Exploring Spins at Surfaces by Spin-Polarized STM

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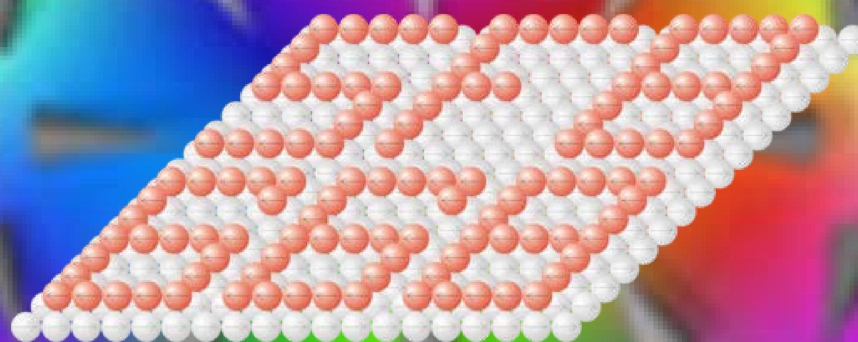
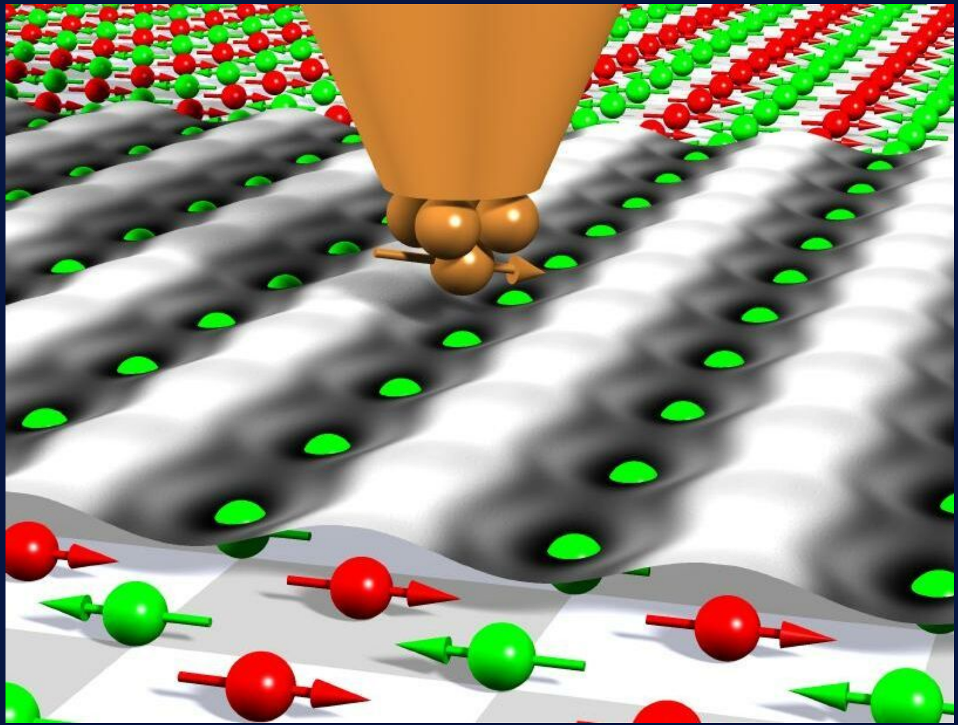


Spin-Polarized STM for Revealing & Manipulating Complex Spin Textures on the Atomic Scale

Correlation between

- **atomic structure**
- **electronic structure**
- **spin structure**

at ultimate spatial, time and energy resolution !

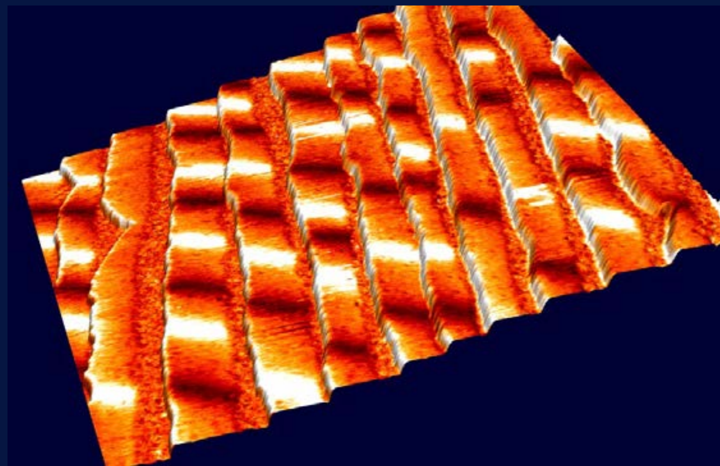


$$I_{sp} = I_0[1 + P_S P_T \cos(\vec{M}_S, \vec{M}_T)]$$

- R. Wiesendanger *et al.*, Phys. Rev. Lett. **65**, 247 (1990)
- R. Wiesendanger *et al.*, Science **255**, 583 (1992)
- R. Wiesendanger, Rev. Mod. Phys. **81**, 1495 (2009)

Milestones in the Development & Application of SP-STM

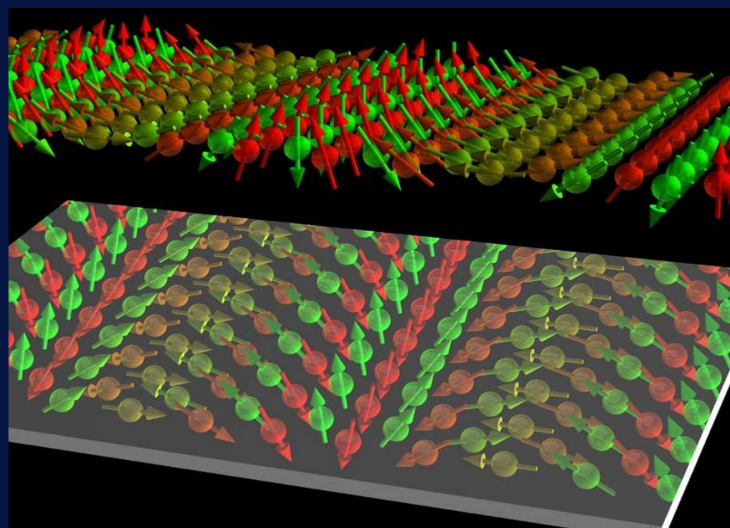
Phys. Rev. Lett. **65**, 247 (1990)
Phys. Rev. Lett. **85**, 4606 (2000)



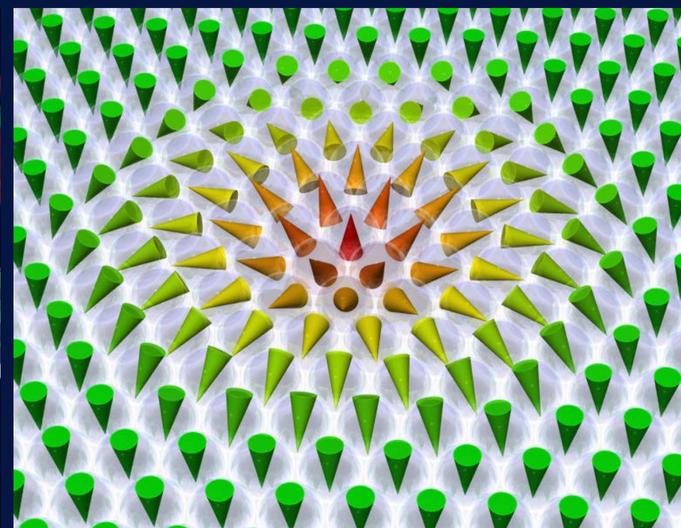
Science **292**, 2053 (2001)
Phys. Rev. Lett. **88**, 057201 (2002)

Science **298**, 577 (2002)

Science **255**, 583 (1992)
Science **288**, 1805 (2000)



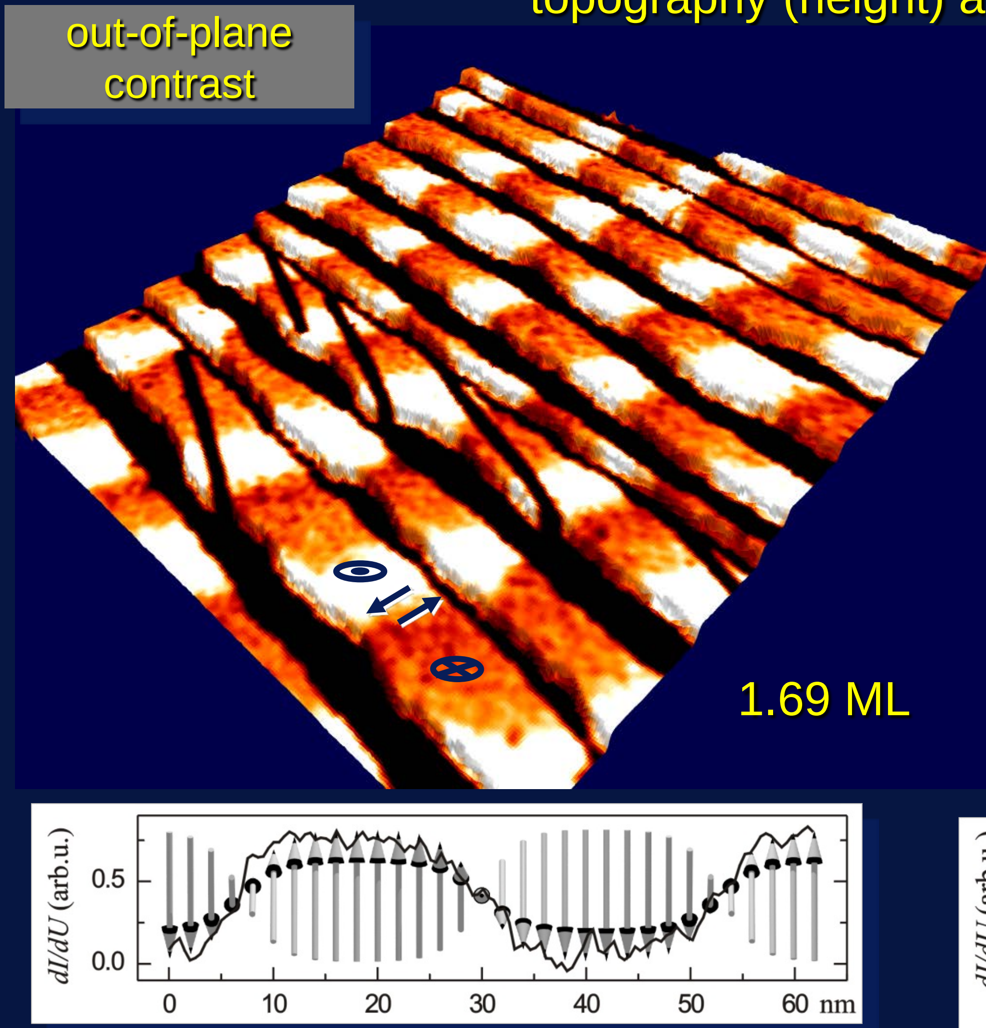
Nature **447**, 190 (2007)
Phys. Rev. Lett. **101**, 027201 (2008)

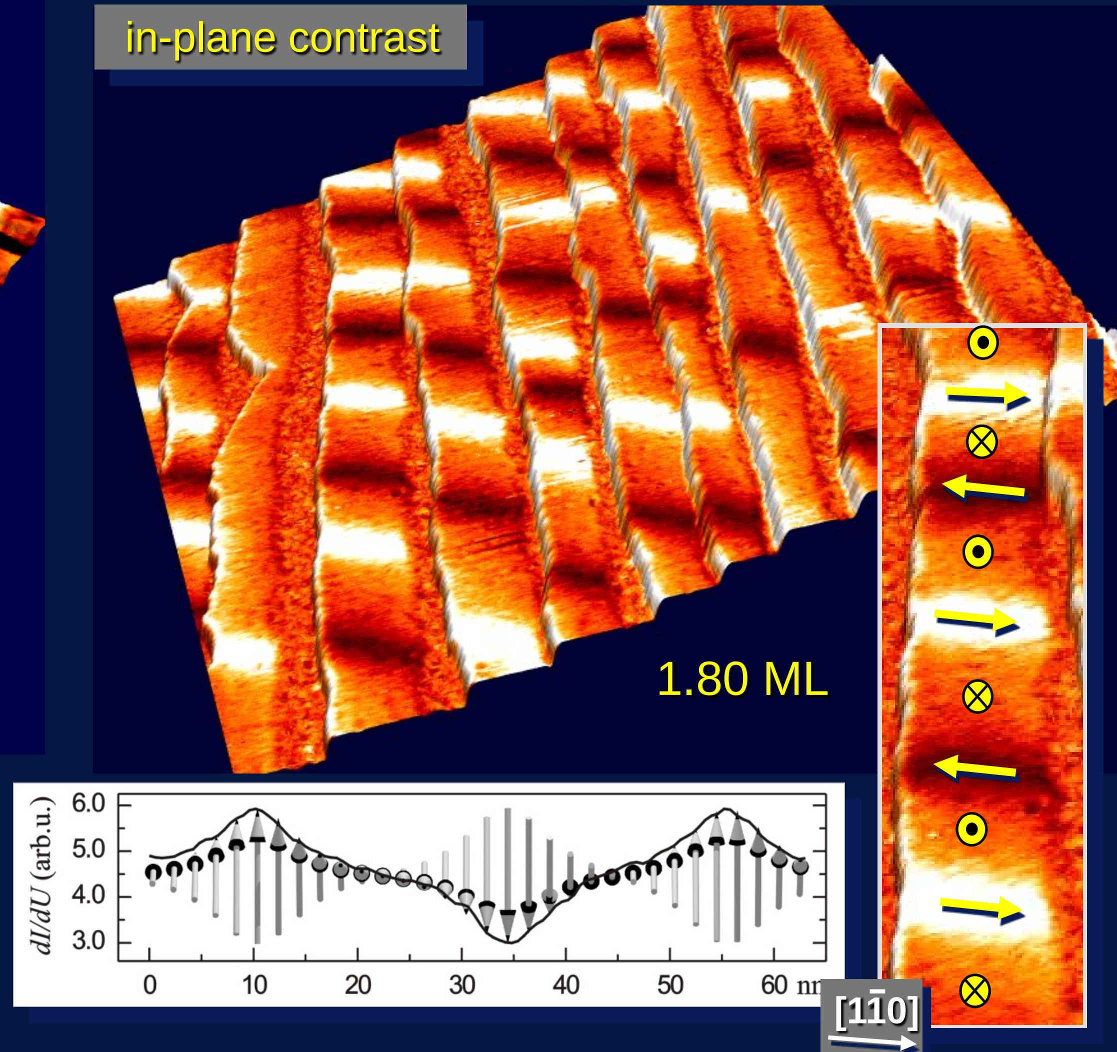


Nature Phys. **7**, 713 (2011)
Science **341**, 6146 (2013)

Domain Structure of Double-Layer Fe Nanowires

3D-Composites of 200 nm × 200 nm
topography (height) and magn. signal (colour)





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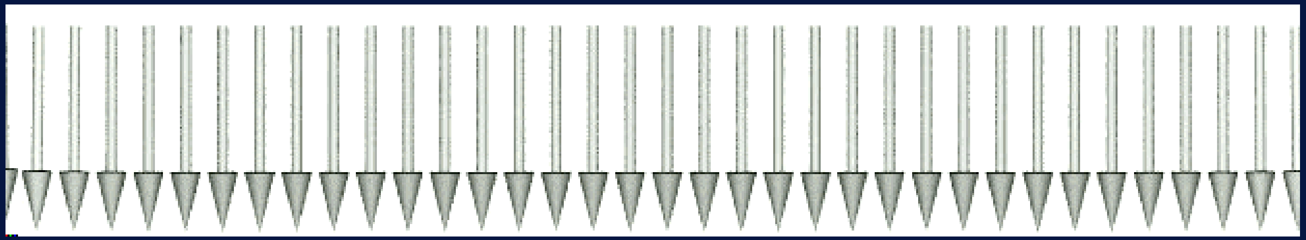
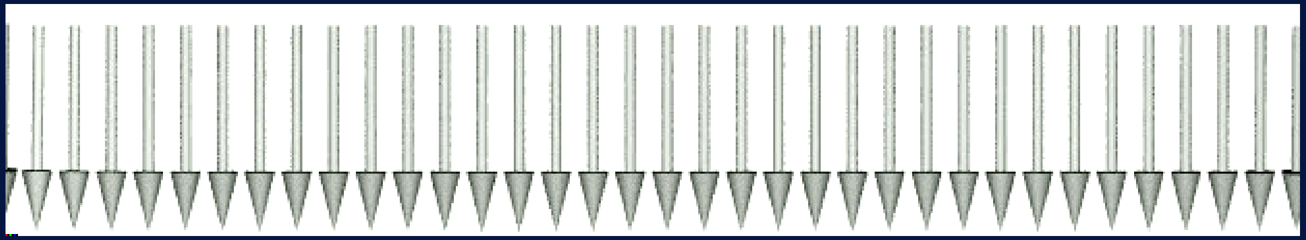
Pairs of Winding and Unwinding Walls

unwinding walls



- opposite sense of rotation
- domains can be annihilated

winding walls



- equal sense of rotation
- stable in saturation fields

→ indistiguishable in their *perpendicular* component,

but distinguishable in their *in-plane* component.

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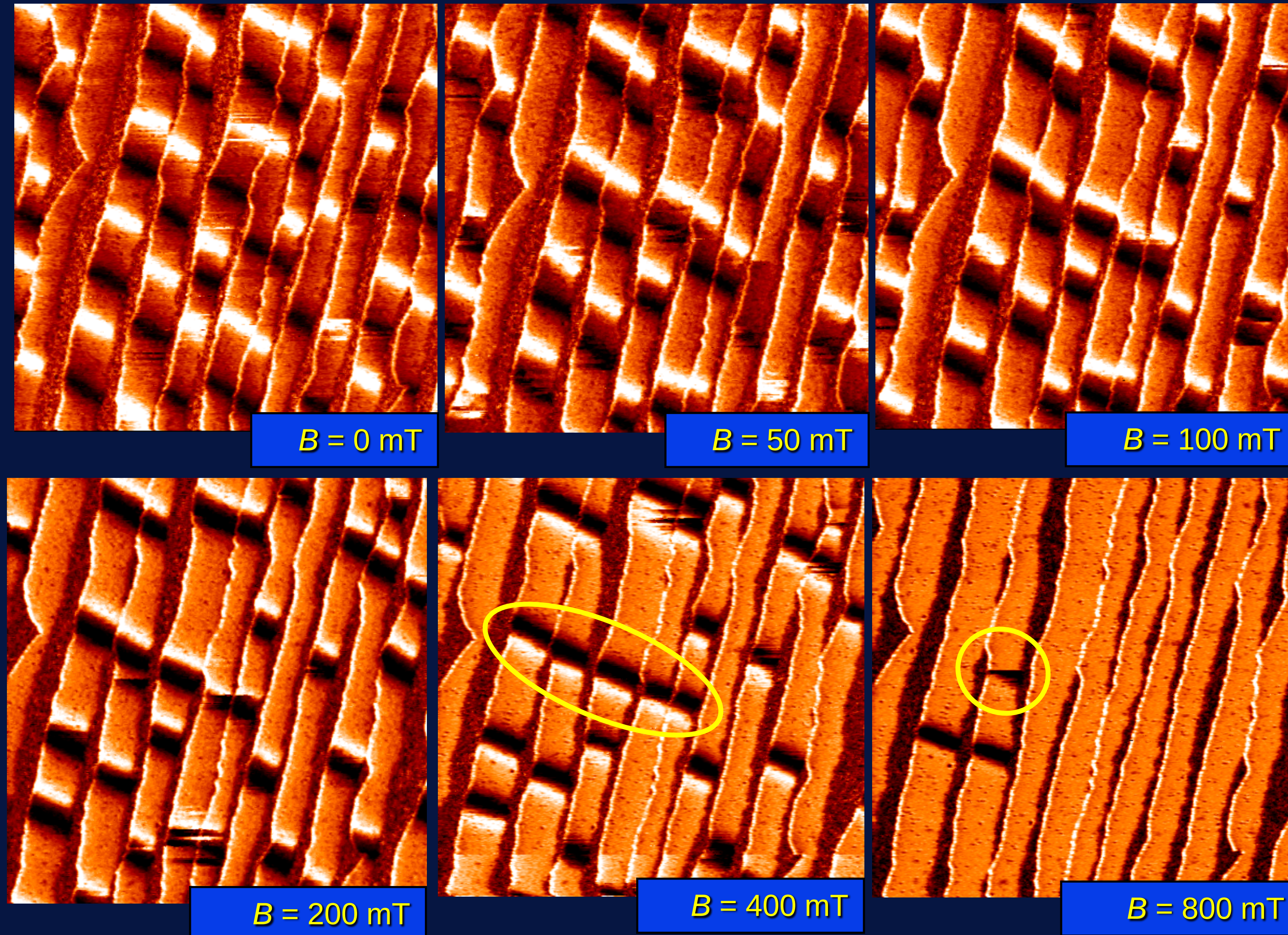
Chiral Domain Walls in a perpendicular Field

(unique rotational sense is a consequence of DM-interaction)



1.8 ML Fe/W(110)

200 x 200 nm^2

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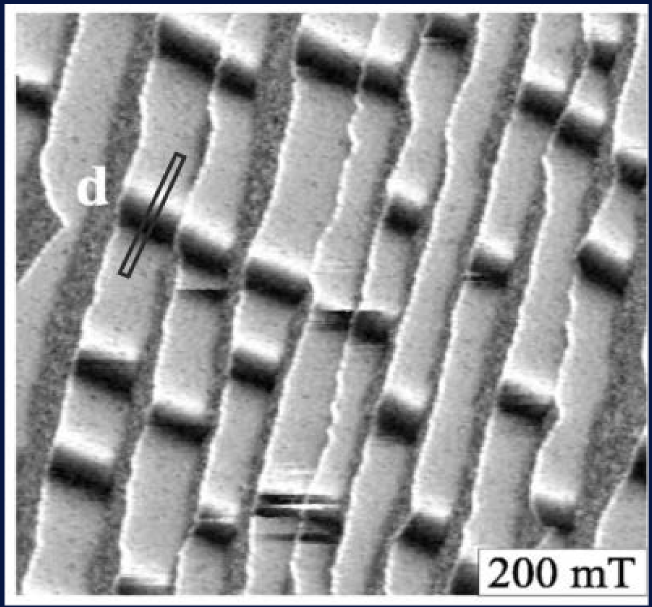
O. Pietzsch et al., Science 292, 2053 (2001)

A. Kubetzka et al., Phys. Rev. Lett. 88, 057201 (2002)

Atomic-Scale Profile of 360° Domain Walls: Comparison of Experiment with Theory

Chiral 360°-domain walls in DL Fe/W(110):



O. Pietzsch *et al.*: Science **292**, 2053 (2001)

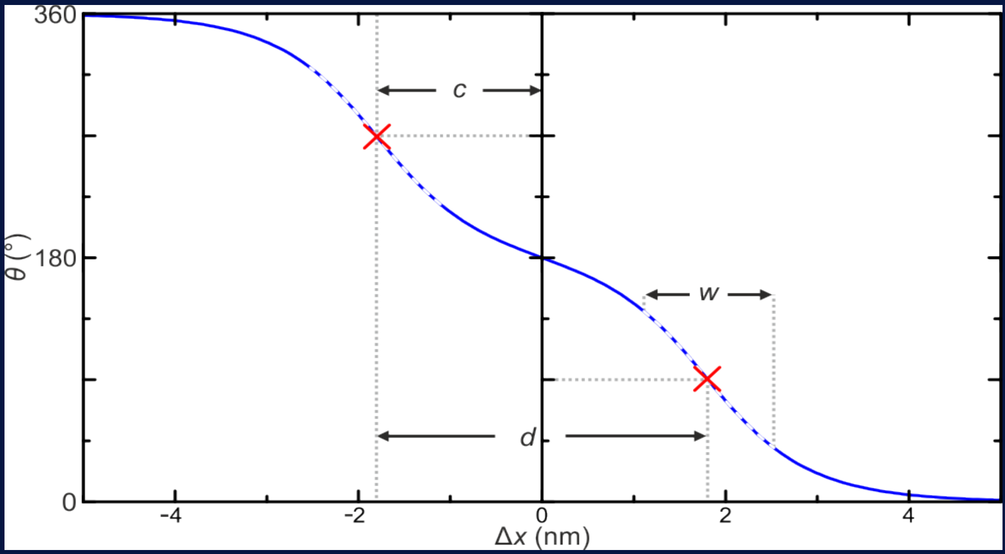
A. Kubetzka *et al.*: PRL **88**, 057201 (2002)

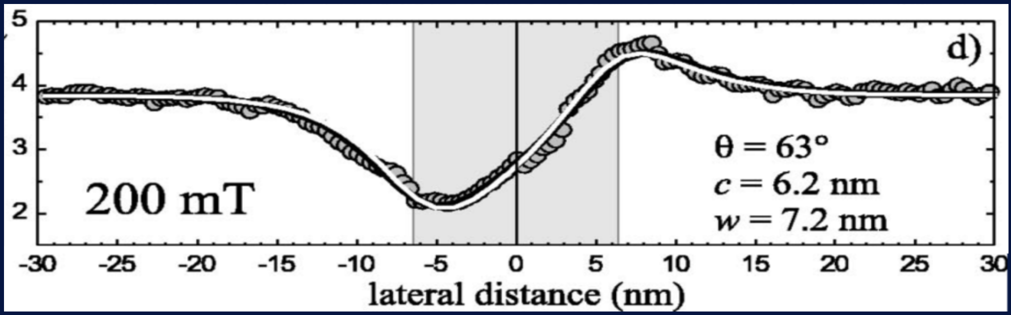
A. Kubetzka *et. al.*: Phys. Rev. B **67**, 020401 (2003)

E. Y. Vedmedenko *et al.*: Phys. Rev. B **75**, 104431 (2007)

Analytical formula for two 180° domain walls:

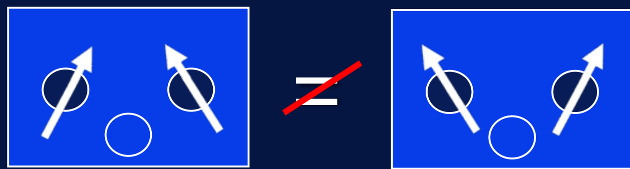
$$\theta(\rho, c, w) = \begin{cases} \sum_{+,-} \left[\arcsin \left(\tanh \frac{-\rho \pm c}{w/2} \right) \right] + \pi & |B_z > 0 \\ \sum_{+,-} \left[\arcsin \left(\tanh \frac{-\rho \pm c}{w/2} \right) \right] & |B_z < 0 \end{cases}$$





Interface-Driven Non-collinear Spin States

Dzyaloshinskii-Moriya interaction due to spin-orbit coupling

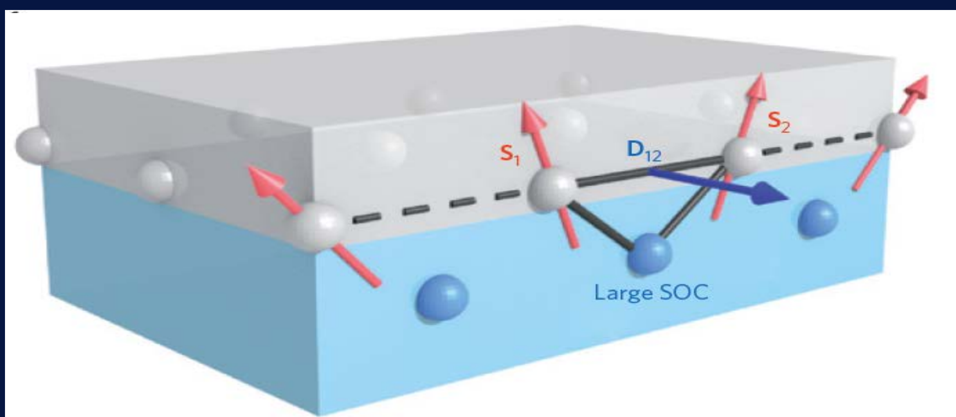


when inversion symmetry is broken

DM always to be considered at surfaces and interfaces

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

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



A. Fert, in:
Materials Science Forum, **59-60**, 439 (1990).
A. Crépieux and C. Lacroix,
J. Magn. Magn. Mat. **182**, 341 (1990).

SPSTM:

- chiral domain walls (2001-2007)
- cycloidal spin spirals with unique rotational sense (since 2007)
- chiral skyrmions (since 2011)

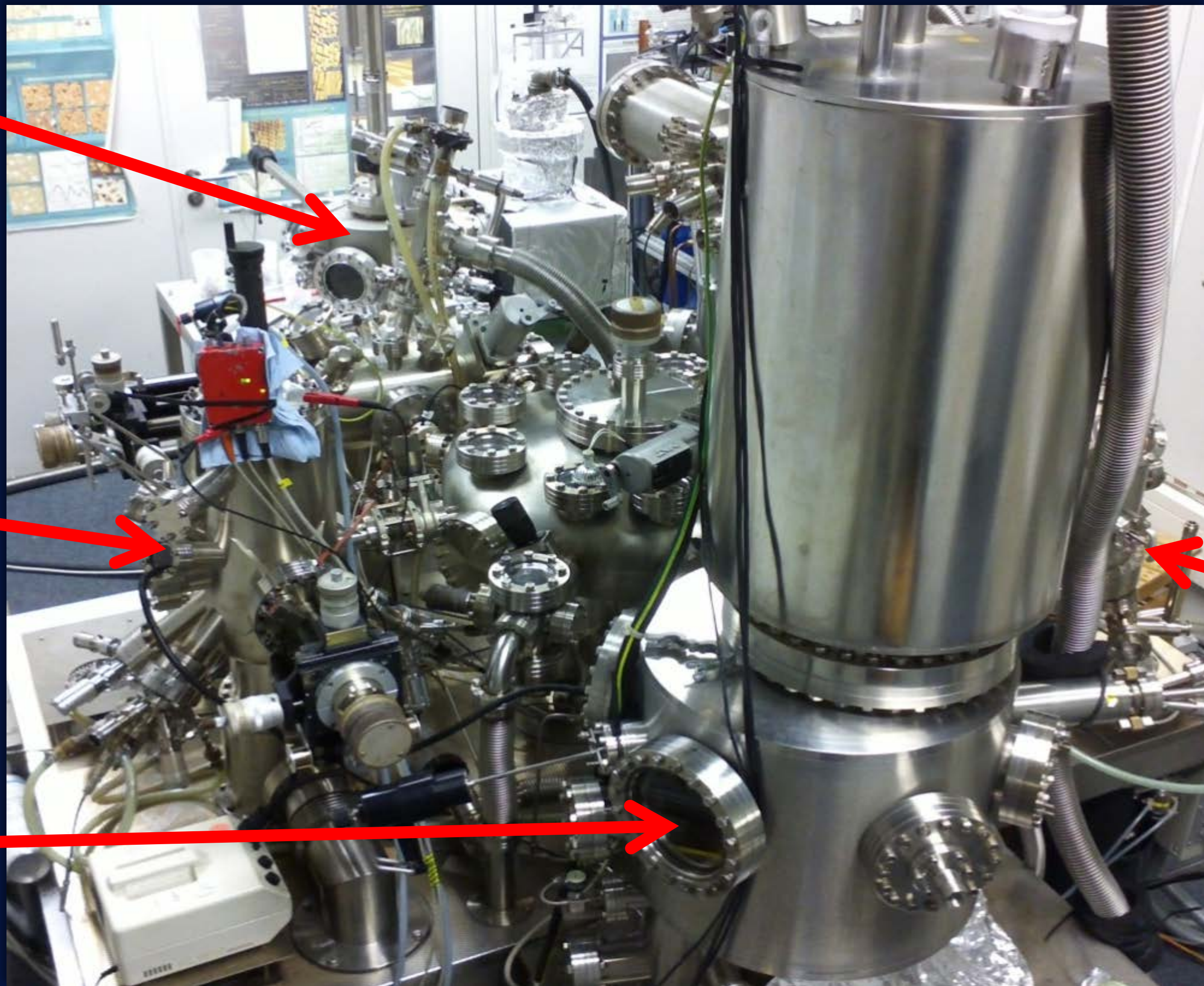
M. Bode et al., Nature **447**, 190 (2007)
P. Ferriani et al., PRL **101**, 27201 (2008)
S. Meckler et al., PRL **103**, 157201 (2009)
M. Menzel et al., PRL **108**, 197204 (2012)

NANOLAB in Hamburg: Metal-MBE combined with SP-STM

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

MBE-STM
T = 300 K

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

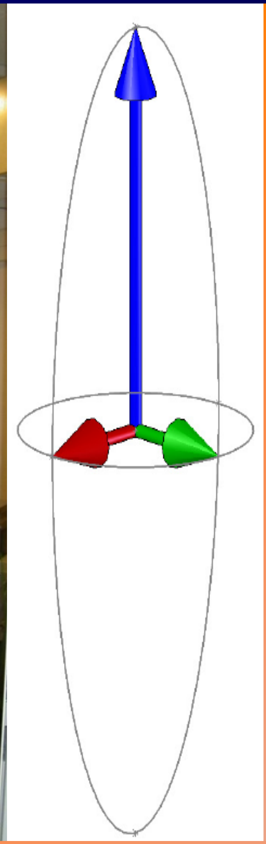


VT-STM
T = 30-1000 K

→ *in situ* preparation of STM tip and sample in UHV

3D Control of Tip Magnetization & Magnetic Contrast

Setup and Magnetic Field Range



Field strengths single direction:

B_x, B_y: 1.3 T

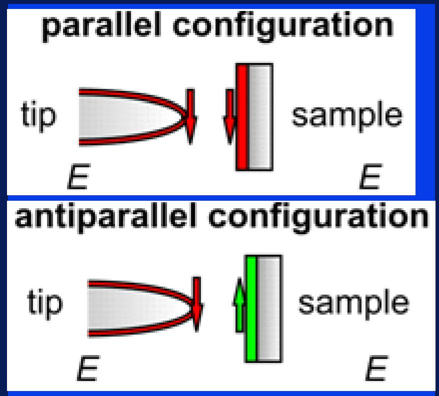
B_z: 5 T

3D mode:

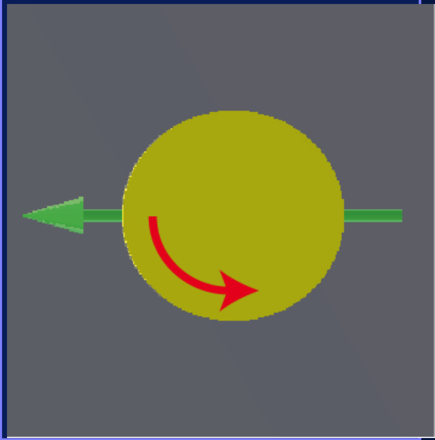
B_x, B_y: 1 T

B_z: 3.5 T

Contrast Mechanism



Top View of the Tip



Alignment of the tip-magnetization in the external field

↓

Investigation of the absolute magnetization direction in the sample is possible

Magnetization Orientation in the Domain Walls

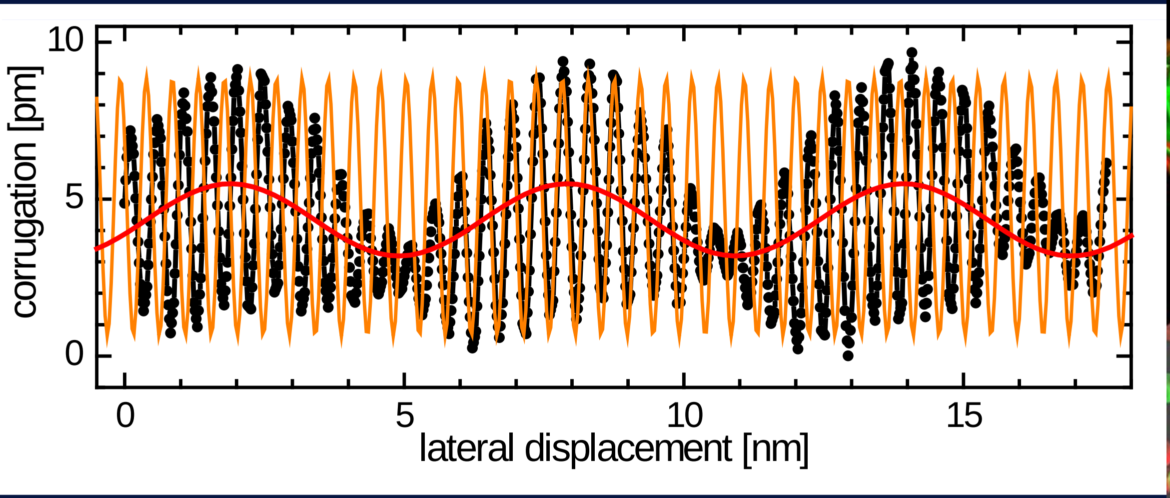
In-Plane Magnetic Field Rotation

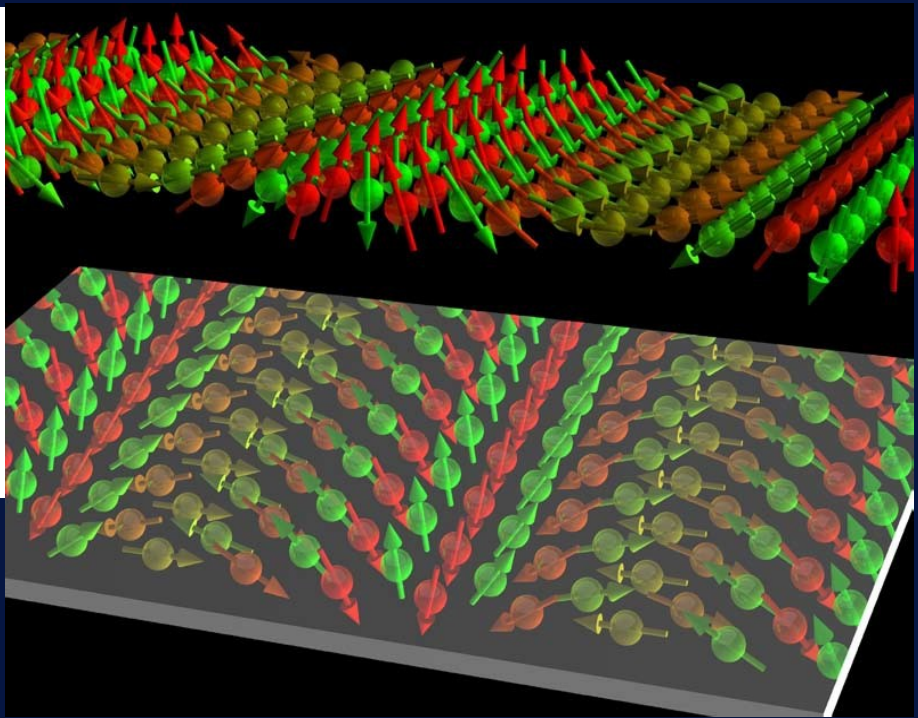
→ Right-rotating cycloidal spin spiral !

(S. Meckler et al., PRL 103, 157201 (2009))

Cycloidal Spin Spiral observed for 1 ML Mn on W(110)

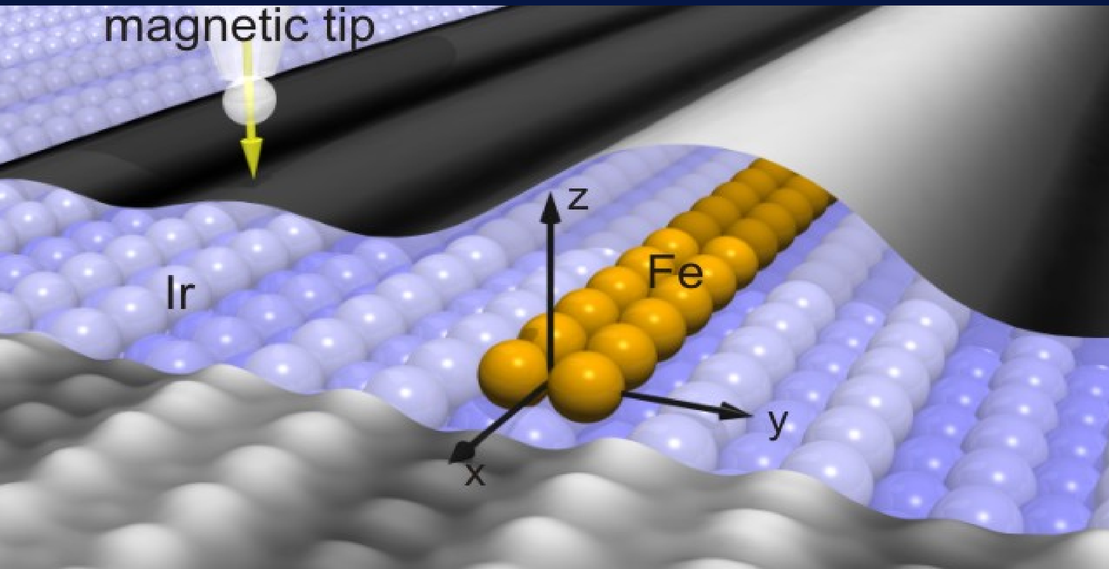
tip:	Cr-coated W-tip
sample:	0.8 ML Mn/W(110)
STM:	U_{bias} = +3 mV
	I_{tun} = 15 nA
	T = 13 K

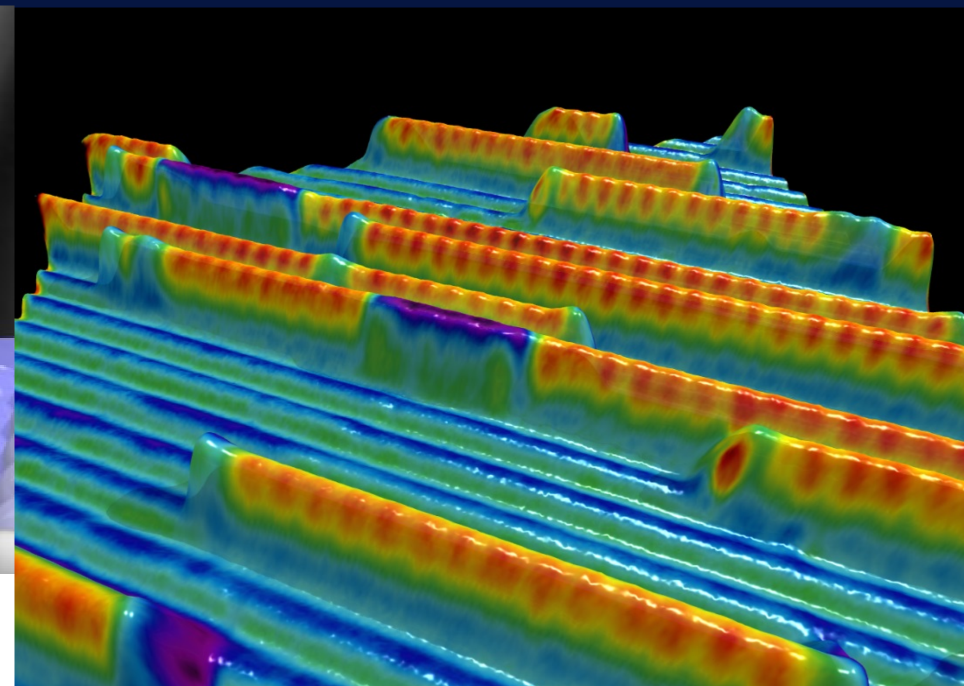


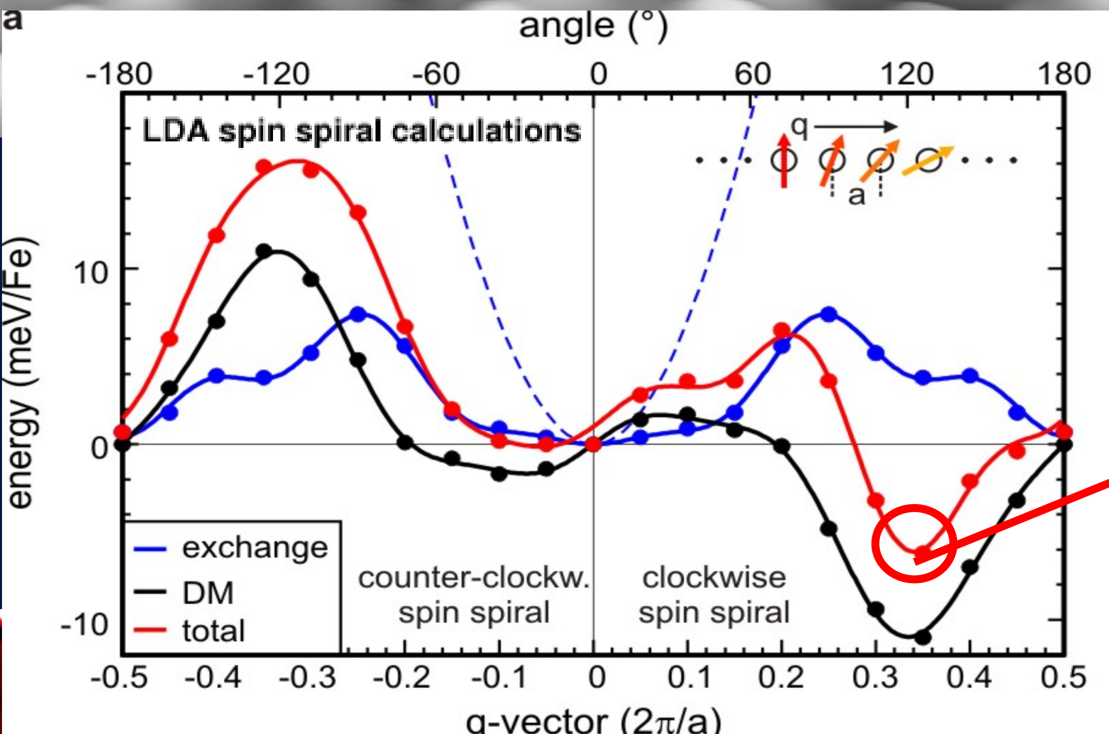


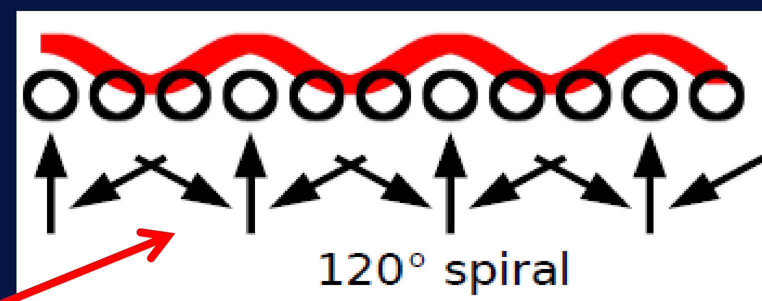
M. Bode et al., Nature 447, 190 (2007)

120° Spin Spiral in Bi-Atomic Fe Chains on Ir(001)







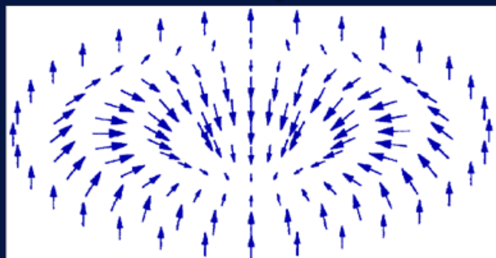


→ **DM-interaction is responsible for chiral spin spiral formation !**

M. Menzel et al., PRL 108, 197204 (2012)

Chiral Magnetic Skyrmions:
From Theoretical Predictions to Experimental Observations

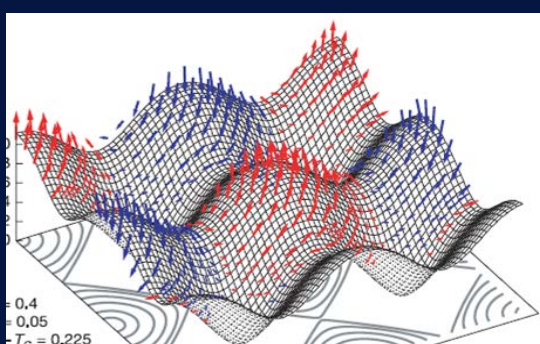
Theoretical predictions:



~1 μm

→ stable defect of FM film

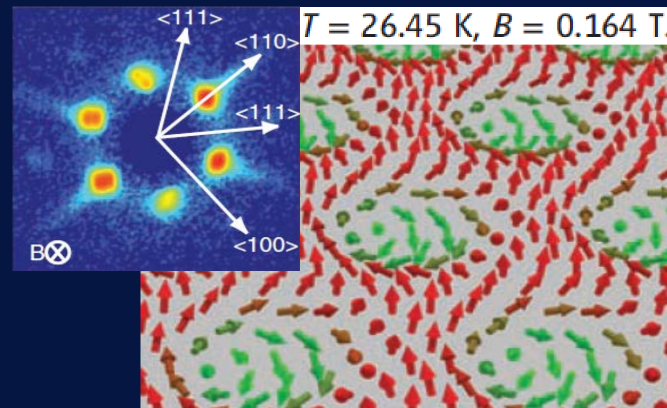
□A. Bogdanov & D. Yablonskii,
Sov. Phys. JETP 68, 101 (1989)

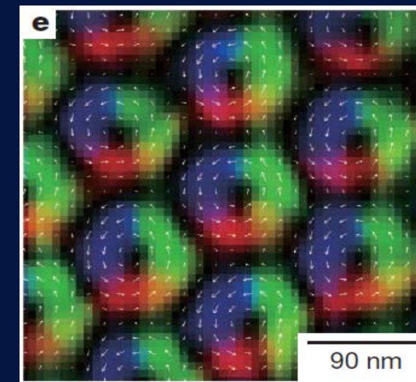


→ stable lattices with modulated
M

□U.K. Rößler *et al.*, Nature 442, 797 (2006)

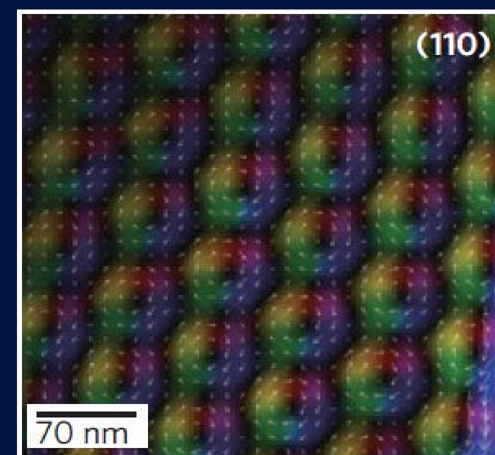
Experimental findings:





Skyrmion lattices in bulk crystals lacking inversion symmetry:

MnSi (bulk)
FeCoSi (~100nm film)
FeGe (15 — 100nm films)

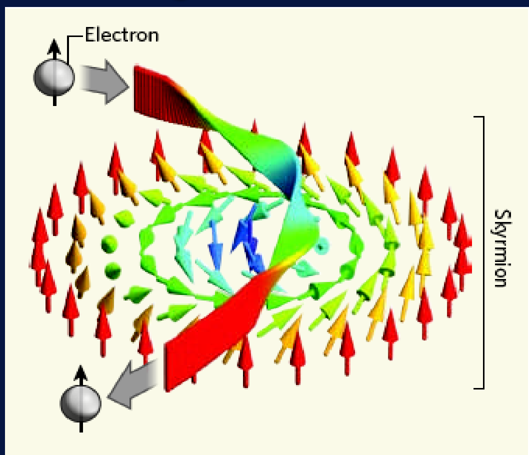


□S. Mühlbauer *et al.*, Science 323, 915 (2009)
□X.Z. Yu *et al.*, Nature 465, 901 (2010)
□X.Z. Yu *et al.*, Nature Mater. 10, 106 (2011)

Motivation for Studying Magnetic Skyrmions

SPINTRONICS:

Electrons interact very efficiently with non-collinear magnetic states



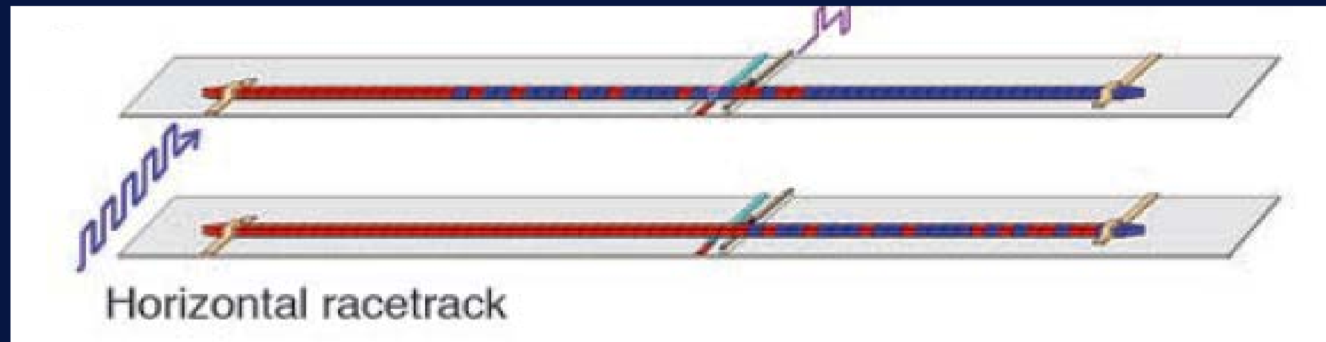
C. Pfleiderer, A. Rosch, Nature **465**, 880 (2010)

How can skyrmions be created and annihilated (or written and deleted) in a controlled fashion?

Do skyrmions exist in ultrathin magnetic films and multilayers?

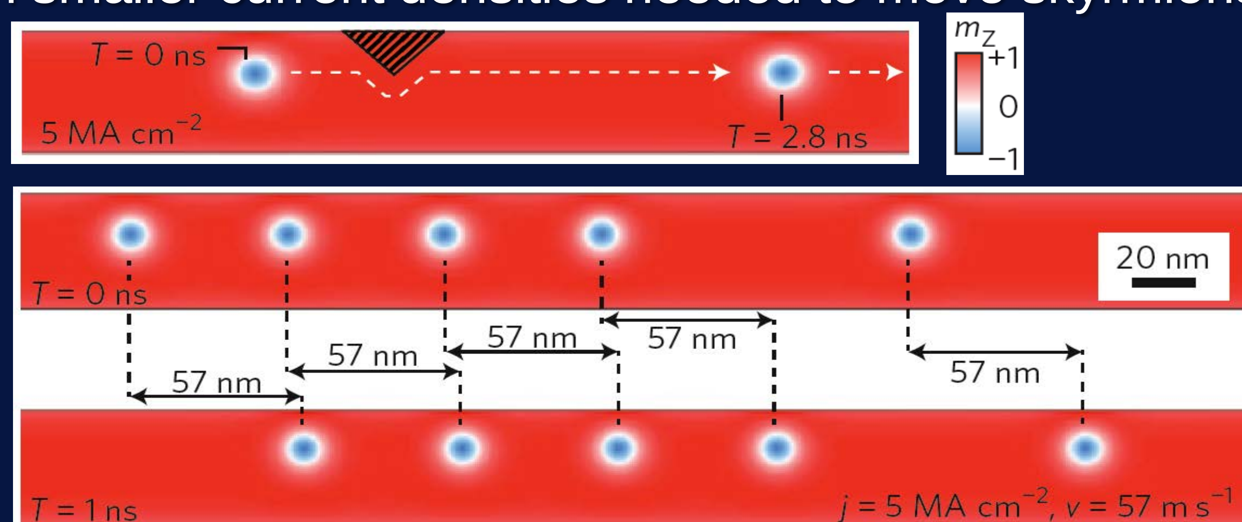
MAGNETIC MEMORIES:

„Racetrack memory“ based on shifting domain walls



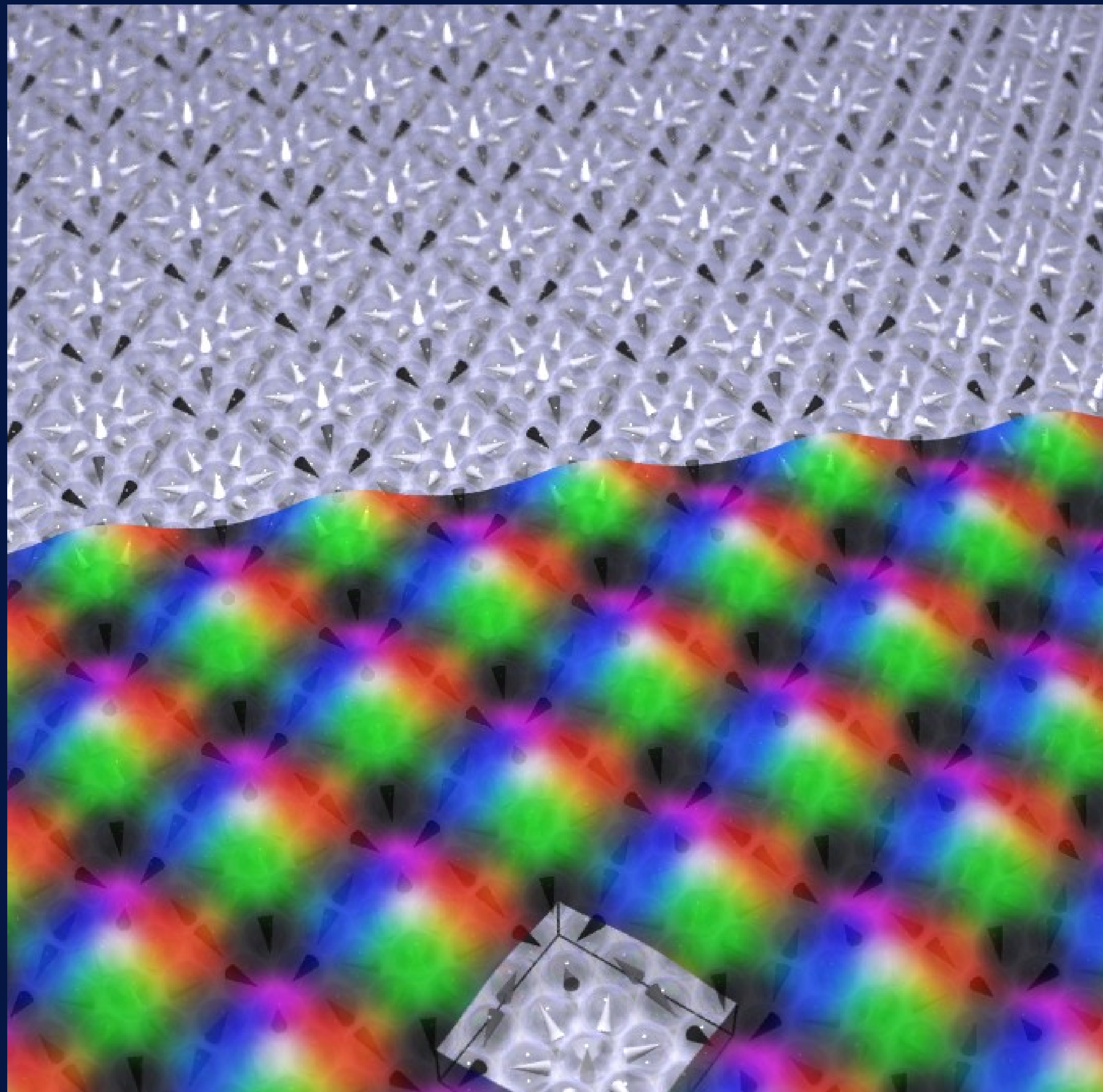
S.S.P. Parkin et al., Science **320**, 190 (2008)

Much smaller current densities needed to move skyrmions:



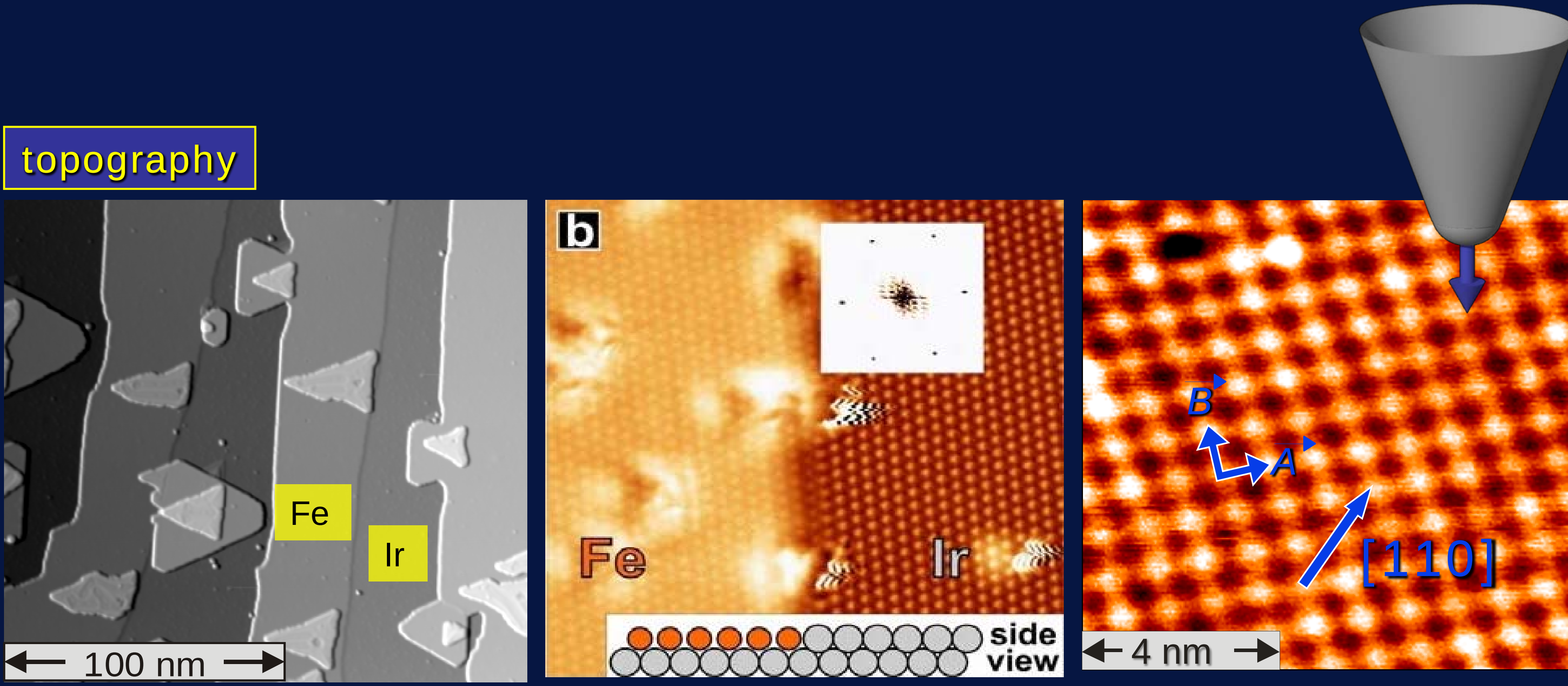
A. Fert et al., Nature Nanotech. **8**, 152 (2013)

Discovery of Interface-Driven Chiral Skyrmionic Lattices in a Monolayer of Fe on Ir(111)



Fe on Ir(111) with out-of-plane magnetized SP-STM tip

topography

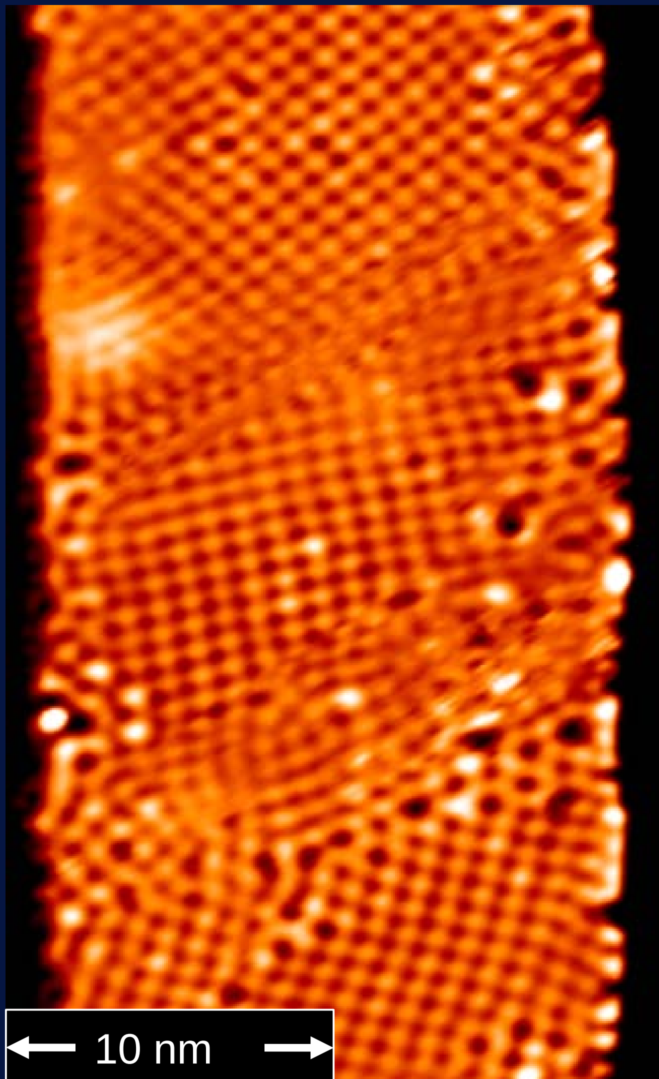


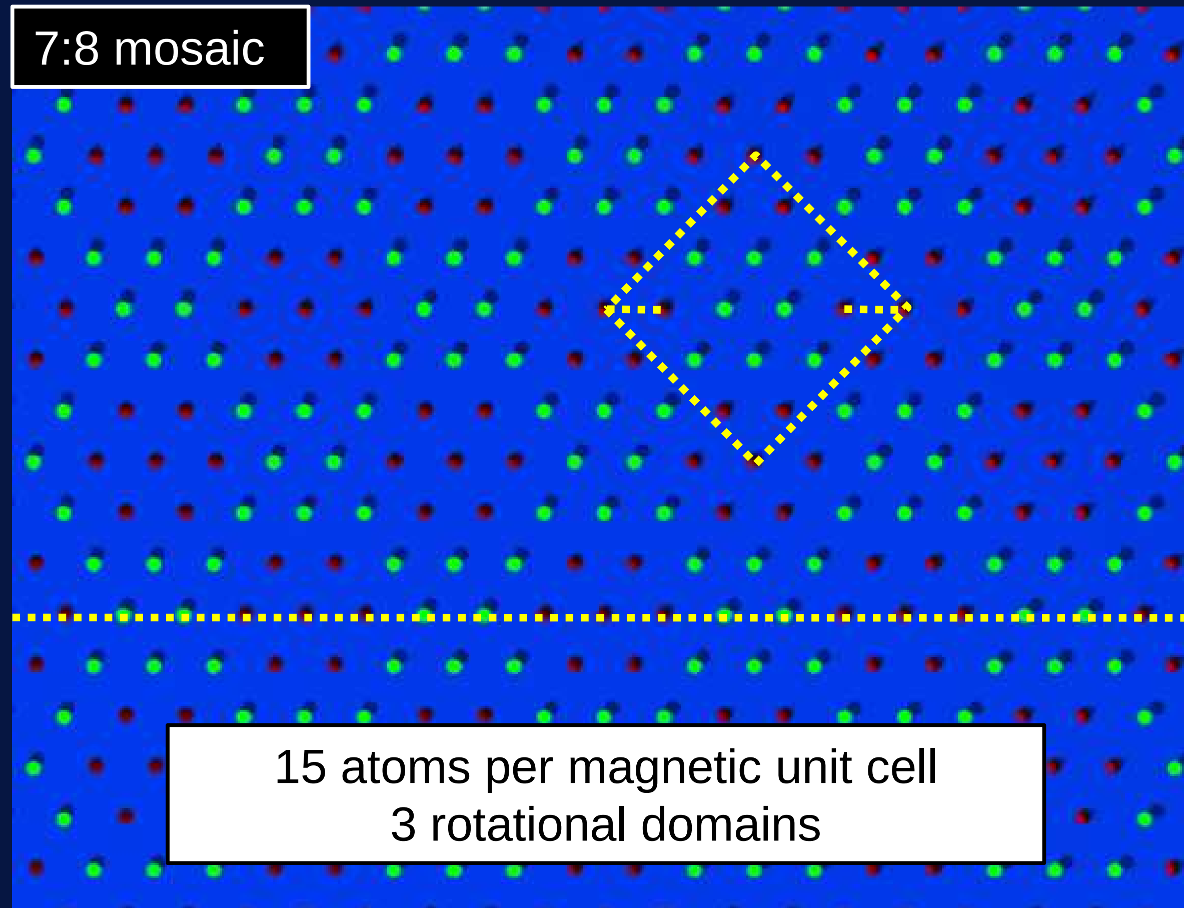
0.6 AL Fe on Ir(111)
1st AL Fe grows pseudomorphically
→ hexagonally arranged surface atoms

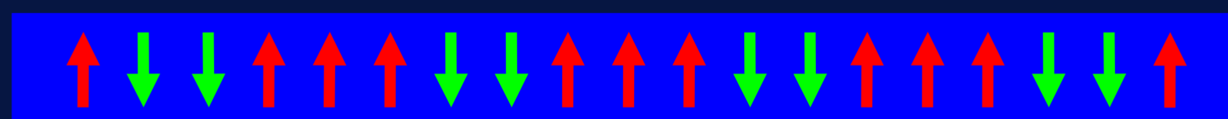
square magnetic unit cell ~15 atoms
$\vec{A}$, $\vec{B}$ ≈ 1 nm, ± 45° to close packed row
out-of-plane component

K. von Bergmann *et al.*, Phys. Rev. Lett. **96**, 167203 (2006)
K. von Bergmann *et al.*, New J. Phys. **9**, 396 (2007)

Fe/Ir(111) with out-of-plane Magnetized SP-STM Tip



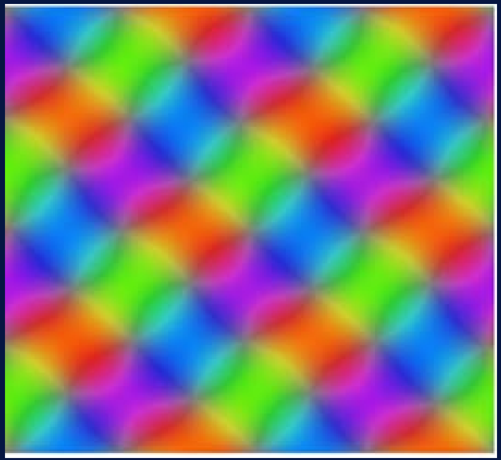




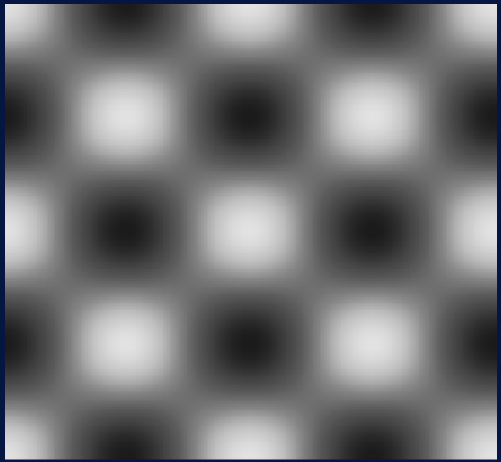
side view

K. von Bergmann *et al.*, Phys. Rev. Lett. **96**, 167203 (2006)
K. von Bergmann *et al.*, New J. Phys. **9**, 396 (2007)

3D Vectorial Spin Map of 1 ML Fe on Ir(111)



in-plane magnetization



out-of-plane magnetization

Microscopic Origin of the Skyrmion Lattice

$$H = -\sum_{i,j} J_{ij}\, \mathbf{S}_i \cdot \mathbf{S}_j + \sum_{i,j} \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j) + \sum_i A_i\, (S_i^z)^2$$

exchange | Dzyaloshinskii-Moriya | anisotropy

$$-\sum_{ij} B_{ij} (\mathbf{S}_i \cdot \mathbf{S}_j)^2 - \sum_{ijkl} K_{ijkl} \left[(\mathbf{S}_i \mathbf{S}_j)(\mathbf{S}_k \mathbf{S}_l) + (\mathbf{S}_j \mathbf{S}_k)(\mathbf{S}_l \mathbf{S}_i) - (\mathbf{S}_i \mathbf{S}_k)(\mathbf{S}_j \mathbf{S}_l) \right]$$

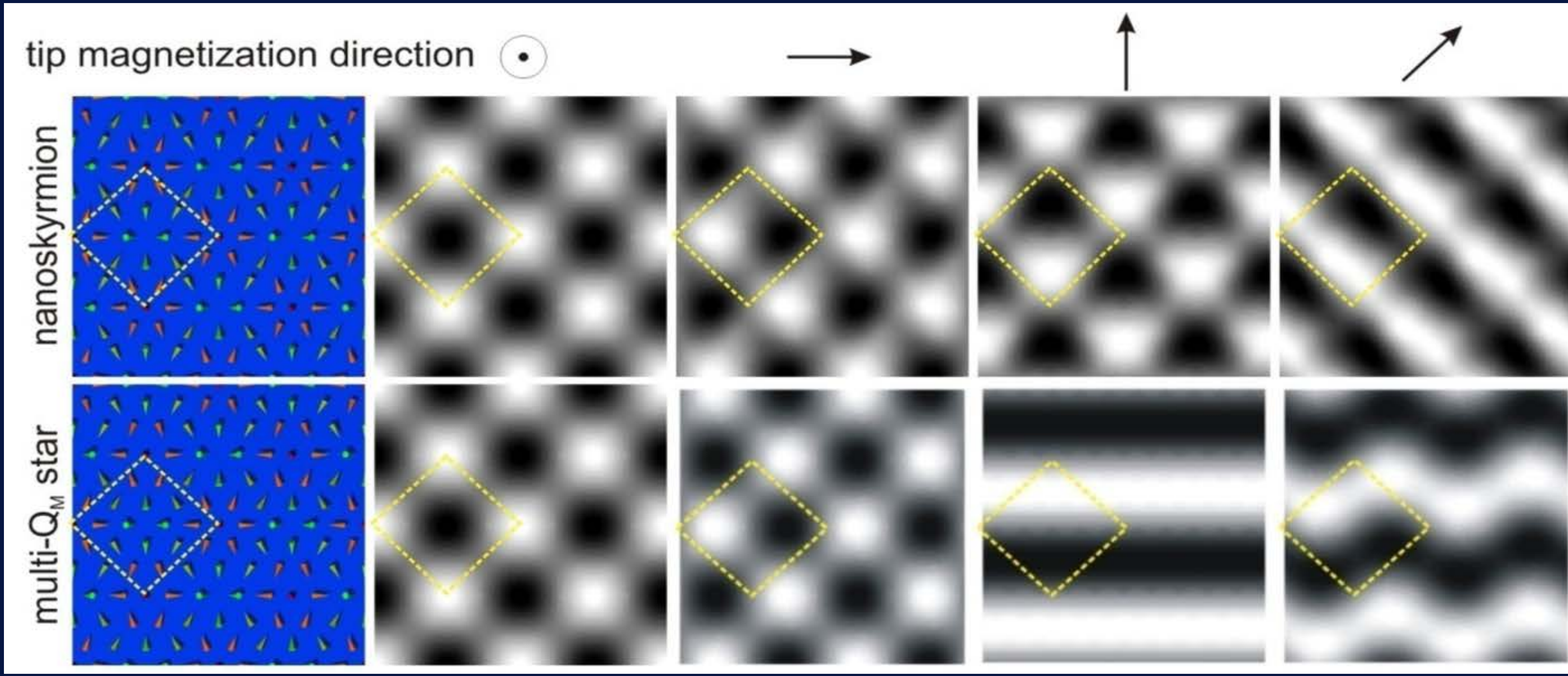
biquadratic | 4-spin

- Dzyaloshinskii-Moriya interaction chooses skyrmion lattice out of several possible 2D spin textures for Fe on Ir(111)
- due to 4-spin interaction 2D spin textures are favored over ferromagnetic and 1D spin spiral states

→ Nanoskyrmion lattice is energetically favorable even in zero field !

Nanoskyrmion Lattice vs. Superposition of Spin Spirals

Simulation of SP-STM images for nanoskyrmion lattice and multi-Q state



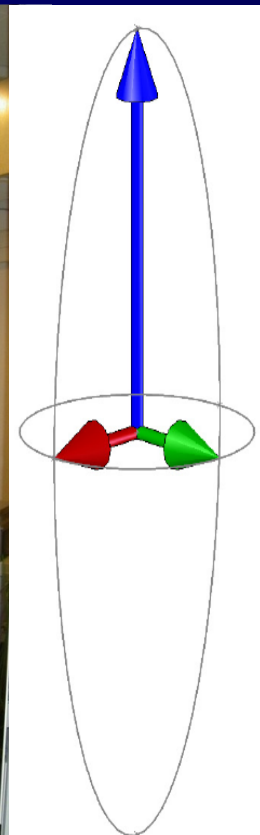
- both states show stripes for certain magnetization directions of the tip
- **but:** distance of stripes in multi-Q state is √2 larger than in experiment
  and observed stripes are in a different crystallographic direction

→ **multi-Q state can be excluded by comparison of experimental data with simulation**

S. Heinze et al., Nature Physics **7**, 713 (2011)

3D Control of Tip Magnetization & Vector-Resolved Spin Contrast

Setup and Magnetic Field Range



Field strengths

single direction:

B_x, B_y: 1.3 T

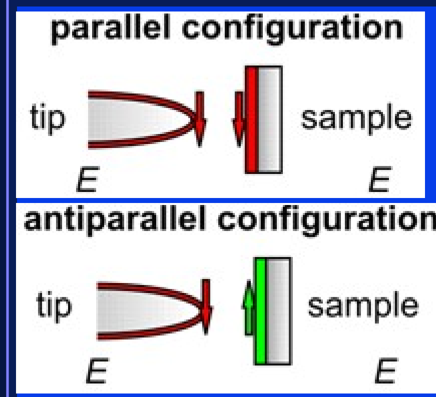
B_z: 5 T

3D mode:

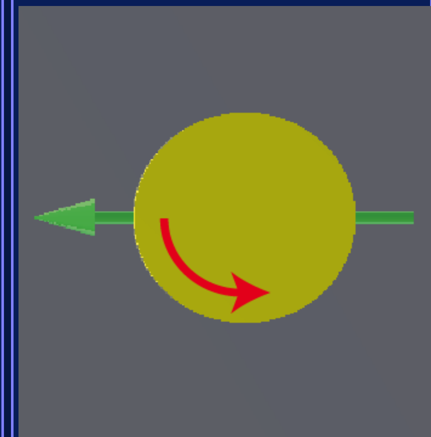
B_x, B_y: 1 T

B_z: 3.5 T

Contrast Mechanism

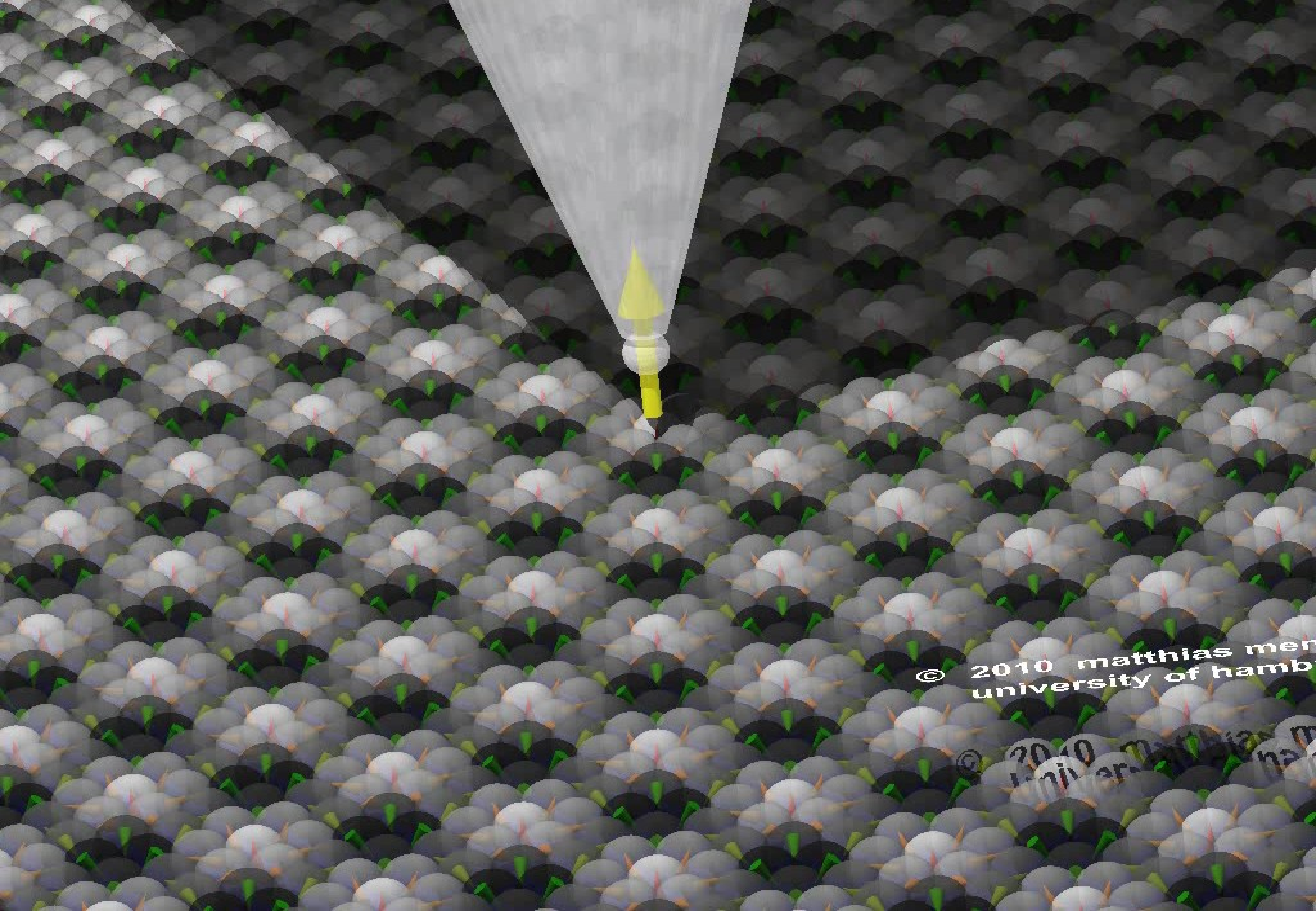


Top View of the Tip

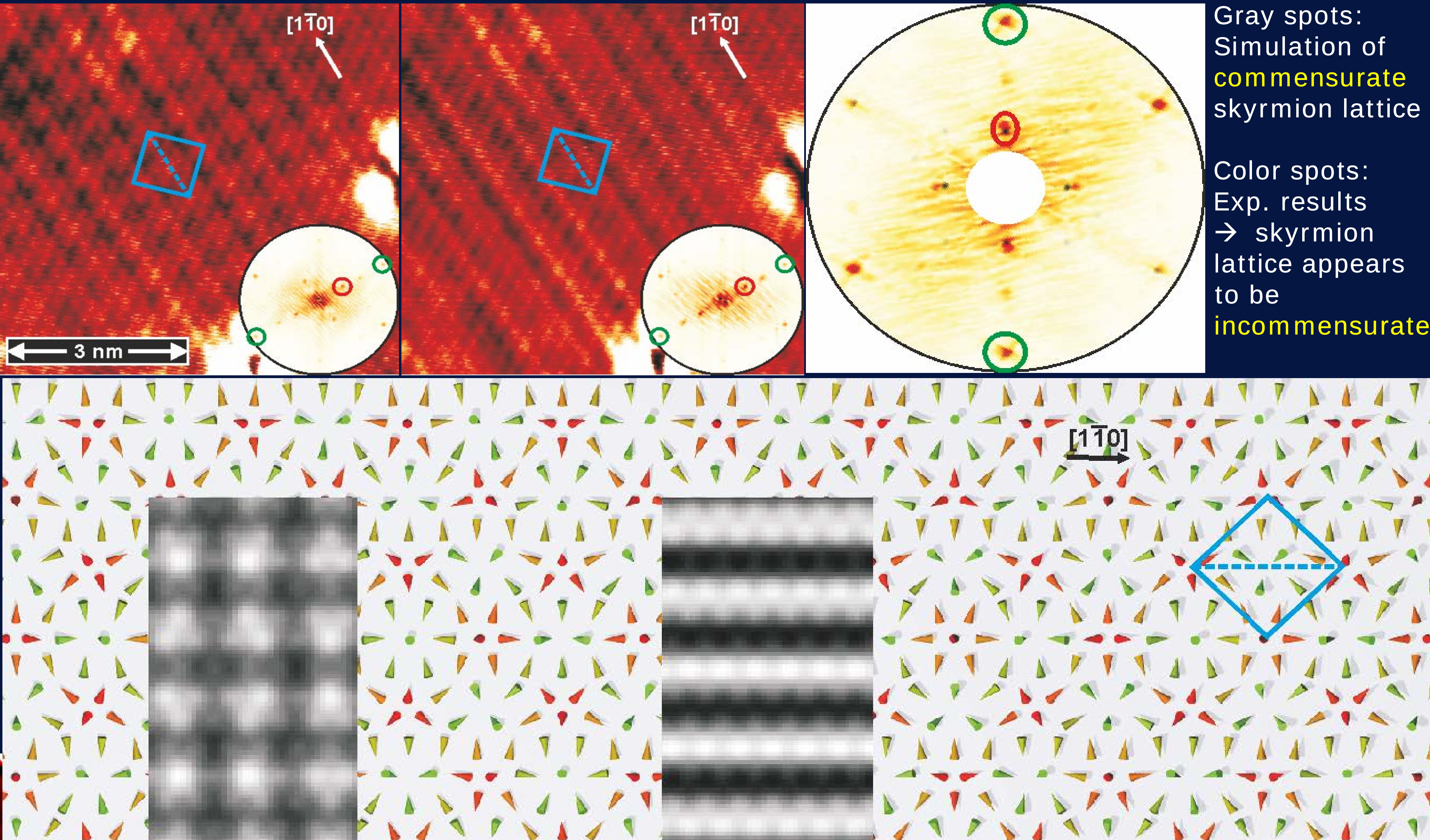


Alignment of the tip-magnetization in the external field

Investigation of the absolute magnetization direction in the sample is possible


© 2010 matthias
university of

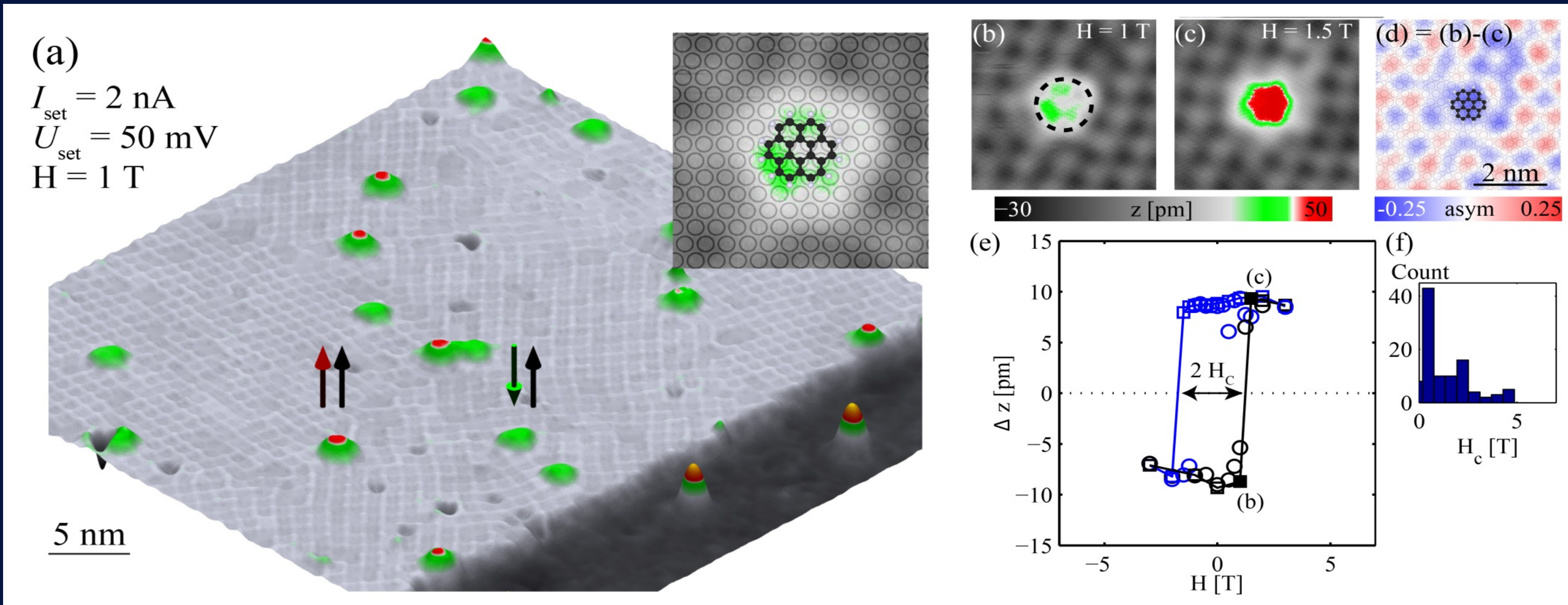
Atomic Resolution for Nanoskyrmion Lattice of 1 ML Fe on Ir(111)



Gray spots: Simulation of commensurate skyrmion lattice

Color spots: Exp. results → skyrmion lattice appears to be incommensurate

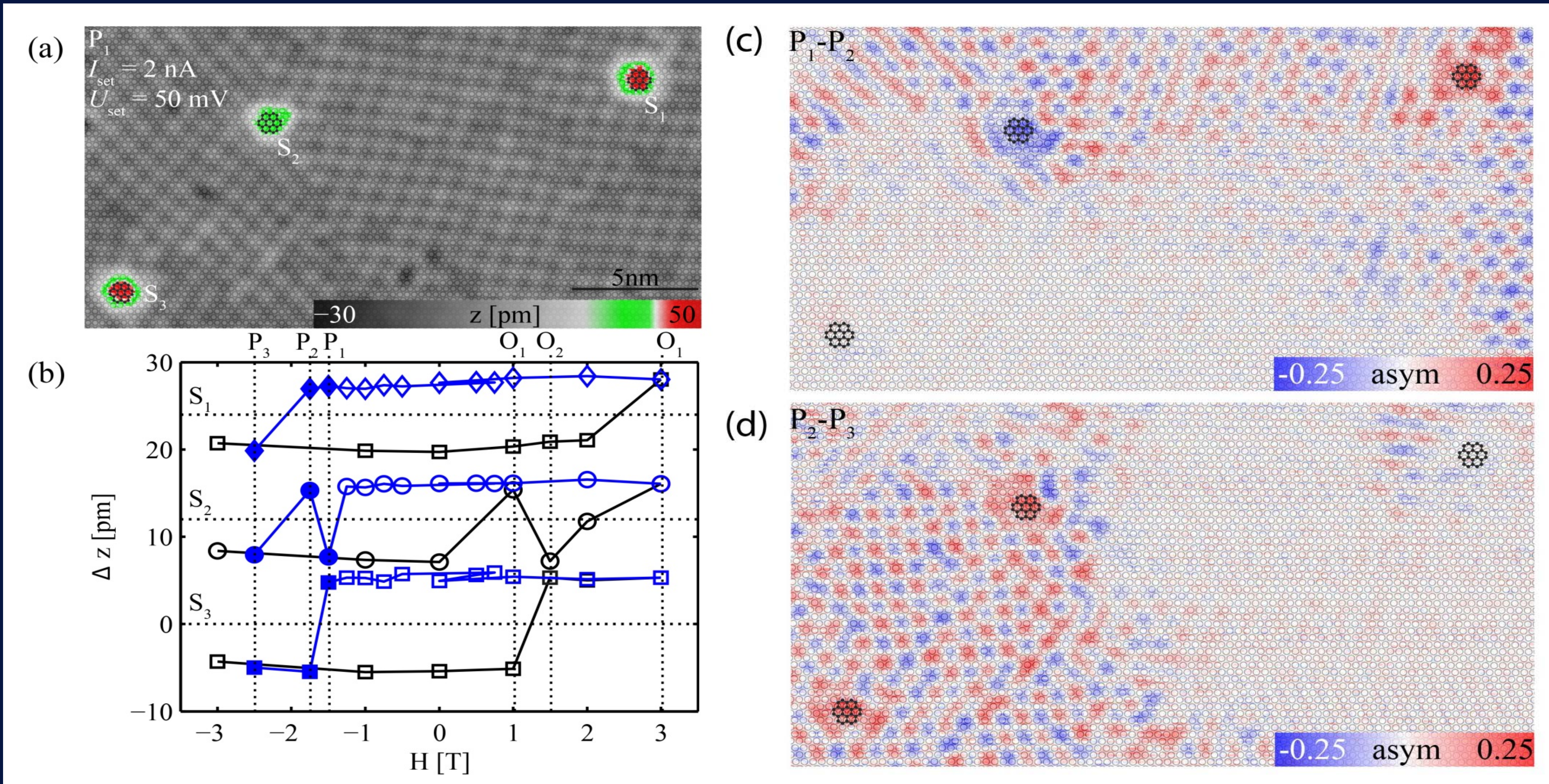
Magnetic Properties of Coronene Molecules on Fe / Ir(111)



→ high coercivity of coronene / Fe / Ir(111) system (1.5 - 2 T)

→ magnetic hardening effect due to organic molecule on top of Fe layer

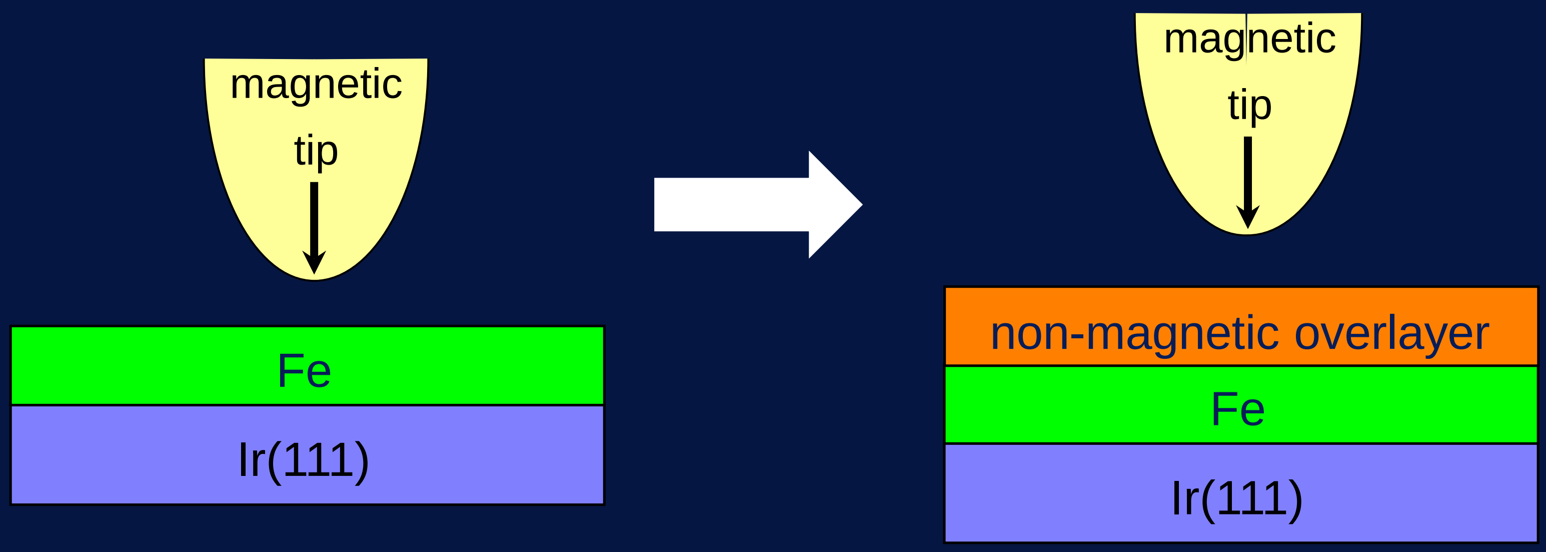
Spin State Information Transmission via a Skyrmion Lattice: Coronene Molecules on Fe/Ir(111)



J. Brede et al., Nature Nanotechnol. **9**, 1018 (2014)

M. Cinchetti, Nature Nanotechnol. **9**, 965 (2014): „Topology communicates“

Tailoring Skyrmionic States by Multiple Interface Engineering

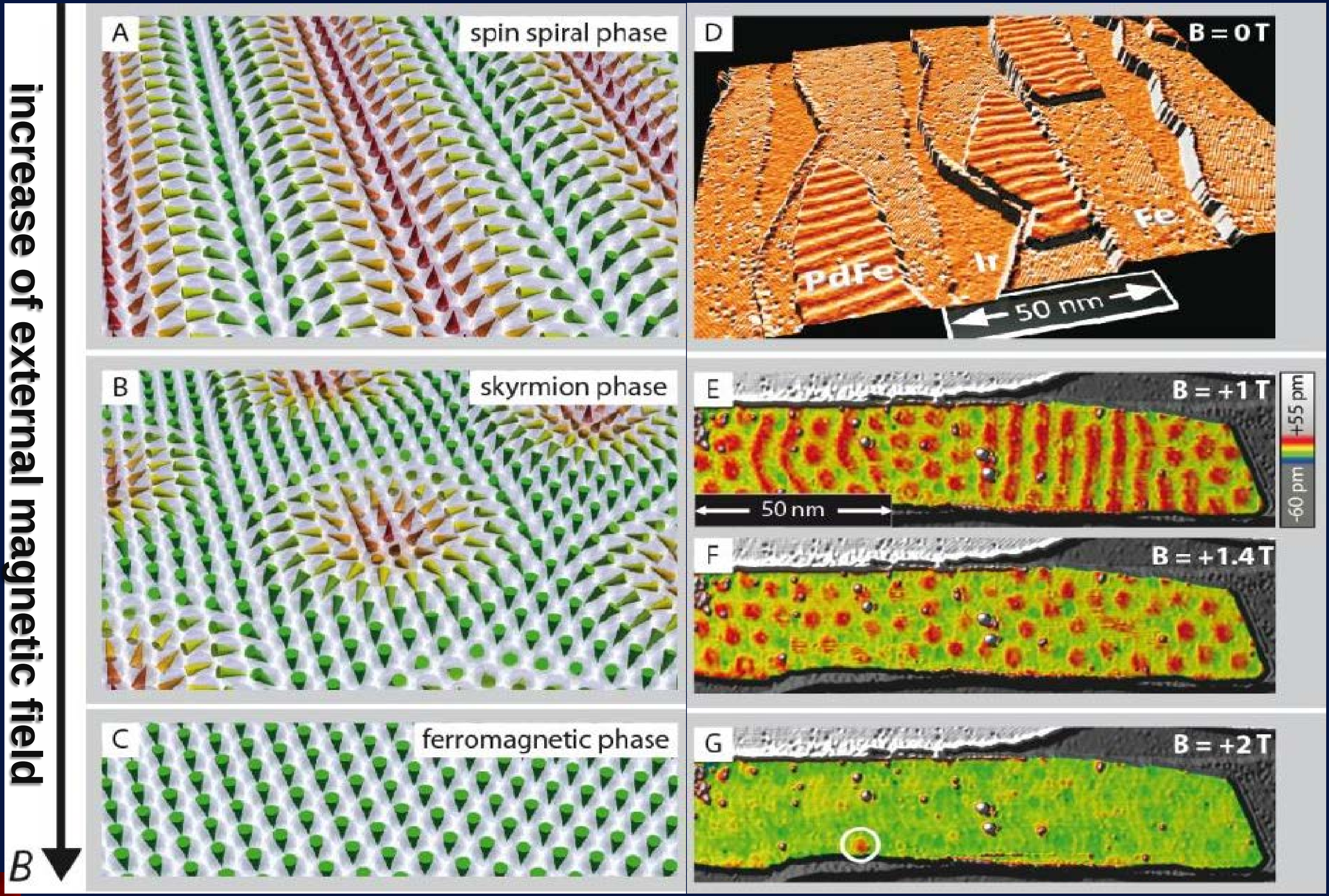


→ Introducing a second interface by a non-magnetic overlayer

→ Tuning of magnetic anisotropies and spin-orbit coupling via the second interface

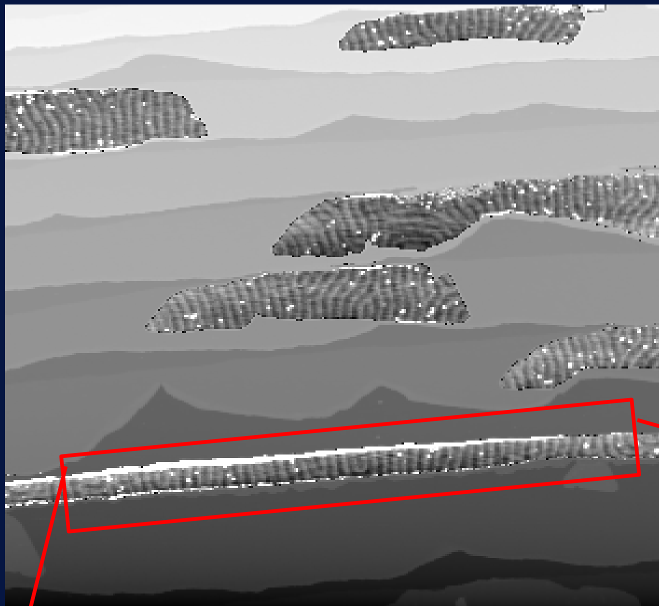
→ Tailoring the overall magnetic state of the hybrid structure

Pd / Fe / Ir(111):
From Spin Spirals to Skyrmions to Ferromagnetic State



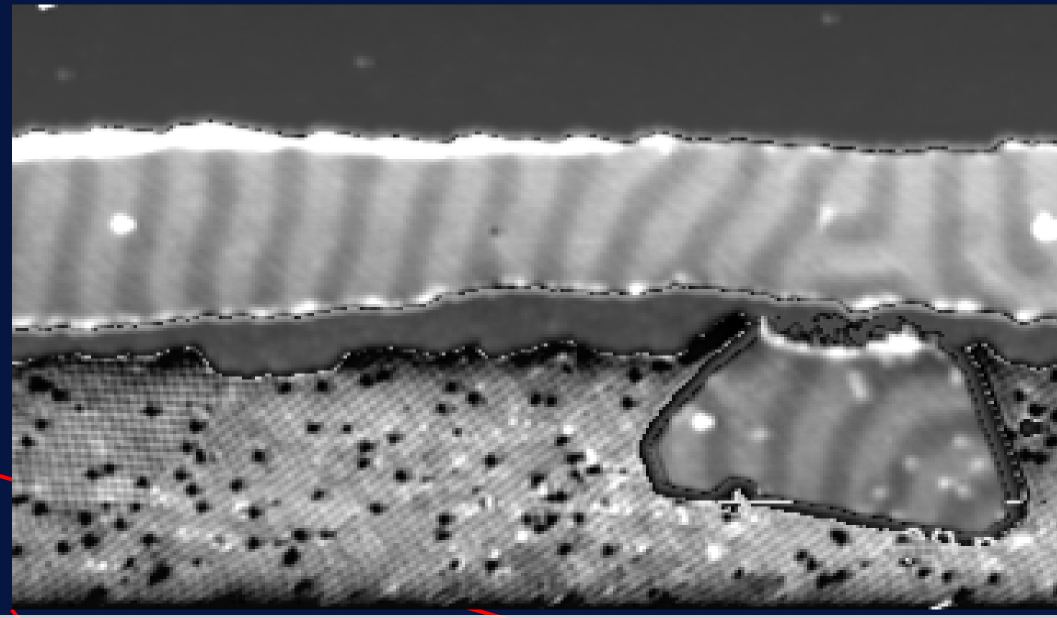
T = 8 K, U = +0.05 V, I = 0.2 A, Cr-bulk tip

Pd monolayer on fcc-Fe / Ir(111) in zero field

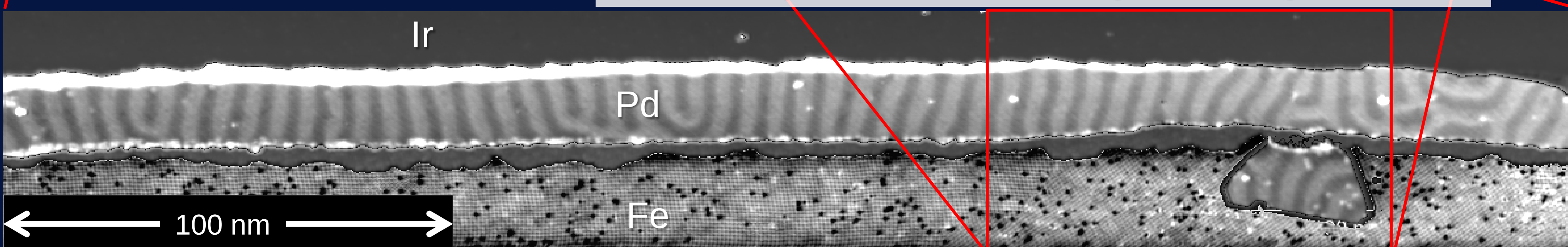


Ir
Fe
Pd

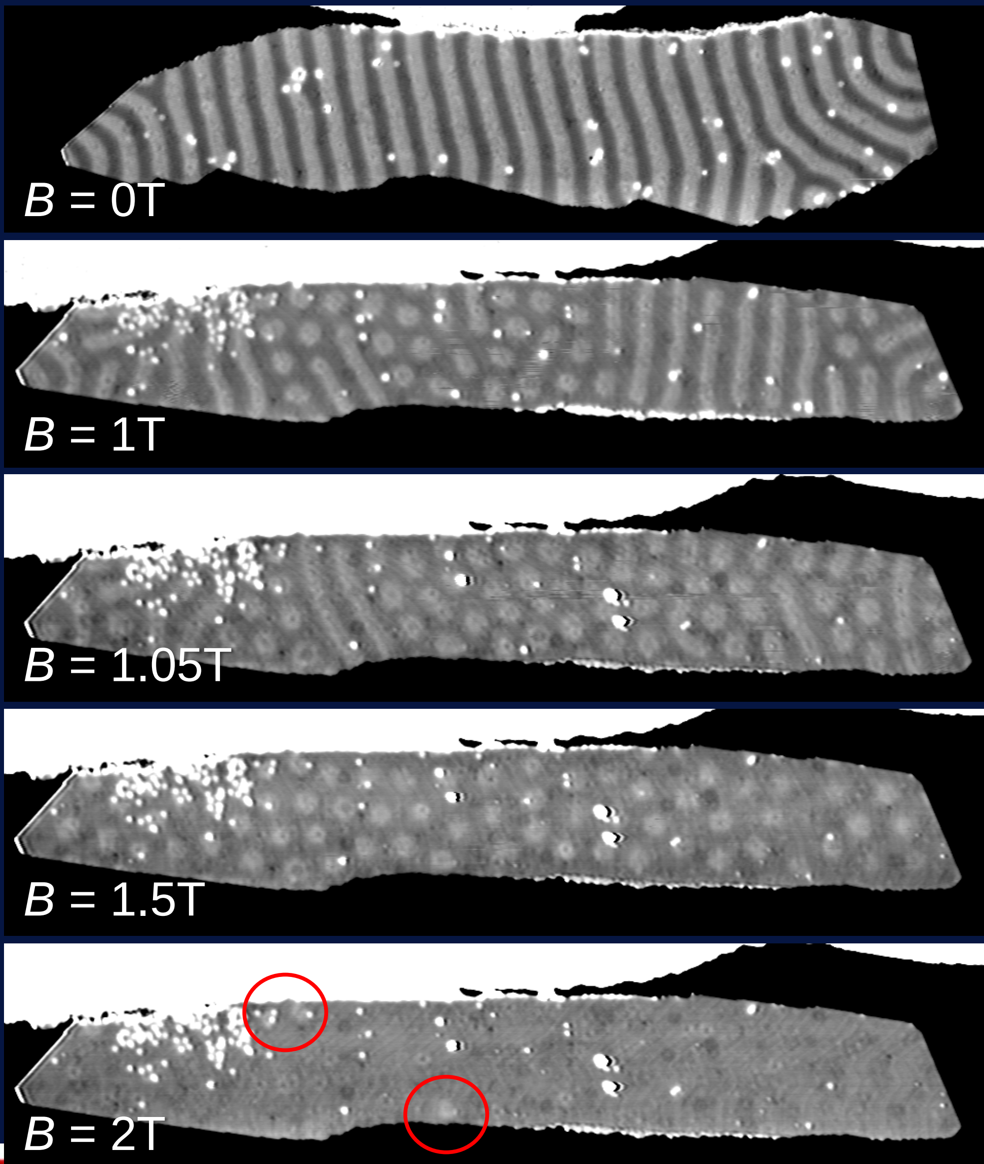
U = +50 mV, I = 200 pA, T = 8 K



- uniaxial spin spiral with ~7 nm periodicity
- spin spiral aligns perpendicular to edges of islands
- periodicity is one order of magnitude larger than Fe



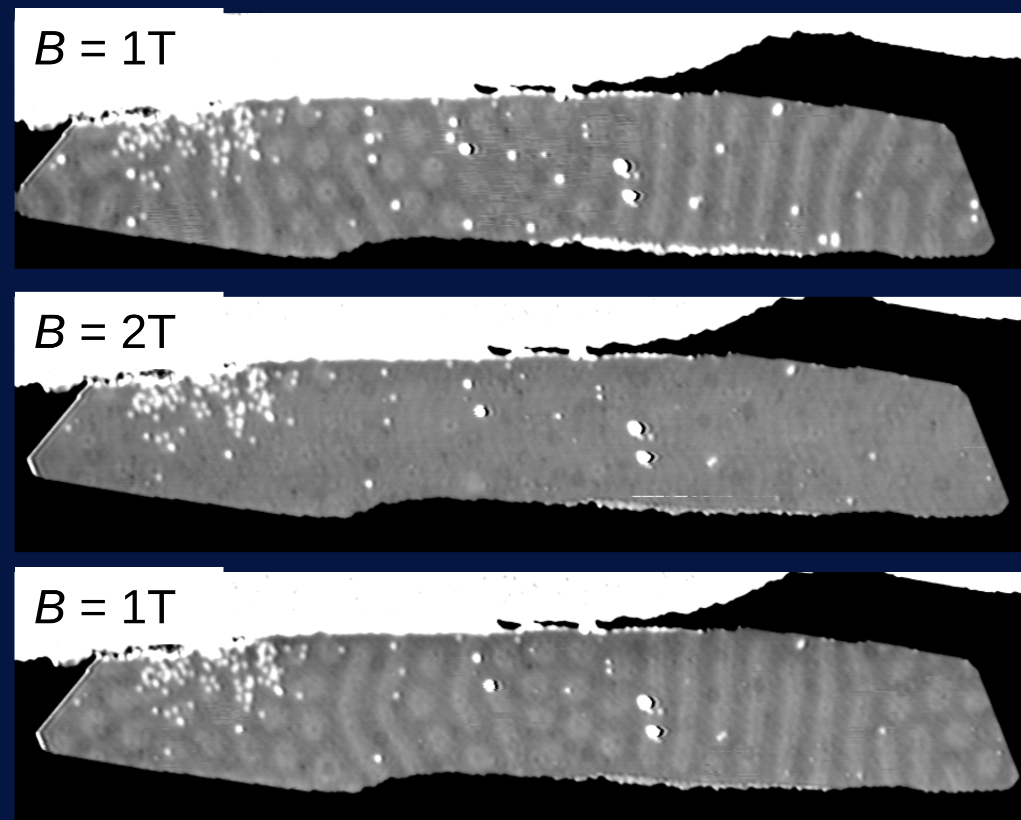
B-field dependence of Pd/Fe bilayer on Ir(111)



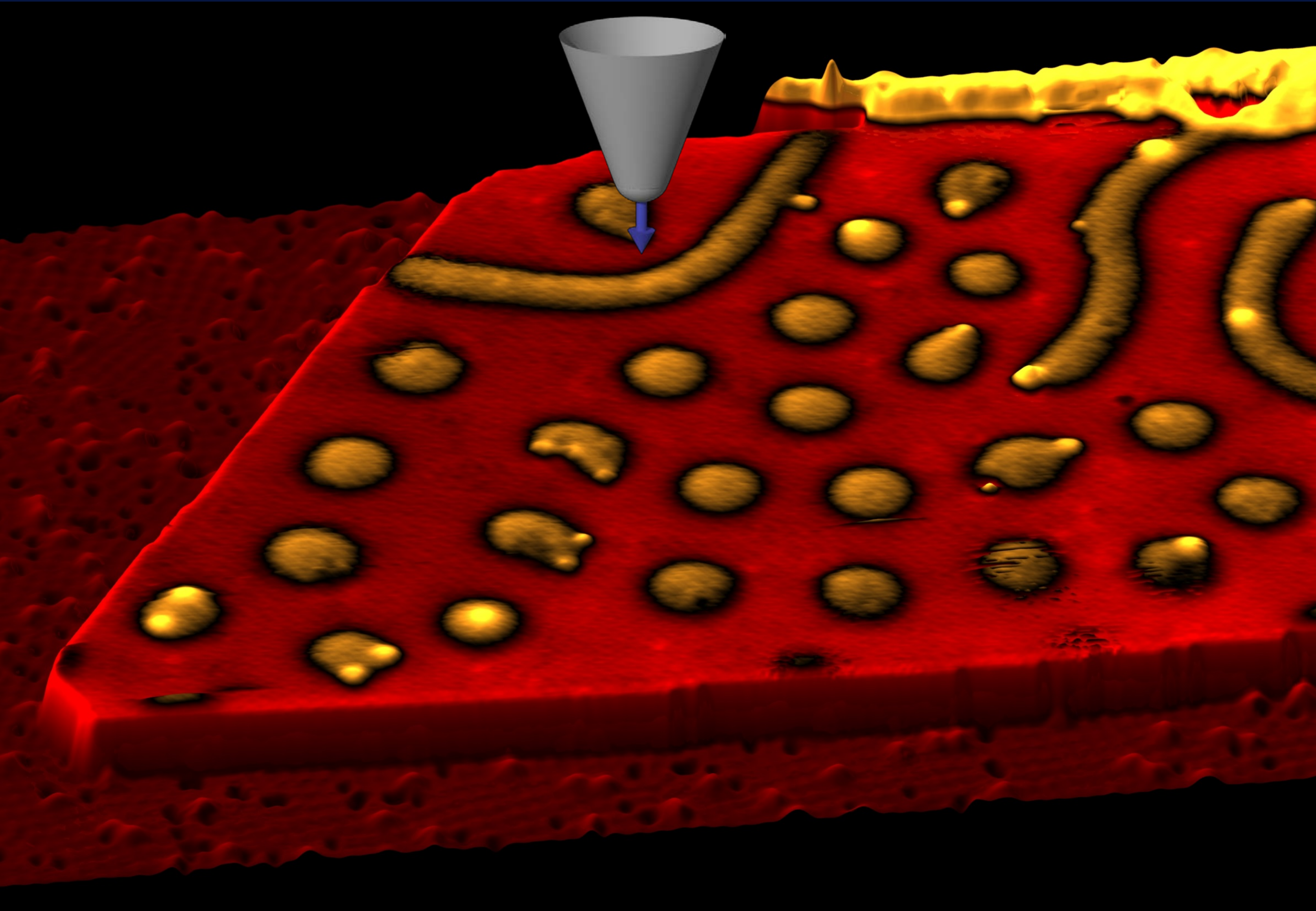
five different phases:

B < 0.8T:	spin spiral phase (ground state)
0.8 < B < 1T:	mixed phase (skyrmions & spiral)
1T < B < 1.5T:	skyrmion crystal
1.5T < B < 2T:	mixed phase (skyrmions & FM)
B > 2T:	saturated ferromagnetic phase

Reversible behaviour at T = 8 K:

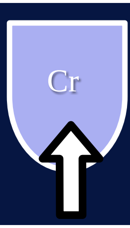


U = +50 mV, *I* = 200 pA, *T* = 8 K

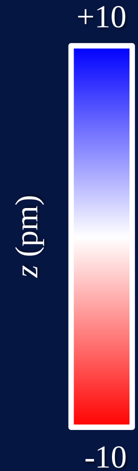


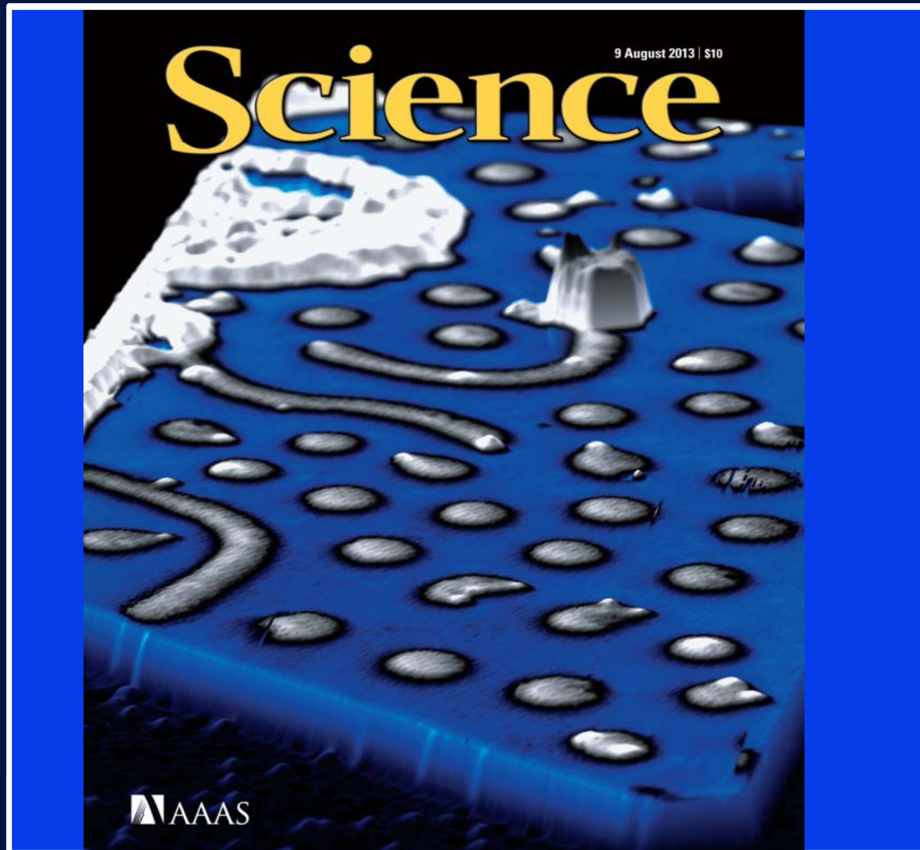
First report on isolated chiral magnetic skyrmions !

U = +200 mV
I = 1.0 nA
T = 2.2 K
B = -1.5 T

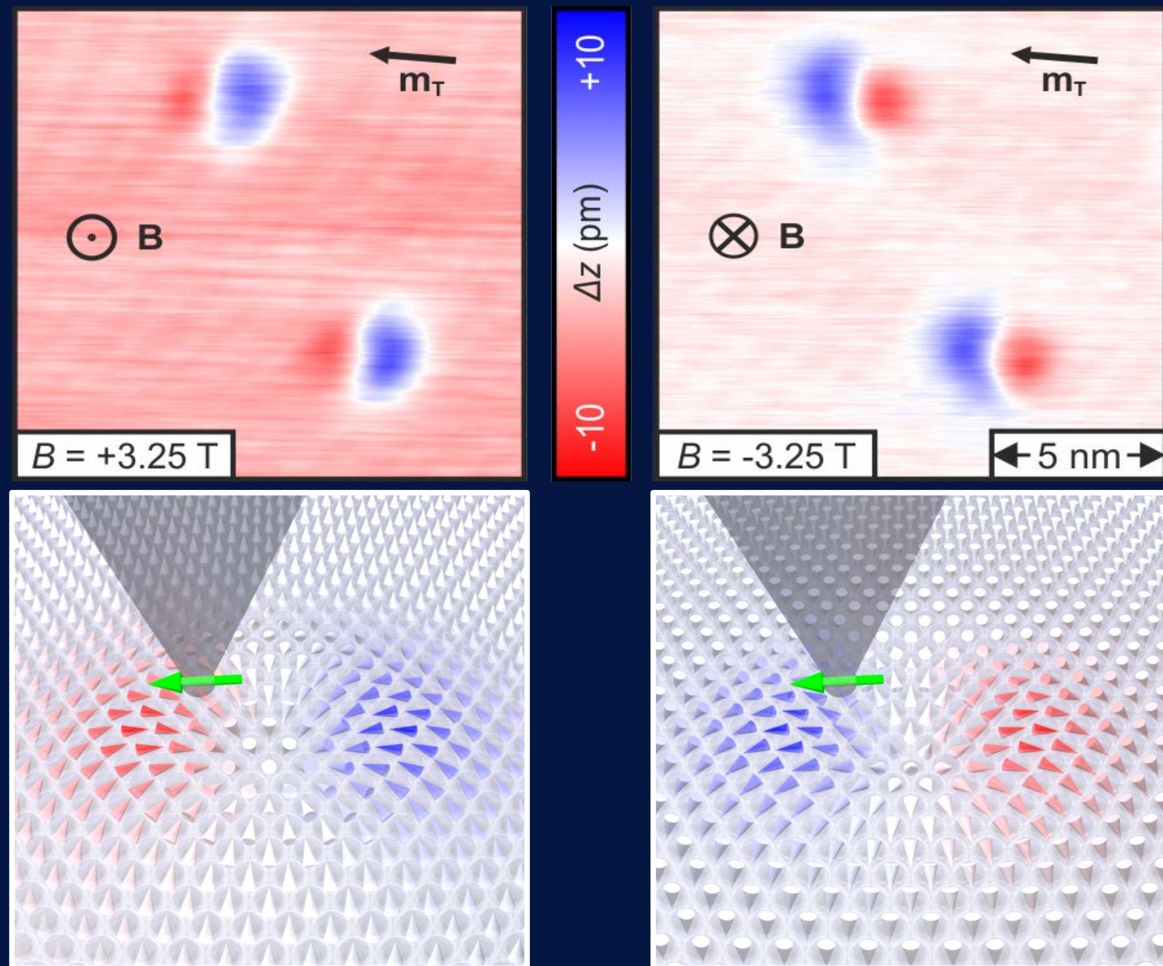


→ skyrmion looks axisymmetric with out-of-plane-tip





Skyrmions in Opposite Magnetic Fields



U = +250 mV I = 1.0 nA
T = 4.2 K

→ canted SPSTM tips lead to an asymmetric appearance of skyrmions

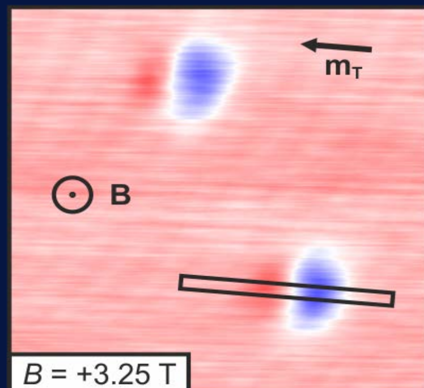
→ skyrmions with the same rotational sense look different in opposite magnetic fields

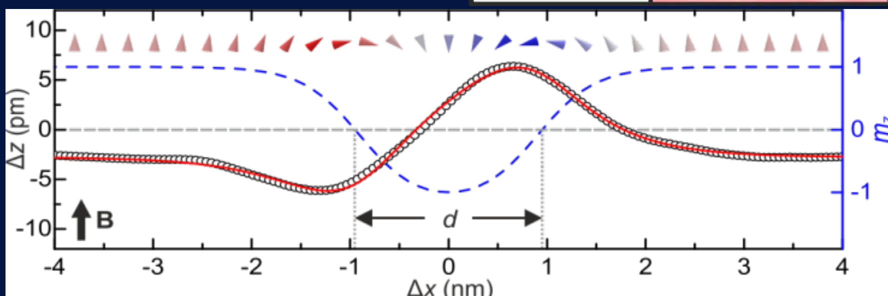
Atomic-Scale Profile of a Single Skyrmion: Comparison of Experiment with Theory

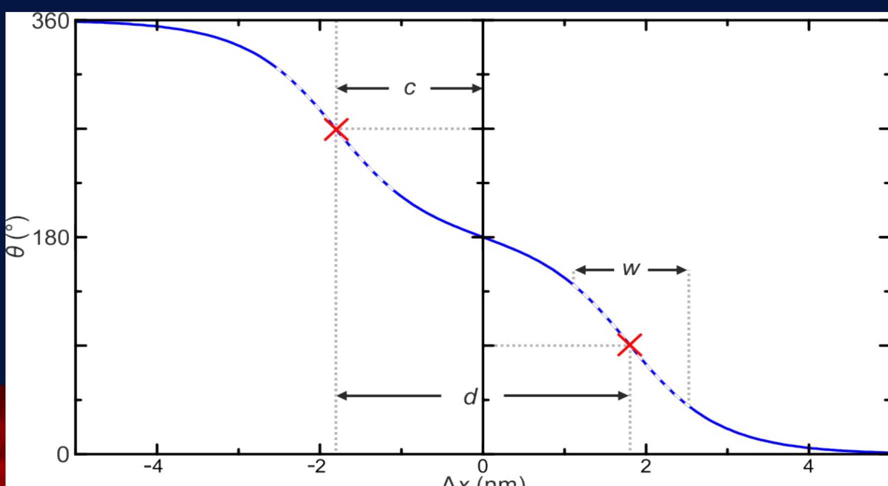
Chiral skyrmions in Pd/Fe/Ir(111)

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

N. Romming *et al.*: PRL 114, 177203 (2015)







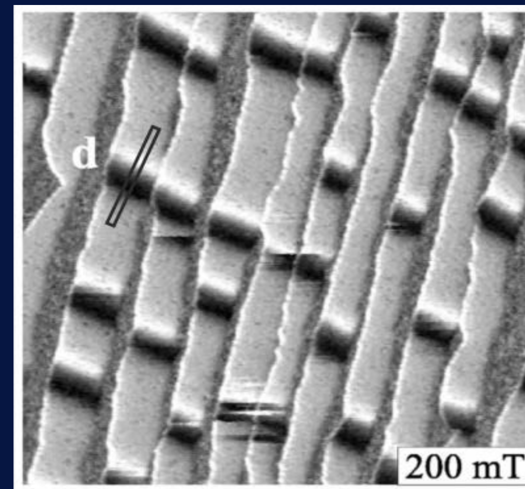
Chiral 360°-domain walls in DL Fe/W(110)

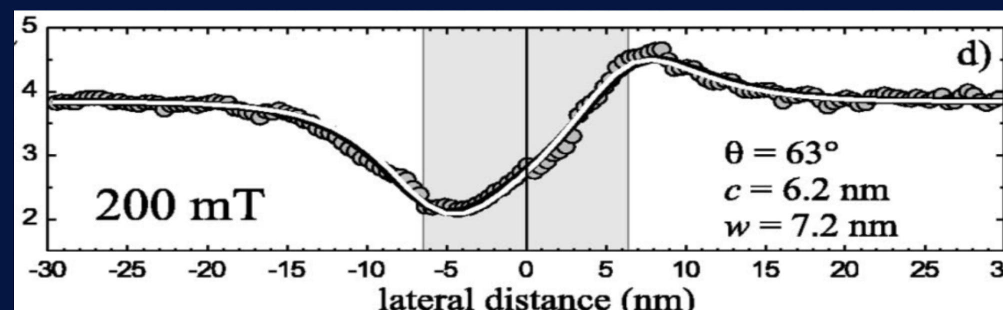
O. Pietzsch *et al.*: Science 292, 2053 (2001)

A. Kubetzka *et al.*: PRL 88, 057201 (2002)

A. Kubetzka *et. al.*: Phys. Rev. B**67**, 020401 (2003)

E. Y. Vedmedenko *et al.*: Phys. Rev. B 75, 104431 (2007)



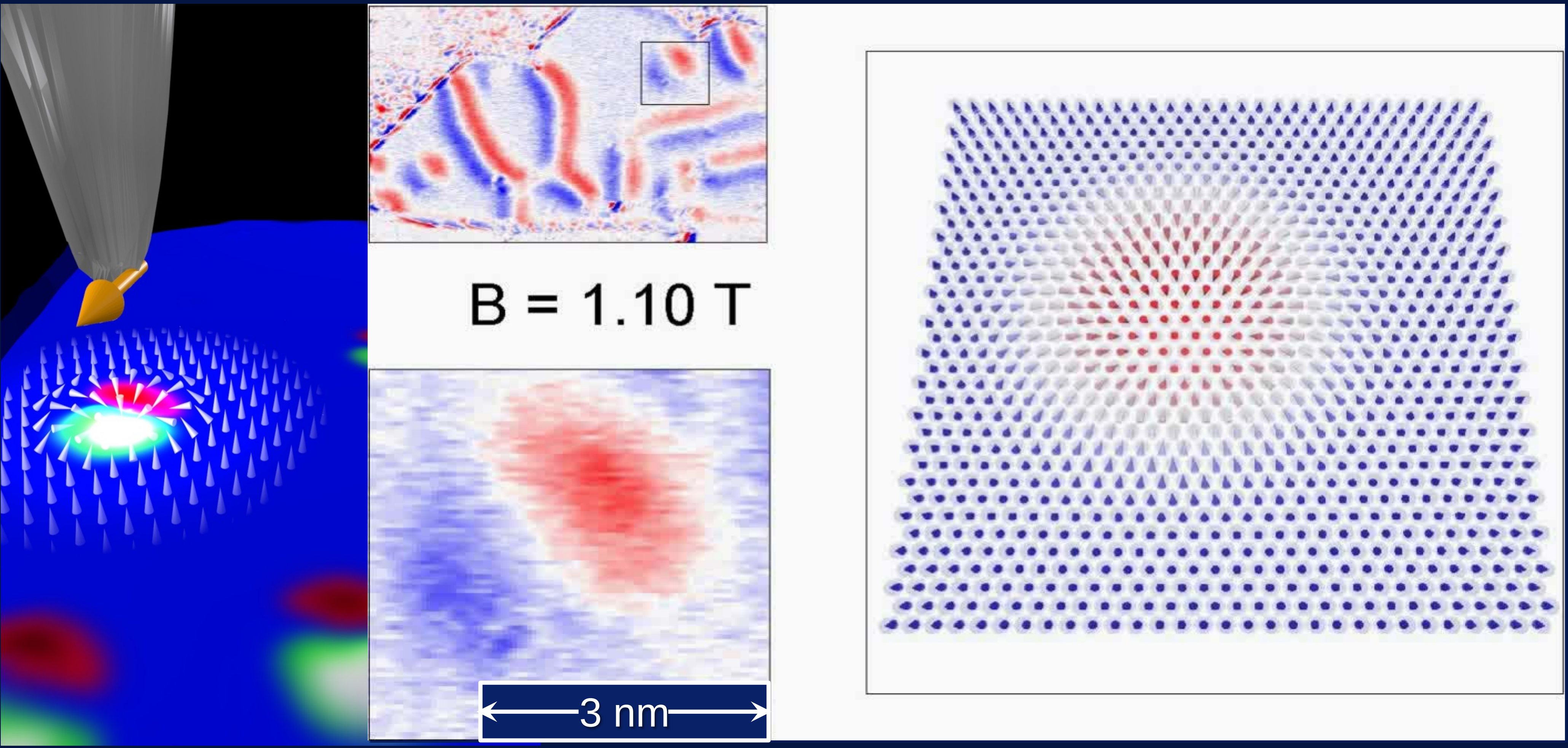


Analytical formula for two 180° domain walls:

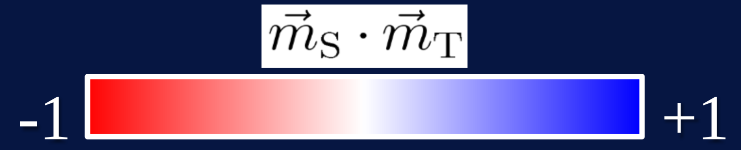
$$\theta(\rho, c, w) = \begin{cases} \sum_{+,-} \left[\arcsin\left(\tanh \frac{-\rho \pm c}{w/2}\right)\right] + \pi & |B_z > 0 \\ \sum_{+,-} \left[\arcsin\left(\tanh \frac{-\rho \pm c}{w/2}\right)\right] & |B_z < 0 \end{cases}$$

N. Romming et al., PRL **114**, 177203 (2015)

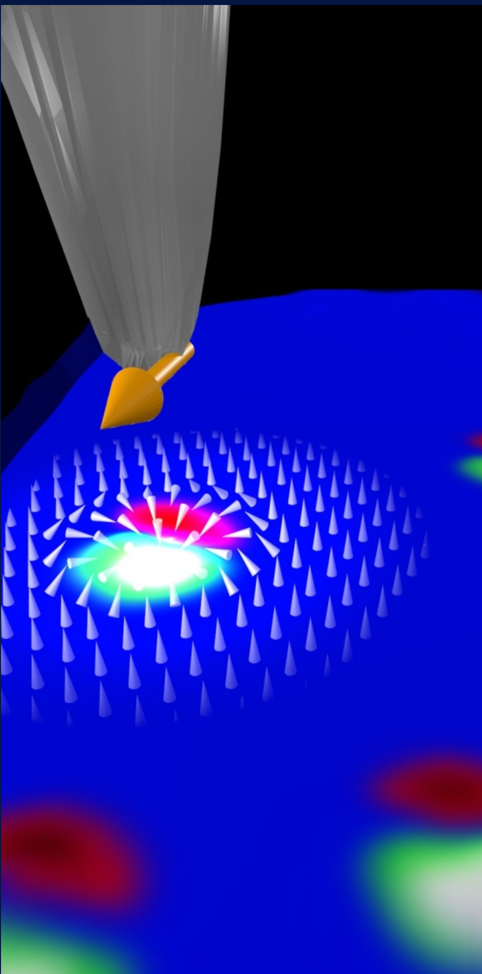
Field-Dependent Skyrmion Diameter

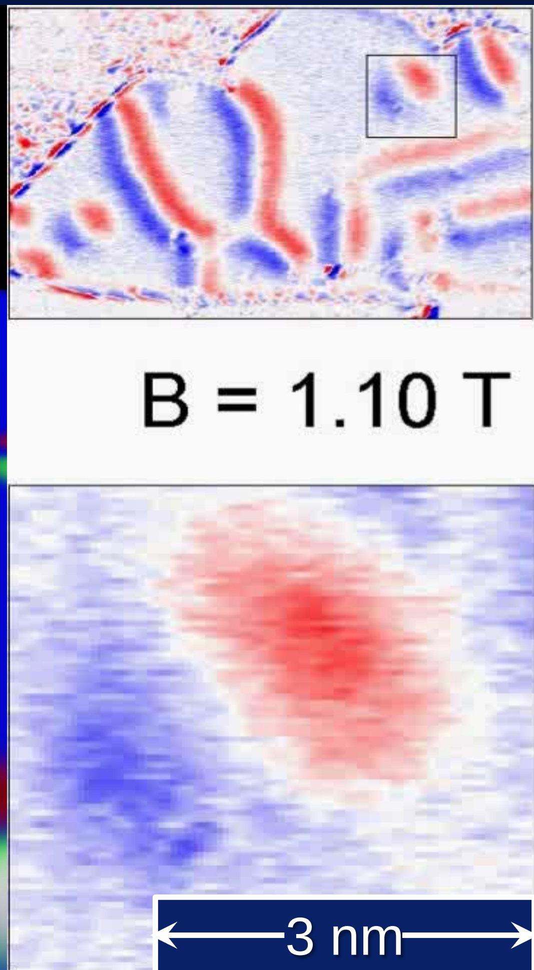


Difference SP-STS data taken during field-sweep from B = -3T to +3T

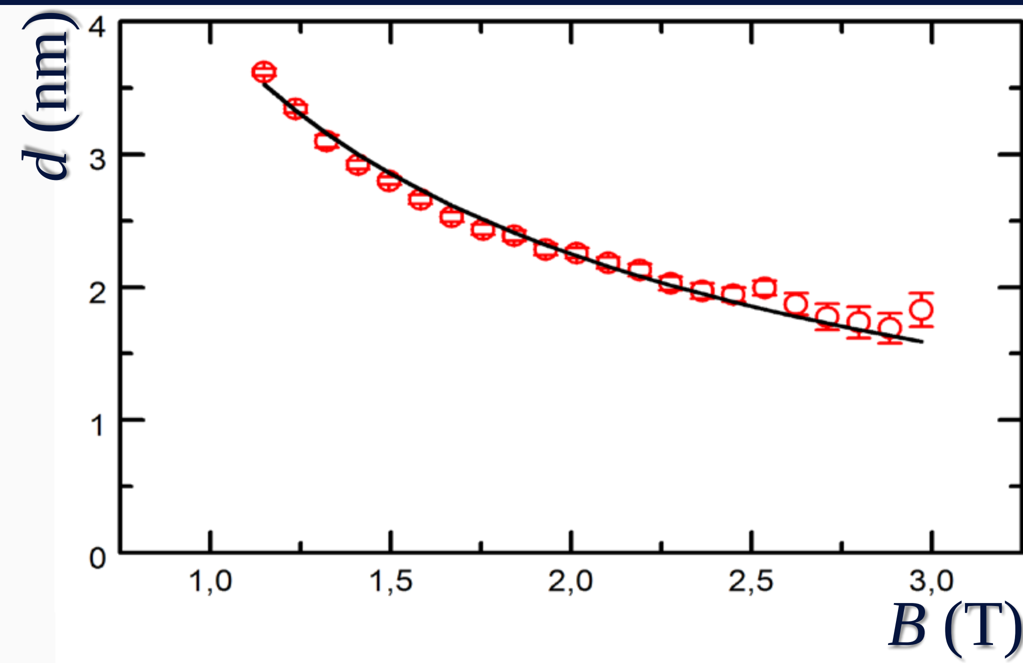


Field-Dependent Skyrmion Diameter





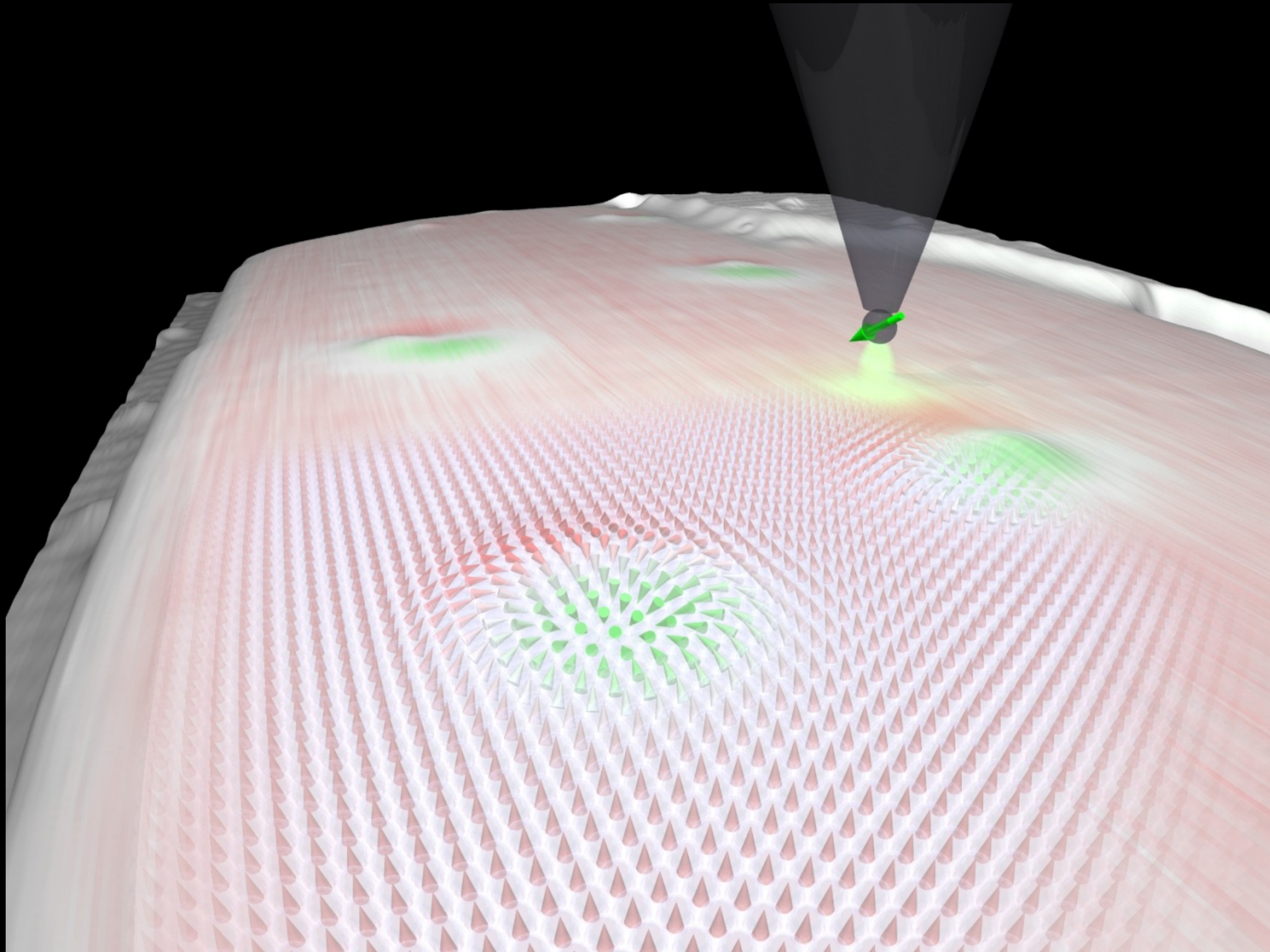
Difference SP-STS data taken during field-sweep from B = -3T to +3T



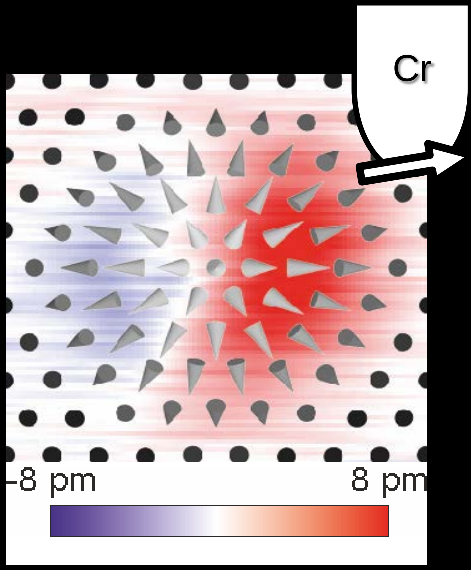
→ Skyrmion size and shape change with magnetic field can be reproduced by micromagnetic simulations with fitting parameters A, D, and K.

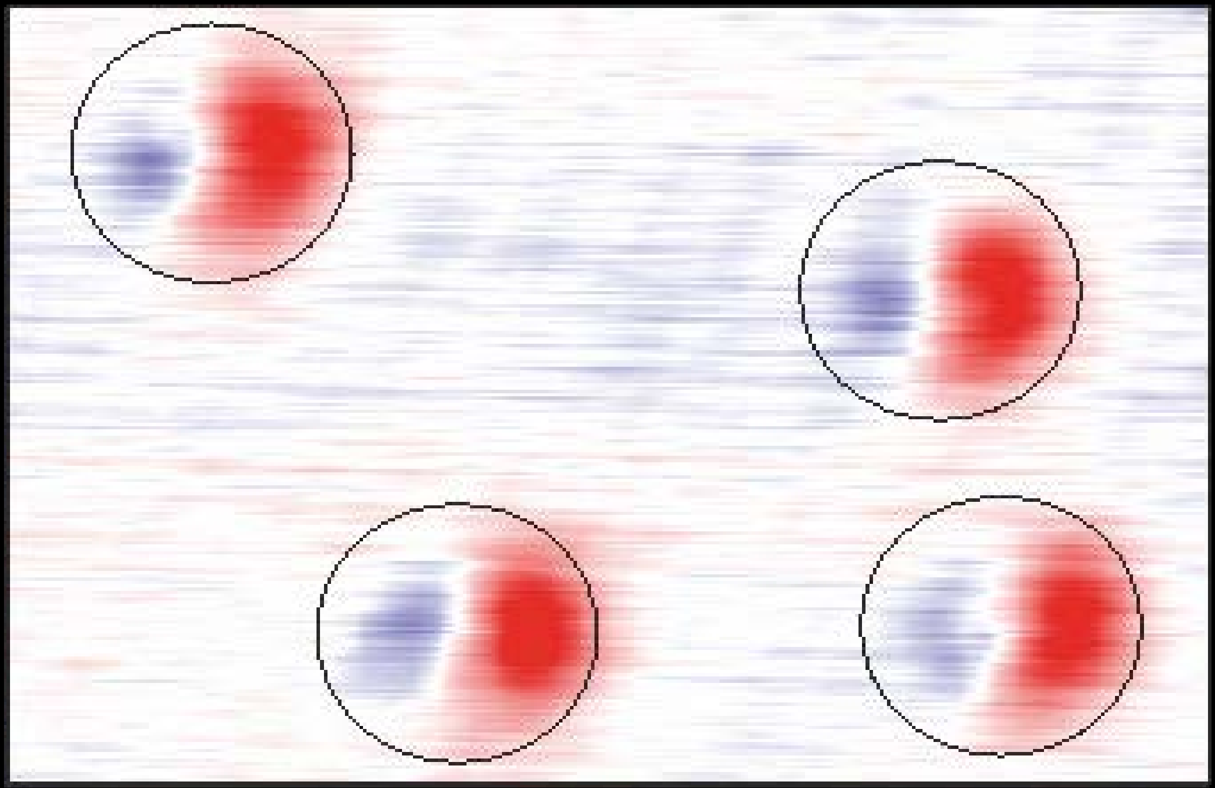
Saturation magnetization: M_s = 1.1 MA/m
Exchange constant: A = 2.0 pJ/m
DMI constant: D = 3.9 mJ/m^2
Anisotropy constant: K = 2.5 MJ/m^3

From Imaging of Individual Skyrmions to Local Manipulation by Spin-Polarized Current Injection



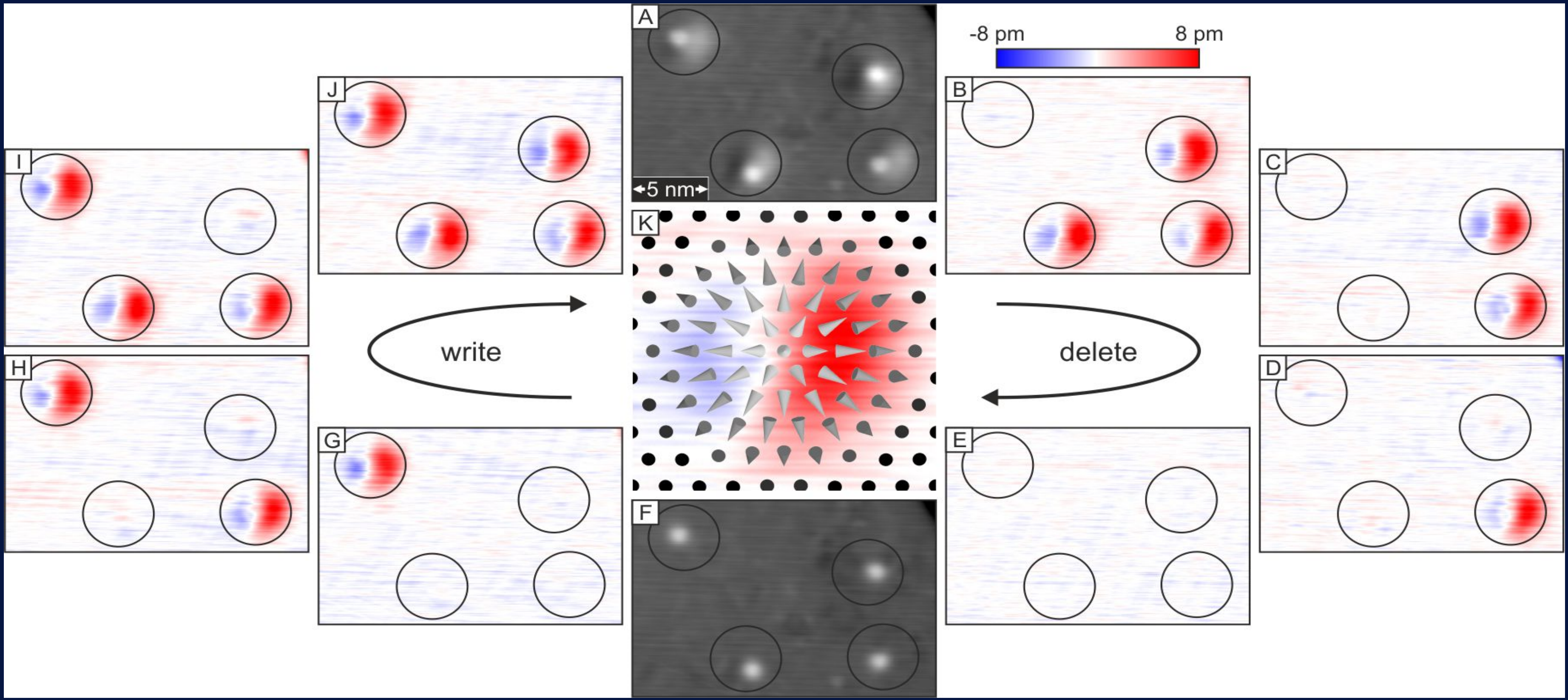
Writing and Deleting Single Skyrmions





N. Romming et al., Science 341, 6146 (2013)

Writing and Deleting Single Skyrmions by a SP-STM tip

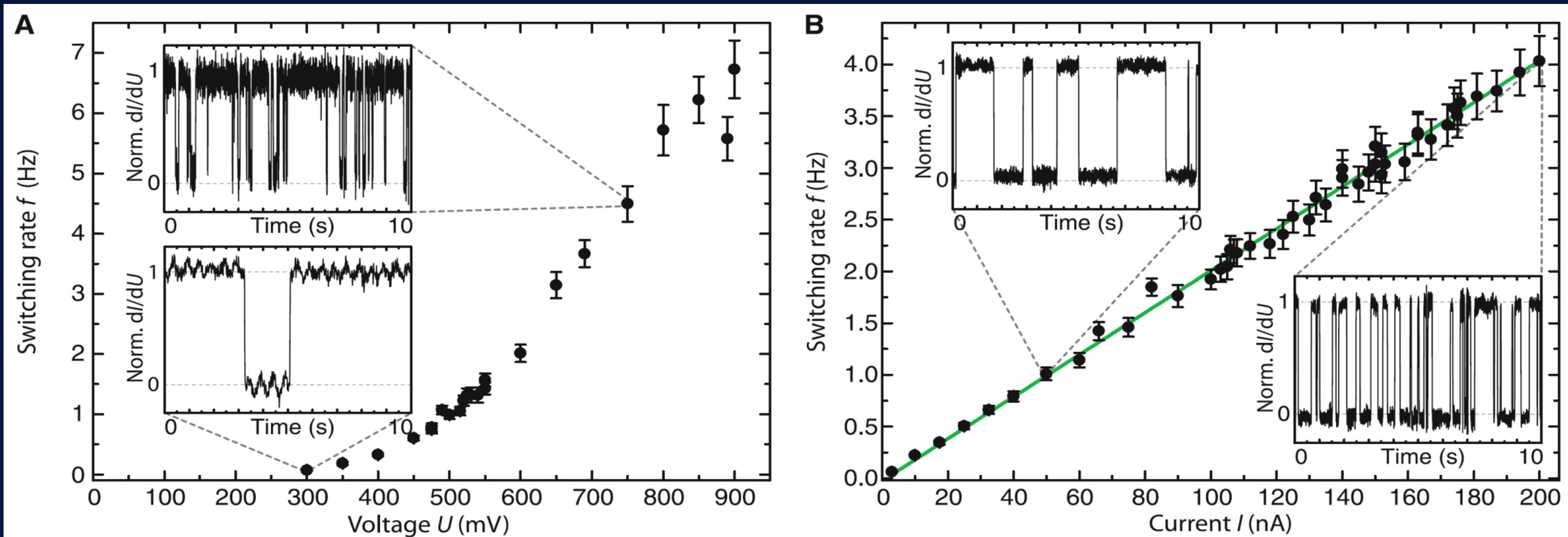


→ Writing and deleting of single skyrmions by localized spin current injection

→ Imaging of individual skyrmions by in-plane sensitive SP-STM probe tip

N. Romming et al., Science 341, 6146 (2013)

Switching Mechanism



low bias: non-perturbing imaging

higher bias: increased switching frequency due to non-thermal excitations by injected electrons

→ switching rate increases linearly with current

At low *U, I* : no switching

→ thermally activated switching does not play a role !

At constant power: switching rate still depends critically on *U*

→ local (Joule-)heating does not play a decisive role !

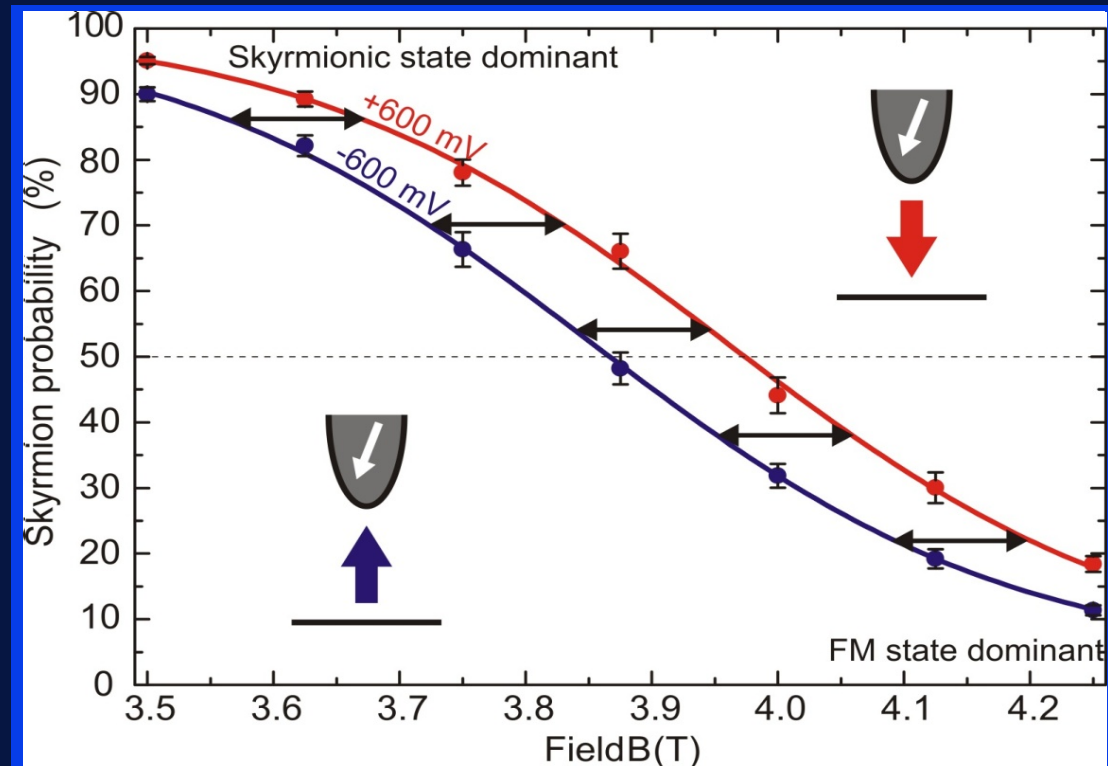
Switching Mechanism

(i) ~~thermal noise~~

(ii) ~~Joule heating~~

(iii) non-thermal excitations from injected electrons

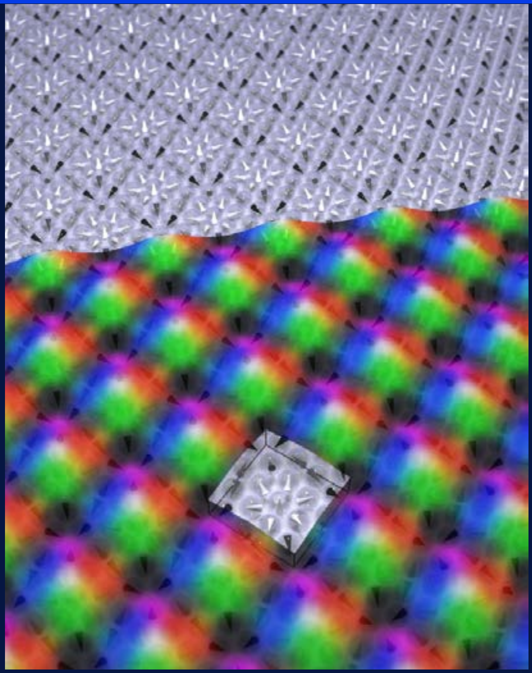
(iv) spin transfer torque



spin transfer torque leads to a shift of ~100 mT
→ induces directionality to the switching !

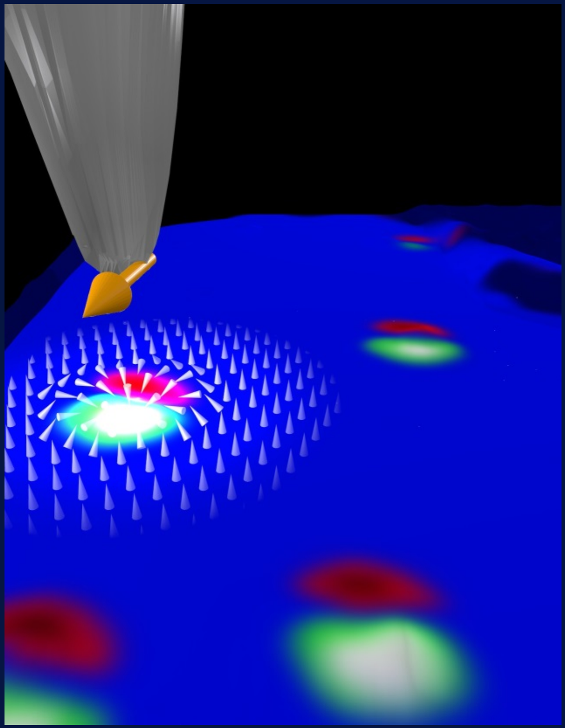
S. Krause et al., Science **317**, 1537 (2007)
A.A. Khajetoorians et al., Science **339**, 55 (2013)

Summary

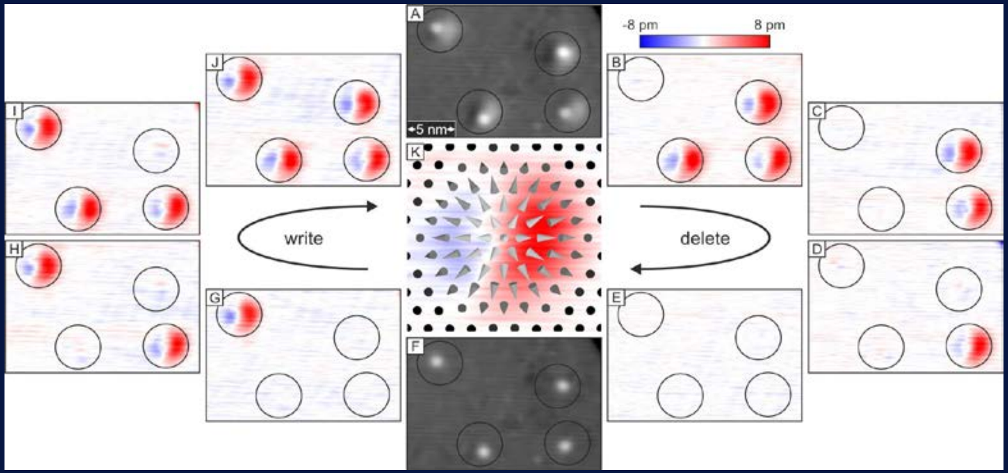


- Interface-driven skyrmionic lattices have been discovered in ultrathin magnetic films and atomically resolved by SP-STM

- The interaction between individual magnetic adatoms and molecules with skyrmionic lattices has directly been observed in real space by SP-STM

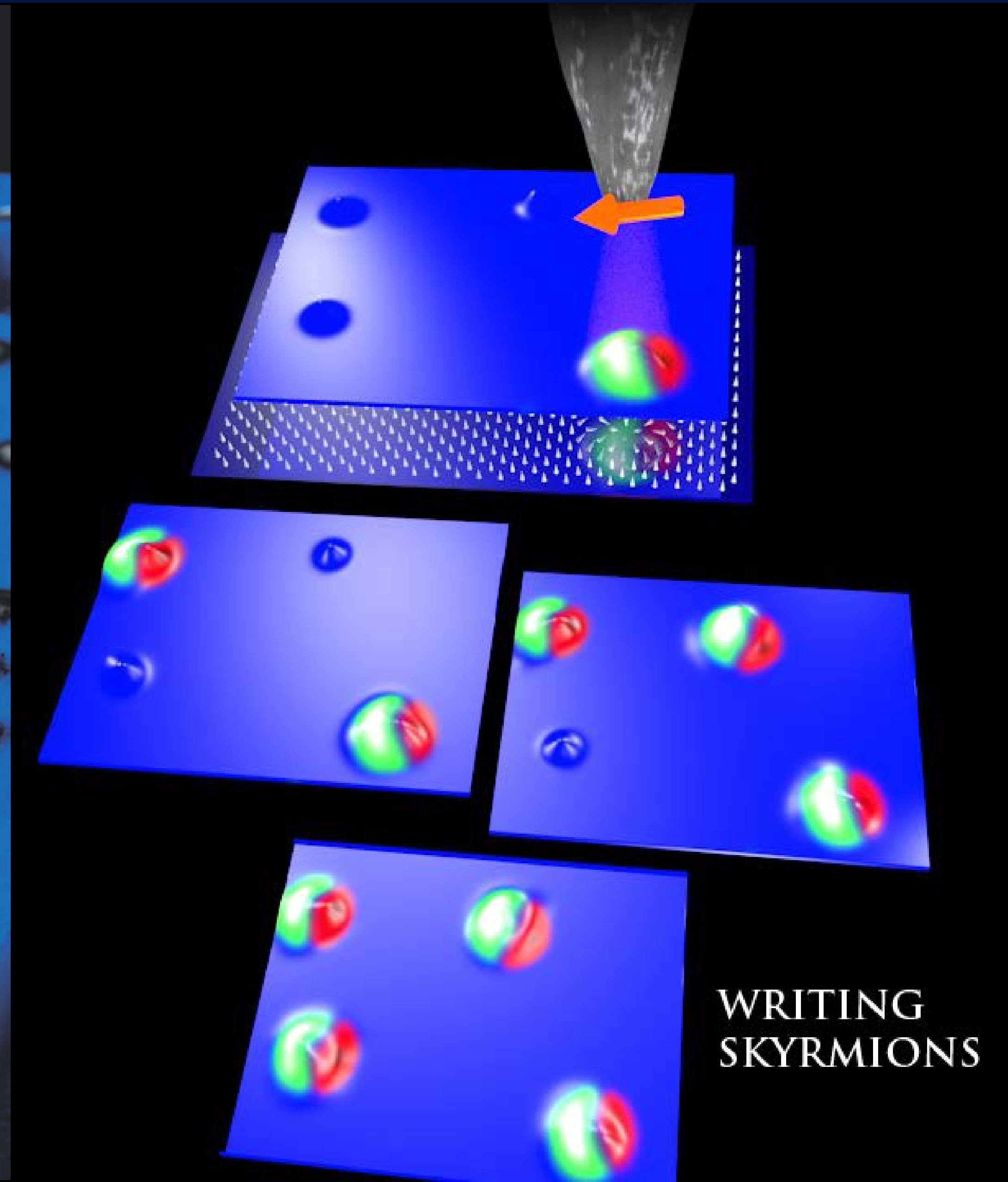


- Individual skyrmions were observed in bilayer films of Fe and Pd



- Individual skyrmions can be created and deleted by local spin-polarized current injection from a spin-polarized STM tip

New SCIENCE & Technology with Skyrmions



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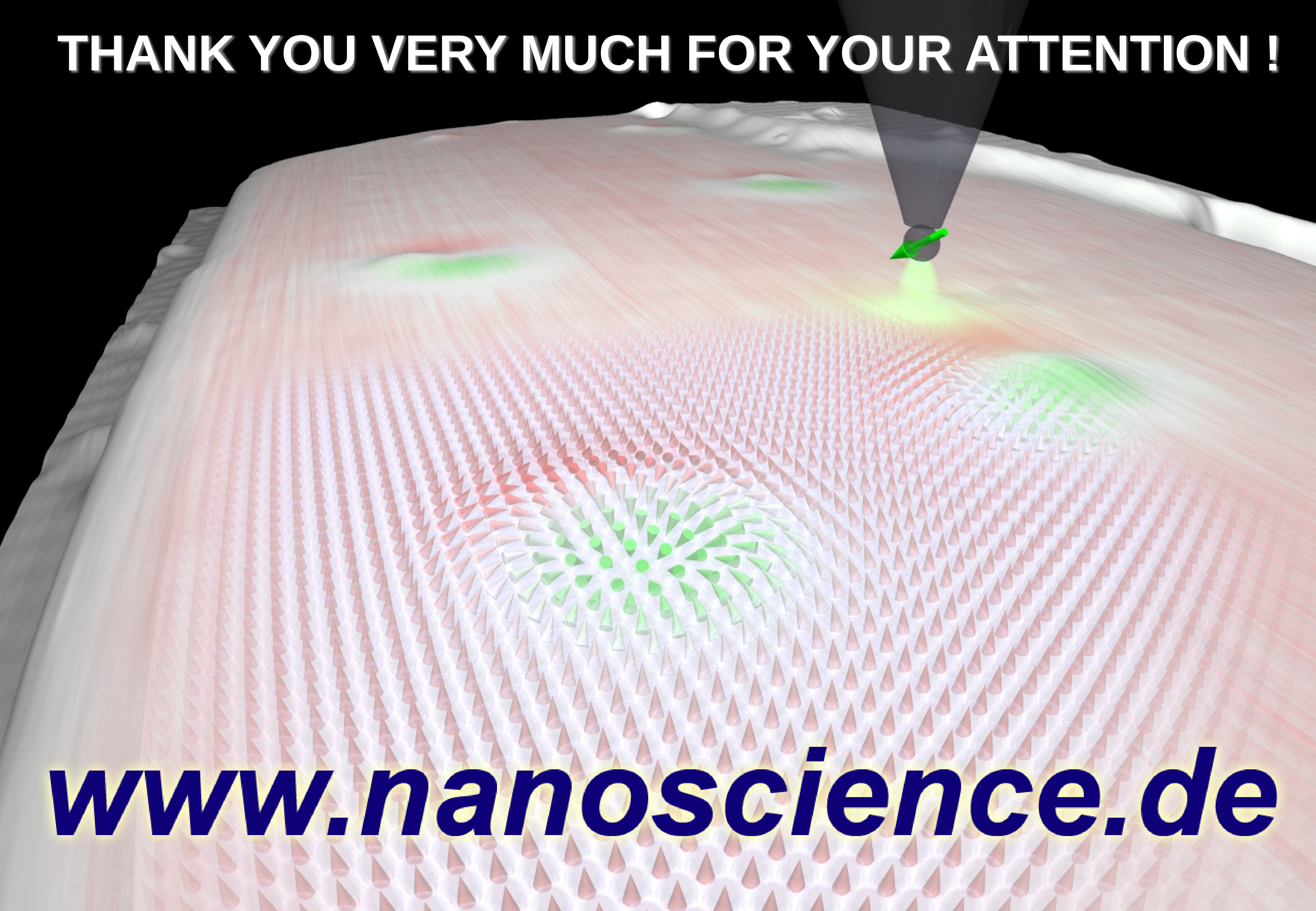
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