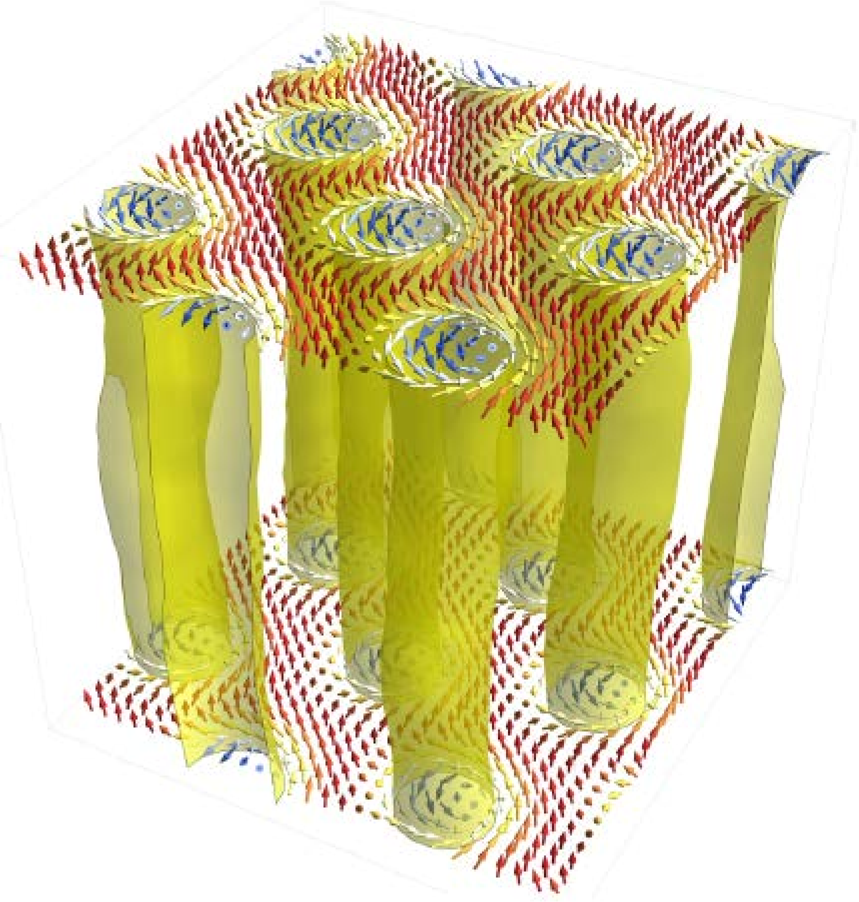
Magnetic whirls and emergent monopoles in chiral magnets

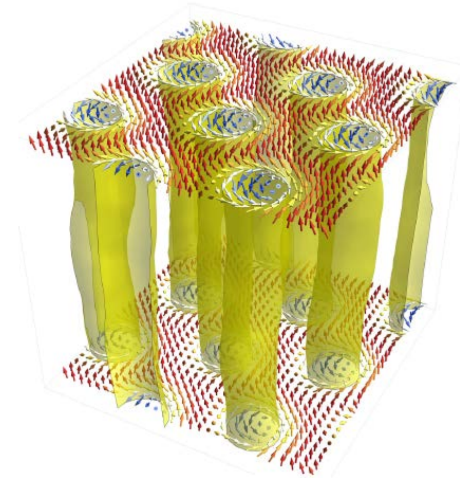
Achim Rosch
Institute for Theoretical Physics
University of Cologne, Germany



- topology & skyrmion phase
  in chiral magnets
- Berry phases & emergent
  electric and magnetic fields
- changing topology:
  emergent magnetic monopoles

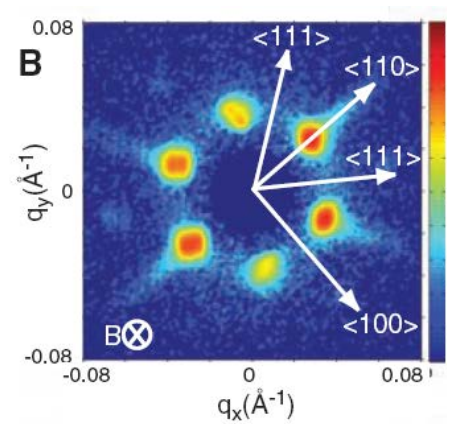
theory @ Cologne, Germany

Stefan Buhrandt, Karin Everschor, Markus Garst, Robert Bamler, **Christoph Schütte**, A. R.



experiments @ TU Munich, Germany

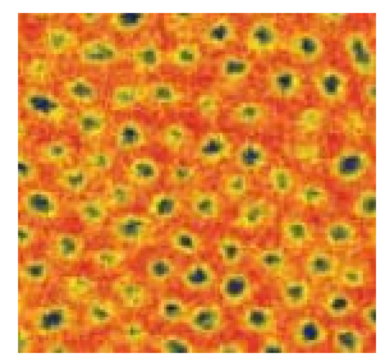
Ch. Pfleiderer, P. Böni, A. Bauer, A. Chacon, T. Schulz, R. Ritz, M. Halder, M. Wagner, C. Franz, F. Jonietz, M. Janoschek, S. Mühlbauer, …



experiments @ TU Dresden, Germany

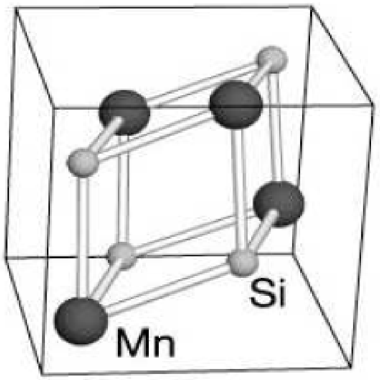
P. Milde, D. Köhler, L. Eng

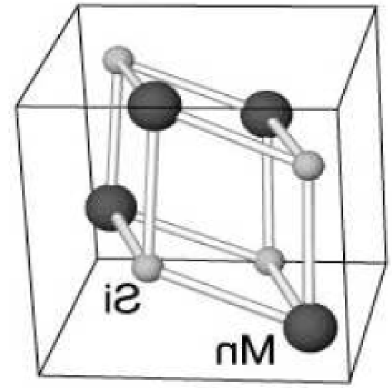
+ Jan Seidel, University of New South Wales, Sydney



Chiral magnets: e.g. MnSi

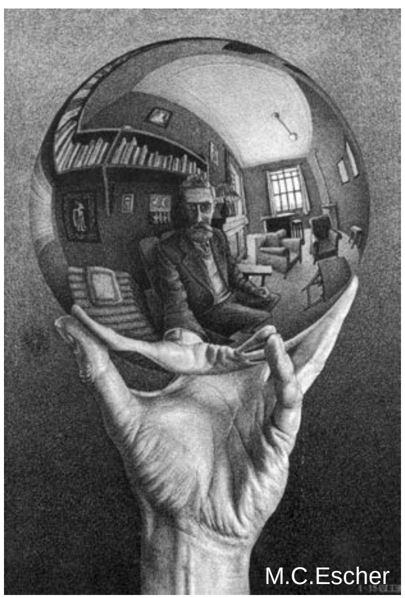
cubic but no inversion symmetry

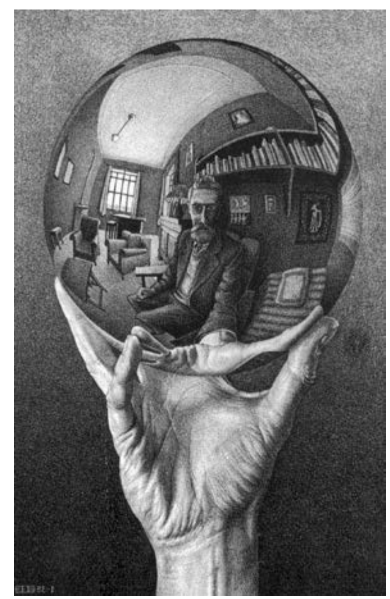




left handed

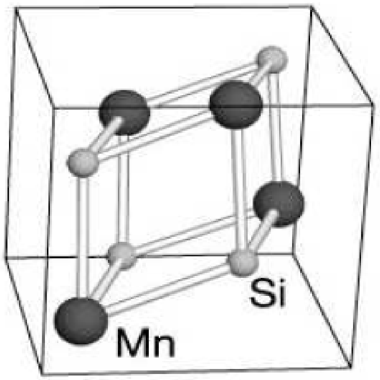
right handed





Chiral magnets: e.g. MnSi

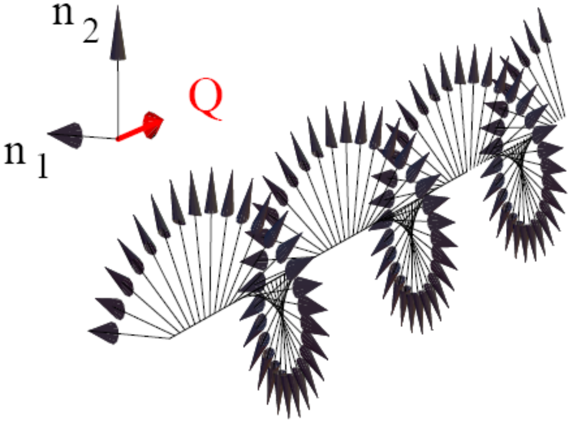
cubic but no inversion symmetry



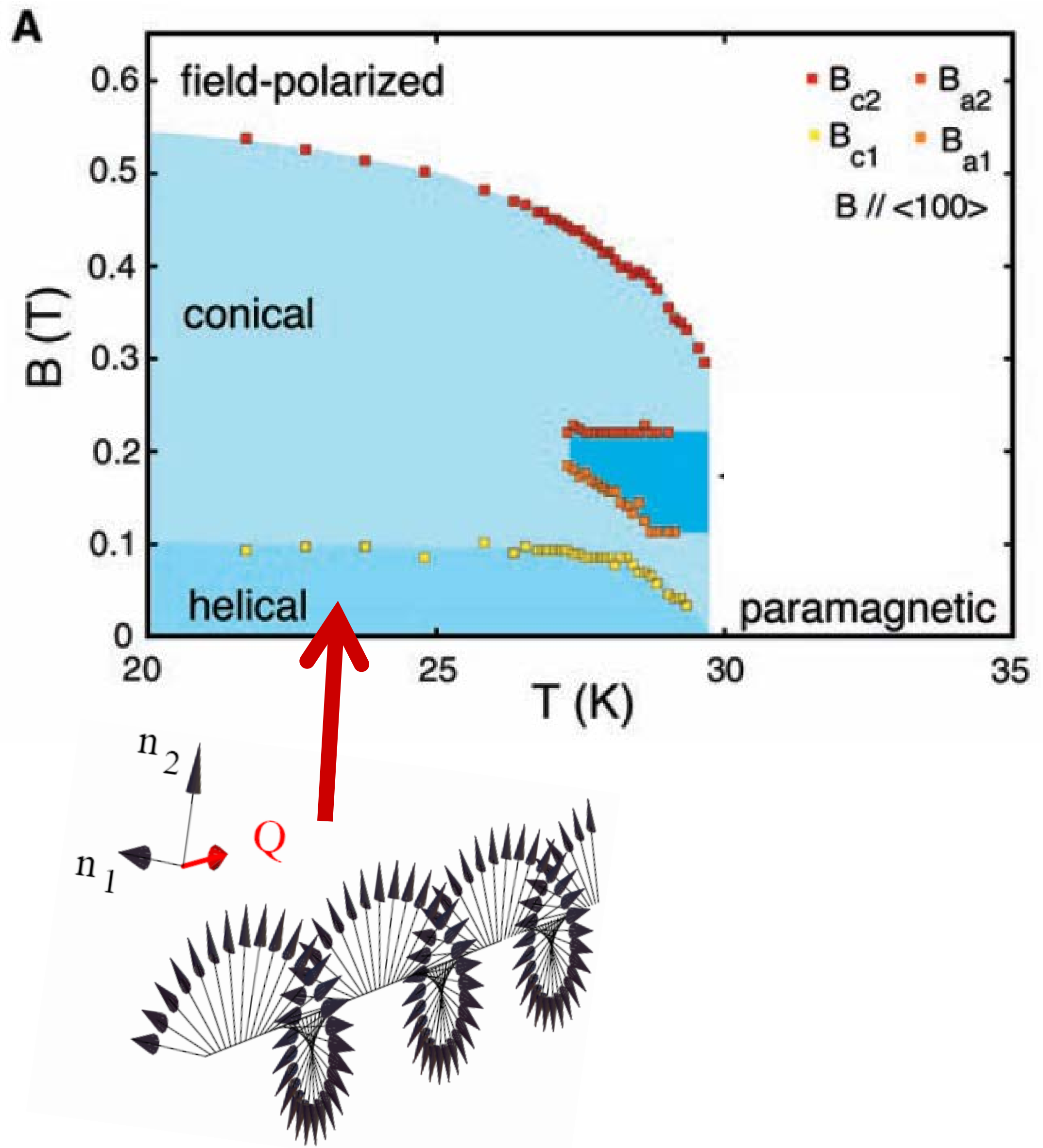
left handed

Dzyaloshinsky-Moriya interactions:
magnetic structures like to twist

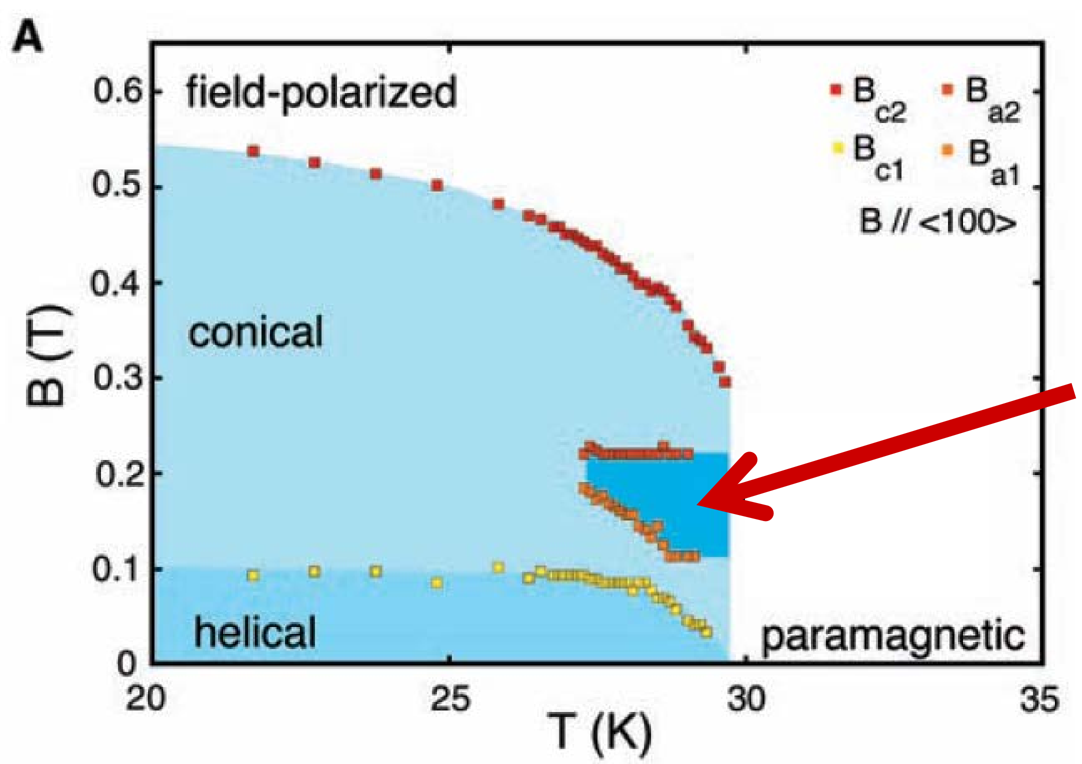
$$\int \vec{M} \cdot (\nabla \times \vec{M})$$

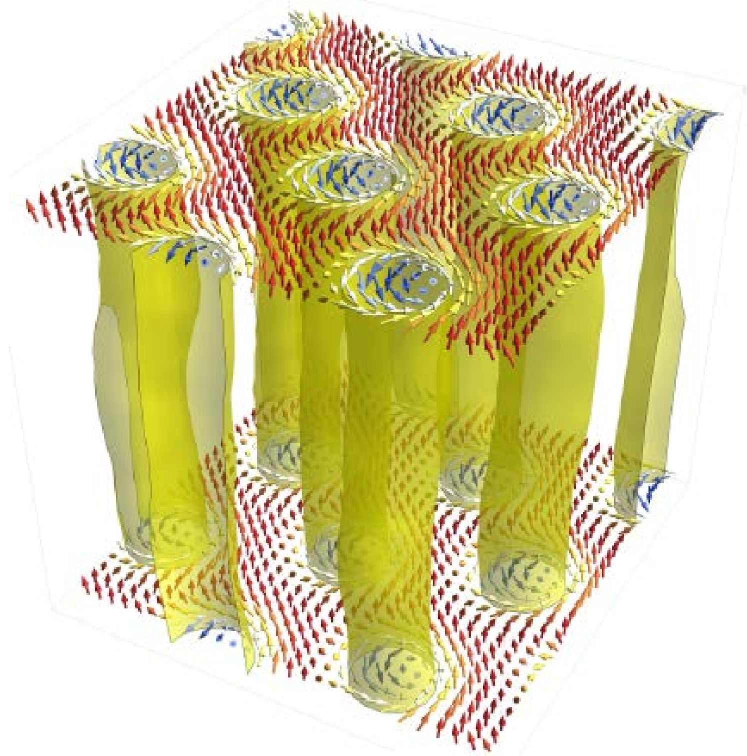


generic phase diagram of cubic magnets without inversion symmetry, here: MnSi



generic phase diagram of cubic magnets without inversion symmetry, here: MnSi

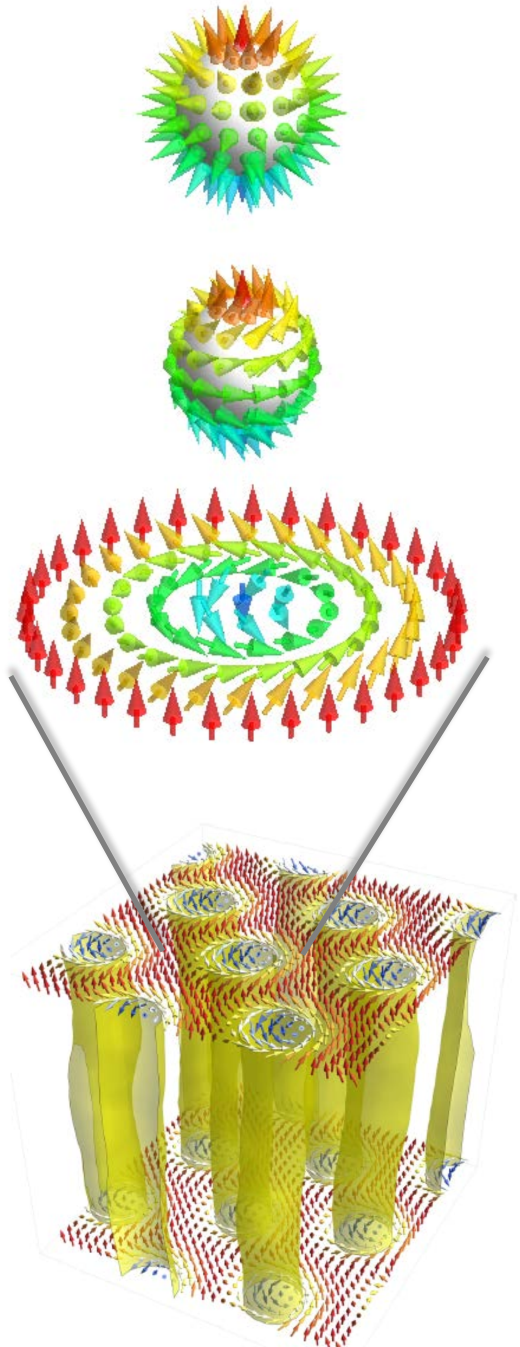




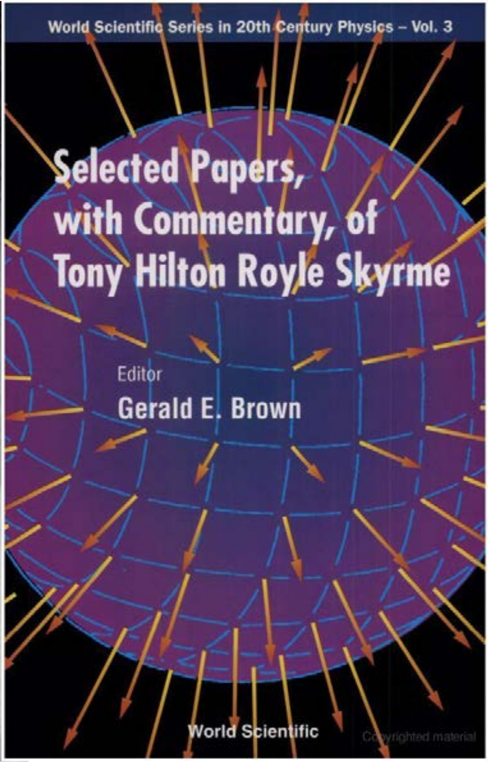
- lattice of magnetic whirls (skyrmion lattice, 2009)
- whirl-lines $\|\mathbf{B}$
  hexagonal lattice $\perp \mathbf{B}$
- length scale in MnSi: $200\,\text{Å}$

Monte Carlo simulation:
Burhandt, Fritz (2013)

skyrmions in chiral magnets



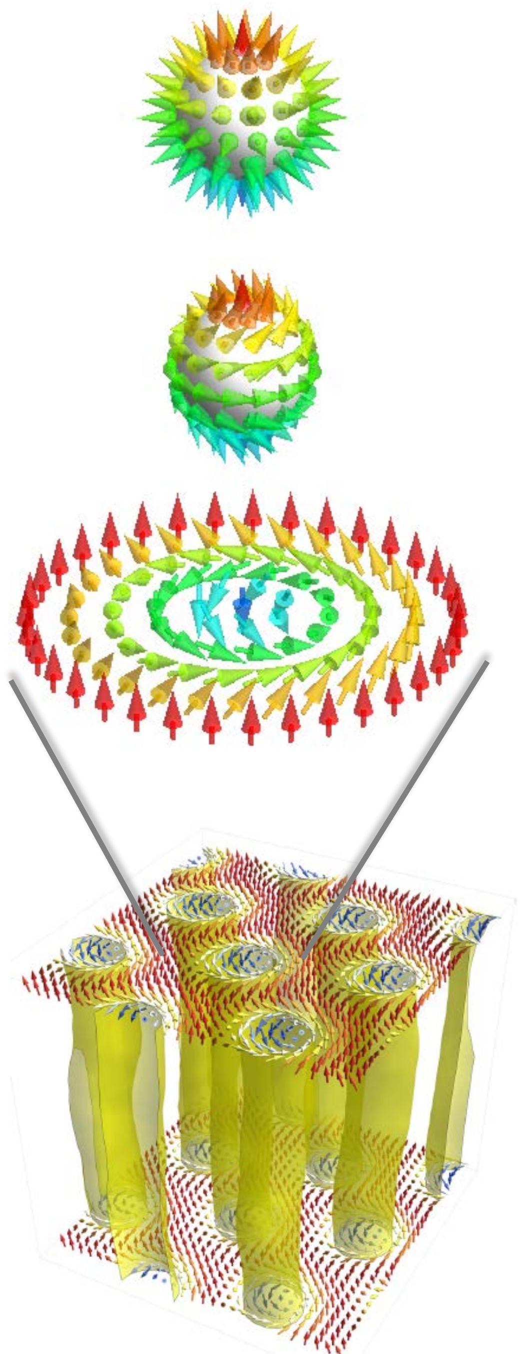
1922-1987



Skyrme (1962):

quantized topological defects in non-linear σ-model (d=3) for pions are baryons, i.e. spin-1/2 **fermions**

skyrmions in chiral magnets:

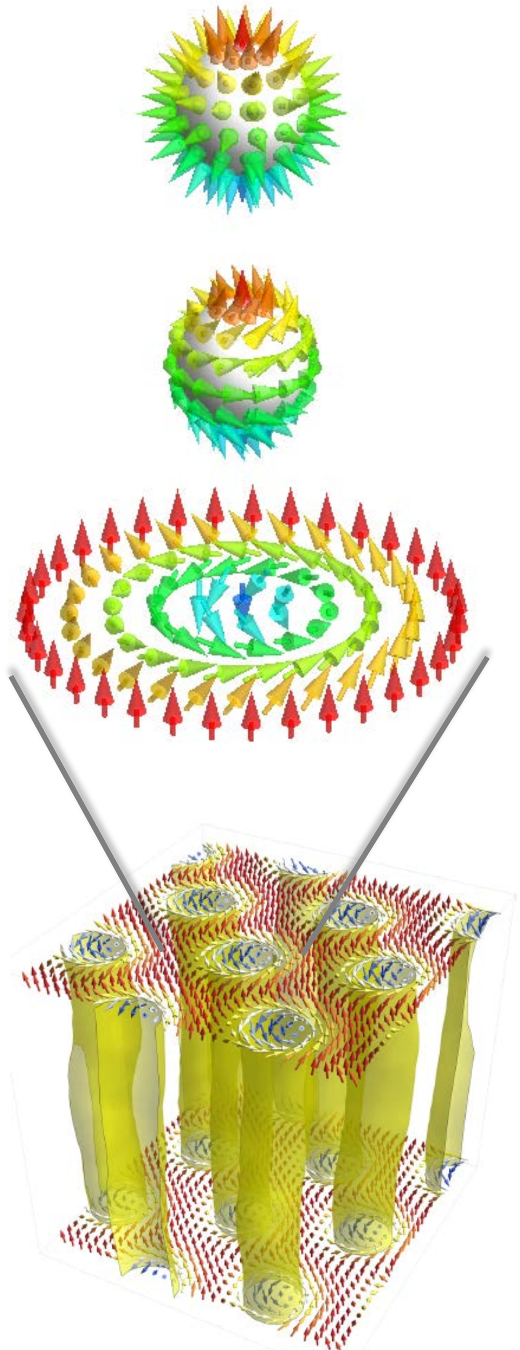


- skyrmion in d=2:
  spin winds once around unit sphere

$$\int \frac{dx\,dy}{4\pi}\ \hat{n}\cdot(\partial_x \hat{n} \times \partial_y \hat{n}) = -1$$

topological quantization

skyrmions in chiral magnets:



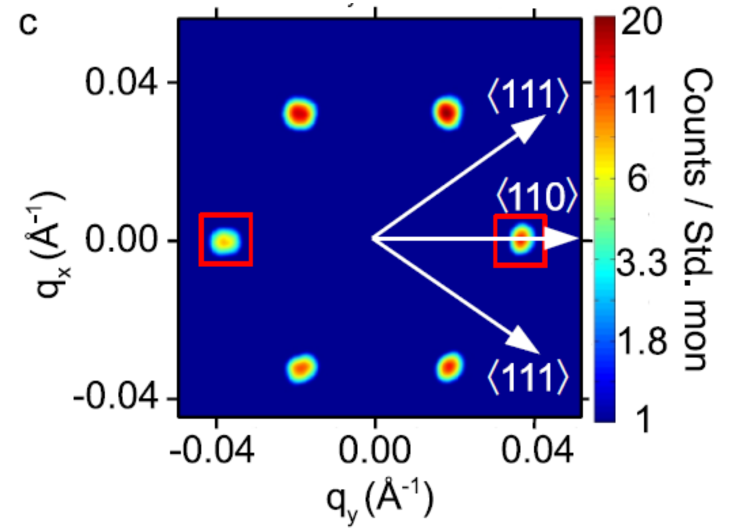
- skyrmion in d=2:
  spin winds once around unit sphere

$$\int \frac{dx\,dy}{4\pi}\ \hat{n}\cdot(\partial_x \hat{n} \times \partial_y \hat{n}) = -1$$

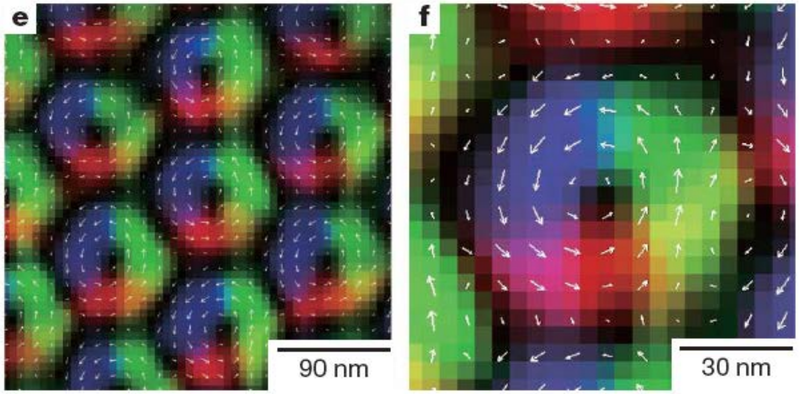
- Bogdanov, Yablonskii (1989): skyrmions metastable in cubic **magnets without inversion symmetry**,
- skyrmions in **quantum Hall systems** close to ν=1
  (Sondhi et al. 1993), lattices (Brey, Fertig, Cote, McDonald 1995, Timm Girvin, Fertig 1998, Green 2000)
  Destrat et al 2002, Gervais *et al.* 2005, Galais *et al.* 2008
- magnetic bubble domains: textures from dipolar interactions
- 2009: experimental discovery in MnSi
  Mühlbauer, A.R. et al. , Science (2009)
- nanoskyrmions at surfaces & writing by spin trasfer torque, Wiesendanger group Hamburg

imaging skyrmions in chiral magnets

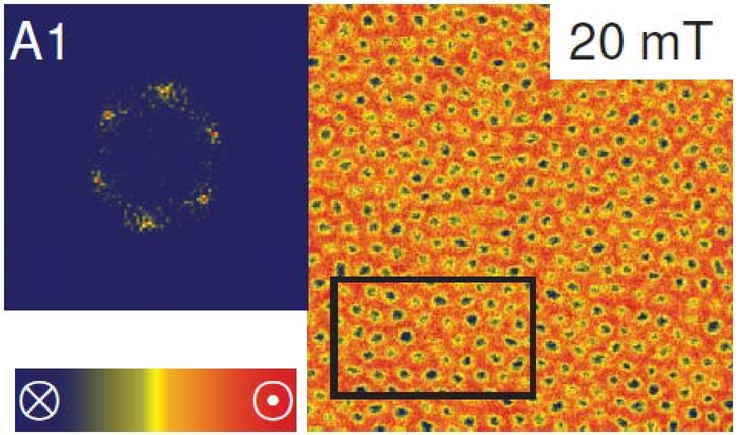
neutron scattering (here MnSi)
Pfleiderer, Böni, et al., 2009-2012



Lorentz transmission electron microscopy, X. Z. Zu et al. 2010
(here: $Fe_{0.5}Co_{0.5}Si$ film)
Tokura group, 2010



magnetic force microscopy
(here: surface of $Fe_{0.5}Co_{0.5}Si$)
Milde, Köhler, Seidel, Eng 2013



theory of skyrmion formation

theory: **generic** phase for all B20 ferromagnets (stabilized by thermal fluctuations in 3D, stable down to T=0 in films)

experiment: **always** observed

many different systems:

MnSi, $Fe_xMn_{1-x}Si$, FeGe, $Fe_xCo_{1-x}Si$, Cu_2OSeO_3 ….

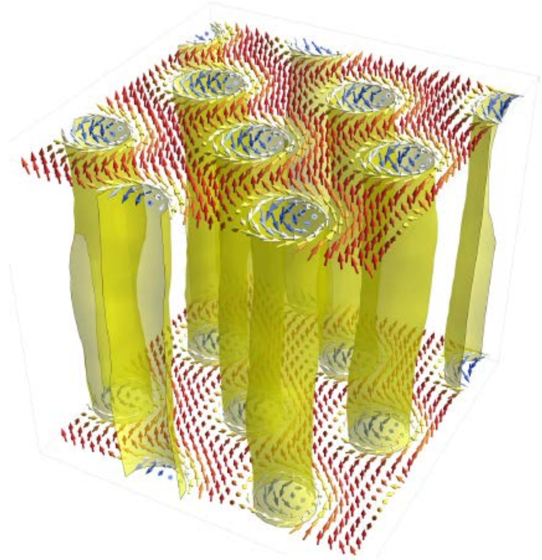
- metals, semiconductors, insulators
- thin films & bulk systems
- low T up to room-temperature
- from 10 to 1000 nm

- manipulation of skyrmions by tiny currents?

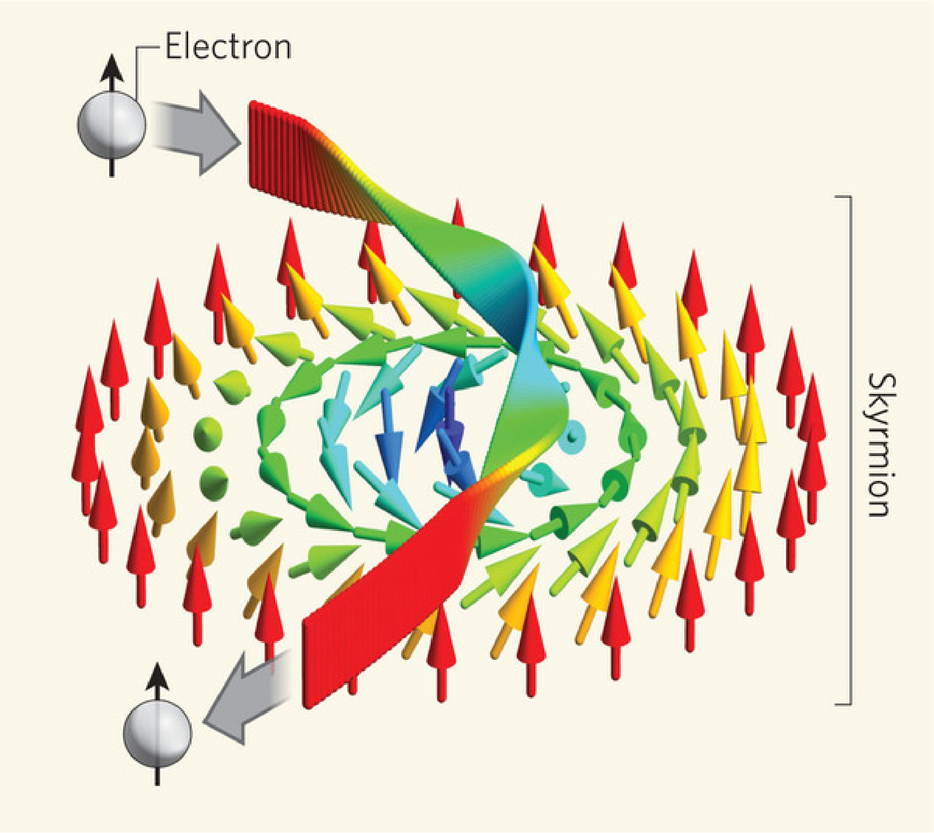
  → emergent electrodynamics

- destroying skyrmions & changing topologogy

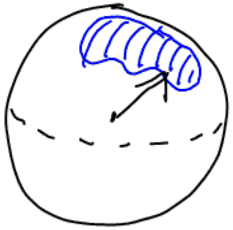
  → magnetic monopoles



coupling of electrons to skyrmions by Berry phases



geometric phase of spin
=
spin size * area on unit-sphere enclosed by spin



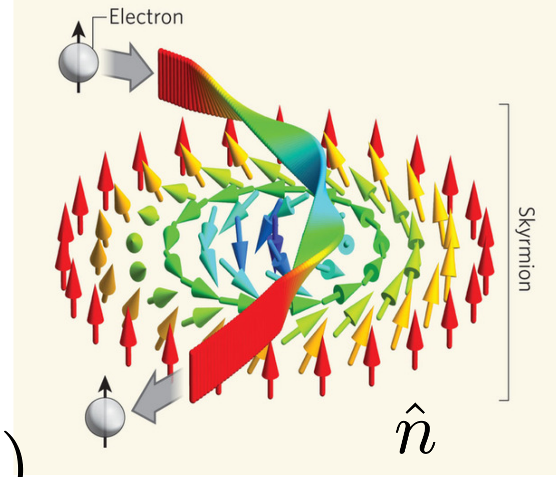
electron spin follows magnetic texture

⇨ Berry phase proportional to winding number

Berry phase as Aharonov Bohm phase ⇨ emergent electrodynamics

Volovik 87

microscopic derivation



electron spins follows adiabatically direction of background magnetization $\hat{n}$

⇒ choose local spin quantization action parallel to $\hat{n}$ by unitary transformation $U(\hat{n})$

rewrite action in new spinless fermion: $\mathbf{d}^\dagger = U^\dagger(\hat{n})c^\dagger U(\hat{n})$

note: ***U*** not unique, U(1) Gauge degree of freedom

to do: gradient expansion of $\int c^\dagger_{\sigma k}(\partial_\tau + \epsilon_k)c_{\sigma k}$

⇒

$$S_B = \int \mathbf{j}^e_\mu \mathbf{A}^\mu_e \, d^3r \, dt$$

$$\mathbf{A}^\mu_e = U^\dagger \partial^\mu U$$

comoving quasiparticles couple to new **emergent electrodynamics**

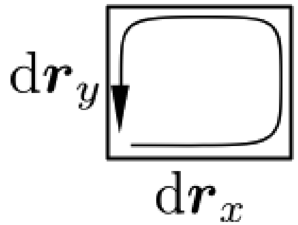
Volovik 87

emergent electrodynamics & topological quantization

- effective electric charge:
  spin parallel/antiparallel to local magnetization
  $$\mathbf{q}^{\mathbf{e}}_{\downarrow/\uparrow} = \mp\frac{1}{2}$$

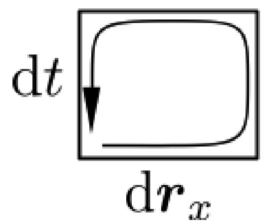
- **emergent magnetic & electric fields**:

  Berry phase for loops in space



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

  Berry phase for loops in space-time



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

- **topological quantization**:
  winding number -1 ⟺ one flux quantum per skyrmion

- more generally: Berry phases in 6-dimensional phase space

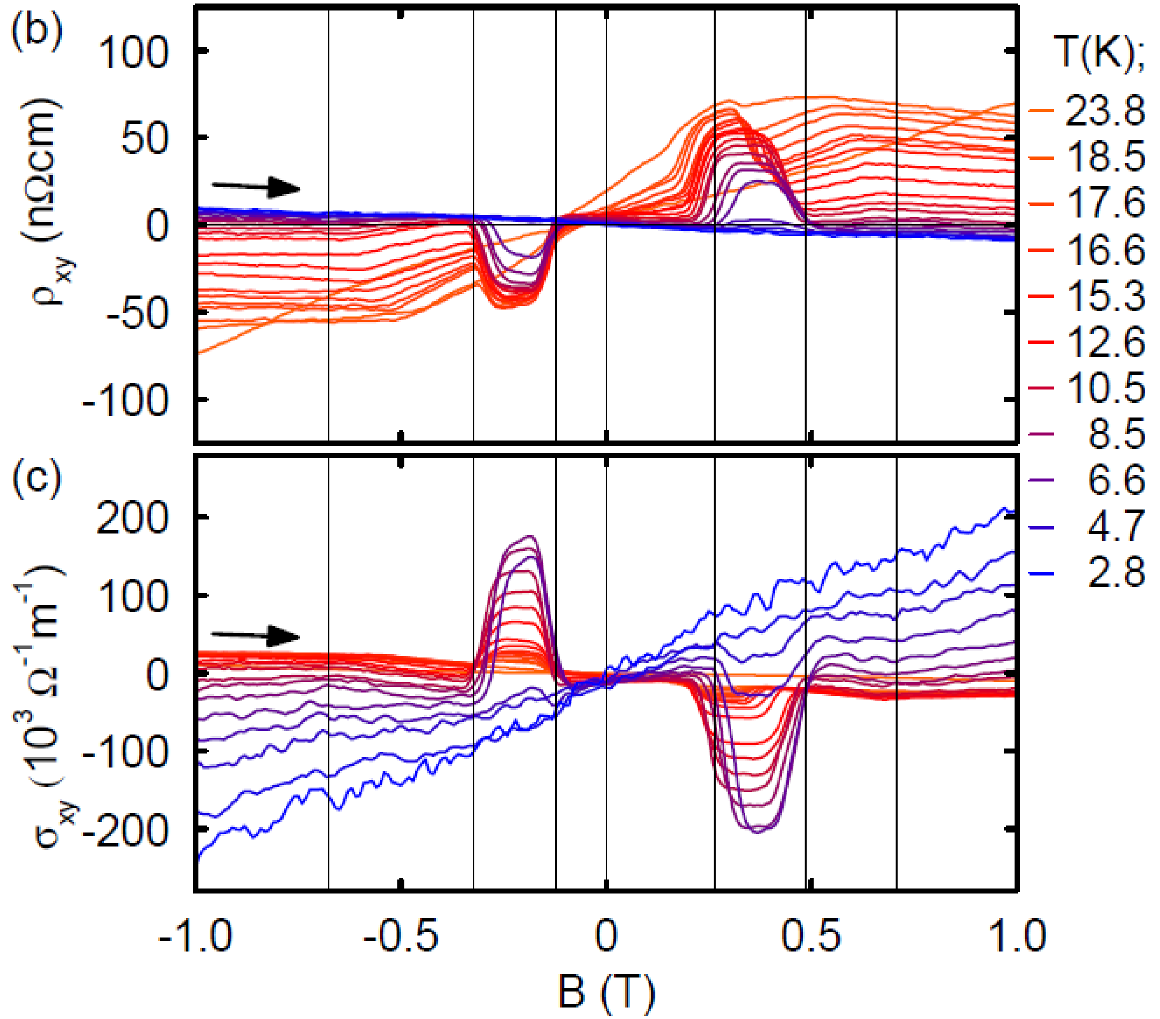
measure skyrmion-winding number by **topological Hall** effect

one flux quantum of emergent magnetic flux per unit cell:

in MnSi

$$\mathbf{B^e} \sim -12\,T$$

Ritz et al. (2013)
A. Neubauer, et al. PRL (2009)



MnSi under pressure (7kbar) for various temperatures emergent **Faraday‘s law of induction**

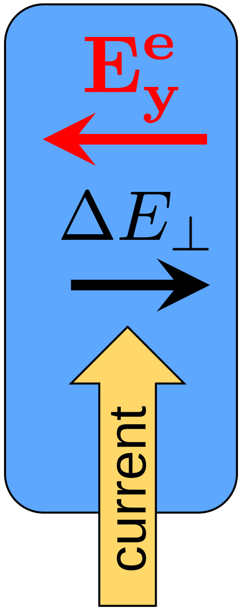
moving magnetic field ⇨ electric field

$$\mathbf{E^e} = -\mathbf{v_d} \times \mathbf{B^e}$$

⇨ detect skyrmion motion

measuring skyrmion motion & emergent **Faraday law**

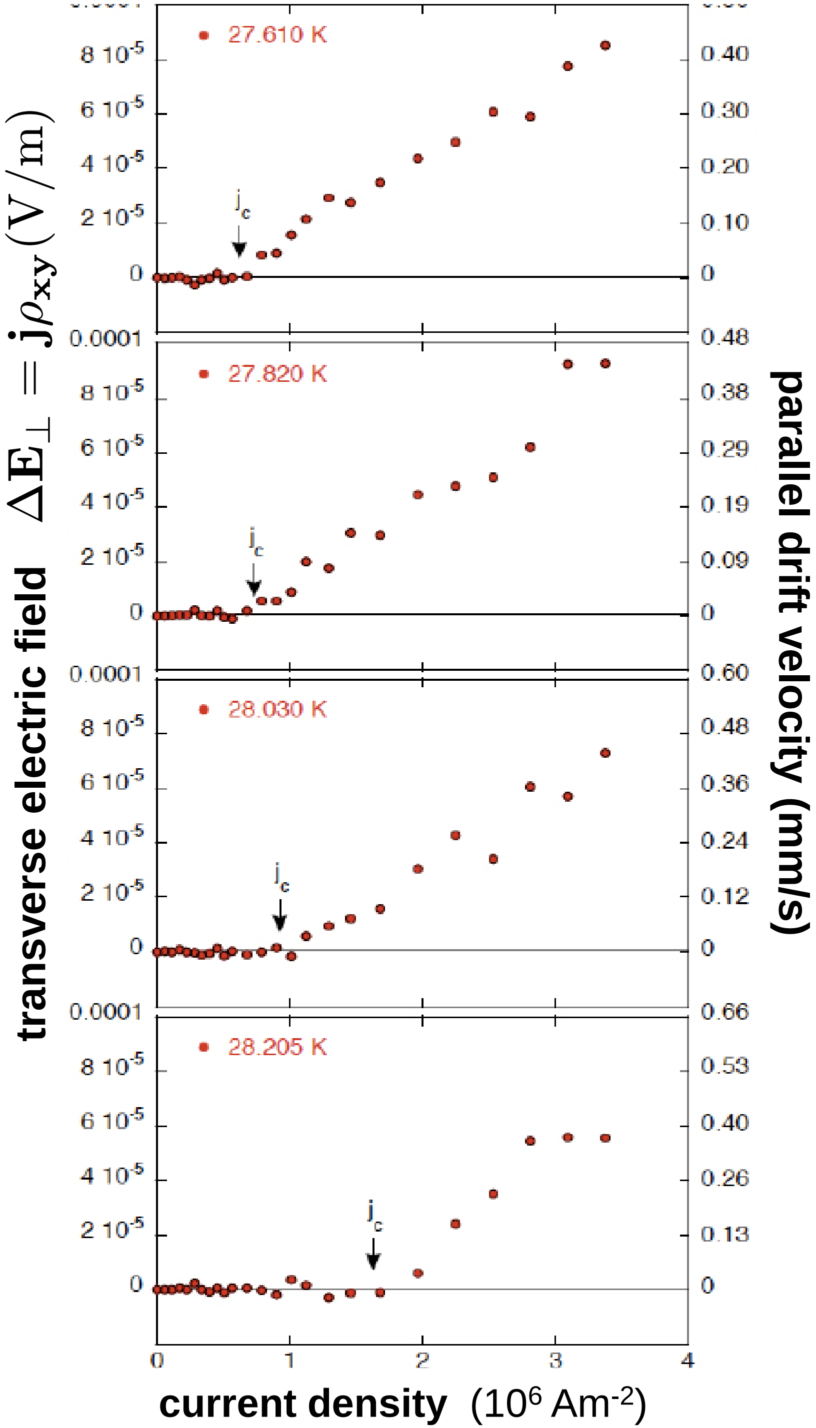
moving skyrmions ⇨ emergent electric field $\mathbf{E^e} = -\mathbf{v_d} \times \mathbf{B^e}$



extra „real“ electric field compensates emergent field

$$\Delta E_\perp \approx -\tilde{P}\,\mathbf{E^e_y}$$

conversion factor:
effective spin polarization $\tilde{P} = \dfrac{\langle\langle j, \mathbf{j^e}\rangle\rangle}{\langle\langle j, j\rangle\rangle}$



skyrmions start to move above ultrasmall critical current density ~ **10^6 Am^{-2}**

critical current **5-6 orders of magnitude smaller** than in typical spin-torque experiments

velocity: comparable to drift velocity of electrons

$$v_{\rm drift} \sim \frac{j}{en} \sim 0.16\, \frac{\rm mm}{s}\, \frac{j}{10^6 Am^2/s}$$

Jonietz, Pfleiderer, A.R., *et al.* (2010)

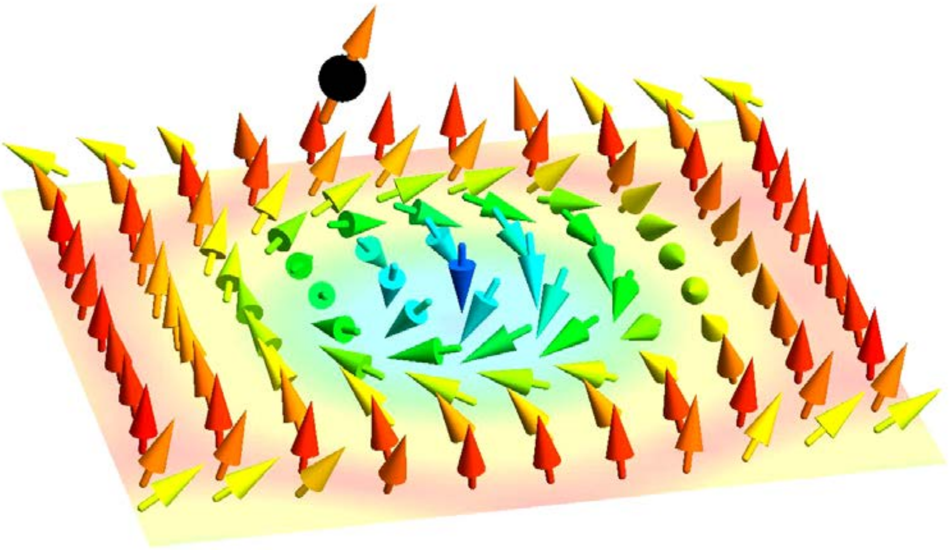
Schulz, Pfleiderer, A.R., *et al.* (2012)

Why ultrasmall critical current densities?

- very **efficient Berry-phase coupling**
  (gyromagnetic coupling by adiabatic spin transfer torques)

- very **weak pinning** due to very smooth magnetic structure

- „**collective pinning**“: pinning forces cancel partially due to rigidity of skyrmion lattice

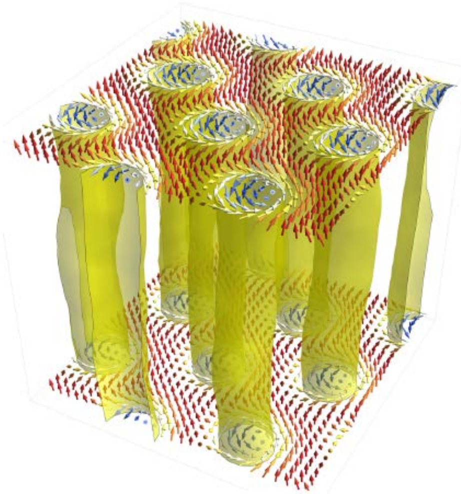


- manipulation of skyrmions by tiny currents?

  ⇨ emergent electrodynamics

- destroying skyrmions & changing topologogy

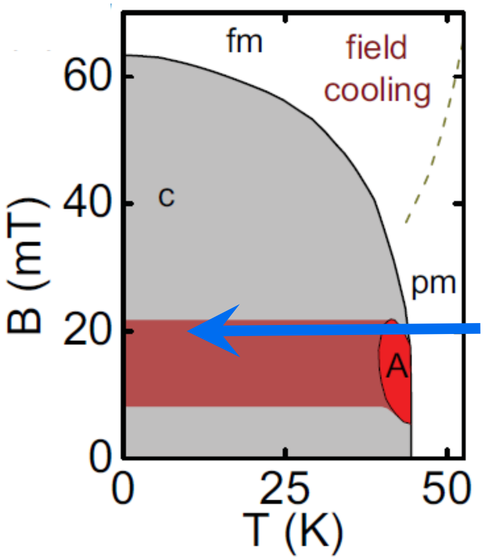
  ⇨ magnetic monopoles



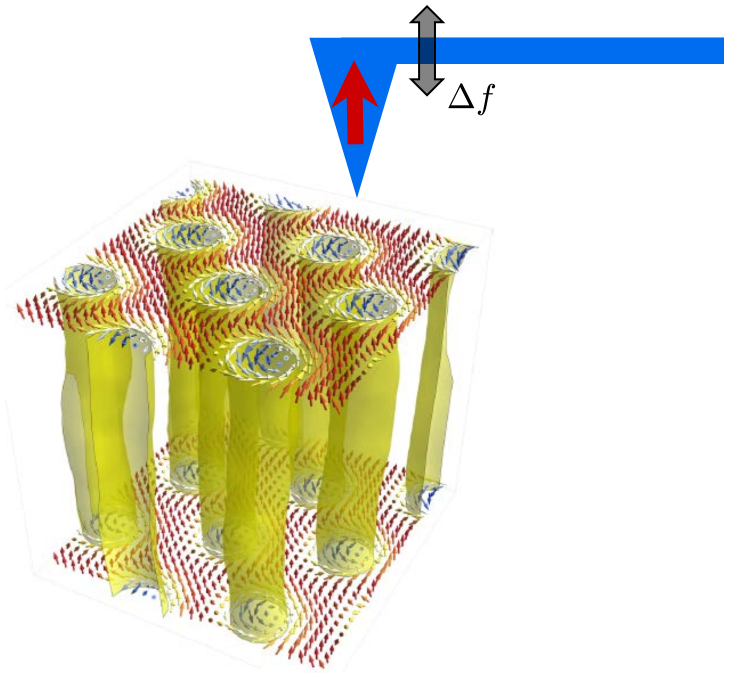
destruction of the skyrmion phase

experiment: track by magnetic force microscopy skyrmions on surface of $Fe_{0.5}Co_{0.5}Si$

Milde, Köhler, Seidel, Eng, TU Dresden



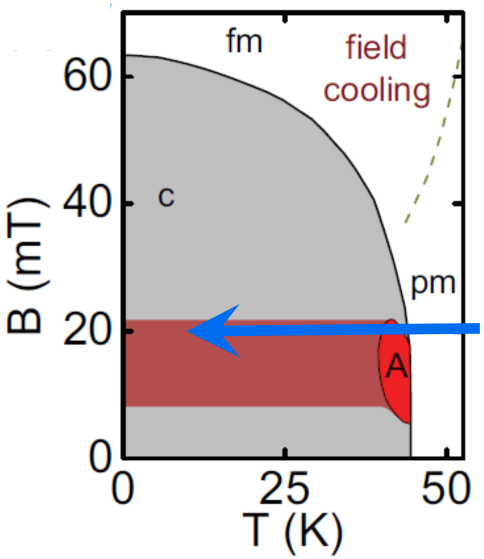
step 1: cool system down to 10 K at B=20 mT
measure z-component of magnetization
by **magnetic force microscopy**



destruction of the skyrmion phase

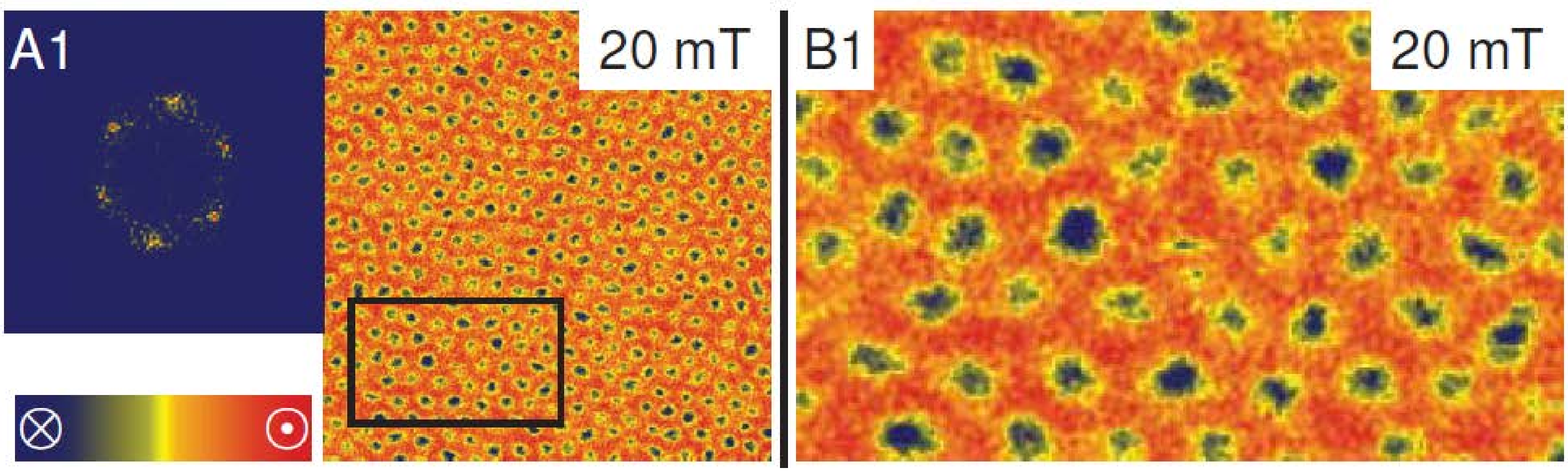
experiment: track by magnetic force microscopy skyrmions on surface of $Fe_{0.5}Co_{0.5}Si$

Milde, Köhler, Seidel, Eng, TU Dresden



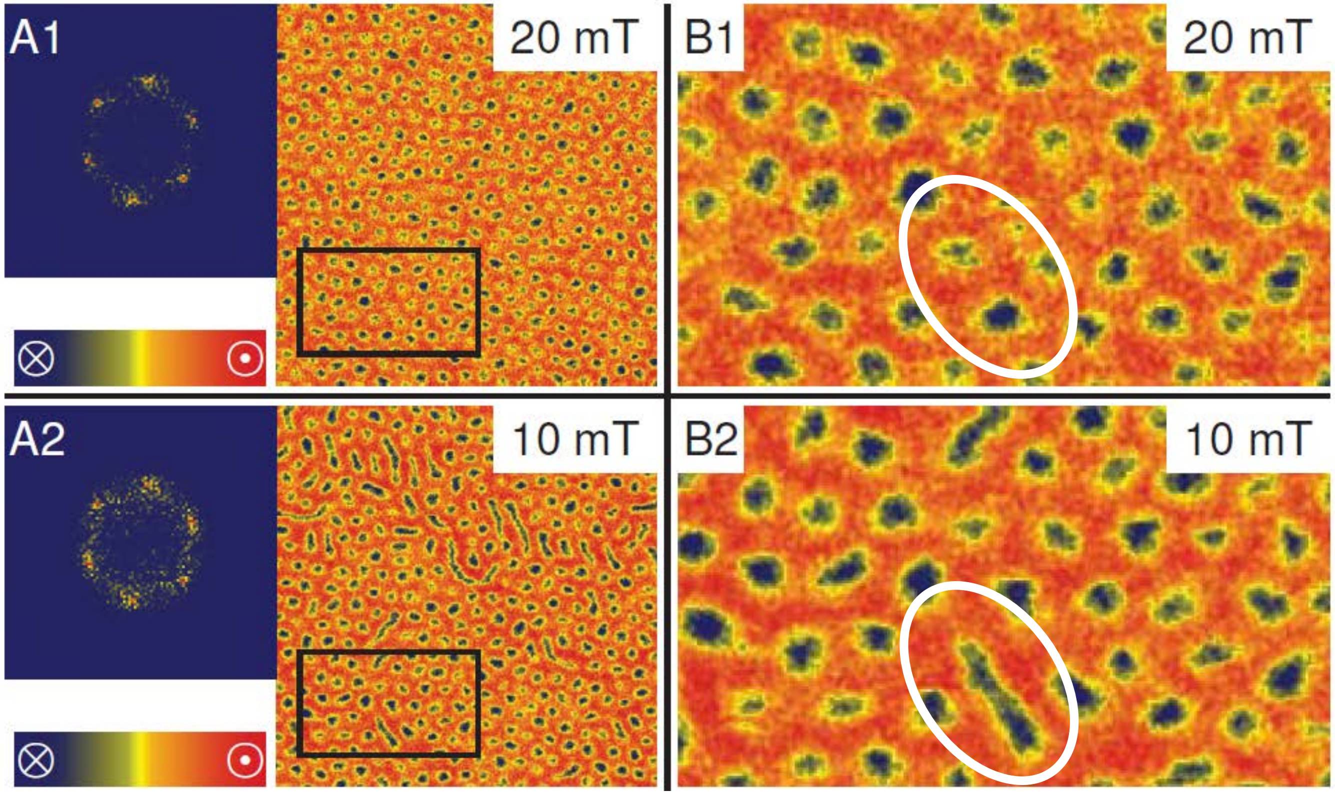
step 1: cool system down to 10 K at B=20 mT
measure z-component of magnetization
by **magnetic force microscopy**

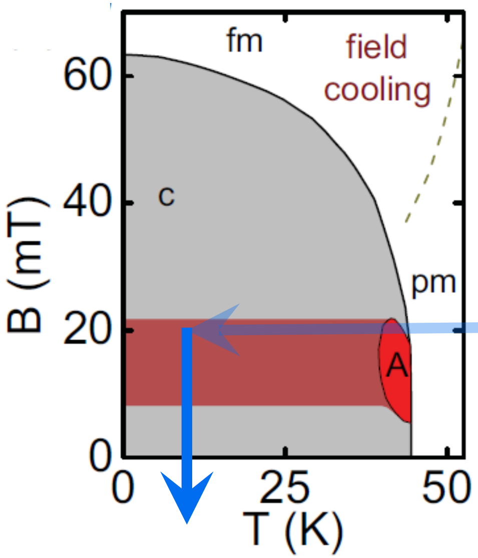
result: metastable skyrmion lattice, slightly disordered
good contrast due to low temperature
few fluctuations (high topolog. stability)



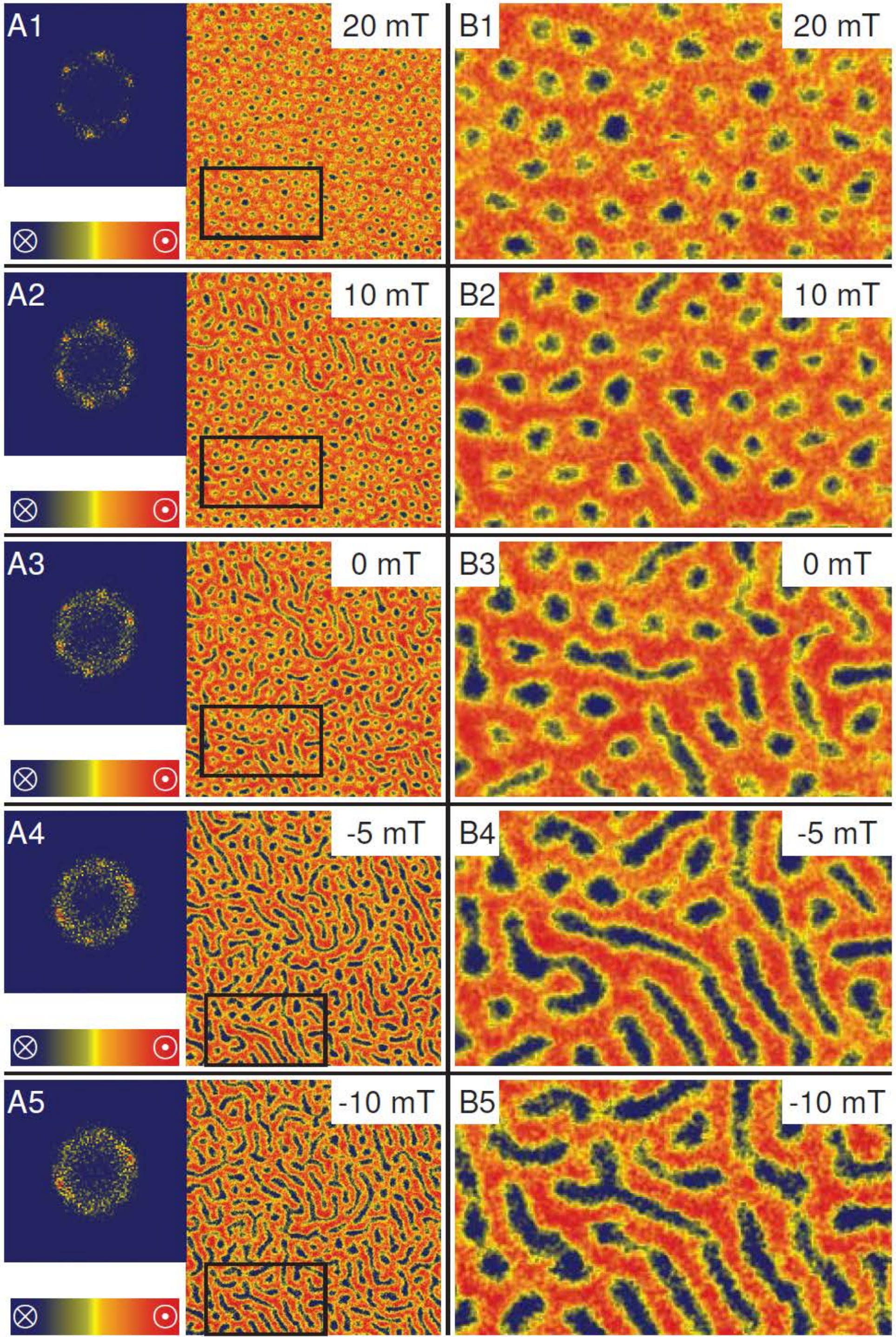
destruction of the skyrmion phase

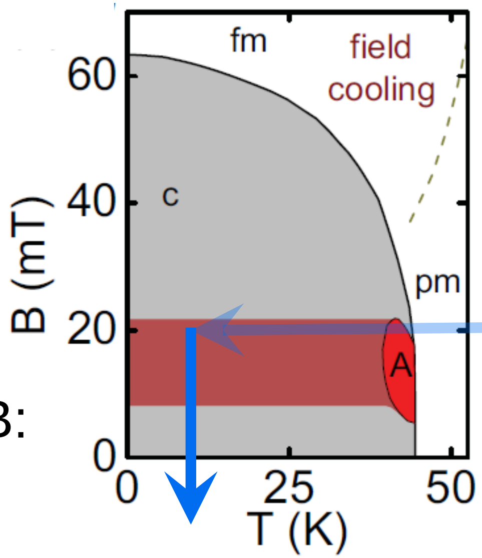
step 2: destroy skyrmion lattice by reducing B-field





observation:
neighboring skyrmions merge, forming elongated objects



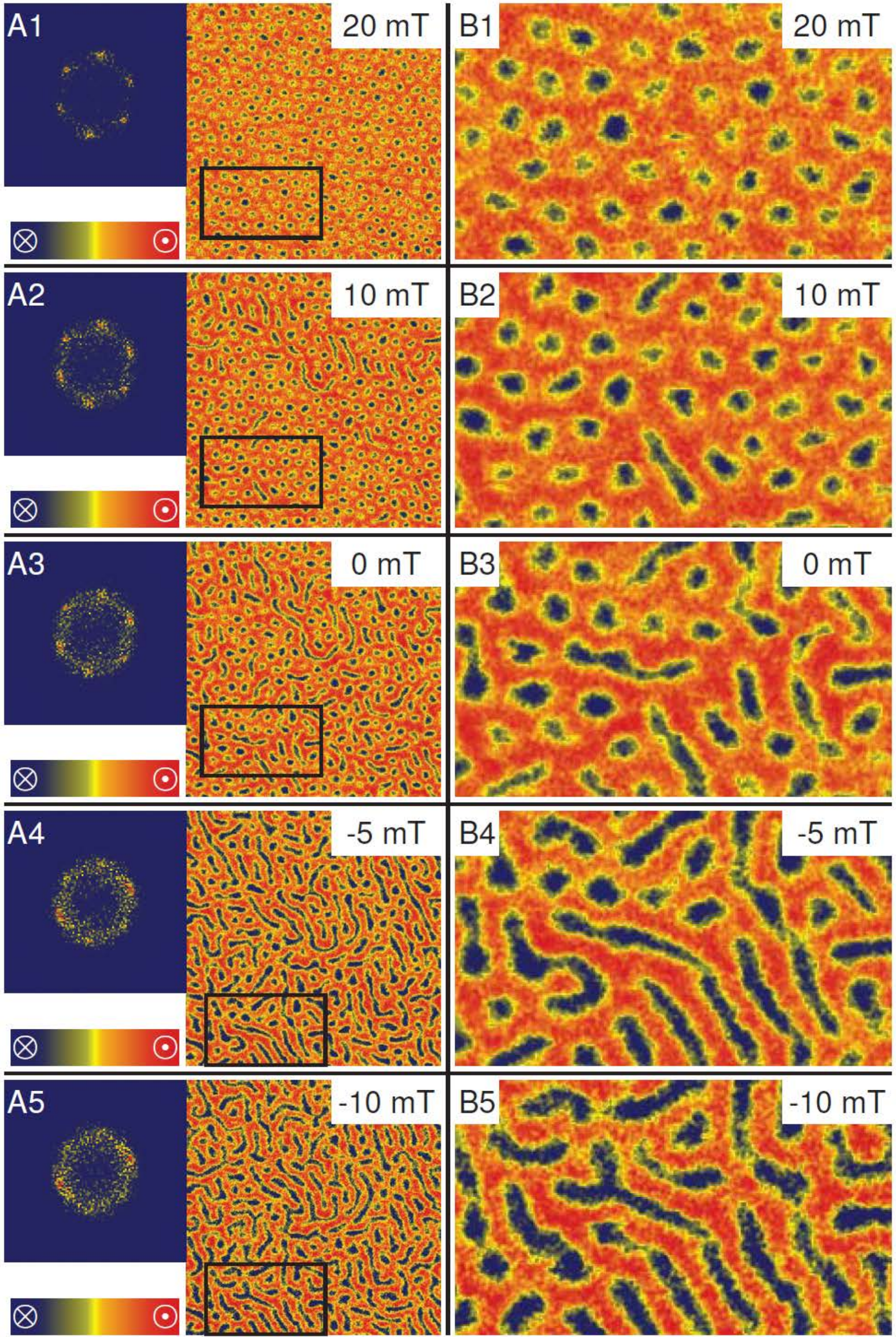


further reducing B:

longer and longer linear structures form by combining skyrmions

realizing helical state with large number of defects

← local helix



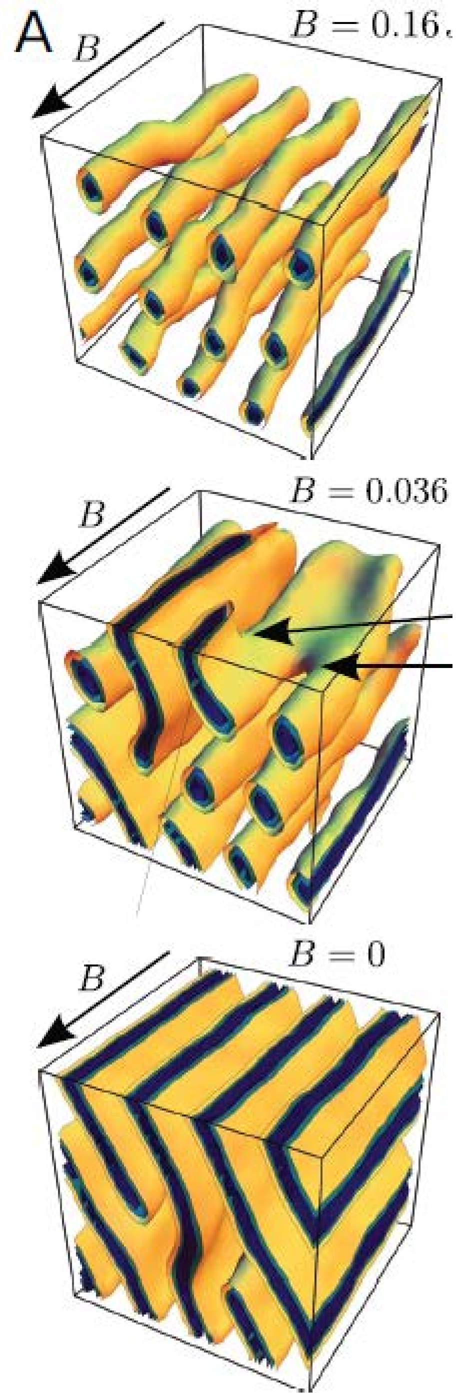
What happens in the bulk?

How does topology change ?

numerical simulations

- Monte Carlo simulations of 30x42x42 classical spins with **local** updates to track metastable state
- Micromagnetic simulations of stochastic Landau-Lifshitz Gilbert equations **including thermal fluctuations**
- follow experimental protocol
- no disorder

surface reflects bulk behavior



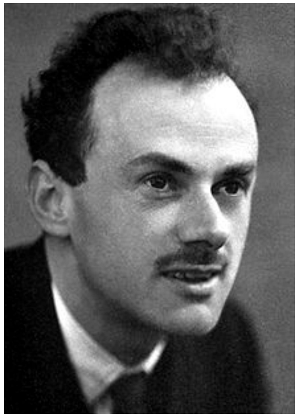
emergent electrodynamics:

winding number of skyrmions
=
one flux quantum of emergent magnetic field

needed to change winding number:

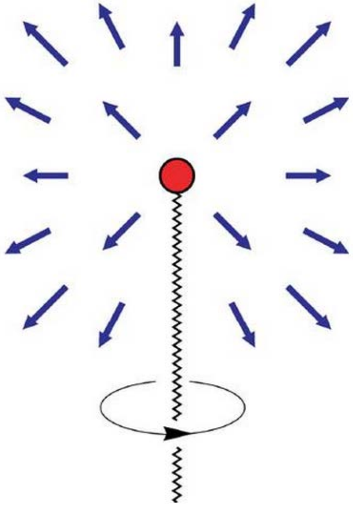
sources and sinks of emergent magnetic field
=
quantized magnetic charges
=
emergent magnetic monopoles and antimonopoles

Historical remarks on magnetic monopoles



Paul Dirac (1931):

why is charge quantized?
magnetic charge = magnetic monopole
would enforces charge quantization



„Dirac string“ invisible only if both electric and magnetic charge are quantized

$$\mathbf{q_m} = n\frac{2\pi\hbar}{\mathbf{e}} \quad \Leftrightarrow \quad \mathbf{e} = n\frac{2\pi\hbar}{\mathbf{q_m}}$$

merging of two skyrmions

- winding number changes from -2 to -1 (top to bottom)

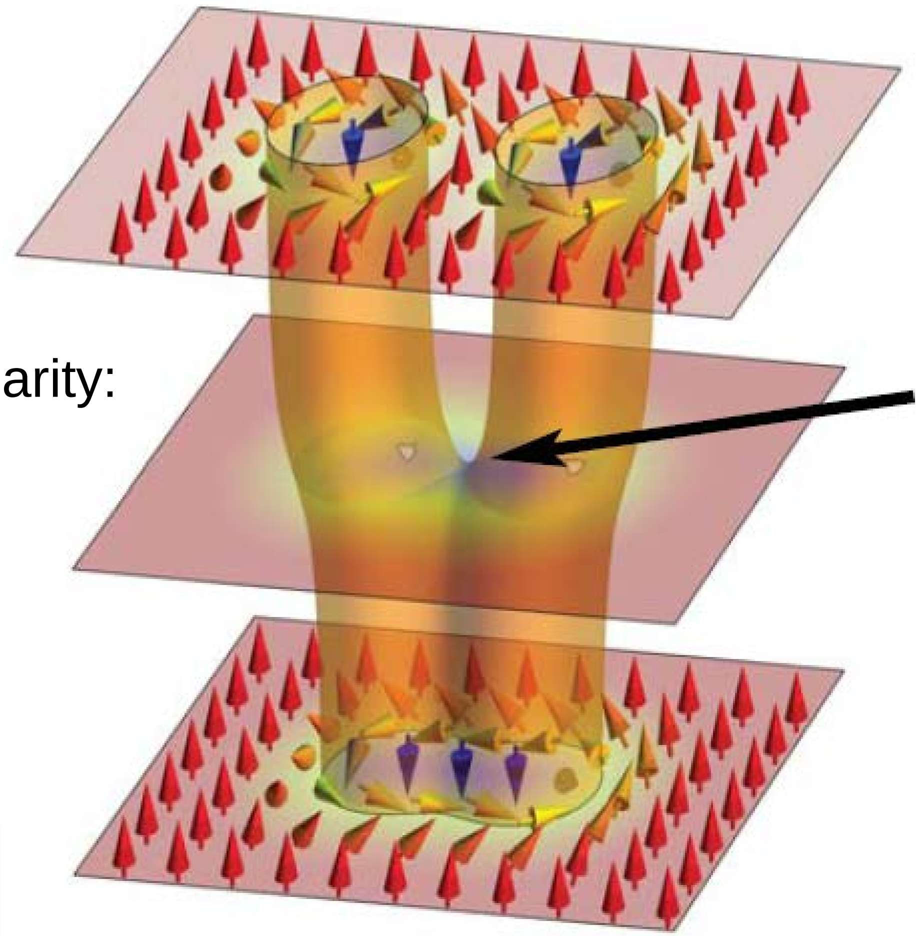
⇨ singularity with **vanishing magnetization**, ***M=0***

- for closed surface encircling singularity: calculate total flux

$$\oint_{\partial\Omega} \mathbf{B_e} d\mathbf{S} = \int_{\mathbf{\Omega}} \nabla \mathbf{B_e}$$

- incoming: two flux quanta
outgoing: one flux quantum

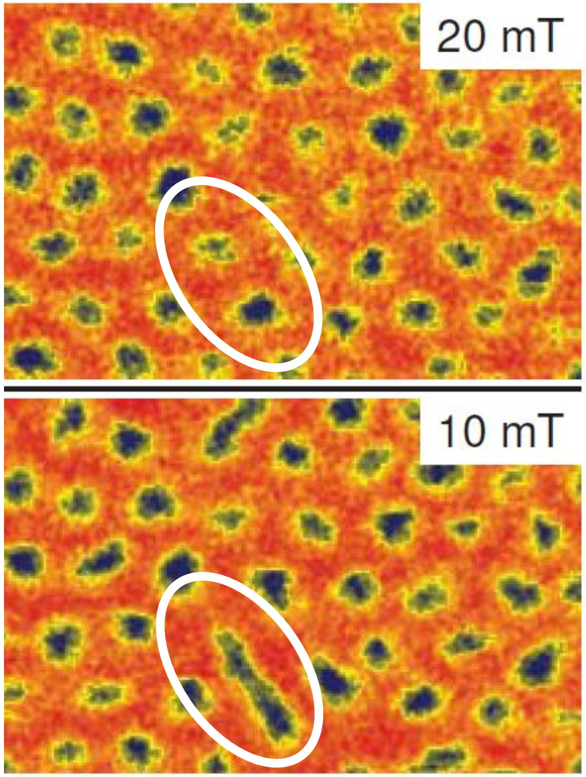
⇨ **singularity = emergent magnetic antimonopoles**

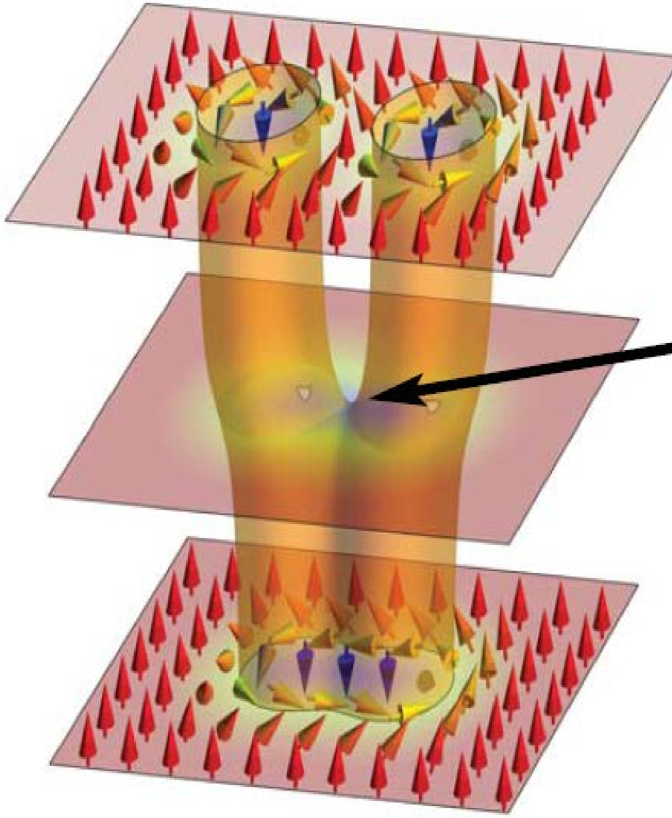


follows Dirac's quantization rule but generically NOT deconfined

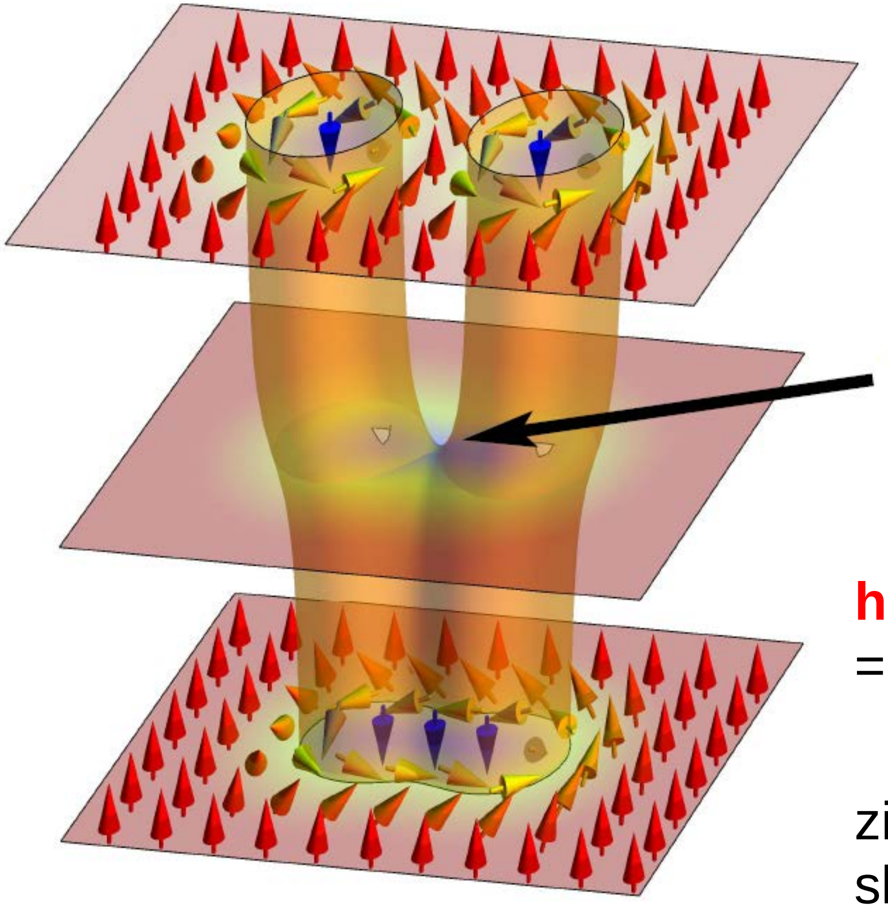
merging of two skyrmions

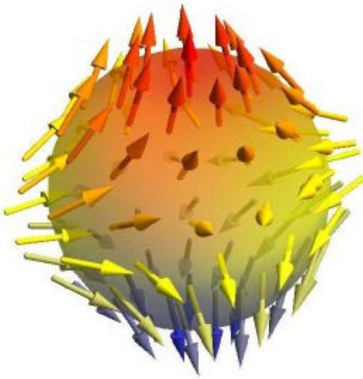
either **antimonopole** flying out of the surface or **monopole** flying into the surface





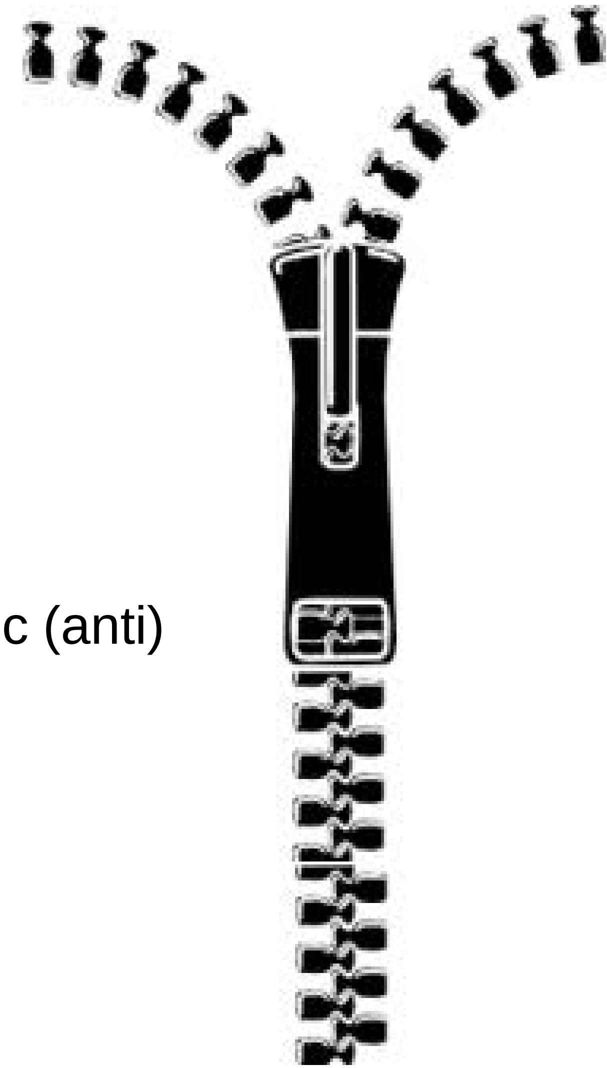
merging of two skyrmions





hedgehog defect
= emegent magnetic (anti)
monopole

zipps two
skyrmions
together



Energetics & dynamics of monopoles

Landau Lifshitz Gilbert equation including thermal fluctuations:

$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times [\mathbf{B}_{eff} + \mathbf{b}_{fl}(t)] - \gamma \frac{\lambda}{M} \mathbf{M} \times (\mathbf{M} \times [\mathbf{B}_{eff} + \mathbf{b}_{fl}(t)])$$

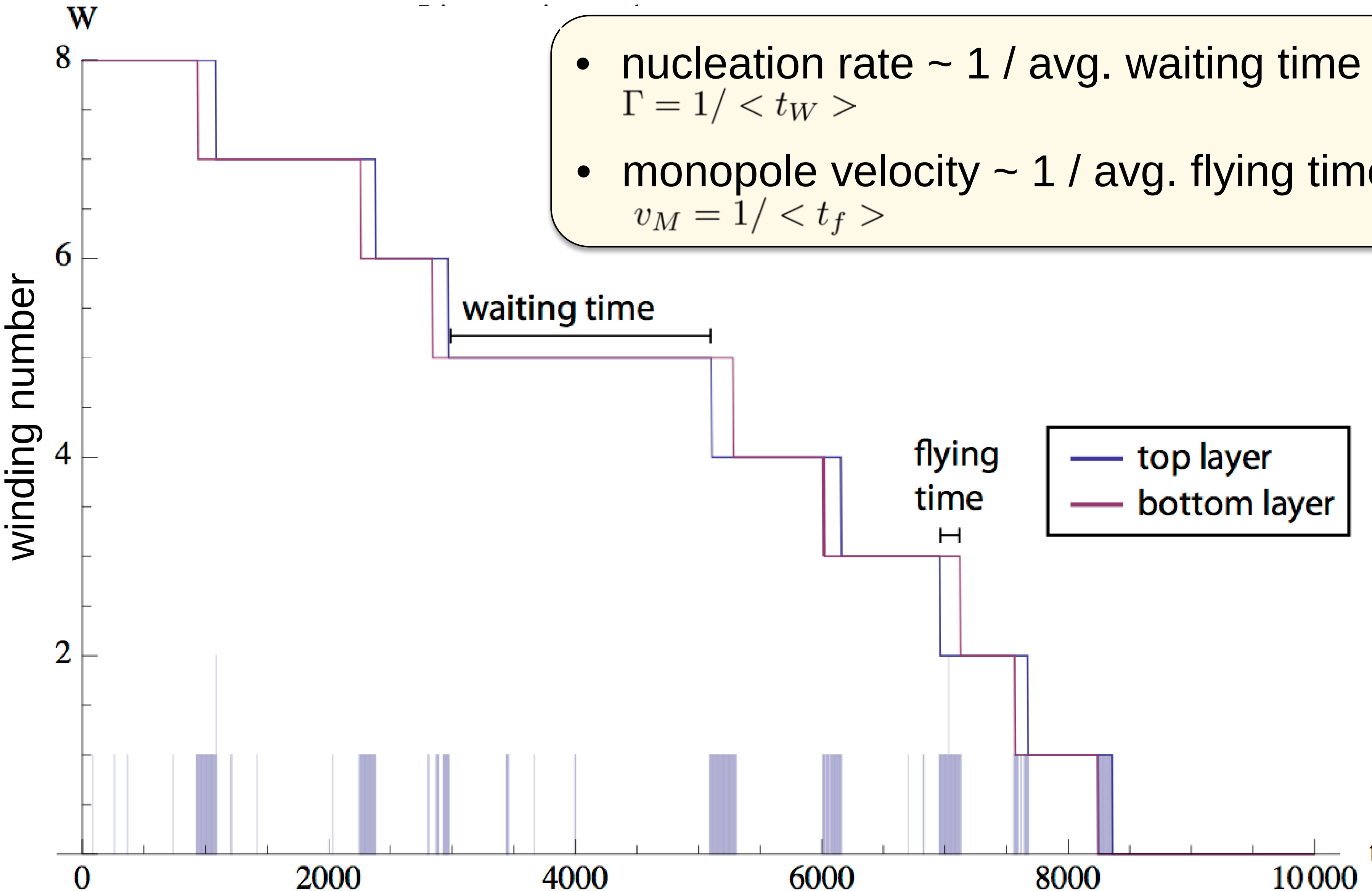
with $< b_{fl,i}(t) >= 0$ $\quad < b_{fl,i}(t) b_{fl,j}(t') >= 2D\delta_{i,j}\delta(t-t')$

$$D = \frac{\lambda}{1+\lambda^2}\frac{k_B T}{\gamma M}$$

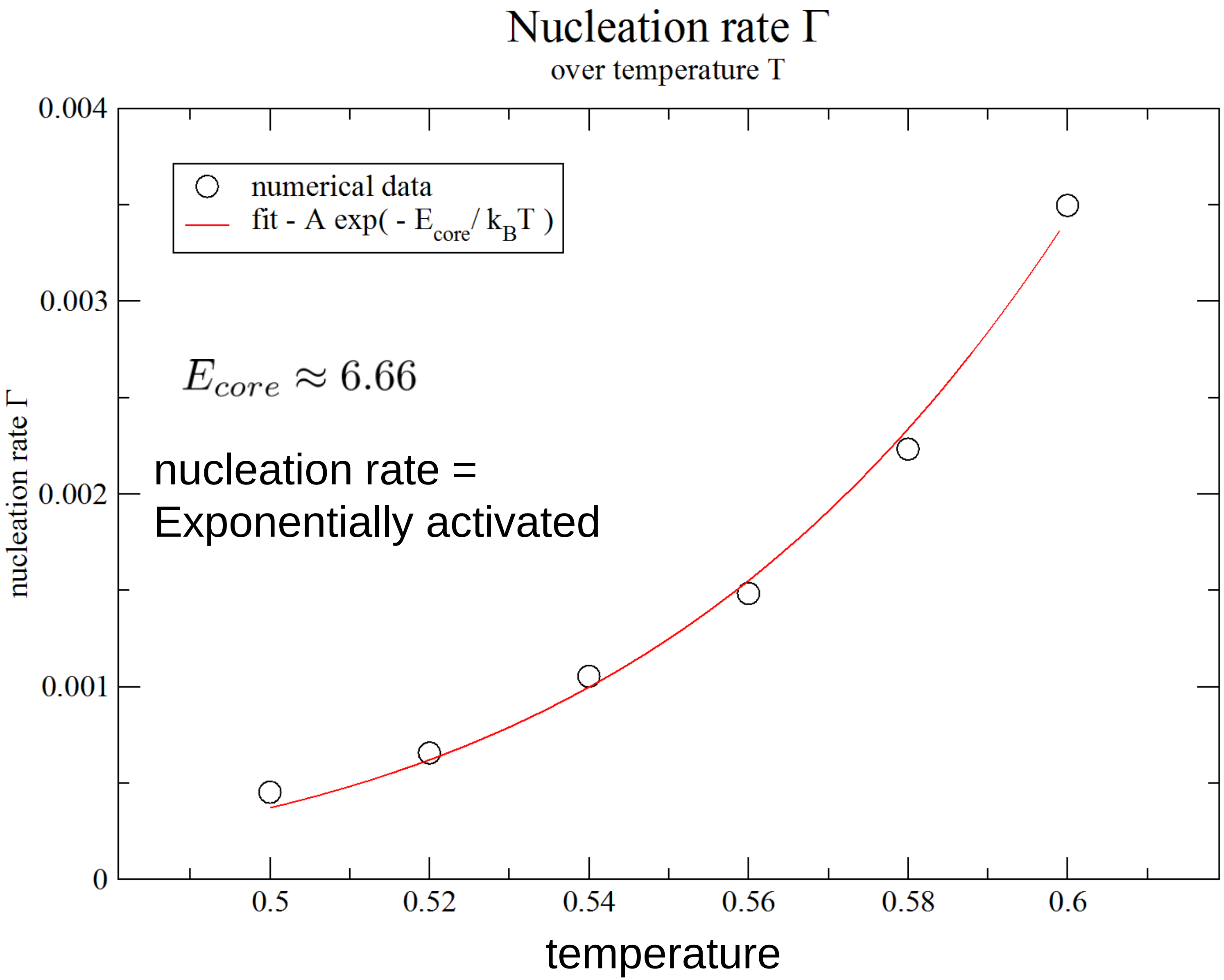
[1] Garcia-Palacios, Lazaro, PRB **58**, 14940 (1998)

Energetics & dynamics of monopoles: B-field quench

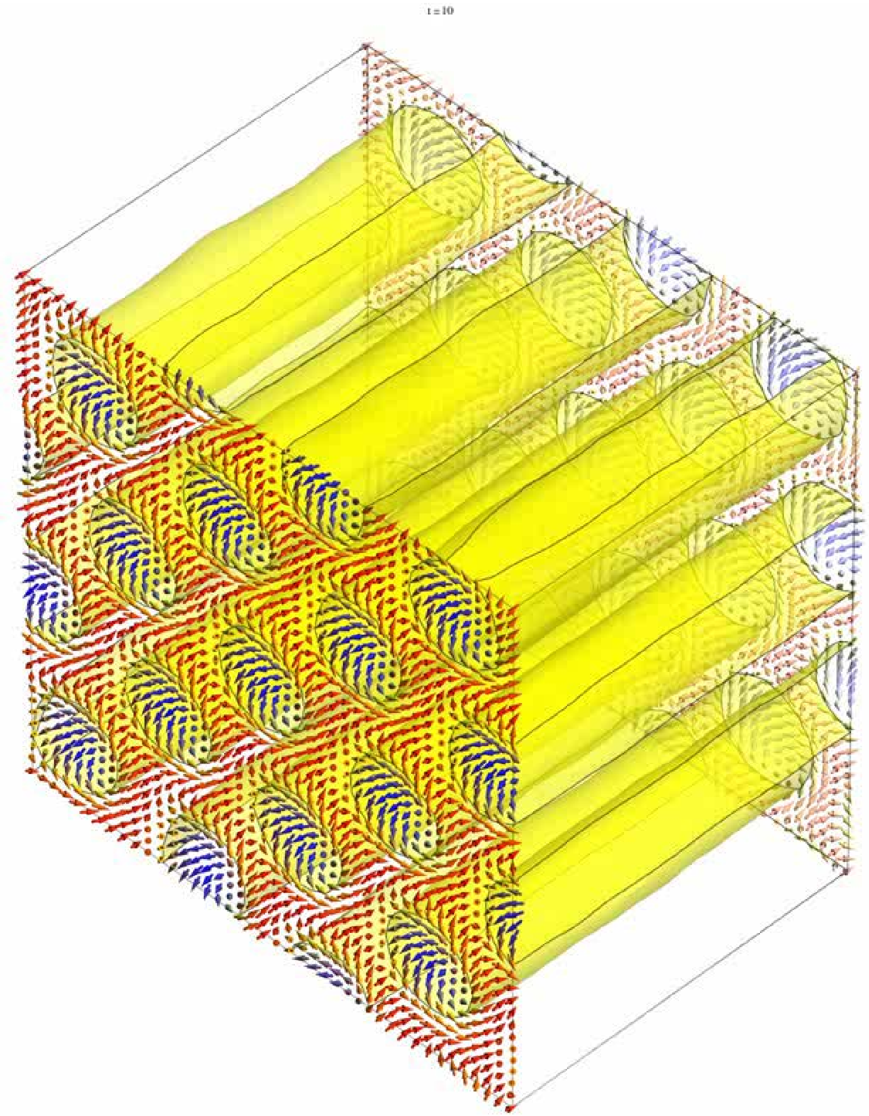
- nucleation rate ~ 1 / avg. waiting time
  $\Gamma = 1/ < t_W >$
- monopole velocity ~ 1 / avg. flying time
  $v_M = 1/ < t_f >$



Energetics & dynamics of monopoles: B-field quench



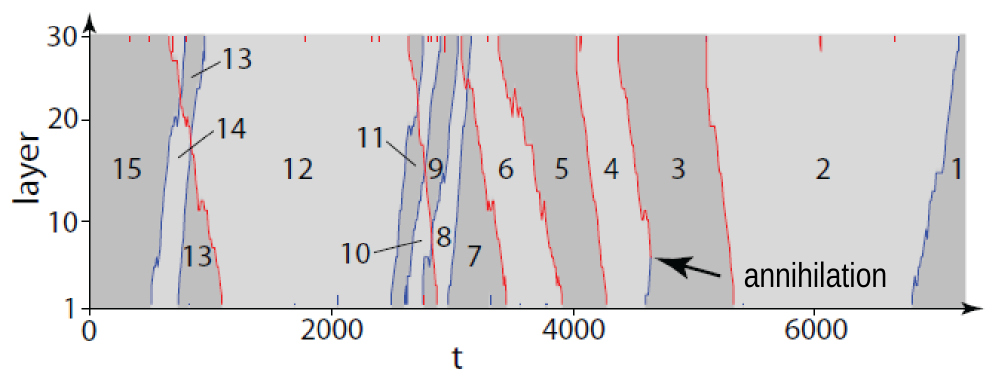
phase conversion with **monopoles** and **antimonopoles**

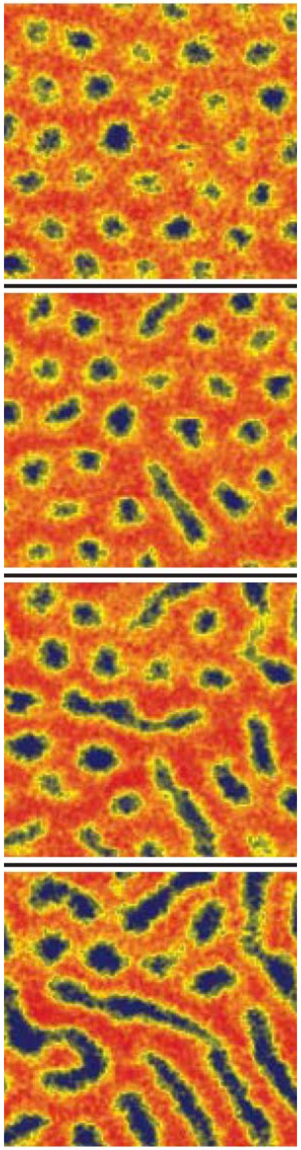


- stochastic Landau-Lifshitz-Gilbert dynamics (including thermal noise)
- spheres: single monopoles

- **antimonopoles** move up
  monopoles move down

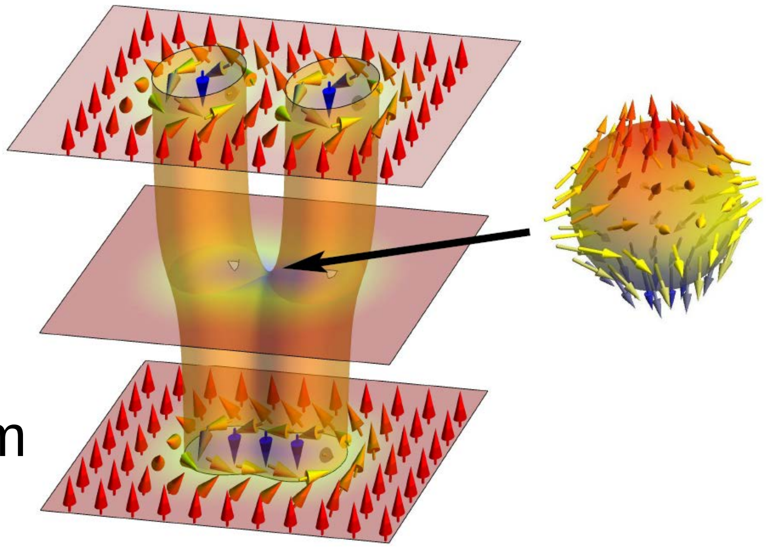
Milde, Köhler, Seidel, Eng, Bauer, Chacon, Pfleiderer, Buhrandt, A. R., 2013





conclusions

- skyrmions universal in chiral magnets
- easy to move around with ultrasmall currents
- Berry phase coupling: emergent electromagnetism
- phase conversion: emergent magnetic monopoles zipping skyrmions together
- MFM: ideal tool to track skyrmions



outlook: exotic non-Fermi liquid phase at high pressure in MnSi: deconfined monopoles & antimonopoles ?

Mühlbauer, Binz, Jonietz, Pfleiderer, A. R., Neubauer, Georgii, Böni, Science (2009)
Jonietz, Mühlbauer, Pfleiderer, Neubauer, Münzer, Bauer, Adams, Georgii, Böni, Duine, Everschor, Garst, A.R., Science (2010).
Schulz, Ritz, Bauer, Halder, Wagner, Franz, Pfeiderer, Everschor, Garst, A.R., Nature Physics, (2012)
Milde, Köhler, Seidel,Eng, Bauer, Chacon, Pfleiderer, Buhrandt, A. R., Science (2013)