Emergence, Nucleation and Stability of Skyrmion Lattice Order

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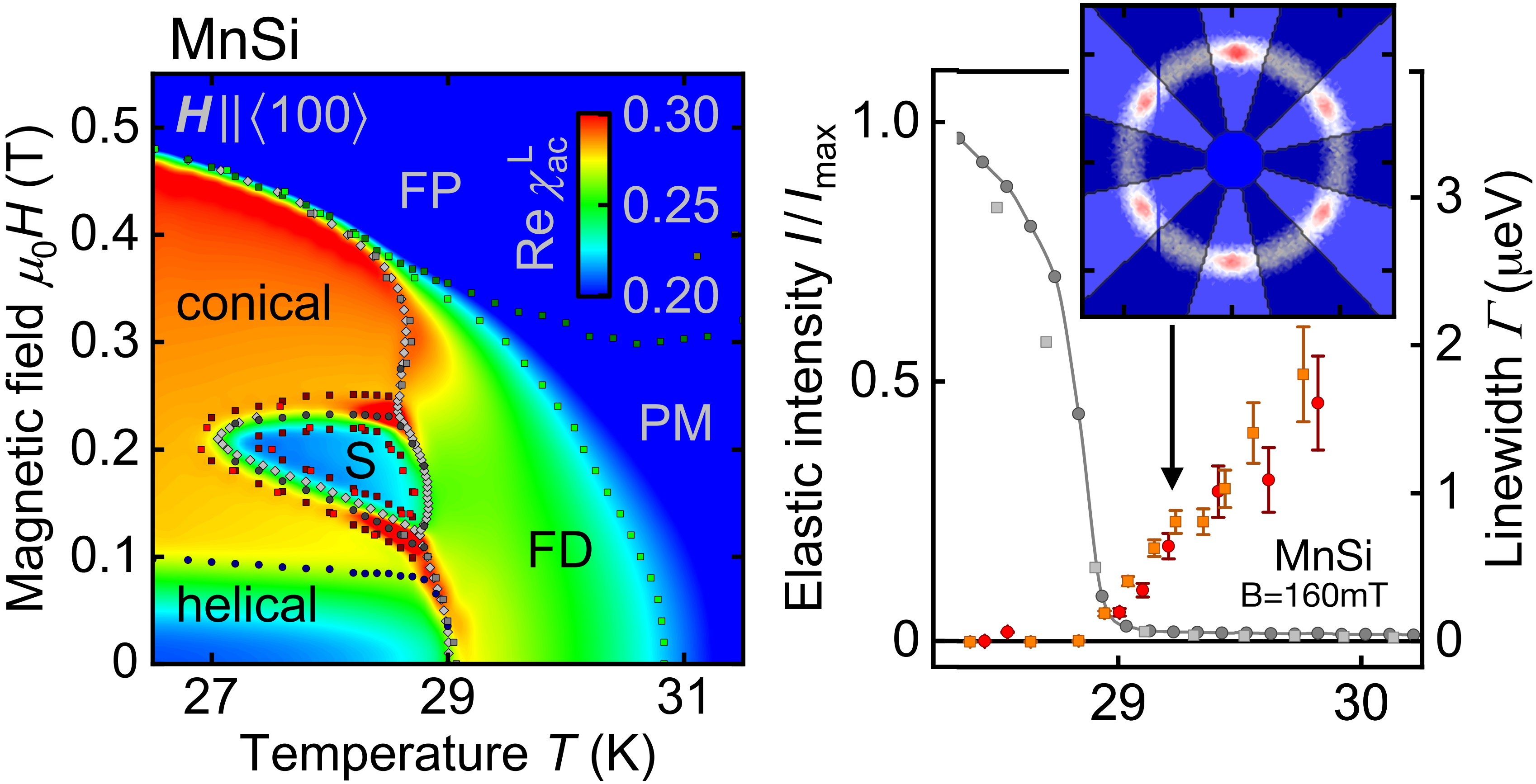
Outline

- Part 1: Results I will not talk about.
- Part 2: Results I will talk about.

Focus of this Talk

Weak Crystallization of Fluctuating Skyrmion Textures



Kindervater et al., arXiv 1911.05095 (2019)

Collaborations

samples &
bulk properties

A. Bauer
F. Rucker

microwaves

I. Stasinopoulous
D. Grundler*

neutron scattering

J. Kindervater
F. Haslbeck
A. Chacon
S. Mühlbauer
C. Franz

theory

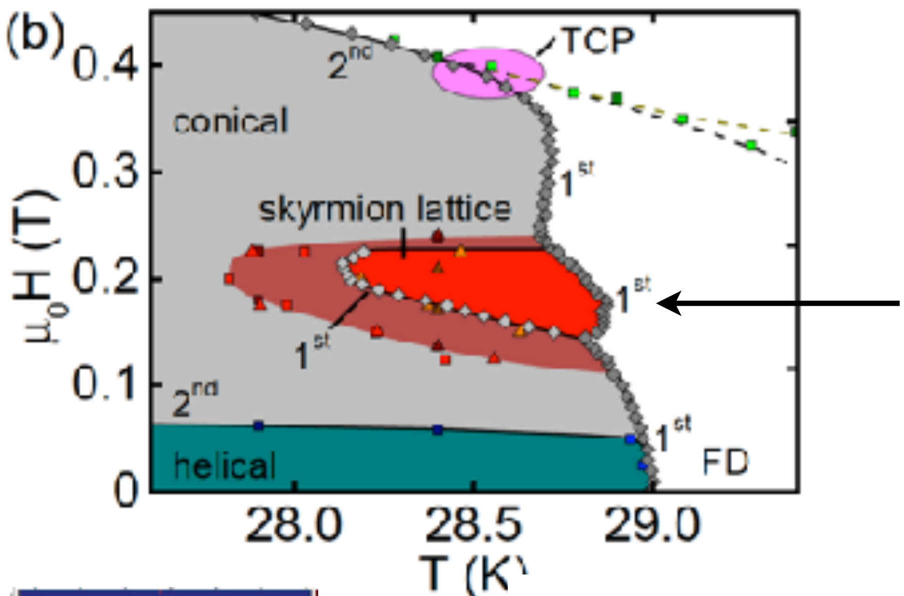
M. Garst**

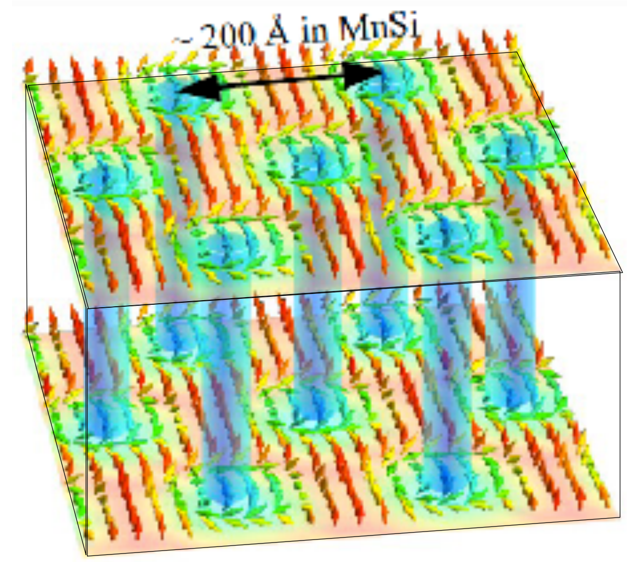
*Lausanne

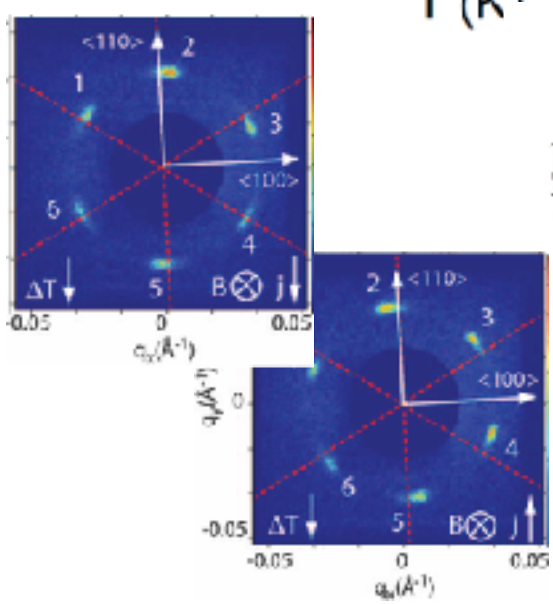
**Karlsruhe

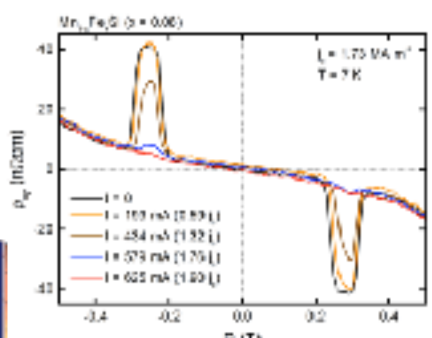
Part 1
Results I will not talk about.

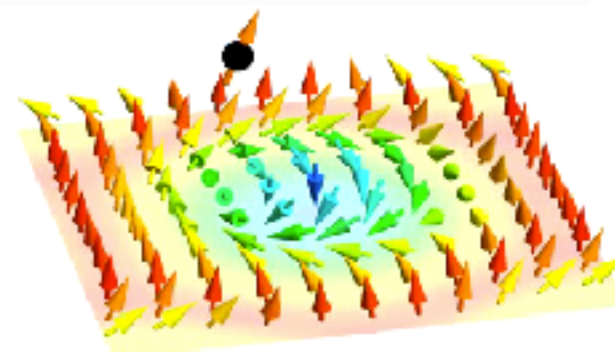
Skyrmion lattice and emergent electrodynamics in MnSi











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

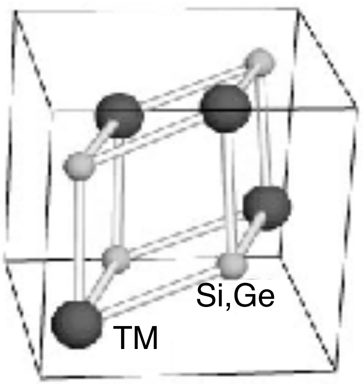
$$\boldsymbol{E}_i^e = \hbar\,\hat{n}\cdot(\partial_i\hat{n}\times\partial_t\hat{n})$$

critical current density: 10^6 A/m^2

Mühlbauer, et al. Science (2009)
Jonietz, et al. Science (2010)
Schulz, et al. Nature Physics (2012)

Hierarchical Energy Scales in B20 compounds

Landau-Lifshitz vol. 8, §52



B20: no inversion center

(1) ferromagnetic exchange

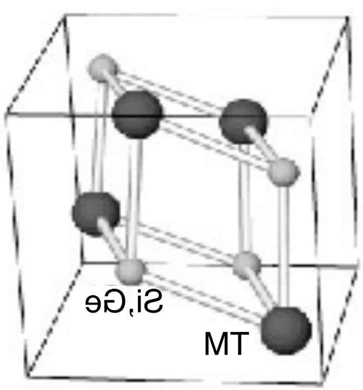
$$\int d^3r\,\left(r_0\vec{M}^2 + J(\nabla\vec{M})^2 + U\vec{M}^4 - \vec{B}\cdot\vec{M}\right)$$

(2) Dzyaloshinsky-Moriya

$$\int d^3r\,\left(2D\,\vec{M}\cdot(\nabla\times\vec{M})\right)$$

(3) crystal fields ($P2_13$)

$$\lambda_1 \sum_q (\hat{q}_x^4 + \hat{q}_y^4 + \hat{q}_z^4)|\vec{m}_{\vec{q}}|^2$$
$$+\lambda_2 \int d^3r\, M_x^4 + M_y^4 + M_z^4$$
$$+\lambda_3 \sum_q \hat{q}_x^2\hat{q}_y^2\hat{q}_z^2\,|\vec{m}_{\vec{q}}|^2 + \dots$$



B20: no inversion center

(*) further terms?

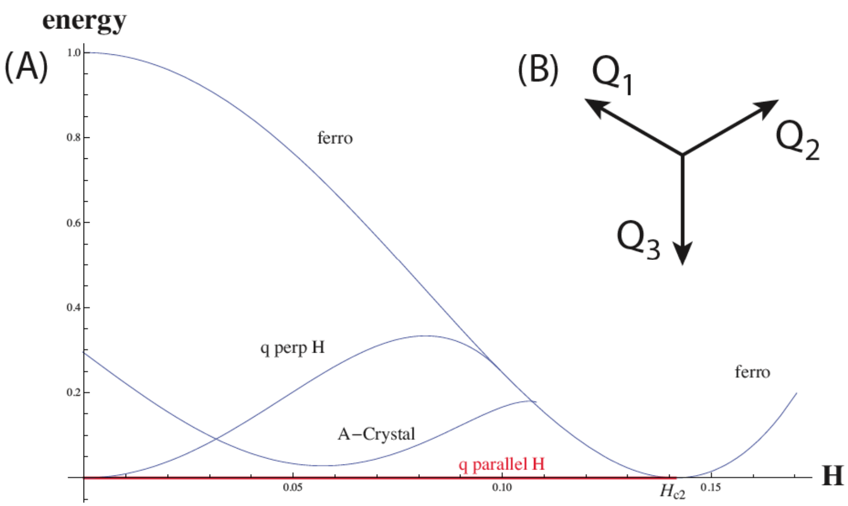
Fluctuation-Stabilized Multi-q Structure

$$F[\mathbf{M}] = \langle r_0 \mathbf{M}^2 + J(\nabla \mathbf{M})^2 + 2D\,\mathbf{M}\cdot(\nabla\times\mathbf{M}) + U\mathbf{M}^4 \rangle$$

$$\propto \langle \mathbf{M}_Q^2\, \mathbf{M}_Q \rangle \cdot \mathbf{m}_0$$

triple-q + uniform M

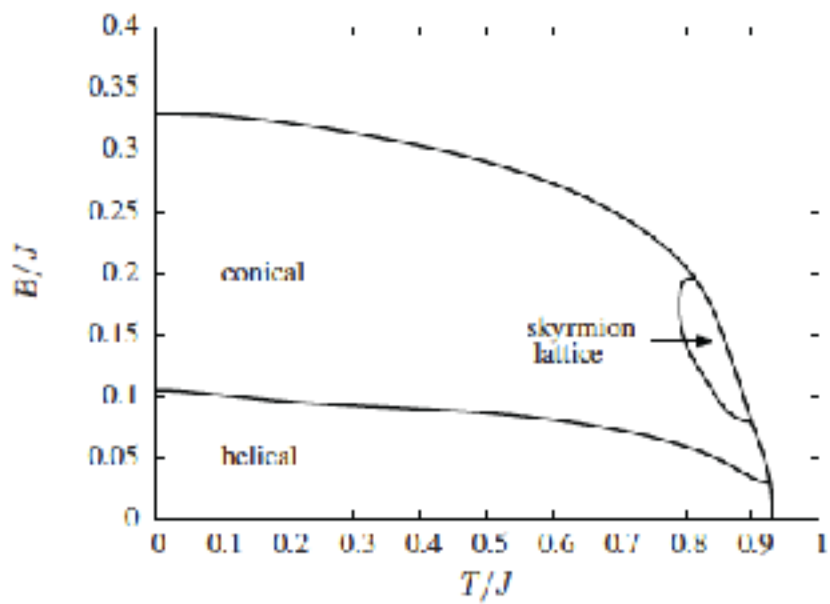
Binz, Vishwanath, Aji PRL (2006)



perp. single-q: **metastable**
triple-q: **metastable**

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

Monte-Carlo
(includes fluctuations)



Buhrandt, Fritz PRB **88**, 195137 (2013)

Zoology of Magnetic-Skyrmion Materials

...

B20 metals & semiconductor

$P2_13$ insulator: Cu_2OSeO_3

$P4_132$ & $P4_332$: $Co_xZn_yMn_z$

$SrFeO_3$, Lacunar Spinels

Sc-doped Ba-Ferrite

Heusler compounds

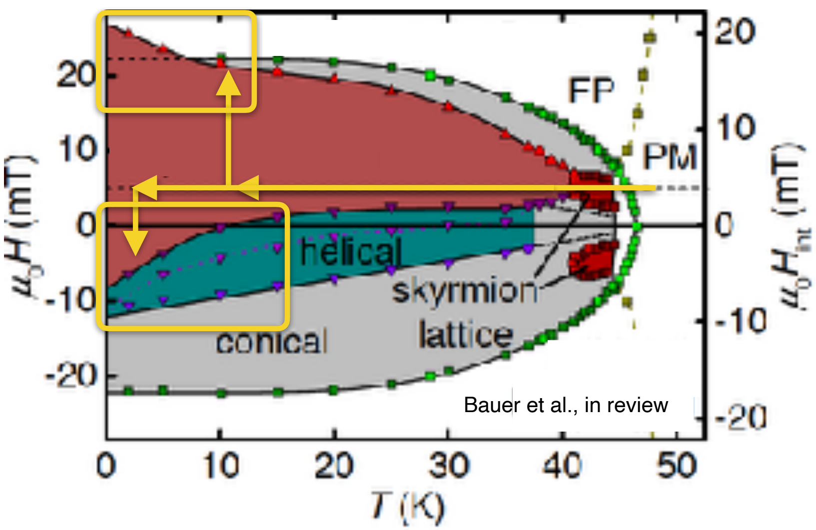
Fe or PdFe-layer on Ir (111)

Heterostructures & Multilayers

http://4.bp.blogspot.com/-23eJwg9ESF0/VI3feW6ysGI/AAAAAAAAAQY/5a5zU4nOMyw/s1600/cartoons+animals.png

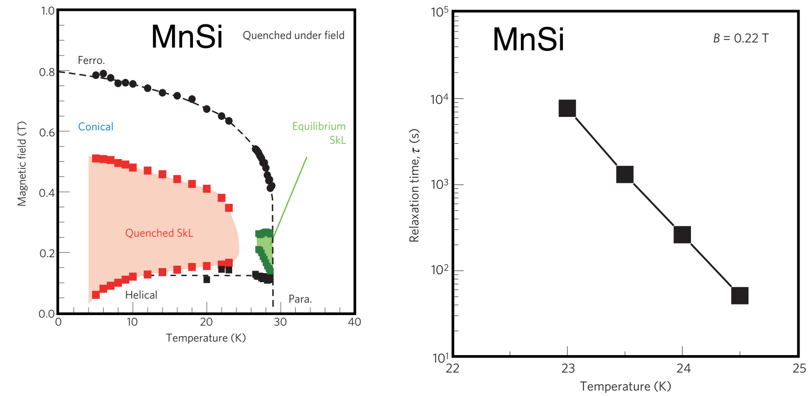
Creation, Stability & Destruction of Skyrmions

unwinding by emergent monopoles

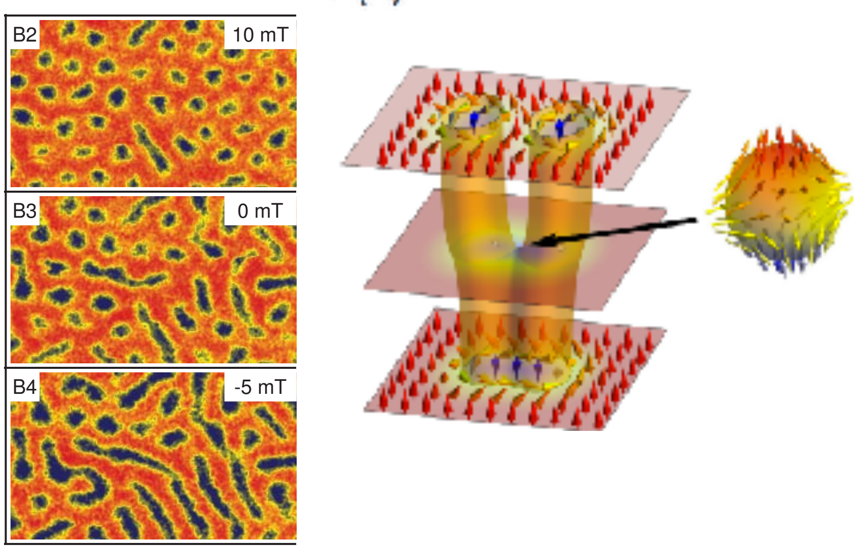


Bauer et al., in review

distribution of energy barriers



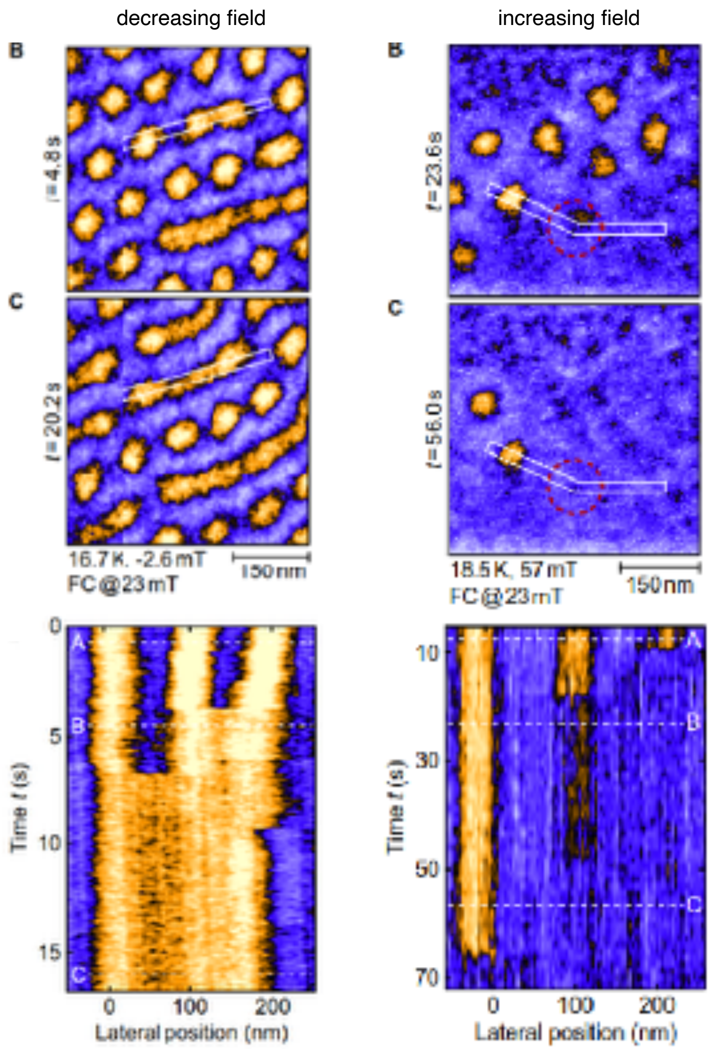
Oike et al, Nature Physics **12**, 62 (2016)



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

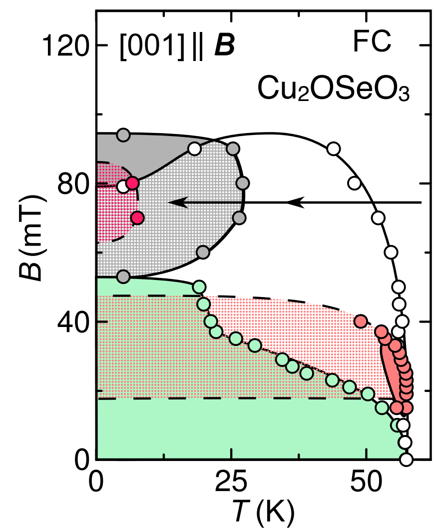
Creation, Stability & Destruction of Skyrmions

extreme entropy compensation



Wild et al., Sci. Adv. **3** e1701704 (2017)

nucleation enabling mechanisms

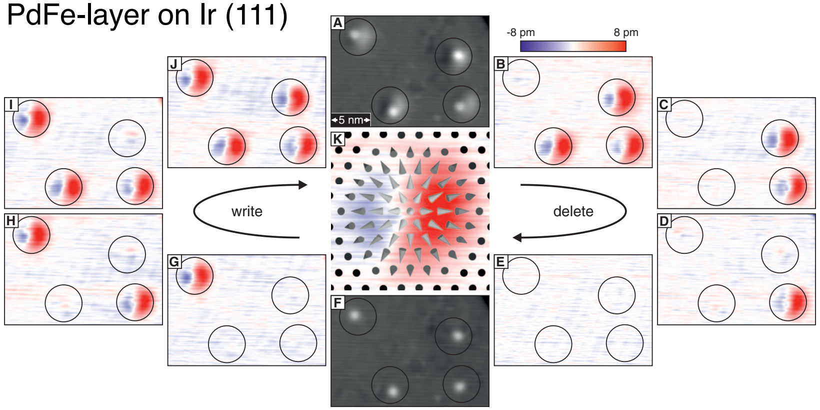


Chacon, et al.
Nat. Phys, **14**, 936 (2018)

Creation, Stability & Destruction of Skyrmions

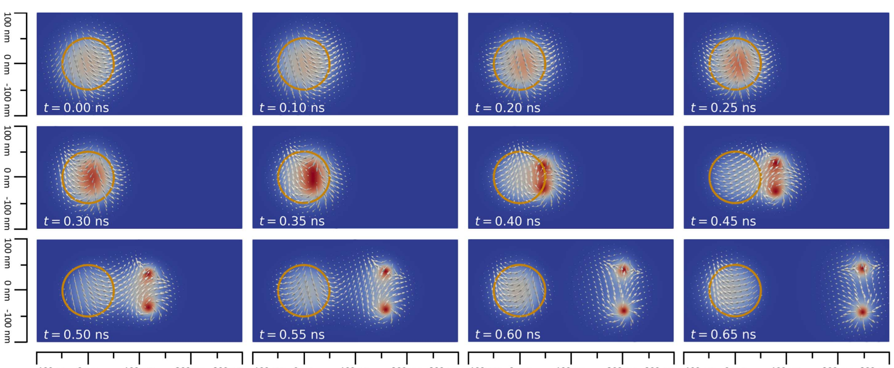
Writing & Deleting Individual Skyrmions

PdFe-layer on Ir (111)



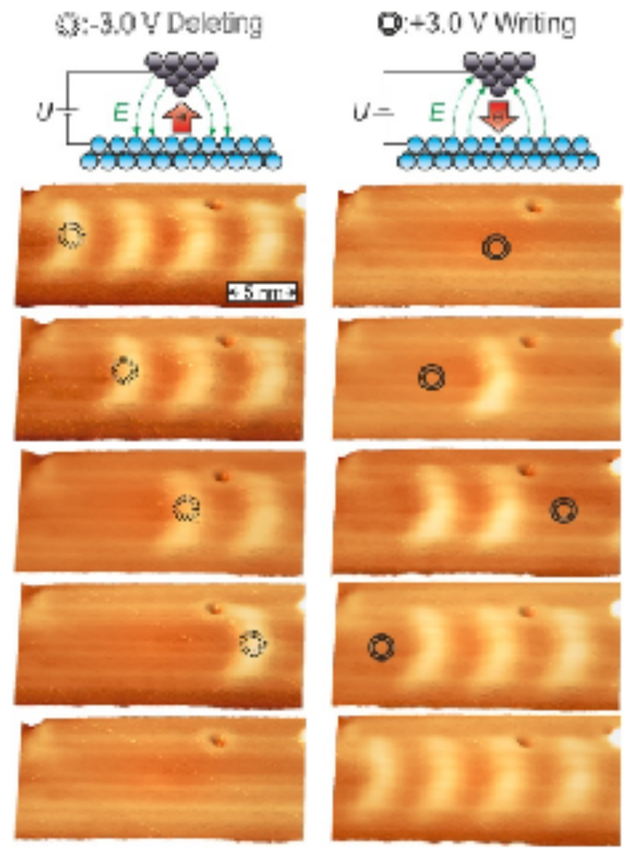
Romming et al. Science **341**, 636 (2013)

Current-Induced Sk-ASk Pair Creation



Everschor-Sitte et al. NJP **19**, 092001 (2017)
cf Stier et al. PRL **118**, 267203 (2017)

Electric Field-Driven Switching



3 layers of Fe on Ir

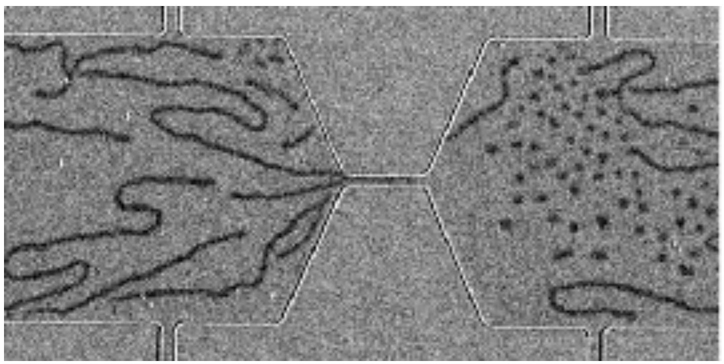
deformation along dislocation lines

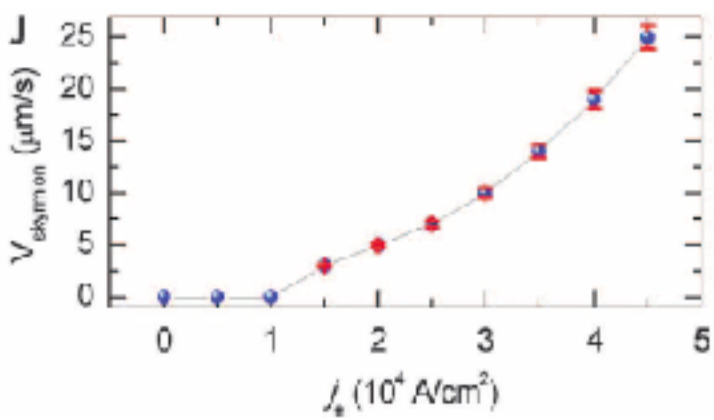
Pin-Jui Hsu et al. Nat. Nano. **12**, 123 (2017)

‚Blowing‘ Skyrmion Bubbles

Skyrmion „Bubbles“ in Trilayers

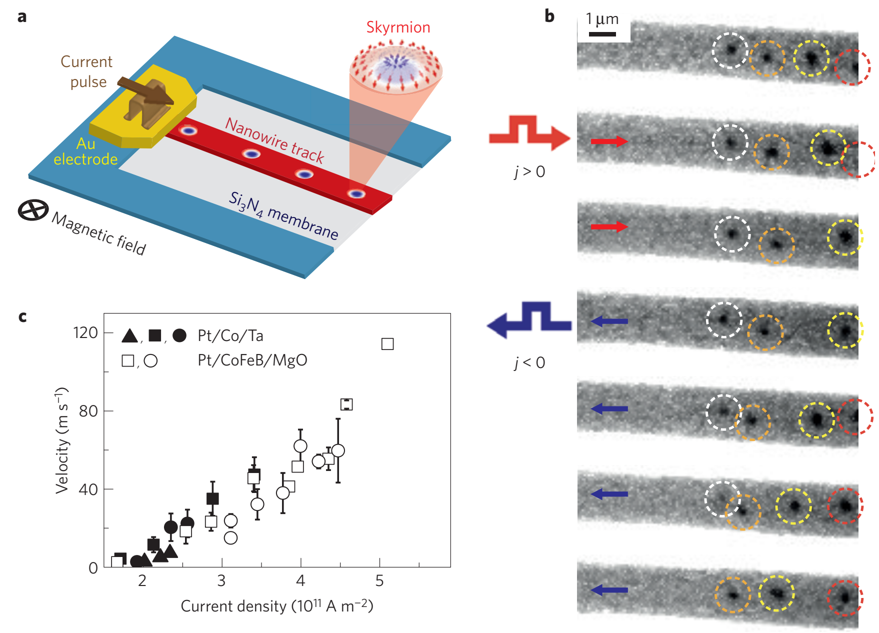
Ta(5nm)/$Co_{20}Fe_{60}B_{20}$(CoFeB)(1.1nm)/TaO_x(3 nm)





Jiang et al. Science **349**, 283 (2015)

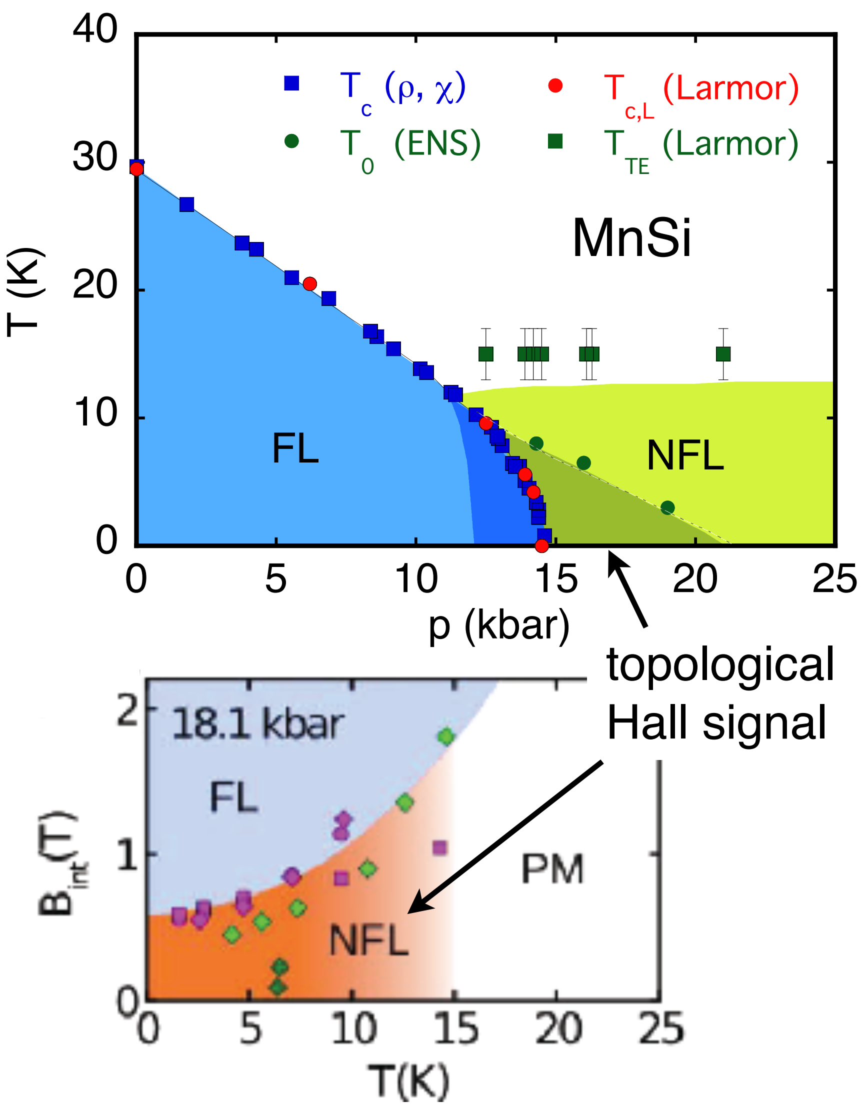
Skyrmion „Bubbles“ in Multilayer Stacks



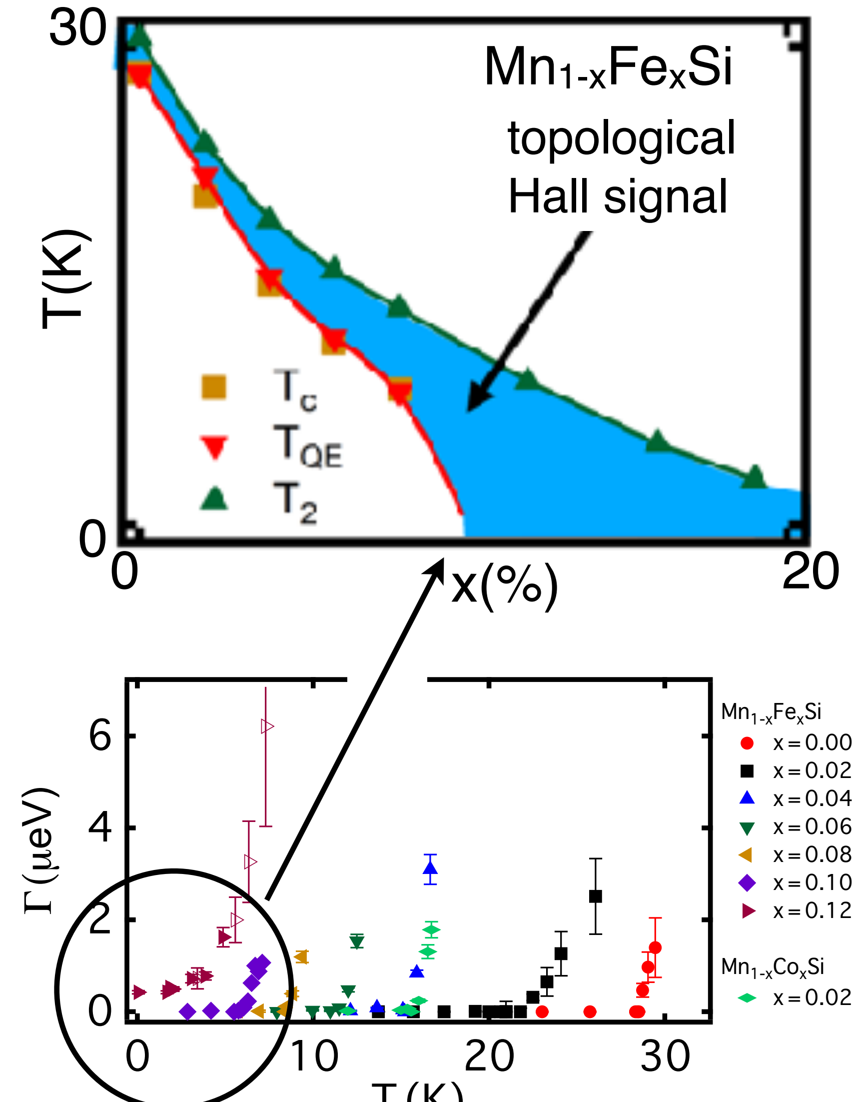
S. Woo et. al, Nature Mater. **15**, 501 (2016)

also: Boulle et al. Nature Nanotechnogy 2016

Topological Hall effect in paramagnetic MnSi and $Mn_{1-x}Fe_xSi$

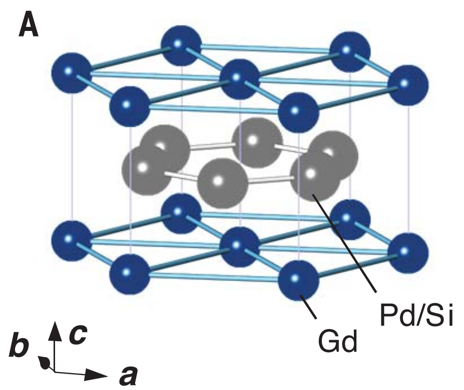


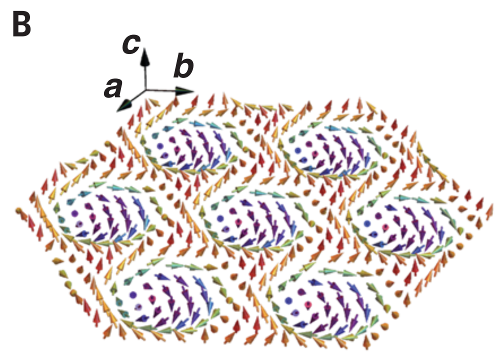
Ritz, et al., Nature **497**, 231 (2013) & PRB **87**, 134424 (2013)

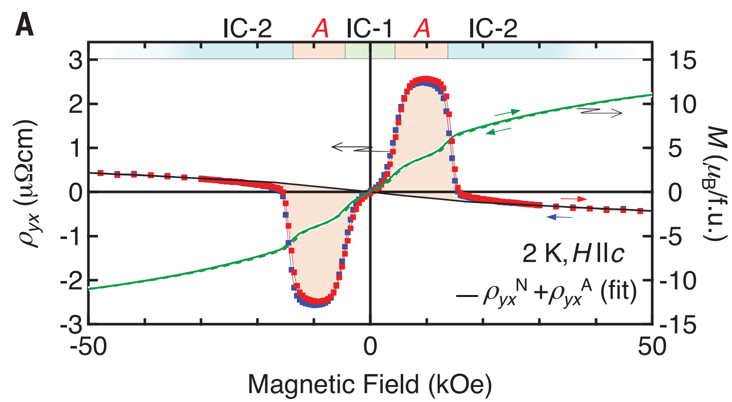


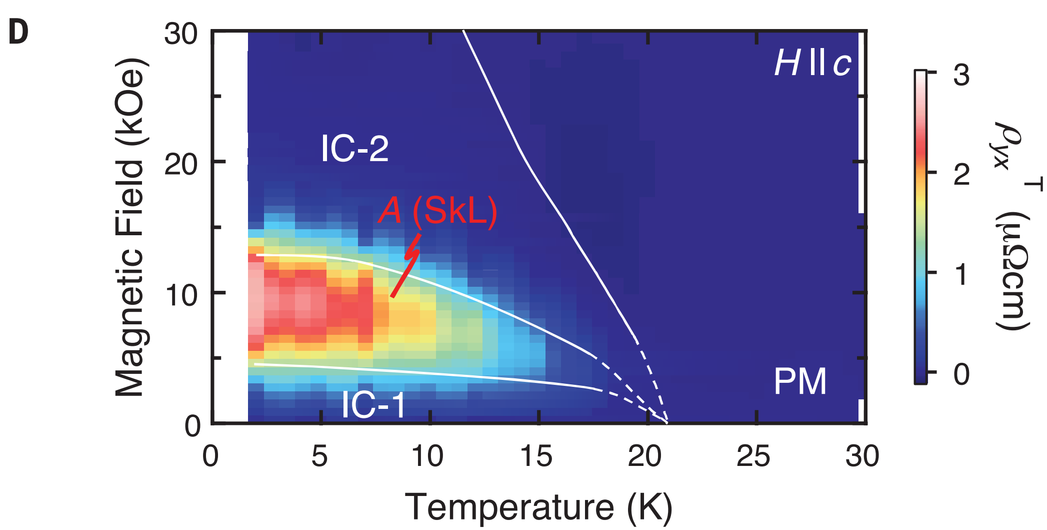
cf. Franz, et al. PRL **112** 186601 (2014)

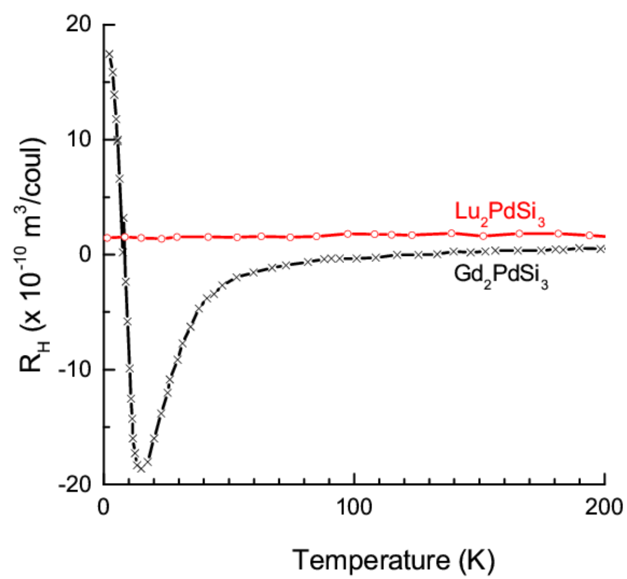
Skyrmion Lattice in Gd_2PdSi_3











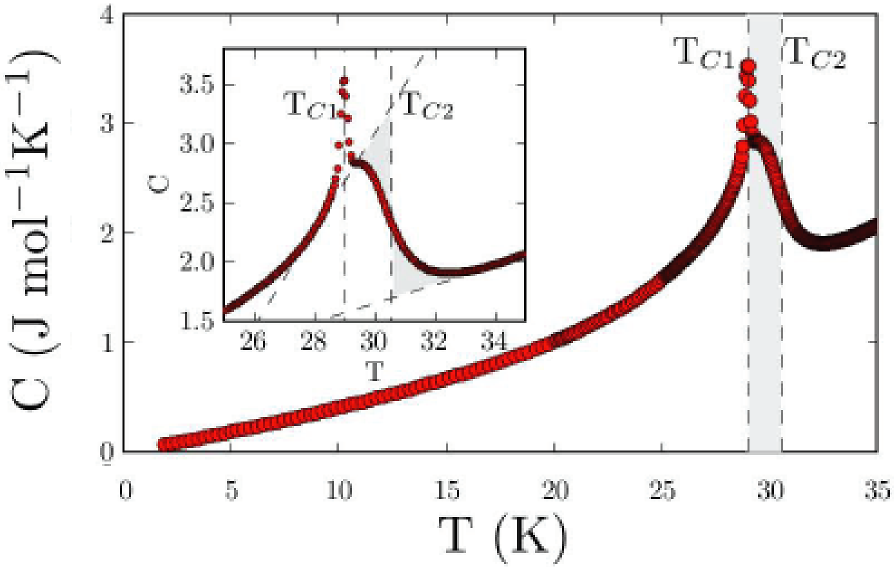
Kurumaji, et al. Science **365** 914 (2019)

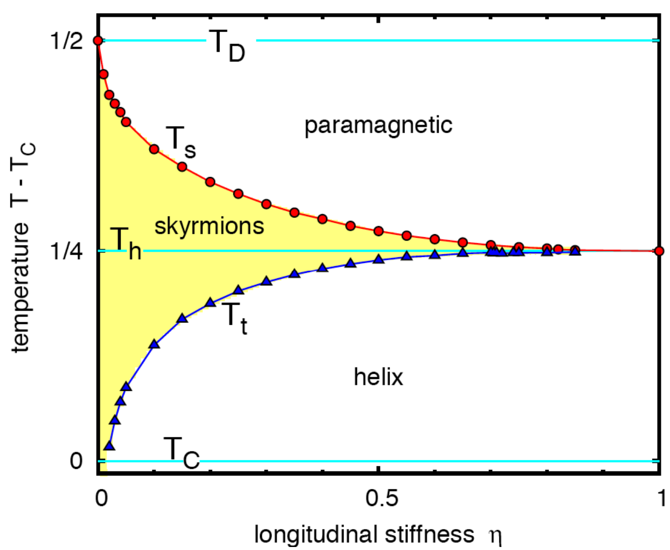
Sampathkumaran et al. arXiv/1910.09194
& series of papers around 1999

Part 2
Results I will talk about

Fluctuation-Induced First Order Transition

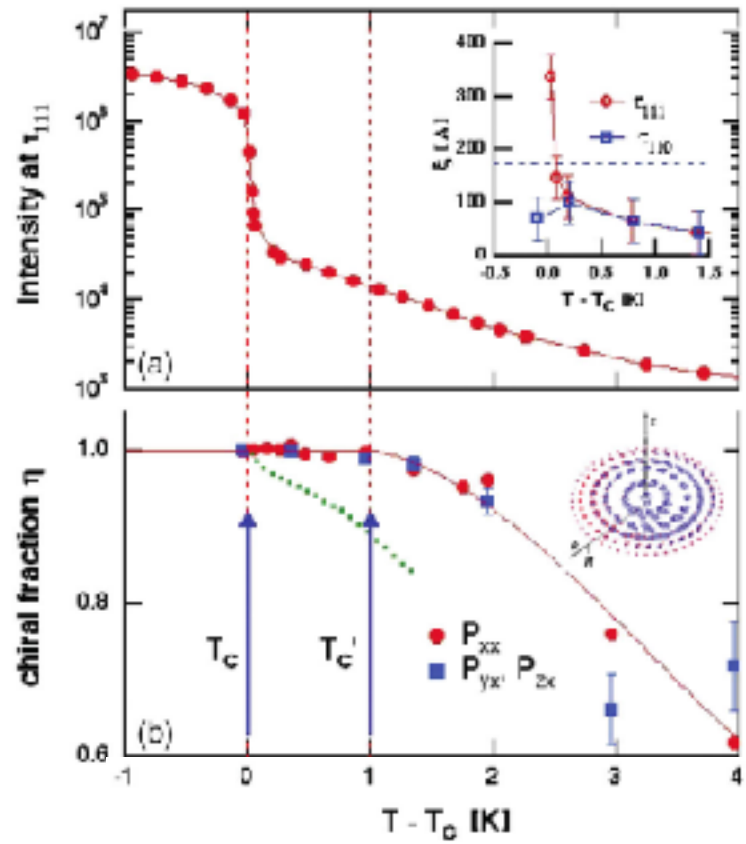
Prediction of a Spontaneous Skyrmion Phase





Rößler, Bogdanov, CP, Nature **442**, 797 (2006)

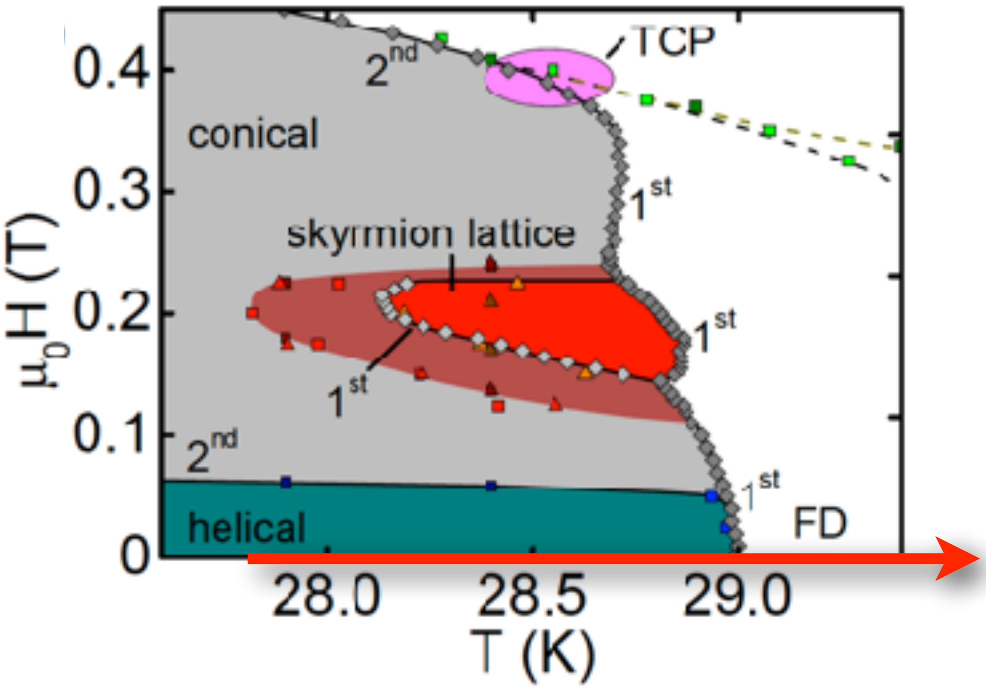
claim of a skyrmion liquid

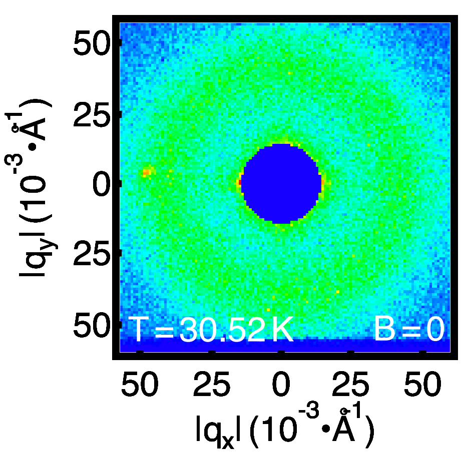


Pappas et al., PRL **102**, 197202 (2009)

cf Hamann et al., PRL **107**, 037207 (2011)

Magnetic Phase Diagram of MnSi





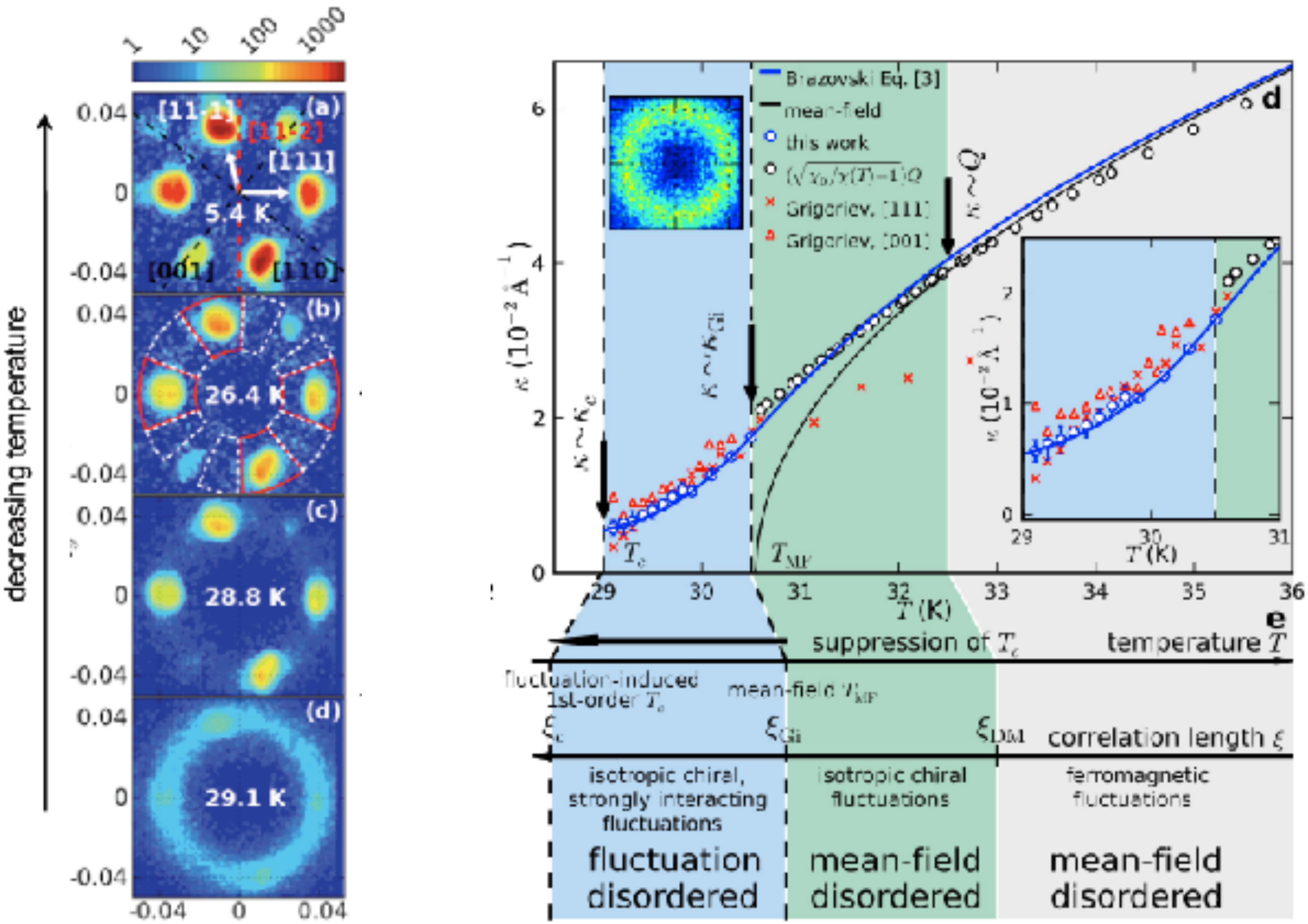
fluctuation-induced 1^{st} order

Janoschek et al.,
PRB **87**, 134407 (2013)

Brazovskii,JETP (1975)

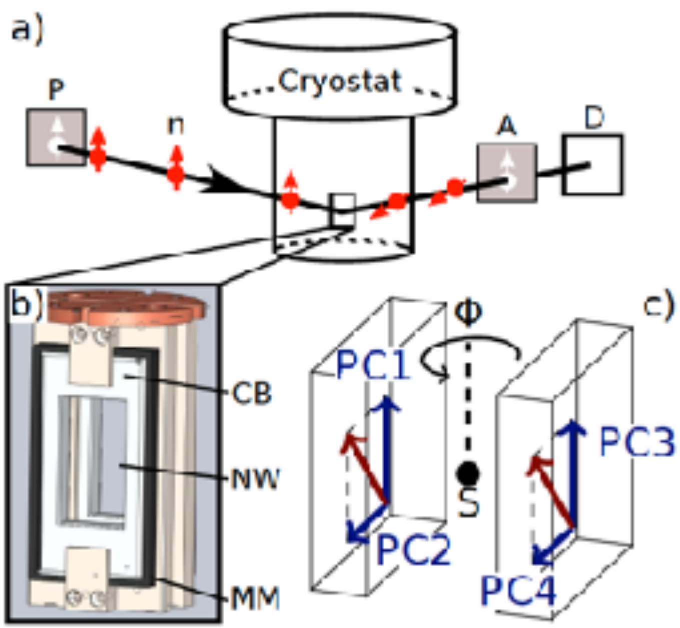
Fluctuation-Induced First Order Transition

a helimagnetic Brazovskii transition



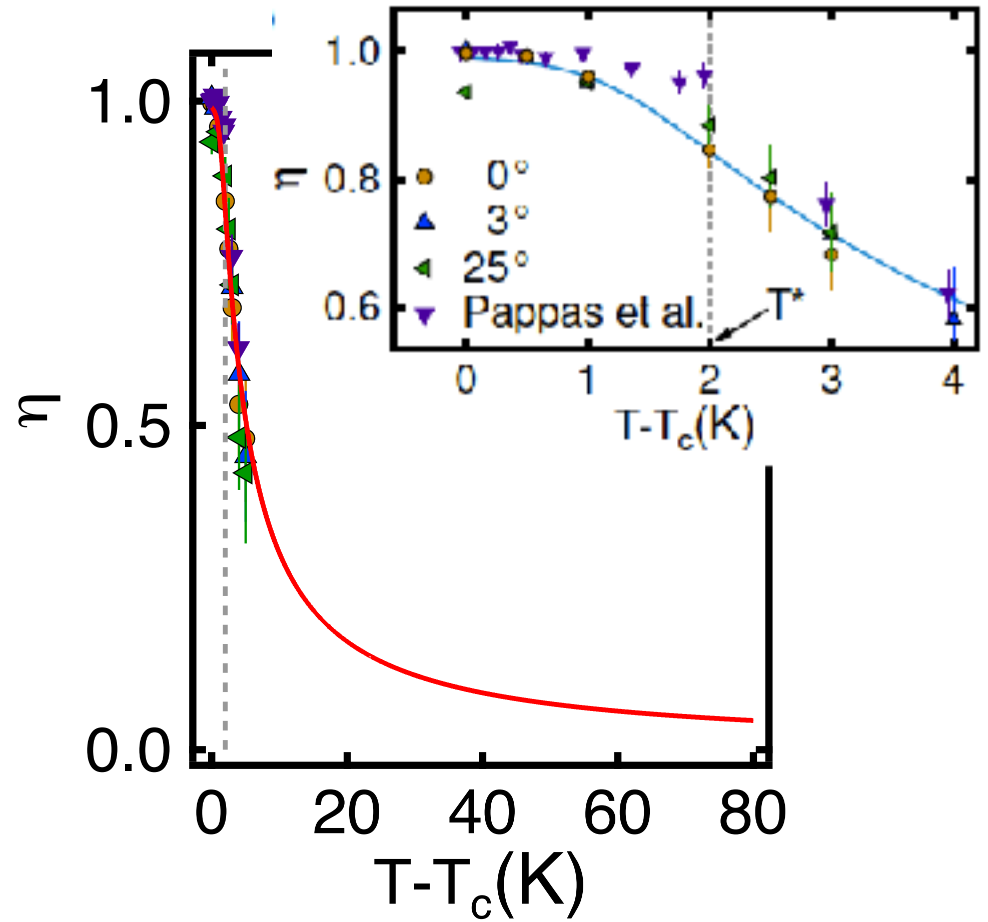
M. Janoschek, M. Garst et al. PRB **87**, 134407 (2013)

Chiral Fraction Revisited



experiment @ RESEDA, FRM II

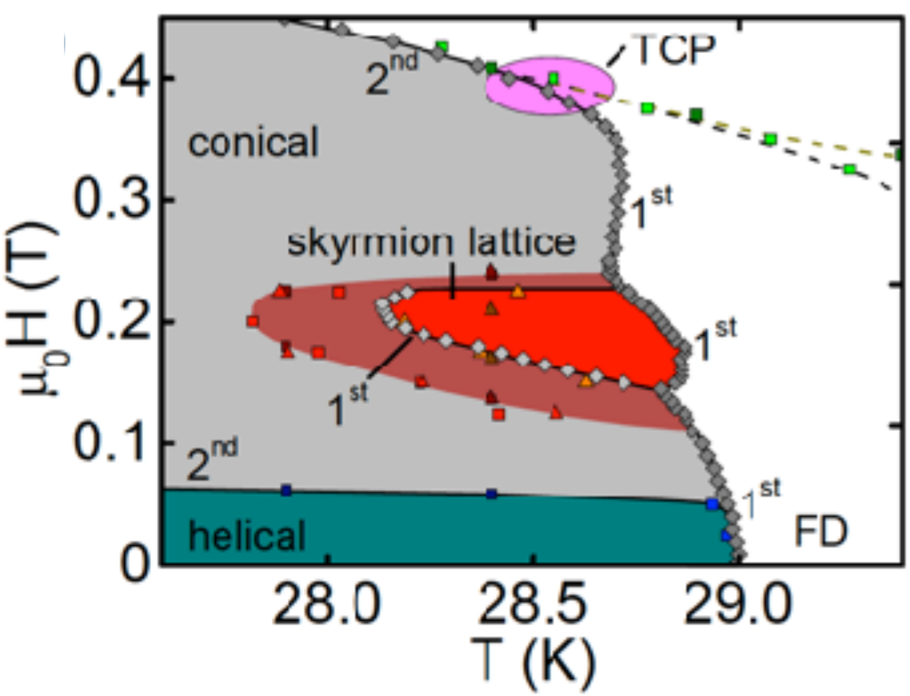
$$\eta = \frac{\sigma^A_{\mathrm{mag}}(\mathbf{k})}{\sigma^S_{\mathrm{mag}}(\mathbf{k})} = \frac{1}{1+\kappa^2(T)/(2k^2)}$$



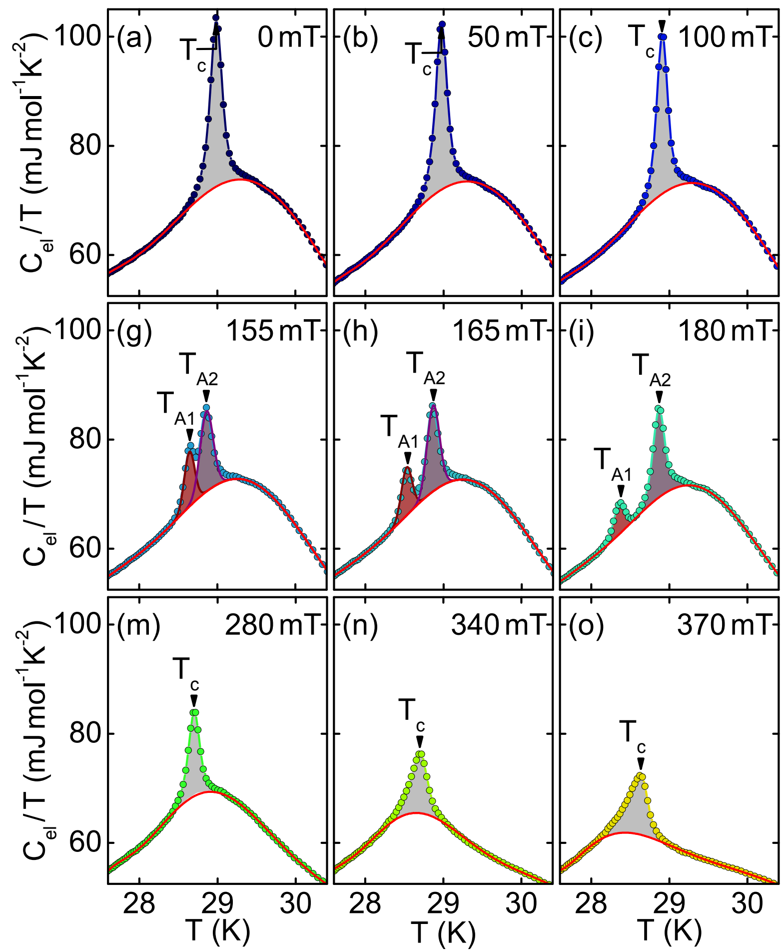
Kindervater et al., PRB **89**, 180408 (2014)

see Pappas et al., PRL **102**, 197202 (2009)

Magnetic Phase Diagram of MnSi



specific heat



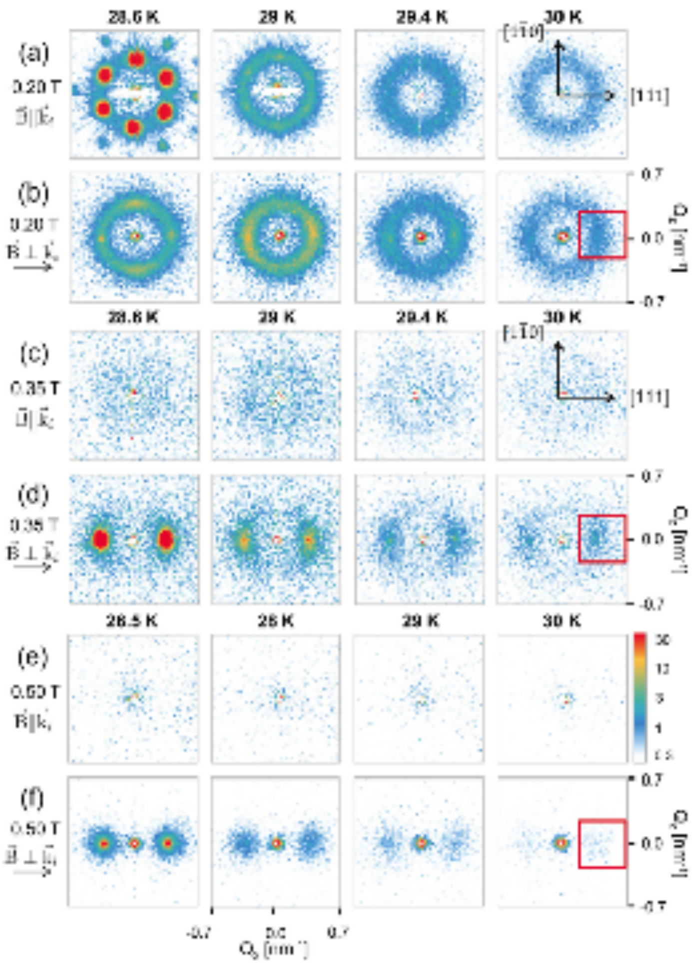
Bauer, Garst, CP, PRL **110**, 177207 (2013)

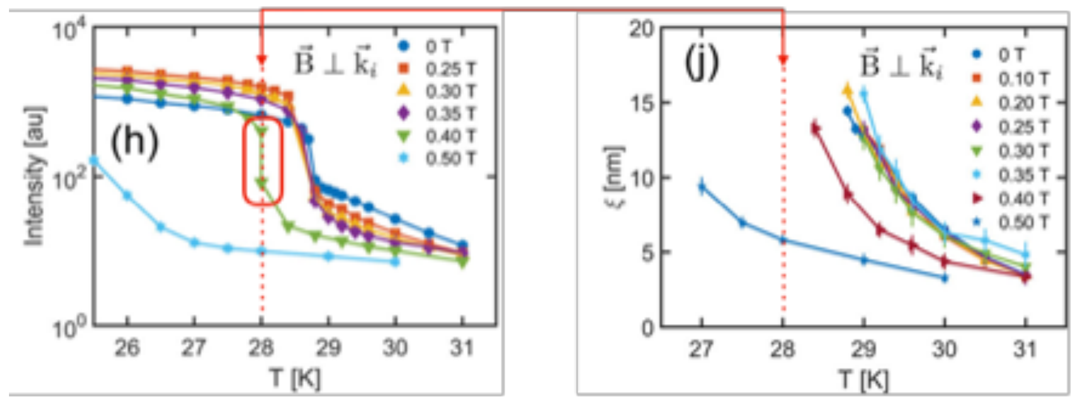
cf. ultrasound absorption

Nii et al., PRL **111**, 267203 (2014)

Magnetic Fluctuations, Precursor Phenomena, and Phase Transition in MnSi under a Magnetic Field

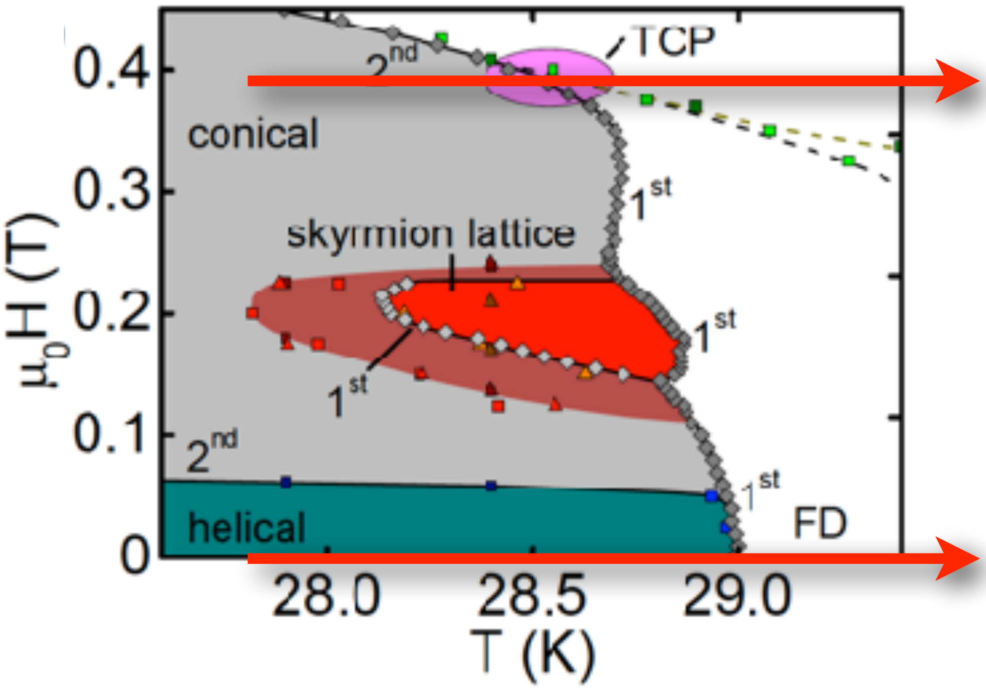
C. Pappas,[1,*] L. J. Bannenberg,[1] E. Lelièvre-Berna,[2] F. Qian,[1] C. D. Dewhurst,[2] R. M. Dalgliesh,[3] D. L. Schlagel,[4] T. A. Lograsso,[4] and P. Falus[2]

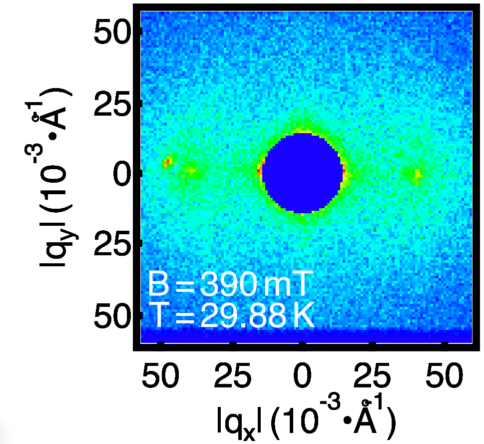




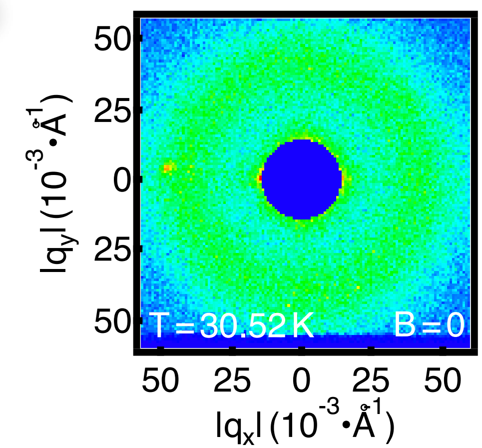
To conclude, neutron scattering does not provide any indication for the existence of a tricritical point separating a first order transition, at low magnetic fields, from a second order one at high magnetic fields. The transition remains of first order under magnetic field and is disconnected from the precursor fluctuating correlations above T_C. These phenomena, which are both of general relevance to chiral magnetism, are thus not accounted for by the Brazovskii approach. Their understanding remains an open question calling for novel theoretical approaches in the future.

Magnetic Phase Diagram of MnSi





tricritical



fluctuation-induced 1^{st} order

Janoschek et al., PRB **87**, 134407 (2013)

Brazovskii, JETP (1975)

Magnetic Phase Diagram of MnSi

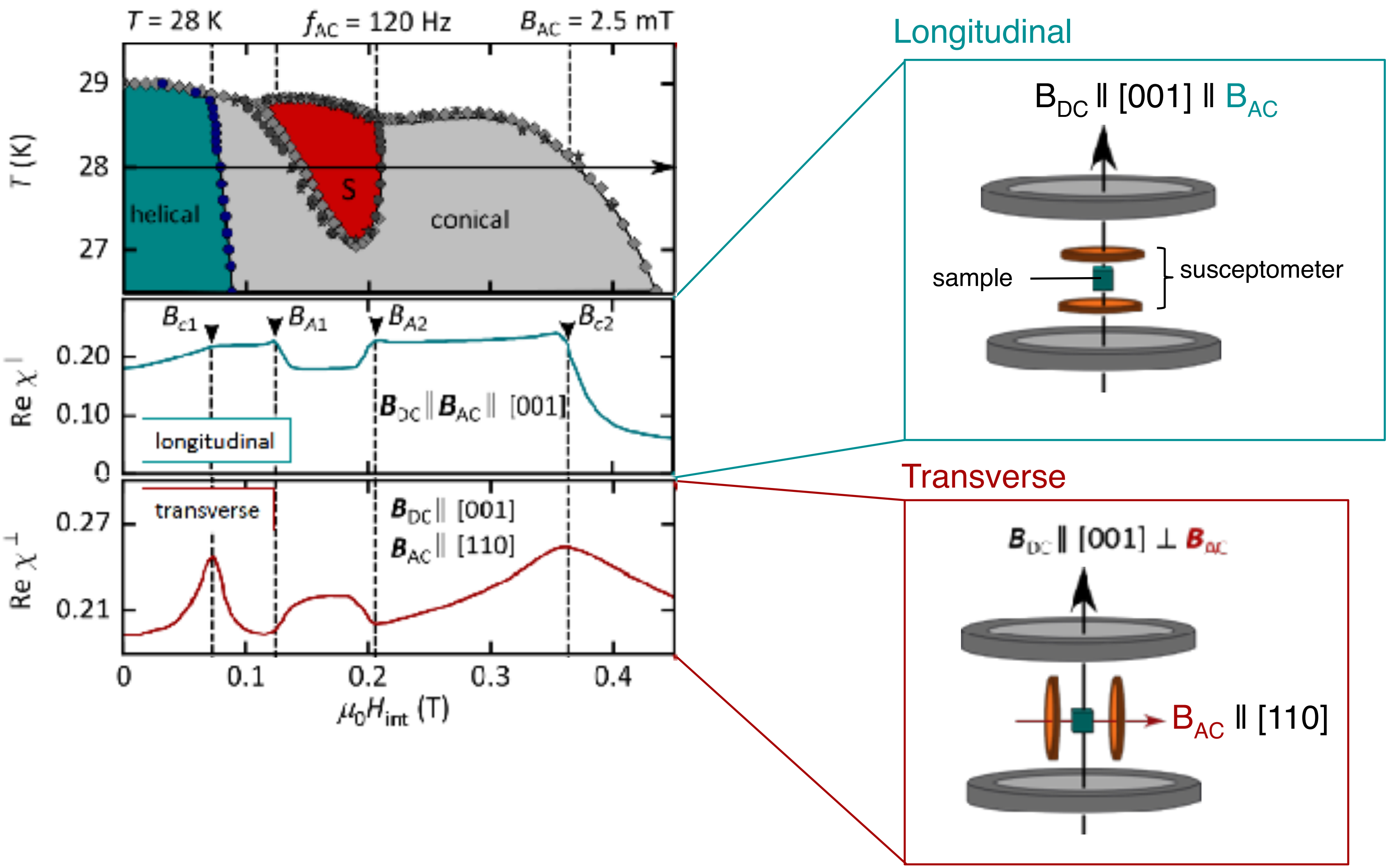
contrasts: Pappas et al., PRL **119**, 047203 (2017)

measurements @ SANS-1 & RESEDA, FRM II

Weak Crystallization of Fluctuating Skyrmion Textures

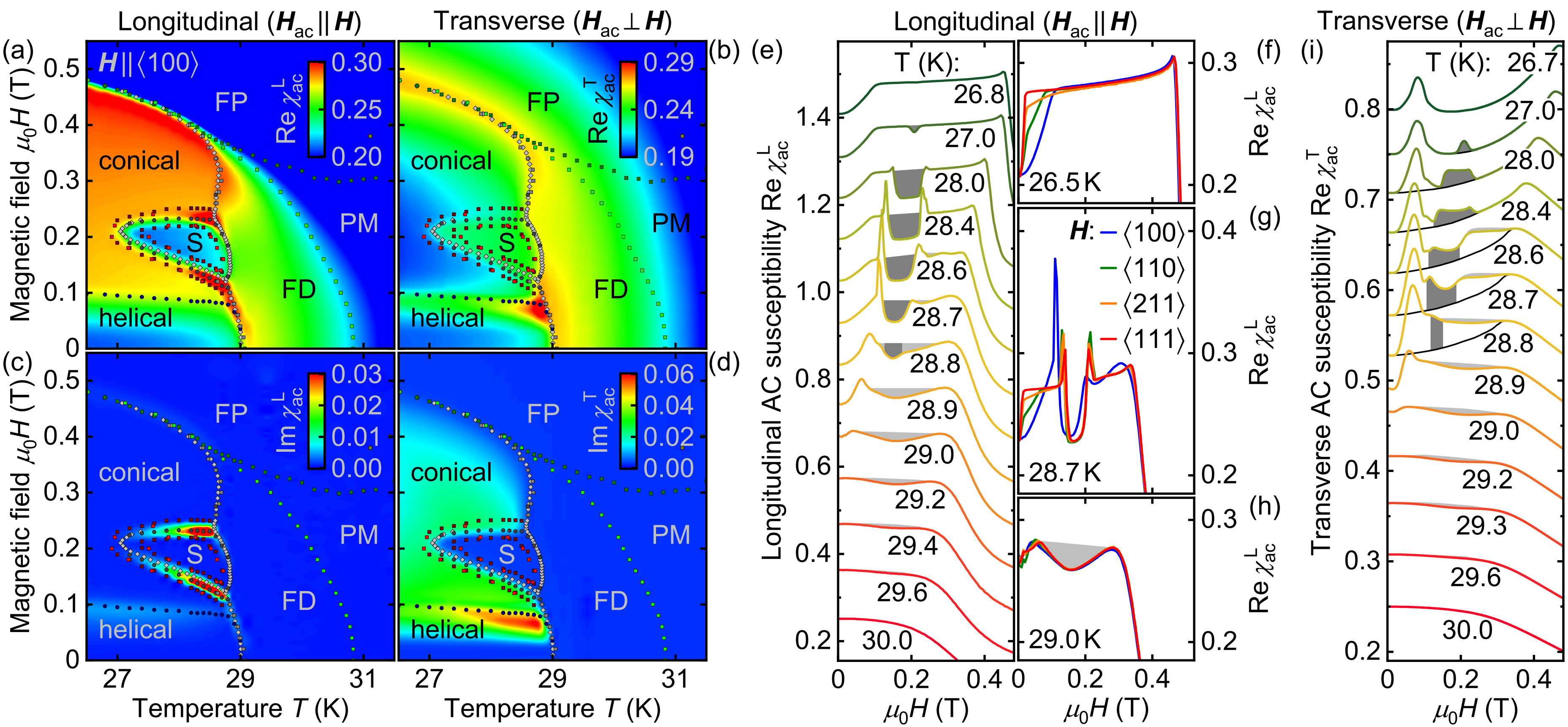
Precursor Phenomena
in Bulk Properties?

Note on the Susceptibility Across Different Phases



geometrically required to search for STT

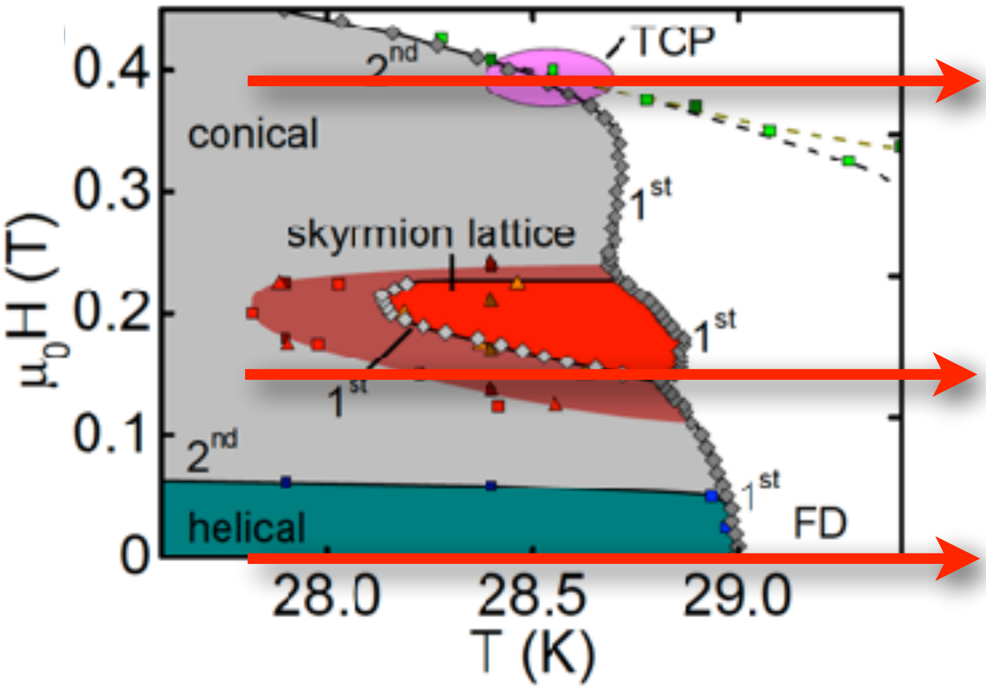
Temperature and Field Dependence of the Susceptibility



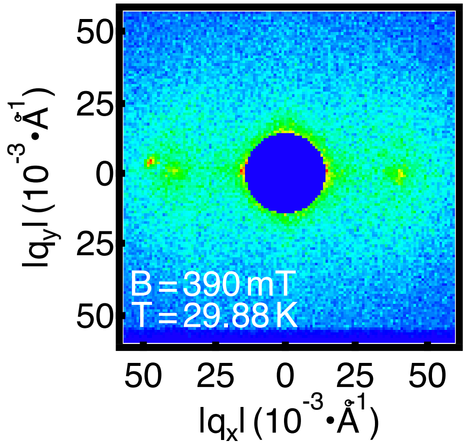
Kindervater et al., arXiv 1911.05095 (2019)

Microscopic Nature of the Precursor Phenomena in the Bulk Properties?

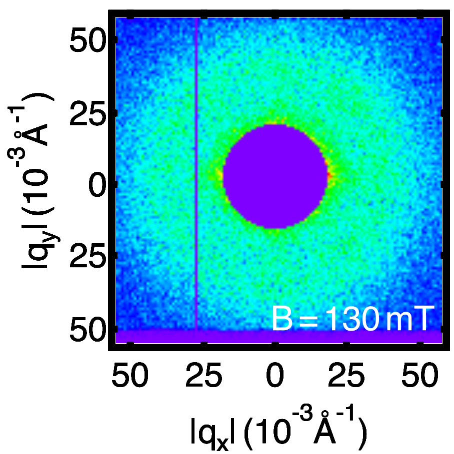
Magnetic Phase Diagram of MnSi

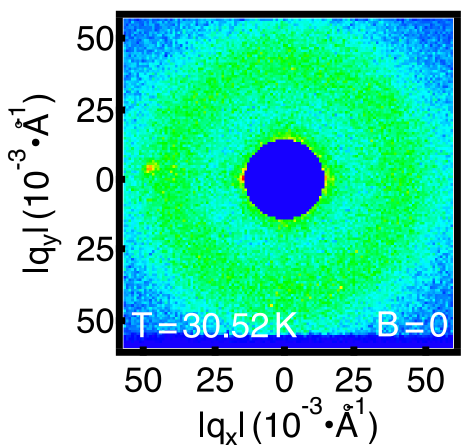


Kindervater et al., arXiv 1911.05095 (2019)



tricritical





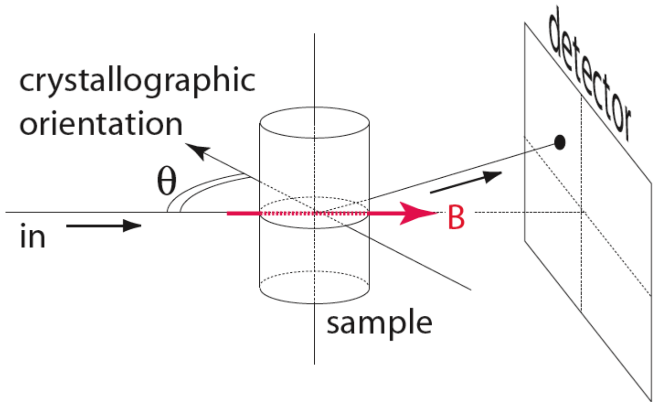
fluctuation-induced 1st order

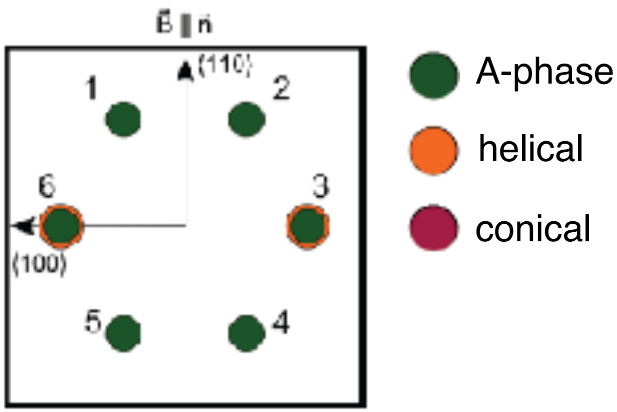
Janoschek et al., PRB **87**, 134407 (2013)

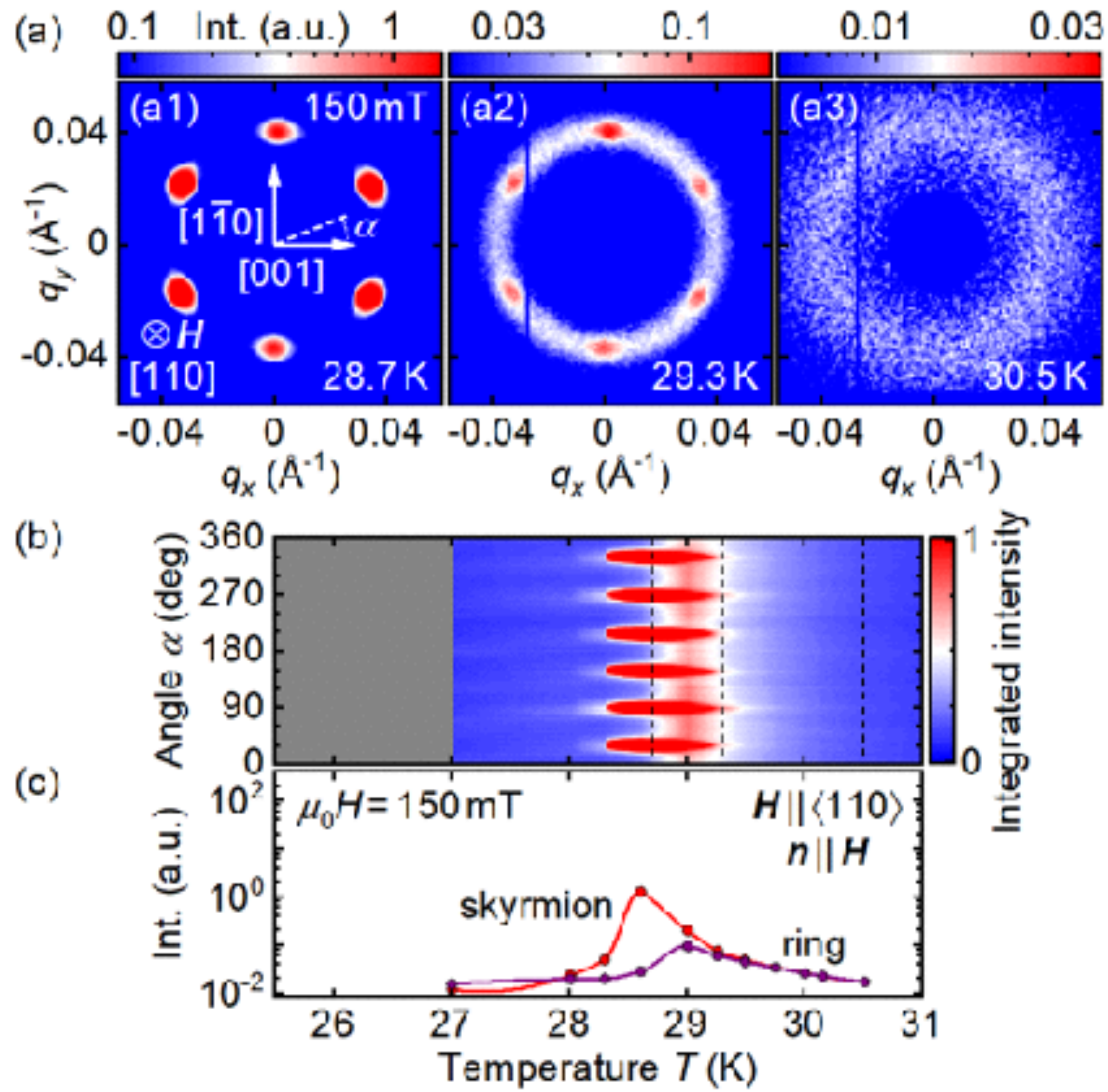
Brazovskii,JETP (1975)

SANS across the Skyrmion-Lattice to PM Transition

field parallel to beam



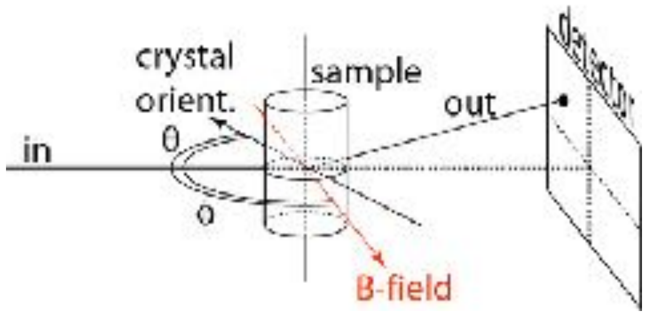


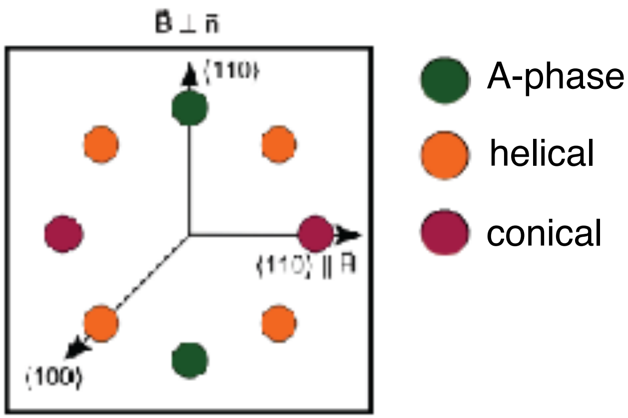


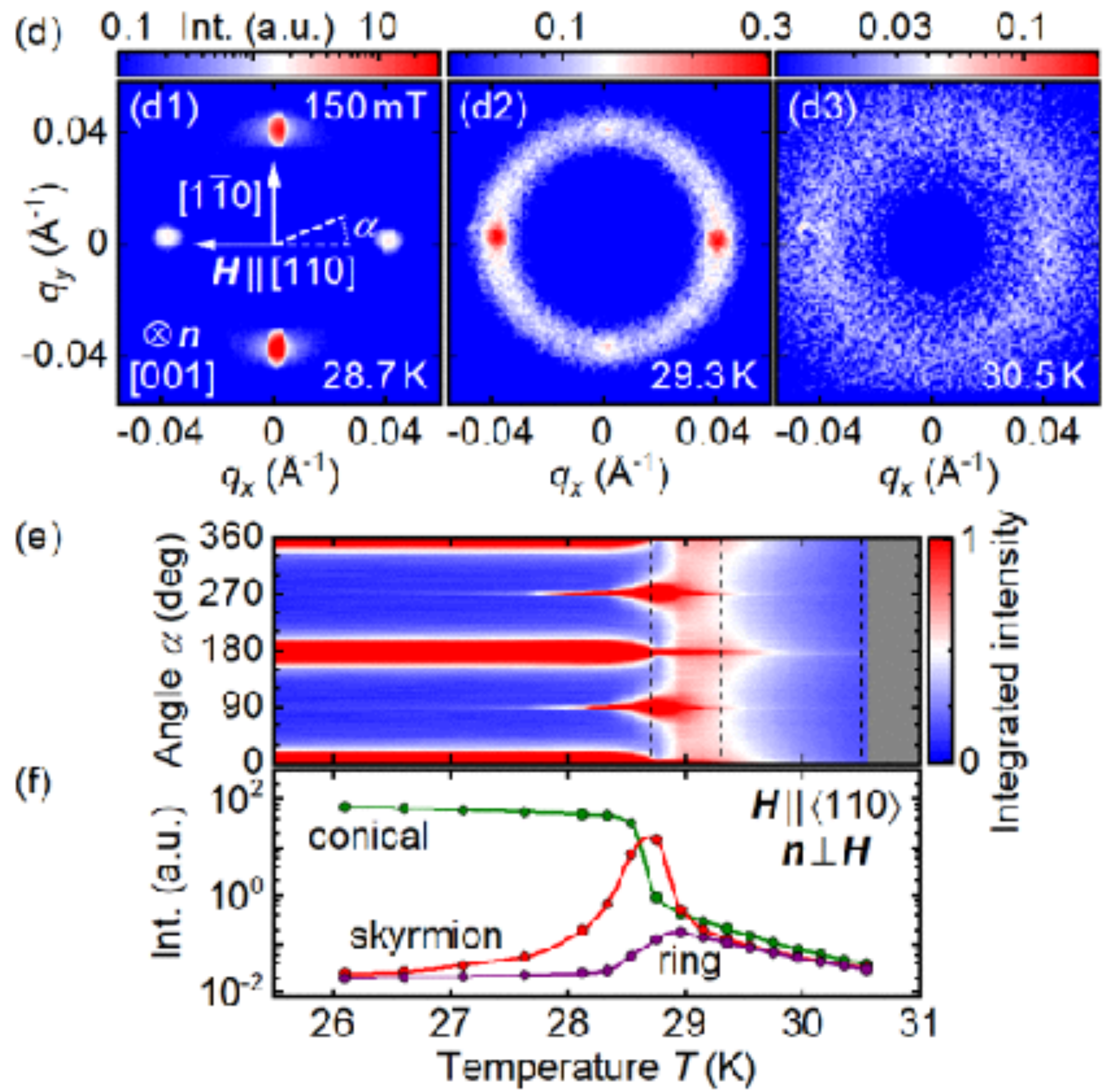
Kindervater et al., arXiv 1911.05095 (2019)

SANS across the Skyrmion-Lattice to PM Transition

field perpendicular to beam





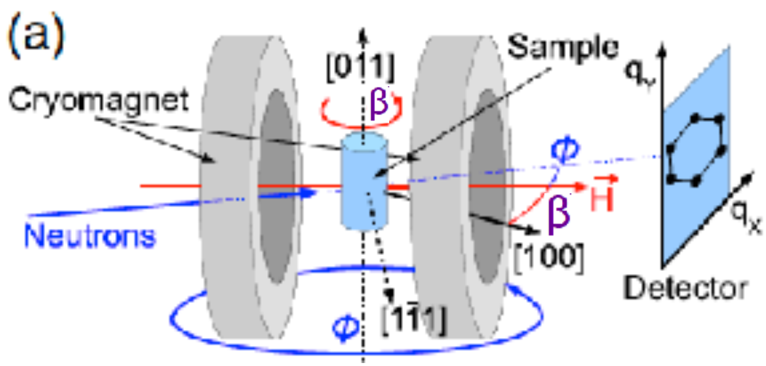


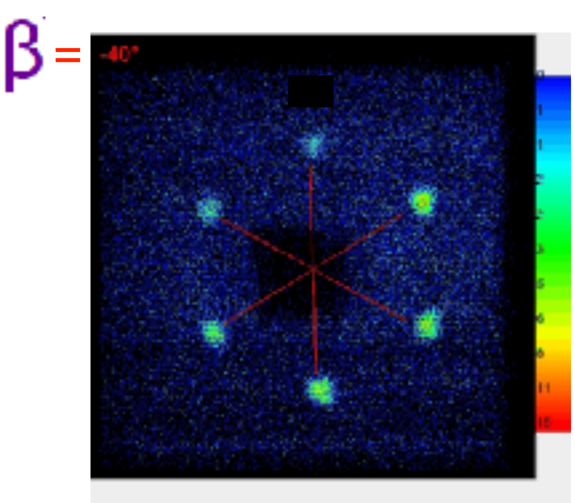
Kindervater et al., arXiv 1911.05095 (2019)

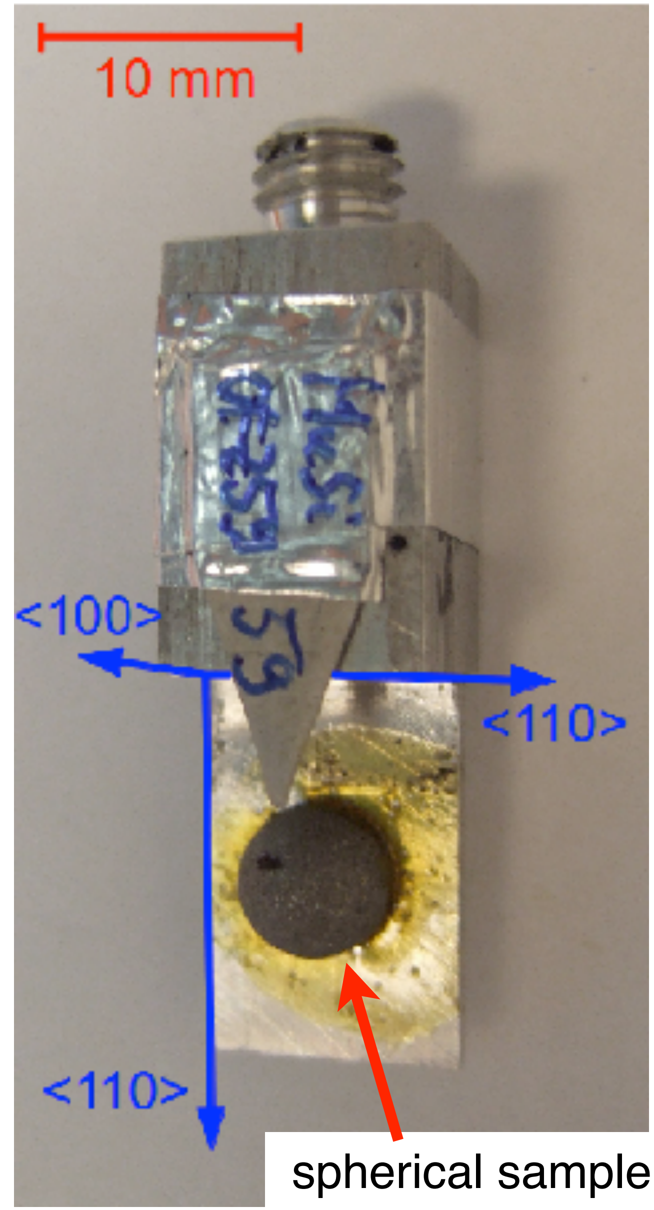
Influence of Magnetocrystalline Anisotropies on the Skyrmion Lattice

Precise Orientation of the Skyrmion Lattice

Set-up from the side



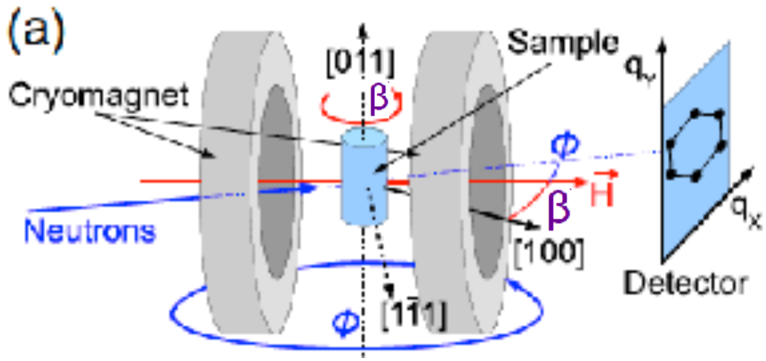


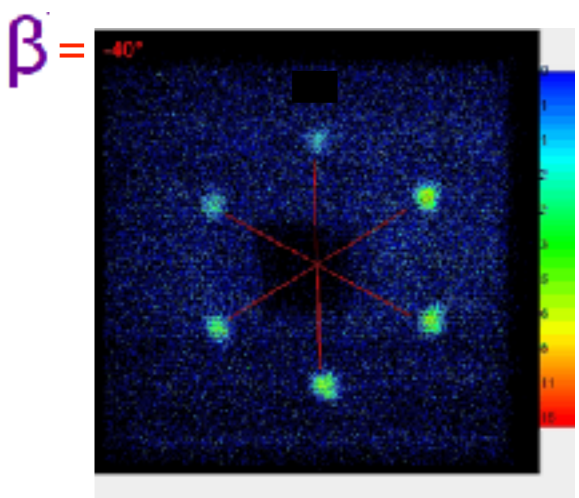


Adams et al., PRL **121** 187205 (2018)

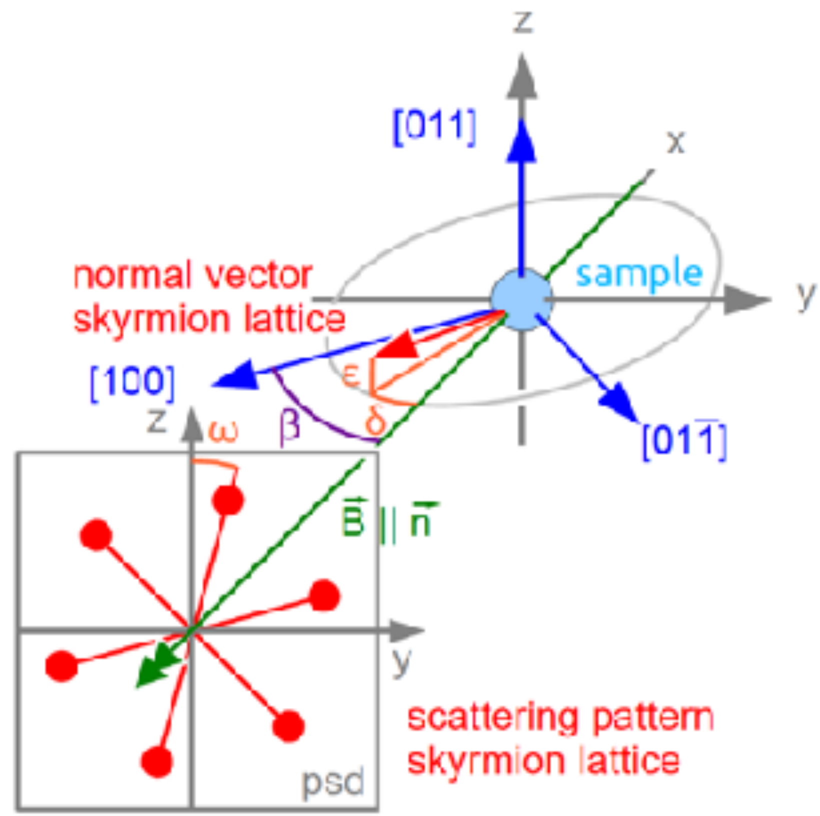
Precise Orientation of the Skyrmion Lattice

Set-up from the side





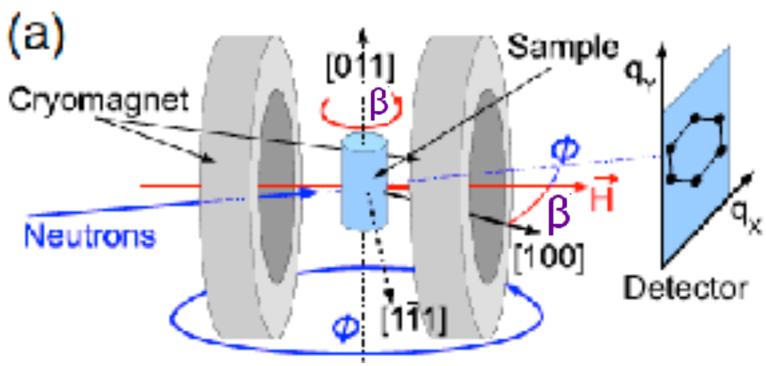
Set-up from the front



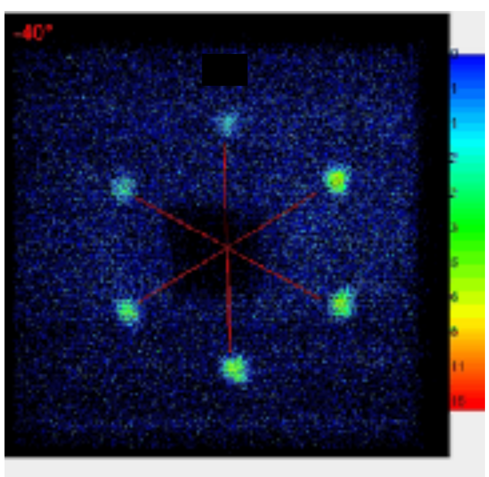
Adams et al., PRL **121** 187205 (2018)

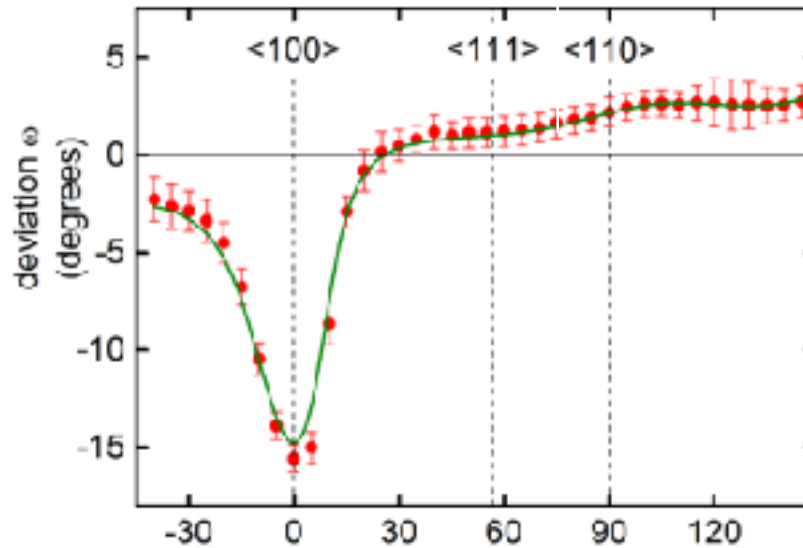
Precise Orientation of the Skyrmion Lattice

Set-up from the side



β =





$$F_{tilt} = k_x^2|M_x(\vec{k})|^2 + k_y^2|M_y(\vec{k})|^2 + k_z^2|M_z(\vec{k})|^2$$

$$F_{azi1} = (k_x^6 + k_y^6 + k_z^6)(\vec{M}(\vec{k})\vec{M}(-\vec{k}))$$

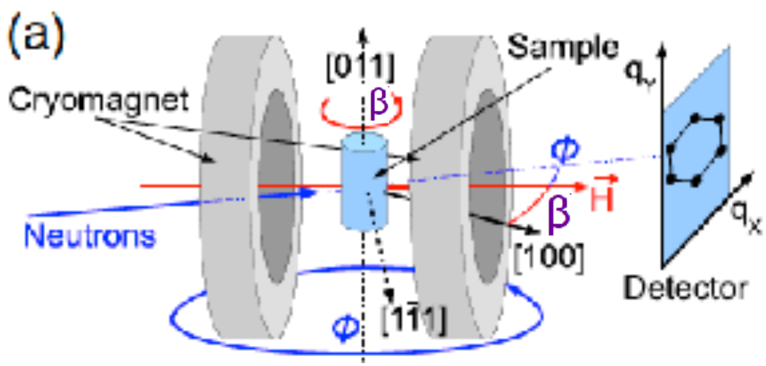
$$\begin{aligned} F_{azi2} \;=\; & k_x^2 M_y(\vec{k}) M_y(-\vec{k}) \\ & + k_y^2 M_z(\vec{k}) M_z(-\vec{k}) \\ & + k_z^2 M_x(\vec{k}) M_x(-\vec{k}) \end{aligned}$$

4th and 6th order anisotropies consistent with Brazovskii-scenario

Adams et al., PRL **121** 187205 (2018)

Precise Orientation of the Skyrmion Lattice

Set-Up from the Side



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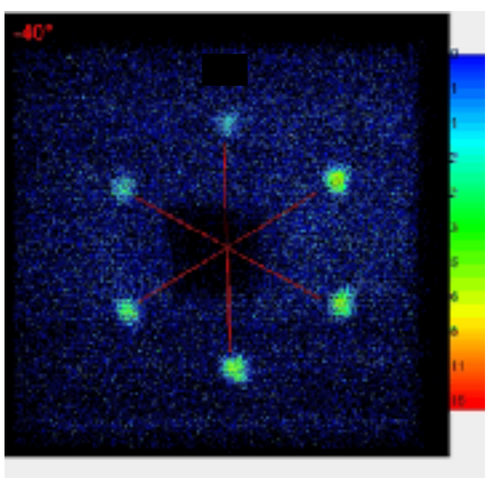

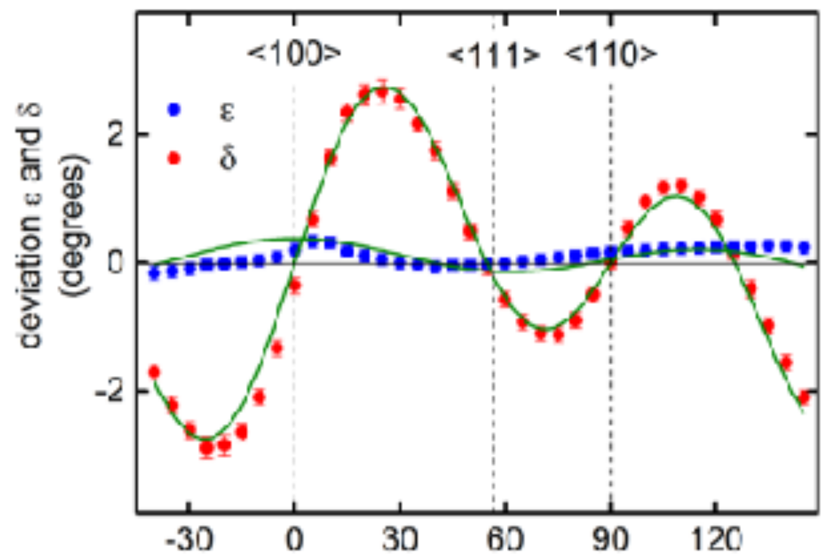

$$F_{tilt} = k_x^2|M_x(\vec{k})|^2 + k_y^2|M_y(\vec{k})|^2 + k_z^2|M_z(\vec{k})|^2$$

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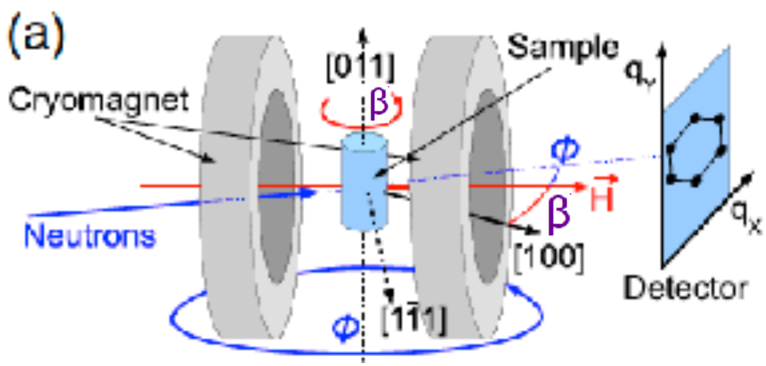
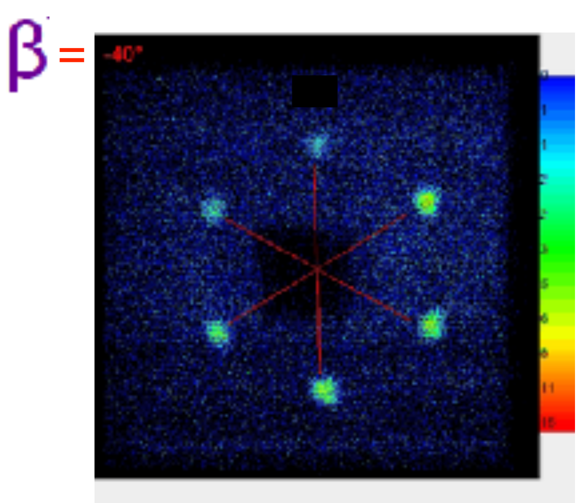
4th and 6th order anisotropies consistent with Brazovskii-scenario

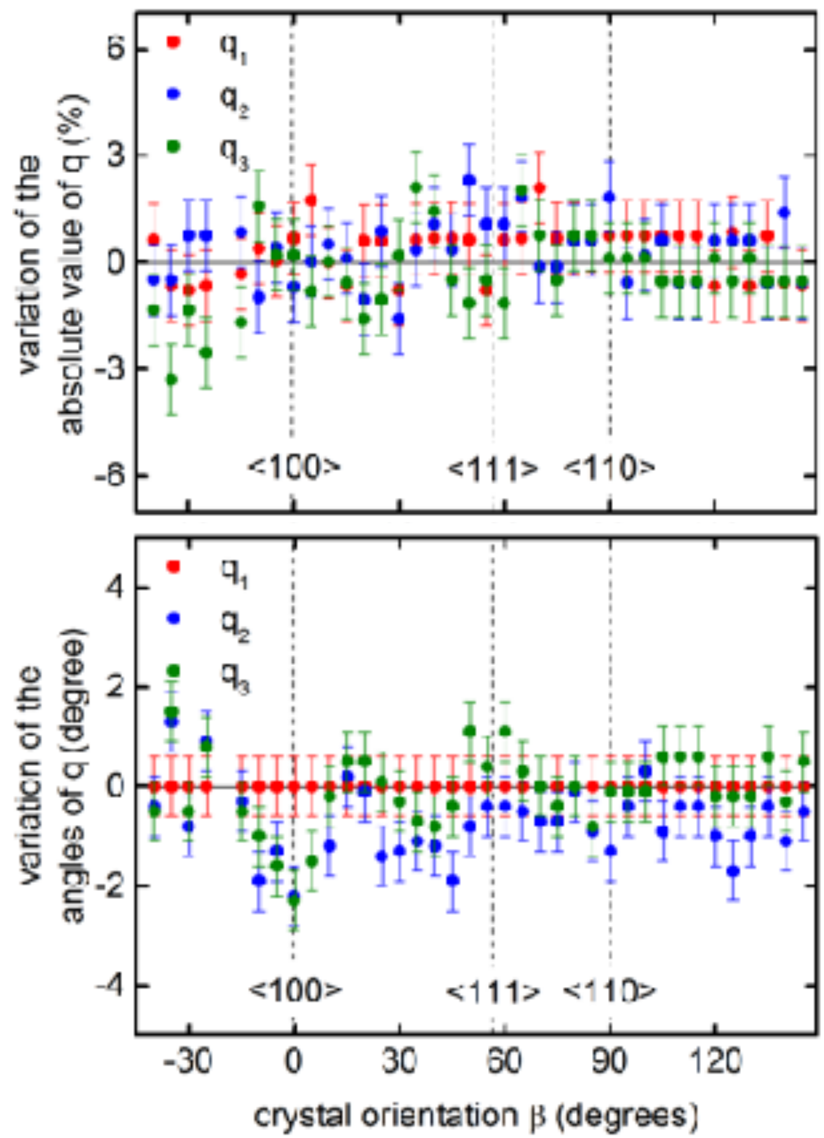
Adams et al., PRL **121** 187205 (2018)

Precise Orientation of the Skyrmion Lattice

Set-Up from the Side

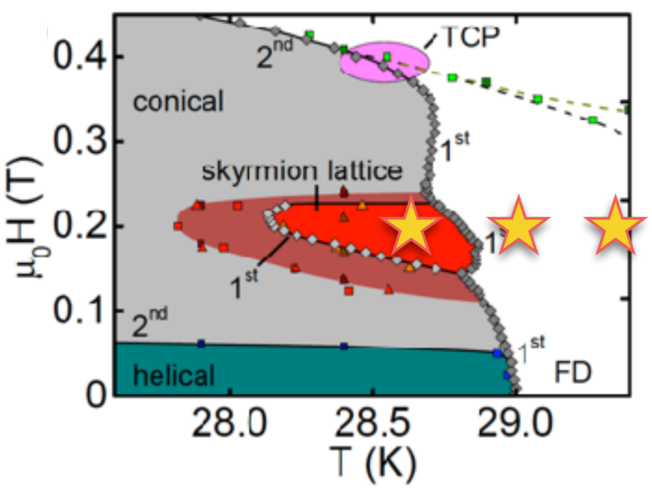


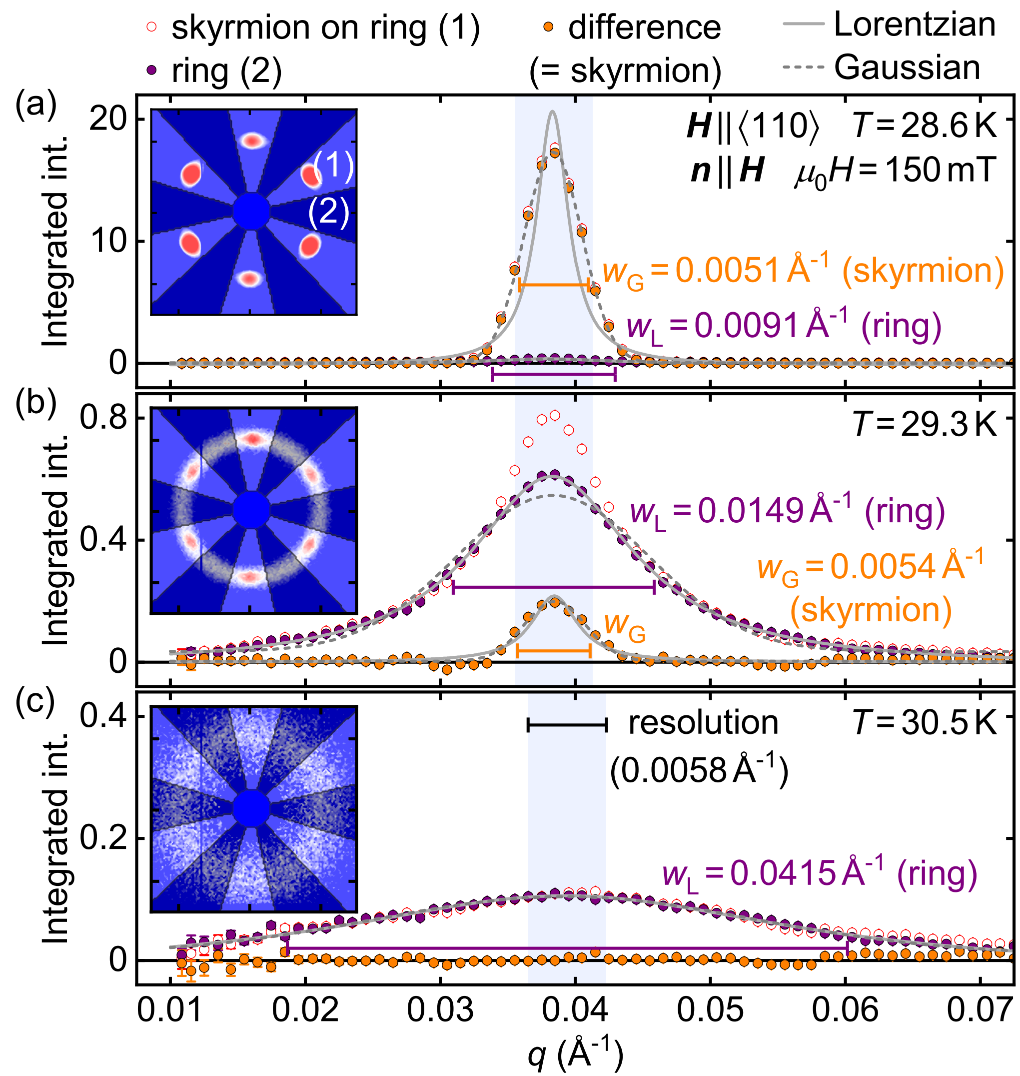




Adams et al., PRL **121** 187205 (2018)

„Fluctuating Skyrmion Textures“ (a Skyrmion Liquid?)





locking scales:

$D \sim \lambda_{\rm SOC}$

$\xi_{\rm DM} = 1/Q \approx 26$ Å

$Q = D/J \approx 0.039$ Å^{-1}

$J_{\rm cub,hel} \sim \lambda_{\rm SOC}^4$

$\xi_{\rm cub,hel} \approx 170$ Å.

$\lambda_{\rm SOC} \sim \xi_{\rm DM}/\xi_{\rm cub,hel} \sim 0.15$

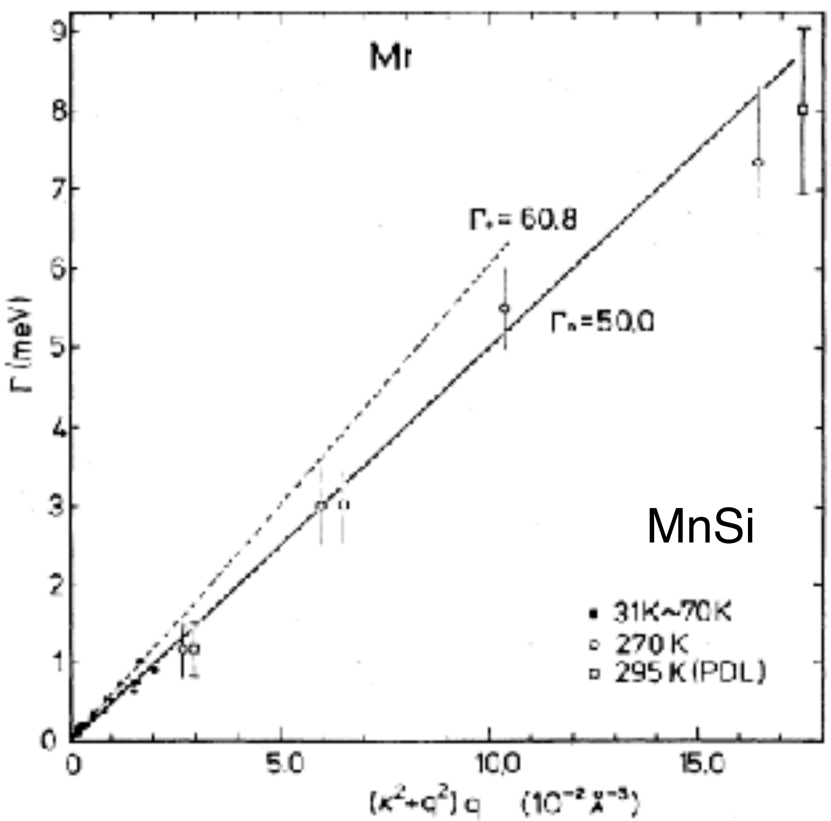
$J_{\rm cub,SkL} \sim \lambda_{\rm SOC}^6$

$\xi_{\rm cub,SkL} \sim \xi_{\rm cub,hel}/\lambda_{\rm SOC} \sim 1133$ Å.

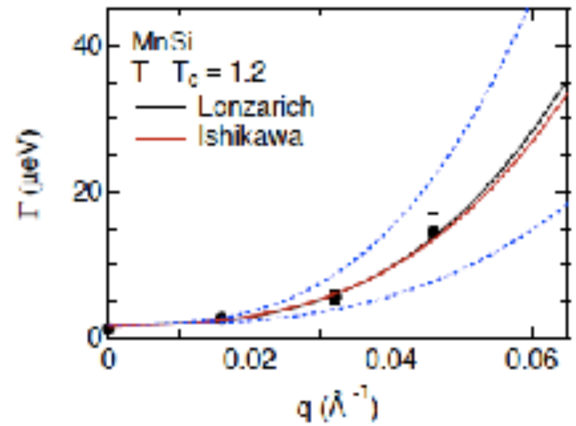
NB: Gaussian for resolution-limited scattering

Lifetime of correlations?

Paramagnons and itinerant-electron magnetism in MnSi



$$\Gamma(\mathbf{q}) = \gamma q\left(\chi^{-1} + cq^2\right)$$



@RESEDA (FRM II)

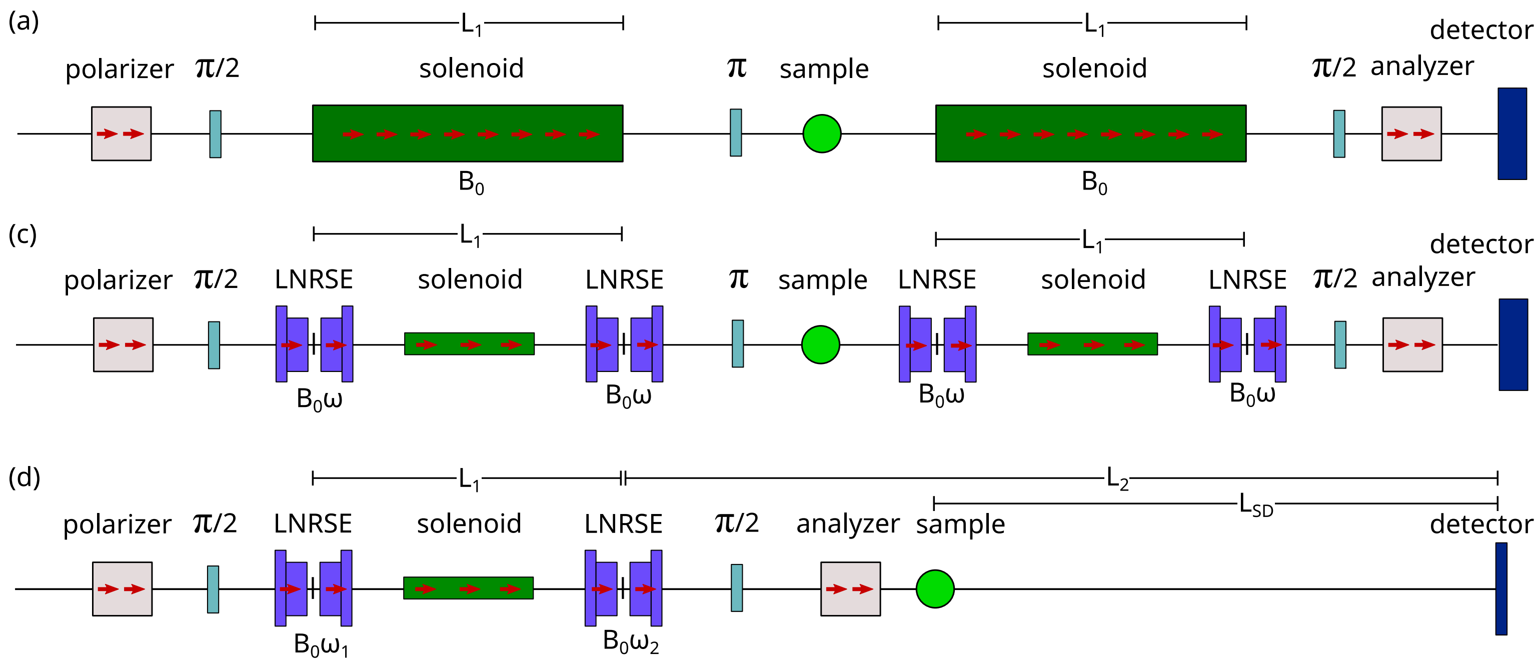
$$T_c = 2.387 c M_0^{3/2} \frac{(\hbar\gamma)^{1/4}}{k_B}$$

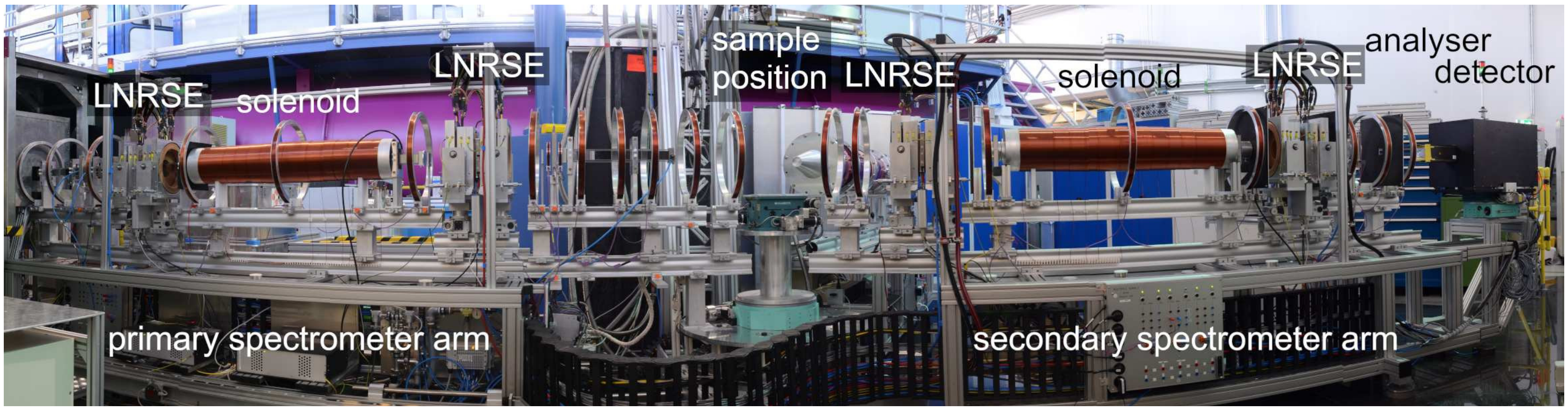
Property	Experiment	Present model
$\chi^{-1}(T)$ $2T_c \leq T \leq 10\,T_c$	Linear[c]	Linear[c,d]
T_c(K)	29.5(5)	31
p_{eff}/p_0[e]	5.5(4)	4.7

Ishikawa et al., PRB **25** 254 (1982)
Ishikawa et al., PRB **31** 5884 (1985)

Lonzarich JMMM **45** 43 (1984)
Lonzarich, Taileffer. J. Phys. Cond. Matter **18** 4339 (1985)

(Longitudinal) Resonance Spin Echo for Diverse Applications
(RESEDA @ FRM II)

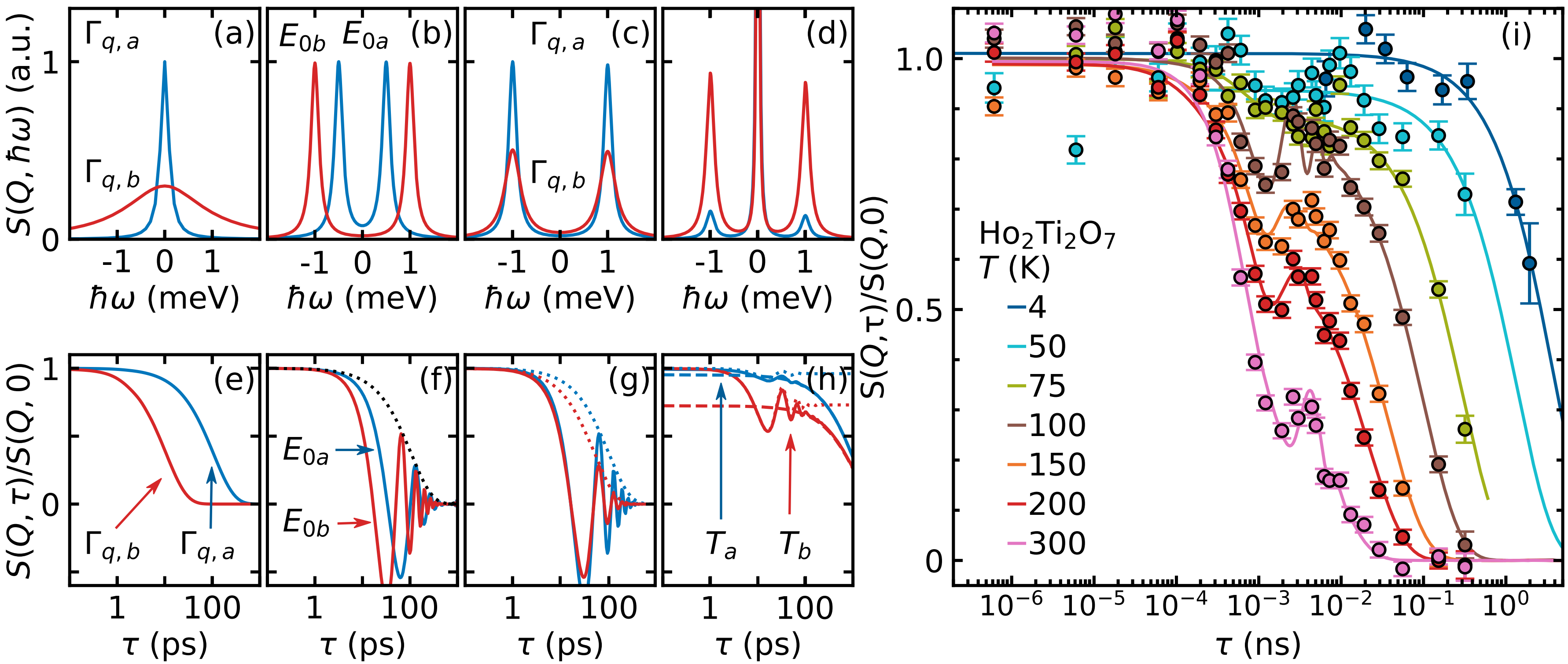




Franz et al., JPSJ **88,** 081002 (2019)

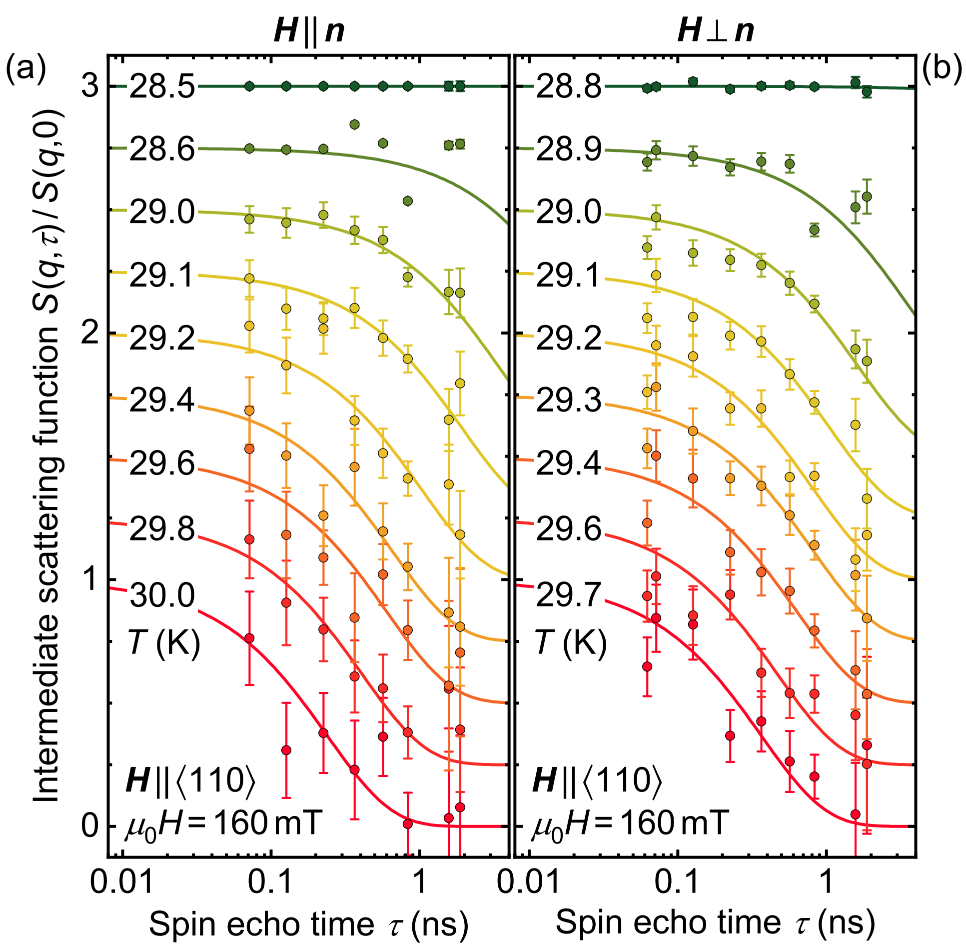
(Longitudinal) Resonance Spin Echo for Diverse Applications

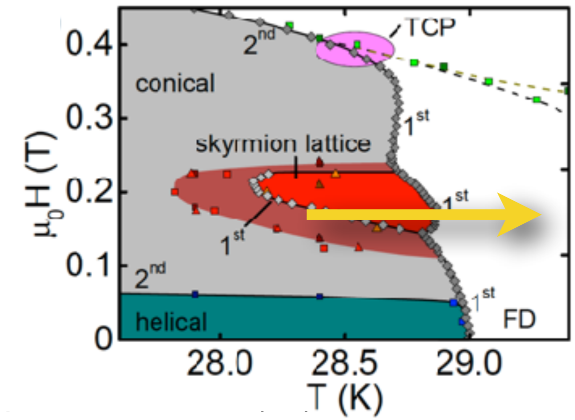
(RESEDA @ FRM II)

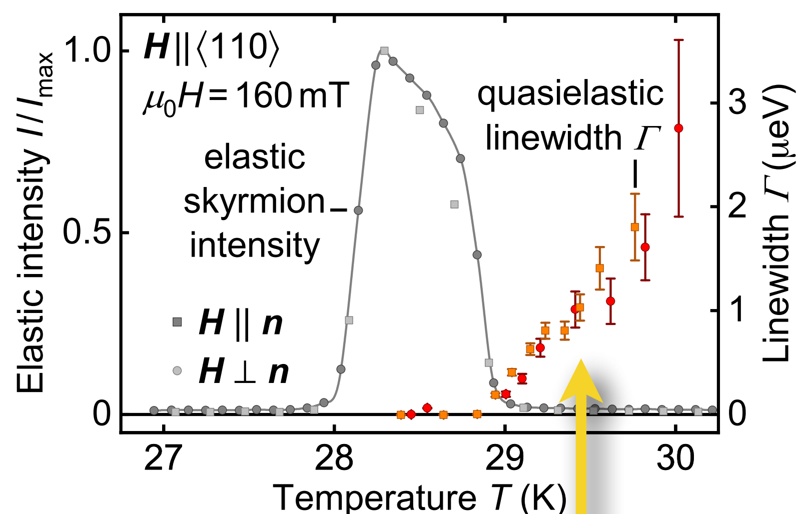


Franz et al., JPSJ **88,** 081002 (2019)

„Fluctuating Skyrmion Textures“ (a Skyrmion Liquid?)





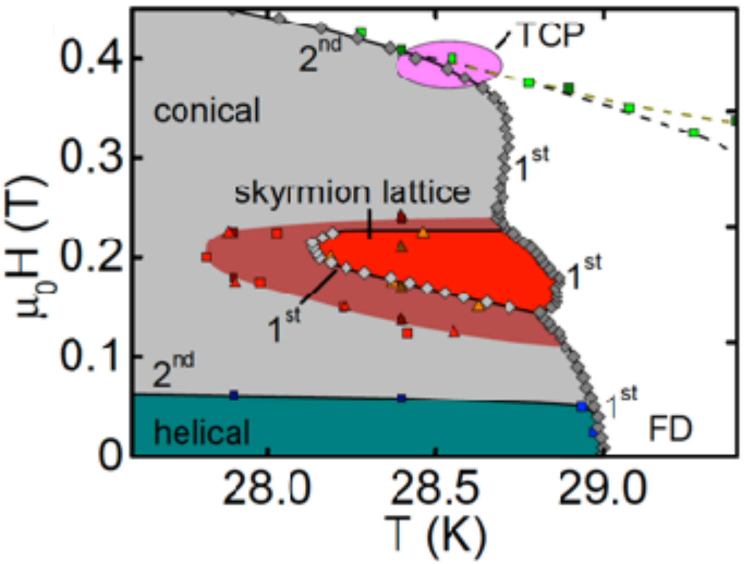


typical life times several 10^{-9} s

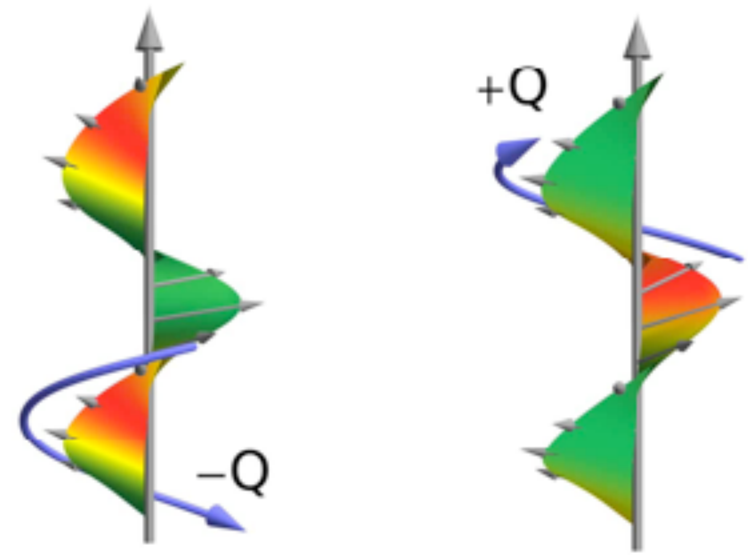
Kindervater et al., arXiv 1911.05095 (2019)

Topological character of fluctuations?

Prediction of Universal Spin Excitations



helical & conical phase

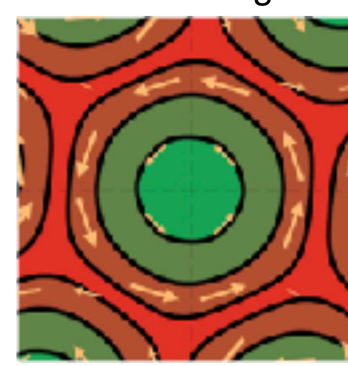


skyrmion lattice

clockwise

counter-clockwise

breathing

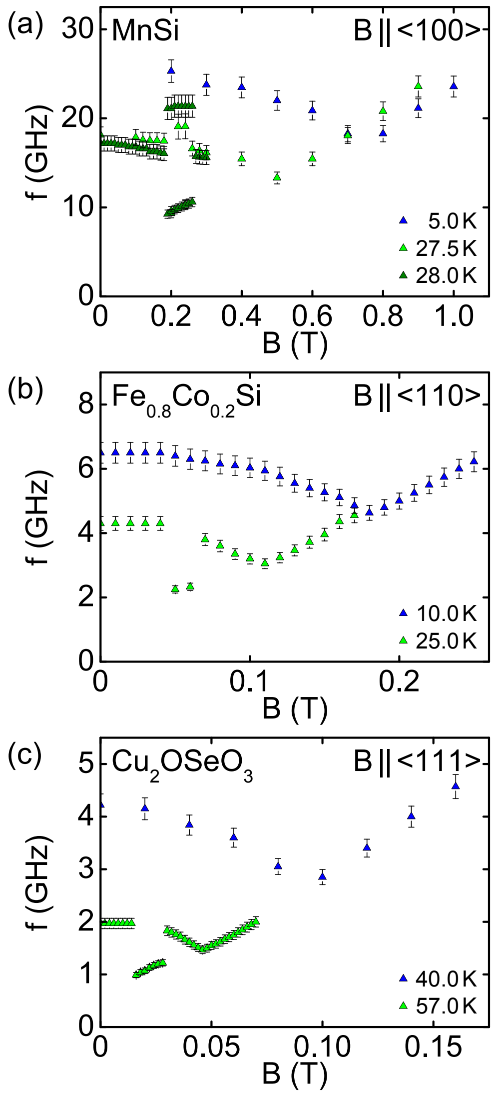


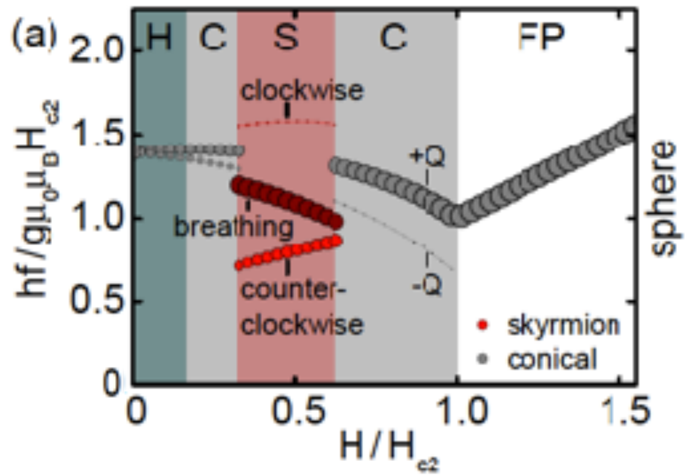
animation: J. Waizner, M. Garst

theory of helimagnons: Belitz, Kirkpatrick, Rosch, Phys. Rev. B

Schwarze et al., Nature Materials **14,** 478 (2015)

Towards a Comparison with Theory





hierarchical scales so far:
FM > DM > CEF

new ingredients:

➜ dipolar interactions

➜ demagnetising fields

➜ neglect: anisotropies

two material-specific parameters:

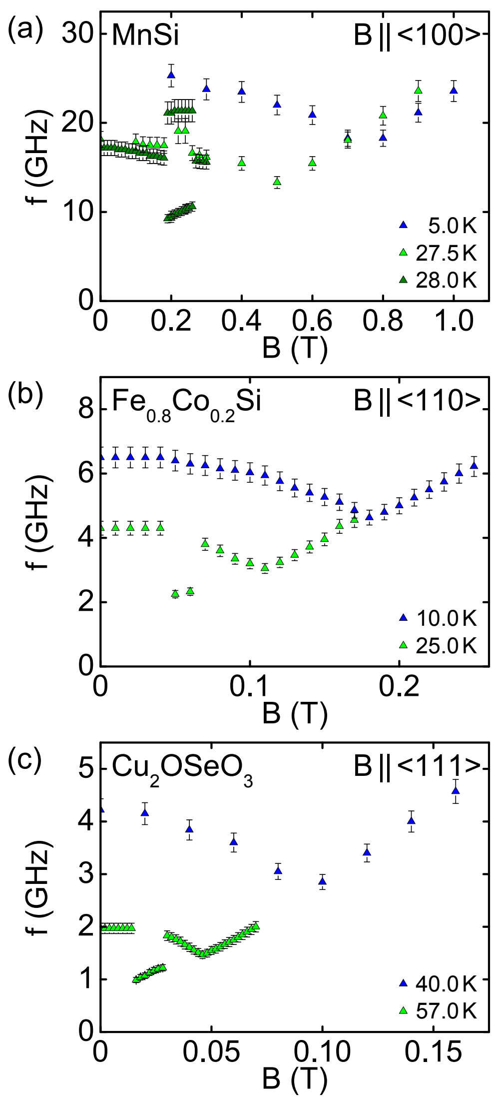
chiral energy: $E_{\rm DM} = \mu_0\mu_B^2/(\chi_{\rm con}^{\rm int}V_{\rm f.u.})$

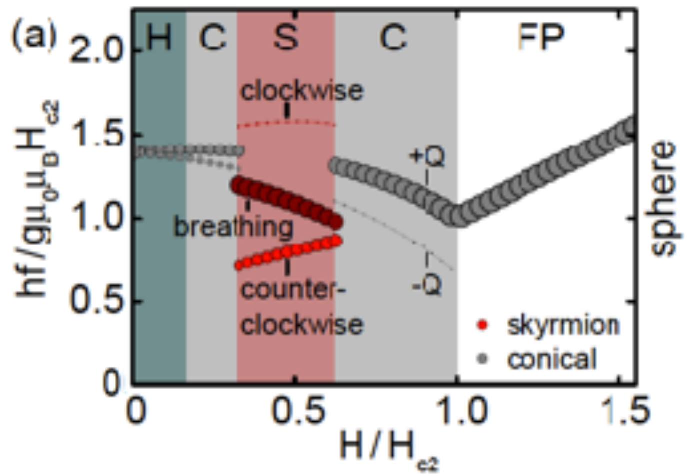
critical field energy: $E_{\rm CF}(T=0) = g\mu_0\mu_B H_{c2}^{\rm int}$

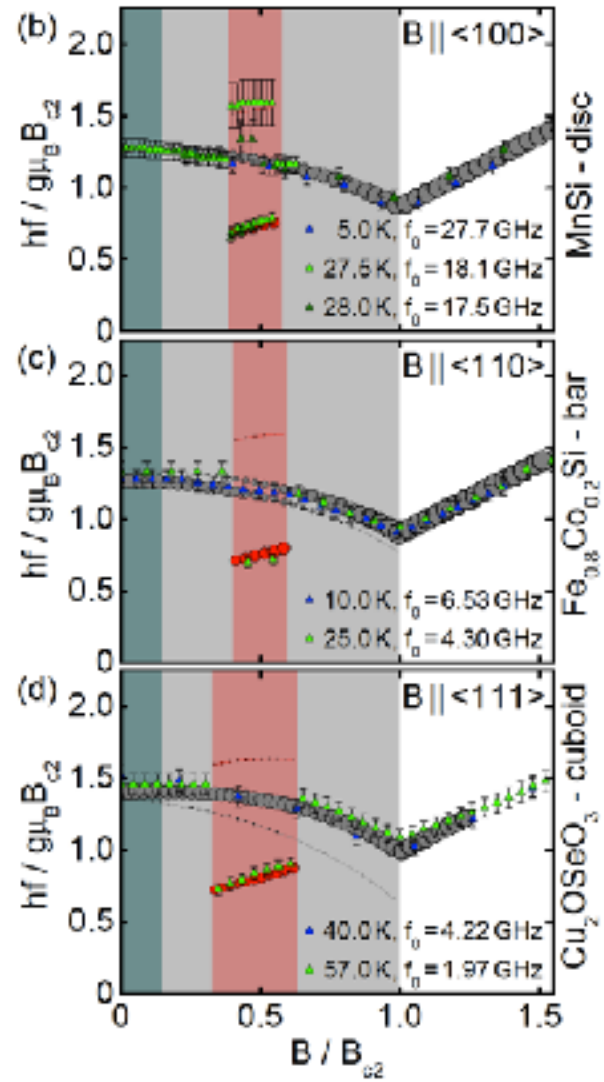
chiral magnet	T_c	$H_{c2}^{\rm int}(T=0)$	$2\pi/Q$	$\chi_{\rm con}^{\rm int}$	$V_{\rm f.u.}$	g	$E_{\rm DM}$	$E_{\rm CF}(T=0)$	N_x	N_y	N_z
MnSi	29 K	0.60 T/μ_0	180 Å	0.34	24.02 Å^3	2.0	83 μeV	69 μeV	0.175	0.175	0.65
$Fe_{0.8}Co_{0.2}Si$	28 K	0.15 T/μ_0	340 Å	0.65	22.52 Å^3	2.1	46 μeV	18 μeV	0.074	0.463	0.463
Cu_2OSeO_3	58 K	0.08 T/μ_0	600 Å	1.76	89.02 Å^3	2.1	4.3 μeV	9.7 μeV	0.39	0.27	0.34

Schwarze et al., Nature Materials **14,** 478 (2015)

Universal Spin Excitations in Chiral Helimagnets



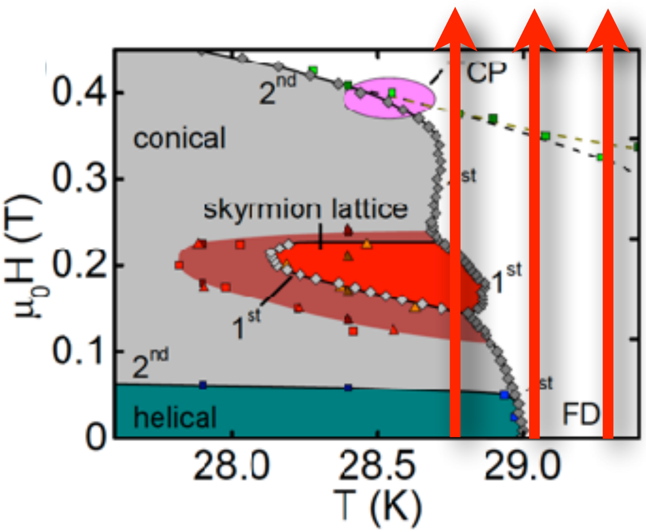


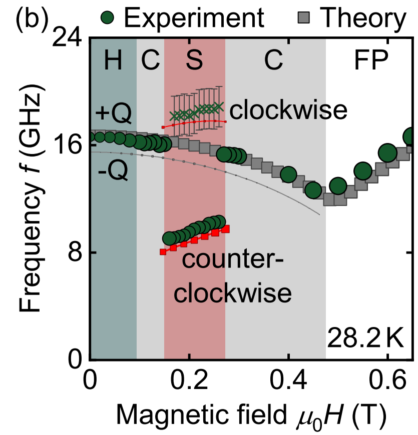


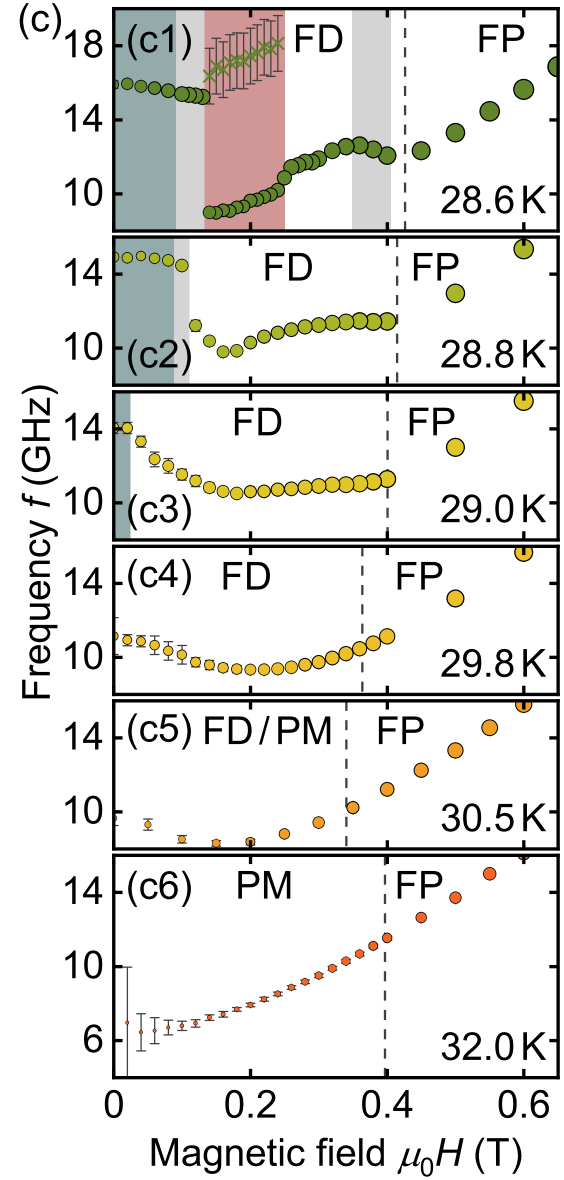
parameter-free agreement:
➜ frequency
➜ field dependence
➜ spectral weight
(mode mixing)

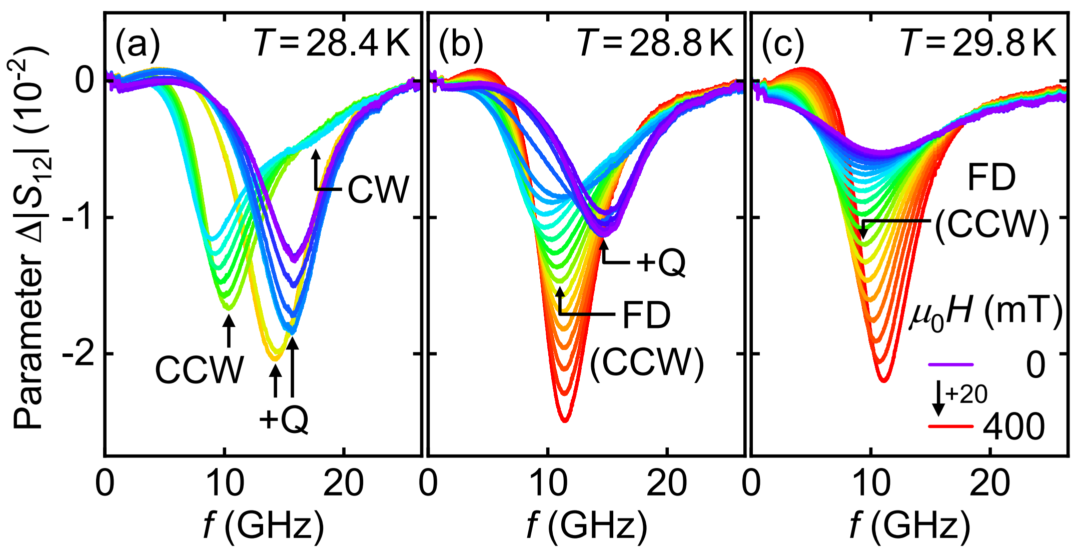
Schwarze et al., Nature Materials **14,** 478 (2015)

„Fluctuating Skyrmion Textures“ (a Skyrmion Liquid?)









Nature of the transition?

Theory of weak crystallization

S. A. Brazovskiĭ, I. E. Dzyaloshinskiĭ, and A. R. Muratov

L. D. Landau Institute of Theoretical Physics, USSR Academy of Sciences

(Submitted 30 March 1987)
Zh. Eksp. Teor. Fiz. **93**, 1110–1124 (September 1987)

Landau ZETZ (1937)
Brazovskii et al., JETP **66**, 625 (1987)

A complete theory, based on the soft mode mechanism proposed by Landau [Zh. Eksp. Teor. Fiz. **7**, 627 (1937)], is developed for a liquid–crystal transition with low latent heat. Thermodynamic fluctuations alter substantially the results and change the form of the phase diagram. Thus, besides the transition from a liquid to a body-centered cube, the only transition possible without allowance for fluctuations, direct transitions appear from the liquid into other cubic phases and a one-dimensional density wave. Transitions into quasicrystalline states, particularly the icosahedral state, are discussed.

1. INTRODUCTION

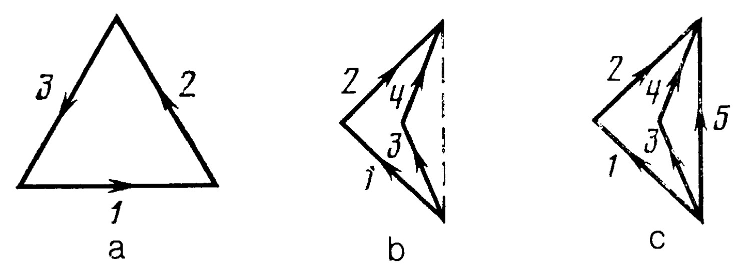
Landau[1] investigated the transition from a liquid to a crystal as far back as in his 1937 studies of phase transitions (see also Ref. 2). He considered, of course, a hypothetical weak crystallization, when a small-amplitude periodic (or quasiperiodic) density component

$$\delta\rho = \sum_{\mathbf{k}} \rho_{\mathbf{k}} e^{i\mathbf{kr}}$$

appears in the liquid. By virtue of the isotropy, this expansion contains in the leading approximation only vectors $\mathbf{k}$ of fixed length k_0, for which the coefficient of the second-order term in the Landau expansion has a minimum. The corresponding Landau energy is[1)]

$$\Phi_L = \tau \sum |\rho_{\mathbf{k}}|^2 + \mu \sum \rho_{\mathbf{k}_1}\rho_{\mathbf{k}_2}\rho_{\mathbf{k}_3} + \sum \lambda(k_1k_2k_3k_4)\,\rho_{\mathbf{k}_1}\rho_{\mathbf{k}_2}\rho_{\mathbf{k}_3}\rho_{\mathbf{k}_4}.$$

Landau's analysis of Eq. (1) has shown immediately that the absolute minimum of the energy (1) is reached for a set of momenta $\mathbf{k}$ from which it is possible to construct a maximum number of closed triangles (Fig. 1). The transition to such a state will take place, regardless of the sign of μ, already at $\tau > 0$, i.e., will be a first-order transition.



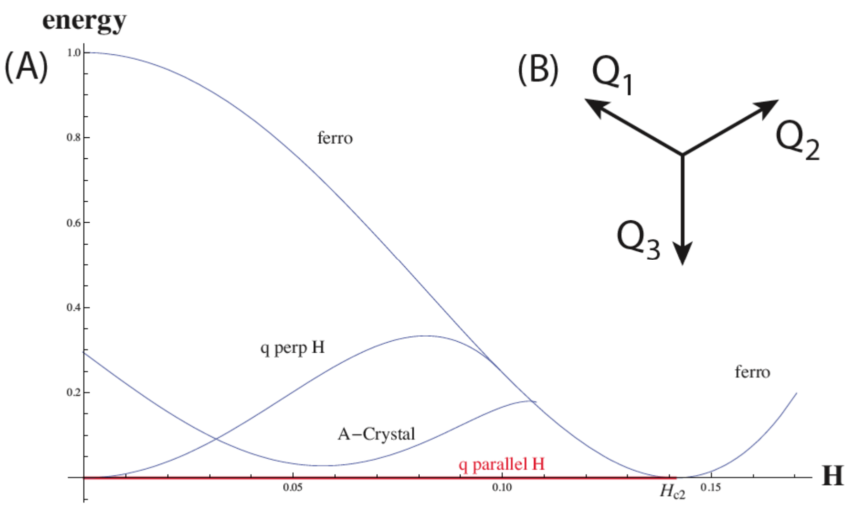
Fluctuation-Stabilized Multi-q Structure

$$F[\mathbf{M}] = \langle r_0 \mathbf{M}^2 + J(\nabla \mathbf{M})^2 + 2D\, \mathbf{M}\cdot(\nabla\times\mathbf{M}) + U\mathbf{M}^4 \rangle$$

$$\propto \langle \mathbf{M}_Q^2\, \mathbf{M}_Q \rangle \cdot \mathbf{m}_0$$

triple-q + uniform M

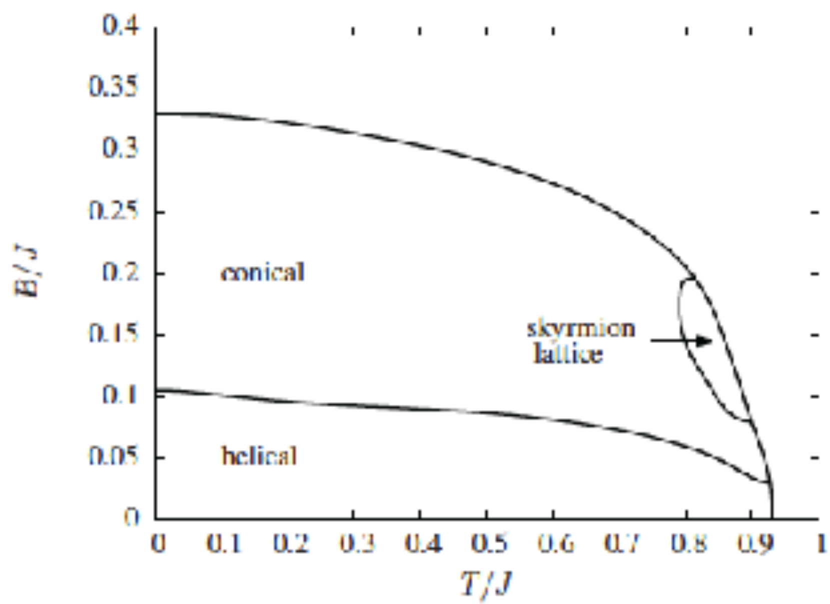
Binz, Vishwanath, Aji PRL (2006)



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

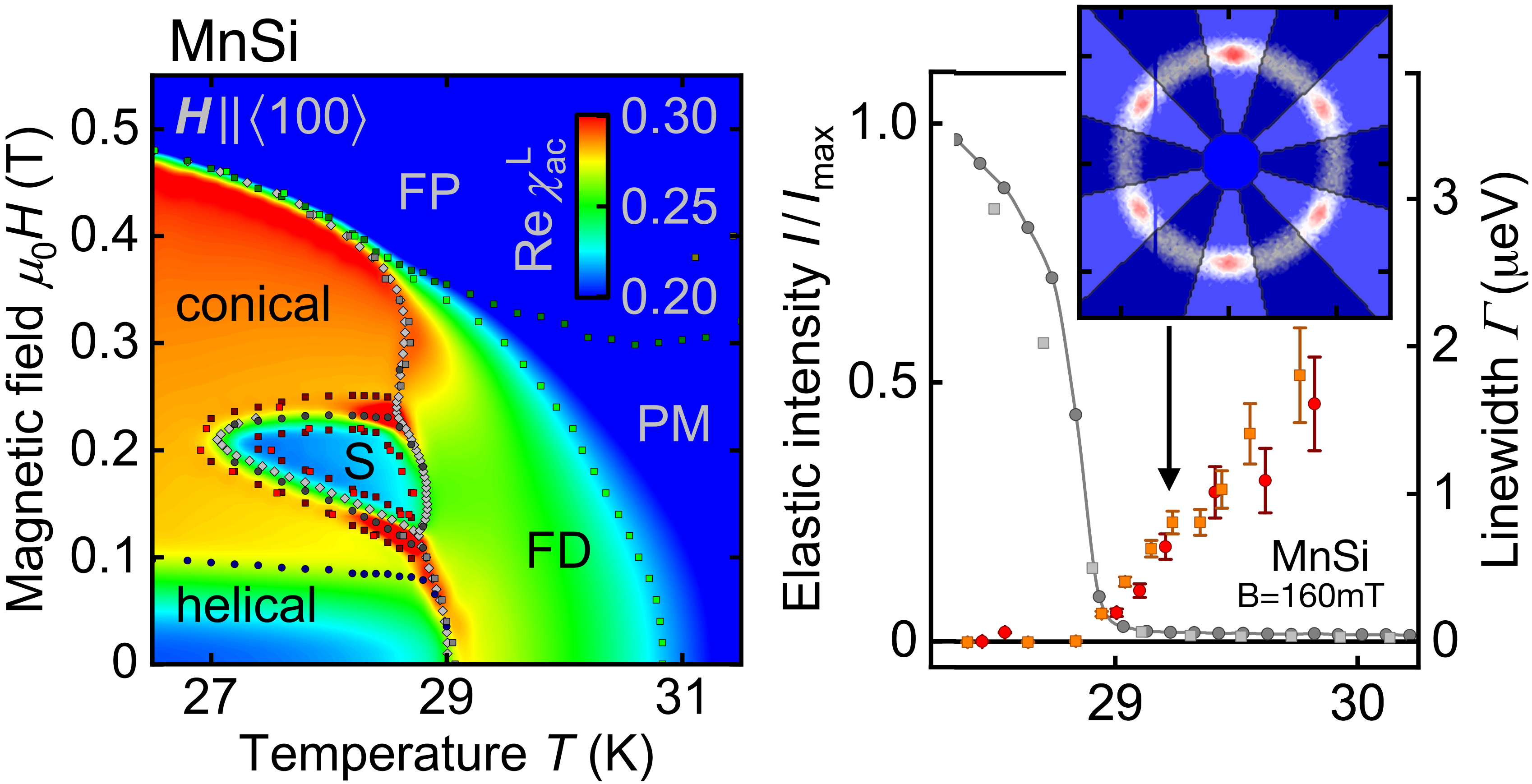
perp. single-q: **metastable**
triple-q: **metastable**

Monte-Carlo
(includes fluctuations)



Buhrandt, Fritz PRB **88**, 195137 (2013)

Weak Crystallization of Fluctuating Skyrmion Textures



Kindervater et al., arXiv 1911.05095 (2019)