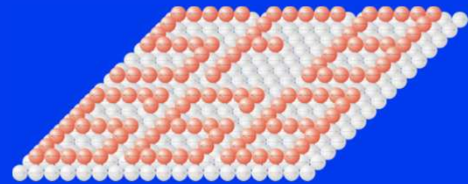
Funded by the Horizon2020 Framework Programme of the European Union



Manipulation of interface-induced Skyrmions studied with STM

Kirsten von Bergmann

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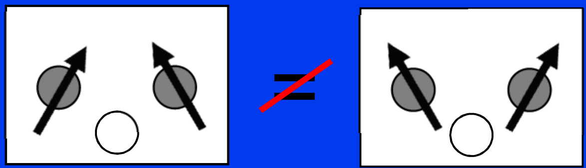
DMI: driving force for non-collinear states

Dzyaloshinskii-Moriya (DM) interaction due to spin-orbit coupling



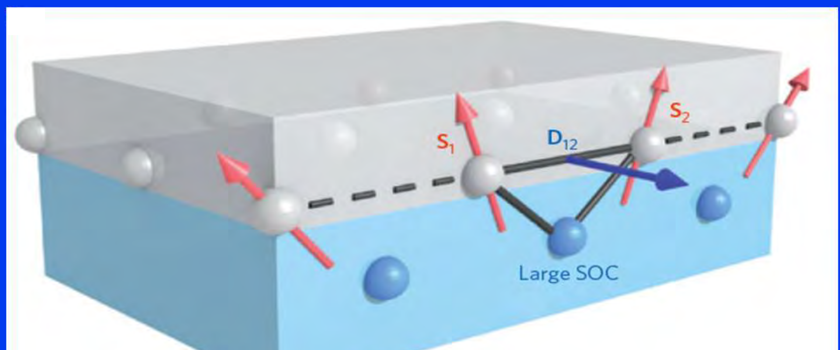
when inversion symmetry is broken

→ in chiral crystal structures

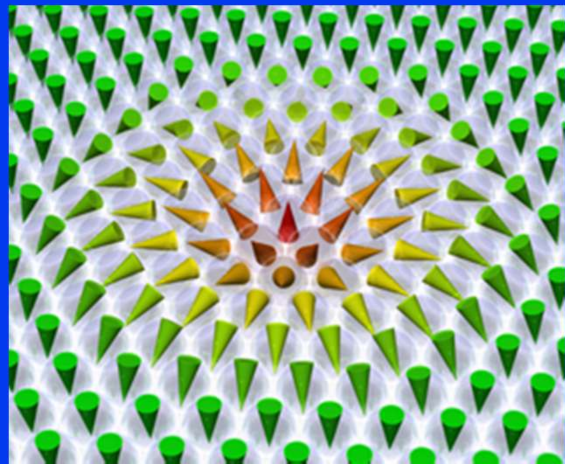
→ at surfaces / interfaces

I. Dzialoshinski, J. Phys. Chem. Solids **4**, 241 (1958).
T. Moriya, Phys. Rev. **120**, 91 (1960).

$$E_{\mathrm{DM}} = -\sum_{i,j} \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$



T. Moriya, Phys. Rev. **120**, 91 (1960).
image taken from:
A. Fert et al., Nature Nanotech. **8**, 152 (2013).



cycloidal spin rotation (Néel-type) with unique rotational sense

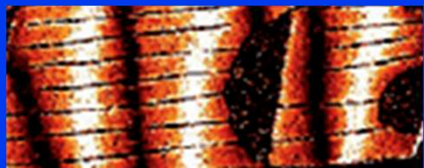
M. Bode, ...KvB, et al., Nature **447**, 190 (2007).

K. von Bergmann
University of Hamburg

Review: Interface-DMI in STM: KvB et al., J. Phys.: Condens. Matter **26**, 394002 (2014).

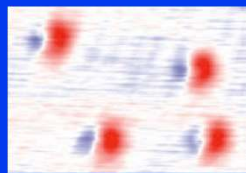
interface-induced DMI

spin spirals and
“chiral” Néel-type domain walls
(with unique rotational sense)



M. Bode, ...KvB et al., Nature **447**, 190 (2007).
P. Ferriani, KvB et al., Phys. Rev. Lett. **101**, 027201 (2008).
M. Heide et al., Phys. Rev. B **78**, 140403 (2008).
S. Meckler et al., Phys. Rev. Lett. **103**, 157201 (2009).
S. Emori et al., Nature Mater. **12**, 611 (2013).
K.-S. Ryu et al., Nature Nano. **8**, 527 (2013).
G. Chen et al., Phys. Rev. Lett. **110**, 177204 (2013).
.....

skyrmions and
skyrmionic bubbles
(with unique rotational sense)



~3 nm

~200 nm

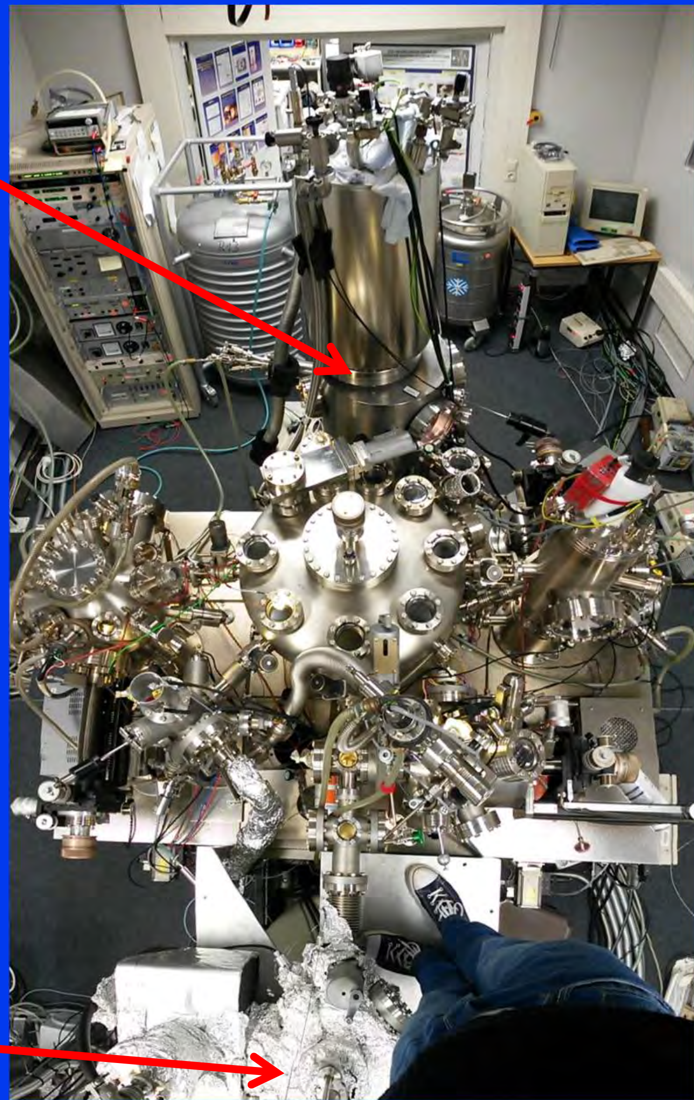
~1000 nm

S. Heinze, KvB et al., Nature Phys. **7**, 713 (2011).
N. Romming, …KvB et al., Science **341**, 636 (2013).
W. Jiang et al., Science **349**, 283 (2015).
G. Chen et al., Appl. Phys. Lett. **106**, 242404 (2015).
O. Boulle et al., Nature Nano **11**, 449-454 (2016).
C. Moreau-Luchaire et al., Nature Nano **11**, 444 (2016).
S. Woo et al., Nature Mater. **15**, 501 (2016).
.....

spin-polarized STM

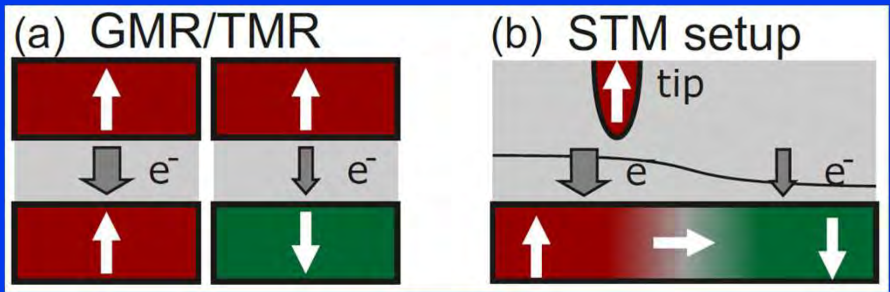
in situ preparation of tip and sample in UHV

STM
T = 8 - 13 K
$B_\perp$ < 2.5 T



STM
T = 1.3 - 4.2 K
$B_\perp$ < 9 T

TMR-effect
(tunnel magnetoresistance)
in STM geometry



M. Bode, Rep. Prog. Phys. **66**, 523 (2003).
R. Wiesendanger, Rev. Mod. Phys. **81** 1495 (2009).

$$I_{\mathrm{SP}}(U_0) = I_0[1 + P_{\mathrm{s}} \cdot P_{\mathrm{t}} \cdot \cos(\vec{M}_{\mathrm{s}}, \vec{M}_{\mathrm{t}})]$$

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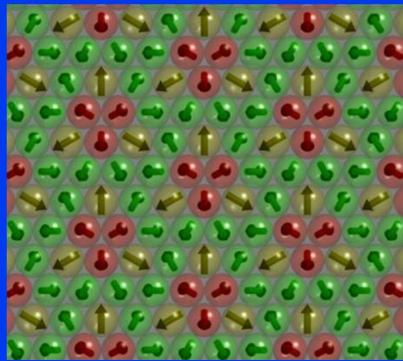
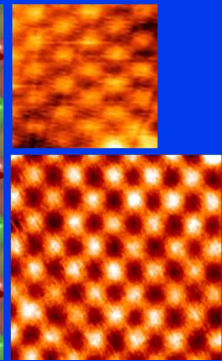
University of Hamburg

tuning of magnetism

nanoskyrmion lattices ML-Fe/Ir(111)
1 nm square fcc-Fe (*B* = 0T)
1nm hexagonal hcp-Fe (*B* = 0T)
DMI is 1.8 meV/atom (fcc)

KvB et al., Phys. Rev. Lett. **96**, 167203 (2006).
S. Heinze, KvB et al., Nature Phys. **7**, 713 (2011).
KvB et al., Nano Lett. **15**, 3280 (2015).





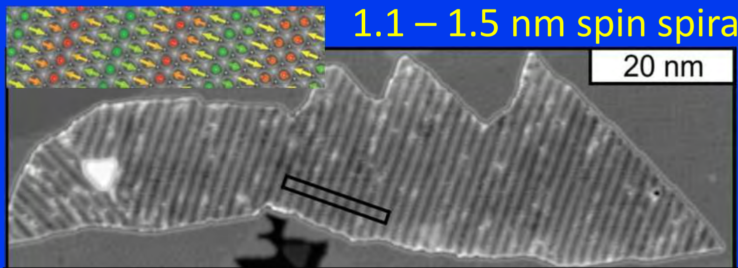
Fe/Ir(111)
strong DMI

PdFe

6 – 7 nm spin spiral
2 – 4 nm skyrmions

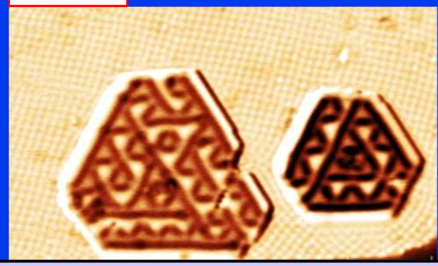
RhFe

1.1 – 1.5 nm spin spiral



N. Romming, ... KvB et al., arXiv 1610.07853.

NiFe ferromagnetic



D. Iaia, ...KvB et al., PRB **93**, 134409 (2016).

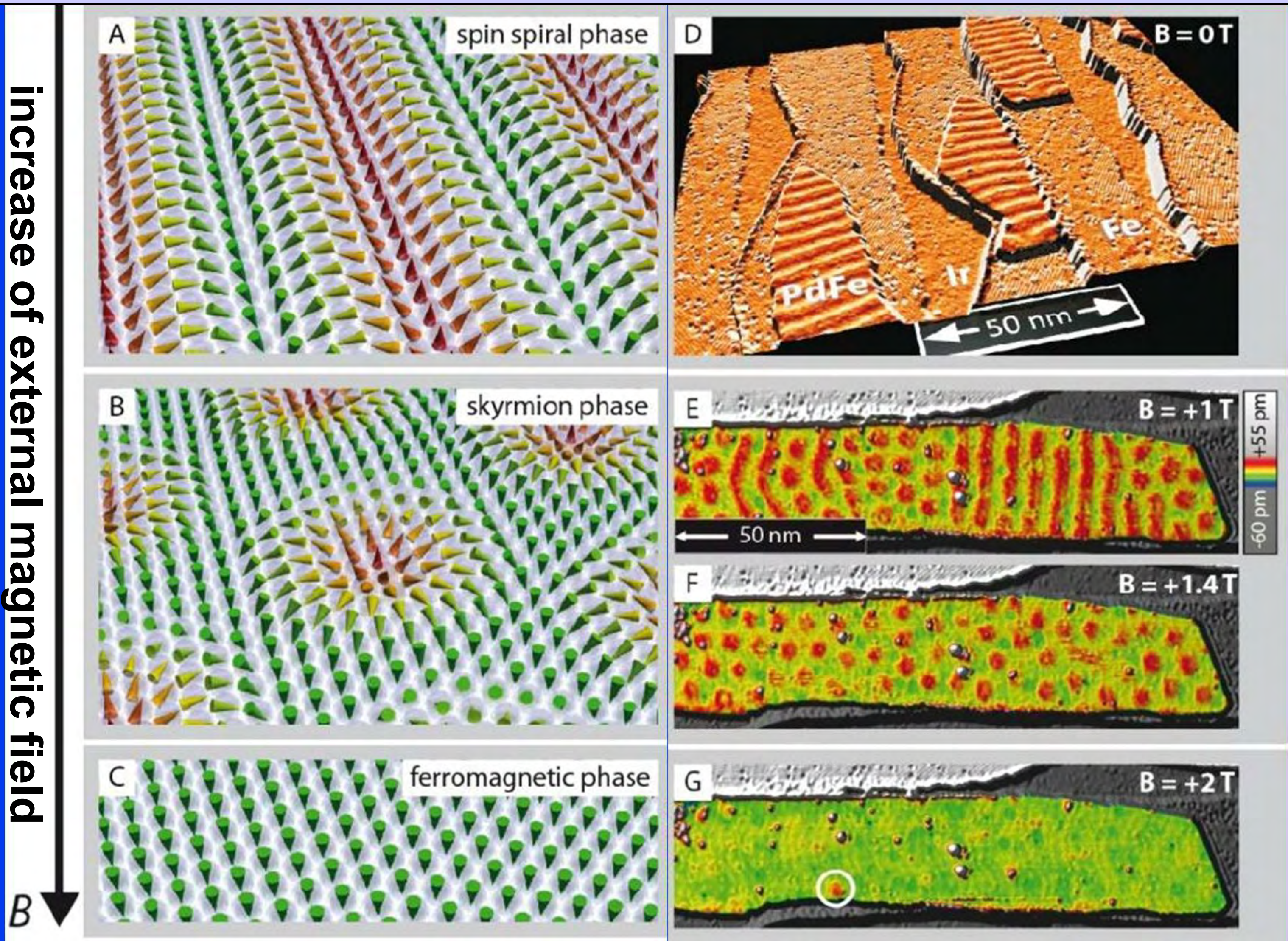
FeFe

1 – 10 nm spin spiral
skyrmions

K. von Bergmann
University of Hamburg

SP-STM: PdFe / Ir(111)

similar to: S. Mühlbauer et al., Science **323**, 915 (2009), X.Z. Yu et al., Nature **465**, 901 (2010).

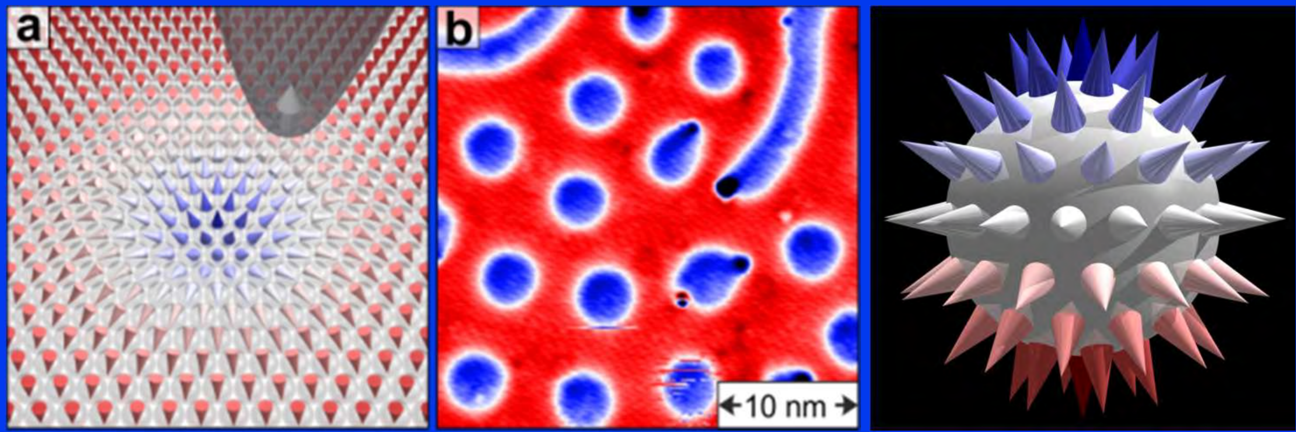


N. Romming, …KvB et al., Science **341**, 636 (2013).

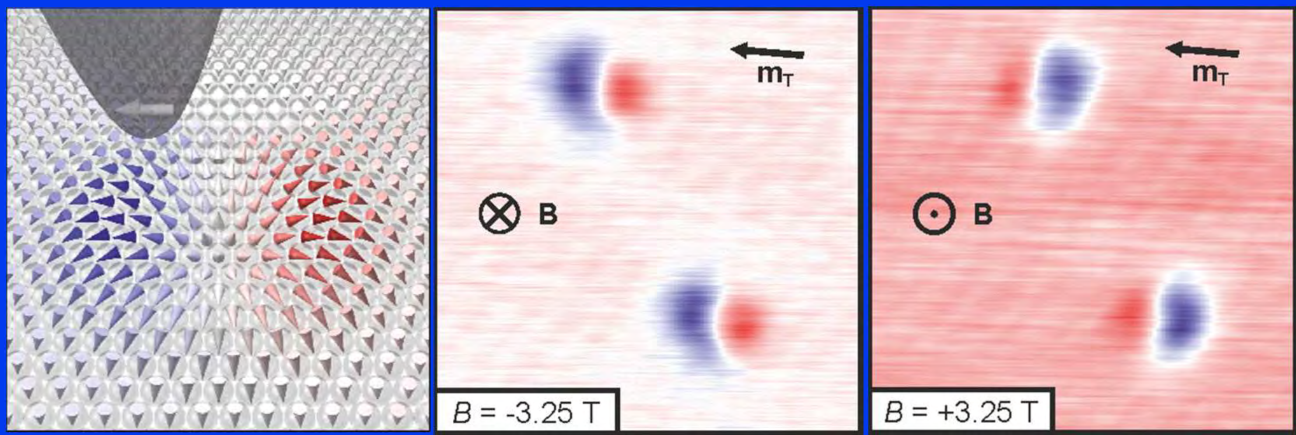
SP-STM contrast for skyrmions

topology $|S| = 1$

out-of-plane components



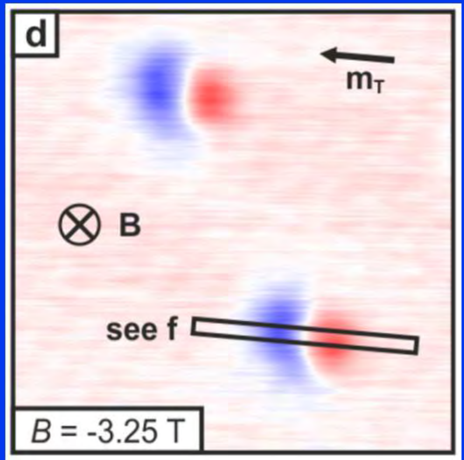
in-plane components



→ rotational sense of skyrmions is unique, and is preserved for opposite magnetic field

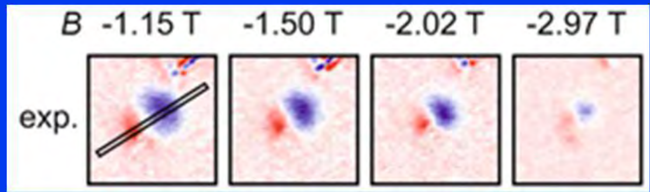
spin structure of an isolated skyrmion

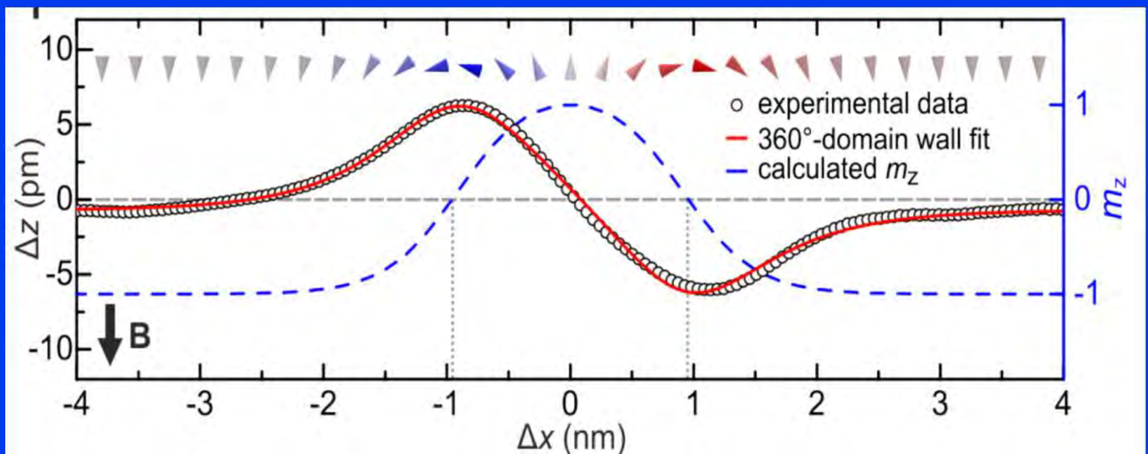
two overlapping 180° domain walls

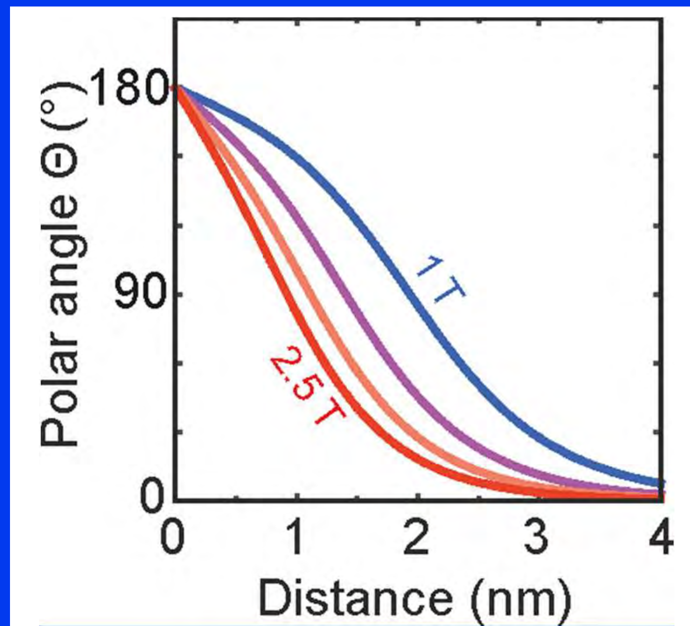


$$\theta(\rho, c, w) = \sum_{+,-} \left[\arcsin \left(\tanh \left(\frac{-\rho \pm c}{w/2} \right) \right) \right]$$

ρ position, c center, w width of wall







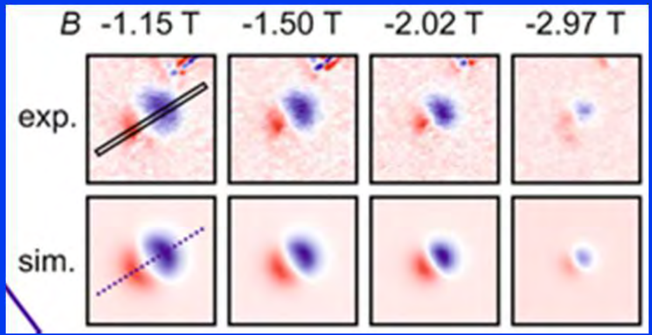
N. Romming, ...KvB et al.,
Phys. Rev. Lett. **114**, 177203 (2015).

material parameters

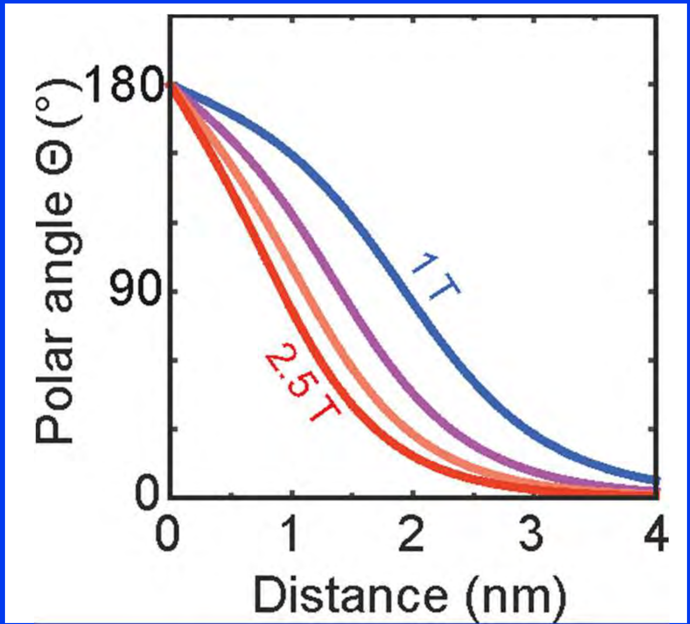
$$E(\theta(\rho)) = 2\pi t \int_0^\infty \left[A\left(\left(\frac{d\theta}{d\rho}\right)^2 + \frac{\sin^2\theta}{\rho^2} \right) - D\left(\frac{d\theta}{d\rho} + \frac{\sin\theta\cos\theta}{\rho} \right) - K\cos^2\theta - B_z M_S \cos\theta \right] \rho \, d\rho$$

A. Bogdanov, A. Hubert, J. Magn. Magn. Mater. **138**, 255 (1994), Phys. Status Solidi B **186**, 527 (1994)

A = 2.0 pJ/m $|D|$ = 3.9 mJ/m² K = 2.5 MJ/m³ M_S = 1.1 MA/m



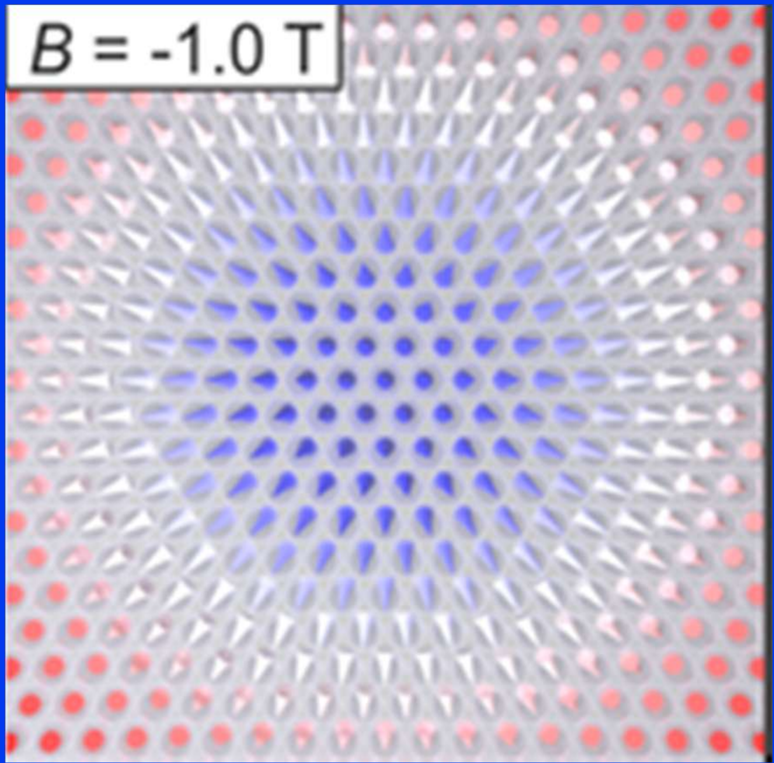
A, D, K
derived experimentally

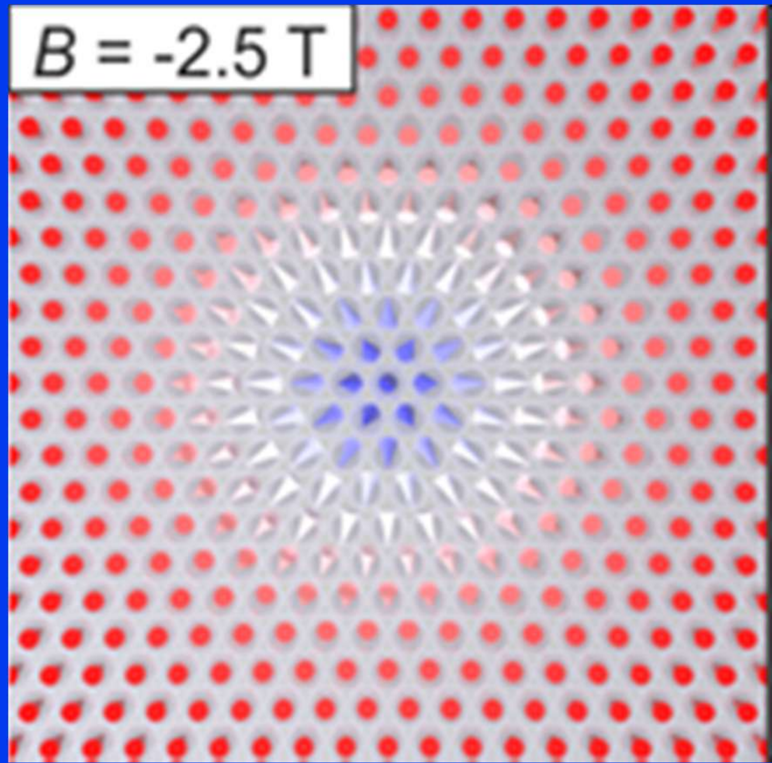


M_s from DFT
B. Dupé et al., Nat. Commun. **5**, 4030 (2014).
E. Simon et al., Phys. Rev. B **90**, 094410 (2014).

N. Romming, ...KvB et al., Phys. Rev. Lett. **114**, 177203 (2015).

B-dependent size and shape of Skyrmions

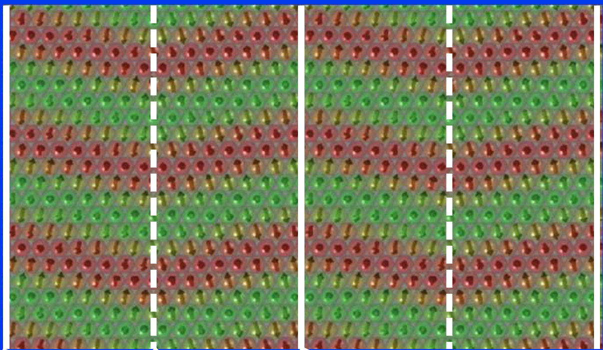


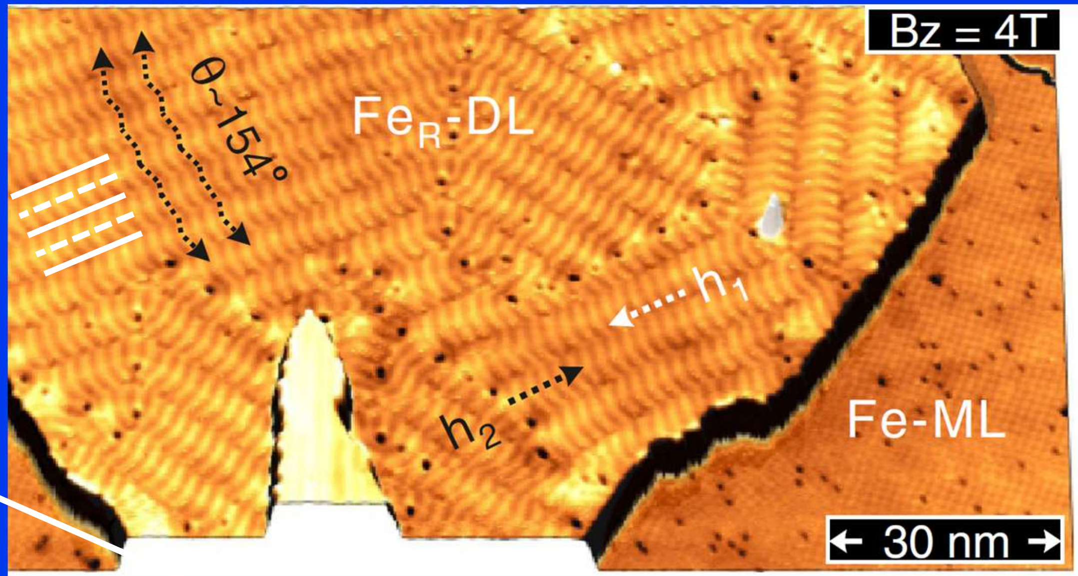


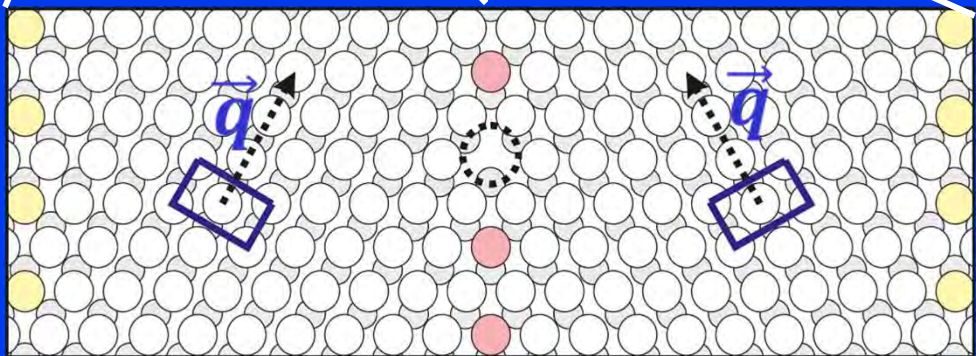
N. Romming, ...KvB et al.,
Phys. Rev. Lett. **114**, 177203 (2015).

double layer DL-Fe / Ir(111)

uniaxial dislocation lines (~5.5nm)
in three rotational domains
spin spiral is coupled to atomic lattice







DL-Fe / Ir(111):
zigzag spin spiral (~1.4 nm)
cycloidal (due to DMI)
no change in *B* < 9T

P.-J. Hsu, ...KvB, et al.,
Phys. Rev. Lett. 116, 017201 (2016).

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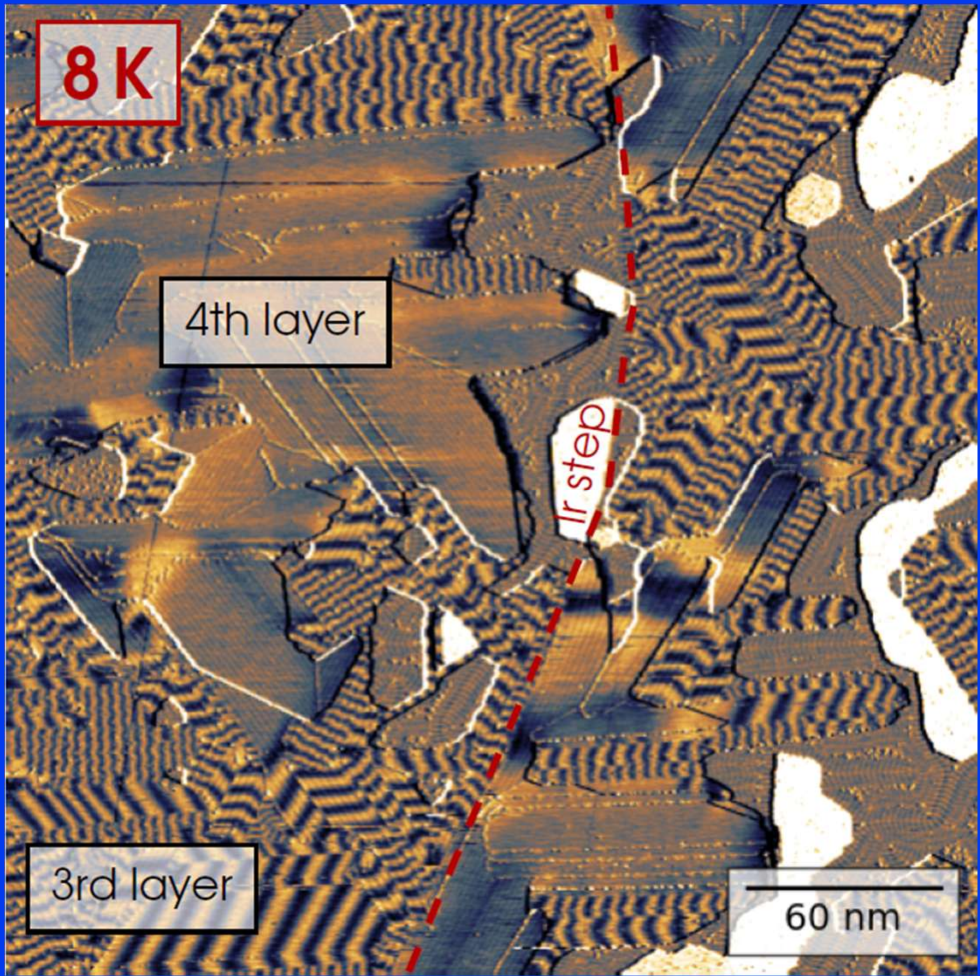
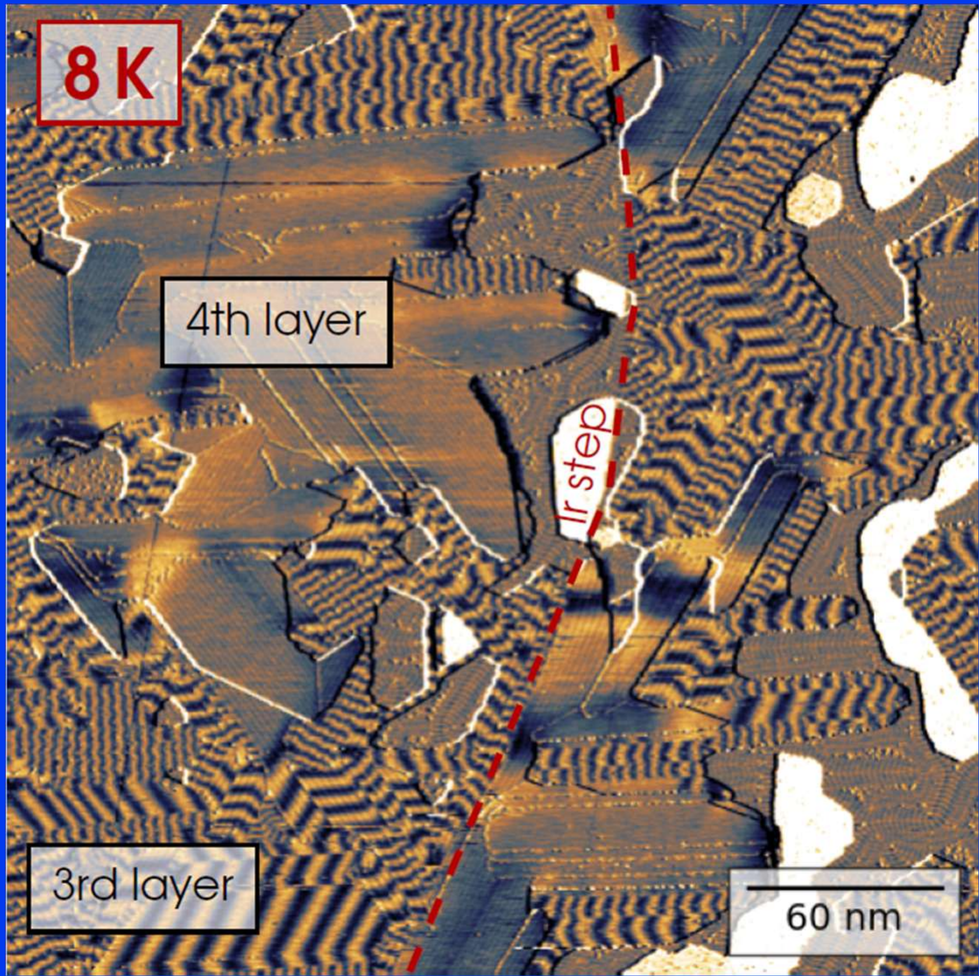
higher Fe layers on Ir(111)

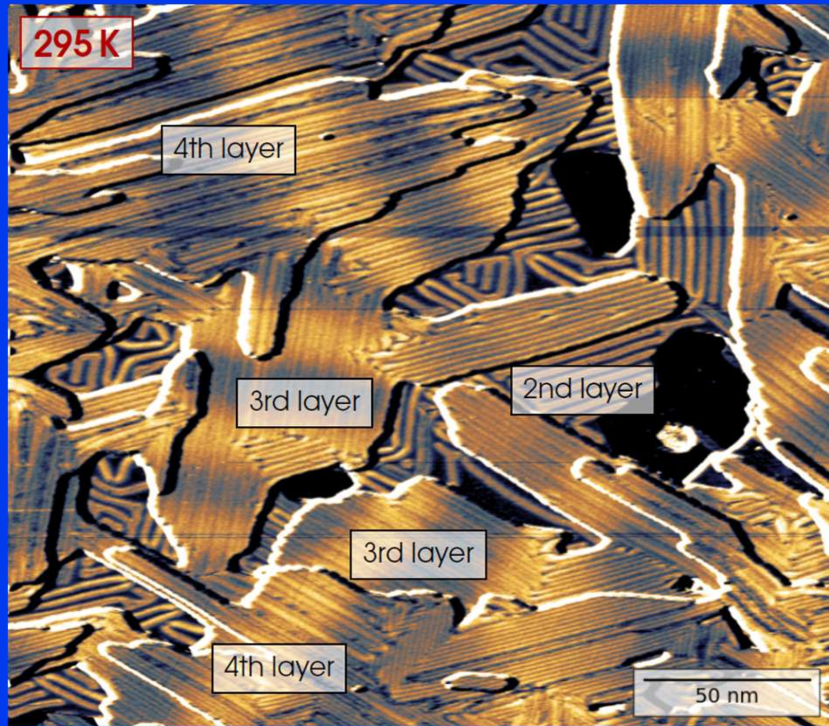


monolayer: nanoskyrmion lattice 1 nm
double layer: spin spiral 1-2 nm
triple layer: spin spiral 3 – 10 nm
quadruple layer: ferromagnetic (?)

A. Finco, ...KvB et al., Phys. Rev. Lett. **119**, 037202 (2017).

higher Fe layers on Ir(111) at RT

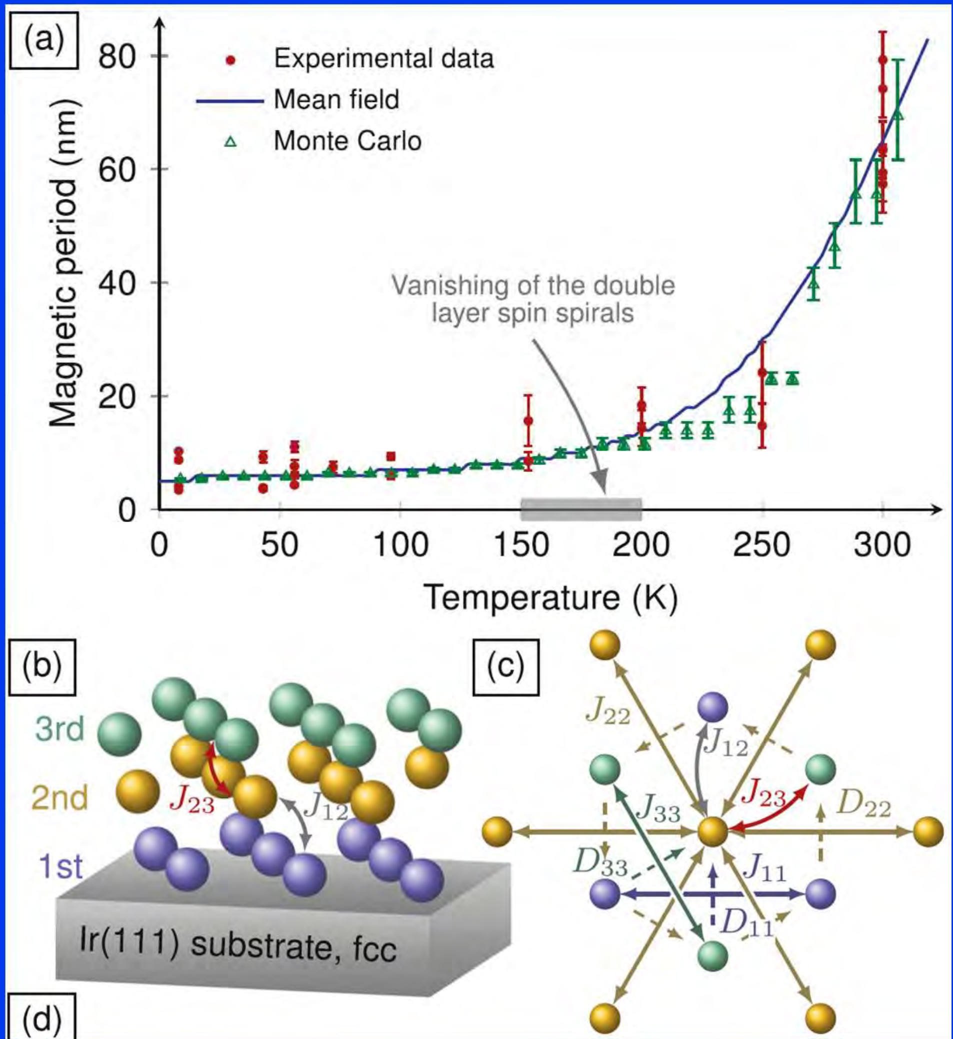


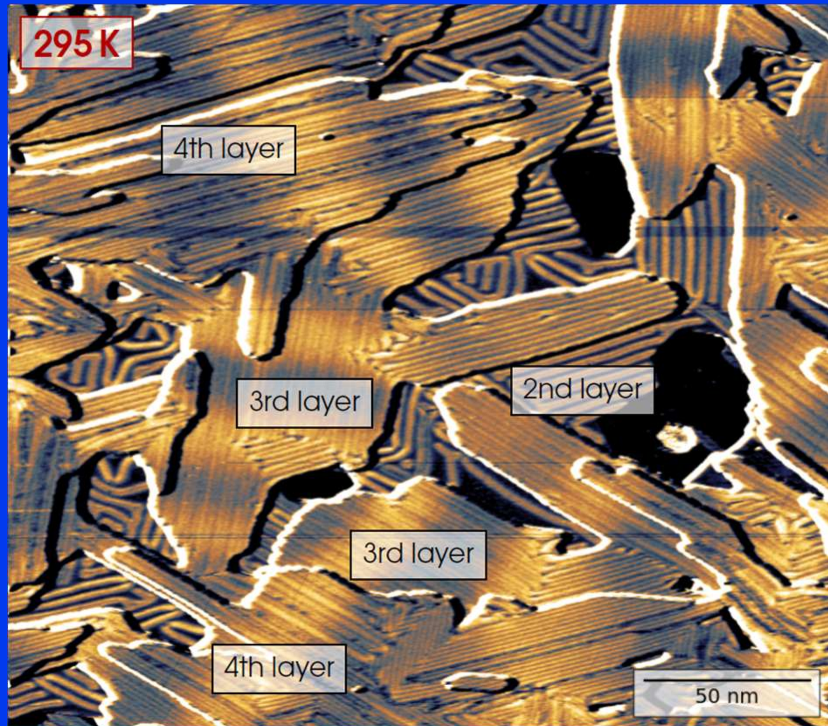


TL - spin spiral stable at RT,
but period is about 10 x larger!
also: at RT spin spiral 3ML ≅ 4ML

A. Finco, ...KvB et al., Phys. Rev. Lett. **119**, 037202 (2017).

TL-Fe layer on Ir(111): period (*T*)





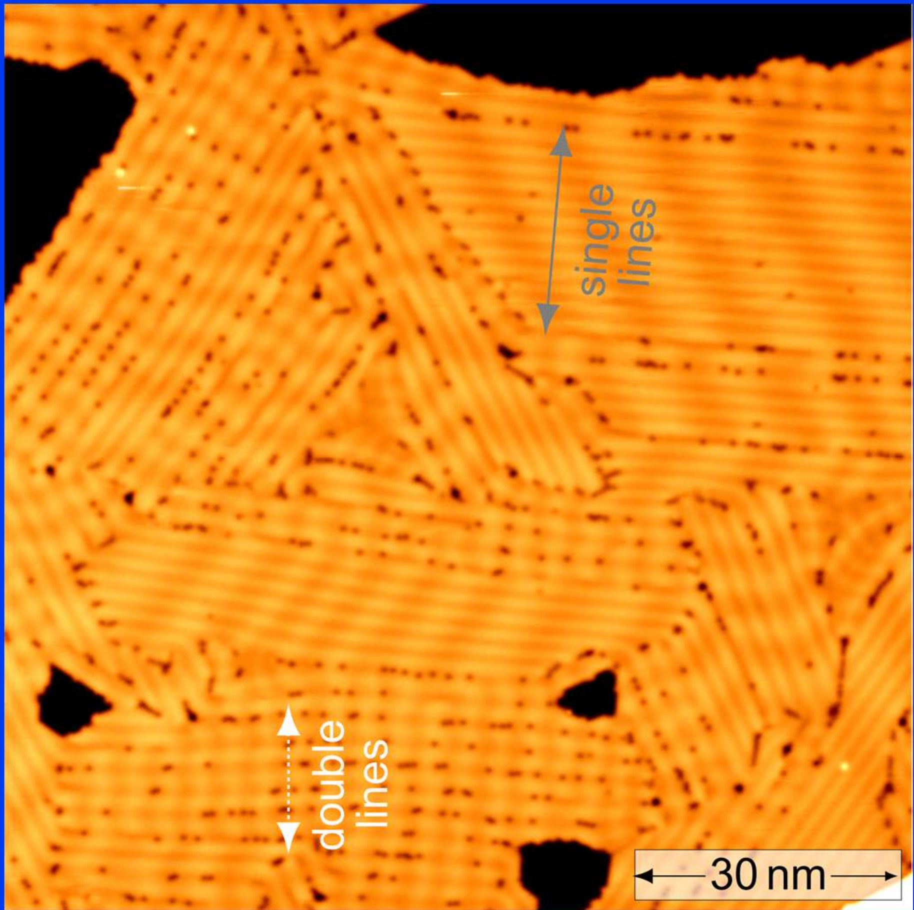
TL - spin spiral stable at RT,
but period is about 10 x larger!

possible explanation:
layer-dependent magnetic interactions

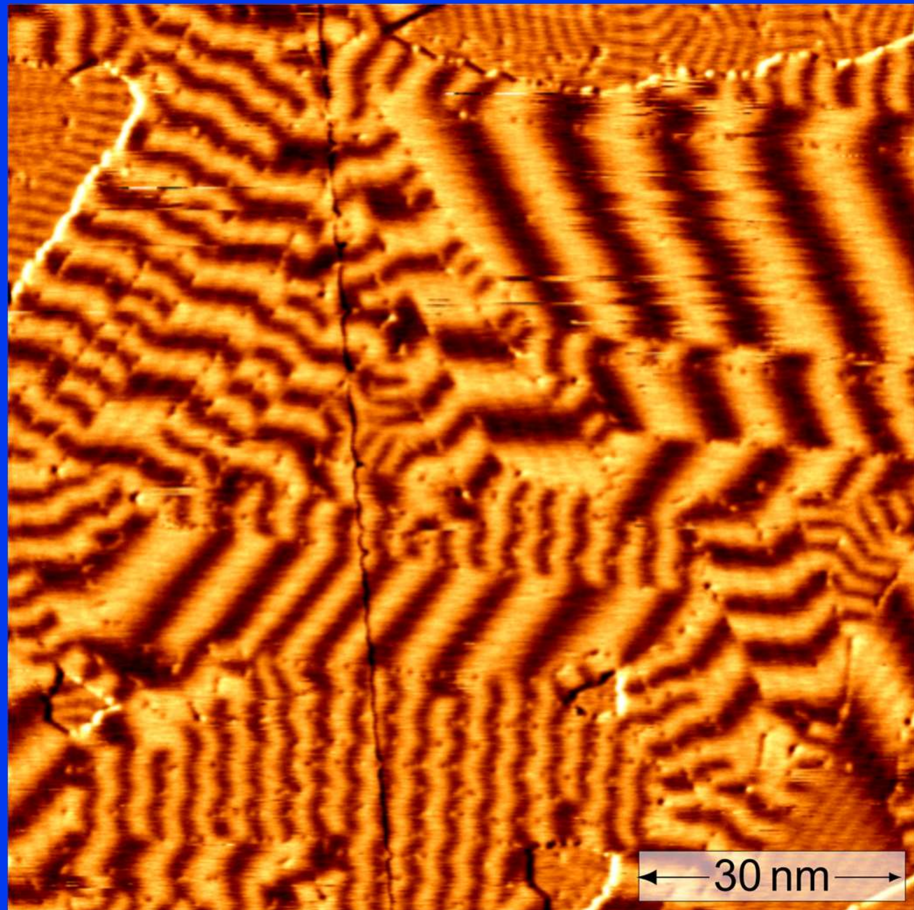
A. Finco, ...KvB et al., Phys. Rev. Lett. **119**, 037202 (2017).

triple layer TL-Fe/Ir(111)

TL-Fe: two different reconstructions with spin spiral ground state, wavefront according to structural symmetry



topography



spin-resolved differential conductance

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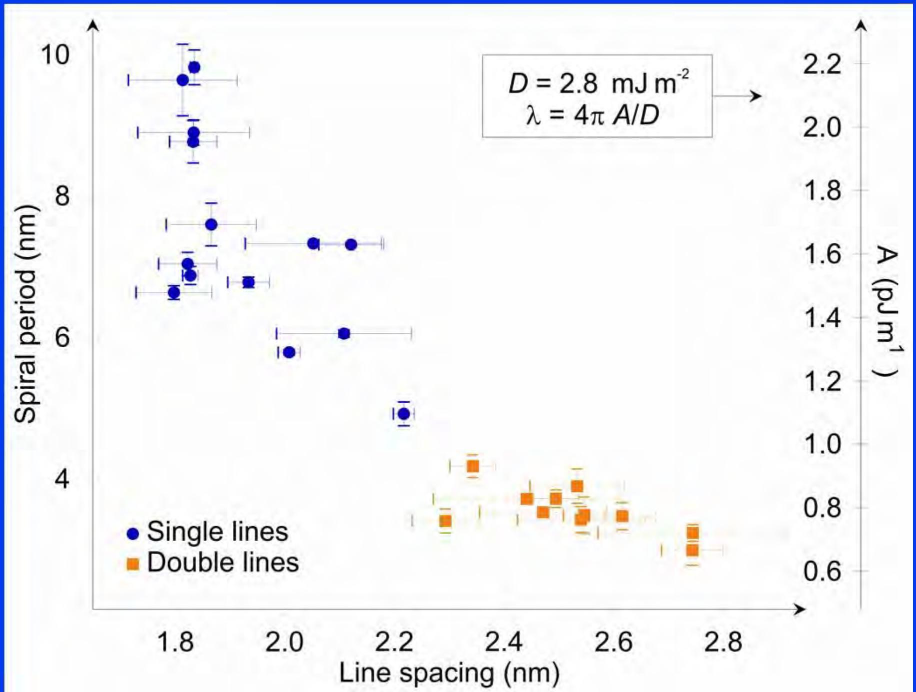
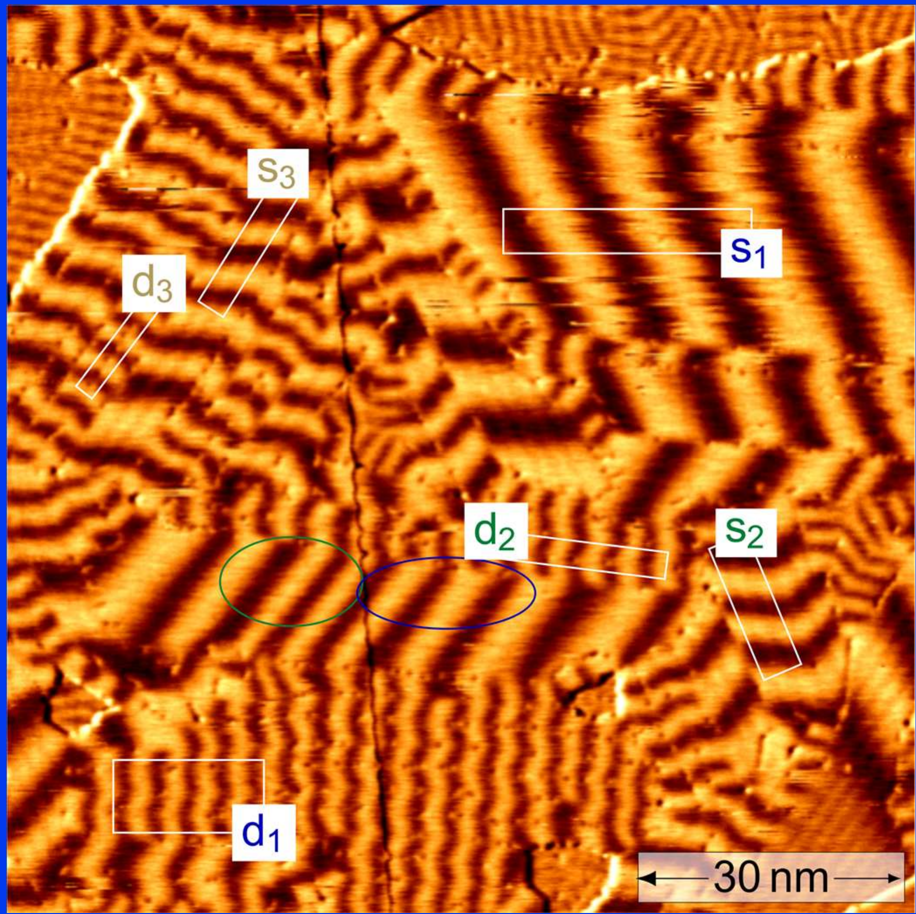
A. Finco, ...KvB, et al., Phys. Rev B 94, 214402 (2016)

triple layer TL-Fe/Ir(111)





the magnetization follows a sine

→ homogeneous spin spiral

→ anisotropy negligible

DMI is governed by the interface

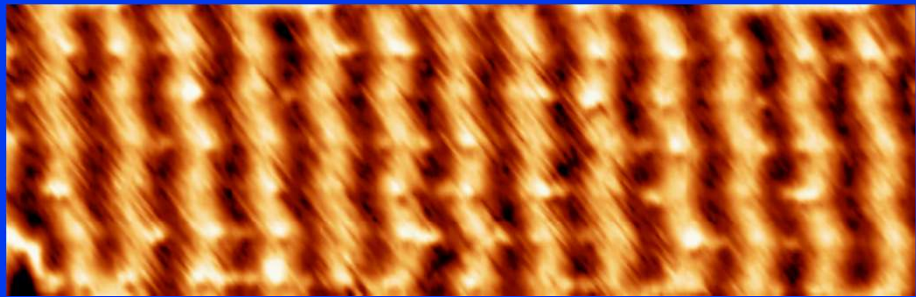
→ change in *A* due to strain

tailoring non-collinear magnetism by misfit dislocation lines

A. Finco, ...KvB, et al., Phys. Rev B 94, 214402 (2016)

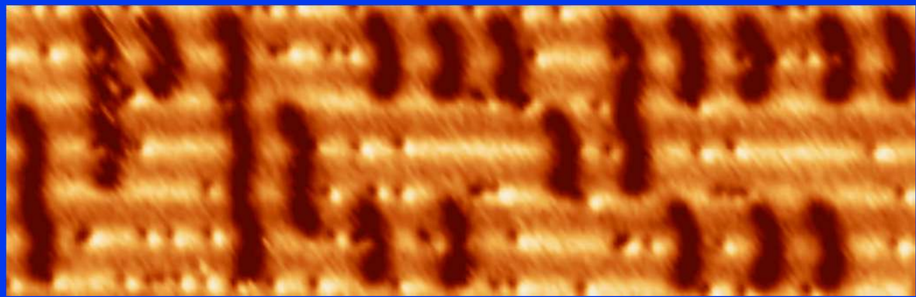
triple layer TL-Fe / Ir(111)

TL-Fe $B = 0\mathrm{T}$ dI/dV ~4 nm



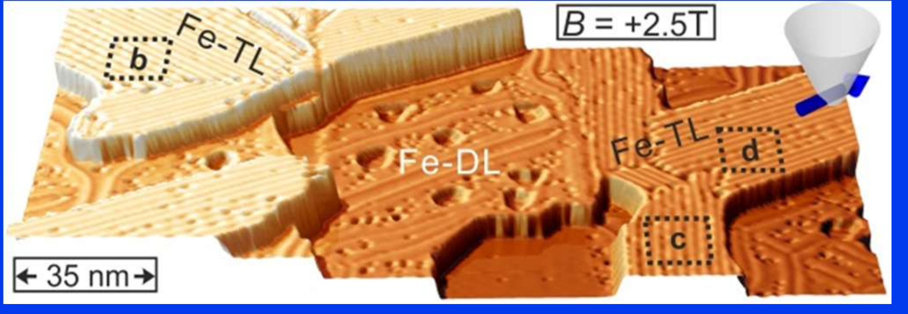
20 nm

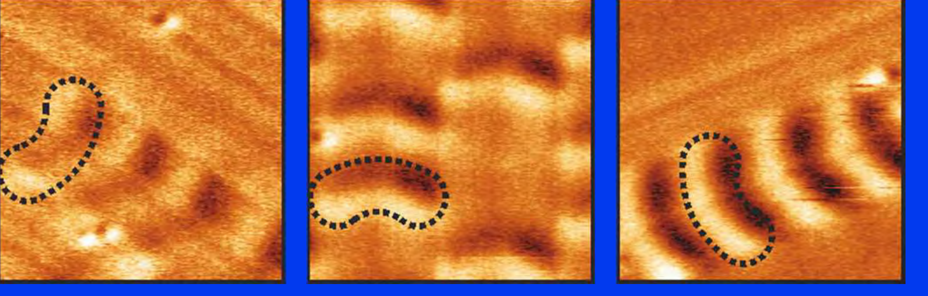
TL-Fe $B = +2.5\mathrm{T}$



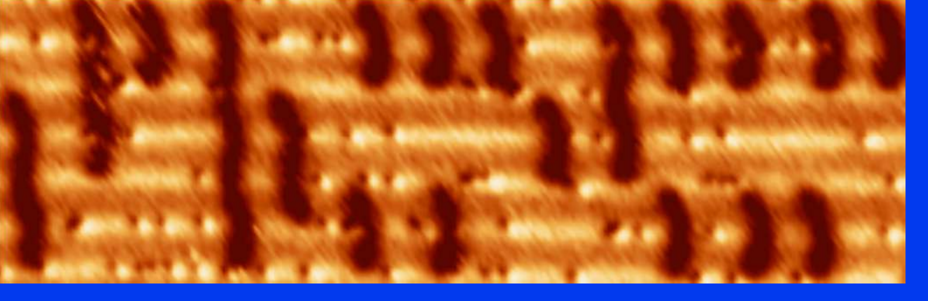
→ single magnetic objects

spin structure





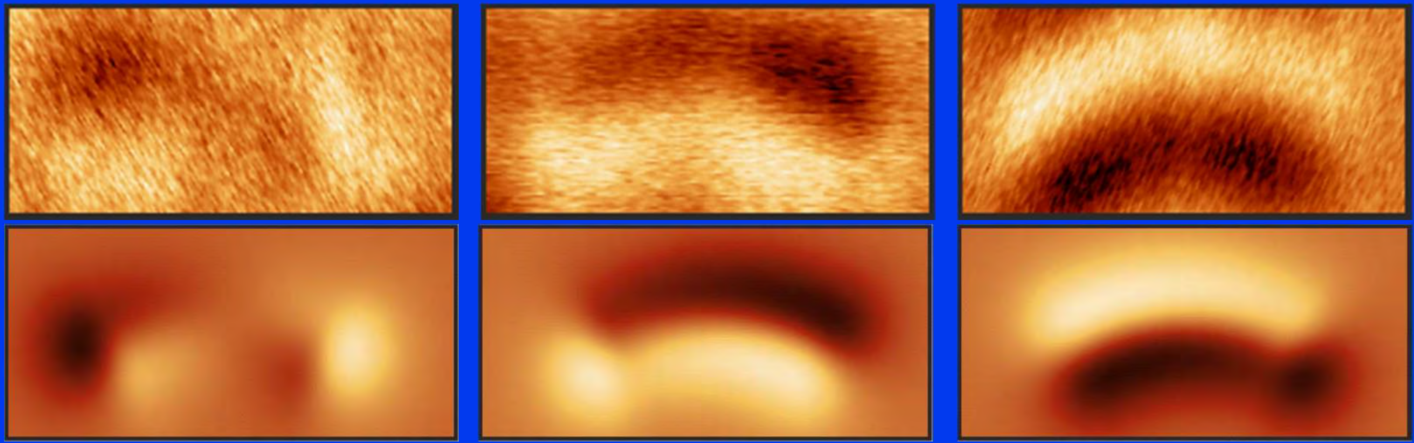
in-plane magnetization components

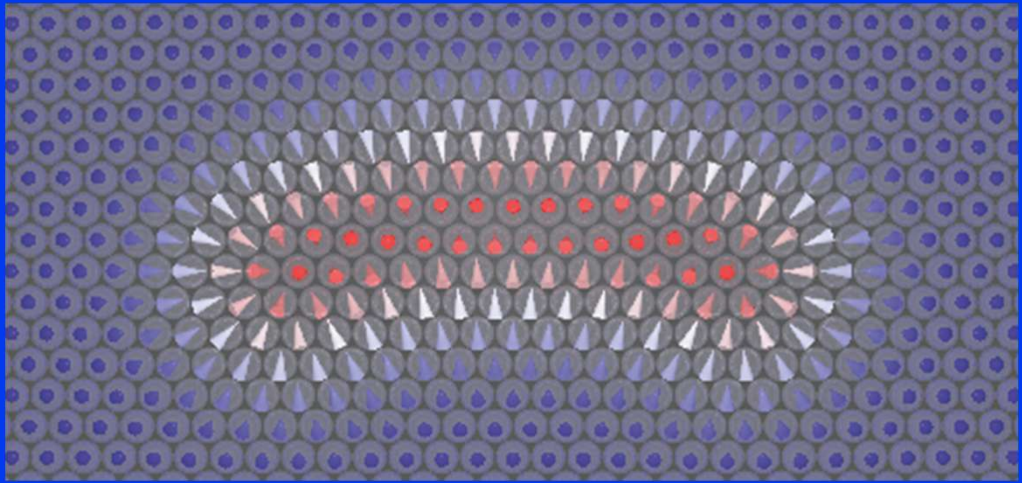


out-of-plane magnetization components

$\rightarrow$ single magnetic objects

are these magnetic skyrmions ?

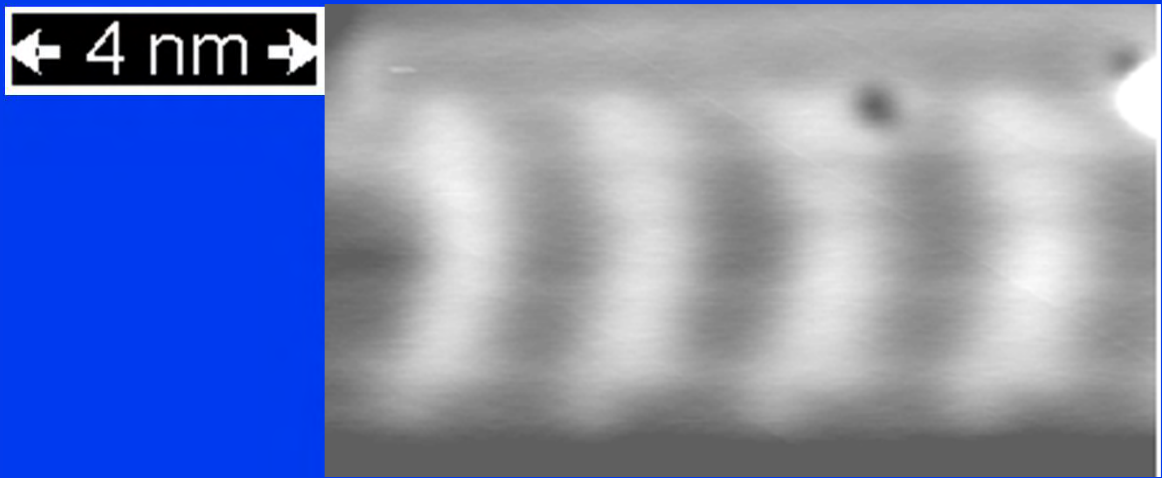


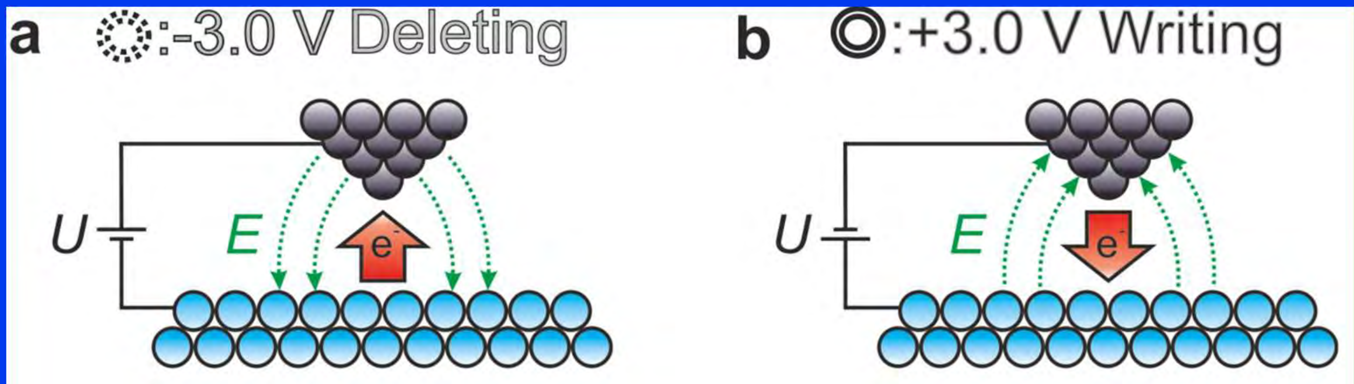


experimentally derived spin structure is equivalent to a distorted magnetic skyrmion, distortion is in agreement with symmetry of underlying atomic structure

switching with spin-polarized tip

deleting with -3V
writing with +3V





directionality connected to the sign of the voltage

~~spin-torque switching?~~ switching works with non-magn. tip

electric field driven?

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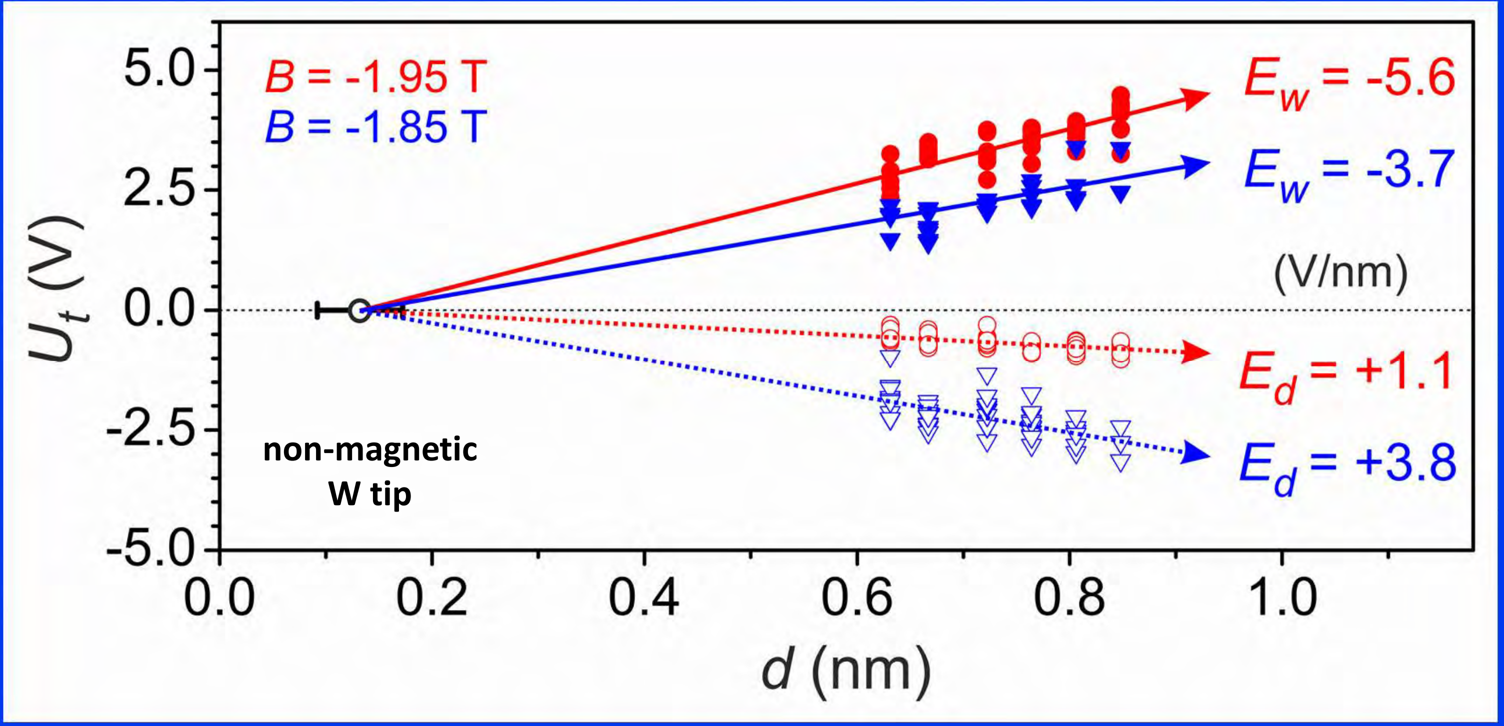
critical electric fields

critical electric field ***E = U/d*** **(upper bound due to parallel plate approximation)**



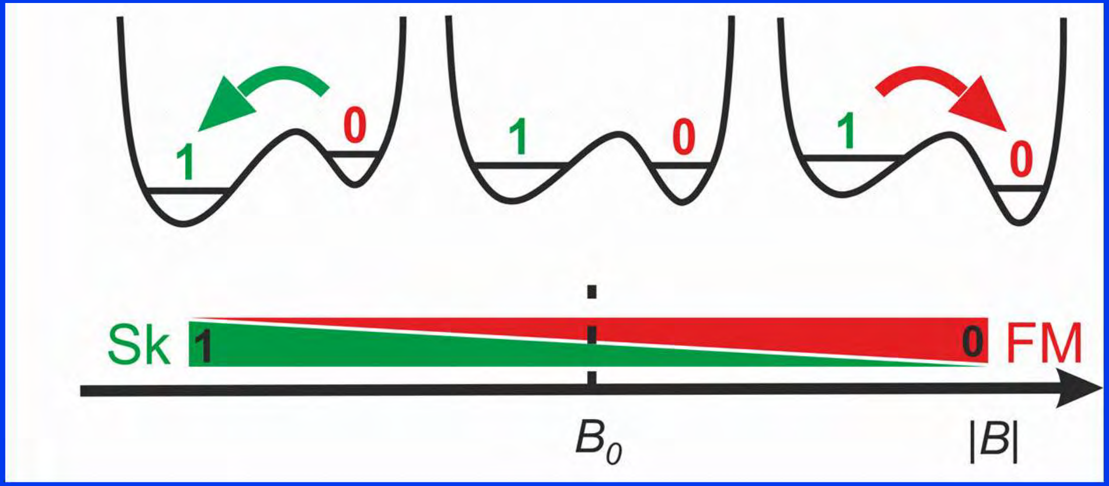
***E*-field: changes surface charge distribution, atom positions**
→ change in *K*? change in *A*? change in *D*?

M. Schott et al., Nano Lett. **17**, 3006 (2017).

P.-J. Hsu, ..., KvB et al., Nature Nanotech. **12**, 123 (2017).

B- and *E*-dependent energy landscape

local *E*-fields: $\rightarrow$ switching of single skyrmions
1 V/nm ~ 40 mT



with the *B*-field we can tune the energy landscape

P.-J. Hsu, ..., KvB et al., Nature Nanotech. **12**, 123 (2017).

summary

tuning of the magnetic state based on the Fe/Ir interface (large DMI)

Nature Phys. **7**, 713 (2011). Nano Lett. **15**, 3280 (2015).

measurement of *B*-dependent size and shape yields *A*, *D*, *K*

Science **341**, 636 (2013). PRL **114**, 177203 (2015).

higher Fe layer on Ir and temperature dependence

PRL **116**, 017201 (2016). PRL **119**, 037202 (2017).

tuning of magnetic lengthscale by strain

PRB **94**, 214402 (2016)

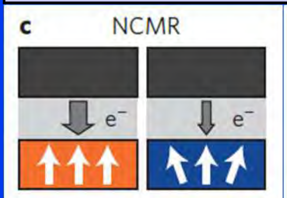
electric field driven switching
between topologicaly distinct states

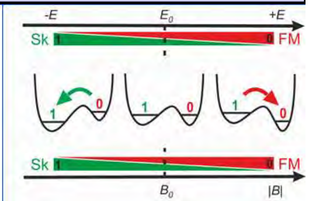
Nature Nanotech. **12**, 123 (2017).

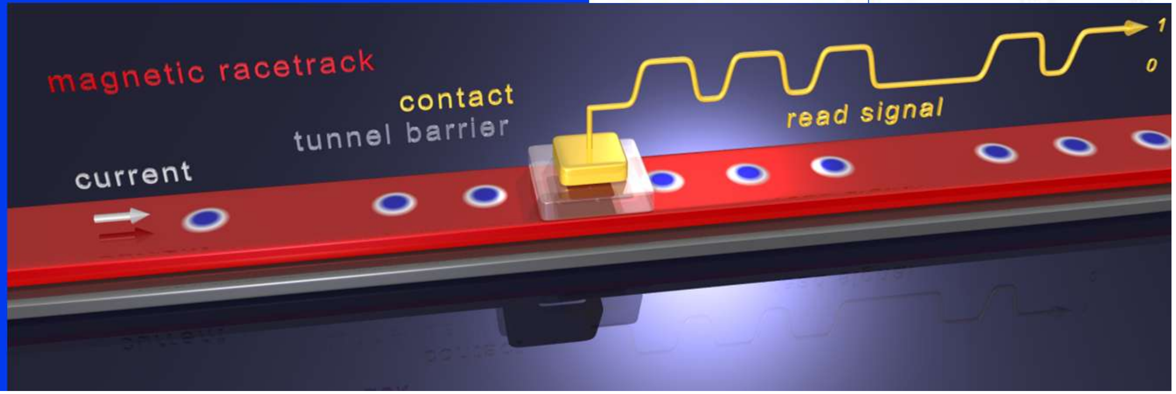
tuning of magnetic length scale
with hydrogen

non-collinear (NC) MR **reading**	electric field **writing**

Nature Nanotechn.
10, 1039 (2015). **12**, 123 (2017).







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Dr. André Kubetzka

Prof. Roland Wiesendanger

Group of Prof. Stefan Heinze (Univ of Kiel, Germany)

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DFG GrK 1286

MAGic Sky

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