Deutsche Forschungsgemeinschaft DFG

Funded by the Horizon2020 Framework Programme of the European Union

Nanometer-scale magnetic Skyrmions studied with STM

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magnetic skyrmions

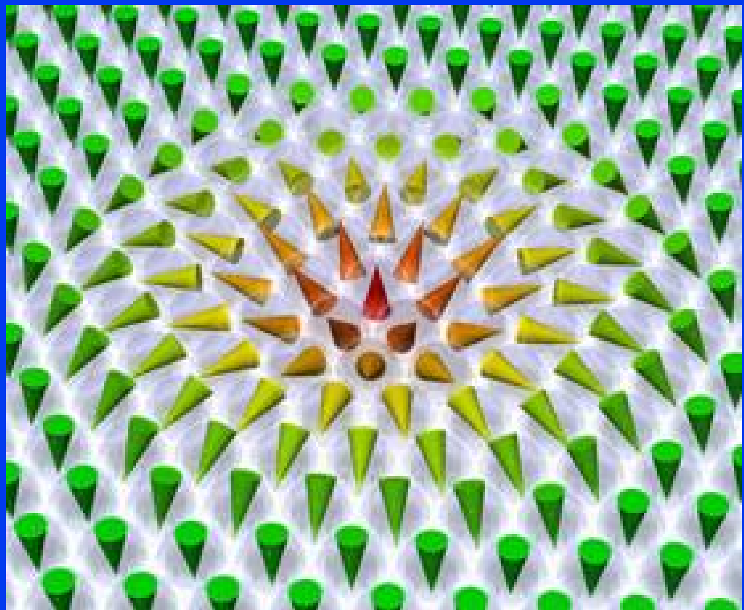
isotropic Heisenberg
exchange interactions

$$E_{\mathrm{H}} = -\sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

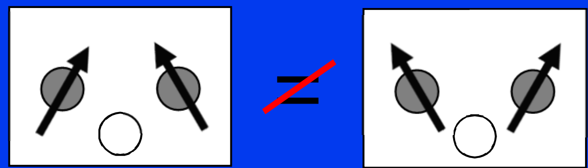
antisymmetric
exchange interaction (DMI)
induced by spin-orbit coupling

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

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

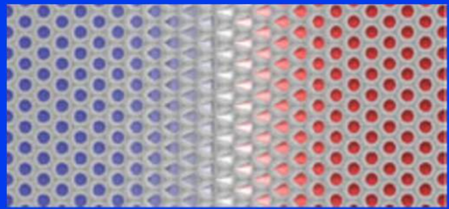


when inversion symmetry is broken
→ in chiral crystal structures
→ at surfaces / interfaces

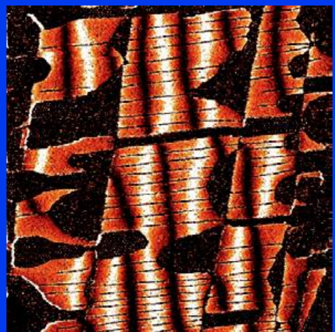


a skyrmion
has unique rotational sense and
is topologically distinct from
the ferromagnetic state

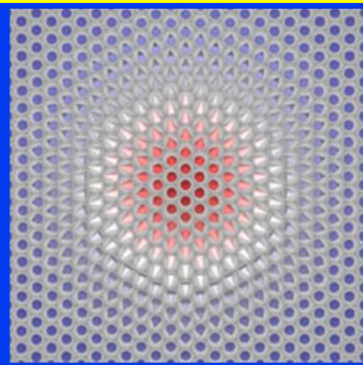
interface-induced DMI



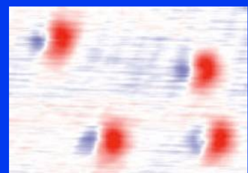
spin spirals / Néel-type domain walls
(with unique rotational sense)



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

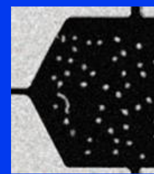


skyrmions or skyrmionic bubbles
(with unique rotational sense of the wall)
(induced by magnetic fields)



~2 nm

~200 nm

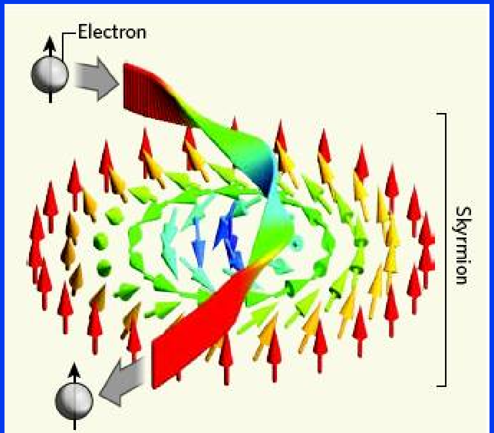


~1000 nm

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).
.....

what is interesting about skyrmions ?

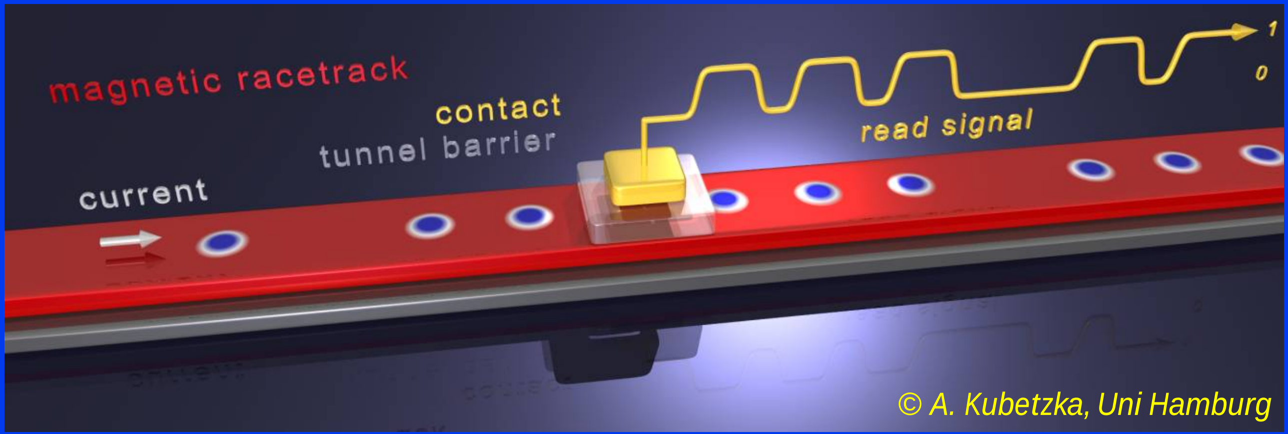
electrons interact very efficiently with non-collinear magnetic states



C. Pfleiderer and A. Rosch, Nature **465**, 880 (2010).

S.S.P. Parkin et al., Science **320**, 190 (2008).

A. Fert et al., Nature Nanotech. **8**, 152 (2013).



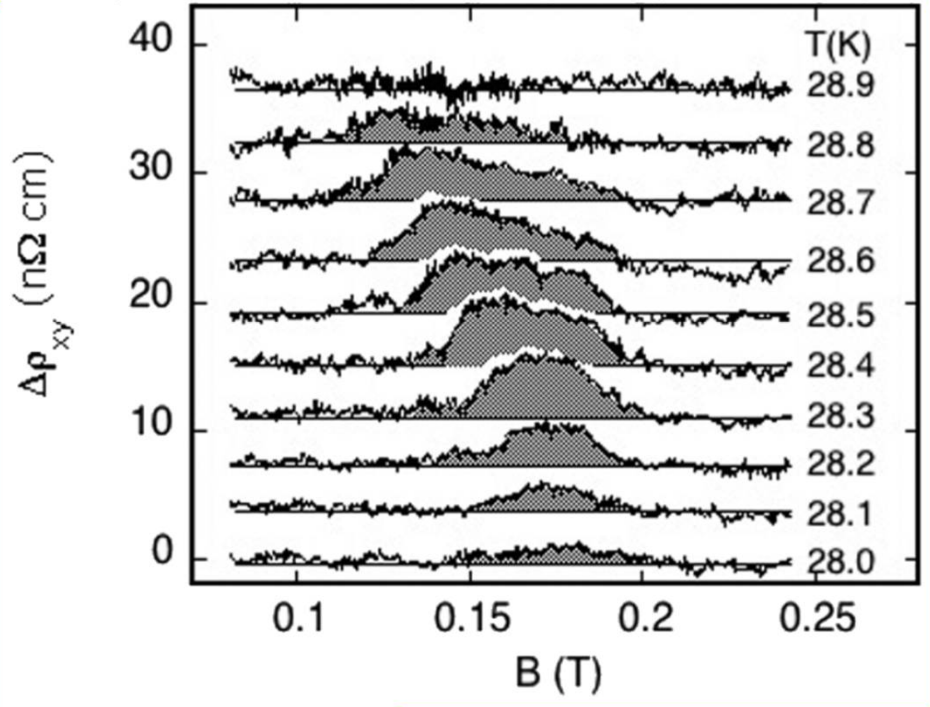
skyrmion lattice vs <u>isolated skyrmions</u>

skyrmions induced by magnetic field vs <u>zero-field skyrmions</u>

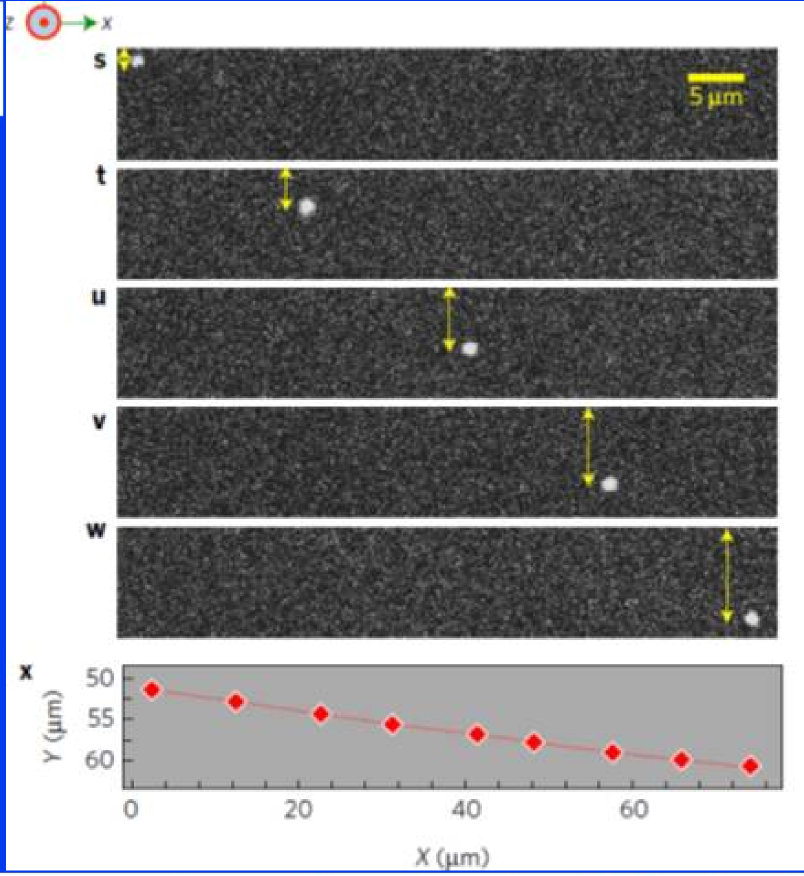
Skyrmion Hall effect / Transverse motion

Topological Hall Effect in the *A* Phase of MnSi

A. Neubauer,[1] C. Pfleiderer,[1] B. Binz,[2] A. Rosch,[2] R. Ritz,[1] P. G. Niklowitz,[1] and P. Böni[1]



PRL **102,** 186602 (2009)



Direct observation of the skyrmion Hall effect

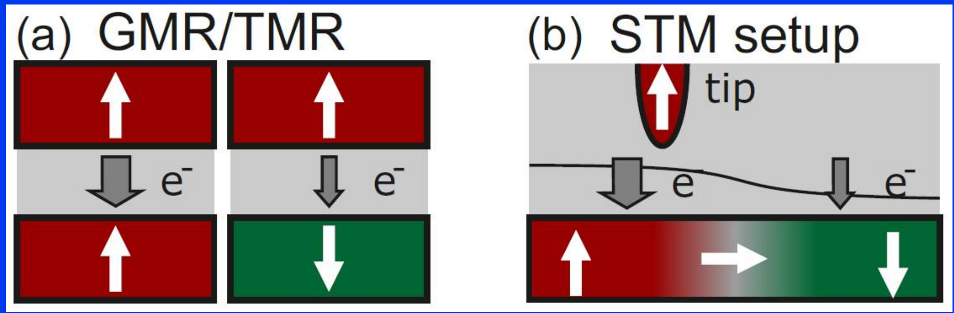
Wanjun Jiang[1,2,3*†], Xichao Zhang[4†], Guoqiang Yu[5], Wei Zhang[1,6], Xiao Wang[7], M. Benjamin Jungfleisch[1], John E. Pearson[1], Xuemei Cheng[7], Olle Heinonen[1,8], Kang L. Wang[5], Yan Zhou[4], Axel Hoffmann[1*] and Suzanne G. E. te Velthuis[1*]

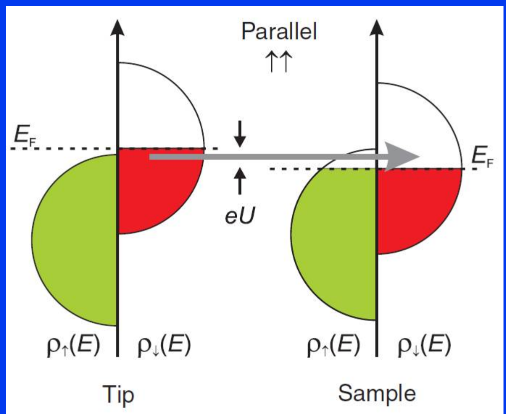
NATURE PHYSICS | VOL 13 | FEBRUARY 201 **162**

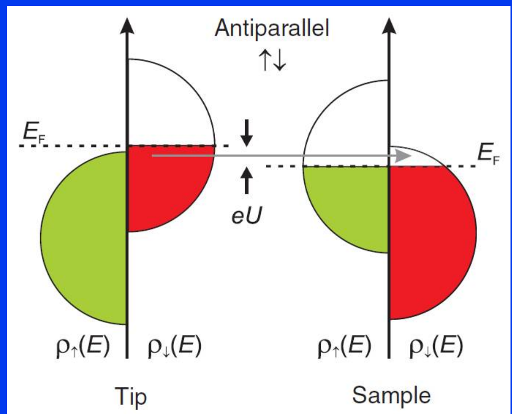
spin-polarized STM

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

TMR-effect
(tunnel magnetoresistance)
in STM geometry





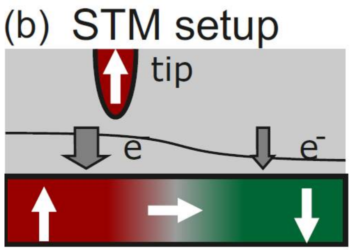


$$I_{\mathrm{SP}}(U_0) = I_0[1 + P_{\mathrm{s}} \cdot P_{\mathrm{t}} \cdot \cos(\vec{M}_{\mathrm{s}}, \vec{M}_{\mathrm{t}})]$$

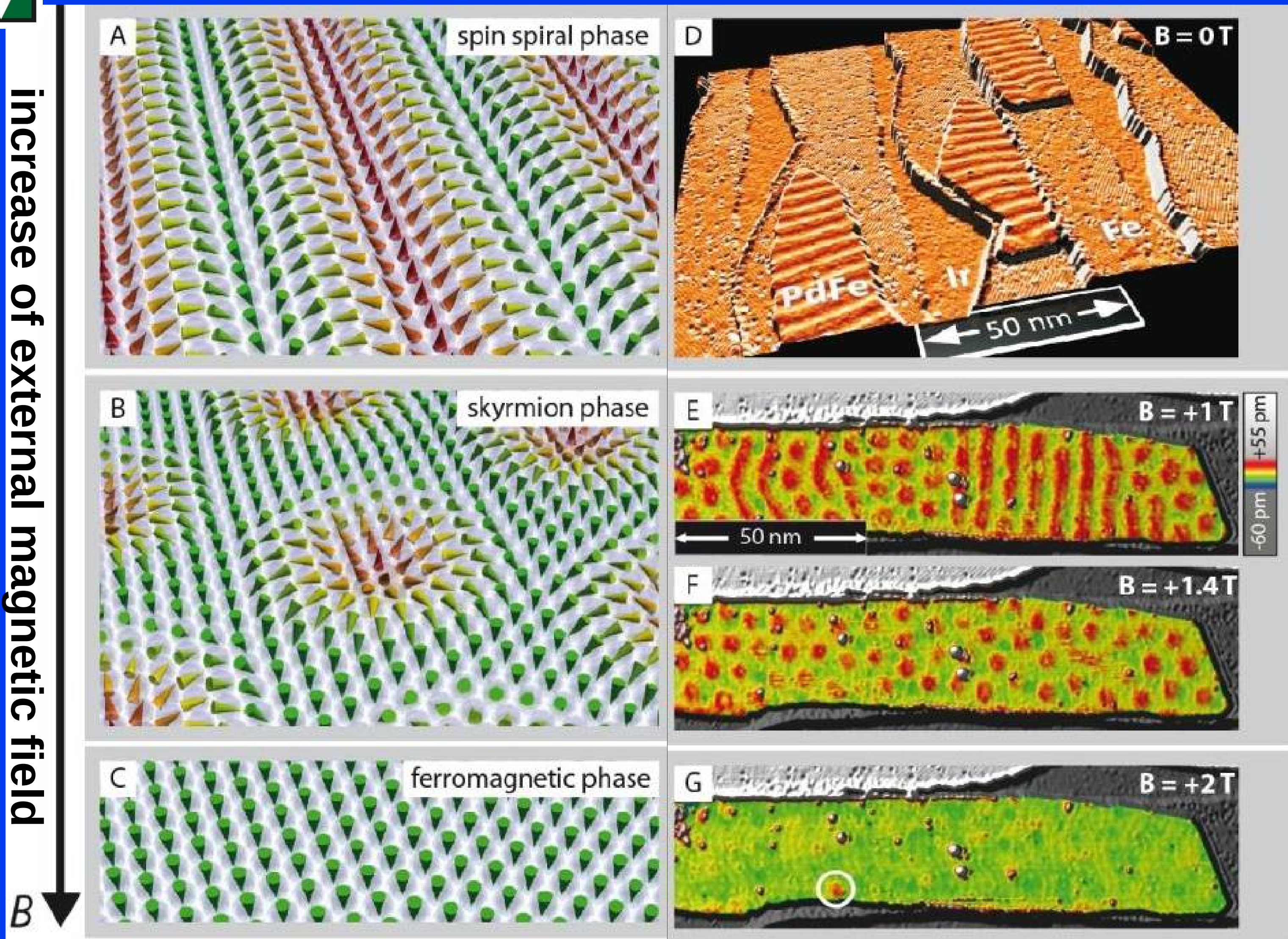
in-situ sample preparation

STM	STM
T = 1.3 - 4.2 K	T = 8 - 13 K
$B_\perp$ < 9 T	$B_\perp$ < 2.5 T

SP-STM: PdFe / Ir(111)



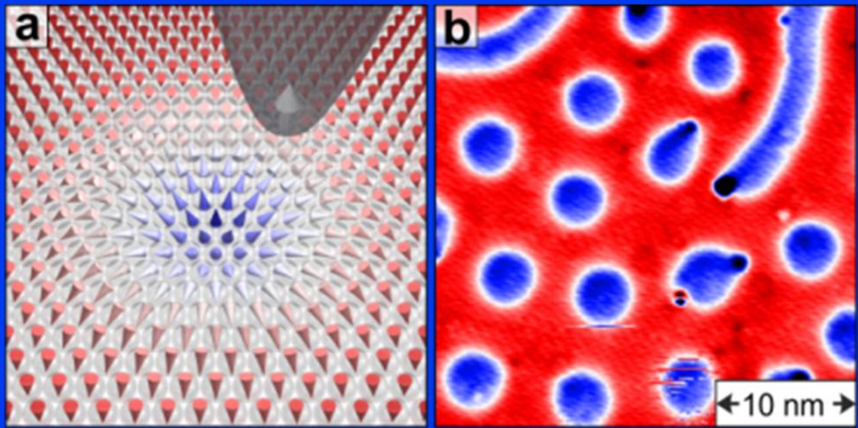
Cr-tip
(AFM: no
change
in *B*)



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

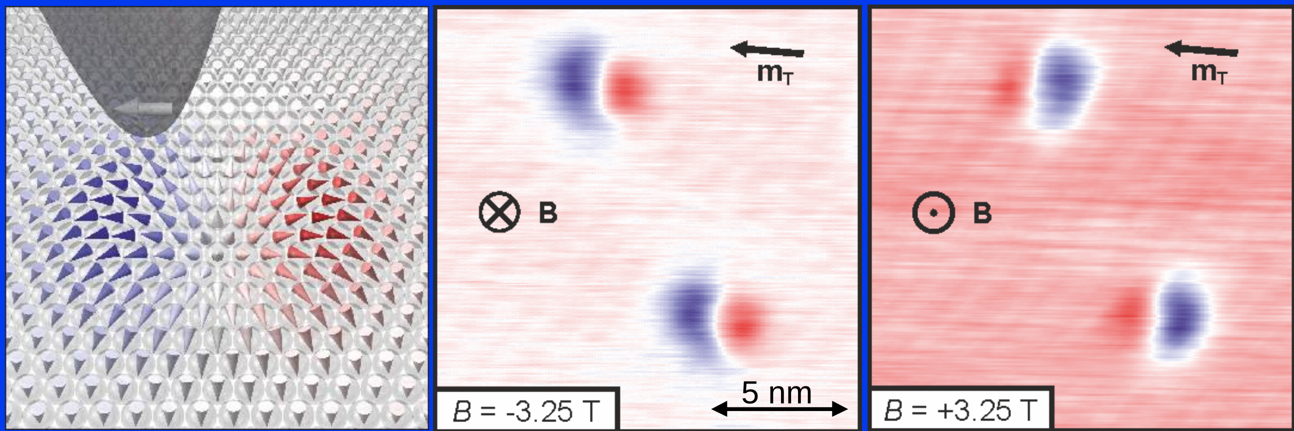
SP-STM contrast for skyrmions

out-of-plane components



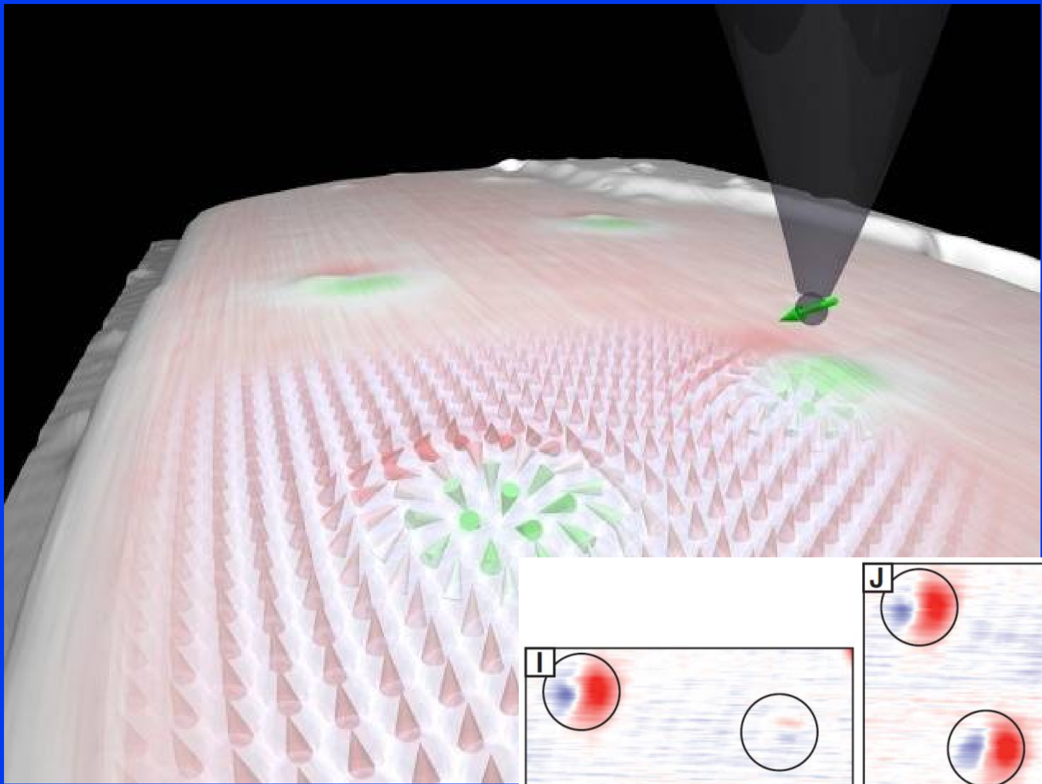
N. Romming, ..., KvB et al., Phys. Rev. Lett. **114**, 177203 (2015).

in-plane components



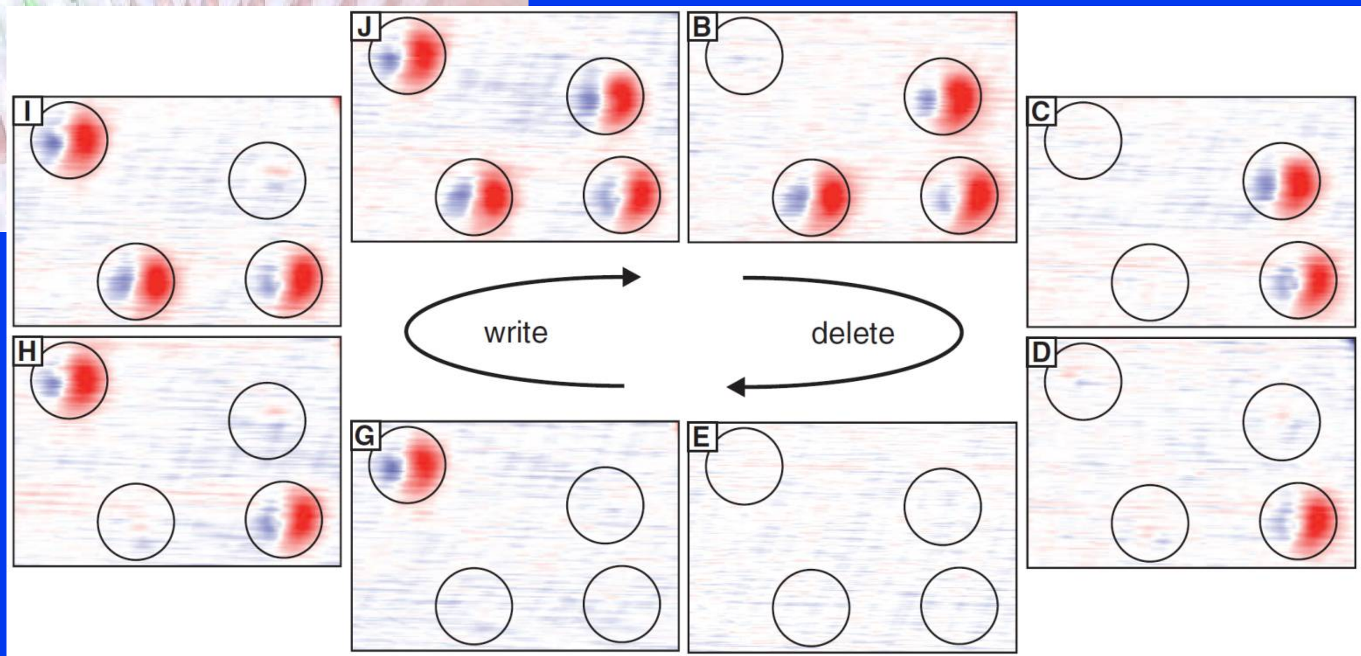
→ **rotational sense of skyrmions is unique, and is preserved for opposite magnetic field**

writing and deleting single skyrmions



manipulating the topology

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



Topology of Skyrmions

Topological charge for continuous magnetization vector fields

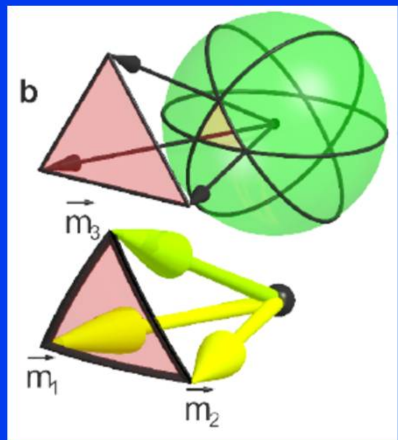
$$Q = -\frac{1}{4\pi}\int_A \vec{m}\cdot\left(\frac{\partial\vec{m}}{\partial x}\times\frac{\partial\vec{m}}{\partial y}\right)dxdy.$$

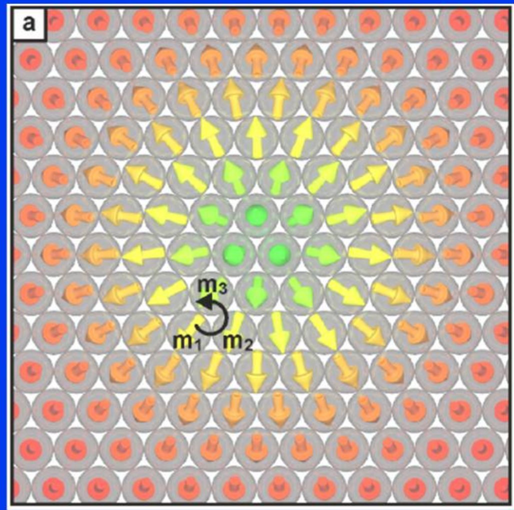
Topological charge on a discrete lattice, plaquettes of triangles

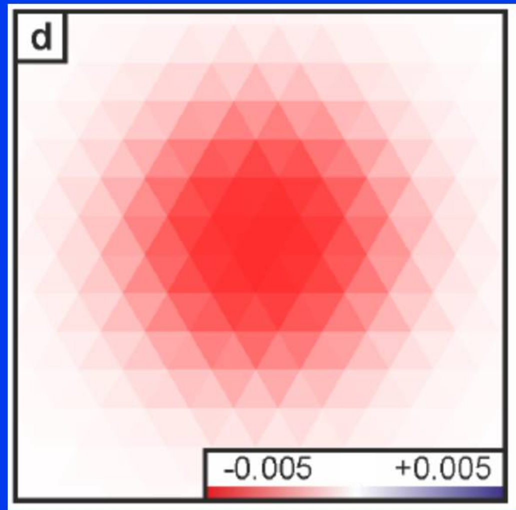
$$\tan\left(\frac{\Omega}{2}\right) = \frac{\vec{m}_1\cdot(\vec{m}_2\times\vec{m}_3)}{1+\vec{m}_1\cdot\vec{m}_2+\vec{m}_1\cdot\vec{m}_3+\vec{m}_2\cdot\vec{m}_3}$$

local topological charge
of three neighboring spins
Q ~ solid angle Ω

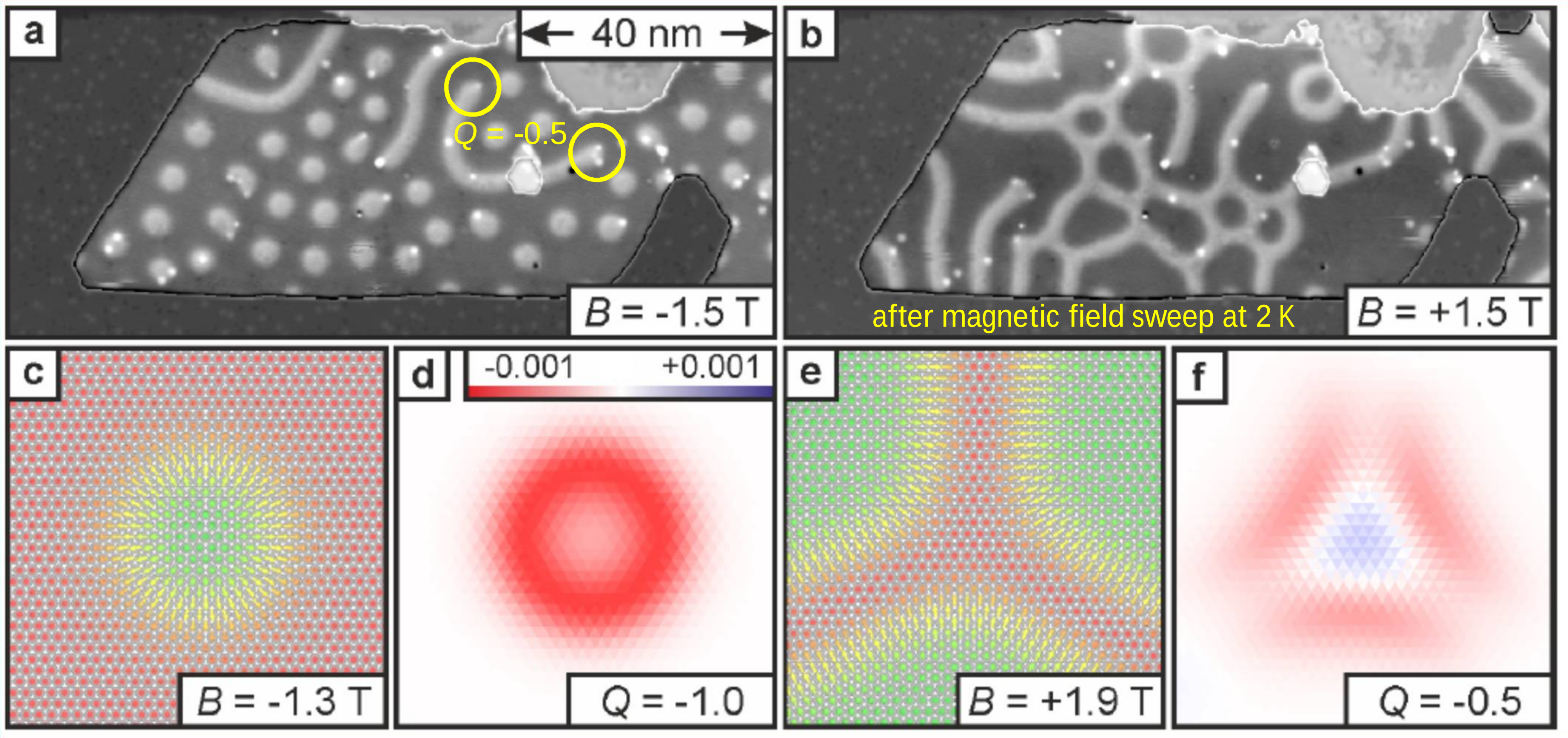
area-integrated topological charge
of a skyrmion Q = |1|







Topology



three capped arms

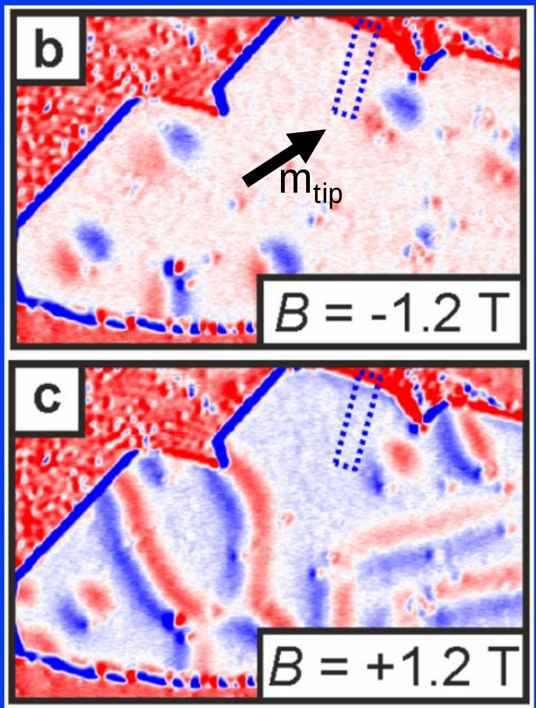
$Q = +1$
equivalent to a skyrmion

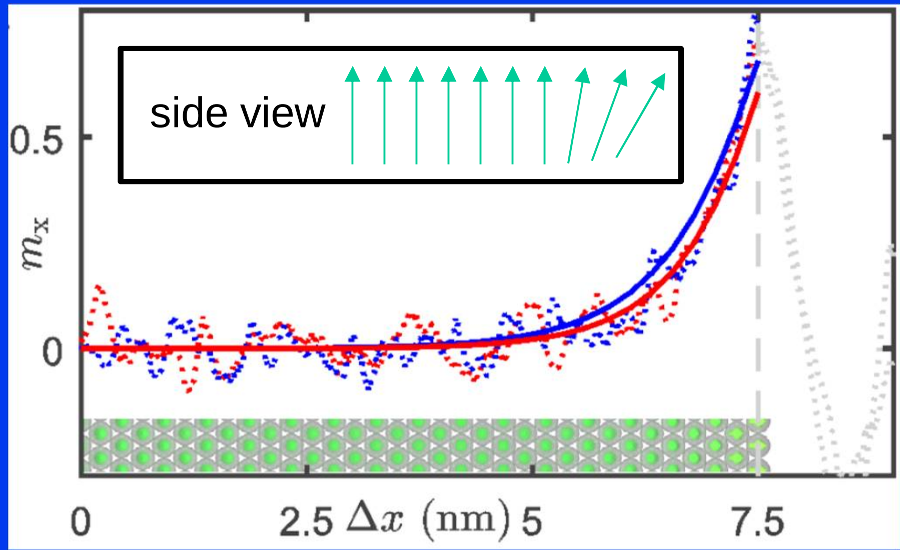
N. Romming, PhD thesis, Univ. of Hamburg (2017).
D. Cortés-Ortuño, ... KvB et al., Phys. Rev. B **99**, 214408 (2019).

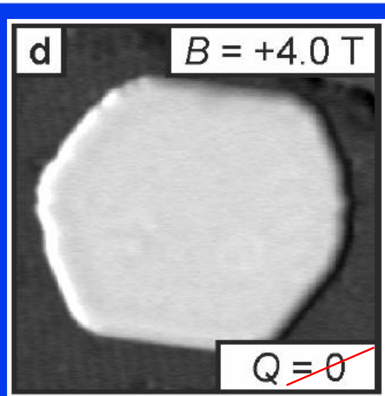
edge tilt at the boundaries

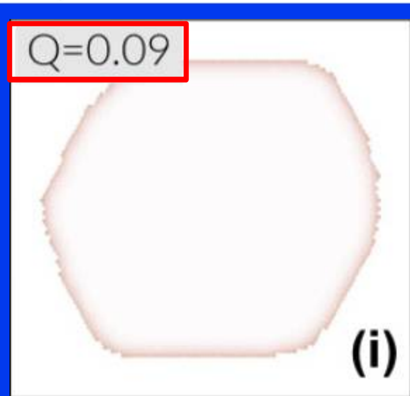
at the boundary the spins tilt,
this is driven by the DMI

S. Rohart and A. Thiaville,
Phys. Rev. B **88**, 184422 (2013).



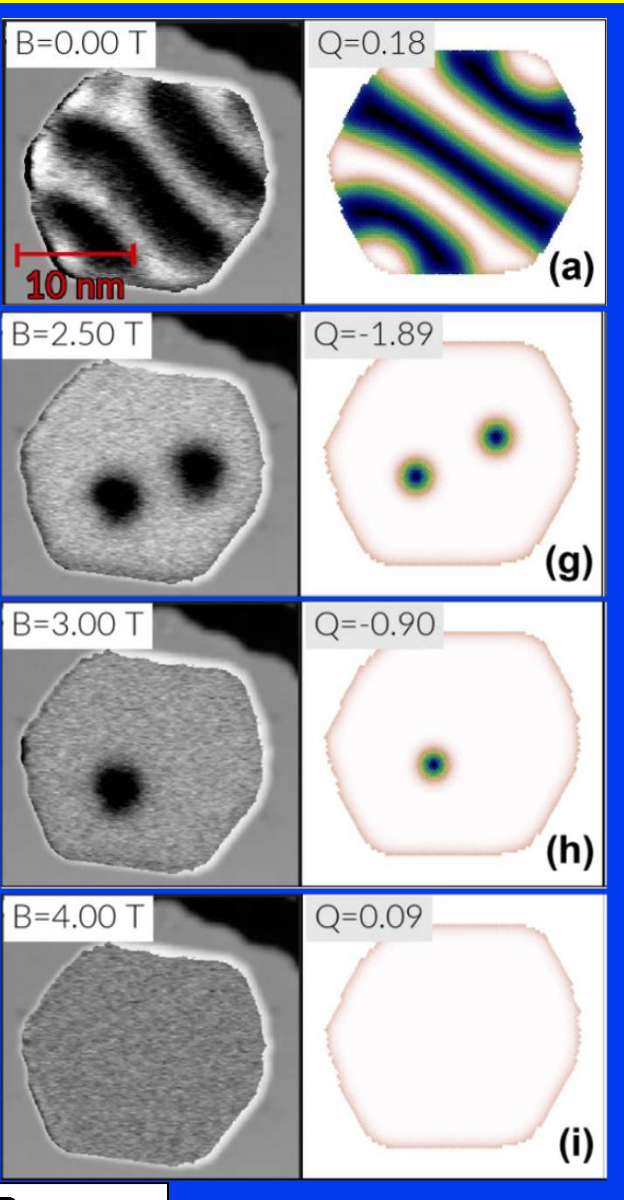




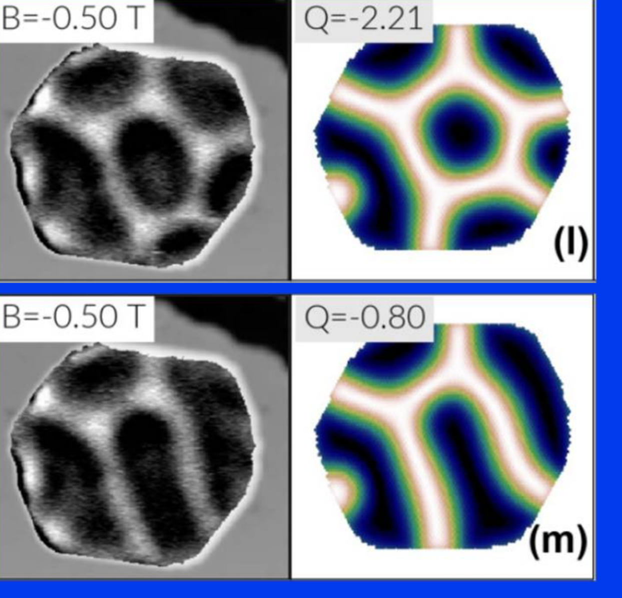


N. Romming, PhD thesis, Univ. of Hamburg (2017).
D. Cortés-Ortuño, ... KvB et al., Phys. Rev. B **99**, 214408 (2019).

magnetic field dependent topology



ramping the external magnetic field back down to zero
and then in the opposite direction
at low temperature 4.2 K



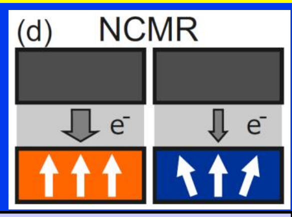
→ spin textures with unusual sign of Q

N. Romming, PhD thesis, Univ. of Hamburg (2017).
D. Cortés-Ortuño, ... KvB et al., Phys. Rev. B **99**, 214408 (2019).

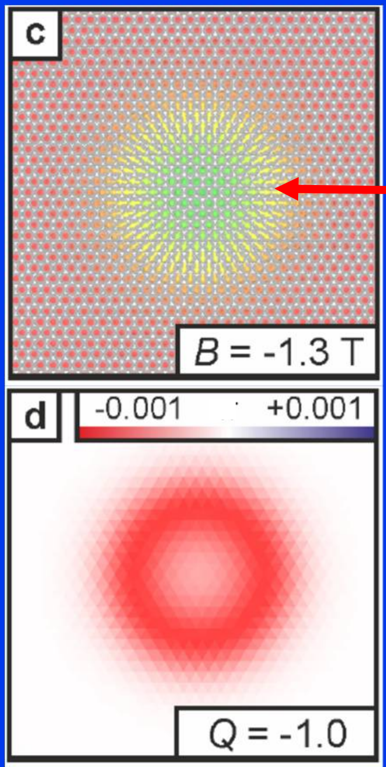
confined states in islands with FM rim

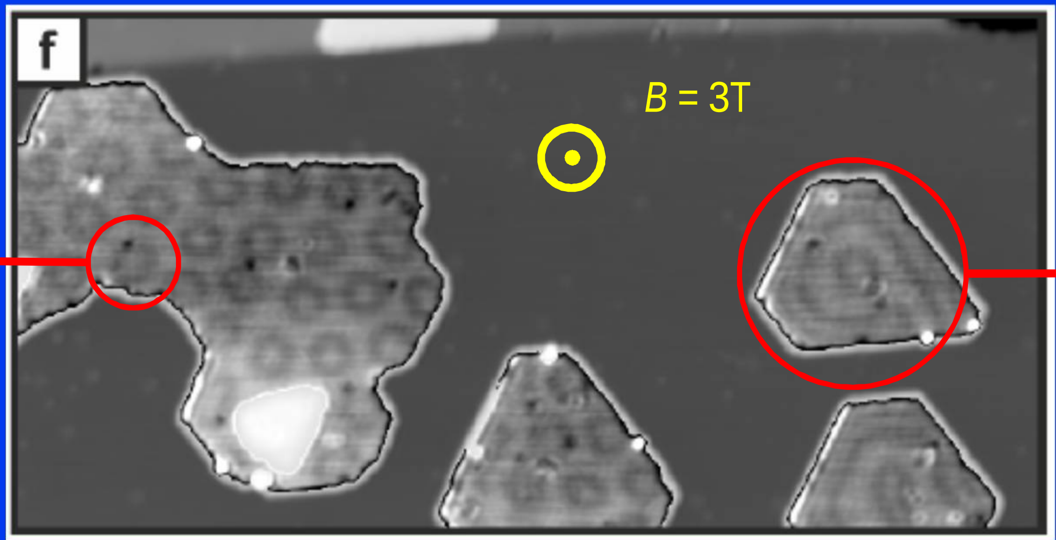
islands of Pd_2/Fe environment is field-polarized Pd/Fe

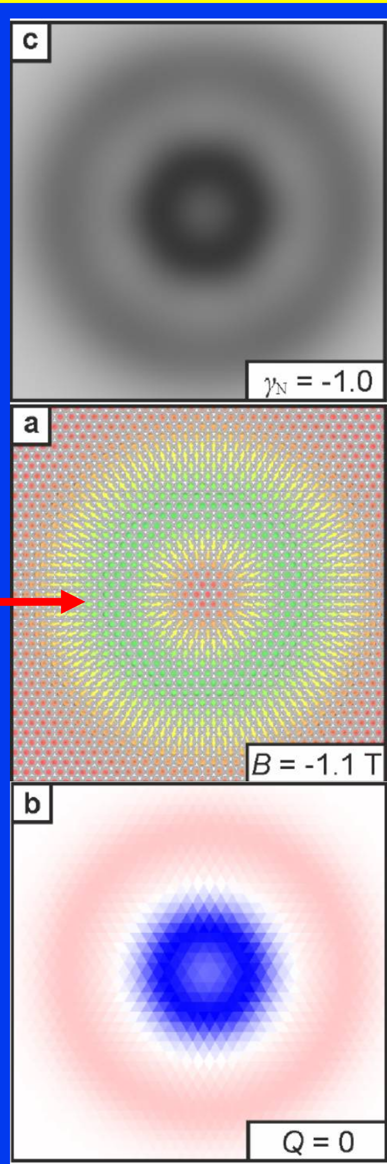
imaging mechanism NCMR
(non-collinear magnetoresistance)
signal scales with the
local magnetization curvature



C. Hanneken, ..., KvB et al., Nature Nanotech. **10**, 1039 (2015).
A. Kubetzka, ..., KvB, Phys. Rev. B **95**, 104433 (2017).





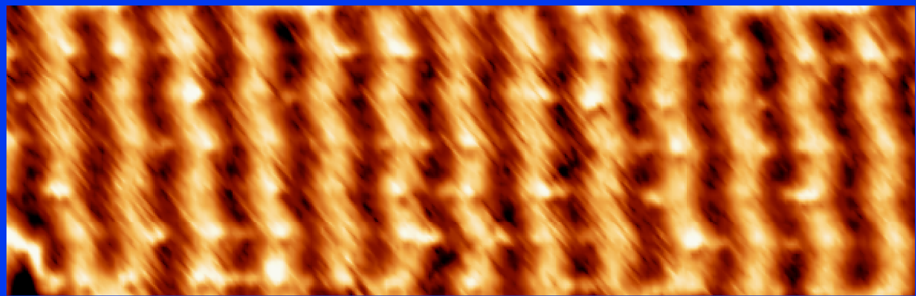


N. Romming, PhD thesis, Univ. of Hamburg (2017).
D. Cortés-Ortuño, ... KvB et al., Phys. Rev. B **99**, 214408 (2019).

target skyrmion / 2π-skyrmion:
because of $Q = 0$ it
moves straight under lateral currents

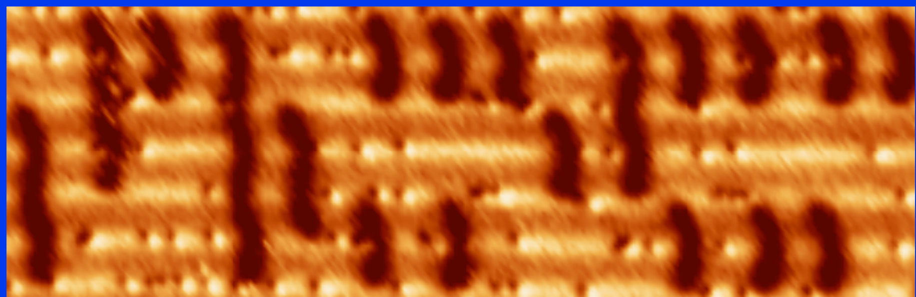
triple layer TL-Fe / Ir(111)

TL-Fe B = 0T dI/dV λ = 4 nm



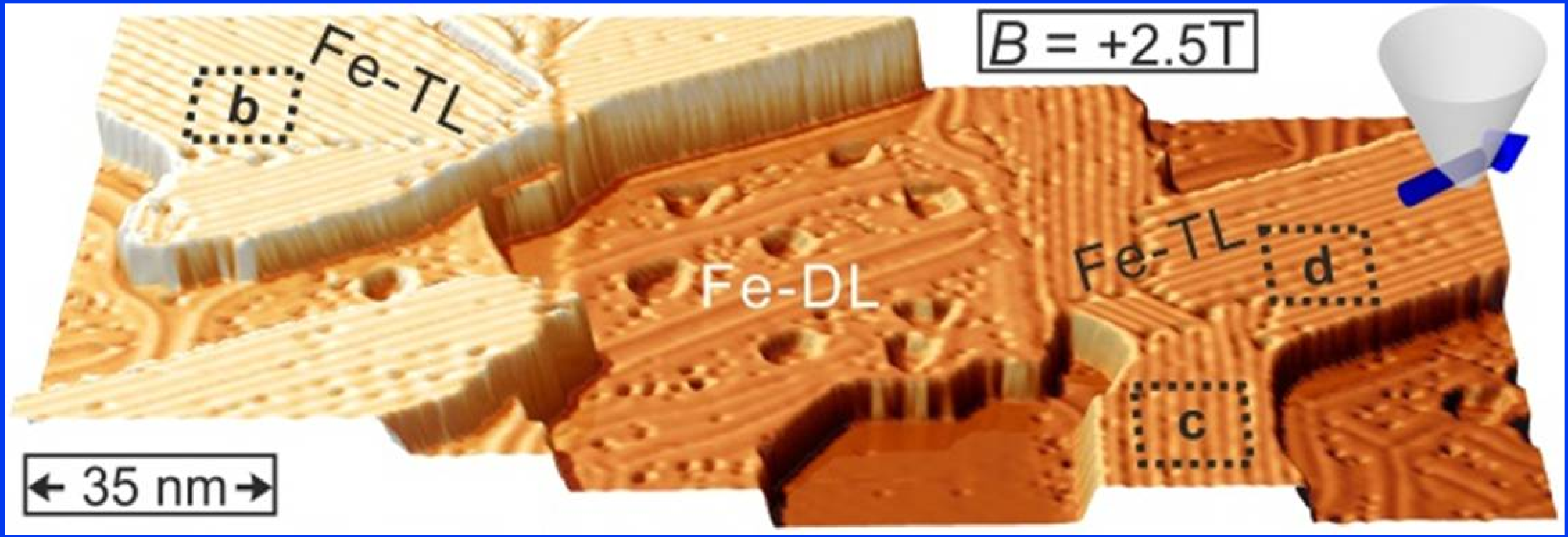
20 nm

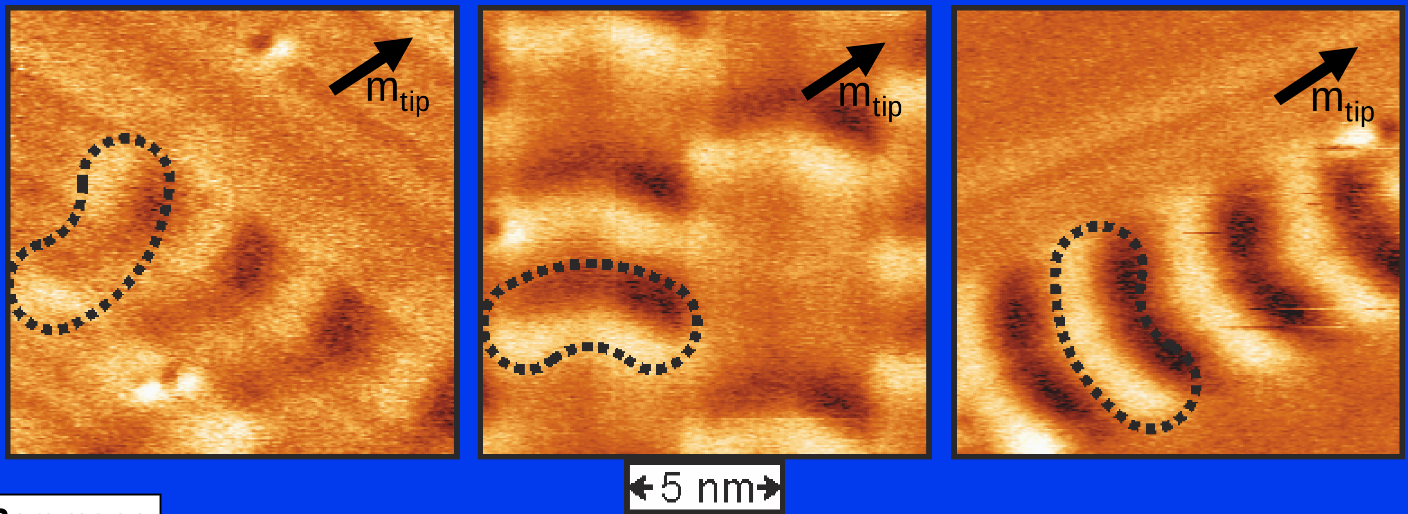
TL-Fe B = +2.5T



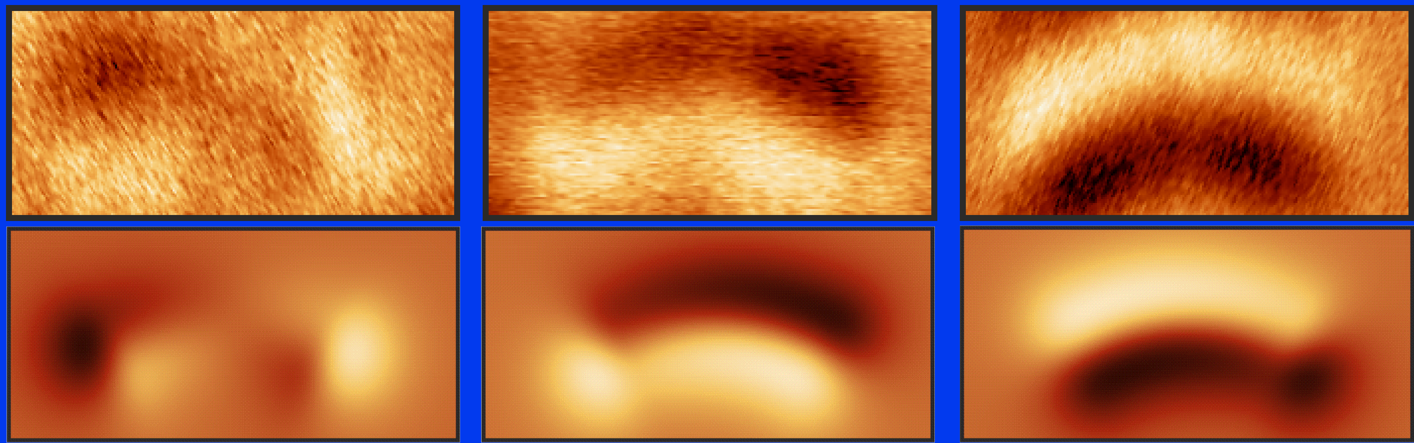
→ single magnetic objects, shape according to the atomic lattice symmetry

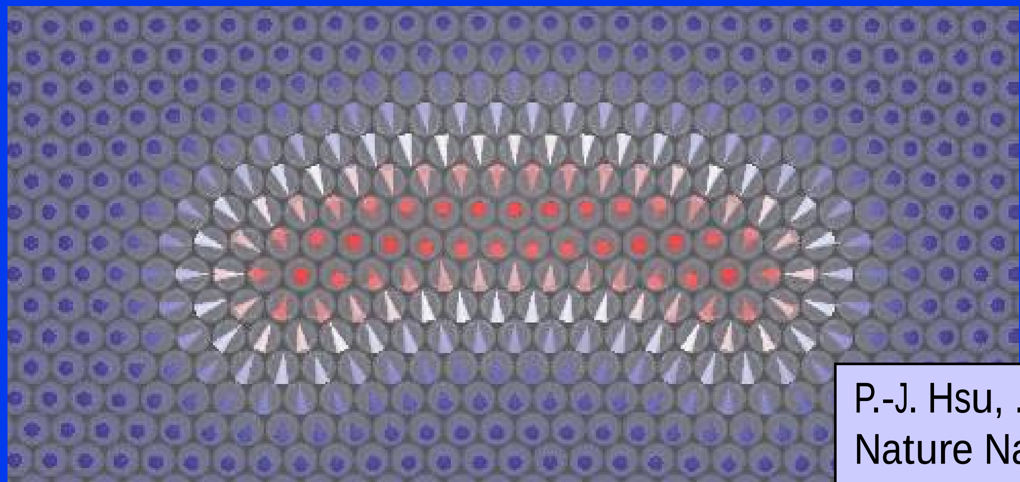
spin structure





are these magnetic skyrmions ?



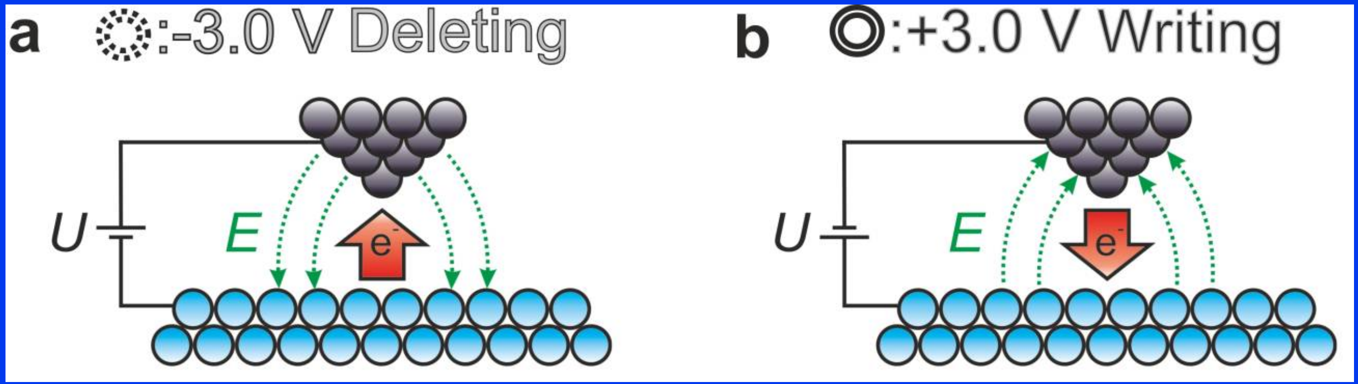


P.-J. Hsu, ..., KvB et al.,
Nature Nanotech. **12**, 123 (2017).

experimentally derived spin structure is equivalent to a distorted magnetic skyrmion,
distortion is in agreement with symmetry of underlying atomic structure
Topological charge $Q = |1|$

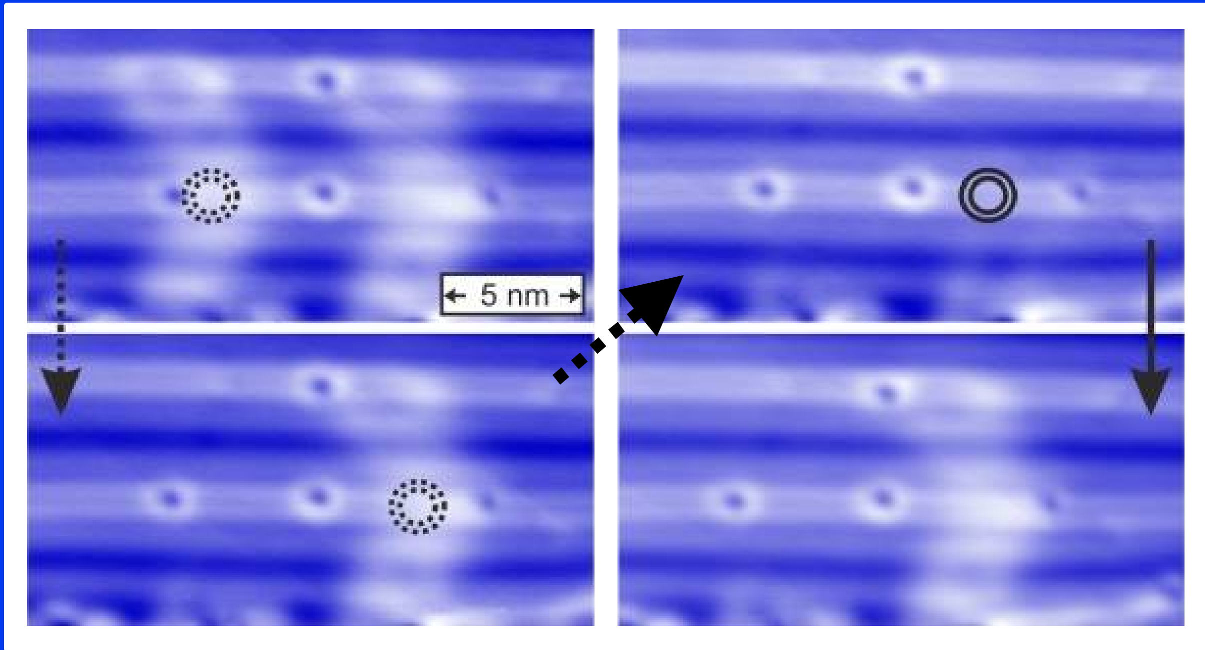
switching with spin-polarized tip

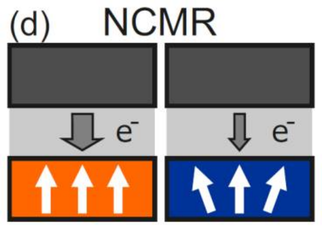
deleting with -3V
writing with +3V



directionality connected to the sign of the voltage
spin-torque switching?
electric field driven?

switching with unpolarized W tip



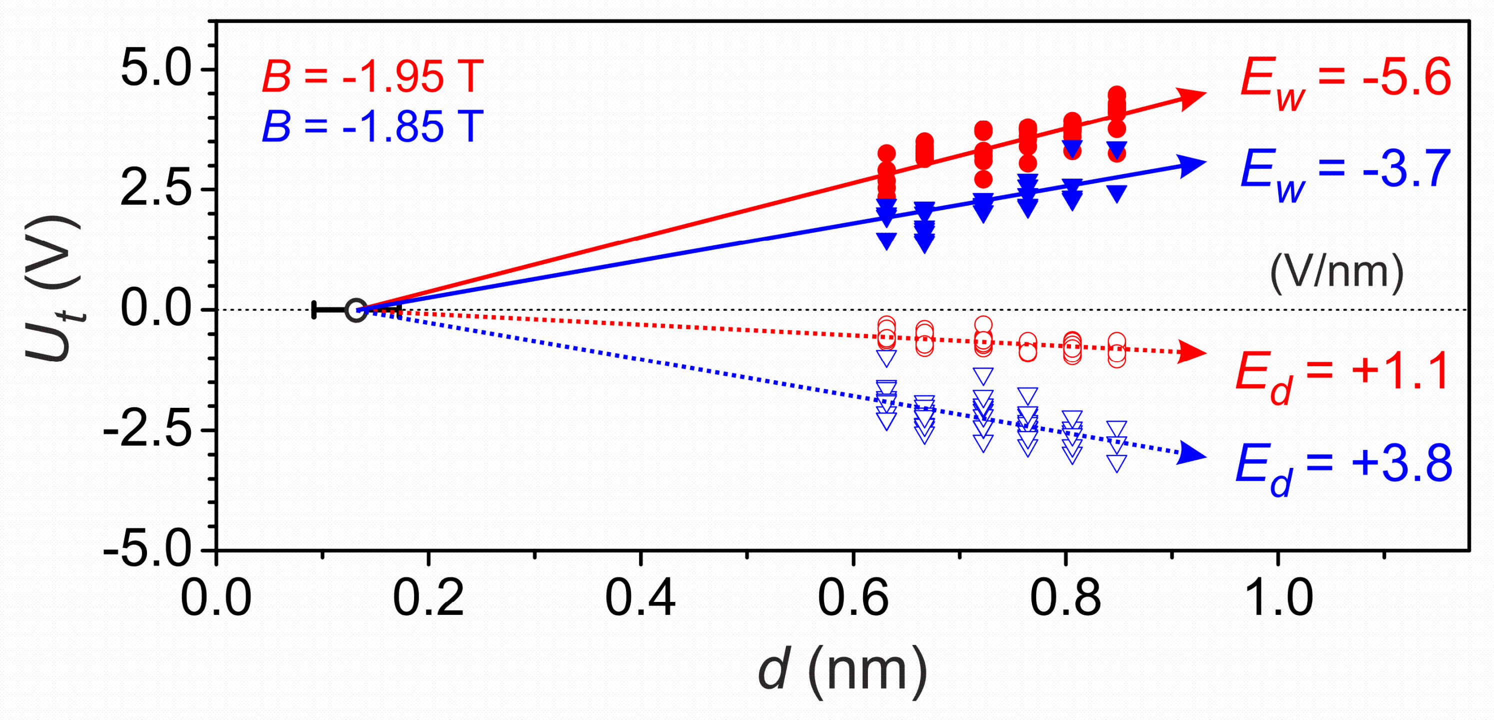


it also works with non-magnetic tip !!!
imaging mechanism: NCMR
switching mechanism: electric field ???

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

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*?

S. Zhang, Phys. Rev. Lett. **83**, 640 (1999).
E.Y. Tsymbal, Nature Mater. **11**, 12 (2012).
M. Oba, ... and A. J. Freeman, Phys. Rev. Lett. 114, 107202 (2015).

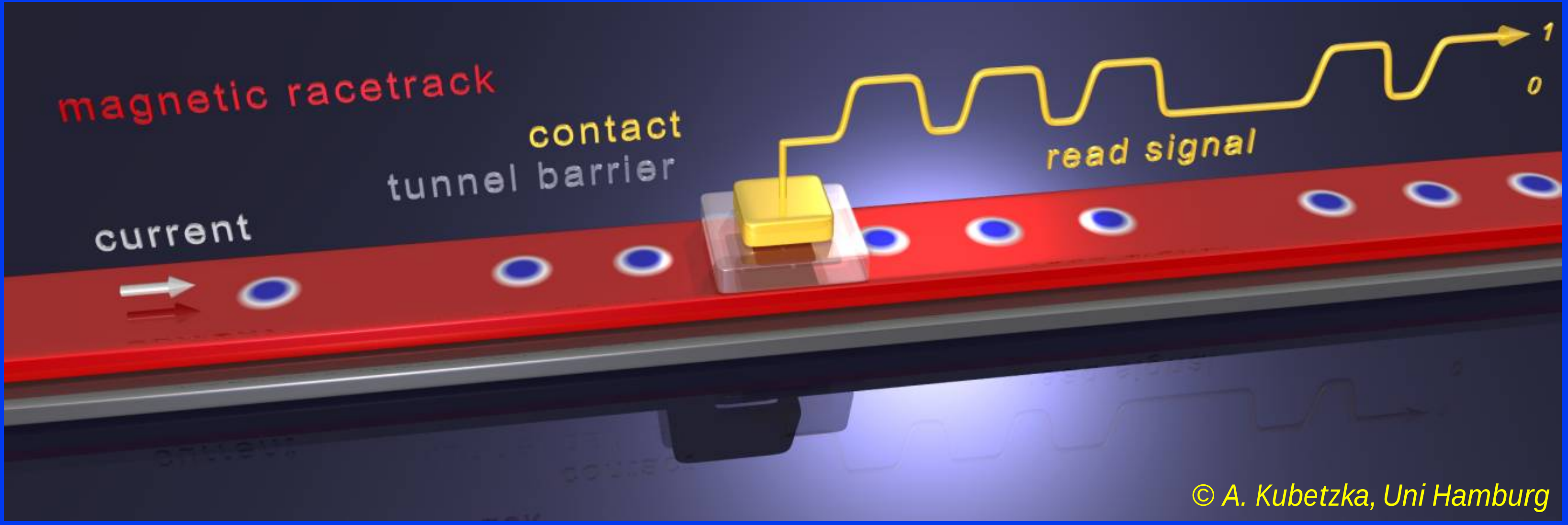
all-electrical reading and writing

NCMR: non-collinear magnetoresistance
all-electrical detection of skyrmions

C. Hanneken, ..., KvB et al.,
Nature Nanotech. **10**, 1039 (2015).

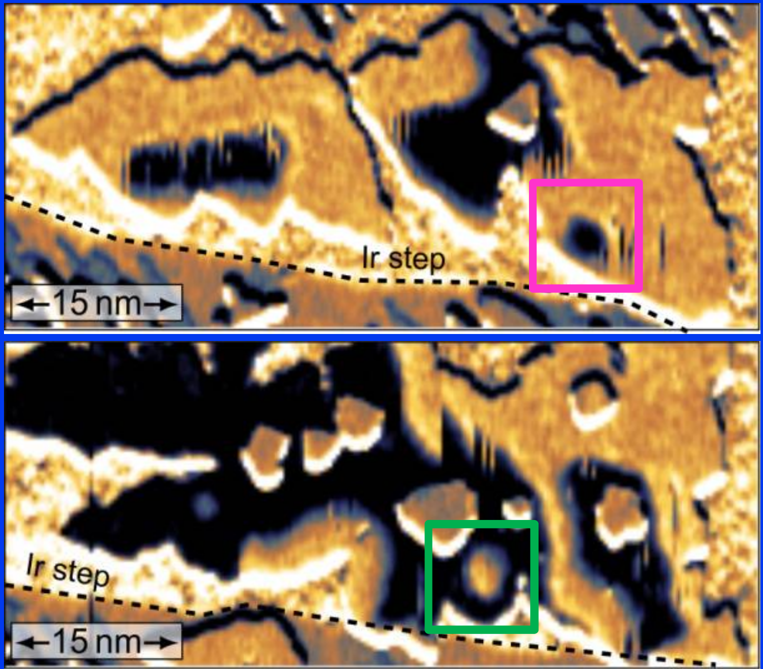
controlled all-electrical switching
of skyrmions via electric fields

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

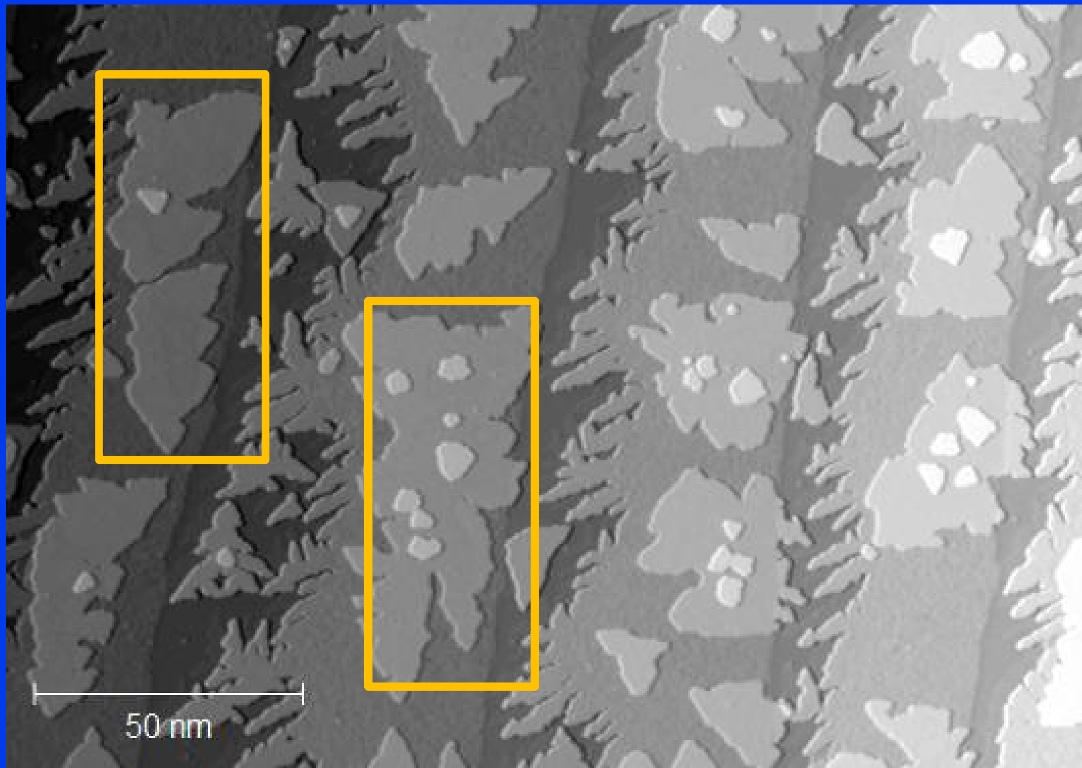


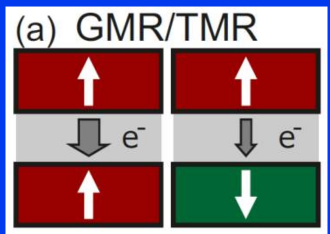
wouldn't it be nice to have isolated zero-field skyrmions ?

skyrmions in hcp-Rh/Co/Ir(111)



U = -0.25 V

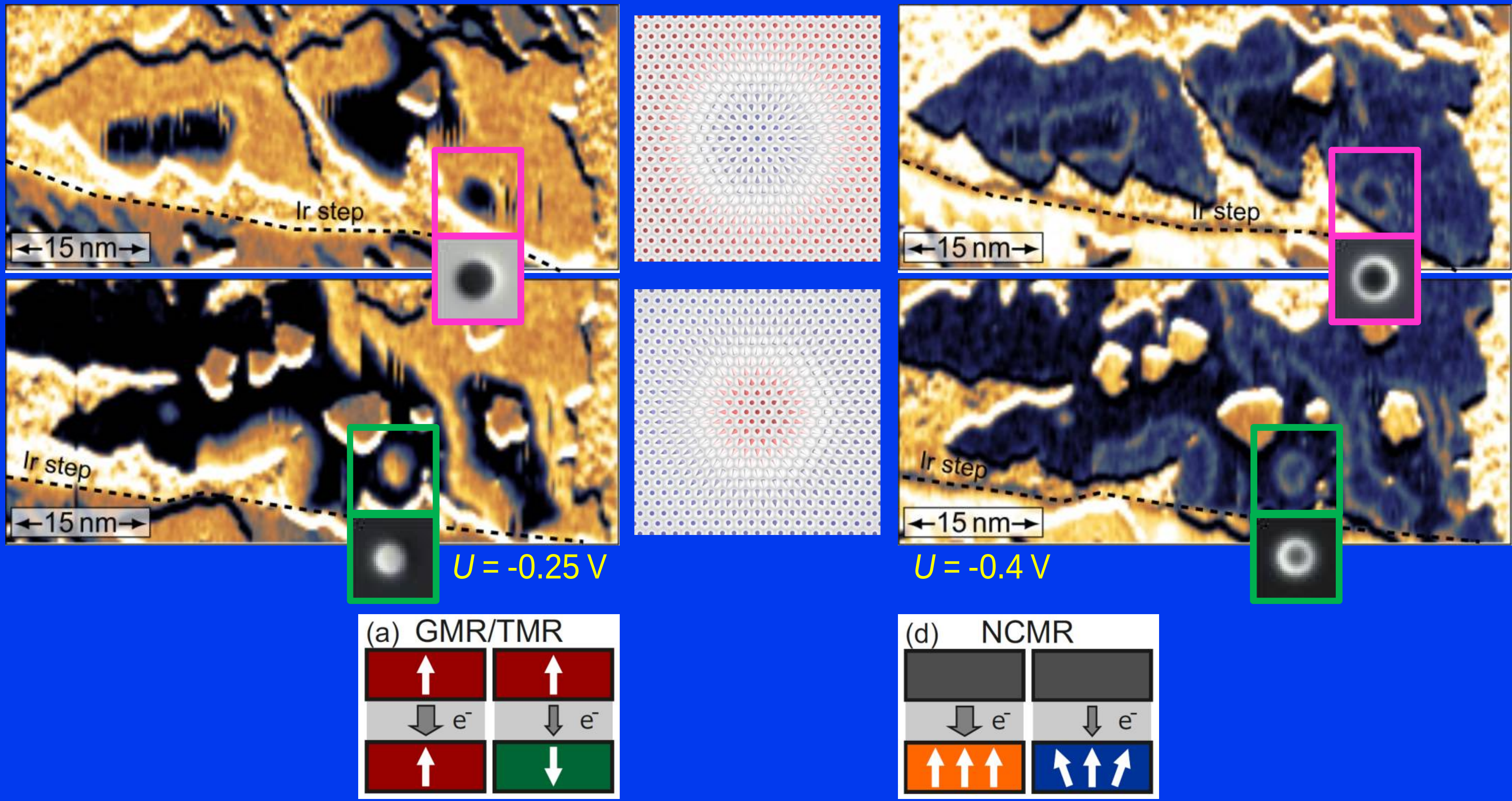




→ domain walls are thin and unusually long
→ they have unique rotational sense

S. Meyer, ..., KvB, S. Heinze, Nature Commun. **10**, 3823 (2019).

skyrmions in hcp-Rh/Co/Ir(111)



wall width w of 180° domain wall: $\cos\theta = \tan$

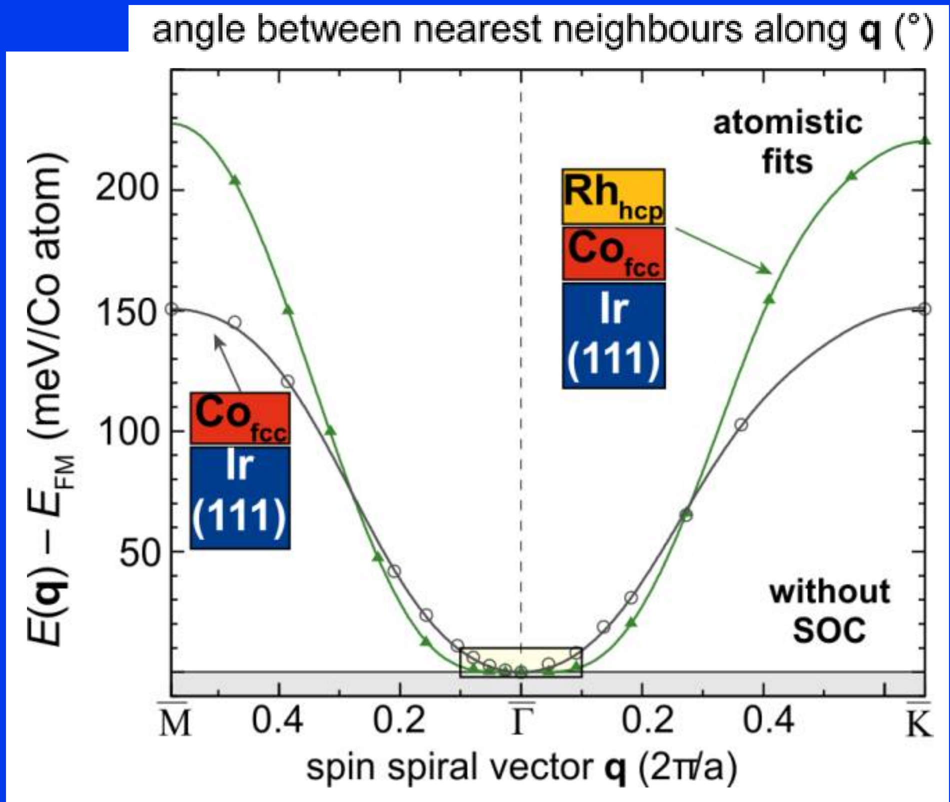
skyrmion diameter ($m_z = 0$) d

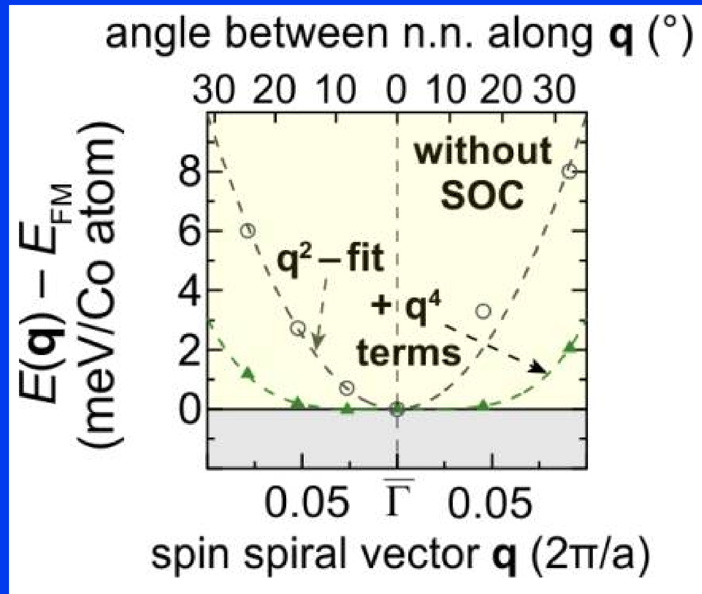
NCMR = non-collinear magnetoresistance

C. Hanneken, ..., KvB et al., Nature Nanotech. **10**, 1039 (2015).
D. Crum et al., Nature Commun. **6**, 8541 (2015).
A. Kubetzka, ..., KvB, Phys. Rev. B **95**, 104433 (2017).

DFT reveals frustrated exchange

DFT = density functional theory





→ the Rh increases the exchange (n.n)

→ flat dispersion around Γ due to exchange frustration

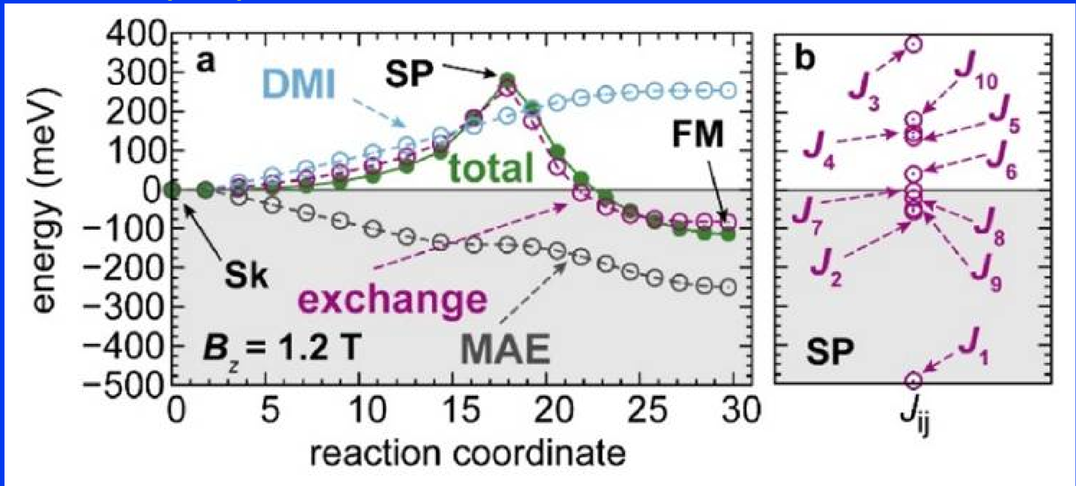
→ small energy cost for spin rotation up to ~15°
domain walls and skyrmions do not cost much energy

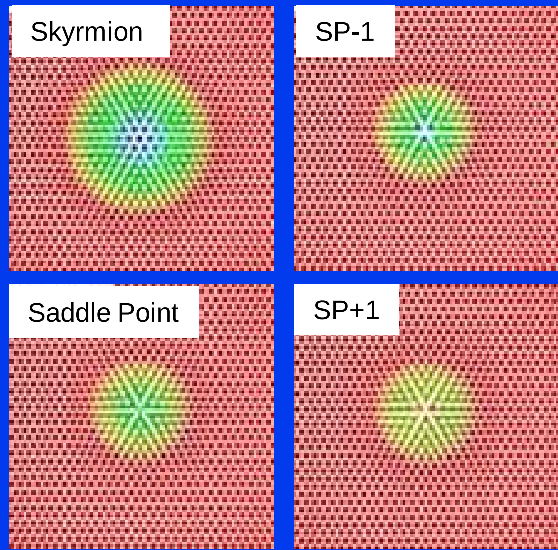
exchange frustration
enhances skyrmion stability

S. von Malottki et al., Sci. Rep. **7**, 12299 (2017).

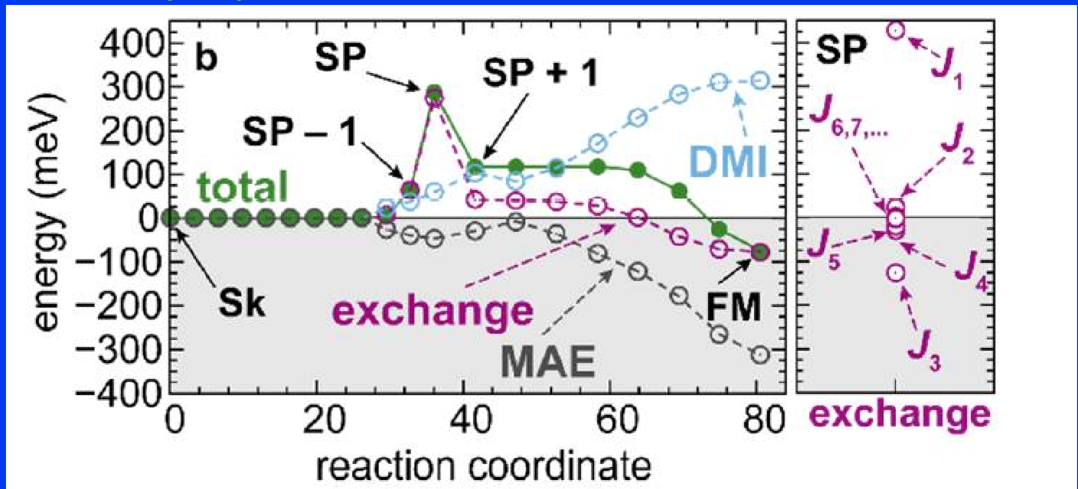
Skyrmion anihilation

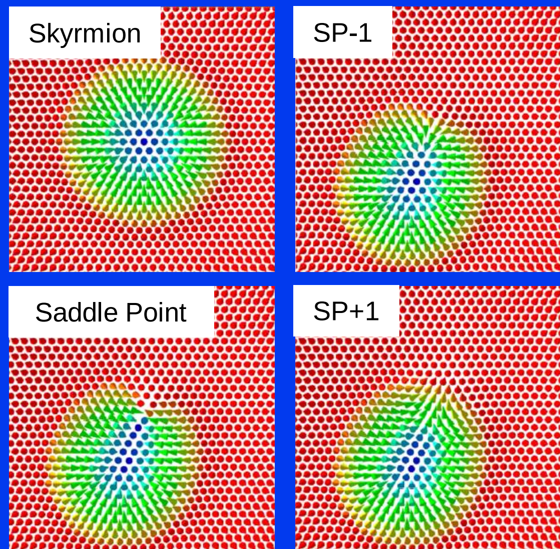
Rh/Co/Ir(111) B = 1.2 T





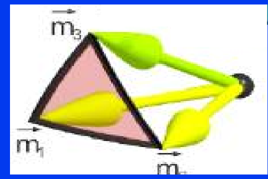
Rh/Co/Ir(111) B = 0 T

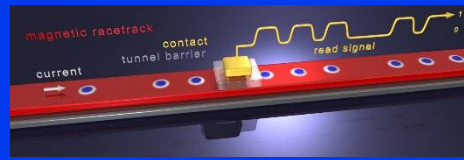




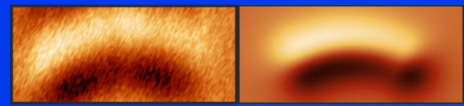
summary

Topology of spin textures on dicrete lattices
can be calculated and it can be non-integer.

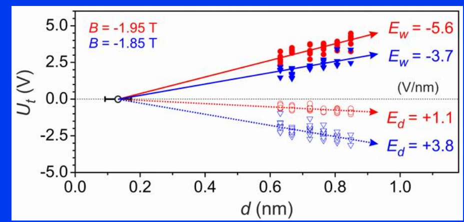




Skyrmions can be distorted according to the
symmetry of the underlying atomic lattice.

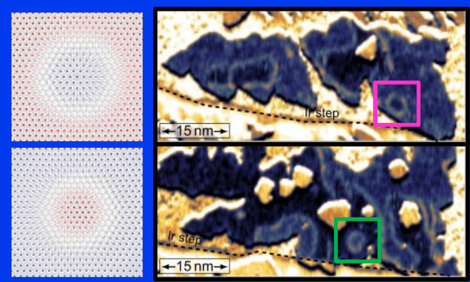


Magnetic skyrmions can be created and deleted
deterministically with electric fields.

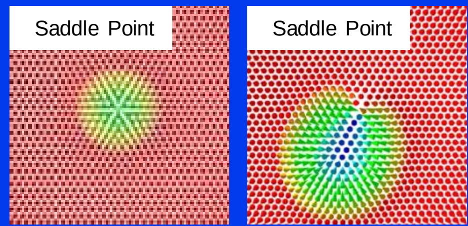


Isolated zero-field sub-5 nm skyrmions
can exist in the magnetic virgin state.

Frustrated exchange plays a crucial role for
the stabilization of metastable zero-field skyrmions.



The topology can be cracked either in the center
or at the rim of a skyrmion.



acknowledgements

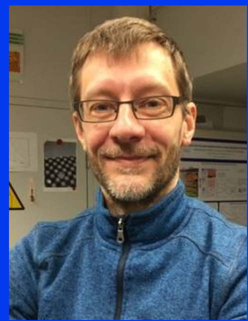
University of Hamburg, Germany

open PhD position

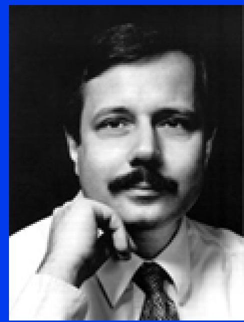
Niklas Romming

Dr. Pin-Jui Hsu

Marco Perini



Dr. André Kubetzka



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Sebastian Meyer
Stephan von Malottki
Prof. Stefan Heinze

Deutsche Forschungsgemeinschaft DFG

DFG SFB 668
DFG SPP 2137

MAGicSky

Funded by the Horizon2020 Framework Programme of the European Union

FET-OPEN
(No. 665095)