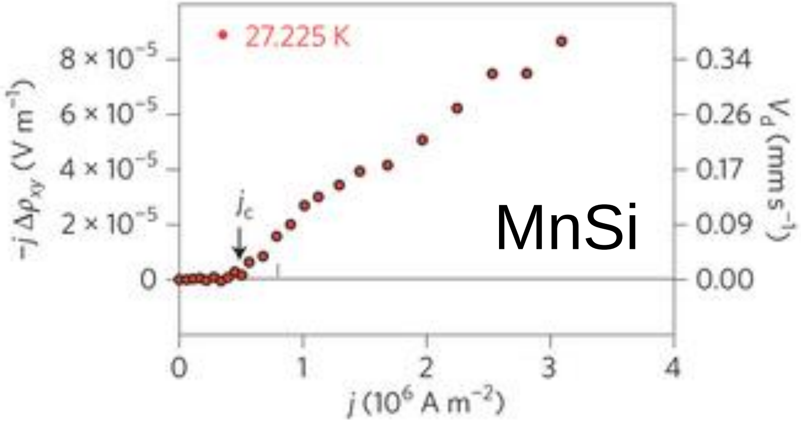
- In plate-geometry bubbles are stabilized by dipole fields
- Hot topic in 1980's
- Reached commercial products, but not competitive

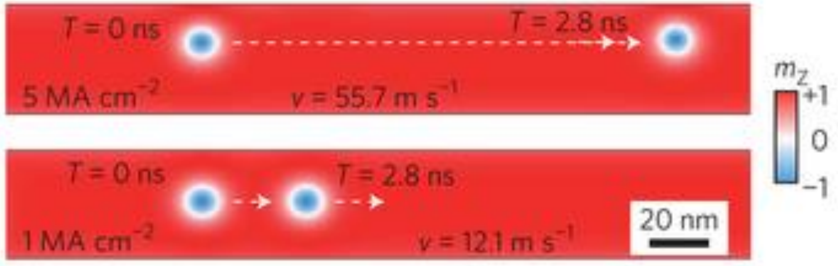




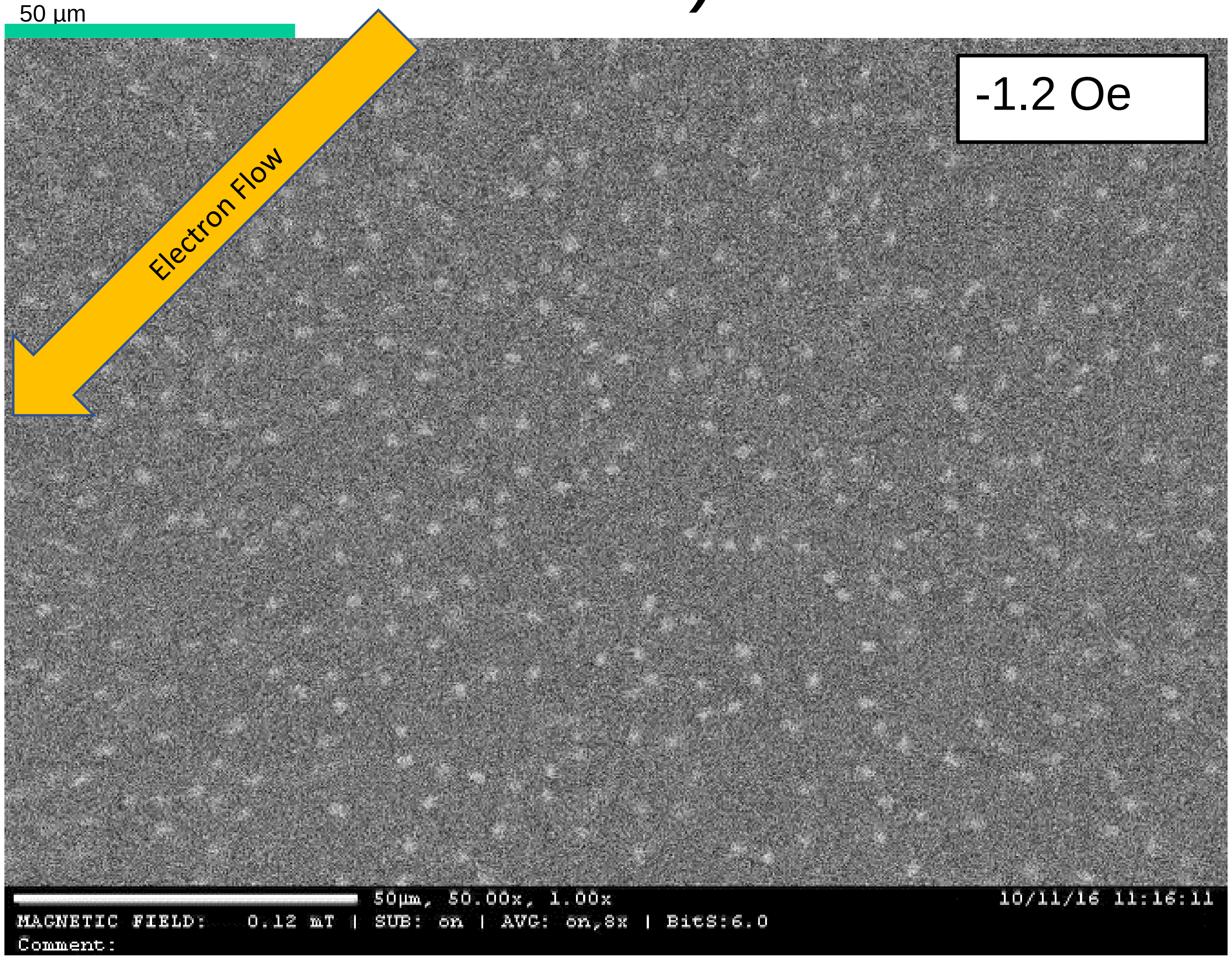


Intel 1Mbit bubble memory

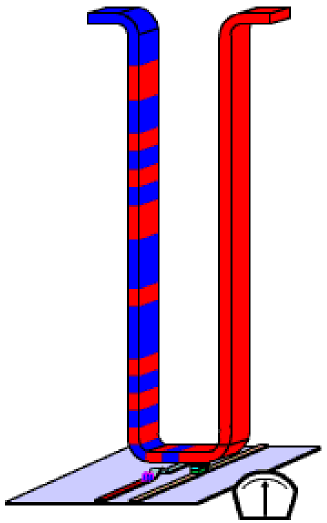




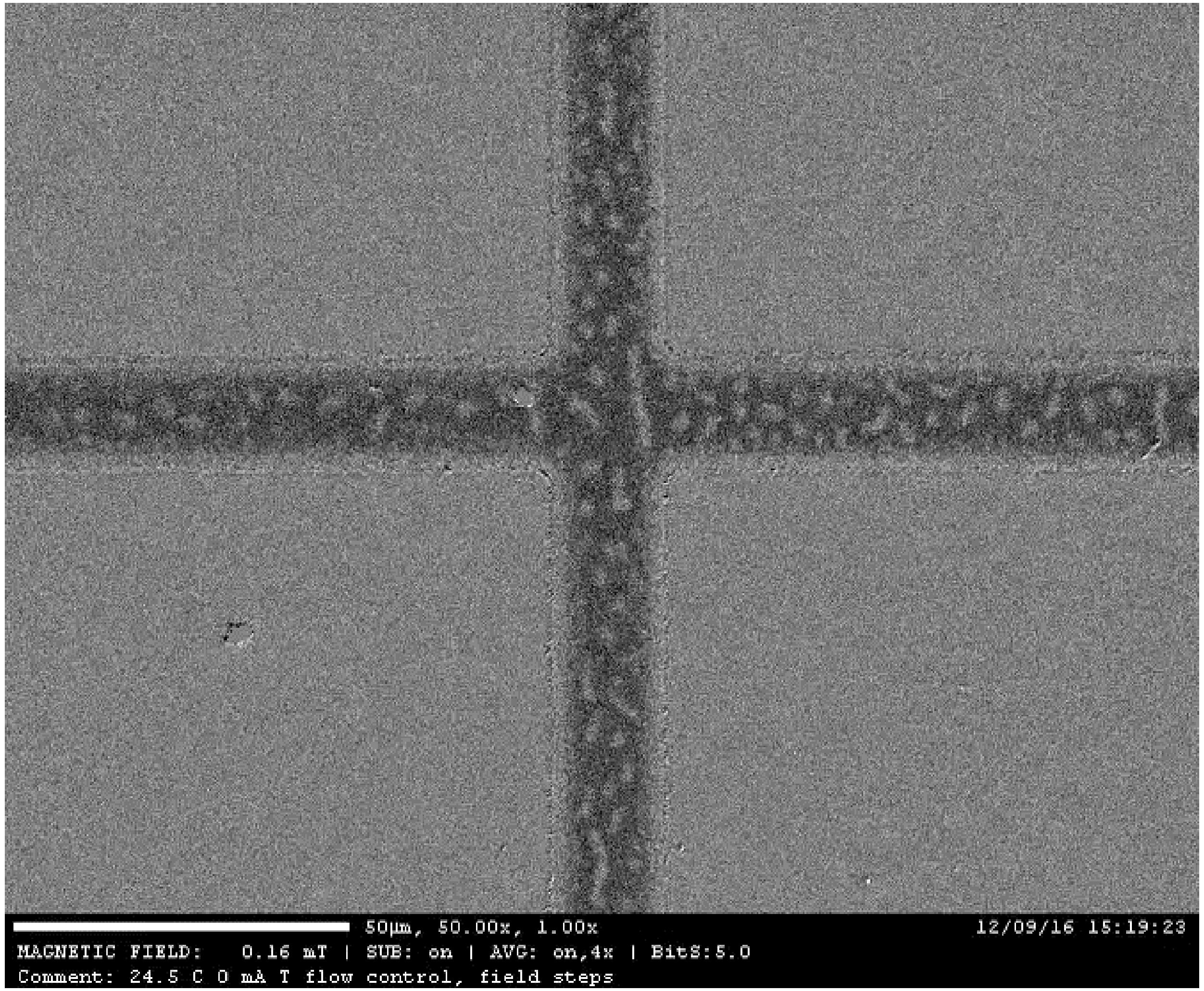
Current Driven Skyrmions (movies Eric Fullerton)

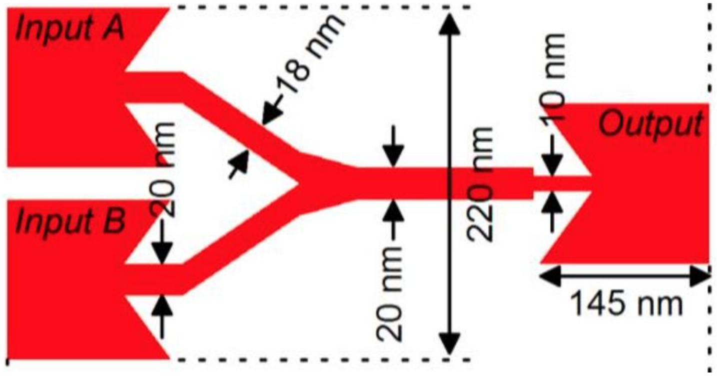


Moving Skyrmions



Racetrack Memory





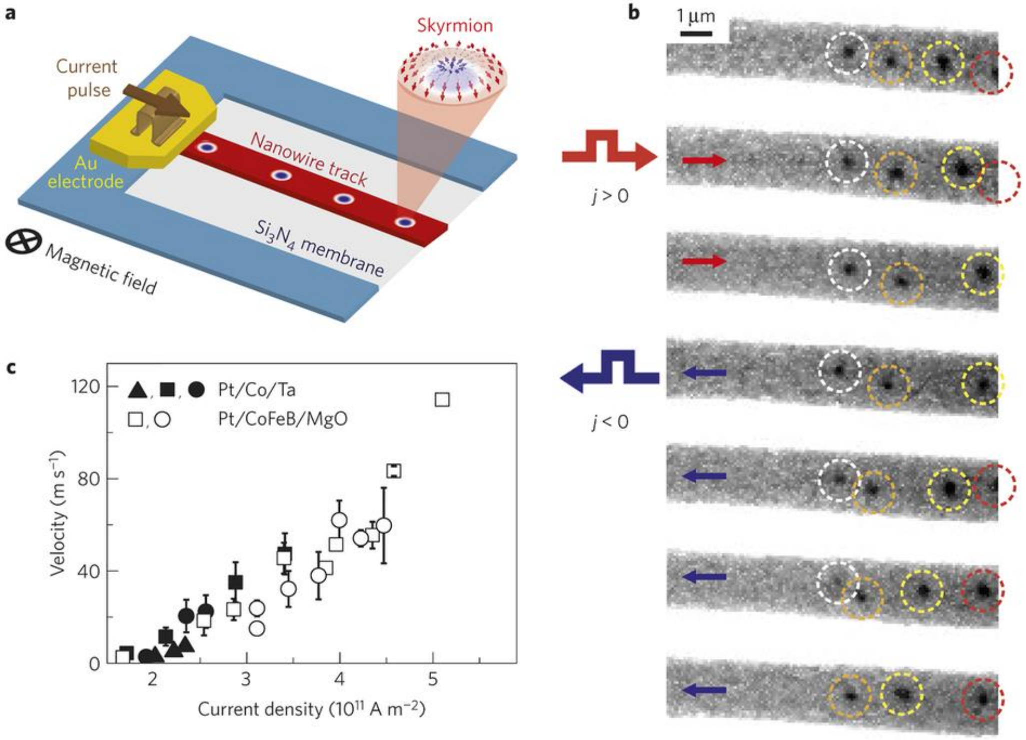
Logic Gates

Skyrmions on the track

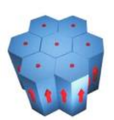
Albert Fert, Vincent Cros and João Sampaio

Magnetic skyrmions are nanoscale spin configurations that hold promise as information carriers in ultradense memory and logic devices owing to the extremely low spin-polarized currents needed to move them.

- Skyrmions move in small currents
- Race-track memory…

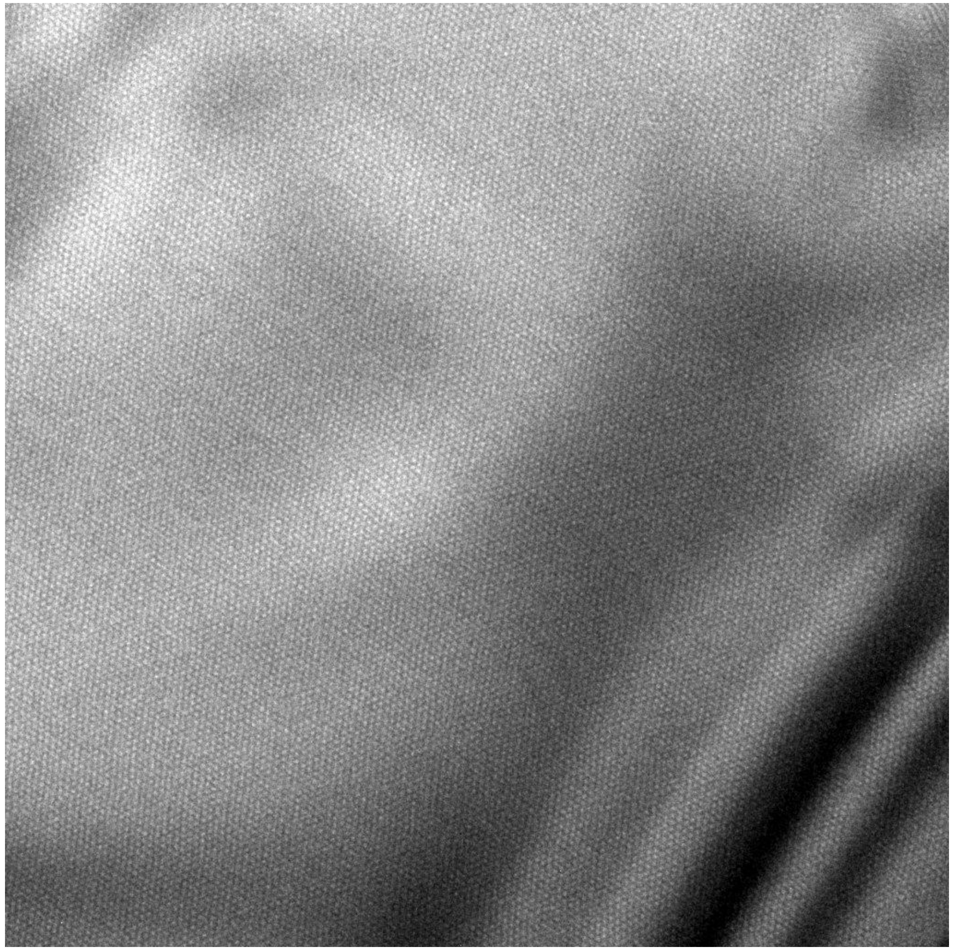


Skyrmion materials: Bulk materials

Material	SG	Ordering Temp	Helimag. Period	Transport property	Skyrmion motion	SkL Dimension	References
MnSi	$P2_13$	30 K	18 nm	Metallic	j_c~10^6A.m^{-2} ΔT	2D 	S. Mühlbauer *et al.*, Science **323**, 915 (2009) F. Jonietz *et al.*, Science **330**, 1648 (2010) M. Mochizuki *et al.*, Nat. Mater. **13**, 241 (2014)
FeGe	$P2_13$	280 K	70 nm	Metallic	j_c<10^6A.m^{-2}	2D	X.Z. Yu *et al.*, Nat. Mater. **10**, 106 (2010) X.Z. Yu *et al.*, Nat. Comm. **3**, 988 (2012)
$Fe_{1-x}Co_xSi$	$P2_13$	11 – 36 K	40-230 nm	Metal / semi-conductor		2D	W. Münzer *et al.*, PRB **81**, 041203(R) (2010) X.Z. Yu *et al.*, Nature **465**, 901 (2010)
$Mn_{1-x}Fe_xSi$	$P2_13$	7-16.5 K	10-12 nm	Metallic		2D	S.V. Grigoriev *et al.*, PRB **79,** 144417 (2009)
$Mn_{1-x}Fe_xGe$	$P2_13$	150-220 K	5 - 220 nm	Metallic		2D	K. Shibata *et al.*, Nature Nano. **8,** 723 (2013)
$Co_xZn_yMn_z$	$P4_132$	140-480K	110-190nm	Metallic		2D	Y. Tokunaga *et al.*, Nat. Com. **6,** 7638 (2015)
GaV_4S_8	C_{3v}	13 K	22nm	Semi-conductor		2D anisotrop	
Cu_2OSeO_3	$P2_13$	58 K	50 nm	Insulating Magneto-electric	ΔT E<10^5 V/m	2D	S. Seki *et al.*, Science **336,** 198 (2012) T. Adams *et al.*, PRL **108**, 237204 (2012) M. Mochizuki *et al.*, Nat Mat **13**, 241 (2014)
MnGe	$P2_13$	170 K	3 nm	Metallic		3D?	N. Kanazawa *et al.*, PRL **106**, 156603 (2011) N. Kanazawa *et al.*, PRB **86**, 134425 (2012)

Bulk systems have more stable skyrmions

- Large sample $\Rightarrow$ 100000 skyrmions resolved (Cu_2OSeO_3)
- Allows quantitative analyses, such as delauney triangulation



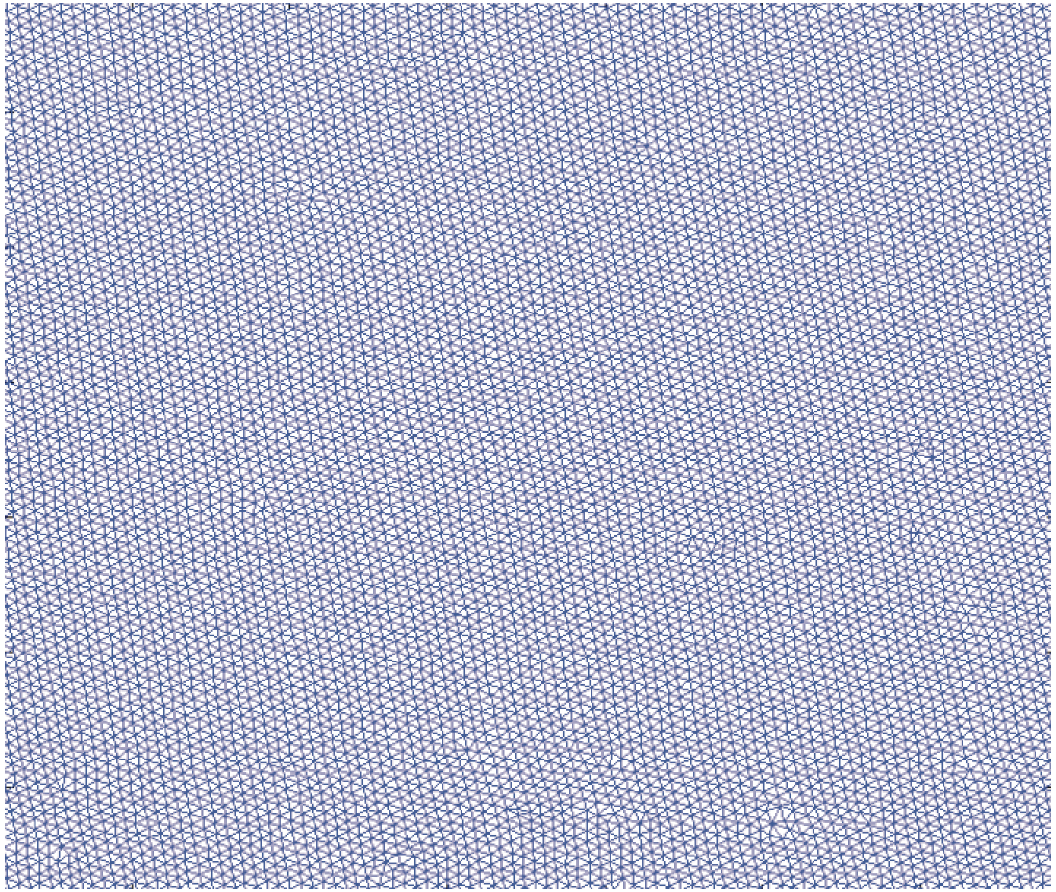
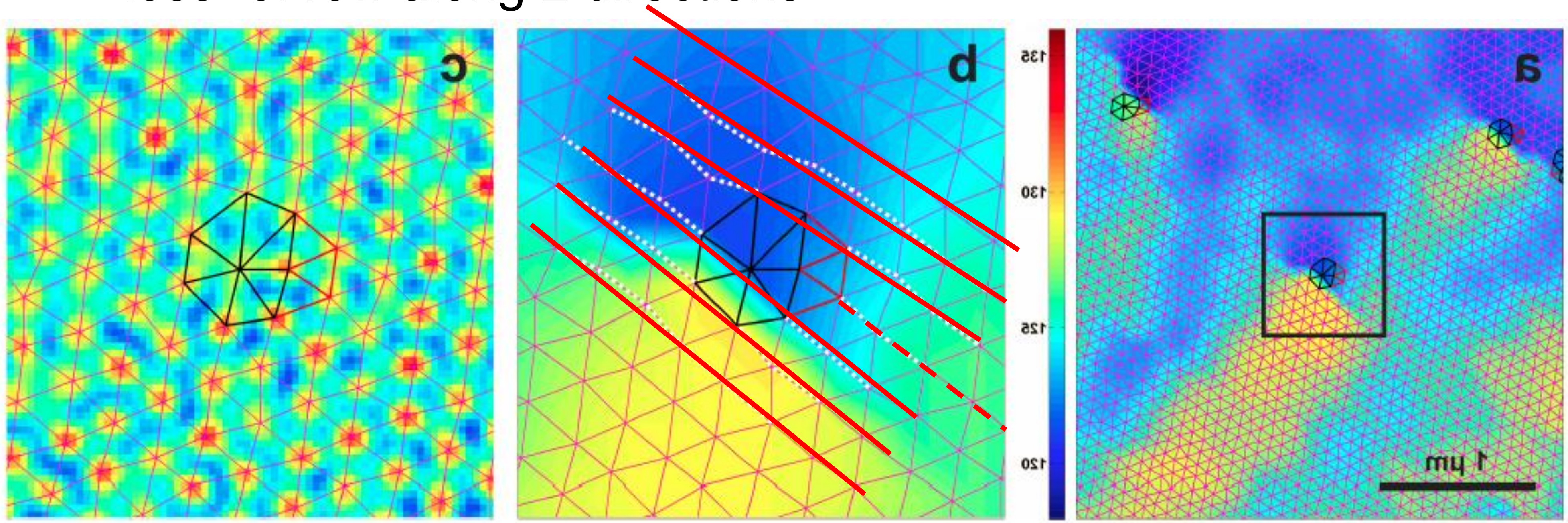


Fig. S4: 7.3x7.3 μm^2 real space image of the skyrmions position at B=192 G obtained by Delauney triangulation.

Defects and angles

- Defects classifiable – eg a 5-7 or a 5-8-5 defect
  - “loss” of row along 2 directions

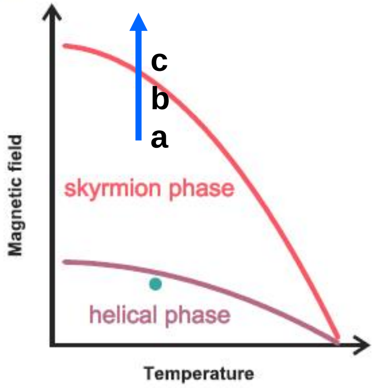


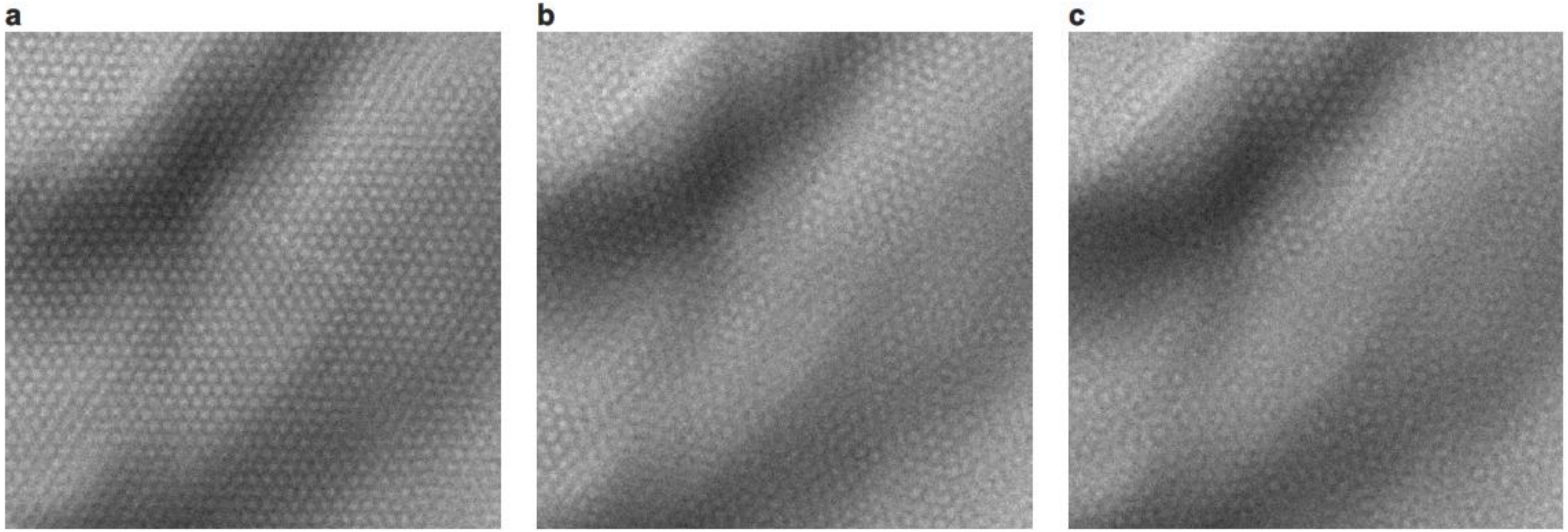
Map SkL angle: $\Psi_6(r_i) = \frac{1}{N_N^i}\sum_k^n e^{i6\theta(r_{ik})}$ or peak in “local Fourrier”

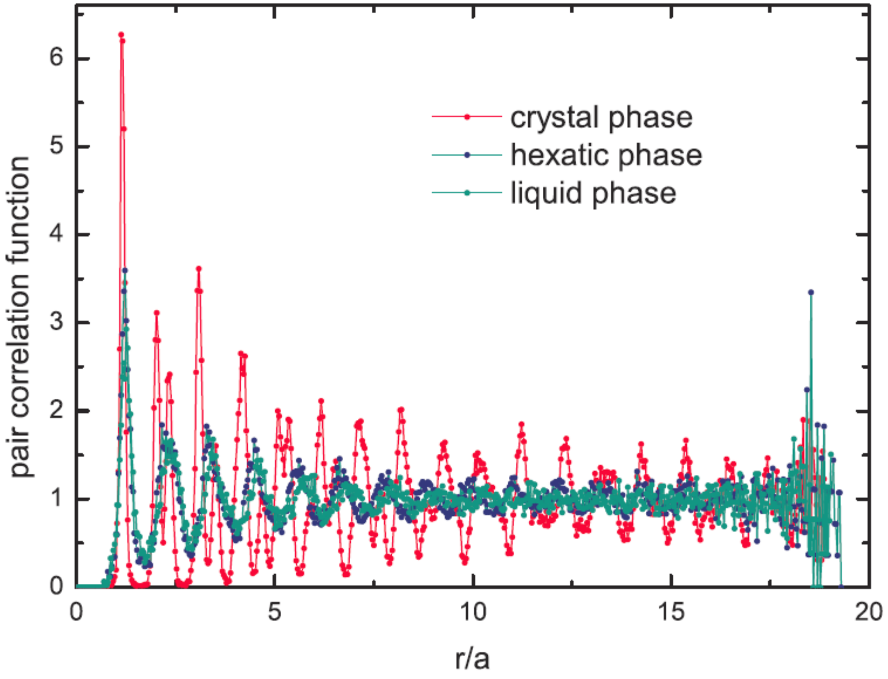
  - Defects creates far-stretching rotations
  - Model system for understanding lattice defects

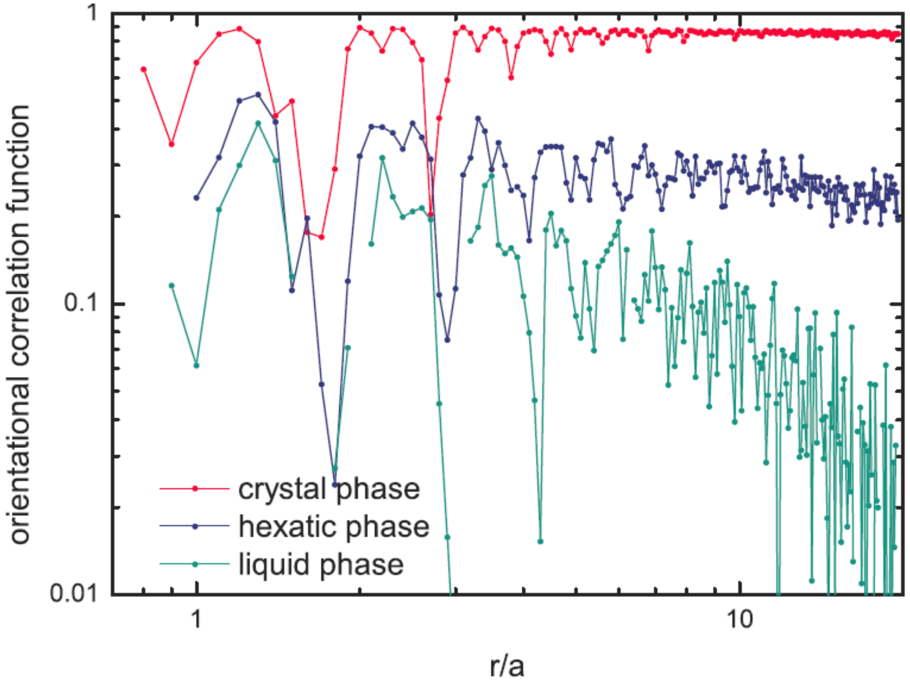
Skyrmions as arena for real-space imaging of phase transitions

Magnetic field induced melting of skyrmion lattice in helimagnet Cu2OSeO3 2

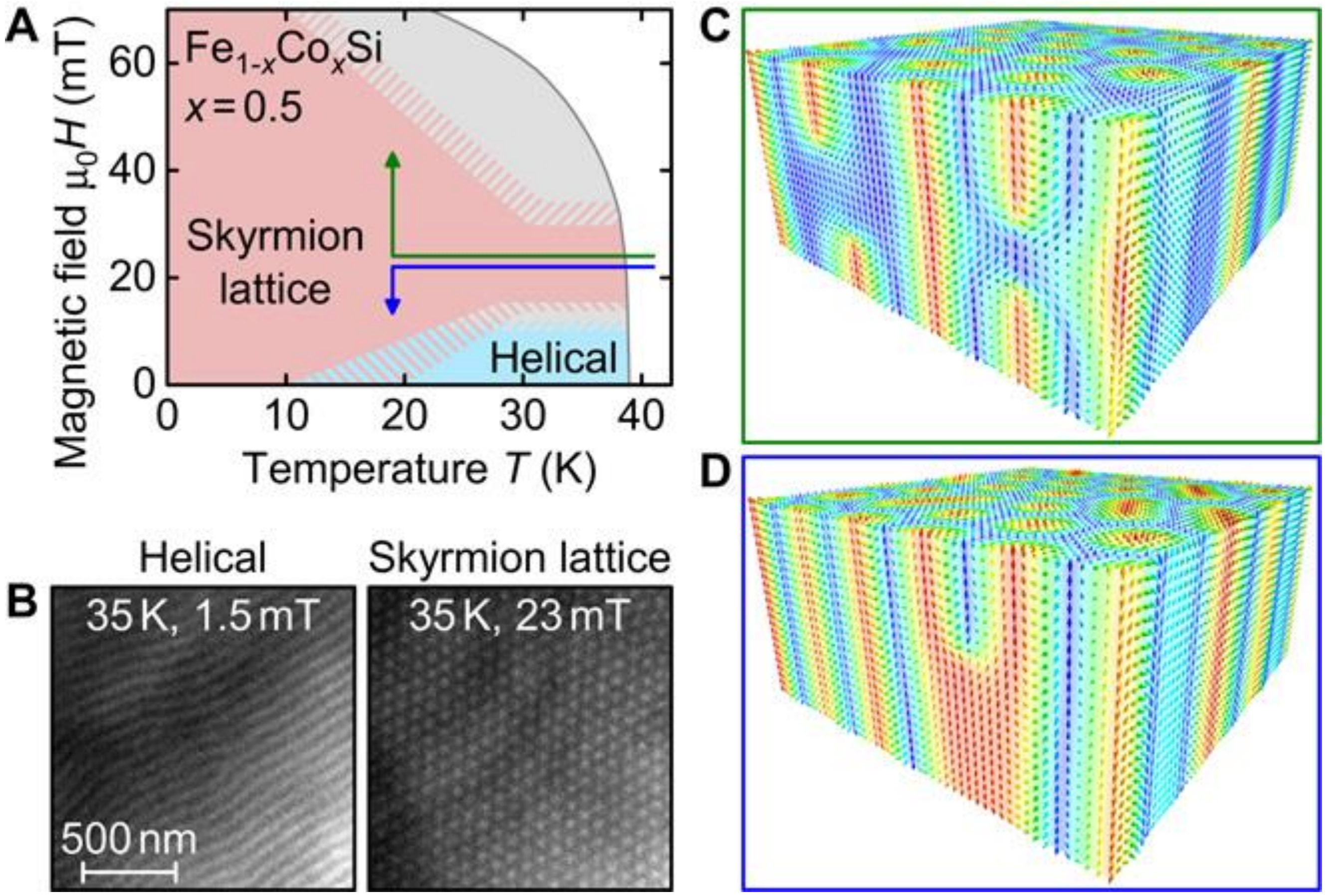


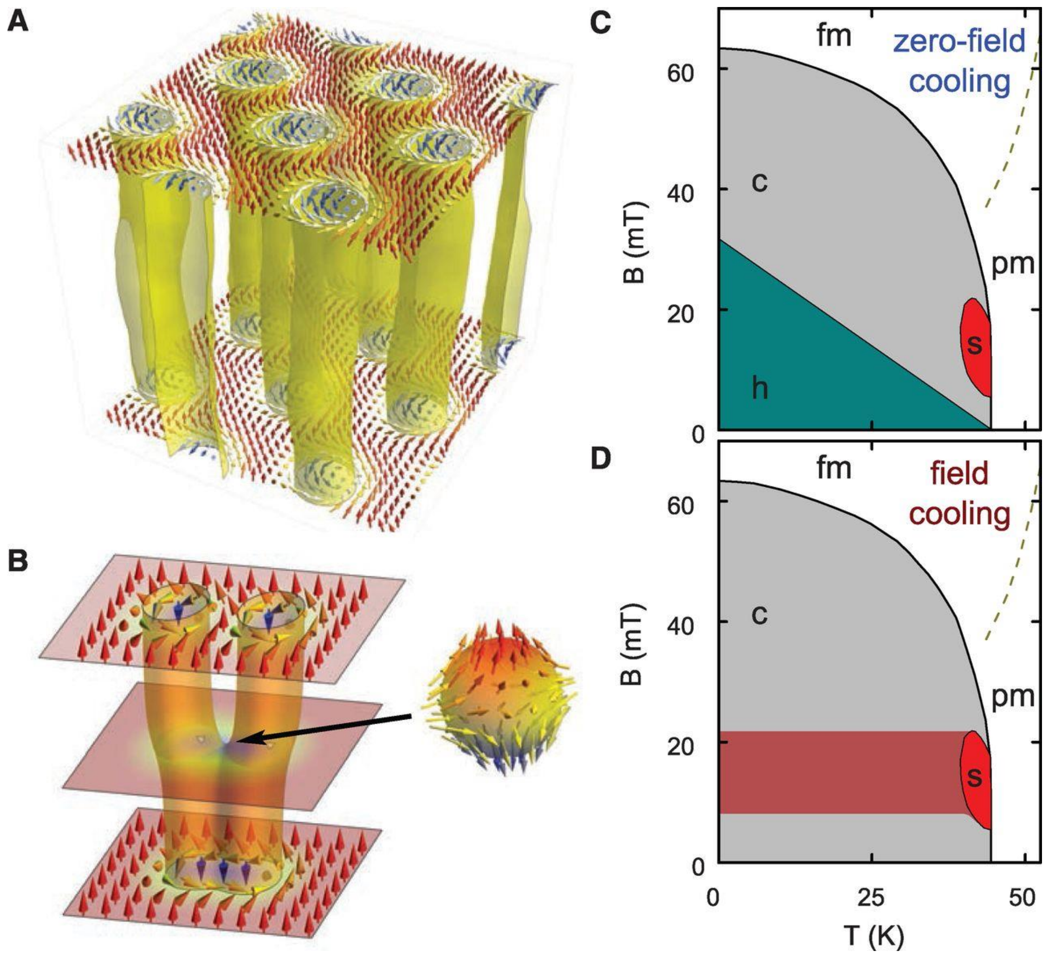






The 3rd dimension – how protected?



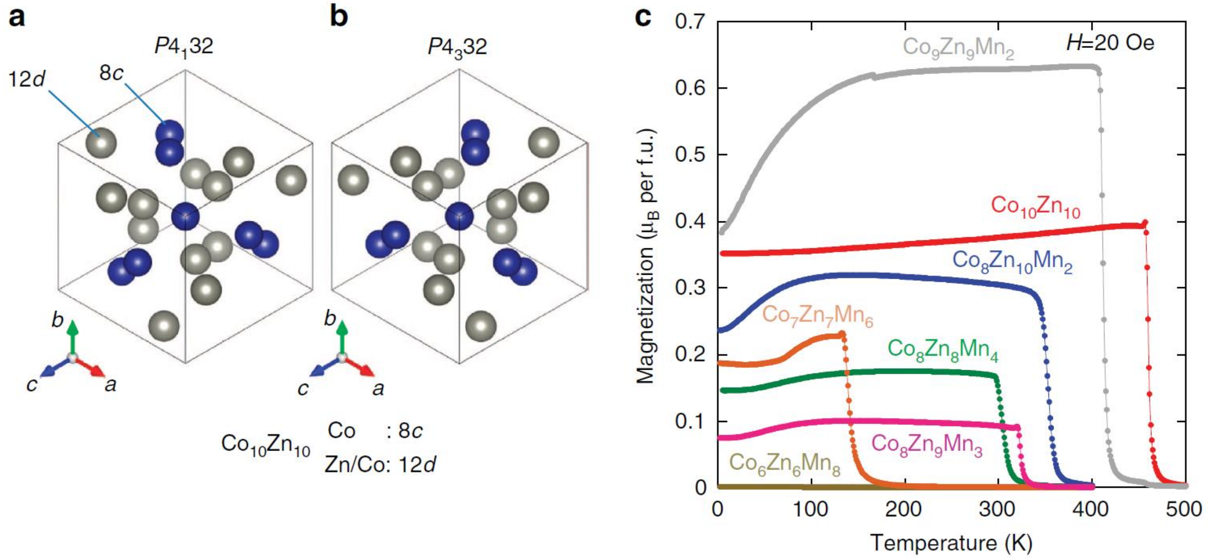


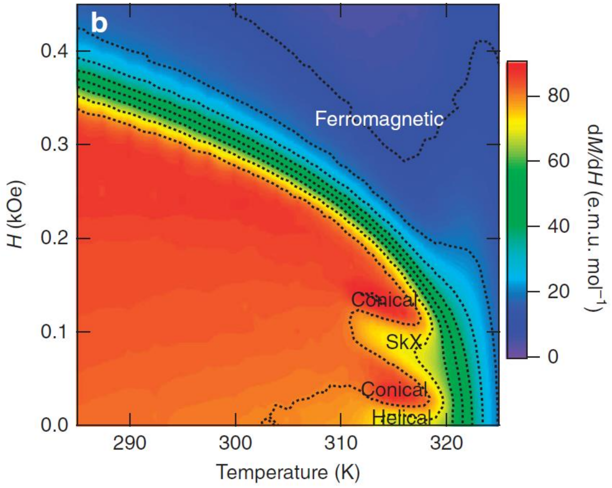
Received 23 Dec 2014 | Accepted 25 May 2015 | Published 2 Jul 2015

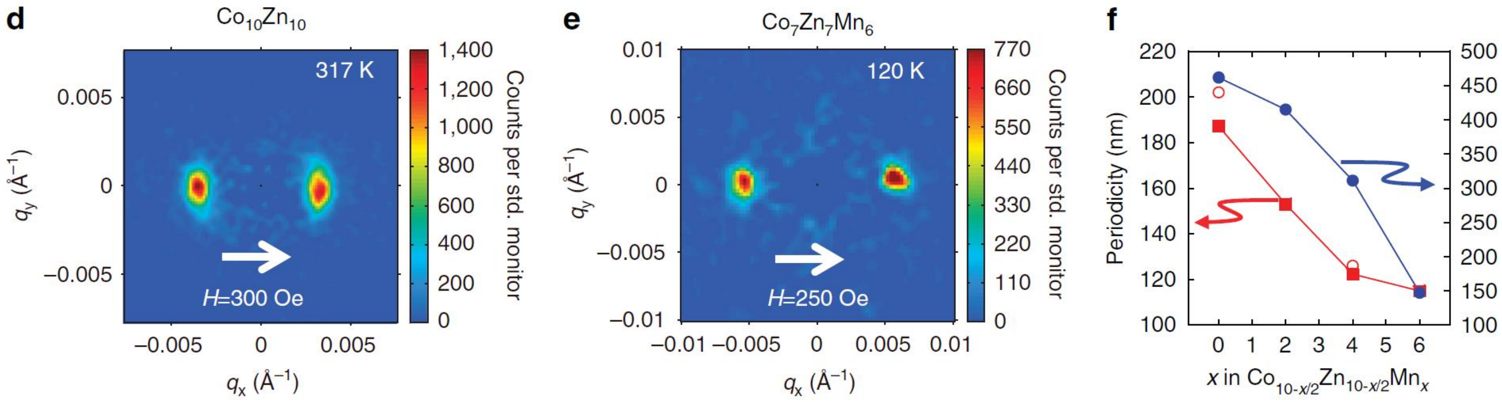
DOI: 10.1038/ncomms8638

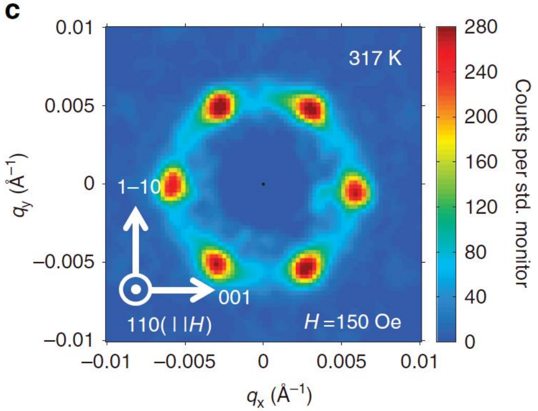
OPEN

A new class of chiral materials hosting magnetic skyrmions beyond room temperature







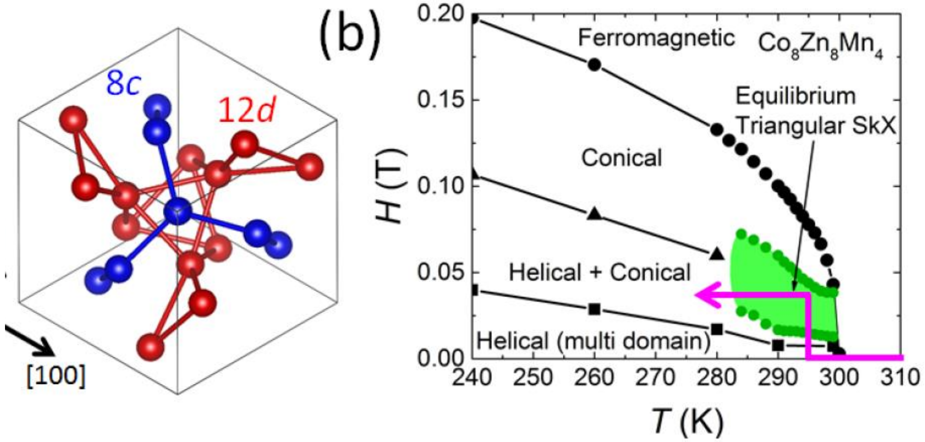


Robust metastable skyrmions and their triangular–square lattice structural transition in a high-temperature chiral magnet

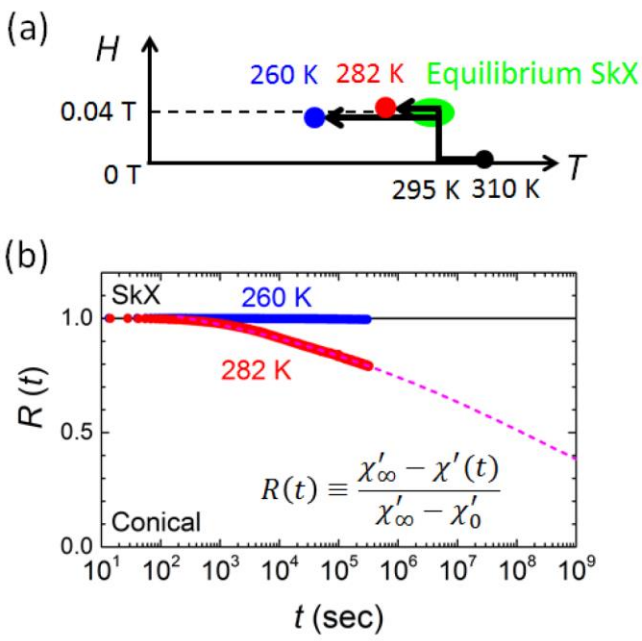
K. Karube, J. S. White, N. Reynolds, J. L. Gavilano, H. Oike, A. Kikkawa, F. Kagawa, Y. Tokunaga, H. M. Rønnow, Y. Tokura & Y. Taguchi

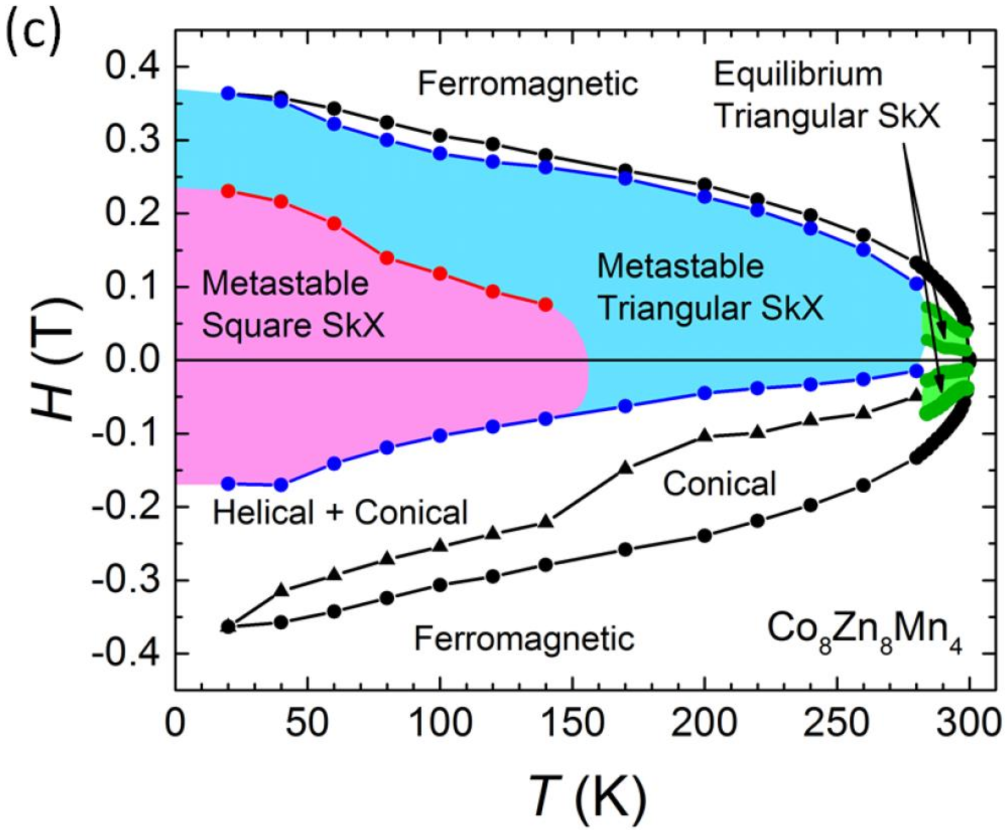
Affiliations | Contributions | Corresponding author

Nature Materials (2016) | doi:10.1038/nmat4752

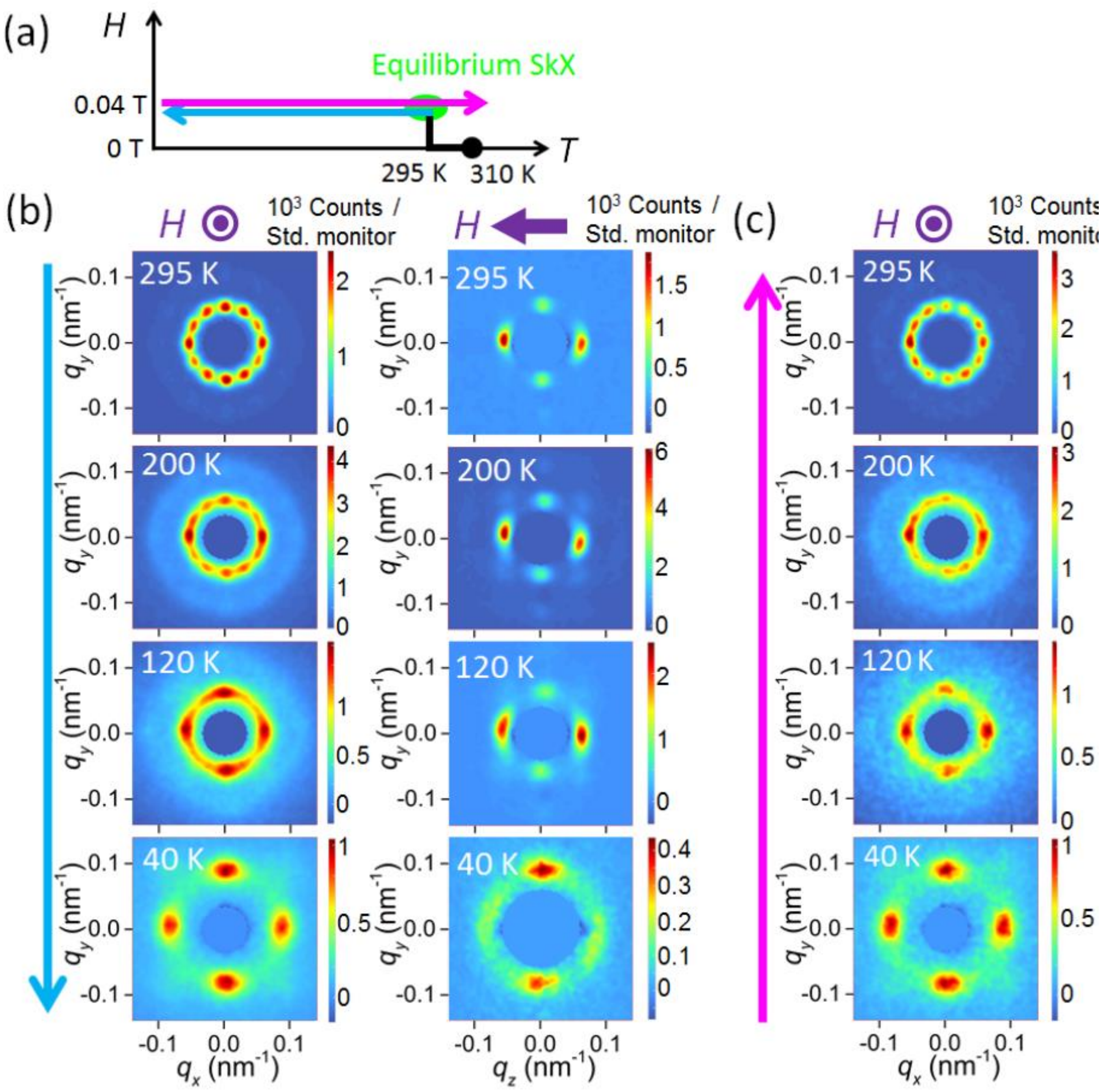


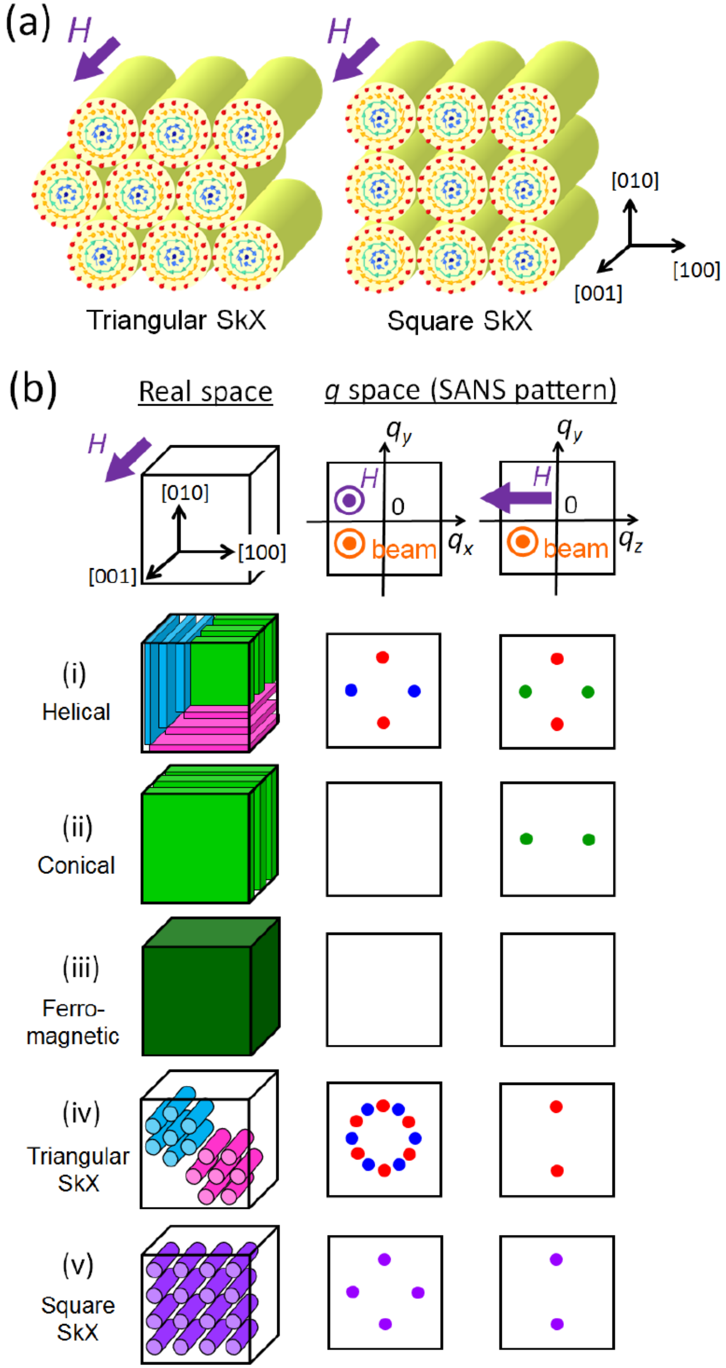
Metastability could come from topological protection ?



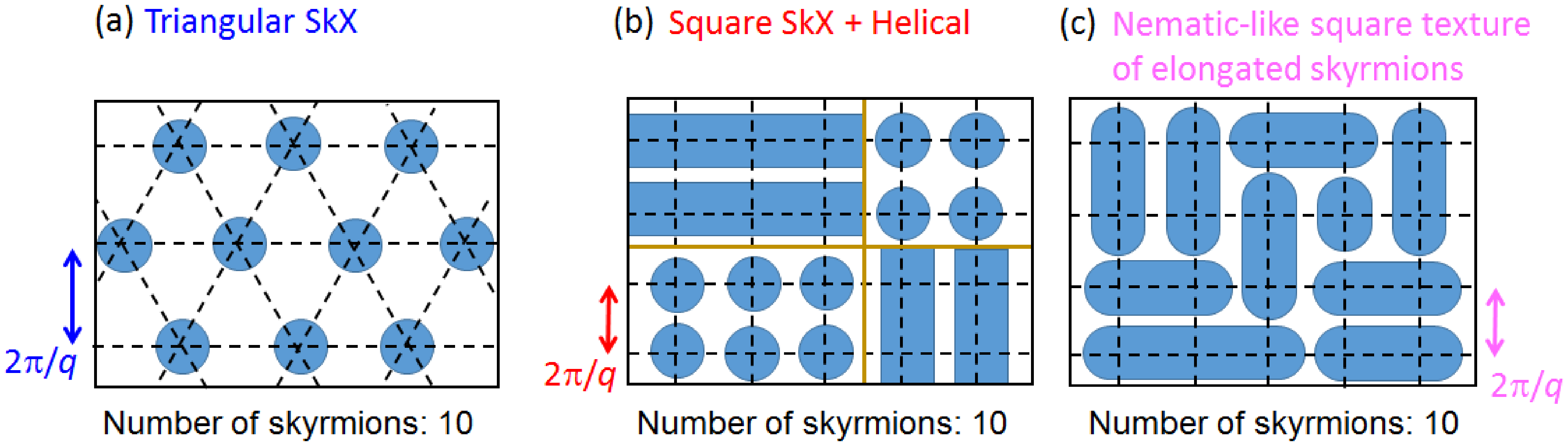


Square lattice ?





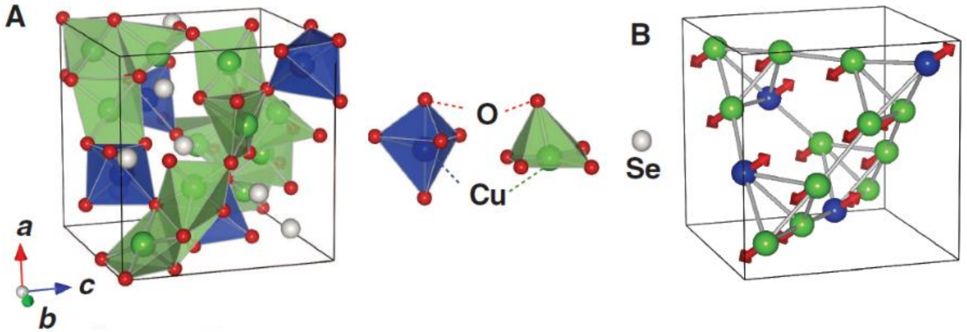
Topological protection + D/J(T) => long skyrmions



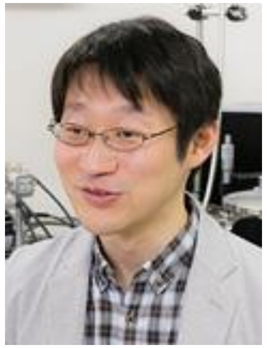
- Consequence:
  - Relationship helical domains / elongated skyrmions
  - Edges of helical domains carry half-skyrmions = merons
  - Crossing phase transition can pump skyrmions

Skyrmion hosting insulator Cu_2OSeO_3

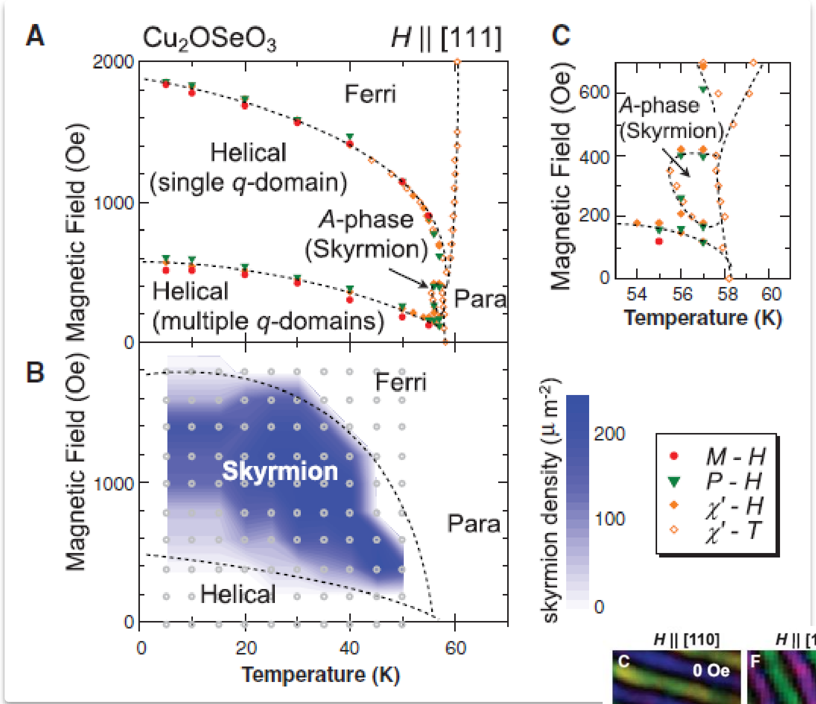
Crystal structure, $P2_13$, no inversion symmetry

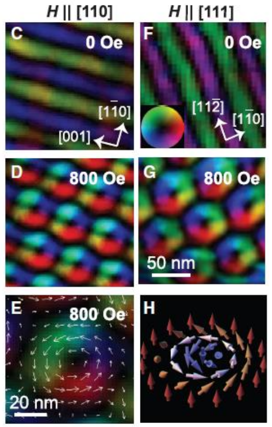


Cubic unit cell contain 16 Cu2+ S=1/2
4 tetrahedral forming "3-up-1-down" S=1
Combined to single S=4 in skyrmion simulations



'Generic' magnetic phase diagram + SkL phase

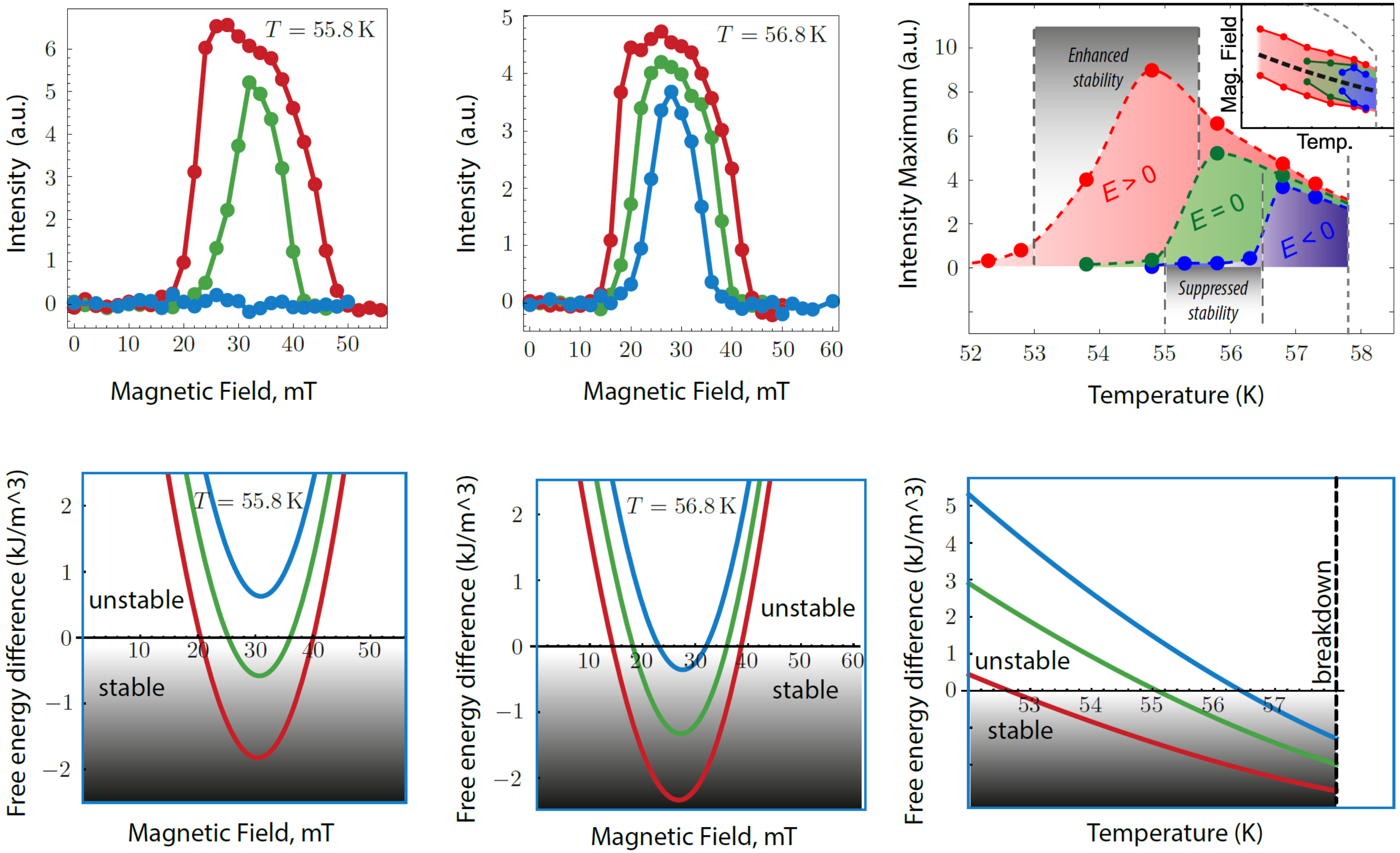




S. Seki *et al.*, Science **336,** 198 (2012)

S. Seki *et al.*, Phys. Rev. B **86,** 060403(R) (2012)

Can create skyrmions with electric field



A. Kruchkov, arxiv 1702.08863 & 1703.06081, to be submitted soon…

Identification of skyrmions in image data – easy if complete skyrmion phase

pre-treatments

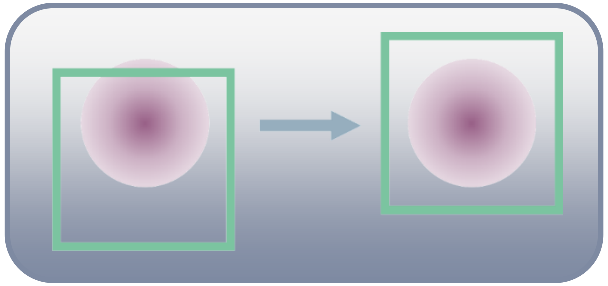
- aligning
- Area selection
- filtering

dynamical box algorithm

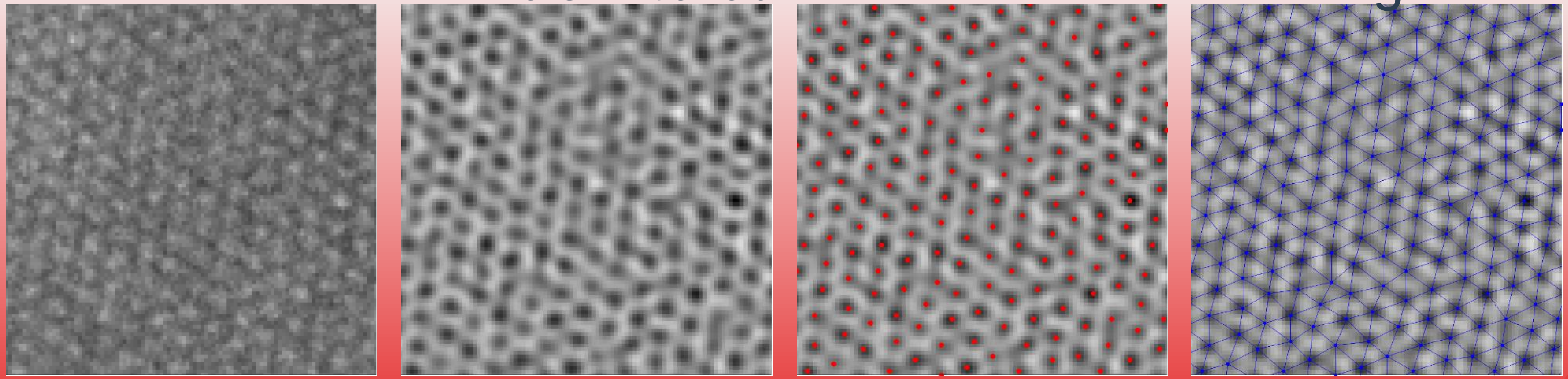
- scanning by a box
- finding local minima
- overlapping minima with centers

manual revisions

- adding and/or removing
- Delaunay triangulation
- interactive programs



raw data | LoG filtered | identification | triangulation



Counting skyrmions in mixed phase

Previous algorithm gets confused

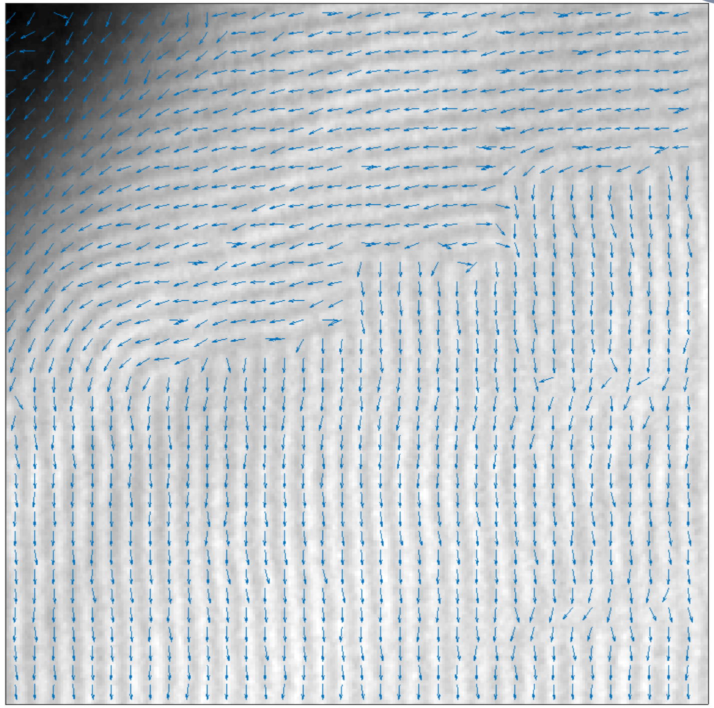
Use orientational map Inspired by finger-print algorithms

Rau & Schunck 1989

$$V_x(u,v) = \sum_{i=u-\frac{w}{2}}^{u+\frac{w}{2}} \sum_{j=v-\frac{w}{2}}^{v+\frac{w}{2}} 2\partial_x(i,j)\,\partial_y(i,j)$$

$$V_y(u,v) = \sum_{i=u-\frac{w}{2}}^{u+\frac{w}{2}} \sum_{j=v-\frac{w}{2}}^{v+\frac{w}{2}} \left(\partial_x^2(i,j)\partial_y^2(i,j)\right)$$

$$\theta(u,v) = \frac{1}{2}\tan^{-1}\left(\frac{V_y(u,v)}{V_x(u,v)}\right)$$

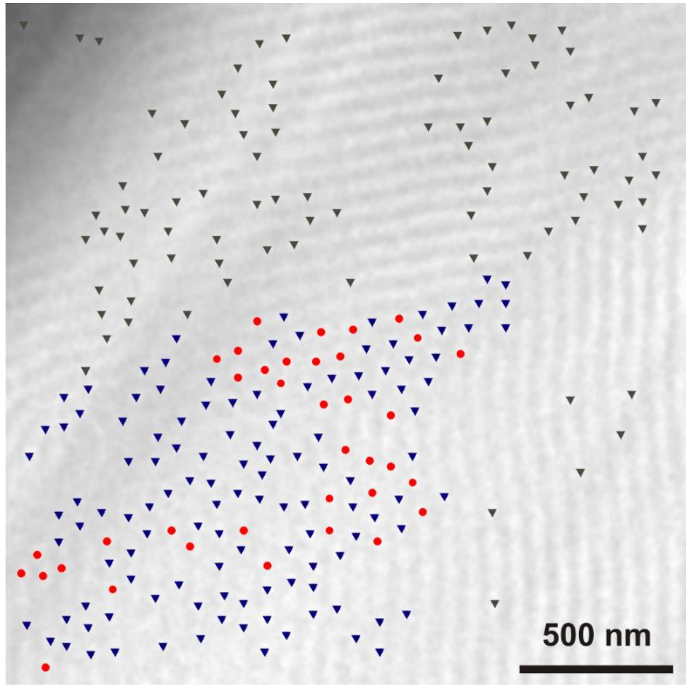


Inspect frame by hand (worst case)

Skyrmion counts:

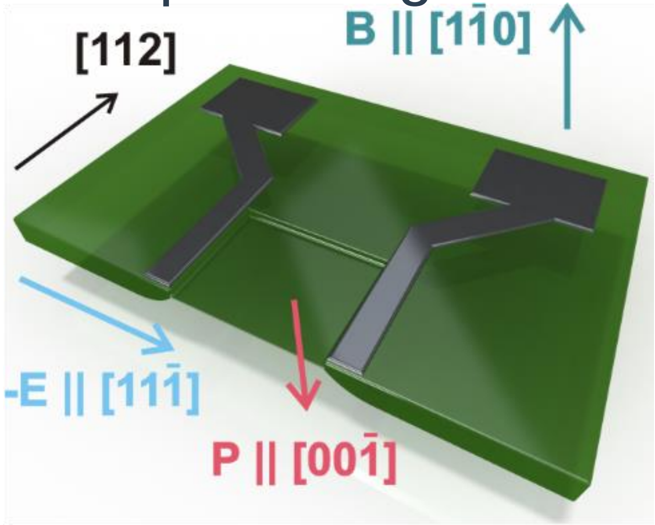
Hand inspection	90
Algorithm:	132
Missed:	37
Extra:	79

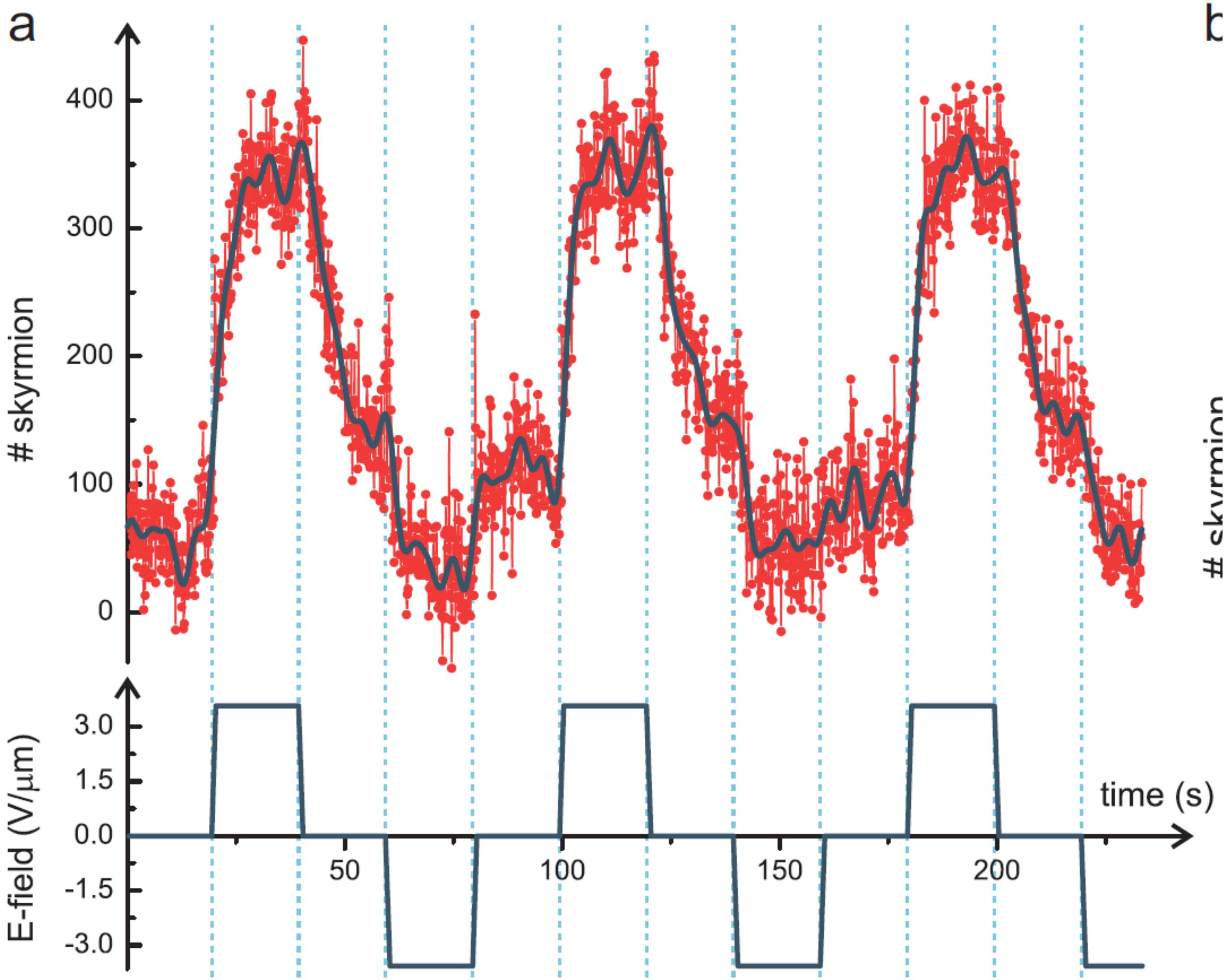
So we count skyrmions with an offset



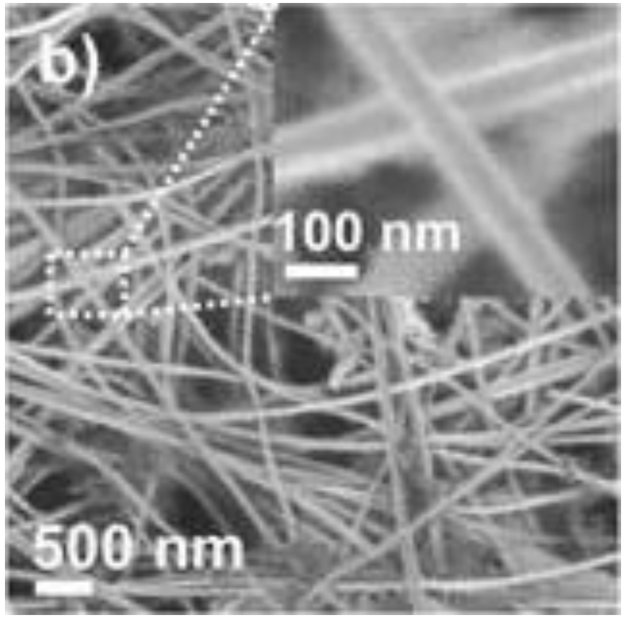
Reproducible writing and erasing

Sample configuration



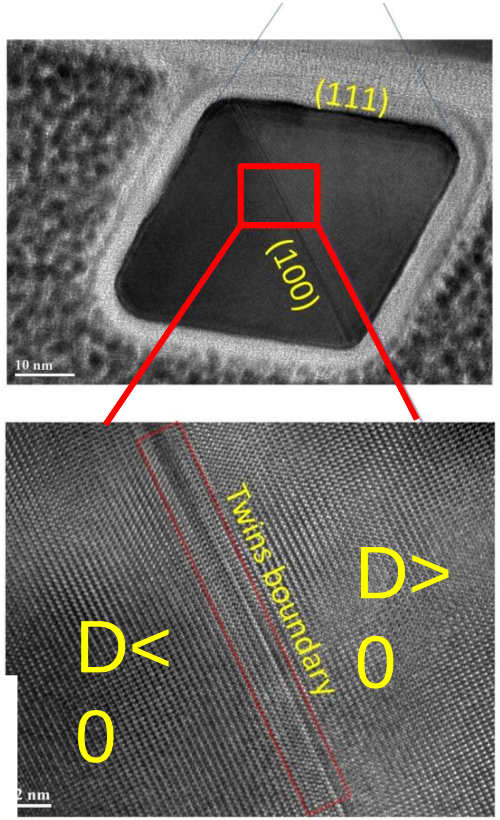


Nano-structured bulk materials: Ultra-narrow MnSi Nanowires

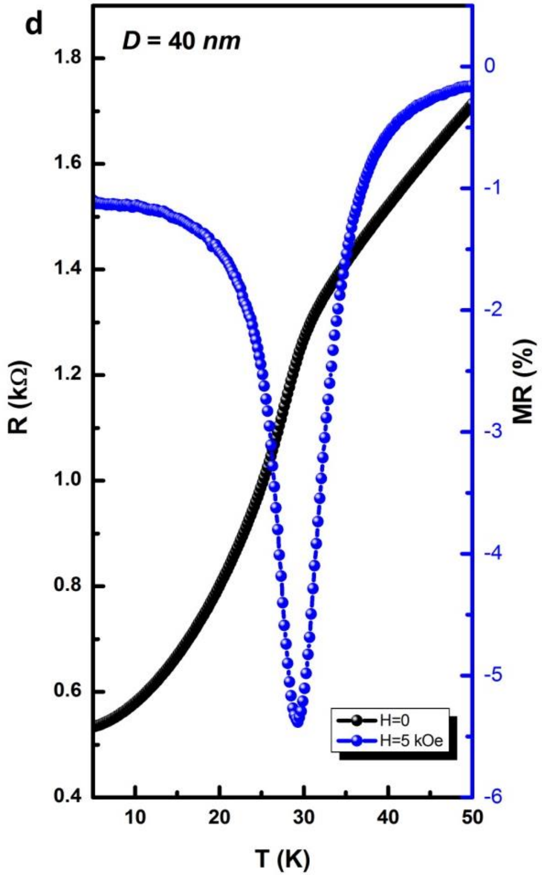


b

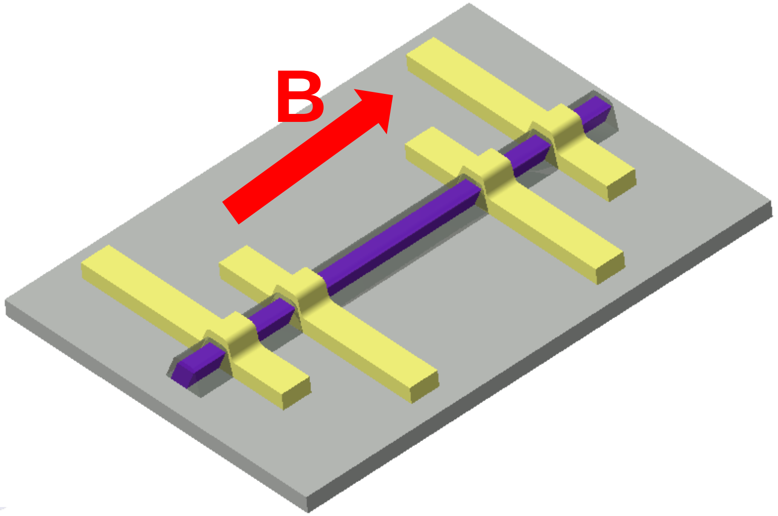
c

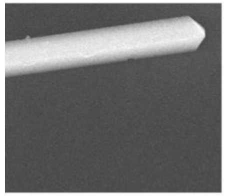


d



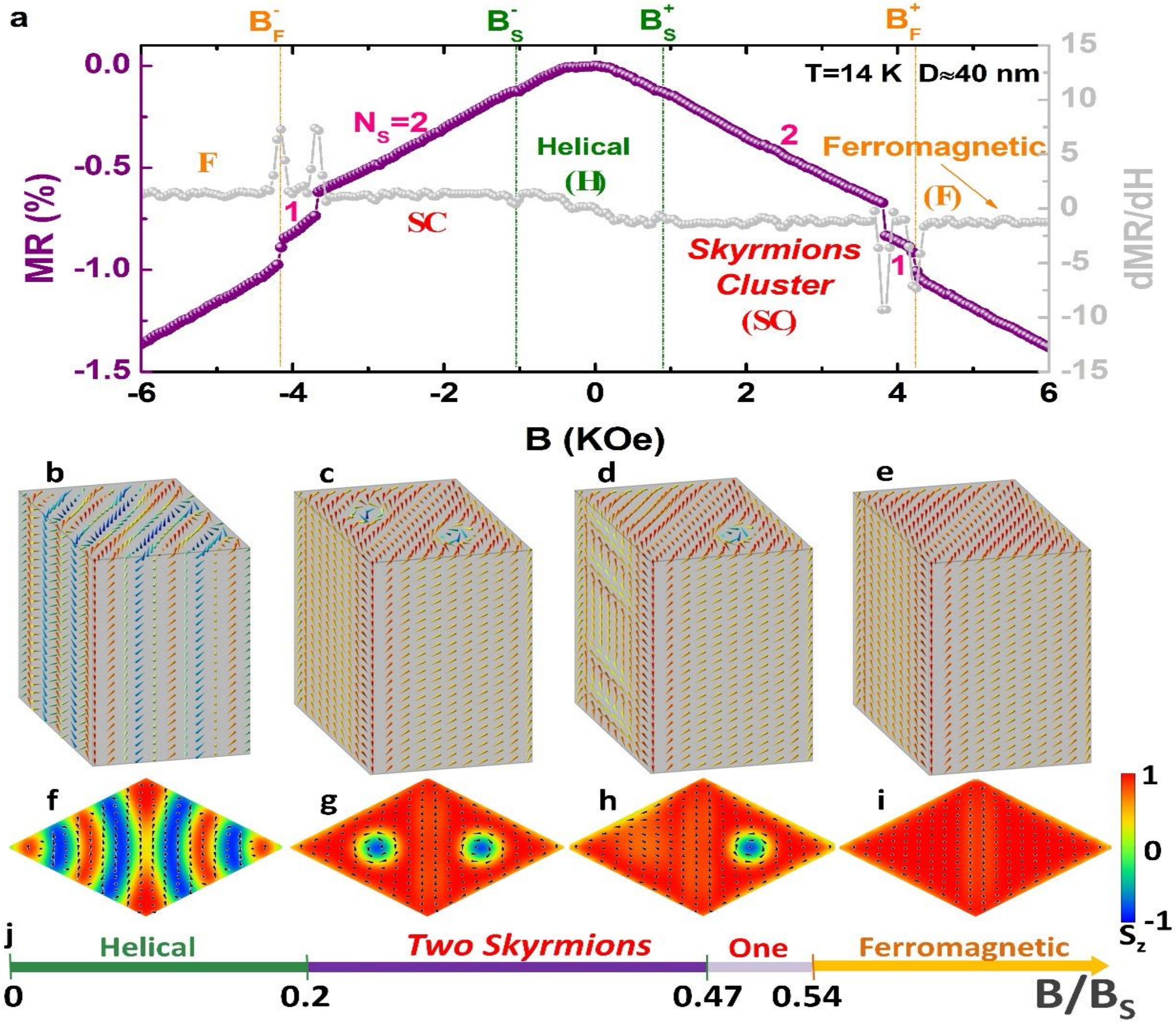
a





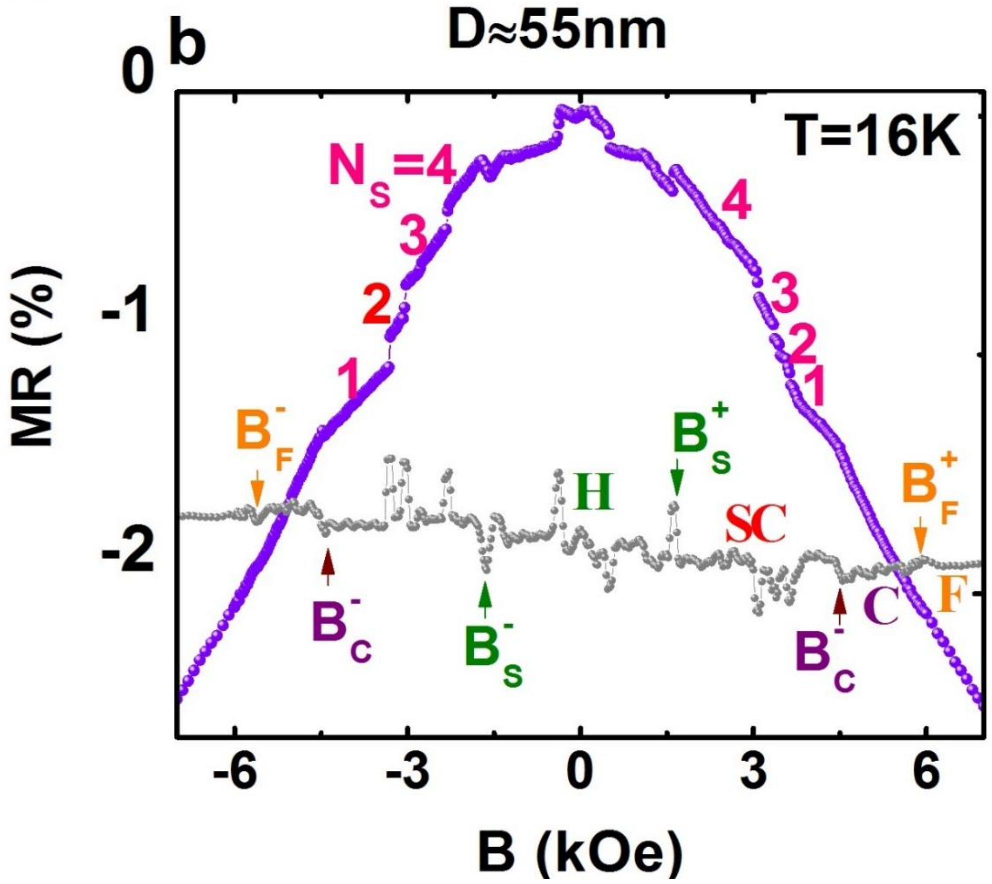
- High quality MnSi nanowires
- Wire width (40 nm) comparable to skyrmion diameter (18 nm)

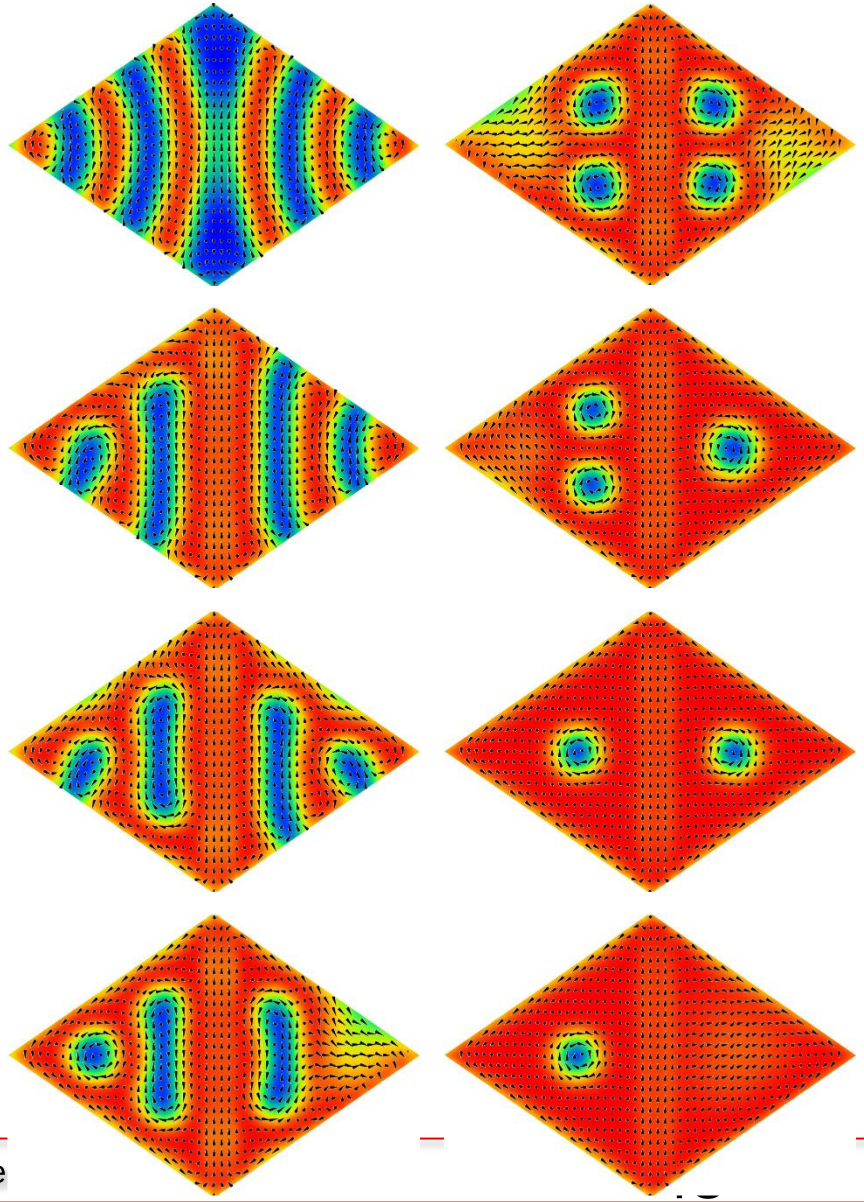
Magnetoresistance



Cascading Transitions of Skyrmion Cluster

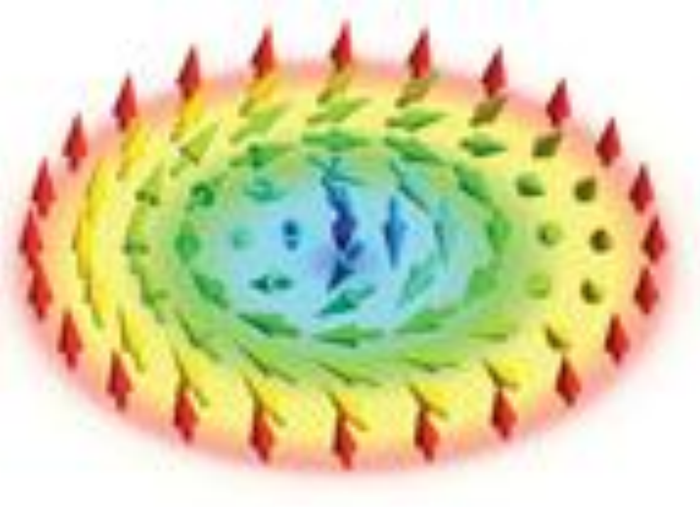
H. Du, ***JZ***, M. Tian, S. Jin et. al, Nature Commun. (2015)





F: Ferromagnet
C: Conical
S: Skyrmion
H: Helical

Skyrmions in Magnetism



- Skyrmions
  - Topological solitons
  - 3-Q magnetic structure
  - Models
- Skyrmion measurements
  - SANS, LTEM, STXM, MFM, SPSTM
- Skyrmion materials
  - Bulk materials: Chiral, Polar, Frustrated
  - Interface systems
- Skyrmion fundamentals
  - Skyrmion types, Lattice effects, dynamics, …
- Skyrmion control