Neutron scattering from Skyrmions in helimagnets

Jonas Kindervater

E21
Arbeitsgebiet stark korrelierte Elektronensysteme

European Research Council
Established by the European Commission

Collaborations

TU München - E21

A. Bauer

F. Rucker

S. Säubert

F. Haslbeck

G. Benka

P. Schmakat

G. Brandl

A. Chacon

P. Böni

C. Pfleiderer

TU München - FRM II

W. Häußler

S. Mühlbauer

C. Franz

T. Schröder

C. Fuchs

R. Georgii

T. Reimann

M. Schulz

Los Alamos

M. Janoschek

TU München - E10

I. Stasinopoulos

S. Weichselbaumer

D. Grundler → *EPFL*

Universität zu Köln

A. Rosch

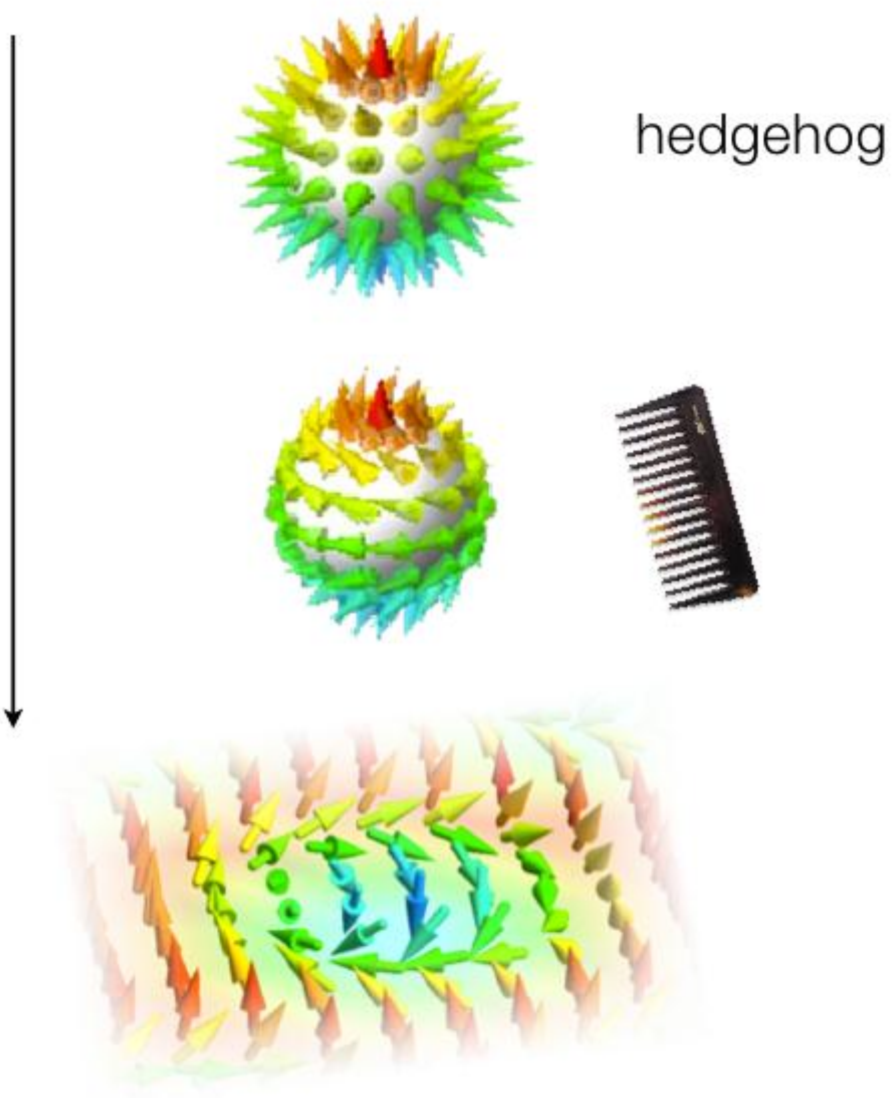
M. Garst

J. Waizner

L. Köhler

Skyrmions

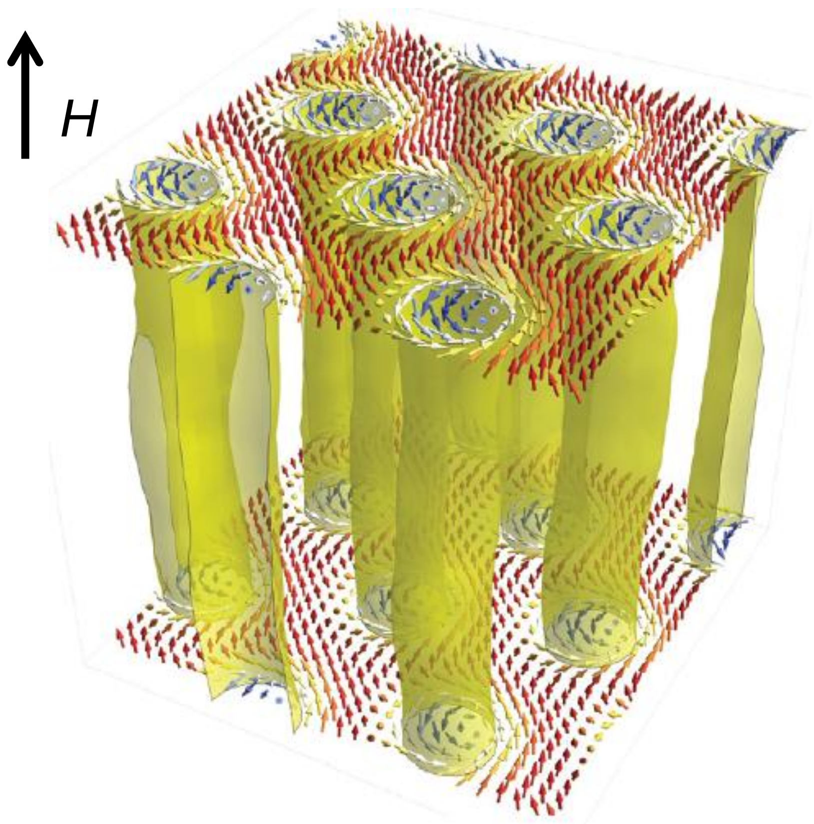
stereographic projection
from sphere to plane:



topologically stable object with
quantized winding number

$$W = \frac{1}{4\pi} \int d^2r \, \hat{M} \left(\partial_x \hat{M} \times \partial_y \hat{M} \right)$$

one flux quantum per skyrmion

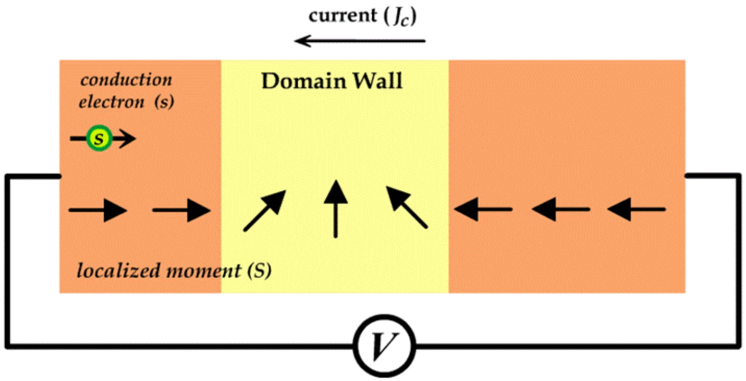


S. Mühlbauer *et al.*, Science **323**, 915 (2009)
P. Milde *et al.*, Science **340**, 1076 (2013)

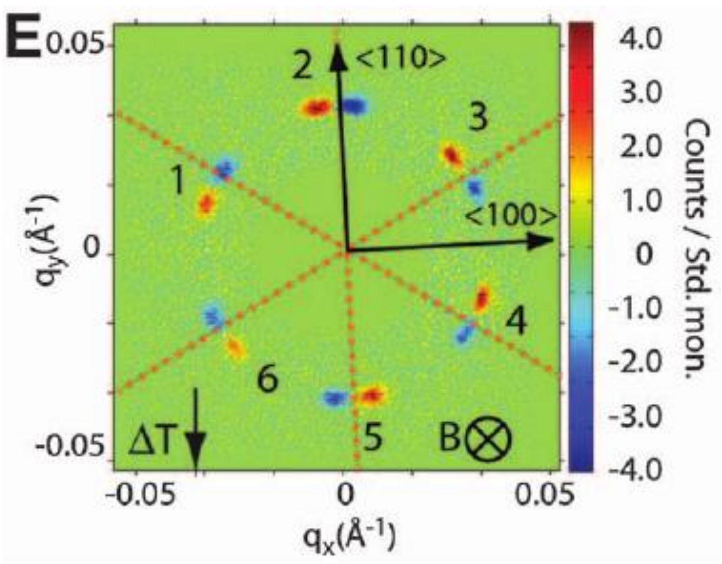
Skyrmions: Spin Transfer Torque

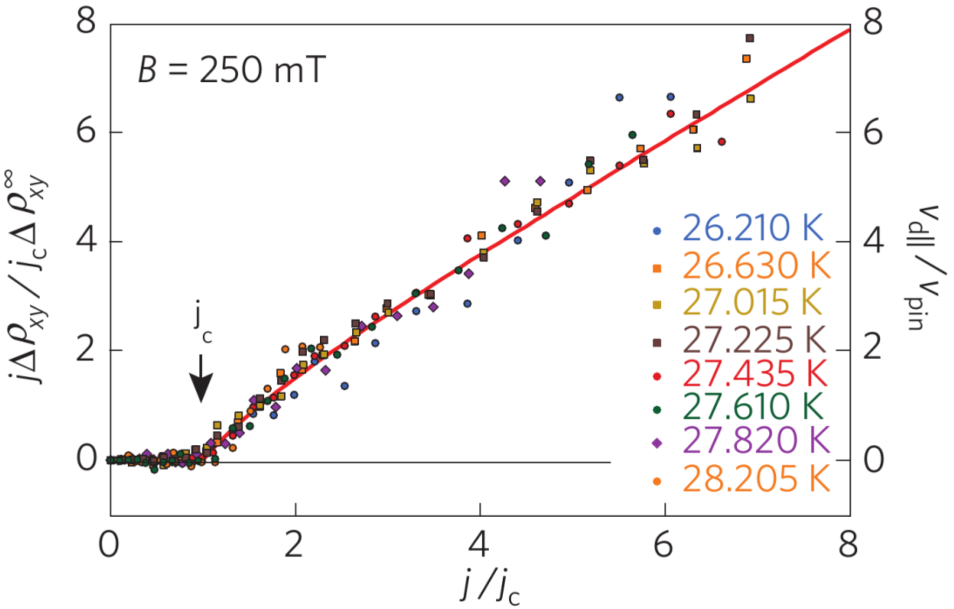
Current driven domain wall motion

figure by S. Maekawa



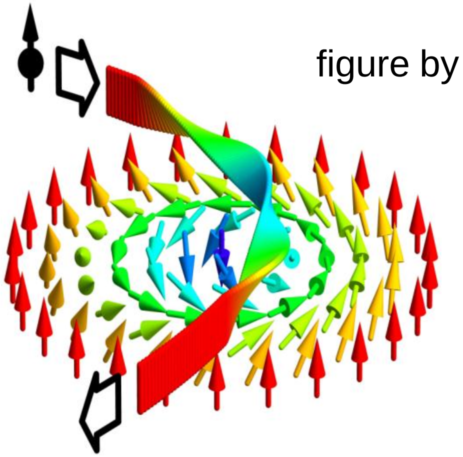
Current Density: ~10^{12}A/m^2





Current driven motion of Skyrmions

figure by A. Rosch



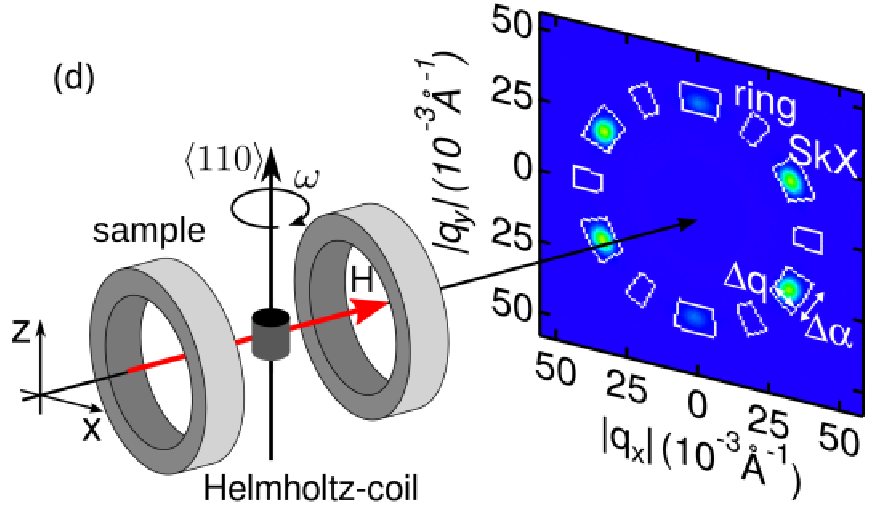
Current Density: ~10^6A/m^2

F. Jomitz *et al.*, Science **330**, 1648 (2010)
T. Schulz *et al.*, Nat. Phys. **8**, 301 (2012)

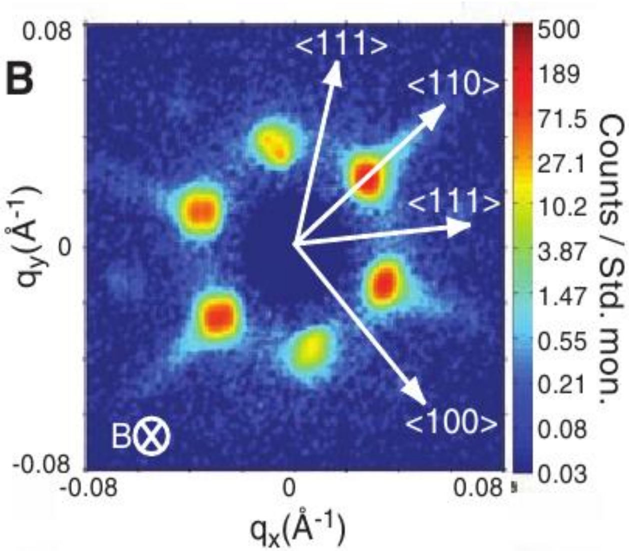
Experimental Evidence for Skyrmions

Small Angle Neutron Scattering (SANS)
on bulk samples

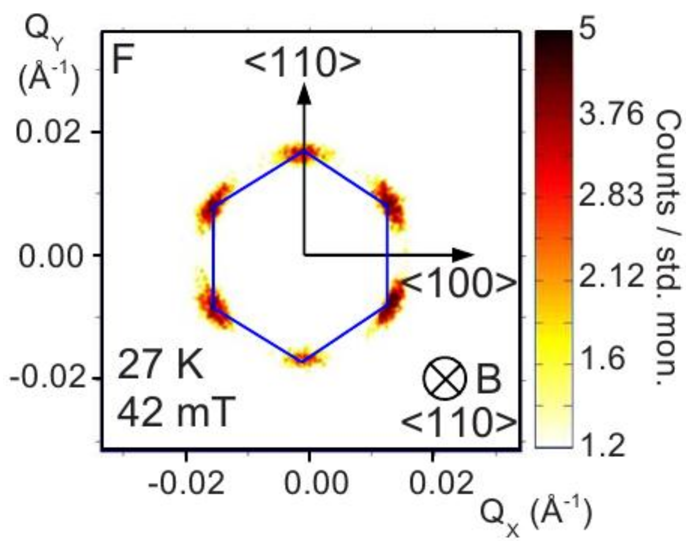
→ reciprocal space image



MnSi



$Fe_{0.8}Co_{0.2}Si$

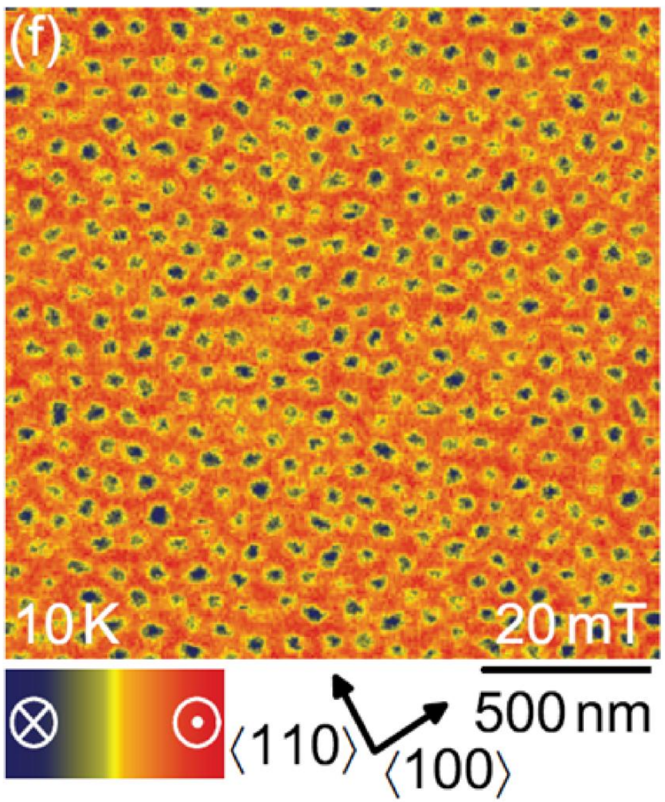


S. Mühlbauer *et al.*, Science **323**, 915 (2009)
T. Adams *et al.*, Phys. Rev. Lett. **107**, 217206 (2011)
W. Münzer *et al.*, Phys. Rev. B **81**, 041203 (2010)

Experimental Evidence for Skyrmions

$Fe_{0.5}Co_{0.5}Si$

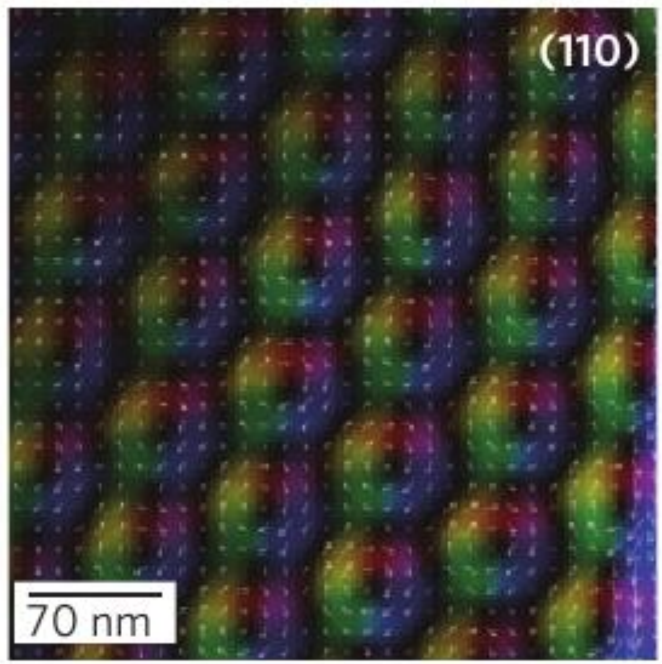
MFM



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

FeGe

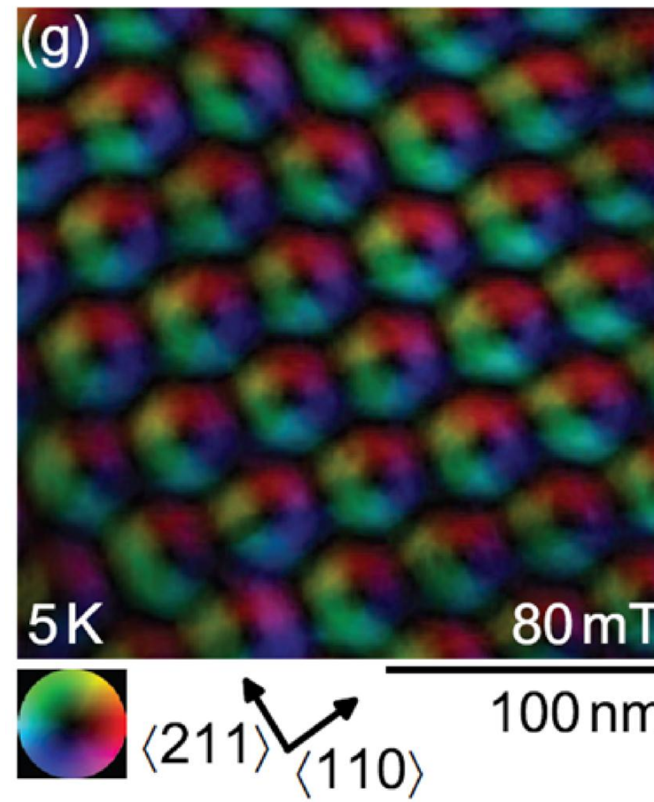
LF-TEM



X. Z. Yu *et al.*, Nature Materials **10**, 106 (2011)

Cu_2OSeO_3

LF-TEM



X. Z. Yu *et al.*, Nature **465**, 901 (2010)

Outline

(1) Introduction to Neutron Scattering

- Neutron scattering
- Small angle neutron scattering
- Neutron Spin Echo

(2) Skyrmions in cubic chiral magnets

- Introduction
- Topological unwinding into helical/conical phase
- Field induced tricritical point in MnSi
- Skyrmionic textures in the paramagnetic phase

(3) Conclusion

Outline

(1) Introduction to Neutron Scattering

- Neutron scattering
- Small angle neutron scattering
- Neutron Spin Echo

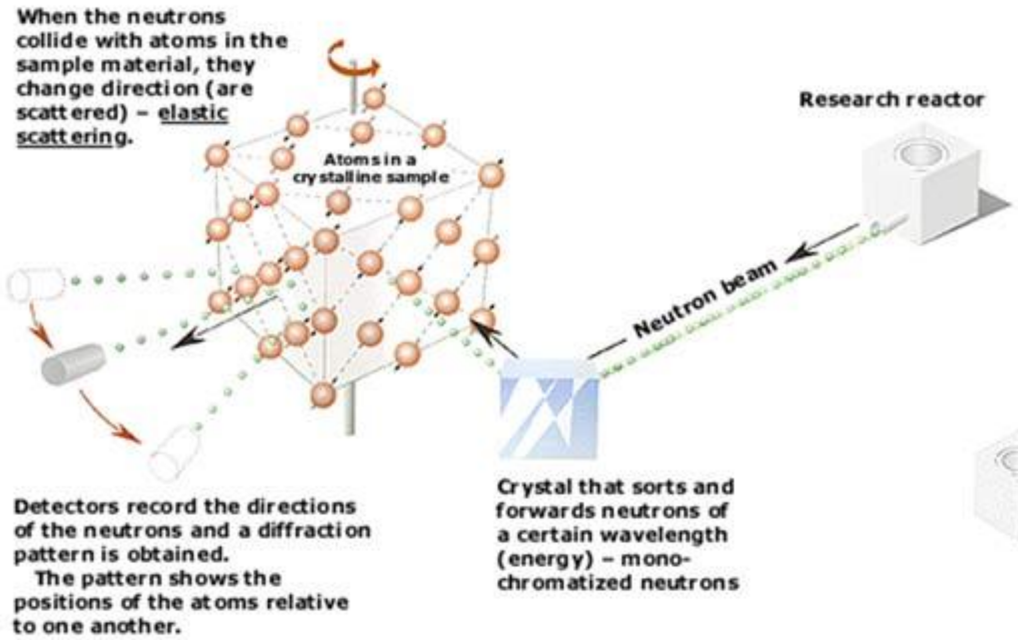
(2) Skyrmions in cubic chiral magnets

- Introduction
- Topological unwinding into helical/conical phase
- Field induced tricritical point in MnSi
- Skyrmionic textures in the paramagnetic phase

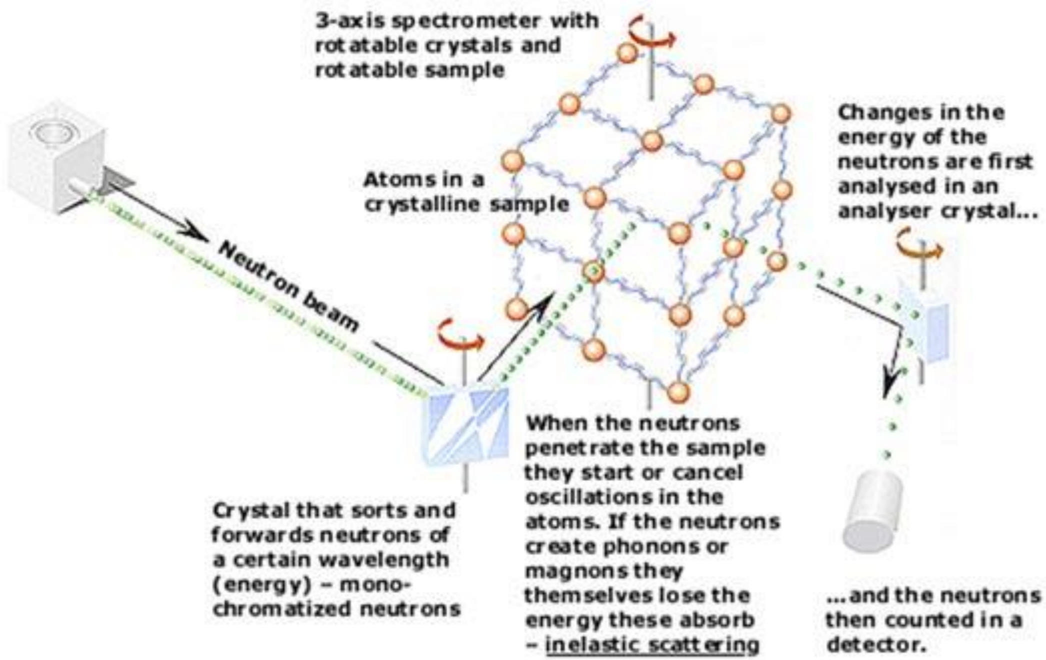
(3) Conclusion

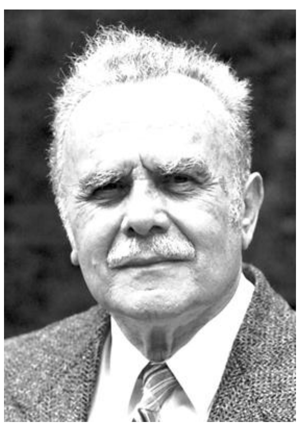
Neutron Scattering

allows to determine where atoms are…

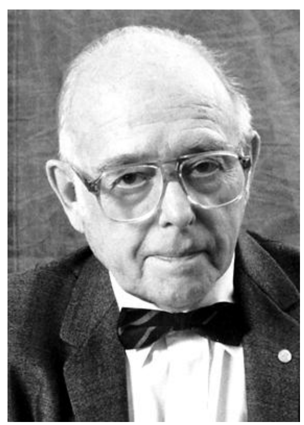


… and what they do!





B. N. Brockhouse



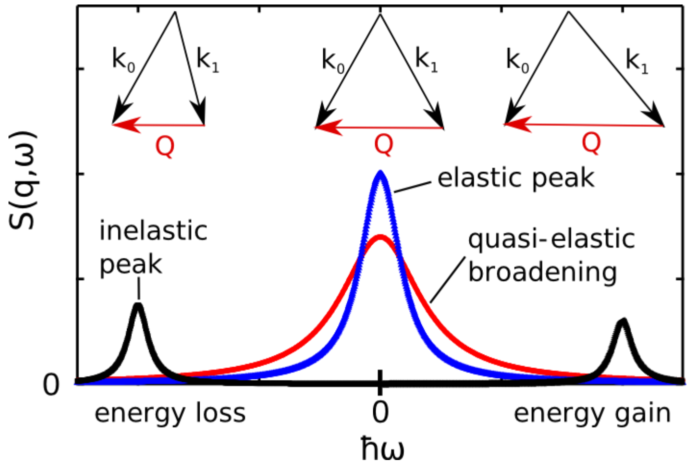
C. G. Shull

Nobel Prize 1994

Elastic Vs. Inelastic Scattering

Elastic scattering

Inelastic scattering



Roger Pynn, „Neutron scattering: a primer“ Los Alamos Science (1990)

Neutron Sources

Fission

FRM II, Germany

ILL, France

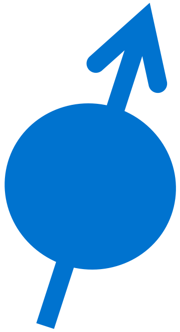
Spallation

SNS, USA

ESS, Sweden

Properties of neutrons

- no charge
- no measurable dipole moment
- spin-1/2 particle -> magnetic moment
- wavelength ~ interatomic distances
- energy ~ energy of excitations in solids



$0.5\,\text{Å} < \lambda < 30\,\text{Å}$ ↔ $300\,\text{meV} < \lambda < 0.1\,\text{meV}$

Roger Pynn, „Neutron scattering: a primer“ Los Alamos Science (1990)

Interaction with matter

Electrons

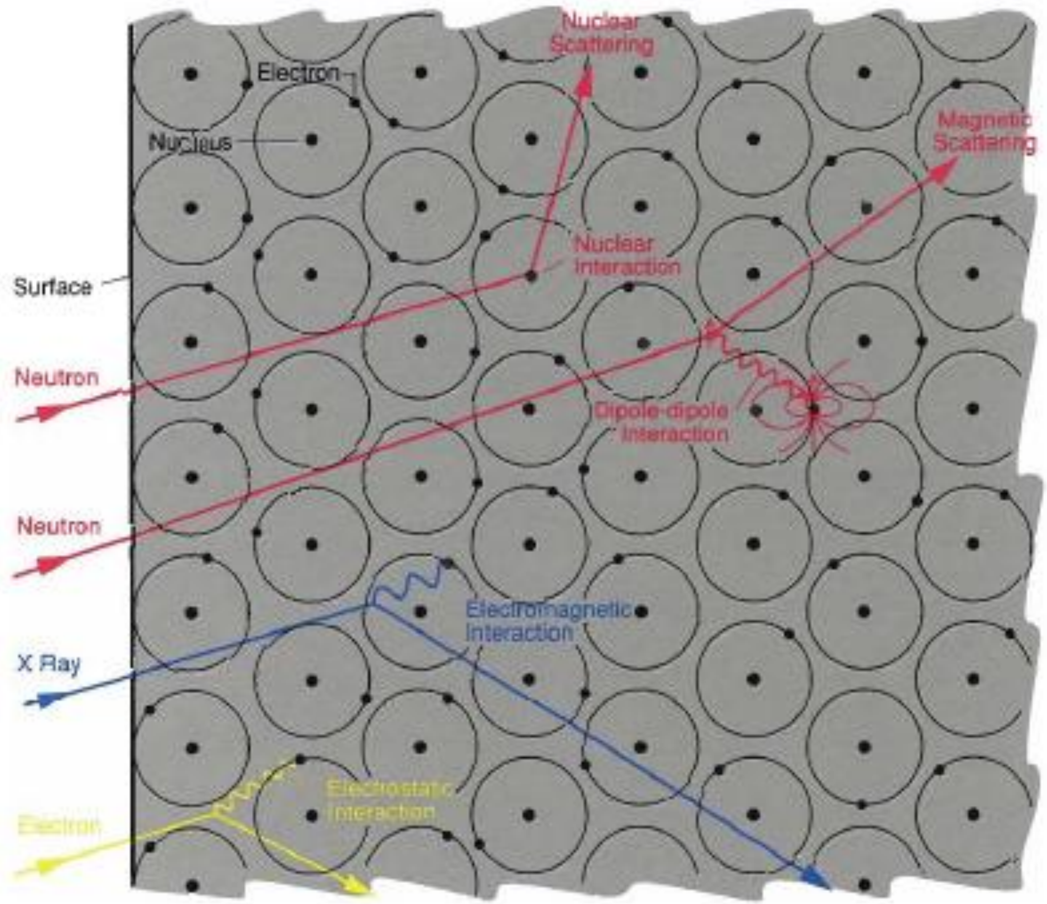
- electrostatic interaction with e⁻
- strong interaction
- small penetration depth

X-rays

- electromagnetic interaction with e⁻
- strong interaction
- small penetration depth

Neutrons

- interaction with nuclei
  - short range
- magnetic dipole-dipole interaction between neutron and unpaired e⁻
  - not short range
- large penetration depth



Roger Pynn, „Neutron scattering: a primer“ Los Alamos Science (1990)

Interaction with matter

Electrons

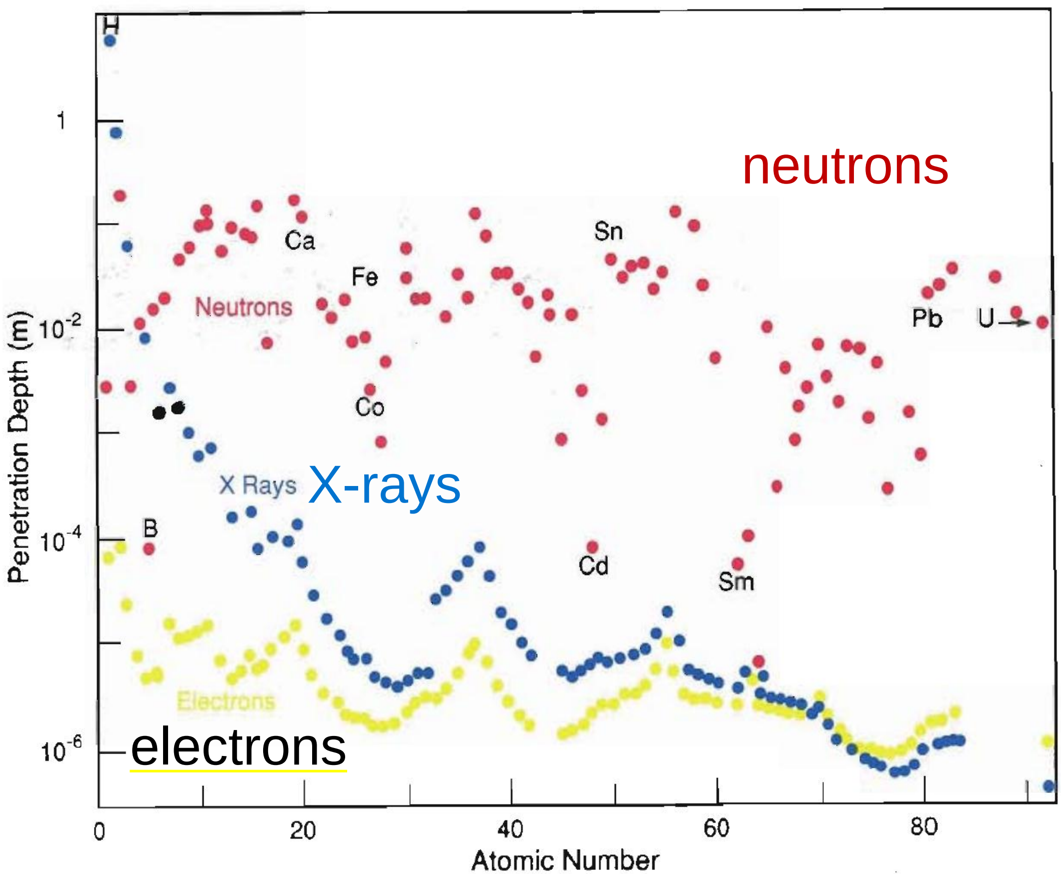
- electrostatic interaction with e⁻
- strong interaction
- small penetration depth

X-rays

- electromagnetic interaction with e⁻
- strong interaction
- small penetration depth

Neutrons

- interaction with nuclei
  - short range
- magnetic dipole-dipole interaction between neutron and unpaired e⁻
  - not short range
- large penetration depth



Roger Pynn, „Neutron scattering: a primer“ Los Alamos Science (1990)

Neutrons: Pros / Cons

Advantages:

- penetrating: bulk properties
- penetrating: extreme sample environments
- isotope sensitive
- magnetic interaction

Disadvantages:

- kinematic restrictions (can’t access all energy & momentum transfers)
- weak scattering
- only weak sources

unique magnetic interaction
very powerful in magnetism

signal limited technique

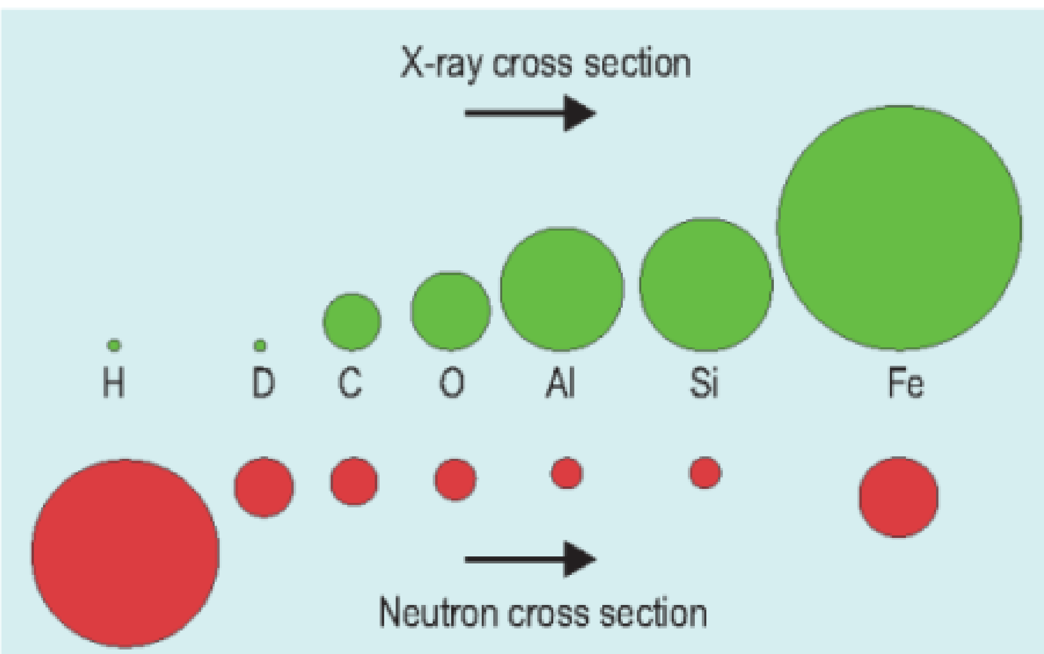
Nuclear Interaction

- short range (~fm)
- isotope dependent (random in Z)
- depends on spin state of nucleus

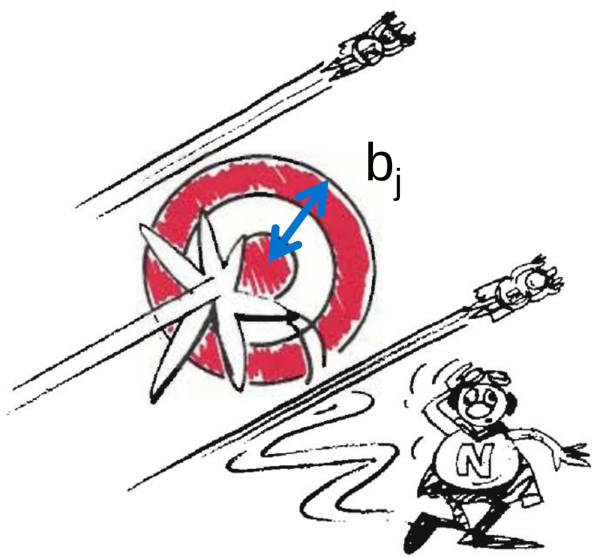
Fermi pseudopotential

$$V_j(\boldsymbol{r}) = \frac{2\pi\hbar^2}{m} b_j\, \delta(\boldsymbol{r})$$

- scattering length: b_j
- $\sigma = 4\pi b^2$



NIST Annual report 2003, https://www.ncnr.nist.gov



Roger Pynn, „Neutron scattering: a primer“ Los Alamos Science (1990)

Nuclear Scattering

Coherent scattering

$$\left(\frac{d^2\sigma}{d\Omega . dE}\right)_{coh} = b_{coh}^2 \frac{k'}{k} N S(\vec{Q},\omega)$$

- elastic coherent scattering: positions of atoms
- inelastic coherent scattering: collective excitations, i.e. phonons, magnons

Incoherent scattering

$$\left(\frac{d^2\sigma}{d\Omega . dE}\right)_{inc} = b_{inc}^2 \frac{k'}{k} N S_i(\vec{Q},\omega)$$

- elastic incoherent scattering: background
- inelastic incoherent scattering: self-correlation, i.e. diffusion processes

Roger Pynn, „Neutron scattering: a primer“ Los Alamos Science (1990)

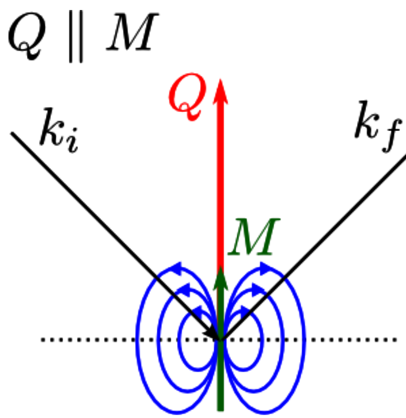
Magnetic Interaction

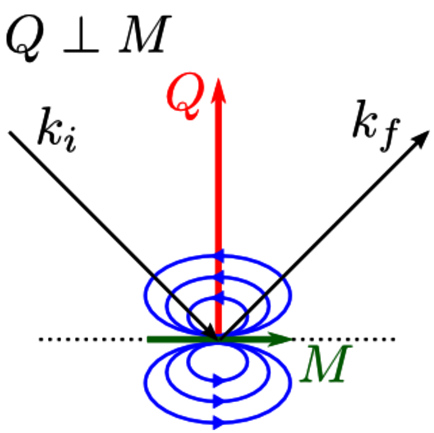
- with unpaired electrons
- dipole-dipole interaction
- weak
- Formfactor
- spin dependent

Dipole interaction

$$\hat{V}_m(\boldsymbol{r}) = -\gamma\mu_N \hat{\boldsymbol{\sigma}}\, \boldsymbol{M(r)}$$

- $\gamma\mu_N$: strenght of neutron’s magnetic moment
- $\hat{\boldsymbol{\sigma}}$: direction of neutron’s spin
- $\boldsymbol{M(r)}$: magnetic moment of the sample





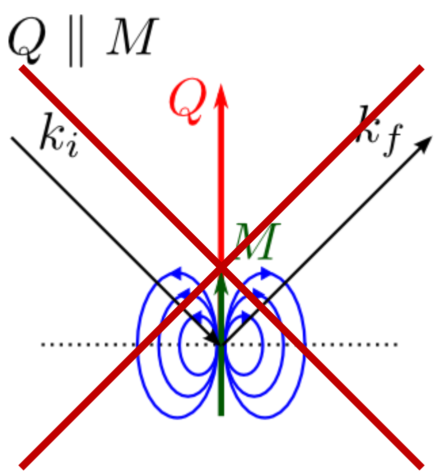
Magnetic Scattering

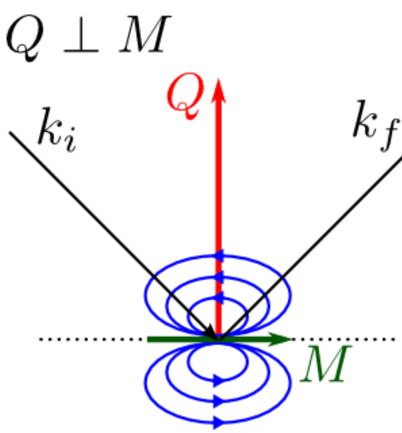
$$\frac{d^2\sigma}{d\Omega d\omega} = (\gamma r_0)^2 \frac{k'}{k} F^2(\boldsymbol{Q}) e^{-2W(\boldsymbol{Q})} \sum_{\alpha,\beta} \left(\delta_{\alpha\beta} - \frac{Q_\alpha Q_\beta}{Q^2} \right) S^{\alpha\beta}(\boldsymbol{Q}, \omega)$$

form factor

selection rule

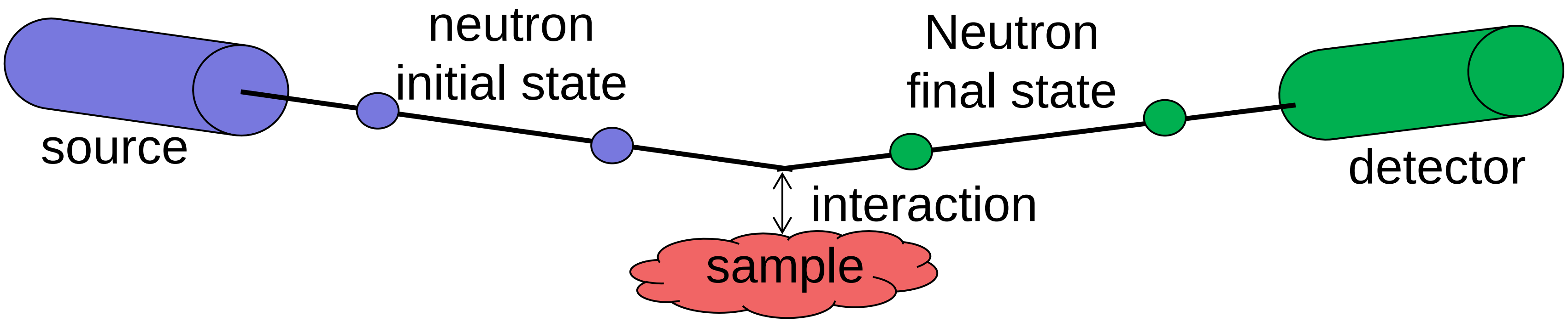
FT of van Hove's spin pair correlation function



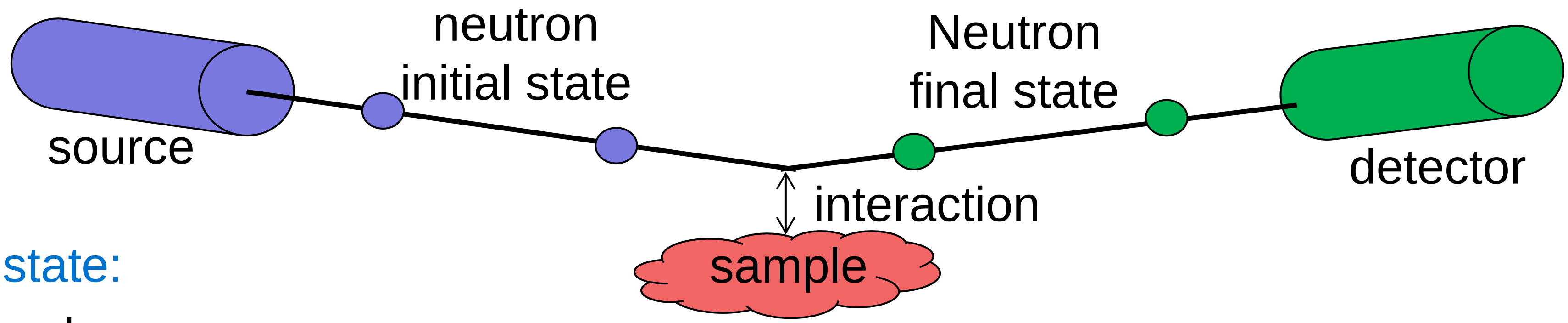


Magnetic diffraction measures the Fourier transform of magnetization density

Neutron Scattering

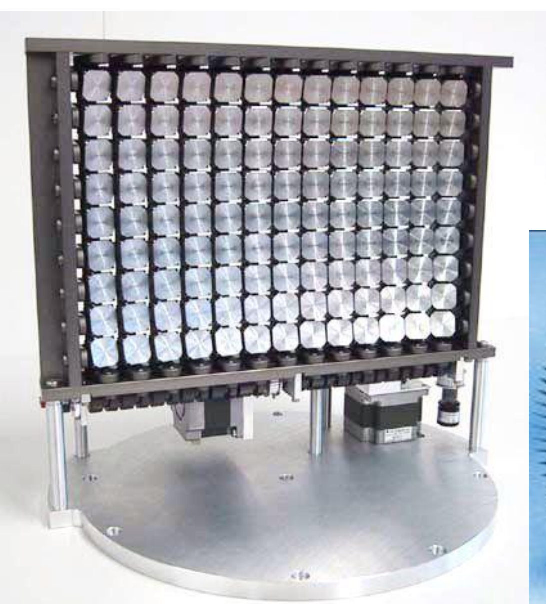


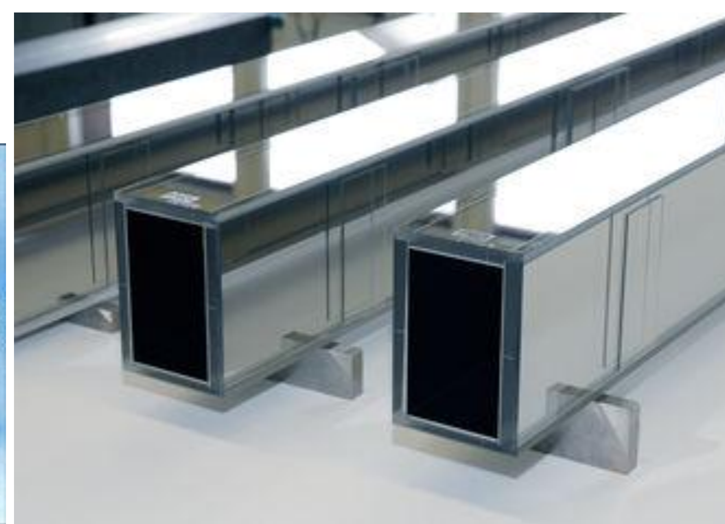
Neutron Scattering



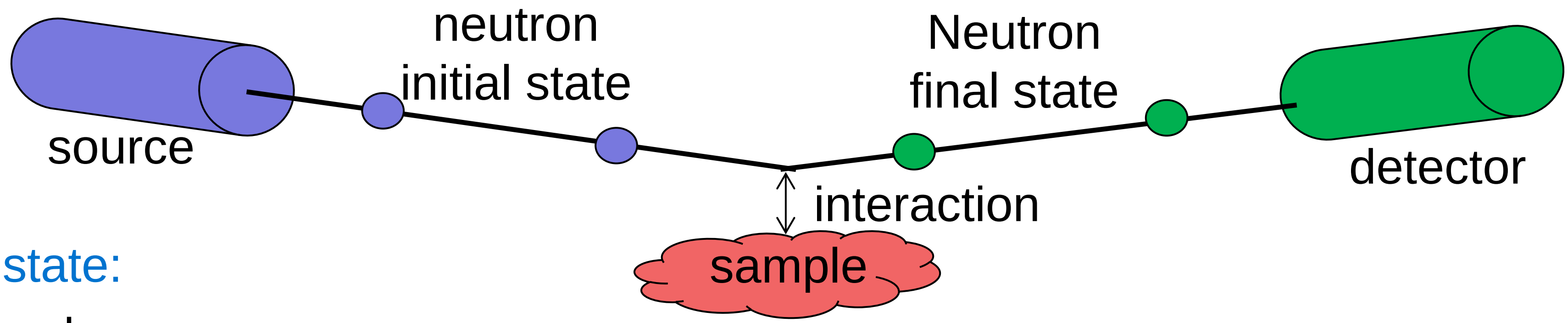
Initial state:

- speed
- direction
- spin state





Neutron Scattering



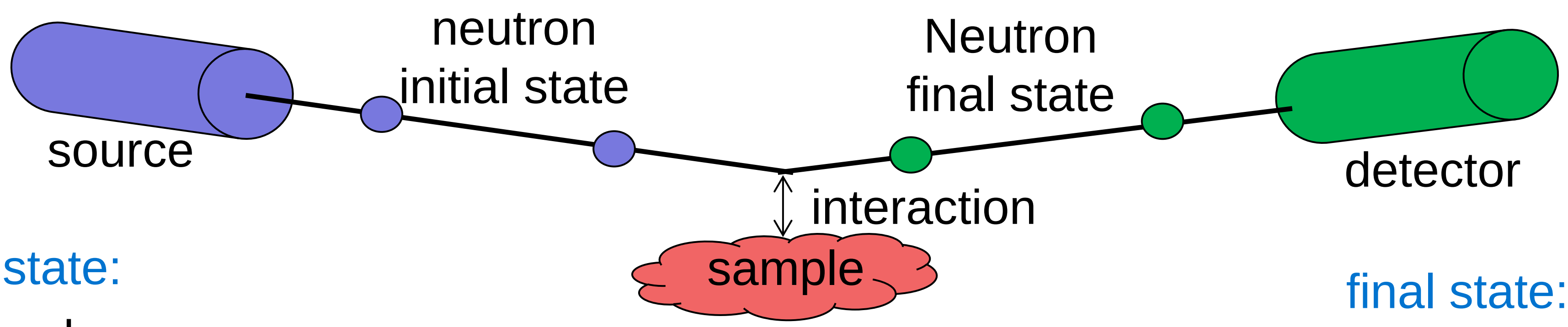
Initial state:

- speed
- direction
- spin state

Sample state:

- cryostat
- magnetic field
- orientation

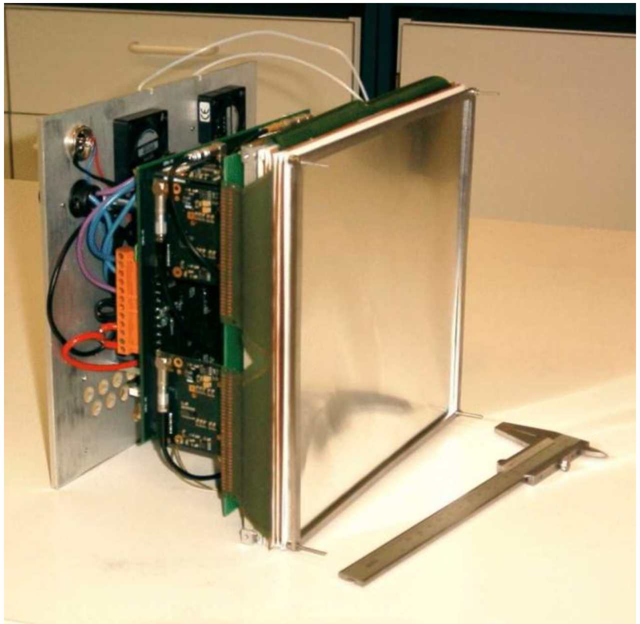
Neutron Scattering

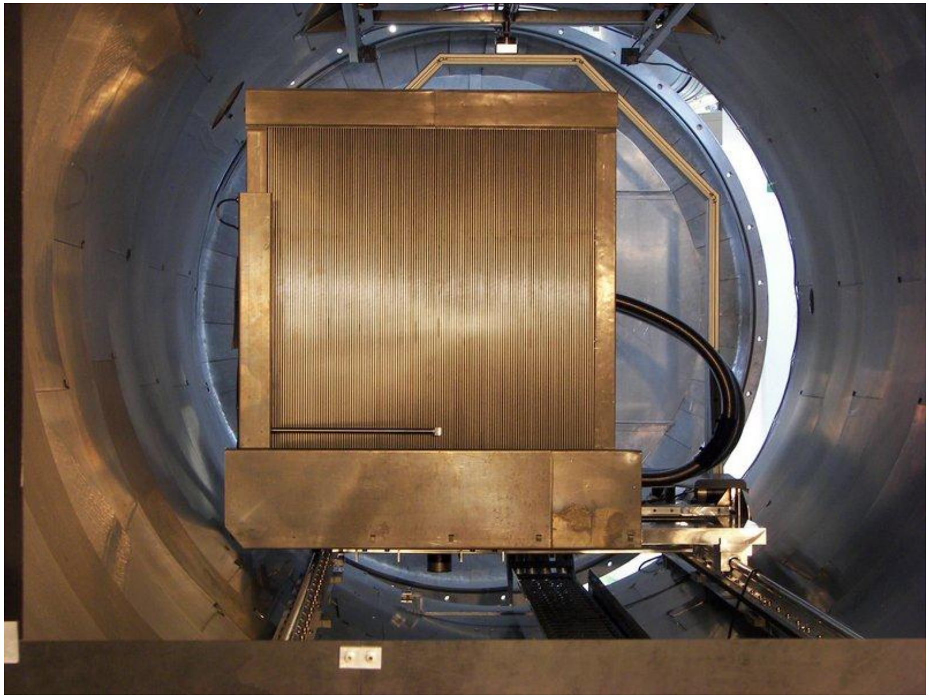


Initial state:
- speed
- direction
- spin state

Sample state:
- cryostat
- magnetic field
- orientation

final state:
- speed:
- direction
- Spin state
- detection

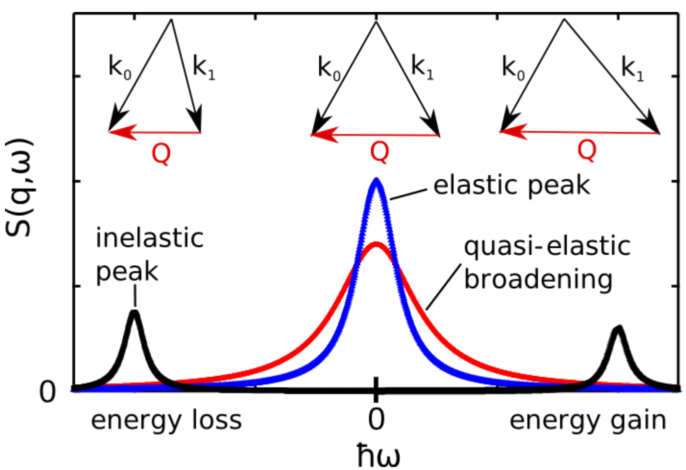




Elastic Scattering on Skyrmions

How to investigate the structue of Skyrmions?

- magnetic lattice
- d ~ 200Å
- Stabalized in magnetic field



Elastic scattering

Roger Pynn, „Neutron scattering: a primer" Los Alamos Science (1990)

Outline

(1) Introduction to Neutron Scattering
- Neutron scattering
- Small angle neutron scattering
- Neutron Spin Echo

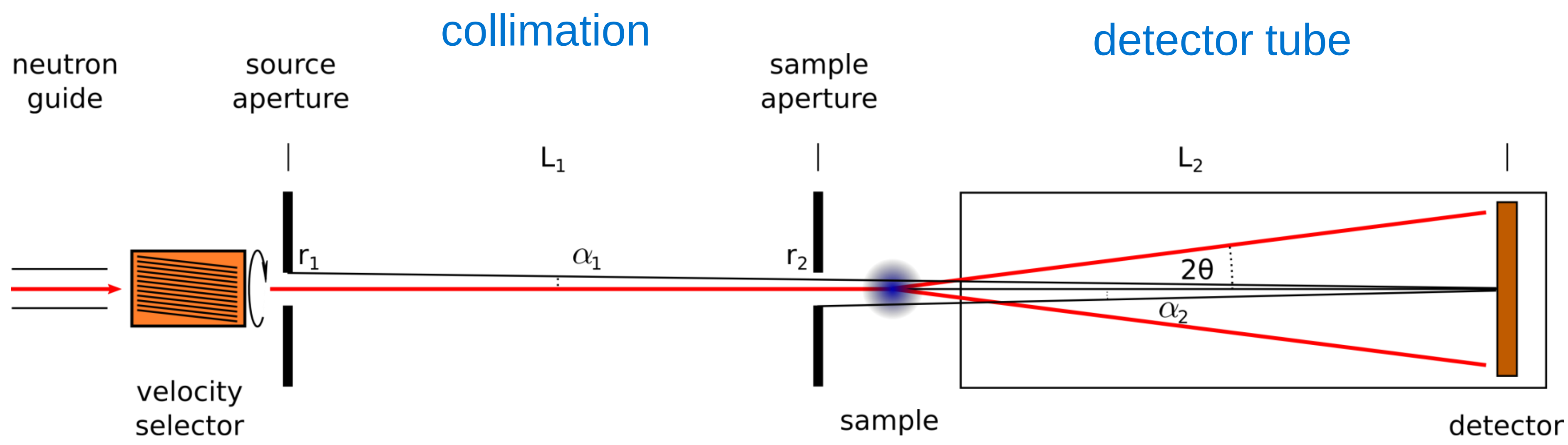
(2) Skyrmions in cubic chiral magnets
- Introduction
- Topological unwinding into helical/conical phase
- Field induced tricritical point in MnSi
- Skyrmionic textures in the paramagnetic phase

(3) Conclusion

Small angle neutron scattering

Large scales in real space
10-40000Å

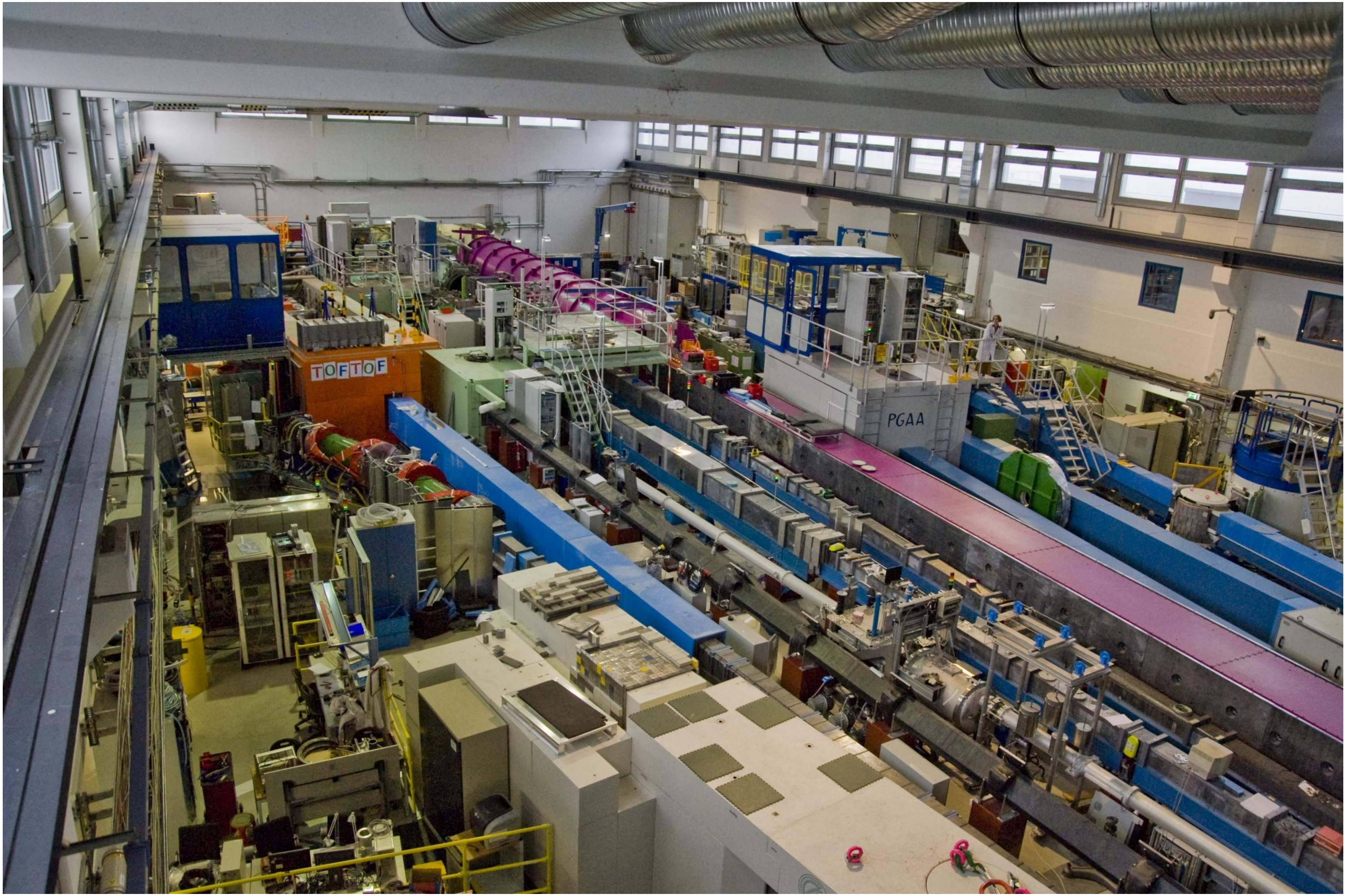
Low Q, small scattering angles
0.54 $Å^{-1}$ - $6 \cdot 10^{-4}$ $Å^{-1}$



Typical Applications:

- Soft matter: structure of proteins, polymers, viruses
- Magnetism: superconducting vortices, Skyrmions
- Material science: Mg hydrides for hydrogen storage, …

SANS-1 @ MLZ



neutron guide hall @ MLZ, Garching Germany

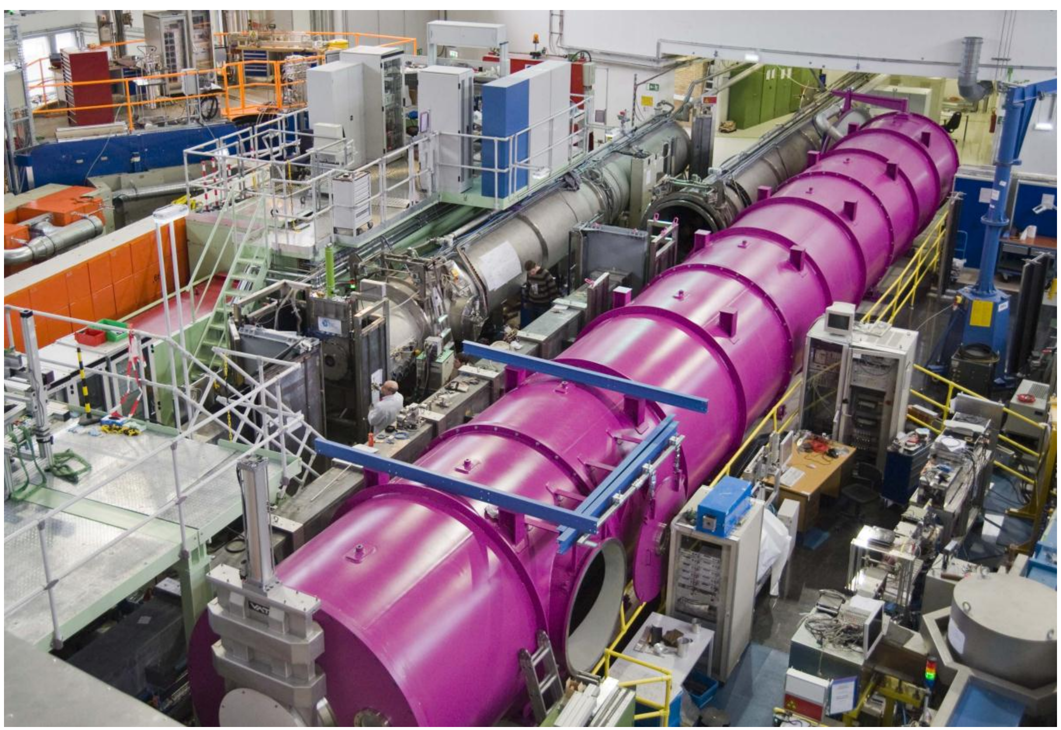
SANS-1 @ MLZ

Velocity selector

- 30.000 rpm max.

Sample position

- Minimize flight path in air
- allow multiple sample environments



Detector tube:

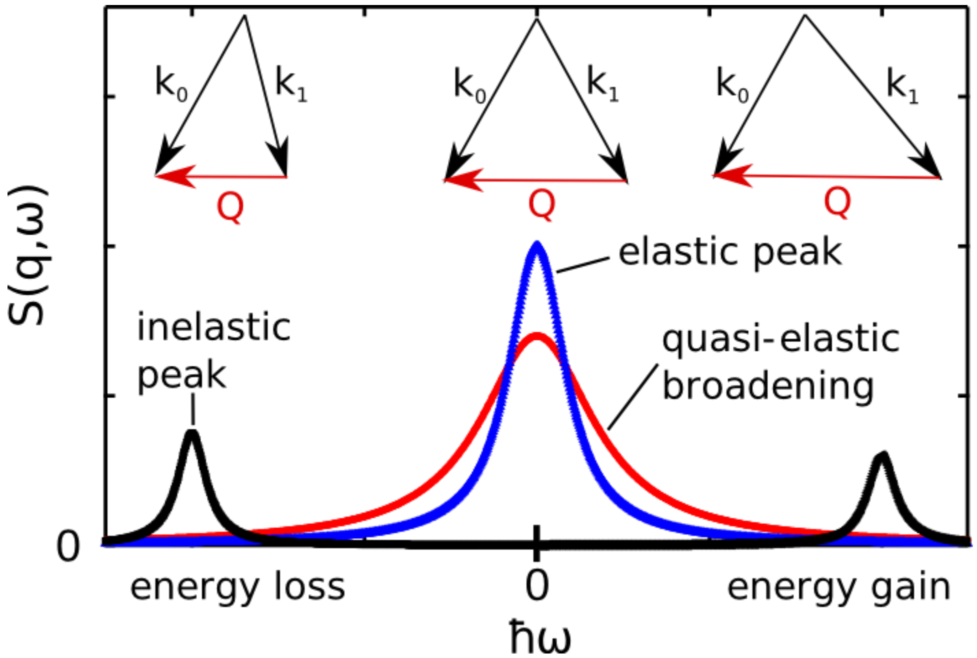
- Vacuum vessel to reduce background
- Sample detector distance 1-40m
- He-3 position sensitive detector $1m^2$
- interior covered with Cadmium

Fluctuations of the Skyrmion lattice

How to investigate fluctuations of the Skyrmion lattice?

- magnetic lattice
- d ~ 200Å
- Stabalized in magnetic field
- High energy resolution!

Inelastic scattering

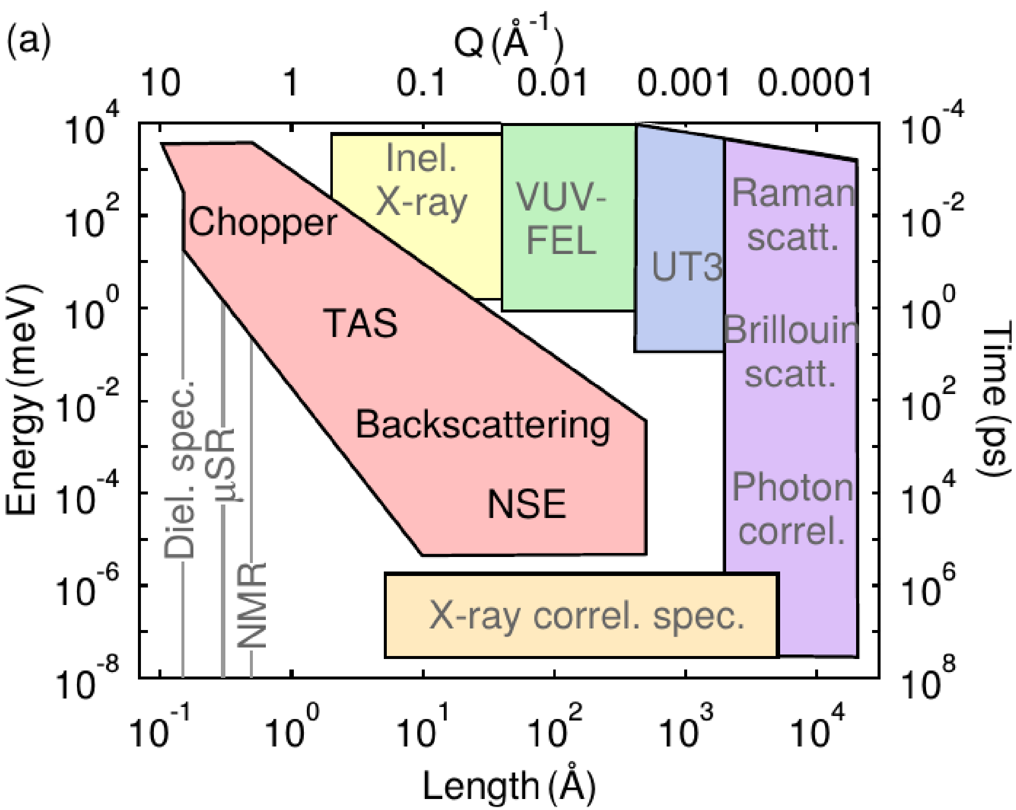


Roger Pynn, „Neutron scattering: a primer“ Los Alamos Science (1990)

Fluctuations of the Skyrmion lattice

How to investigate fluctuations of the Skyrmion lattice?

- magnetic lattice
- d ~ 200Å
- Stabalized in magnetic field
- High energy resolution!



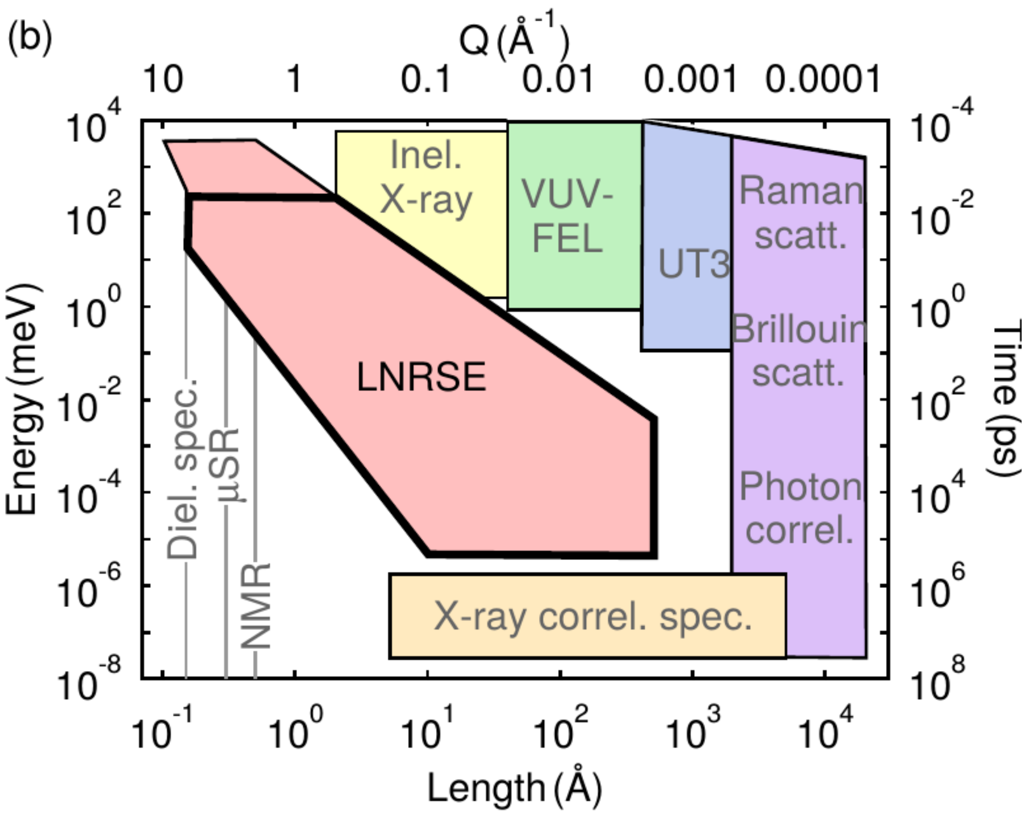
Inelastic scattering

Roger Pynn, „Neutron scattering: a primer“ Los Alamos Science (1990)

Fluctuations of the Skyrmion lattice

How to investigate fluctuations of the Skyrmion lattice?

- magnetic lattice
- d ~ 200Å
- Stabalized in magnetic field
- High energy resolution!



Inelastic scattering

Roger Pynn, „Neutron scattering: a primer“ Los Alamos Science (1990)

Outline

(1) Introduction to Neutron Scattering

- Neutron scattering
- Small angle neutron scattering
- Neutron Spin Echo

(2) Skyrmions in cubic chiral magnets

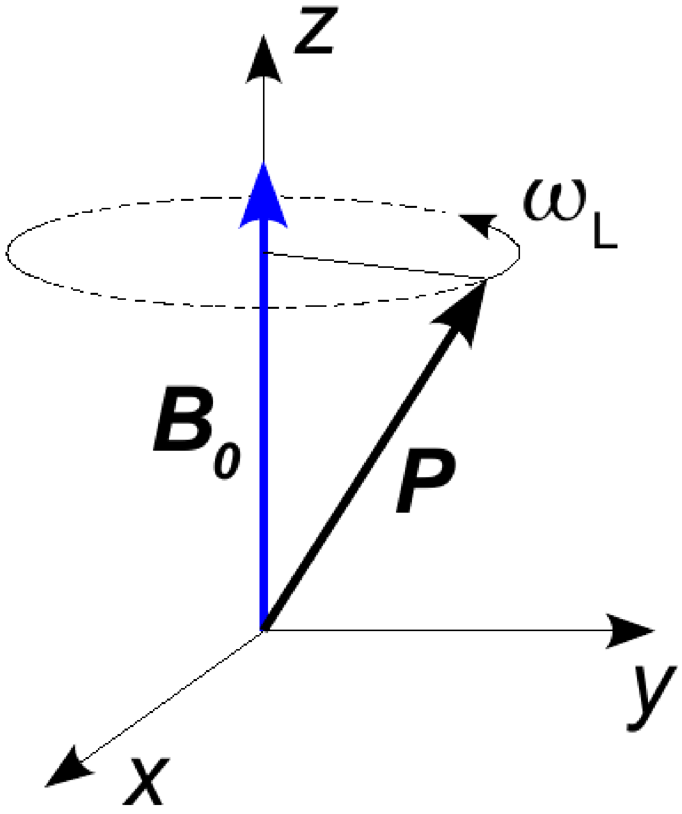
- Introduction
- Topological unwinding
- Field induced tricritical point in MnSi
- Skyrmionic textures in the paramagnetic phase

(3) Conclusion

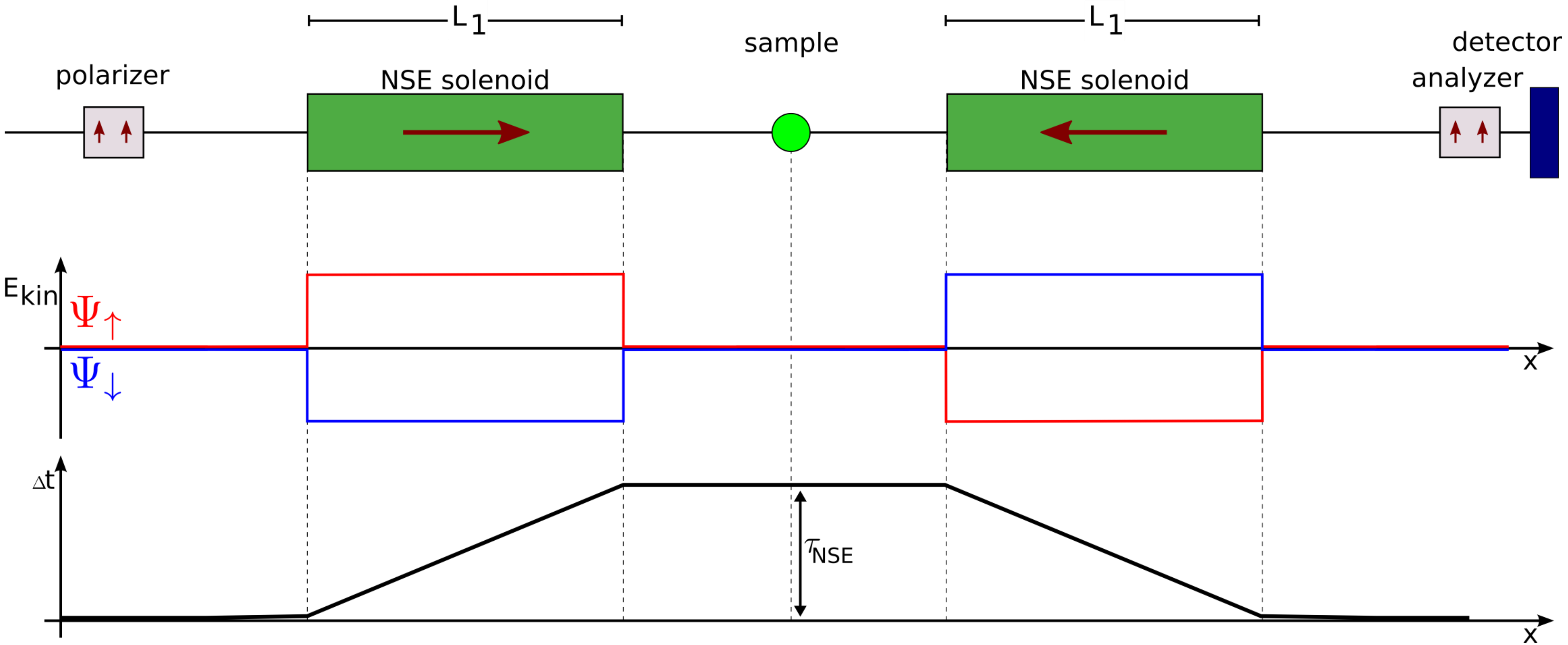
Larmor precession

- Magnetic moment of neutron precesses with the Larmor frequency

$$\omega_L = \gamma_L \cdot H$$

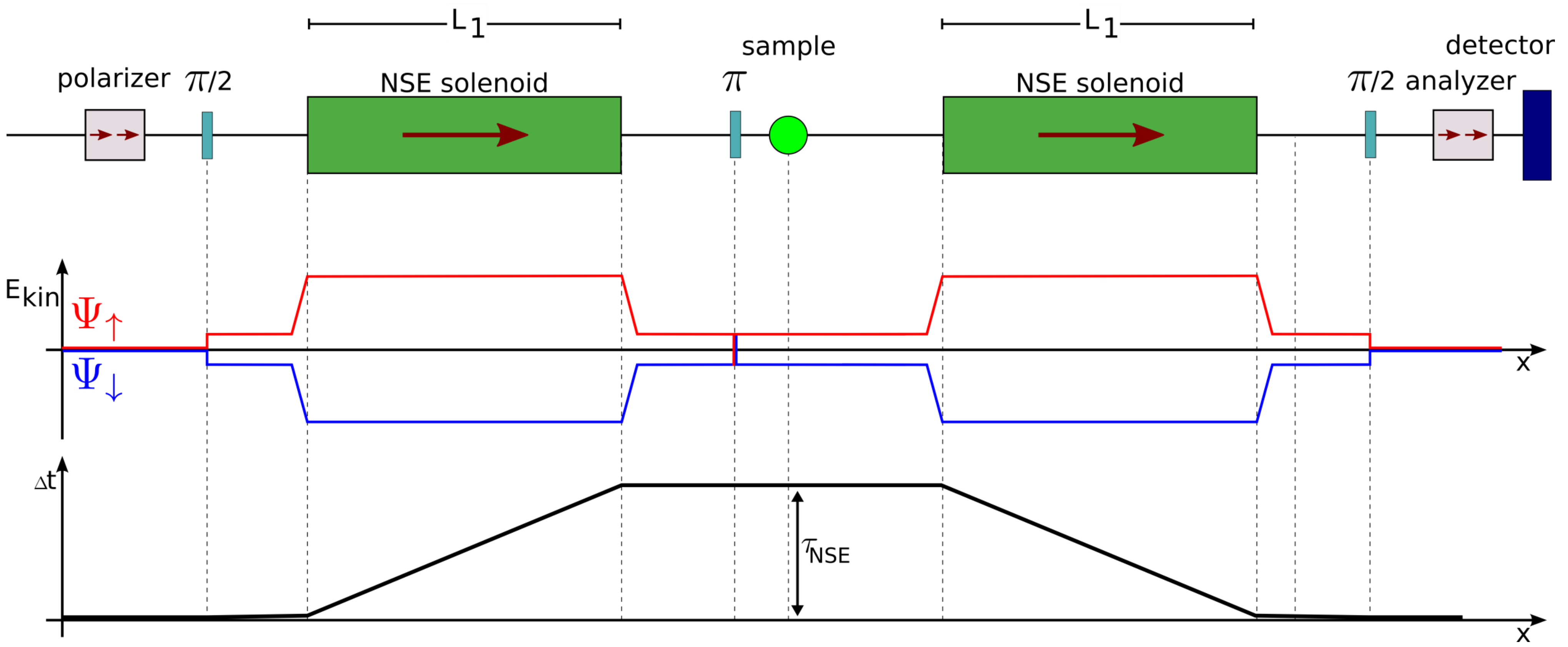


Neutron Spin Echo



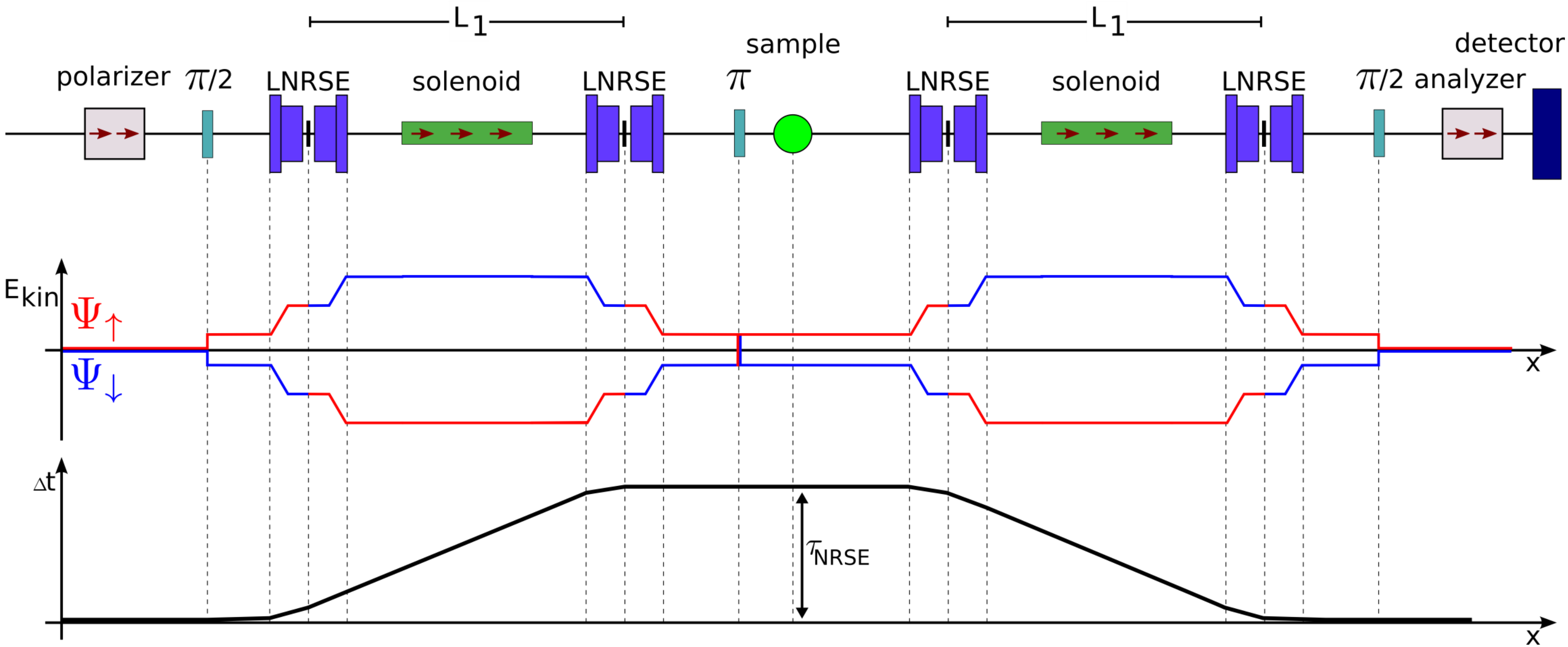
- invented by F. Mezei in 1972
- highest energy resolution among all neutron spectroscopic techniques

Neutron Spin Echo



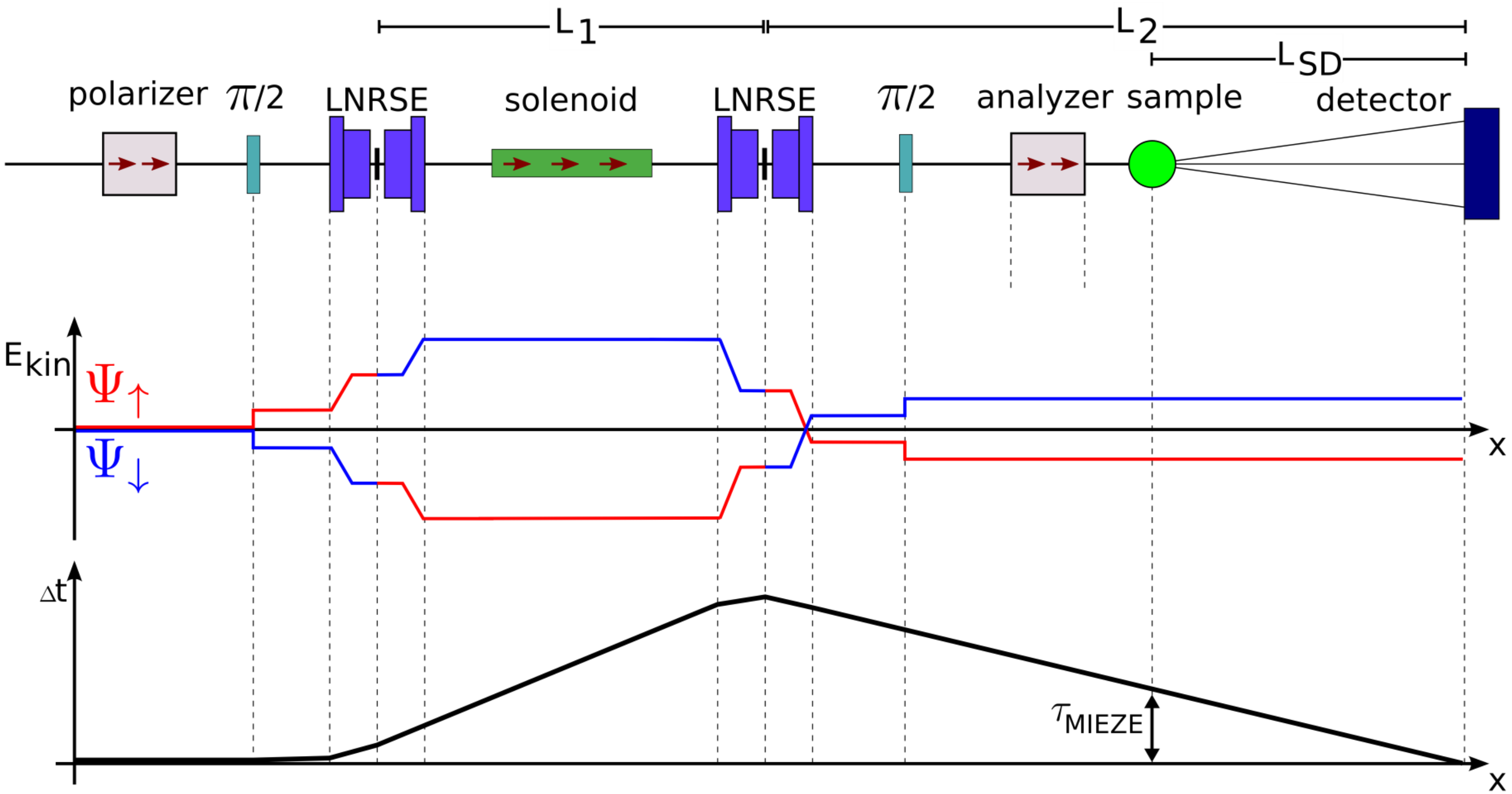
- invented by F. Mezei in 1972
- highest energy resolution among all neutron spectroscopic techniques

Neutron Resonance Spin Echo



- invented by R. Golub & R. Gähler in 1992
- Exchange contant field by constant + rf-field
- allows adjust the resolution according to Dispersion in inelastic measurements

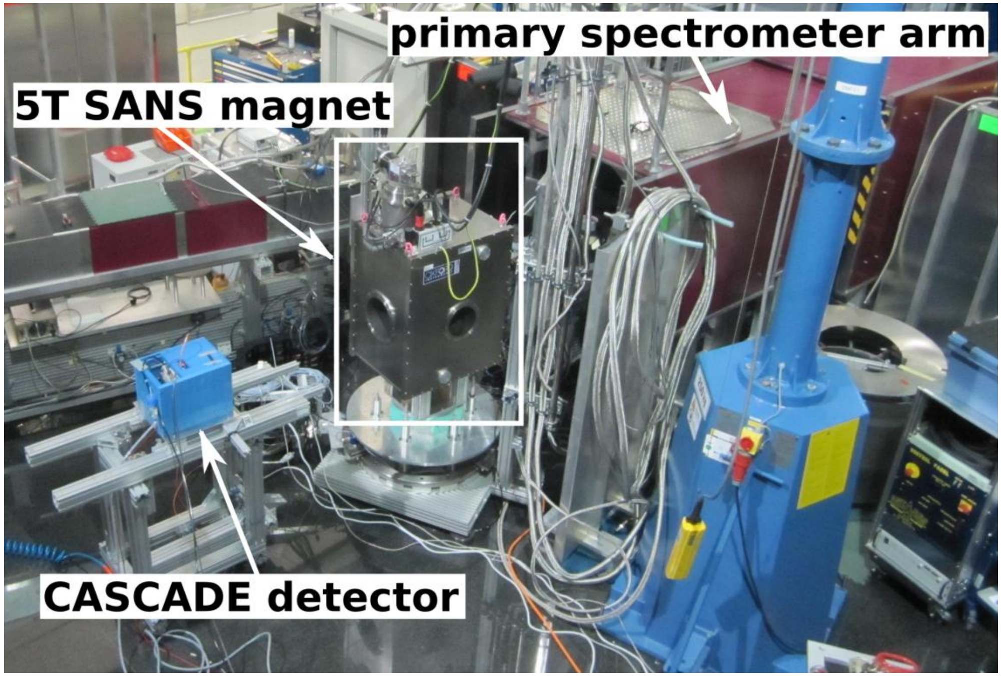
MIEZE



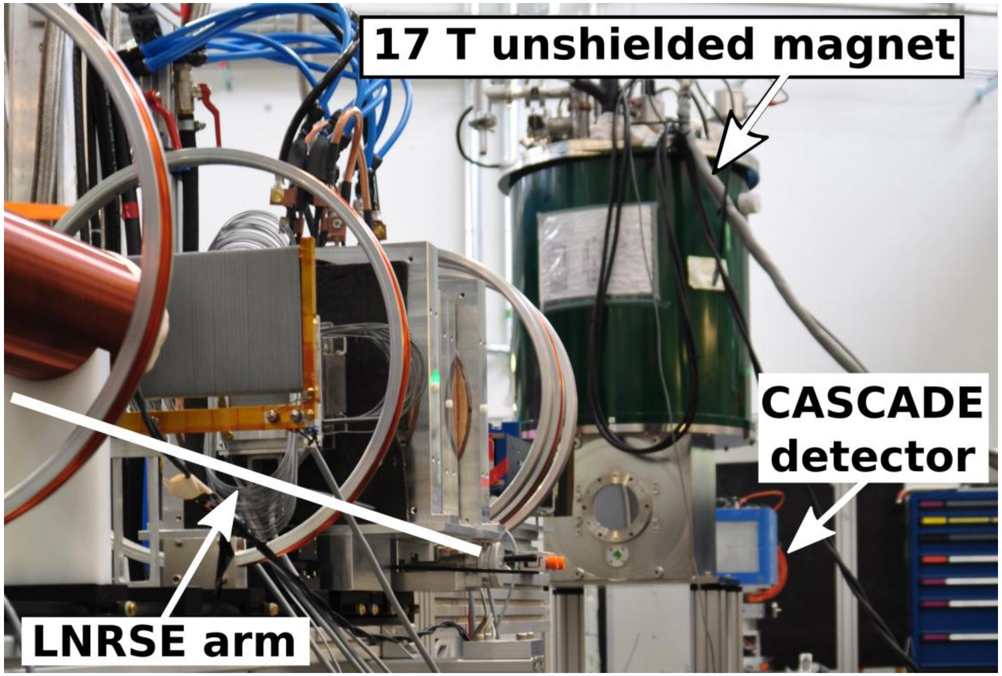
- invented by R. Gähler
- independent from Neutron beam polarization at sample position
- allows measurements under depolarizing conditions at the sample

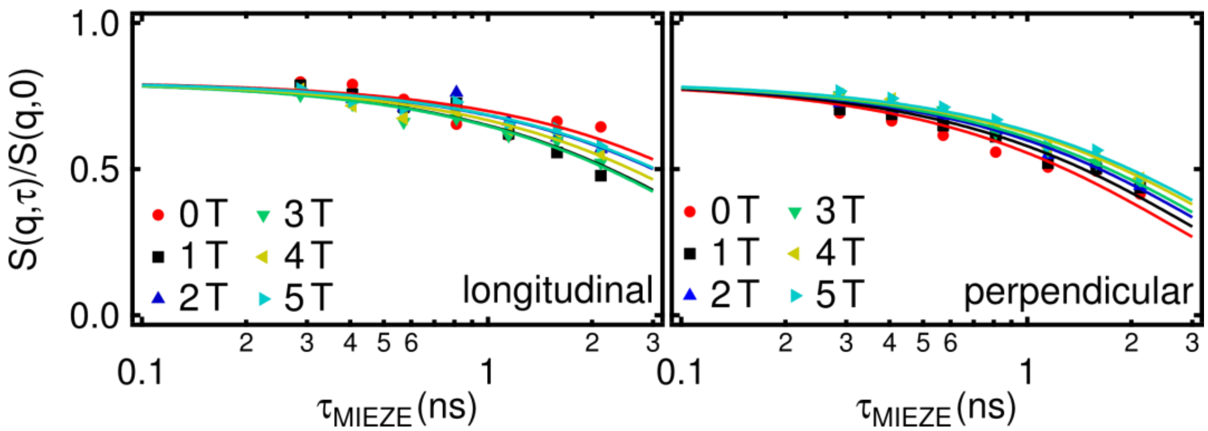
MIEZE in strong magnetic fields

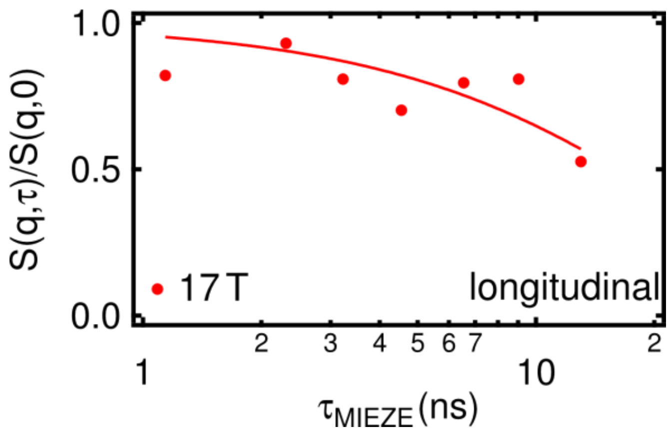
5 T Magnet (SANS-1)



17 T Magnet (B‘ham, UK)

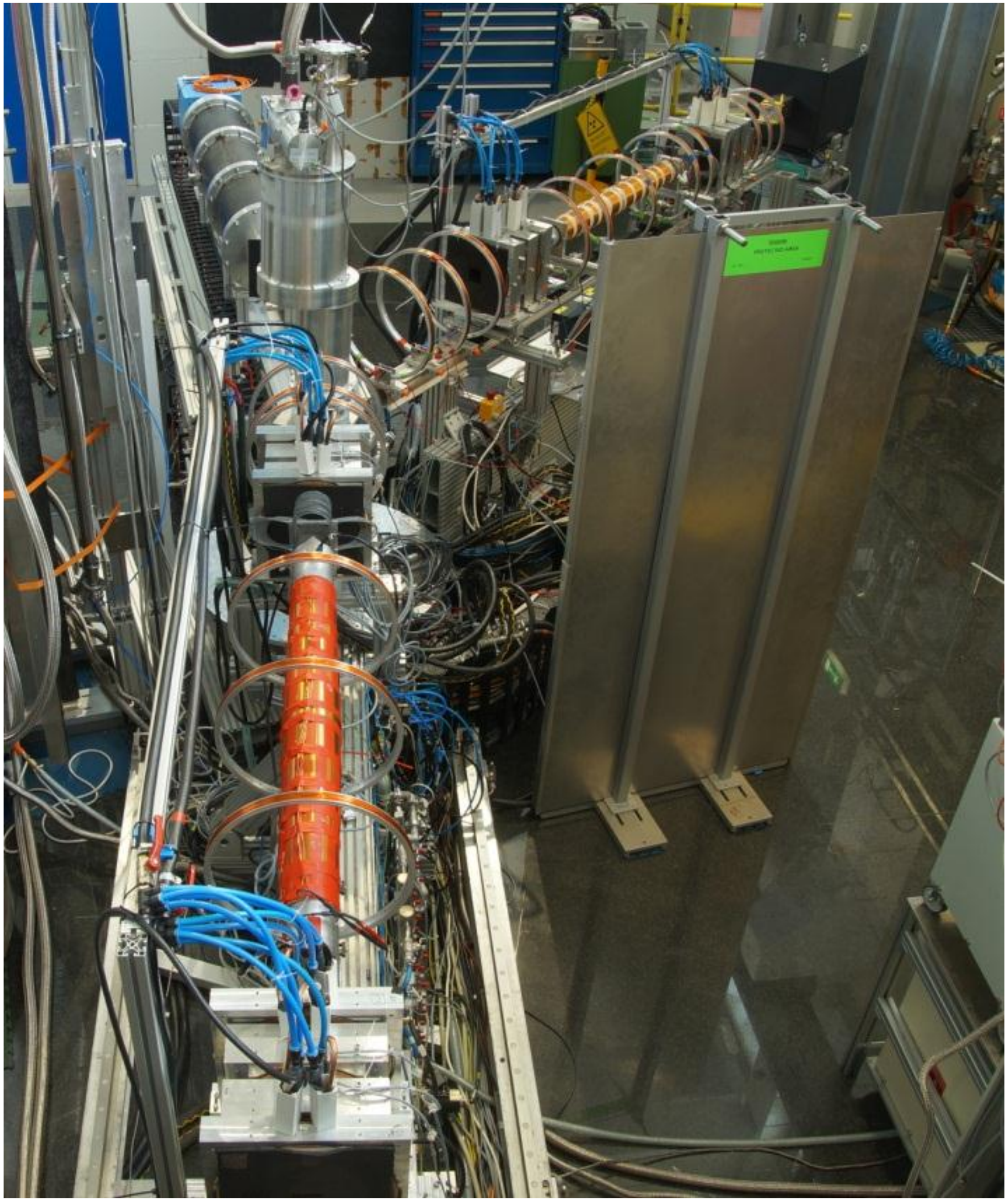




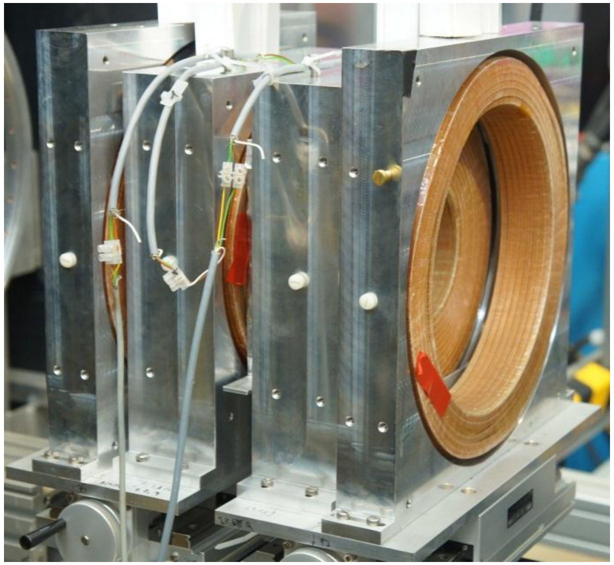


J. Kindervater *et al*. EPJ Web of Conf. **83**, 03008 (2015)

RESEDA



- **RE**sonance **S**pin **E**cho for **D**iverse **A**pplications
- NSE/NRSE
- MIEZE
- Dynamic range
- τ = 0.0001 – 20 ns
- $E = 2\text{meV} - 0.02\mu\text{eV}$
- $Q_{max} = 2.5$ Å^{-1} (at λ = 3 Å)



Outline

(1) Introduction to Neutron Scattering

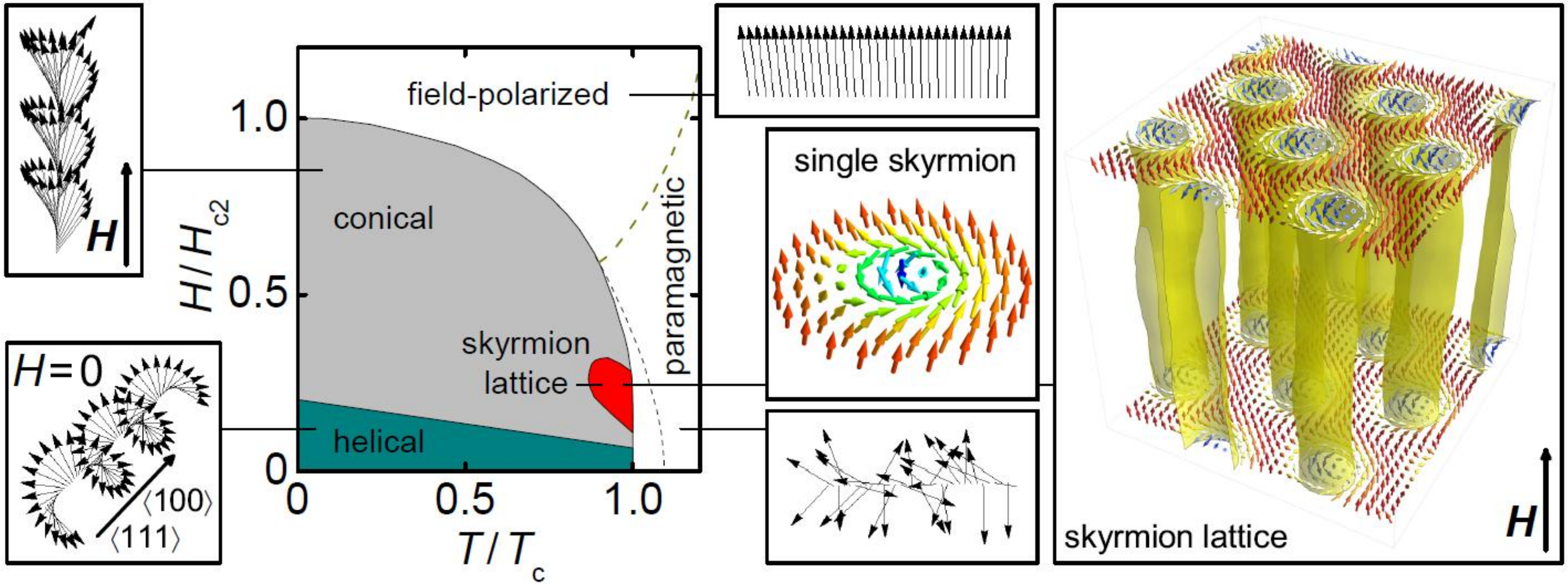
- Neutron scattering
- Small angle neutron scattering
- Neutron Spin Echo

(2) Skyrmions in cubic chiral magnets

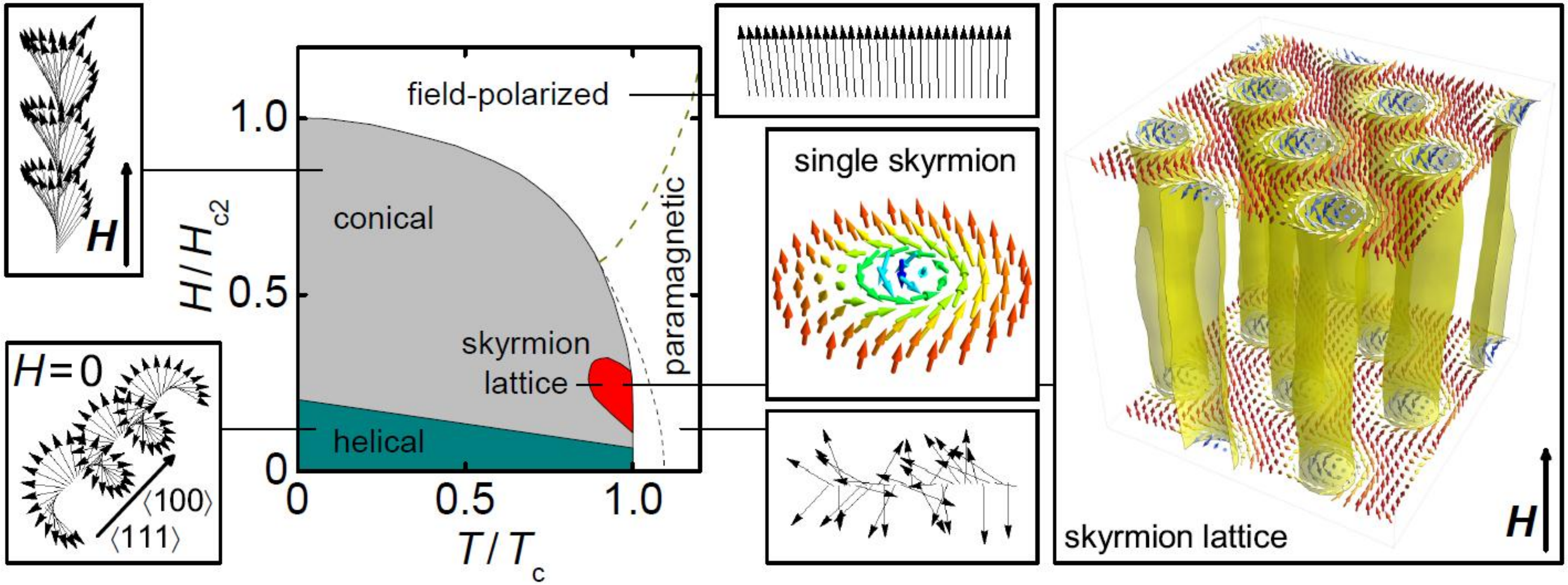
- Introduction
- Topological unwinding
- Field induced tricritical point in MnSi
- Skyrmionic textures in the paramagnetic phase

(3) Conclusion

Skyrmions in cubic chiral magnets

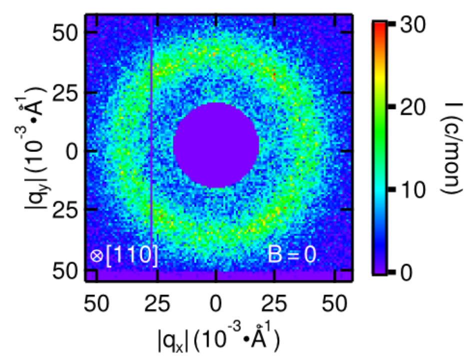


Skyrmions in cubic chiral magnets

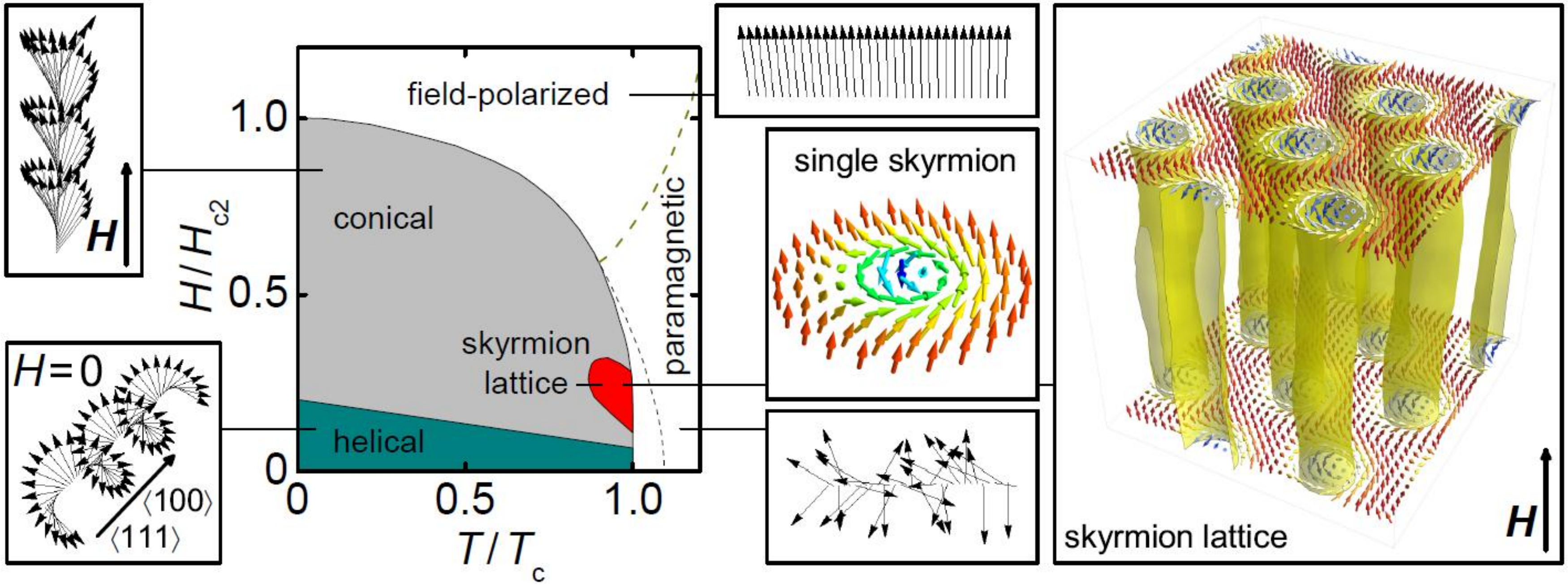


Hierarchy of energy scales:

- ferromagnetic exchange
- Dzyaloshinskii-Moriya
- cubic anisotropies

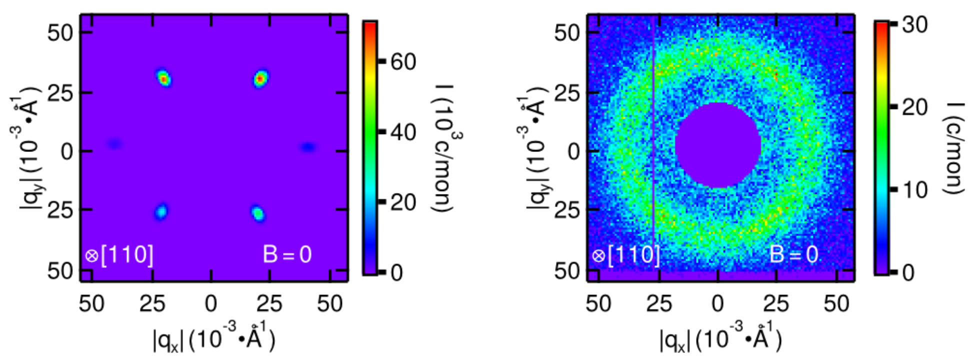


Skyrmions in cubic chiral magnets

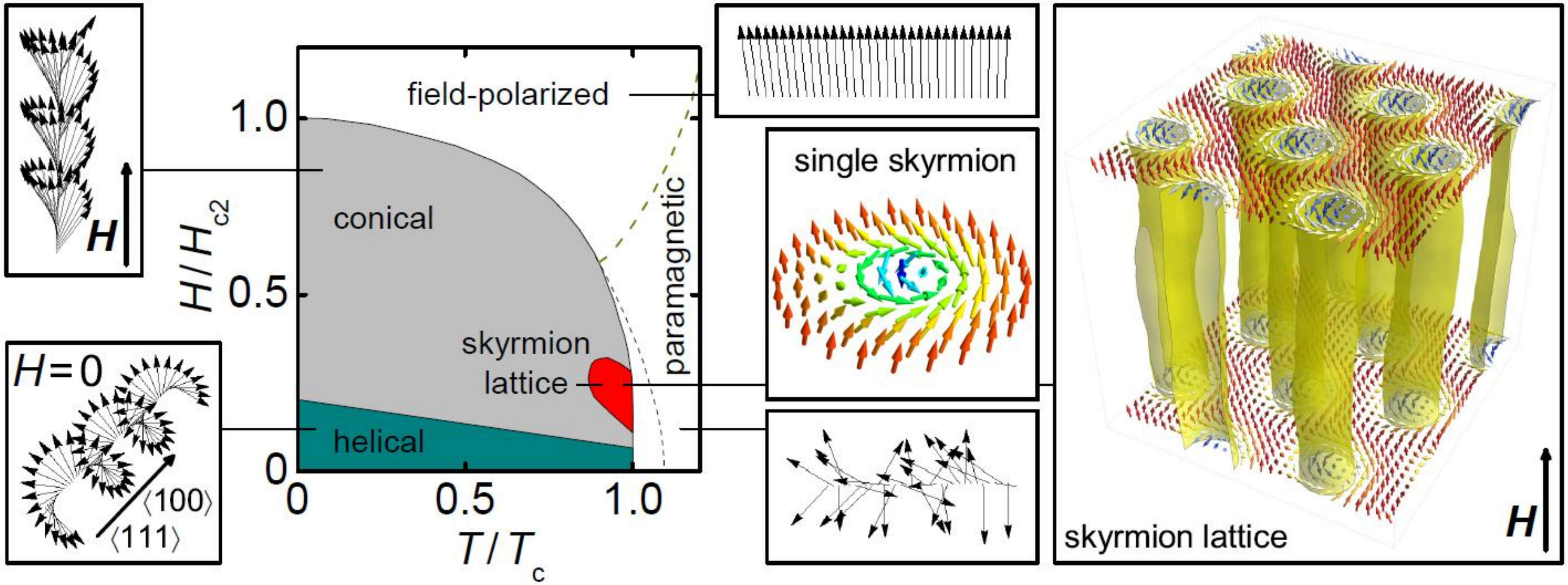


Hierarchy of energy scales:

- ferromagnetic exchange
- Dzyaloshinskii-Moriya
- cubic anisotropies

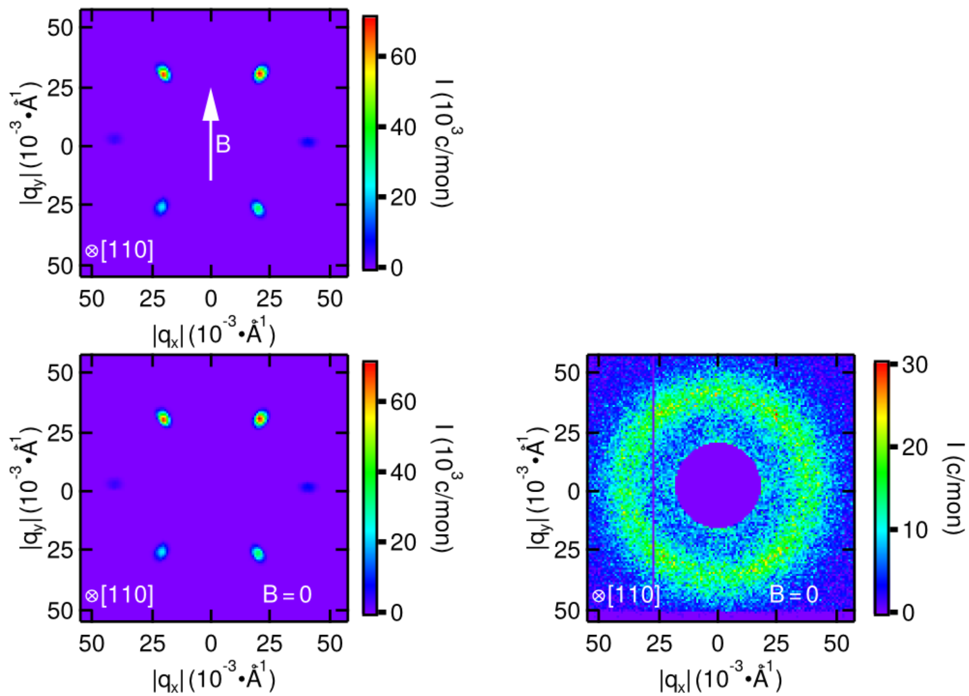


Skyrmions in cubic chiral magnets

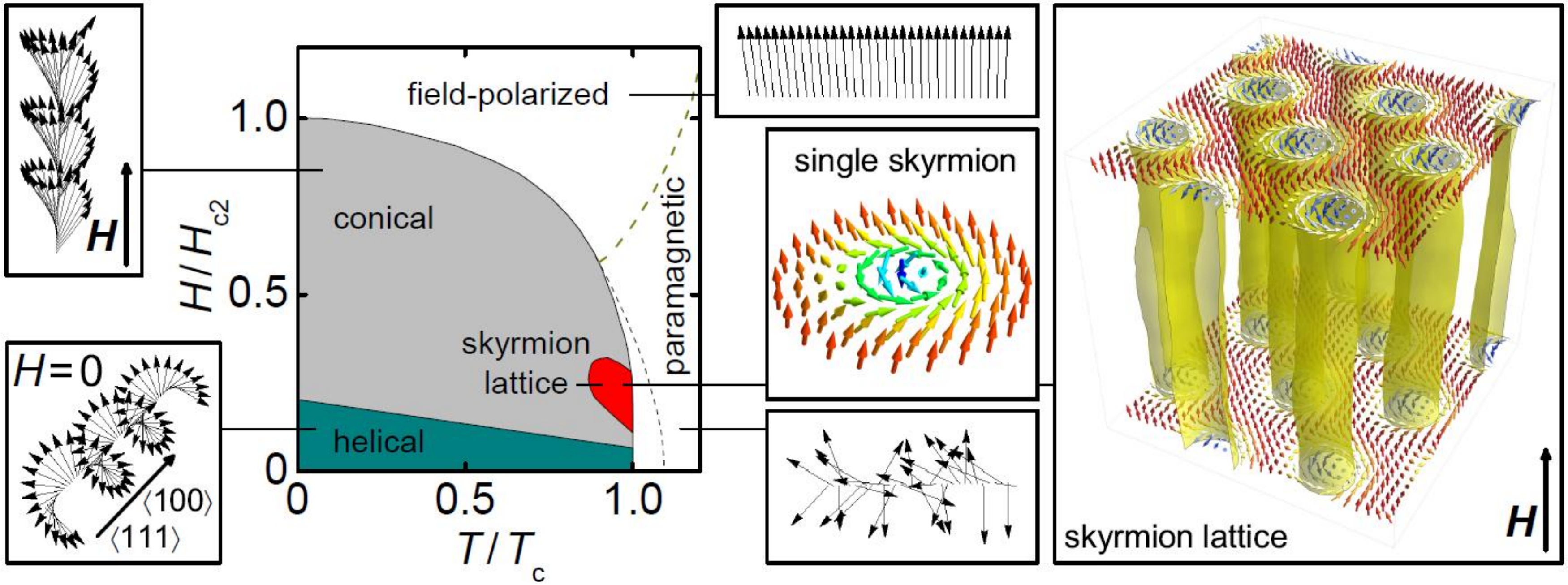


Hierarchy of energy scales:

- ferromagnetic exchange
- Dzyaloshinskii-Moriya
- cubic anisotropies

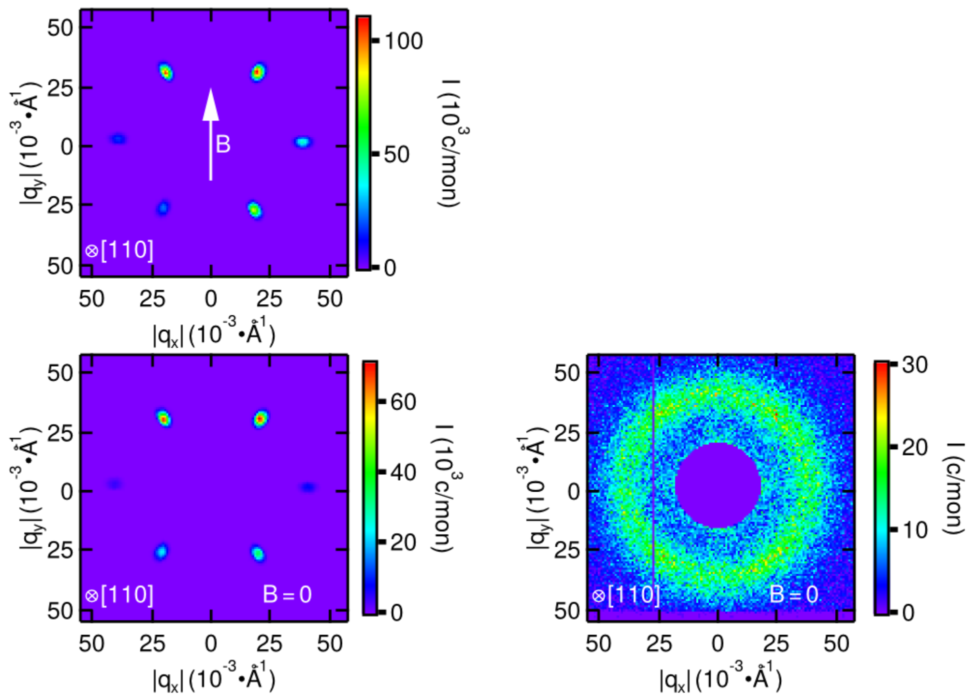


Skyrmions in cubic chiral magnets

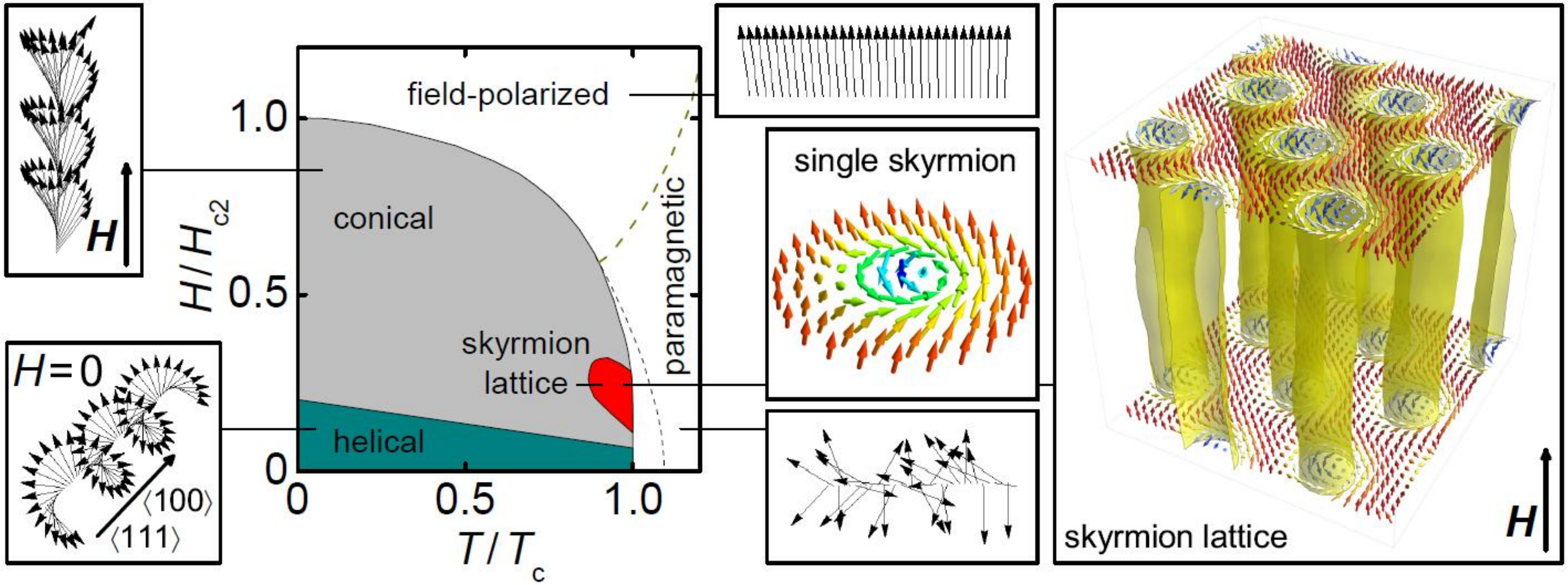


Hierarchy of energy scales:

- ferromagnetic exchange
- Dzyaloshinskii-Moriya
- cubic anisotropies

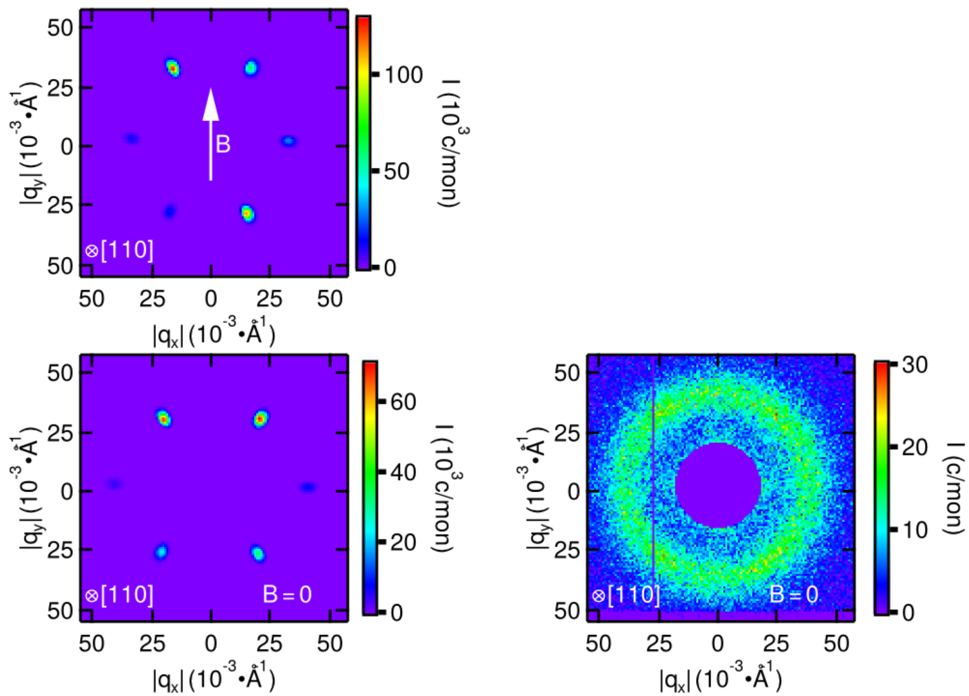


Skyrmions in cubic chiral magnets

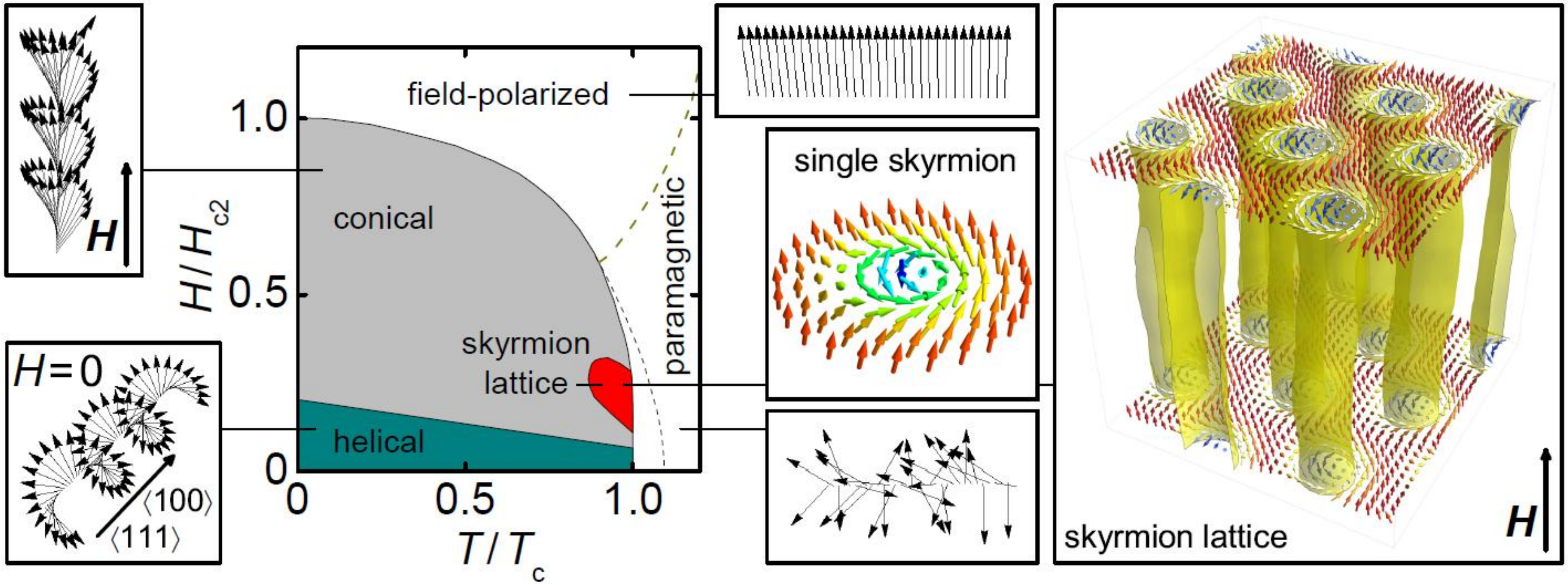


Hierarchy of energy scales:

- ferromagnetic exchange
- Dzyaloshinskii-Moriya
- cubic anisotropies

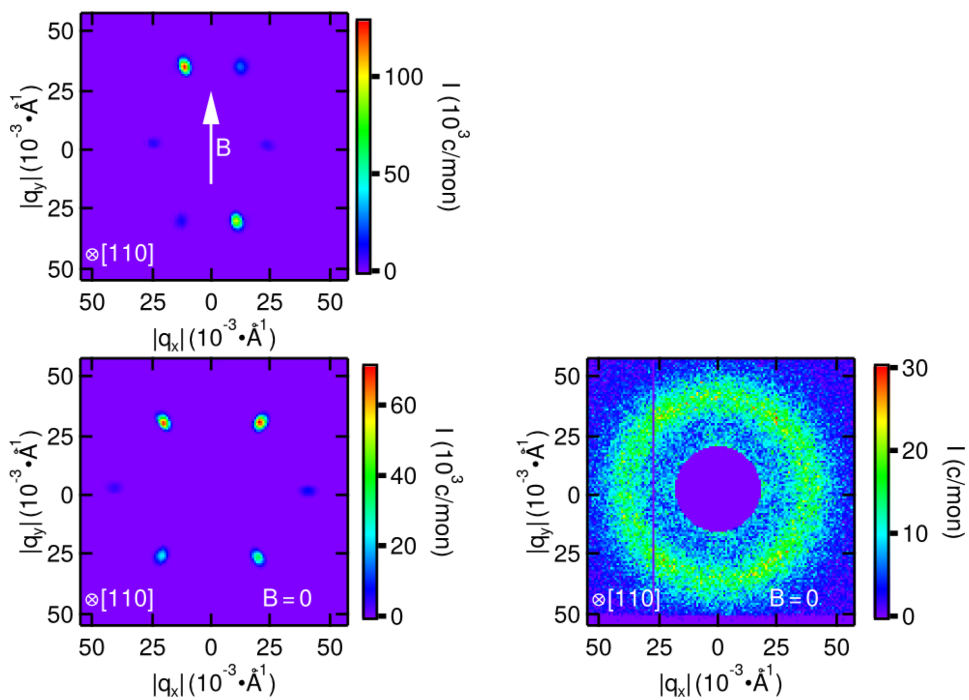


Skyrmions in cubic chiral magnets

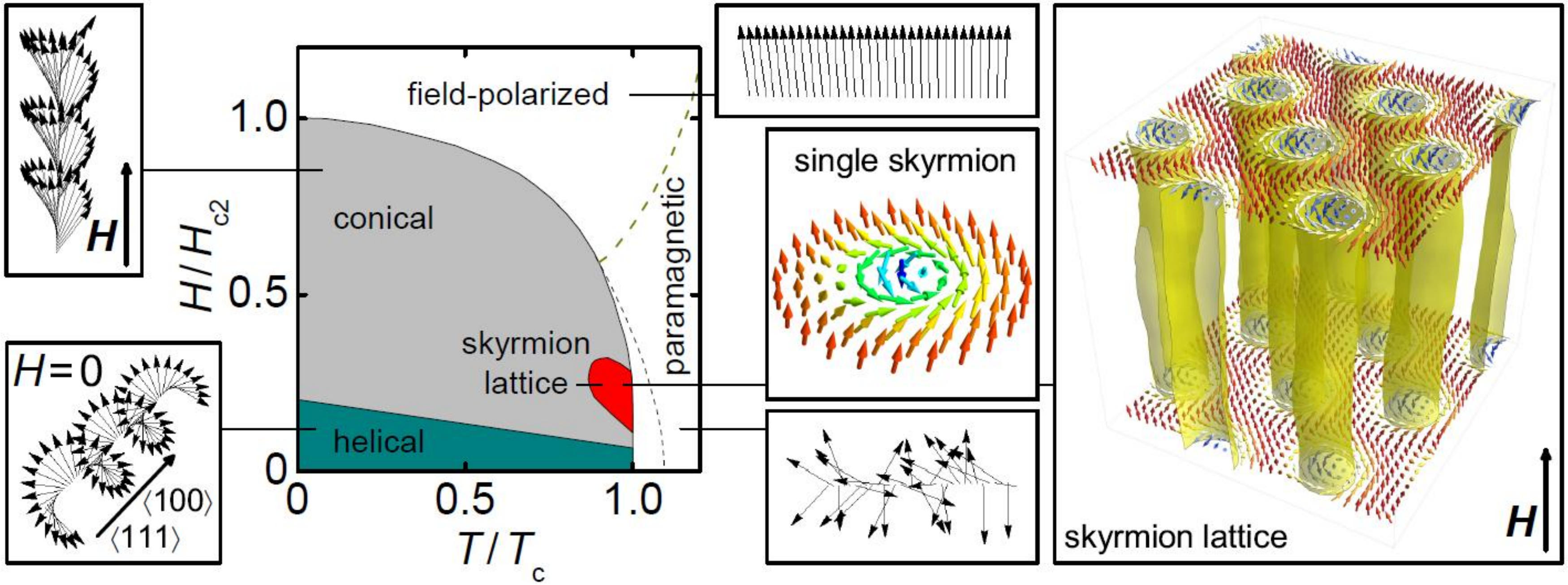


Hierarchy of energy scales:

- ferromagnetic exchange
- Dzyaloshinskii-Moriya
- cubic anisotropies

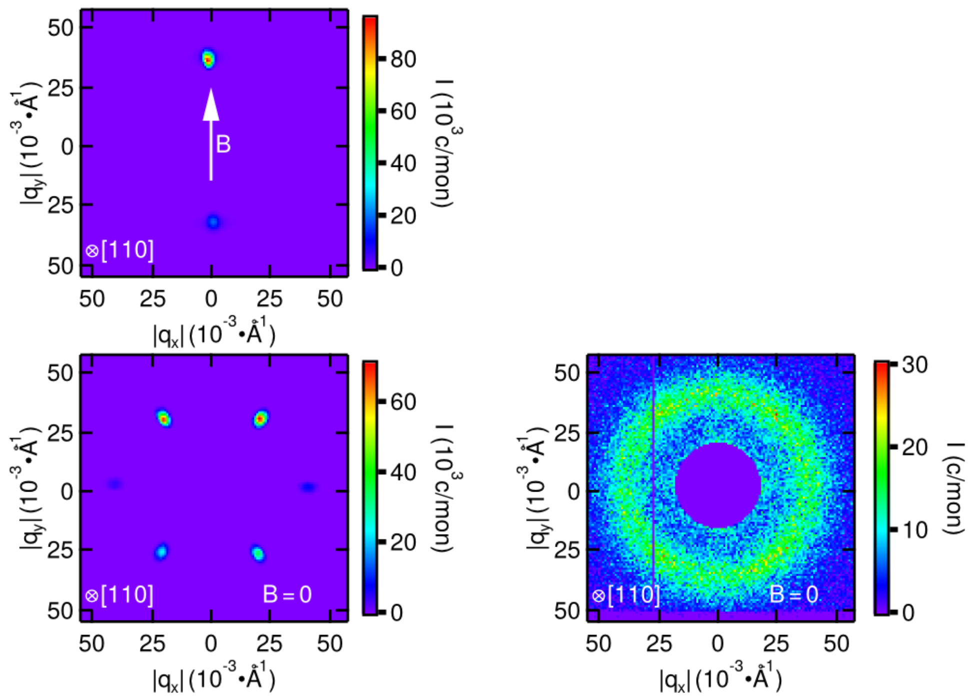


Skyrmions in cubic chiral magnets

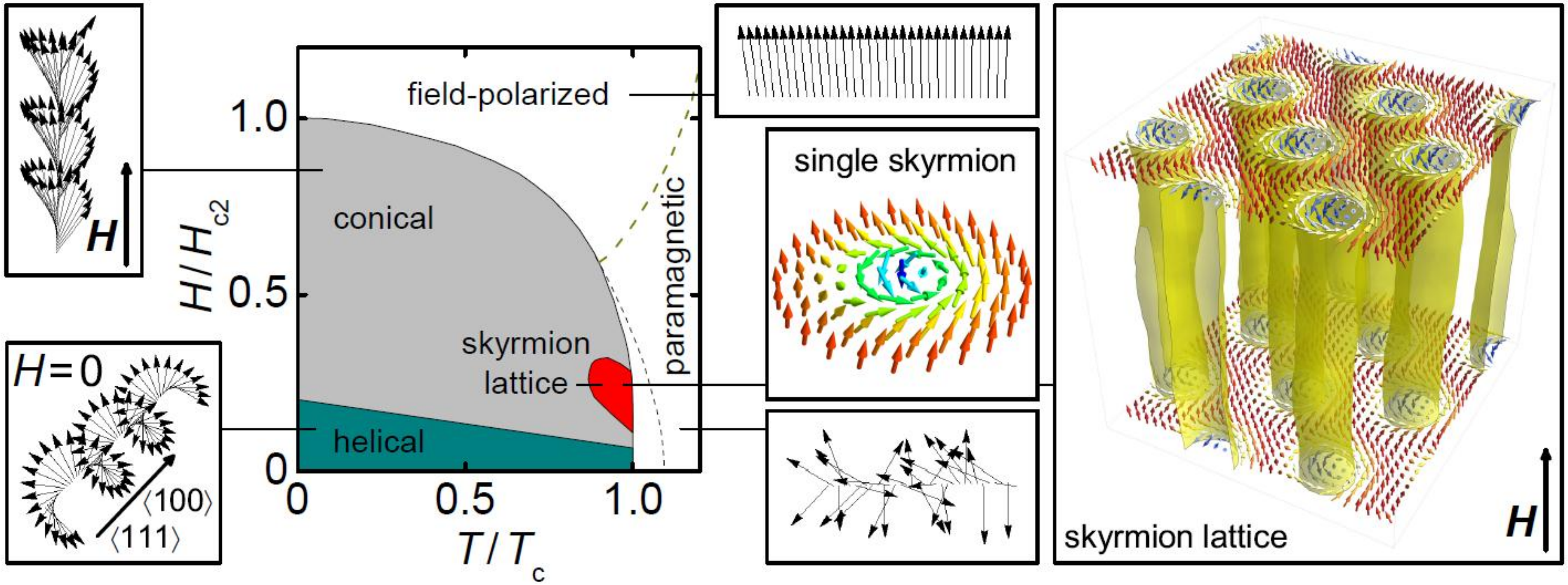


Hierarchy of energy scales:

- ferromagnetic exchange
- Dzyaloshinskii-Moriya
- cubic anisotropies

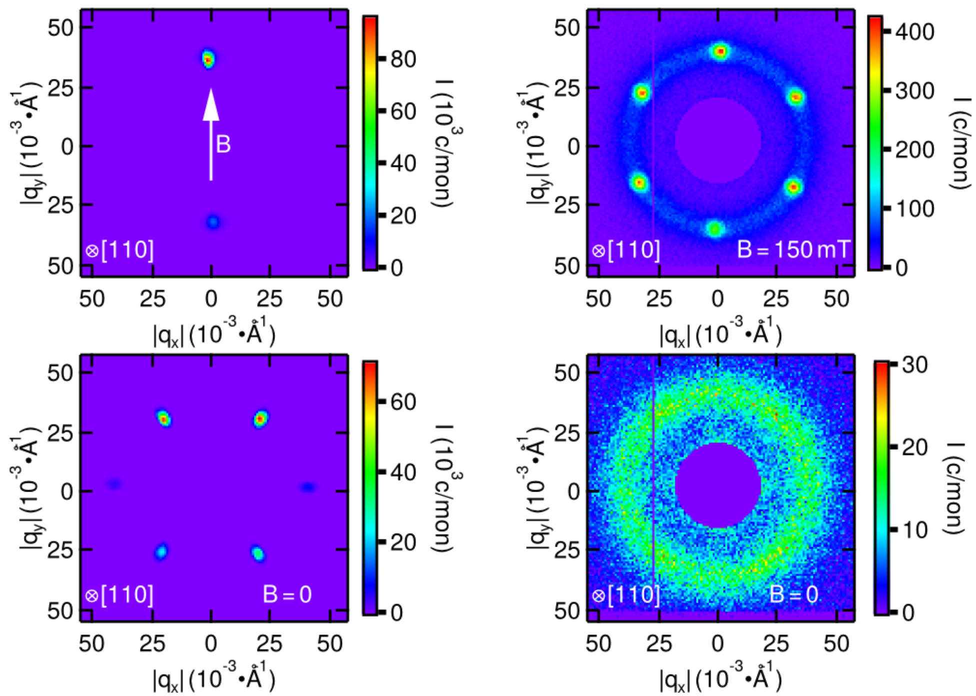


Skyrmions in cubic chiral magnets



Hierarchy of energy scales:

- ferromagnetic exchange
- Dzyaloshinskii-Moriya
- cubic anisotropies



Outline

(1) Introduction to Neutron Scattering

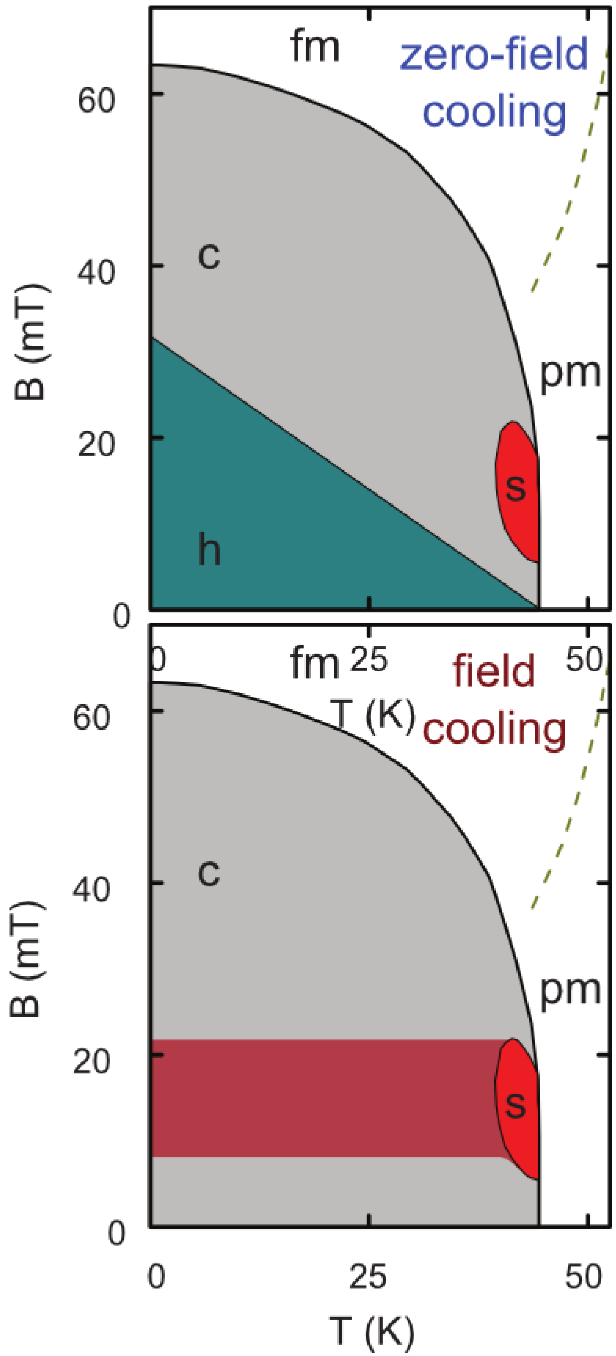
- Neutron scattering
- Small angle neutron scattering
- Neutron Spin Echo

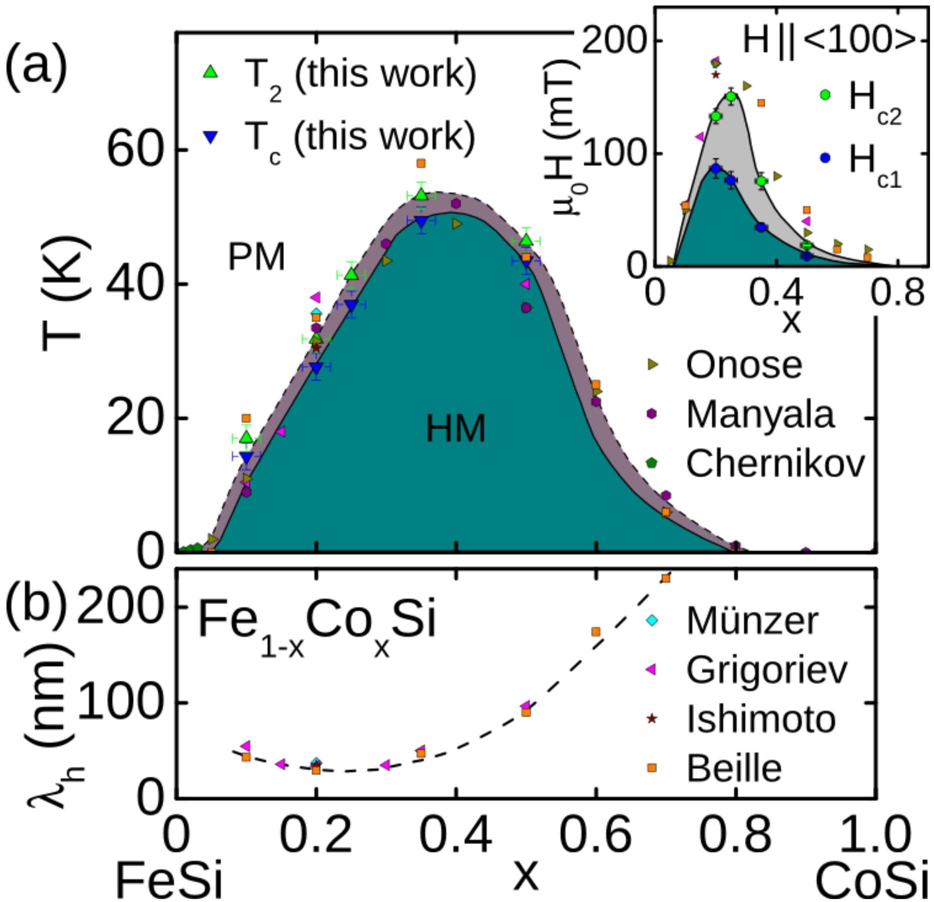
(2) Skyrmions in cubic chiral magnets

- Introduction
- Topological unwinding into helical/conical phase
- Field induced tricritical point in MnSi
- Skyrmionic textures in the paramagnetic phase

(3) Conclusion

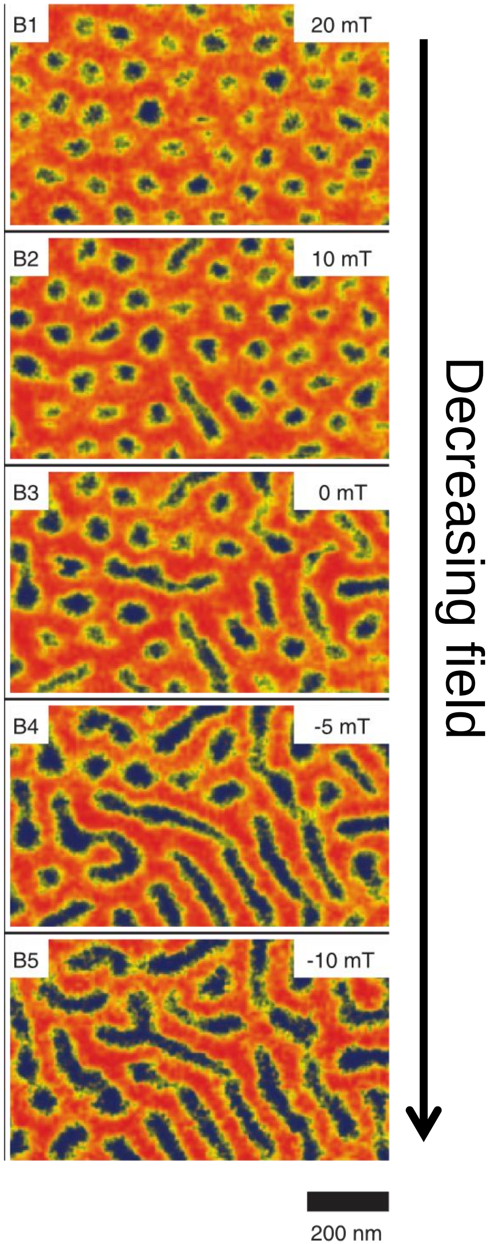
Magnetic phase diagram of $Fe_{1-x}Co_xSi$





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

Topological unwinding in $Fe_{1-x}Co_xSi$

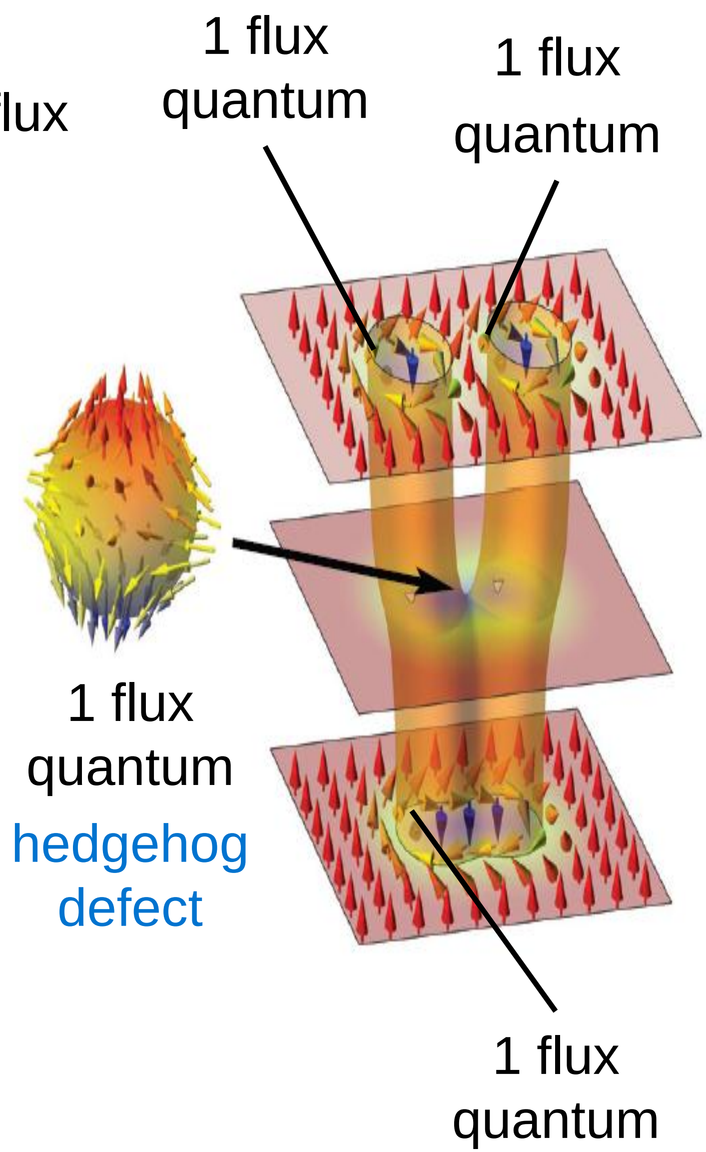


Skyrmion lattice state

- non-trivial topology
- emergent magnetic flux

sources/sinks of emergent *B*-field

quantized magnetic charge
magnetic (anti-) monopole

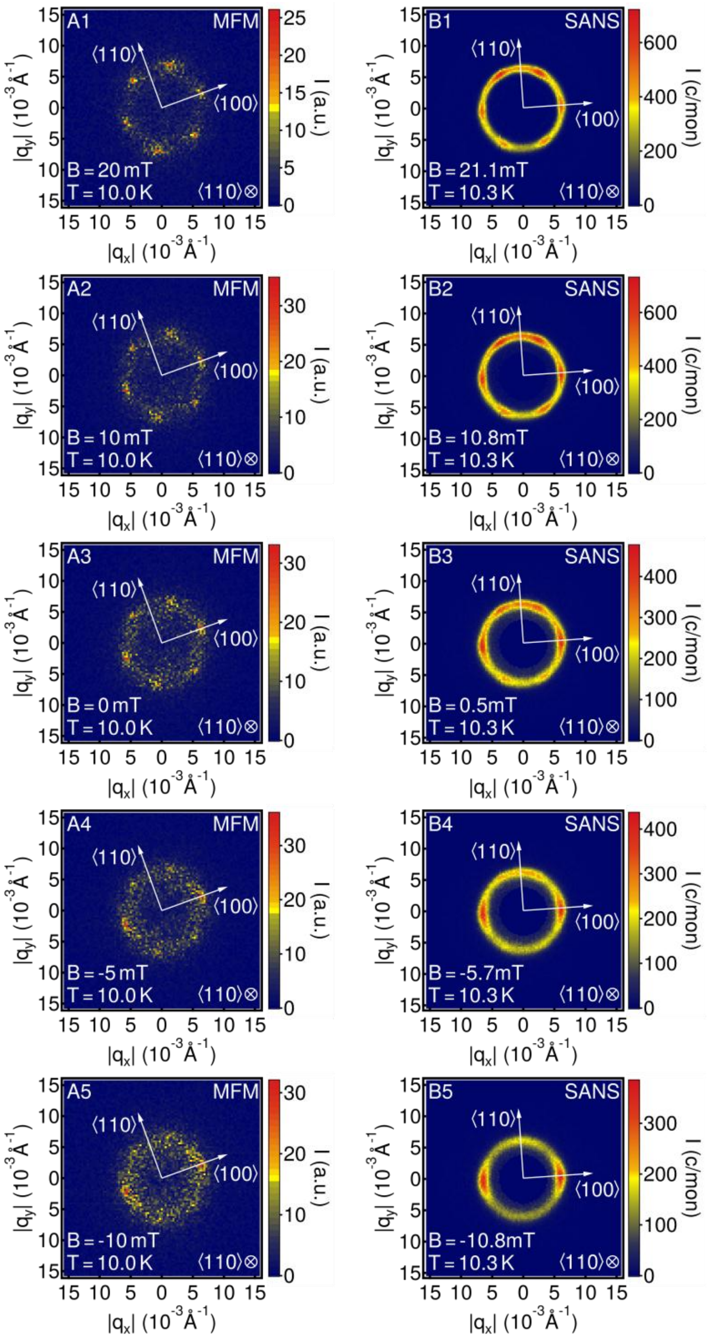


Helical state

- trivial topology
- no emergent magnetic flux

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

Topological unwinding in $Fe_{1-x}Co_xSi$

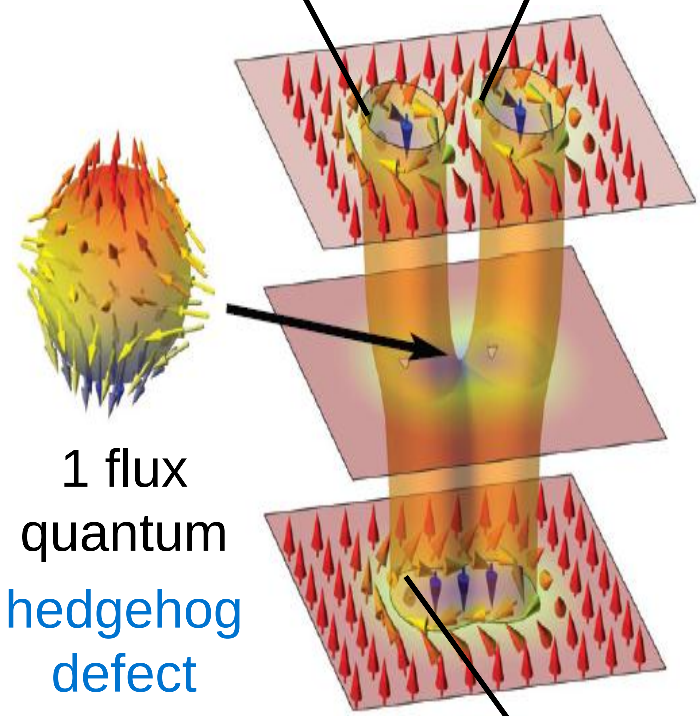


Skyrmion lattice state

- non-trivial topology
- emergent magnetic flux

sources/sinks of emergent *B*-field

quantized magnetic charge
magnetic (anti-) monopole



Helical state

- trivial topology
- no emergent magnetic flux

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

Outline

(1) Introduction to Neutron Scattering

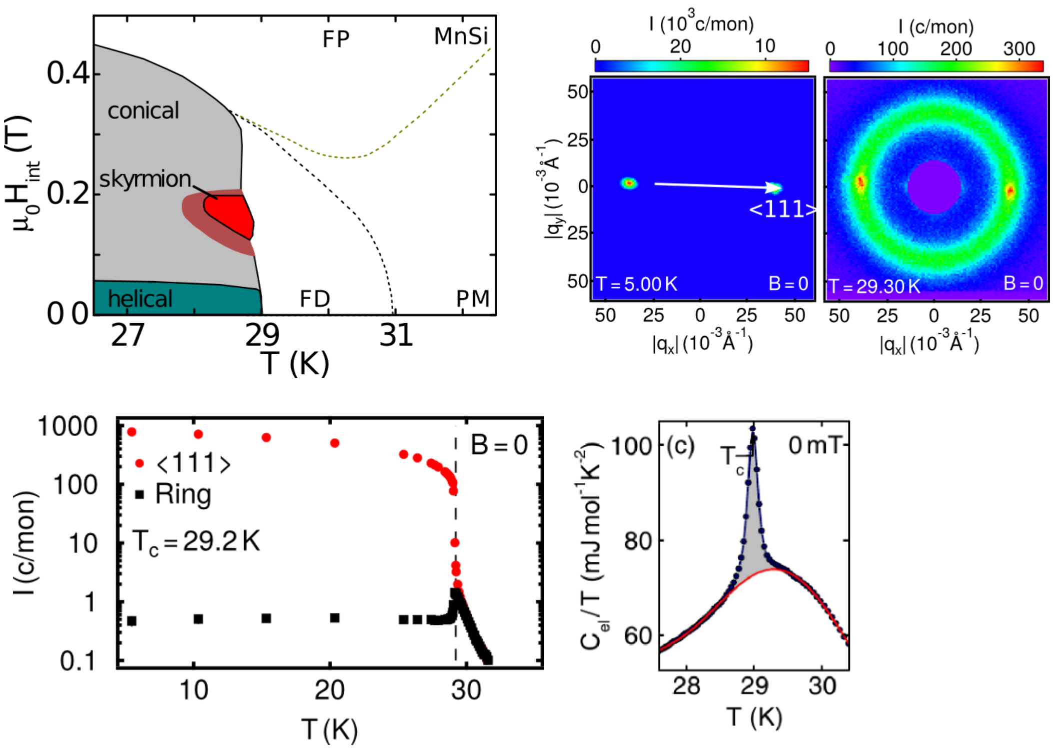
- Neutron scattering
- Small angle neutron scattering
- Neutron Spin Echo

(2) Skyrmions in cubic chiral magnets

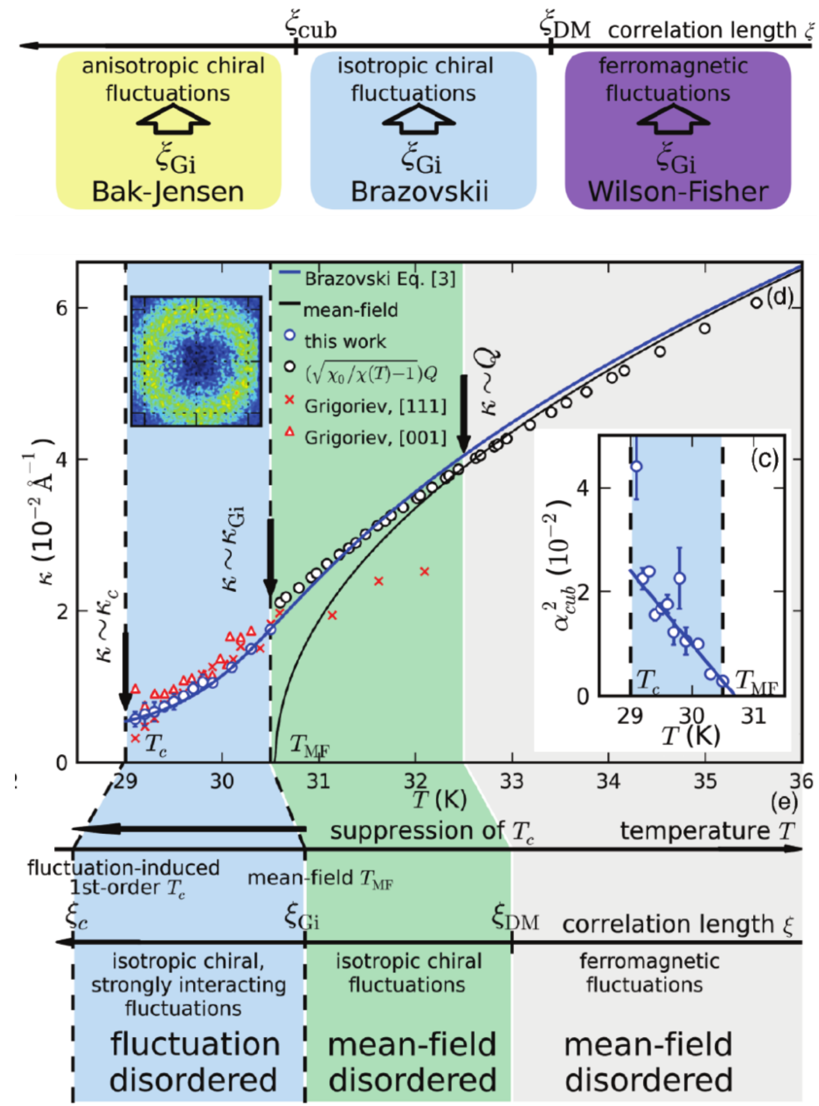
- Introduction
- Topological unwinding into helical/conical phase
- Field induced tricritical point in MnSi
- Skyrmionic textures in the paramagnetic phase

(3) Conclusion

Brazovskii scenario in MnSi



Unpolarized SANS:

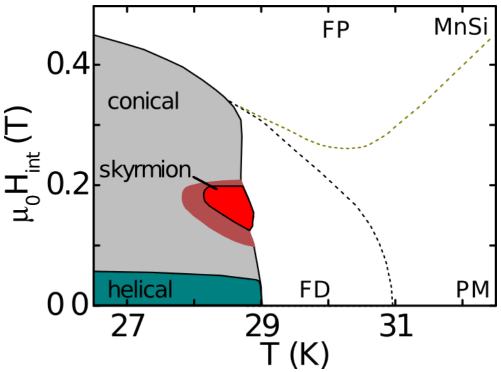


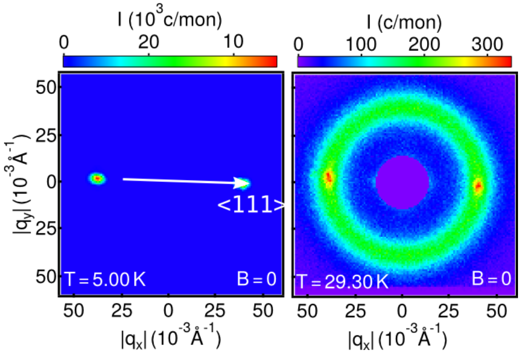
Hierarchy of energy scales reflected in fluctuations:

- FM fluctuations for $T \gg T_c$
- isotropic chiral fluctuations
- anisotropic chiral fluctuations

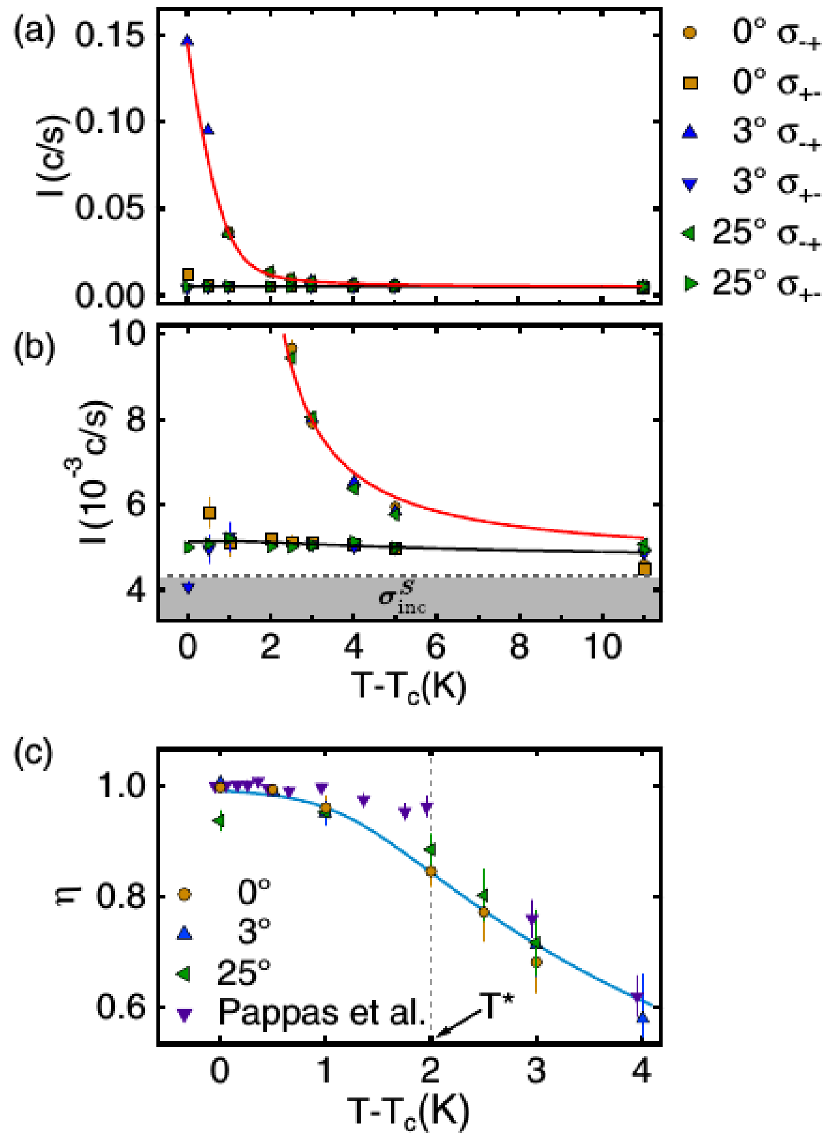
M. Janoschek *et al*. Phys. Rev. B **87**, 134407 (2013)
A. Bauer *et al.*, Phys. Rev. Lett. **110**, 177207 (2013)

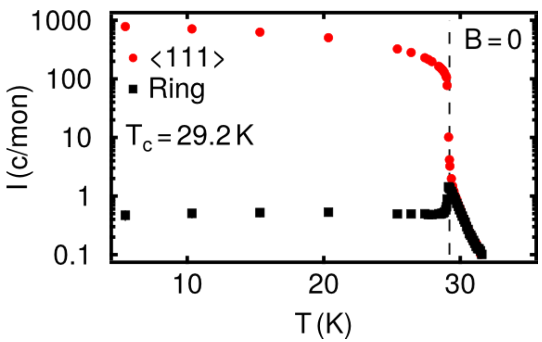
Brazovskii scenario in MnSi

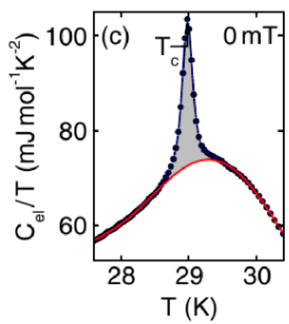




Polarized SANS:



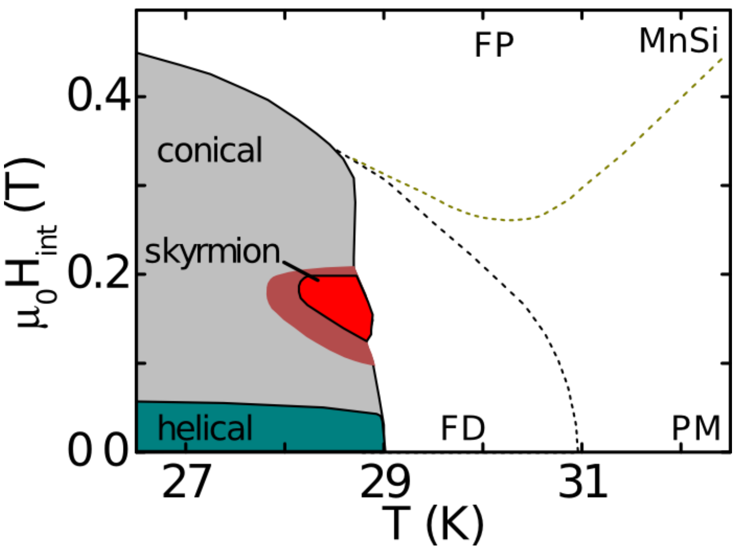




Hierarchy of energy scales reflected in fluctuations:

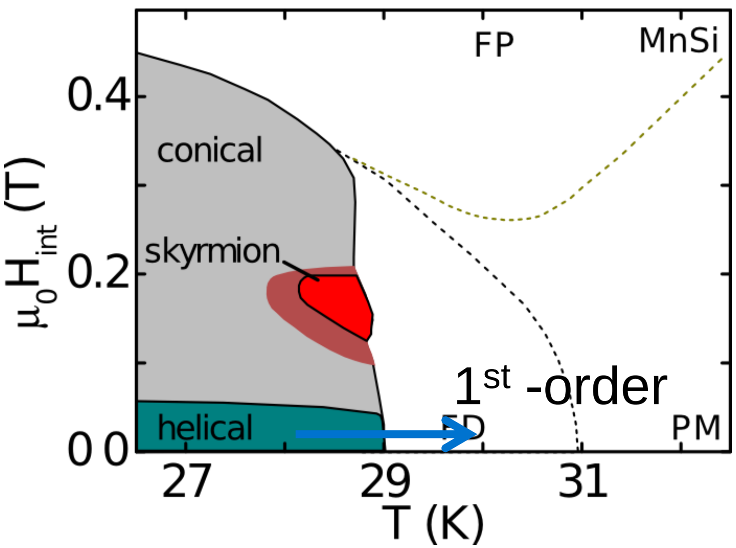
- FM fluctuations for $T \gg T_c$
- isotropic chiral fluctuations
- anisotropic chiral fluctuations

J. Kindervater *et al.*, Phys. Rev. B **89**, 180408(R) (2014)
M. Janoschek *et al*. Phys. Rev. B **87**, 134407 (2013)
A. Bauer *et al.*, Phys. Rev. Lett. **110**, 177207 (2013)


FP
MnSi
conical
skyrmion
helical
FD
PM
0.4
0.2
0 0
27
29
31
T (K)
$\mu_0 H_{int}$ (T)

1^{st} -order

Field-induced tricritical point



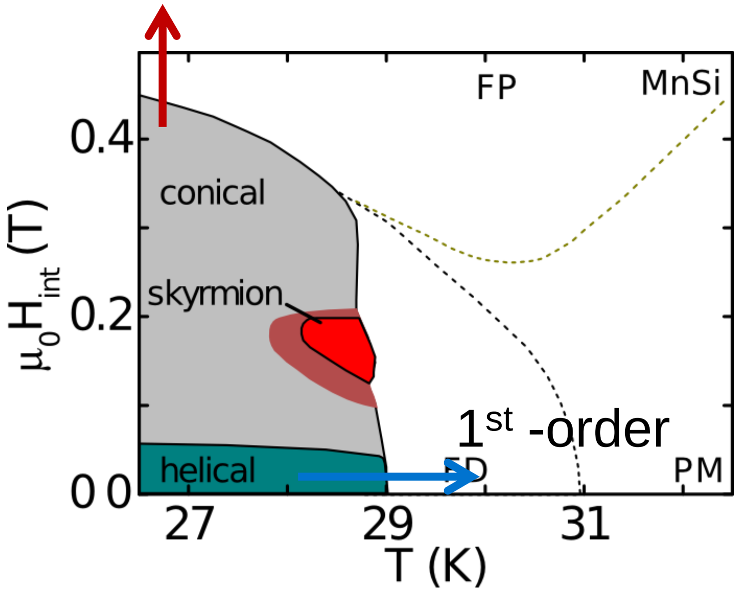
1st -order

helical ⇒ paramagnetic (@ B = 0):

1st -order Brazovskii transition

Field-induced tricritical point

2nd -order



1st -order

helical ⇒ paramagnetic (@ B = 0):

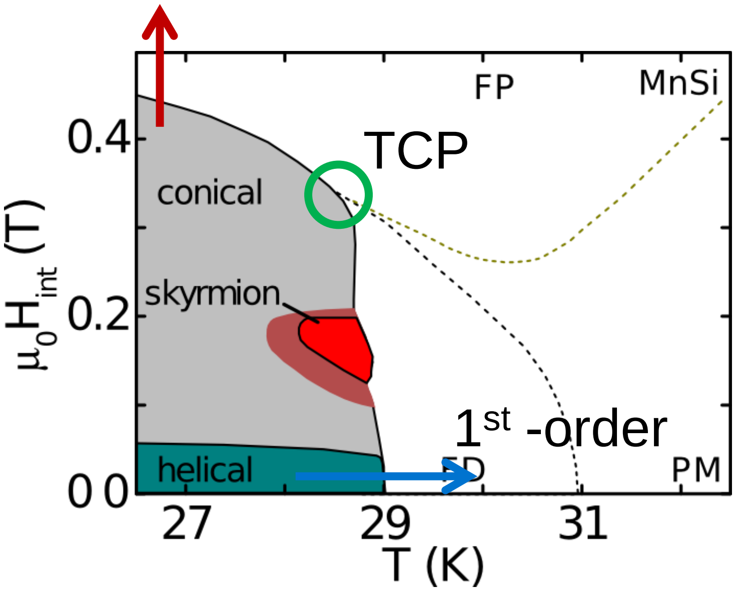
1st -order Brazovskii transition

conical ⇒ field polarized (@ T = 0):

2nd -order transition

Field-induced tricritical point

2nd -order



1st -order

helical ⇒ paramagnetic (@ B = 0):

1st -order Brazovskii transition

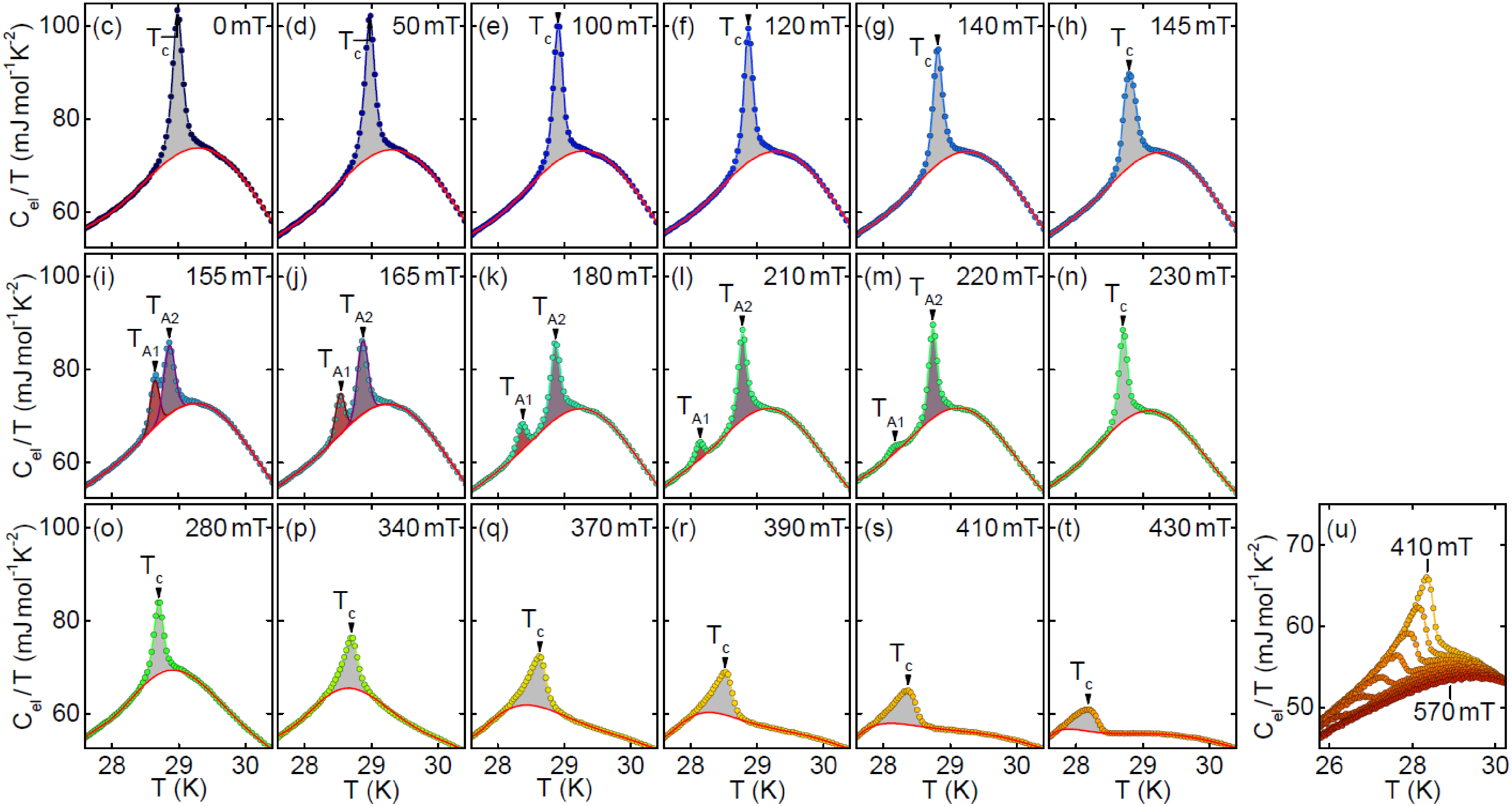
conical ⇒ field polarized (@ T = 0):

2nd -order transition

character of the phase transition has to change

field-induced tricritical point

Field-induced tricritical point



- small fields: symmetric δ-spike (1st order)
- intermediate fields: two peaks (1st order, skyrmion lattice)
- higher fields: asymmetric λ-anomaly (2nd order)

A. Bauer *et al.*, Phys. Rev. Lett. **110**, 177207 (2013)

Thank you for your attention.