



Topological magnon band structure of emergent Landau levels in a skyrmion lattice

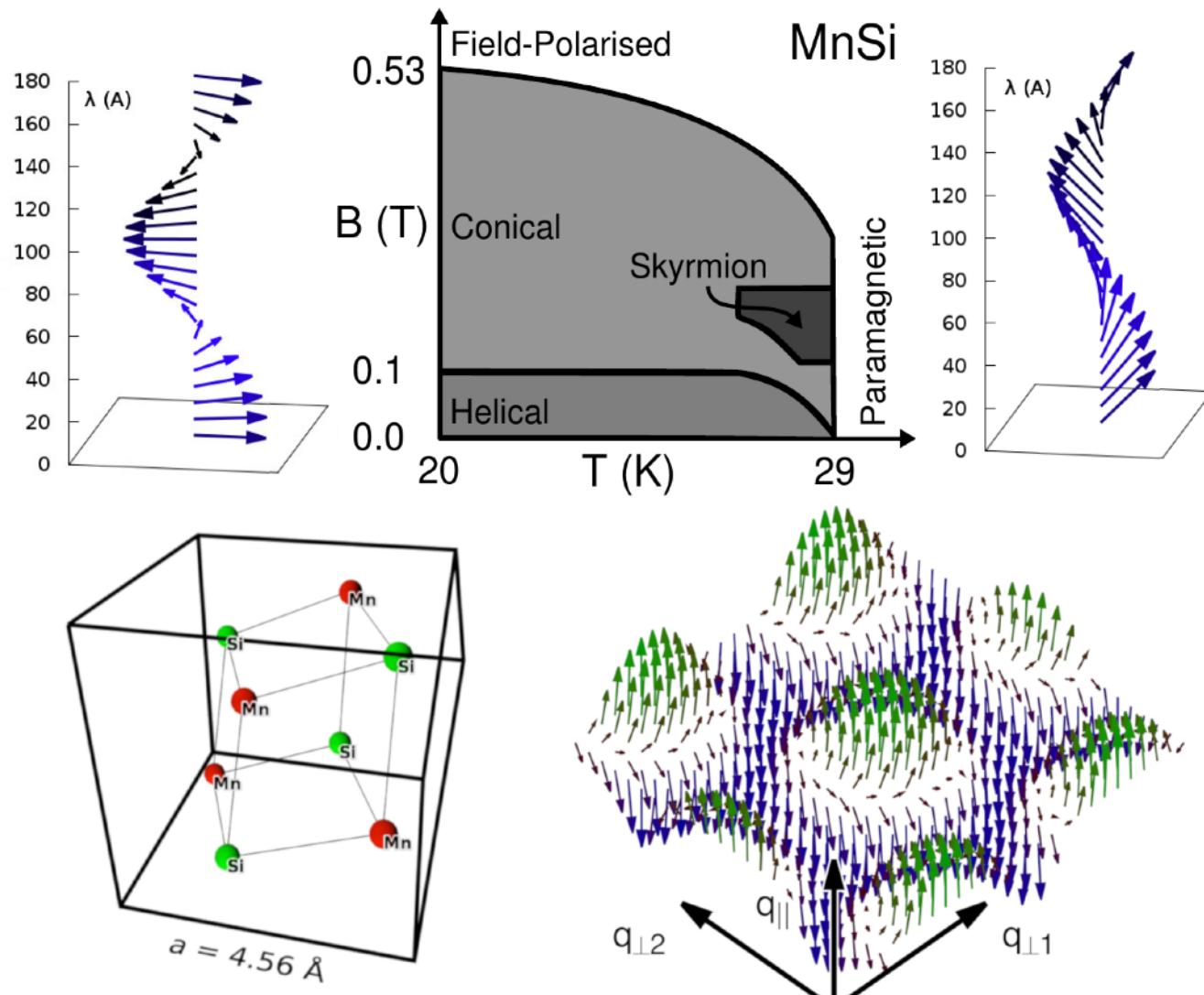
Tobias Weber <tweber@ill.fr>
Institut Laue-Langevin (ILL), Grenoble, France

Collaborators

- **Core team:**
M. Garst (KIT), C. Pfleiderer (TUM), P. Böni (TUM), and M. Janoschek (PSI).
- **Theory:**
M. Garst (KIT) and J. Waizner (Univ. Cologne).
- **Crystals:**
A. Bauer (TUM) and C. Pfleiderer (TUM).
- **Unpolarised helimagnon experiments:**
G. Tucker (PSI, TASP), M. Kugler (TUM), and R. Georgii (TUM, MIRA).
- **Unpolarised skyrmion experiments:**
D. Fobes (LANL), L. Beddrich (TUM, MIRA), G. Tucker (PSI, TASP),
R. Georgii (TUM, MIRA), M. Skoulatos (TUM, MIRA),
R. Bewley (ISIS, LET), D. Voneshen (ISIS, LET).
- **Spin-echo skyrmion experiments:**
C. Franz (TUM, RESEDA), H. Gabold (TUM, RESEDA), J. K. Jochum (TUM, RESEDA).
- **Polarised helimagnon & skyrmion experiments:**
P. Steffens (ILL, ThALES) and M. Böhm (ILL, ThALES).
- **Initial implementations of the theoretical models:**
Matlab: J. Waizner and M. Garst, *Python*: M. Kugler (TUM) and G. Brandl (Jülich).
- **Early experimental attempts on skyrmion dynamics:**
M. Kugler (TUM), R. Georgii (TUM, MIRA), and G. Tucker (PSI, TASP).

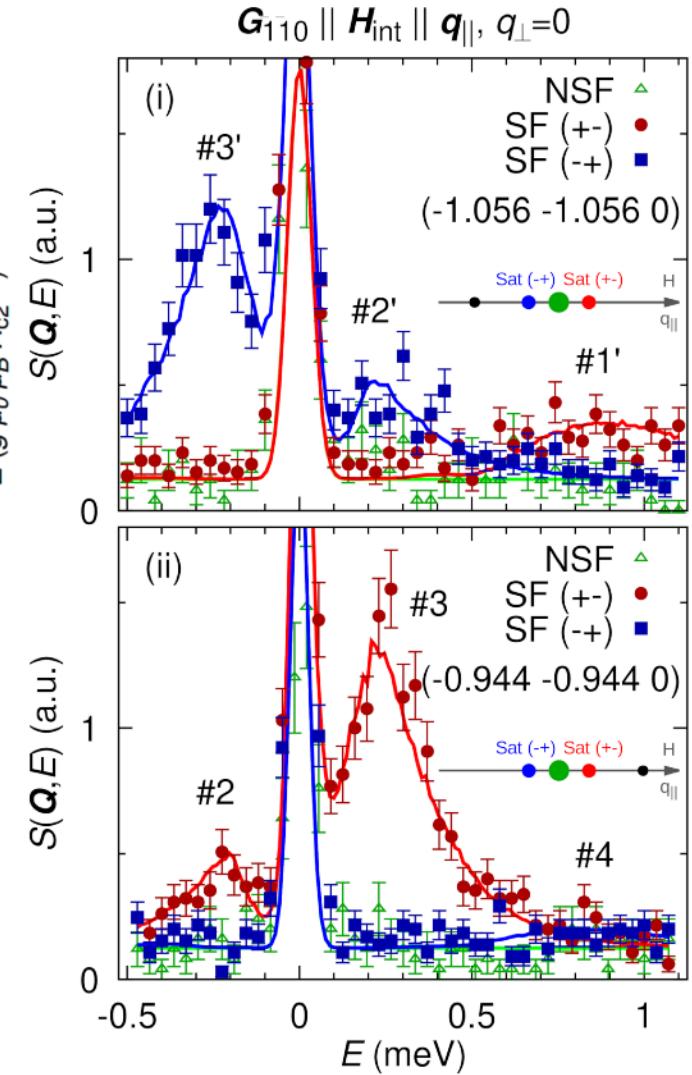
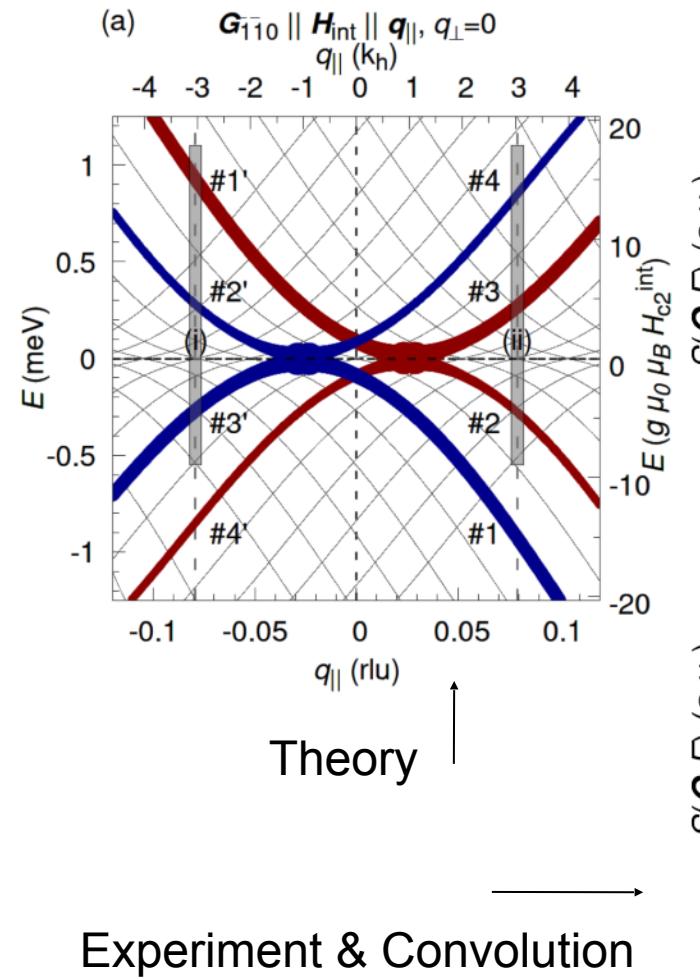
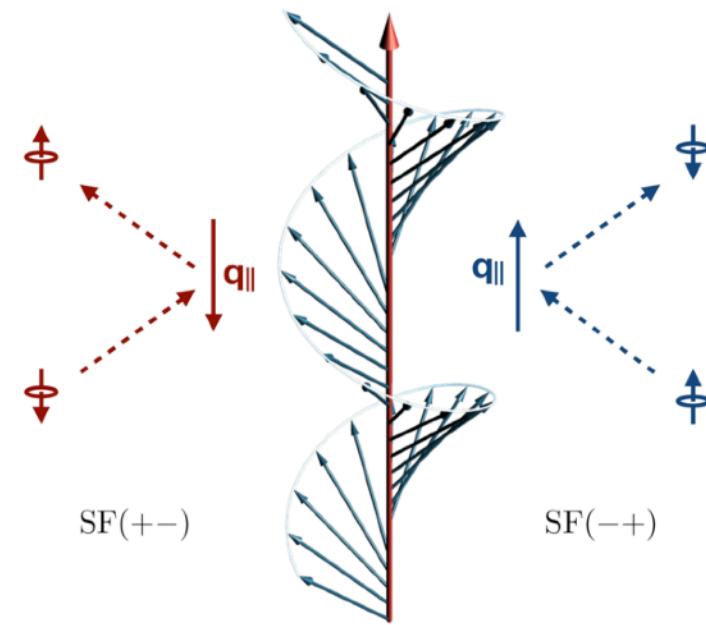
Conical Dynamics

Magnetic Phases of MnSi

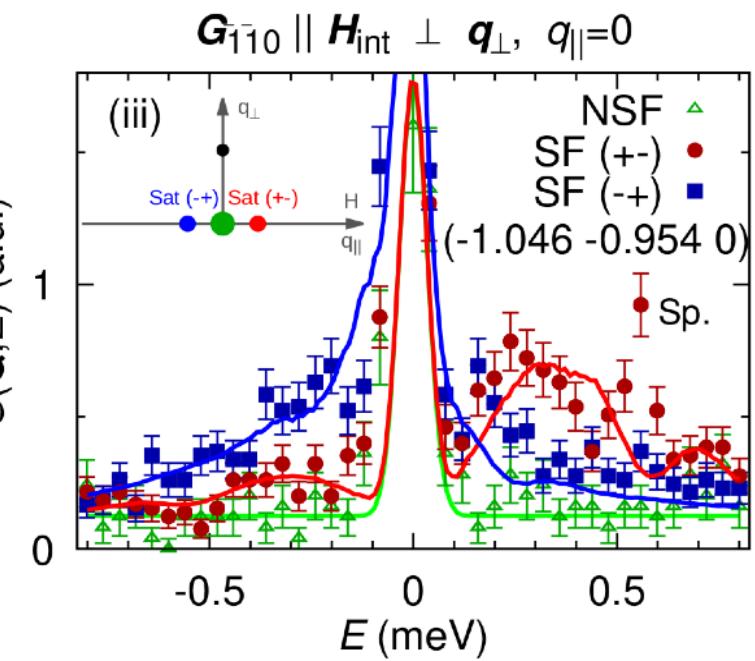
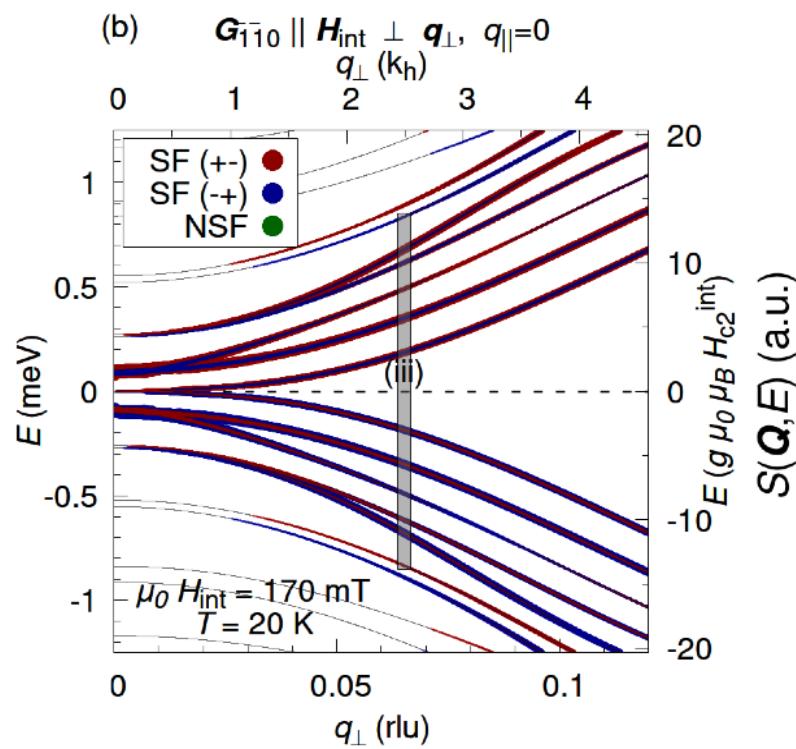
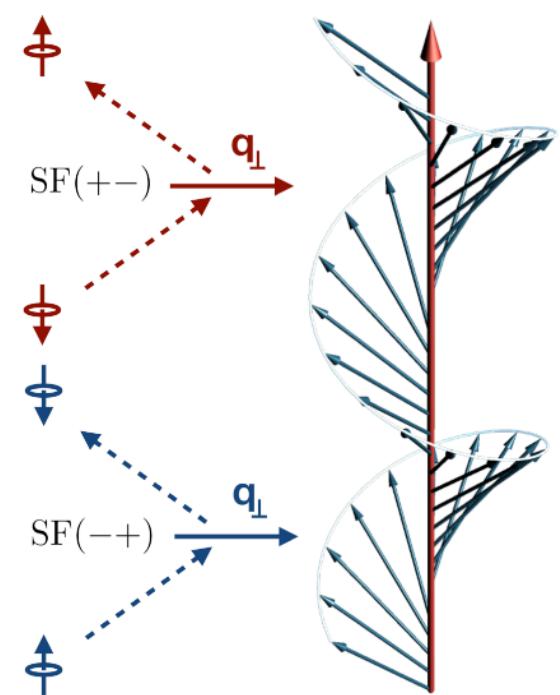


Infos, see e.g.: S. Mühlbauer, *et al.*, Science 323 (5916), pp. 915-919 (2009).

Dynamics of a Single Helix for $\mathbf{q} \parallel \mathbf{H}$



Dynamics of a Single Helix for $\mathbf{q} \perp \mathbf{H}$



Figures: Phys. Rev. B **100**, 060404(R) (2019).

Resolution of helimagnon bands: M. Kugler, et al., Phys. Rev. Lett. **115**, 097203 (2015).

Skyrmion Dynamics

Skyrmion Dynamics – Theory

- **Ground state via minimisation of Free Energy:**

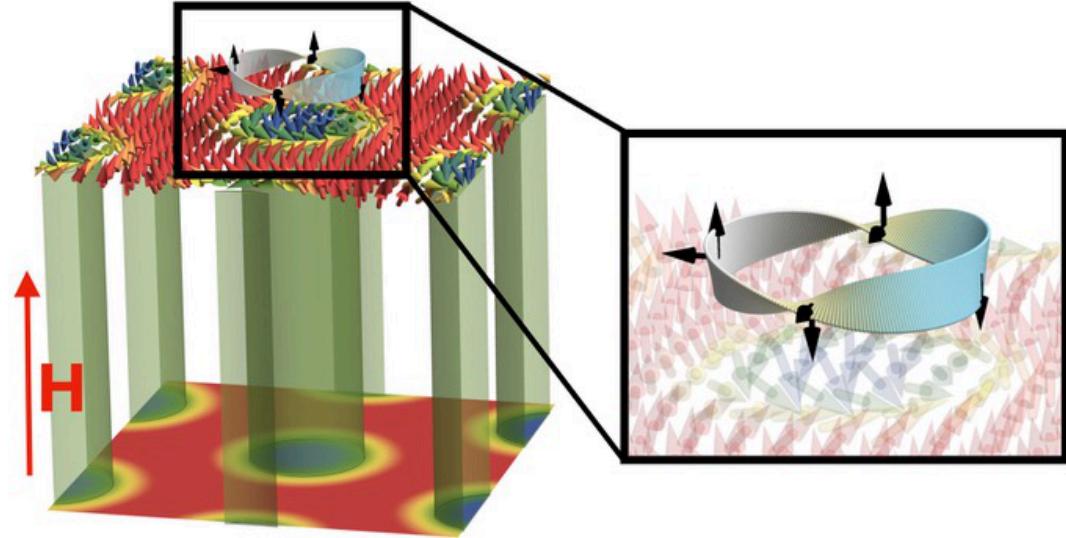
$$F = \underbrace{\int A \left(\partial_i \hat{M}_j \right)}_{(1)} + \underbrace{D \hat{M} \left(\nabla \times \hat{M} \right)}_{(2)} - \underbrace{\mu_0 \vec{M} \vec{H}}_{(3)} + \underbrace{\frac{\mu_0 M^2}{2} \int \hat{M}_i(\vec{r}) \chi_{\text{dip},ij}^{-1}(\vec{r} - \vec{r}') \hat{M}_j(\vec{r}') d\vec{r}' d\vec{r}}_{(4)}$$

- (1) Exchange interaction
- (2) Dzyaloshinskii-Moriya interaction
- (3) Zeeman term
- (4) Dipolar interaction

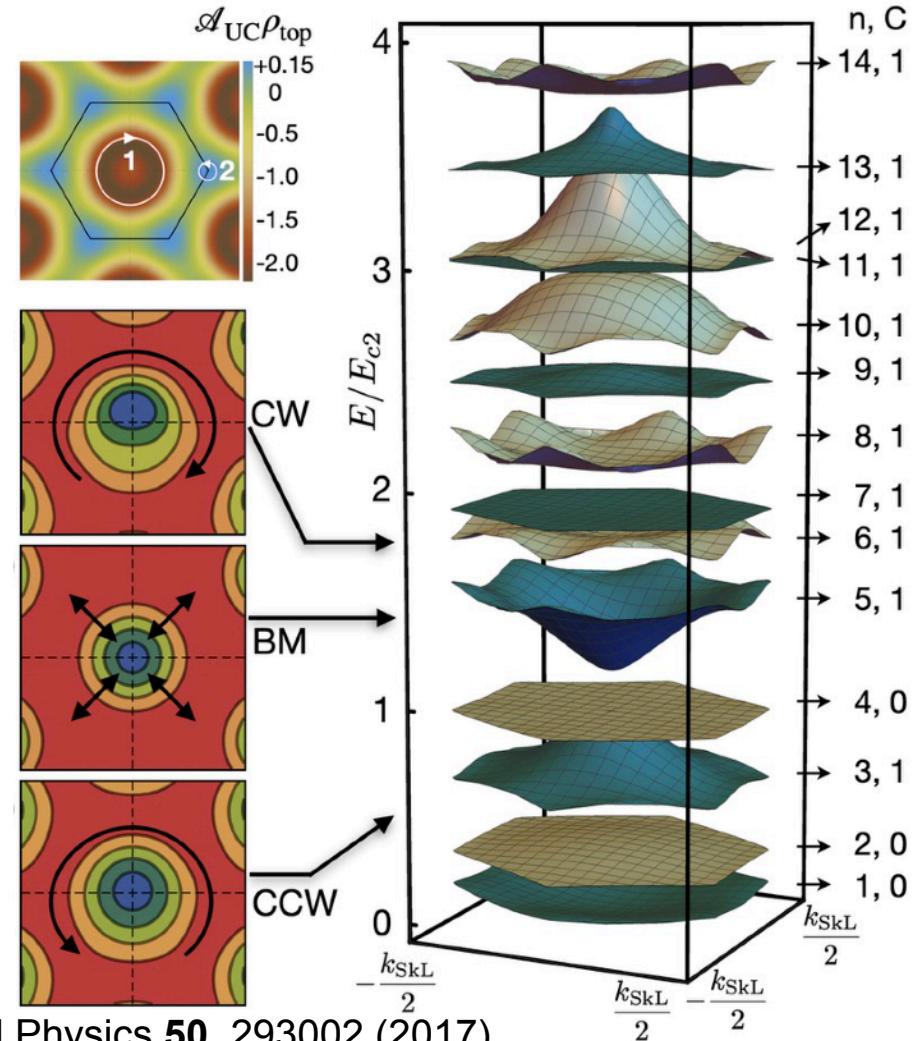
- **Magnon dynamics via Landau-Lifshitz equation.**

- Source code available: <https://doi.org/10.5281/zenodo.5718363>.

Skyrmion Dynamics in First BZ – Theory



- **Skyrmion lattice in a field H.**
- **Magnon motion under local magnetisation.**
- **Formation of bands, three fundamental modes.**



Figures: Science 375 (6584), pp. 1025-1030 (2022).

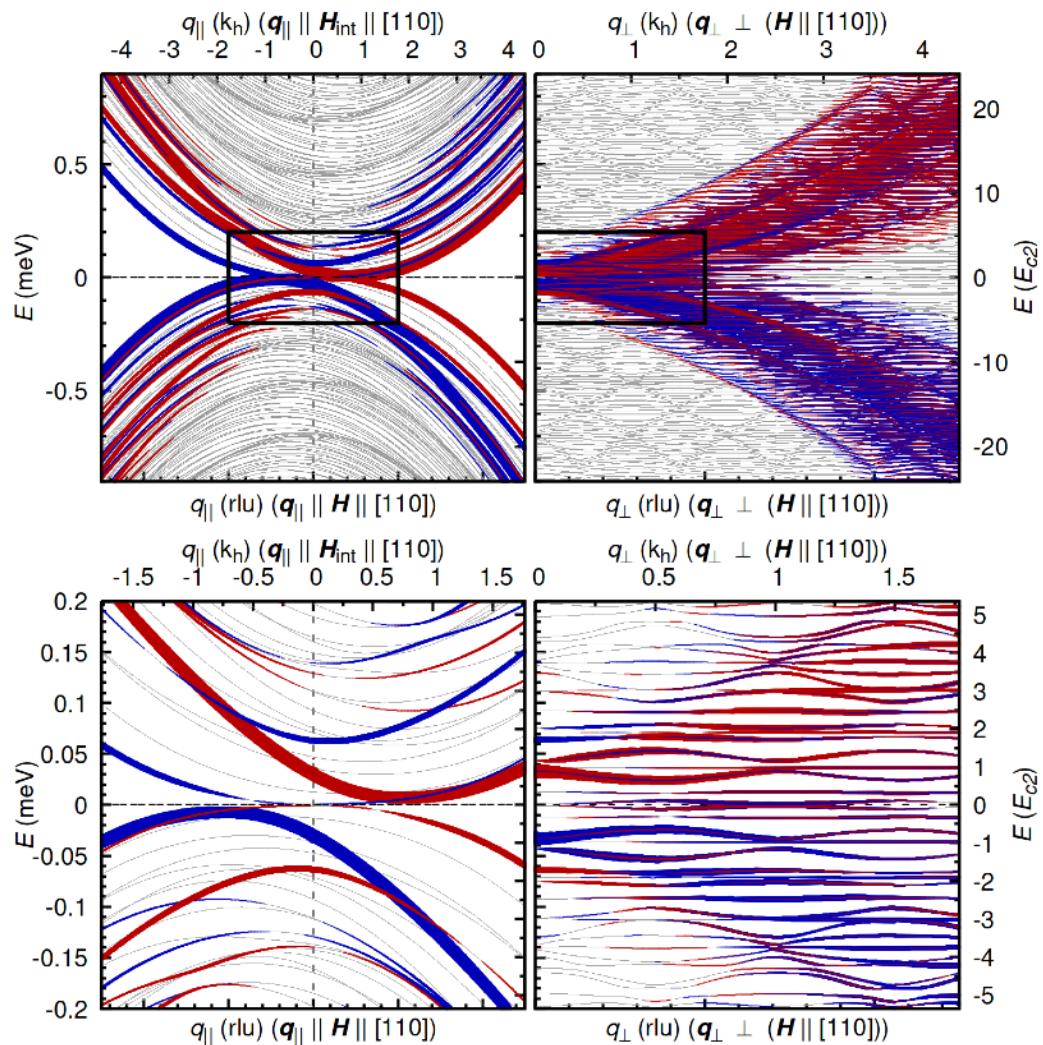
M. Garst, J. Waizner, D. Grundler, Journal of Physics D: Applied Physics 50, 293002 (2017).

J. Waizner, PhD Thesis, Universität zu Köln, <https://kups.ub.uni-koeln.de/7937/> (2016).

T. Schwarze, et al., Nature Materials 14, pp. 478–483 (2015).

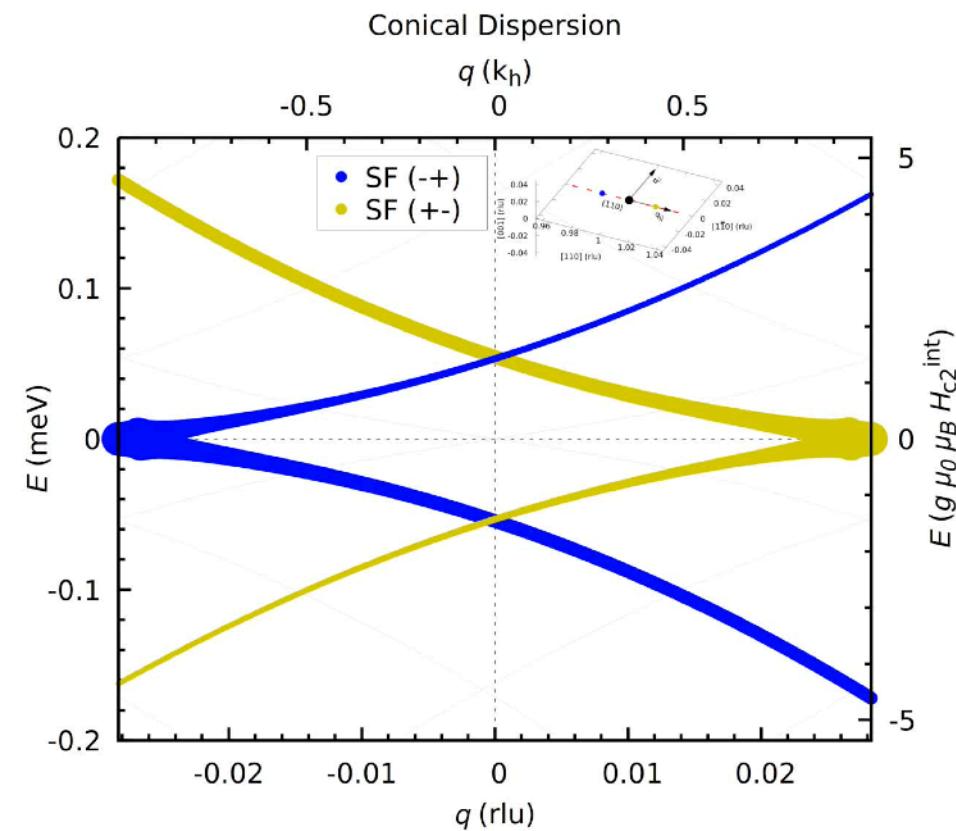
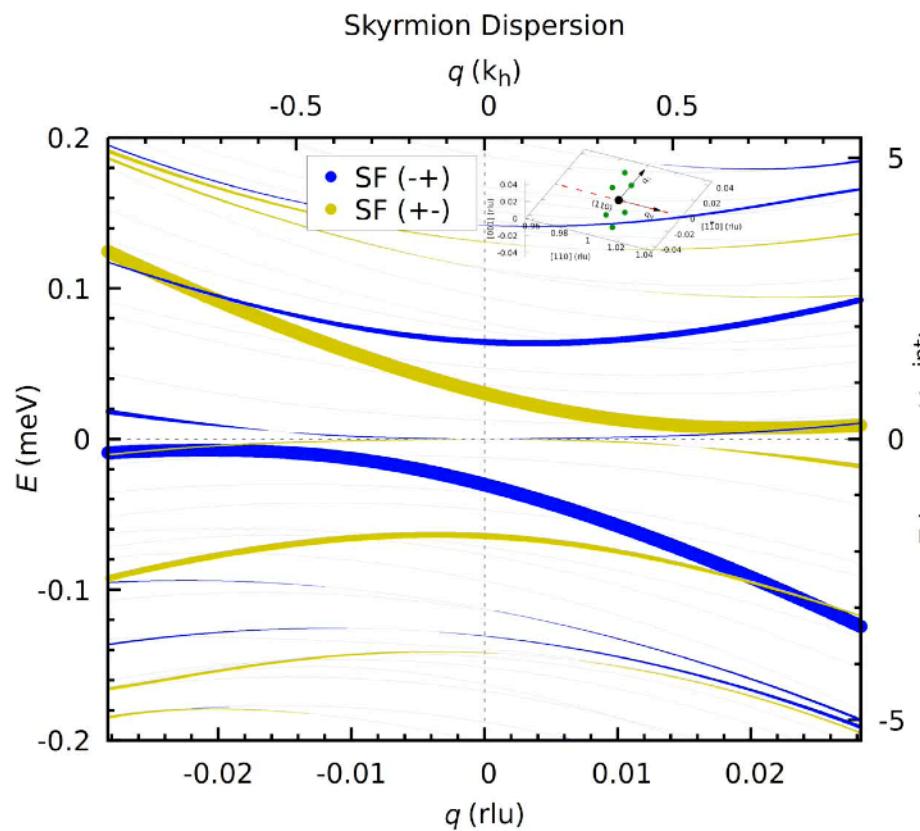
Skyrmion Dynamics – Theory

- Higher Brillouin zones:
Video: <https://youtu.be/CuoA6sIM2oM>
- First Brillouin zone:
Video: https://youtu.be/TGT07x_UupU



Skyrmion Dynamics – First Brillouin Zone

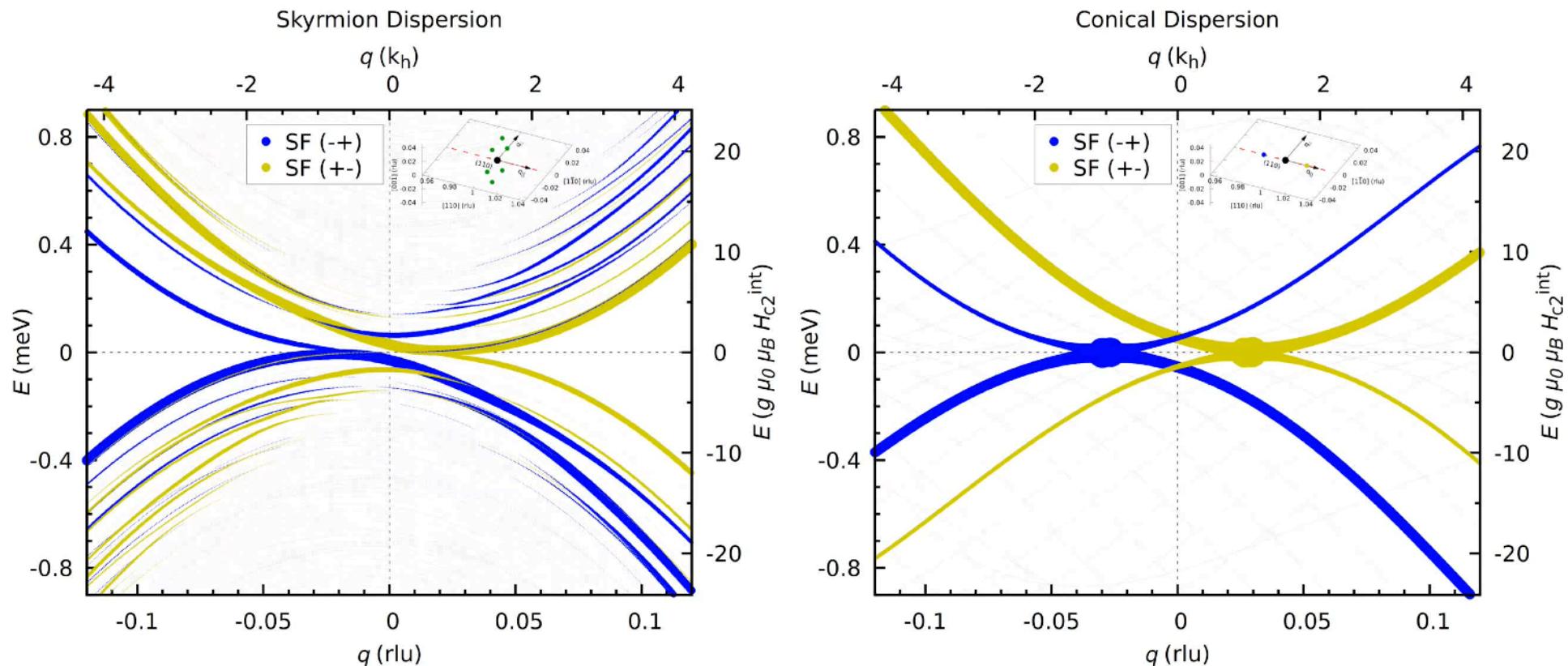
Animation



<https://doi.org/10.5281/zenodo.5718363>

Skyrmion Dynamics – High Brillouin Zones

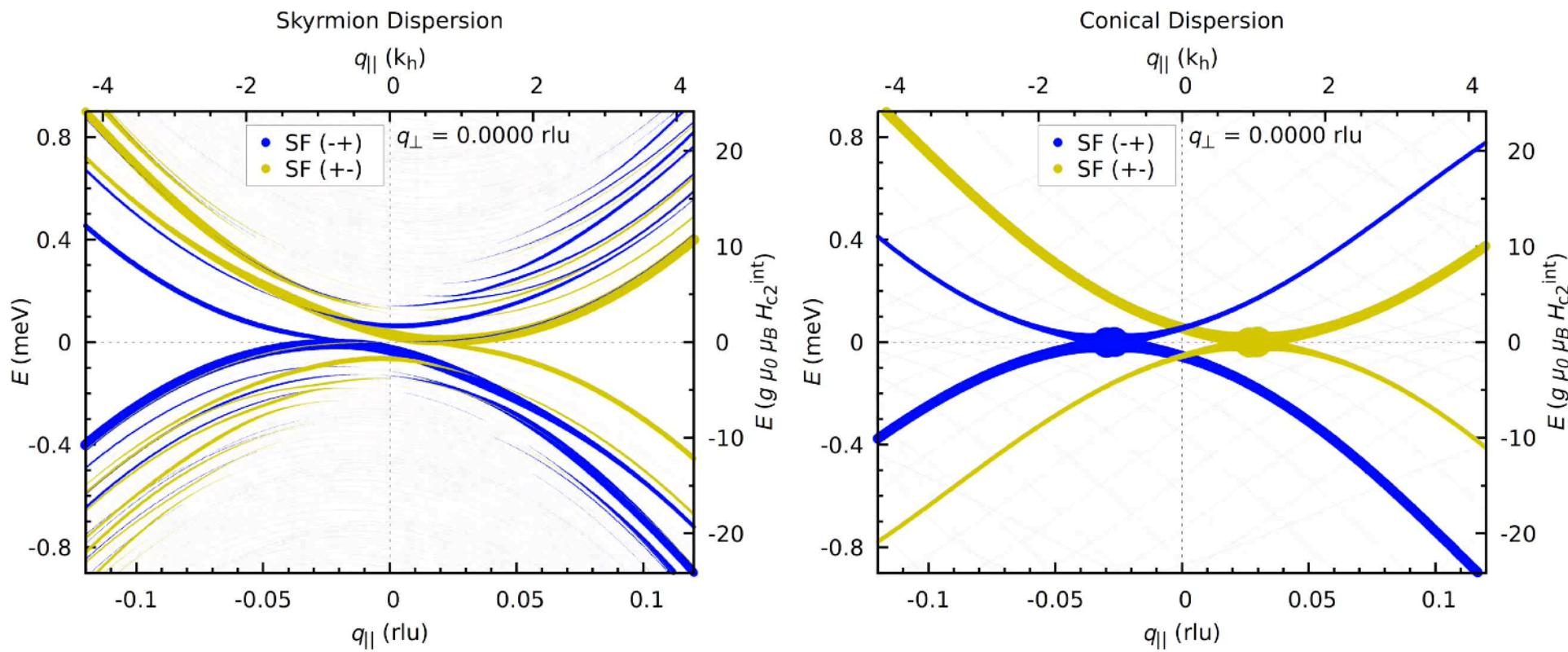
Animation



<https://doi.org/10.5281/zenodo.5718363>

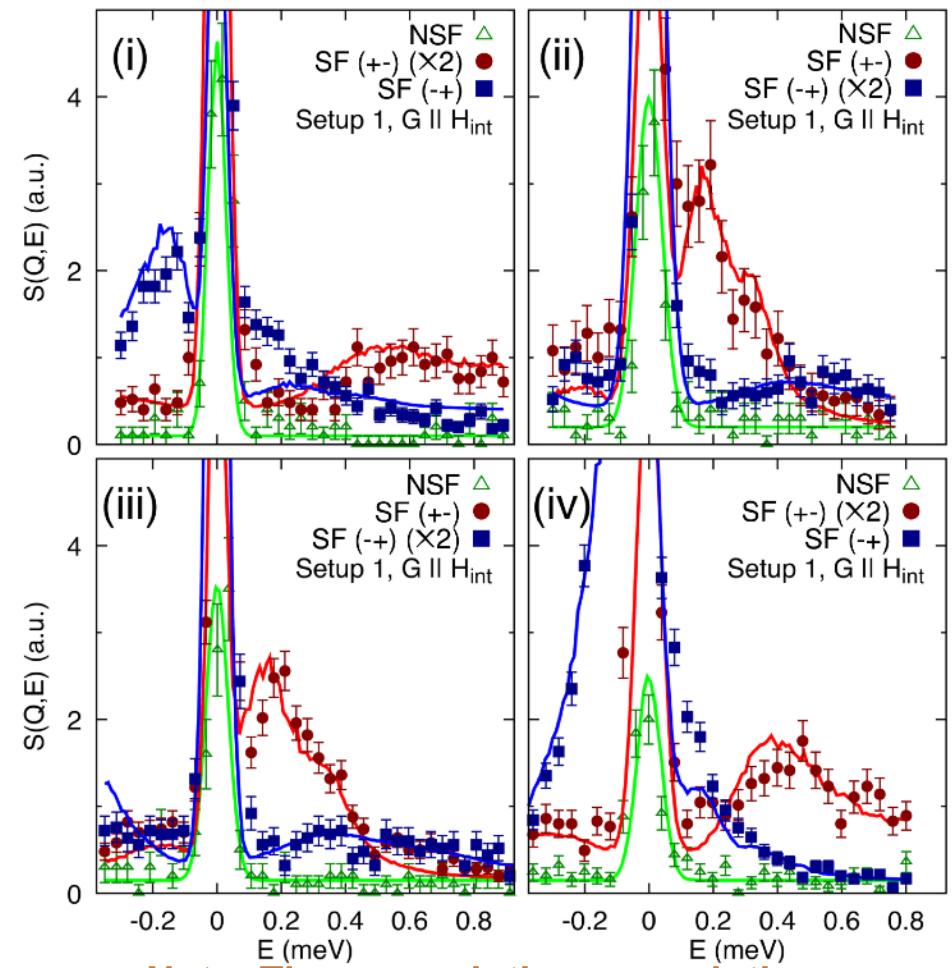
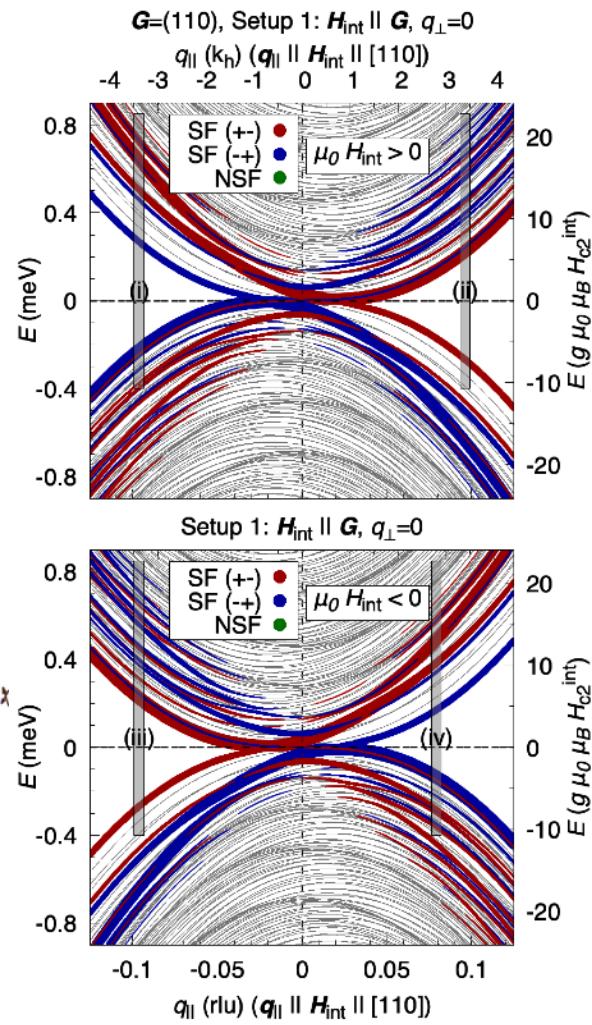
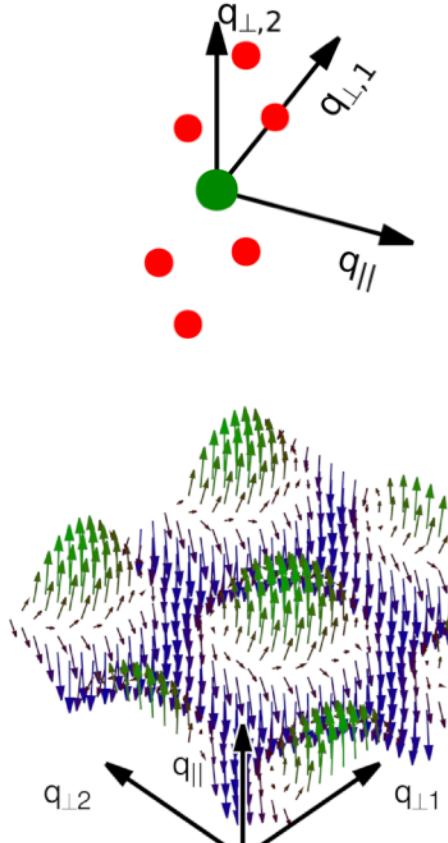
Skyrmion Dynamics – Band Formation

Animation



<https://doi.org/10.5281/zenodo.5718363>

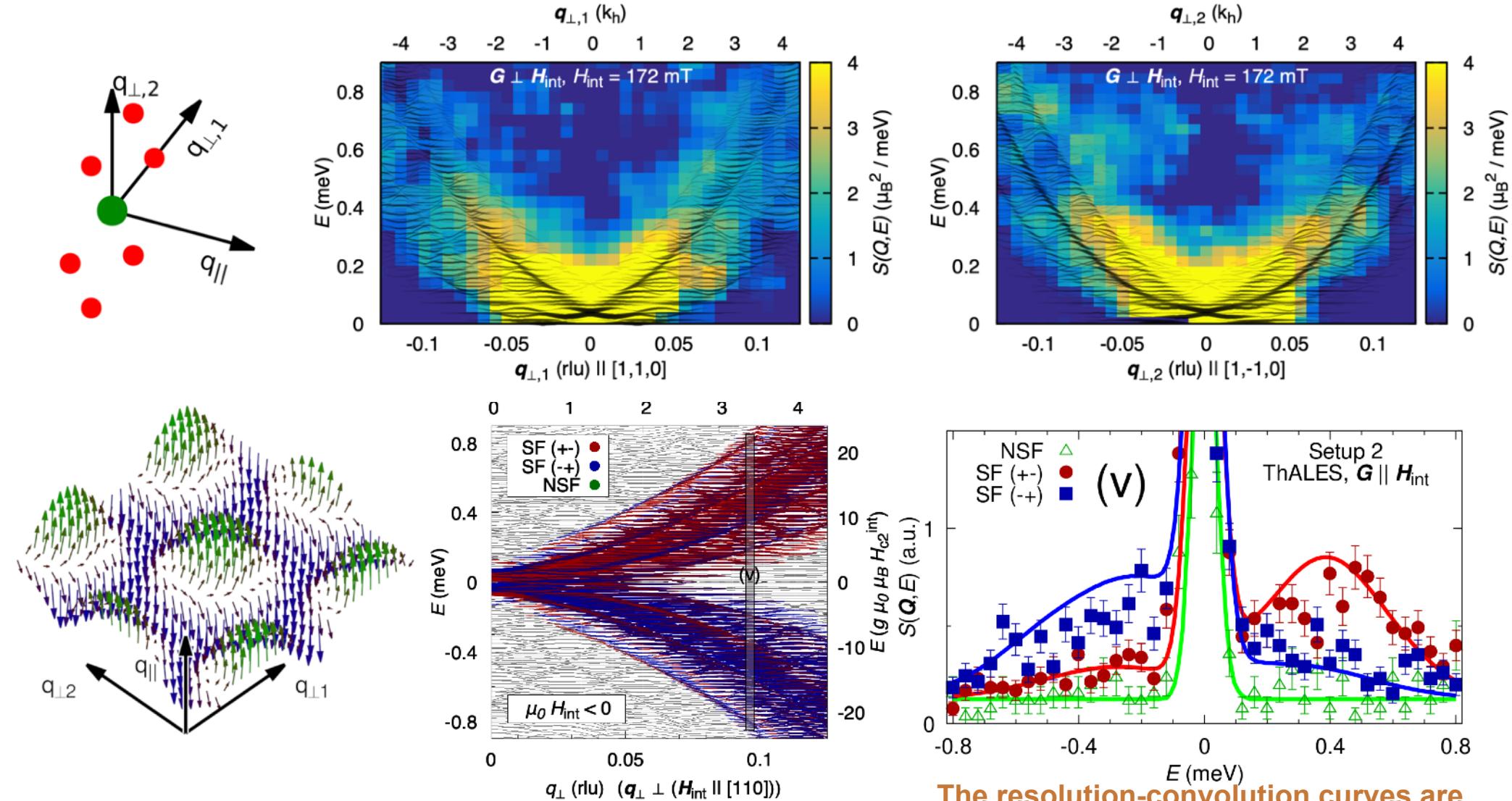
Skyrmion Measurements for $\mathbf{q} \parallel \mathbf{H}$



Science 375 (6584), pp. 1025-1030 (2022).

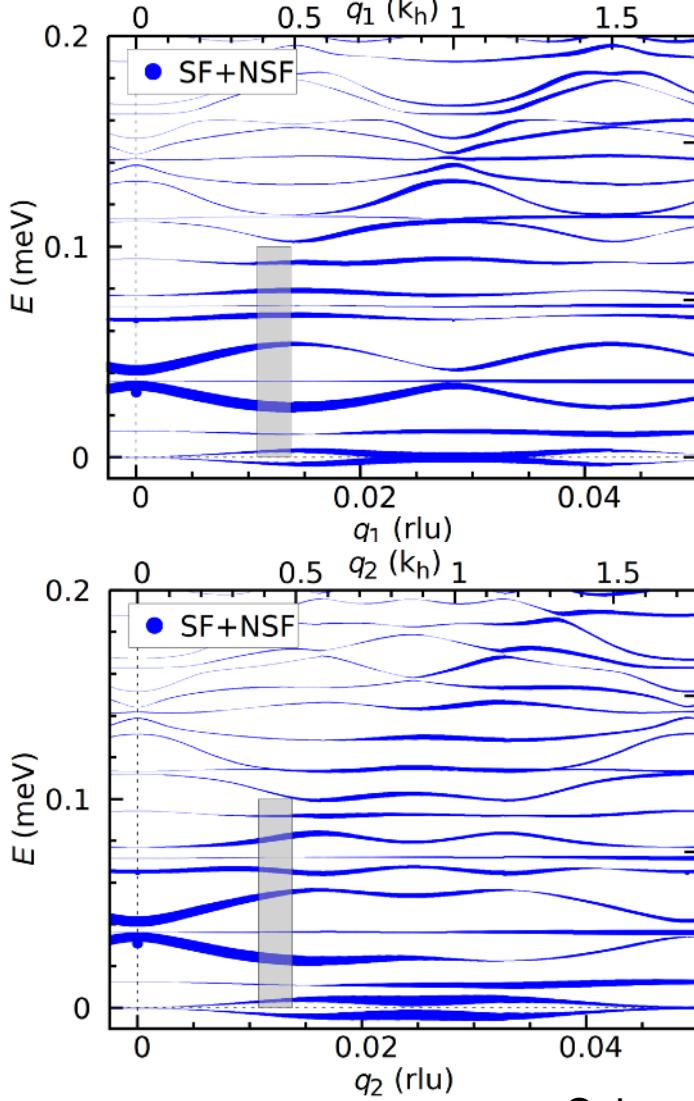
Note: These resolution-convolution curves are preliminary, see the paper for the final results!

Skyrmion Measurements for $\mathbf{q} \perp \mathbf{H}$

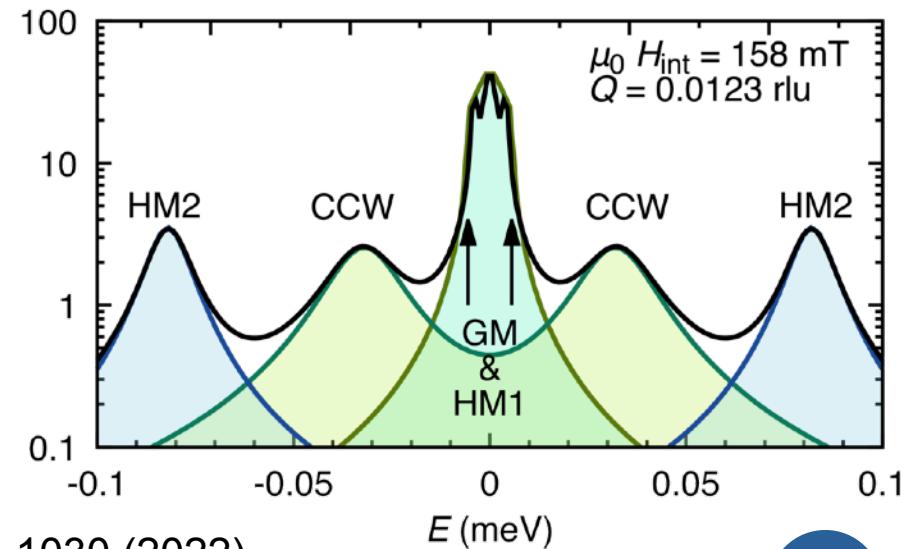
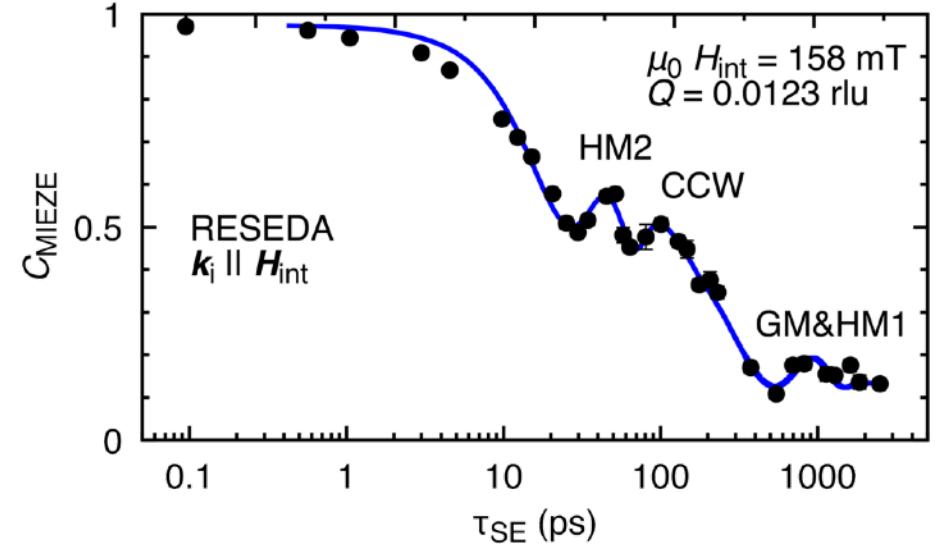
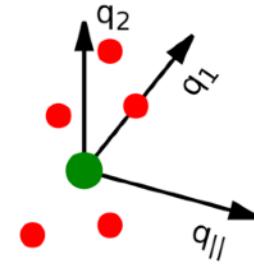


The resolution-convolution curves are preliminary, see paper for final results!

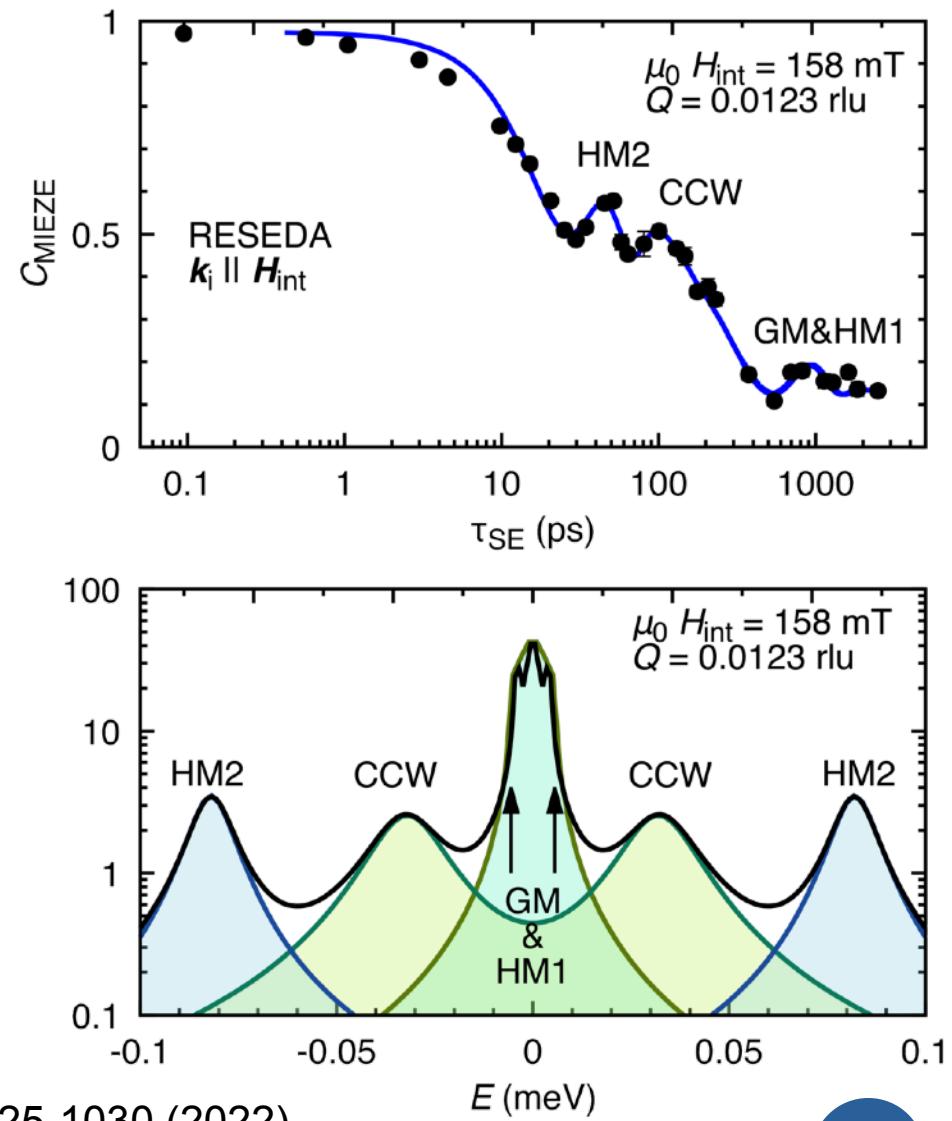
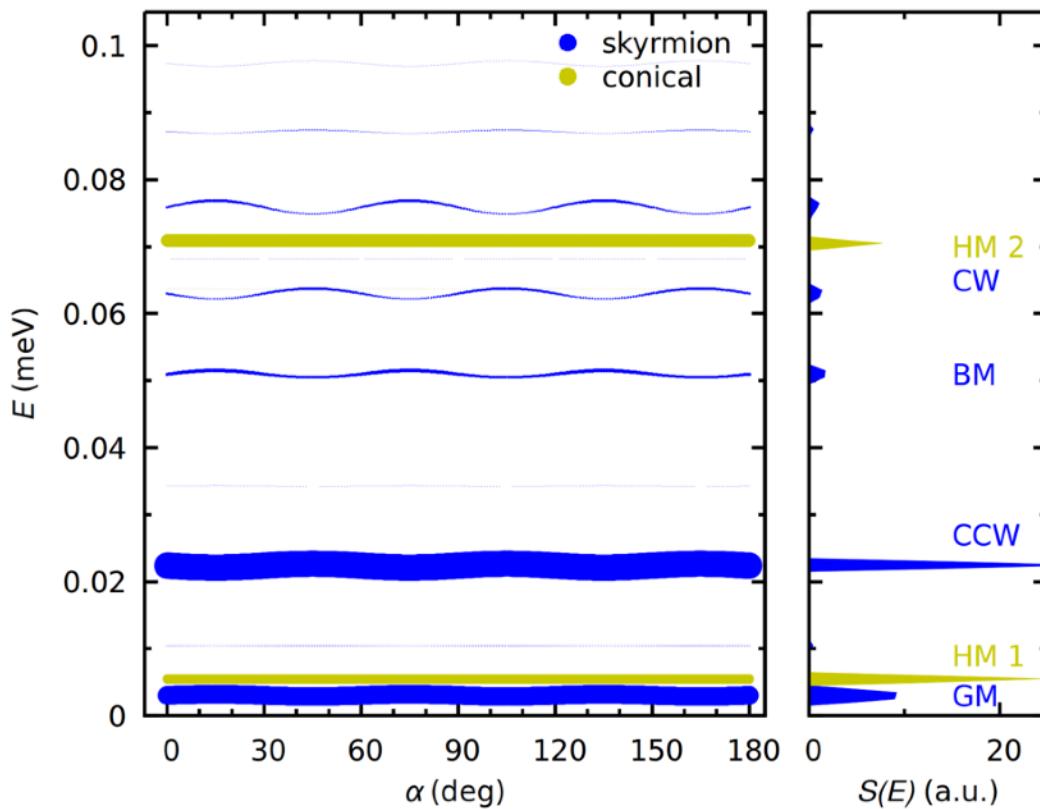
Low-q Skyrmion Measurements



$$E (g \mu_0 \mu_B H_{c2}^{\text{int}})$$



Low-q Skyrmion Measurements



Summary

- We performed comprehensive studies on the magnetic skyrmion dynamics in MnSi.
- $\mathbf{q} \parallel \mathbf{H} \Rightarrow$ asymmetric spectra.
- $\mathbf{q} \perp \mathbf{H} \Rightarrow$ symmetric Landau levels.
- Resolution-corrected data show excellent match between theory and experiments.
- Skyrmion dynamics are similar to single-helix dynamics.

**Thank you
for your attention!**

References and Links

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