Skyrmions in symmetric bilayers

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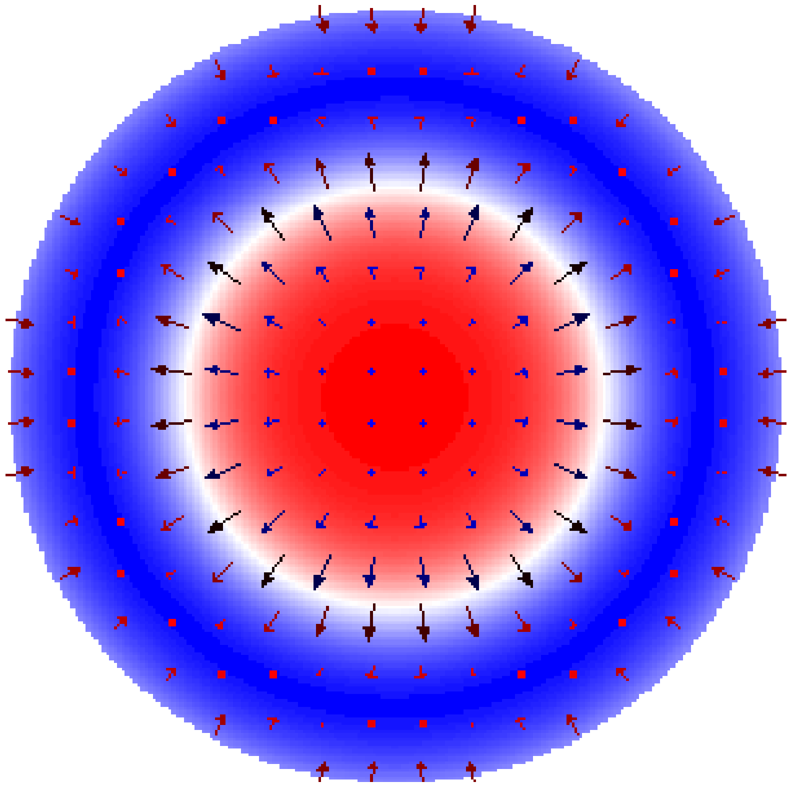
ANR

ULTRASKY

Magnetic skyrmions in a nutshell



hedgehog skyrmion
stabilized by the
interfacial DMI

Can be very small (few nm)

Covers the magnetization sphere once

⟹ topological protection

Structure and chirality fixed by DMI

Similar properties to a vortex core (gyrovector, motion by spin transfer torque)

Moves also by spin Hall effect

No (simple) motion by field

Isolated when metastable, but appears in lattice when DMI too large (and …)

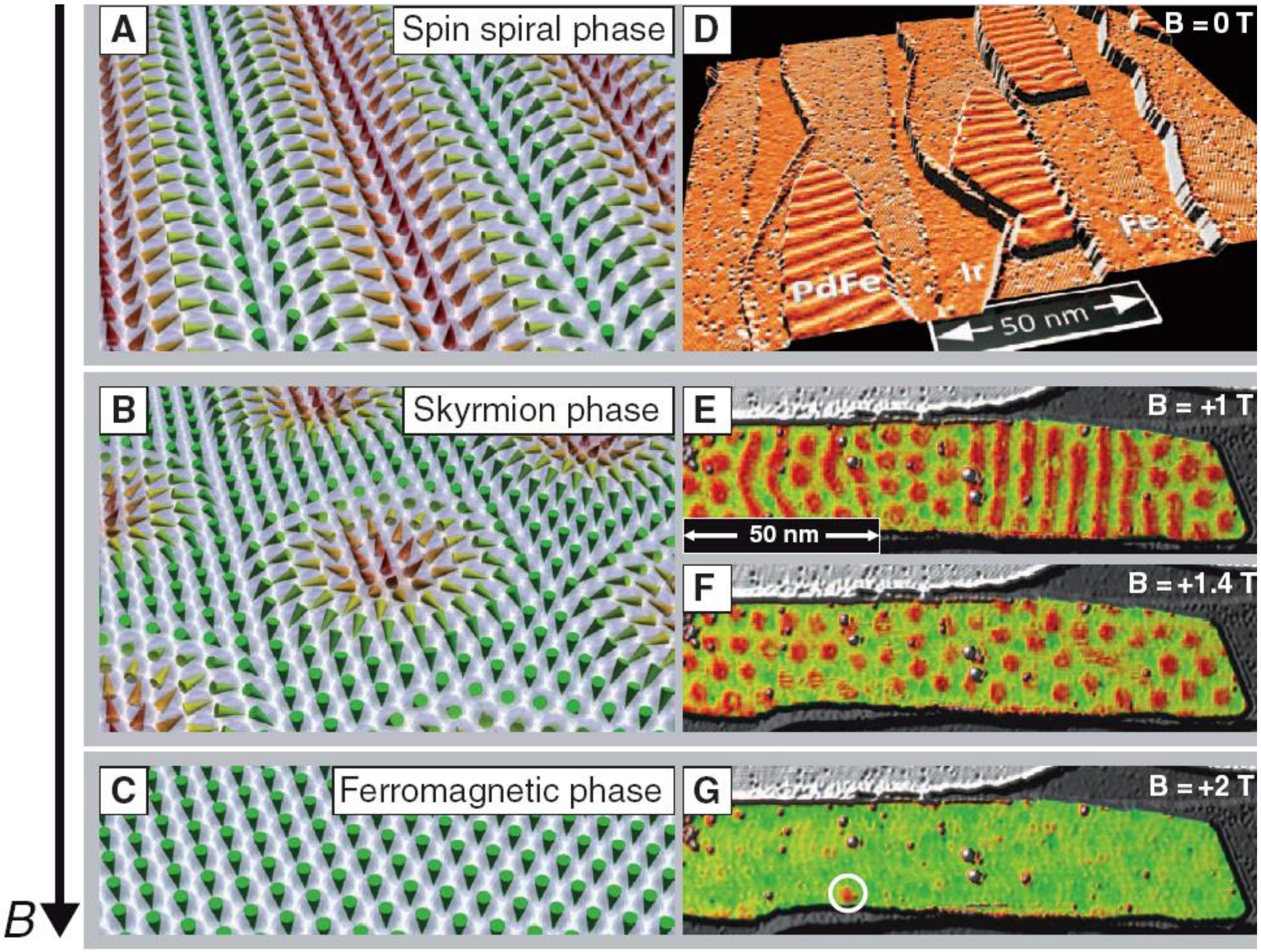
Magnetic skyrmions observed in

Atomic monolayers (based on Fe/Ir(111), low temperatures, SP-STM)

Single-layer ultrathin films (based on Co/Pt, CoFeB/Ta, …)

Multilayers of ultrathin films

Skyrmions in atomic monolayers

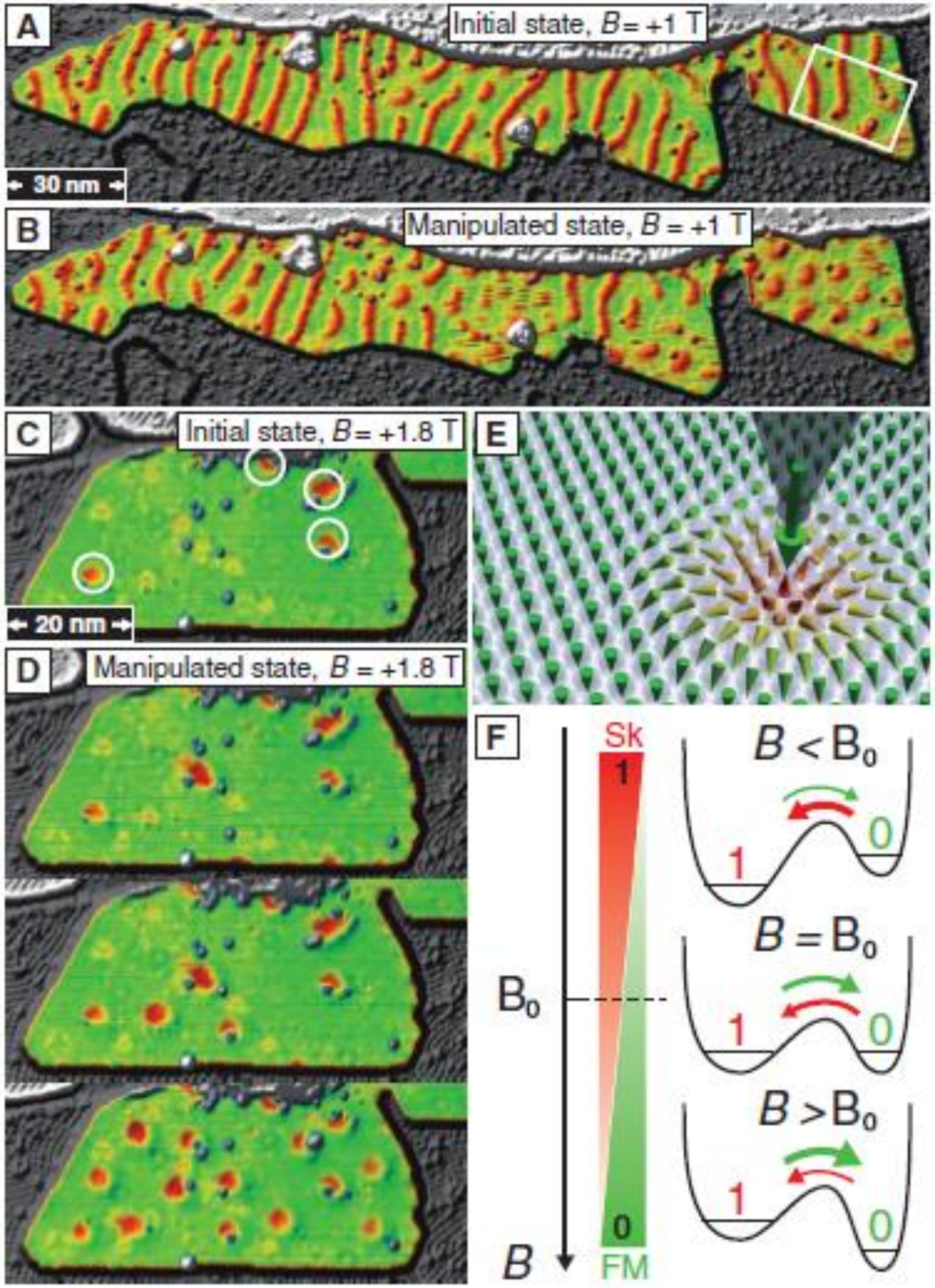


T= 8K
Diameter 3 nm

Romming et al., Science (2013)

Pd 1ML / Fe 1ML / Ir(111)

Skyrmions in atomic monolayers

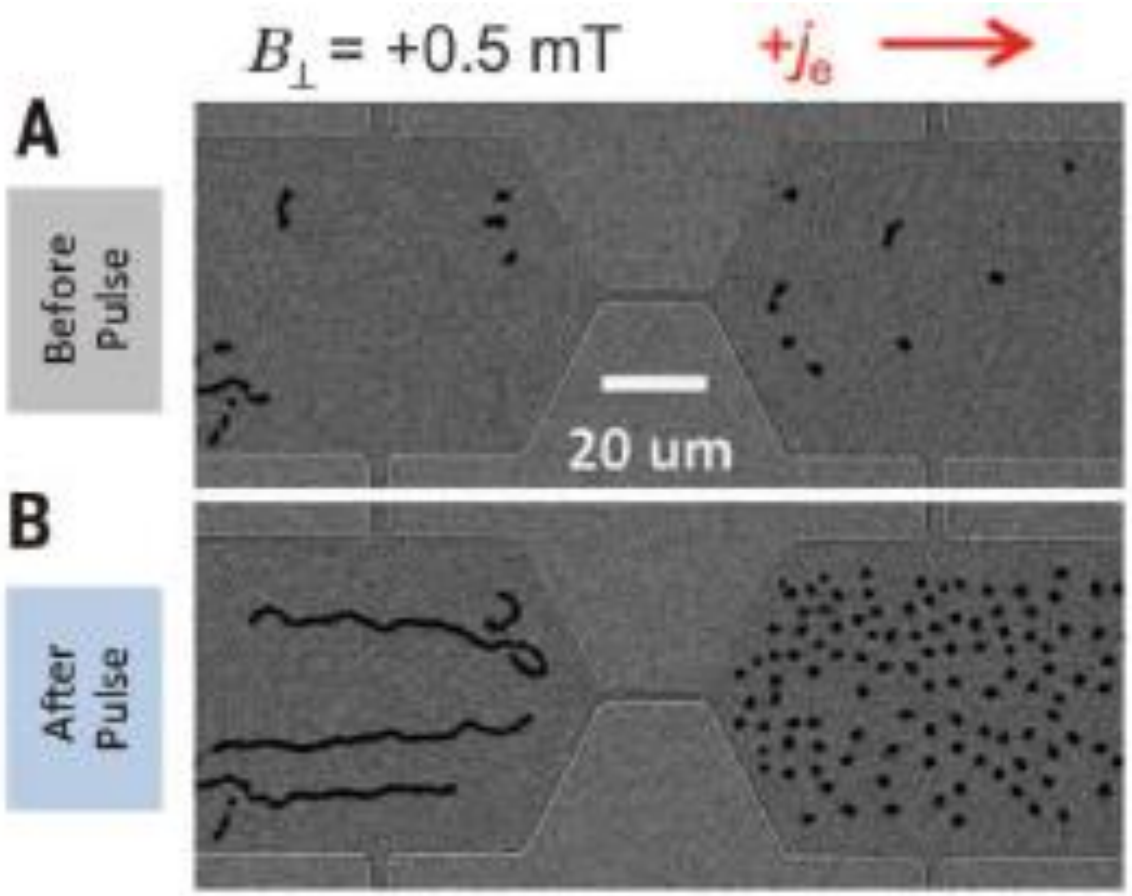


Write and delete
by local current (STM)

Romming et al.,
Science (2013)

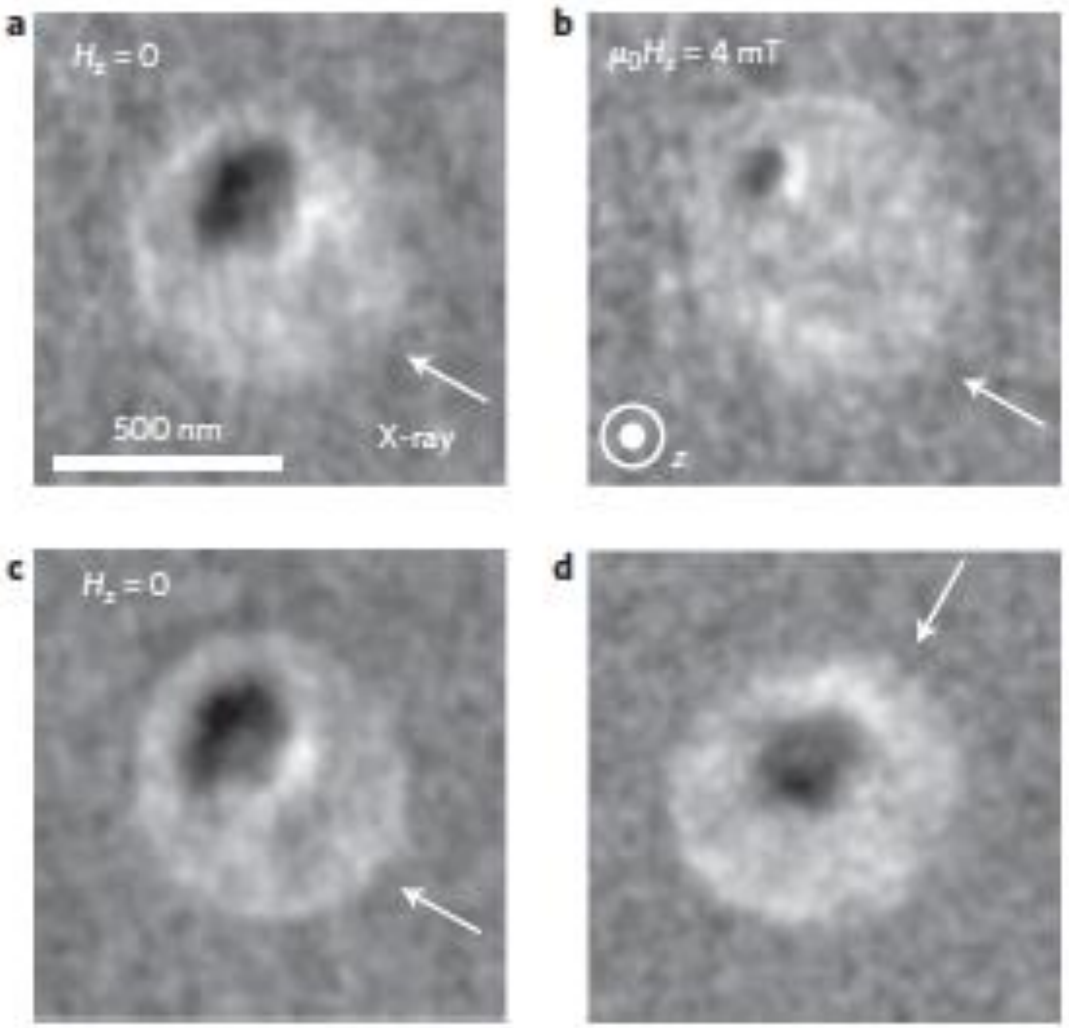
Pd 1ML / Fe 1ML / Ir(111)

Skyrmions in single-layer ultrathin films



T= 300K
Diameter 700-2000 nm
Injection/creation by focussed current

W. Jiang et al.,
Science (2015)
Ta 5nm \ $Co_{20}Fe_{60}B_{20}$ 1.1 \TaOx 3



T= 300K
Diameter 100-300 nm

O. Boulle et al.,
Nat. Nanotechnol. (2016)
Pt 3nm \ Co 1.08 \MgOx \Ta 1

Skyrmions in single-layer ultrathin films

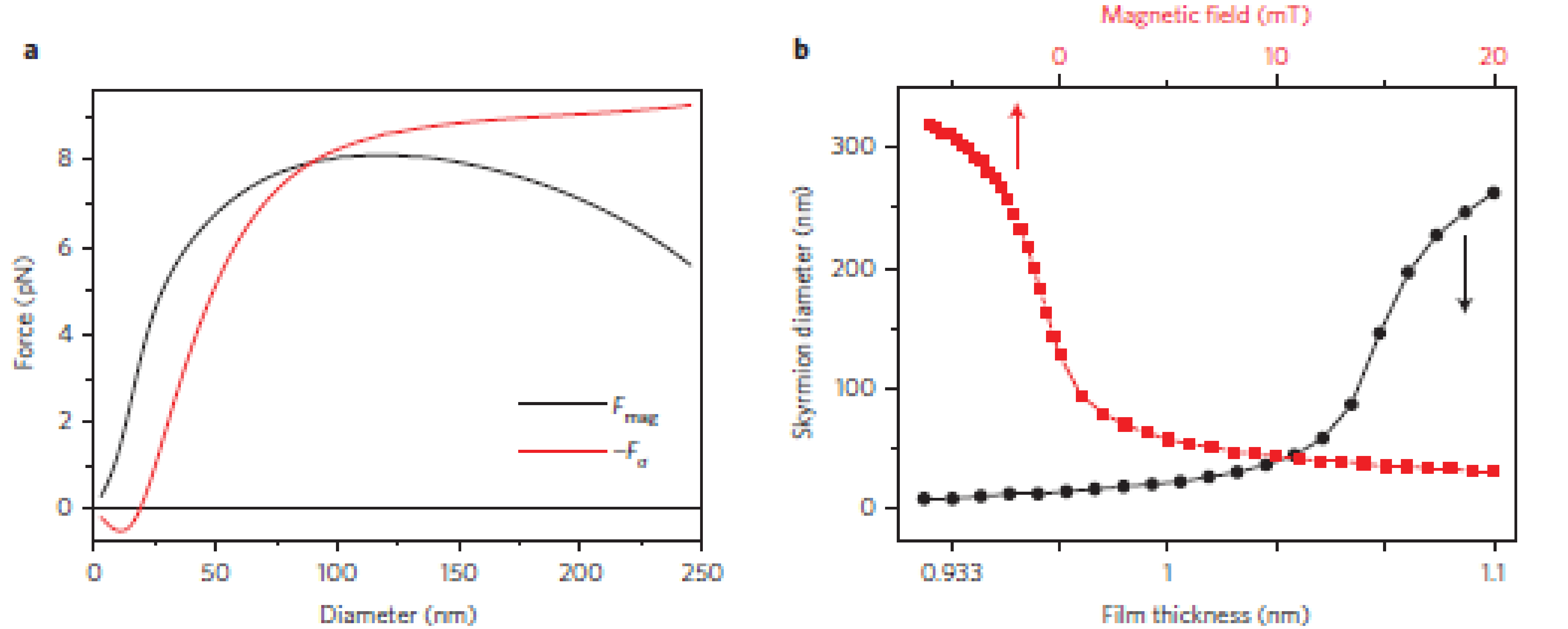


Figure 6 | Forces acting on the the skyrmion and dependence of the skyrmion diameter on a perpendicular magnetic field and the film thickness. **a**, Forces acting on the DW as a function of the skyrmion diameter. F_σ is the force due to the exchange and effective anisotropy, F_{mag} is the force due to the magnetostatic interaction between the domains. **b**, Skyrmion diameter as a function of the film thickness (black dots) and as a function of a perpendicular external magnetic field (red squares) for $t = 1.06$ nm computed using micromagnetic simulations.

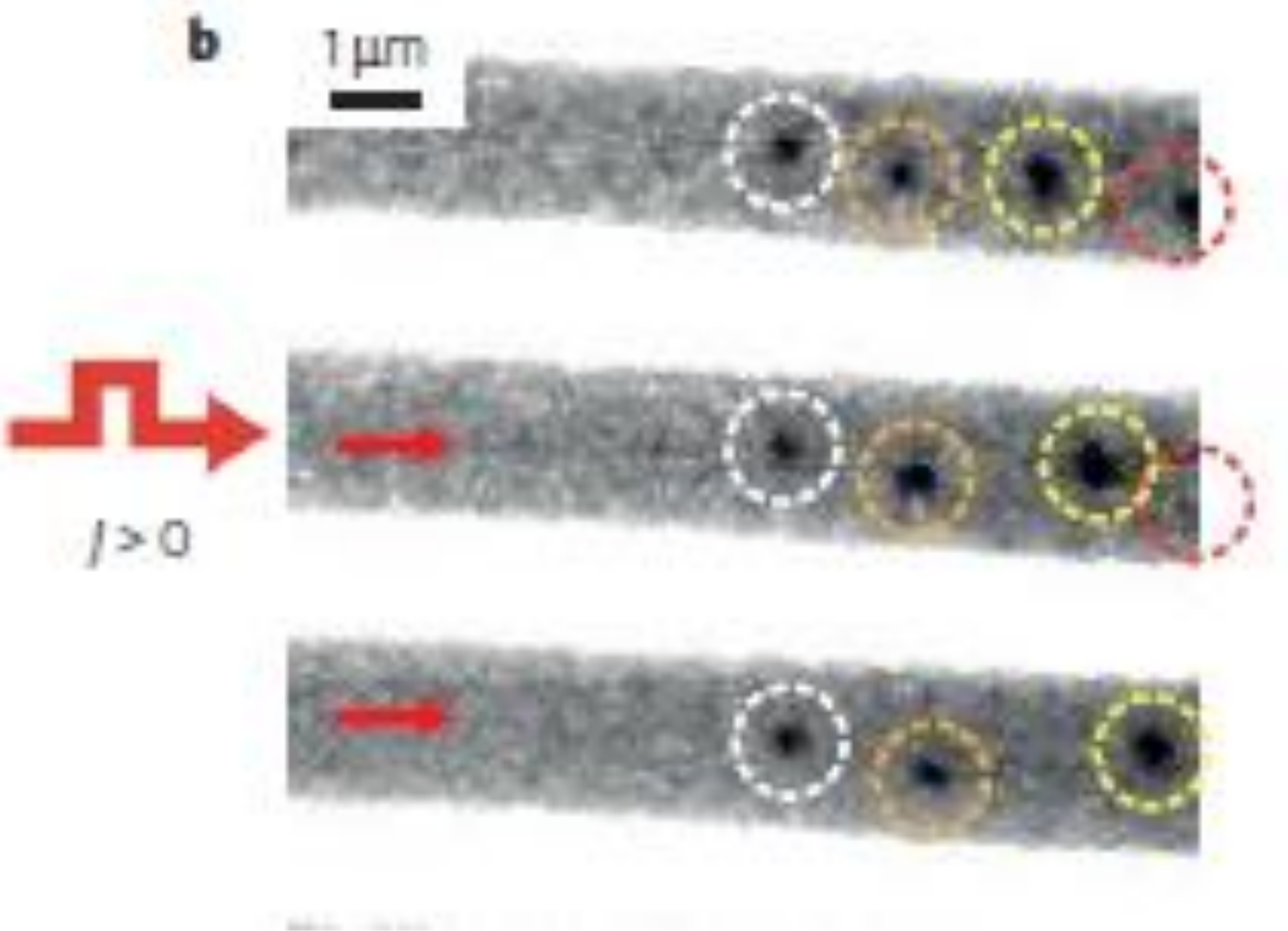
Important role of the magnetostatic interaction

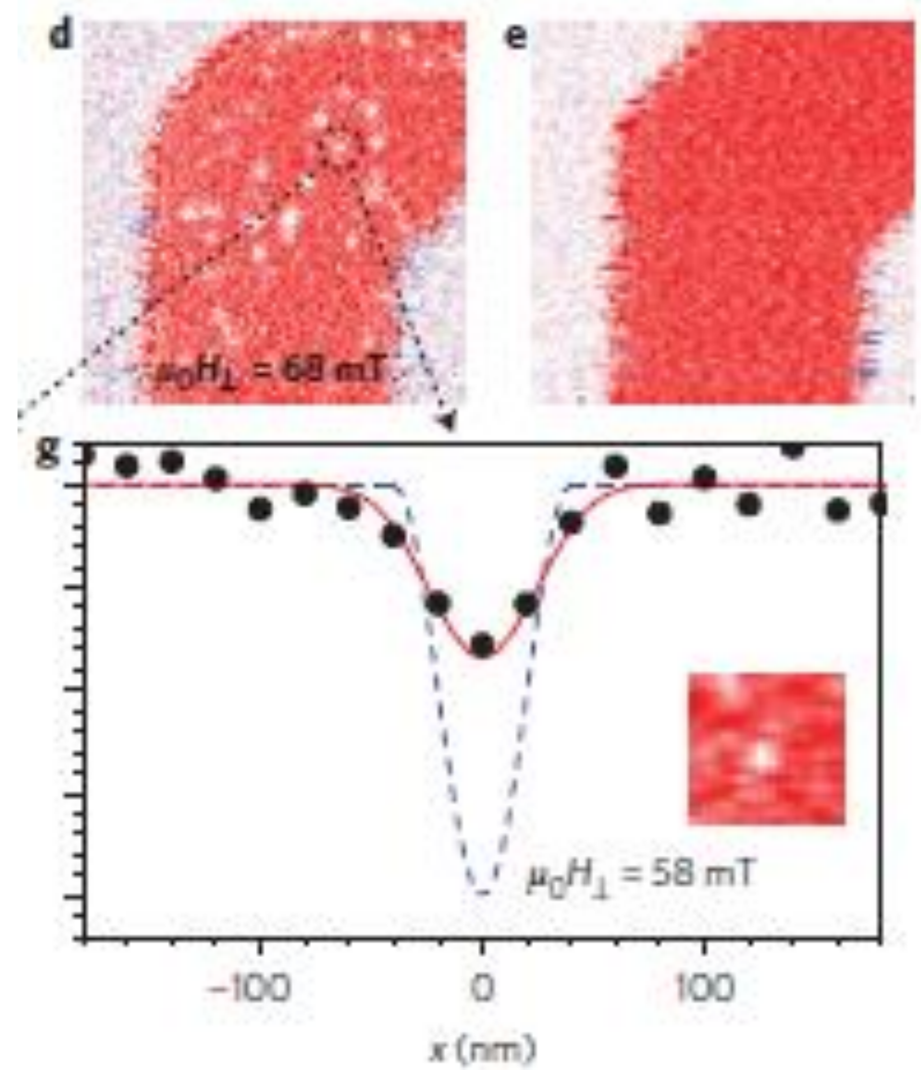
Very sensitive to all parameters

O. Boulle et al., Nat. Nanotechnol. (2016)

See also F. Büttner et al., arXiv1704.08489
A. Bernand-Mantel et al., arXiv1712.03154

Skyrmions in multilayer ultrathin films





T= 300K
Diameter 50-200 nm

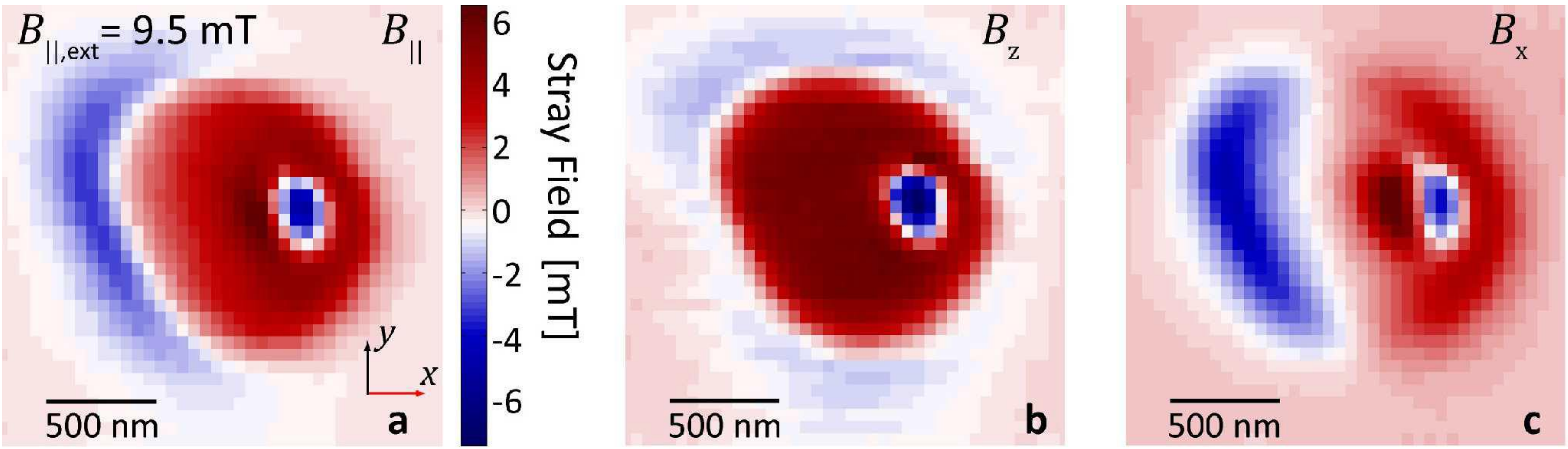
T= 300K
Diameter 30-80 nm

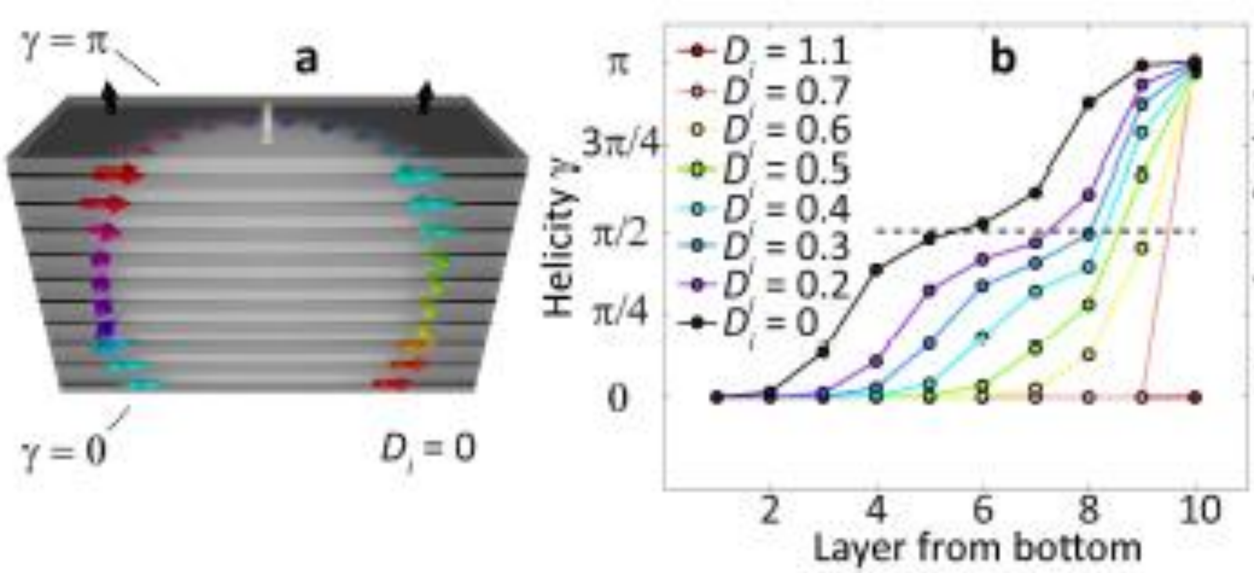
S. Woo et al.,
Nat. Mater. (2016)
(Pt 3nm \ CoFeB 0.9 \Ta 4)x15

C. Moreau-Luchaire et al.,
Nat. Nanotechnol. (2016)
(Ir 1nm \ Co 0.6 \ Pt 1)x10

Skyrmions in multilayer ultrathin films

Quantitative NV-center scanning stray field microscopy





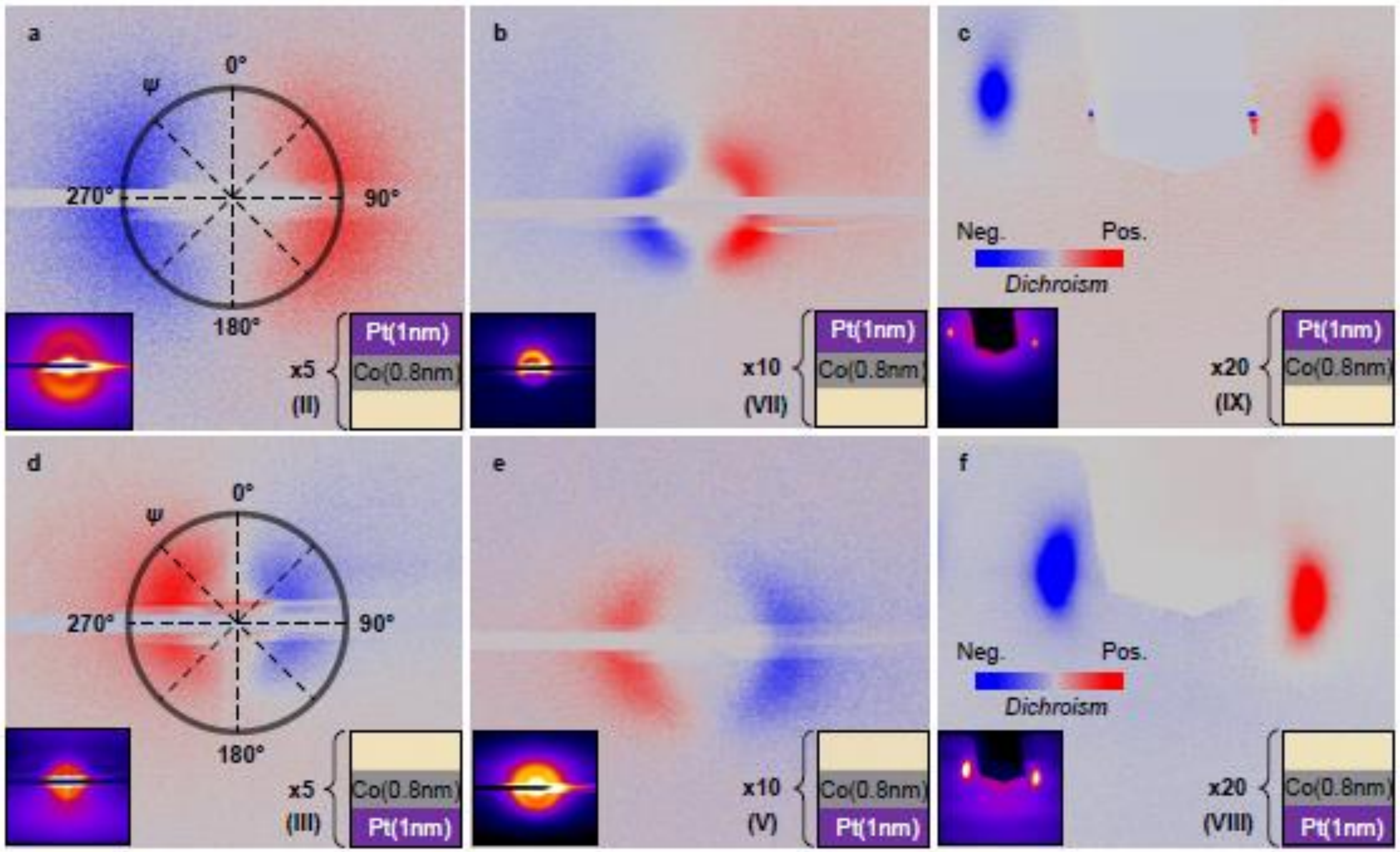
Right-handed Néel wall stray field !

Magnetostatic energy overcomes DMI at one surface

Y. Dovzhenko et al., arXiv 1611.00673v2

(Pt 3 nm \Co 1.1 \ Ta 4)x10

Skyrmions in multilayer ultrathin films



CD-XRMS patterns

Magnetostatic energy overcomes DMI at one surface

Opposite chirality

opposite

same !

W. Legrand et al., arXiv 1712.05978

(Ir 1 nm \Co 0.8 \ Pt 1)xN

(Pt 1 nm \Co 0.8 \ Ir 1)xN

Magnetic skyrmions observed in

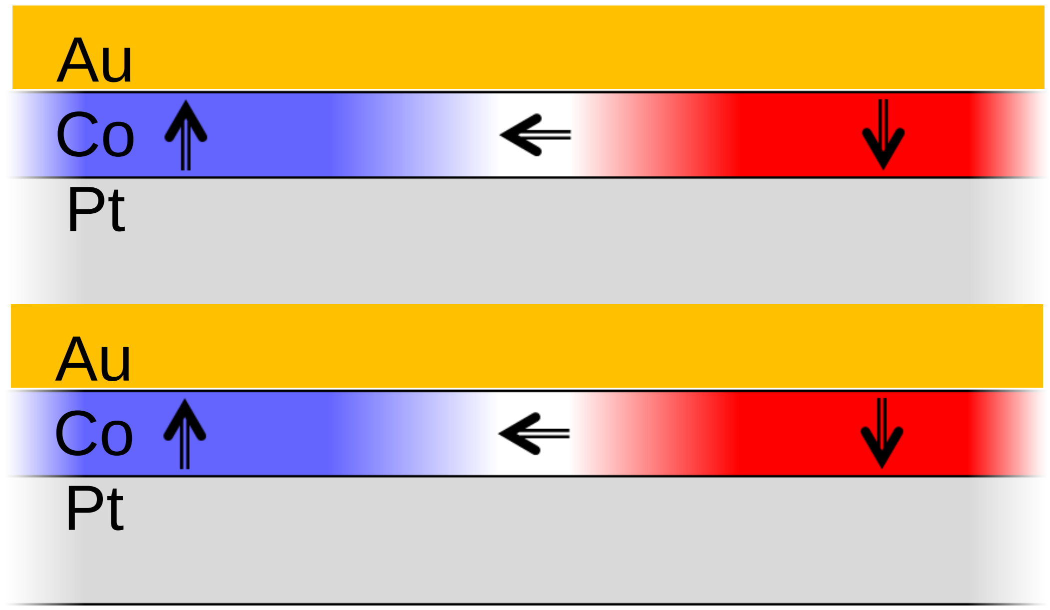
Atomic monolayers (based on Fe/Ir(111), low temperatures, SP-STM)
small but only at low T

Single-layer ultrathin films (based on Co/Pt, CoFeB/Ta, …)
room temp. but large size
extremely sensistive to parameters

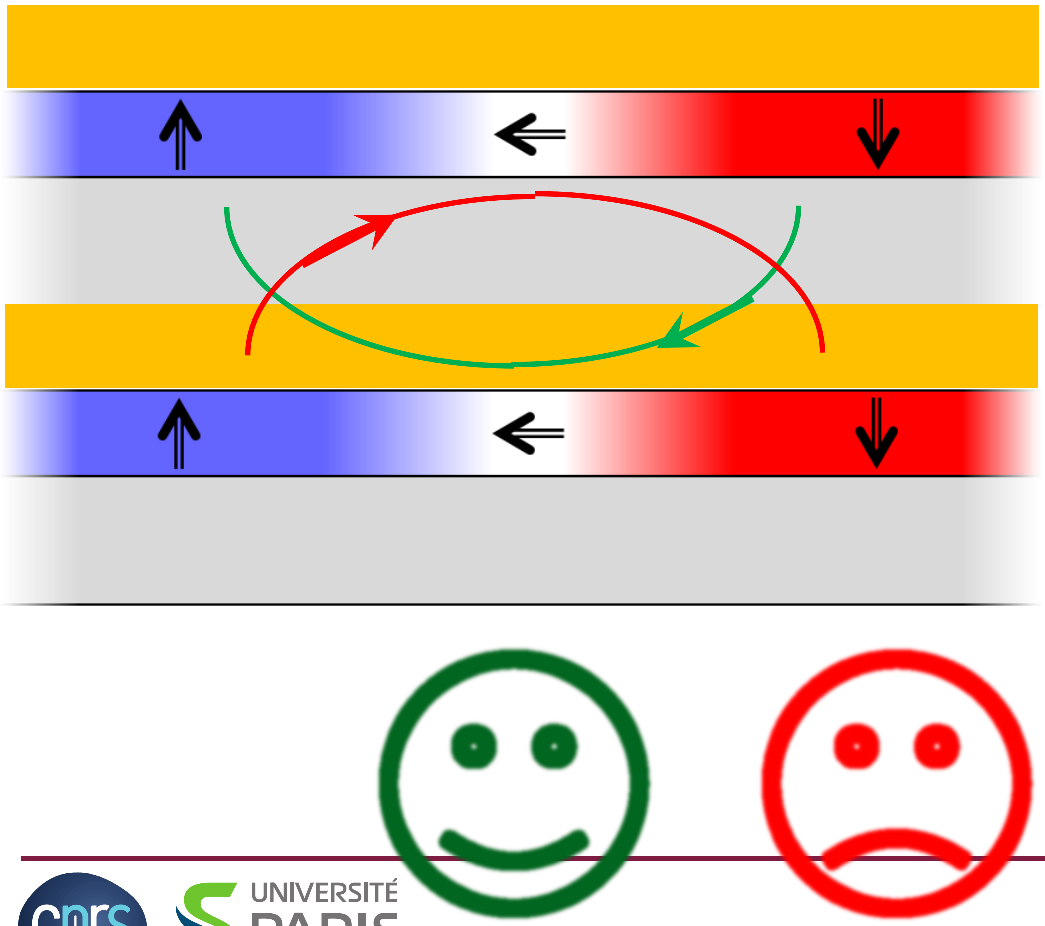
Multilayers of ultrathin films
room temp. but chirality affected by magnetostatics
not sensitive

Can be get the best out of the last two ?

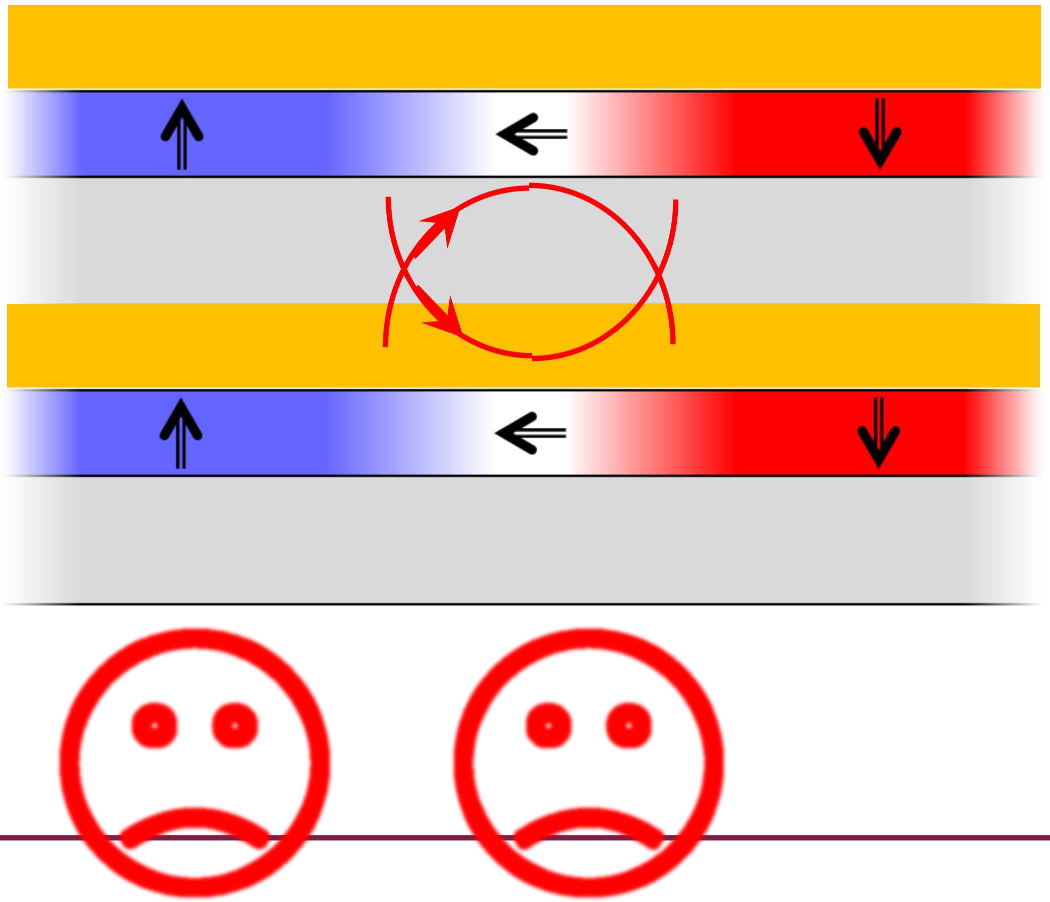
Case of two ultrathin films : repetitive stacking



Domains stray field

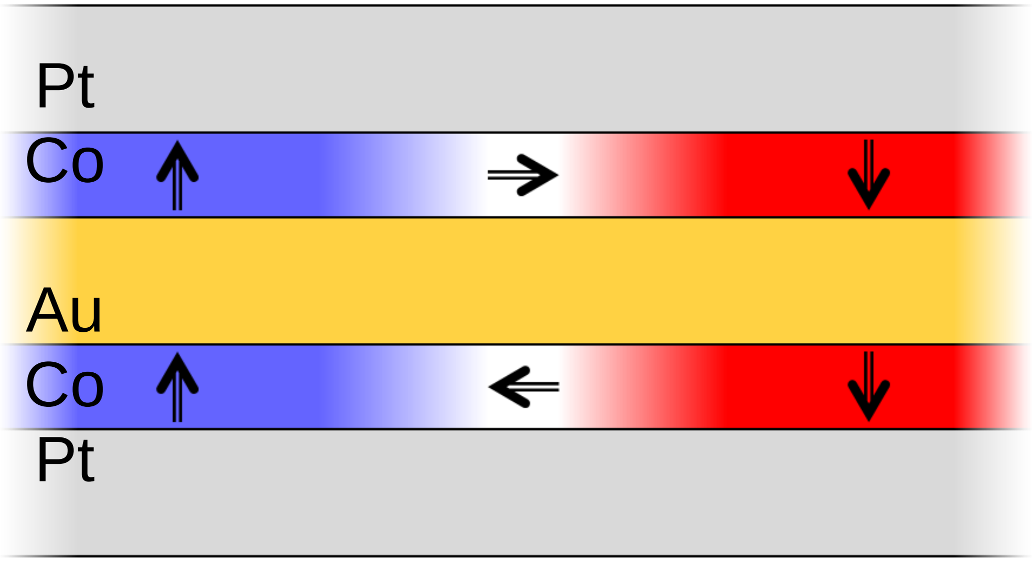


Domain walls stray field

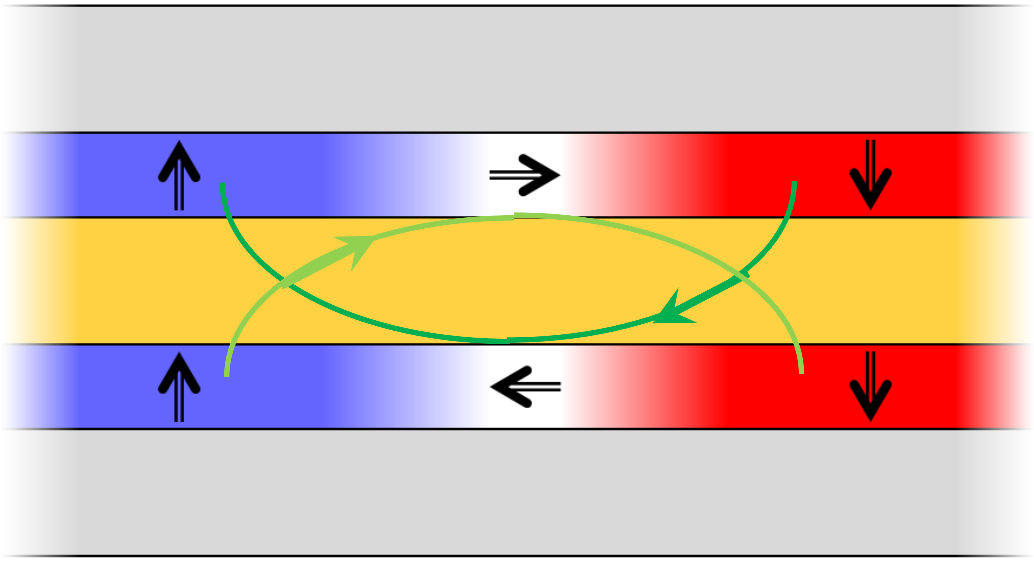


Case of two ultrathin films : symmetric stacking

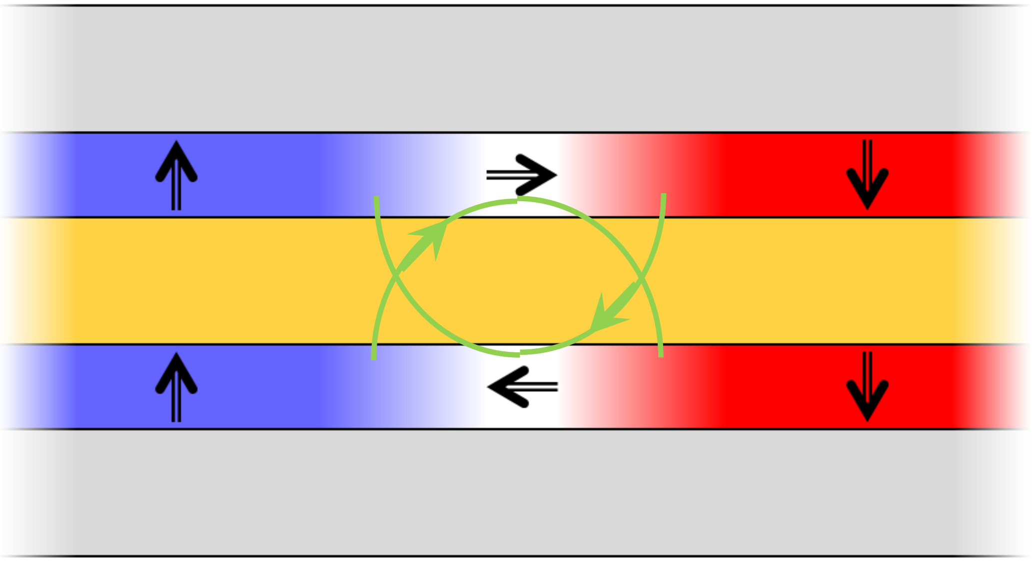
Negative DMI case



Domains stray field



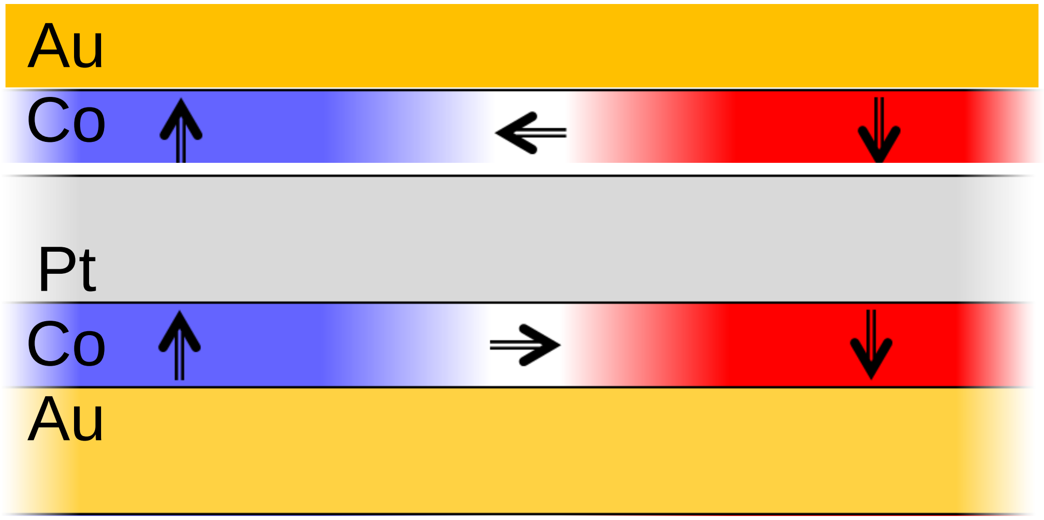
Domain walls stray field



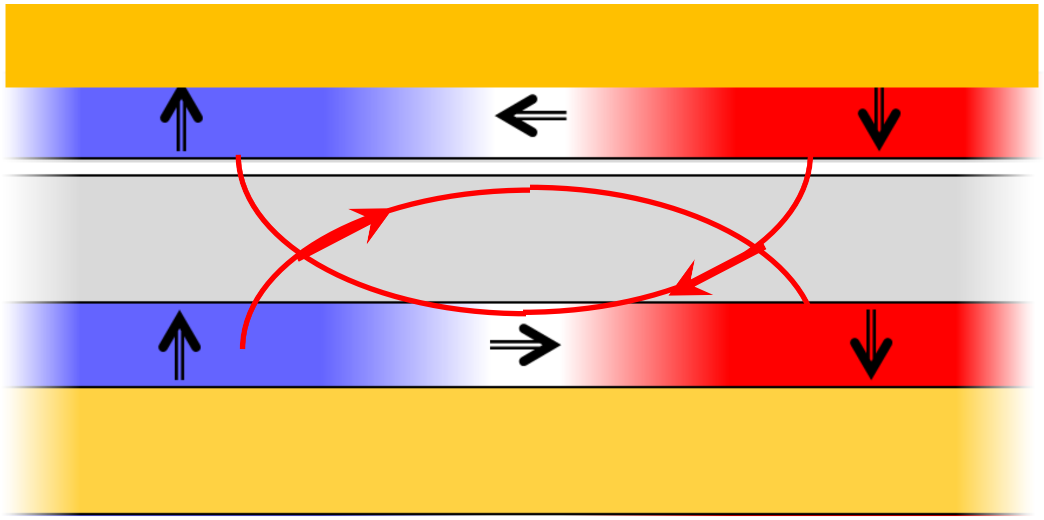
Case of two ultrathin films : symmetric stacking

If positive DMI:

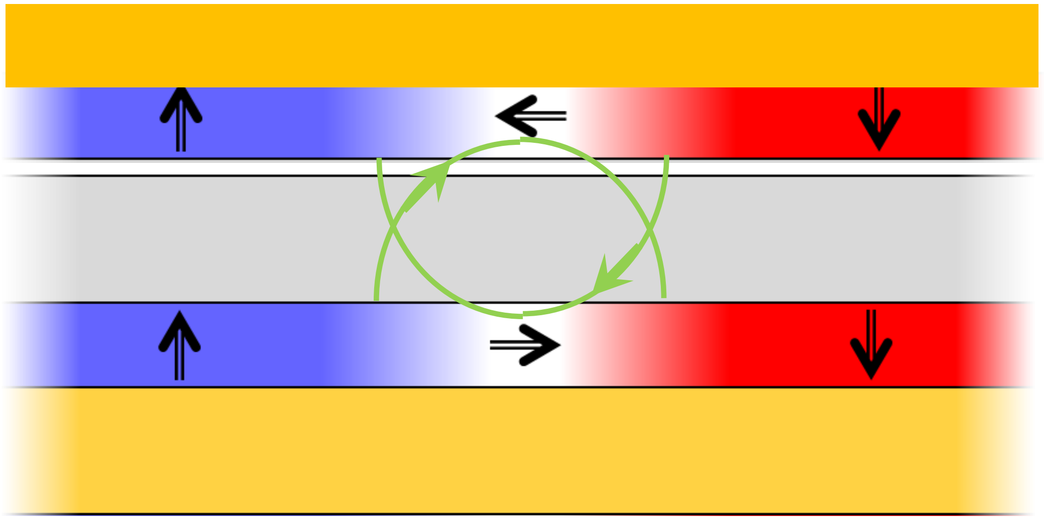
The stray field favors a given chirality !



Domains stray field

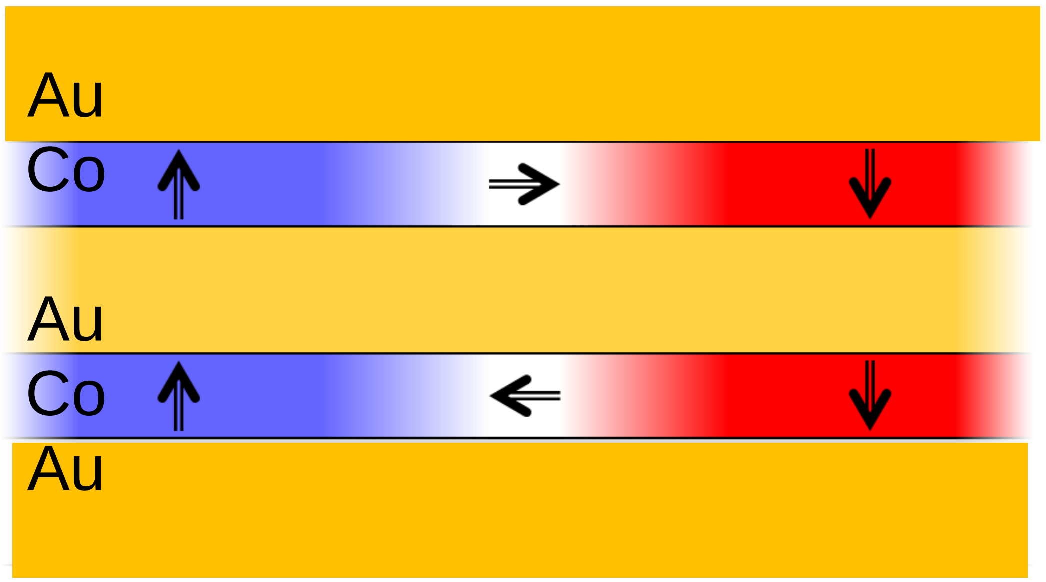


Domain walls stray field

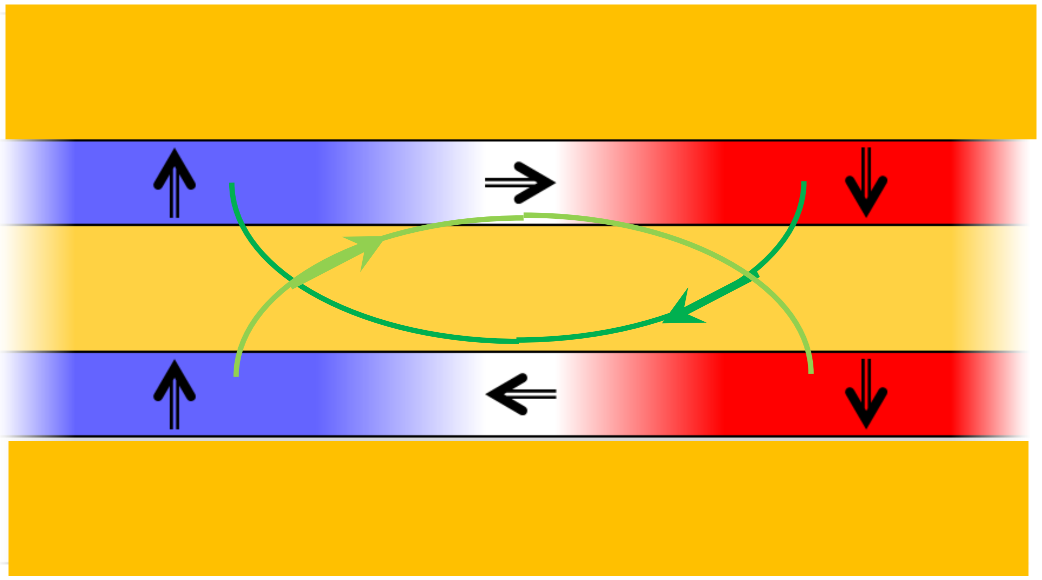


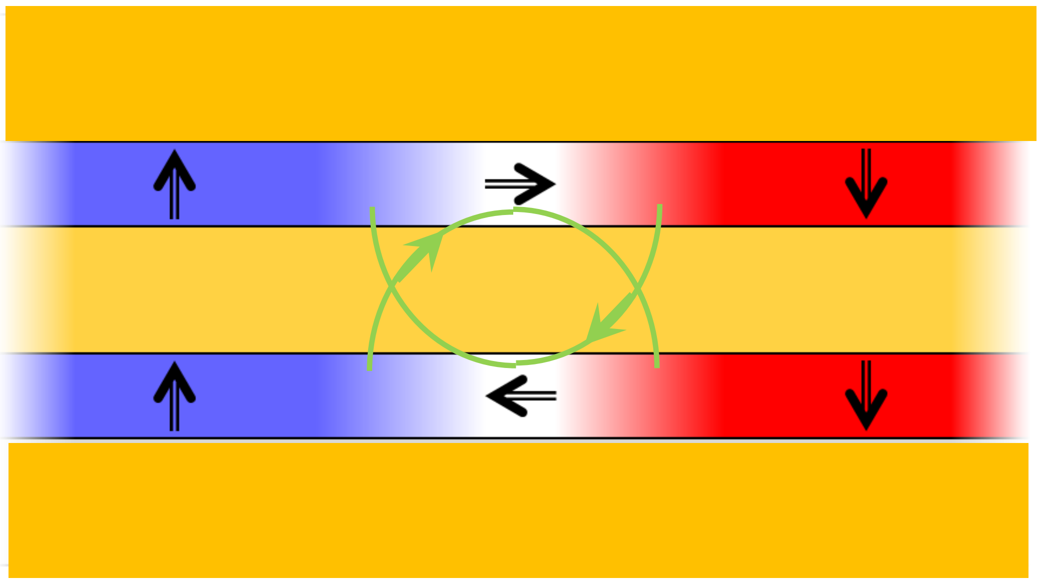
Case of two ultrathin films : symmetric stacking

No DMI case



Domains stray field forces antiparallel Néel walls, reinforced by domains walls stray field





Observation by ballistic electron emission microscopy

MFM

BEEM

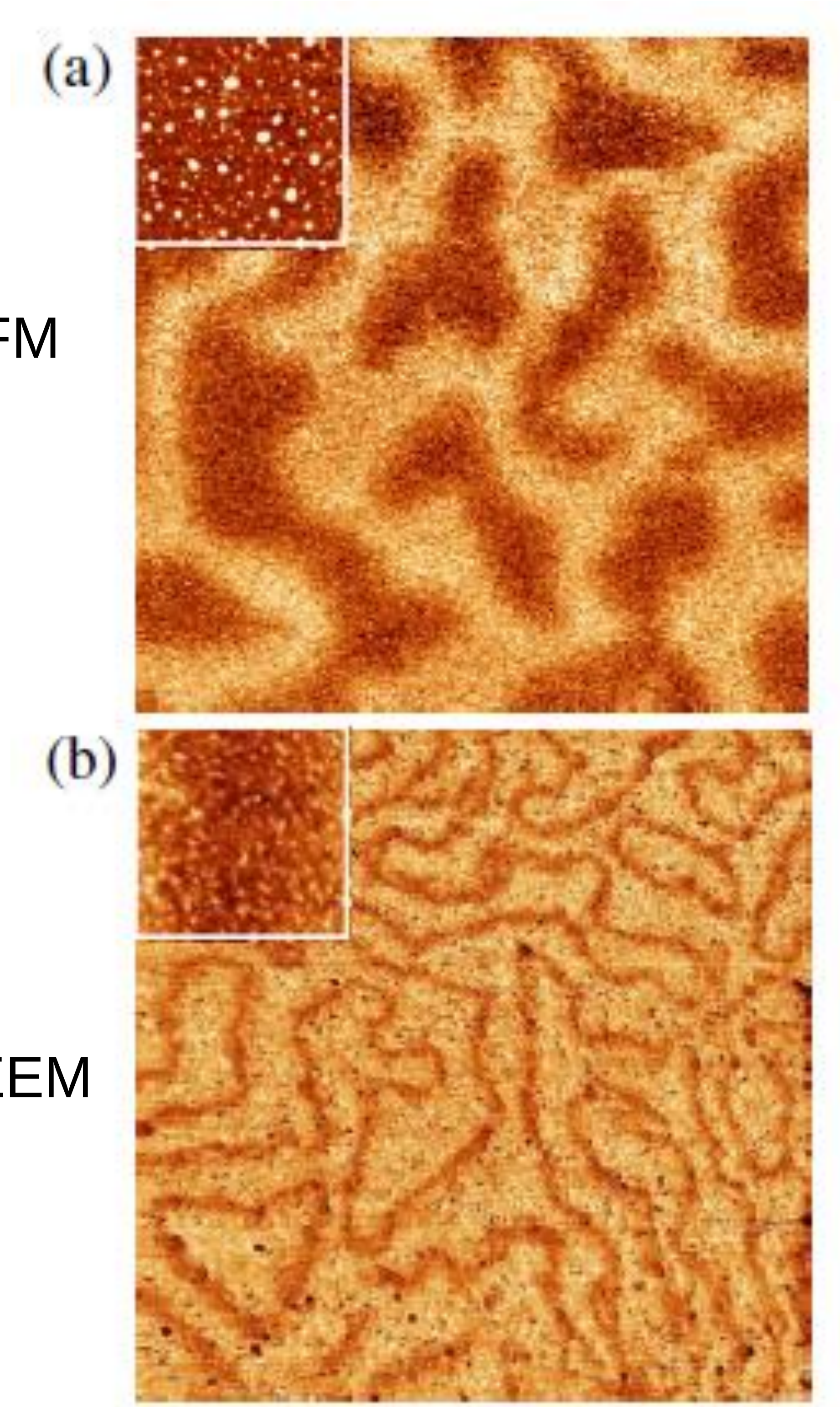


Fig. 1: (Color online) Images ($2 \times 2\,\mu m^2$) of the Co(1.6 nm)/Au(5 nm)/Co(1.4 nm) sample. (a) MFM phase image (inset topography) (b) BEEM (ballistic current) image (inset topography) (imaging conditions: $V_T = 1.5\,V$, $I_T = 20\,nA$).

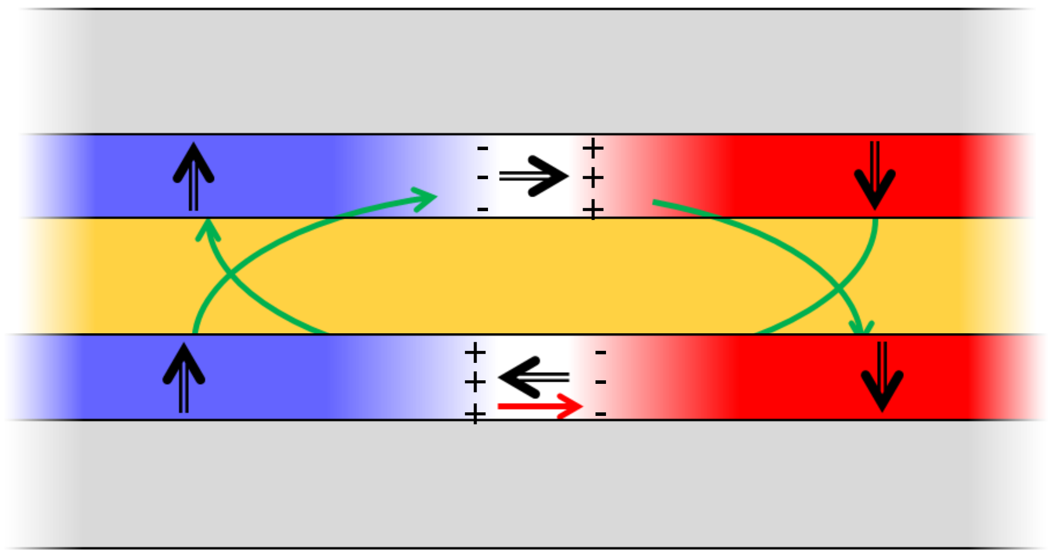
BEMM contrast : $\propto \vec{m}_{top} \cdot \vec{m}_{bottom}$

domains : P

domain walls : AP

A. Bellec, S. Rohart, M. Labrune, J. Miltat, A. Thiaville
Europhys. Lett. ***91****, 17009 (2010)*

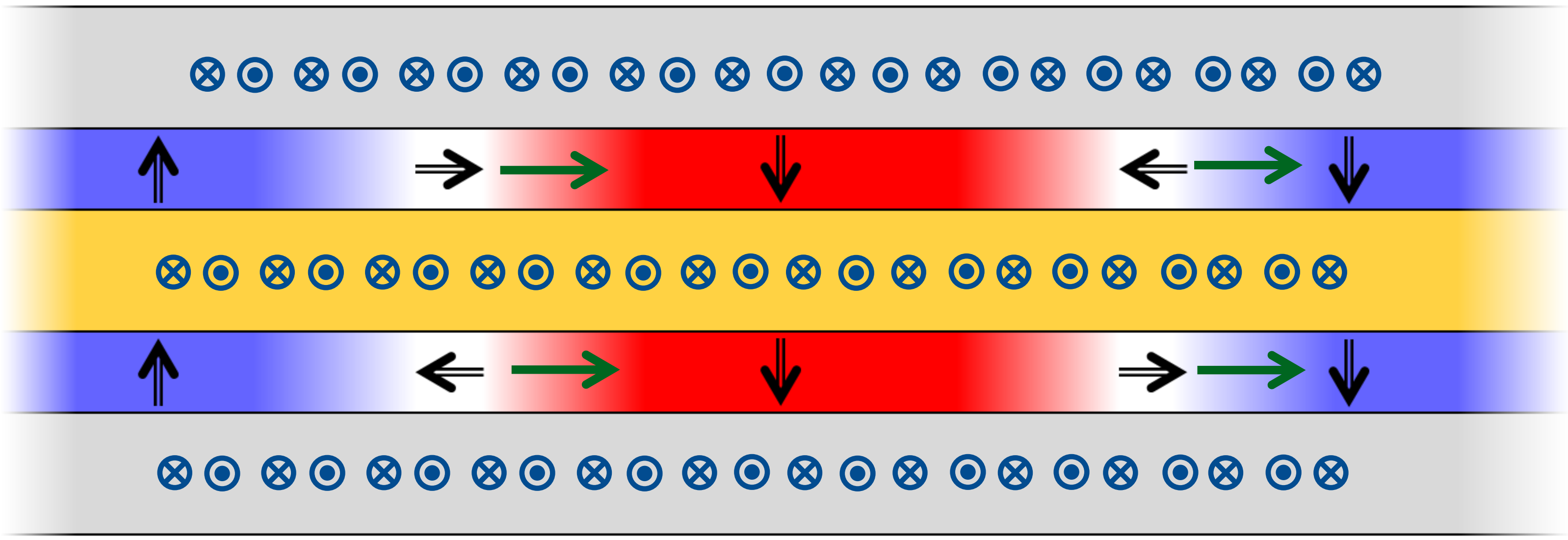
Domain wall energy



$$\sigma = \sigma_0 - \pi D + \delta_{\mathrm{N}} - \delta_{\mathrm{qp}} - \delta_{\mathrm{D-DW}}$$

Domain-domain wall magnetostatic coupling adds to DMI

Motion by the spin Hall effect



Thiele equation

$$\vec{G} \times \vec{v} - \alpha \overleftrightarrow{D} \cdot \vec{v} + \vec{F}_{\mathrm{SH}} = 0$$

Gyrotropic force

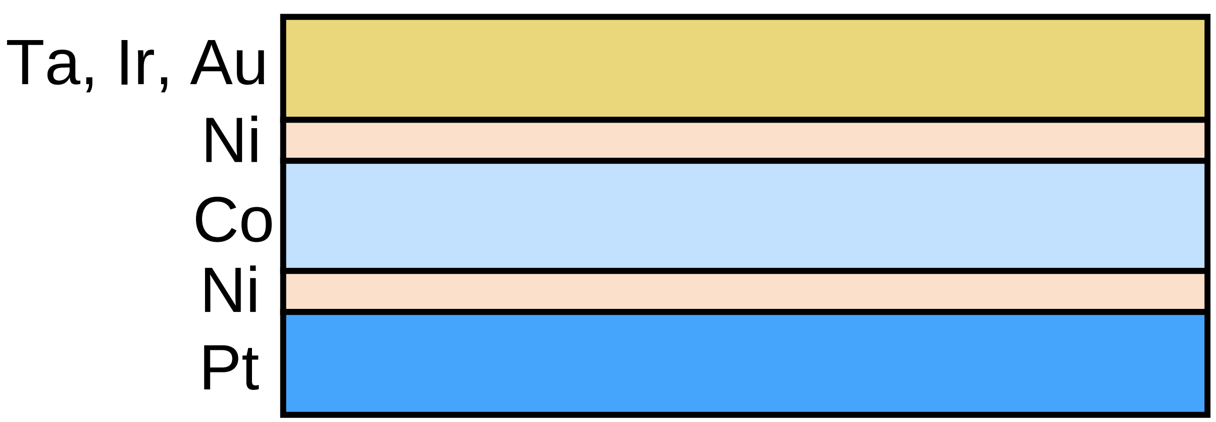
Driving force

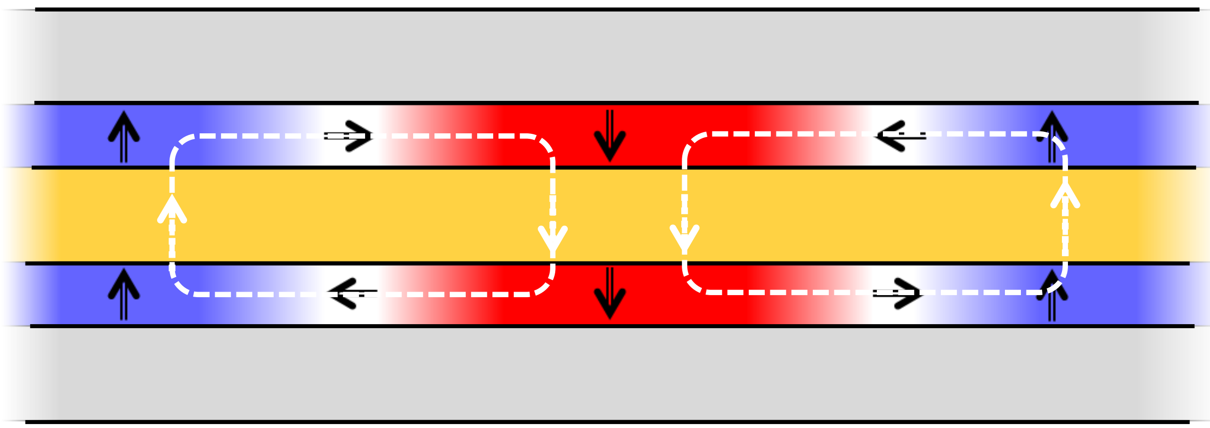
$$\vec{F}_{\mathrm{SH}} = \pm \frac{\hbar}{2e} \pi J \theta_{\mathrm{SH}} b \vec{e}_z \times \vec{e}_p$$

- On either side we reverse spin accumulation and chirality
- The two skyrmion system moves as a rigid particle

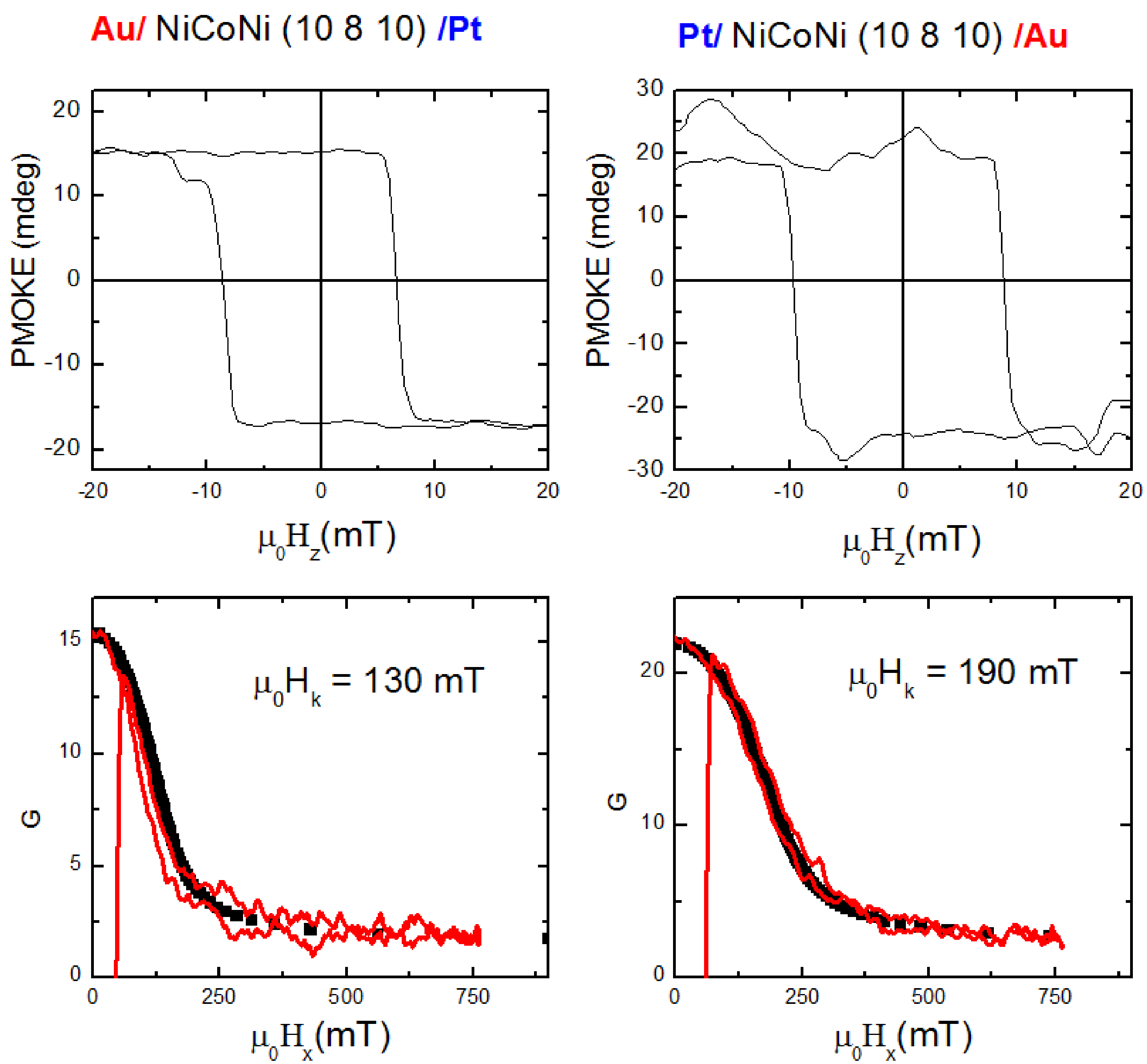
Design of the stack

- Perpendicular anisotropy. Ideally independent of surrounding metals
- Large effective DMI
- Large effective SHE
- Dipolar coupling



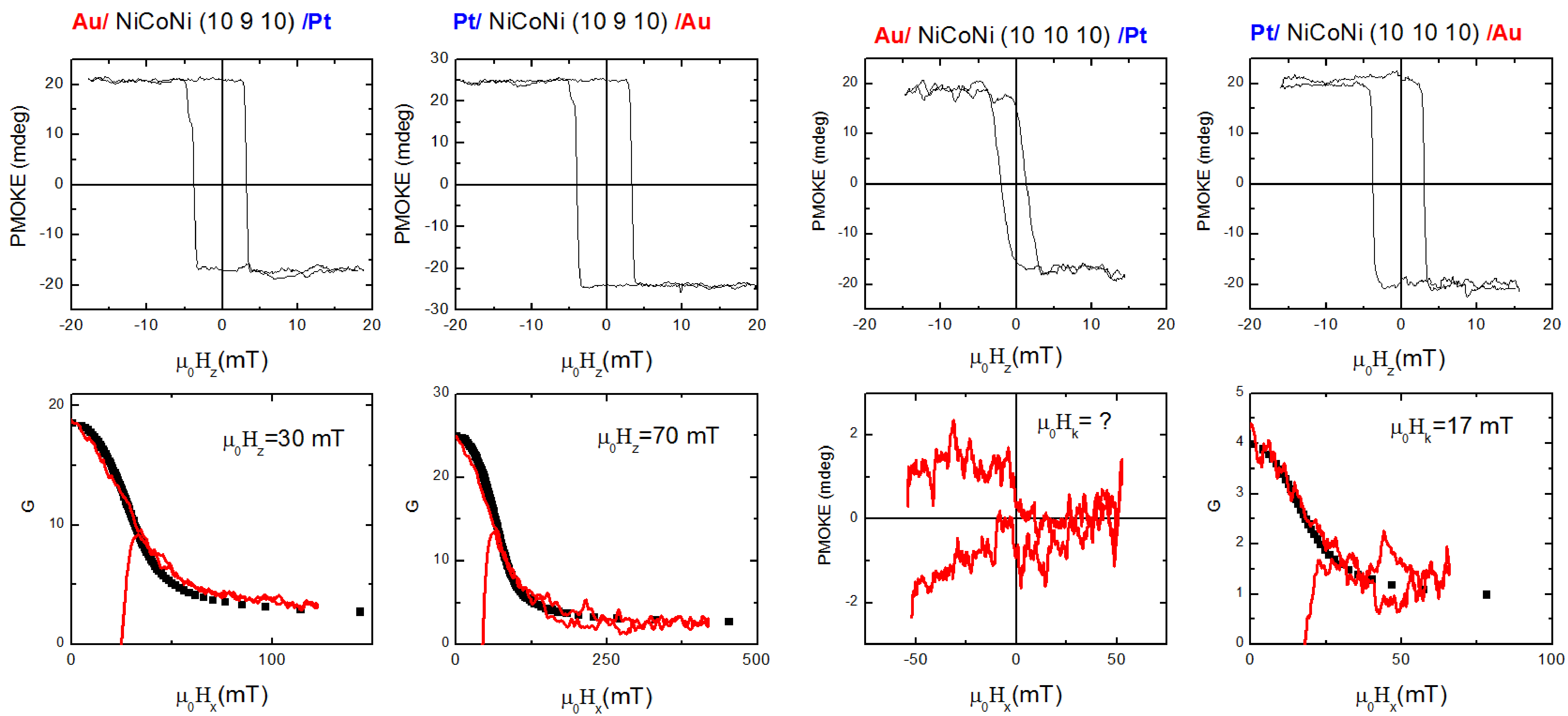


Anisotropy of single layers



- Anisotropy is slightly weaker when Au is at the bottom

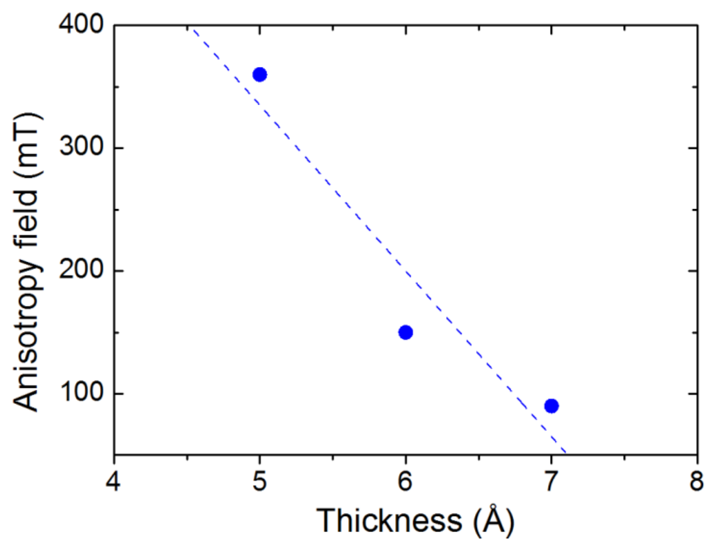
Anisotropy of single layers



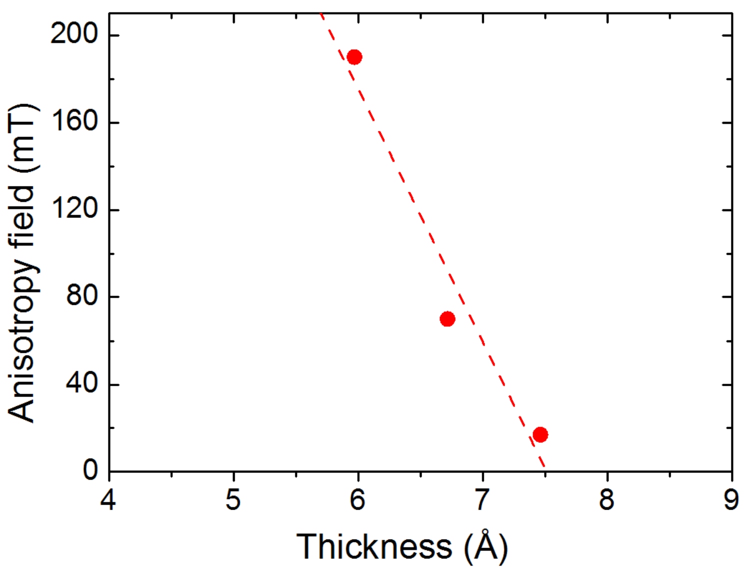
- Further increase of Co layer leads to a decrease of anisotropy

Insight into individual layers

Pt\Ni\Co(3)\Ni\Au

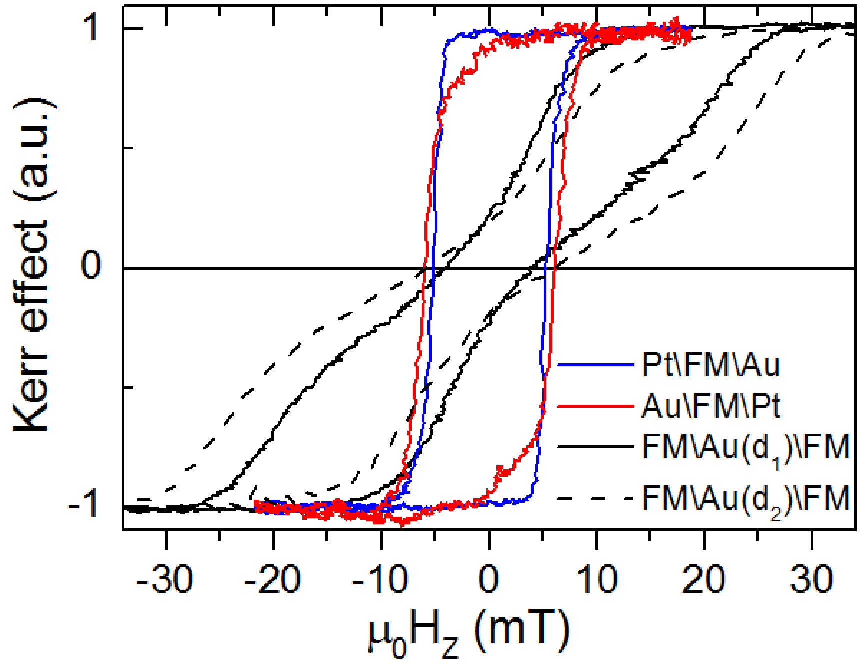


Pt\Ni(4)\Co\Ni(4)\Au

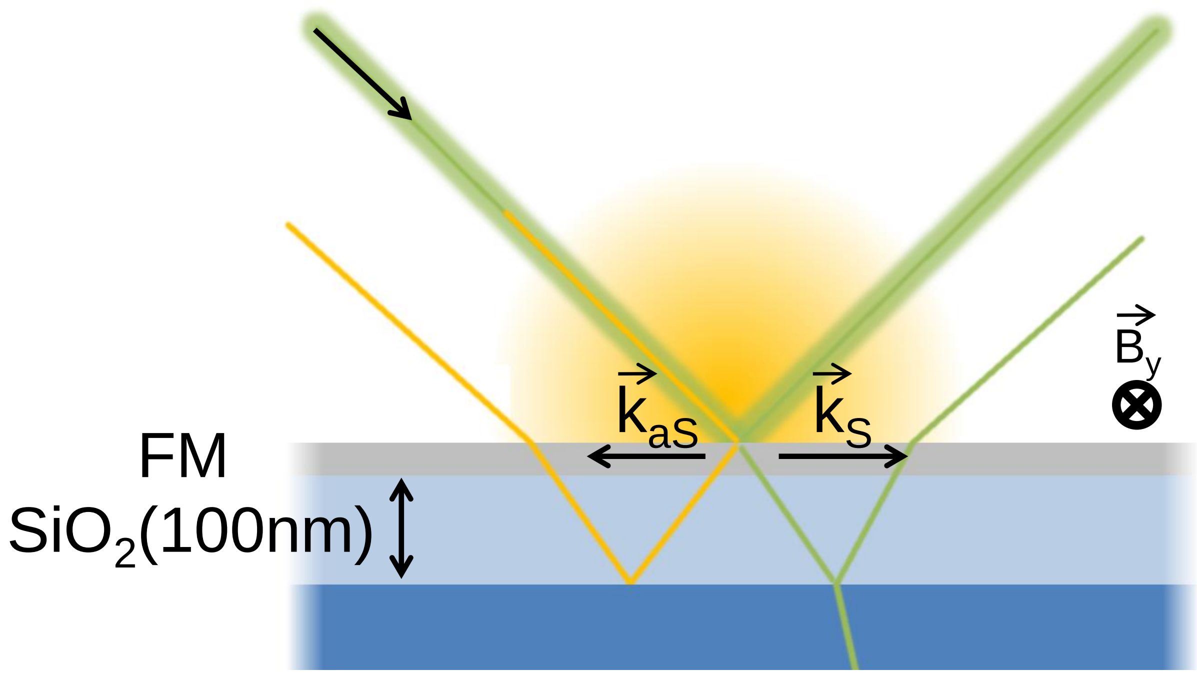


- Anisotropy/DMI can be controlled by Ni or Co thickness
- Dipolar field

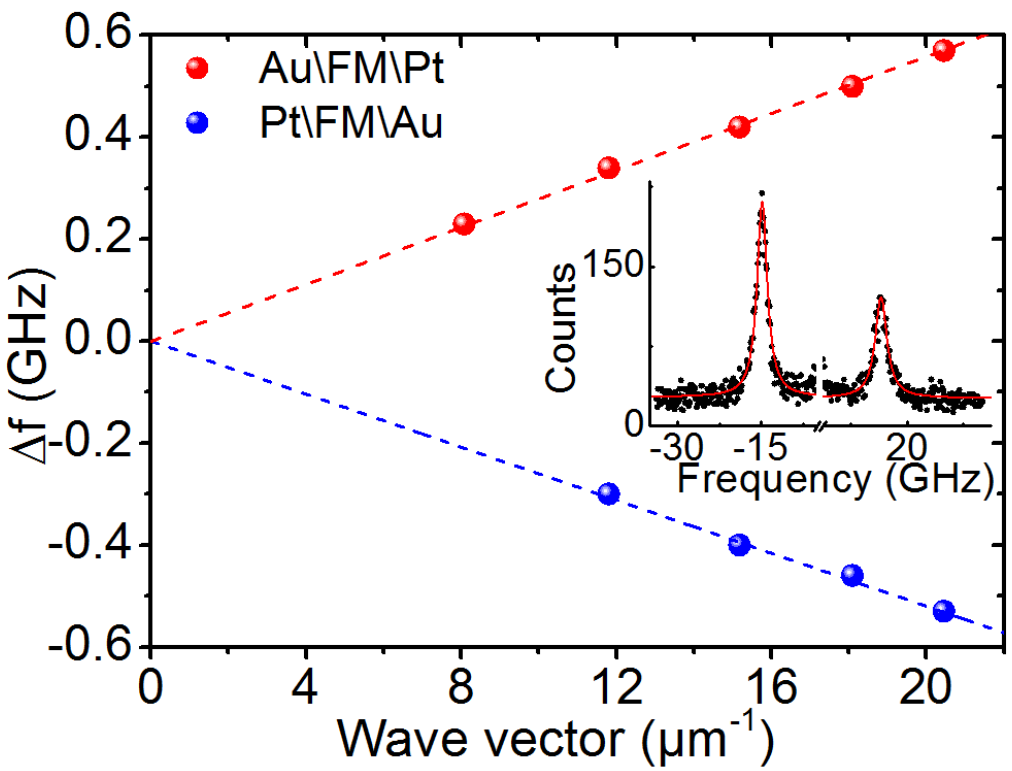
Pt\Ni(4)\Co\Ni(4)\Au(50)\Ni(4)\Co\Ni(4)\Pt



DMI measured by Brillouin light spectroscopy (collab. LSPM, Uni Paris-Nord)



(Role of SiO_2 : *A. Hrabec et al., APL (2017)*)



- Frequency splitting

$$\Delta f = f_{\rm S} - f_{\rm AS} = 2\gamma k_x D/\pi M_{\rm s}$$

K. Di et al., PRL (2015)

M. Belmeguenai et al., PRB (2015)

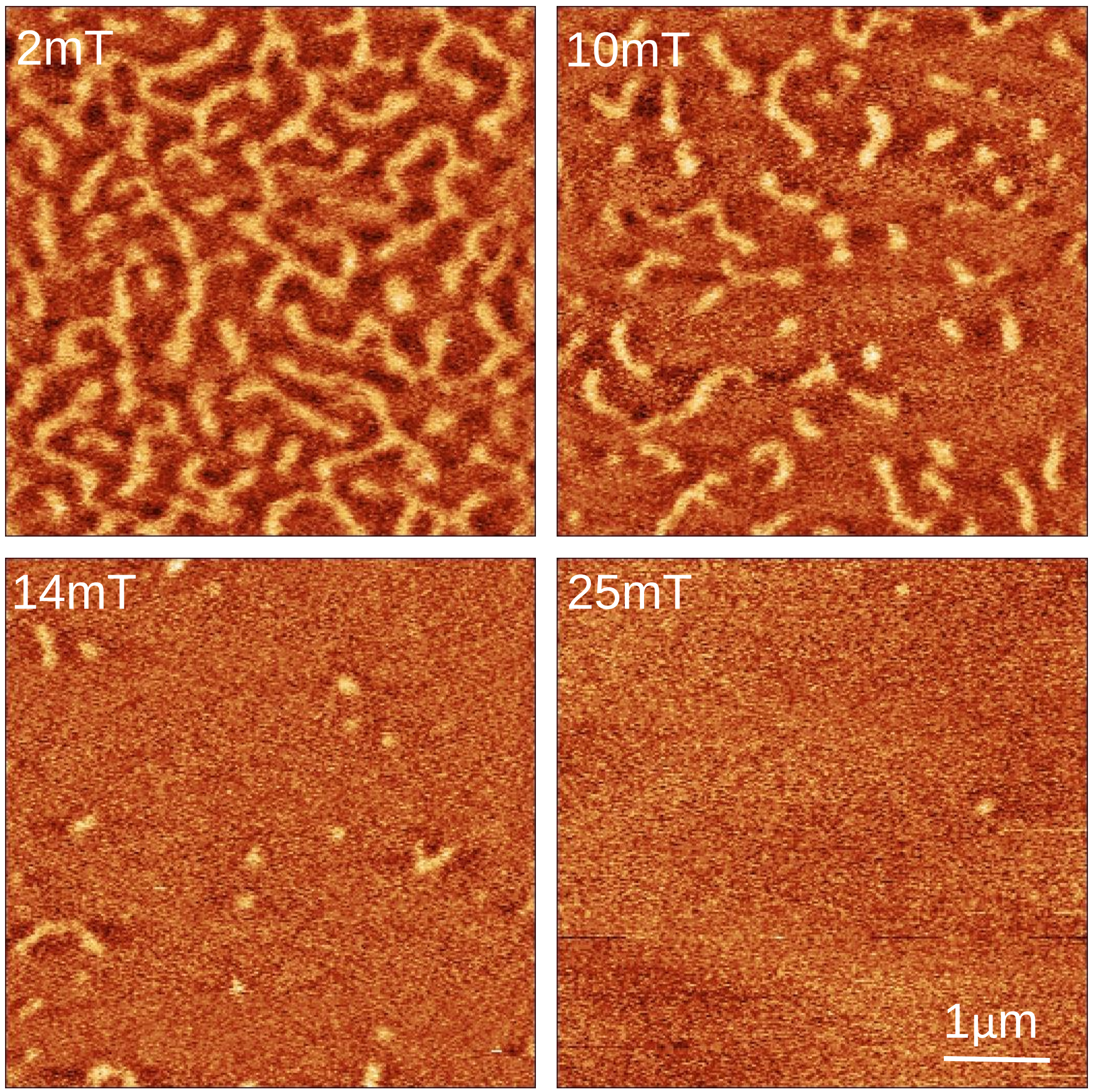
● $D = +0.24 \pm 0.01 \ \mathrm{mJ/m^2}$

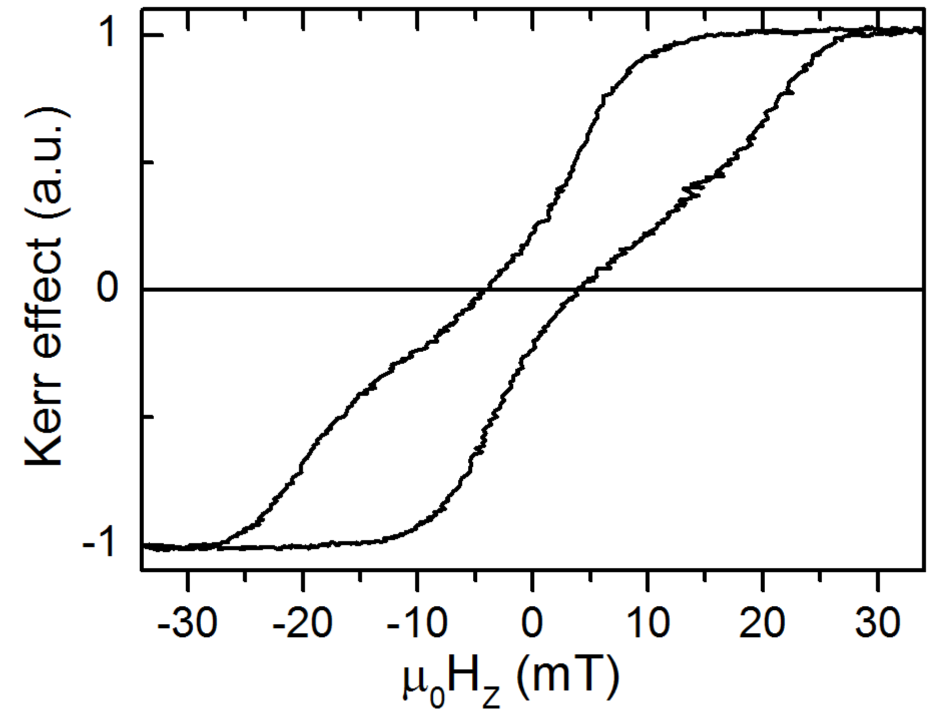
● $D = -0.21 \pm 0.01 \ \mathrm{mJ/m^2}$

- Left-handed chirality (Pt\Ni)
- The total effective DMI is zero (in bilayer)

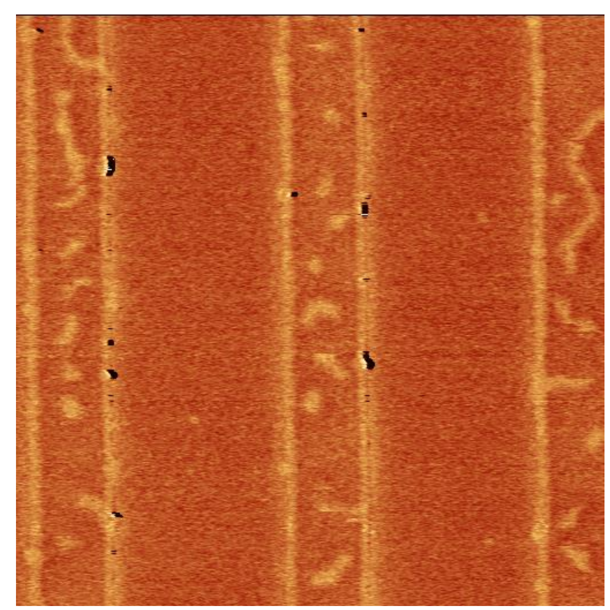
Skyrmion condensation: by field, by confinement

Magnetic force microscopy (MFM)



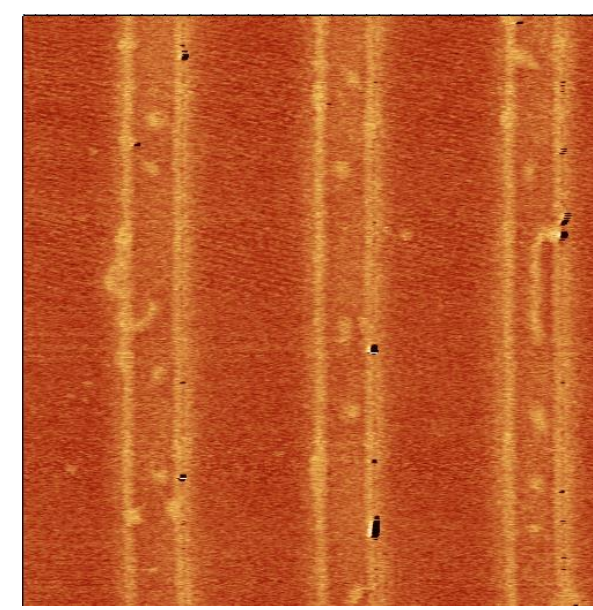


500nm



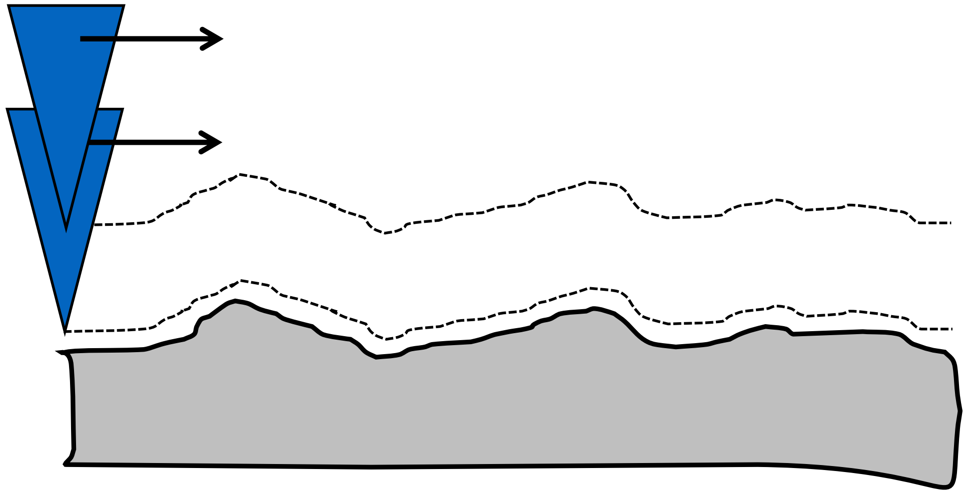
2.5 mT

300nm

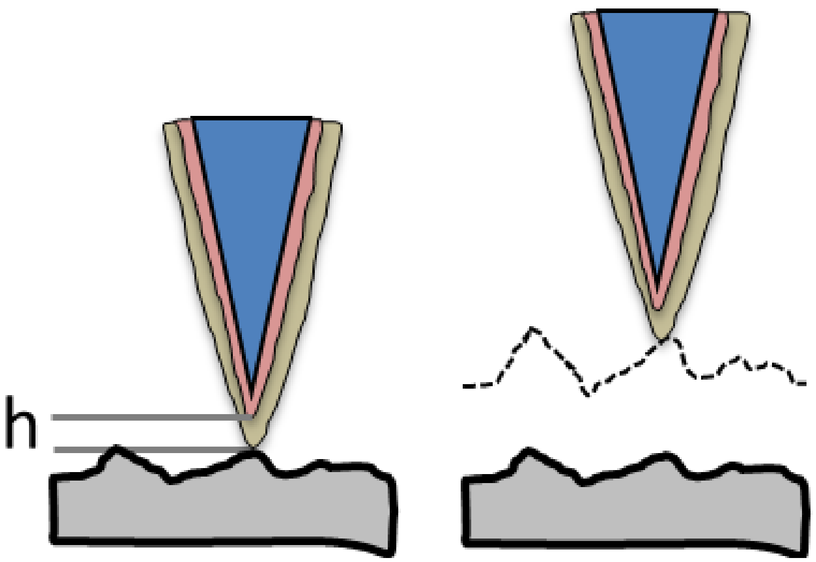


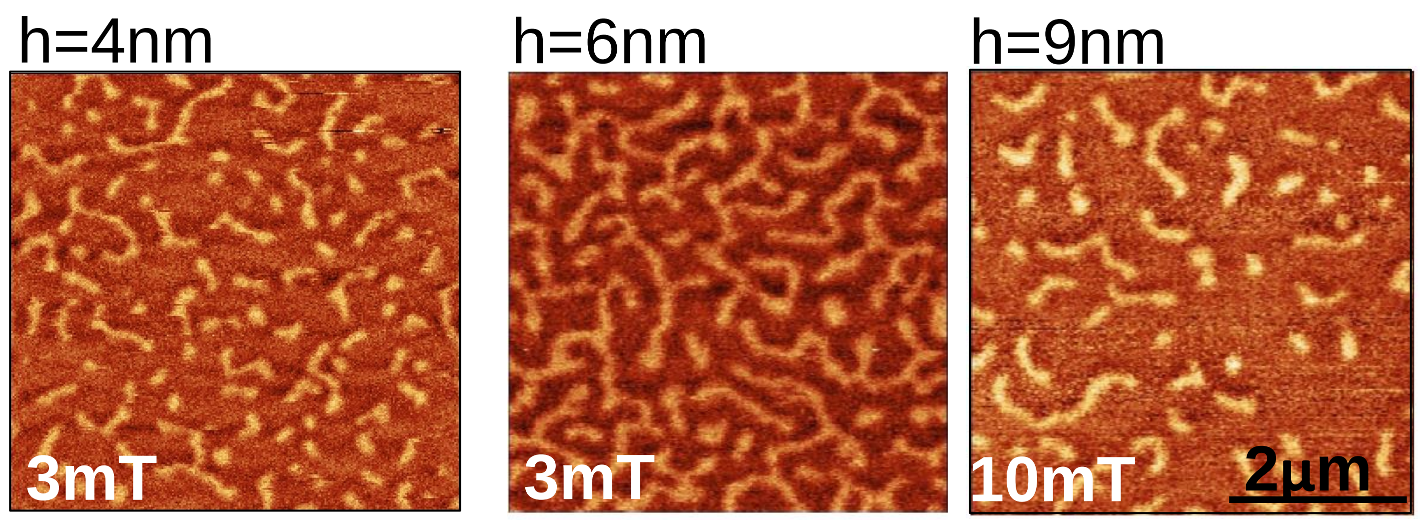
2.5 mT

Skyrmion imaging technique : MFM



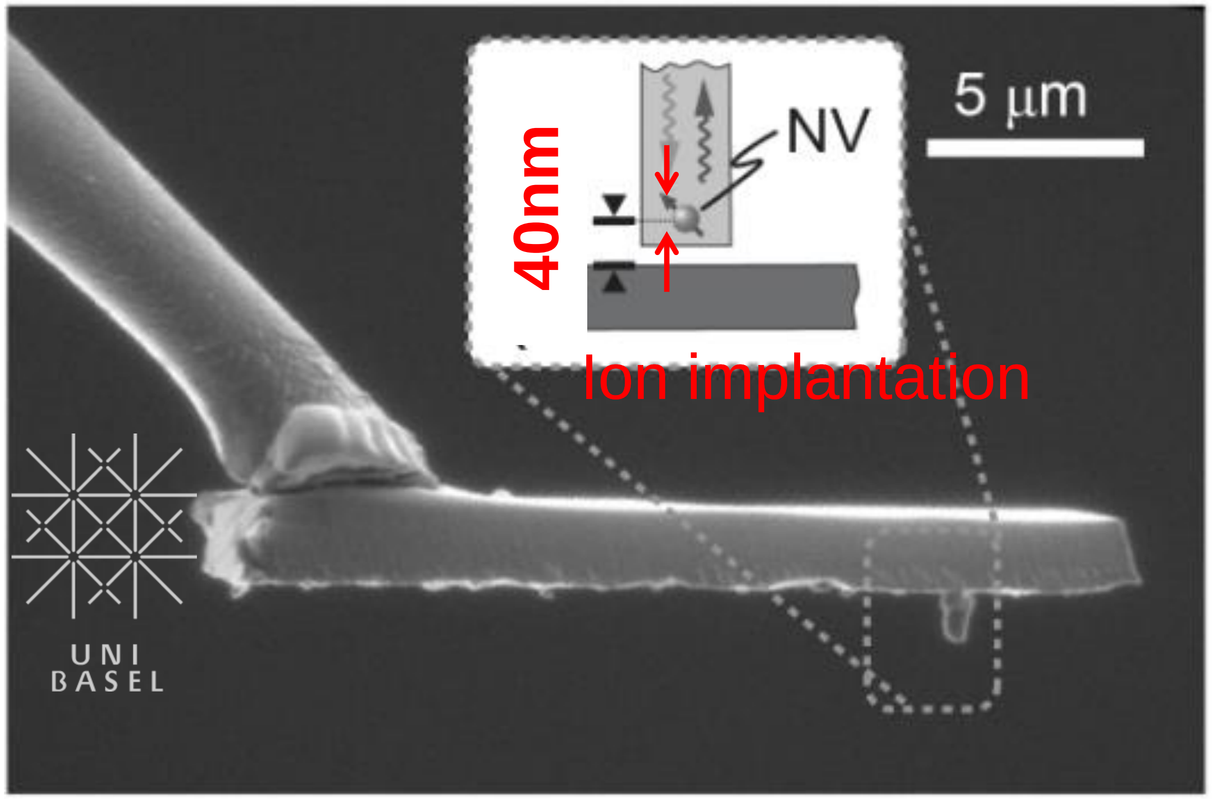
- AFM ‘tapping’scan
- MFM constant height scan
- The AFM scan is most important for interaction between tip and magnetic texture





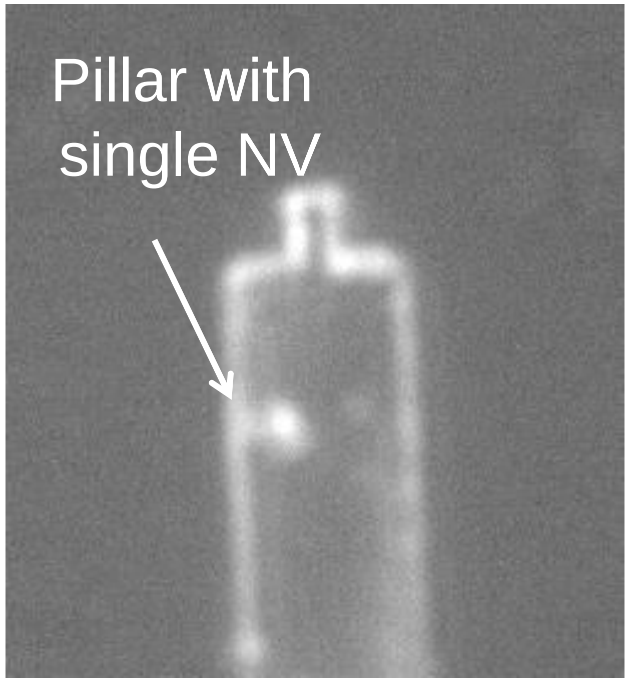
- MFM is invasive
- Relies on magnetic textures pinning

NV center magnetic stray field microscopy (collab. V. Jacques, L2C Uni Montpellier)



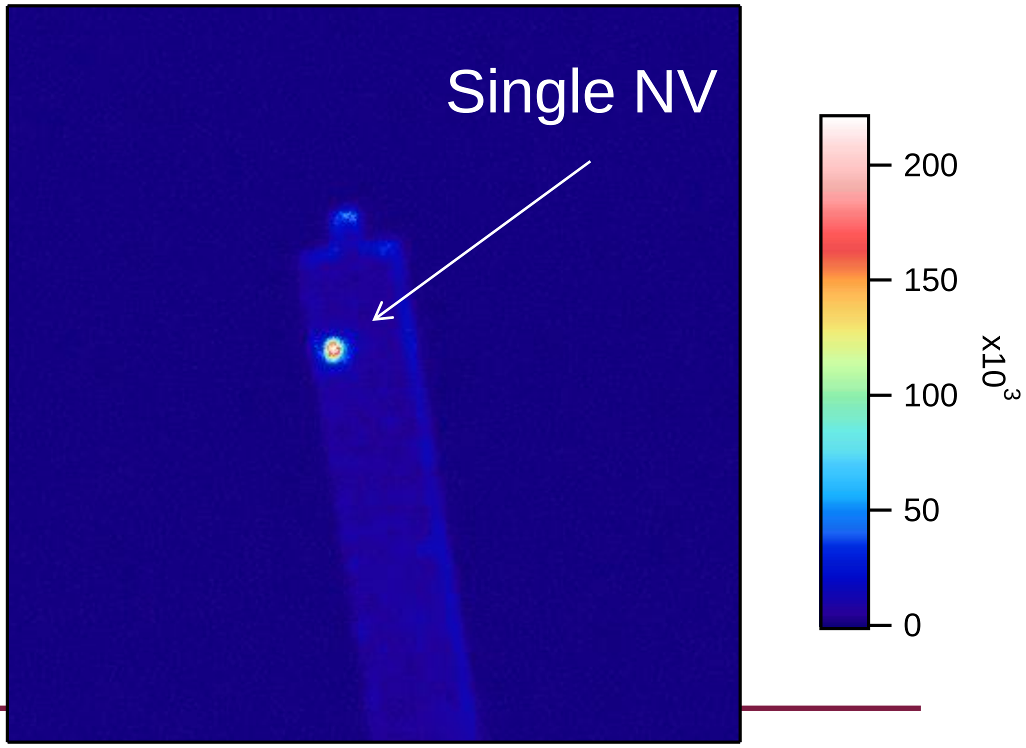
Top views

optical image



Diamond tip from P. Maletinsky (Basel)

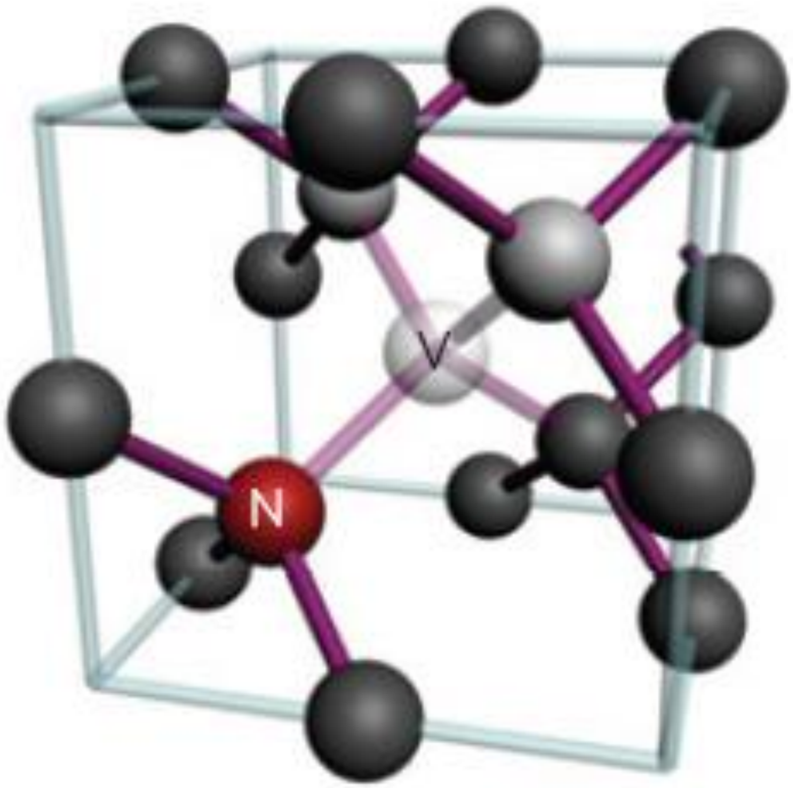
PL image

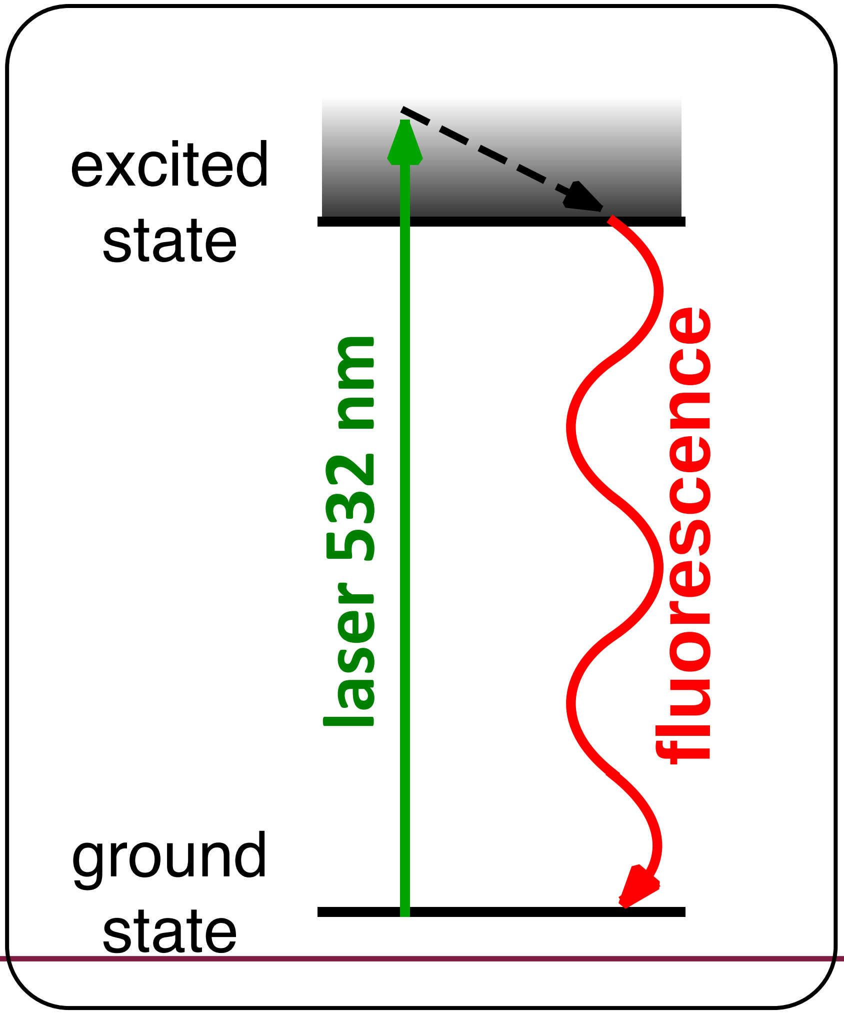


P. Maletinsky et al.
Nat. Nanotechnol. ***7***, *320–324 (2012)*

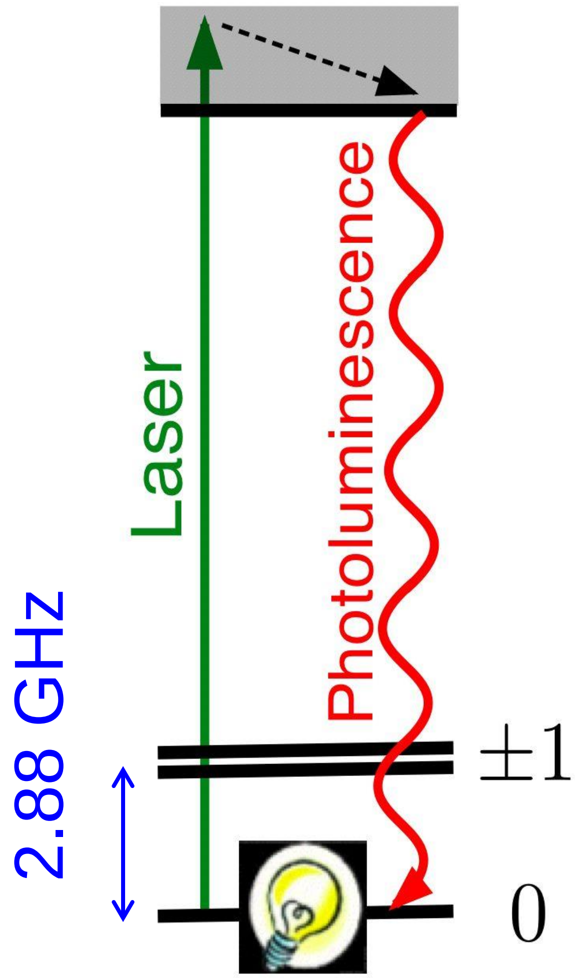
Nitrogen-vacancy (NV) center in diamond

- Substitutional nitrogen atom **(N)** and a vacancy **(V)** in the adjacent lattice site of the diamond matrix.
- Artificial atom « trapped » in the diamond lattice.



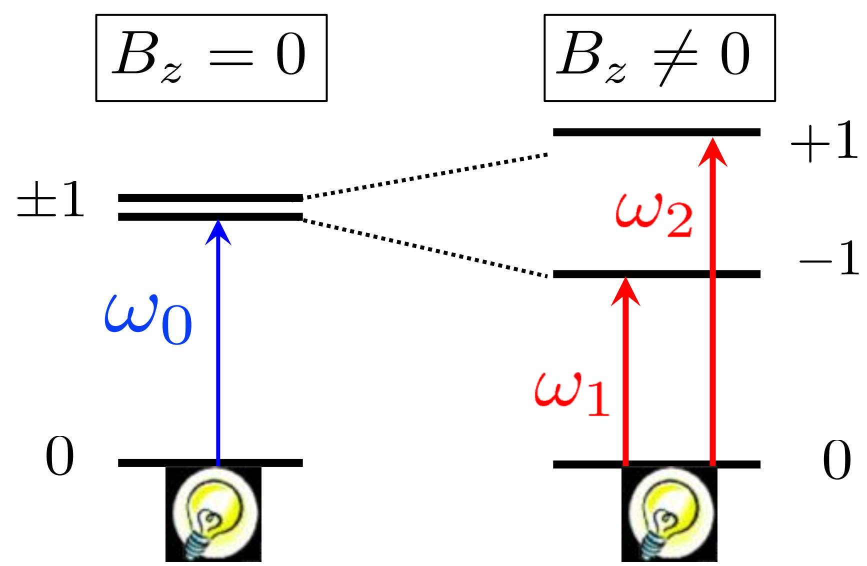


NV ground state is a spin triplet

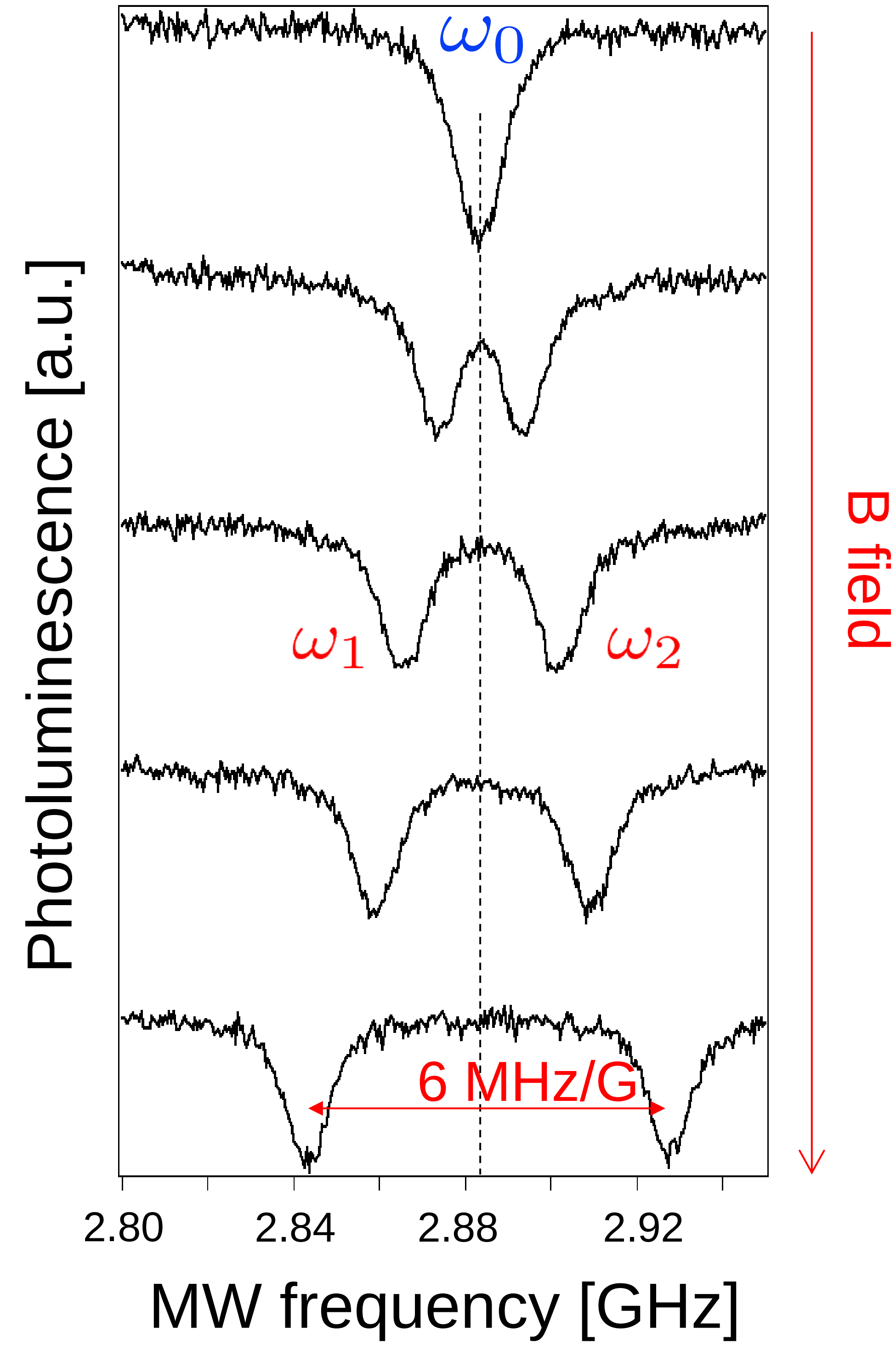


z = N-V axis

$$H = \hbar D S_z^2 + g\mu_b B_z S_z$$



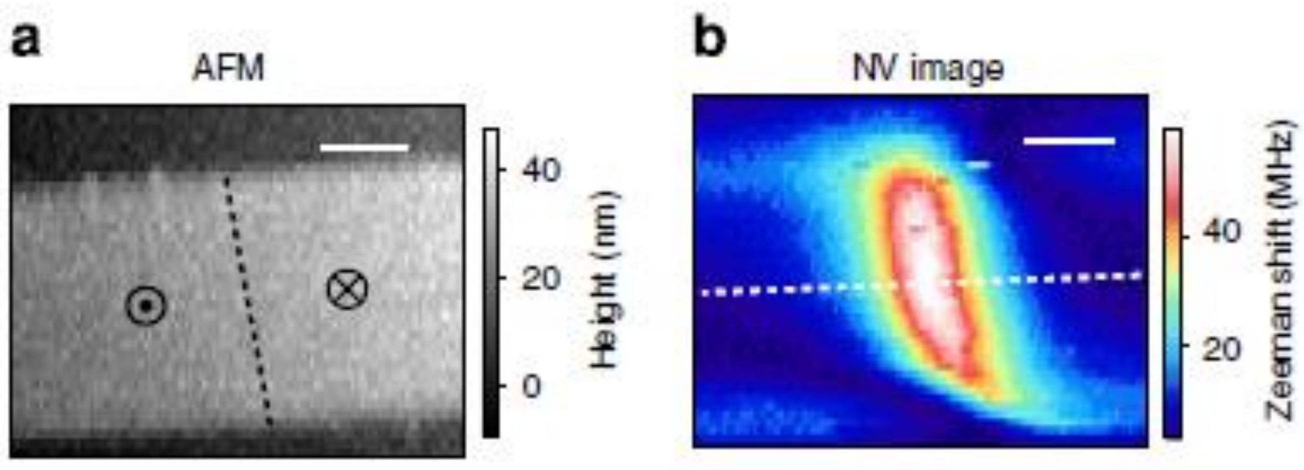
J. Maze et al., Nature (2008)
G. Balasubramanian et al., Nature (2008)

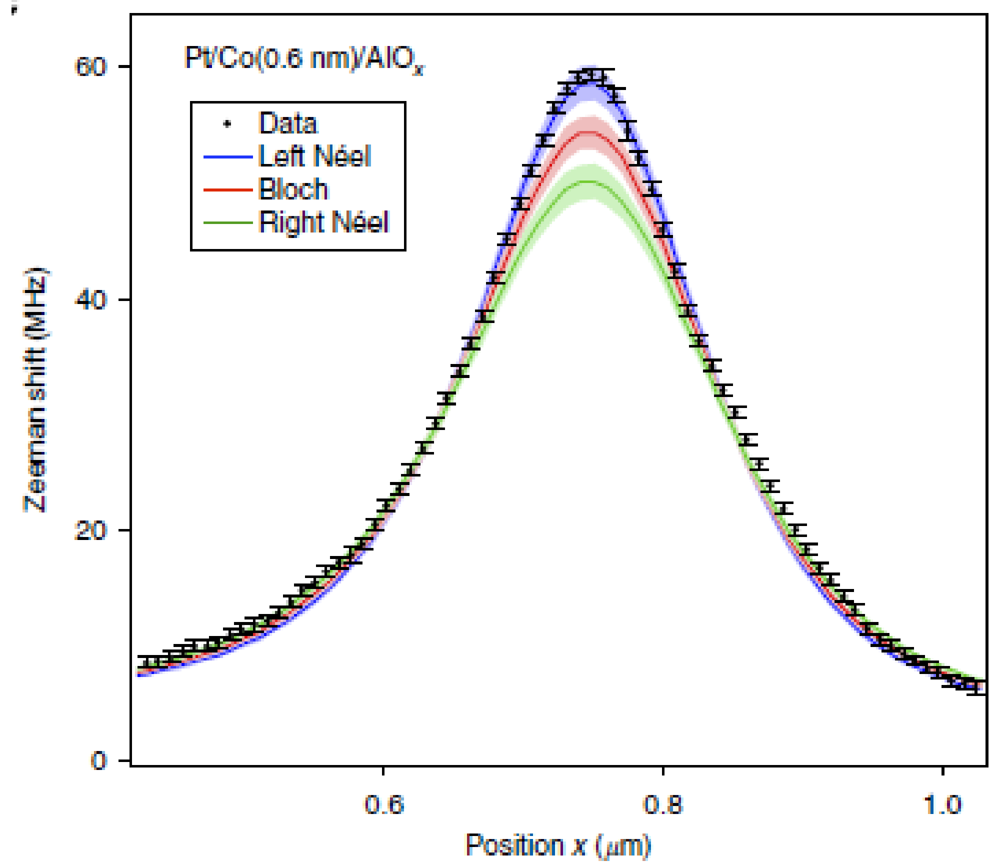


Zeeman splitting by the axial field

Two imaging modes

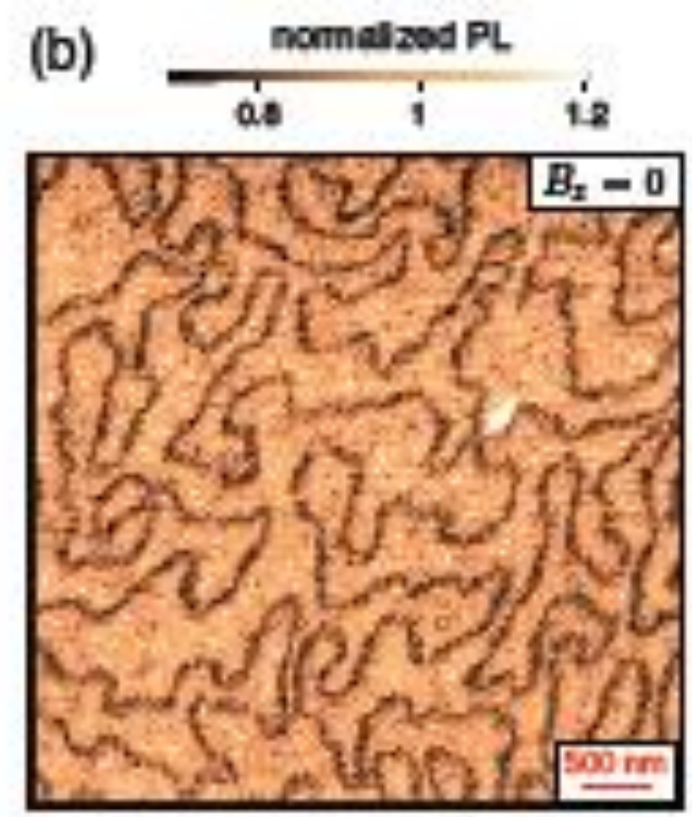
1) Quantitative mapping of the axial stray field:
left-handed Néel domain walls in Pt\Co\AlOx





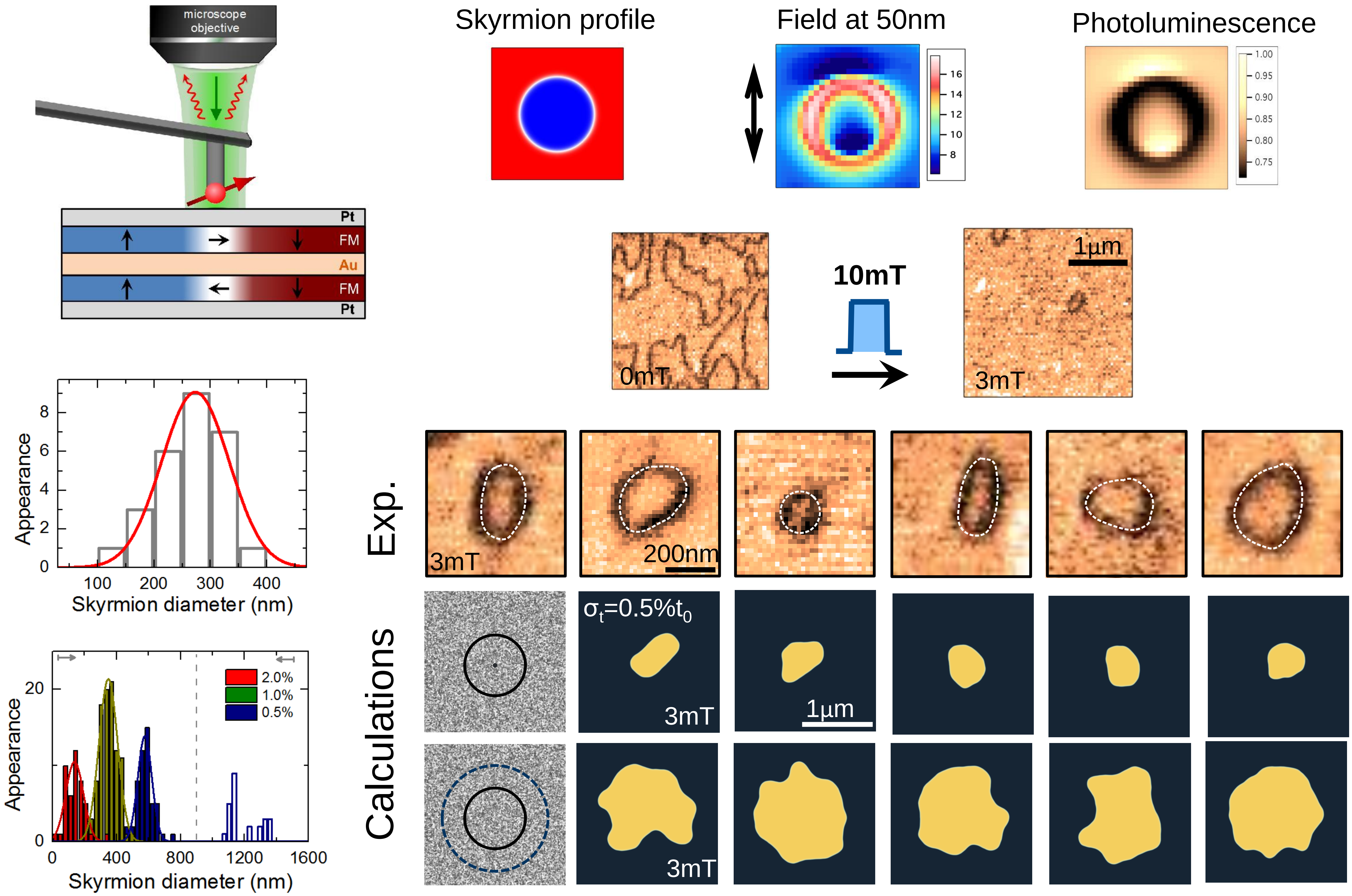
J.-P. Tetienne et al., Nat. Commun. ***6****, 6733 (2015)*

2) For too large transverse field (~5 mT):
Photo-luminescence quenching



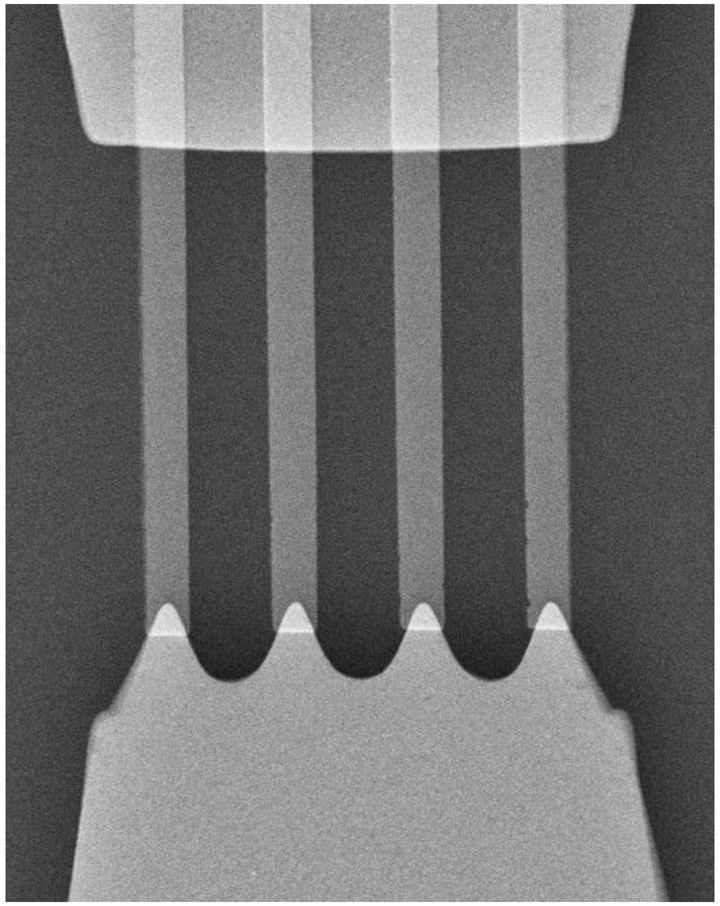
I. Gross et al., Phys. Rev. Mater., in press, arXiv1709.06027

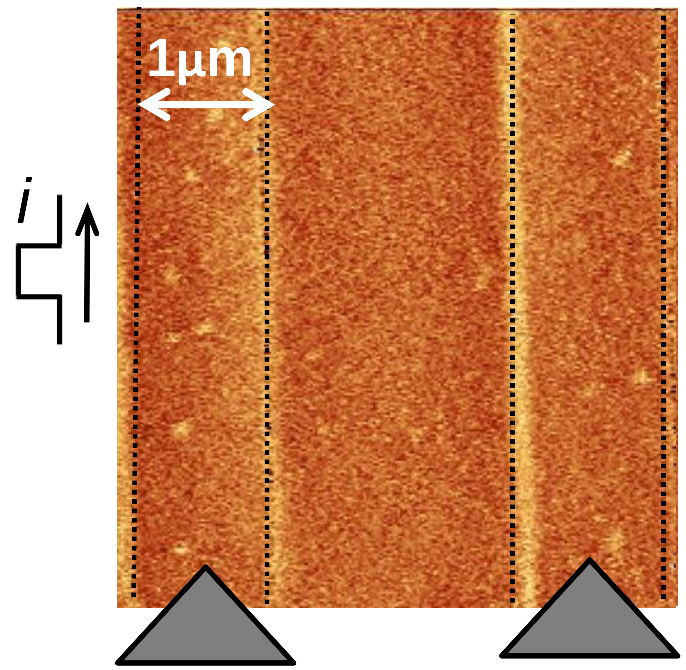
NV microscopy: variation of skyrmion shapes



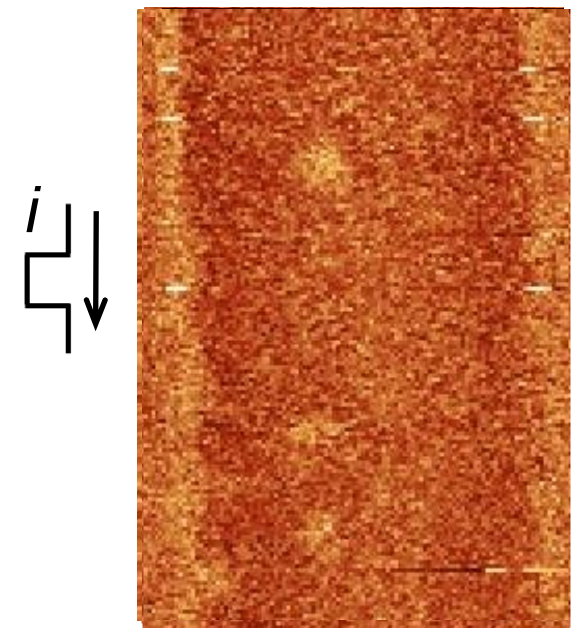
Skyrmion writing and displacement

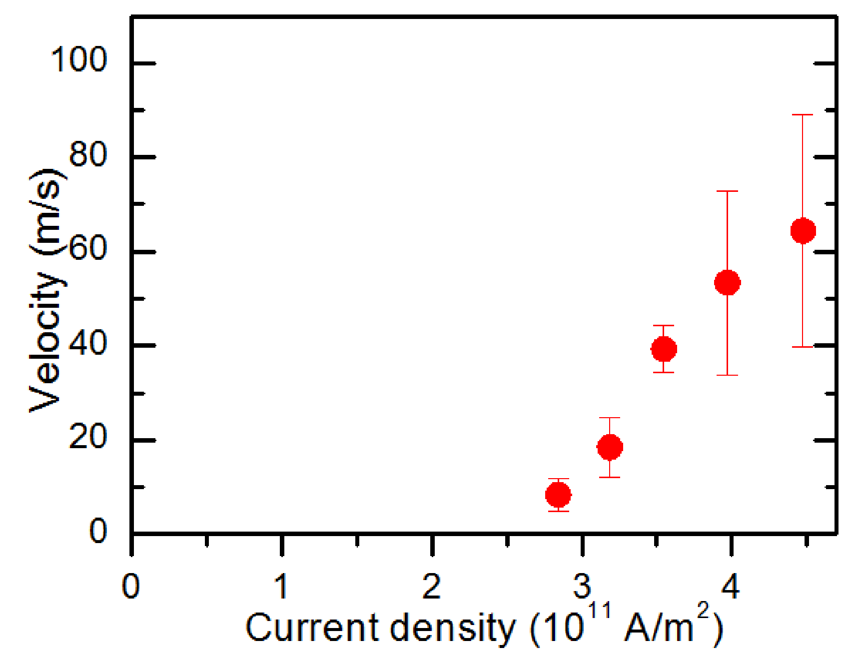
2 regimes:
- Skyrmion writing
- Skyrmion displacement





4 mT, 7ns





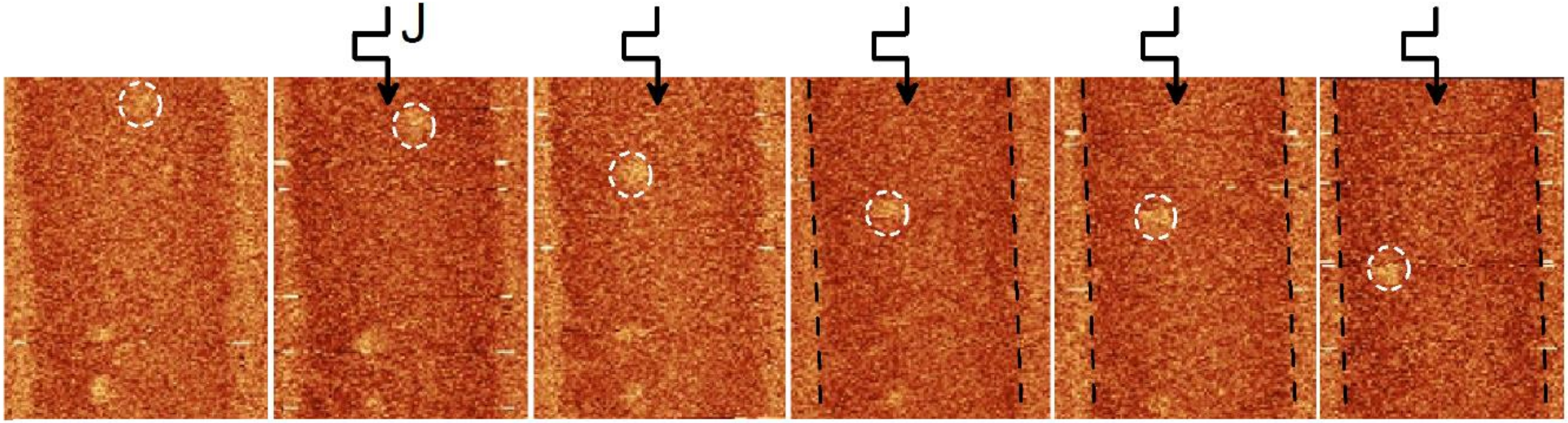
Models for skyrmion writing:

O. Heinonen et al: PRB (2016)

K. Everschor-Sitte et al., NJP (2017)

- Skyrmions move against electrons, at large velocities

Skyrmions displacement

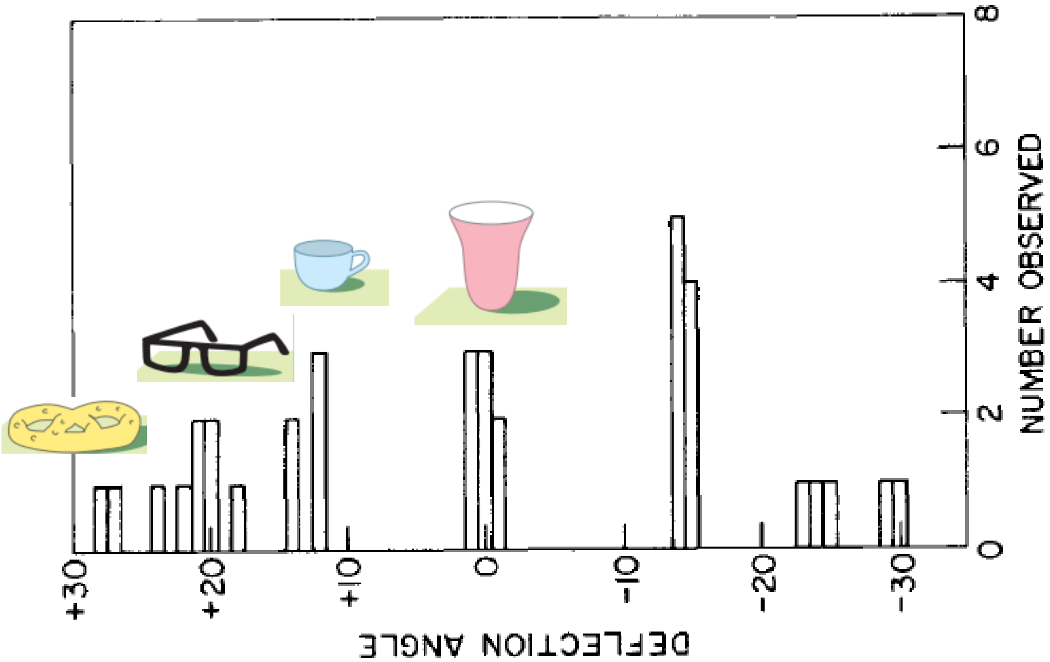


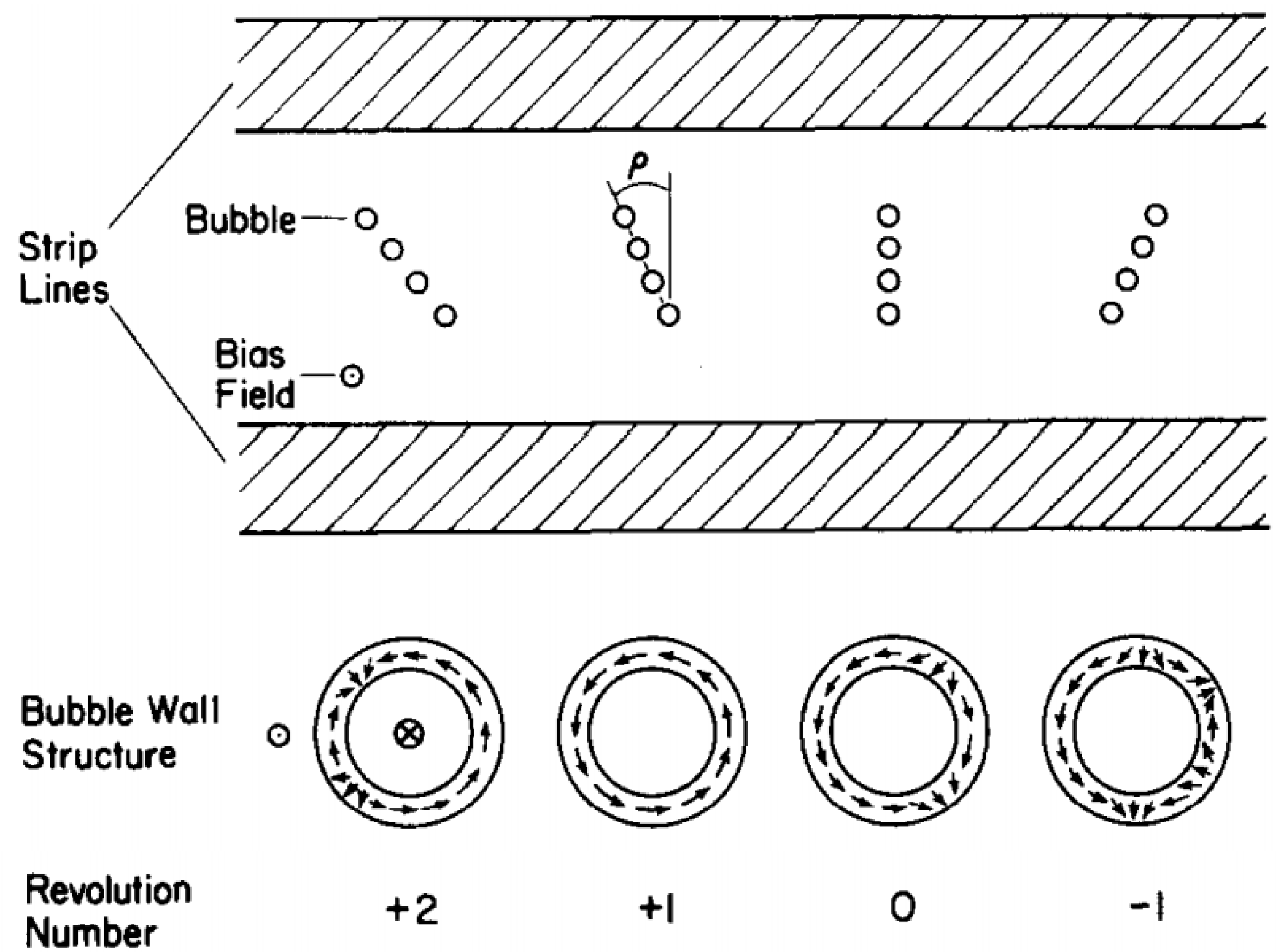
Gyrotropic motion?

Gyrotropic force (bubbles)

$$\vec{F}_{\mathrm{g}} = \vec{G} \times \vec{v} = \left(0, 0, -\frac{\mu_0 M_{\mathrm{s}} t}{\gamma_0}\Omega\right) \times (v_x, v_y, 0)$$

$$\Omega = 4\pi S p$$



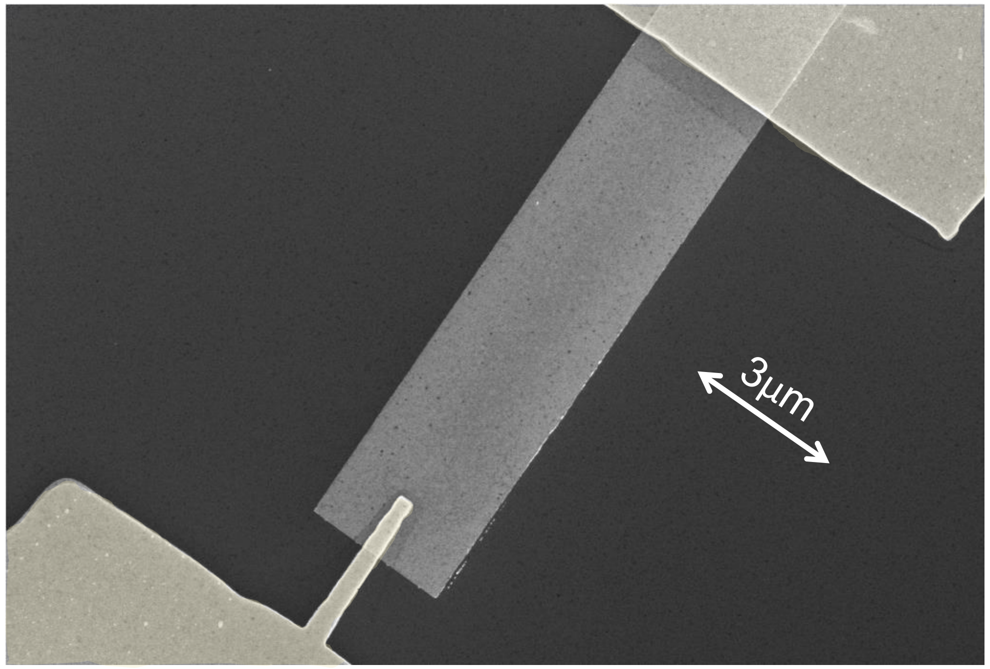


A.P. Malozemoff et al, JAP (1973)

J.C. Slonczewski et al, AIP Conf. Proc. (1973)

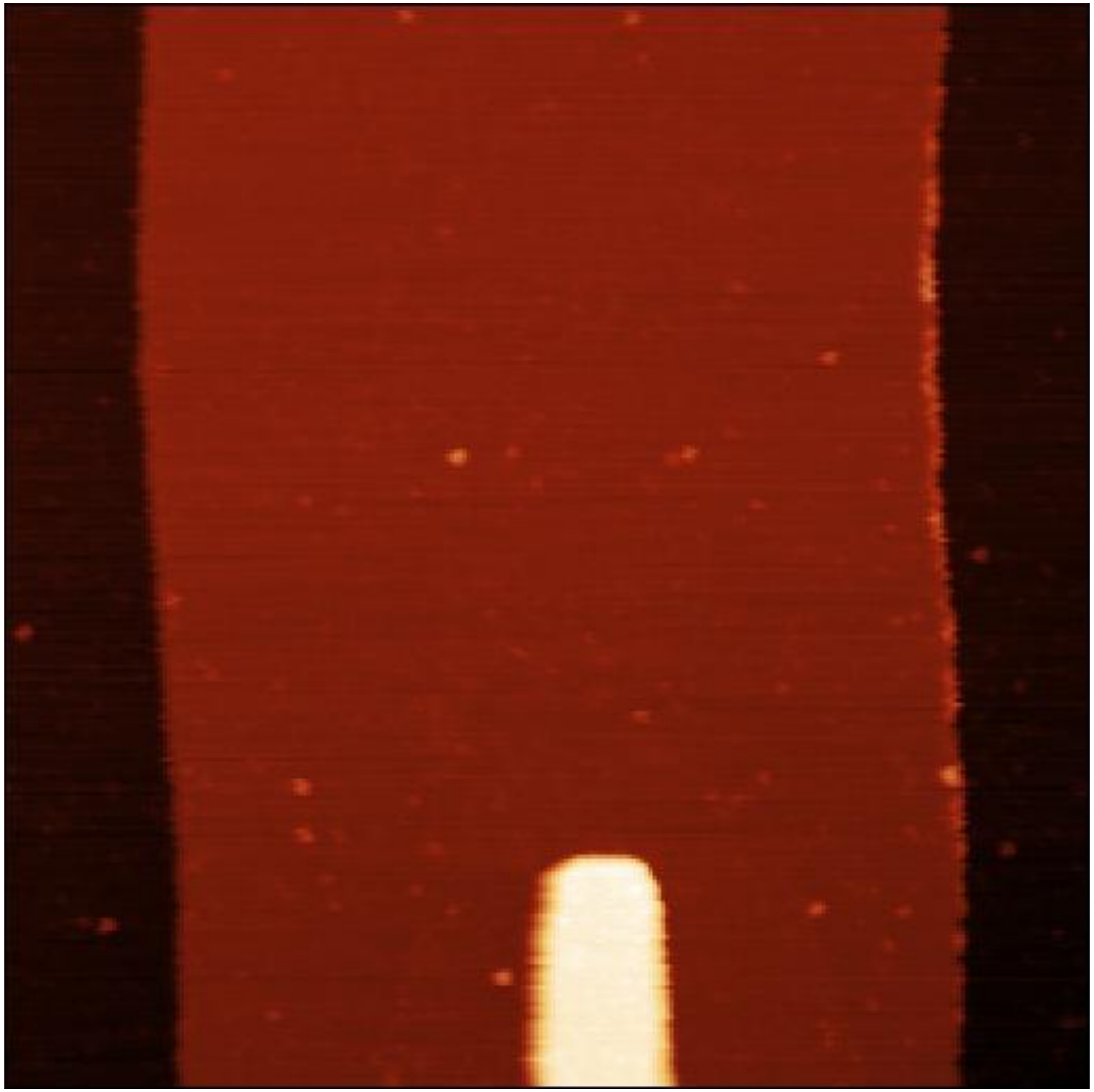
- Gyrovector independent of chirality
- Distribution of <u>winding numbers</u> in a classical bubble material

Skyrmion motion with no geometrical restrictions



6 ns, $J=3\times10^{11}$ A/m^2

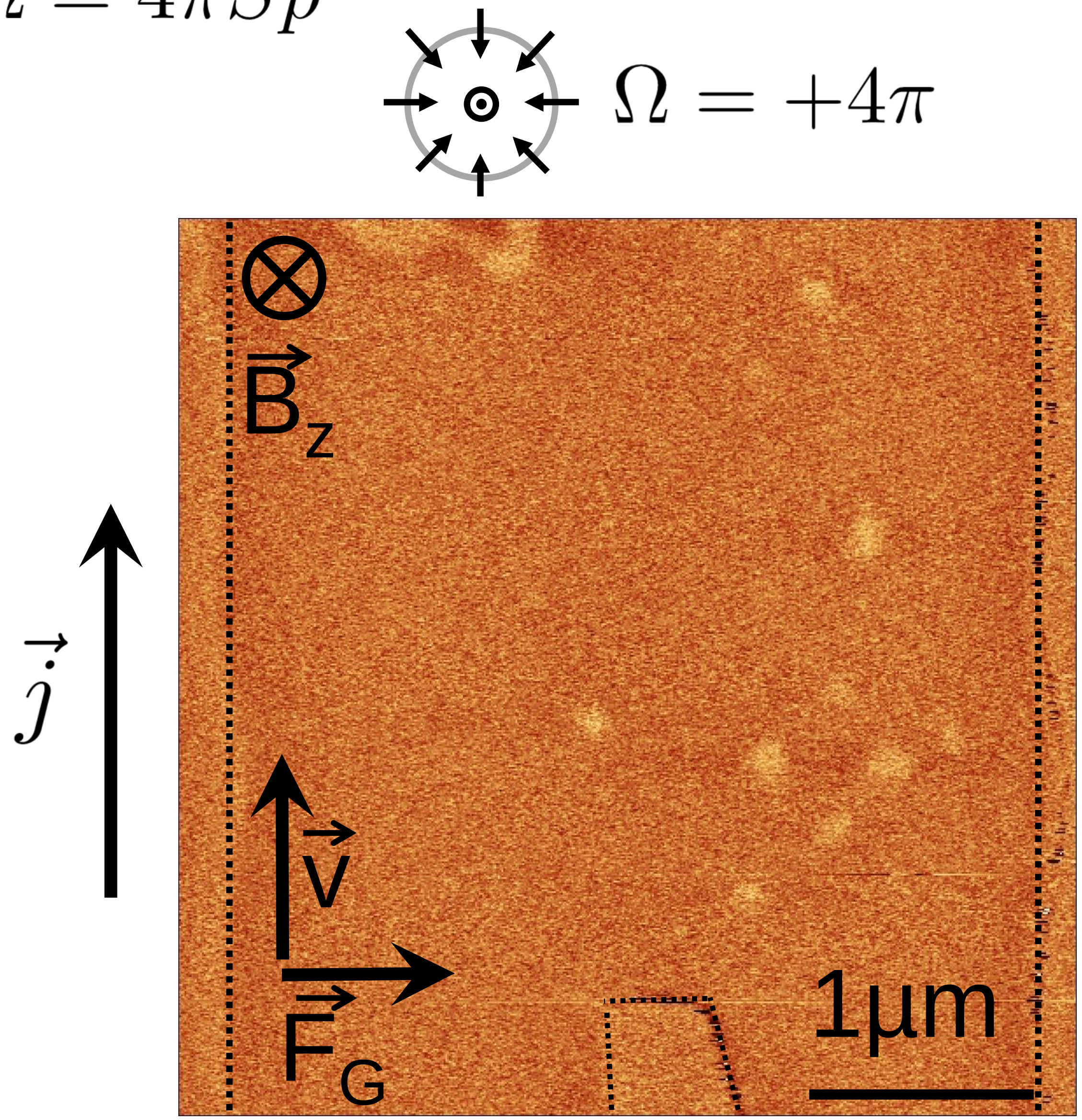
e^-



Gyrotropic force

$$\Omega = 4\pi S p$$

$$\Omega = +4\pi$$

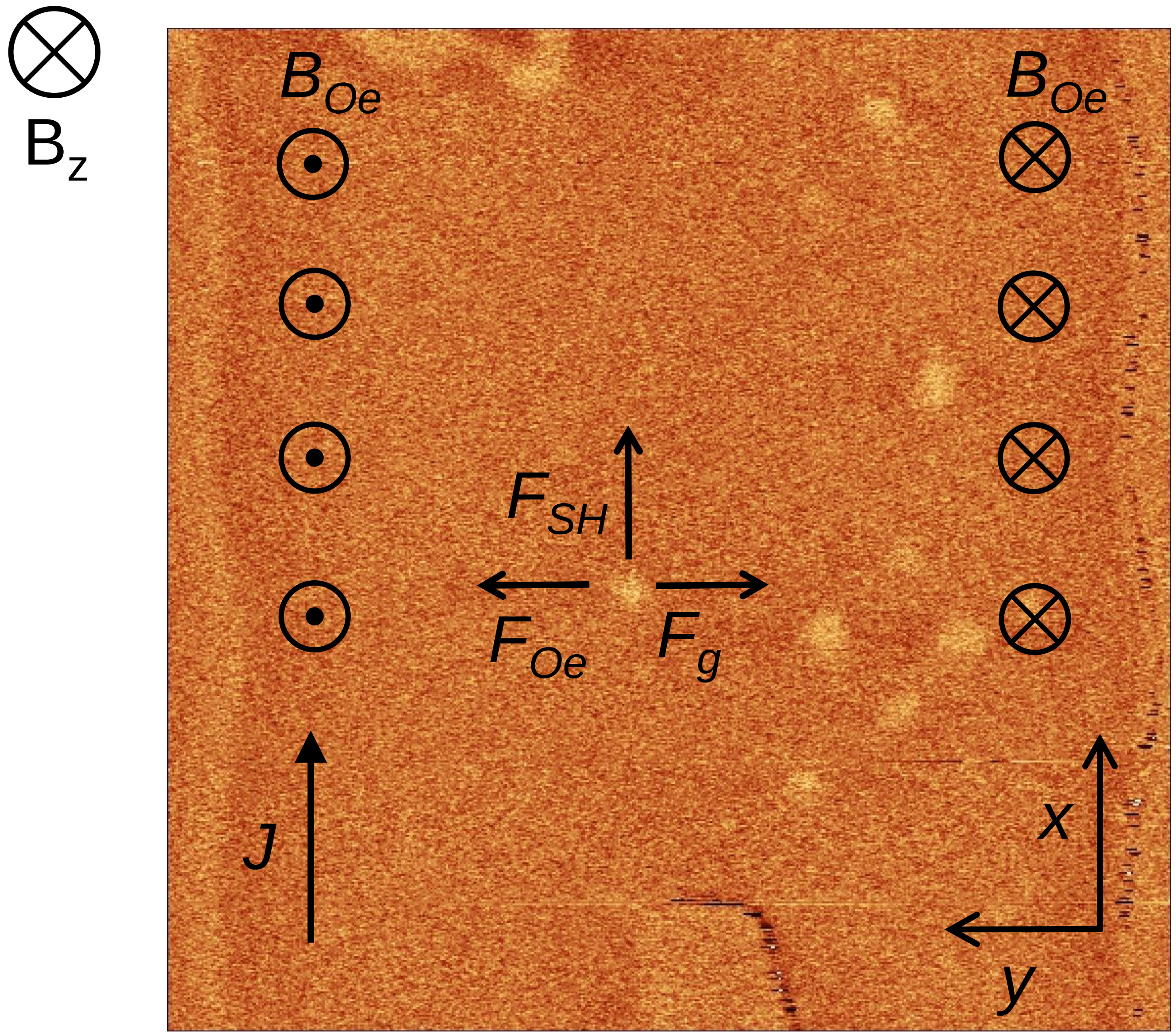


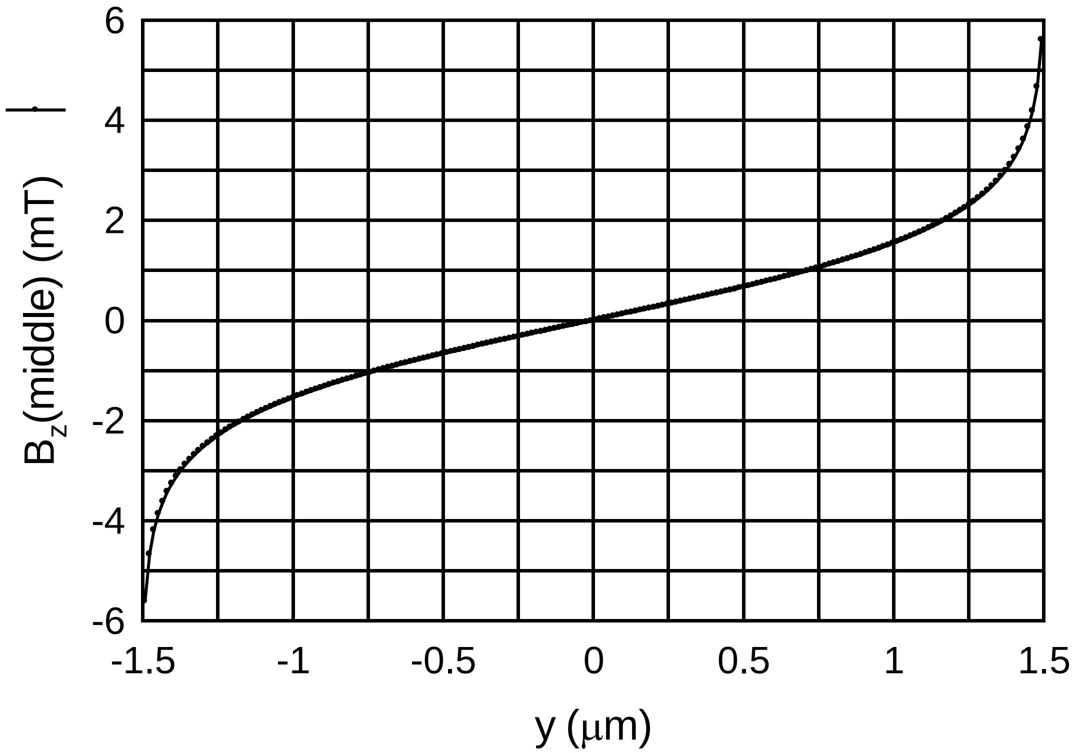
Jiang et al., Nature Phys. (2015)

Yu et al., Nano Lett (2016)

Litzius et al., Nature Phys. (2017)

Oersted field effect ?



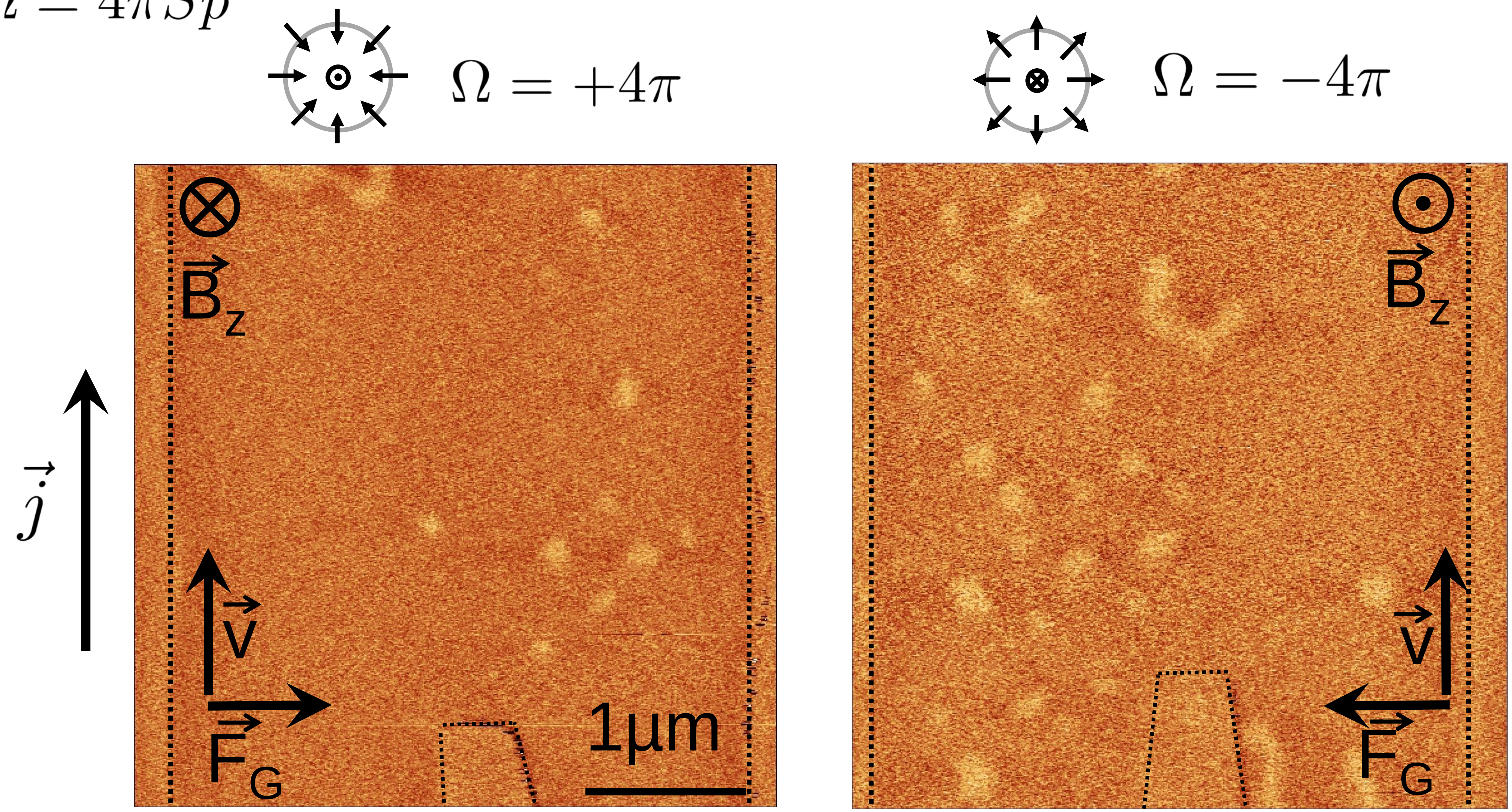


$$F_{\mathrm{SH}} = 21.4 \text{ pN}$$
$$F_{\mathrm{G}} = 11.0 \text{ pN}$$
$$F_{\mathrm{Oe}} = 2.0 \text{ pN}$$

- Oe force relatively small compared to the gyrotropic force
- Pointing in the opposite direction

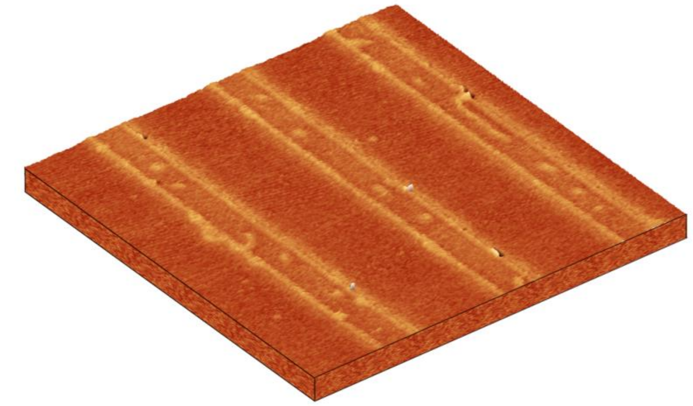
Gyrotropic force

$\Omega = 4\pi S p$

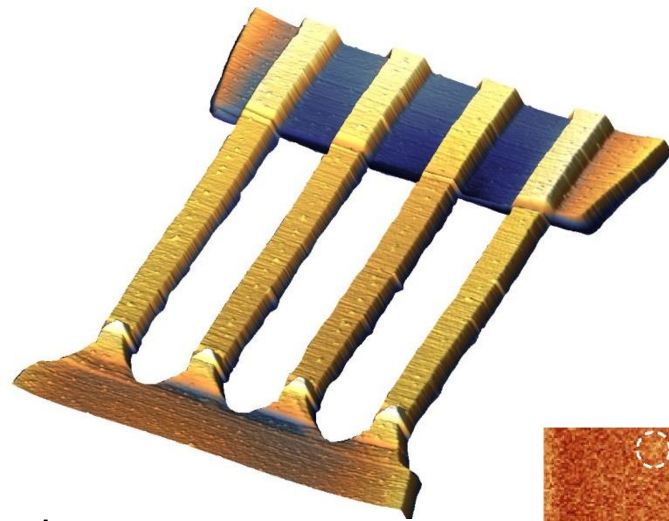


S=1 (…or at least S>0)

Conclusion



- Developing of a new system for isolated skyrmions phase, with additional magnetostatic stabilization

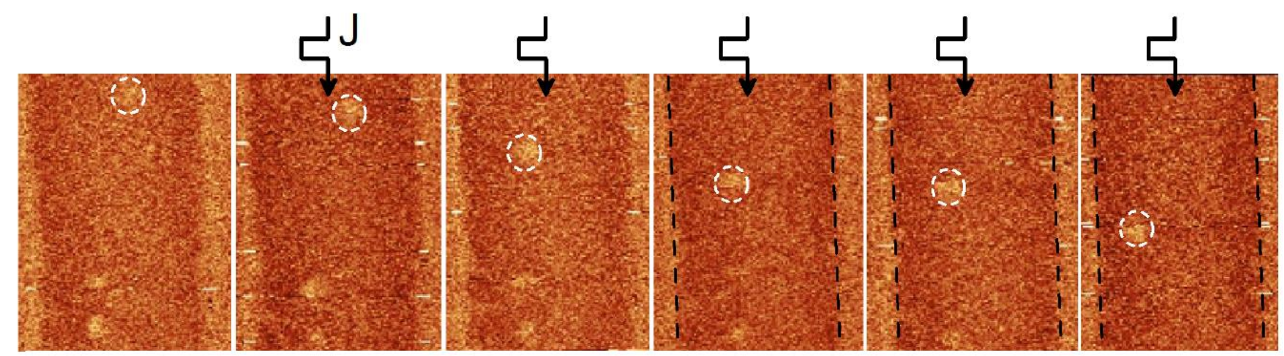


- Skyrmion generation

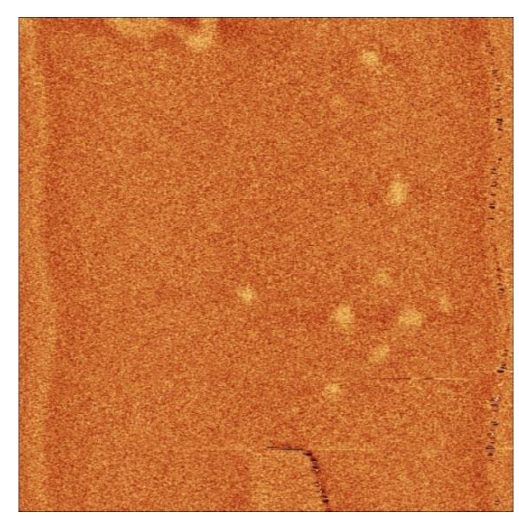
  and

- Skyrmion fast displacement

  in the same device



- Skyrmion deflection demonstration



ULTRASKY

References

- *Current-induced skyrmion generation and dynamics in symmetric bilayers*

A. Hrabec, J. Sampaio, M. Belmeguenai, I. Gross, R. Weil, S.M. Chérif, A. Stashkevich, V. Jacques, A. Thiaville, S. Rohart

Nat. Commun. 8, 15765 (2017)

- *Skyrmion morphology in ultrathin magnetic films*

I. Gross, W. Akhtar, A. Hrabec, J. Sampaio, L.J. Martinez, S. Chouaieb, B.J. Shields, P. Maletinsky, A. Thiaville, S. Rohart, V. Jacques

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