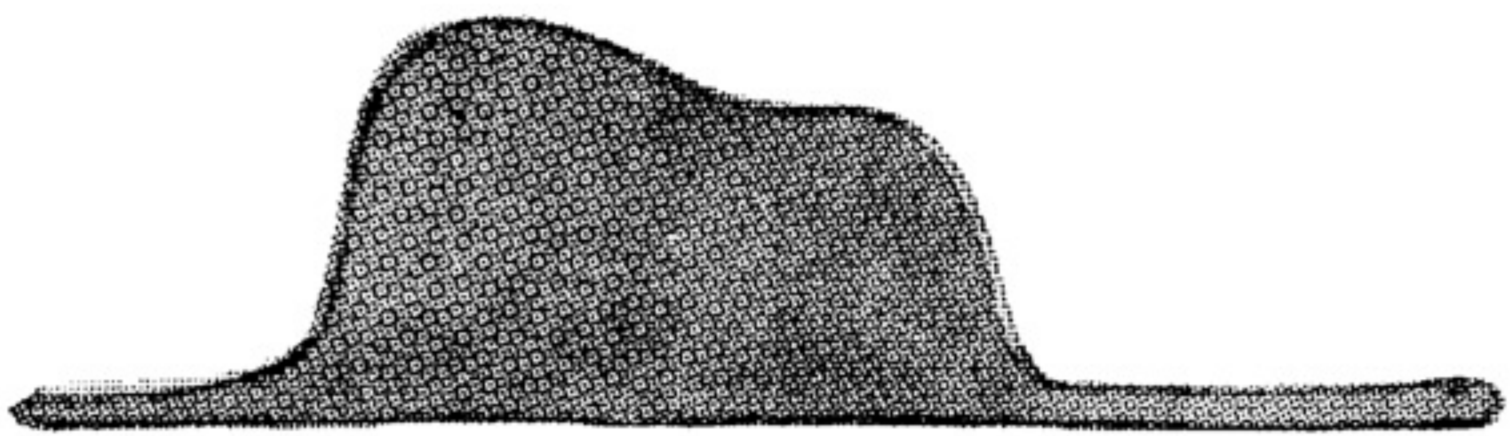
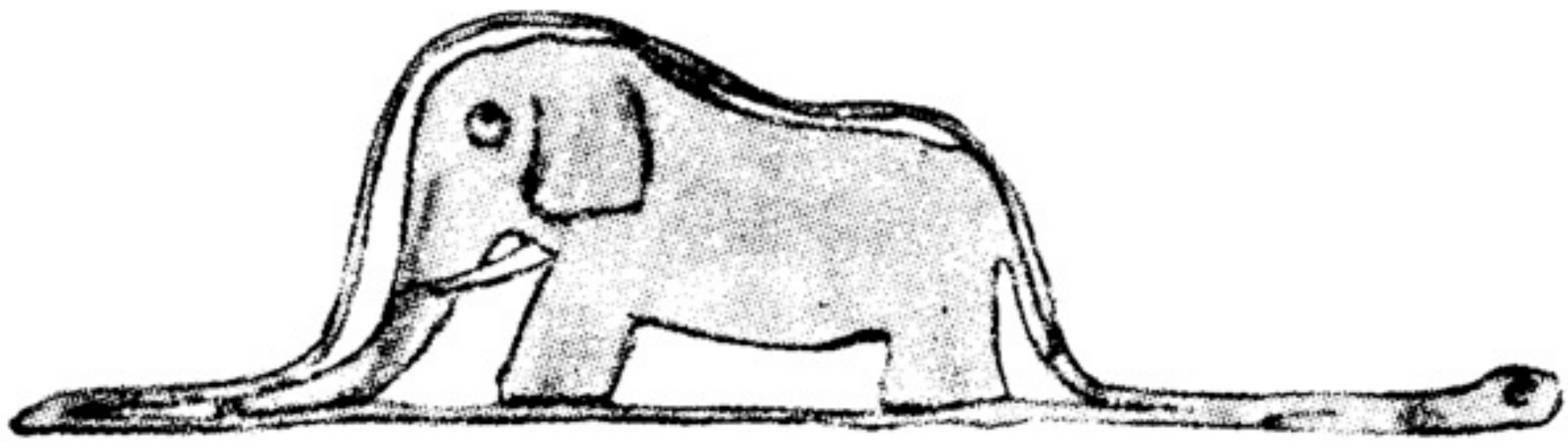
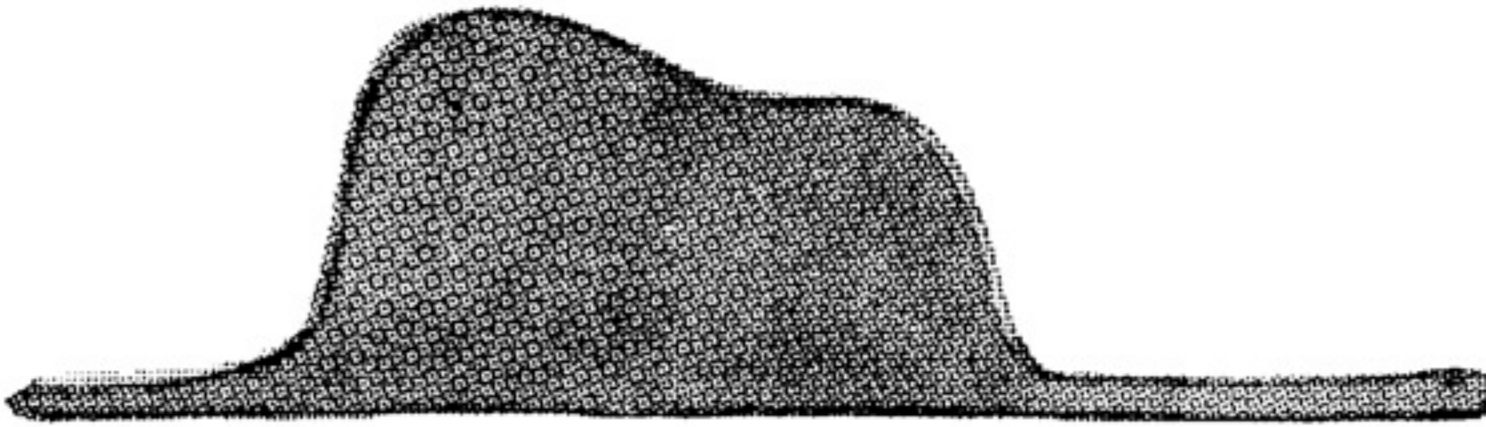
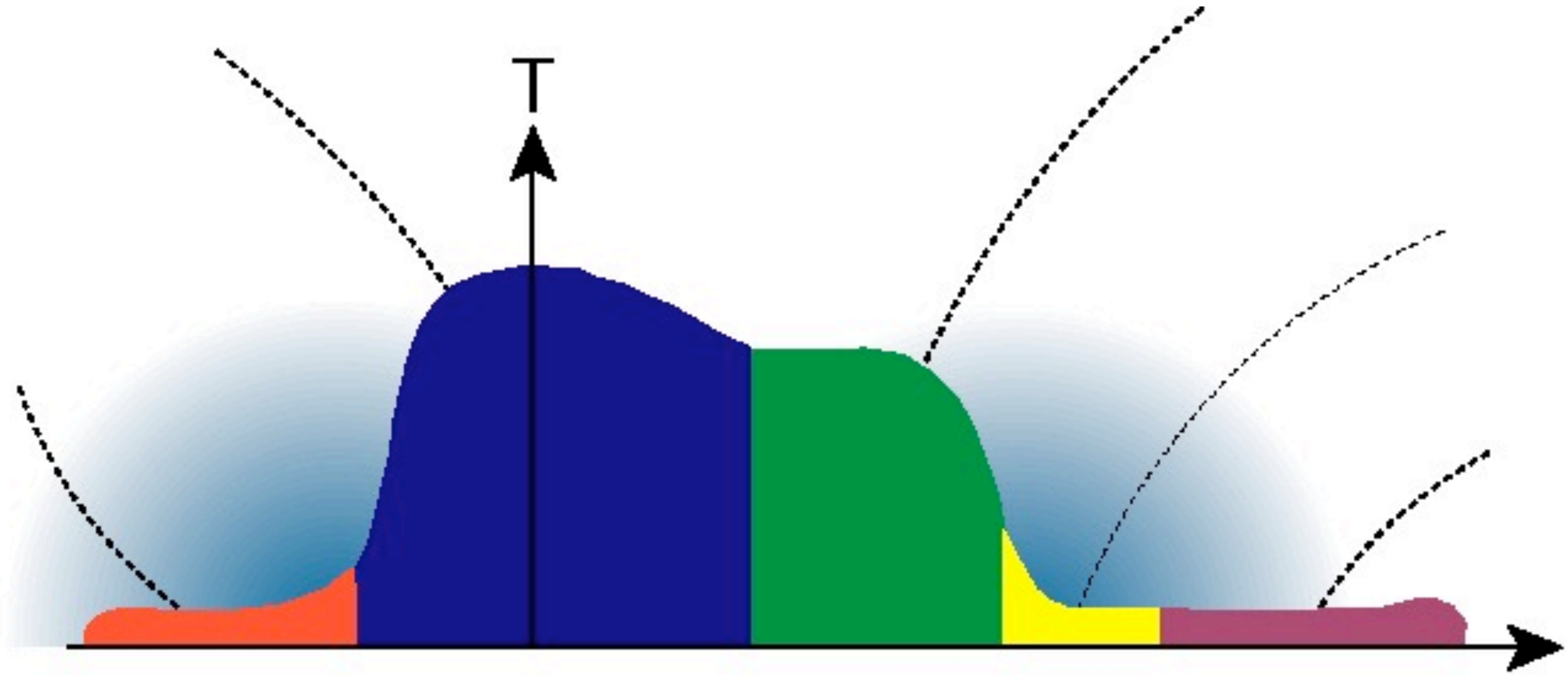


A. de Saint-Exupéry (1943)



A. de Saint-Exupéry (1943)

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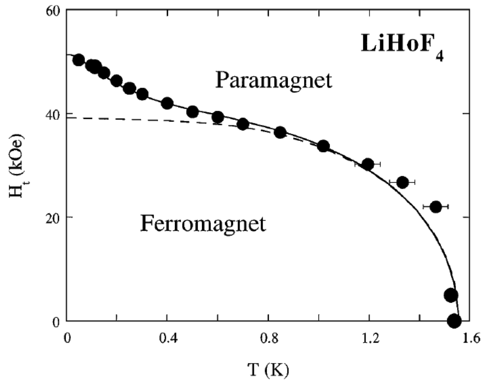
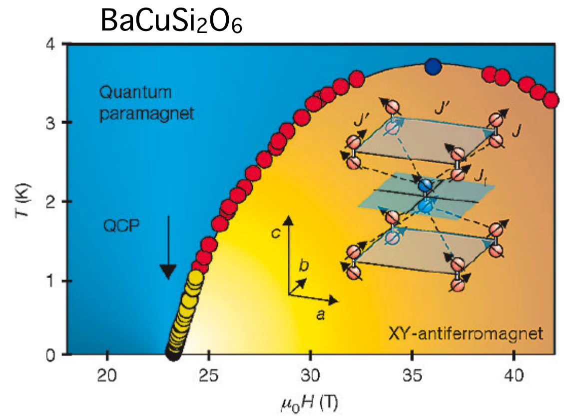
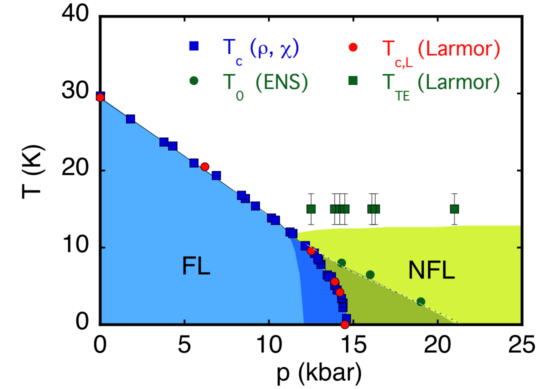
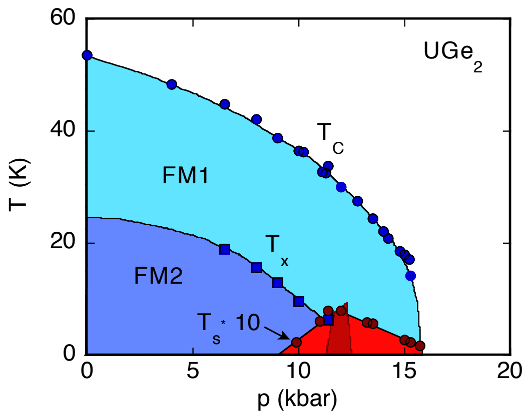
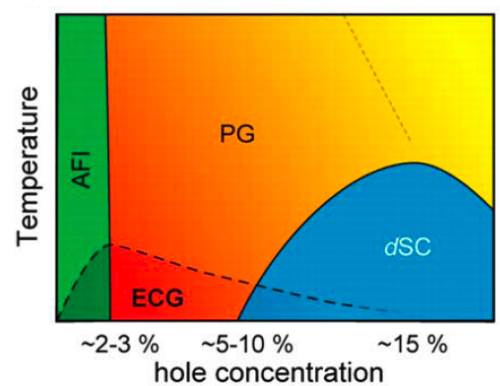
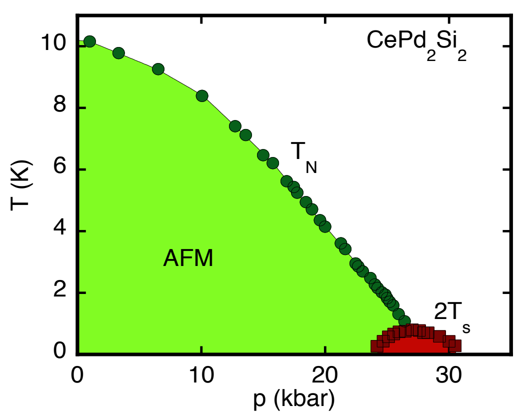


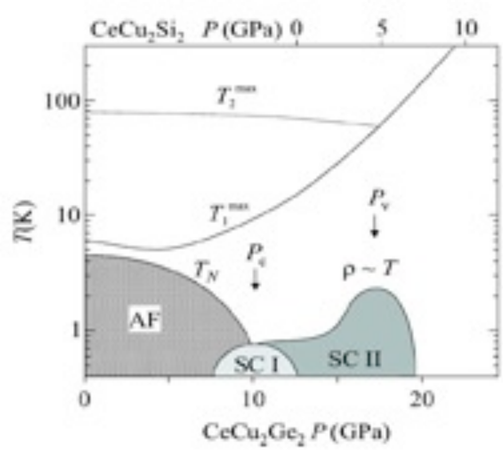




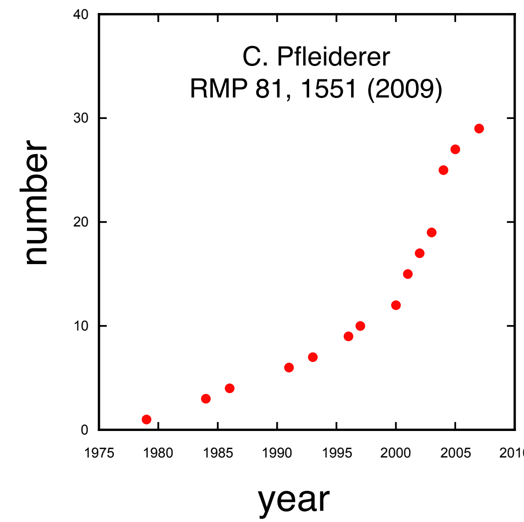








number of f-electron SC



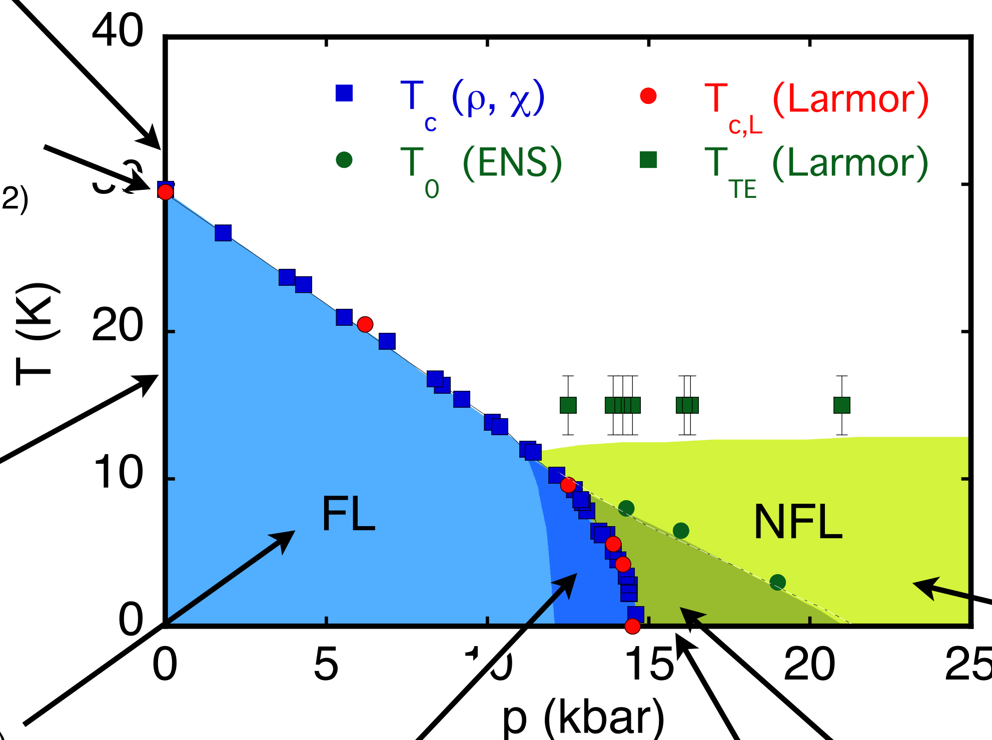
Why we find MnSi interesting...

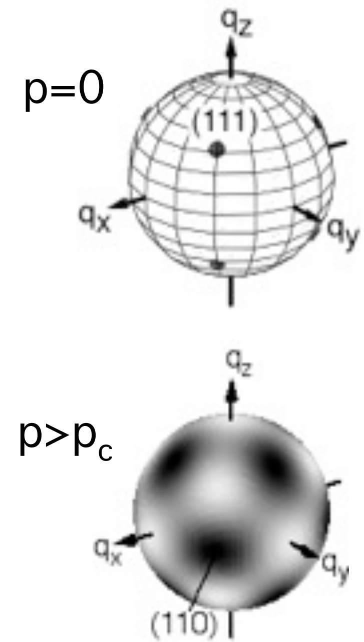
Nature **442**, 797 (2006)

Science **323**, 915 (2009)
PRL **102**, 186602 (2009)
Science **330,** 1648 (2010)
Nature Physics **8** 301 (2012)

PRB **81**, 214436 (2010)

PRB **55**, 8330 (1997)





Nature **414**, 427 (2001)

Nature **427**, 227 (2004)

Nature Physics **3**, 29 (2007)

PRL **99**, 156406 (2007)

Science **316**, 1871 (2007)

$MnSi$ = Manganese Silicon

Manganese Silicide

Manganese Suicide

Results Topic=(manganese suicide)
Timespan=All Years.
Search language=English Lemmatization=On

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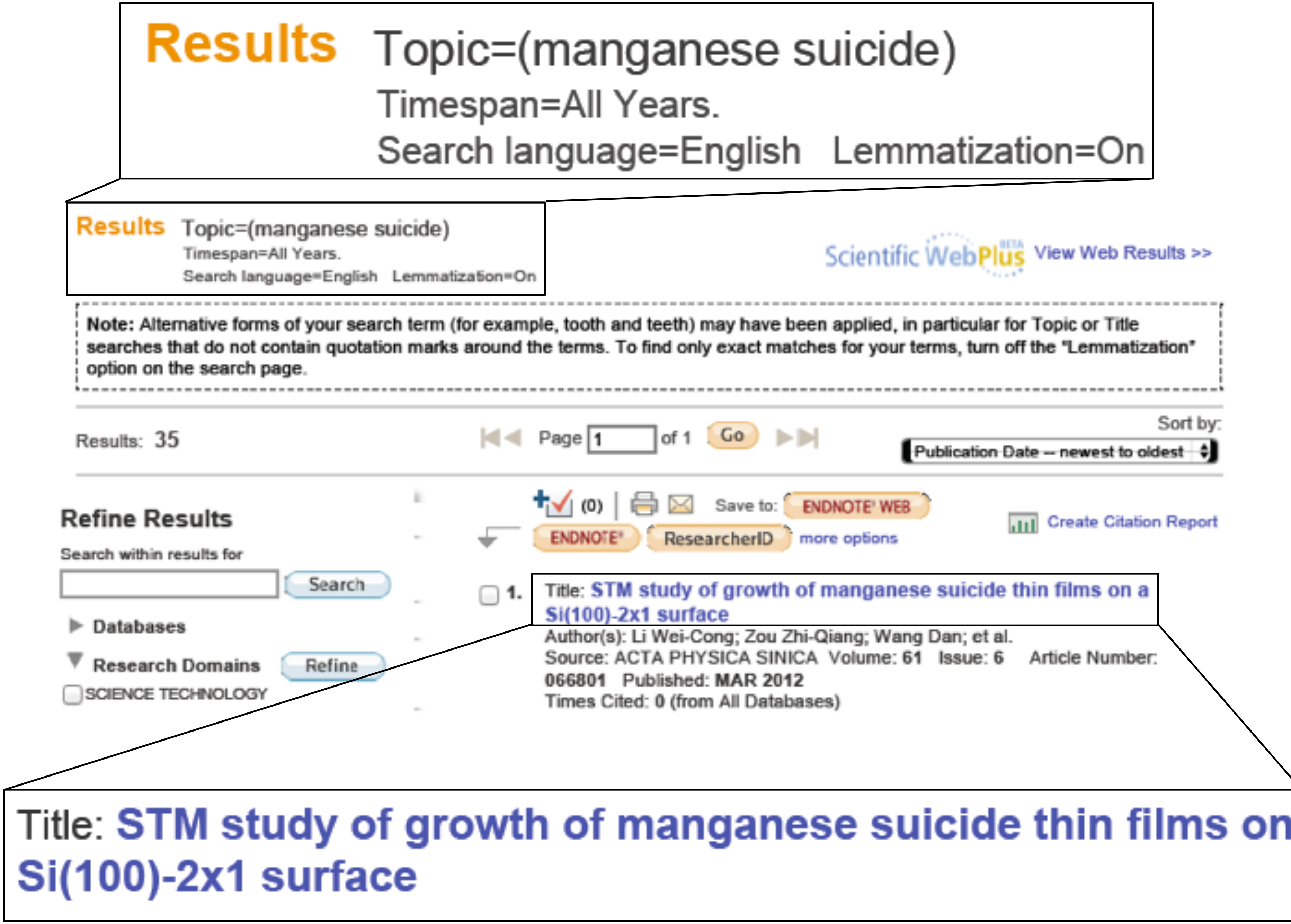
Source: ACTA PHYSICA SINICA Volume: **61** Issue: **6** Article Number: **066801** Published: **MAR 2012**
Times Cited: **0** (from All Databases)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Timespan=All Years.
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Results Topic=(manganese suicide)
Timespan=All Years.
Search language=English Lemmatization=On
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Si(100)-2x1 surface

物 理 学 报 Acta Phys. Sin. Vol. 61, No. 6 (2012) 066801

STM study of growth of manganese silicide thin films on a Si(100)-2×1 surface*

Li Wei-Cong[1)] Zou Zhi-Qiang[1)2)†] Wang Dan[1)] Shi Gao-Ming[1)2)]

Emergent Electrodynamics of Skyrmions in Chiral Magnets

Christian Pfleiderer

Collaborations

München

S. Mühlbauer
F. Jonietz
T. Adams

A. Bauer
A. Neubauer
W. Münzer
S. Gottlieb
P. Niklowitz[3]

M. Janoschek[2]
F. Bernlochner
J. Kindervater
M. Tischendorf
G. Brandl
S. Dunsiger

R. Ritz
T. Schulz
M. Halder
C. Franz
M. Wagner
A. Chacon
M. Hirschberger[1]
F. Birkelbach

R. Georgii
T. Keller (MPI)
W. Häußler
P. Link
B. Pedersen
P. Böni
R. Hackl (WMI)

Köln

K. Everschor
M. Garst
B. Binz
A. Rosch

Utrecht

R. Duine

Lausanne

H. Berger

Berkeley

J. Koralek
D. Maier
J. Orenstein
A. Vishwanath

Braunschweig

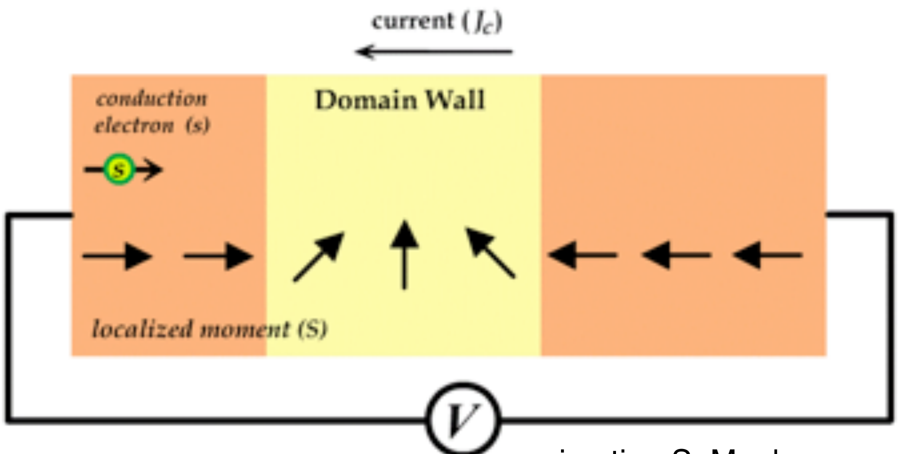
P. Lemmens

[1]Princeton [2]Los Alamos [3]London

DFG

erc TOPFIT

Challenges in Spintronics



animation S. Maekawa

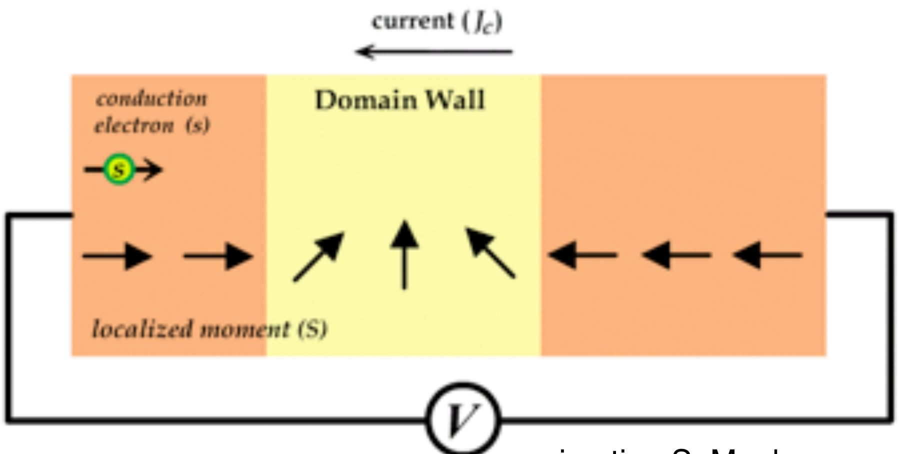
typical current density
10^{12} A/m^2

example for a Landau-Lifshitz Gilbert equation

$$\underbrace{(\partial_t + \vec{v}_s \nabla)\hat{M}}_{\text{Berry-phase spin torque}} = \underbrace{-\hat{M} \times \vec{H}_{\text{eff}}}_{\text{precession in effective field}} + \underbrace{\hat{M} \times (\alpha \partial_t + \beta \vec{v}_s \nabla)\hat{M}}_{\text{damping}} + \dots$$

What about Spin Transfer Torques in Helimagnets?

A. Rosch, R. Duine et al. (November 2006)

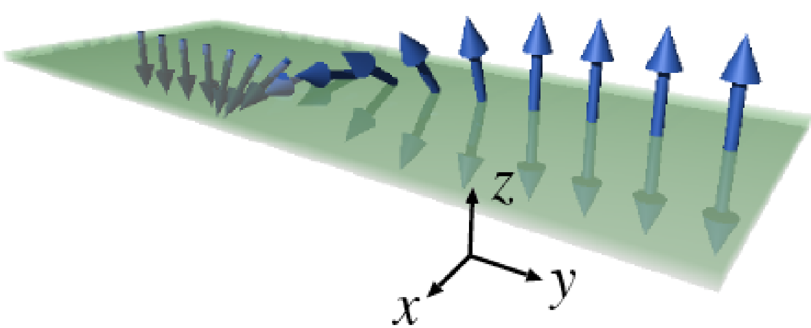


animation S. Maekawa

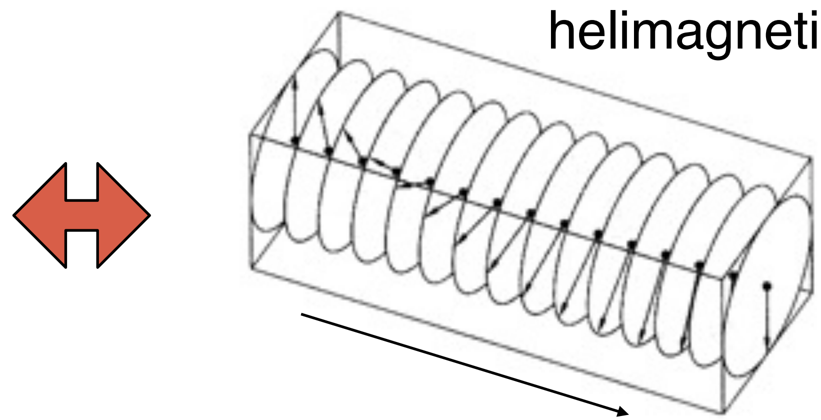
typical current density

10^{12} A/m^2

Bloch wall



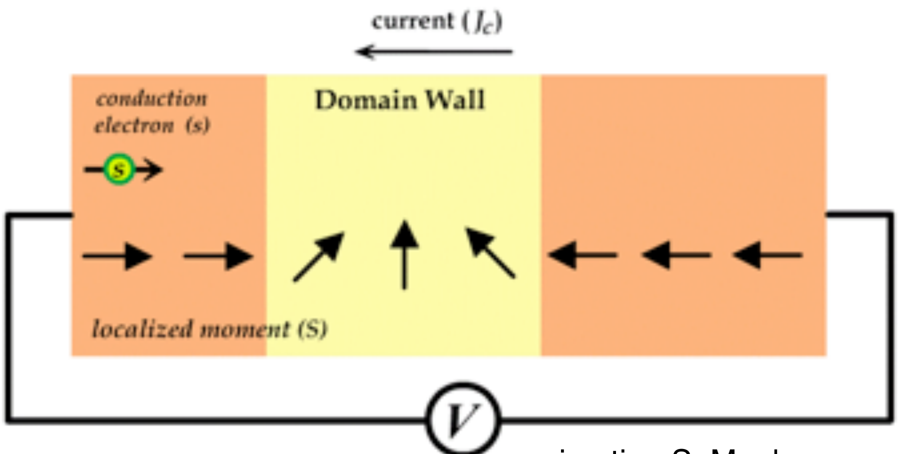
helimagnetism



cf. Goto, et al. condmat/0807.2907; Wessely et al., PRL **96**, 256601 (2006); both consider $j \approx 10^{12}$ Am^{-2}

What about Spin Transfer Torques in Helimagnets?

A. Rosch, R. Duine et al. (November 2006)



animation S. Maekawa

typical current density

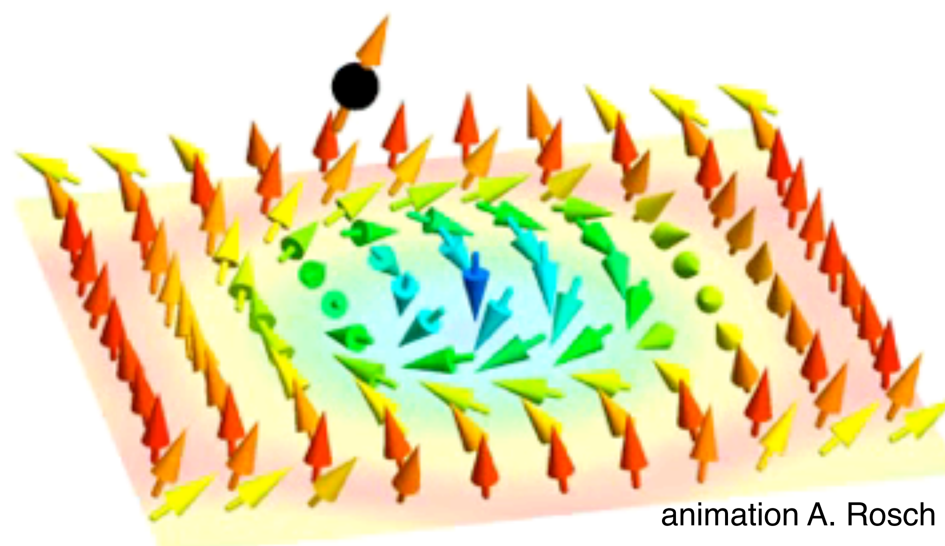
10^{12} A/m^2

emergent electrodynamics:

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

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

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



animation A. Rosch

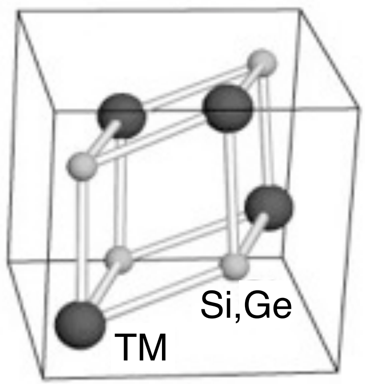
Outline

- A Very Short Introduction to B20 Compounds
- Exploring Spin Torques with Neutrons
- Rôle of Emergent Magnetic Field
- Emergent Electric Field
- Perspectives & Summary

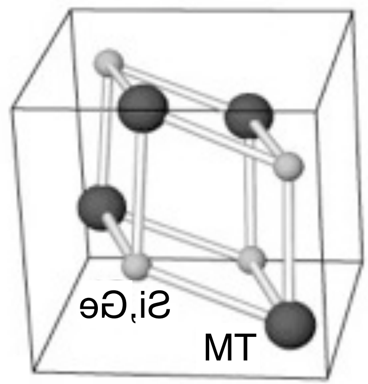
A Very Short Introduction to B20 Compounds

Hierarchical Energy Scales in B20 compounds

Landau-Lifshitz vol. 8, §52



B20: no inversion center



B20: no inversion center

left-handed

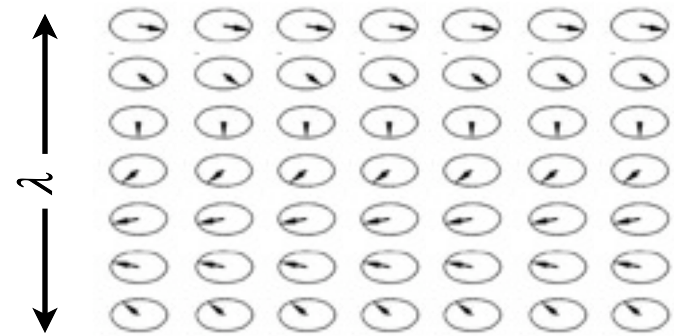
right-handed

(1) ferromagnetism

(2) Dzyaloshinsky-Moriya

(3) crystal field ($P2_13$):

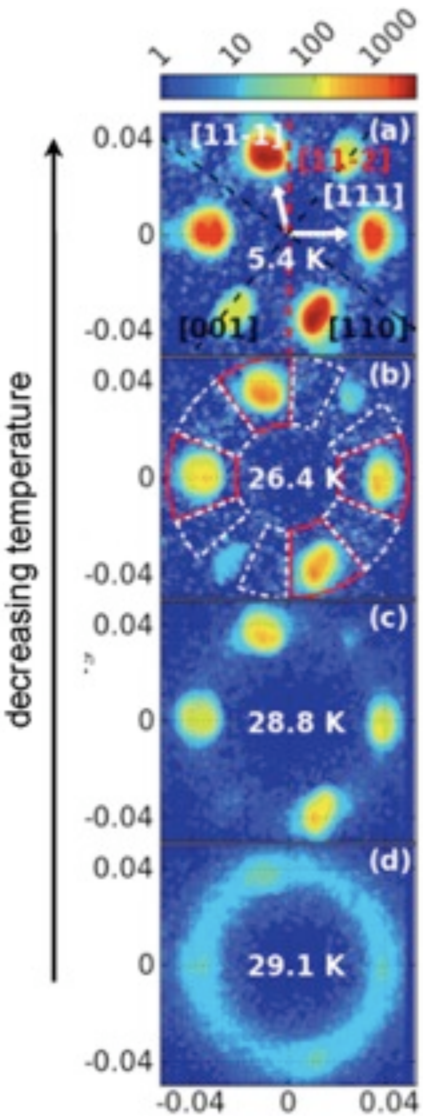
locked to <111> or <100>

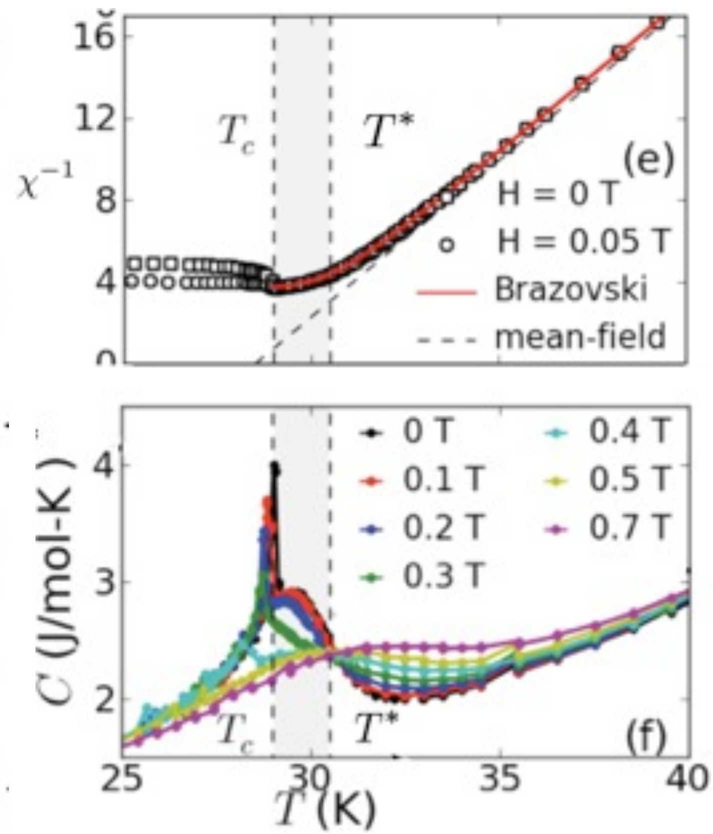


	T_N (K)	λ (Å)
MnGe	170	30 to 60
$Mn_{1-x}Fe_xSi$	< 28	180 to 120
$Fe_{1-x}Co_xSi$	< 45	> 300
FeGe	280	700
Cu_2OSeO_3	54	620

Fluctuation-Induced First Order Transition

a helimagnetic Brazovskii transition





experiments @ MIRA, FRM II

M. Janoschek, M. Garst et al.
arXiv/1205.4780

FM exchange
$J\,a$ = 11meV

DM-interaction
$D\,a^2 = J\,Q\,a^2$ = 1.7meV

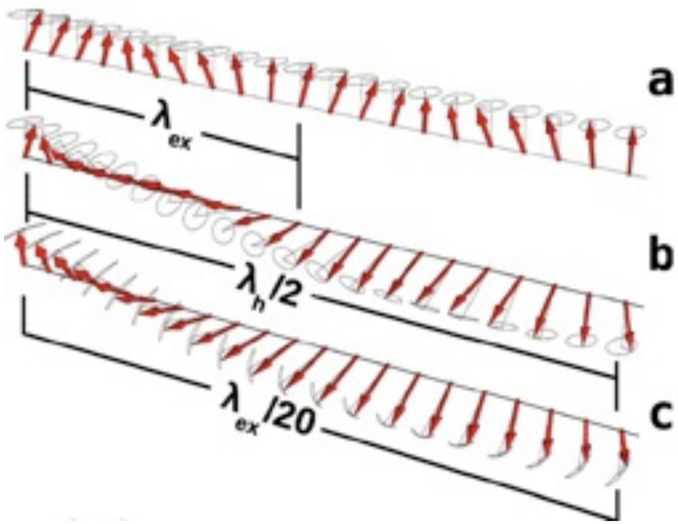
cubic anisotropy
$J_1\,a$ = 0.37meV

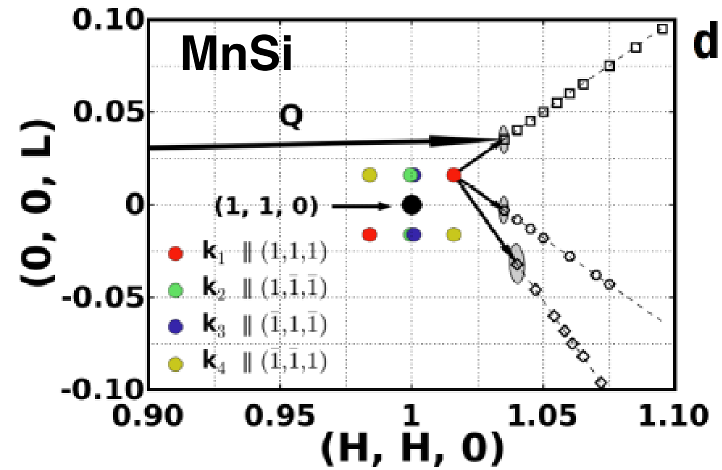
(a: lattice constant)

cf. claim of a Bak-Jensen
1st order transition

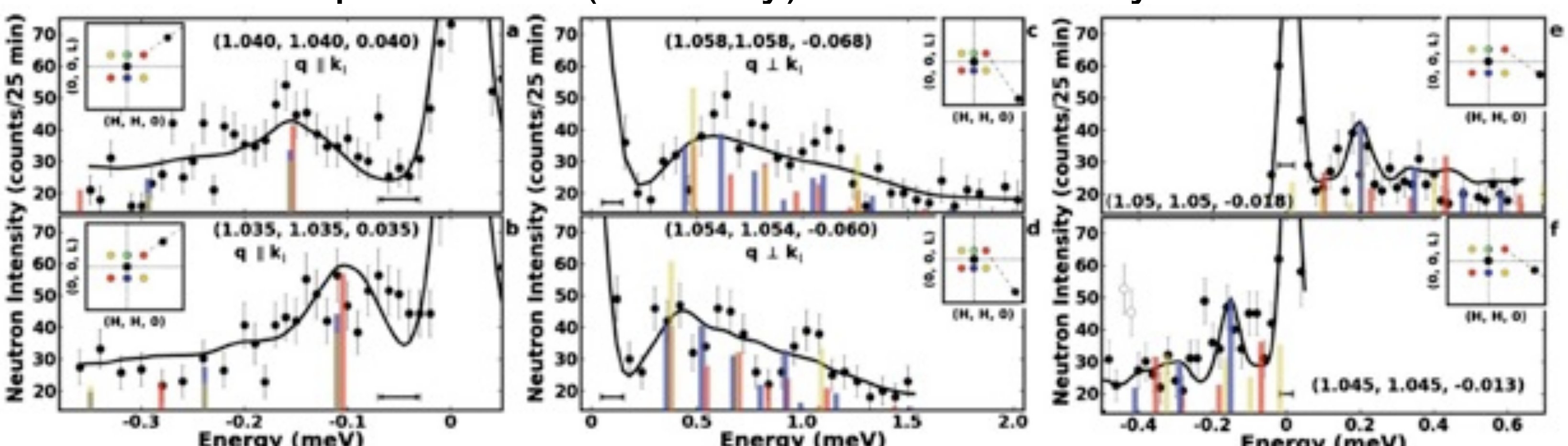
S. Grigoriev et al., PRB **81**, 144413 (2010)

Helimagnon-Bands as Universal Excitations





one parameter (intensity) simultaneously fits all data

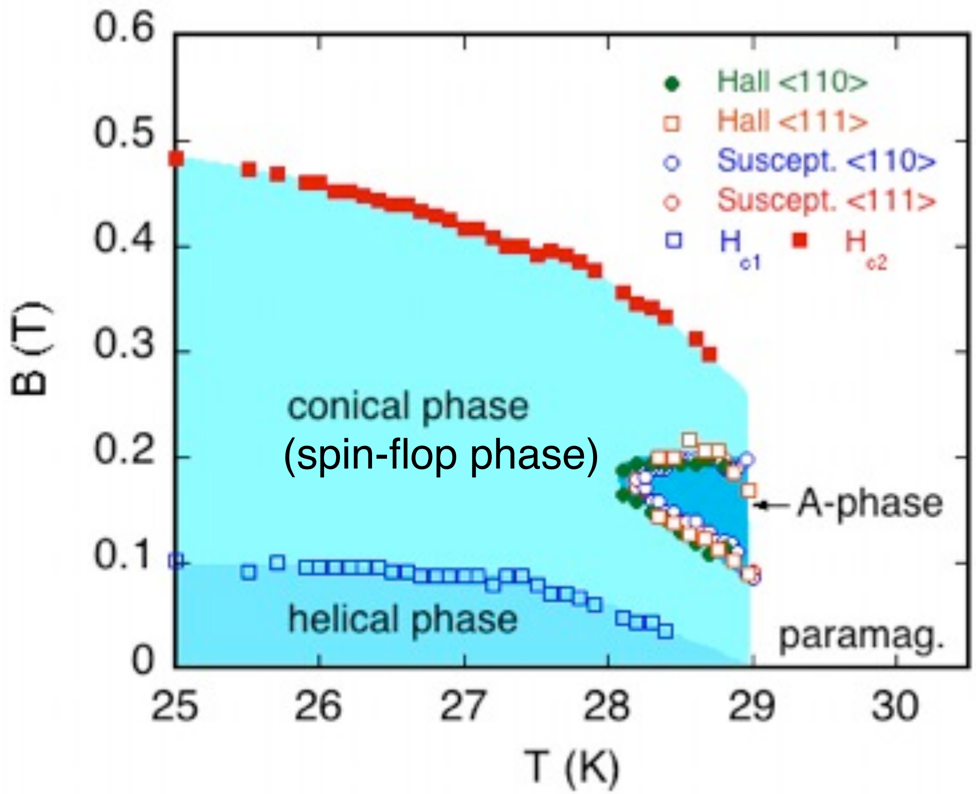


Janoschek, Bernlochner, Dunsiger, CP, Böni, Roessli, Link, Rosch, PRB **81**, 214436 (2010)

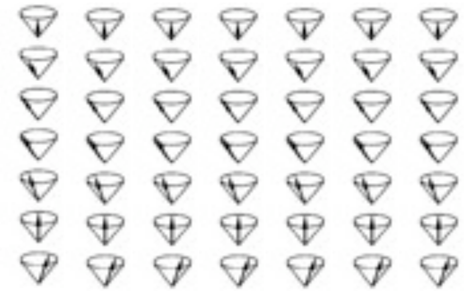
cf. pump-probe measurements in $Fe_{1-x}Co_xSi$: Koralek et al., arXiv/1208.1462

Magnetic Phase Diagram of MnSi

and similar B20 TM compounds

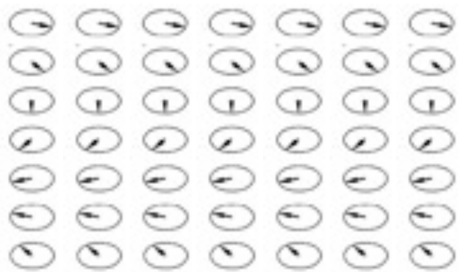


conical phase



A phase

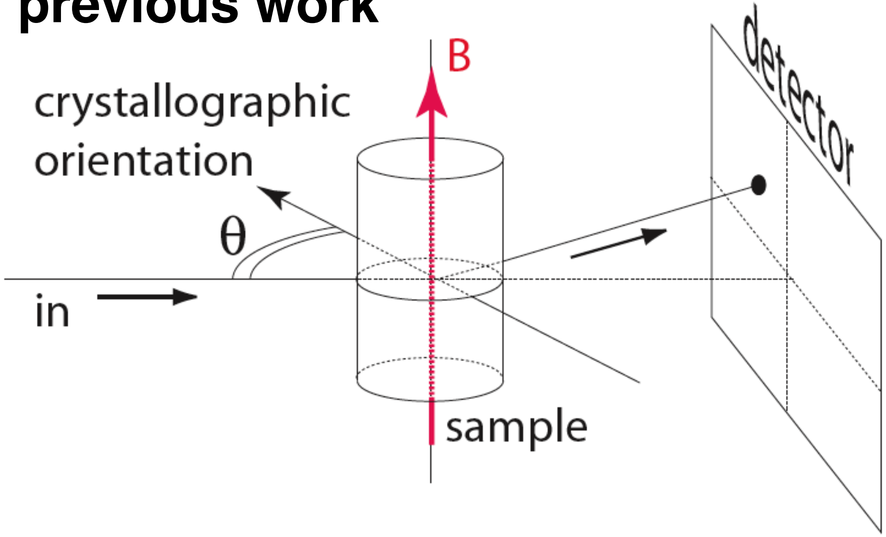
helical phase



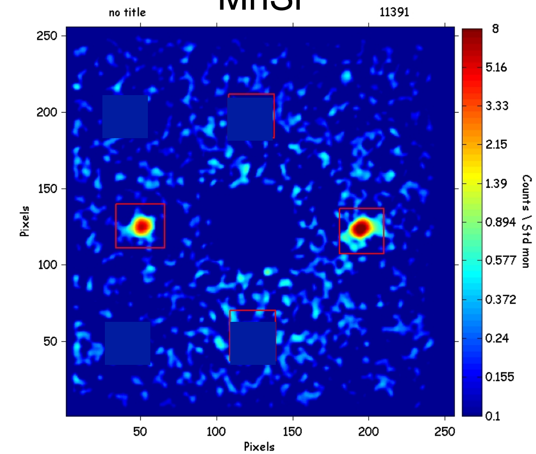
Mühlbauer et al, Science **323**, 915 (2009)

Neutron Scattering Pattern in the A-Phase

previous work

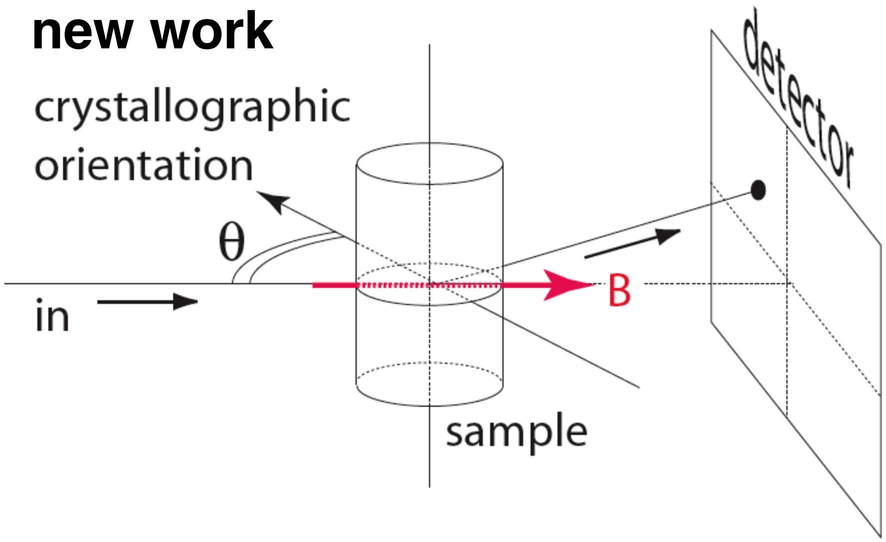


MnSi



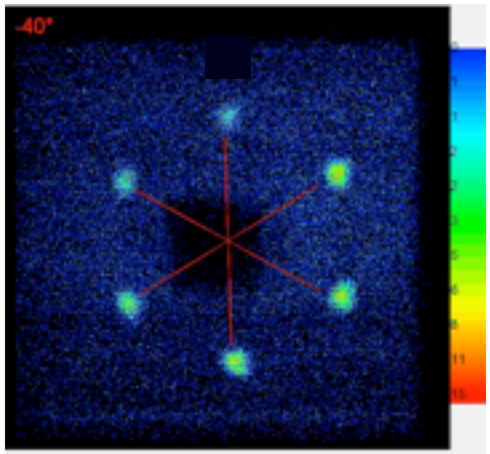
cf. Lebech, Bernhoeft (1993)
Grigoriev, et al. (2006)

new work



angular variation

$\theta =$



measurements @ MIRA, FRM II

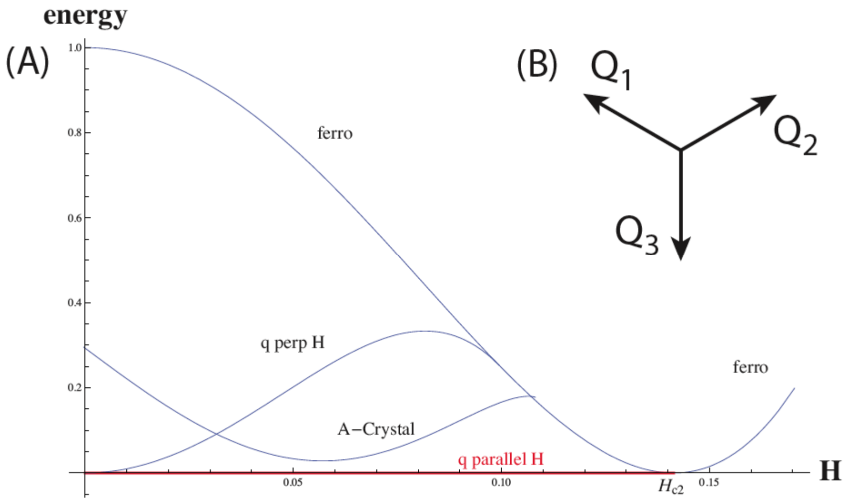
Fluctuation-Stabilized Multi-q Structure

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

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

triple-q + uniform m

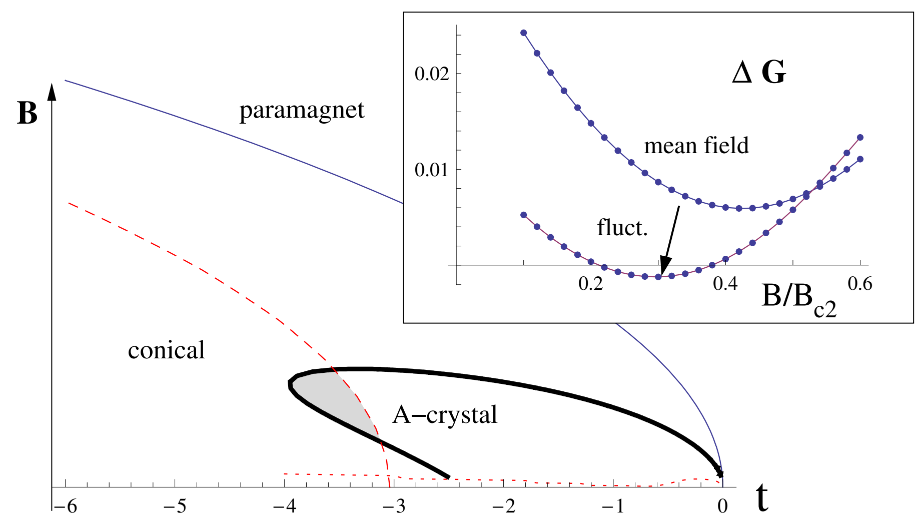
Binz, Vishwanath, Aji PRL (2006)



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

thermal Gaussian fluctuations

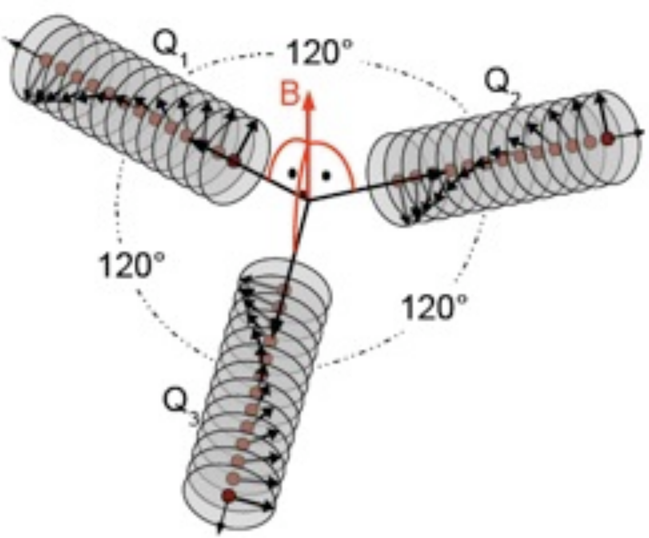
$$F \approx F_0 + \mathrm{tr}\log\frac{\partial^2 F}{\partial\Phi\partial\Phi}$$



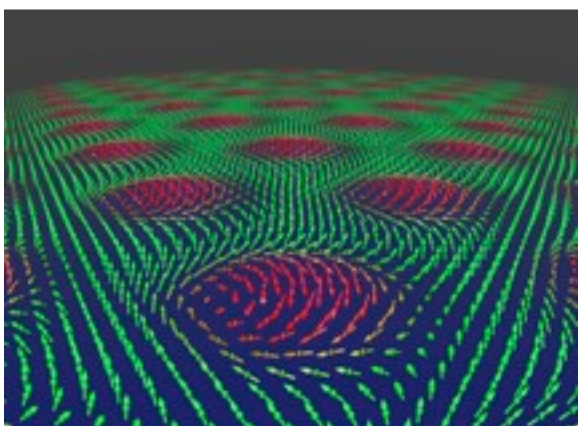
Mühlbauer et al, Science **323**, 915 (2009)

Topological Properties of the Rigorous Solution

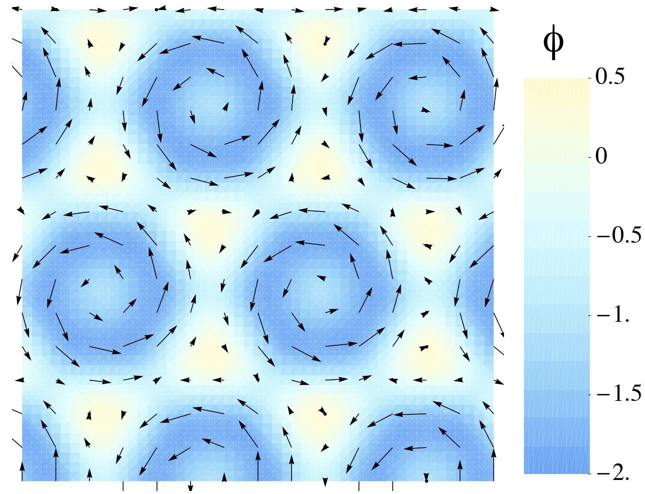
phase btw fundamental modes



center: M antiparallel B



projection from above



$$\phi = \frac{1}{4\pi}\vec{n}\cdot\frac{\partial\vec{n}}{\partial x}\times\frac{\partial\vec{n}}{\partial y}$$

winding number per unit cell:

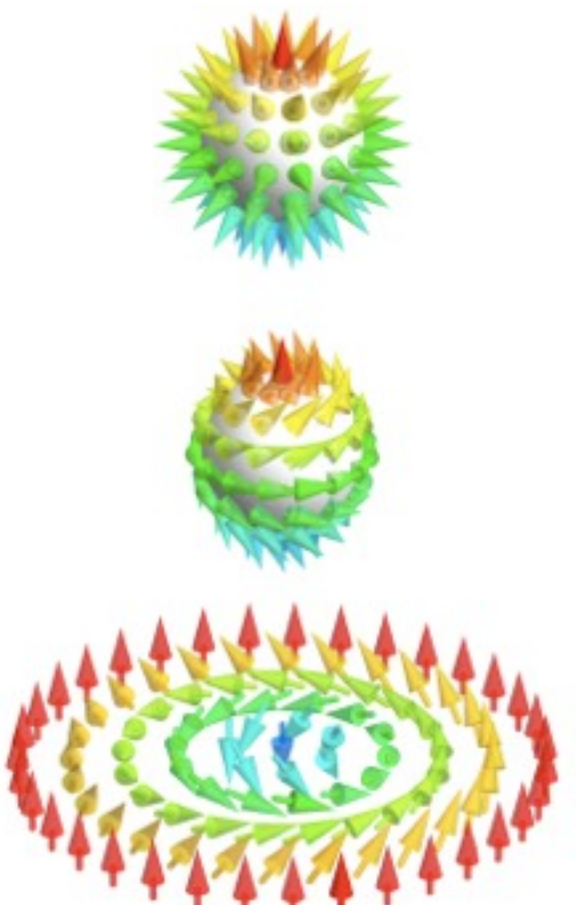
$$\Phi = -1$$

lattice of topological knots

skyrmions

Adams et al., PRL **107**, 217206 (2011)

From „Hairy Balls“ to Skyrmion Lattices



Werner Heisenberg

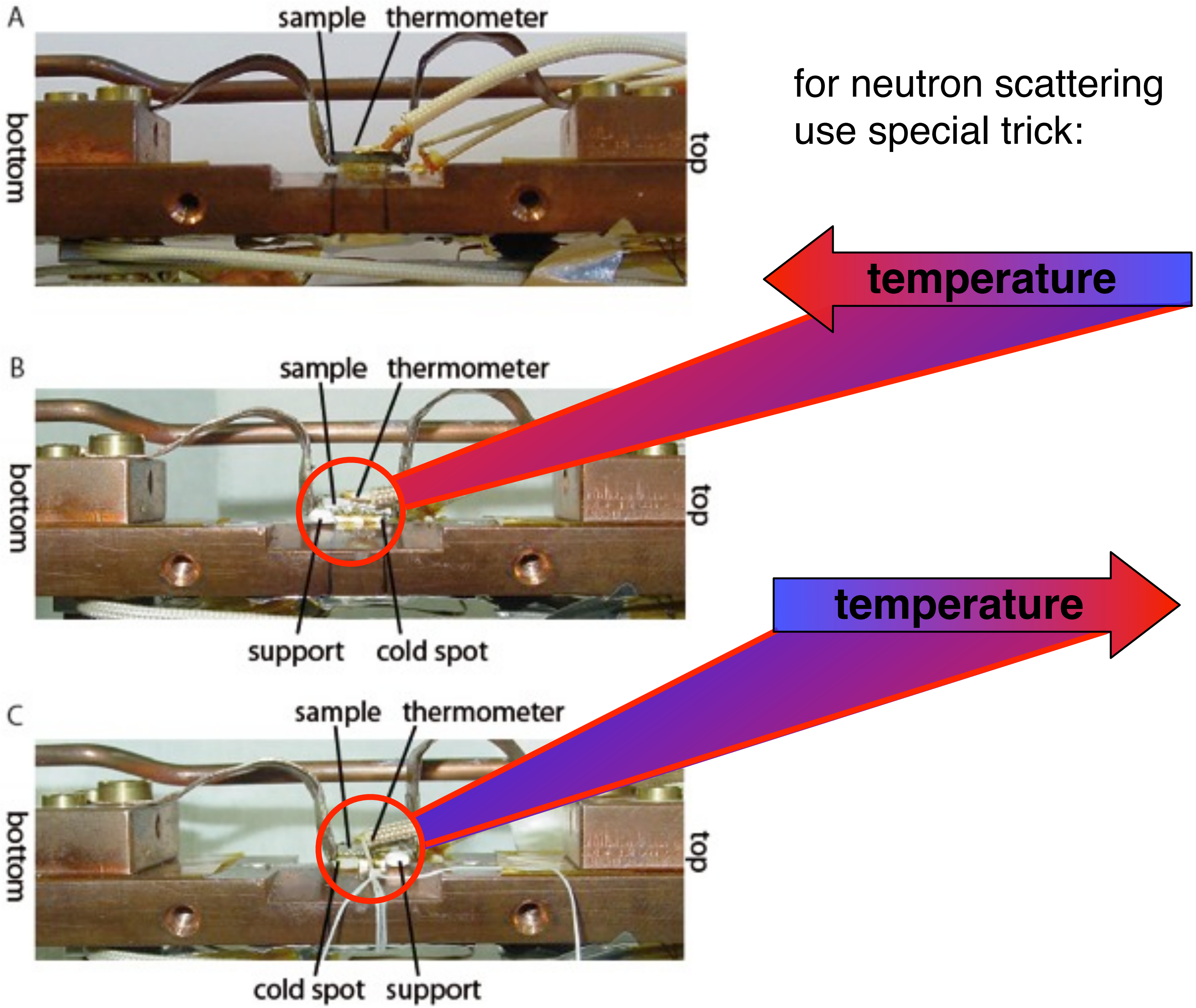
RMP **29** 296 (1957)

Tony Skyrme

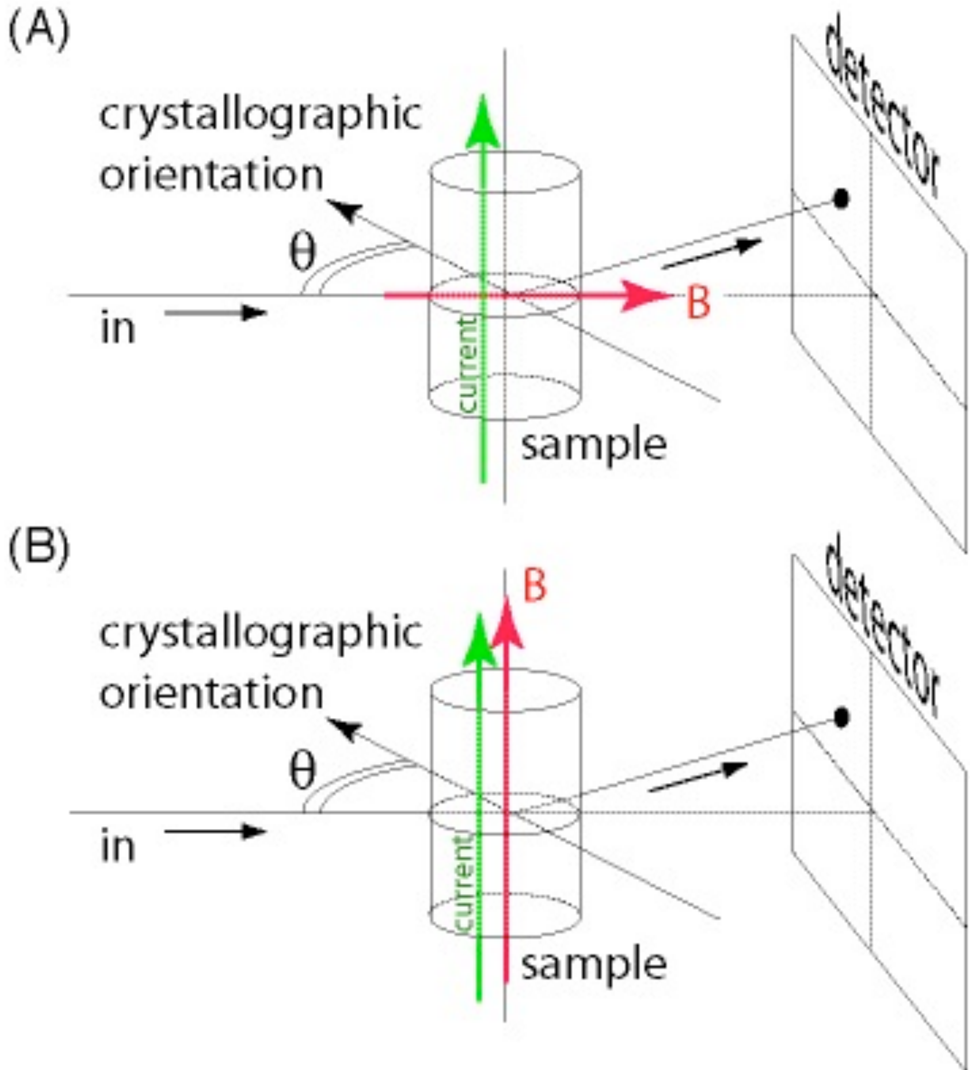
Nucl. Phys. **31** 556 (1962)

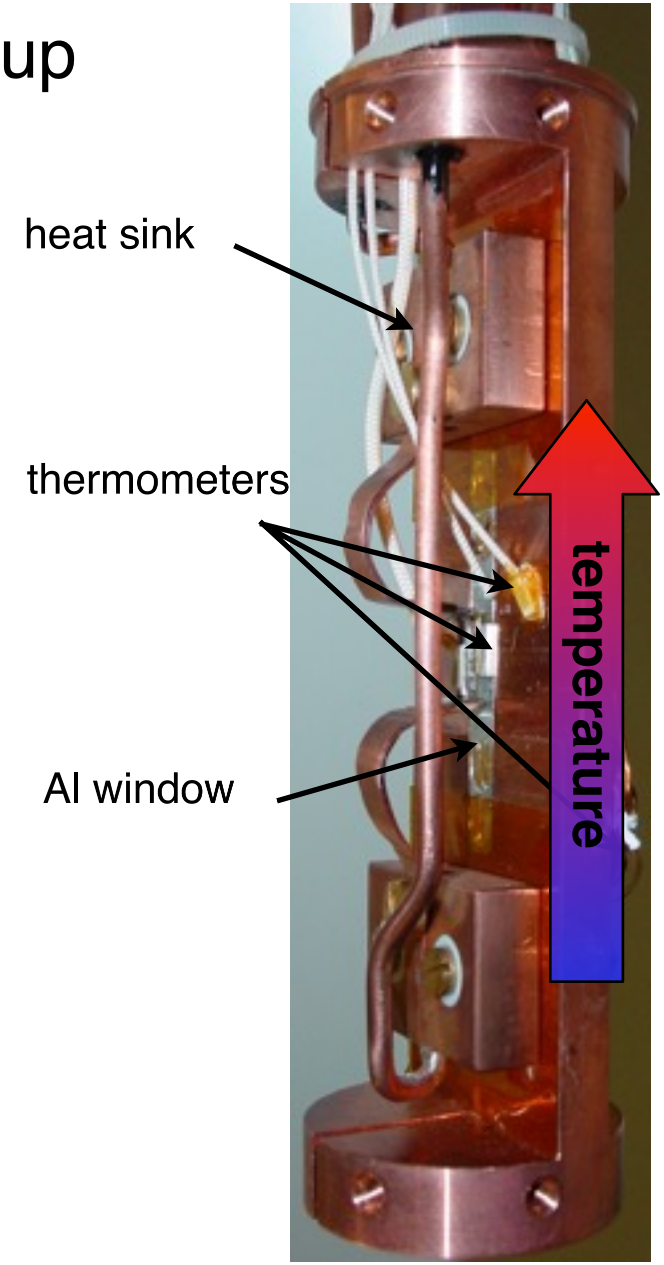
Exploring Spin Torques with Neutrons

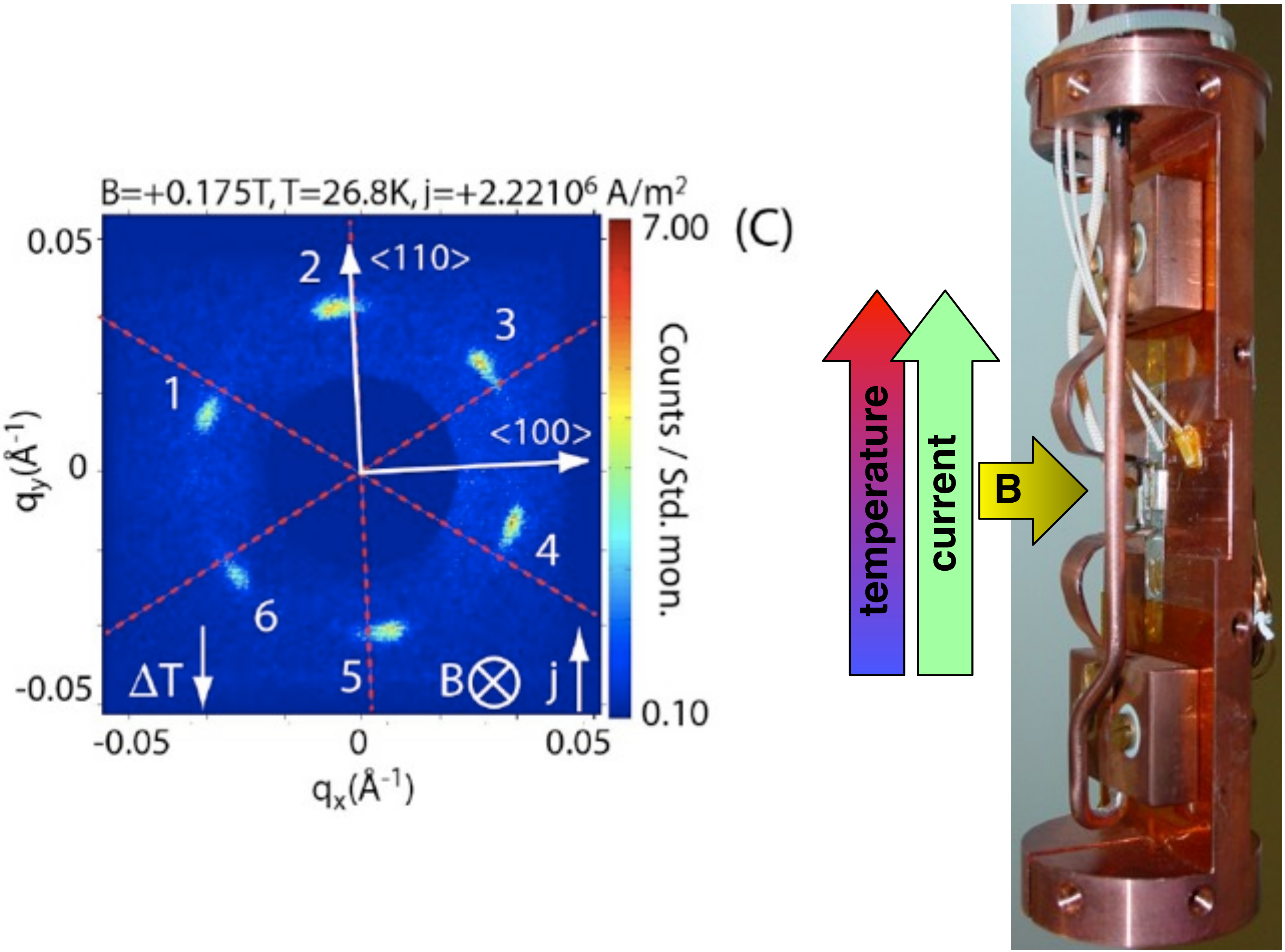
for neutron scattering use special trick:

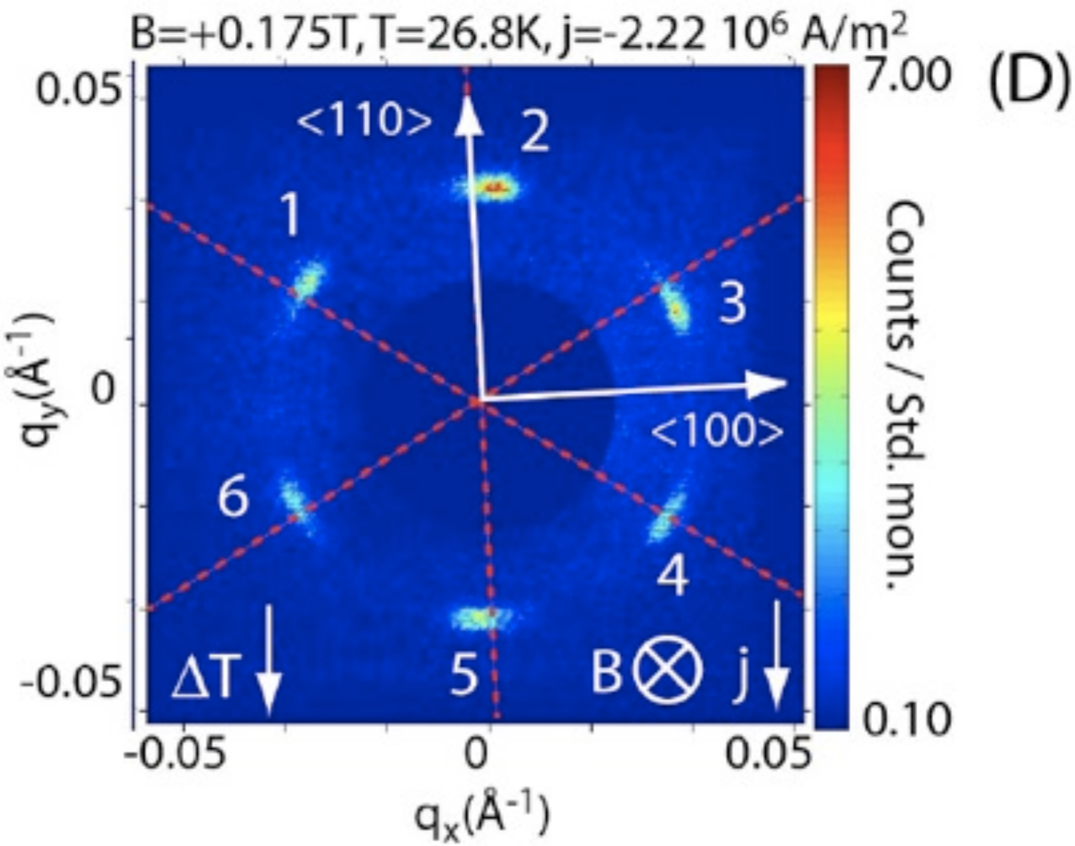


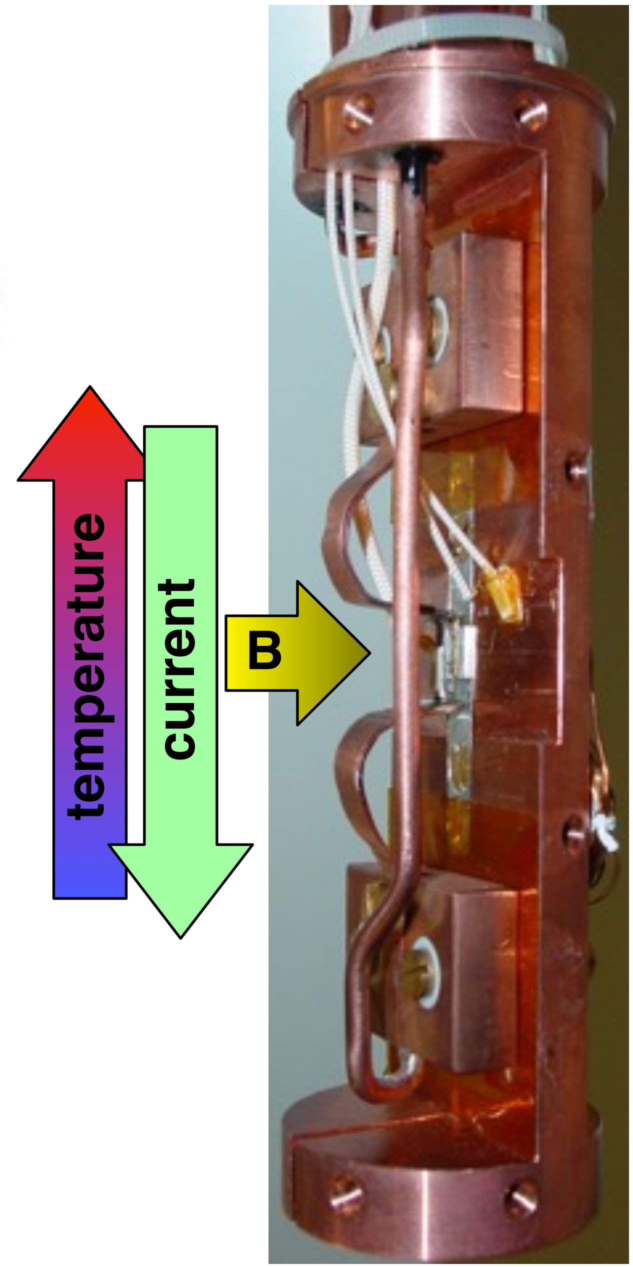
Experimental Setup



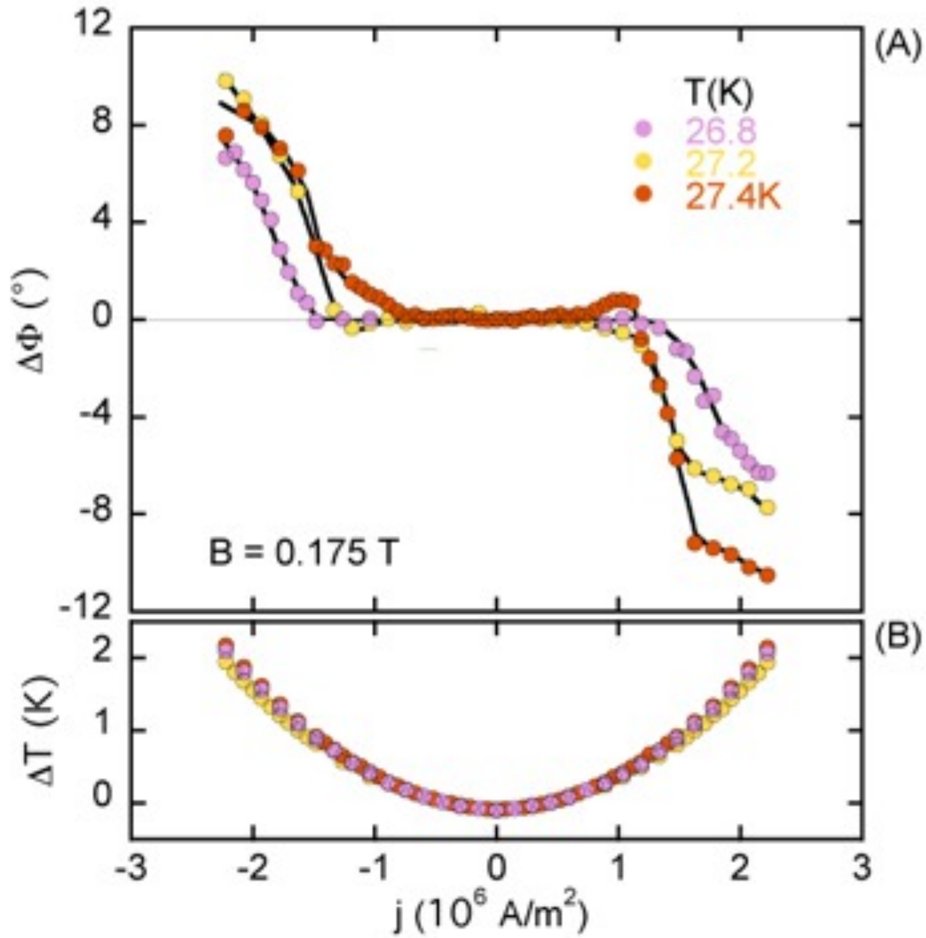



B=+0.175T, T=26.8K, j=+2.2210⁶ A/m²
0.05
0
-0.05
$q_y(Å^{-1})$
-0.05
0
0.05
$q_x(Å^{-1})$
<110>
<100>
1
2
3
4
5
6
ΔT
B
j
7.00
0.10
Counts / Std.mon.
(C)
temperature
current
B


B=+0.175T, T=26.8K, j=-2.22 10⁶ A/m²
(D)
0.05
0
-0.05
-0.05
0
0.05
qy(Å-1)
qx(Å-1)
<110>
<100>
1
2
3
4
5
6
ΔT
B
j
7.00
0.10
Counts / Std. mon.


temperature
current
B

Current Dependence of the Rotation Angle



antisymmetric rotation
threshold: 10^6 Am^{-2}

temperature at surface
kept constant

Jonietz et al, Science **330**, 1648 (2010)

Summary of Experimental Observations

- rotation for current perpendicular to field
- no effect for current parallel to applied field
- no effect in helical state
- no effect in conical state

sense of rotation changes under:

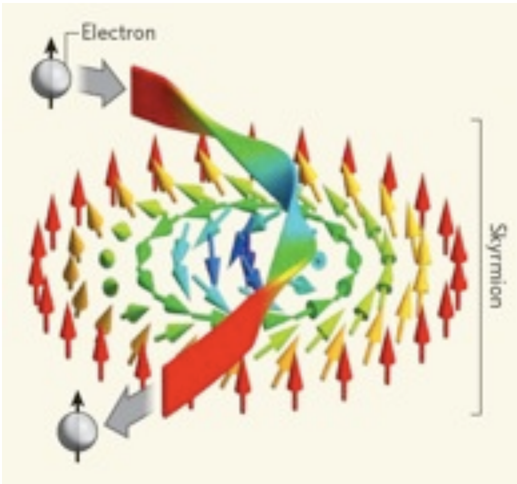
- inversion of current direction
- inversion of field direction
- inversion small T gradient

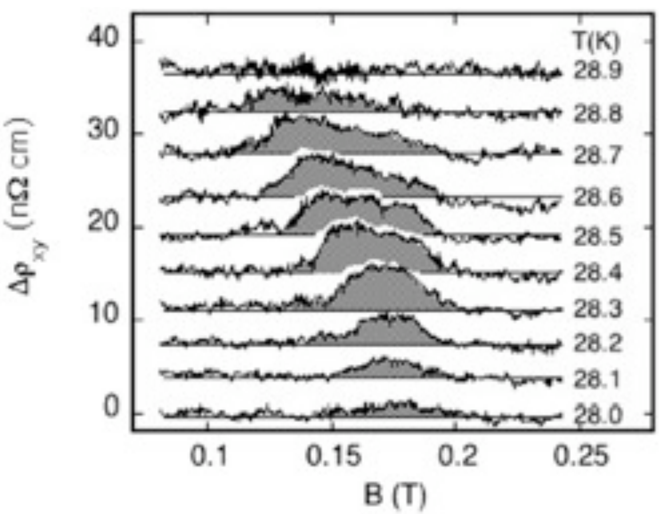
- low threshold for rotation: 10^6 Am^{-2}
- same behavior for different sample shapes and orientations

Rôle of Emergent Magnetic Field

Emergent Magnetic Field of Skyrmions

Pfleiderer, Rosch Nature (N&V) **465** 880 (2010)





conduction electron tracks spin structure:

- collect Berry phase
- express as Aharonov-Bohm phase
- represents effective field

$$\vec{B}_{\text{eff}} = \Phi_0 \, \vec{\Phi}$$

$$\Phi_0 = h/e$$

$$\Phi^\mu = \frac{1}{8\pi} \epsilon_{\mu\nu\lambda} \hat{n} \cdot (\partial_\nu \hat{n} \times \partial_\lambda \hat{n})$$

trivial topology: $\Phi = 0$

non-trivial topology: $\Phi = -1$

$\Rightarrow$ $\vec{B}_{\text{eff}} \approx -2.5\,\text{T}$

BUT: complex band structure!

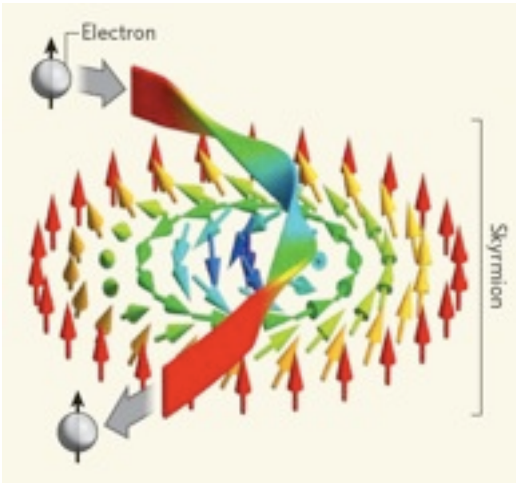
$\Delta\rho_{xy} \approx P\, R_0\, B^z_{\text{eff}}$ $\Rightarrow$ $\Delta\rho_{xy} \approx 4 \text{ n}\Omega\,\text{cm}$

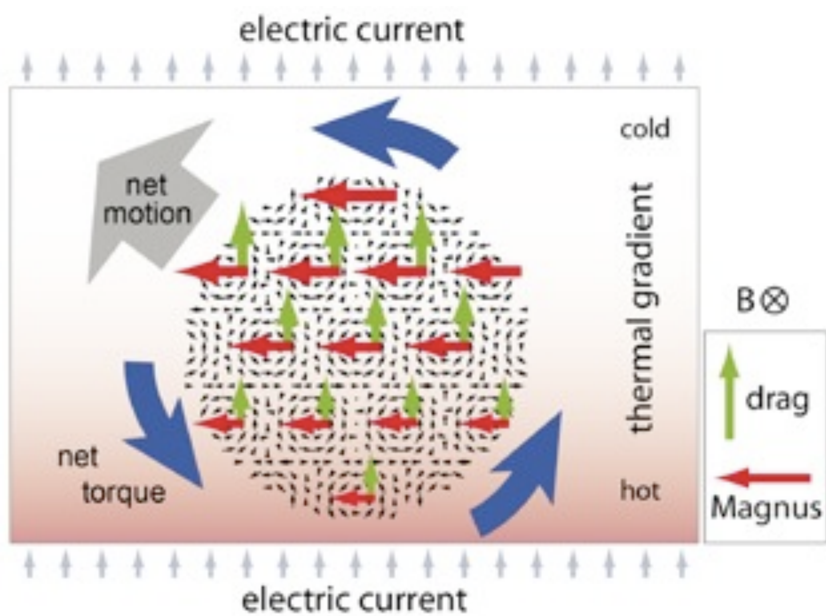
Binz, Vishwanath Physica B **403** 1336 (2008)

Neubauer, et al. PRL **102** 186602 (2009)

Rôle of the Temperature Gradient

Pfleiderer, Rosch Nature (N&V) **465** 880 (2010)





counter-force to „effective Lorentz force“

$$f_M \approx e j_s B_{\text{eff}} \qquad p(T) = e j_s / j$$

$$\approx p(T) \cdot \frac{j}{10^6 \mathrm{A\,m^{-2}}} \frac{2.7 \cdot 10^{-10} k_B T_c}{a^4}$$

T gradient ⇒ gradient of spin current

$$\nabla p \approx \frac{\partial p}{\partial T} \nabla T$$

resulting torque on skyrmion lattice

$$\boldsymbol{\tau}_M \sim \int \mathbf{r} \times \mathbf{f}_M(\mathbf{r}) d^3 r / V$$

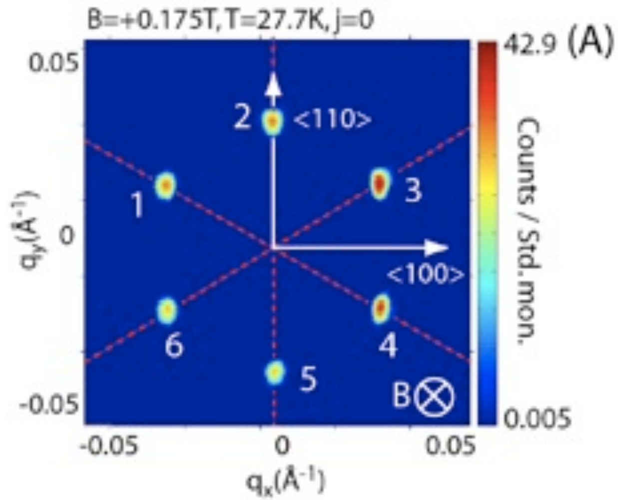
$$\tau_M \sim 10^{-10} \frac{\mathbf{j} \cdot \nabla p}{10^6 \mathrm{A\,m^{-2}}} \frac{R^2}{a} \frac{k_B T_c}{a^3}$$

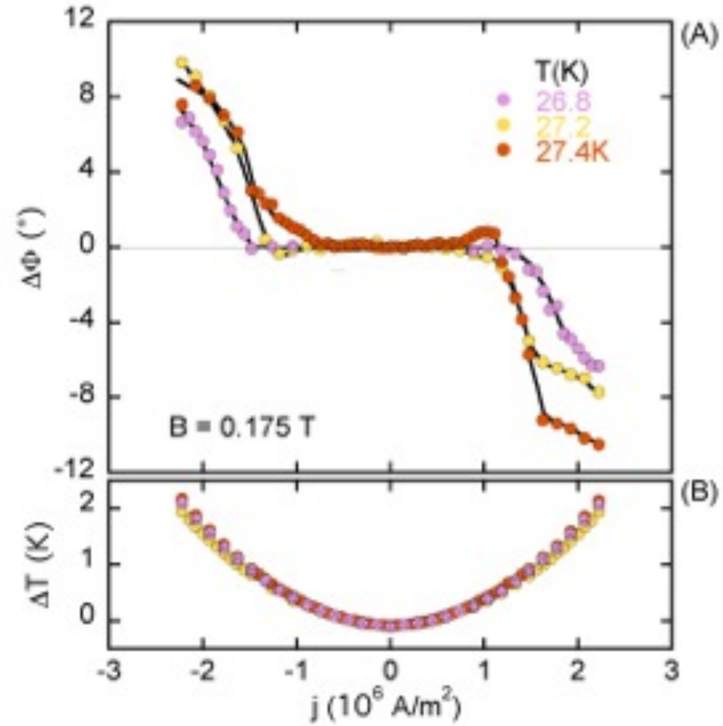
(assumes rigid skyrmion lattice)

Jonietz et al, Science **330**, 1648 (2010)

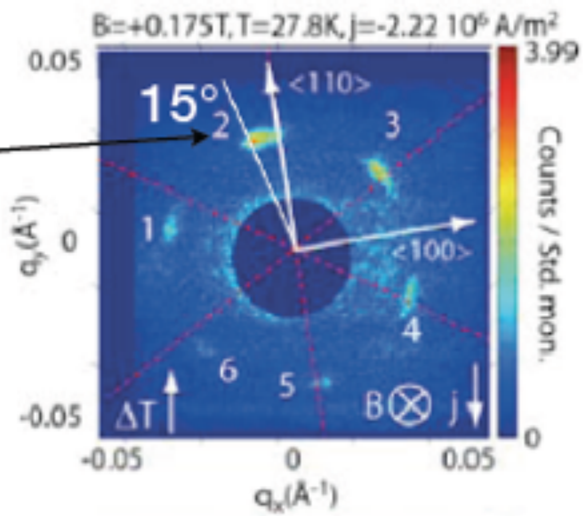
Proposal of Rotating Skyrmion Lattices in Temperature or Field Gradients

restoring force: higher-order spin-orbit cplg.





some domains continuously rotate (comet tails)



Everschor et al., PRB **86** 054432 (2012)

Why ultra-low current densities?

very efficent gyro-coupling via Berry phase
+ coupling over entire magnetic domains

very weak pinning forces
+ low defect concentration (RRR>100)
+ very smooth magnetic texture (200Å)
+ very stiff magnetic order
    cf. collective pinning in superconductors

consider Landau-Lifshitz-Gilbert equation

$$\underbrace{(\partial_t + \vec{v}_s \nabla)\hat{M}}_{\text{Berry-phase spin torque}} = \underbrace{-\hat{M} \times \vec{H}_{\text{eff}}}_{\text{precession in effective field}} + \underbrace{\hat{M} \times (\alpha\partial_t + \beta\vec{v}_s \nabla)\hat{M}}_{\text{damping}} + \dots$$

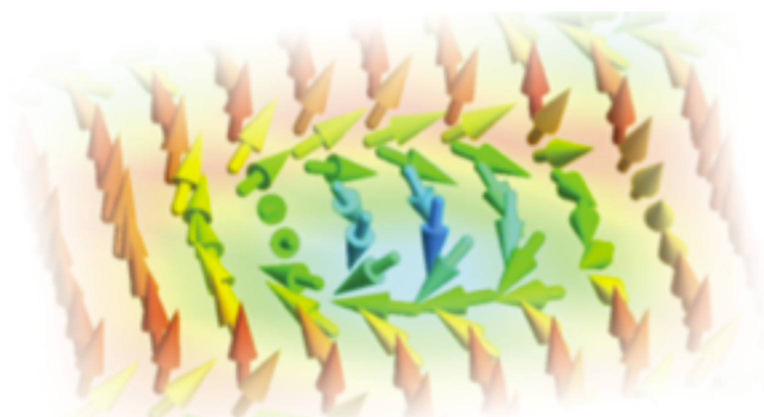
cf Zhang & Lee PRL (2004)
addt'l damping, cf Zang et al PRL (2010)

two types spin currents:
(1) difference of spin polarisation of charge currents

$$j_s = j_\uparrow - j_\downarrow$$

(2) gradients in spin orientation:
here super-spin current

cf charge supercurrents
due to phase gradients



consider Landau-Lifshitz-Gilbert equation

$$(\partial_t + \vec{v}_s \nabla)\hat{M} = -\hat{M} \times \vec{H}_{\text{eff}} + \hat{M} \times (\alpha\partial_t + \beta\vec{v}_s\nabla)\hat{M} + \ldots$$

Berry-phase spin torque — precession in effective field — damping

cf Zhang & Lee PRL (2004)
addt'l damping, cf Zang et al PRL (2010)

two types spin currents:
(1) difference of spin polarisation of charge currents

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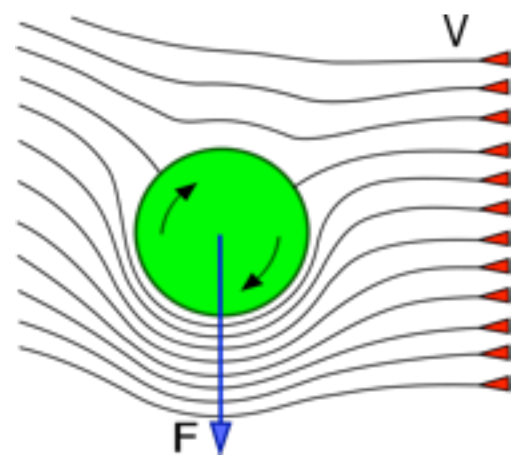
(2) gradients in spin orientation:
here super-spin current

cf charge supercurrents
due to phase gradients

„spin current Magnus force"



consider Landau-Lifshitz-Gilbert equation

generalized Thiele approach (project LLG on zero modes)

$$\vec{G} \times (\vec{v}_s - \dot{\vec{x}}(t)) + \mathcal{D}(\beta\,\vec{v}_s - \alpha\,\dot{\vec{x}}(t)) = \vec{F}_{\mathrm{pinning}}$$

$$G_i = \frac{1}{2}\varepsilon_{ijk} \int d\mathbf{r}\,\hat{M}(\partial_j\hat{M} \times \partial_k\hat{M})$$

topological winding number

gyrocoupling vector

$$\mathcal{D}_{ij} = \int d\mathbf{r}\,\partial_i\hat{M}\,\partial_j\hat{M}$$

dissipative tensor

consider Landau-Lifshitz-Gilbert equation

generalized Thiele approach (project LLG on zero modes)

$$\vec{G} \times (\vec{v}_s - \dot{\vec{x}}(t)) + \mathcal{D}(\beta\, \vec{v}_s - \alpha\, \dot{\vec{x}}(t)) = \vec{F}_{\text{pinning}}$$

$$G_i = \frac{1}{2}\varepsilon_{ijk} \int d\mathbf{r}\, \hat{M}(\partial_j \hat{M} \times \partial_k \hat{M})$$

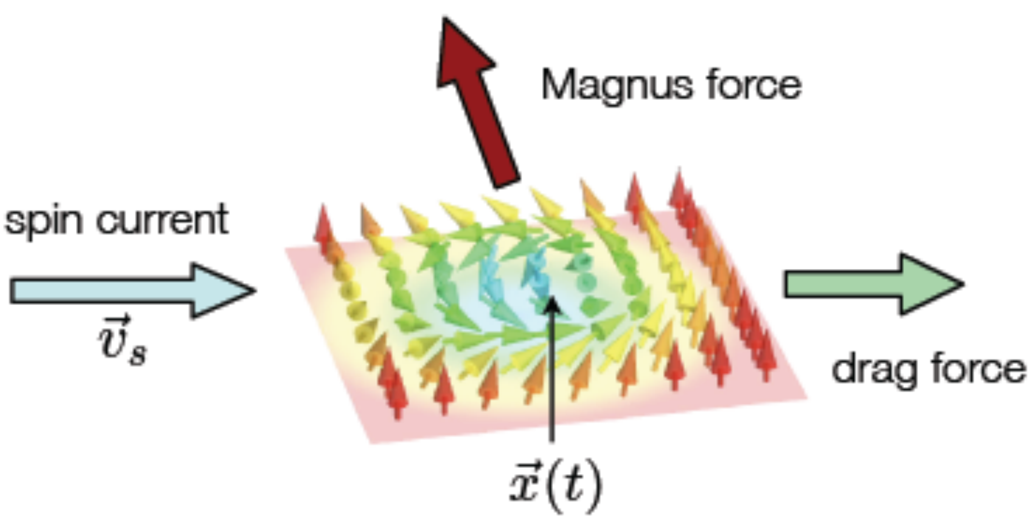
topological winding number

gyrocoupling vector

$$\mathcal{D}_{ij} = \int d\mathbf{r}\, \partial_i \hat{M}\, \partial_j \hat{M}$$

dissipative tensor

for $F_{pin} \approx 0$ drift and spin-Magnus force



$$\vec{F}_{\text{Magnus}} \propto \vec{B} \times (\vec{v}_{\text{s}} - \vec{v}_{\text{d}})$$

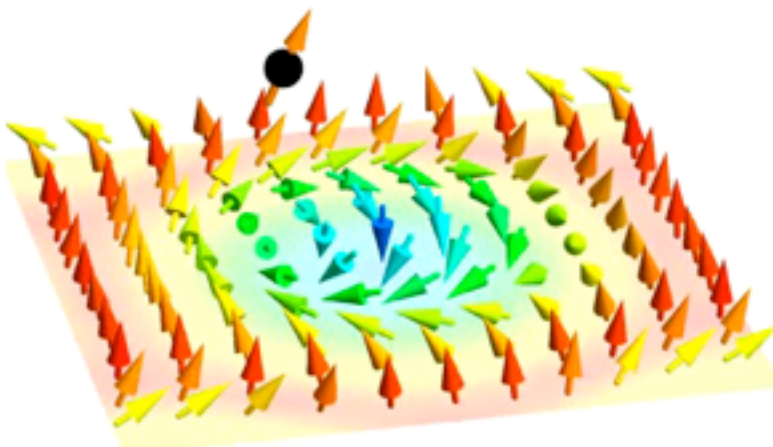
$$\vec{F}_{\text{Magnus}} + \vec{F}_{\text{fric}} = 0$$

no friction: $\vec{v}_{\text{d}} = \vec{v}_{\text{s}}$

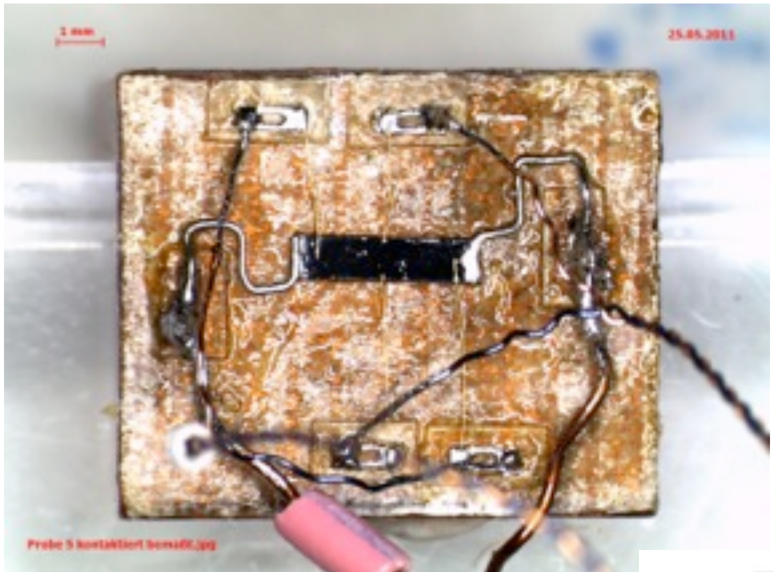
with friction: $\vec{F}_{\text{fric}} \sim \gamma \vec{v}_{\text{d}}$

$$\vec{v}_{\text{d}} \approx \gamma^{-1} \vec{B} \times \vec{v}_{\text{s}}$$

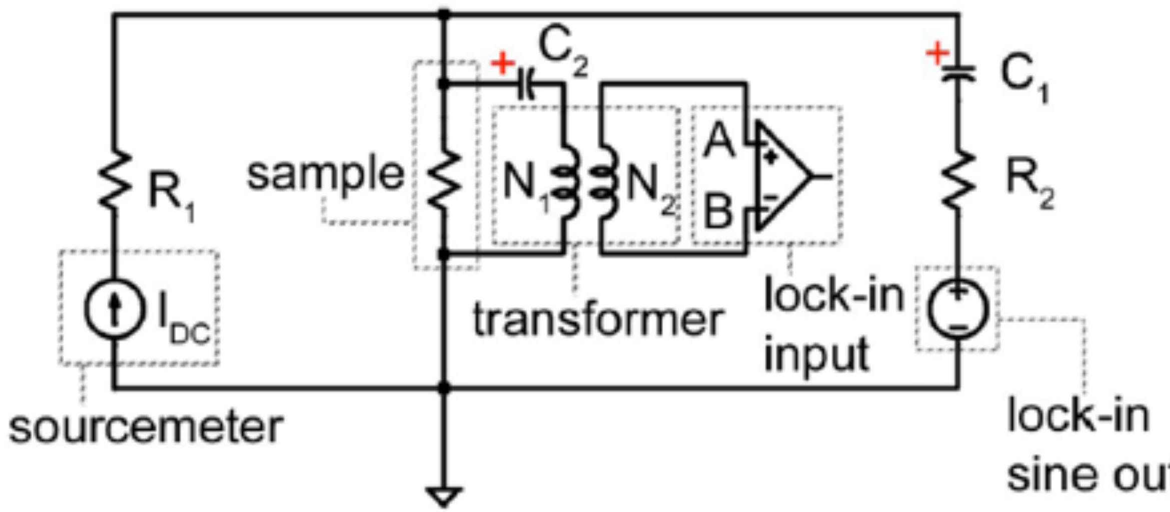
Emergent Electric Field



Emergent Electric Field due to Skyrmion Motion

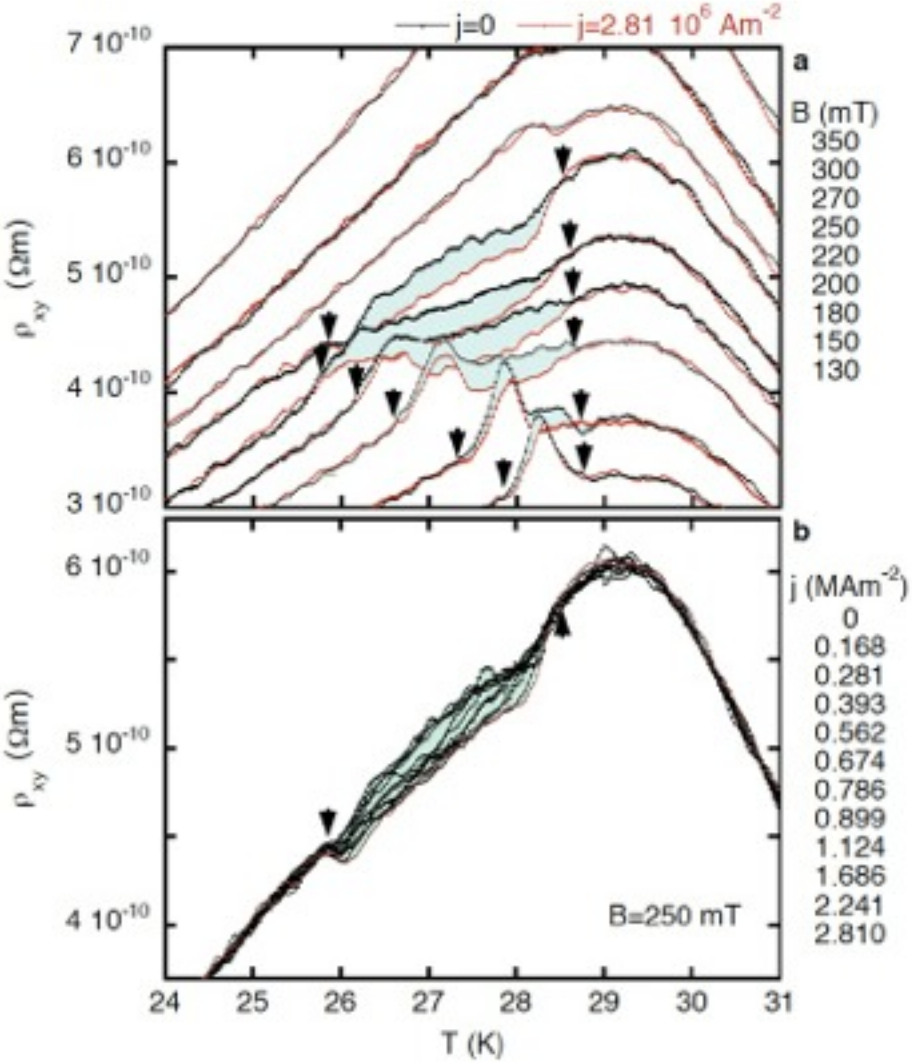


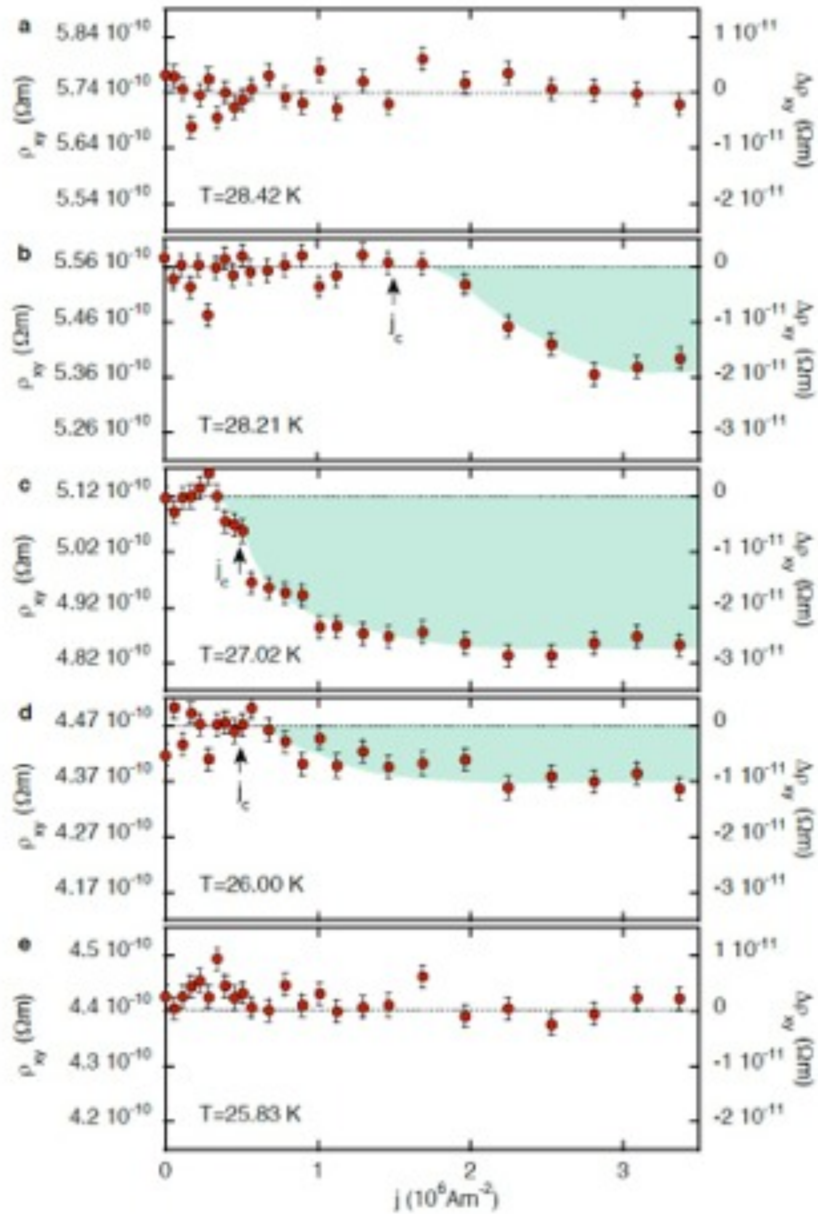
standard 6-terminal
‚no‘ T-gradient!



Schulz et al. Nature Physics **8** 301 (2012)

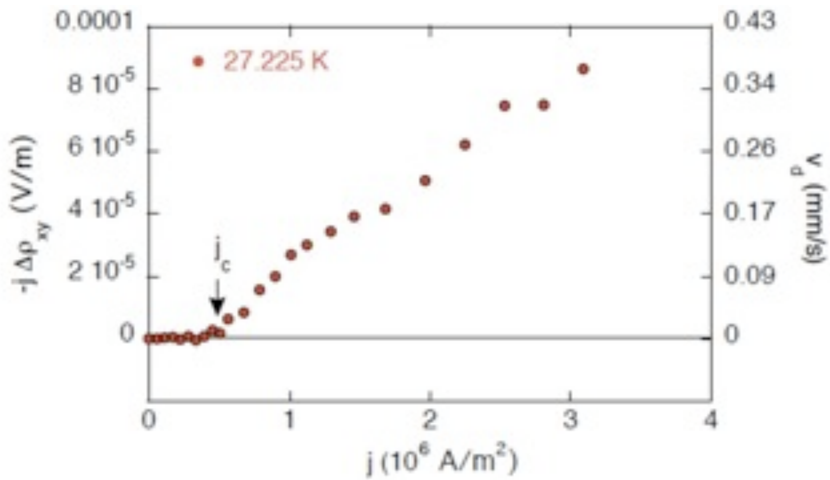
Emergent Electric Field due to Skyrmion Motion





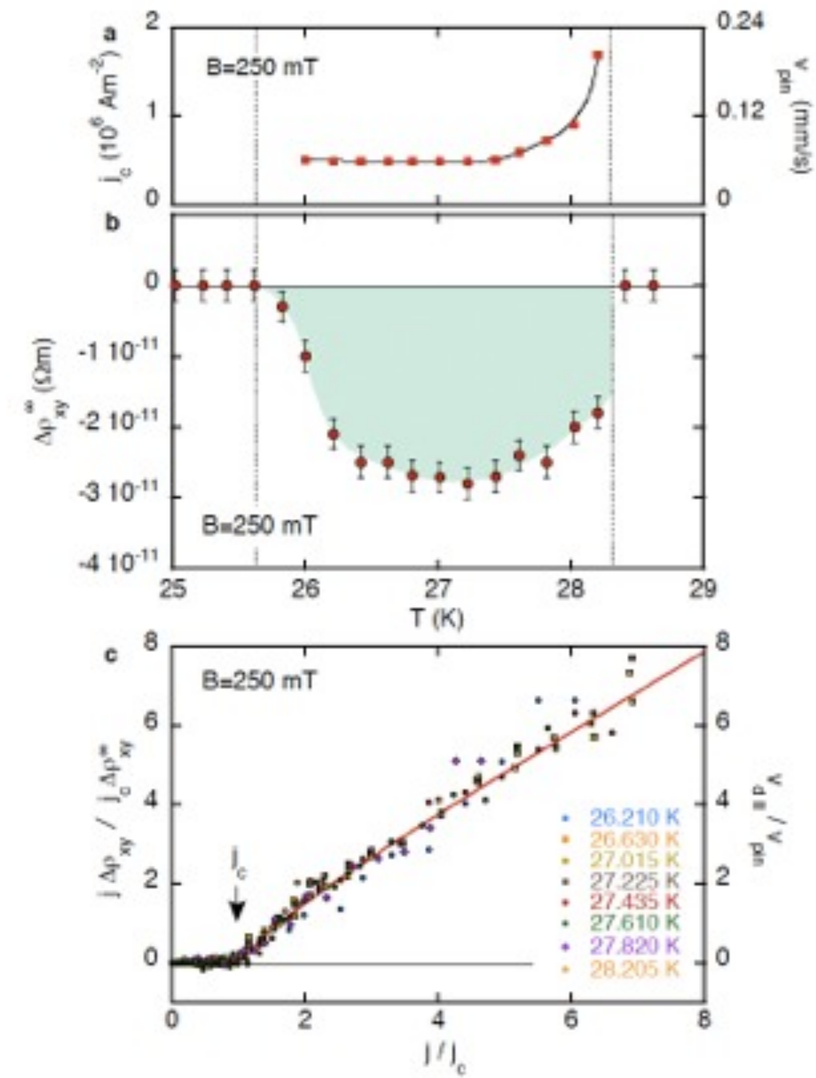
Schulz et al. Nature Physics **8** 301 (2012)

Emergent Electric Field due to Skyrmion Motion



$$\boldsymbol{E}^e = -\boldsymbol{v}_d \times \boldsymbol{B}^e$$

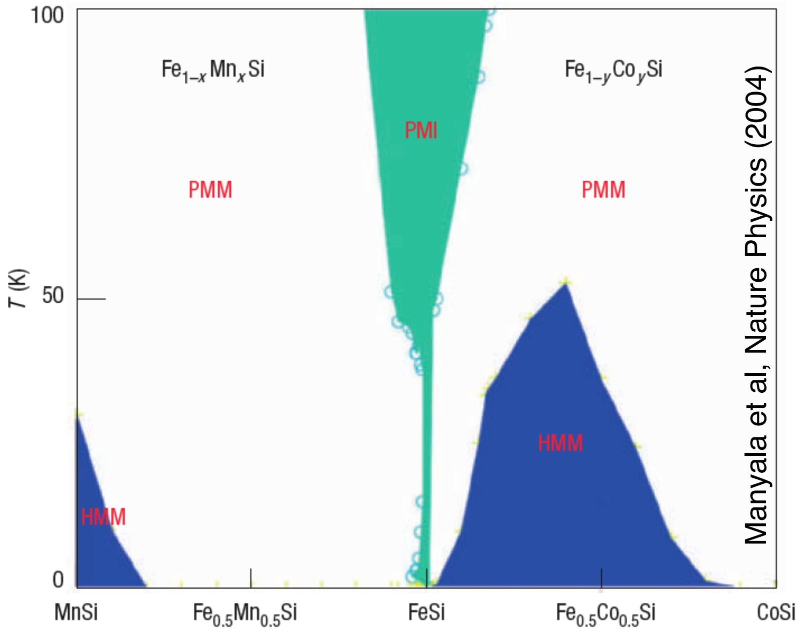
$$\begin{aligned} v_{d\|} &\approx -\left|\frac{e}{q^e}\right| \frac{j\Delta\rho_{xy}}{B^e\tilde{P}} \\ &= v_{\mathrm{pin}}\,\frac{j\Delta\rho_{xy}}{j_c\Delta\rho_{xy}^{\infty}} \\ &\approx \frac{j}{10^6\,\mathrm{Am}^{-2}}\,\frac{\Delta\rho_{xy}}{\Delta\rho_{xy}^{\infty}}\,0.12\frac{\mathrm{mm}}{\mathrm{s}} \end{aligned}$$

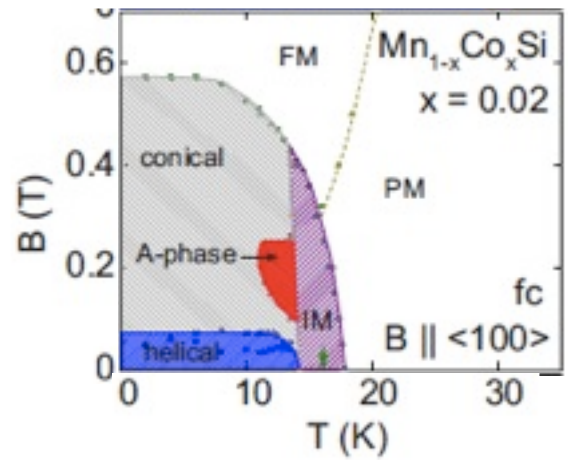


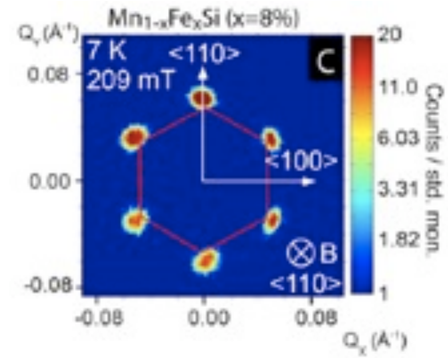
Schulz et al. Nature Physics **8** 301 (2012)

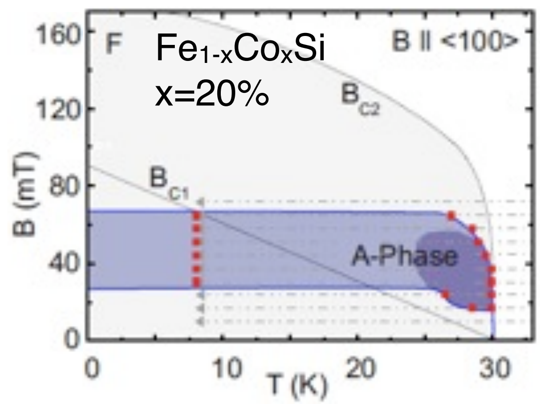
Perspectives & Summary

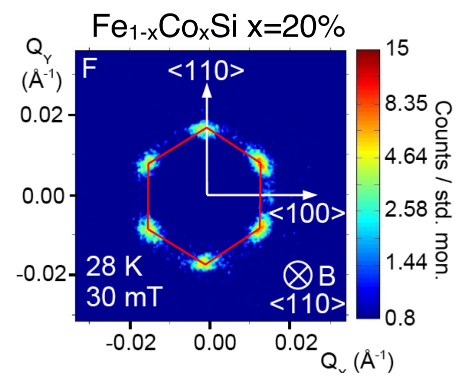
Magnetic Phase Diagram of B20 Compounds











Mühlbauer, et al. Science **323**, 915 (2009)
Neubauer, et al. PRL **102** 186602 (2009)
Janoschek, et al. J. Phys. Conf. Series (2010)

Münzer, et al. PRB(R) **81** 041203 (2010)
Adams, et al. J. Phys. Conf. Series (2010)
Bauer, et al. PRB(R) **82** 064404 (2010)

$P2_13$ insulators

Cu_2OSeO_3

Seki al., Science **336** 198 (2012)
Adams et al., PRL, **108** 237204 (2012)

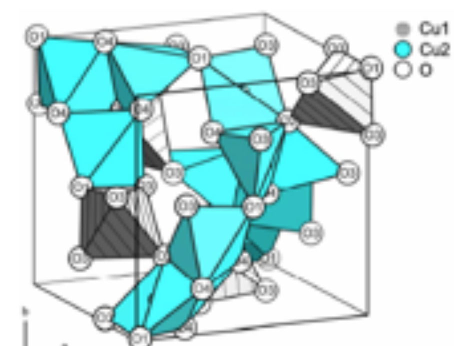
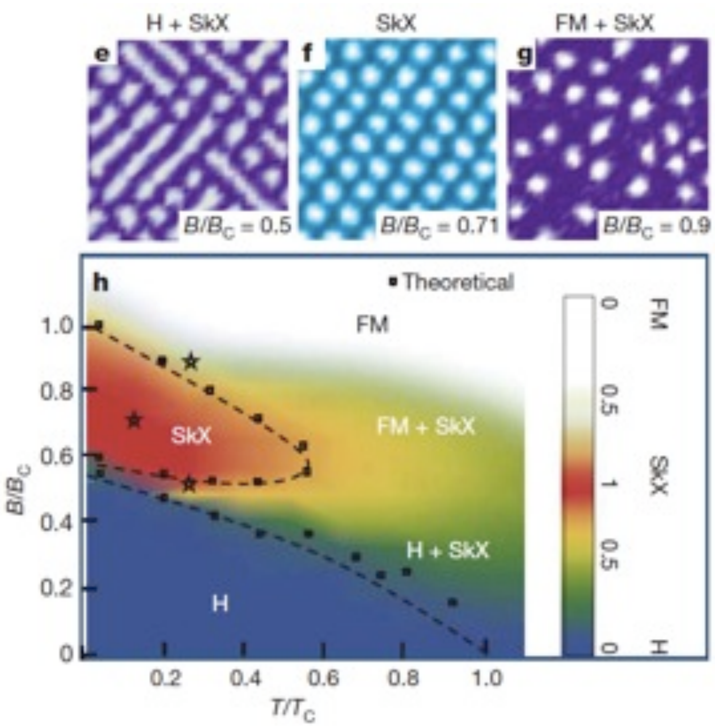


illustration from Bos et al. (2008)

Real Space Observation with Lorentz Force Microscopy

individual skyrmions

$Fe_{0.5}Co_{0.5}Si$

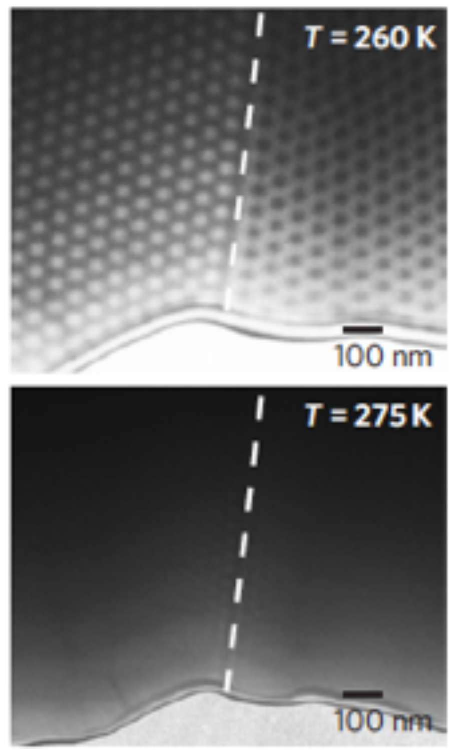


Münzer, et al. PRB(R) **81** 041203 (2010)
Yu et al., Nature **465** 901 (2010)

CP & Rosch, Nature (N&V) **465** 880 (2010)

near room temperature

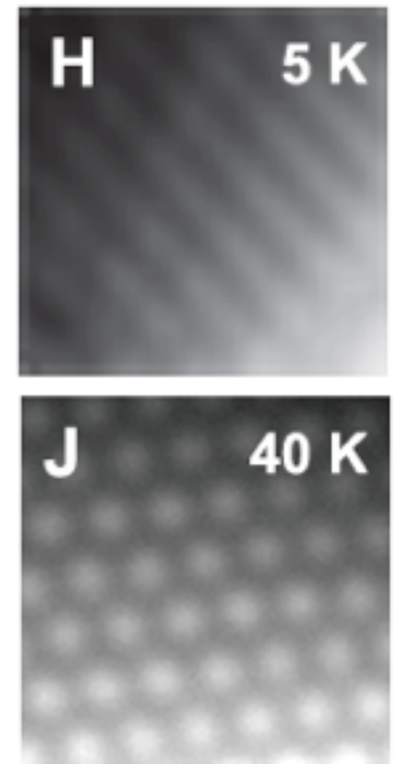
FeGe



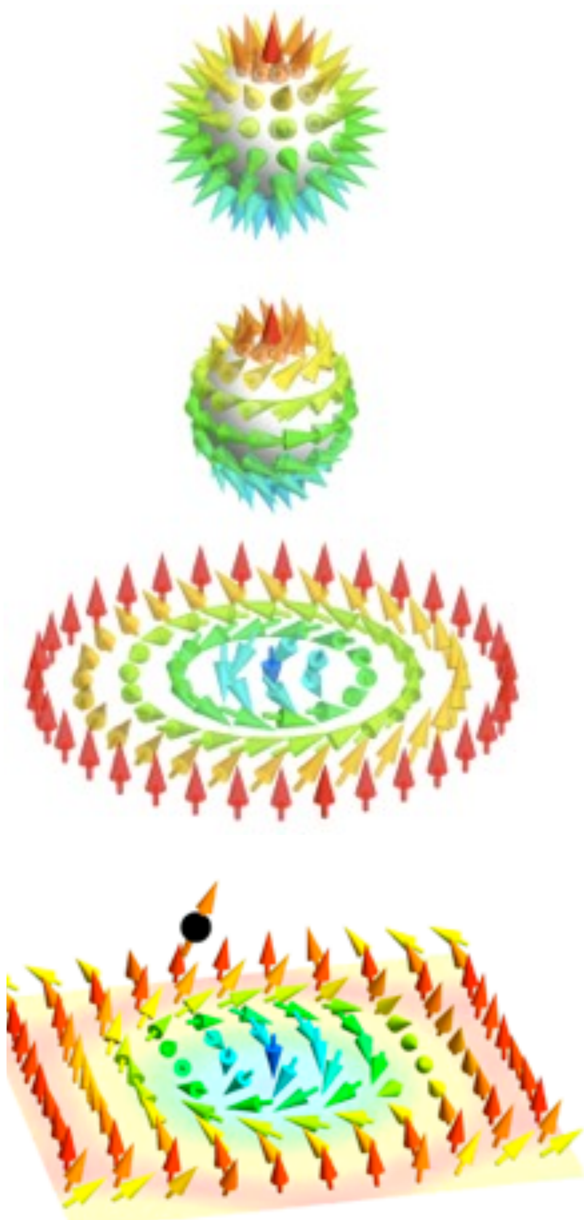
Yu et al., Nat. Mater. **10** 106 (2010)

in multiferroics

Cu_2OSeO_3



Seki al., Science **336** 198 (2012)



Summary

Skyrmion Lattices in Chiral Magnets

» basic phenomonology in MnSi

» theoretical account

» proof of topology

Emergent Electrodynamics

» spin torque effects (SANS)

» emergent magnetic field

» topological Hall effect

» emergent electric field