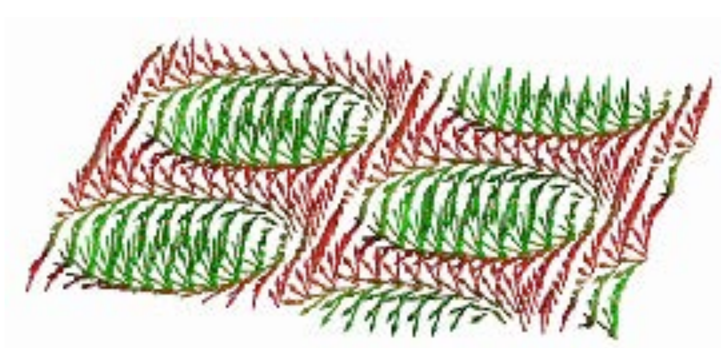
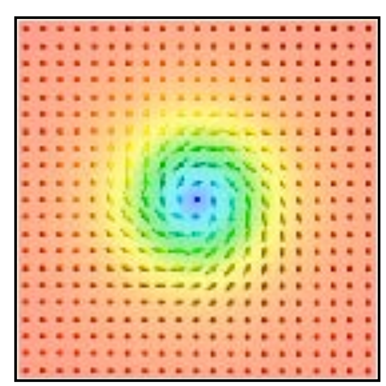
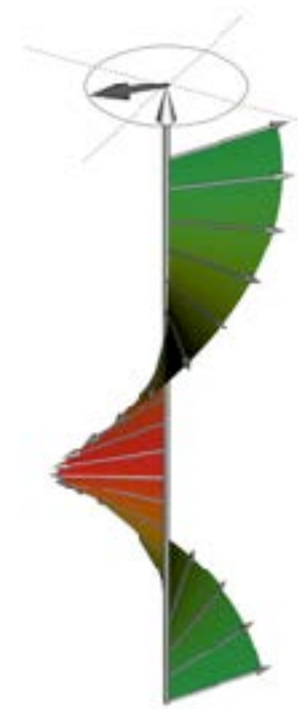
Magnonics in skyrmion-hosting chiral magnetic materials

Markus Garst

TU Dresden





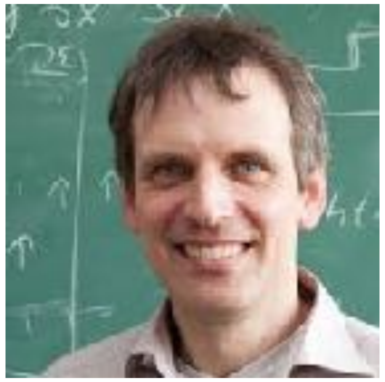


Collaboration

theory:

Johannes Waizner

Achim Rosch (Köln)



experimental groups:

Peter Böni (München)

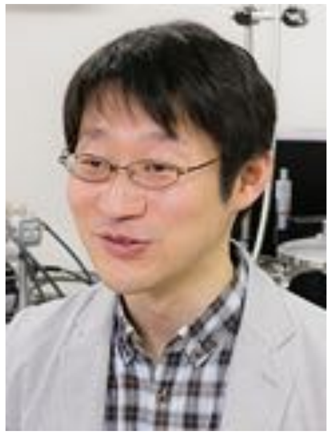
Neutron scattering

Dirk Grundler (Lausanne)

Magnetic resonance

Shinichiro Seki (Riken)

Spinwave spectroscopy



Outline:

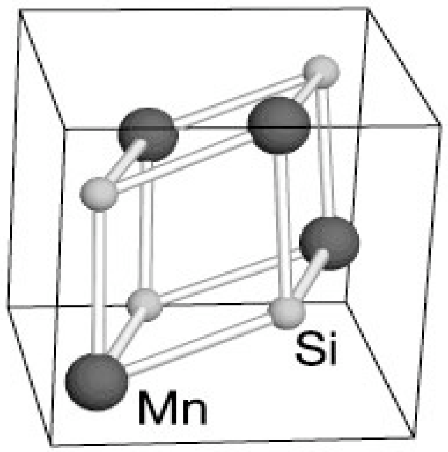
- Introduction to chiral magnets
- Spin-wave dynamics of the magnetic helix
- Spin-wave dynamics of the magnetic skyrmion
- Spin-wave dynamics of the magnetic skyrmion lattice

Introduction to chiral magnets

Chiral magnets

non-centrosymmetric, cubic magnets: MnSi, FeGe, $Fe_xCo_{1-x}Si$, Cu_2OSeO_3, …

Bravais lattice: simple cubic
space group: $P2_13$ (B20)

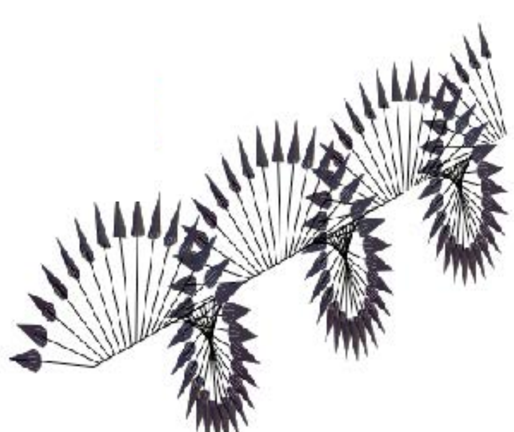


chiral atomic crystal lattice

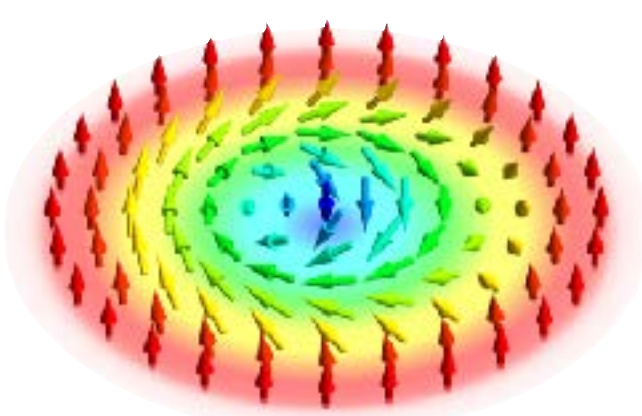
⇨ $$D\vec{M}(\nabla \times \vec{M})$$
Dzyaloshinskii-Moriya interaction

crystal chirality inherited by magnetism

chiral magnetic textures



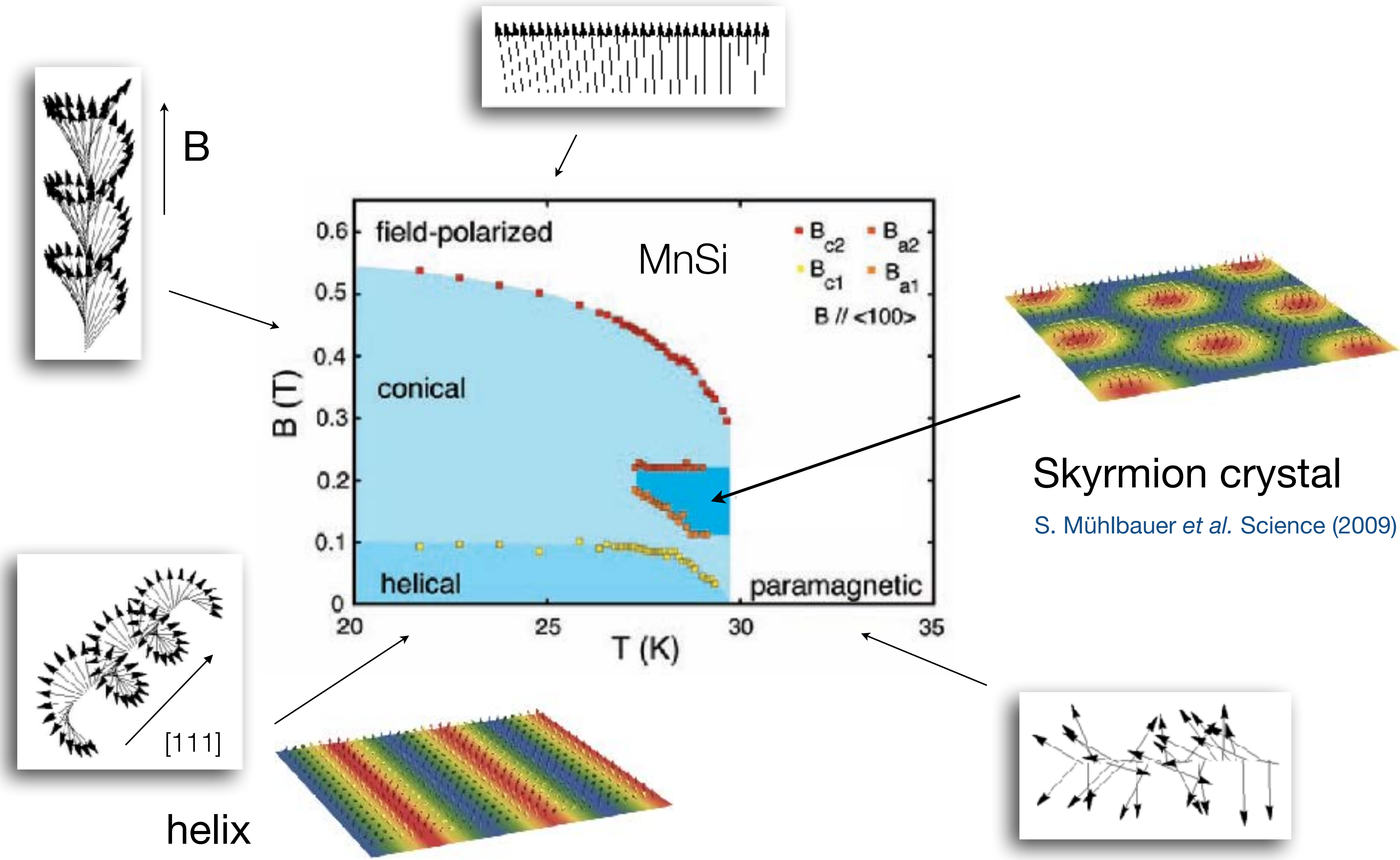
helices



skyrmions

Phase diagram of chiral magnets

example: MnSi



Skyrmions

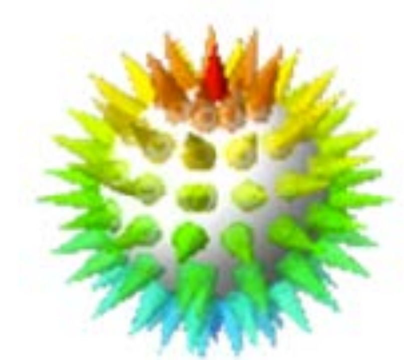
Tony Skyrme (1961,1962)

solutions of a non-linear field theory,
model for baryons

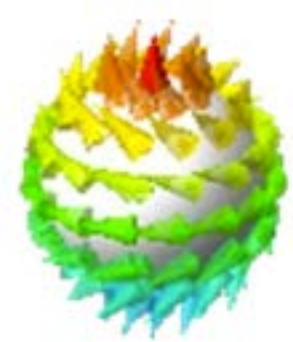
B=3

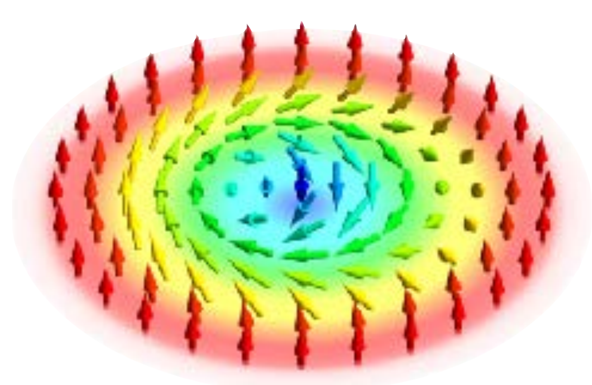
(isospin doublet $^3H/^3He$)

stereographic projection from sphere to plane: $\Pi_2(S^2) = \mathbb{Z}$



hedgehog





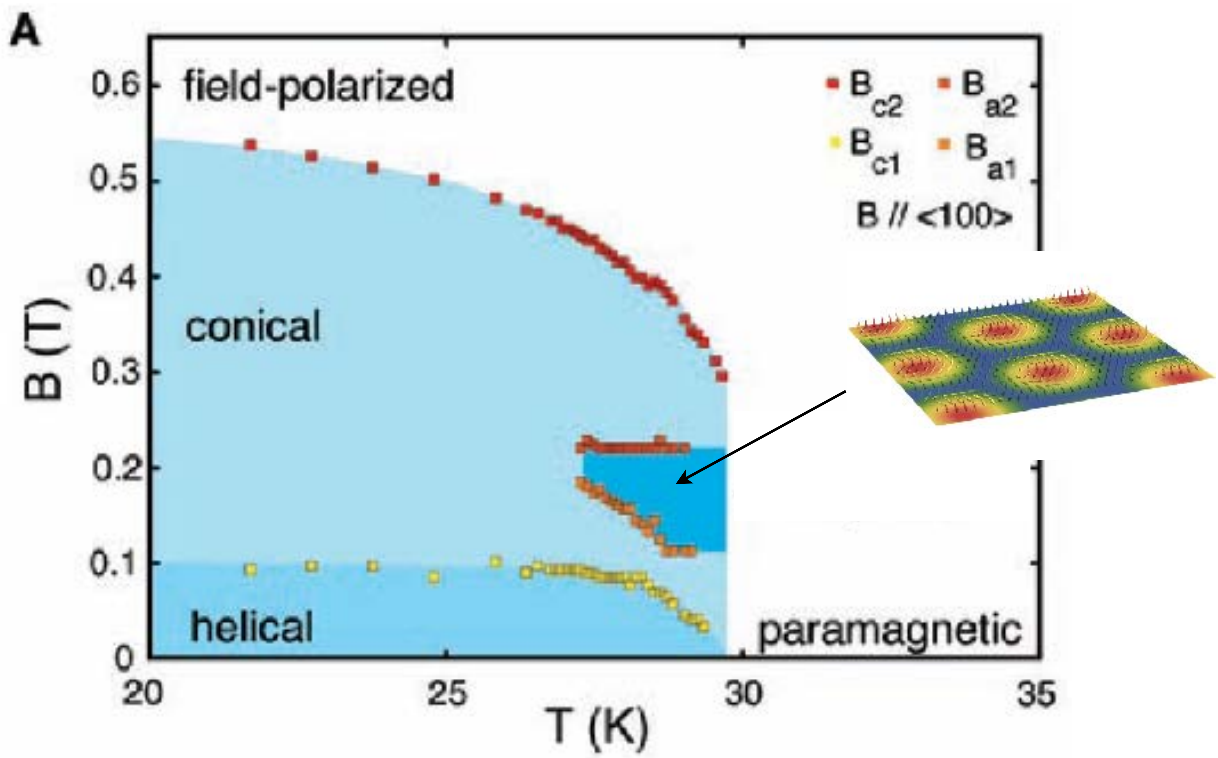
topologically stable object with quantized winding number

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

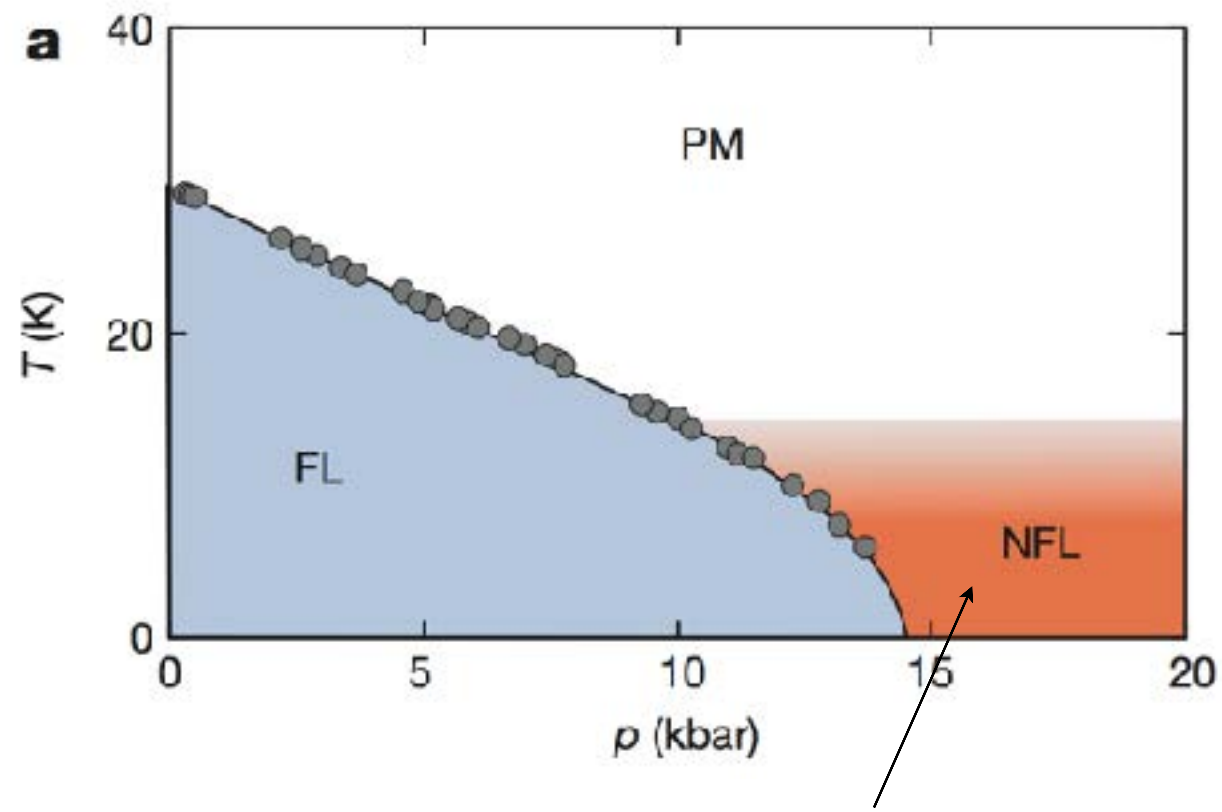
essential for skyrmion dynamics!

Phase diagram of MnSi con‘t.

in a magnetic field



under pressure



unexplained mystery!

slow magnetisation dynamics destroying the Fermi liquid?

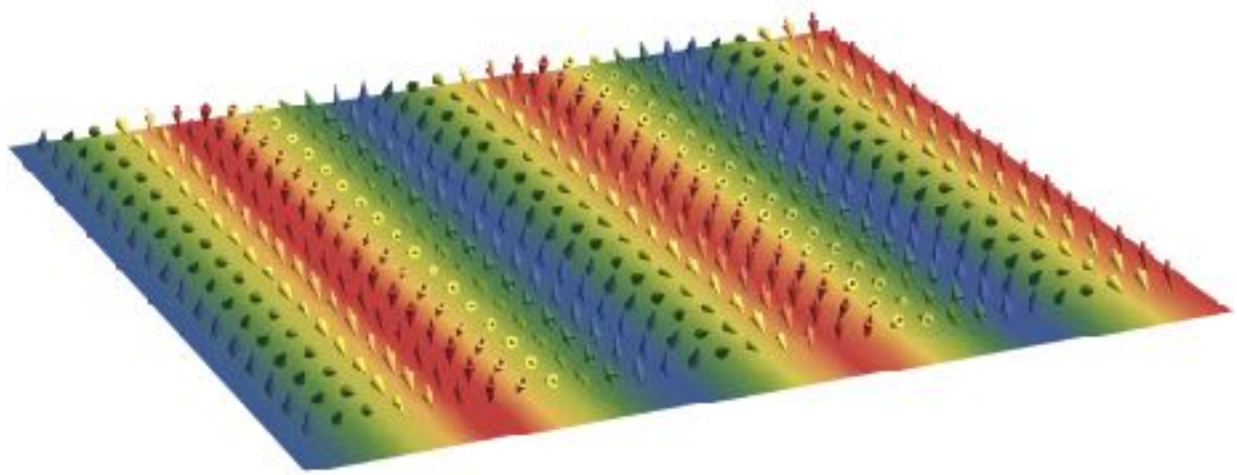
resistivity $\delta\rho \sim T^{3/2}$

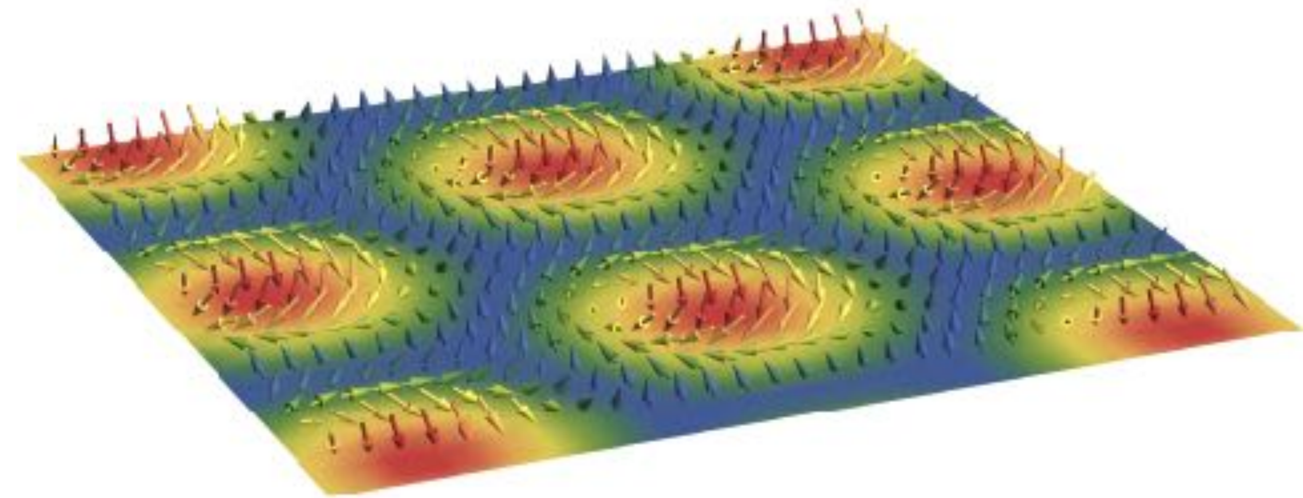
extended non-Fermi liquid regime
three (!) decades in temperature

Pfleiderer, Julian, Lonzarich, Nature 2001
Ritz … Pfleiderer, Nature 2013

This talk:

Spin-wave dynamics of chiral magnetic textures





1d helix

2d skyrmion lattice

wavelength: $\lambda \approx$ 18 nm in MnSi

70 nm in FeGe

Magnetization dynamics

Landau-Lifshitz-Gilbert equation

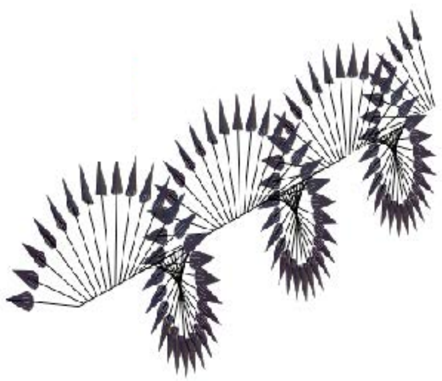
$$\partial_t \vec{M} = -\gamma \vec{M} \times \vec{B}_{\text{eff}} \quad + \ldots.$$

precession in effective field — damping, driving currents etc.

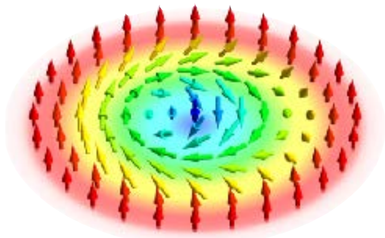
wikipedia

effective field is determined by the magnetic texture:

$$\vec{B}_{\text{eff}} = -\frac{1}{M_s} \frac{\delta F}{\delta \hat{M}}$$



with the energy functional $F = \int d\vec{r}\, \mathcal{V}(\hat{M})$



Linear spin-wave theory

small amplitude excitation of the equilibrium magnetisation texture $\hat{M}_{\rm eq}$

$$\hat{M} = \hat{M}_{\rm eq}\sqrt{1-2|\psi|^2} + \hat{e}^+\psi + \hat{e}^-\psi^*$$

with local orthogonal frame $\hat{e}_1(\mathbf{r}) \times \hat{e}_2(\mathbf{r}) = \hat{M}_{\rm eq}(\mathbf{r})$

$$\hat{e}_\pm = \frac{1}{\sqrt{2}}(\hat{e}_1 \pm i\hat{e}_2)$$

Landau-Lifshitz equation

$$\partial_t \vec{M} = -\gamma \vec{M} \times \vec{B}_{\rm eff} \quad \Rightarrow \quad i\hbar\tau^z\partial_t\vec{\Psi} = H\vec{\Psi}$$

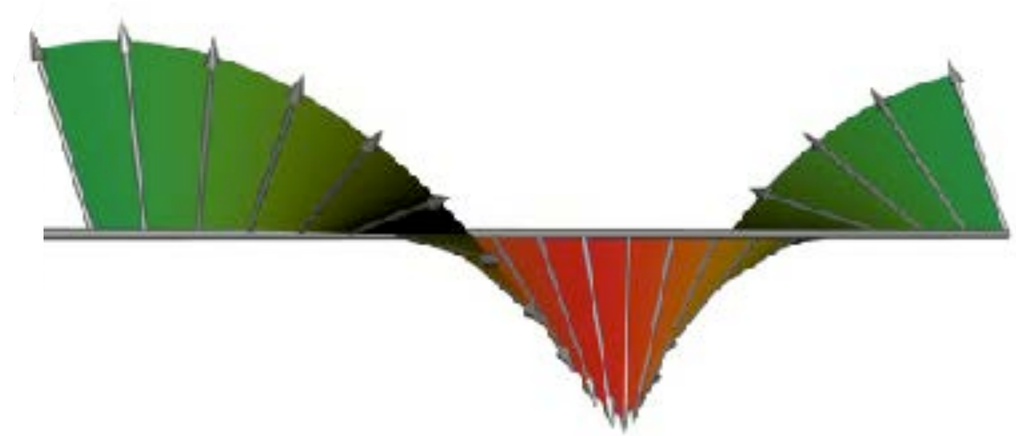
magnon spinor wave function $\vec{\Psi}^T = (\psi, \psi^*)$

U(1) charge = spin angular momentum of magnon not conserved!

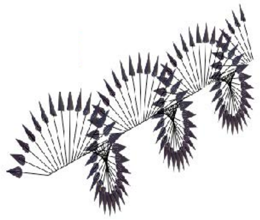
due to spin-orbit coupling, texture and dipolar interactions

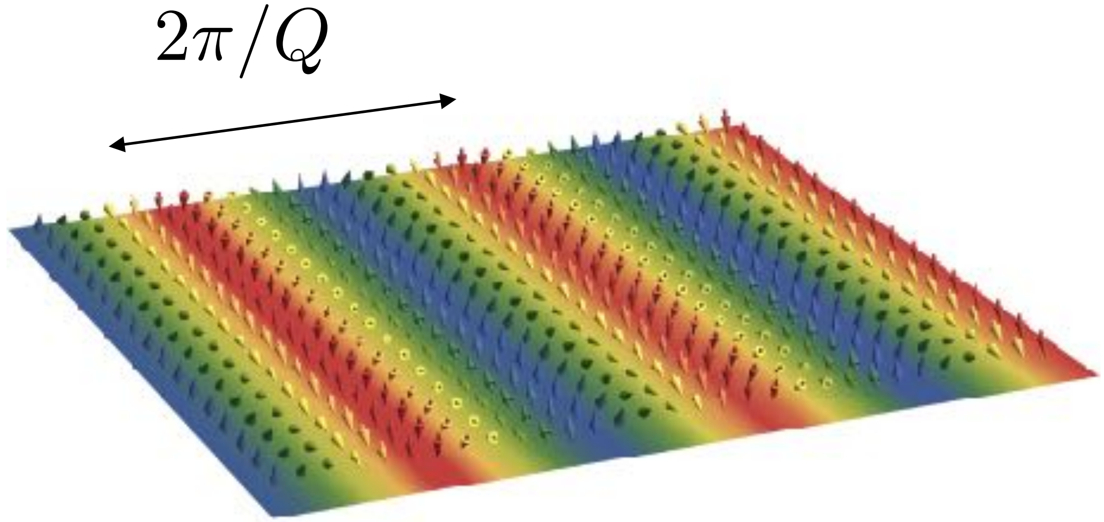
Bogoliubov-deGennes 2×2 matrix Hamiltonian H

Spin-wave dynamics of the magnetic helix



Magnon excitations of the magnetic helix





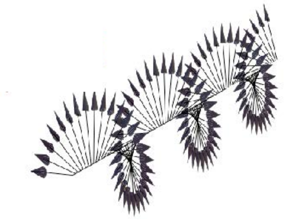
helix = 1d magnetic crystal

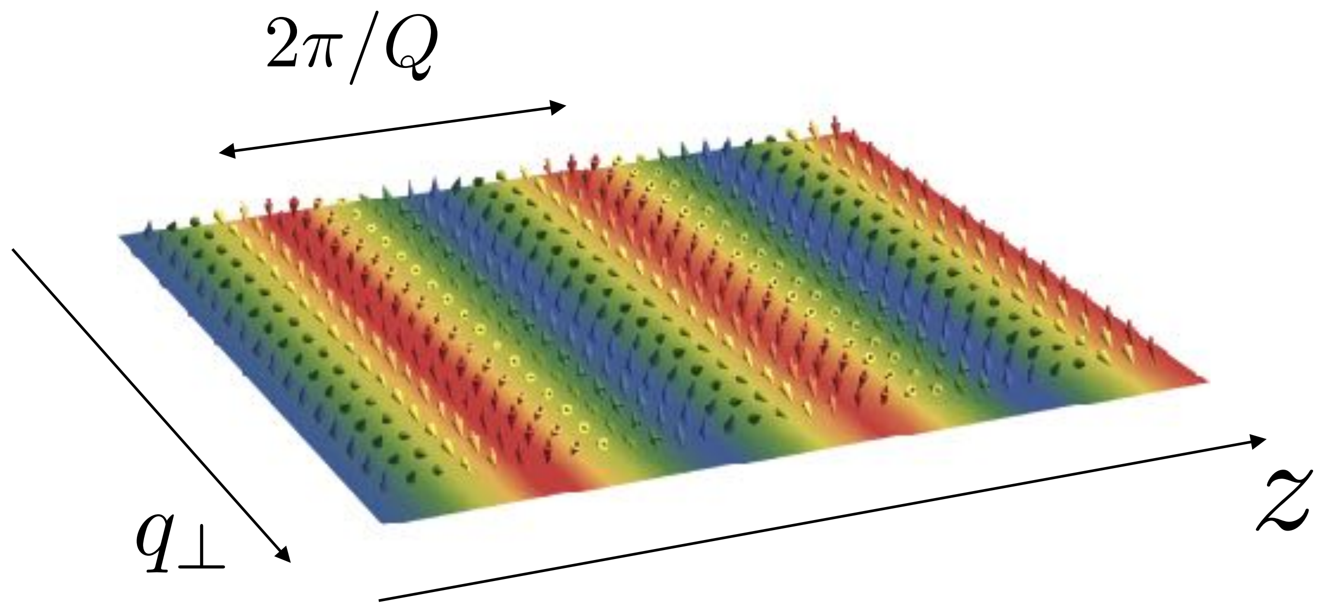
magnon excitations should obey Bloch's theorem

⇨ magnon band structure

Kugler, MG *et al* PRL (2015)

Magnon excitations of the magnetic helix





helix = 1d magnetic crystal

magnon excitations should obey Bloch's theorem

$\Rightarrow$ magnon band structure

magnon wave equation $i\hbar\tau^z\partial_t\vec{\Psi} = \mathcal{H}\vec{\Psi}$ for spinor $\vec{\Psi} = (\psi, \psi^*)$

with the magnon Hamiltonian:

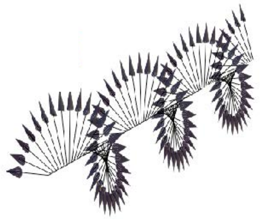
$$\mathcal{H}_0 = \mathcal{D}\left[\mathbb{1}(q_\perp^2 - \partial_z^2) - i2\tau^z Q q_\perp \cos(Qz) + \frac{Q^2}{2}(\mathbb{1} - \tau^x)\right]$$

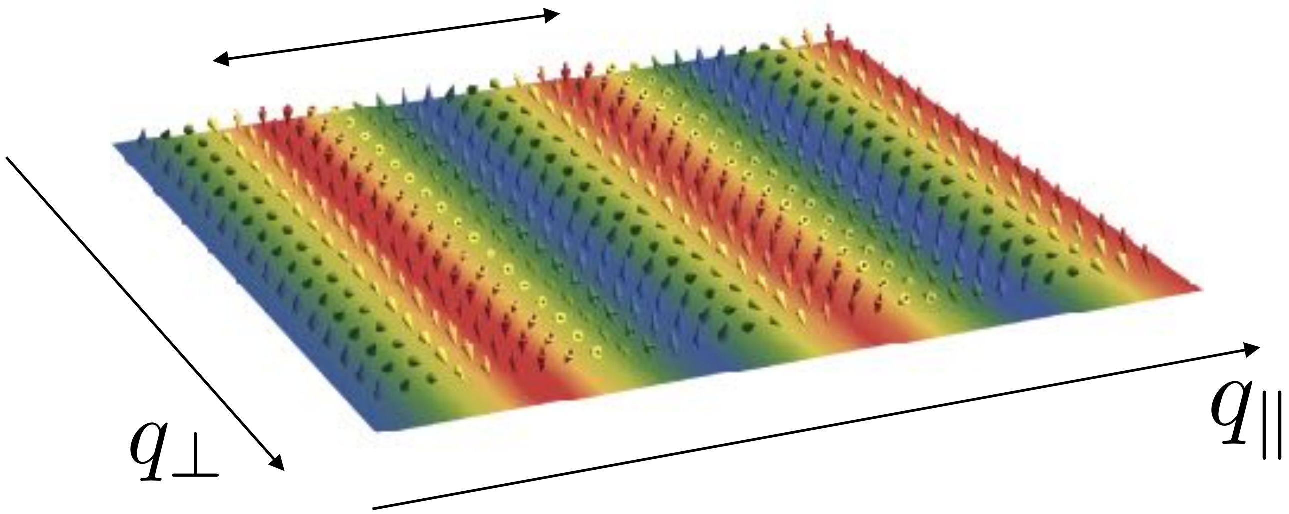
variant of the Mathieu equation

particle in a one-dimensional periodic cosine potential

Kugler, MG *et al* PRL (2015)

Magnon excitations of the magnetic helix



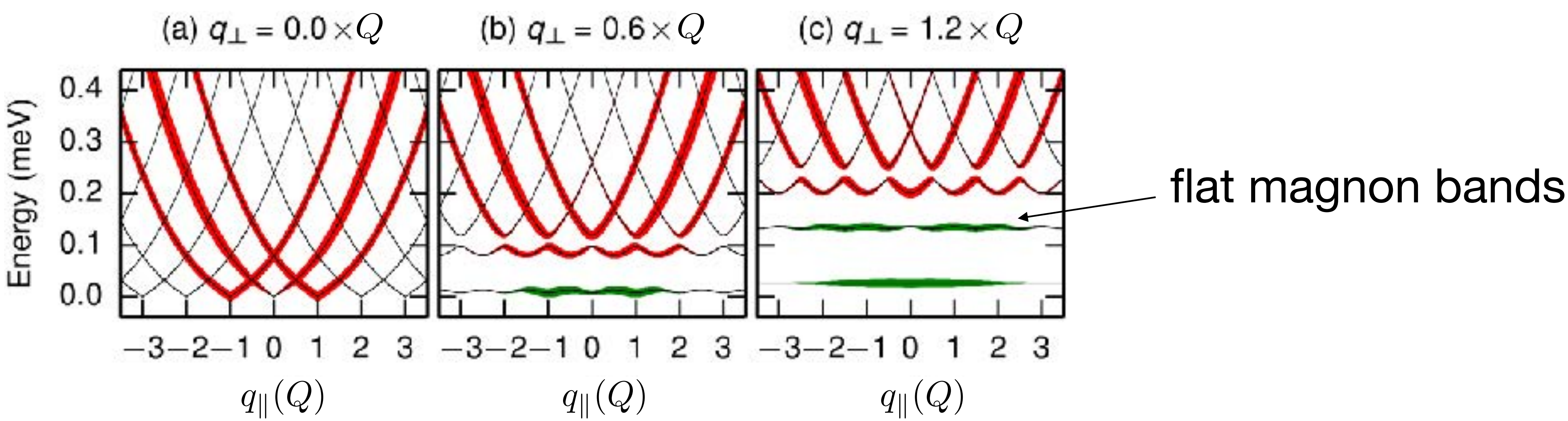


helix = 1d magnetic crystal

magnon excitations should obey Bloch's theorem

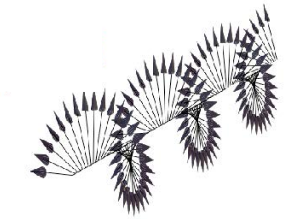
⇨ magnon band structure

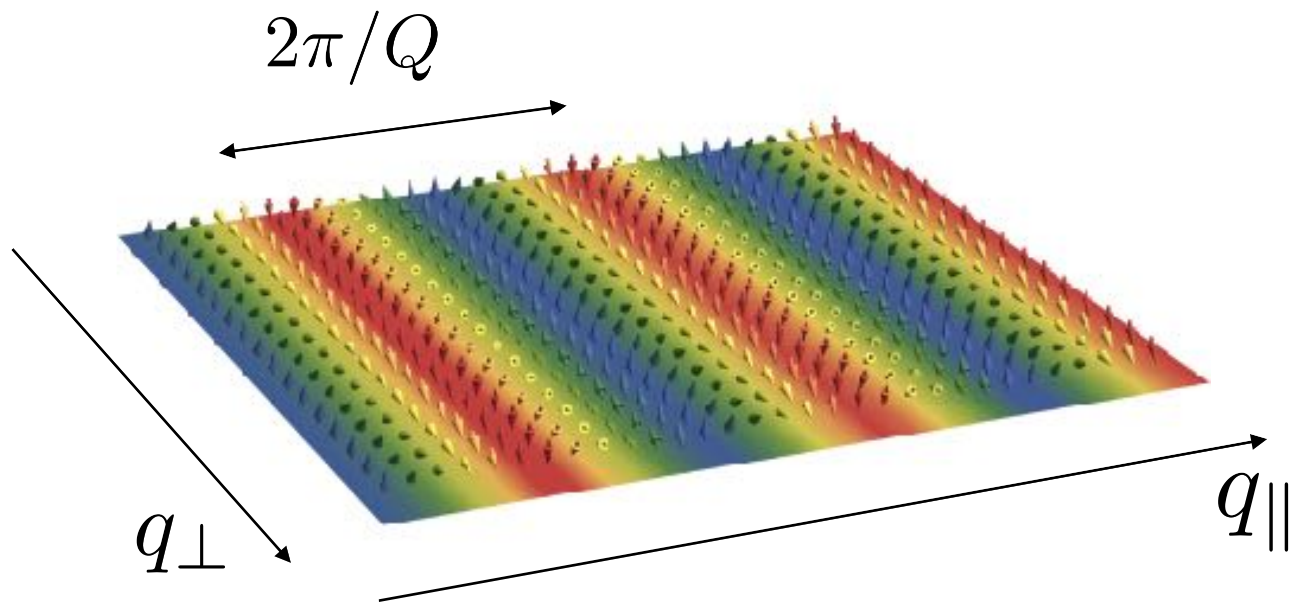
transversal momentum $q_\perp$ tunes strength of periodic potential
crossover from weak to tight-binding limit



Kugler, MG *et al* PRL (2015)

Magnon excitations of the magnetic helix



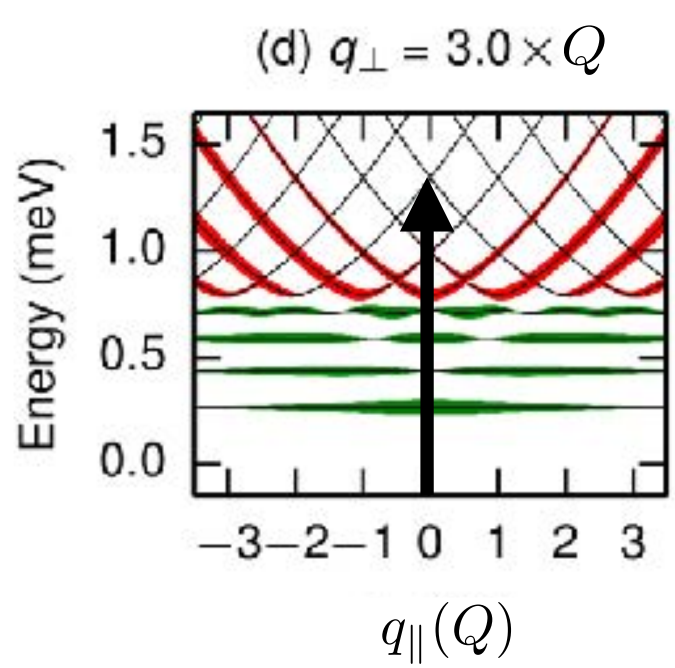


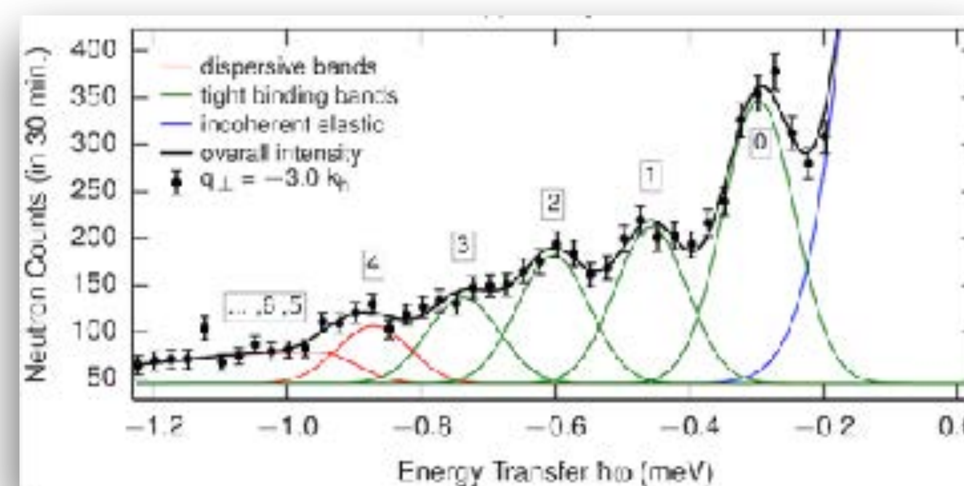
helix = 1d magnetic crystal

magnon excitations should obey Bloch's theorem

⇨ magnon band structure

Inelastic neutron scattering on MnSi:



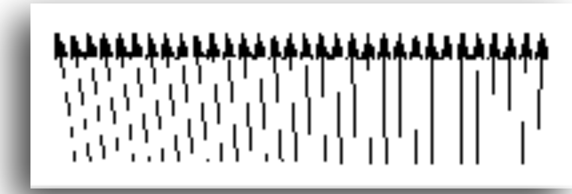


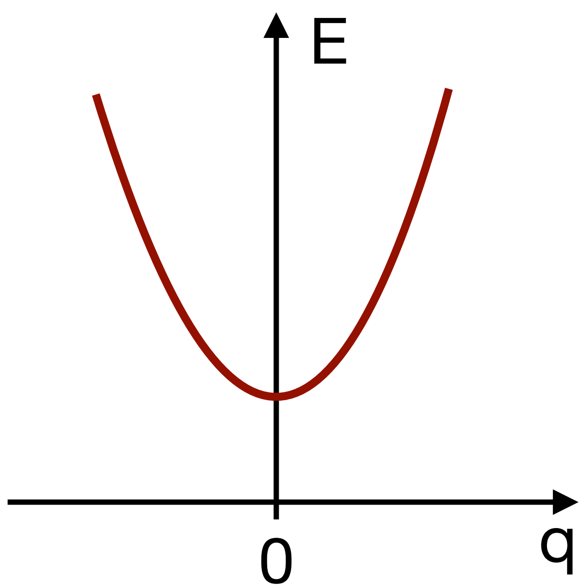
five magnon bands well-resolved

Kugler, MG *et al* PRL (2015)

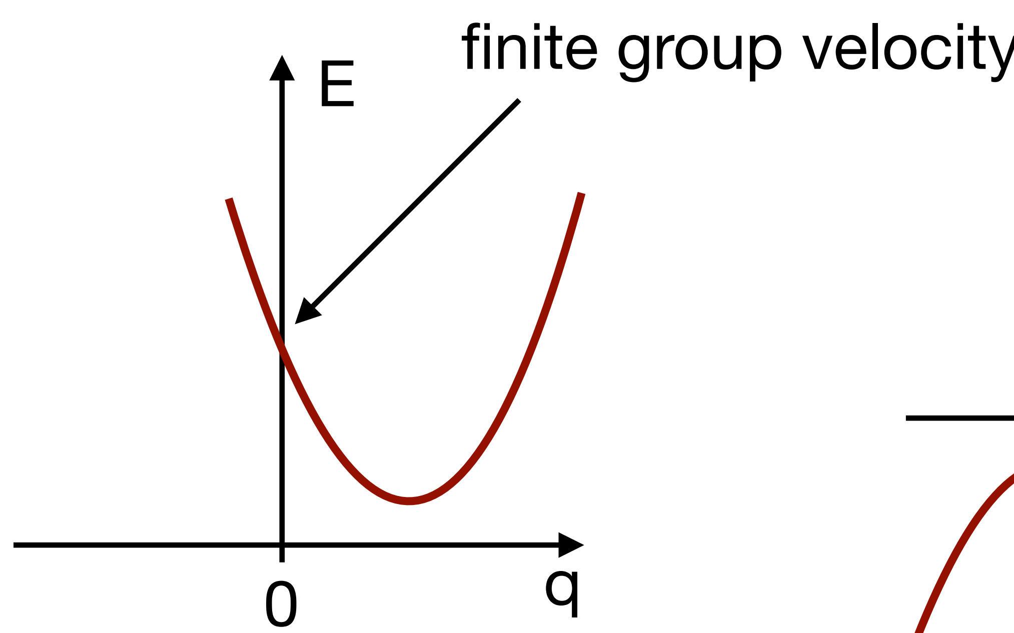
Non-reciprocal magnon dynamics

magnon dispersion in the background of field-polarised state:





without
Dzyaloshinskii-Moriya
interaction (DMI)

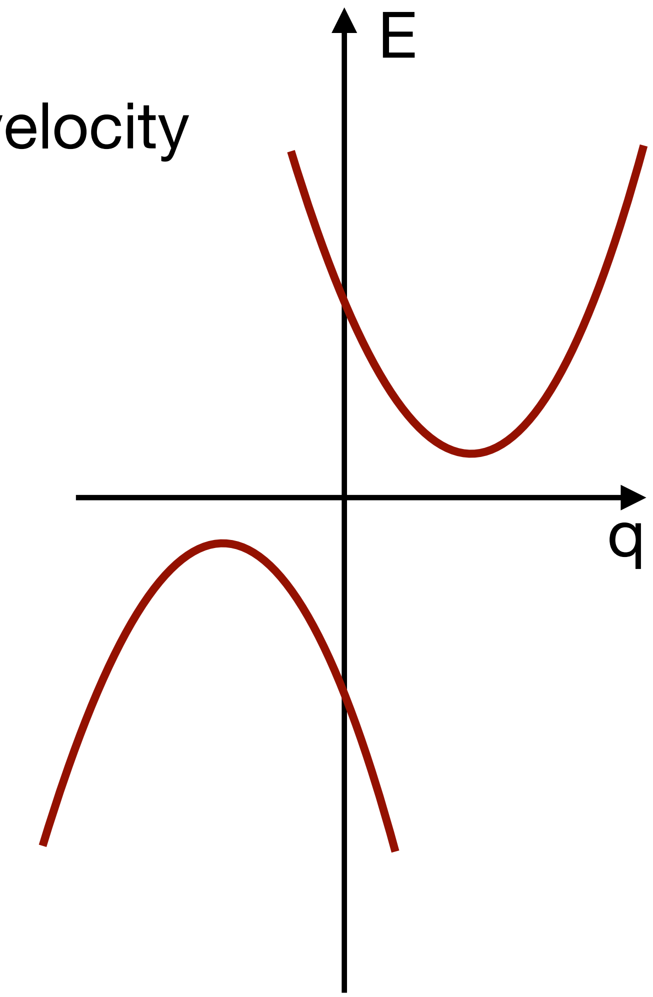


with DMI:

shifted parabola

non-reciprocal dispersion

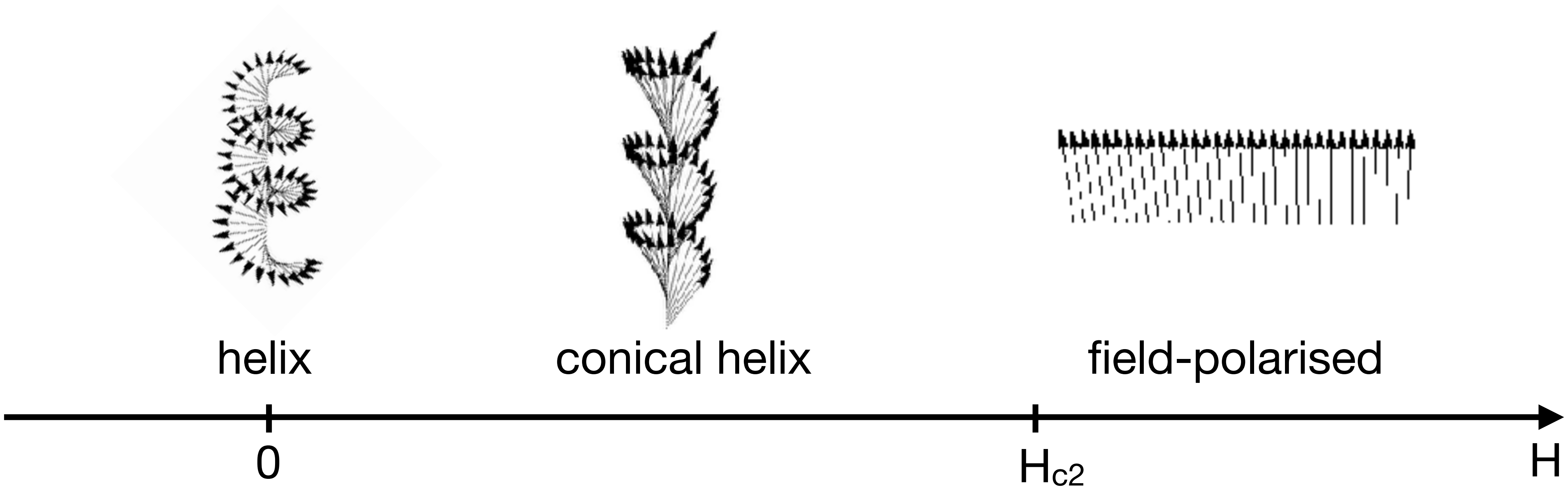
$$E(q) \neq E(-q)$$



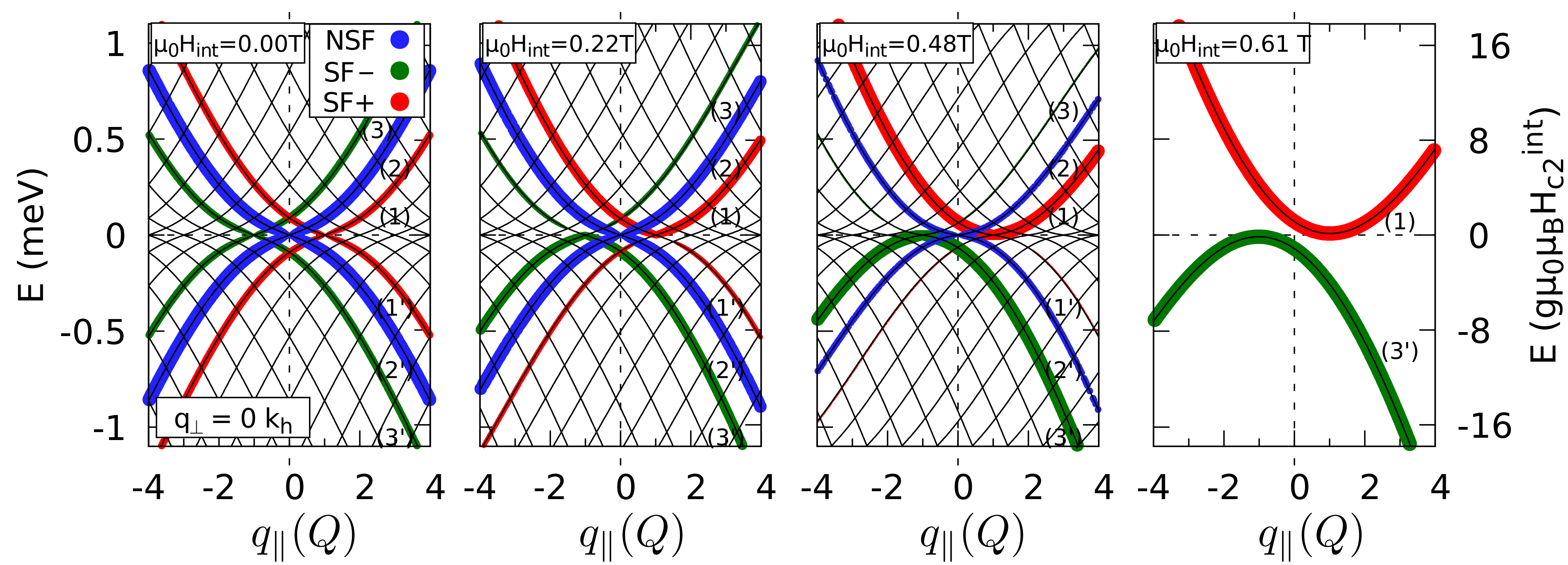
magnon emission and absorption at different energies

Magnon spectrum as a function of magnetic field

magnetic state



magnon spectrum for $q_\perp = 0$



spin-flip channels

non spin-flip channel

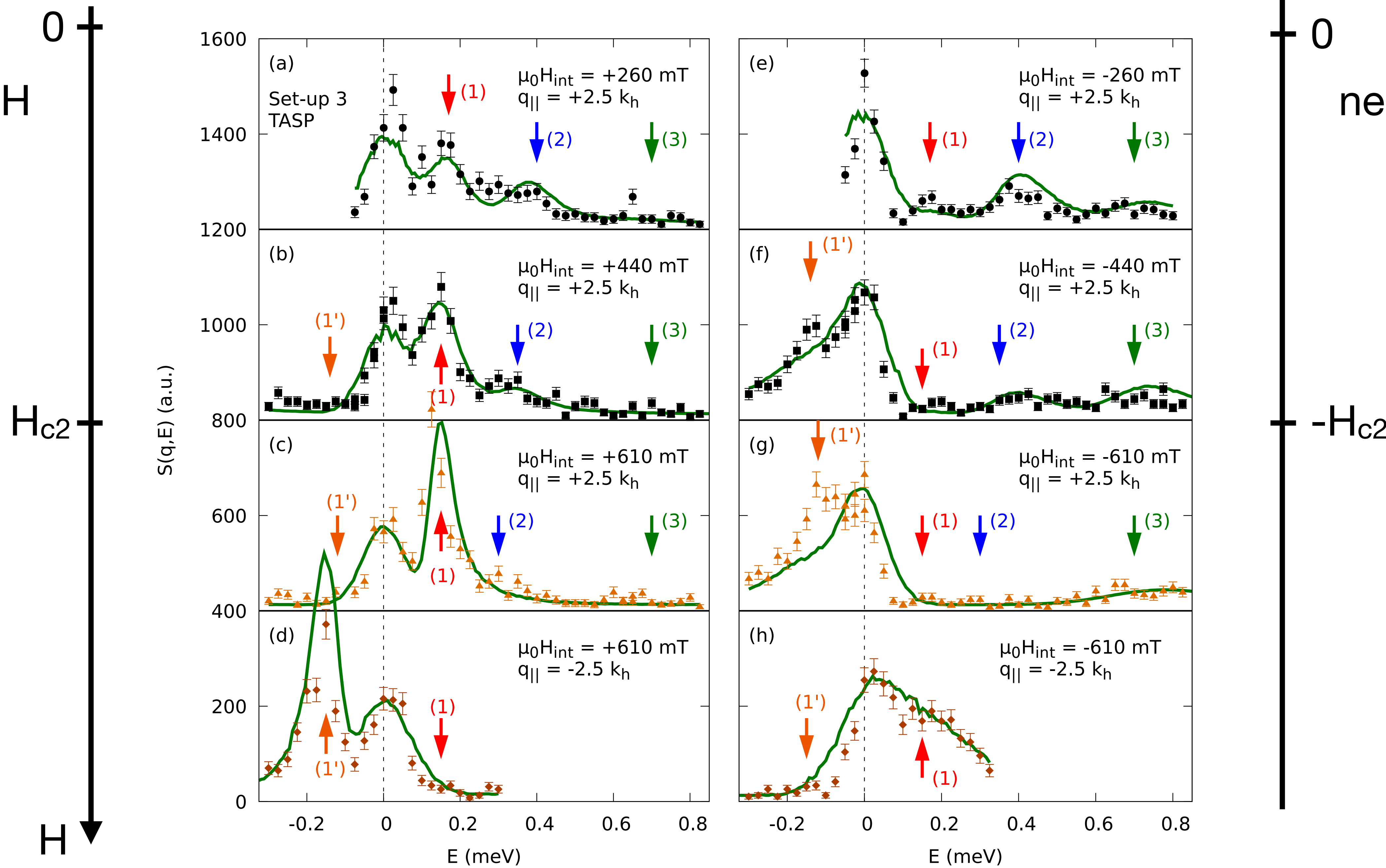
reciprocal spectrum but non-reciprocal weight distribution

non-reciprocal spectrum

Weber, MG *et al* arXiv:1708.02098

Inelastic neutron scattering on MnSi

non-reciprocal magnon spectrum $\omega(q_{\|}) \neq \omega(-q_{\|})$



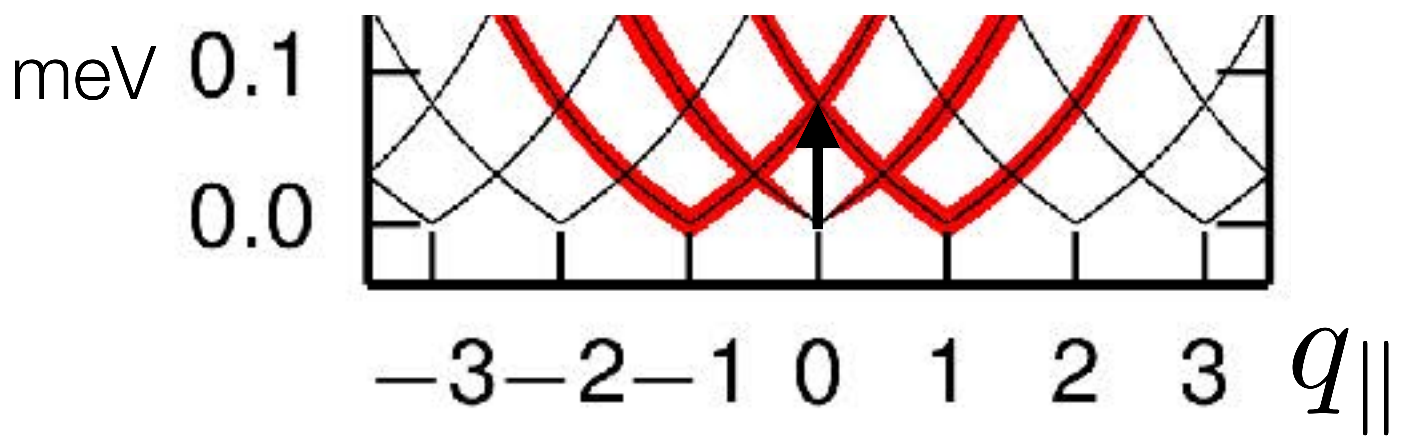
quantitative agreement between theory and experiment (including instrumental resolution)

Weber, MG *et al*
arXiv:1708.02098

Magnetic microwave resonances

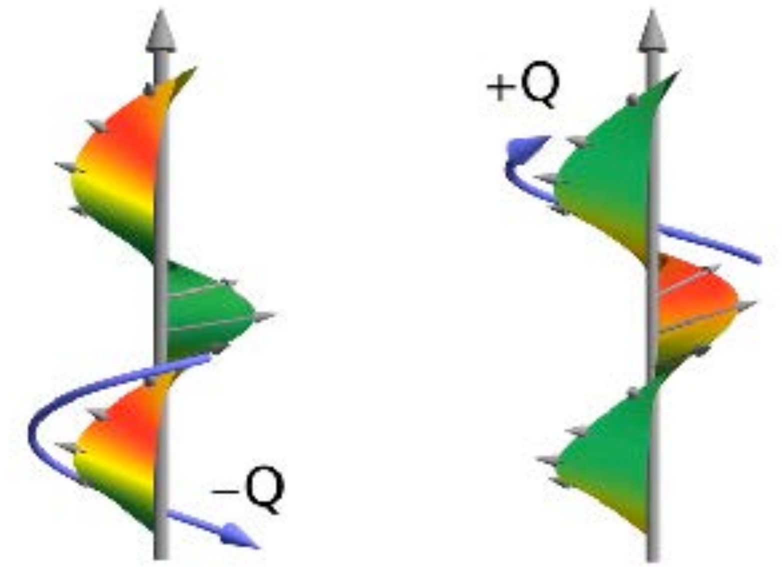
ac magnetic field ⇨ exciting magnons at zero momentum

two resonances:

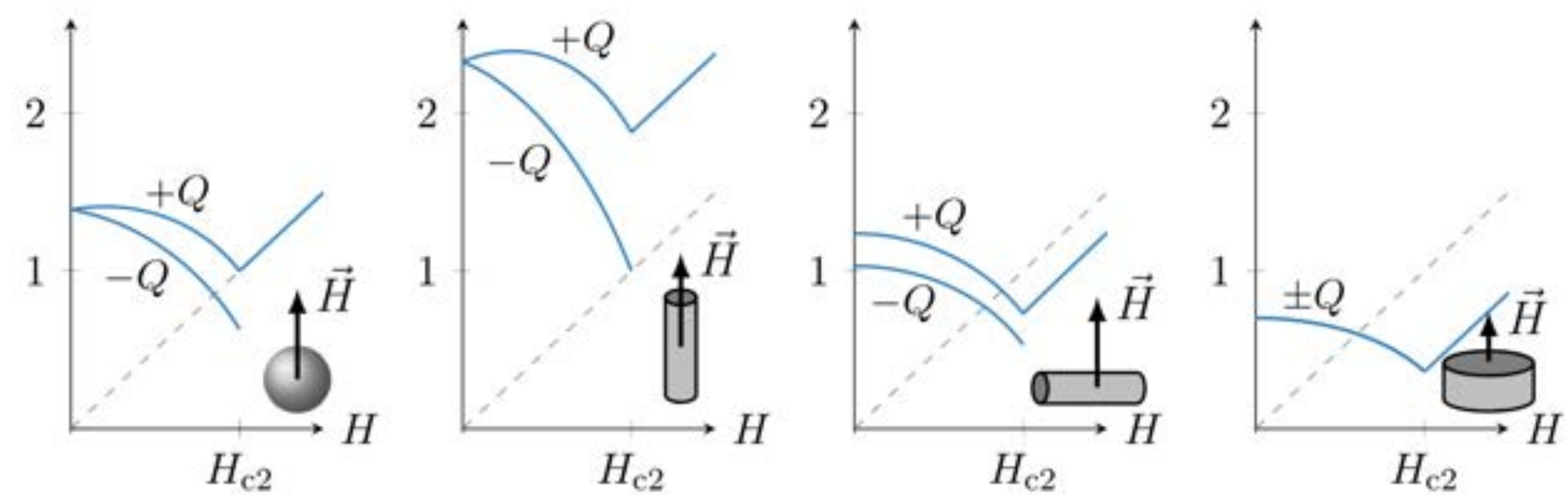


mean magnetisation oscillates

clockwise counter-clockwise



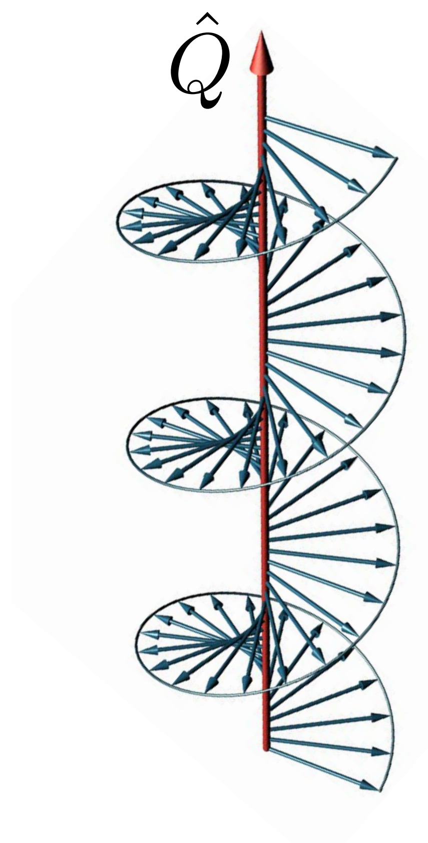
Demagnetization field splits the degeneracy:



Schwarze, MG *et al* Nat Mater (2015)

Polarization dependence of the helix modes

at zero field: helix possesses π-rotation symmetry



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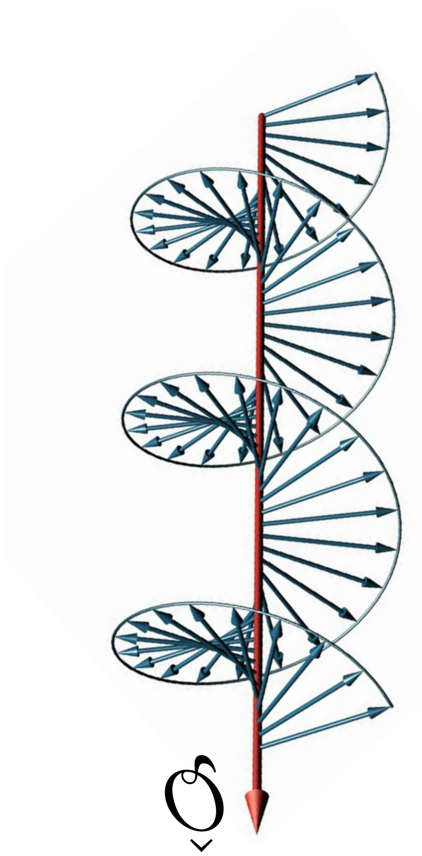

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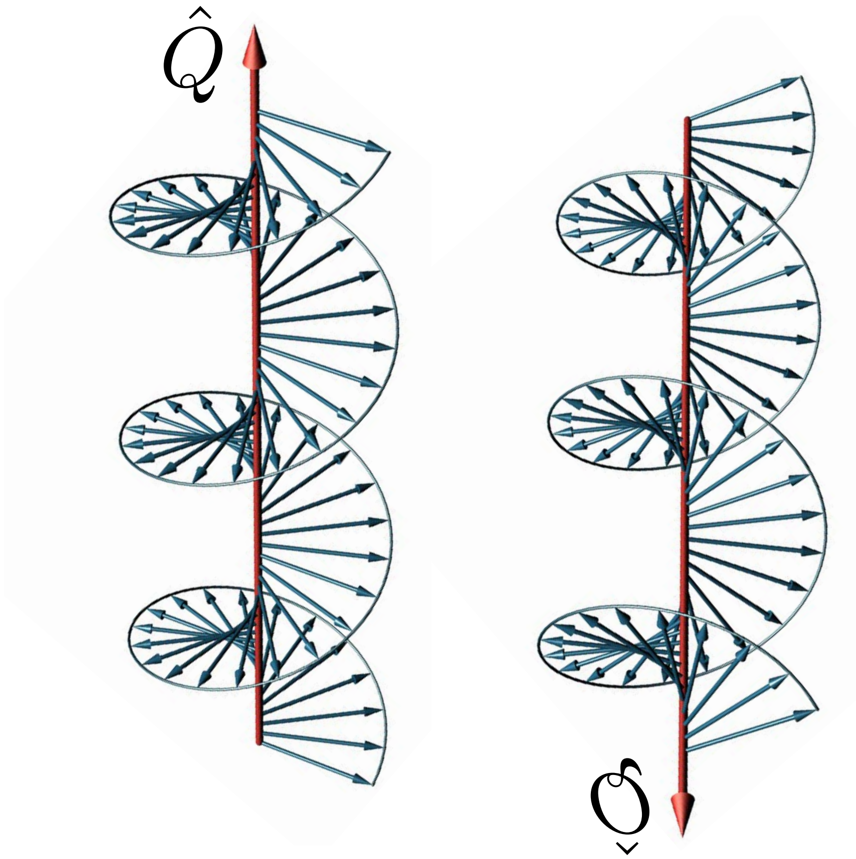

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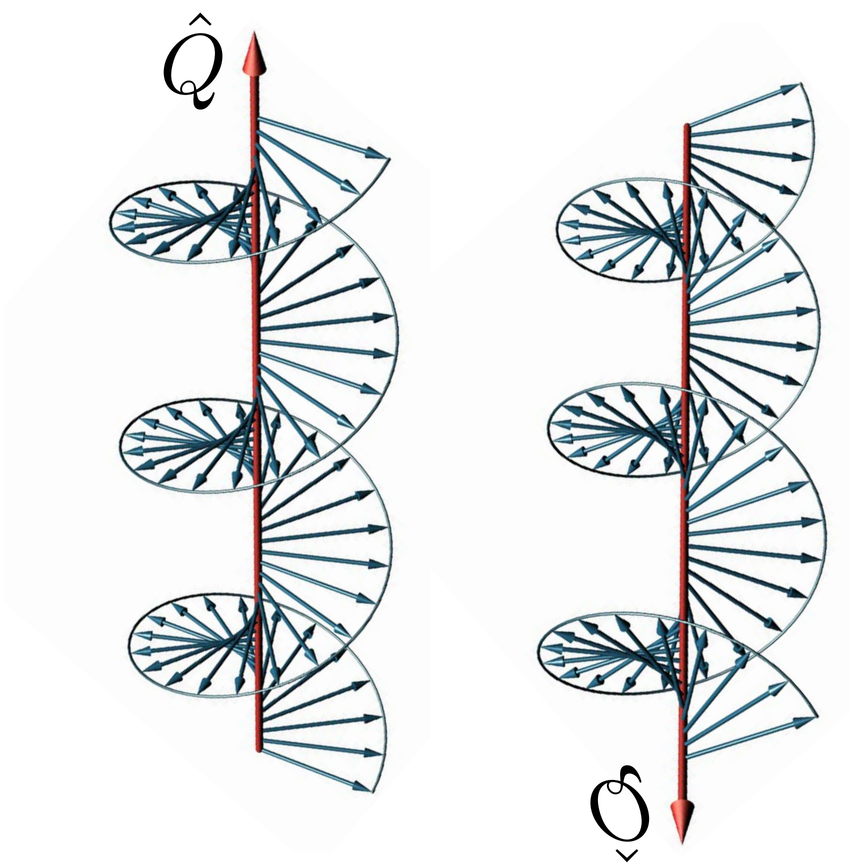
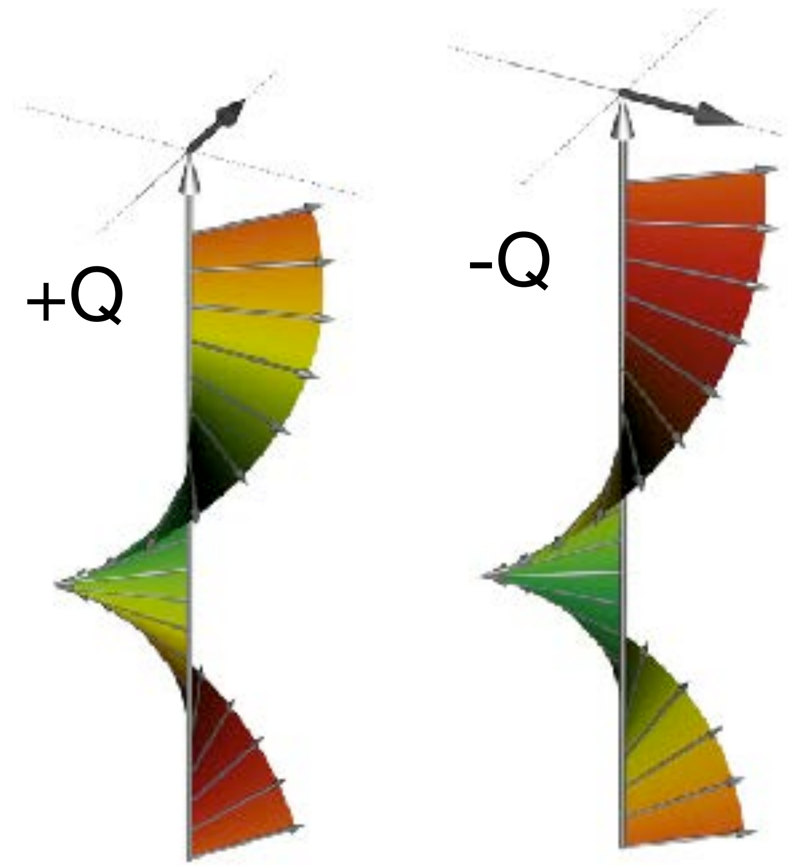




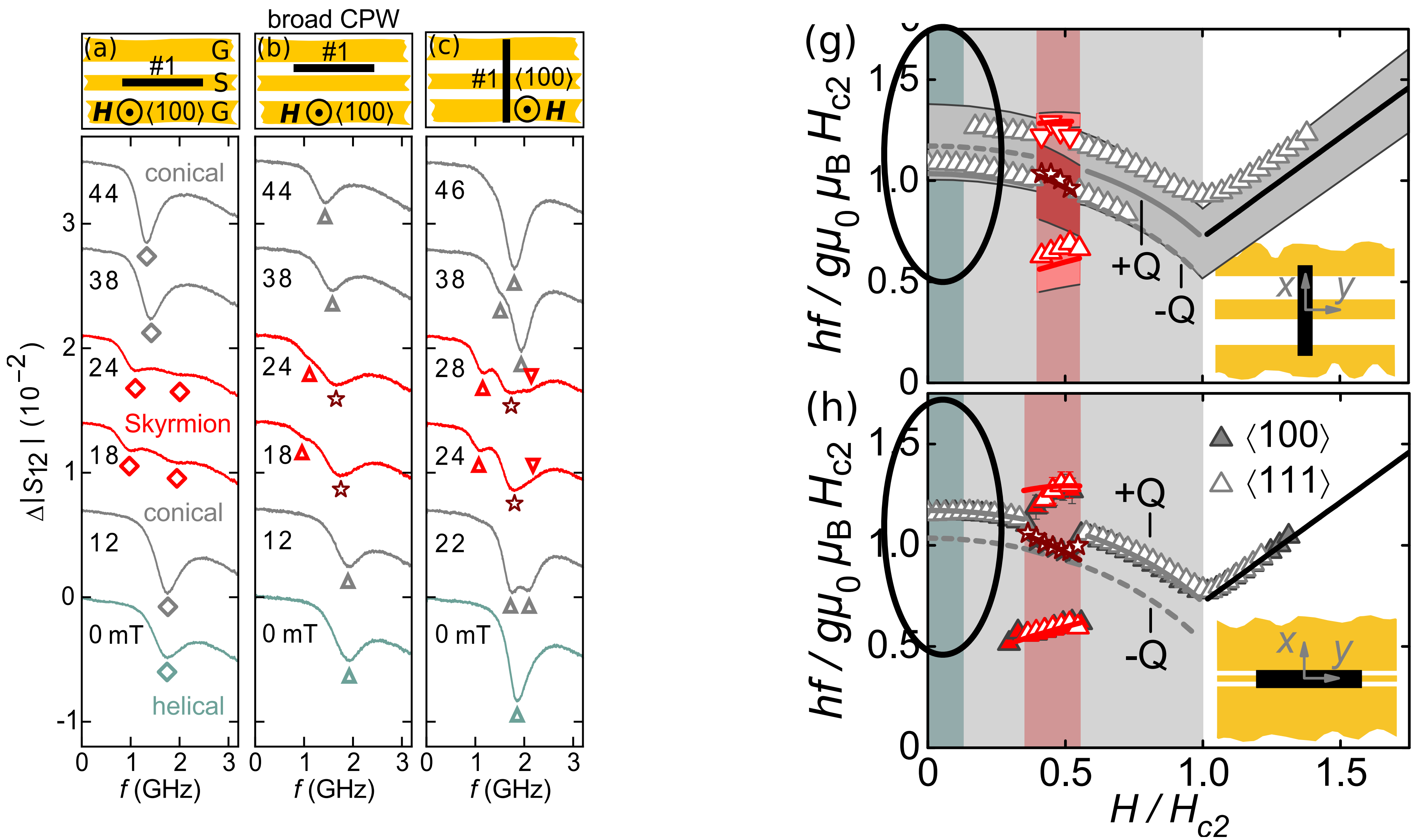
⇨ +/- Q modes strictly linearly polarized at zero field!
(for non-circular sample shape)

similar to easy-plane antiferromagnets

Polarization dependence of the helix modes

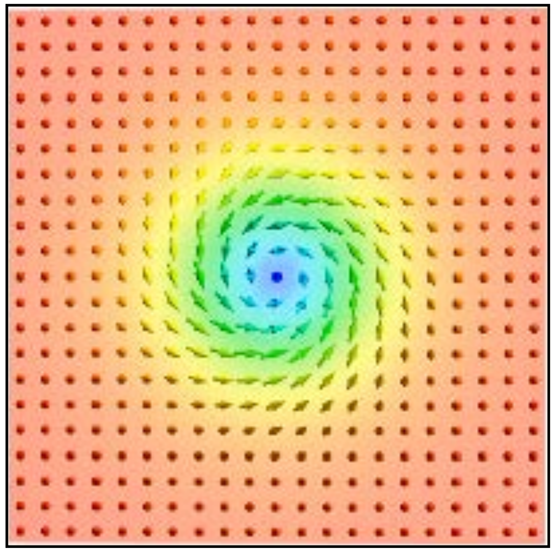
+/- Q modes strictly linearly polarized at zero field!

allows to address each mode selectively



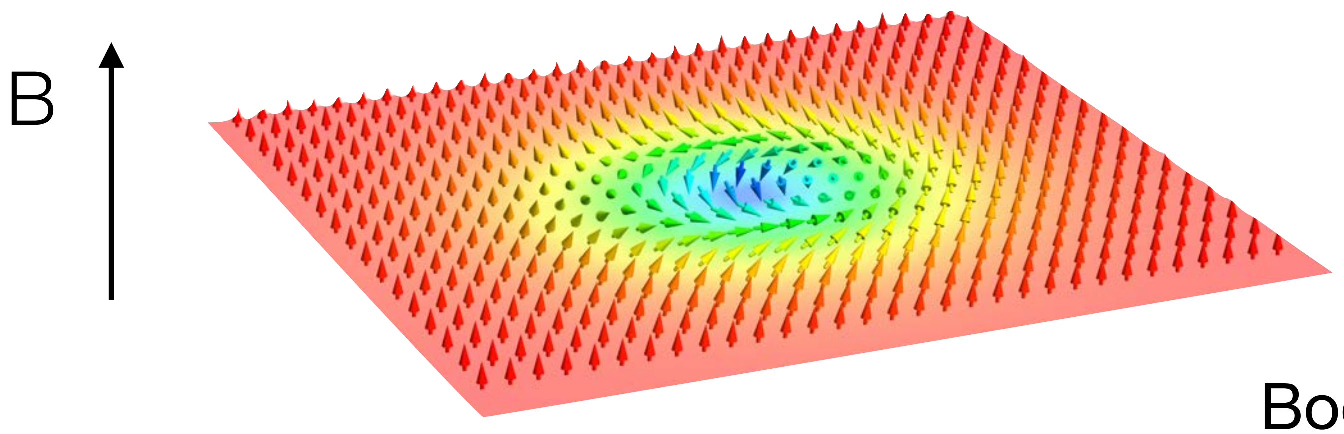
I. Stasinopolous, MG, et al,
Scientific Reports (2017)

Spin-wave dynamics of the magnetic skyrmion



Skyrmion in a field-polarised background

static skyrmion-soliton solution



Bogdanov & Hubert (1994)

spin-waves scatter off the skyrmion ⇨ magnon scattering problem

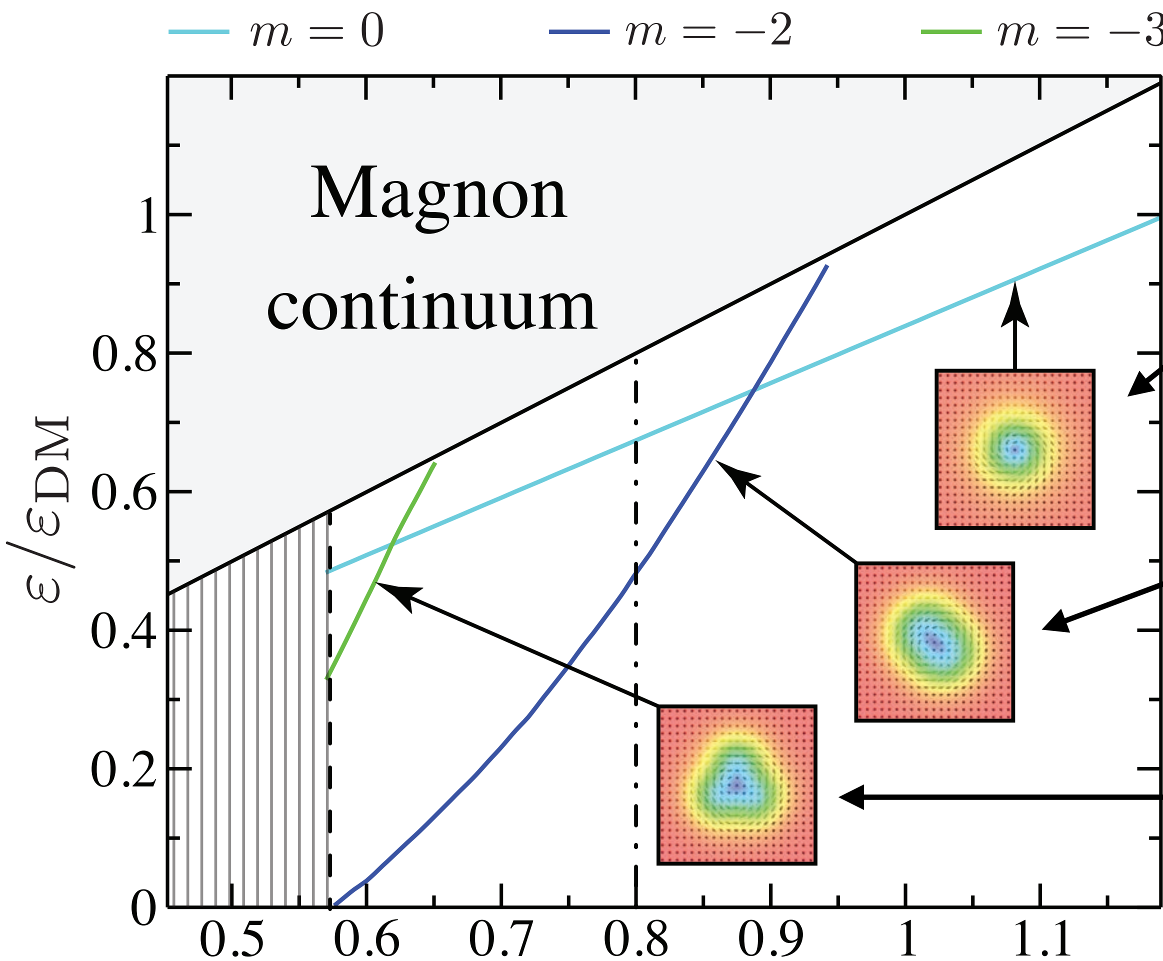
magnon Hamiltonian

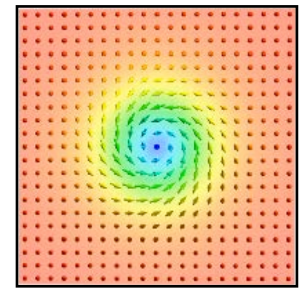
$$\mathcal{H} = \frac{\hbar^2(-i\tau^z\vec{\nabla} - \mathbf{1}\vec{a})^2}{2M_{\rm mag}} + \mathbf{1}\mathcal{V}_0 + \tau^x\mathcal{V}_x$$

scattering vector potential

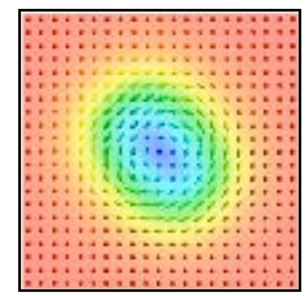
scattering potentials

Magnon-skyrmion bound states

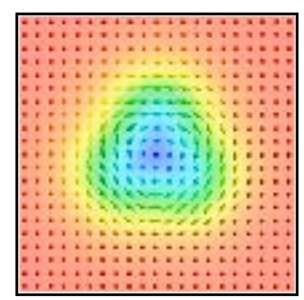




breathing mode



quadrupolar mode



sextupolar mode

magnetic field

local elliptical instability

global instability

magnon-skyrmion bound states

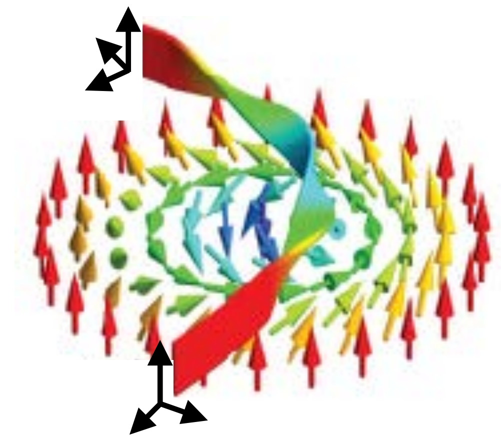
⇨ thermally excited subgap states!

see also Lin, Batista & Saxena PRB (2014)

Schütte & MG PRB (2014)

Emergent magnon Lorentz force

adiabatic adjustment of local frame ⇨ Berry phase



vector scattering potential

$$\vec{a} = \left(\frac{\cos\theta}{\rho} - Q\sin\theta\right)(-\sin\chi, \cos\chi)$$

with quantised total flux

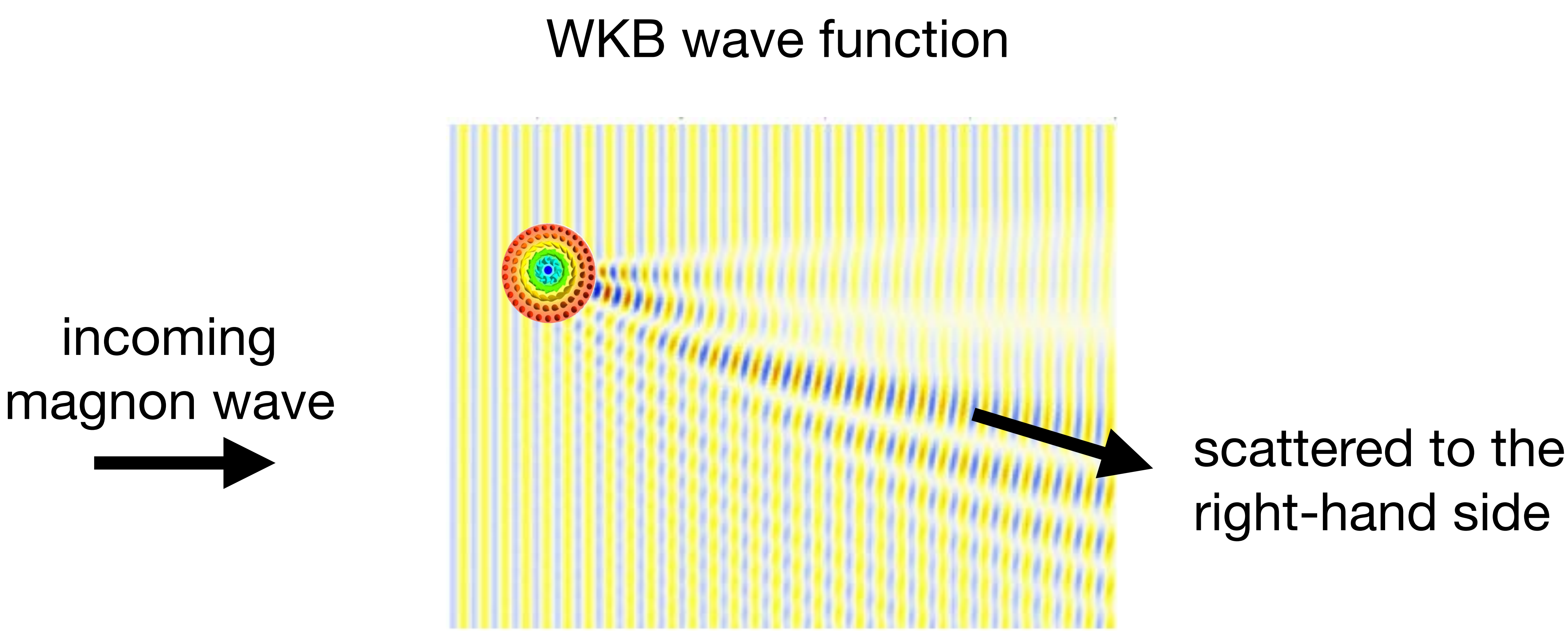
$$\int d^2\mathbf{r}(\nabla \times \vec{a}) = \int d^2\mathbf{r}\hat{M}(\partial_x\hat{M} \times \partial_y\hat{M})$$

⇦ topological winding number

magnon scatter off a localised emergent magnetic flux due to non-trivial topology of skyrmion

⇨ emergent Lorentz force

Topological magnon skew scattering



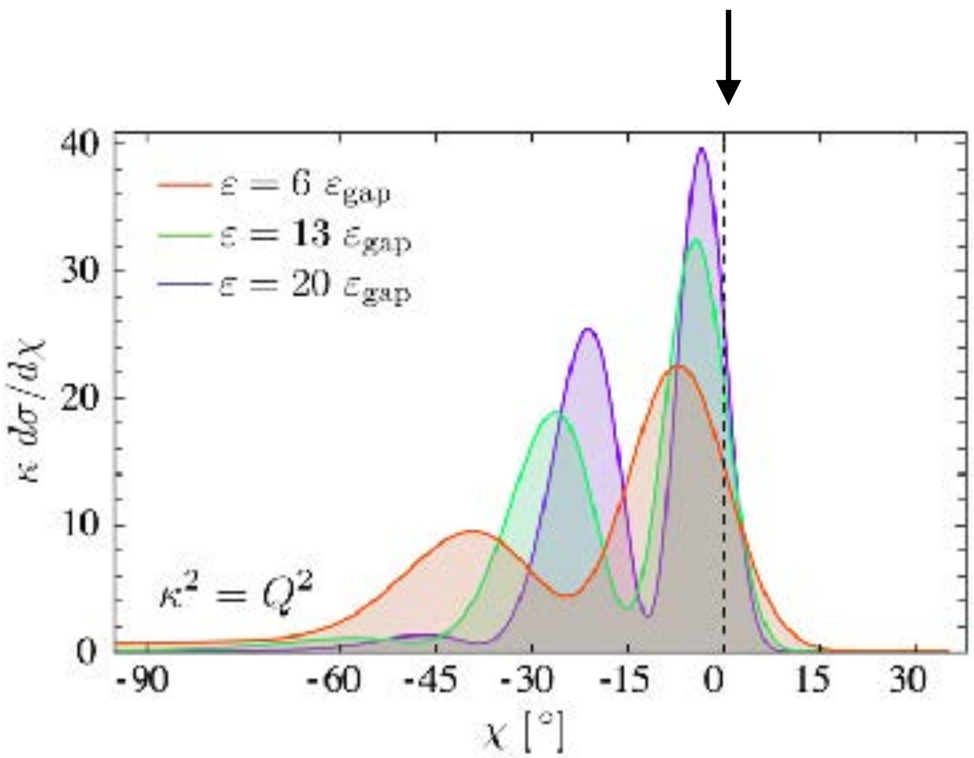
emergent Lorentz force leads to skew scattering!

⇨ topological magnon Hall effect!

see also Iwasaki, Beekman & Nagaosa PRB (2014)
Mochizuki *et al.* Nat. Mat. (2014)

Schütte & MG PRB (2014)
Schroeter & MG LTP (2015)

Skew & rainbow scattering

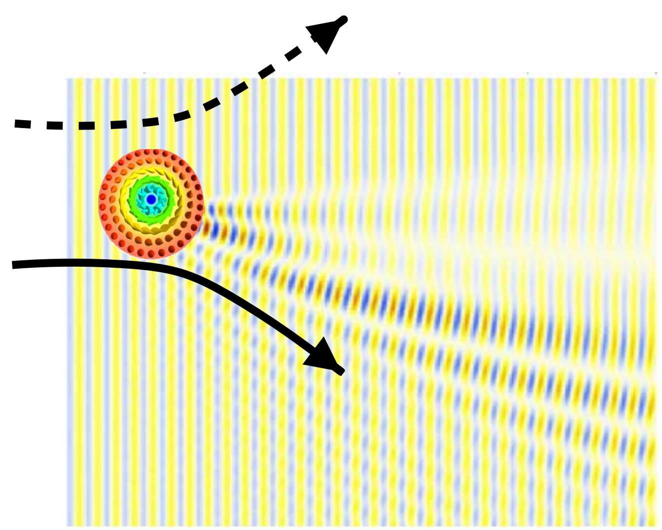


magnon differential cross section

asymmetric & oscillations

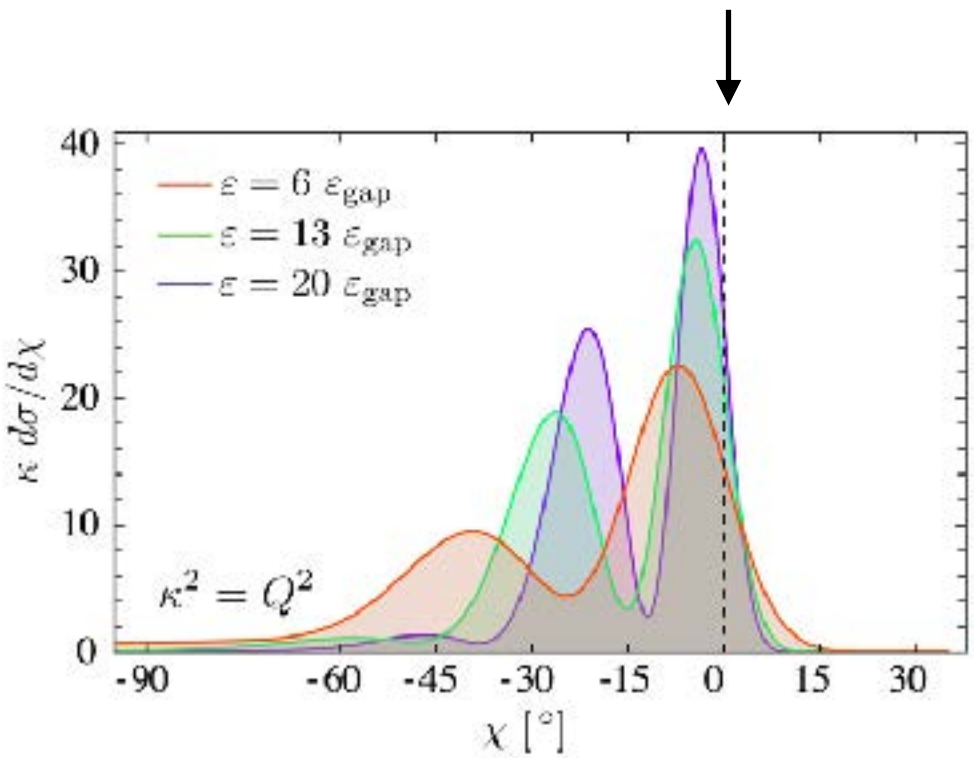
Different classical trajectories contribute and interfere!

rainbow scattering!



Schütte & MG PRB (2014)
Schroeter & MG LTP (2015)

Skew & rainbow scattering



magnon differential cross section

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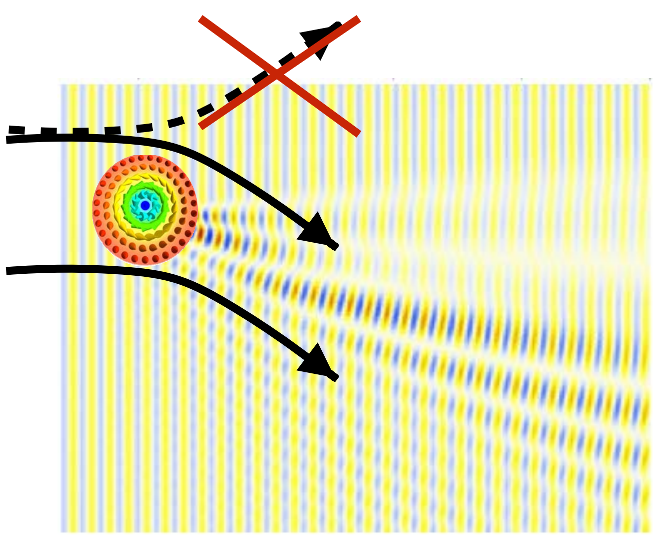
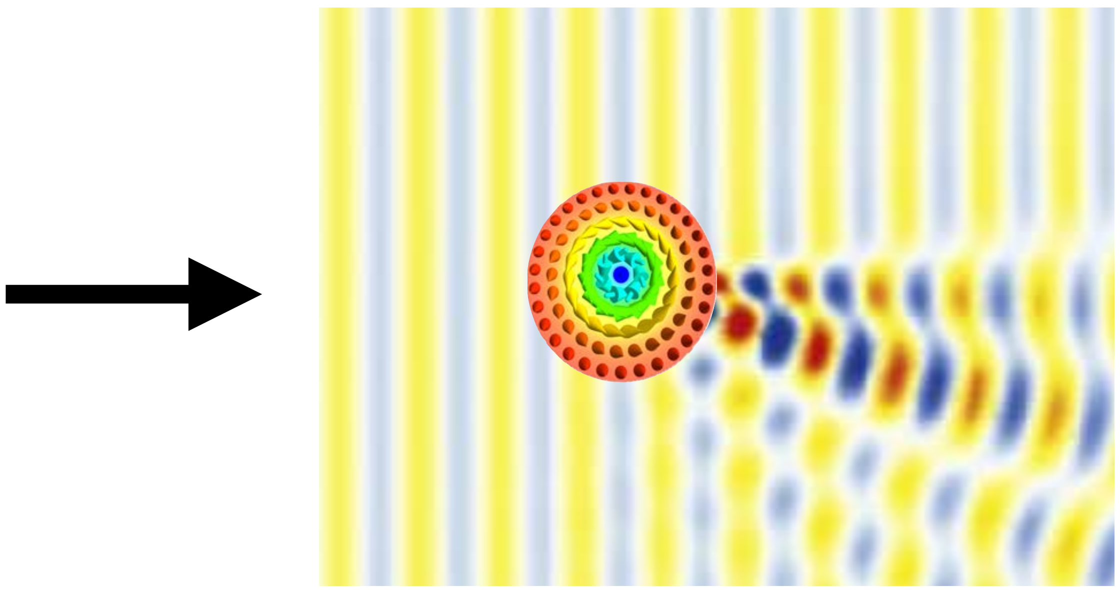


rainbow scattering!

Schütte & MG PRB (2014)
Schroeter & MG LTP (2015)

How to drive skyrmions with magnon currents?

incoming
momentum



magnon wave exerts a pressure on the skyrmion…

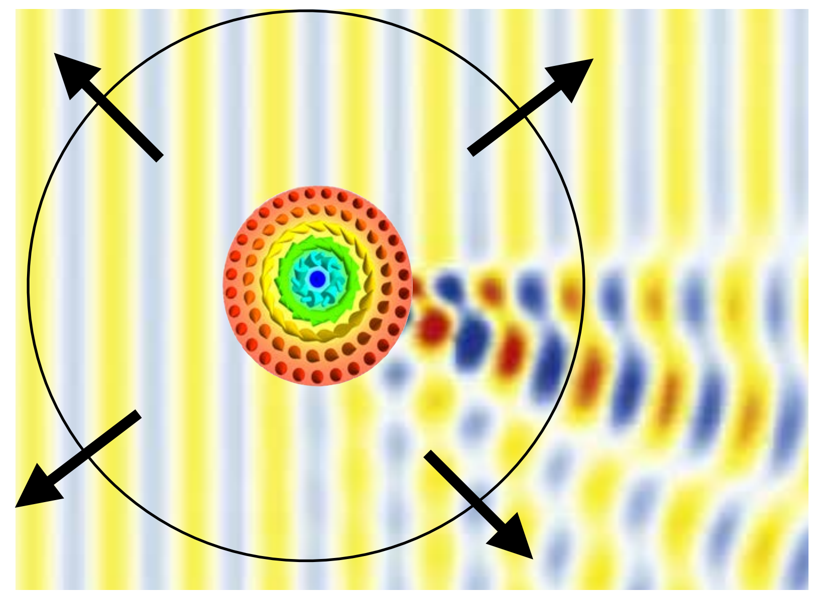
in which direction will it move?

momentum conservation?

Driving skyrmions with magnon currents

counting net flux of incoming & outgoing momentum

incoming momentum



outgoing momentum

conservation law of linear momentum

$$4\pi \mathcal{S} \varepsilon_{0\mu\nu} j_\mu^{\text{top}} + \partial_\mu T_{\mu\nu}^{\text{stat}} = 0$$

space-time topological current

energy-momentum tensor (static part)

$$j_\mu^{\text{top}} = \frac{1}{8\pi} \epsilon_{\mu\nu\lambda} \hat{M} (\partial_\nu \hat{M} \times \partial_\lambda \hat{M})$$

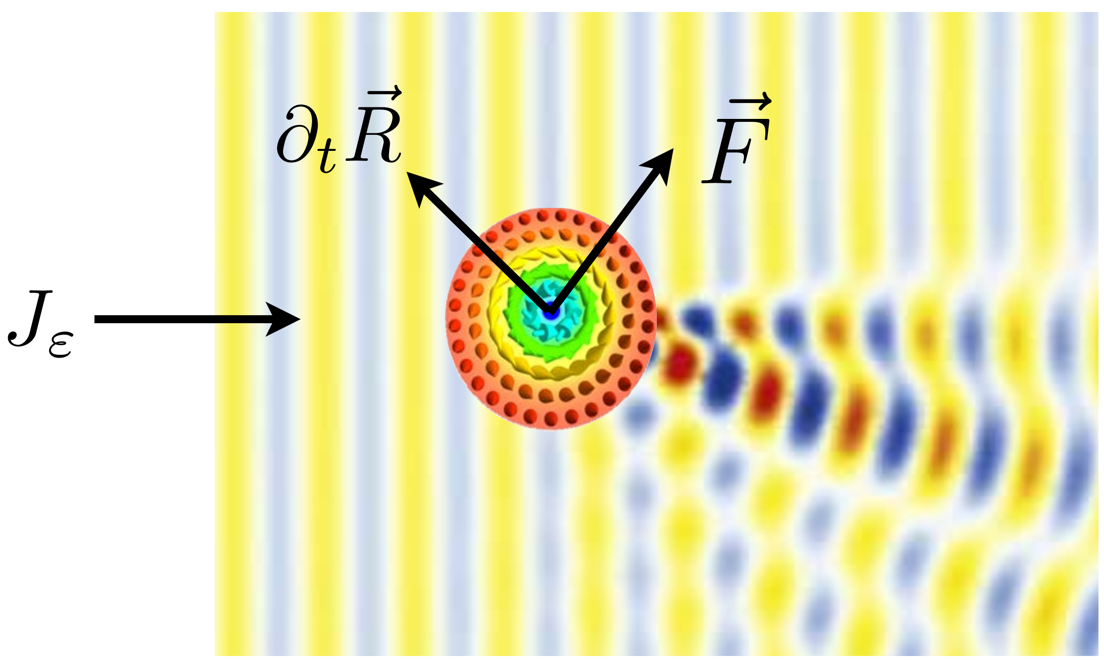
expanding conservation law up to quadratic order in ψ and integrating over the space

Linear response approximation

Thiele equation with a magnon force

$$\vec{G} \times \partial_t \vec{R}(t) = \vec{F}$$

Linear response: evaluate force F
for skyrmion at rest $\dot{R} = 0$



momentum-transfer force

after some algebra
using optical theorem:

$$\vec{F} = J_\varepsilon\, k \begin{pmatrix} \sigma_\parallel(\varepsilon) \\ \sigma_\perp(\varepsilon) \end{pmatrix}$$

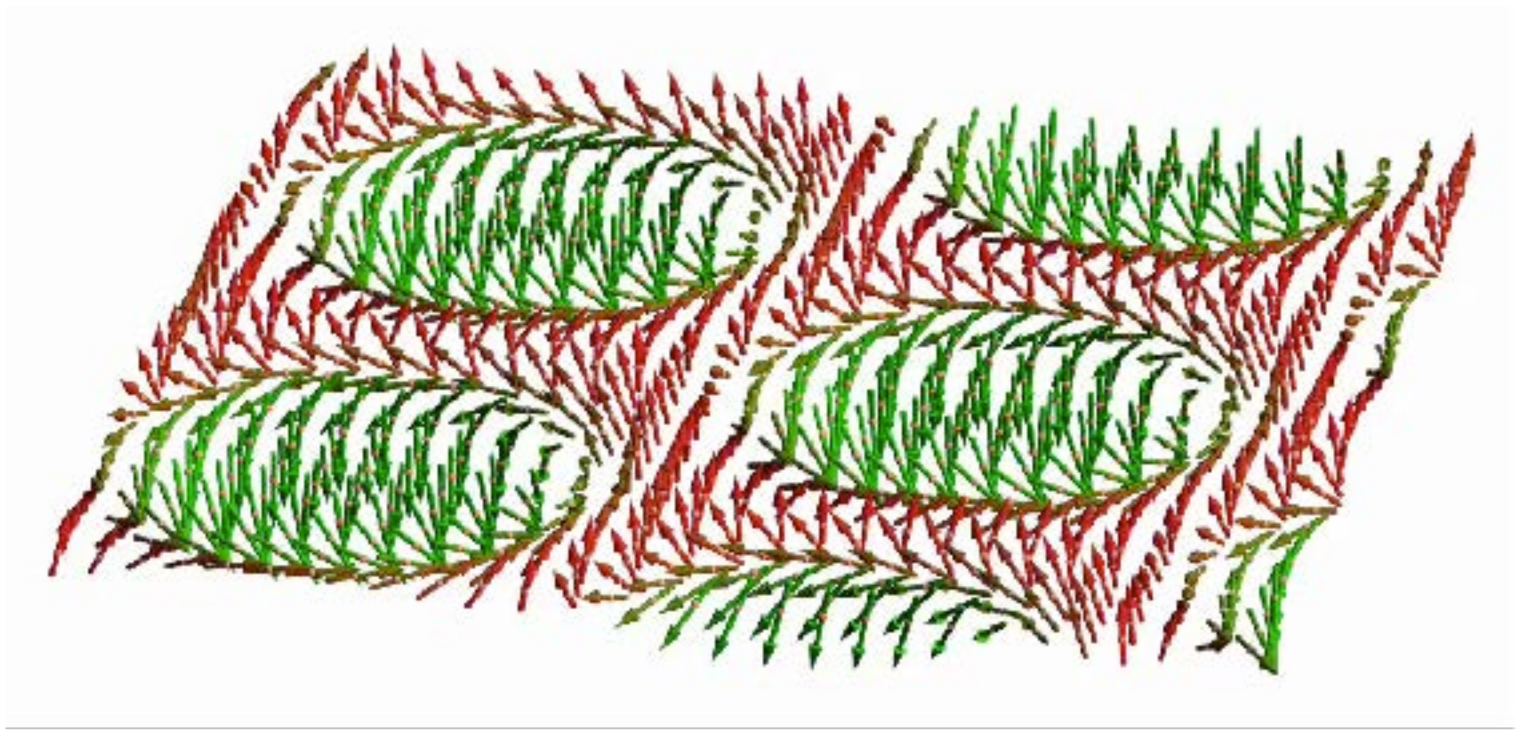
magnon force determined by
transport scattering cross sections:

with

$$\begin{pmatrix} \sigma_\parallel(\varepsilon) \\ \sigma_\perp(\varepsilon) \end{pmatrix} = \int_0^{2\pi} d\chi \begin{pmatrix} 1 - \cos\chi \\ -\sin\chi \end{pmatrix} \frac{d\sigma(\varepsilon)}{d\chi}$$

skew scattering → finite transversal force

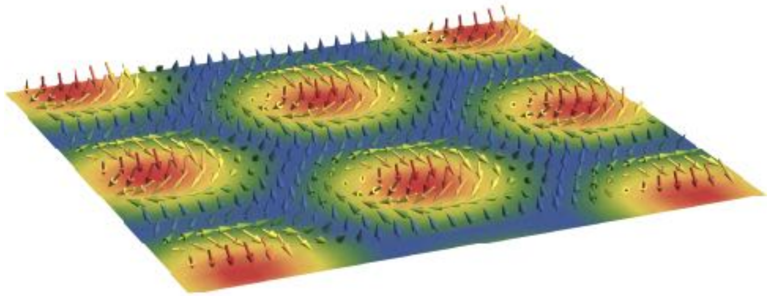
Spin-wave dynamics of the magnetic skyrmion lattice

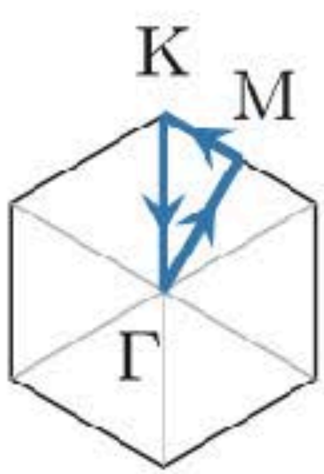


Magnon-band structure of skyrmion lattice

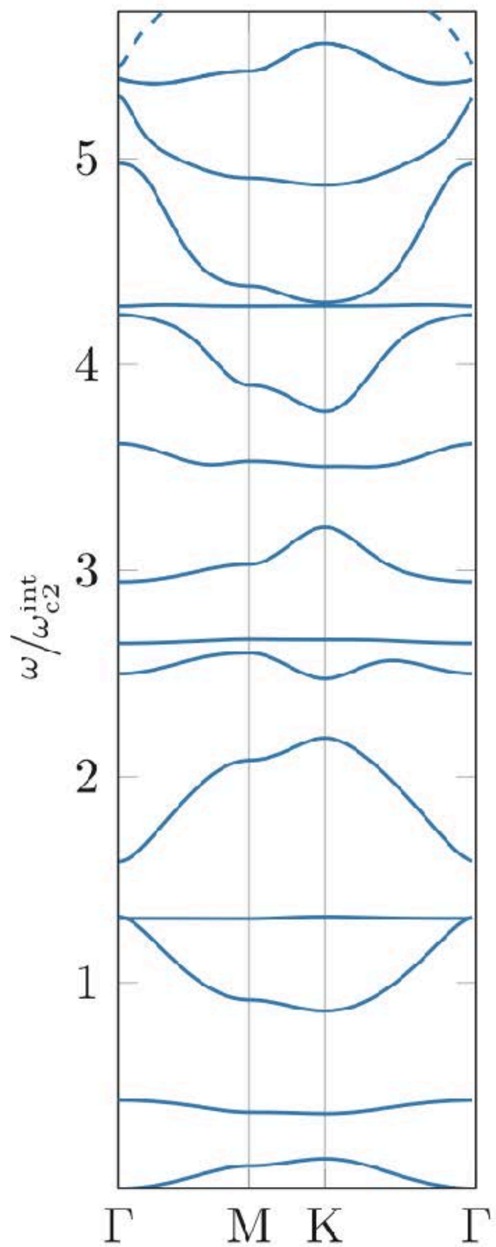
magnon dispersion for in-plane momenta

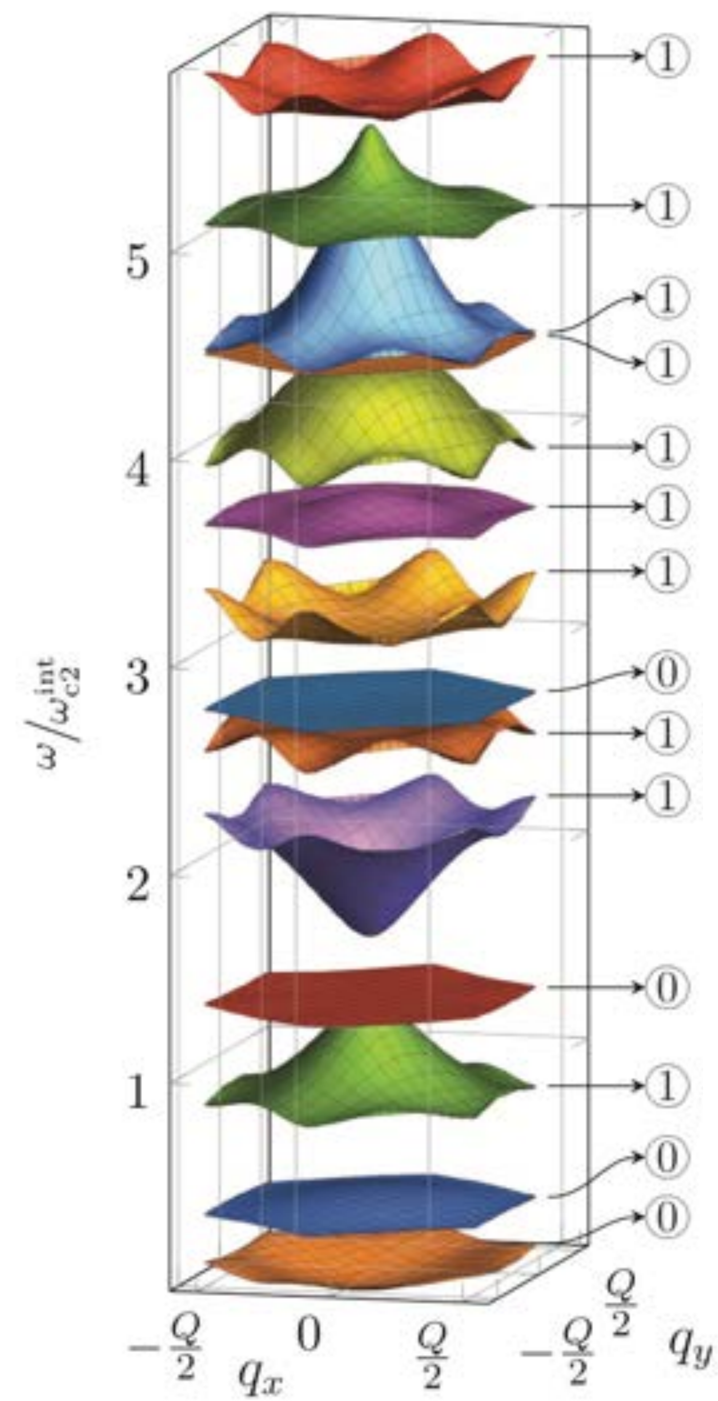
skyrmion lattice





2d magnetic
Brillouin zone





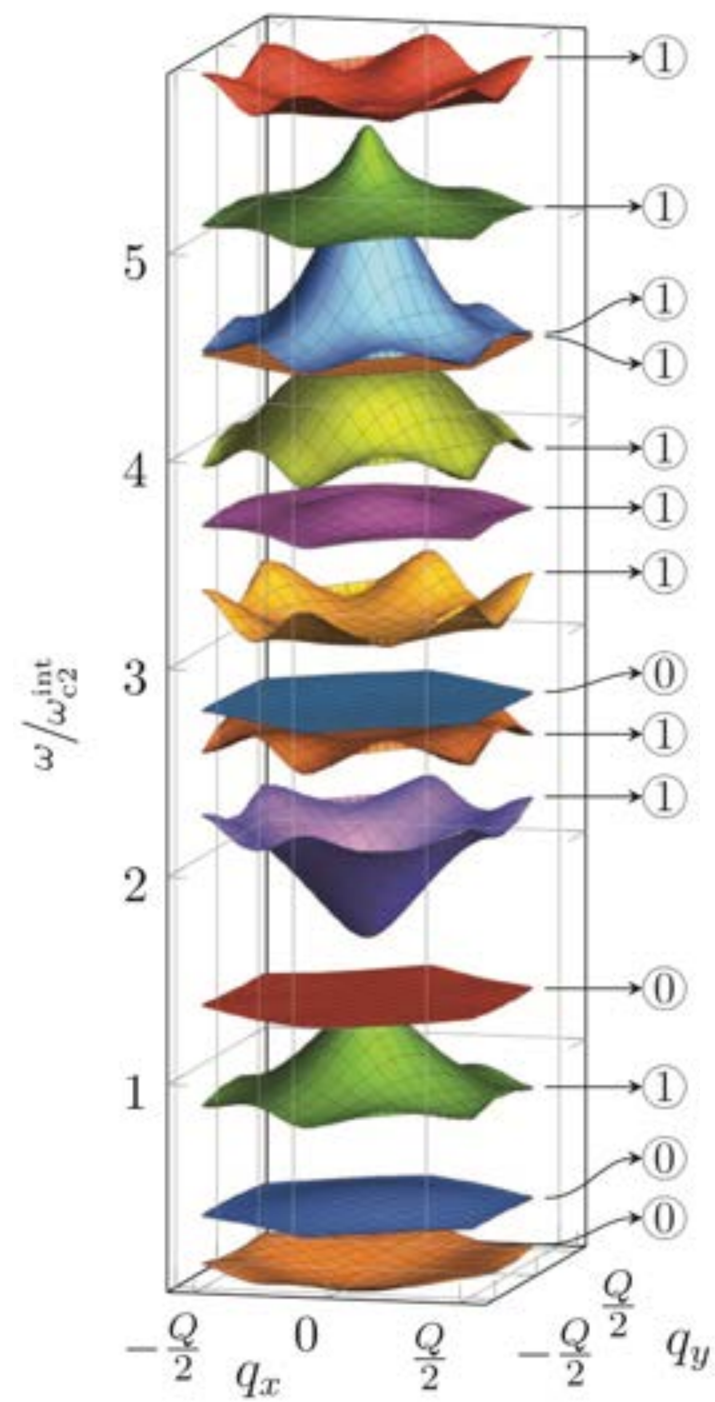
Topological magnon-band structure

non-trivial topology of skyrmions ⇨ topological magnon band structure

each skyrmion acts like a source
of emergent magnetic flux

emergent magnon electrodynamics

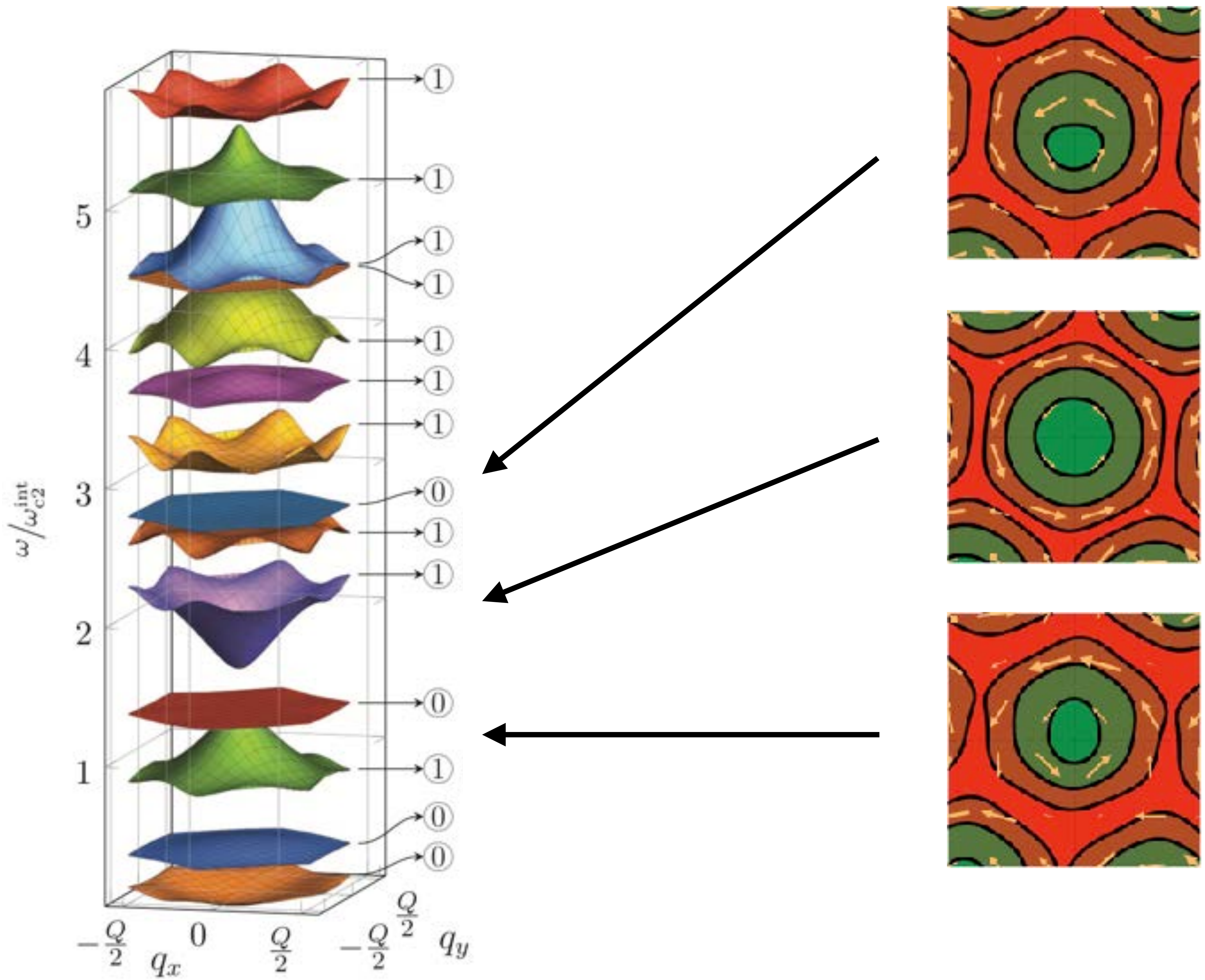
- emergent magnon Landau levels
- bands with finite Chern numbers
- topologically protected
  magnon edge states



Chern numbers

Magnetic skyrmion resonances

magnetic resonances at the Γ point



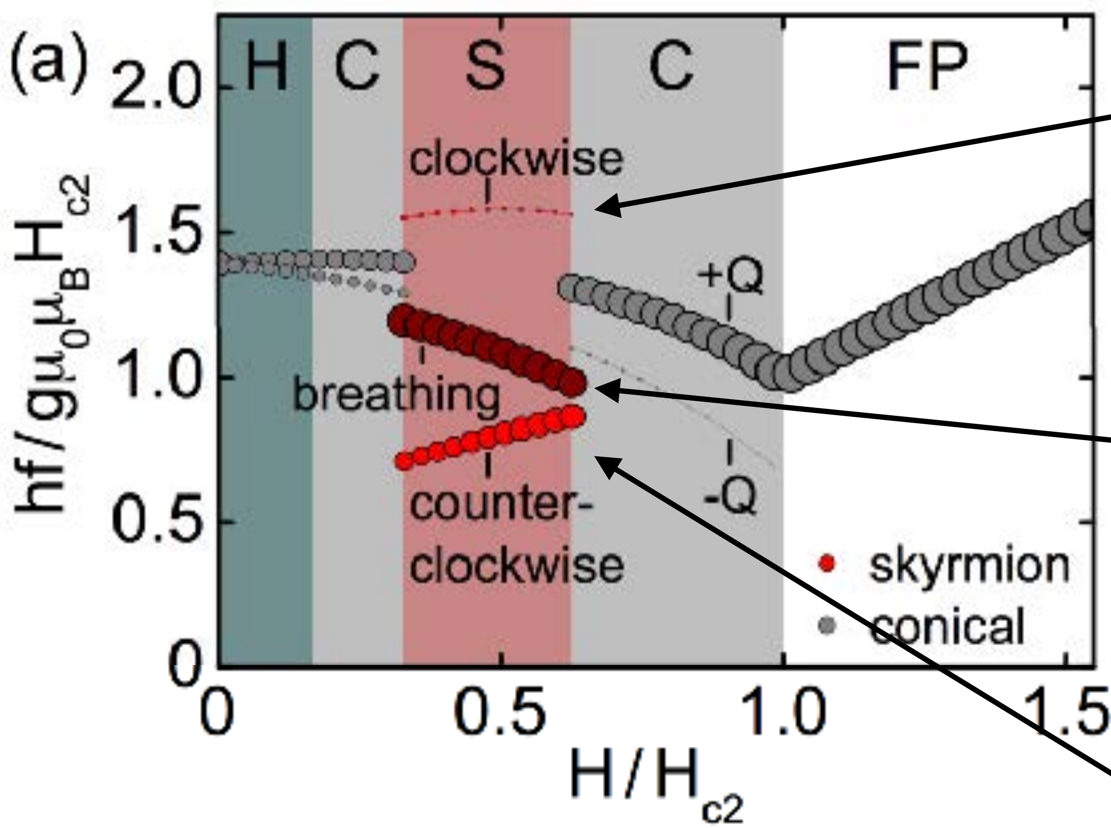
clockwise (CW)

breathing

counter-clockwise (CCW)

Magnetic skyrmion resonances

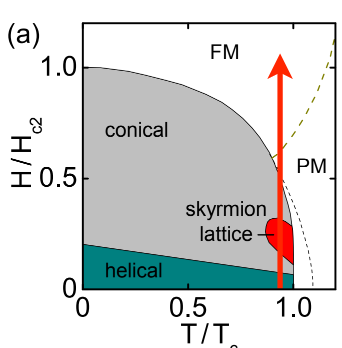
field-dependence of the resonance frequencies



clockwise (CW)

breathing

counter-clockwise (CCW)



for a field sweep through the phase diagram

see also Mochizuki PRL (2012); Onose et al. PRL (2012)

Comparison experiment & theory

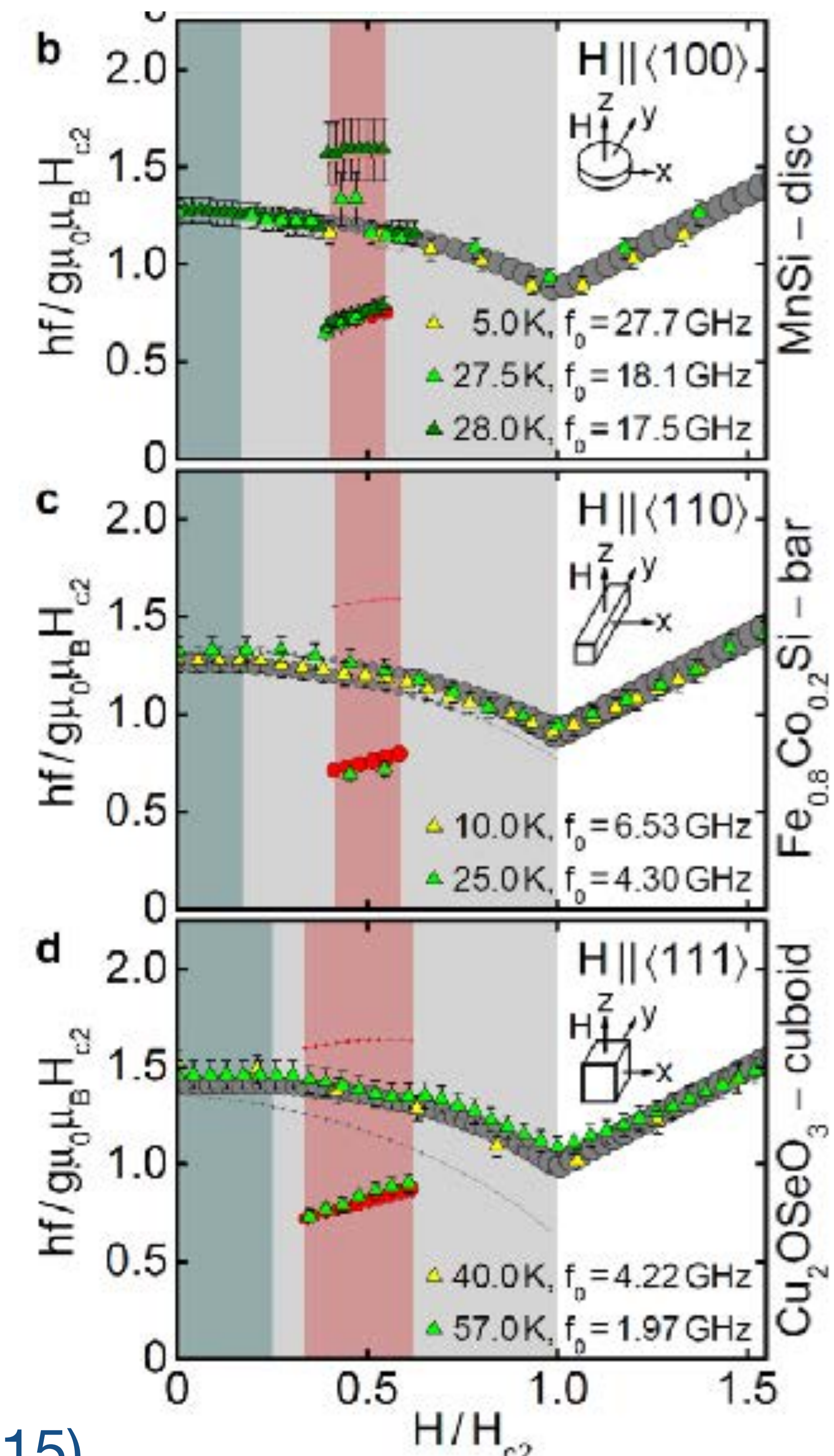
different field sweeps
normalized with $H_{c2}(T)$

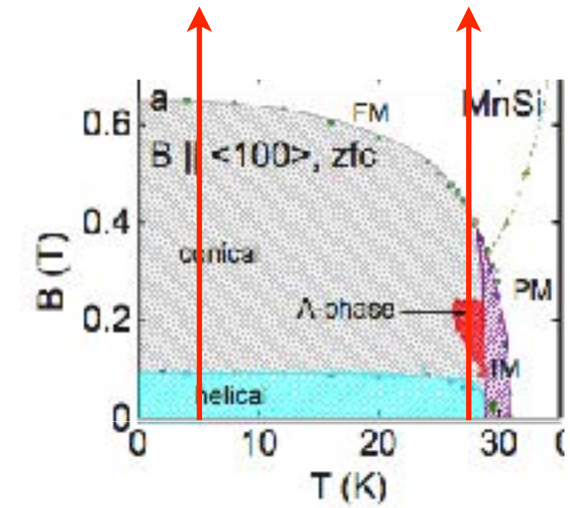
three different materials

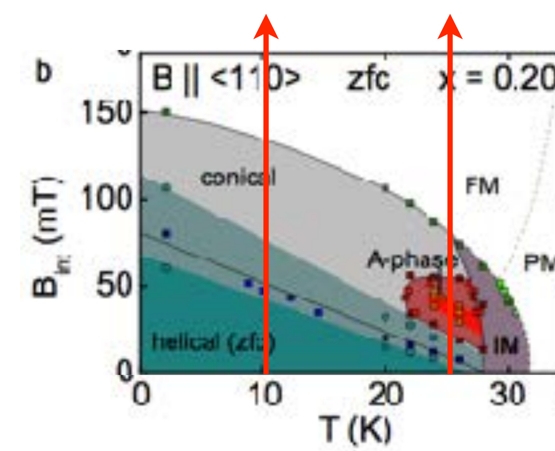
MnSi, $Fe_{0.8}Co_{0.2}Si$ and
Cu_2OSeO_3

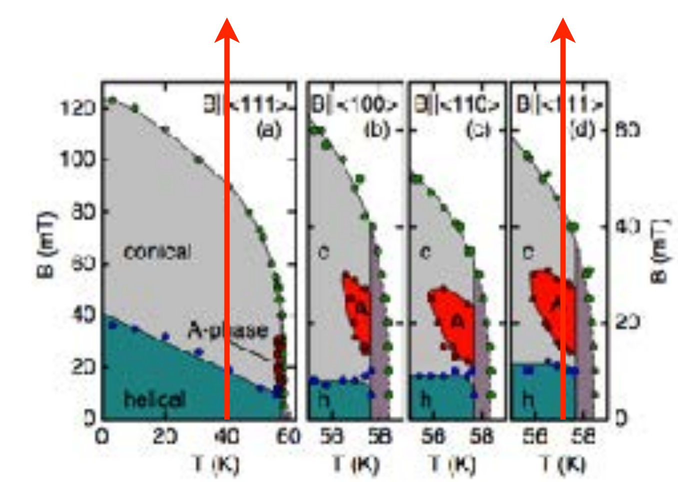
with three different shapes

(demagnization factors)









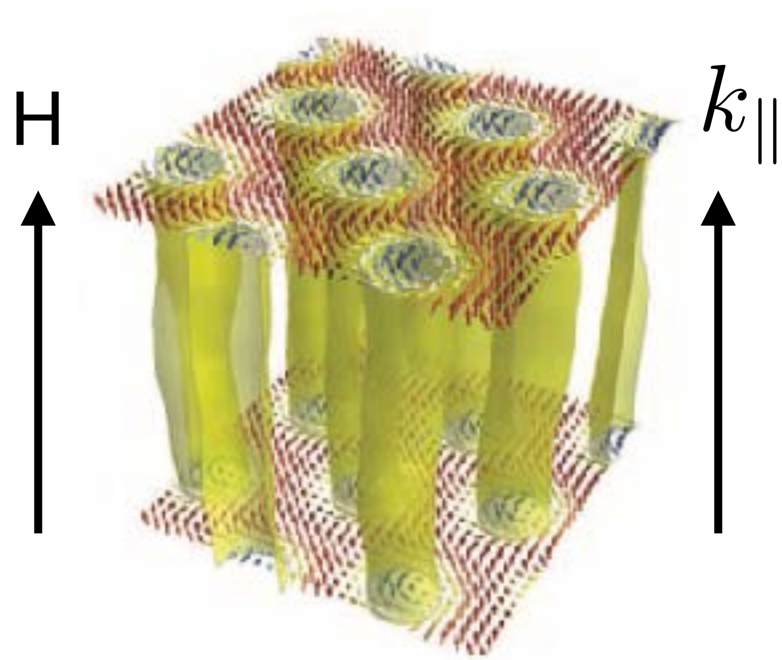
excellent quantitative theoretical understanding

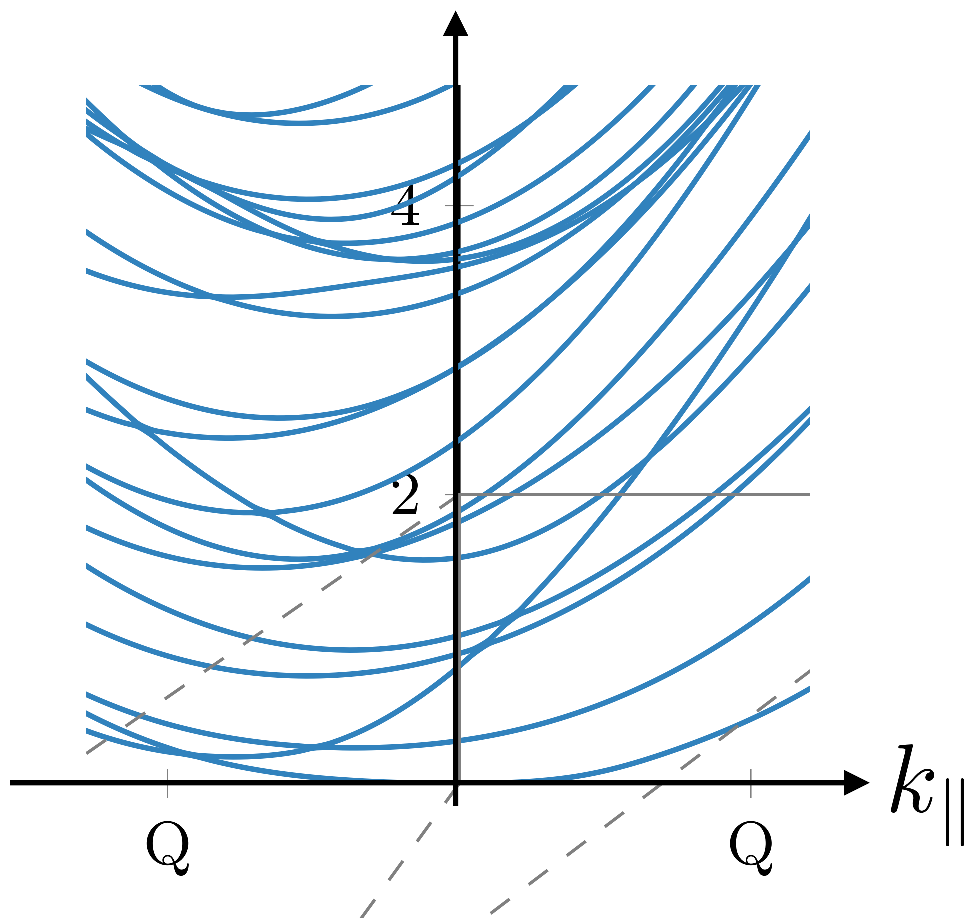
T. Schwarze, *et al.* Nat Mater (2015)

Non-reciprocity of skyrmion-lattice magnons

magnon dispersion for out-of-plane momenta

skyrmion lattice:



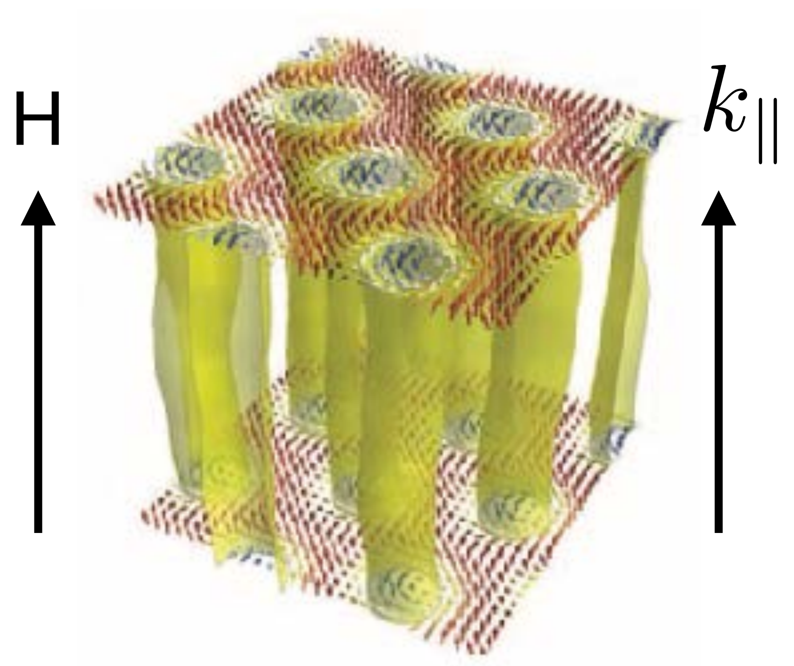


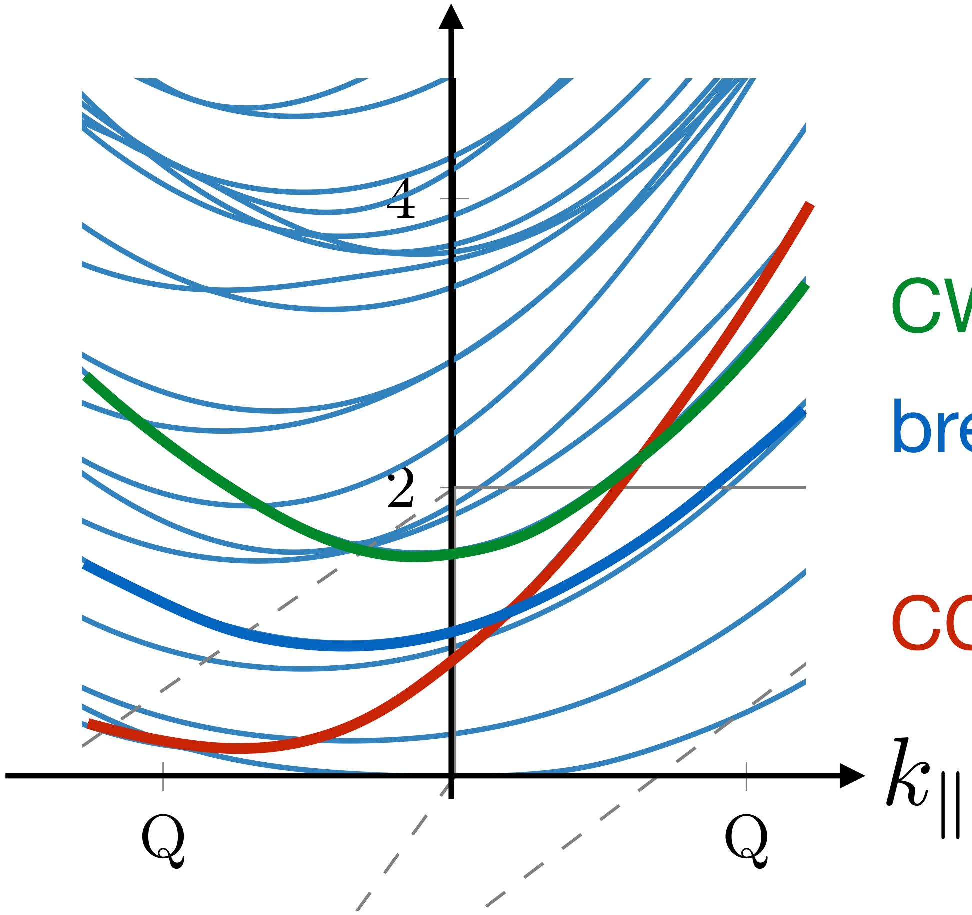
non-reciprocity $\omega(k_{||}) \neq \omega(-k_{||})$

Non-reciprocity of skyrmion-lattice magnons

magnon dispersion for out-of-plane momenta

skyrmion lattice:





non-reciprocity $\omega(k_{||}) \neq \omega(-k_{||})$

most pronounced for the CCW mode!

confirmed by spin-wave spectroscopy experiments by S. Seki!

Non-linear excitations…

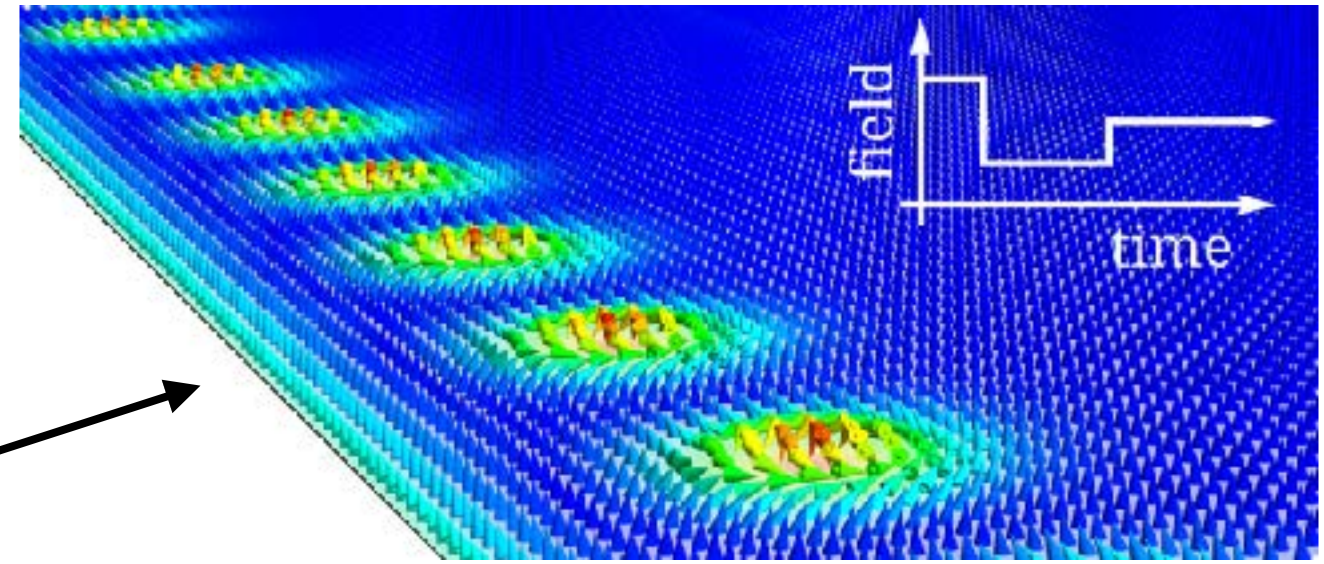
Skyrmion creation at the edge

uncompensated Dzyaloshinskii-Moriya interaction at the edge:

boundary condition:

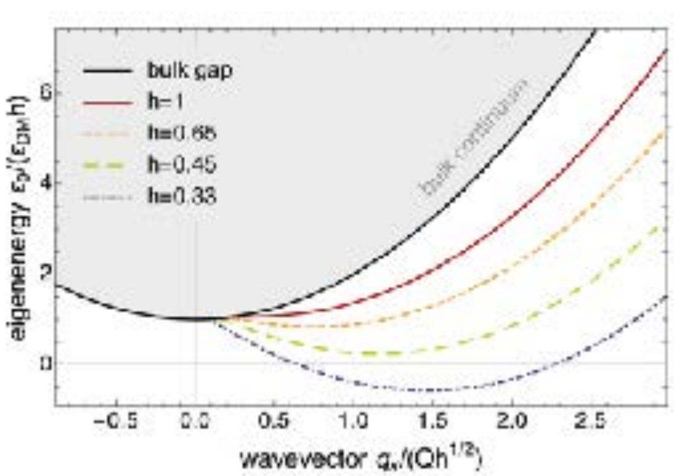
$$\hat{n}\vec{\nabla}\hat{M} - Q\hat{n}\times\hat{M} = 0$$

Rohart & Thiaville, PRB (2013)
Meynell et al PRB (2014)

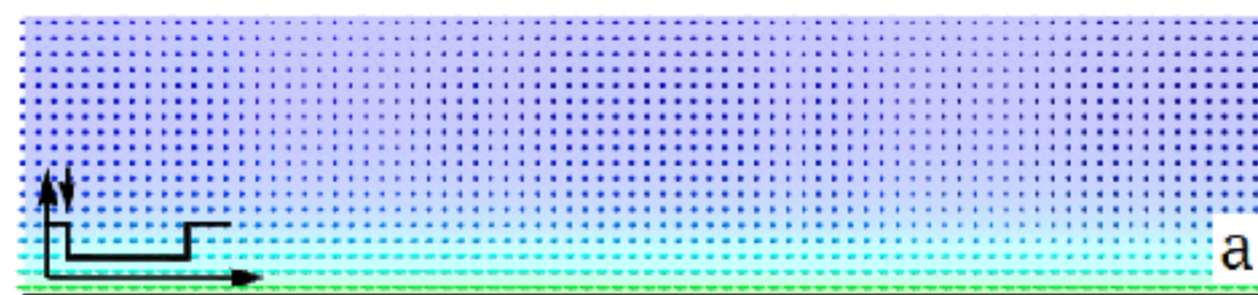


twist of the magnetisation
even in the field-polarised state

attractive potential for spin waves:



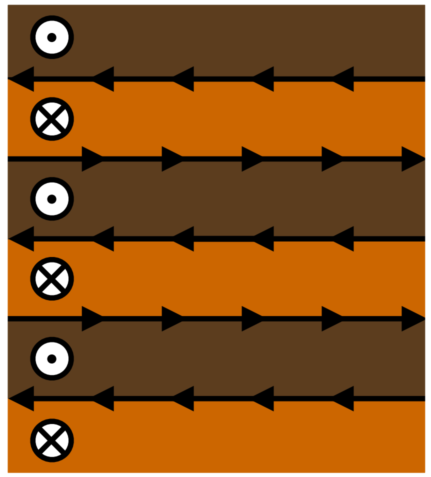
magnon localised to the edge



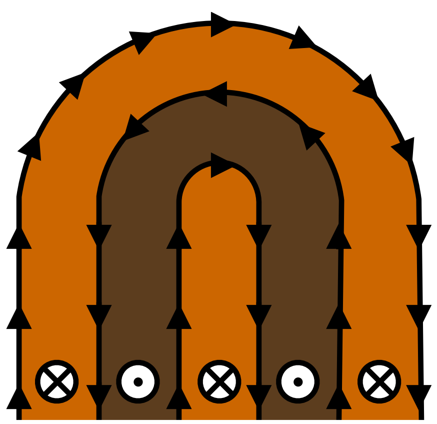
creation of skyrmions using
condensation of edge magnon

Müller, Rosch, MG, New J. Phys. (2016)

Topological defects of helimagnetic order



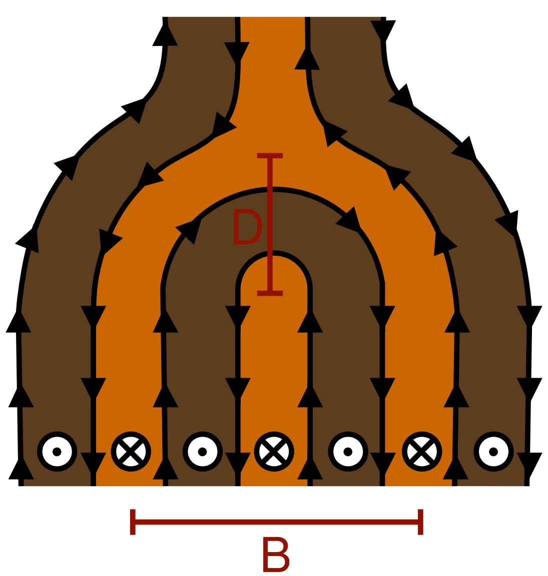
magnetic helix = lamellar structure similar to cholesteric liquid crystals or stripe domain patterns



pitch $\hat{Q}$ is a director

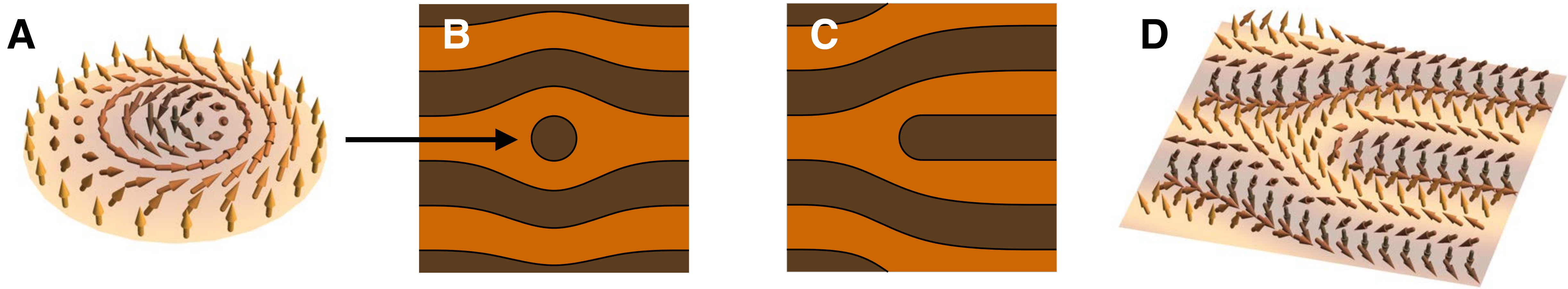
$\Rightarrow$ $\pm\pi$ vortices are possible

= disclinations defects



disclinations combine to form a dislocation with Burgers vector B

Skyrmion winding number of dislocations



skyrmion number W = -1

skyrmion number W = -1/2

skyrmion embedded in a topologically trivial background

dislocation (with B = λ) = meron

general relation for skyrmion number of dislocation with Burgers vector B:

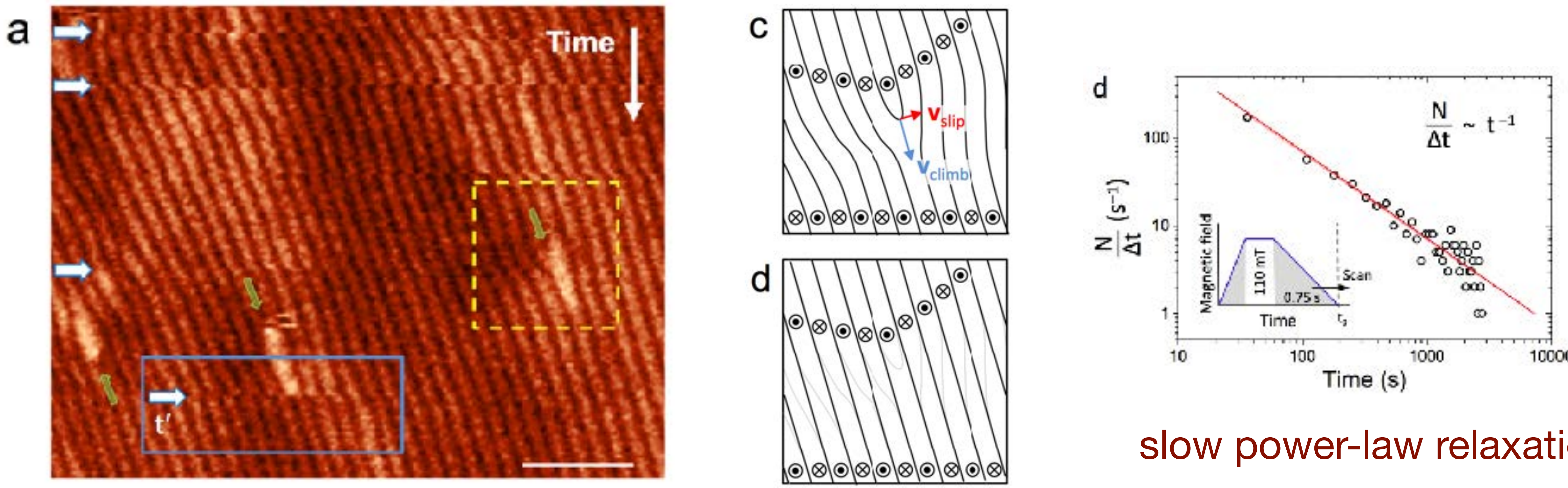
$$|W| = \frac{1}{2}\mathrm{mod}_2\left(\frac{B}{\lambda}\right)$$

⇨ only dislocations with half-integer B contribute to

topological Hall effect & emergent electrodynamics

Magnetic relaxation by climb motion of dislocations

magnetic force microscopy: surface of FeGe



slow power-law relaxation

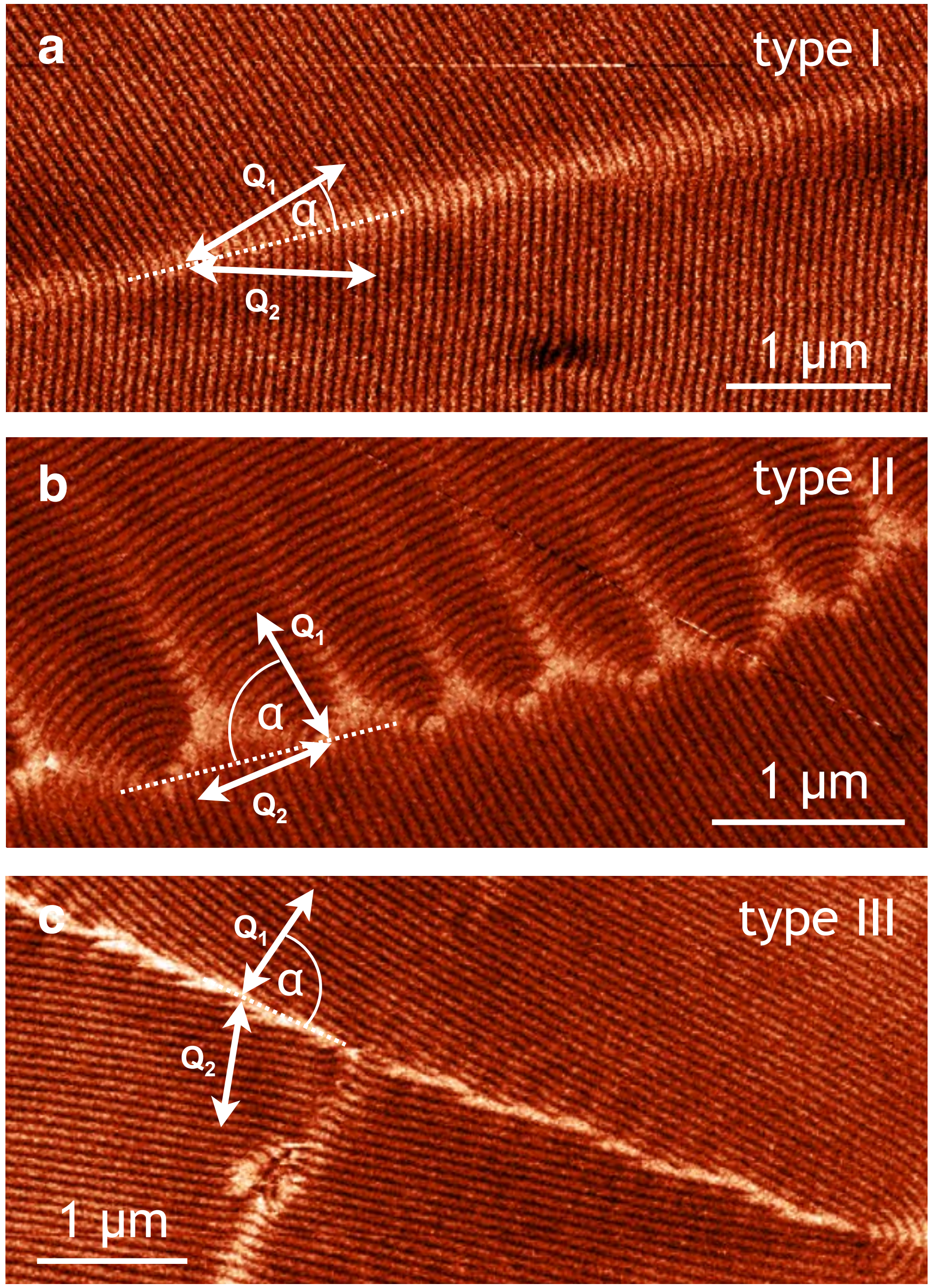
~ 1000 sec!

climb motion of dislocations ⇨ 180° phase shift

A. Dussaux et al., Nat Comm 2016

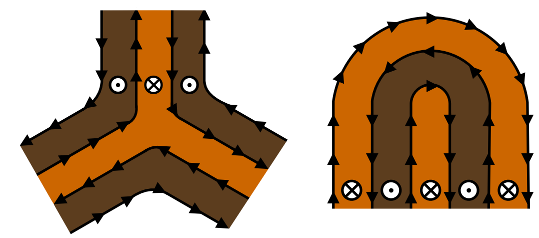
Topological domain walls

depending on relative angle: three types of domain walls

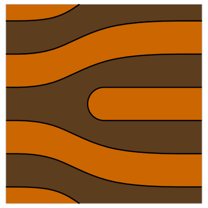


curvature wall

zig-zag
disclination wall



dislocation wall

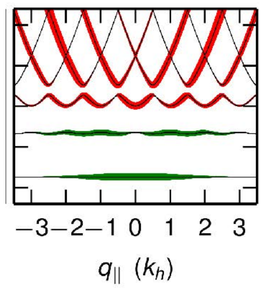


MFM: surface of FeGe

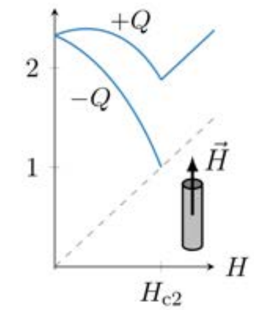
P. Schoenherr, … MG, D. Meier, arXiv:1704.06288

Summary:

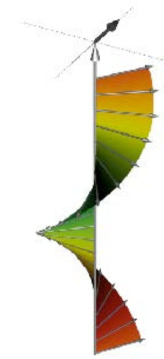
- Spin-wave dynamics of the magnetic helix



band structure

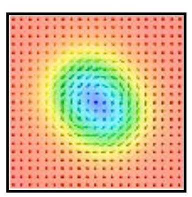


resonances

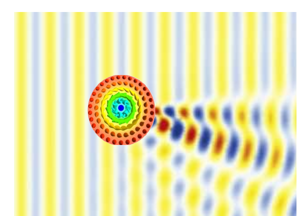


linear polarisation

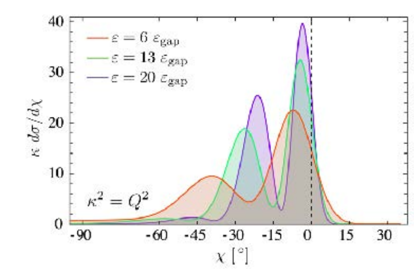
- Spin-wave dynamics of the magnetic skyrmion



internal modes

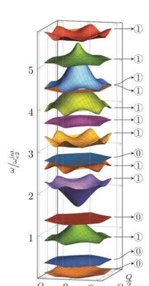


skew scattering



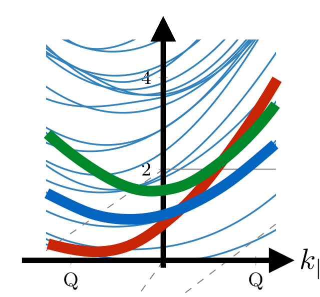
rainbow scattering

- Spin-wave dynamics of the magnetic skyrmion lattice



topological band structure

resonances



non-reciprocity

REVIEW: MG, J. Waizner, D. Grundler, J. Phys. D: Appl. Phys. 50, 293002 (2017)