PAUL SCHERRER INSTITUT


WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Jonathan White :: Laboratory for Neutron Scattering and Imaging :: Paul Scherrer Institute

Application of scattering techniques for the study of skyrmionics

13th May, 2019

Fasem

Joint French-Swedish school on X-rays and Neutrons techniques for the study of functional materials for energy

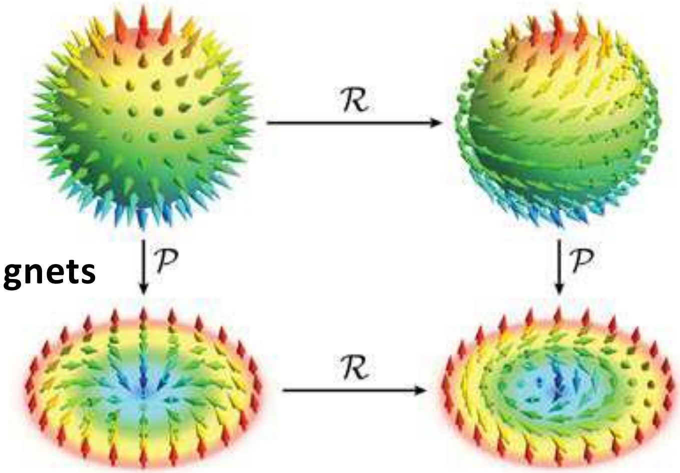
13-17 May 2019 Lund (Sweden)

Overview

- What are magnetic Skyrmions, and where do we find them?
  - Non-centrosymmetric crystals
  - Synthetic systems
- Application of scattering techniques
  - Neutron and resonant x-ray scattering
- Magnetic Skyrmions for Applications – ‘Skyrmionics’
  - Concepts, status and challenges
- Summary

Magnetic skyrmions

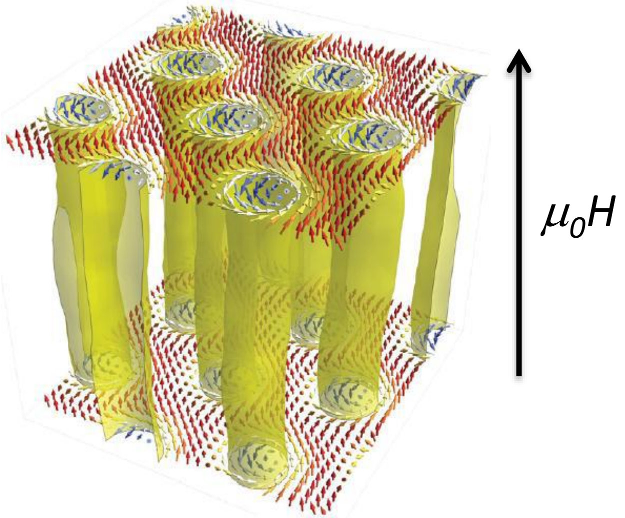
In 'original' sense as a 'particle'



In magnets

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

In magnets

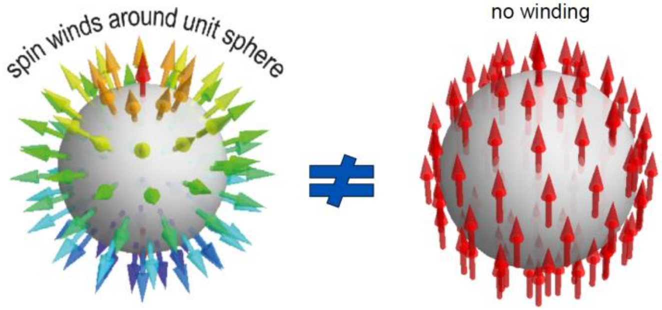


P. Milde *et al.*, Science **340**, 1076 (2013)

Intuitive picture for topological winding of skyrmion:

$$\int \mathrm{d}^2 r \left(\frac{\partial \hat{\boldsymbol{n}}}{\partial x} \times \frac{\partial \hat{\boldsymbol{n}}}{\partial y} \right) \cdot \hat{\boldsymbol{n}} = \pm 4\pi Q$$

|Q| = 1



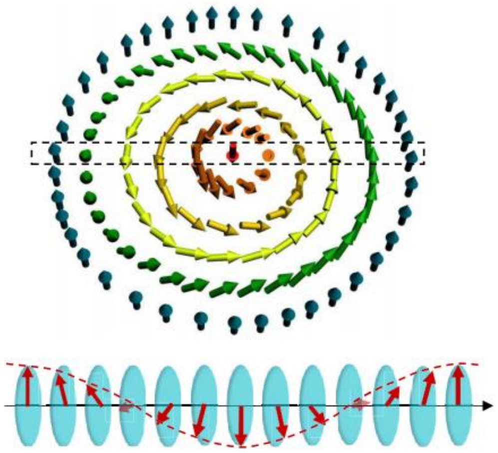
Courtesy: A. Rosch

Topologically non-trivial (countable objects)

Closed particle-like state (physical stability)

Skyrmion types

Bloch-type



Chiral (not polar)

Cubic* - *P*2_13 - *T

MnSi (2009)

FeGe (2010)

$Fe_{1-x}Co_xSi$ (2010)

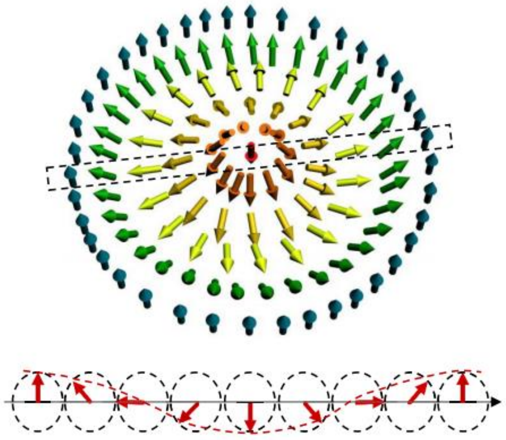
Cu_2OSeO_3 (2012)

Cubic* - *P*4_132 - *O

Co-Zn-Mn (2015)

$(Fe,Co)_2Mo_3N$ (2016)*

Néel-type



Polar (not chiral)

***Rhom.* - *R*3m - C_{3v}**

GaV_4S_8 (2015)

GaV_4Se_8 (2017)

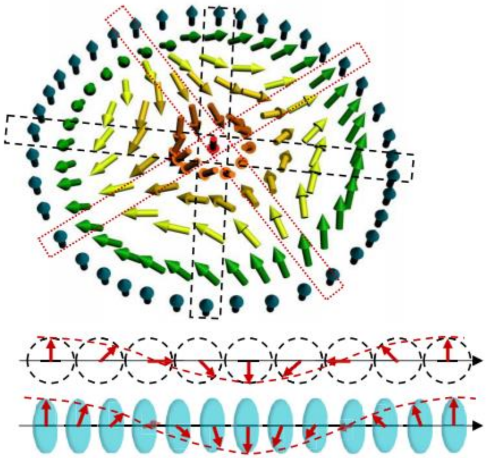
***Tetr.* - *P4cc* - C_{4v}**

$VOSe_2O_5$ (2017)

PdFe on Ir(111)*

Ir/Co/Pt multilayers* …

‘anti-skyrmion’



A.K. Nayak et al., Nature **548**, 561 (2017)

Neither chiral, nor polar

***Tetr.* - $I\bar{4}2m$ - D_{2d}**

$Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ (2017)*

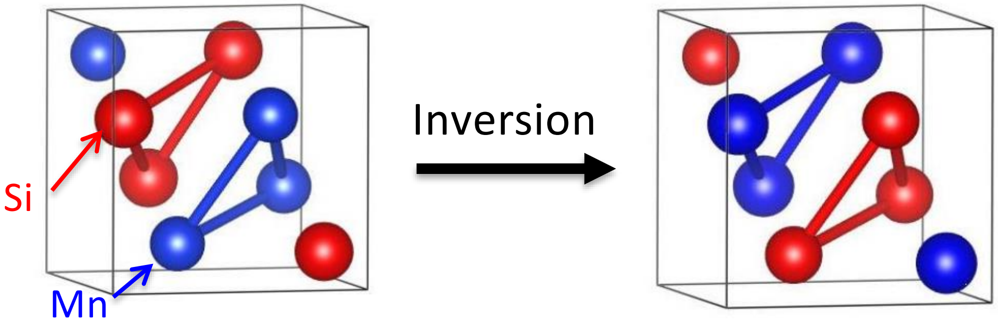
*** Thin film/plates, synthetic systems**

Common features:

- ***Dominant FM exchange***
- ***Broken inversion symmetry***

Effect of broken inversion symmetry

MnSi



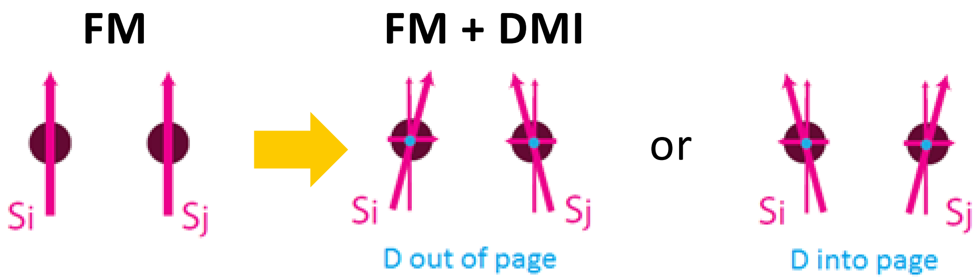
Physical Consequence in systems with SOC

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

FM interaction

Dzyaloshinskii-Moriya interaction (DMI)

I. Dzyaloshinskii, J. Phys. Chem. Sol. **4**, 241 (1958)
T. Moriya, Phys. Rev. **120**, 9 (1960)



- Spins cant by θ~D/2J
- Sign of *D* defines canting sense

Courtesy: H.M. Rønnow

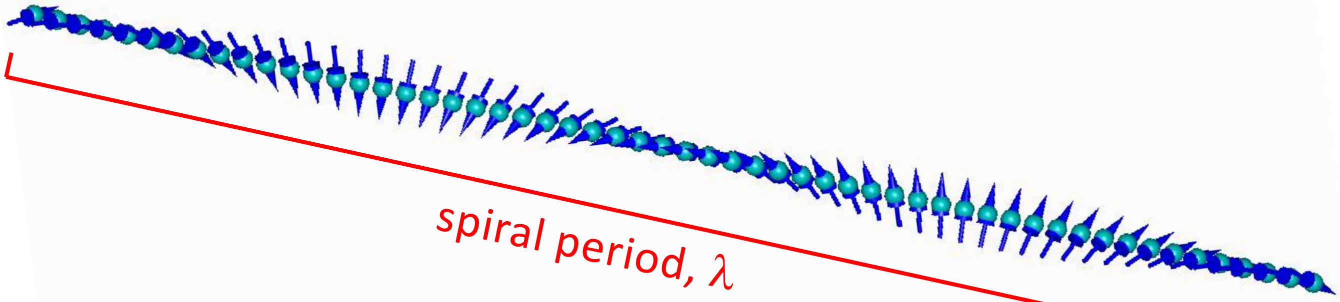
Long period spiral magnetism

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

J favours parallel moments

D favours perpendicular moments

Their competition leads to DMI spirals of long period with $\lambda = 2\pi a \frac{J}{D}$

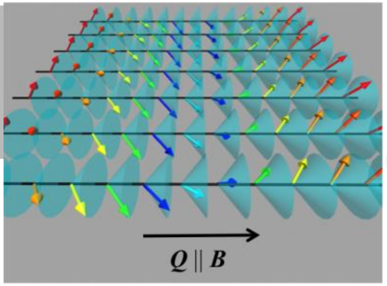


The DMI is a key ingredient of skyrmion formation

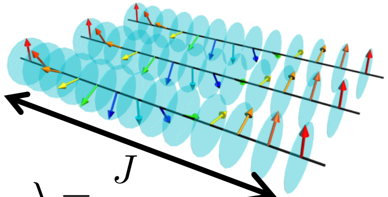
First observation in MnSi

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

Conical phase



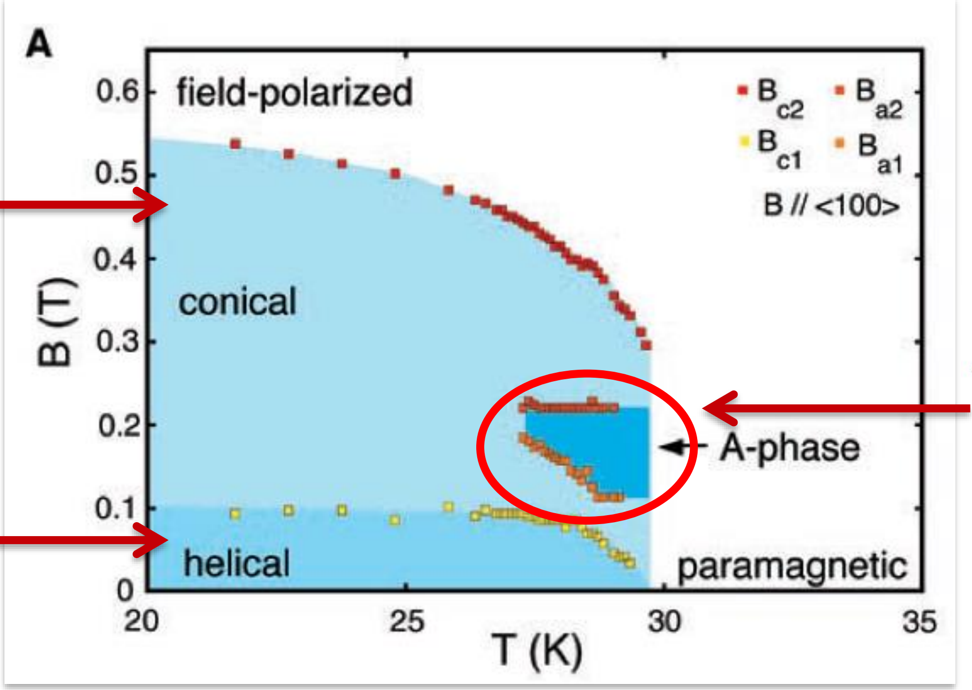
Helical phase



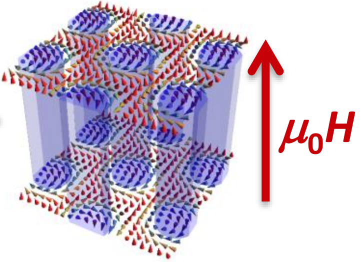
$$\lambda = \frac{J}{D}$$

= 18nm

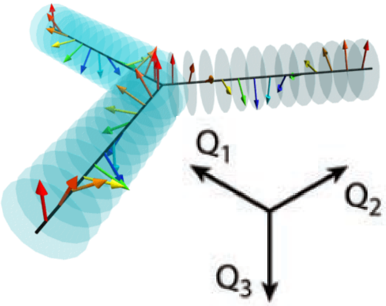
~ 40a_0

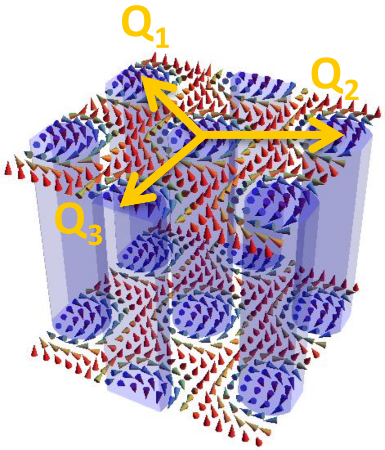


Skyrmion phase



'triple-***q***' spin model



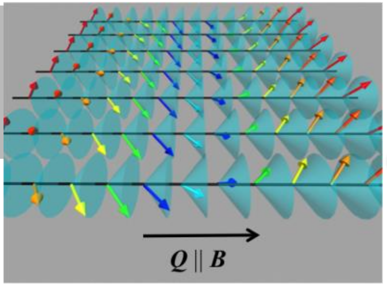


First observation in MnSi

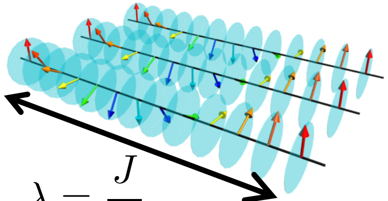
S. Mühlbauer *et al.*, Science **323**, 915 (2009)

Phase diagram

Conical phase



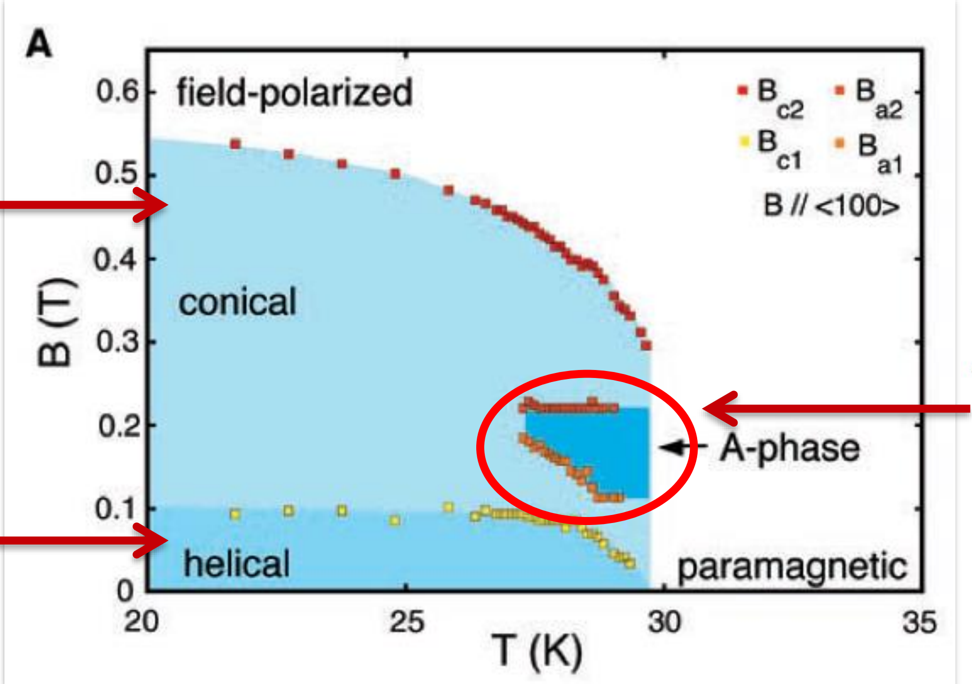
Helical phase



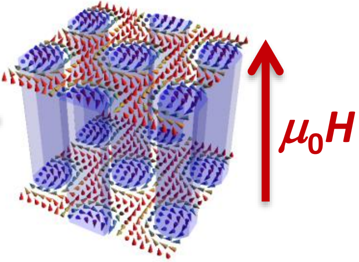
$$\lambda = \frac{J}{D}$$

= 18nm

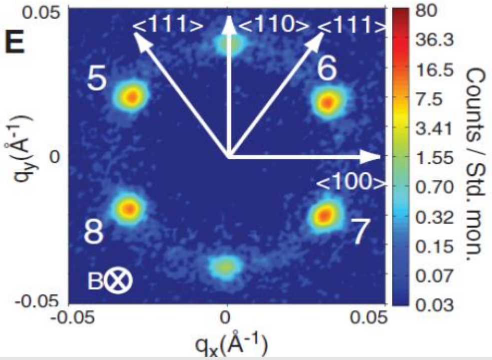
~ $40a_0$



Skyrmion phase

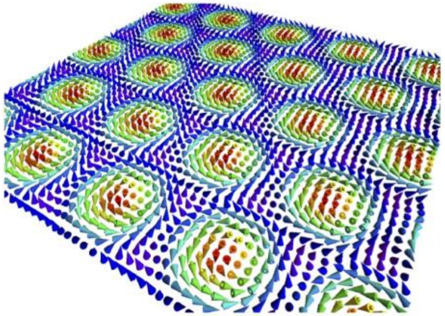


Reciprocal space (SANS)



F.T.

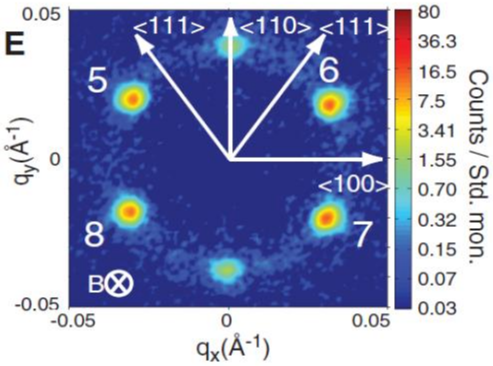
Real space?



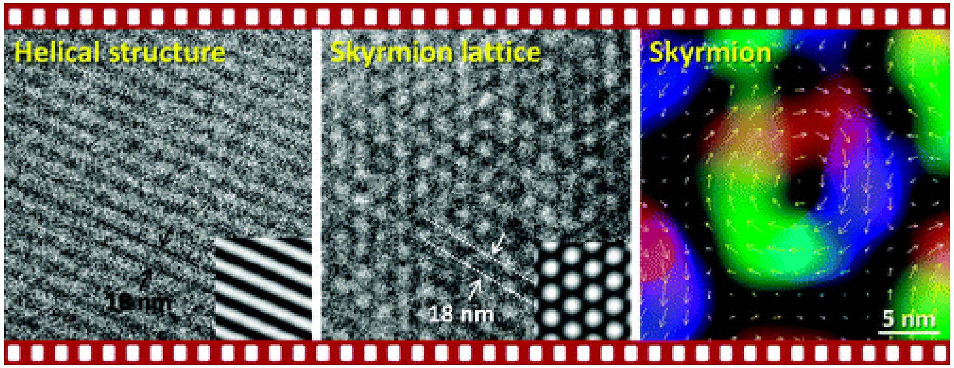
Neutron scattering does not directly 'see' individual skyrmions

Real-space imaging of the Skyrmion particle

SANS - bulk MnSi



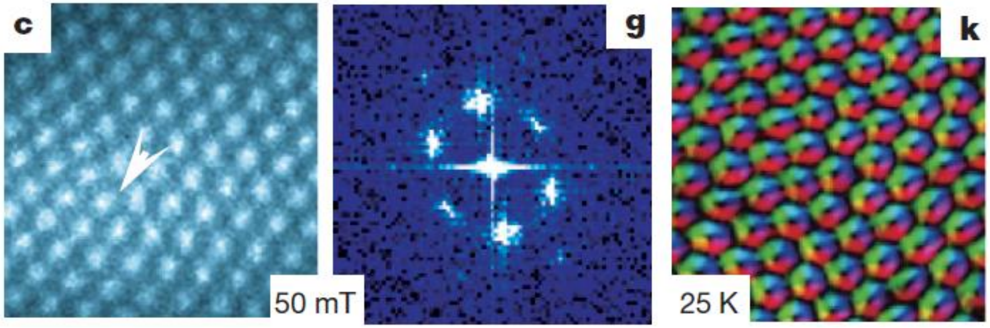
Spin-polarised TEM – thin samples MnSi



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

Lorentz force TEM – thin samples

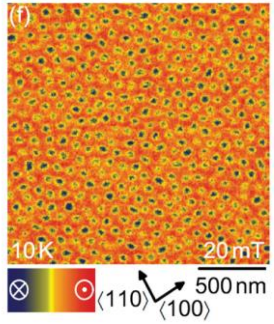
$Fe_{0.5}Co_{0.5}Si$ and FeGe



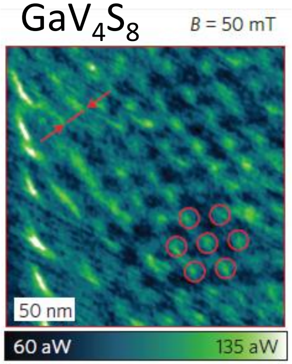
Z.X. Yu *et al.*, Nature **465**, 901 (2010), Nat. Mater. **10**, 106 (2011)

Magnetic tip AFM (MFM) – surfaces

$Fe_{0.5}Co_{0.5}Si$



GaV_4S_8

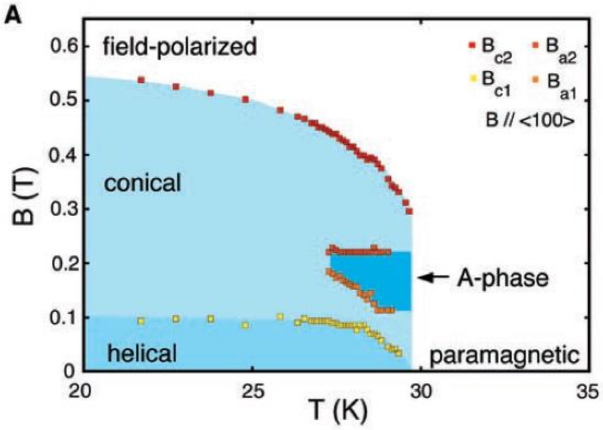


P. Milde *et al.*, Science **340**, 1076 (2013)

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

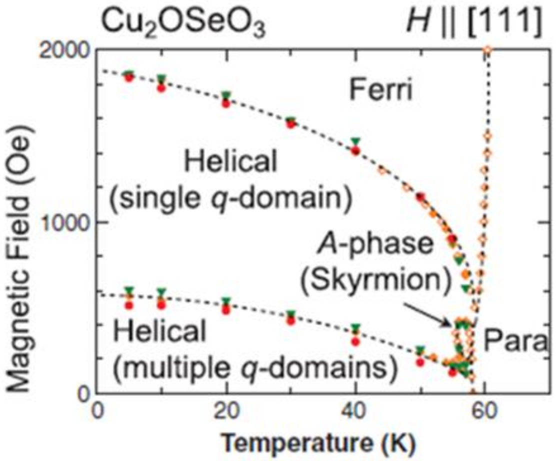
Skyrmion phase stability

MnSi



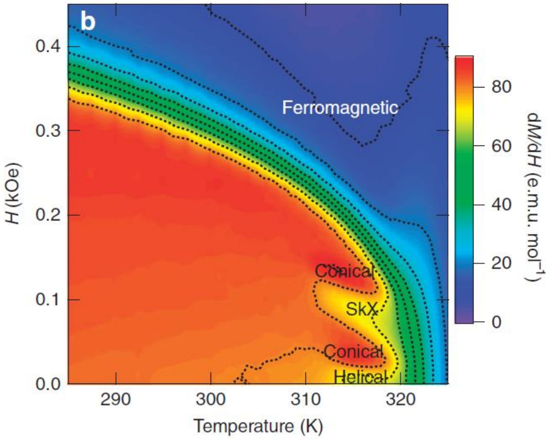
S. Mühlbauer *et al.*, Science (2009)

Cu_2OSeO_3



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

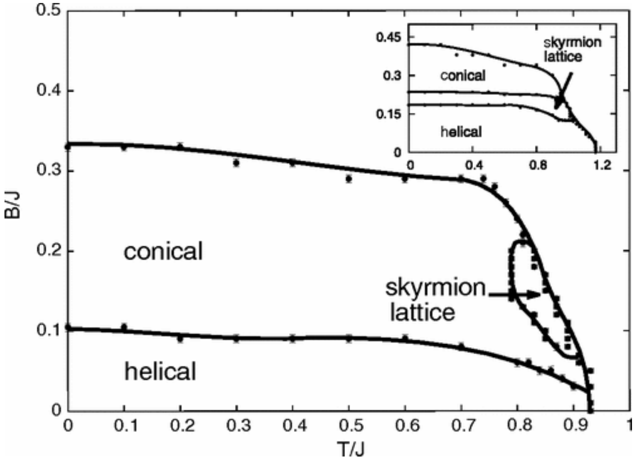
Co-Zn-Mn alloys

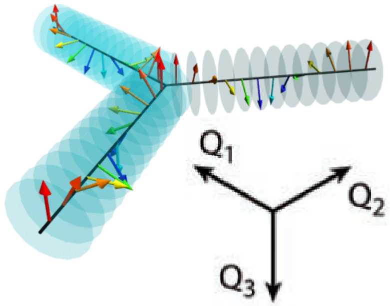


Y. Tokunaga *et al.*, Nat. Commun. (2015)

In mean-field theory, *J*, DMI and Zeeman terms only give a helical + conical phases

Monte-Carlo simulations with thermal fluctuations



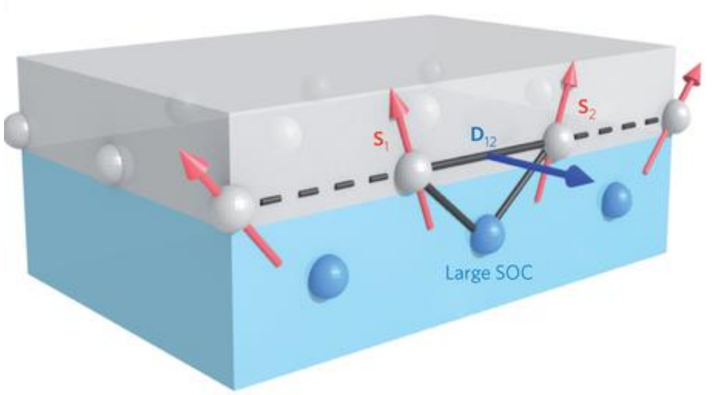


S. Buhrandt and L. Fritz Phys. Rev. B **88**, 195137 (2013)

Skyrmions stabilized by **DMI spiral magnetism + spiral mode-coupling + thermal fluctuations**

Synthetic systems: Metallic multilayers

Interfaces break inversion symmetry!



Interfacial DMI emerges between:

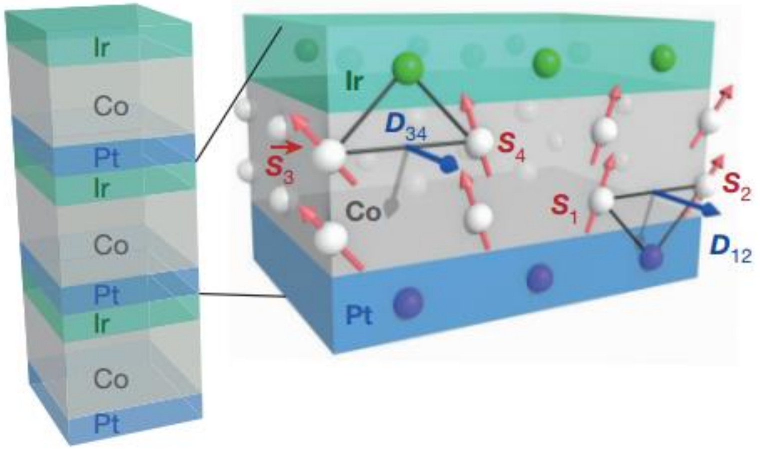
- Ferromagnetic layers, e.g. Co, CoFeB, Fe
- Heavy metal layers **with SOC**, e.g. Ir, Pt

Tune effective strength of DMI:

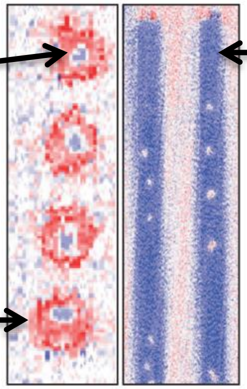
- Vary number of interfaces, and layer thicknesses
- **Additive interfacial chiral interactions** → strong DMI at room temperature

Ir/Co/Pt multilayer

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



Scanning X-ray transmission microscopy



90 nm diameter Néel-type Skyrmions

300 nm diameter disks

200 nm wide tracks

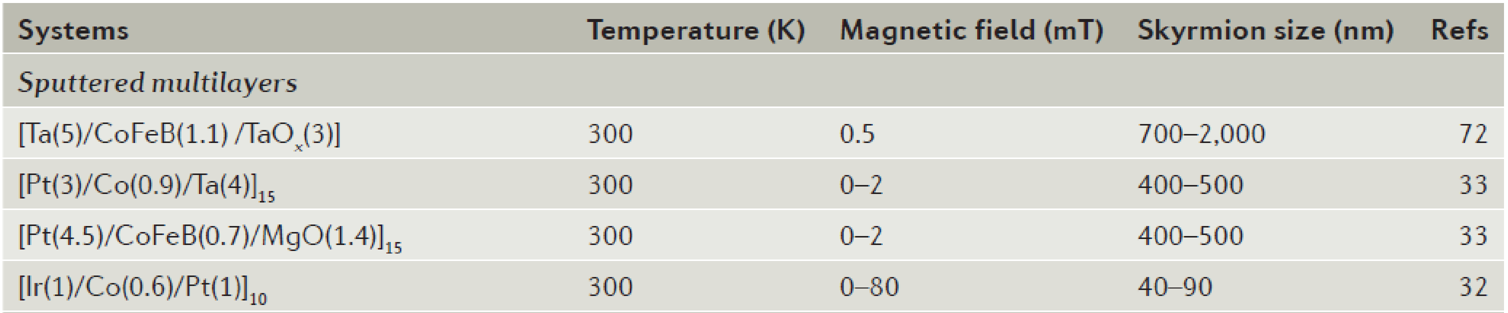
T = 300 K

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

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

Synthetic systems: skyrmion stability

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



Systems	Temperature (K)	Magnetic field (mT)	Skyrmion size (nm)	Refs
Sputtered multilayers				
[Ta(5)/CoFeB(1.1) /TaO$_x$(3)]	300	0.5	700–2,000	72
[Pt(3)/Co(0.9)/Ta(4)]$_{15}$	300	0–2	400–500	33
[Pt(4.5)/CoFeB(0.7)/MgO(1.4)]$_{15}$	300	0–2	400–500	33
[Ir(1)/Co(0.6)/Pt(1)]$_{10}$	300	0–80	40–90	32

Energetics

A. Siemens, *et al.* New J. Phys. **18**, 045021 (2016).

Generic Hamiltonian: $H = -J\sum_{<i,j>} S_i \cdot S_j - \sum_{<i,j>} D_{i,j} \cdot (S_i \times S_j) - \mu\sum_i B \cdot S_i - K\sum_i S_{i,z}^2,$

Exchange

DMI

Zeeman

Uniaxial anisotropy

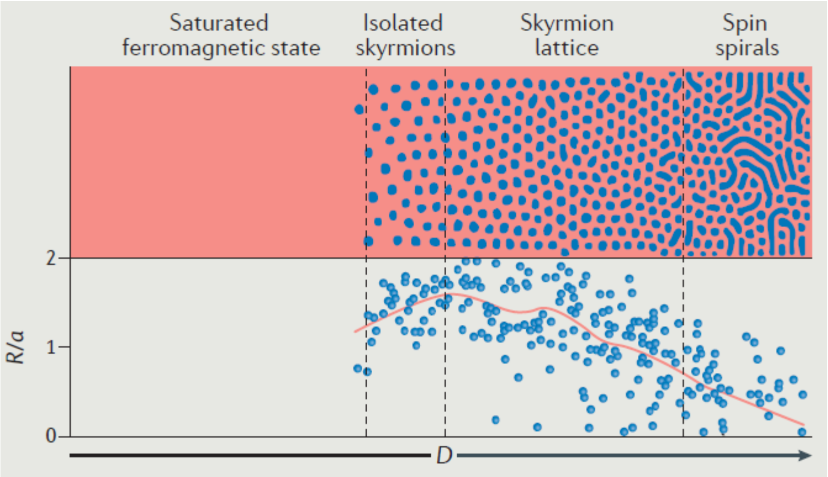
MC simulations:

Fixed $\mu B/J = 0.7$

$k_B T/J = 8.5 \times 10^{-3}$

$K = 0$

Skyrmion radius *R*



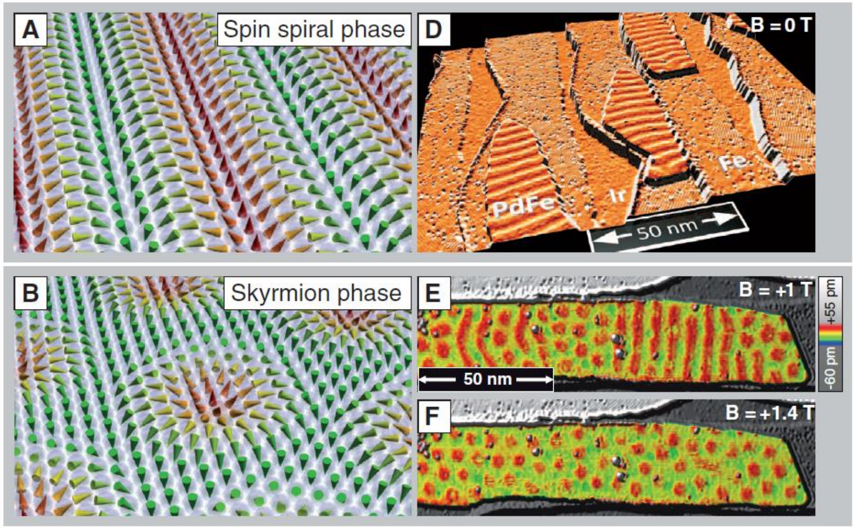
Increasing strength of DMI

Critical size of DMI for skyrmion generation in B=0:

$D_c = 4(JK)/\pi$

Synthetic systems: Ultra thin films

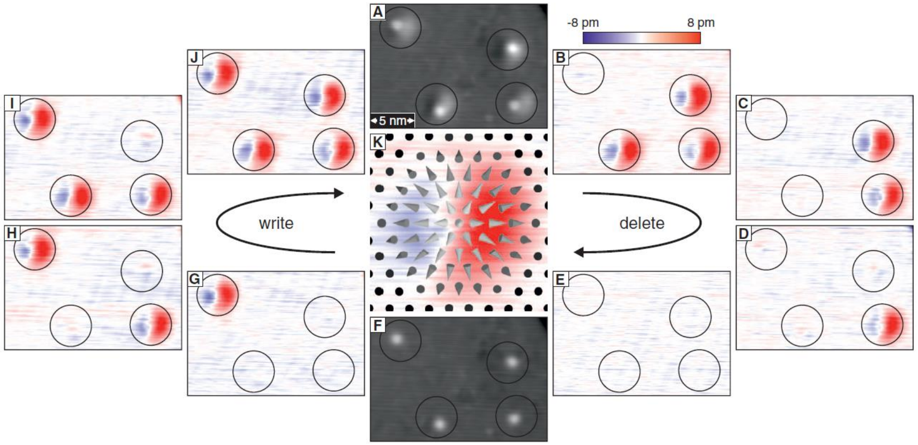
PdFe bilayer on Ir(111) – 3 nm diameter Skyrmions

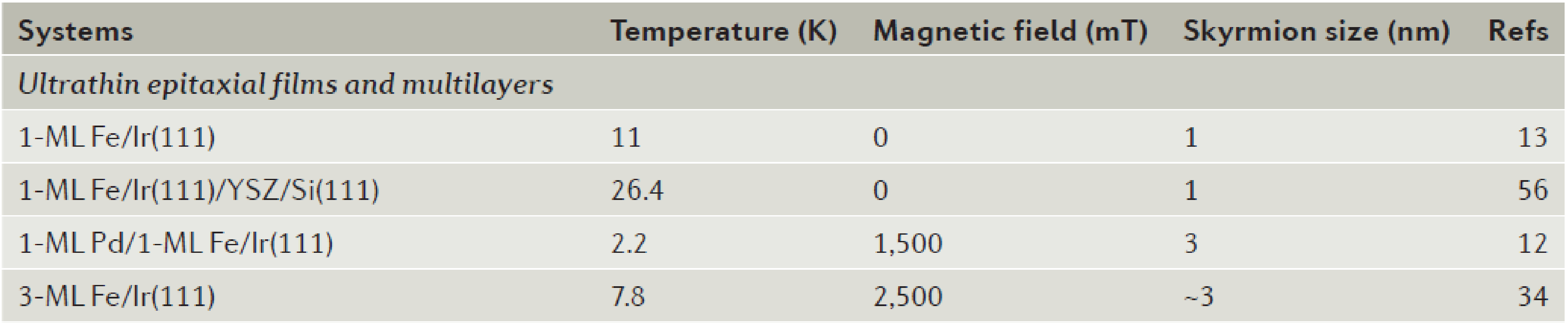


N. Romming *et al.*, Science **341**, 636 (2013)
S. Heinze *et al*., Nat. Phys., **7**, 713 (2011)

Writing and erasing of individual Skyrmions

SP-STM imaging



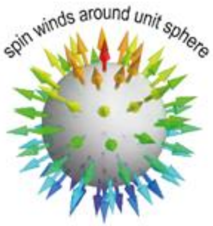


Systems	Temperature (K)	Magnetic field (mT)	Skyrmion size (nm)	Refs
Ultrathin epitaxial films and multilayers				
1-ML Fe/Ir(111)	11	0	1	13
1-ML Fe/Ir(111)/YSZ/Si(111)	26.4	0	1	56
1-ML Pd/1-ML Fe/Ir(111)	2.2	1,500	3	12
3-ML Fe/Ir(111)	7.8	2,500	~3	34

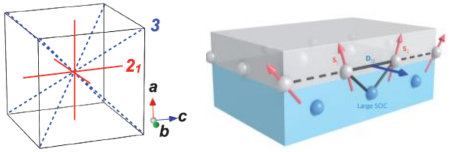
R. Wiesendanger, Nat. Rev. Mater. **1**, 16044 (2016)

Summary: Part 1

Skyrmions are topologically non-trivial magnetic objects described by an integer winding number.



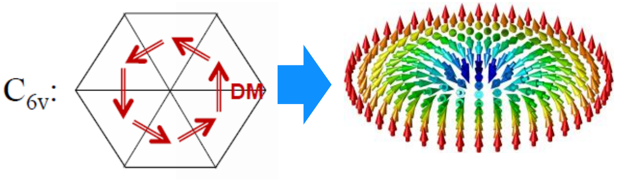
Found in some non-centrosymmetric crystals and various synthetic systems (metallic multilayers)



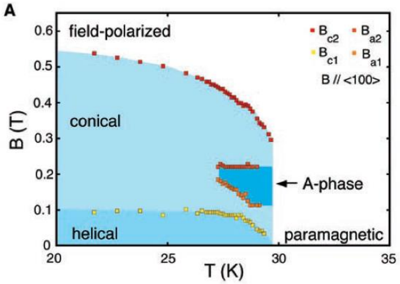
The Dzyaloshinskii-Moriya interaction (DMI) is a common aspect behind skyrmion formation.

$$H_{DM} = \sum_{i,j} D_{ij} \cdot (S_i \times S_j)$$

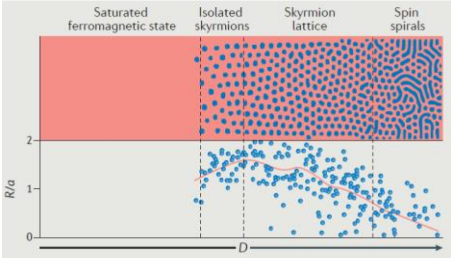
The skyrmion type is determined by the local symmetries; this determines the pattern of DMIs.



In non-centrosymmetric magnets, the skyrmion phase is stabilized by mode coupling and fluctuations just below to T_c.



In multilayers, skyrmions are stabilized by balance between exchange, DMI, Zeeman, and anisotropy energies. Balance is tunable by sample synthesis.



Overview

- What are magnetic Skyrmions, and where do we find them?
  - Non-centrosymmetric crystals
  - Synthetic systems
- Application of scattering techniques
  - Neutron and resonant x-ray scattering
- Magnetic Skyrmions for Applications – ‘Skyrmionics’
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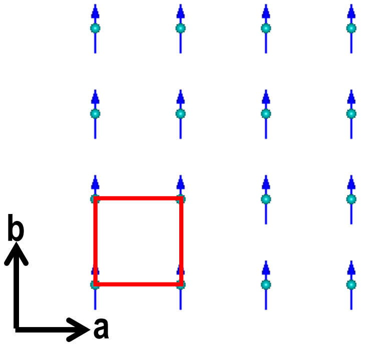
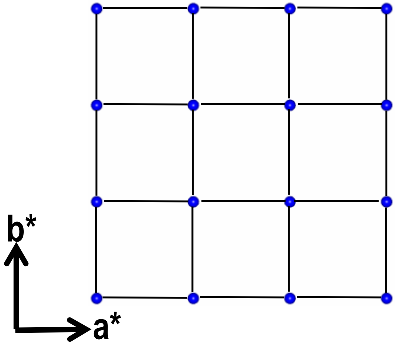
Reminder : magnetic order in reciprocal space

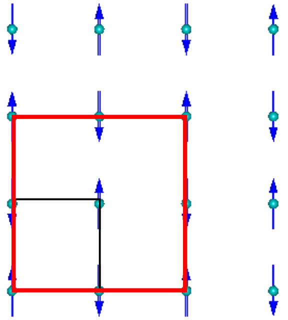
Ferromagnet

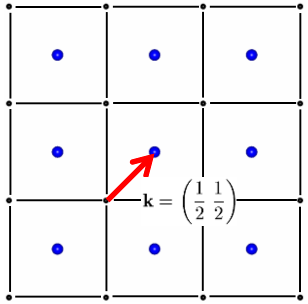




Magnetic scattering overlaps nuclear scattering in reciprocal space.

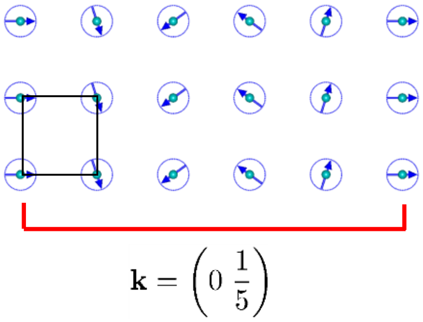
Commensurate antiferromagnet

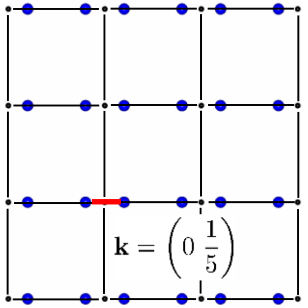




Magnetic scattering separated from nuclear scattering by $\mathbf{k}$.

Incommensurate structures



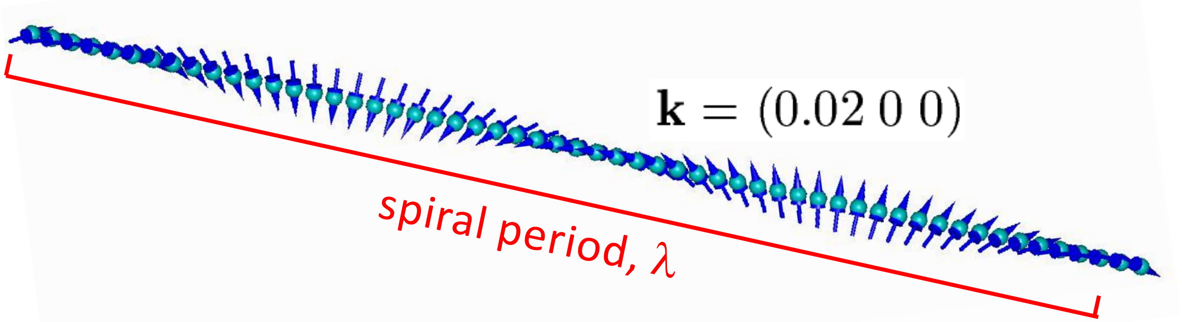


Magnetic scattering is separate from nuclear scattering.

Each node of the nuclear reciprocal lattice is flanked by a pair of satellites due to $\mathbf{k}$ & $-\mathbf{k}$.

Spirals in non-centrosymmetric magnets

Non-centrosymmetric magnets host long period spirals and skyrmions.

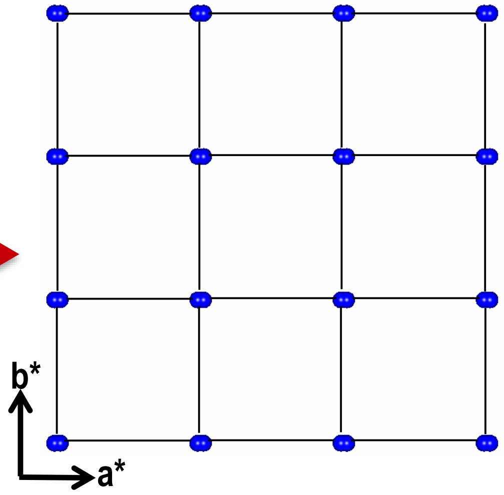


Material	**Skyrm?**	***T*** **(K)**	**λ (Å)**	**|Q| (Å^{-1})**
MnSi	✓	30	180	0.034
Cu_2OSeO_3	✓	58	620	0.010
$Co_8Zn_8Mn_4$	✓	300	1250	0.005
GaV_4S_8	✓	13	180	0.034
$TbMnO_3$	✗	42	21	0.300

More typical IC pitch

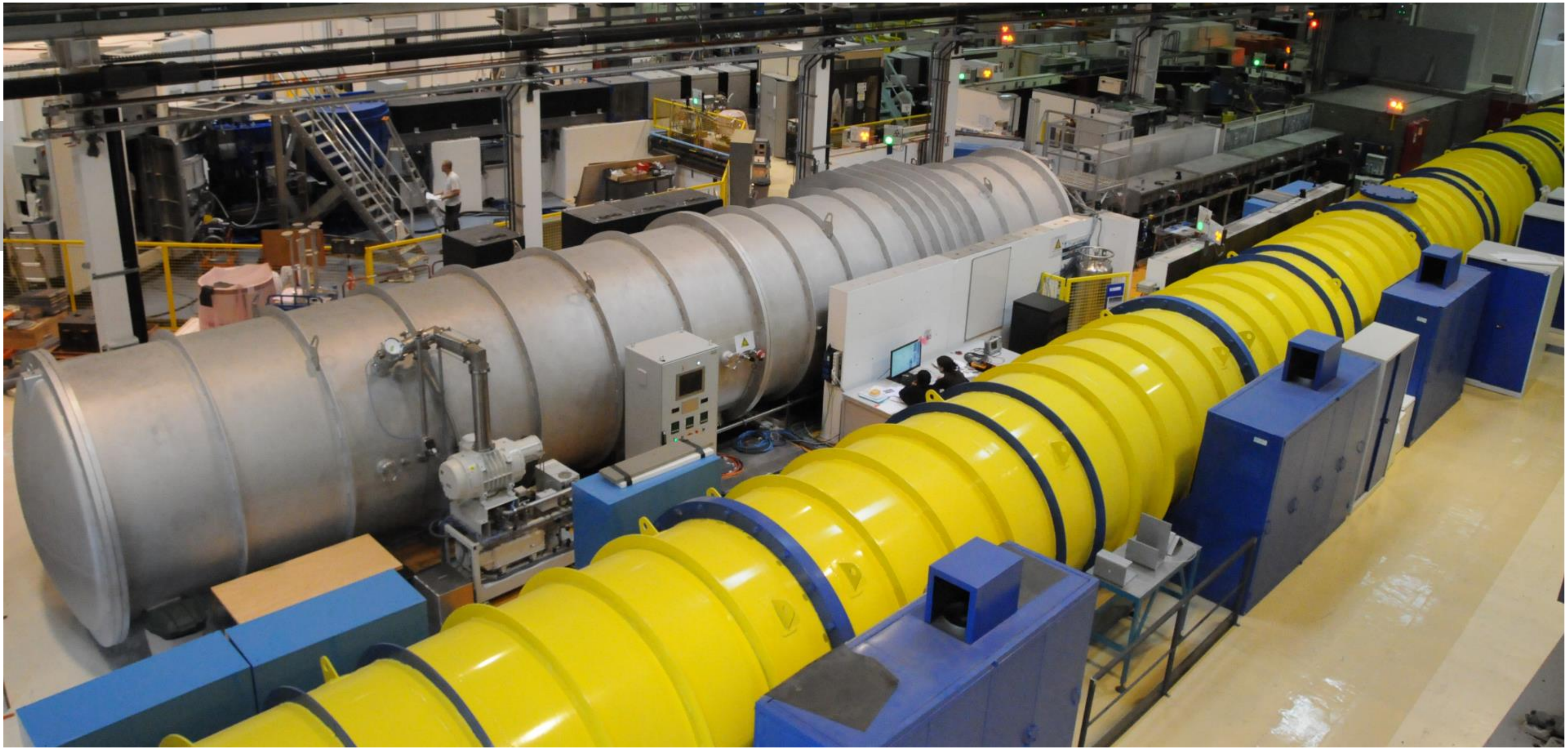
Very small (absolute) wavevectors

In reciprocal space



- **IC satellites are *very close* to reciprocal nuclear lattice points.**
- **Could appear FM with insufficient wave vector resolution.**

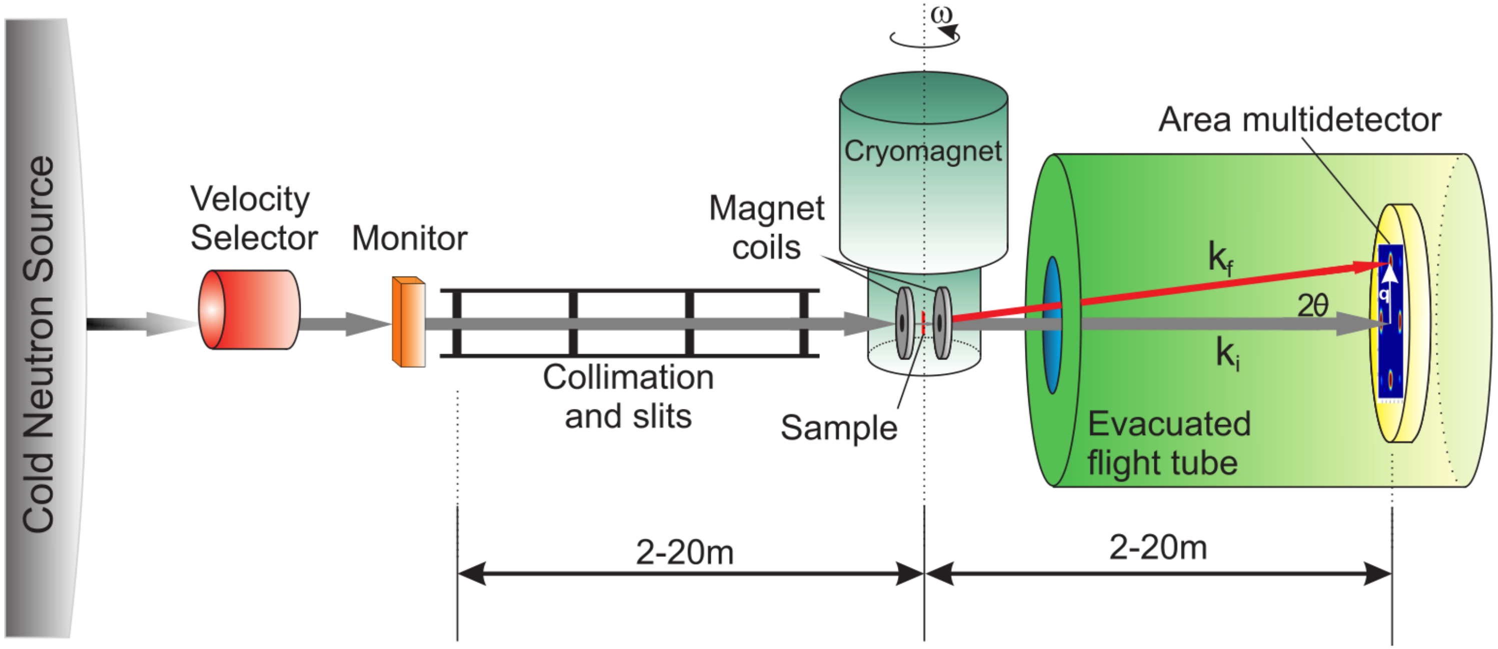
D33 SANS at the Institut Laue-Langevin (ILL), France



D33 @ ILL (Courtesy C. Dewhurst)

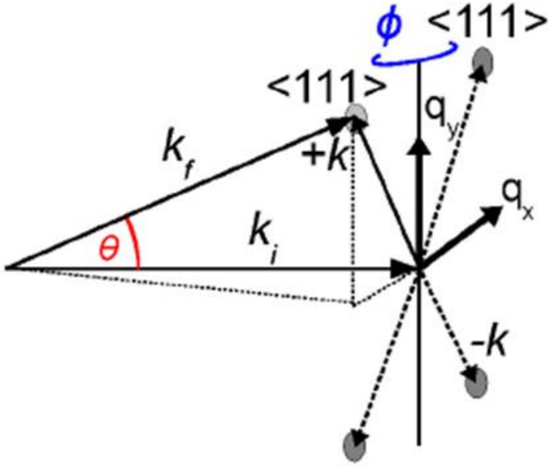
- **SANS provides the sufficient wavevector resolution at low momentum transfers.**
- **Neutron scattering is an established and sensitive probe of magnetic structures.**
- **Diffraction in transmission geometry**

Small-angle neutron scattering (SANS)

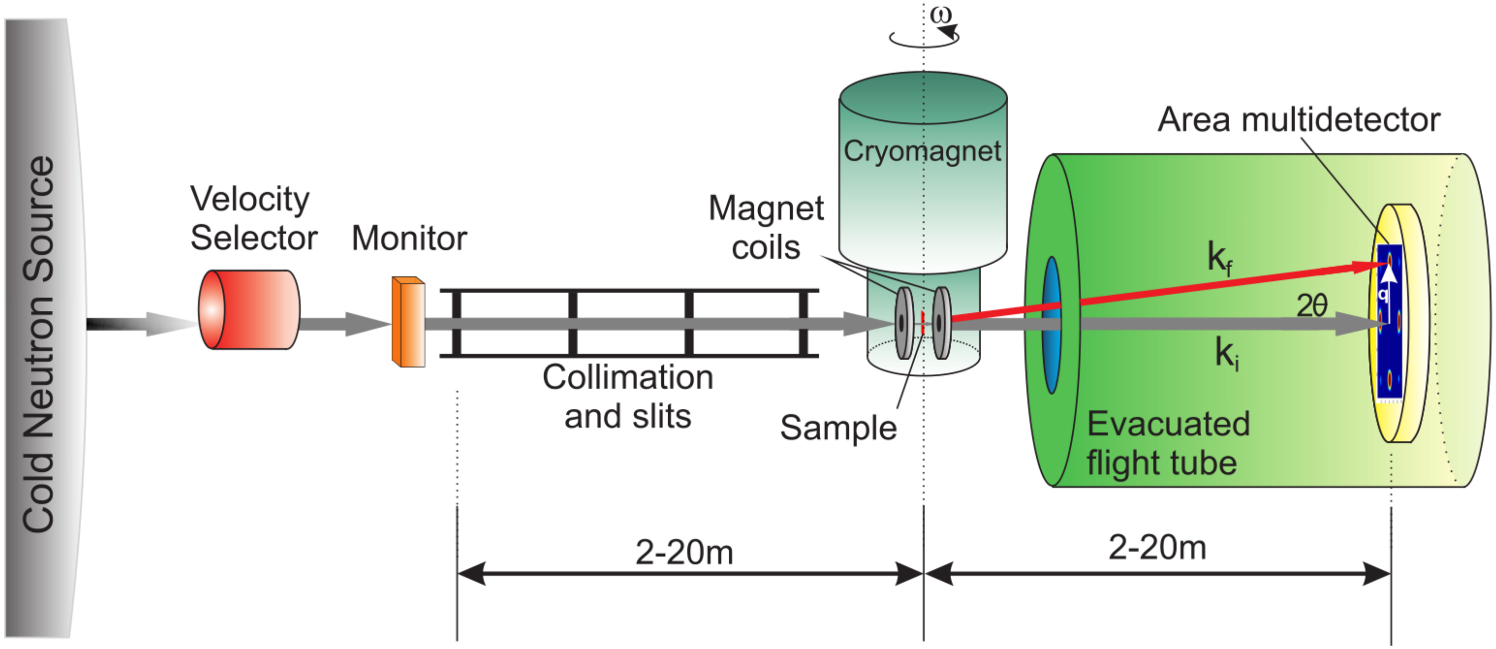


- **Length of instrument: 4-40 m**
- **Large period structures (nm to µm) → low *q***
- **Low q scattering range : 0.002 to 0.5 Å^{-1}.**
- **Small scattering angles: ~1-5°** $\lambda = 2d\sin\theta$
- **Neutron spin polarisation analysis**

Magnetic peaks in reciprocal Space

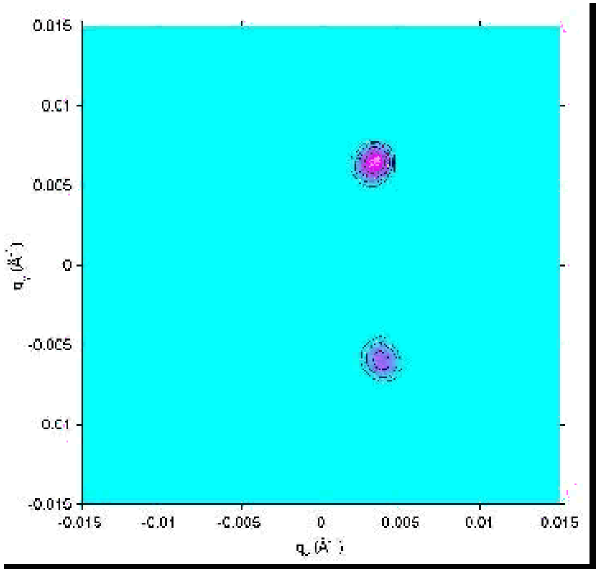


Small-angle neutron scattering (SANS)



‘Rocking curve’ measurement

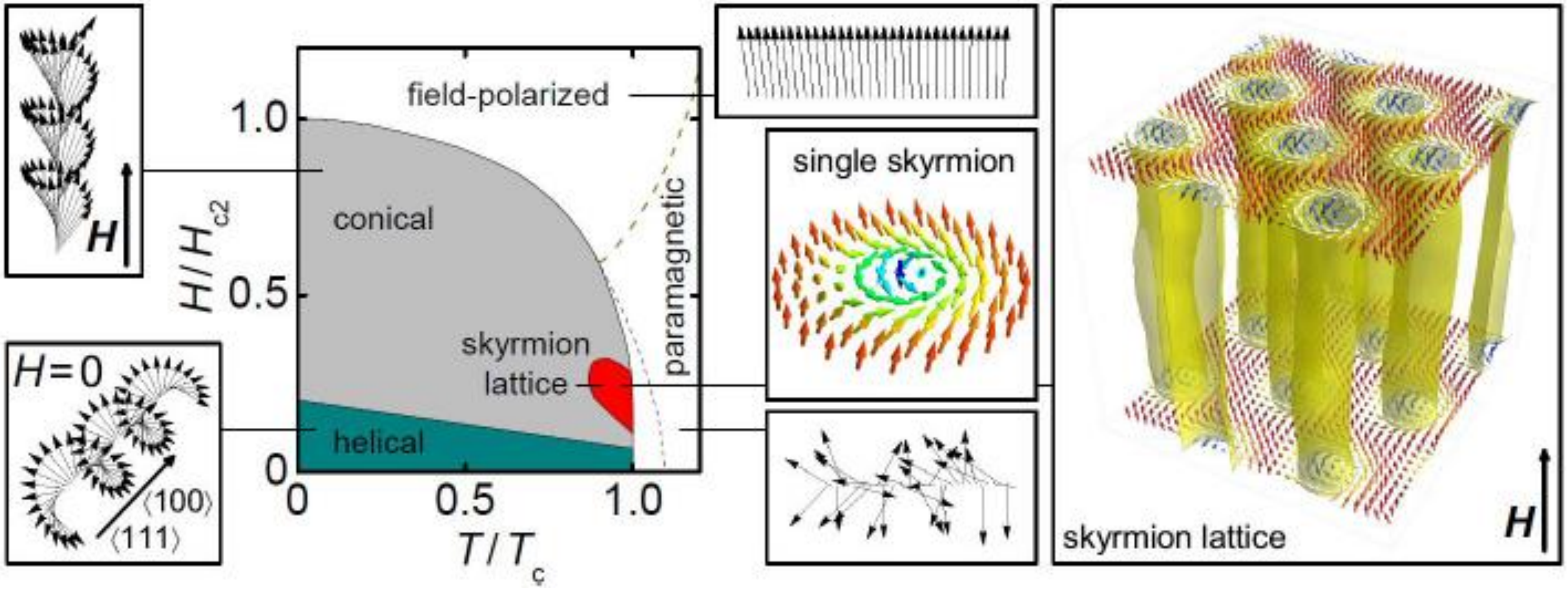
➔ Ewald sphere rotation



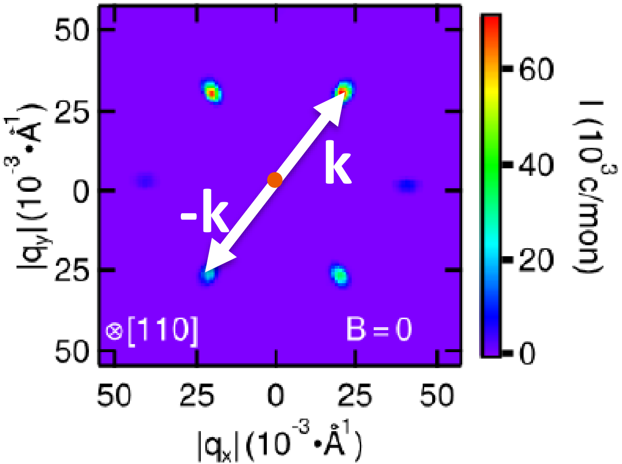
Bloch-type skyrmions in chiral magnets

e.g. MnSi, FeGe, Cu_2OSeO_3, $Co_8Zn_8Mn_4$ ..

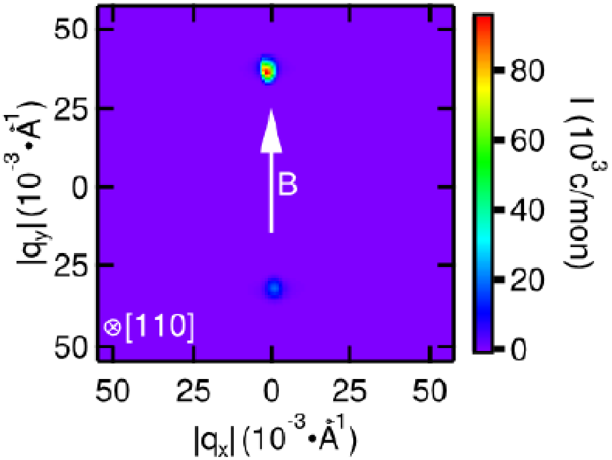
Slide courtesy J. Kindervater



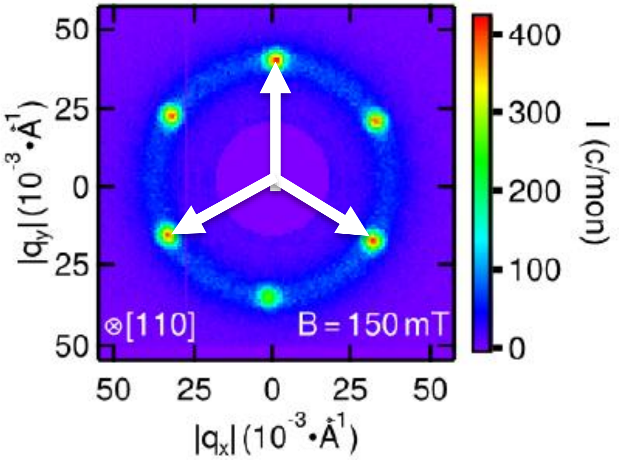
Helical (2 domains)



Conical



Skyrmion phase



X-ray magnetic scattering

$$f_n\left(\mathbf{k}_\mathrm{i},\mathbf{k}_\mathrm{f},\hbar\omega\right)=f_n^{(\mathrm{charge})}\left(\mathbf{Q}\right)+f_n^{(\mathrm{non-res})}\left(\mathbf{Q},\mathbf{k}_\mathrm{i},\mathbf{k}_\mathrm{f}\right)+f_n^{(\mathrm{res})}\left(\mathbf{Q},\mathbf{k}_\mathrm{i},\mathbf{k}_\mathrm{f}\right)$$

Atomic electrons
(Thomson scat.)

Sensitive to
magnetism

Few unpaired electrons contribute to the magnetic scattering vs. all electrons in the Thomson scattering.

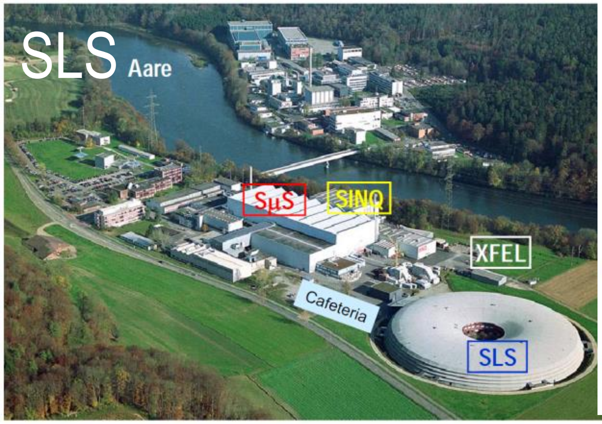
Non-resonant magnetic signal is weak:

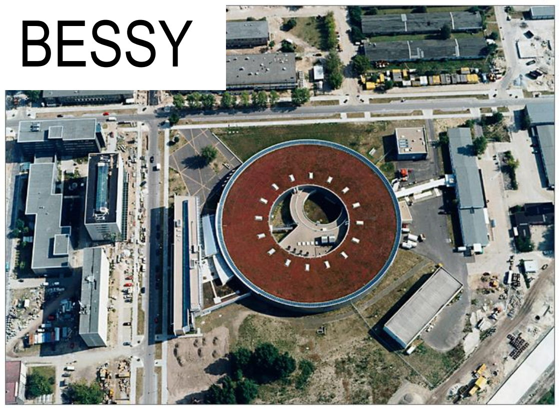
Intensity ratio between **charge** and
non-resonant magnetic scattering

$$\left(\frac{\hbar\omega}{mc^2}\right)^2\sim 10^{-4}$$ for 10keV x-rays

Help 1: Modern, high brilliance synchrotron sources (>10^{12} ph/mm^2/s)


ESRF


SLS


BESSY

Improving sensitivity to magnetism

Help 2: X-ray beam polarization analysis

Non-resonant scattering amplitude

$$f_n^{(\mathrm{non-res(mag)})} \propto i r_0 \left(\frac{\hbar\omega}{mc^2}\right)\left[\frac{1}{2}\mathbf{L}(\mathbf{Q})\cdot\mathbf{A} + \mathbf{S}(\mathbf{Q})\cdot\mathbf{B}\right]$$

Orbital density

Spin density

$$\mathbf{A} = 2\left(1-\hat{\mathbf{k}}_i\cdot\hat{\mathbf{k}}_f\right)(\hat{\epsilon}'\times\hat{\epsilon}) - \left(\hat{\mathbf{k}}_i\times\hat{\epsilon}\right)\left(\hat{\mathbf{k}}_i\cdot\hat{\epsilon}'\right) + \left(\hat{\mathbf{k}}_f\cdot\hat{\epsilon}'\right)\left(\hat{\mathbf{k}}_f\cdot\hat{\epsilon}\right)$$

$$\mathbf{B} = (\hat{\epsilon}'\times\hat{\epsilon}) + \left(\hat{\mathbf{k}}_f\times\hat{\epsilon}'\right)\left(\hat{\mathbf{k}}_f\cdot\hat{\epsilon}\right) - \left(\hat{\mathbf{k}}_i\times\hat{\epsilon}\right)\left(\hat{\mathbf{k}}_i\cdot\hat{\epsilon}'\right) - \left(\hat{\mathbf{k}}_f\cdot\hat{\epsilon}'\right)\times\left(\hat{\mathbf{k}}_i\cdot\hat{\epsilon}\right)$$

$\hat{\epsilon}$ incoming x-ray polarisation

$\hat{\epsilon}'$ outgoing x-ray polarisation

Polarization analysis allows

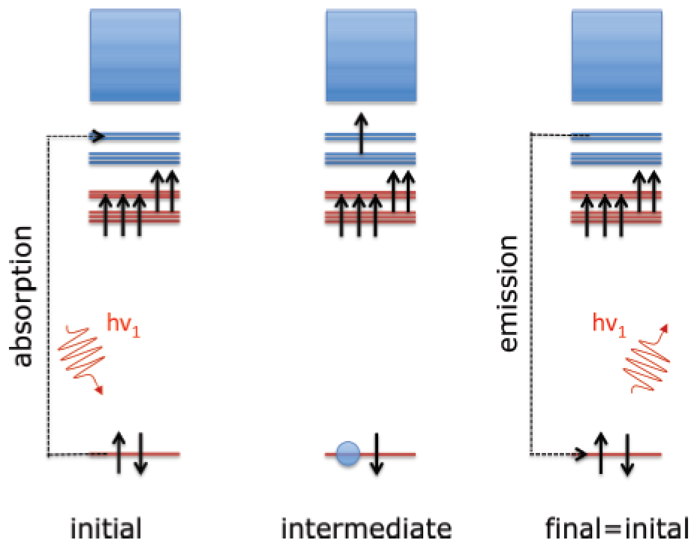
- **S/L separation (unlike neutrons)**
- **Distinction between magnetic and charge scattering**

Help 3: Wide x-ray energy selectivity

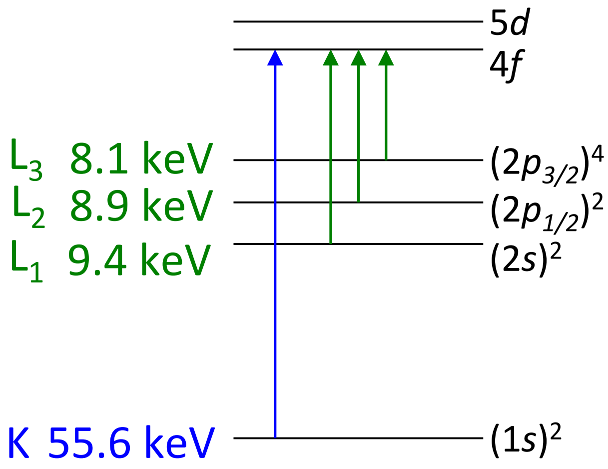
Tune the x-ray energy to match atomic transitions →
resonance effects →
leads to large magnetic intensities

Resonant X-ray scattering

'Virtual transition' process



Example : Ho (4*f* magnet)



- Photon excites a core-level electron into a partly filled shell.
- Spontaneously decays through the emission of an elastically scattered photon with particular polarization.
- Scattering amplitude dependent on the relative directions of the local *E*-field (incoming polarization) and local quantization axes (magnetic state of level probed)

Enhanced sensitivity to magnetism and elemental sensitivity

Most common transition is electric dipole $\Delta\ell = \pm 1$, e.g. 2*p* to 3*d*:

$$f_n^{(\mathrm{res})}(E1) = F^{(0)}\left(\hat{\epsilon}\cdot\hat{\epsilon}'\right) - \underline{iF^{(1)}\left(\hat{\epsilon}'\times\hat{\epsilon}\right)\cdot\boldsymbol{\mu}_j} + \underline{F^{(2)}\left(\hat{\epsilon}'\cdot\boldsymbol{\mu}_j\right)\left(\hat{\epsilon}\cdot\boldsymbol{\mu}_j\right)}$$

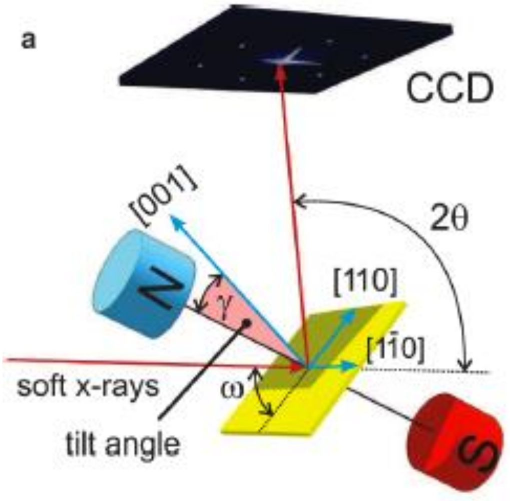
Resonant magnetic soft x-ray scattering

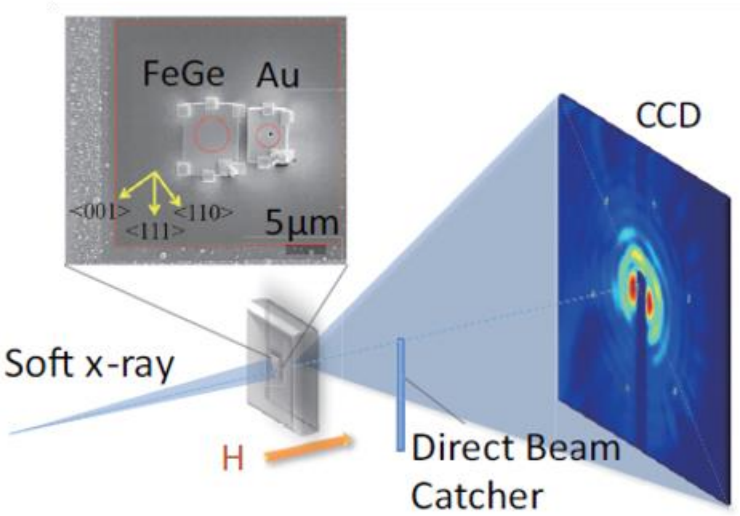
- **For Bloch-type skyrmion materials – excite 2*p* to 3*d* transitions of the TM element (the *L* edge), e.g. Fe in FeGe or Cu in Cu_2OSeO_3**
- **At the Fe $L_{2,3}$, x-ray energy is in the 'soft' range 480 – 950 eV, $\lambda \sim$ 15-20 Å**
- Avoid air absorption of x-ray beam by placing the entire diffractometer in vacuum (10^{-8} torr).
  - **Very restricted** wavevector range at soft x-ray energies.
  - Rare to be able to reach ***any*** Bragg spots, including structural peaks.
  - **But** possible to measure spiral/skyrmion peaks at low wavevectors (like SANS).

Reflection geometry (bulk crystals)

SAS transmission geometry (~100nm thick)

No pol. anal!





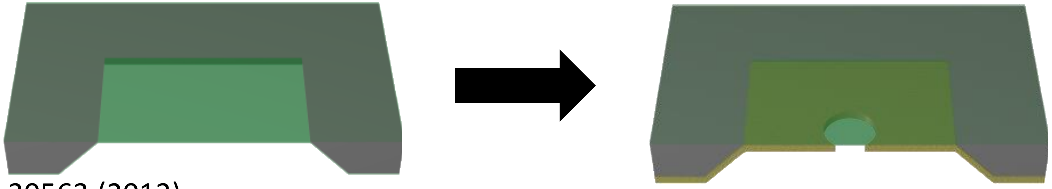
Y. Yamasaki *et al.*, Phys. Rev. B **92**, 220421 (2015)

Sample preparation for soft X-ray experiment

- Sample size is limited by the attenuation length of soft X-ray beam (~100 - 1000 nm thick for TM) and size of the beam (aperture size of 5-10 µm)
- Method: thin plates prepared by Focused Ion Beam (FIB) milling

Membrane preparation

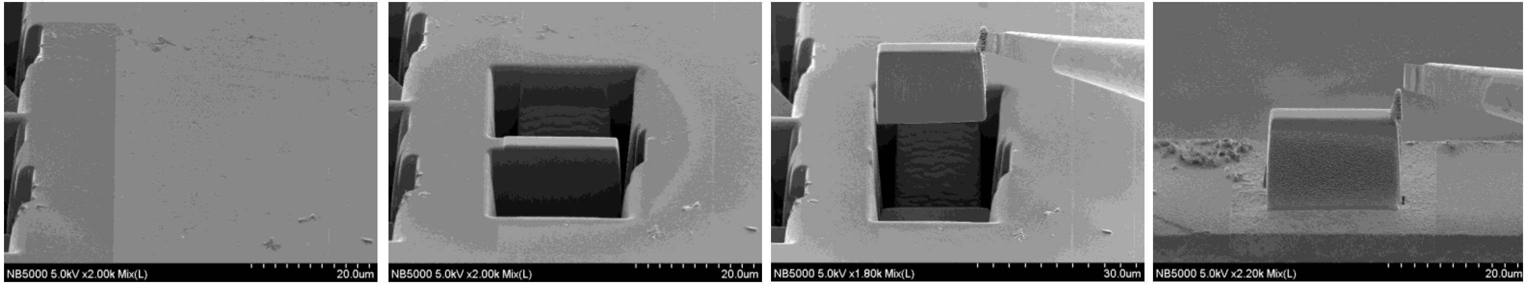
Si_3N_4 membrane: thickness of 200 nm (transparent for soft X-rays)



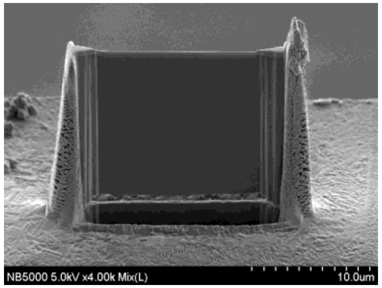
Coating membrane with a few micron of Au to block the beam

F. Büttner *et al.*, Optics Express **21**, 30563 (2013).

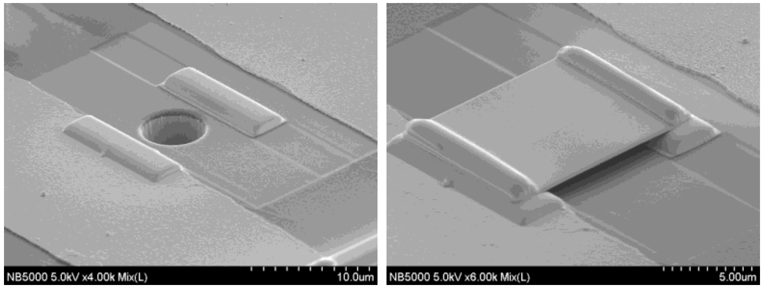
Specimen preparation by FIB



Bulk single crystal (FeGe)



Thinning process (100-200 nm)

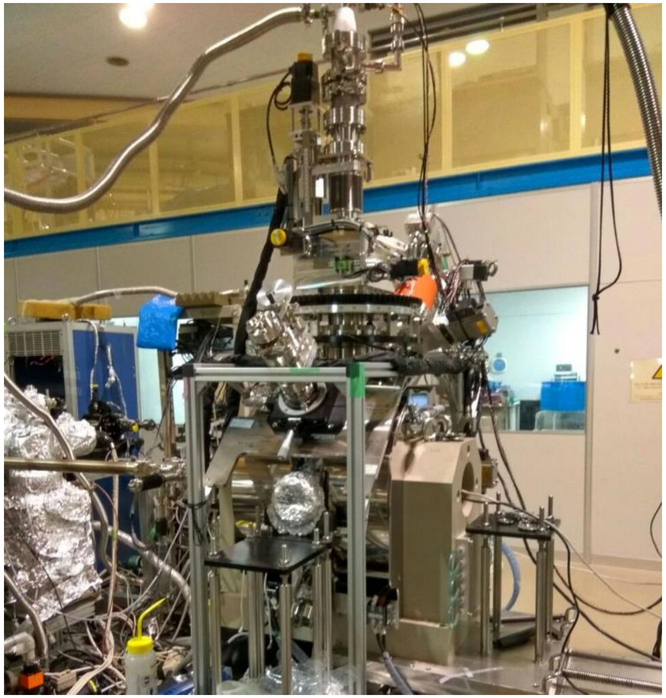


Making an aperture and specimen attachment to SiN membrane

Slide: courtesy V. Ukleev

Resonant soft x-ray scattering from FeGe

Slide: courtesy V. Ukleev

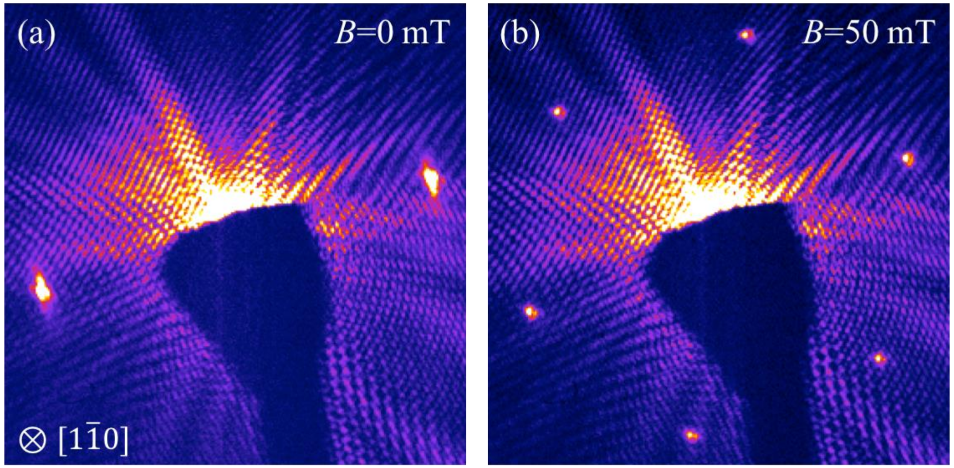


RSXS endstation, Photon Factory, BL-16A

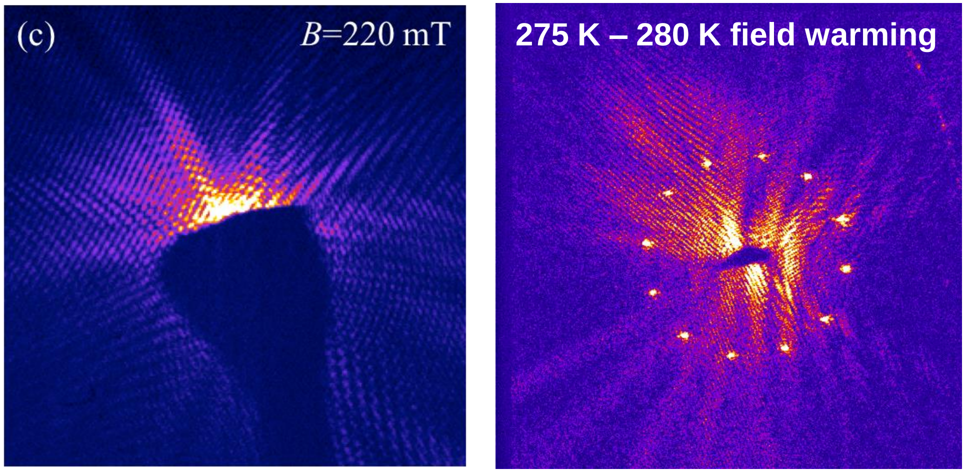
Y. Yamasaki *et al.*, Phys. Rev. B **92**, 220421 (2015)

V. Ukleev *et al.*, Quantum Beam Science **2**, 3 (2018)

T=275 K (a) Helical state **(b) Skyrmion lattice**



(c) Field-polarized / conical **(d) Sk. lattice field-warming**



3 s per exposure

c.f. SANS pattern takes 10-30 mins!

Summary: Part 2

Compare between x-rays and neutrons for magnetism

Pros

Resonant X-rays

- **Improved sensitivity due to high flux**
- **High spatial resolution**
- **Spatial and temporal beam coherence**
    - **Real-space imaging**
    - **Pump-probe**
- **Element specificity**
- **Electron shell selective**
- S/L separation
- **Tiny crystals (< 1mg) /surfaces/thin films**
- **Identification of magnetic ions**
- Wide x-ray energy tunability
- Polarimetry in reflection geometry

Cons

- **Resonance edge may not accessible**
- Hard x-rays (indirect probe states)
- **Soft x-rays (very limited Ewald sphere)**
- Data modelling is complex
- Full magnetic structure refinements not possible by resonant x-rays.
- Heat loading can prevent low *T*s.
- **For thin samples, unavoidable strain effects with *T* variation.**

Neutrons

- **High magnetic sensitivity**
- **Polarization techniques**
- **Highly penetrating probe of bulk samples**
- **Highly penetrating probe of complex sample environments**
- **Magnetic structure calculations simpler**
- **Bulk crystals/thin film stacks**
- **Strain free bulk measurements.**

- **Flux limited**
- **Insensitive to tiny magnetic moments**
- **Low spatial resolution**
- Some elements are too neutron absorbing to study e.g. Dy, Gd, B
- Magnetic scattering not element specific
- **Needs larger sample masses (> 2 mg)**
- **Challenging to study surfaces and thin films.**
- Low temporal resolution

Overview

- What are magnetic Skyrmions, and where do we find them?
  - Non-centrosymmetric crystals
  - Synthetic systems
- Application of scattering techniques
  - Neutron and resonant x-ray scattering
- Magnetic Skyrmions for Applications – ‘Skyrmionics’
  - Concepts, status and challenges
- Summary

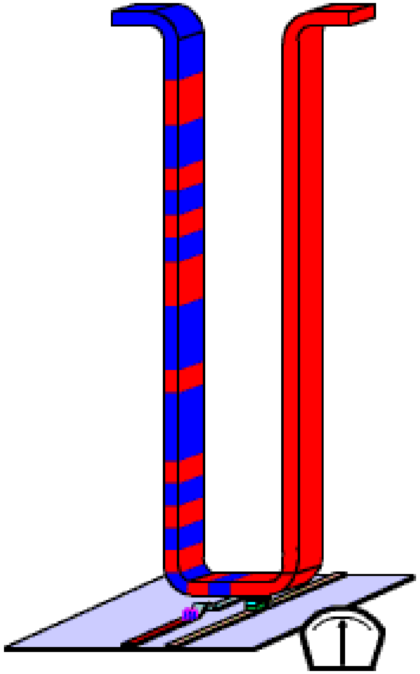
Magnetic Skyrmions for Applications – ‘Skyrmionics’

Skyrmionics:

Demonstrate the **motion**, **creation**, **annihilation** of **small** (< 10 nm) skyrmions in **confined geometries**, using **electric currents** (or **electric fields**) at **room *T***.

Concept: Racetrack Memory

S.S.P. Parkin *et al.*, Science **320**, 190 (2008).



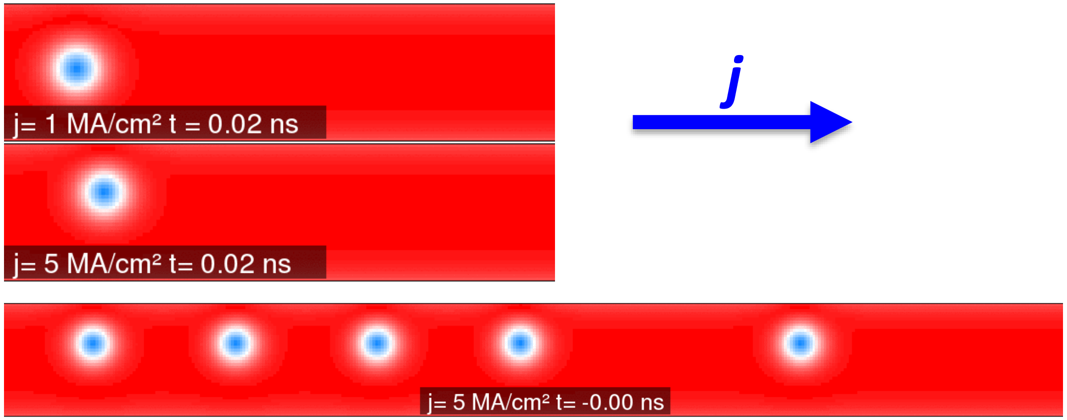
No mechanical parts

High domain densities

Skyrmion racetrack

A. Fert *et al.*, Nat. Nanotech. **8**, 152 (2013)

Theory: skyrmions move under very low current densities!

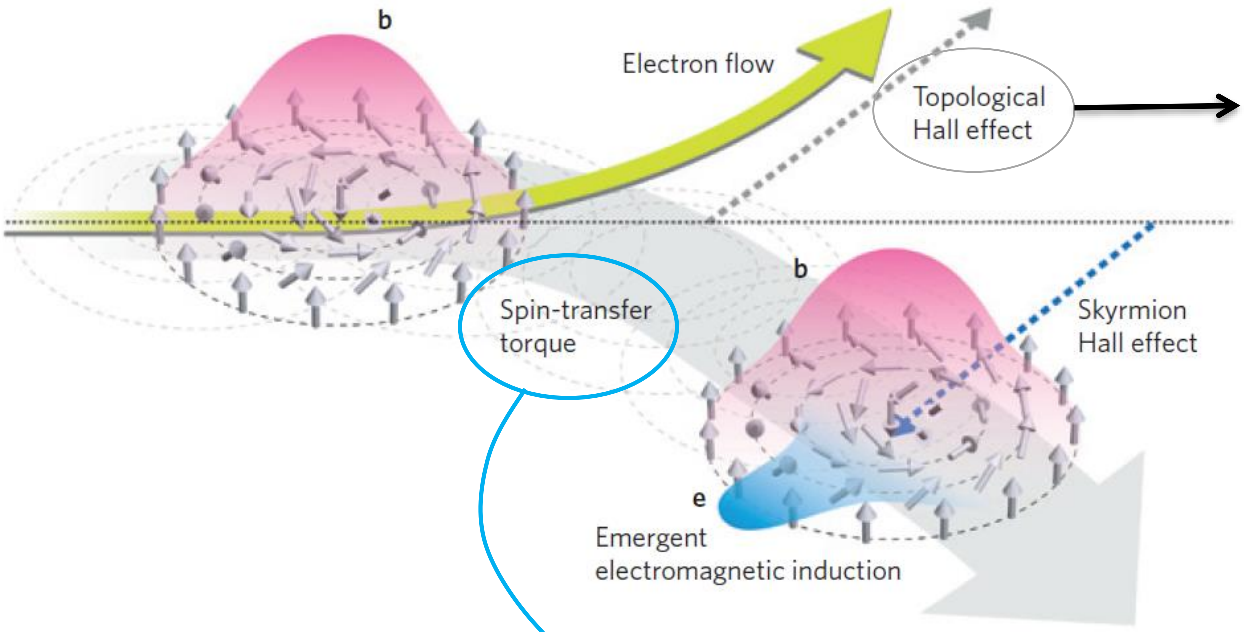


Potential skyrmion applications

- build non-volatile computer **memories**
- superfast devices with **low dissipation**
- low power-dissipation **transistors**
- efficient GHz **oscillators**
- other exotic ideas out there..

Conduction electrons and skyrmions

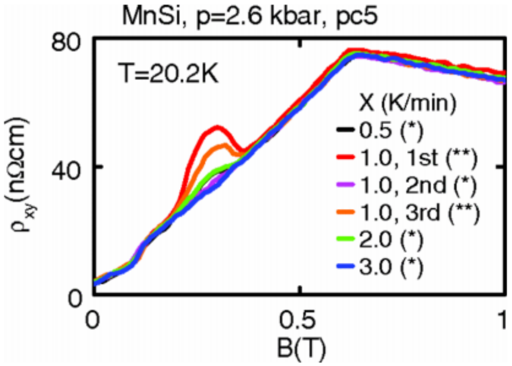
N. Nagaosa and Y. Tokura, Nat. Nanotech. **8**, 899 (2013)



Usual Hall effect ∝ B

Anomalous Hall effect ∝ M

Topological Hall effect ∝ Q



Skyrmions move! Collective motion of skyrmion lattice can be studied by scattering

(from **Berry phase**)

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

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

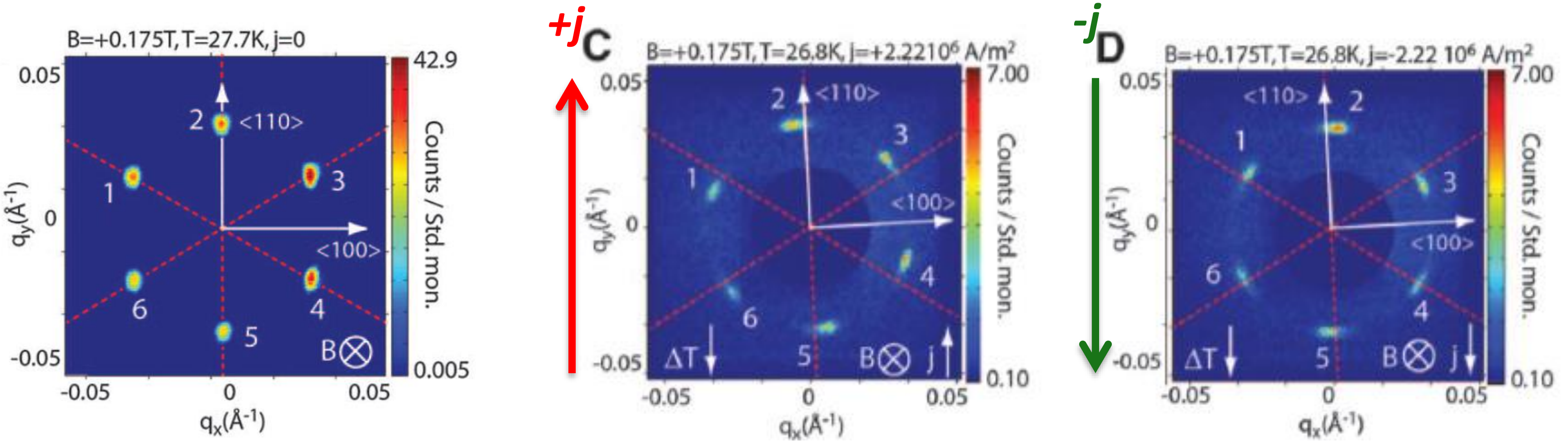
Skyrmion density $$\phi = \frac{1}{4\pi}\vec{n}\cdot\frac{\partial\vec{n}}{\partial x}\times\frac{\partial\vec{n}}{\partial y}$$

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).

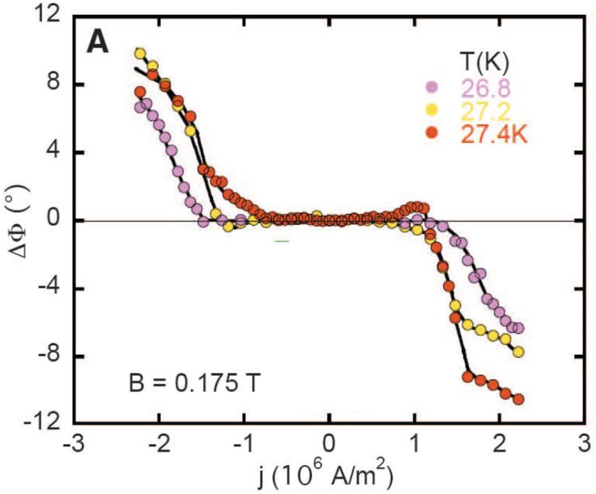
Spin transfer torques and SANS

MnSi at low temperature

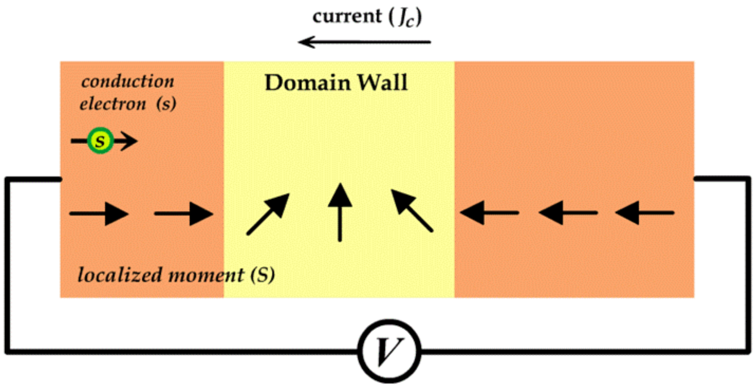
F. Jonietz *et al.*, Science **330**, 1648 (2010)



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



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

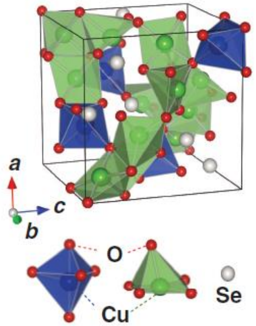


Tiny current densities needed to drive skyrmions compared with FM domains – energy efficient!

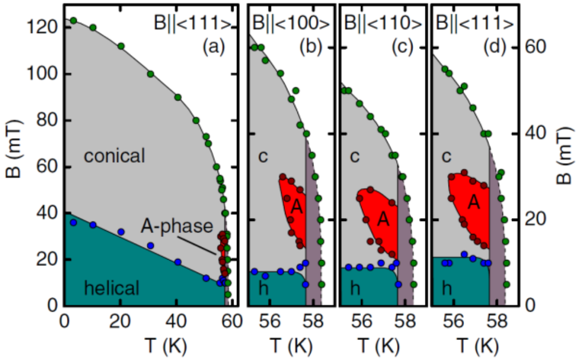
Electric field control

Magnetoelectric <u>insulator</u> Cu_2OSeO_3

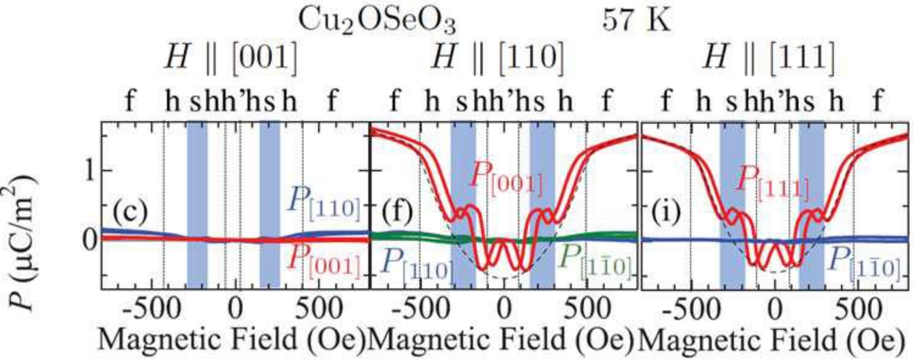
S. Seki, *et al.*, Science **336**, 198, (2012)
T. Adams *et al.*, Phys. Rev. Lett. **108**, 237204 (2012)



Class *T* ($P2_13$)



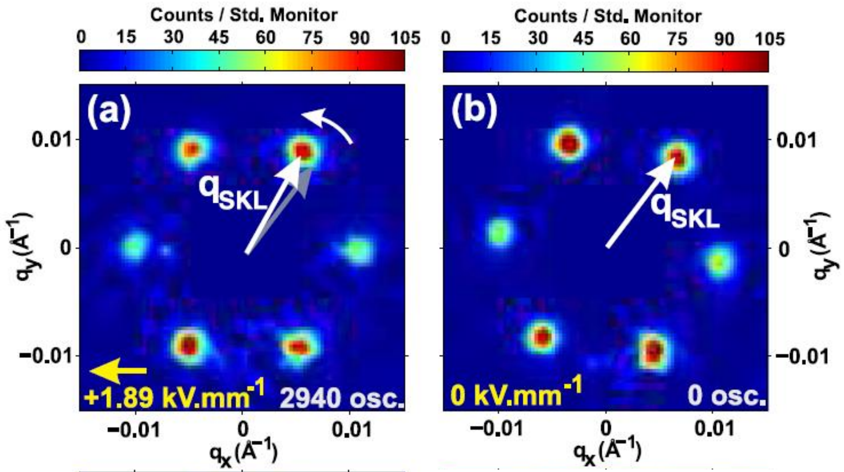
Magnetoelectric coupling in Skyrmion phase

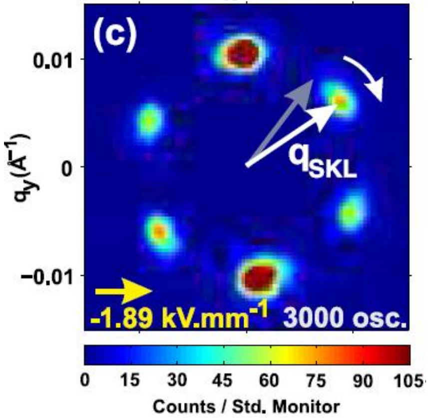


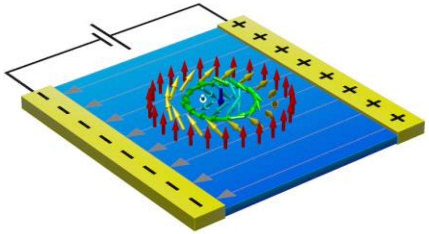
Symmetry of ME coupling: *d-p* hybridization model

Electric field control of the Skyrmion lattice

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







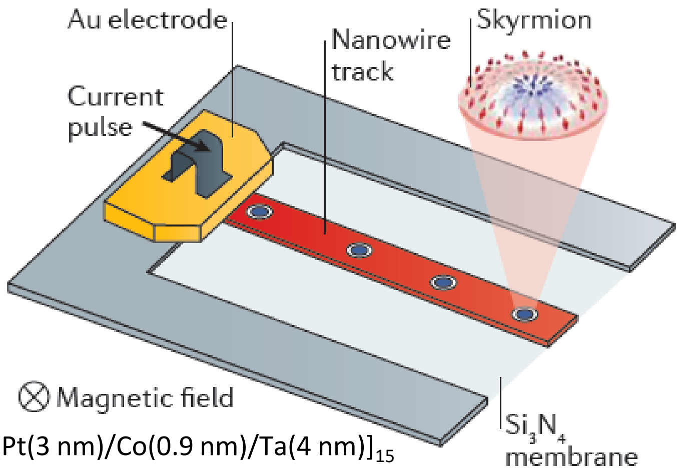
Skyrmion lattice rotations achieved with no STTs – i.e. no current or magnon flows

Microscopic explanation for rotation still missing!

Skyrmion motion in nanostructures

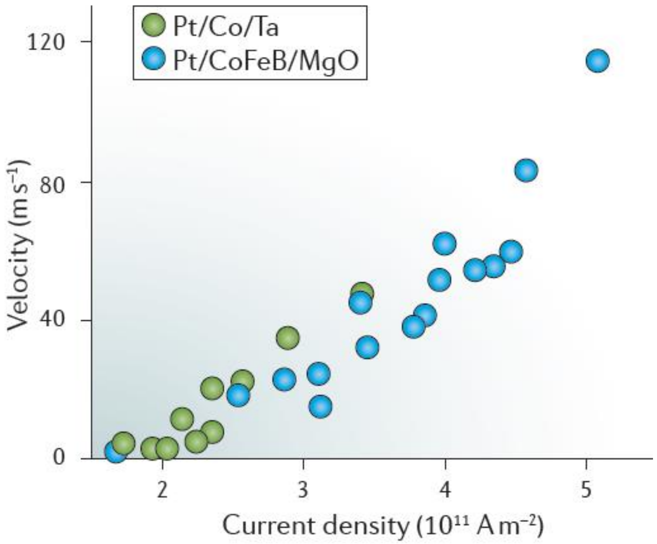
Room temperature, current pulse-driven motion of skyrmions at high speeds

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



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

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

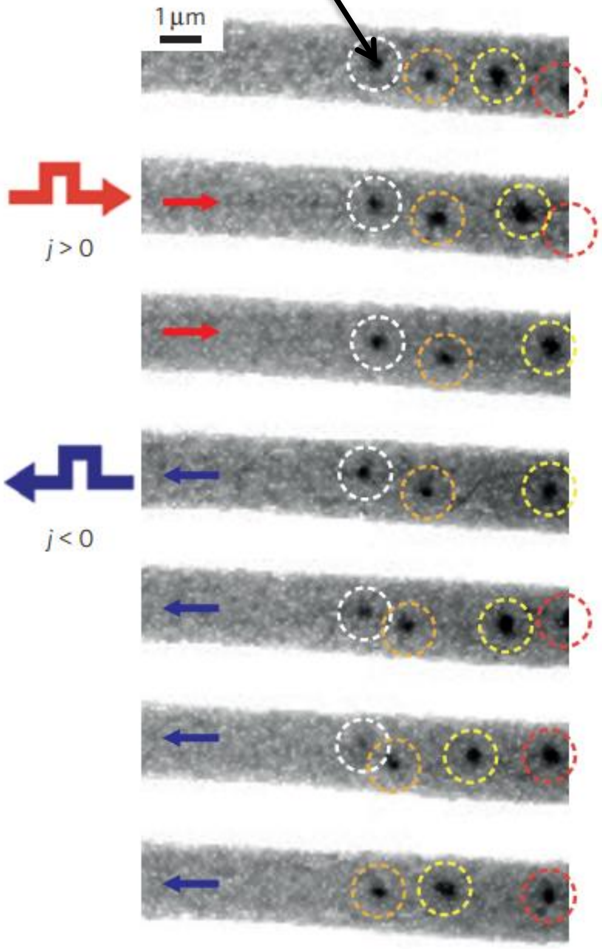


10^{11} A.m^{-2}!

400 nm diameter Néel-type Skyrmions

T = 300 K

$\mu_0 H_\perp < 2$ mT



Summary: Part 3

Skyrmionics:

Demonstrate the **motion**, **creation**, **annihilation** of **small** (< 10 nm) skyrmions in **confined geometries**, using **electric currents** (or **electric fields**) at **room *T***.

Initial challenges for skyrmionics:

- stability: skyrmions at room temperature ✓
- creation/destruction of skyrmions ✓
- control of skyrmions in bulk / nanostructures ✓

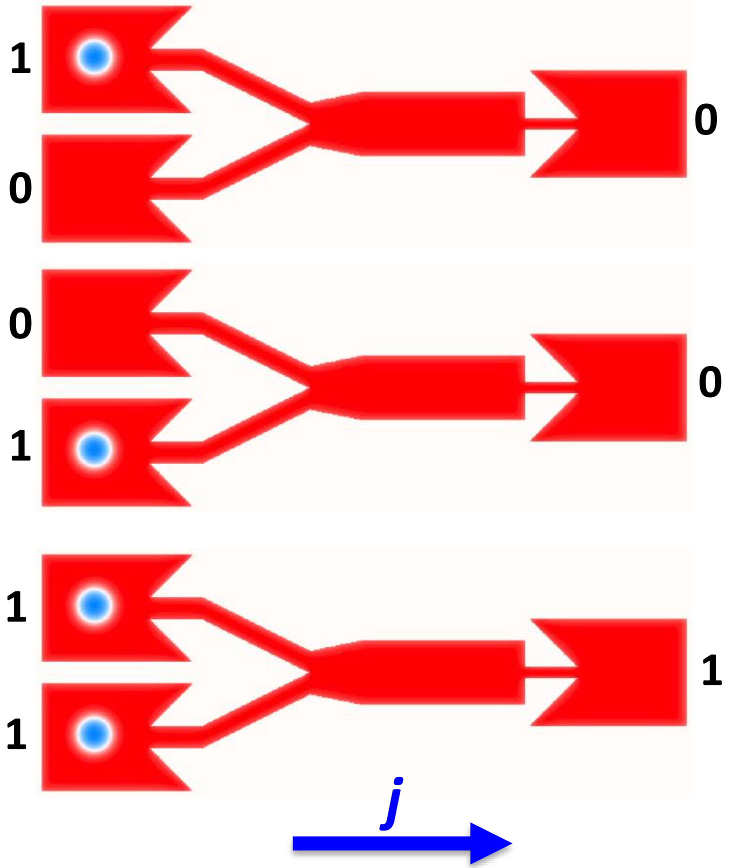
Present challenges:

- More materials and systems
- creation /demonstration of functional / integrated devices
- materials synthesis and technology

most promising materials: multilayer systems
BUT: problems with defects induced by synthesis.

- Identify "killer applications" that are properly competitive (e.g. for memories)

An AND gate



X. Zhang et al., Sci. Rep. **5,** 9400 (2015)

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    - Synthetic systems
- Application of scattering techniques
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Sinergia project **‘NanoSkyrmionics’**

https://skyrmions.epfl.ch/