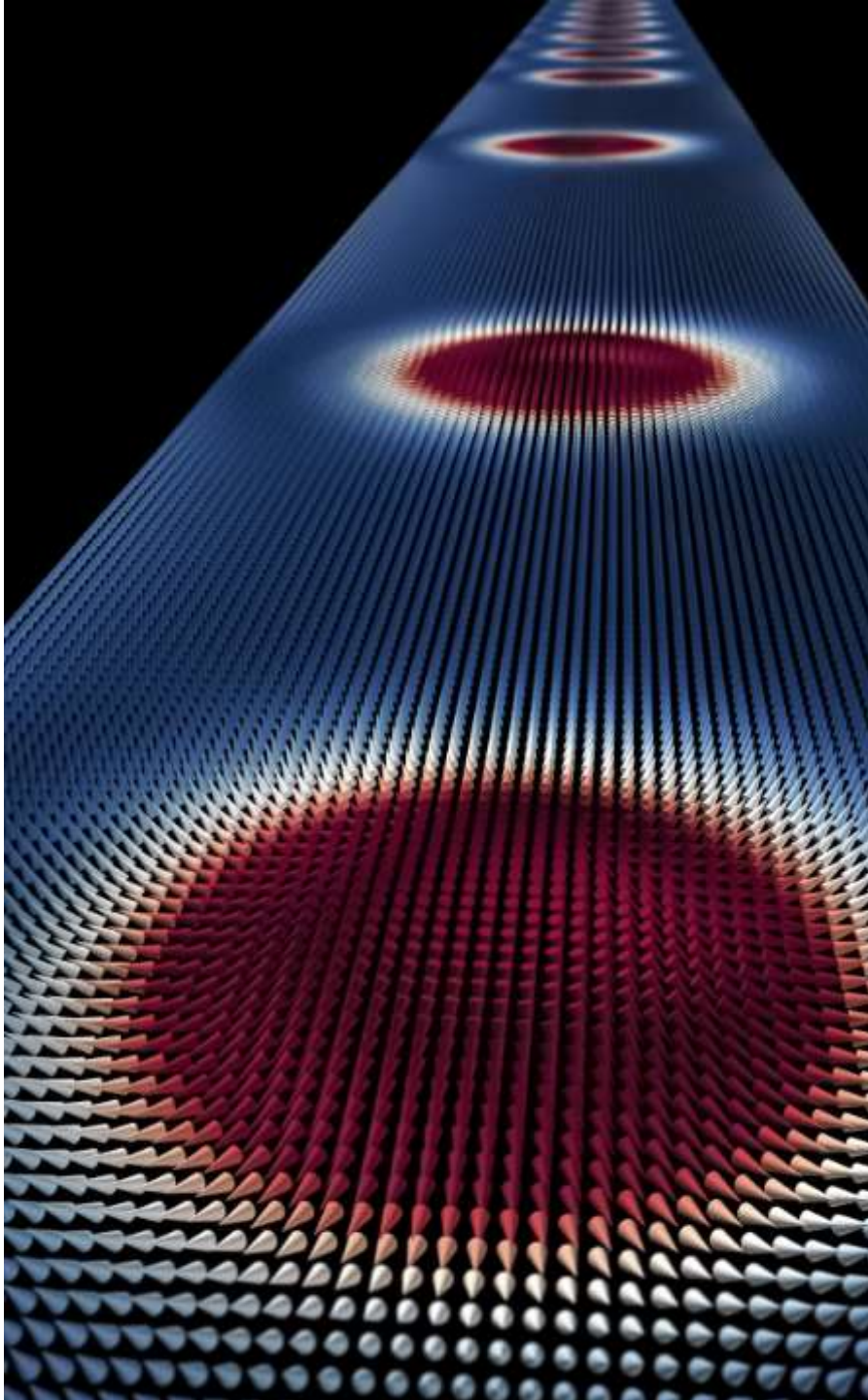
Magnetic Skyrmions (stabilized by interfacial DMI in thin metallic multilayers)

NICOLAS REYREN

http://www.cnrs-thales.fr



Acknowledgments





MAGic Sky

SKYTOP
Skyrmion-Topological Insulator and Weyl semimetal technology

ANR
TOPSKY

DARPA

Unité Mixte de Physique CNRS/Thales, France

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Swiss Light Source - PSI, Switzerland **(STXM)**

C. Moutafis^{+}, **J. Raabe**, C.A.F. Vaz, P. Warnicke, P. Wohlhütter

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Now at: * CEA Saclay ; ° UPV/EHU San Sebastian ; ^{x} LPS, Univ. Paris-Sud ; $^{+}$ Manchester University

Overview

Magnetic skyrmions

- topology and definitions
- Interfacial Dzyaloshinskii-Moriya interaction (DMI) and other energies - *reminders*

QUESTIONS

Technological motivation and technical means

- Skyrmions in metallic multilayers – principles and characterizations
- Means of observations of isolated skyrmions: STXM, L-TEM, MFM, etc.

QUESTIONS

External control of magnetic skyrmions

- Stability and nucleation means
- Skyrmion motion

QUESTIONS

- Skyrmion electrical detection
- Hybrid chirality (XRMS and L-TEM) and consequences

QUESTIONS

- Conclusion

BONUS - Perspectives for SAF systems
Detailed model for better predictions and experimental fit

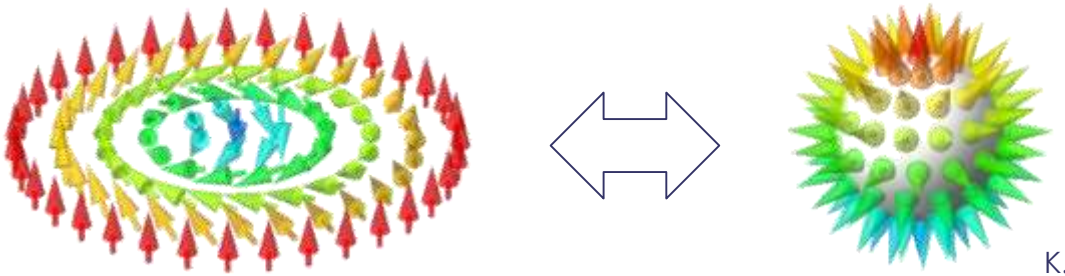
What is a Magnetic Skyrmion?

Remarkable properties:

- Topology different than the ferromagnetic state ("topological protection"):

$$N_{Sk} = \frac{1}{4\pi}\int_{uc} \hat{m}\cdot\left(\partial_x\hat{m}\times\partial_y\hat{m}\right)\mathrm{d}x\,\mathrm{d}y = \pm 1$$

3D spin texture lying in 2D plane

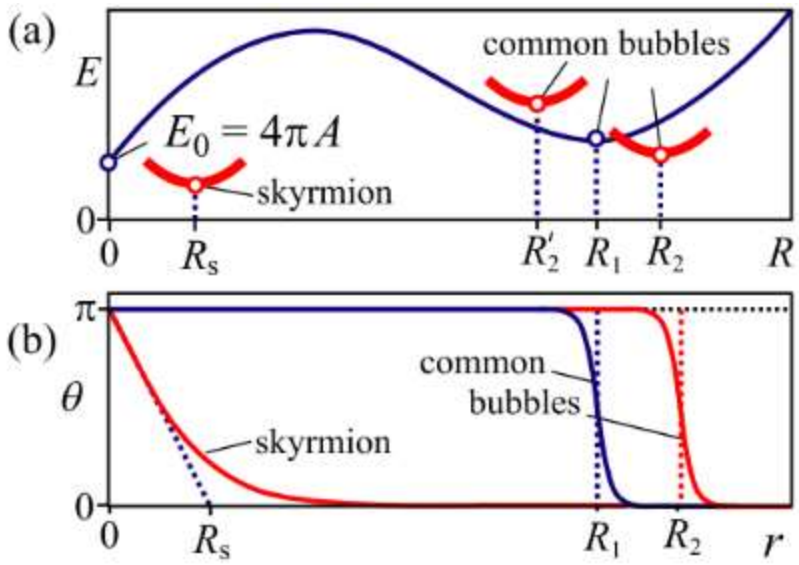


K. Everschor, thesis (2012)

- Behaves like a particle: soliton
- Size as small as a few crystalline lattice parameters

  → "…the smallest conceivable micromagnetic configuration."

N. S. Kiselev *et al*, *J. Phys. D: Appl. Phys.* **44**, 392001 (2011)

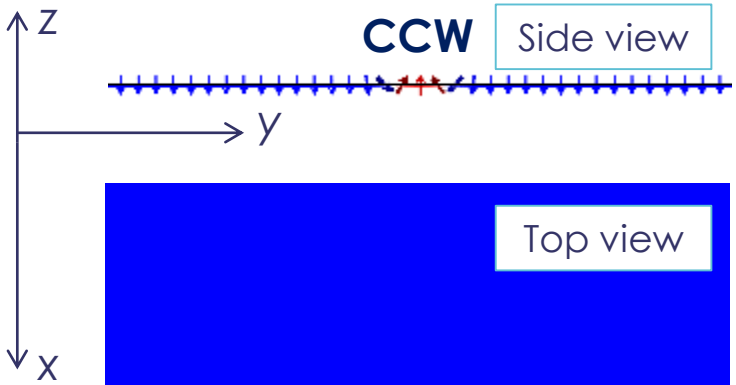


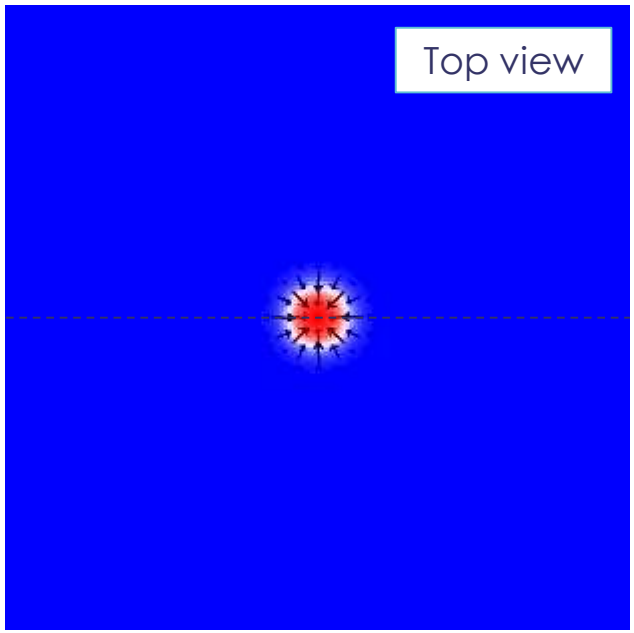
Topology of the Magnetic Skyrmions

The winding or skyrmion number

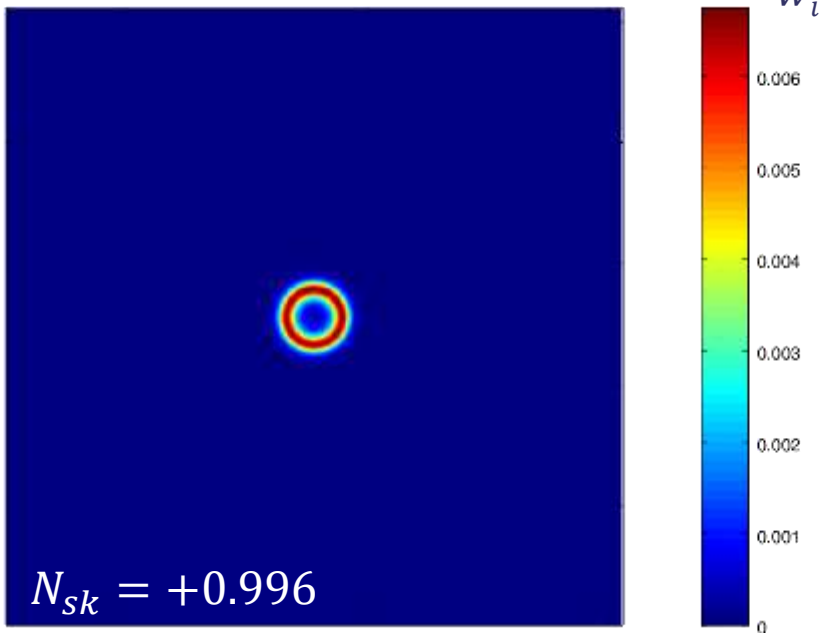
- Topology different than the ferromagnetic state ("topological protection"):

$$N_{Sk} = \frac{1}{4\pi}\int_{uc} \underbrace{\hat{m}\cdot\left(\partial_x\hat{m}\times\partial_y\hat{m}\right)}_{w_i} \mathrm{d}x\,\mathrm{d}y = \pm 1$$





magnetization



whirling

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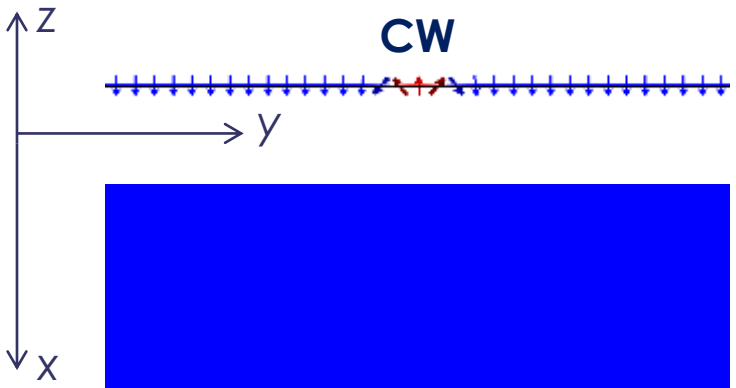
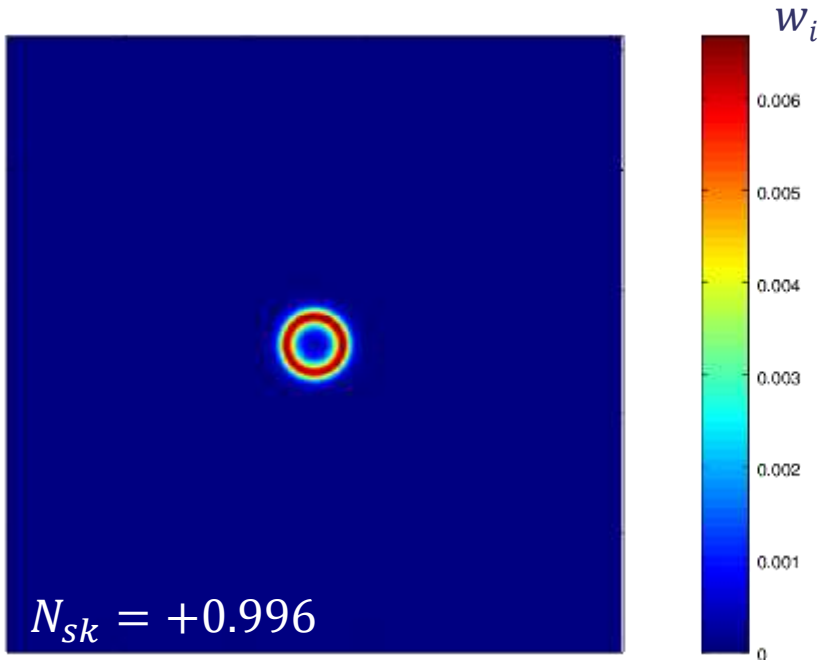


magnetization



whirling

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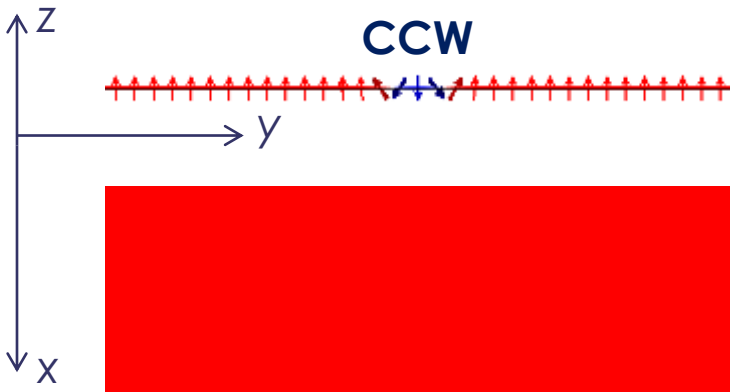
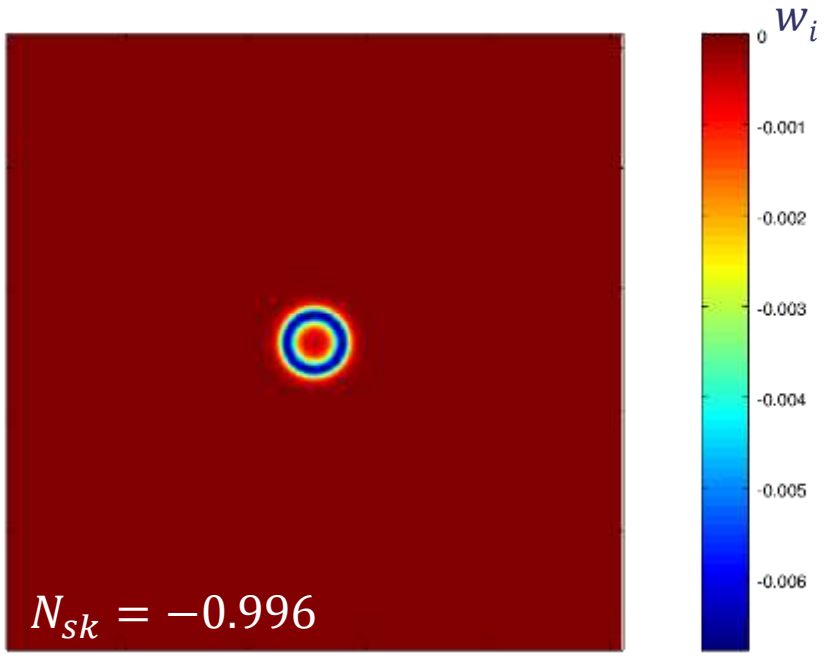


magnetization



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Topology of the Magnetic Skyrmions

The winding or skyrmion number

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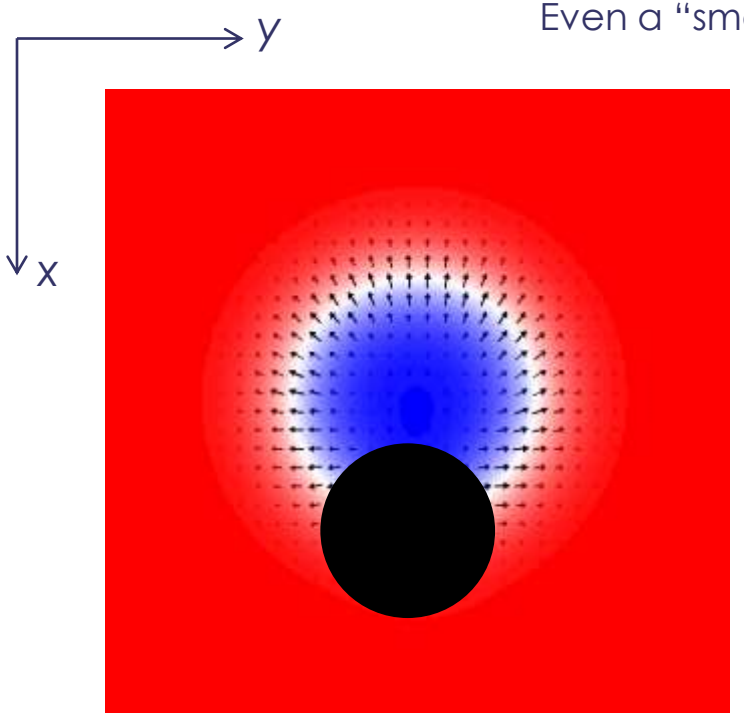
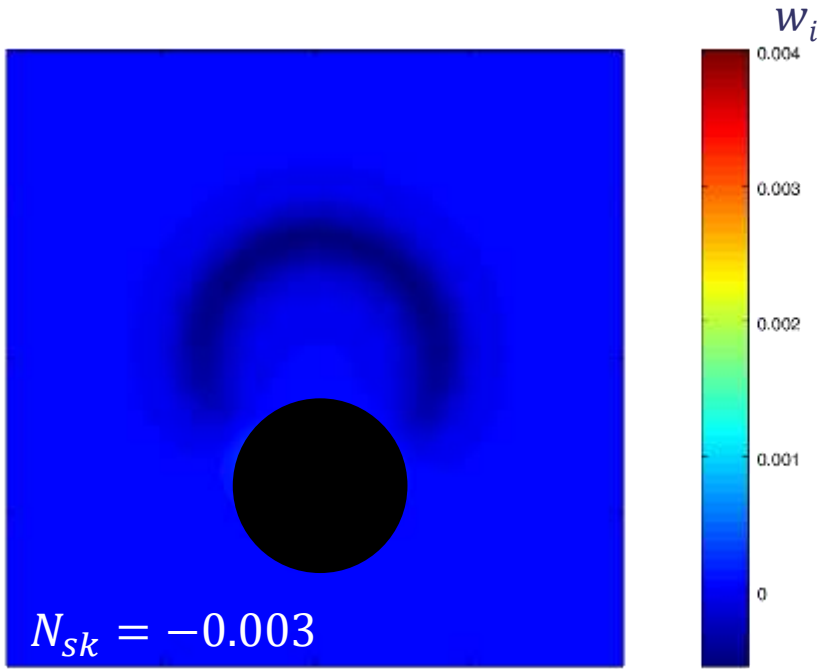
Even a "small" localized defect leads to zero winding



magnetization



whirling

Topology of the Magnetic Skyrmions

Winding number, vorticity, helicity, polarity, etc.

- Topology different than the ferromagnetic state ("topological protection"):

$$N_{Sk} = \frac{1}{4\pi}\int_{uc} \hat{m}\cdot\left(\partial_x\hat{m}\times\partial_y\hat{m}\right)\mathrm{d}x\,\mathrm{d}y = \pm 1$$

- If an axial symmetry (as expected for skyrmions) is considered:

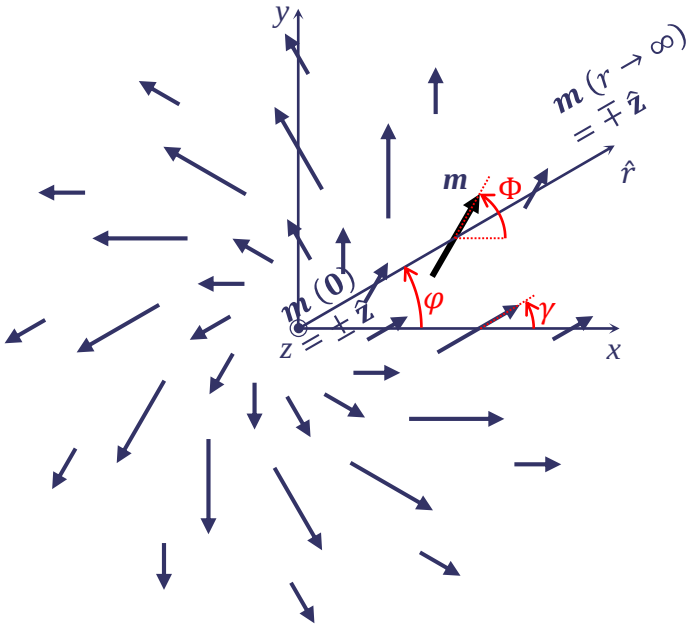
$$N_{Sk} = \frac{1}{4\pi}\int_0^{\infty} dr \int_0^{2\pi} d\varphi \frac{d\Theta(r)}{dr}\frac{d\Phi(\varphi)}{d\varphi}\sin\left(\Theta(r)\right) = \frac{1}{4\pi}\underbrace{\left[\cos\left(\Theta(r)\right)\right]_0^{\infty}}_{-2P}\underbrace{\left[\Phi(\varphi)\right]_0^{2\pi}}_{2\pi V}$$

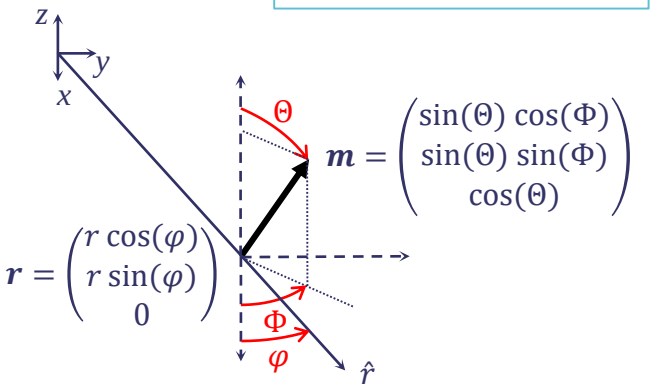
"core polarity" "vorticity"

$$\Phi(\varphi) = V\varphi + \underbrace{\gamma}_{\text{"helicity"}}$$

"chirality"

For skyrmions $V = 1$





N. Nagaosa and Y. Tokura, *Nat. Nanotechnol.* **8**, 899 (2013)
W. Legrand *et al*, *Phys. Rev. Appl.* **10**, 064042 (2018)

Topology of the Magnetic Skyrmions

Skyrmion zoo:

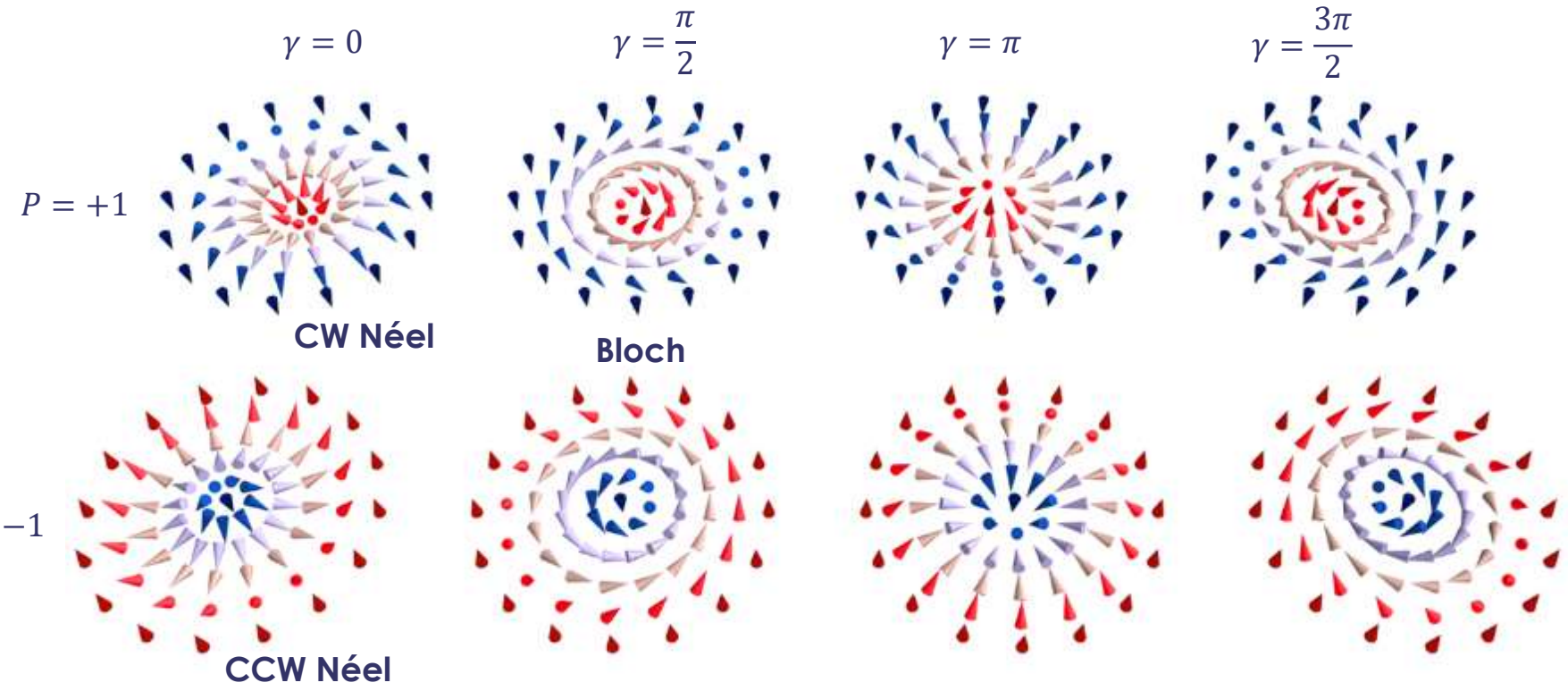
- If an axial symmetry is considered:

"core polarity" "vorticity" "chirality"

$$N_{Sk} = \frac{1}{4\pi}\int_0^{\infty} dr \int_0^{2\pi} d\varphi \frac{d\Theta(r)}{dr}\frac{d\Phi(\varphi)}{d\varphi}\sin(\Theta(r)) = \frac{1}{4\pi}\overbrace{\left[\cos\left(\Theta(r)\right)\right]_0^{\infty}}^{-2P}\overbrace{\left[\Phi(\varphi)\right]_0^{2\pi}}^{2\pi V}$$

$$\Phi(\varphi) = V\varphi + \overbrace{\gamma}^{\text{"chirality"}}$$

N. Nagaosa and Y. Tokura, *Nature Nanotechnol.* **8**, 899 (2013)



Is topology enough to define a skyrmion?

Remarkable properties:

- Topology different than the ferromagnetic state ("topological protection"):

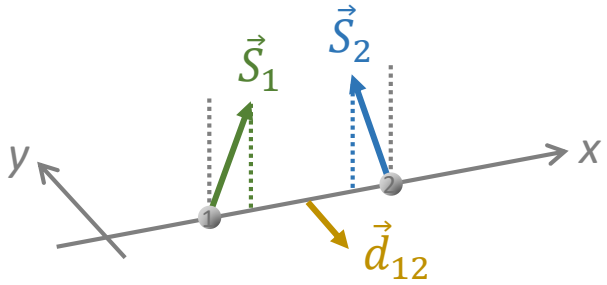
$$N_{Sk} = \frac{1}{4\pi}\int_{uc} \hat{m}\cdot\left(\partial_x\hat{m}\times\partial_y\hat{m}\right)\mathrm{d}x\,\mathrm{d}y = \pm 1$$

- Behaves like a particle (soliton)
- Size as small as a few crystalline lattice parameters

More stringent definition:

- Not stabilized by dipolar coupling only (unlike classical bubbles)
- Continuous rotation of the magnetization through the core
- Fixed chirality

$$H_{H+DM} = -J\sum(\vec{S}_i\cdot\vec{S}_j) - \sum\vec{d}_{ij}\cdot(\vec{S}_i\times\vec{S}_j)$$



Essential role of Dzyaloshinskii-Moriya interaction

Dzyaloshinskii-Moriya Interaction

Reminder from the *Spinorbitronics* lecture

Antisymmetric exchange term:

$$H_{H+DM} = -J\sum(\vec{S}_i \cdot \vec{S}_j) - \sum \vec{d}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$$

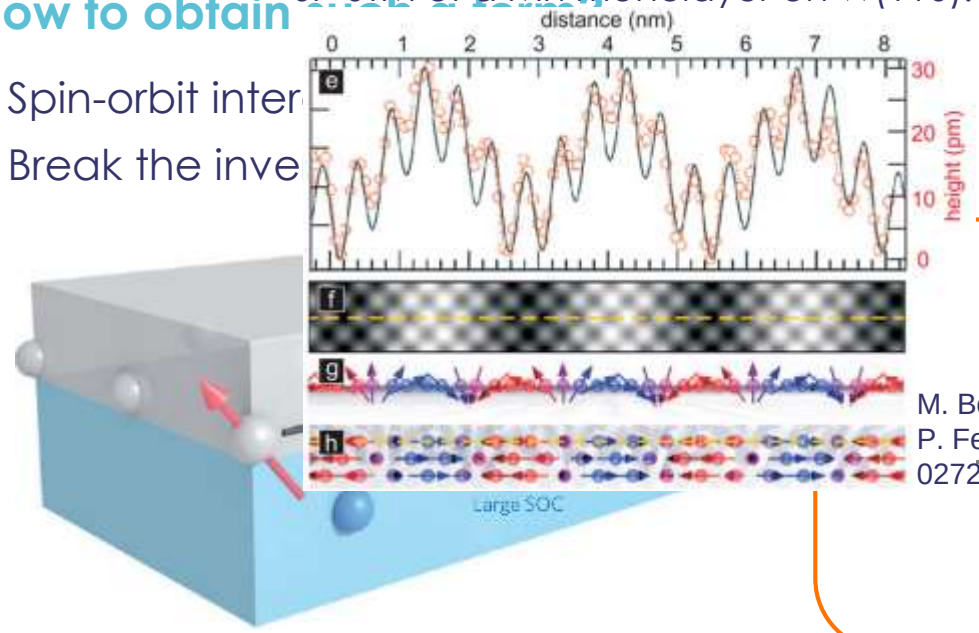
Exchange DMI

I. Dzyaloshinskii, *J. Phys. Chem. Solids* **4**, 241 (1958)
T. Moriya, *Phys. Rev. Lett.* **4**, 228 (1960)

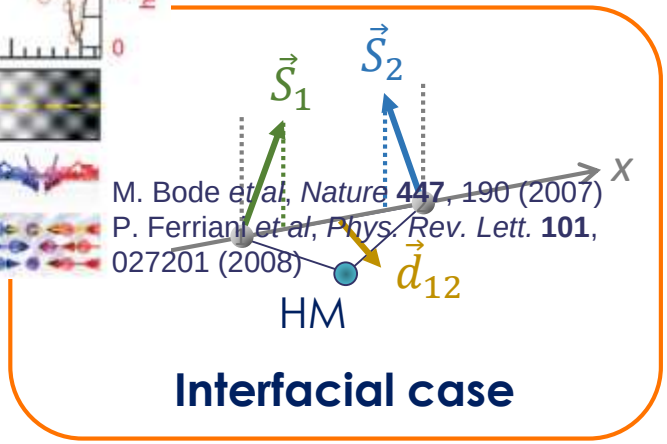
How to obtain such a term?

- Spin-orbit inter
- Break the inve

SP-STM of a Mn monolayer on W(110):



M. Bode *et al*, *Nature* **447**, 190 (2007)
P. Ferriani *et al*, *Phys. Rev. Lett.* **101**, 027201 (2008)



Interfacial case

A. Fert *et al*, *Nat. Nanotechnol.* **8**, 152 (2013)

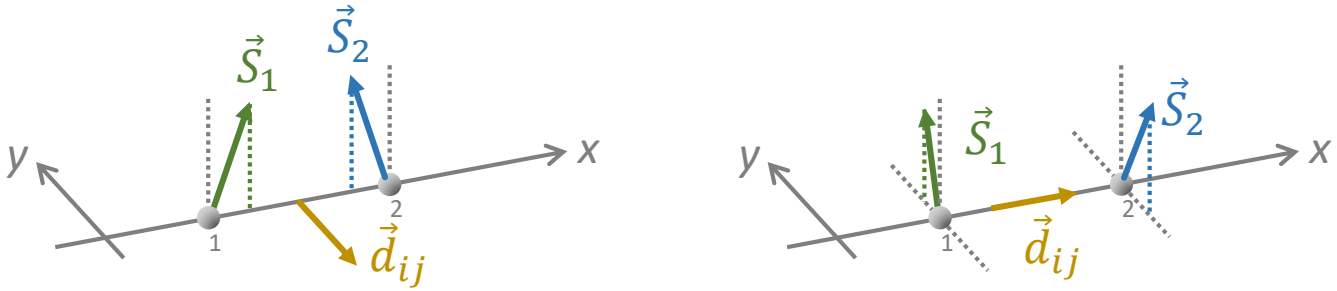
A. Fert, *Mater. Sci. Forum* **59-60**, 439 (1990)

Magnetic Skyrmions stabilized by DMI

Does topology change with DM vector direction?

$$H_{H+DM} = -J\sum(\vec{S}_i \cdot \vec{S}_j) - \sum \vec{d}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$$

Exchange DMI

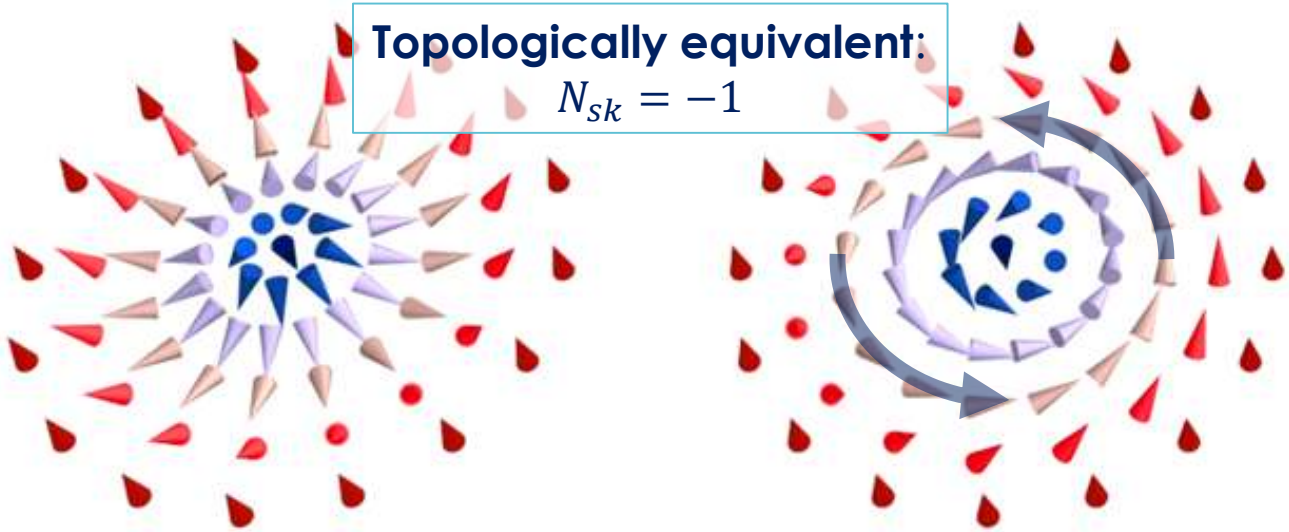


Topologically equivalent:

$N_{sk} = -1$

$P = -1$

$\gamma = 0$



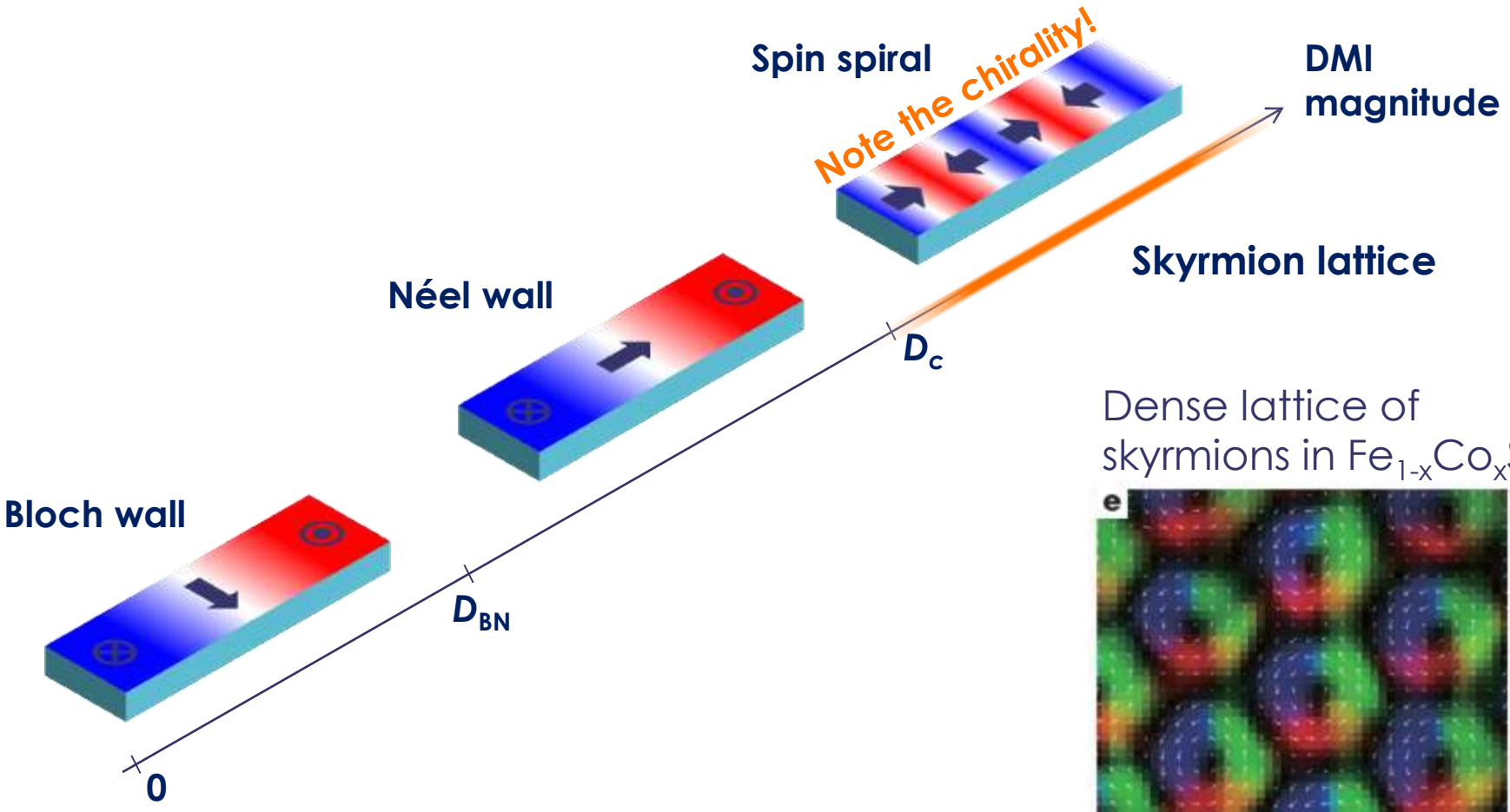
$P = -1$

$\gamma = \frac{\pi}{2}$

But different exchange DMI energy for a given type of DMI!

Dzyaloshinskii-Moriya Interaction

Reminder from the *Spinorbitronics* lecture



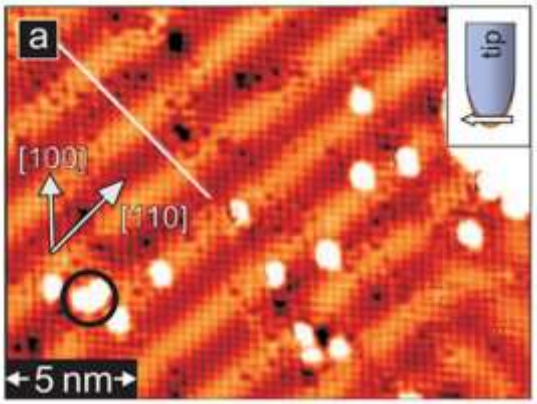
Dense lattice of skyrmions in $Fe_{1-x}Co_xSi$

X. Z. Yu *et al*, *Nature* **465**, 901 (2010)

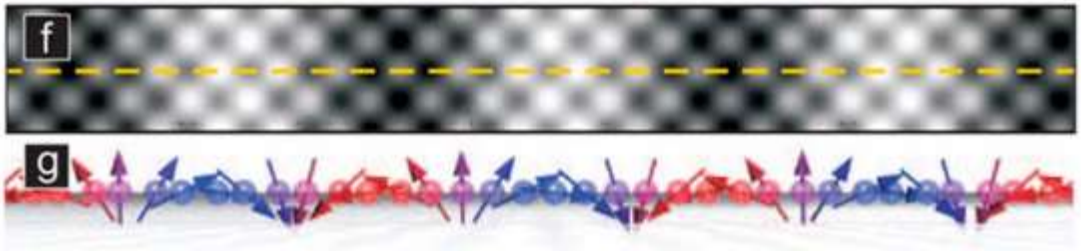
Dzyaloshinskii-Moriya Interaction (Strong Case $D > D_c$)

Consequences of the DMI

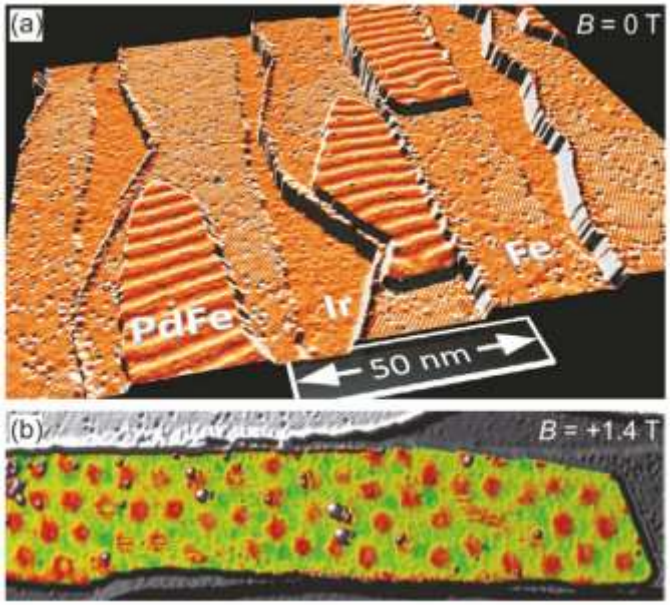
- Very strong DMI: Domain wall energy density ($\sigma_{DW} = 4\sqrt{AK} - \pi D$) is negative
- stabilize spin spirals, skyrmions, etc.



SP-STM observation of spin spirals in a monolayer of Mn on W (001)…



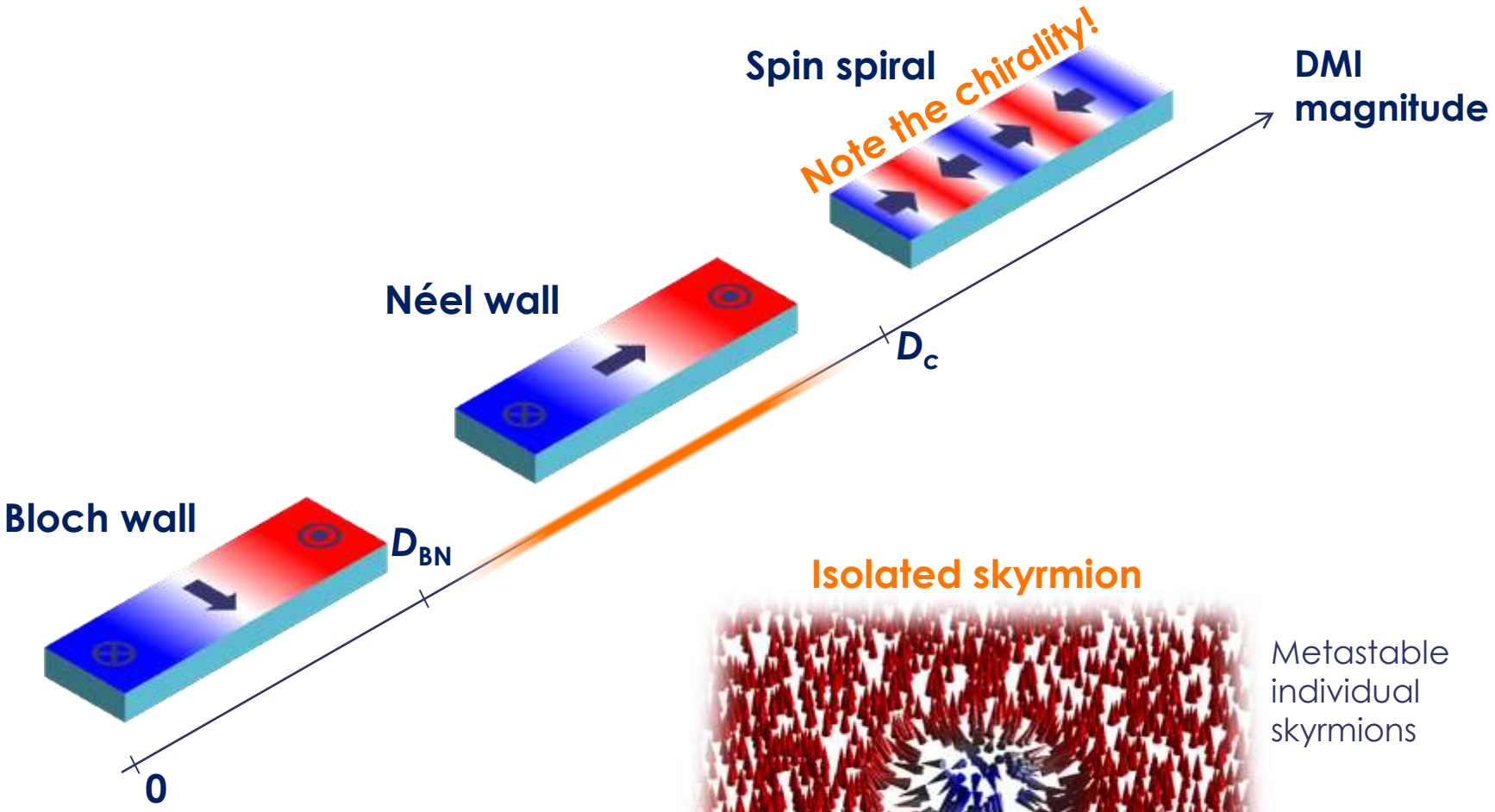
P. Ferrianni *et al*, *Phys. Rev. Lett.* **101**, 027201 (2008)



…and skyrmions in
Ir(111) | Fe (1 ML) | Pd (1 ML)

K. von Bergmann *et al*, *J. Phys.: Condens. Matter* **26**, 394002 (2014)

Dzyaloshinskii-Moriya Interaction

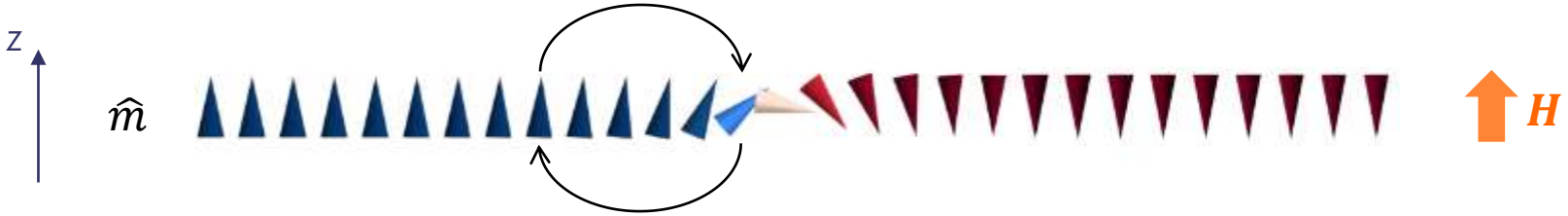


Isolated skyrmion

Metastable individual skyrmions

Other Energy Terms at Play: Anisotropy and Zeeman Energies

- $\hat{m}$ is continuous in space (micromagnetic approximation):
  → discrete differences turn into derivatives.
- Different interactions favour different magnetic configurations:
  → the magnetic textures result from delicate energy balance.
- The dipolar energy (or demagnetizing "demag" energy) is the tricky one! (Computationally expensive, non-local, …)

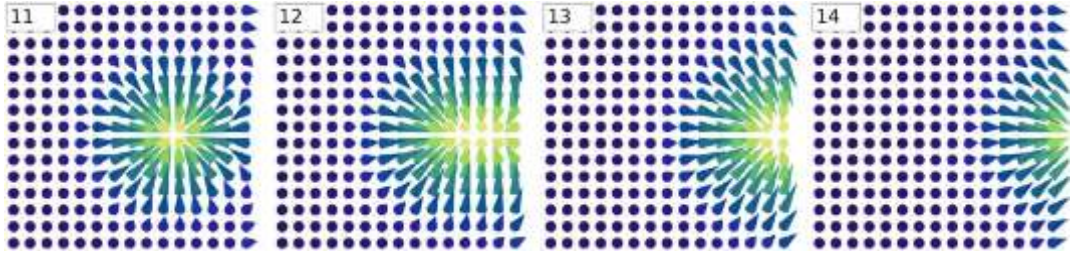


	Heisenberg exchange	Dzyaloshinskii-Moriya interaction	Perp. anisotropy	Zeeman
Atomistic formulation	$J\sum(\vec{S}_i \cdot \vec{S}_j)$	$\sum \vec{d}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$	$K_u \sum(\hat{z} \cdot \vec{S}_i)^2$	$\mu \sum(\vec{H} \cdot \vec{S}_i)$
Micromagnetic energy density	$E_A = A\left(\frac{\partial m_i}{\partial x_j}\right)^2$	$E_D = D(m_z \operatorname{div} \hat{m} - (\hat{m} \cdot \nabla) m_z)$	$E_K = K_u (m_z)^2$	$E_z = M_s \mu_0 \vec{H} \cdot \hat{m}$
	$E($  $) < E($  $)$	$E($  $) < E($  $)$	$E($  $) < E($ $)$	$E($  $) < E($  $)$

Topological Protection?

Mathematical concept in the continuous magnetization limit

- Impossible to unwind an isolated skyrmion in an infinite film.
- Possibility at edges of magnetic films (1D demo)



In practice, there is a barrier of a few *J* at the edge.

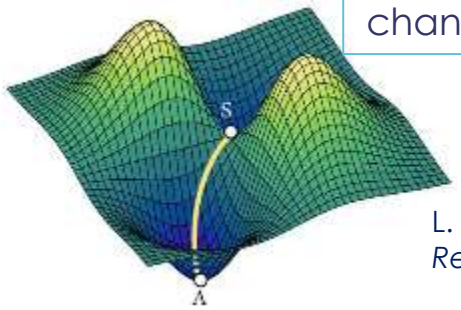
L. Desplat *et al*,
Phys. Rev. B **98**, 134407 (2018)

Real system is "discrete"

Final exchange energy

- Even in the micromagnetic limit,
  the energy barrier is expected to
  be finite and approx. equal to $8\pi At$.

"Attempt rate" might change with topology



L. Desplat *et al*, *Phys. Rev. B* **98**, 134407 (2018)

S. Rohart *et al*, *Phys. Rev. B* **93**, 214412 (2016)
F. Büttner *et al*, *Sci. ReP.* **8**, 4464 (2018)

Skyrmion Lifetime

Arrhenius expression for transition rate

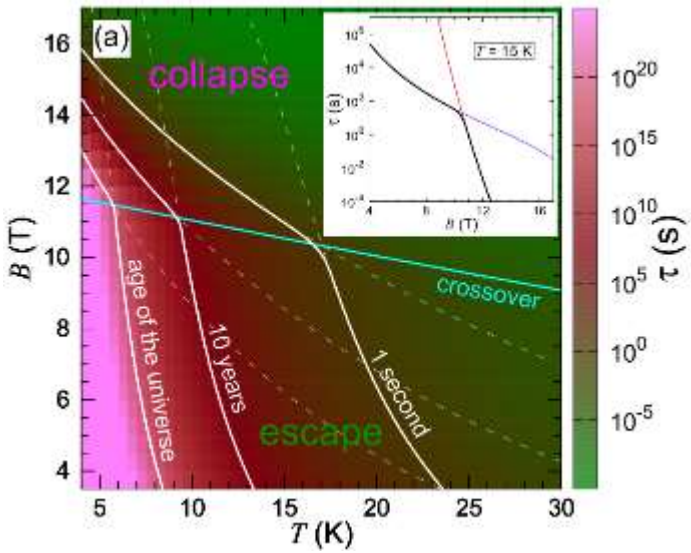
$$\frac{1}{\tau} = \nu(T, B, \ldots) \exp\left(-\frac{\Delta E}{k_B T}\right)$$

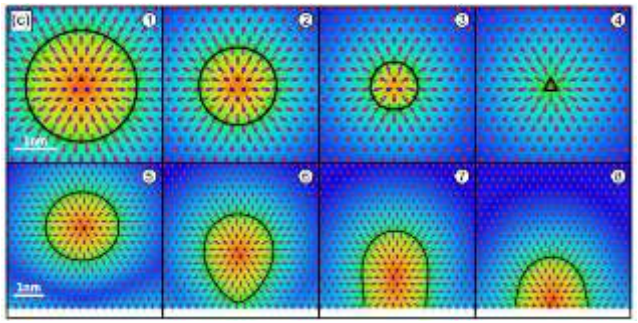
Energy barrier

Attempt frequency

What is the attempt frequency?

- It depends on the different annihilation paths (in the energy landscape), and hence on the detailed annihilation conditions (*e.g.* proximity to the edge in a skyrmion racetrack).





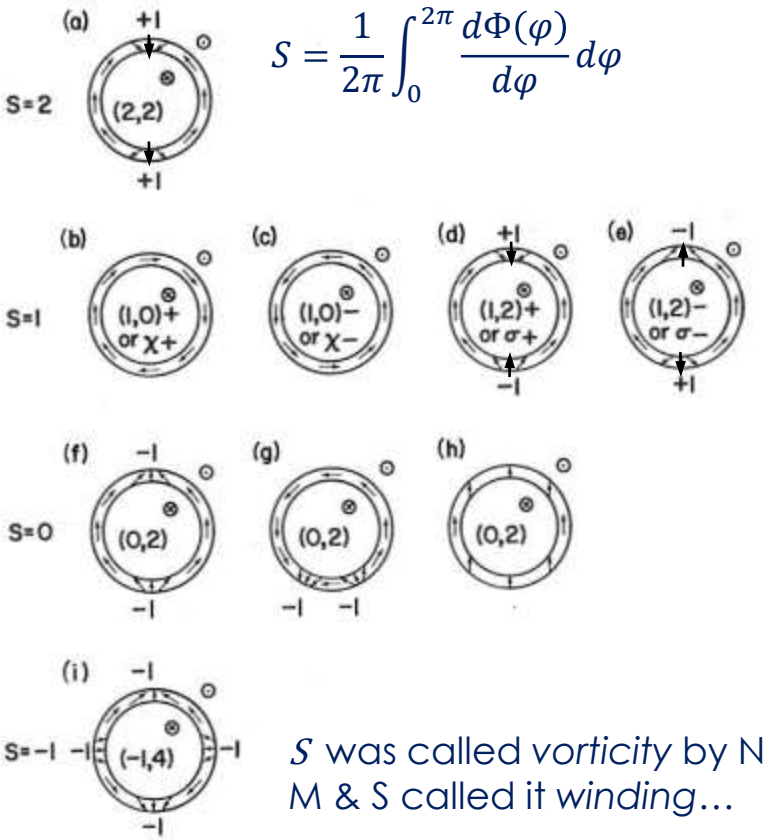
Lifetime of a skyrmion calculated (*ab initio*) in a Pd/Fe/Ir(111) racetrack (atomistic, fcc stacking).

P. S. Bessarab *et al*, *Sci. Rep.* **8**, 3433 (2018)

Question session

My Question: "*How to distinguish chiral bubble from skyrmions?*"

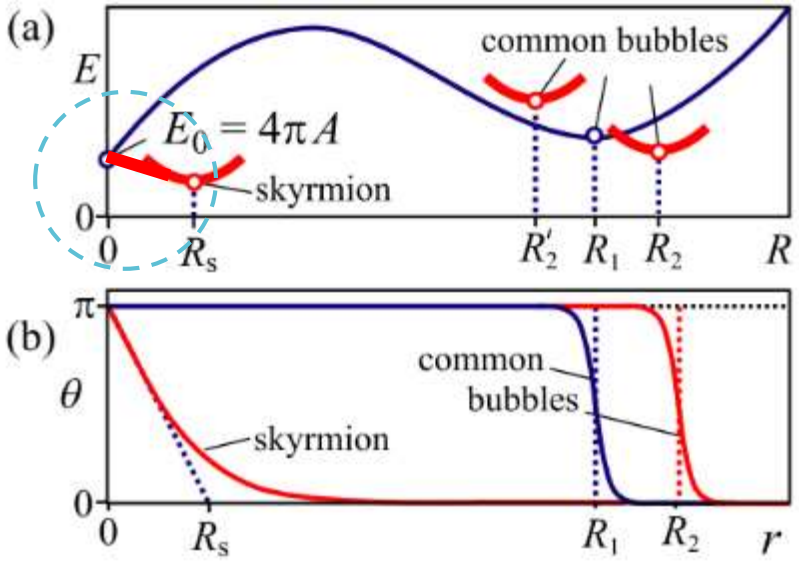
The topology was already discussed at the "magnetic bubble time"



S was called *vorticity* by N & T, M & S called it *winding*…

Fig. 8.5. Schematic illustrations of selected bubble wall states viewed from the $+z$ direction (bias-field direction). Conventional state notation is indicated inside the bubble, and the winding number S [Eq. (8.22)] is given on the left. ± 1 beside each Bloch line is the handedness index [Eq. (8.23)].

A. P. Malozemoff & J. C. Slonczewski, "*Magnetic Domain Walls in Bubble Materials*", Academic Press, 1979.

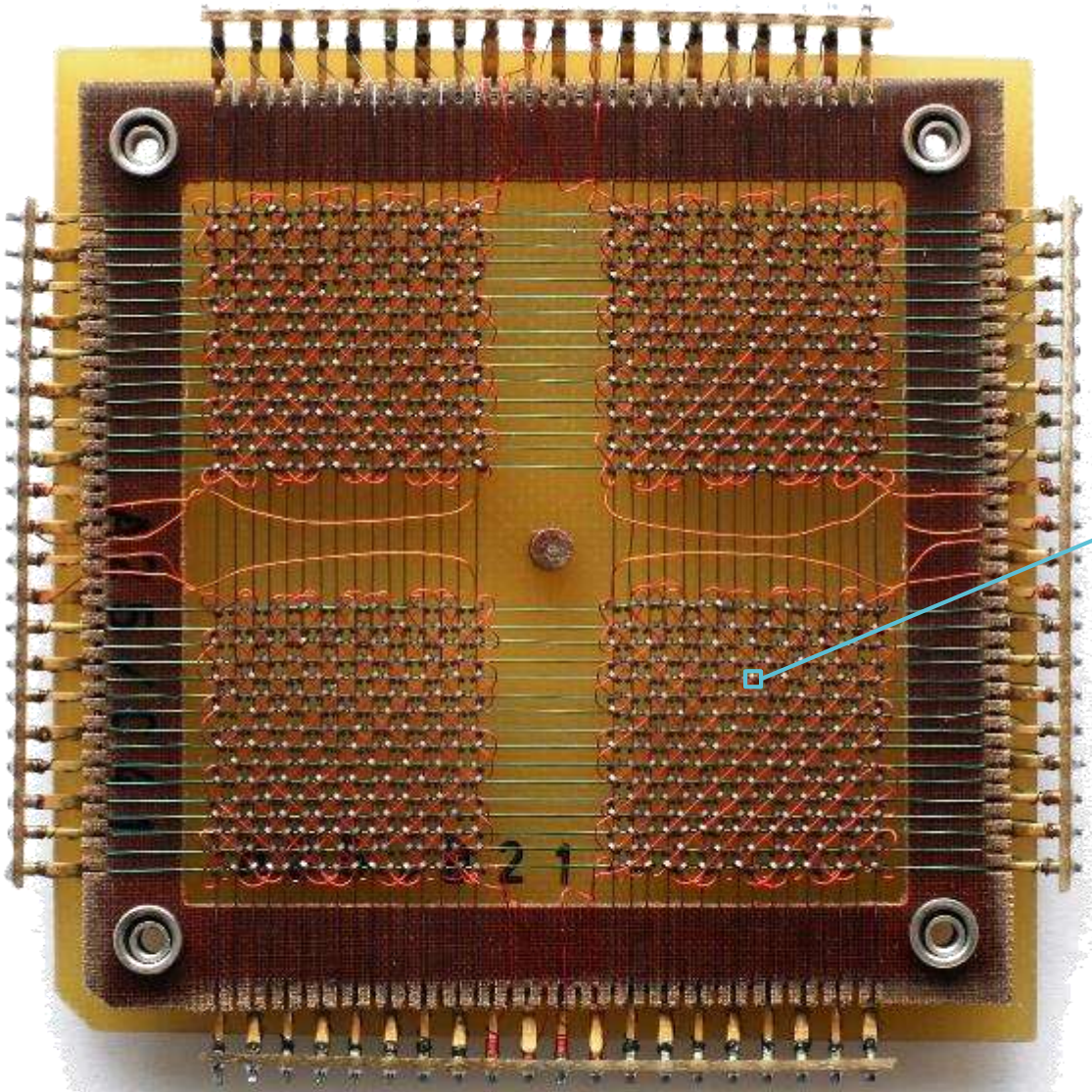


N. S. Kiselev *et al*, *J. Phys. D: Appl. Phys.* **44**, 392001 (2011)

Roughly:
dE/dR<0 needs an energy term that decreases with radius for small radius: the DMI!

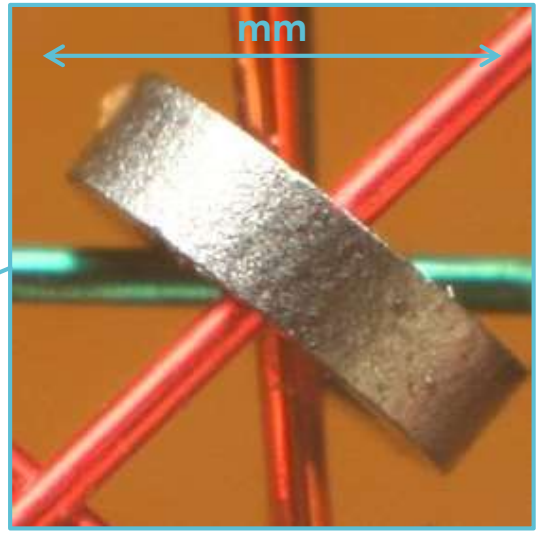
Technological motivation

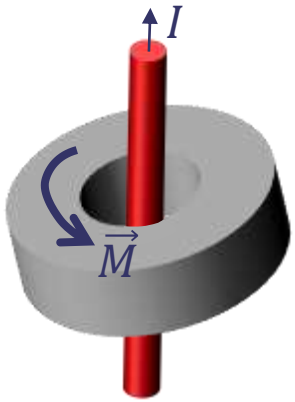
Magnetic Memories 1955~1975



A 32 x 32 core memory plane storing 1024 bits of data.

Reach 32 kB at 1 MHz in the 70's.





These types of memory were used in place with high level of radiations, *e.g.* the space shuttle.

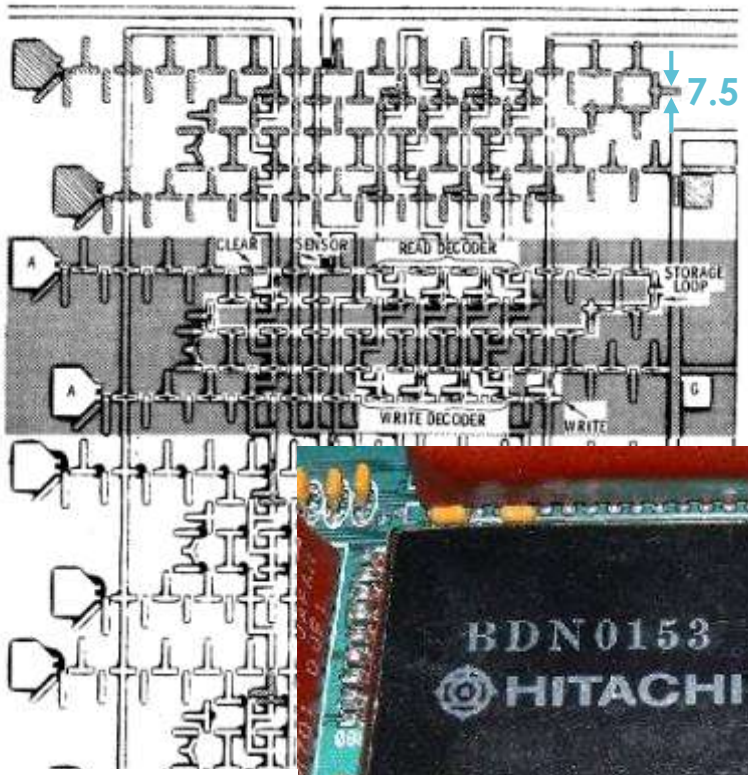
https://en.wikipedia.org/wiki/Magnetic-core_memory

Bubble Memories

FABRICATION AND OPERATION OF A SELF-CONTAINED BUBBLE DOMAIN MEMORY CHIP*

G.S. Almasi, B.J. Canavello, E.A. Giess, R.J. Hendel, R.E. Horstmann,
T.F. Jamba**, G.E. Keefe, J.V. Powers, and L.L. Rosier
IBM Thomas J. Watson Research Center, Yorktown Heights, N.Y. 10598

* Supported in part by NASA contract NAS-8-26671



Demonstration device 1971

https://www.gsalmasi.com/almasiconsulting/bubbles/chip2.html

Hitachi 4 Mb BDN0153 bubble memory module

Bubble-Memory Board Protects Data In the Face of Adverse Conditions

Magnetic disk media are not designed to operate reliably in many industrial or otherwise-unfriendly work environments. The PCH-3 Bubbl-Board, $1,257 with ½ megabyte of RAM, from the **Bubbl-Tec** division of **PC/M**, is aimed at just such difficult applications.

The board provides up to 1½ megabytes of nonvolatile mass storage on a standard full-length PC adapter card, and it is unaffected by dust, smoke, and airborne dirt, Bubbl-Tec says.

Expansion to 6 megabytes is possible with available add-on boards, and removable bubble-cassette capability can be added with Bubbl-Tec's BD-series Bubbl-Dek.

Access time of the PCH-3 system averages below 20 milliseconds, and the effective data transfer rate to and from the bubble device exceeds 190K bits per second. System power is derived from the host PC bus.

List Price: PCH-3 Bubbl-Board, with 1½ Mbytes of on-board storage, $2,297; with 1 Mbyte, $1,789; with ½ Mbyte, $1,257. Bubbl-Tec, 6805 Sierra Ct., Dublin, CA 94568; (415) 829-8700.

CIRCLE 429 ON READER SERVICE CARD

Adverse operating conditions that rule out magnetic disk media are less of a problem for the PCH-3 Bubbl-Board, from Bubbl-Tec. The board can be configured with up to 1½ megabytes of nonvolatile RAM ($2,297).

PC MAGAZINE ■ MARCH 31, 1987
45

http://www.wylie.org.uk/technology/computer/bubblmem/bubblmem.htm

From Theory to Actual Experiments…

A source of excitement:

Skyrmions on the track

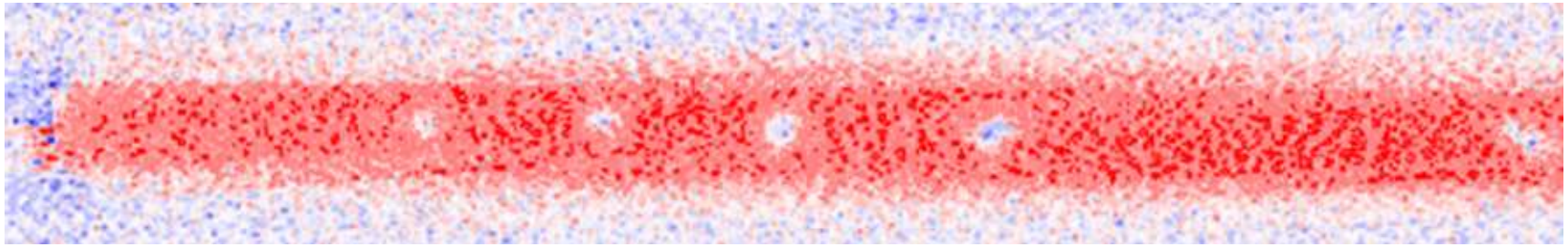
Albert Fert, Vincent Cros and João Sampaio

Magnetic skyrmions are nanoscale spin configurations that hold promise as information carriers in ultradense memory and logic devices owing to the extremely low spin-polarized currents needed to move them.

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

J. Sampaio *et al*, *Nat. Nanotech*. **8**, 839 (2013)

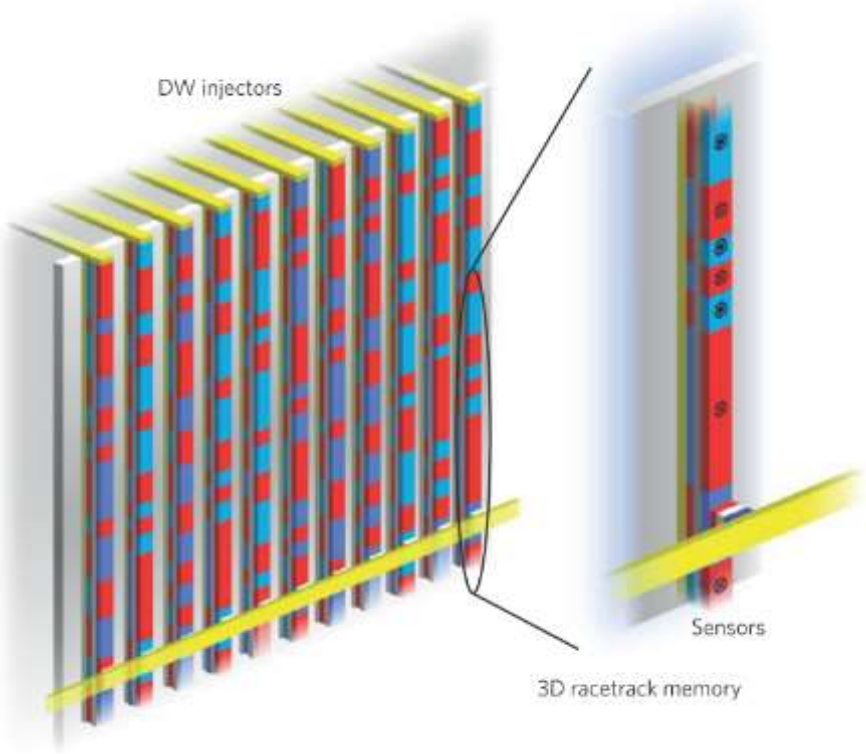
2013-2016, from numerical simulations to actual experiments:



C. Moreau-Luchaire *et al*, *Nat. Nanotech*. **11**, 444 (2016)

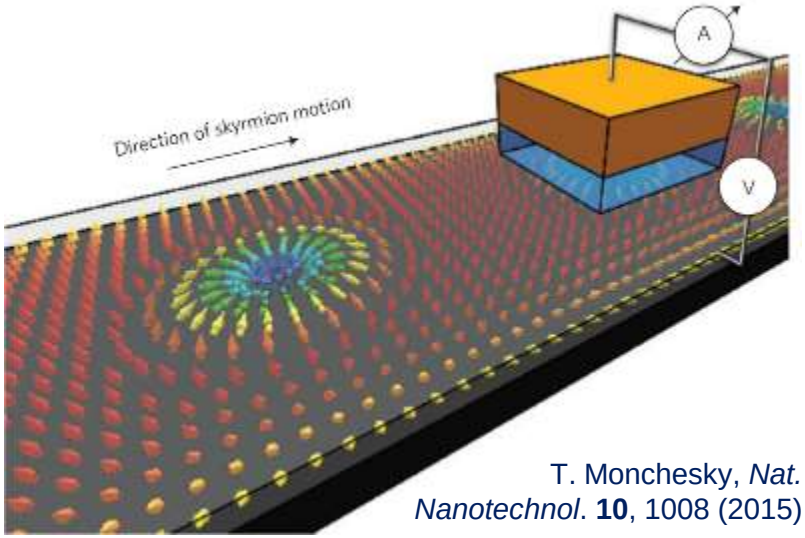
Possible Application

Racetrack-memory… a shift register memory



S. Parkin, M. Hayashi, L. Thomas, *Science* **320**, 190 (2008)
S. Parkin, S.-H. Yang, *Nat. Nanotechnol*. **10**, 195 (2015)

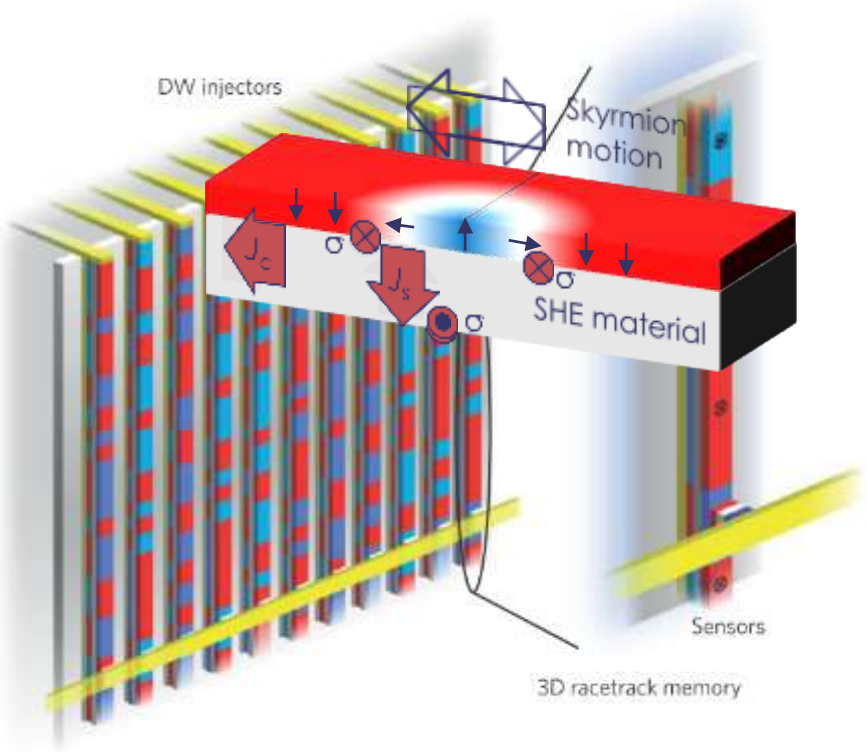
- *Hard disk on a chip*, no moving parts
- Resistant against vibrations, radiations, etc.
- Simple lithography in 2D
- Possibility of 3D architecture → huge information density
- Speed between HDD and DRAM.



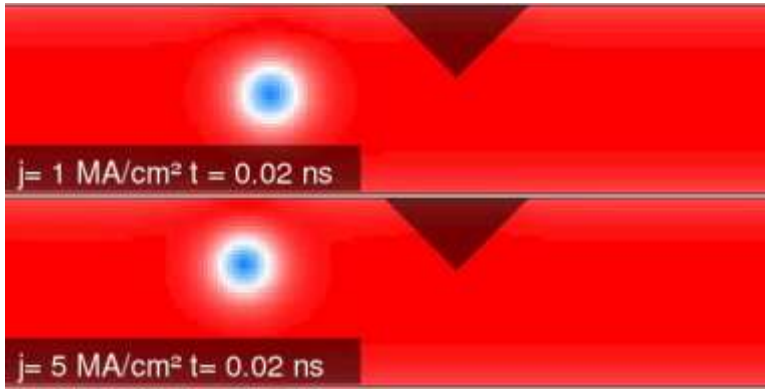
T. Monchesky, *Nat. Nanotechnol*. **10**, 1008 (2015)

Possible Application

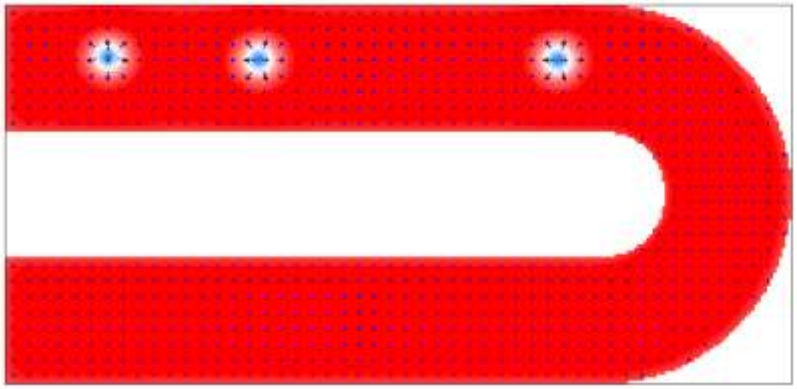
Racetrack-memory… domains versus skyrmions



- Less sensitive to edge defects



- Better behavior around sharp turns



S. Parkin, M. Hayashi, L. Thomas, *Science* **320**, 190 (2008)
S. Parkin, S.-H. Yang, *Nat. Nanotechnol*. **10**, 195 (2015)

J. Sampaio *et al*, *Nat. Nanotechnol*. **8**, 839 (2013)

Other Type of Devices

Multiple states memory

- Increase memory density.

Logical operation

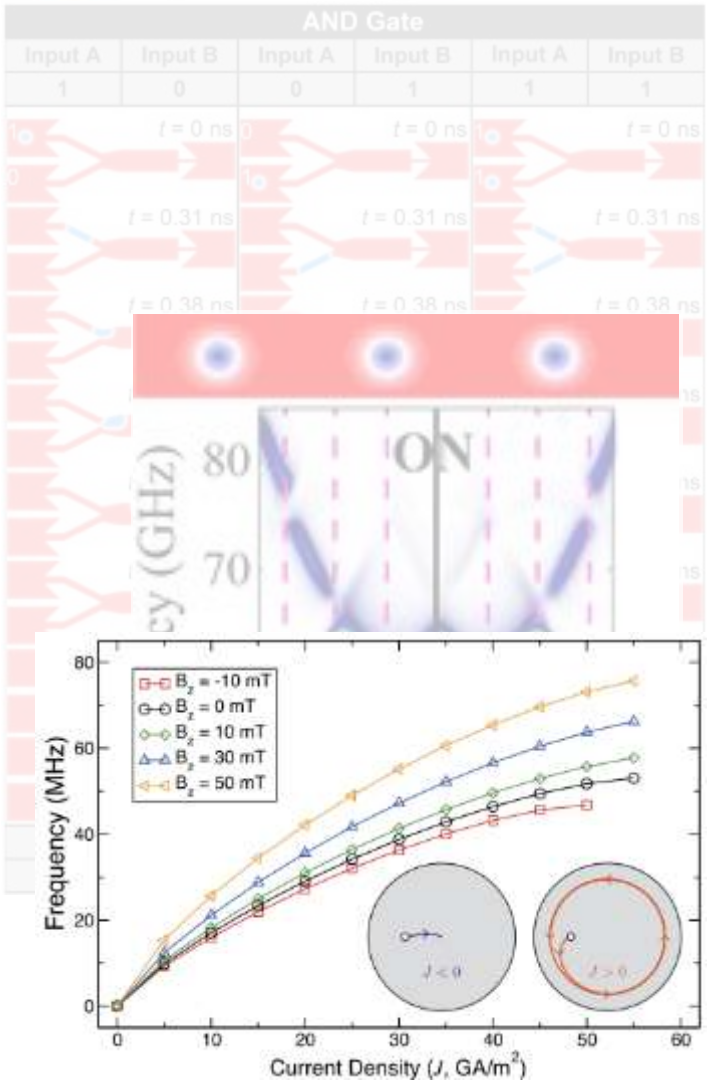
- OR and AND gates are numerically "demonstrated" using skyrmion-domain wall transformations.

Reconfigurable magnonic crystals

- A skyrmion lattice acts as a magnon filter.

Rf sources

- Peculiar modes of excitations.



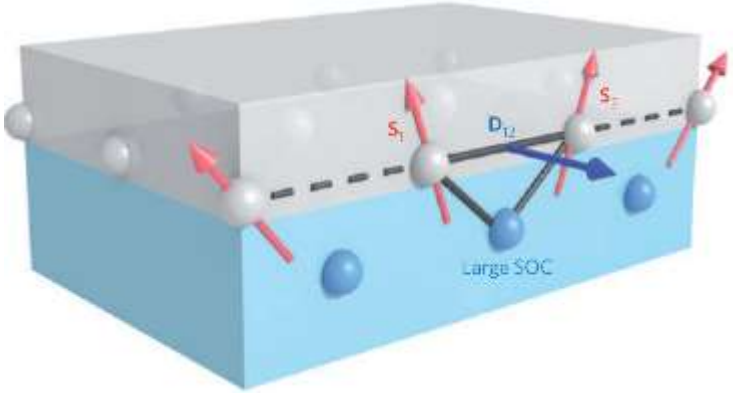
F. Garcia-Sanchez *et al*, *New J. Phys*. **18**, 075011 (2016)

Technical means: How to make them? How to observe them?

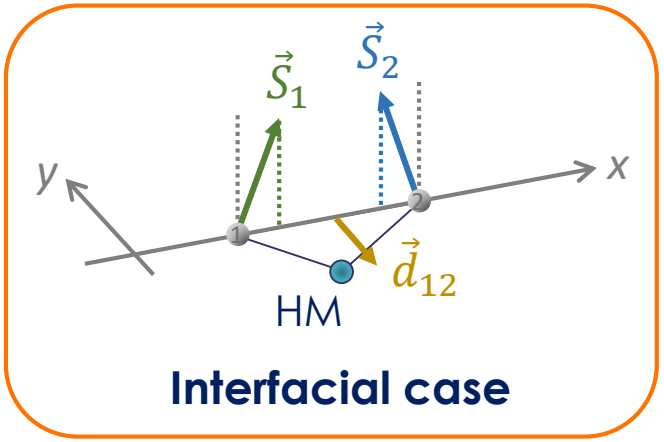
Dzyaloshinskii-Moriya Interaction in Bilayers

How to obtain DMI?

- Spin-orbit interaction
- Break the inversion symmetry



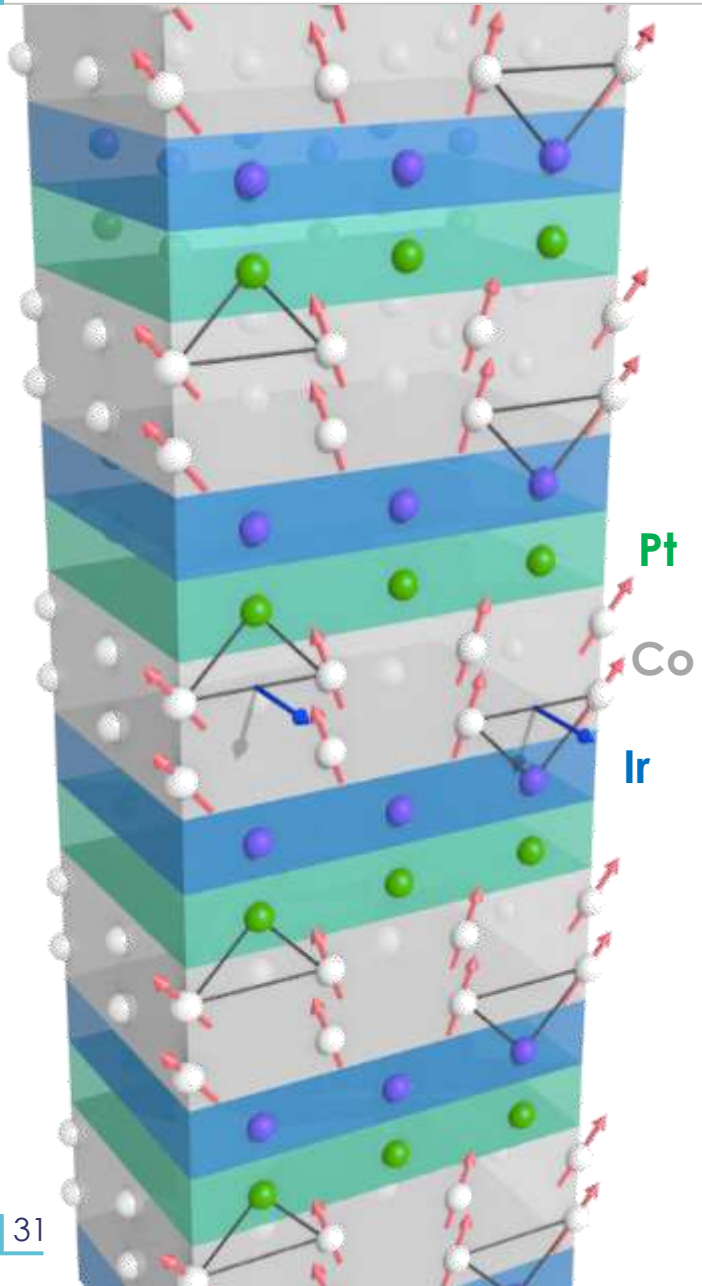
A. Fert *et al*, *Nat. Nanotechnol.* **8**, 152 (2013)



A. Fert, *Mater. Sci. Forum* **59-60**, 439 (1990)

How to increase room stability against thermal fluctuations?

Design of Magnetic Multilayers (an example)



From bilayer to multilayers:

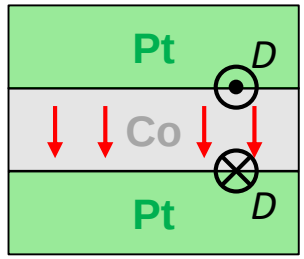
- Increase of the thermal stability
- Increase magnetic contrast in imaging experiments

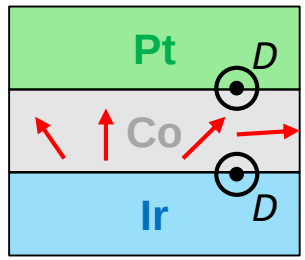
Different top and bottom interfaces around the ferromagnetic layers: control of the amplitude of the DMI

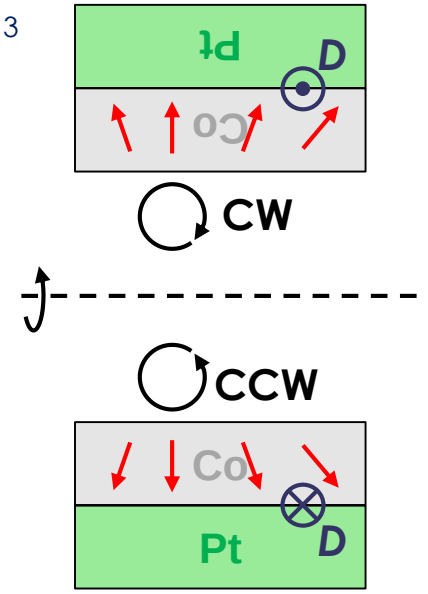
- Use of materials with opposite DMI sign to add up the effects, *e.g*:

$\| \text{Pt}_{10} \mid (\text{Ir}_{1} \mid \text{Co}_{0.8} \mid \text{Pt}_{1})_n \mid \text{Pt}_{3}$

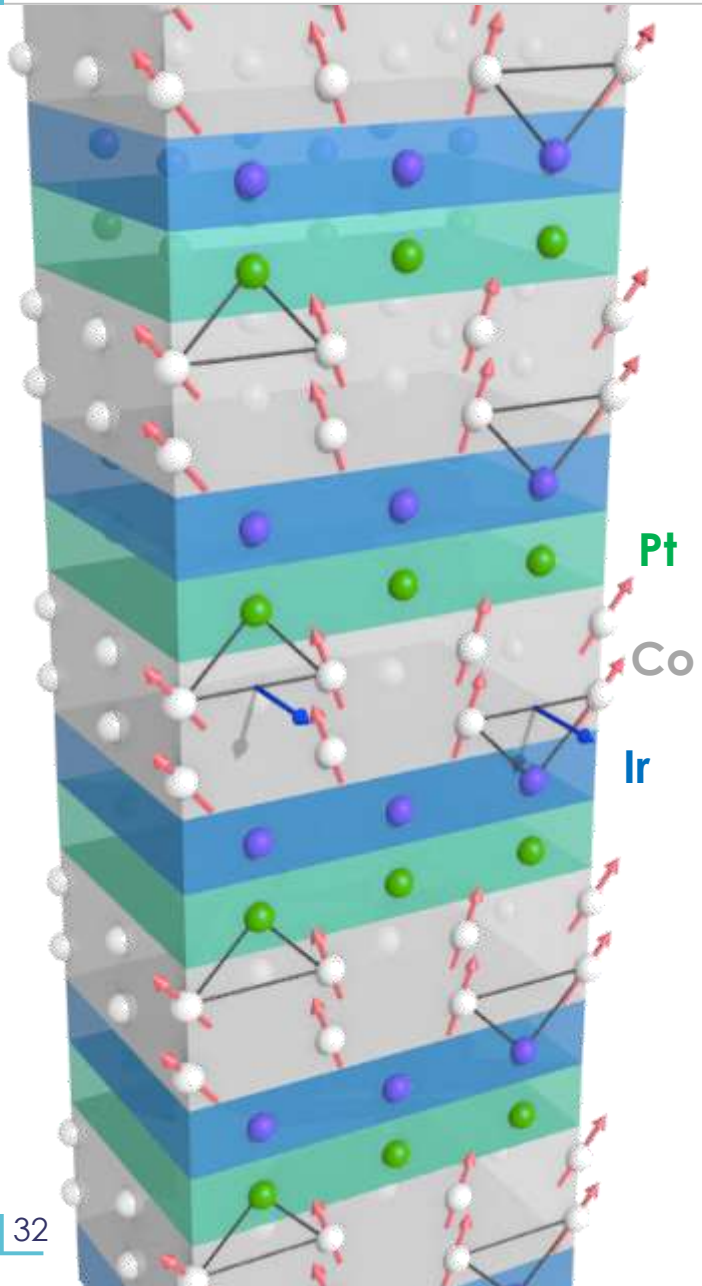
$D_{\text{eff}} \approx 0$







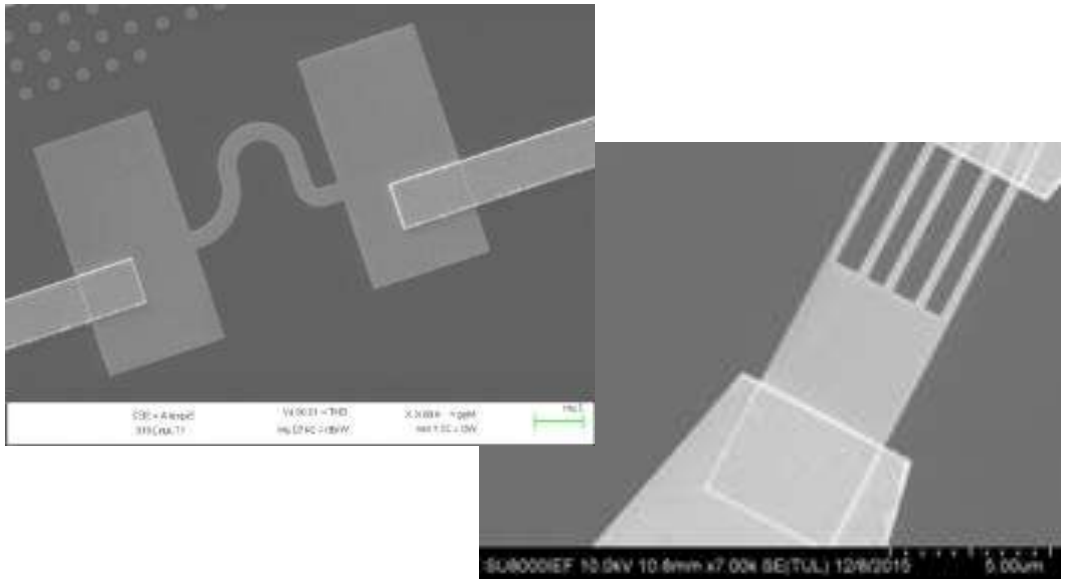
Growth and Patterning of Multilayers



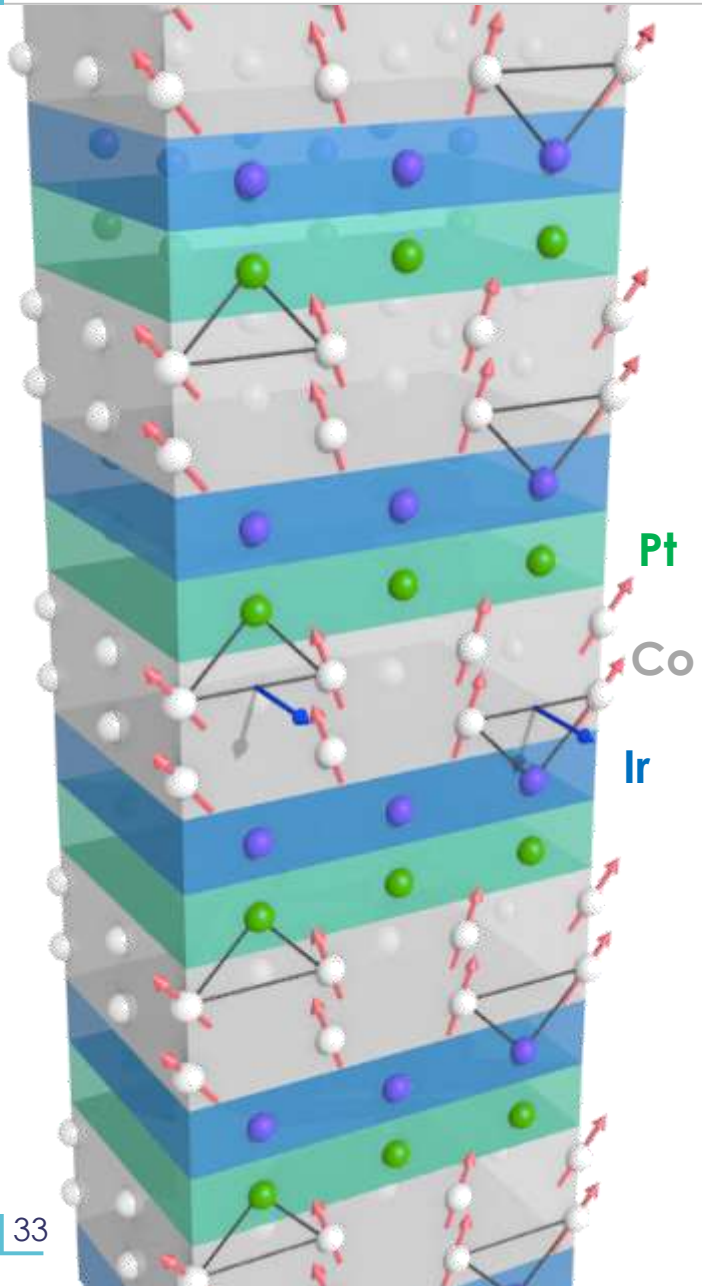
Growth and patterning

- Sputtering growth at room temperature
- SiO_2/Si wafer substrates
- Si_3N_4 membranes for STXM or TEM imaging
- Textured polycrystalline films (rc FWHM ~8°)

e-beam patterning hard mask, IBE (SIMS)



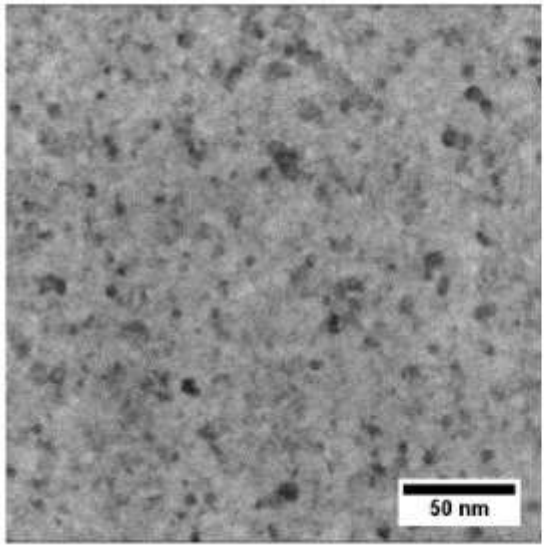
Growth of Multilayers – Grains from out-of-Plane TEM



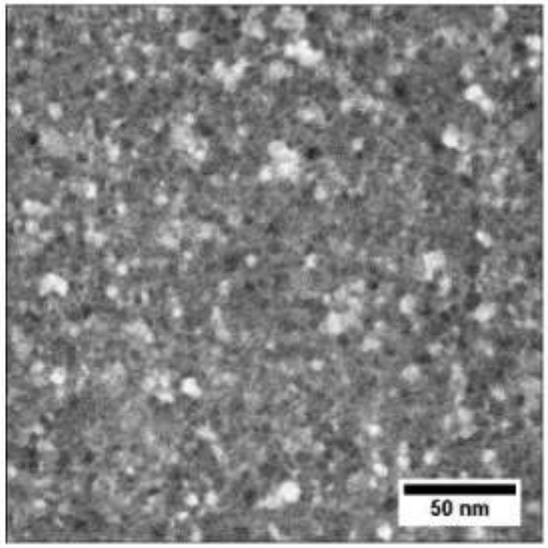
Presence of grains

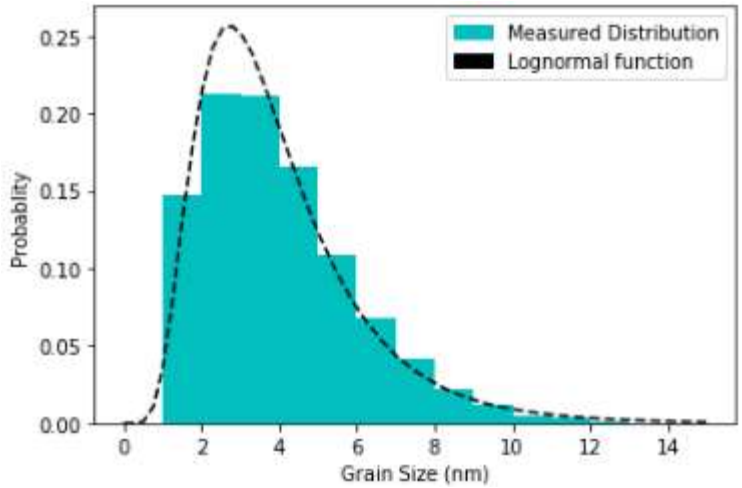
University of Glasgow

Dark field



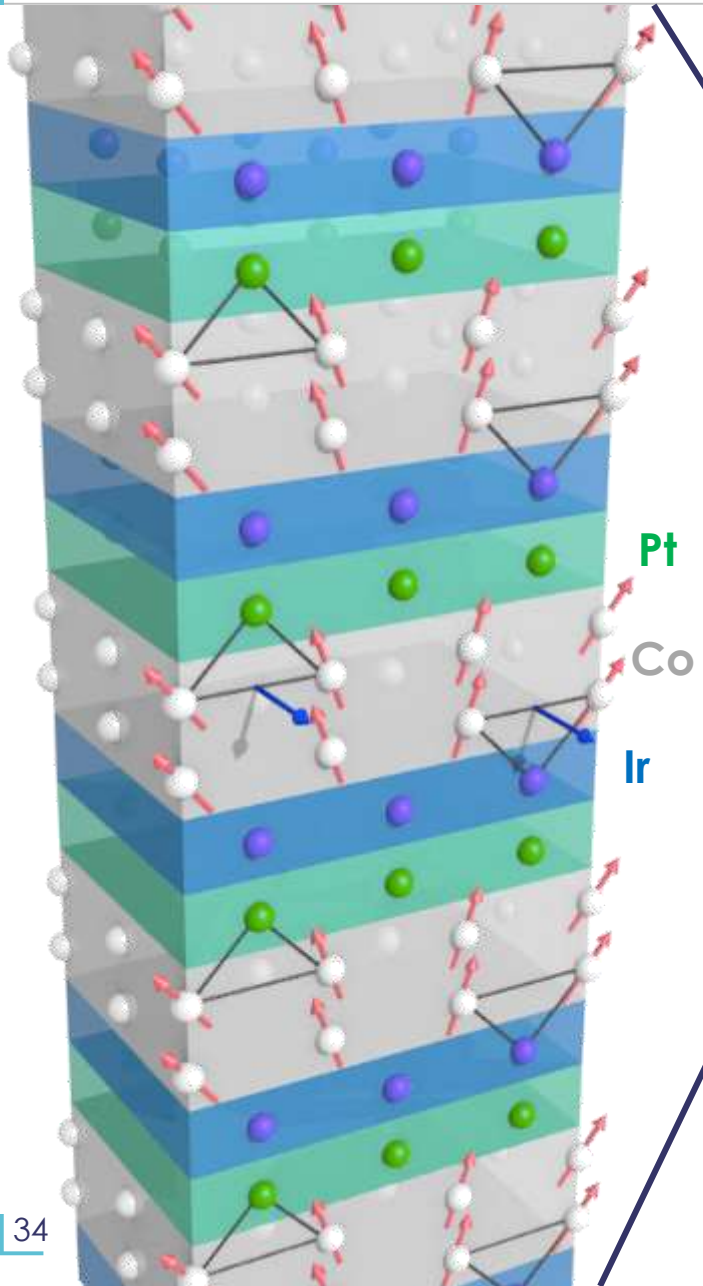
HAADF

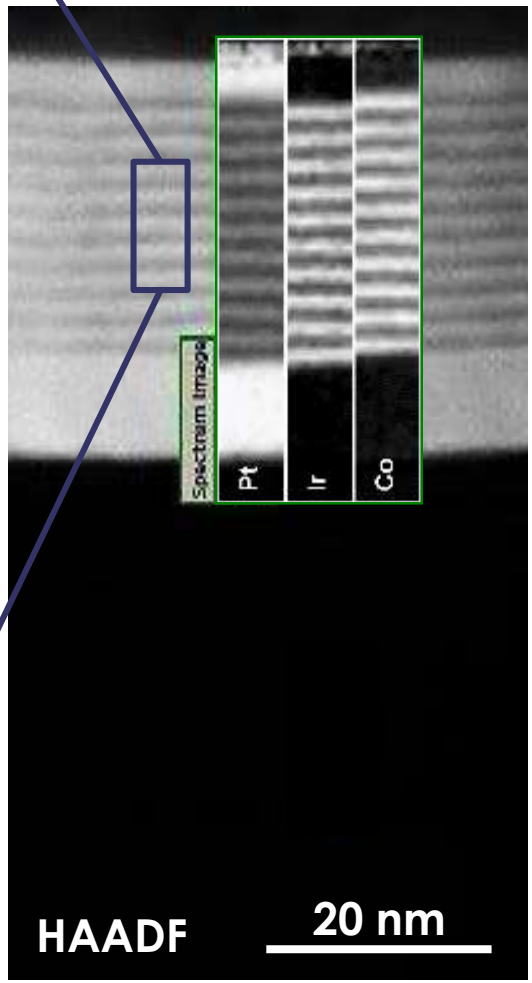




S. McVitie *et al*, *Sci. Rep.* **8**, 5703 (2018)

Growth of Multilayers – Cross-Section TEM





capping layer

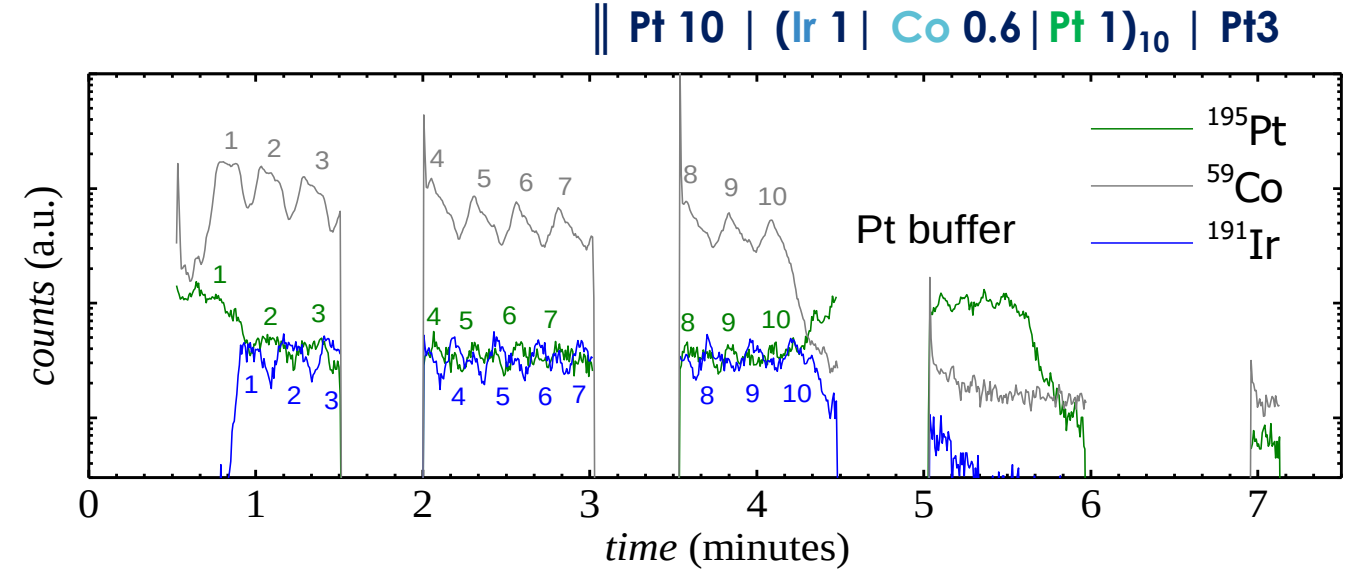
MML (n = 10)

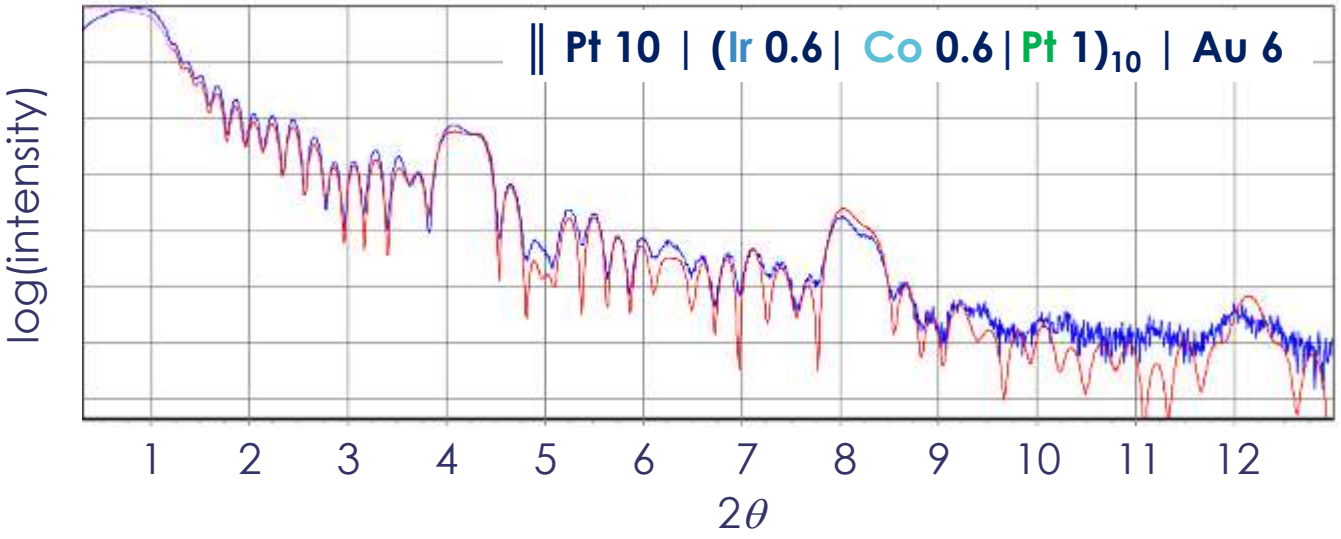
buffer

SiO_2/Si wafer

S. McVitie *et al*, *Sci. Rep.* **8**, 5703 (2018)

Growth of Multilayers – SIMS, x-rays, …



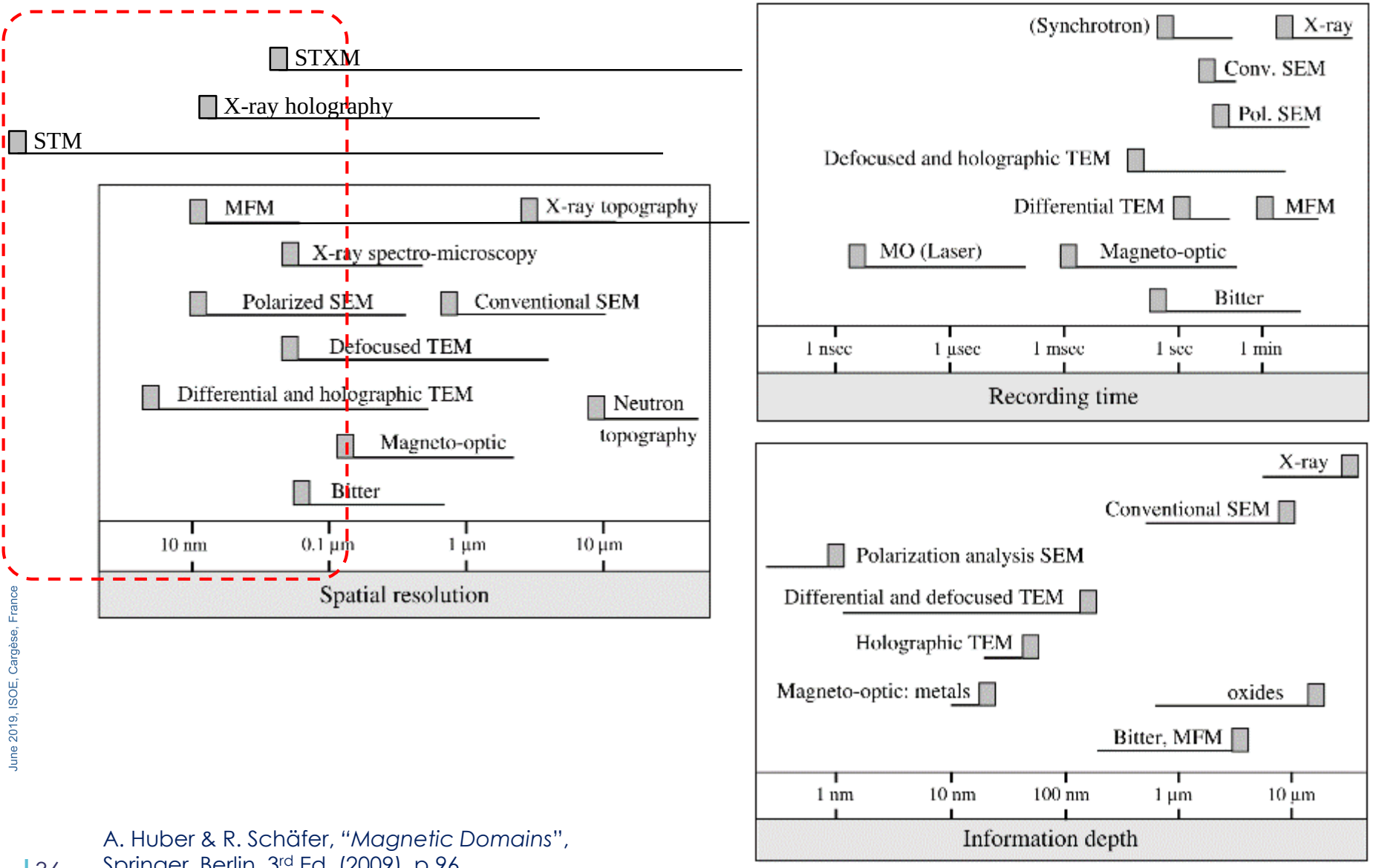


t_{Pt} = 0.95 nm
r_{Pt} = 0.10 nm

t_{Co} = 0.64 nm
r_{Co} = 0.31 nm

t_{Ir} = 0.61 nm
r_{Ir} = 0.33 nm

How to Observe Isolated sub-100nm-diameter Skyrmions?

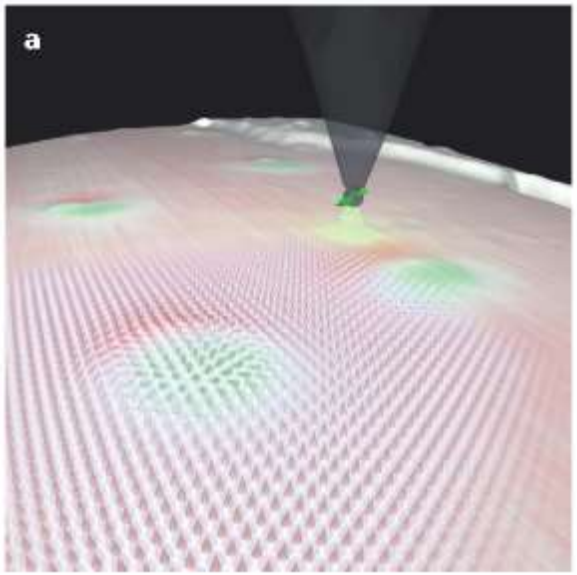


A. Huber & R. Schäfer, "*Magnetic Domains*", Springer, Berlin, 3rd Ed. (2009), p.96

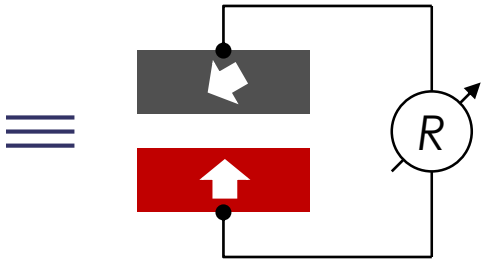
How to Observe Isolated sub-100nm-diameter Skyrmions?

(Spin-Polarized) Scanning Tunneling Microscopy (SP-STM)

- "Ultimate" resolution (atomic) ☺
- Need clean surface (no capping) ☹

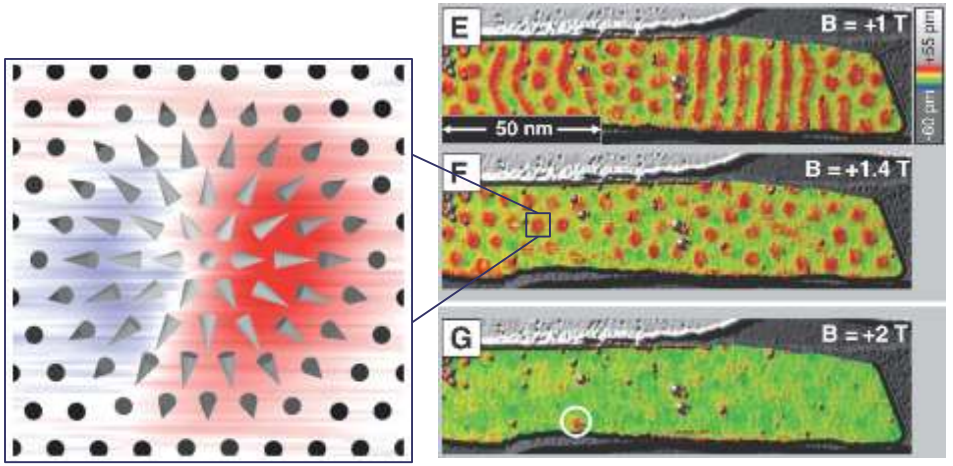


R. Wiesendanger, *Nat. Rev. Mater.* **1**, 16044 (2016)



TMR measurement:
Resistance (or tunnel current at fixed voltage) depends on the relative orientation of the magnetization.

- Using "TXMR" or "NCMR" a non-magnetic tip can be used.

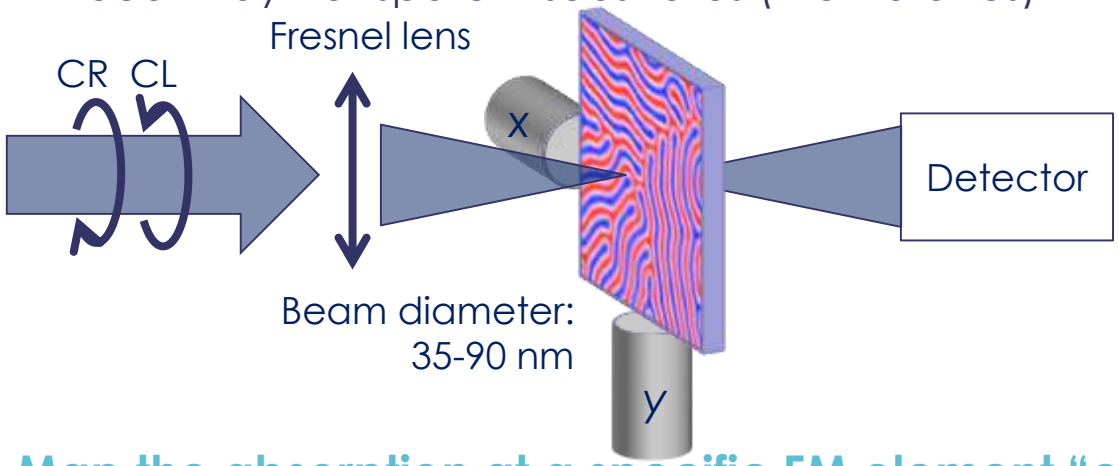


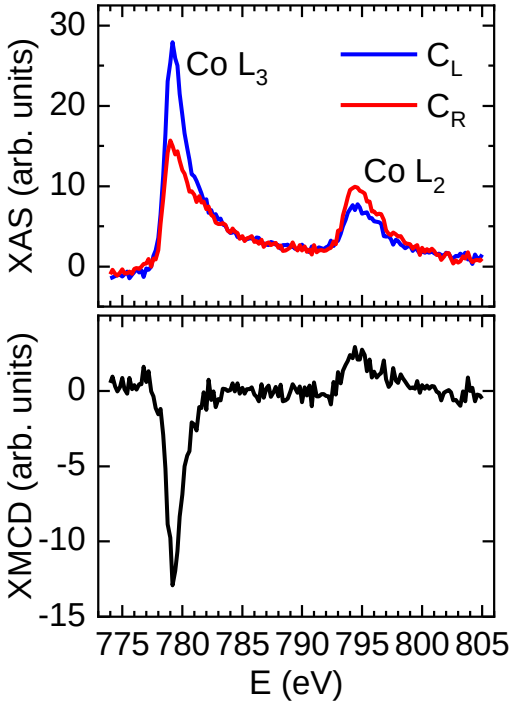
N. Romming *et al*, *Science* **341**, 636 (2013)

How to Observe Isolated sub-100nm-diameter Skyrmions?

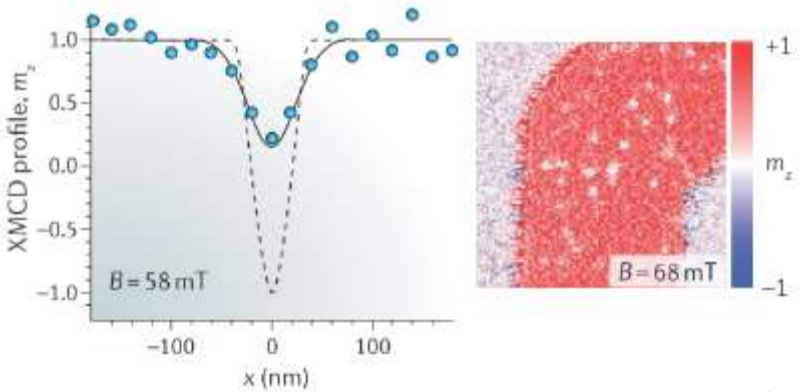
Scanning Transmission X-ray Microscopy

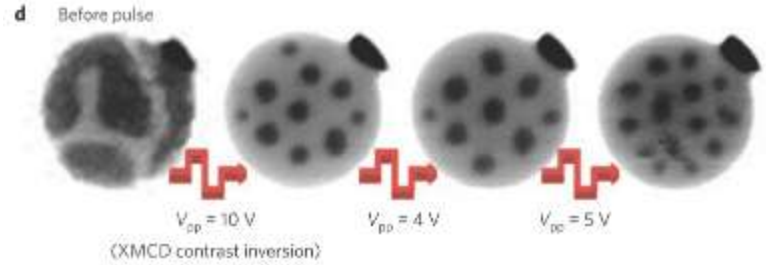
- Element specific, probe through capping layers, etc. ☺
- External fields, currents, etc. can be applied ☺
- Need x-ray transparent substrates (membranes) ☹





Map the absorption at a specific FM element "edge"





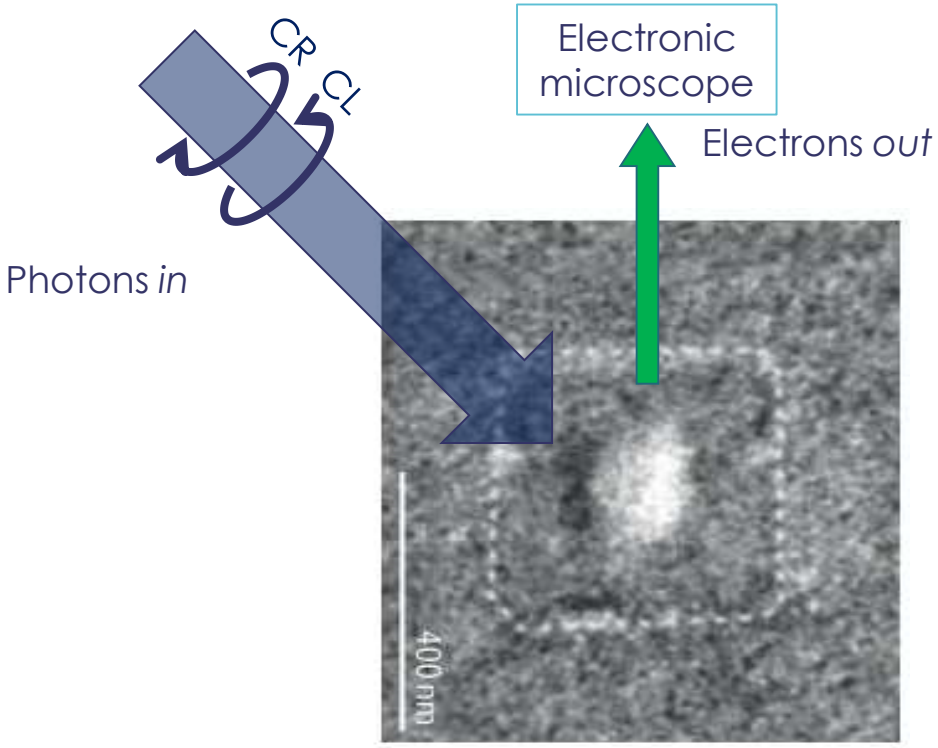
C. Moreau-Luchaire *et al*, *Nat. Nanotechnol.* **11**, 444 (2016)

S. Woo *et al*, *Nat. Mater.* **15**, 501 (2016)

How to Observe Isolated sub-100nm-diameter Skyrmions?

X-ray magnetic circular dichroism photoemission electron microscopy (XMCD-PEEM)

- Element specific ☺
- Need magnetic layer very close to surface ☹
- Limited magnetic field ☹



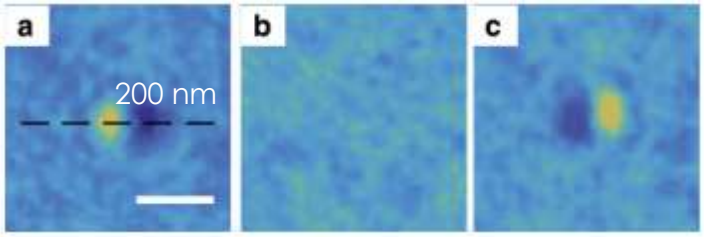
O. Boulle *et al*, *Nat. Nanotechnol.* **11**, 449 (2016)

How to Observe Isolated sub-100nm-diameter Skyrmions?

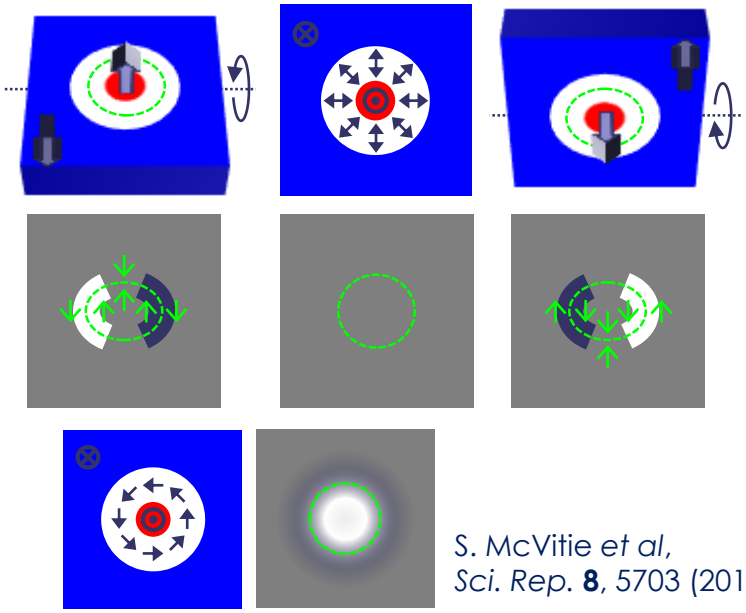
Lorentz-TEM, Differential Phase Contrast, Electron holography, etc.

- Probe magnetization ☺ Only probe the surface ☹

Lorentz transmission electron microscopy (L-TEM)

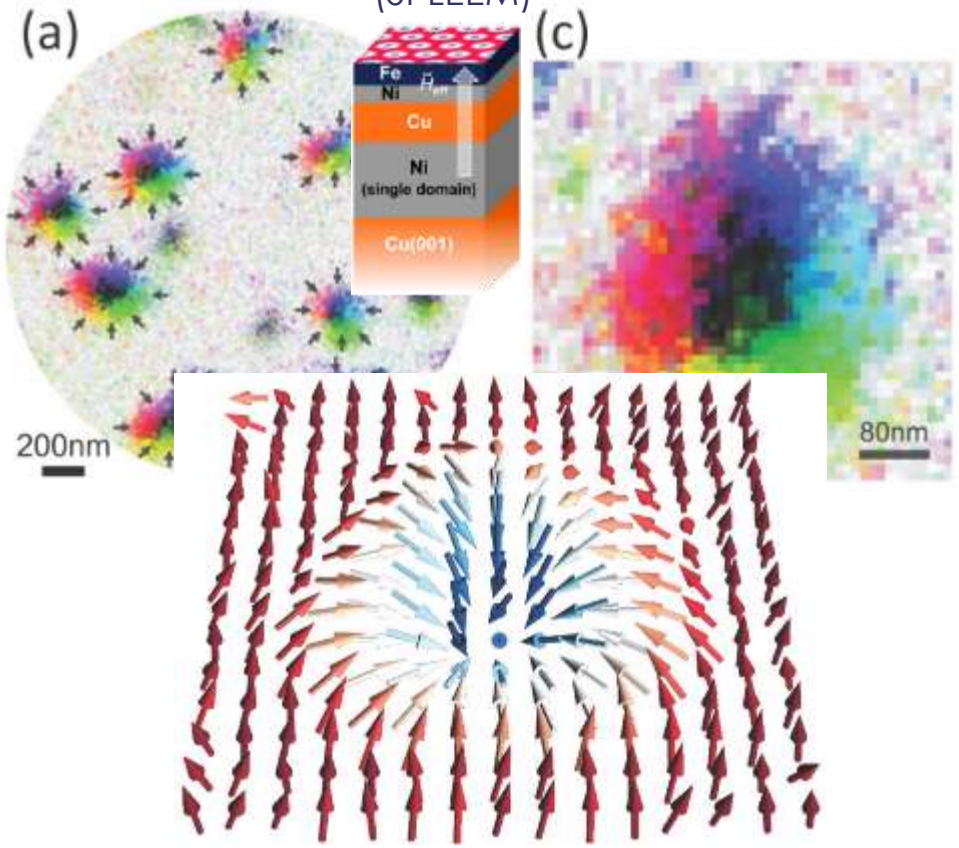


S. D. Pollarde *et al*, *Nat. Commun.* **8**, 14761 (2017)



S. McVitie *et al*, *Sci. Rep.* **8**, 5703 (2018)

Spin polarized low-energy electron microscopy (SPLEEM)

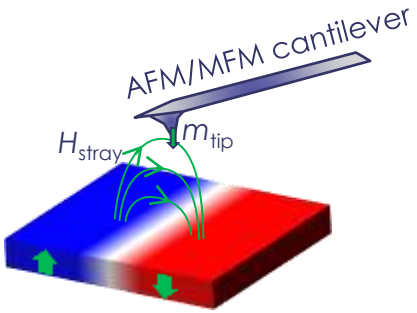


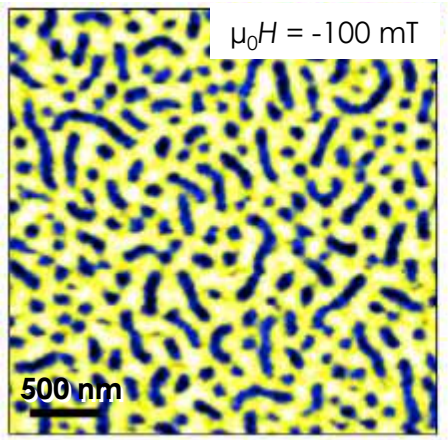
G. Chen *et al*, *Appl. Phys. Lett.* **106**, 242404 (2015)

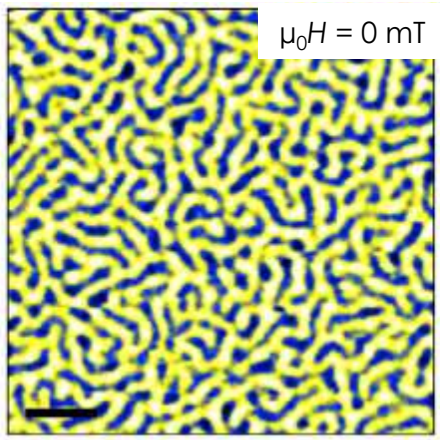
How to Observe Isolated sub-100nm-diameter Skyrmions?

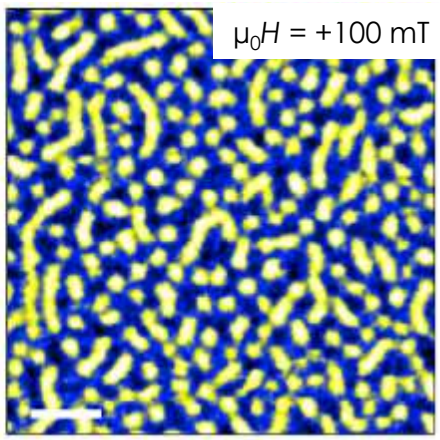
Magnetic Force Miroscopy (MFM)

- Tabletop laboratory technique ☺
- Measure (mostly) stray fields (of buried layer) ☺
- Measure (mostly) stray fields ☹



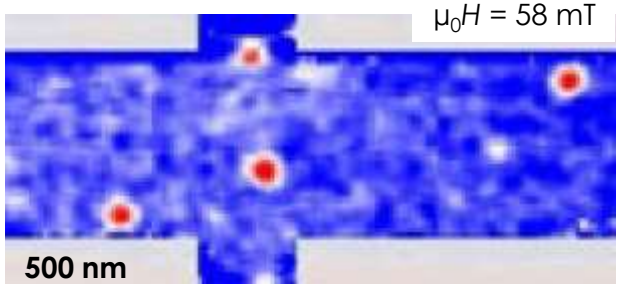






[Pt (1) / Co (0.6) / Fe (0.3) / Ir (1)] x20

A. Soumyanarayanan *et al*, *Nat. Mater.* **16**, 898 (2017)



[Ir (1) / Co (0.8) / Pt (1)] x20

D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

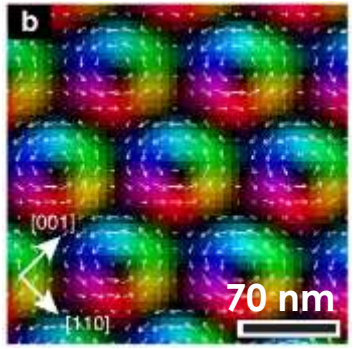
Question session

Skyrmion stability, nucleation, motion…

Field-Temperature Phase Diagram in B20 materials

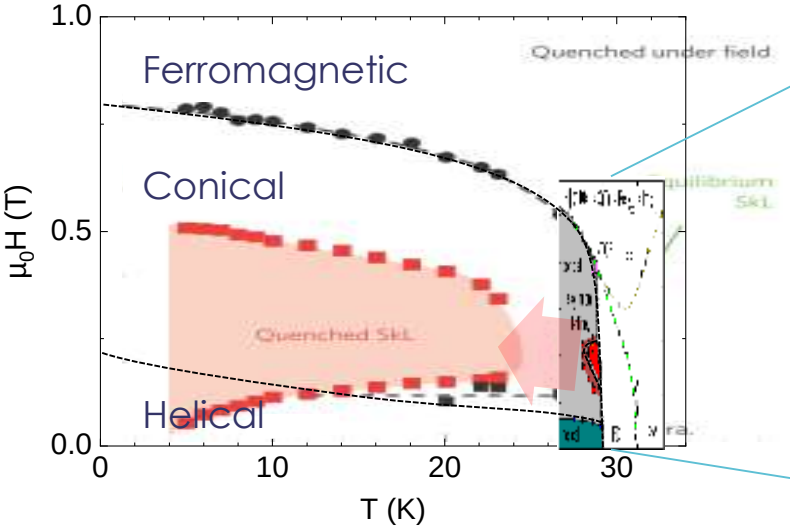
In B20-types of materials

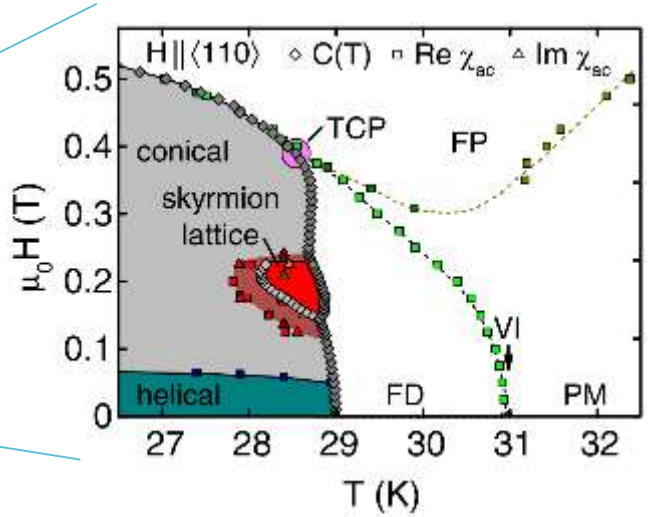
- Narrow range of stability
- Ground state → skyrmion array



Skyrmion lattice in FeGe

X. Z. Yu *et al*, *Nat*. Commun. **3**, 988 (2012)





A. Bauer *et al*, *Phys. Rev. Lett*. **110**, 177207 (2013)

H. Oike *et al*, Nat. *Phys.* **12**, 62 (2016)

Metastable skyrmions

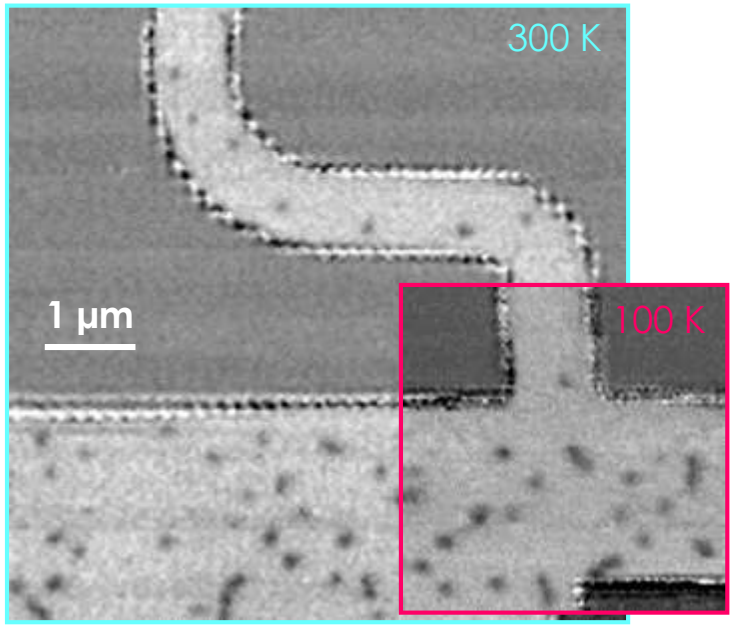
- Obtained by temperature quench from the lattice phase

H-T Phase Diagram for Metallic Multilayers

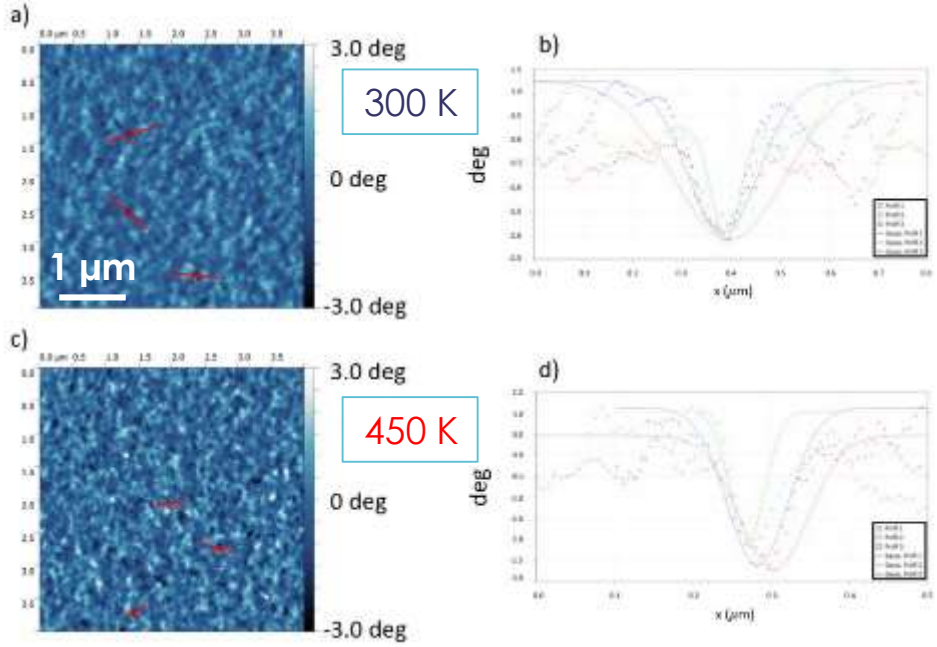
No real phase diagram published (yet)?

Metastability → isolated skyrmions

- For Pt | Co system, isolated skyrmions are observed (at least) in the temperature range 100 - 400 K, and $|\mu_0 H| < 200$ mT (typical value…).



STXM



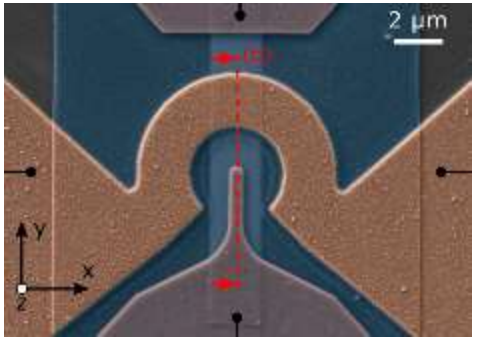
MFM

CNRS/Thales and PSI, unpublished

Means of Nucleation

Field and temperature sweeps

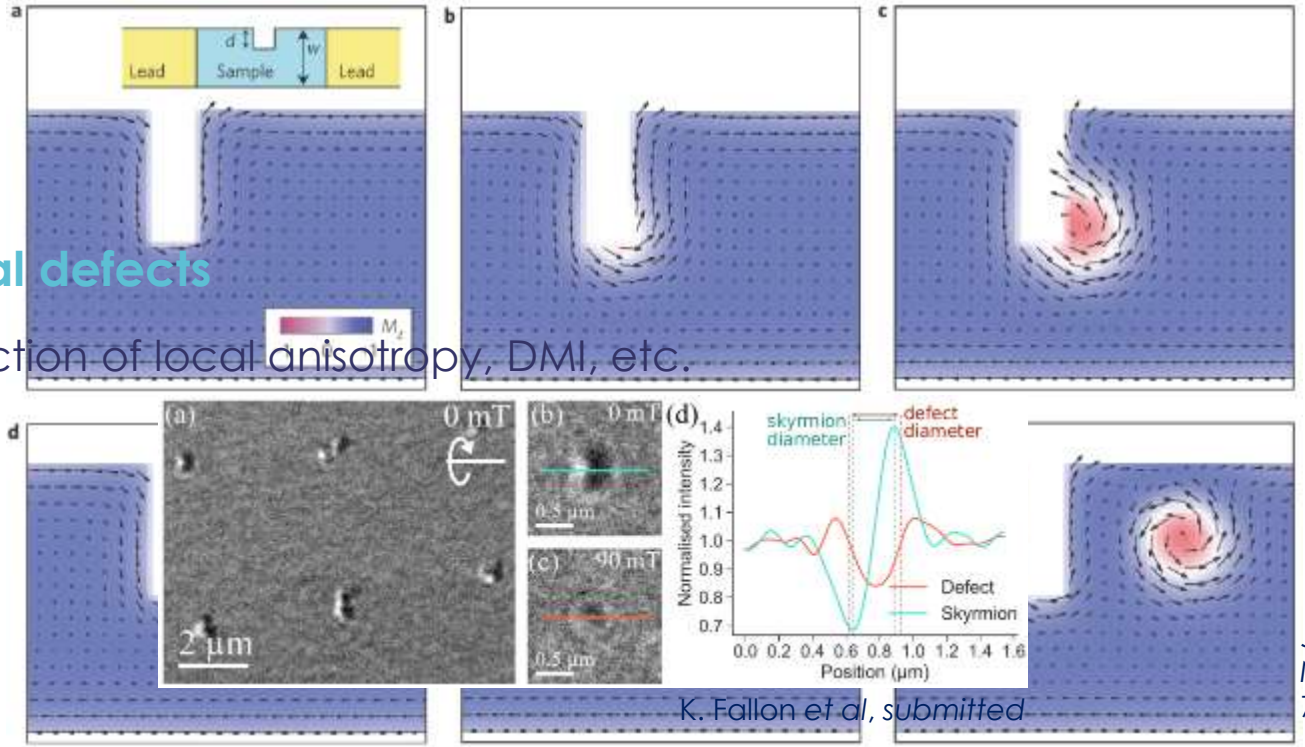
- Possibility to apply rather local fields



S. Finizio *et al*,
arxiv: ***1902****.10435*

Use of the geometrical boundaries

- Boundary "breaks" the topological protection



K. Fallon *et al*, *submitted*

Artificial defects

- Reduction of local anisotropy, DMI, etc.

J. Iwasaki *et al*, *Nat. Nanotechnol.* **8**, 742 (2013)

Current-induced Skyrmion Nucleation in a Track

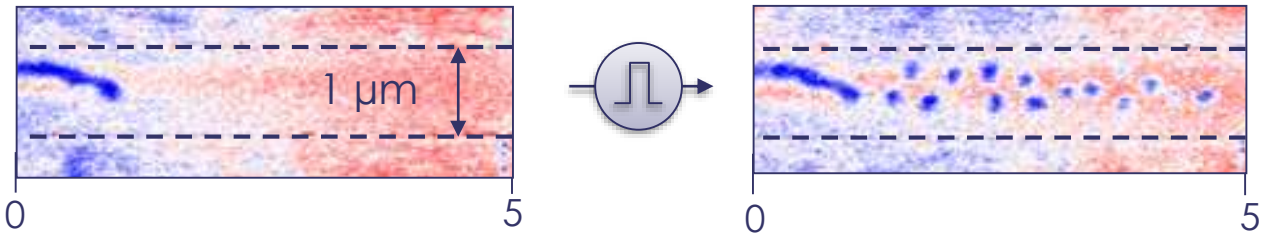
Sputtered samples structure – difficult field nucleation

- #1: | |Ta 15 | Co 0.6 | (Pt 1 | Ir 1 | Co **0.6**)$_{x10}$ | Pt 3
- #2: | |Ta 15 | Co 0.8 | (Pt 1 | Ir 1 | Co **0.8**)$_{x10}$ | Pt 3
- #3: | |Ta 15 | Co 1.0 | (Pt 1 | Ir 1 | Co **1.0**)$_{x10}$ | Pt 3

1000 pulses of 200ns

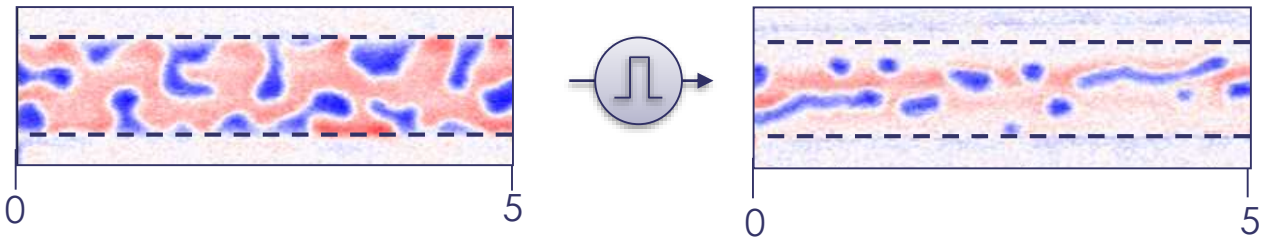
#1 (0.6 nm Co)

$J_n = \pm 1.43 \cdot 10^{11}$ A m^{-2}



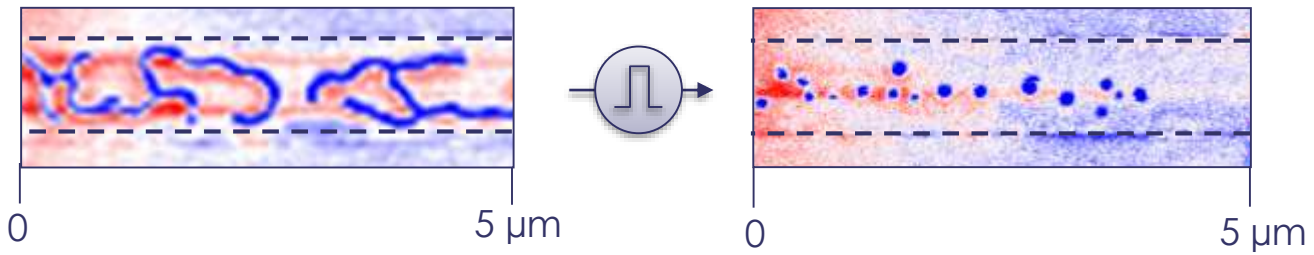
#2 (0.8 nm Co)

$J_n = \pm 2.38 \cdot 10^{11}$ A m^{-2}



#3 (1.0 nm Co)

$J_n = \pm 2.96 \cdot 10^{11}$ A m^{-2}



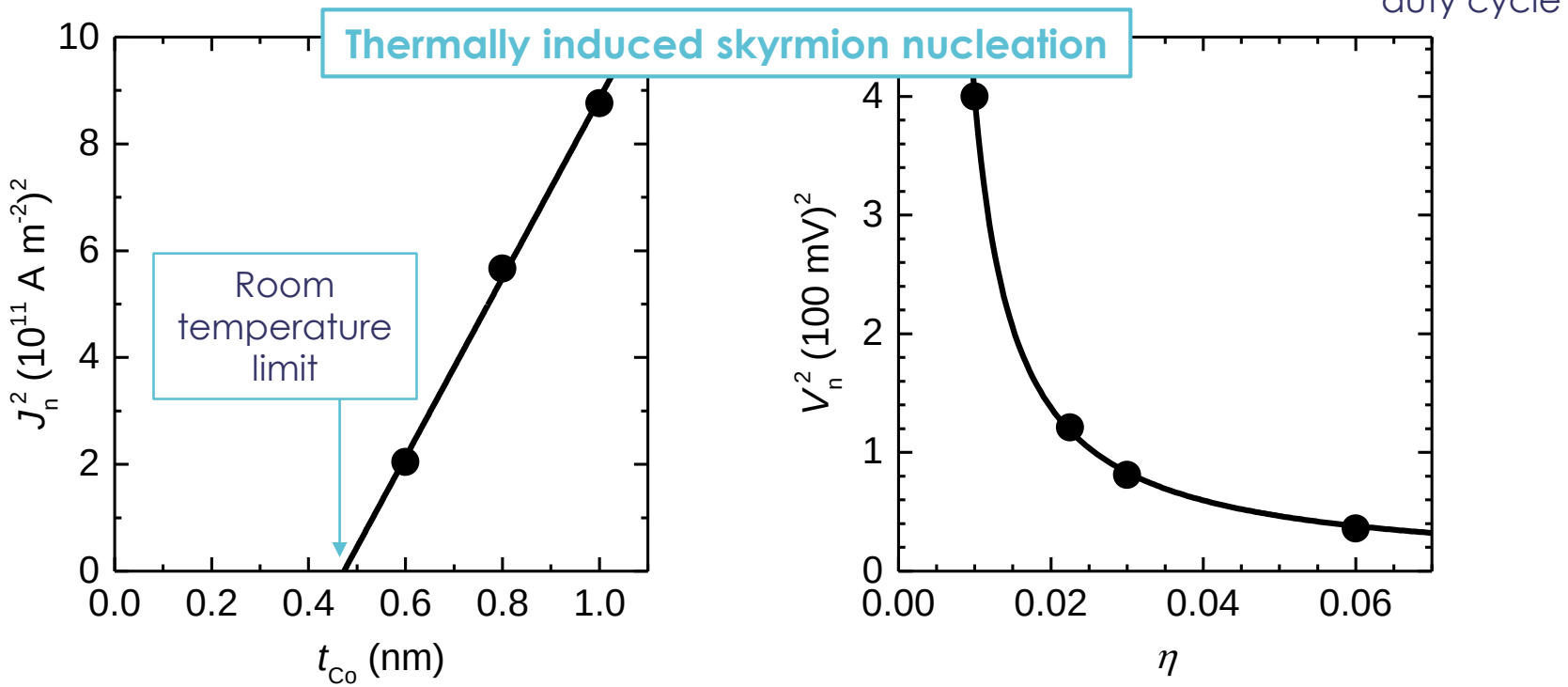
W. Legrand *et al*, *Nano Lett.* **17**, 2703 (2017)

(Mainly) Thermal Origin of the Nucleation

Hypothesis of the thermal nucleation

- Stability of domains proportional to magnetic volume => Co thickness t_{Co}
- Joule heating proportional to J^2
- Role of room temperature: minimum thickness for stabilization
- Temperature elevation ~ Joule power: $\Delta T_n \propto P_n \propto \eta V_n^2(\eta)$ => $V_n^2(\eta) \propto \frac{1}{\eta}$

duty cycle

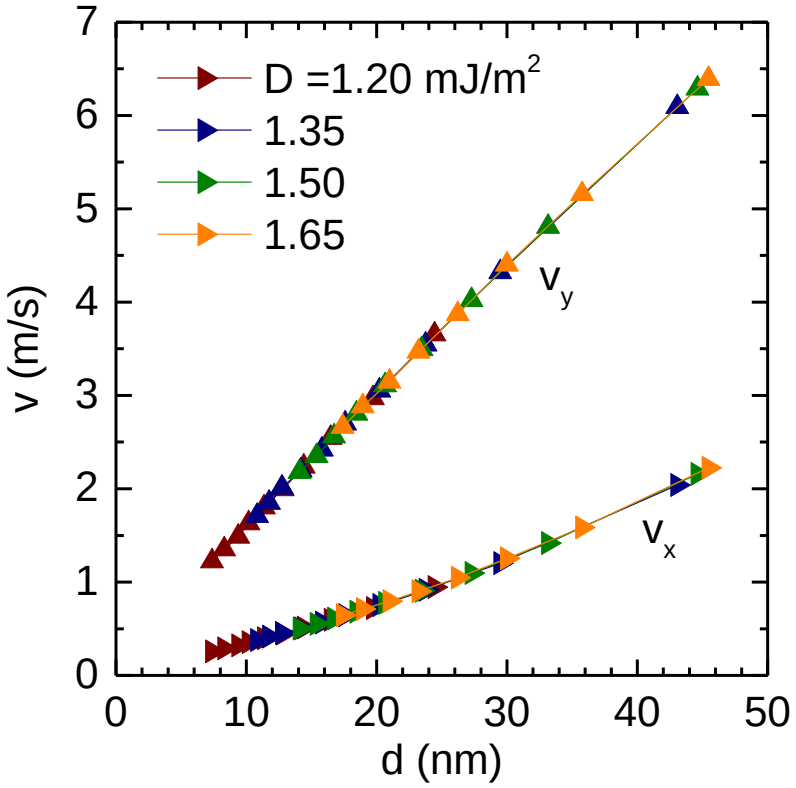


W. Legrand *et al*, *Nano Lett.* **17**, 2703 (2017)

Velocity and Diameter in "Plain Films"

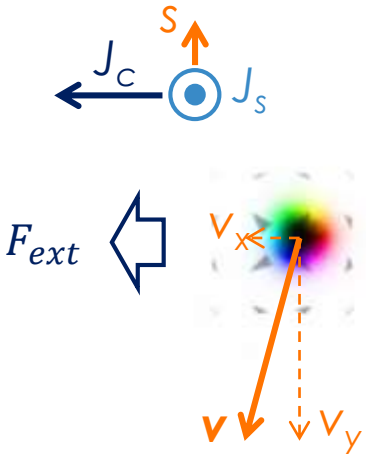
The velocity of a "compact skyrmion" depends on its size

- Micromagnetic simulations for J = 67 GA/m²
- M_S = 956 kA/m ; K_U = 717 kJ/m³ ; A = 10 pJ/m ; α = 0.2 ; θ_{SHE} = 0.06
- various D and H_z



Without confinement

30 mT, D = 1.35 mJ/m²



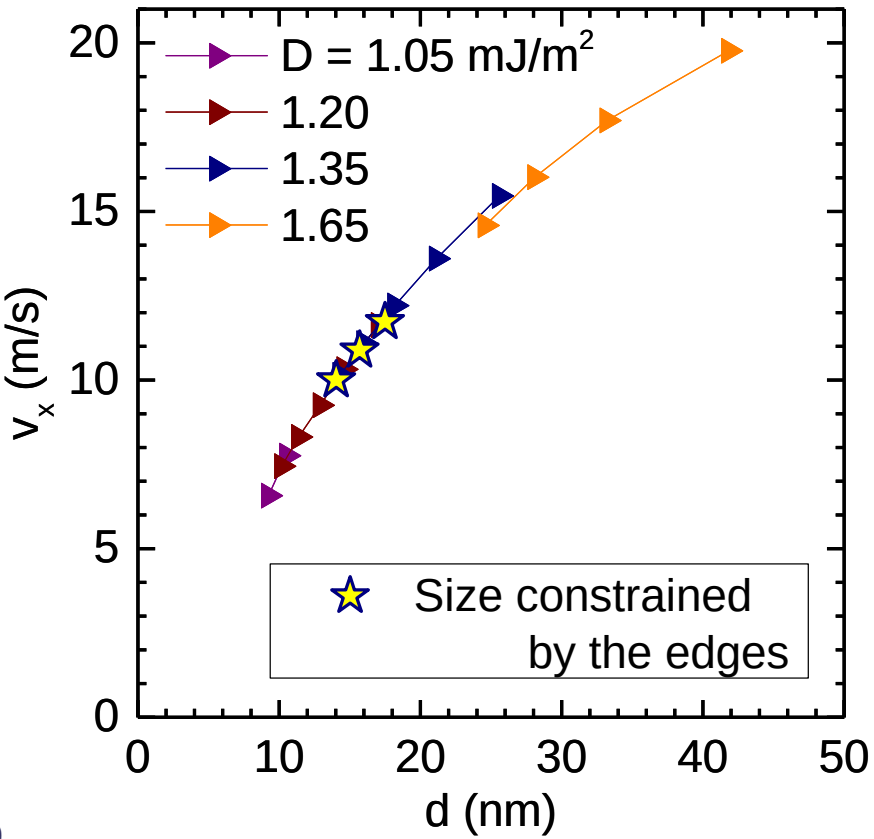
$$\boldsymbol{G} \wedge \boldsymbol{v} + \alpha \mathcal{D} \boldsymbol{v} + \boldsymbol{F}_{\text{ext}} = 0$$

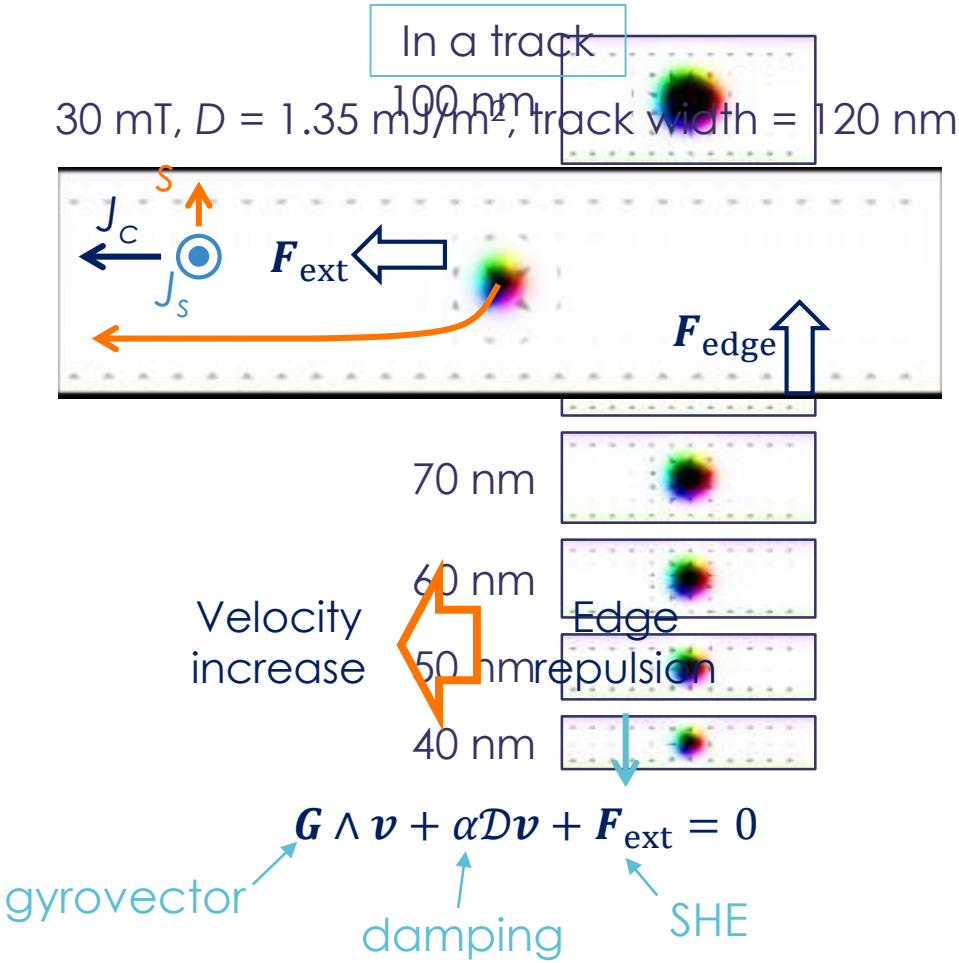
gyrovector — damping — SHE

Velocities in Track: Still Proportional to Diameter

The velocity of a "compact skyrmion" depends on its size

- Micromagnetic simulations for J = 67 GA/m²
- M_S = 956 kA/m ; K_U = 717 kJ/m³ ; A = 10 pJ/m ; α = 0.2 ; θ_{SHE} = 0.06
- various D and H_z + Track width!





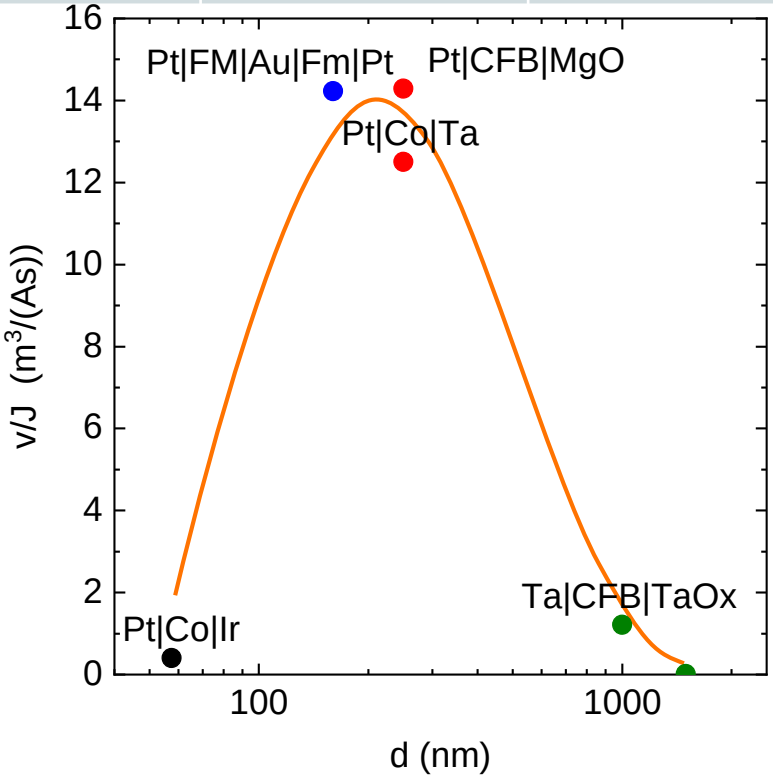
Velocities and Sizes Reported in the Literature

Composition	Laboratory	Skyrmion diameter *d* (nm)
Pt|Co|Ir	CNRS/Thales...	35 to 80
Pt|CoFeB|MgO	MIT+Mainz+…	250
Pt|Co|Ta	MIT+Mainz+…	250
Pt|FM|Au|FM|Pt	LPS+…	160
Ta|CoFeB|TaO_x	ANL+…	~1000 700 to 2000

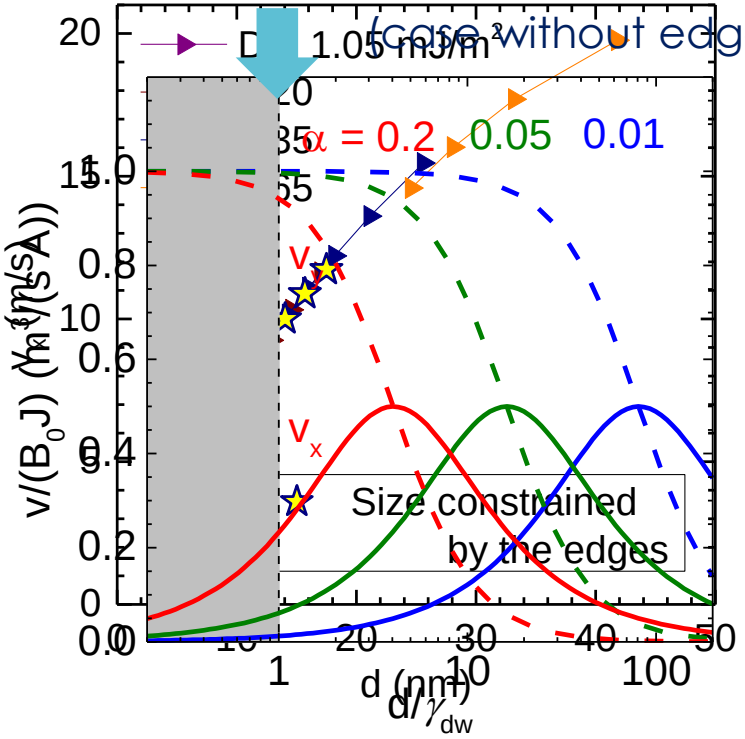
Thiele equation developed by Tomasello *et al*, and also used in Jiang *et al*:

$$\begin{cases} v_x = \frac{\alpha \mathcal{D}}{1+\alpha^2\mathcal{D}^2} B_0 J_x, & \text{with } \mathcal{D} = \frac{\pi^2}{8}\frac{d}{\gamma_{DW}} \\ v_y = \frac{1}{1+\alpha^2\mathcal{D}^2} B_0 J_x. \end{cases}$$

R. Tomasello *et al*, *Sci. Rep.* **4**, 6784 (2014)
W. Jiang *et al*, *Nat. Phys.* **13**, 162 (2017)



"Compact" skyrmion (case without edges)



Moving Skyrmions using Electrical Current

Series of MFM images after electrical pulses

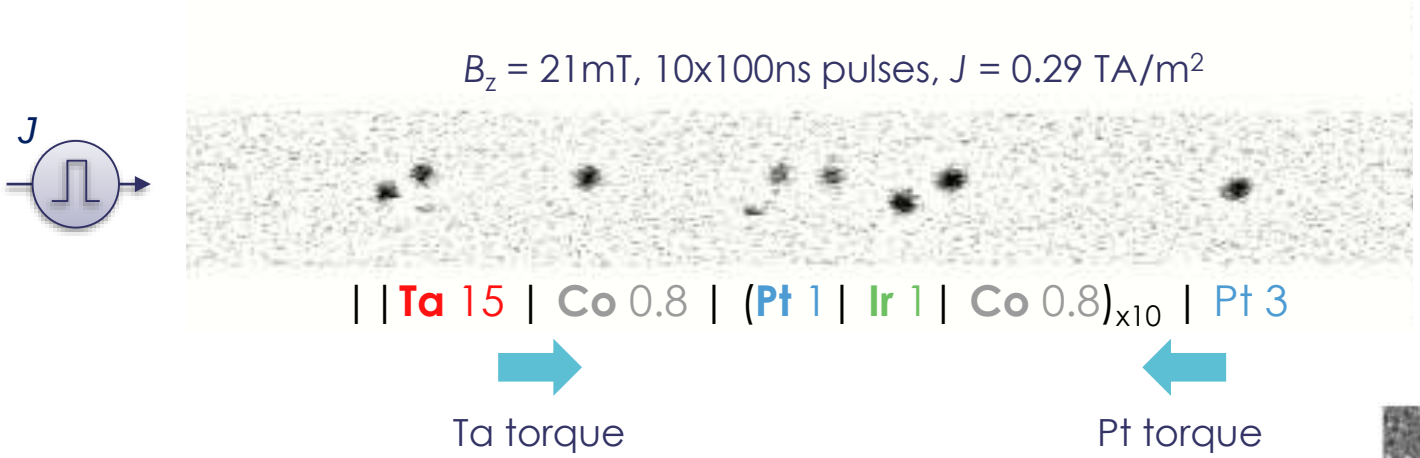
200 ns; $J \approx 2\ 10^{11}$ A/m^2; $\mu_0 H$ = 35 mT; T = 300K

What is the origin of their "chaotic" motion?

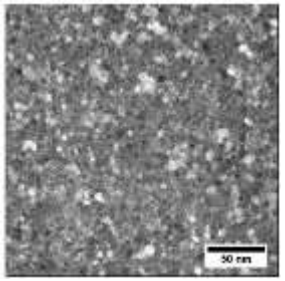
Skyrmion Motion under Current Pulses

Motion is observed using short pulses just below nucleation threshold

- No clear skyrmion Hall effect (in any of our sample)
- Low velocity (typically 50 mm/s, up to 0.5 m/s)
- Disordered motion against the electron flow



Presence of grains with different properties?



- Grains observed by TEM
- Variation of the properties reported by quantitative MFM (Bacani *et al*, arXiv:1609.01615)

W. Legrand *et al*, *Nano Lett.* **17**, 2703 (2017)

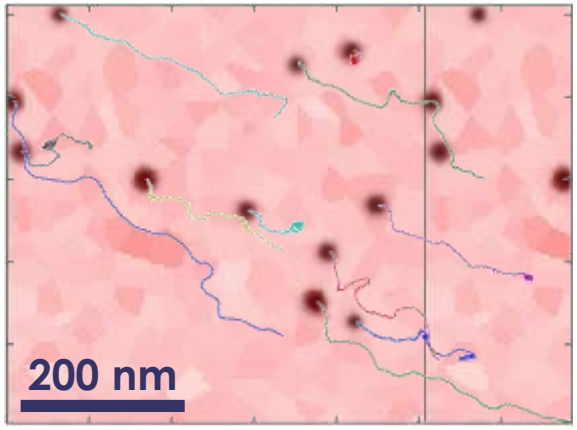
Creep-Like Regime

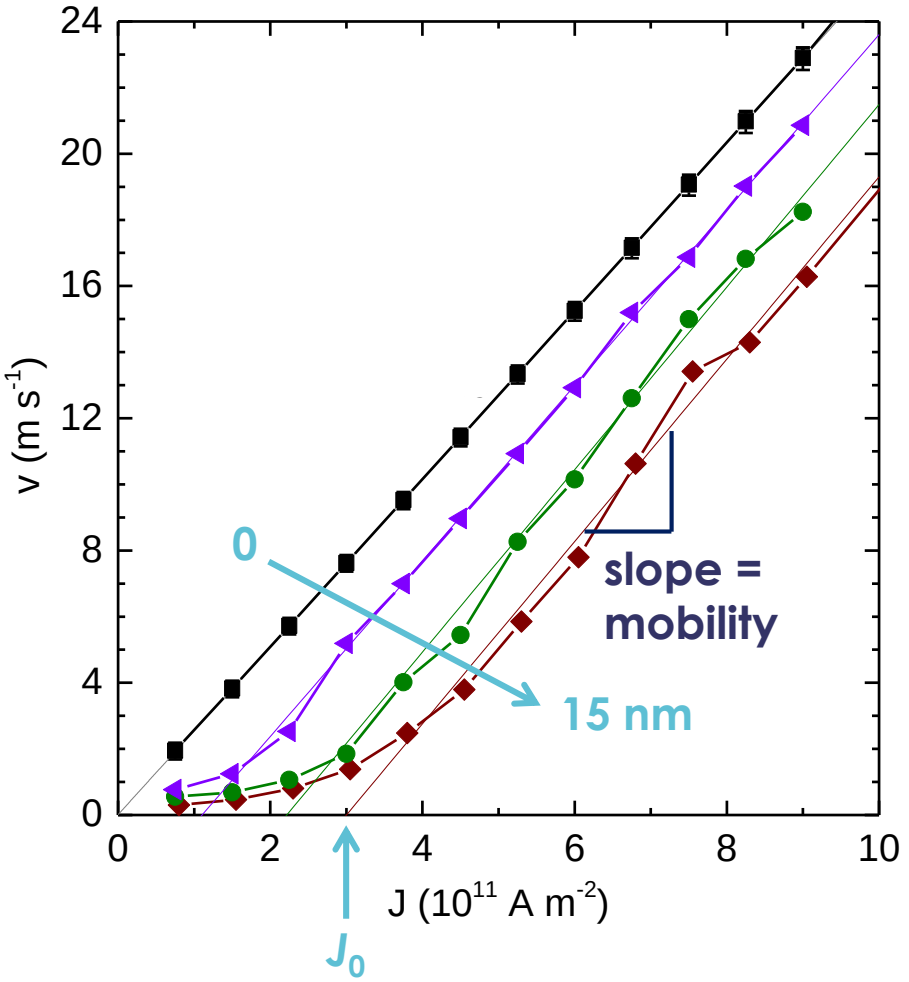
Existence of a "mobility edge" and a "depinning current"

- Due to the distribution of grains properties => existence of a potential barrier at grain boundaries
- As grain size is increased the "depinning current" increases…

- **the velocity is never recovered**
- **the mobility is recovered above J_0**

10% *D* variation

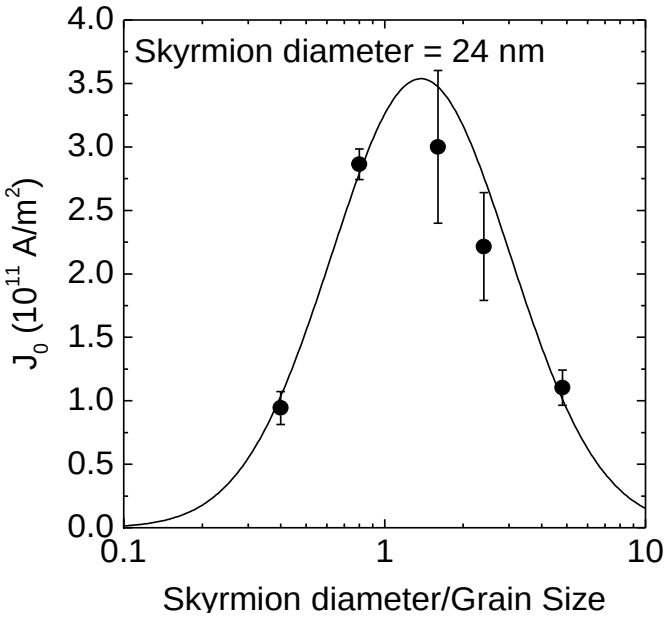


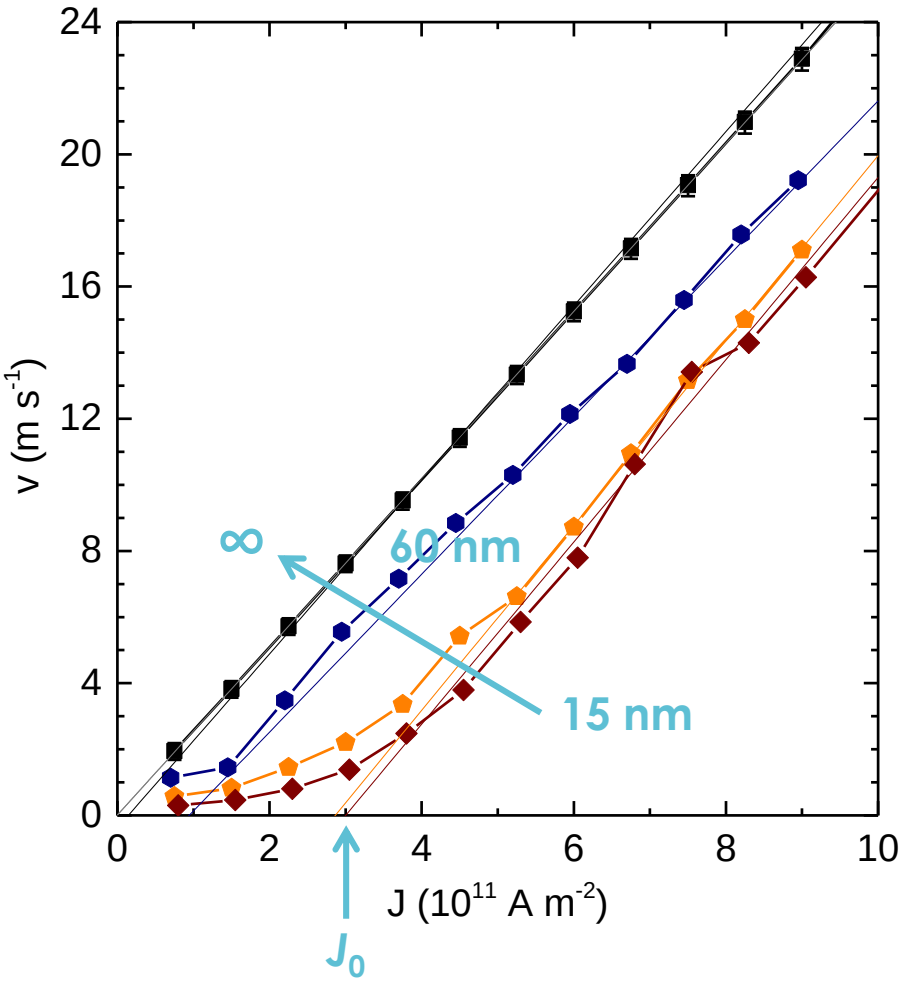


Creep-Like Regime

Existence of a “mobility edge” and a “depinning current”

- Due to the distribution of grains properties => existence of a potential barrier at grain boundaries.
- As grain size is increased the “depinning current” increases…
- … and decreases again once the grains sizes largely exceed the skyrmions sizes.

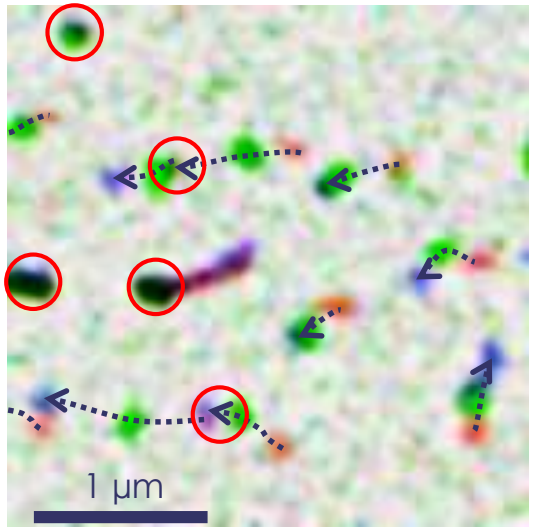




Skyrmion velocity (and data rate)

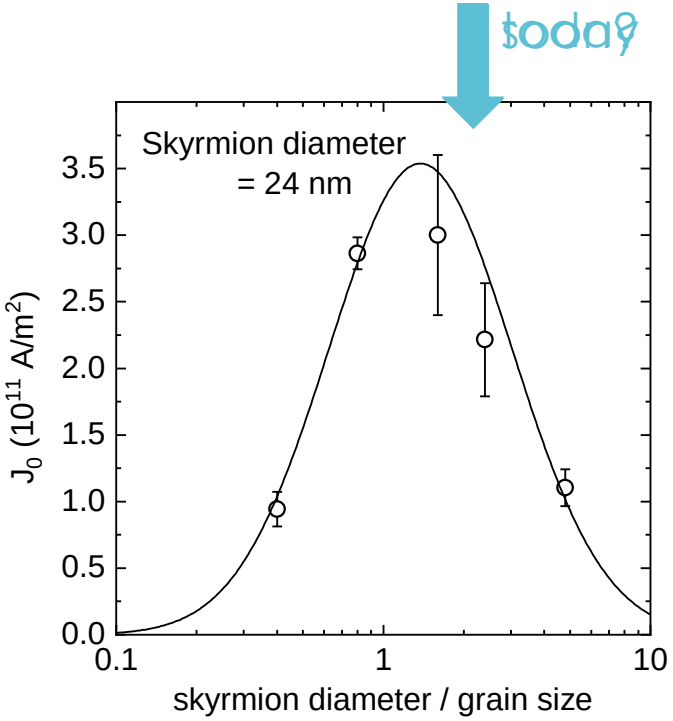
Improve of design: increased velocity

Pinnning points



| Ta10 | Pt8 | (Co1.4 | Ru1.2 | Pt0.6)x3 | Pt2.4
7x10¹¹ A/m² pulses of **12 ns**

$v \approx$ 30-40 m/s

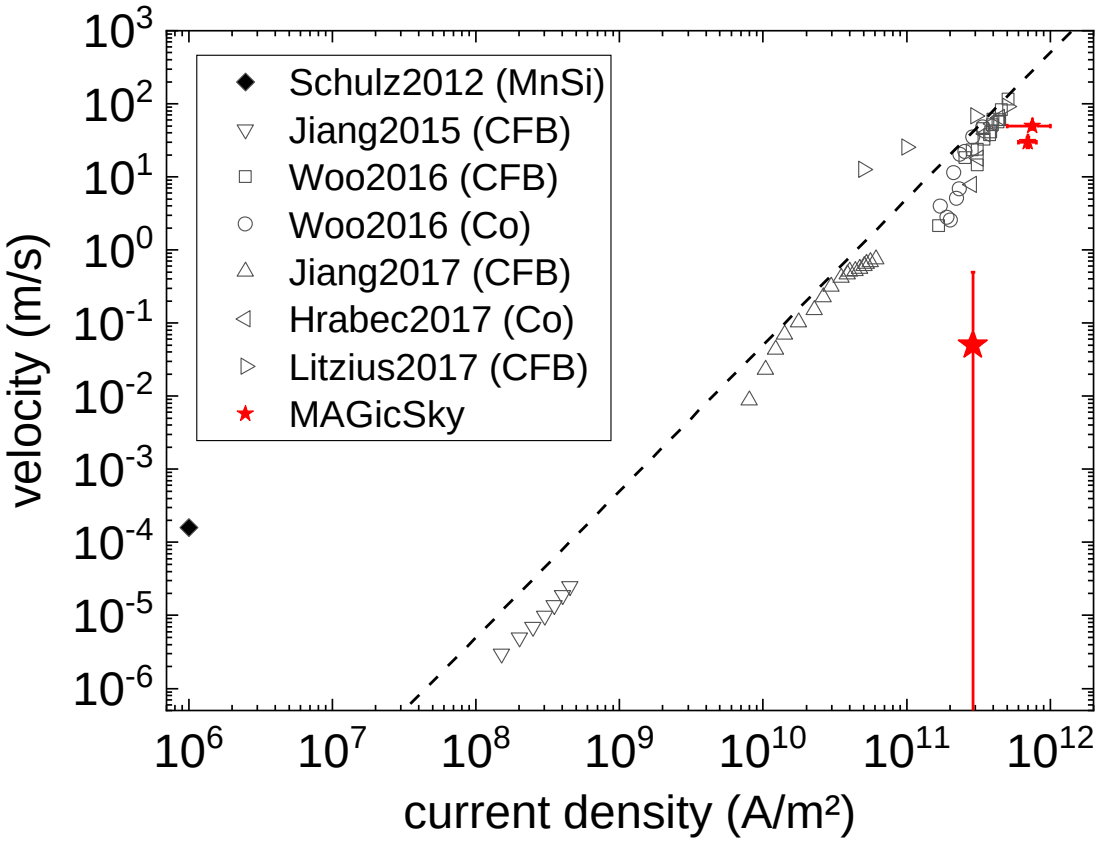


W. Legrand *et al*, *Nano Letters* **17**, 2703 (2017)

J.-V. Kim & M.-W. Yoo, *Appl. Phys. Lett.* **110**, 132404 (2017)

Skyrmion Velocity: State of the Art

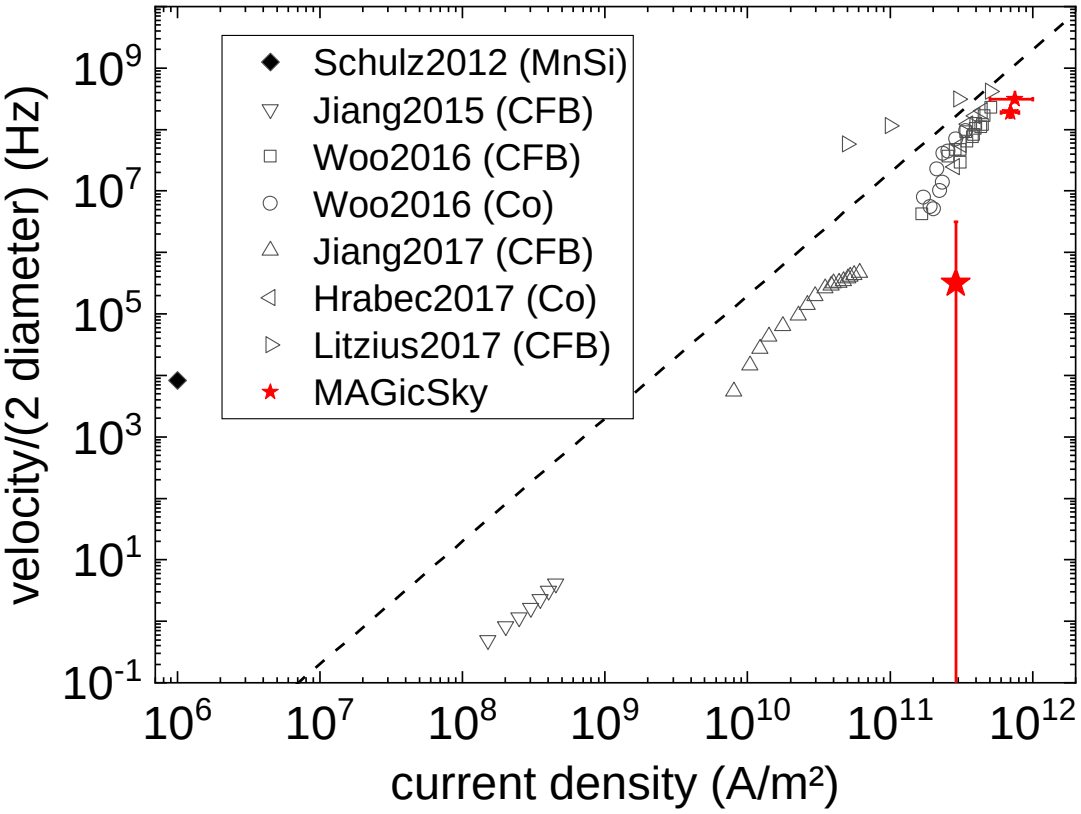
Velocity as a function of the current density in tracks



Skyrmion Velocity: State of the Art

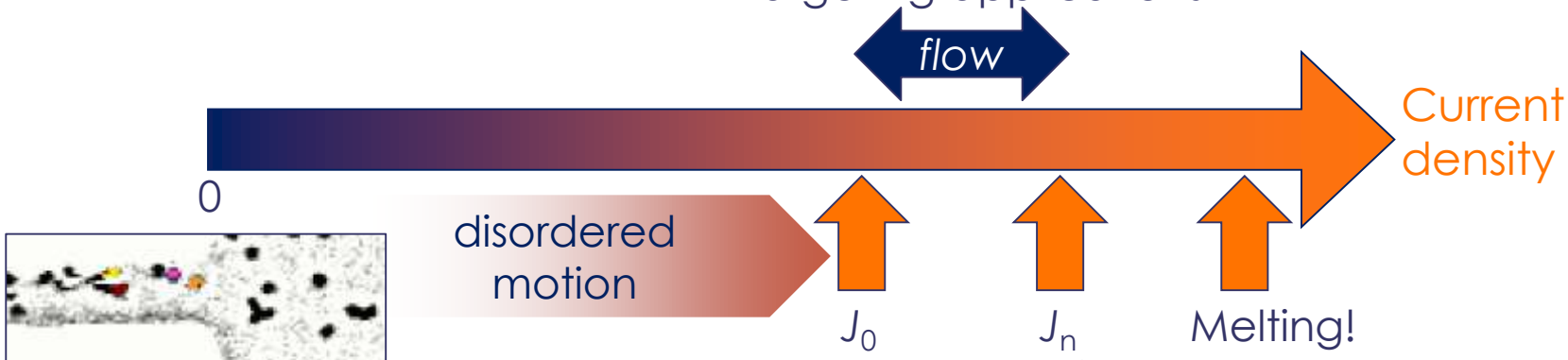
Velocity/diameter as a function of the current density in tracks

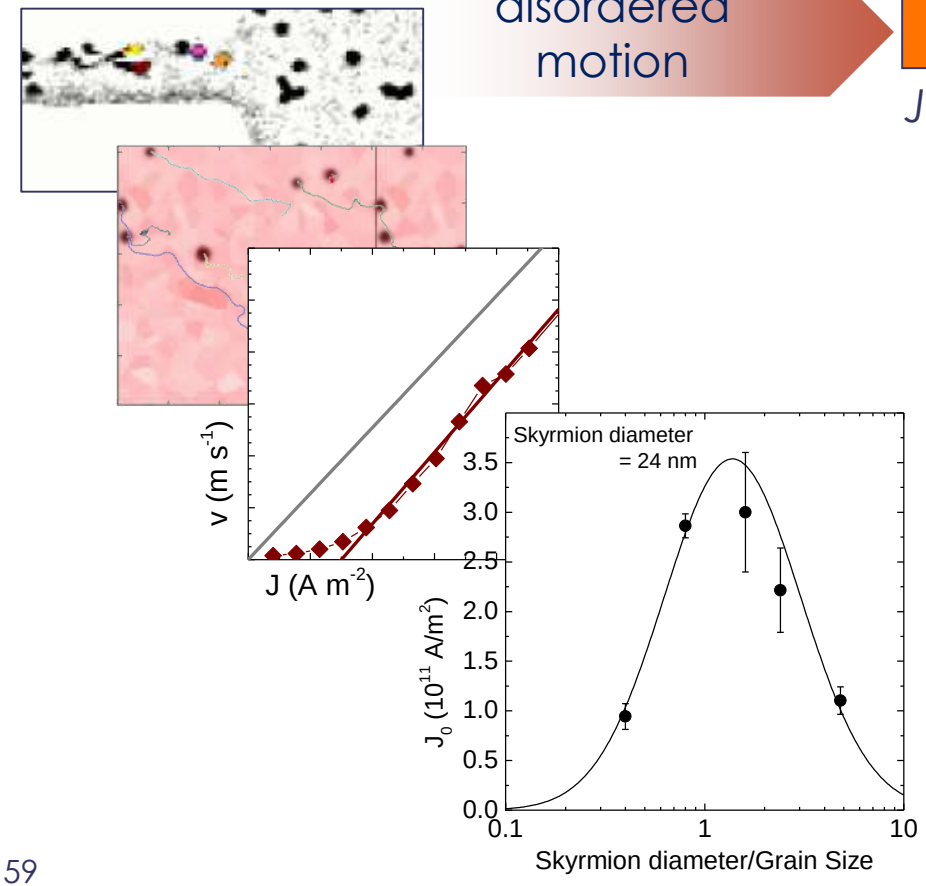
- Proper figure of merit is the bit rate: how many skyrmions are read per unit of time

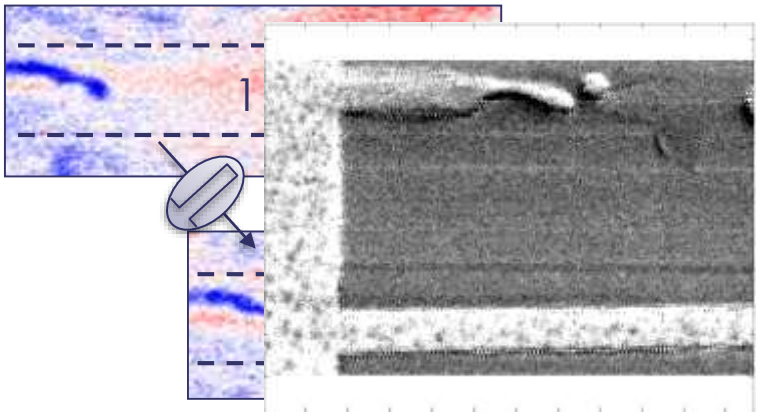


Summary of the Current-induced Phenomena

Need to enlarge this regime targeting applications



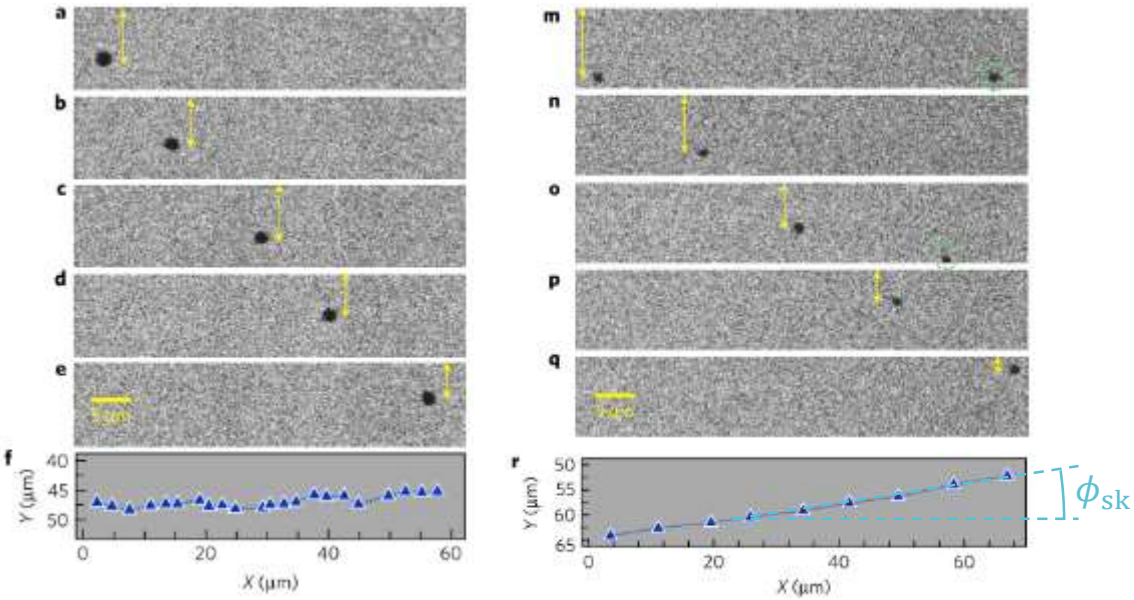




W. Legrand *et al*, *Nano Letters* **17**, 2703 (2017)

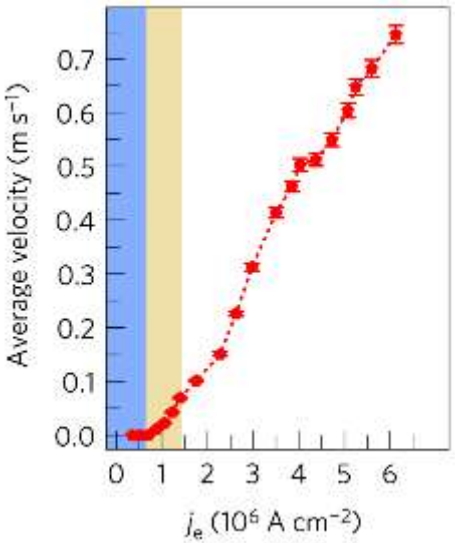
Observation of the Skyrmion Hall Effect

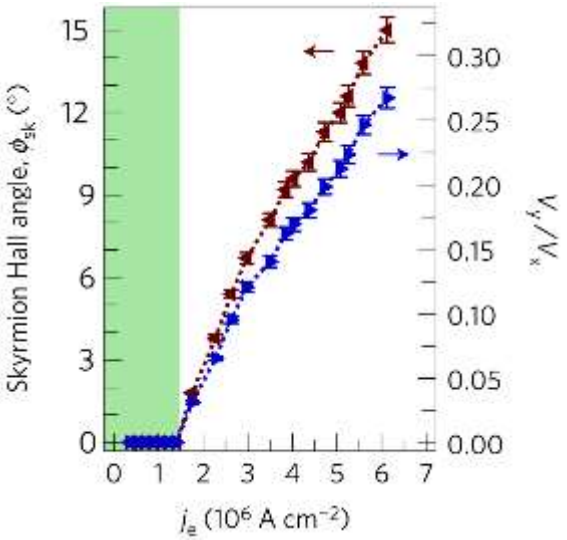
- Chiral Néel bubble in $Ta(5)/Co_{20}Fe_{60}B_{20}(1.1)/TaO_x(3)$
- Observed by optical Kerr microscopy



13 GA/m²
50 μs

28 GA/m²
50 μs

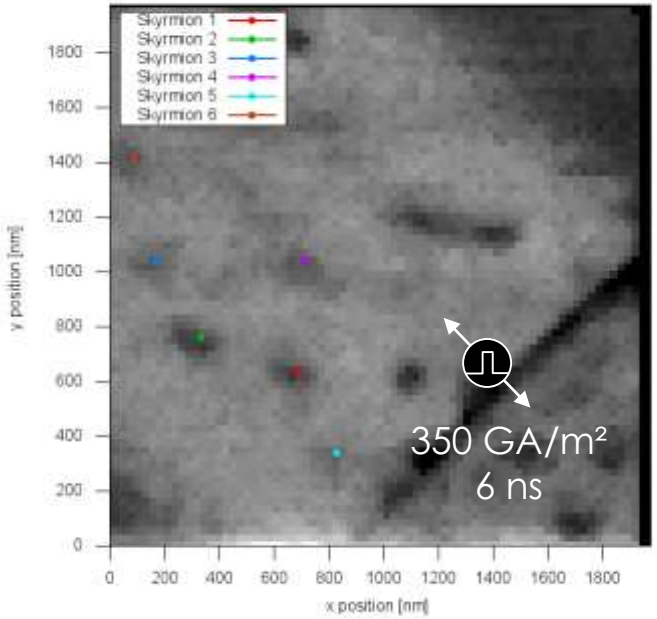


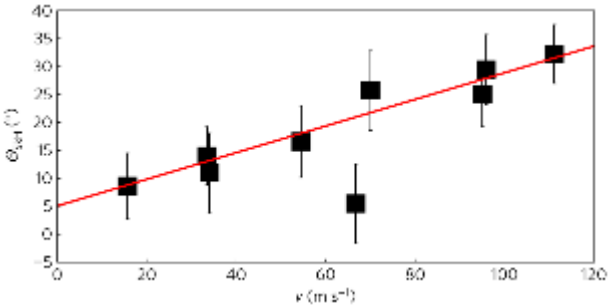


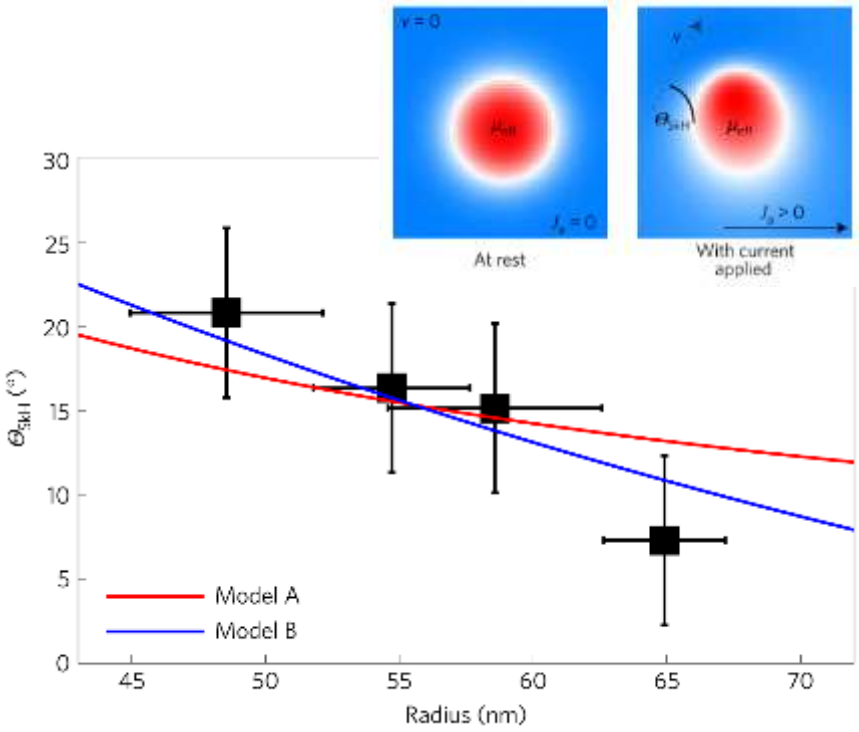
W. Jiang *et al*, *Nat. Phys.* **13**, 162 (2017)

Observation of the Skyrmion Hall Effect

- Skyrmions in $[Pt(3.2)/CoFeB(0.7)/MgO(1.4)]_{15}$
- Observed by "pump-probed" STXM







Deformation of the skyrmion during its motion

→ modify the dynamics.

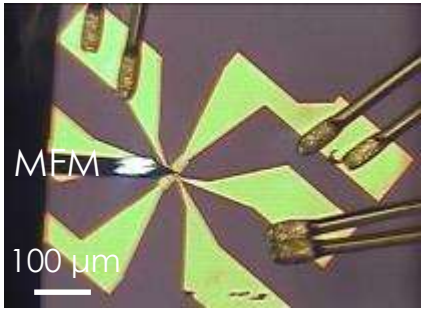
K. Litzius *et al*, *Nat. Phys.* **13**, 170 (2017)

Question session

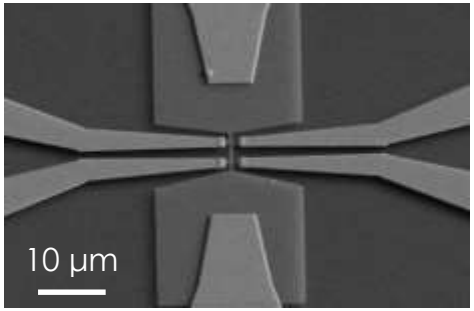
Combining MFM and Transport Measurements

Combined magnetic field and current pulses can be used to control skyrmion density in tracks, 200-nm to 1-µm wide:

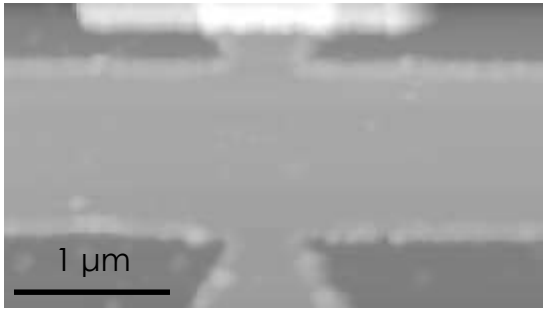
Optical



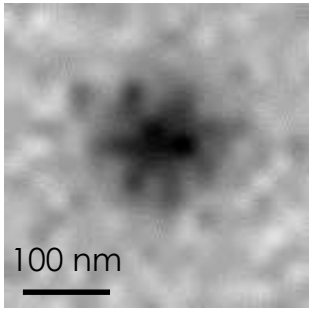
SEM

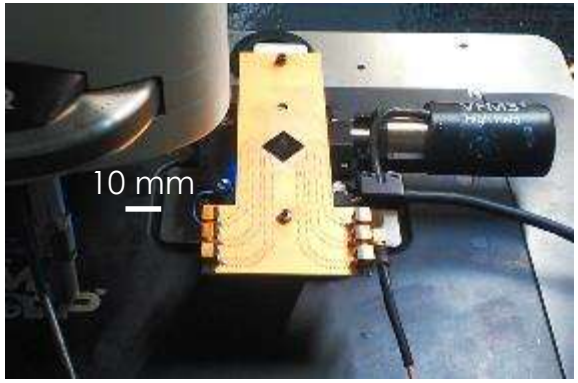


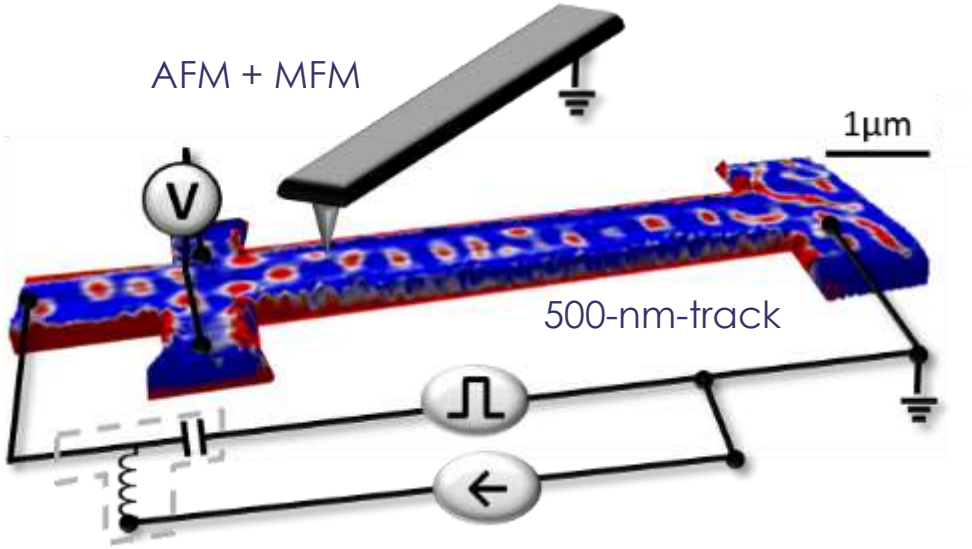
AFM



STXM

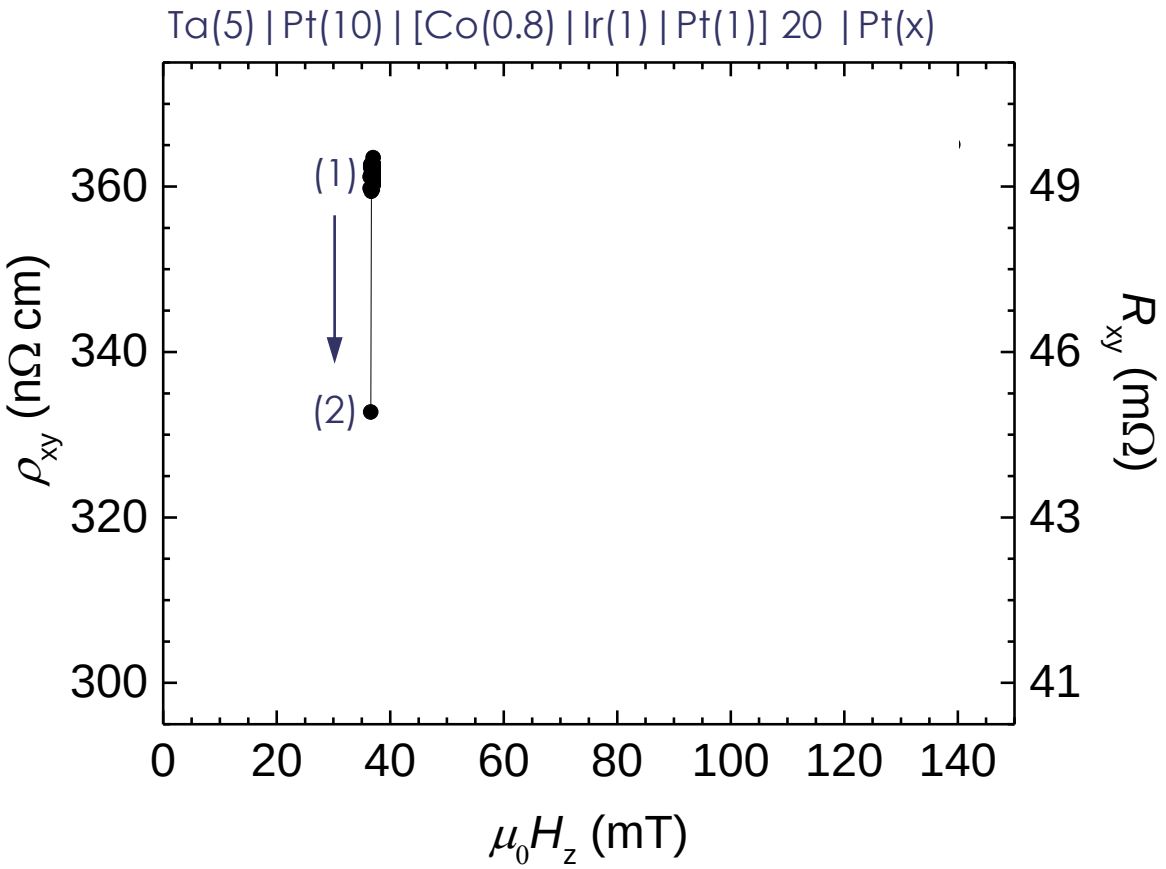


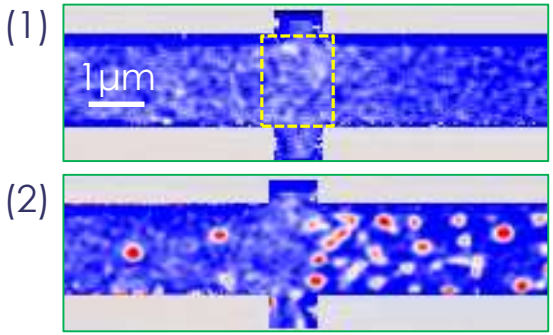




D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

Electrical Signal from Skyrmions



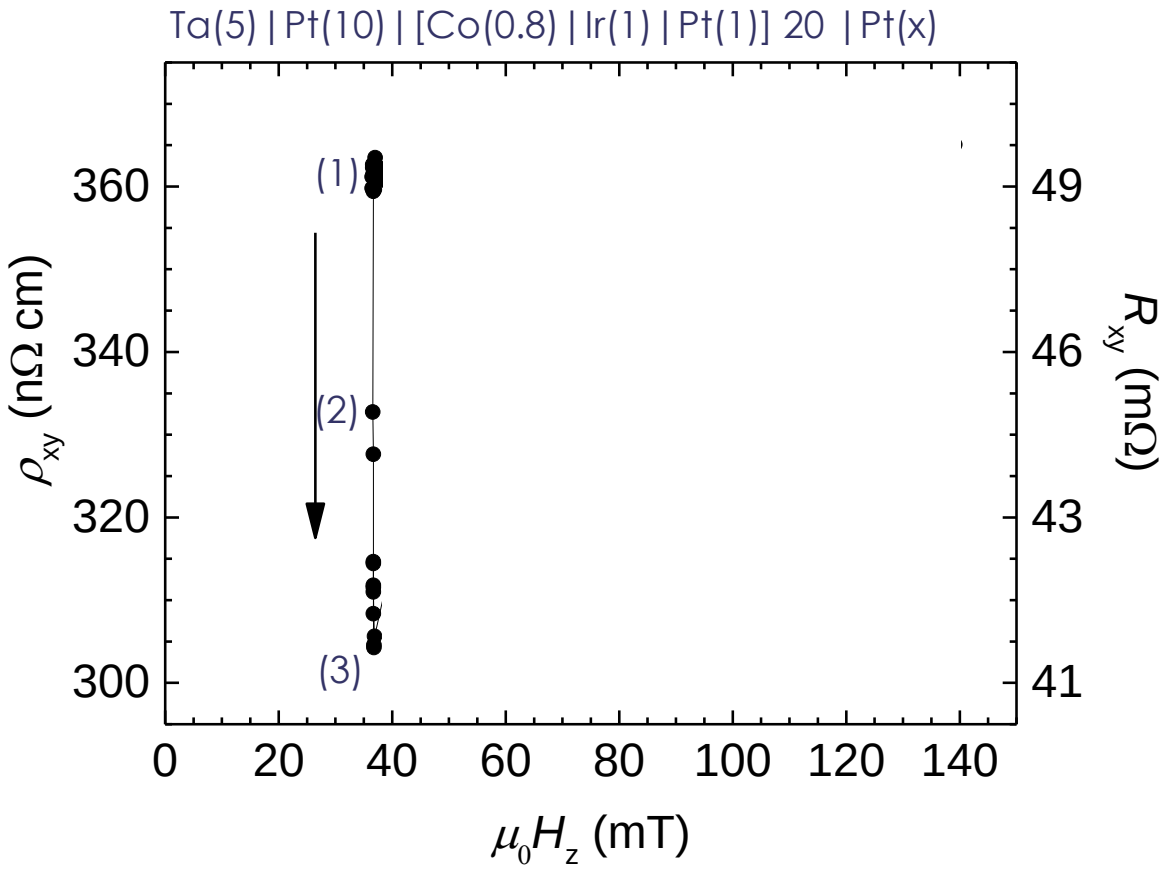


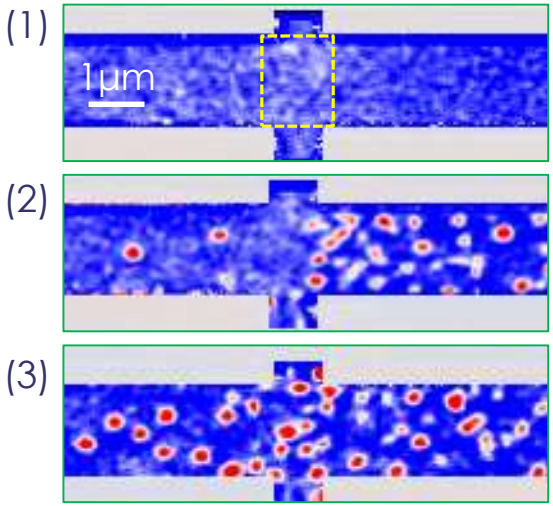
Nucleation by current pulses

- 20 pulses 100-ns-long, J = 2x10^{11} A/m^2.

D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

Electrical Signal from Skyrmions



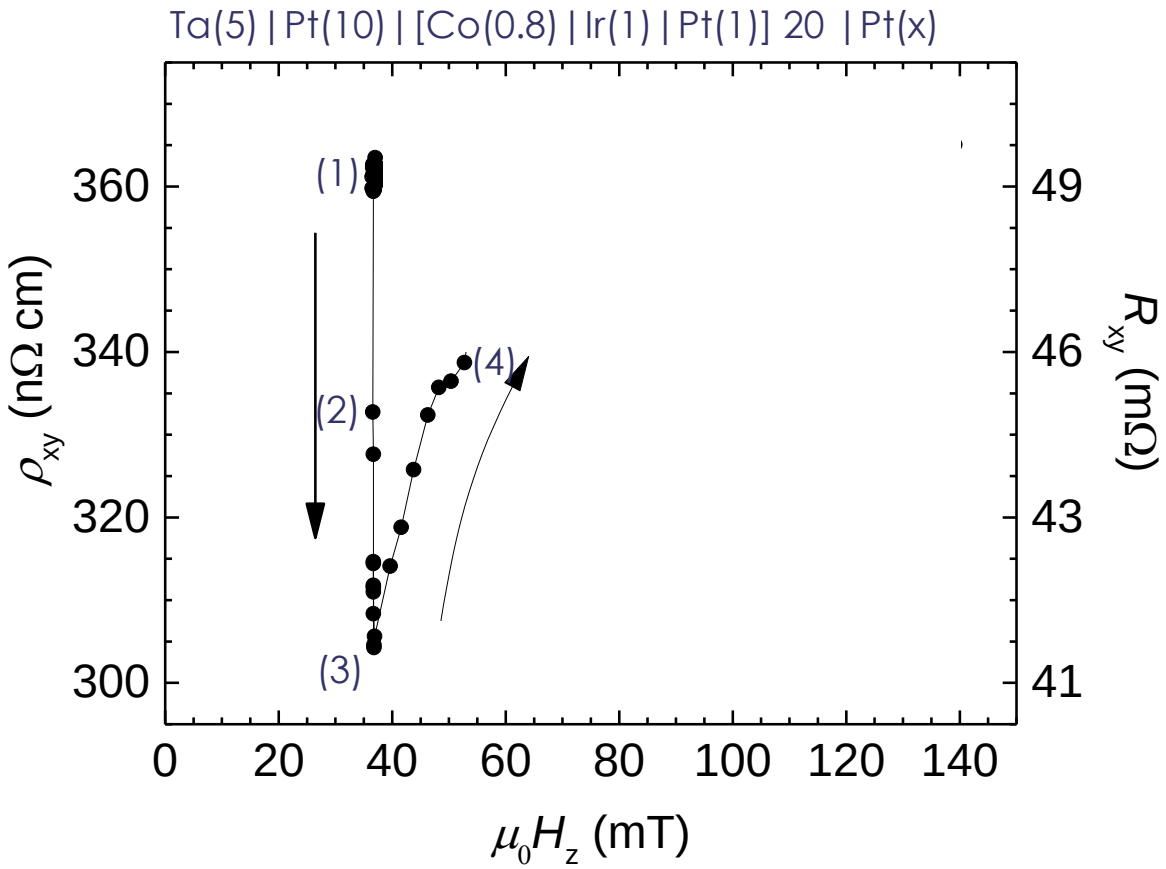


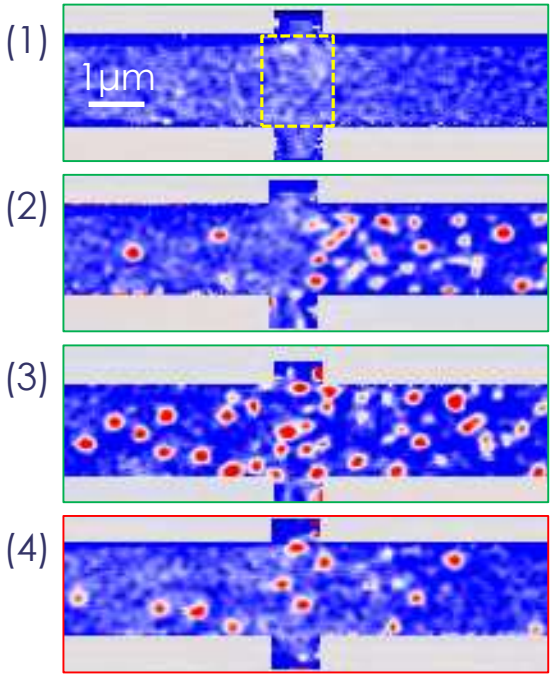
Nucleation by current pulses

- 20 pulses 100-ns-long, $J = 2 \times 10^{11}$ A/m^2.
- Maximum density for given magnetic field.

D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

Electrical Signal from Skyrmions





Nucleation by current pulses

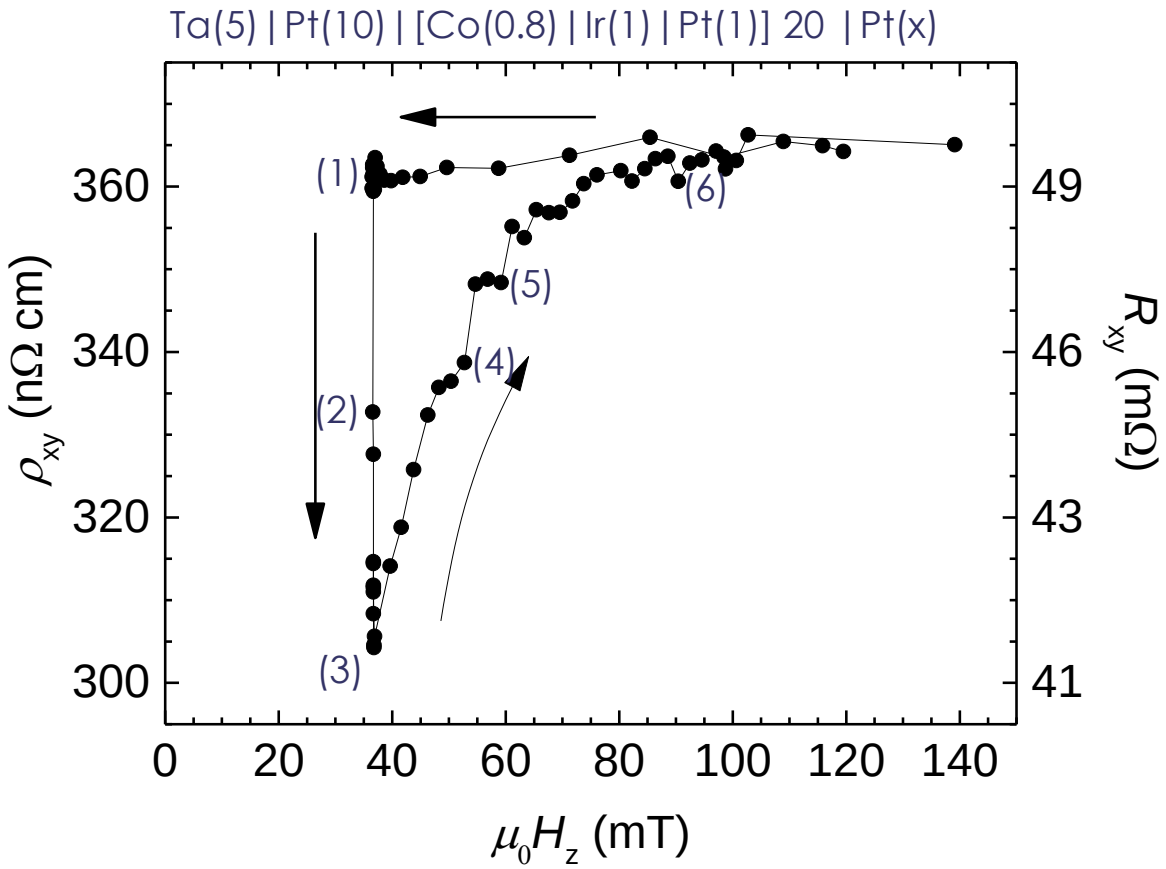
- 20 pulses 100-ns-long, J = 2x10^{11} A/m^2. Maximum density for given magnetic field.

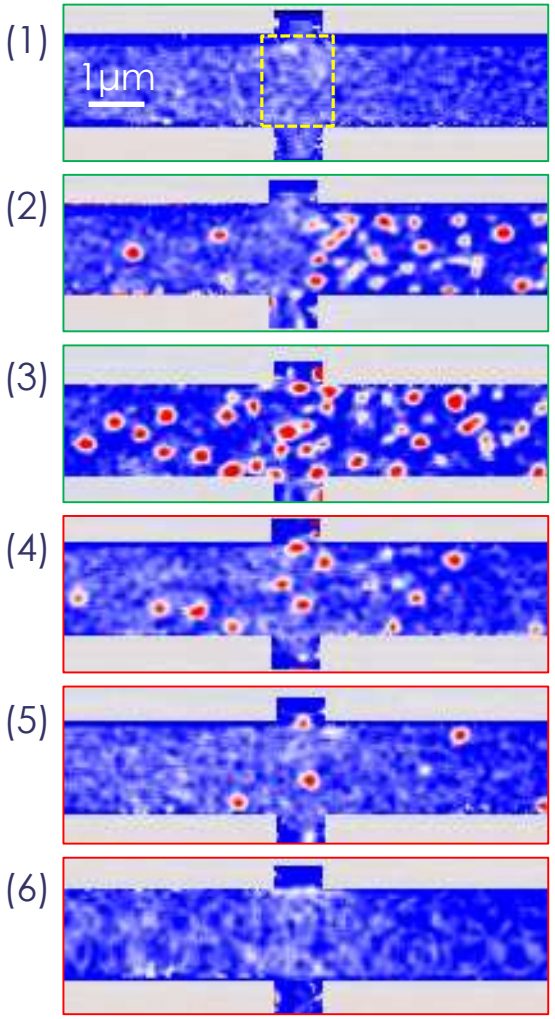
Annihilation with magnetic field and current pulses

- 20 pulses 100-ns-long, J = 2x10^{11} A/m^2, $\mu_0 H$ increasing...

D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

Electrical Signal from Skyrmions





Nucleation by current pulses

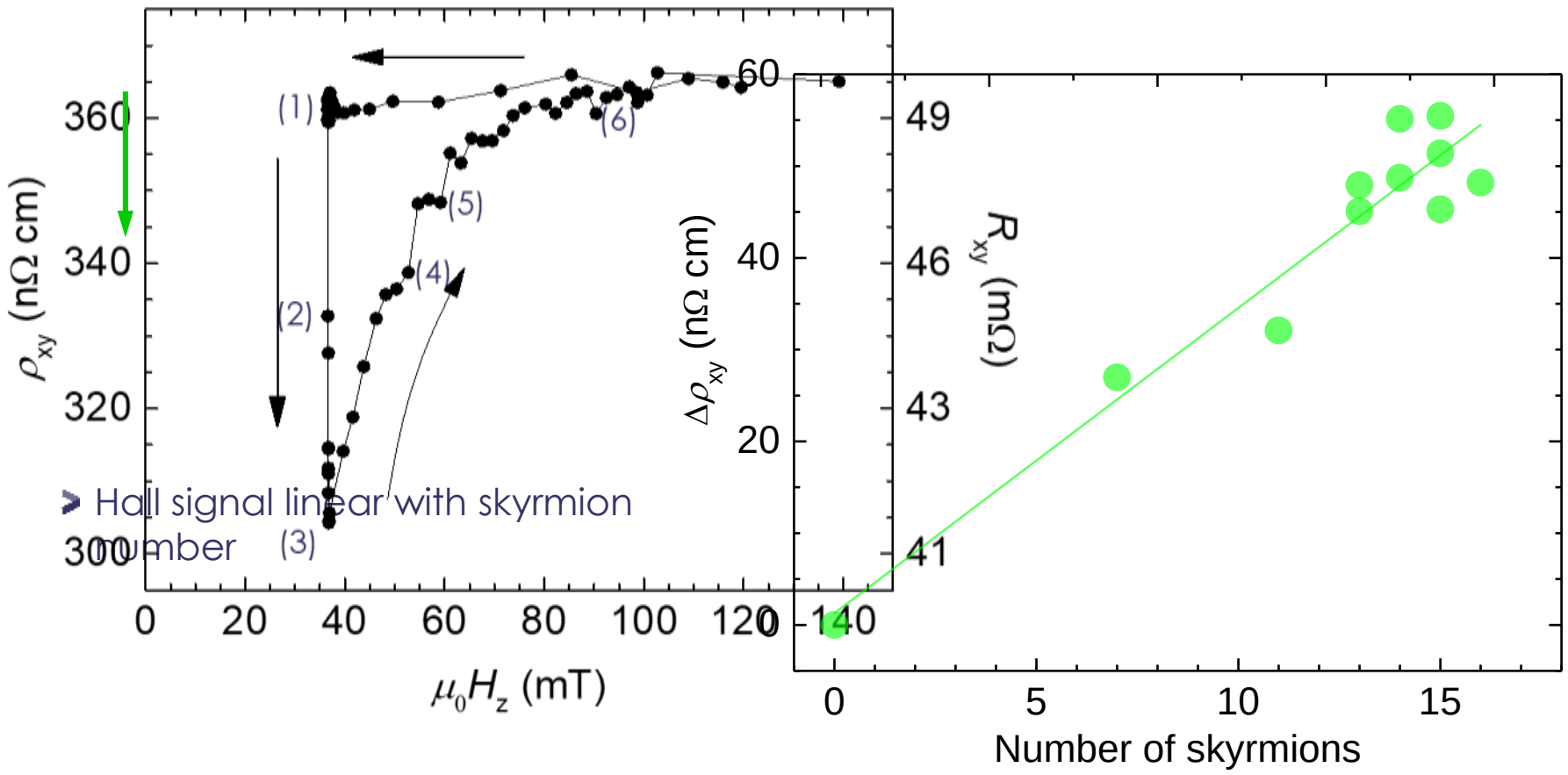
- 20 pulses 100-ns-long, J = 2x10^{11} A/m^2.

Annihilation with magnetic field and current pulses

- 20 pulses 100-ns-long, J = 2x10^{11} A/m^2, $\mu_0 H$ increasing...

D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

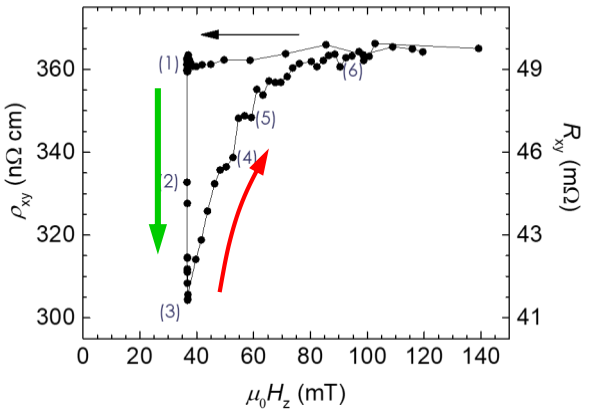
Electrical Signal from Skyrmions



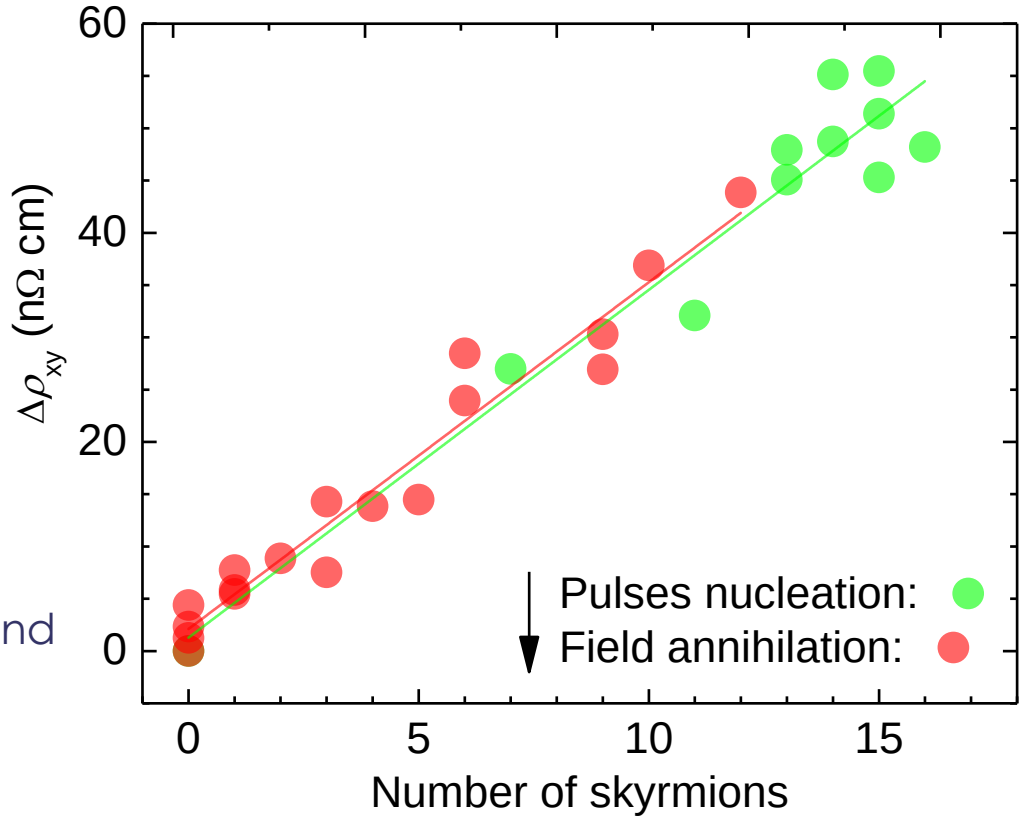
- Hall signal linear with skyrmion number

D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

Electrical Signal from Skyrmions

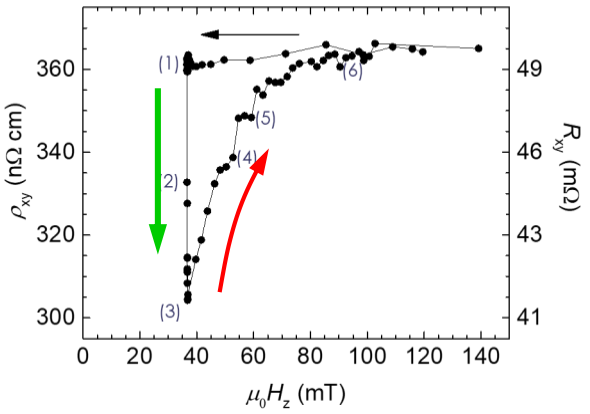


- Hall signal linear with skyrmion number
- Same behavior for nucleation and annihilation

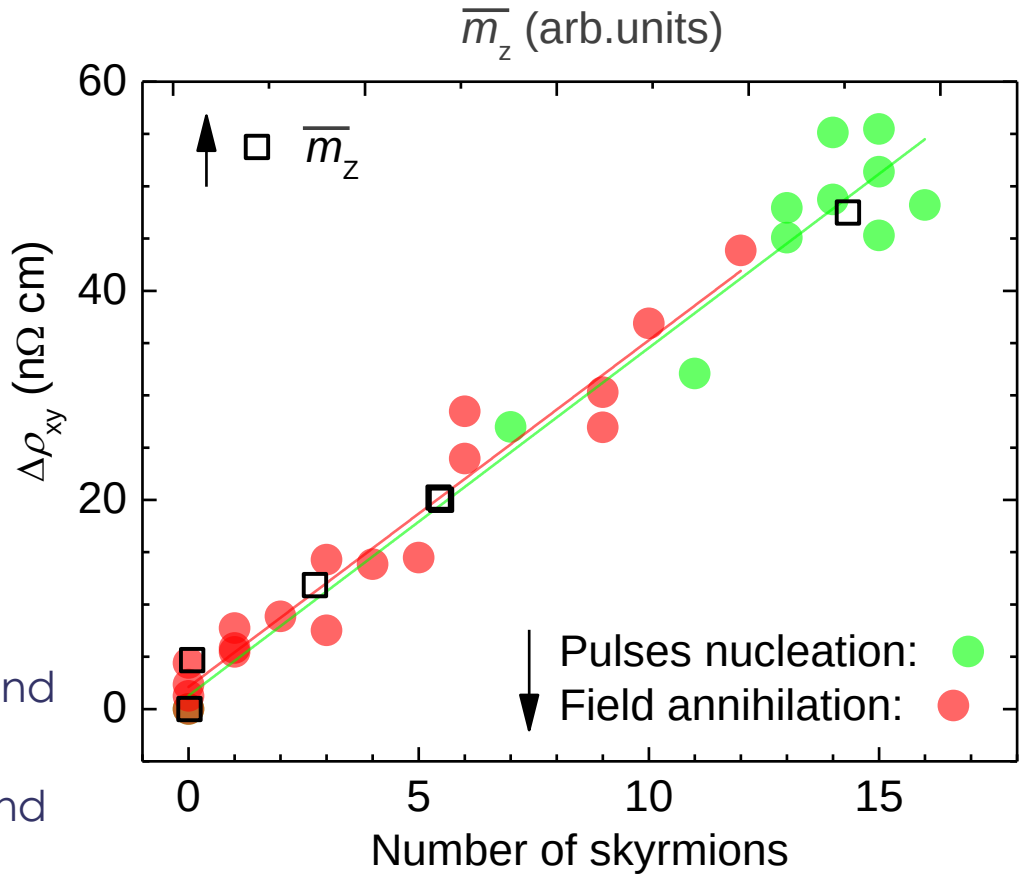


D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

Electrical Signal from Skyrmions



- Hall signal linear with skyrmion number
- Same behavior for nucleation and annihilation
- Correspondence of mean m_z and skyrmion number



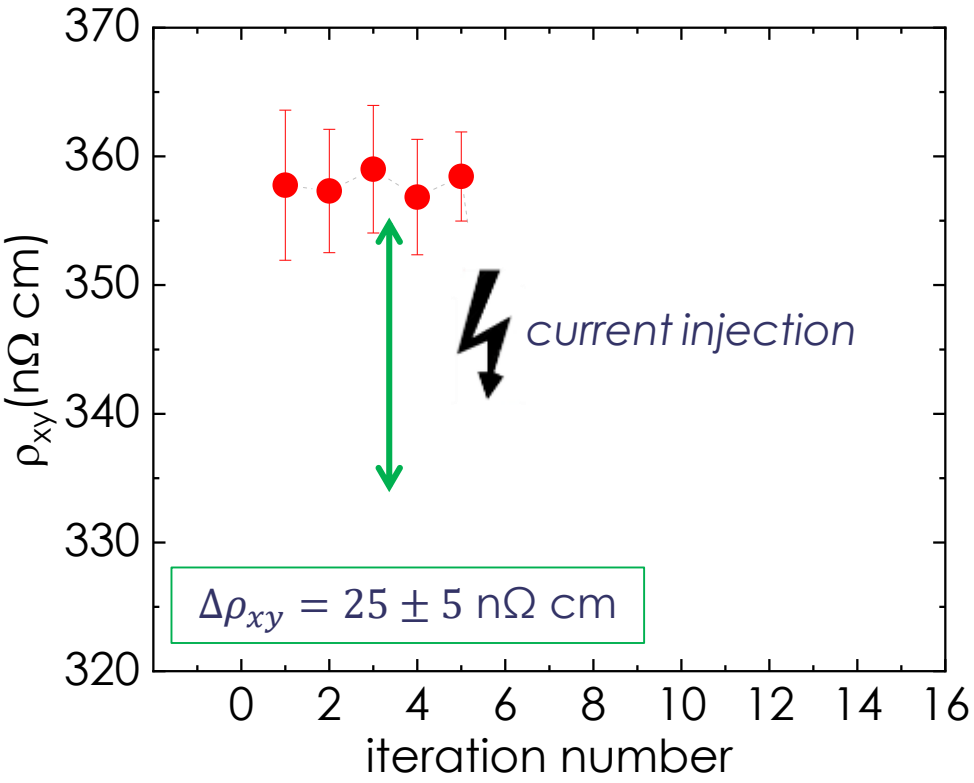
Experimental transverse resistivity of the single skyrmion: $\Delta\rho_{xy} = 3.5 \pm 0.5$ nΩ cm

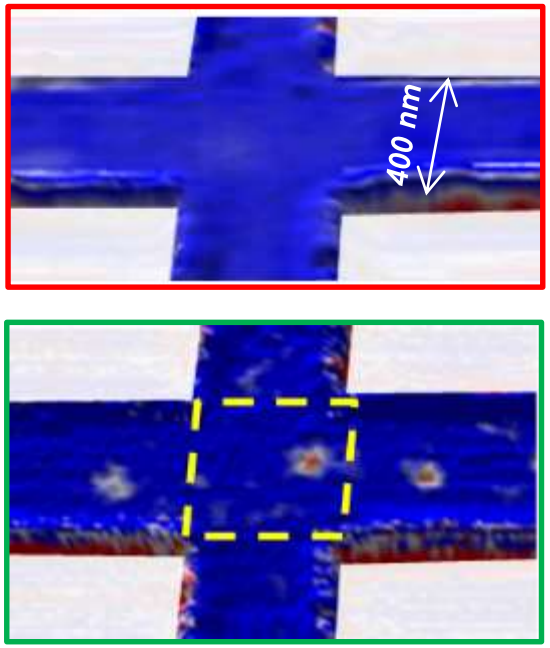
D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

Electrical Detection of a Single Skyrmion

The AHE signal increases as the track width decreases

- Signal is proportional to ratio "skyrmion area" over "track area"





D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

What is the Origin of the Hall Signal?

Estimation of the anomalous Hall effect (AHE):

- Proportional to mean m_z (from STXM). For a single skyrmion, the change in ρ_{xy} is:

$$\overline{m_z} = \frac{1}{S}\int_S m_z ds \approx 0.5$$

From STXM:
d_{sk} = 85 ± 10 nm

$$\Delta\rho_{\mathrm{AHE}} = \rho_{\mathrm{AHE}}\frac{\overline{m_z}\pi\, d_{\mathrm{sk}}^2}{a_{\mathrm{cross}}} \approx \rho_{\mathrm{AHE}}\frac{1}{2}\frac{a_{\mathrm{sk}}}{a_{\mathrm{cross}}} = 23 \pm 3\ \mathrm{n\Omega\ cm}$$

What about the topological Hall effect (THE)?

- Most optimistic approach for THE is 1 flux quantum per skyrmion area:

$$\Delta\rho_{\mathrm{THE}} = P\rho_{\mathrm{OHE}}\frac{\Phi_0}{a_{\mathrm{sk}}}\frac{a_{\mathrm{sk}}}{a_{\mathrm{cross}}} \leq \rho_{\mathrm{OHE}}\frac{\Phi_0}{a_{\mathrm{cross}}} \approx 1\cdot 10^{-2}\ \mathrm{n\Omega\ cm}$$

There are theories to address the non-adiabatic cases:
e.g, K. S. Denisov, I. V. Rozhansky *et al*, *Sci. Rep.* **7**, 17204 (2017)

AHE is enough to explain the experimental observation, THE is orders of magnitude weaker.

Experimental transverse resistivity of the single skyrmion is detected and corresponds to the expected AHE

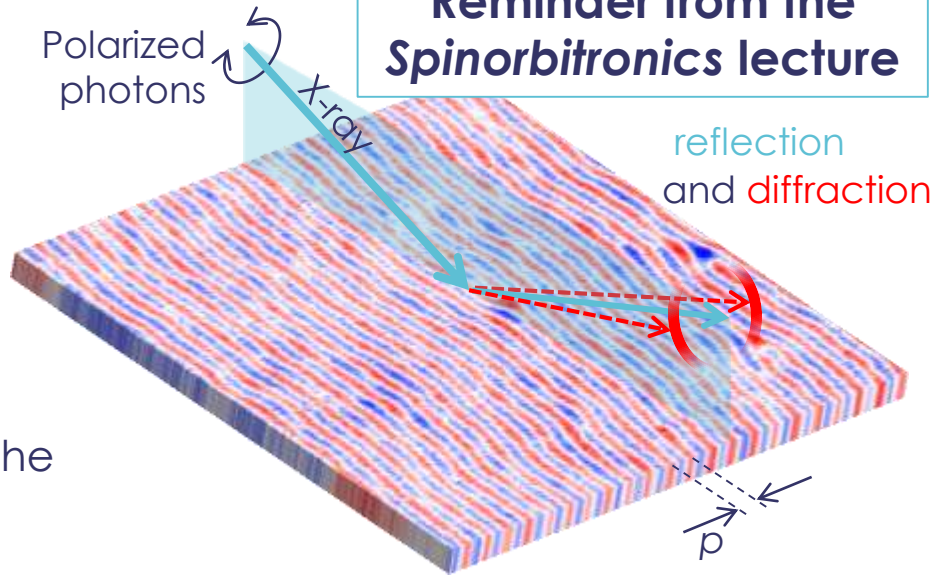
D. Maccariello *et al*, *Nat. Nanotechnol.* **13**, 233 (2018)

X-ray Resonant Magnetic Scattering probes the Wall Structures

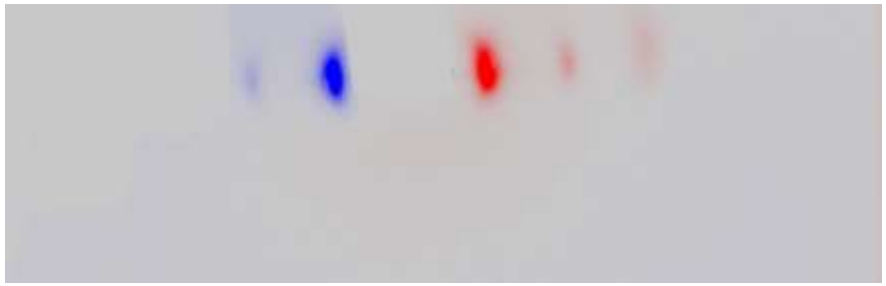
Reminder from the *Spinorbitronics* lecture

Synchrotron technique: probe magnetism using photons at the Co L_3-edge energy

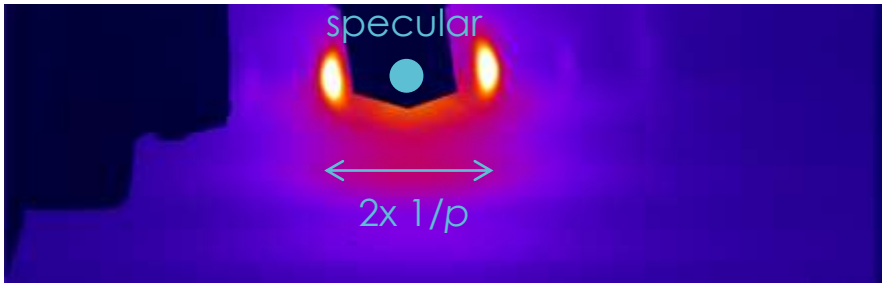
- 2D detector on SEXTANTS beamline at Synchrotron SOLEIL: get real-space periodicity of the domains
- Circular dichroism: get the chirality of the structure



(CL-CR)/(CL+CR)



CCD signal (CL+CR)



Strong circular dichroism of the XRMS diffraction peaks in our multilayers

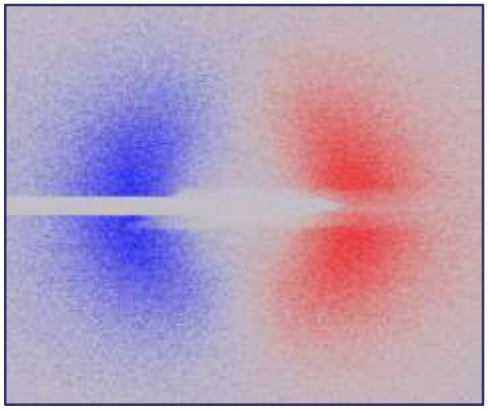
H. A. Dürr *et al*, *Science* **284**, 2166 (1999)
J.-Y. Chauleau *et al*, *Phys. Rev. Lett.* **120**, 037202 (2018)

Definite Determination of the Chirality of the Multilayers

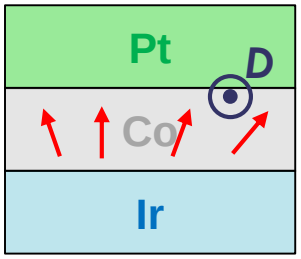
Reminder from the *Spinorbitronics* lecture

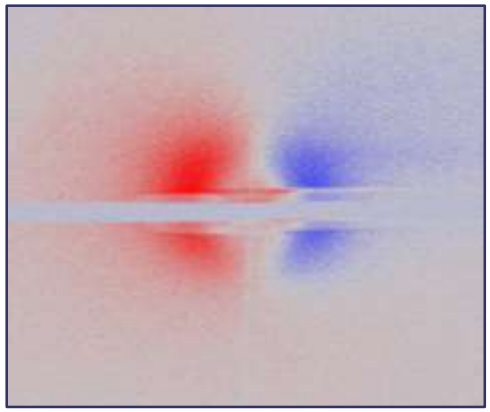
Inversion of the multilayer stack

- Pure Néel walls in both case
- Inverted chirality: CCW for Co on top of Pt, CW for Pt on top of Co

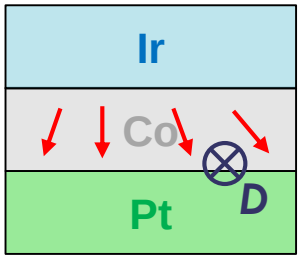


$[Ir(1) | Co(0.8) | Pt(1)]_{x5}$





$[Pt(1) | Co(0.8) | Ir(1)]_{x5}$



Just *looking* at a couple of XRMS images without analysis directly reveals the domain structure!

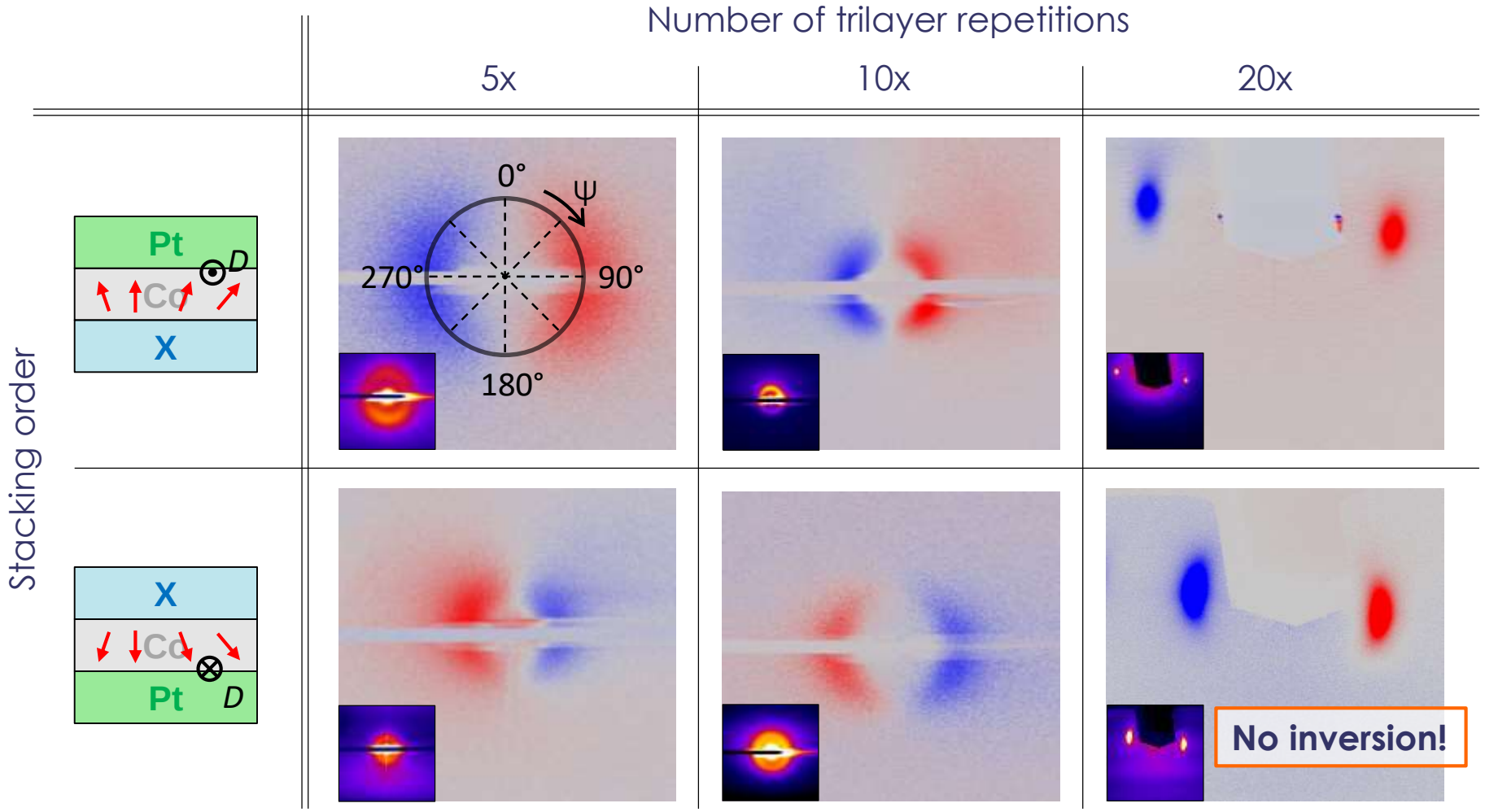
- Fast (10 minutes)
- No need to pattern
- No parameter to know
- Probe under a capping layers
- Sensitive to few nm of magnetic materials
- No effect on magnetization
- Possibility to apply field
- Possibility to probe insulating sample ($BiFeO_3$)
- …

J.-Y. Chauleau *et al*, *Phys. Rev. Lett.* **120**, 037202 (2018)

So, we understood everything?

Reminder from the *Spinorbitronics* lecture

Something happens at large repetition number…



W. Legrand *et al*, *Science Adv.* **4**, eaat0415 (2018)

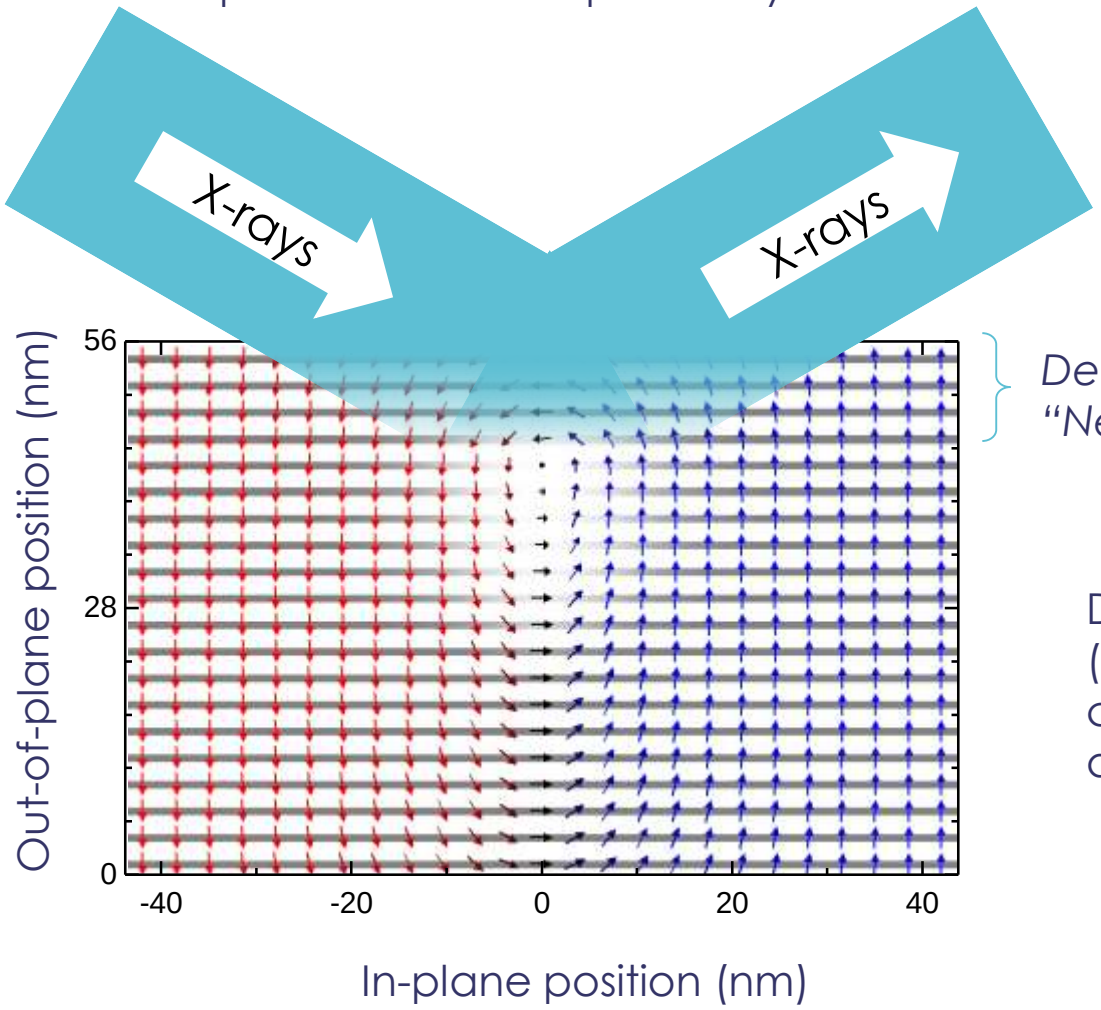
Recently reproduced in W. Li *et al*, *Adv. Mater.* **31**, 1807683 (2019)

Explanation of the XRMS

Resonant X-rays at Co L_3 edge penetrate only the first nm

M_S = 1370 kA/m
K_U = 1430 kJ/m^3
A = 10 pJ/m
D = 1.0 mJ/m^2

- XRMS corresponds to a few topmost layers with reversed chirality.

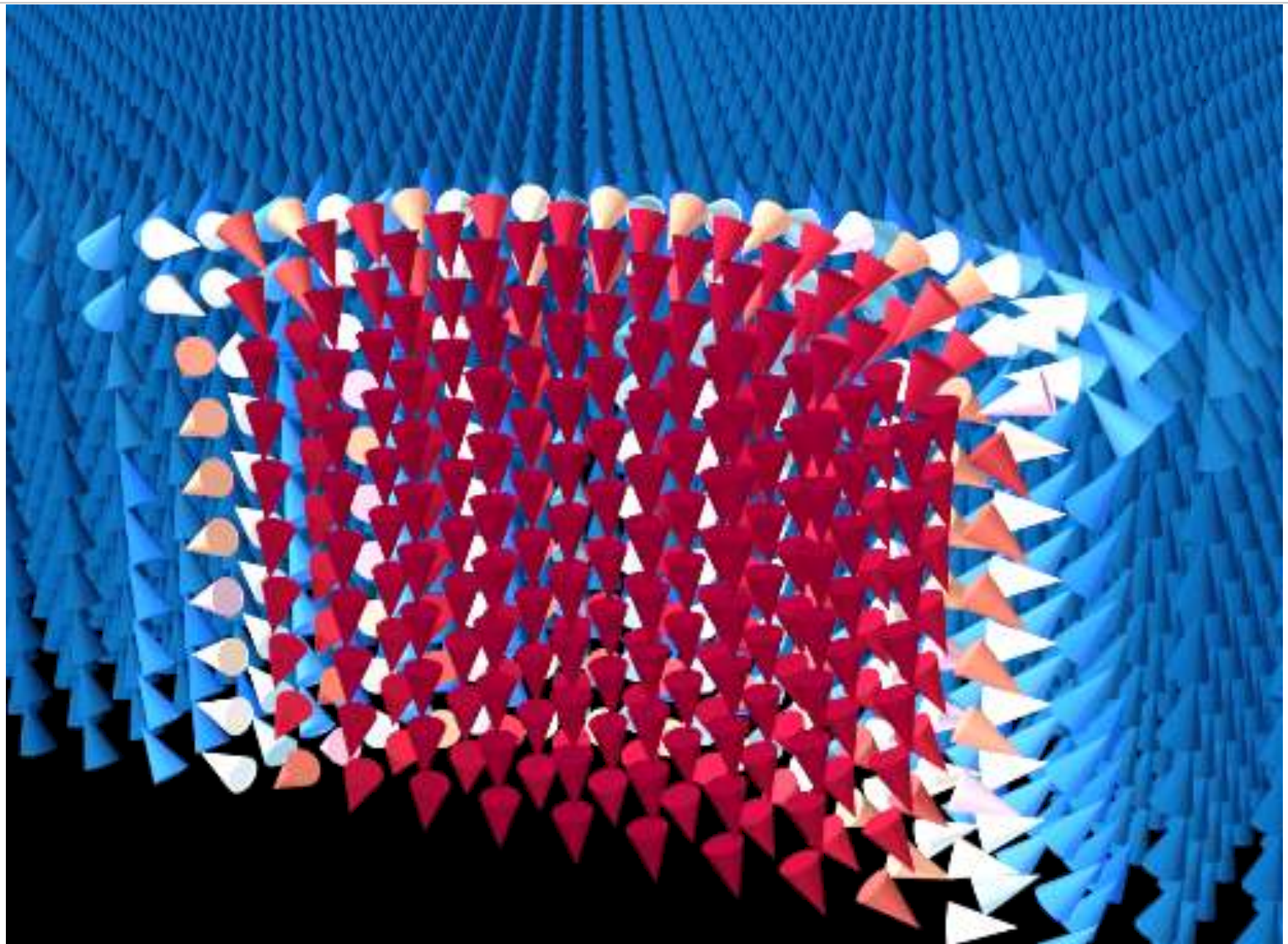


Detection of the "Néel cap" only.

Domain wall texture (including chirality) changes through the different Co layers.

W. Legrand *et al*, *Science Adv.* **4**, eaat0415 (2018)

Skyrmions with hybrid chirality

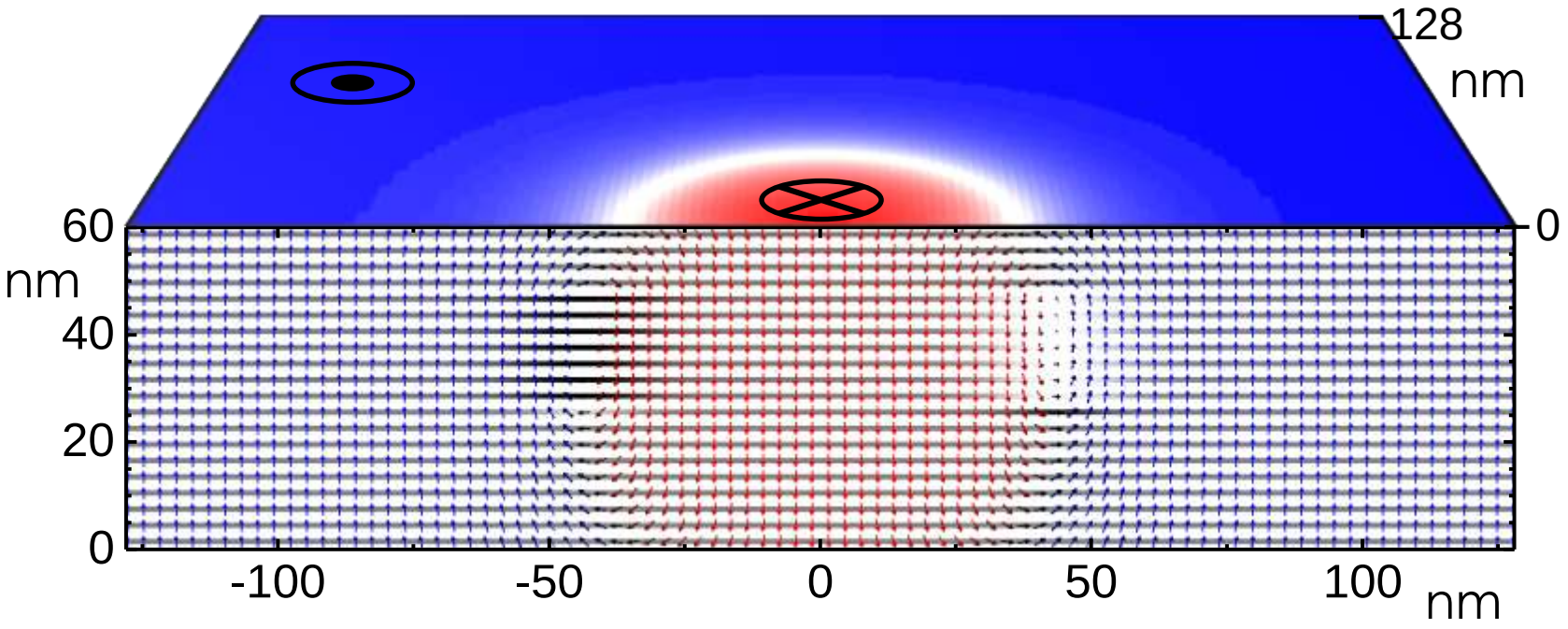


Consequences for Skyrmion Motion and SOT Engineering

Chirality depends on position in the stack

- Inverted chirality at the top and the bottom
- SOT must be adapted for more efficient motion

M_S = 1306 kA/m
K_U = 1230 kJ/m^3
A = 10 pJ/m
D = 0.8 mJ/m^2

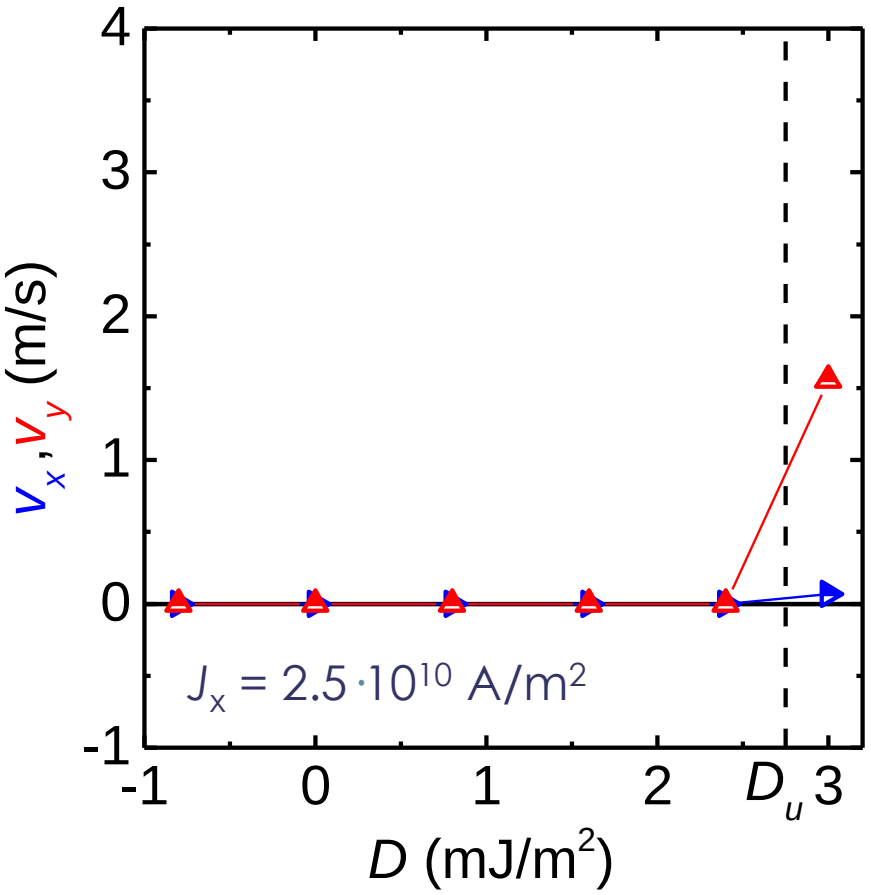


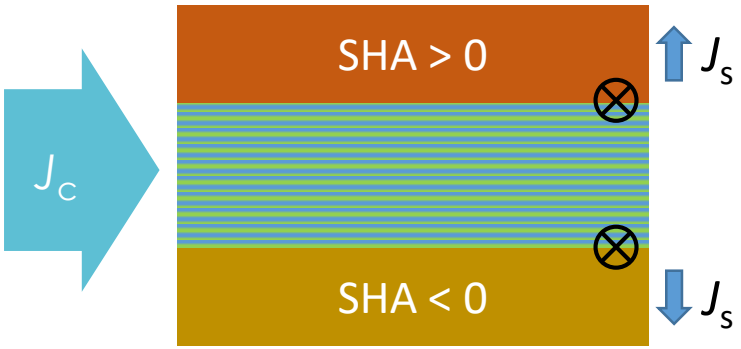
W. Legrand *et al*, *Science Adv.* **4**, eaat0415 (2018)

Torques from Buffer and Capping Layers

Opposite chirality for bottommost and topmost layer up to D_u

- Heavy metal layers with opposite spin Hall angles will result in opposite torques due to opposite chiralities





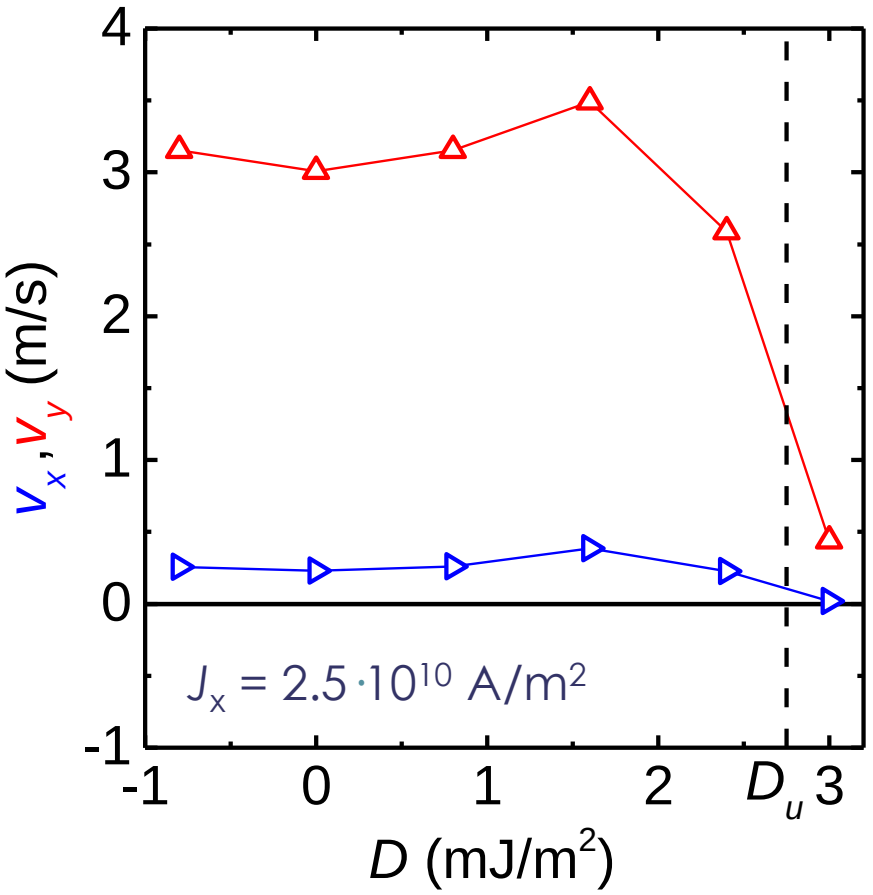
| **Pt** 8 | (**Co** 1 | **Z** 1 | **X** 1)$_{x20}$ | **Ta** 10

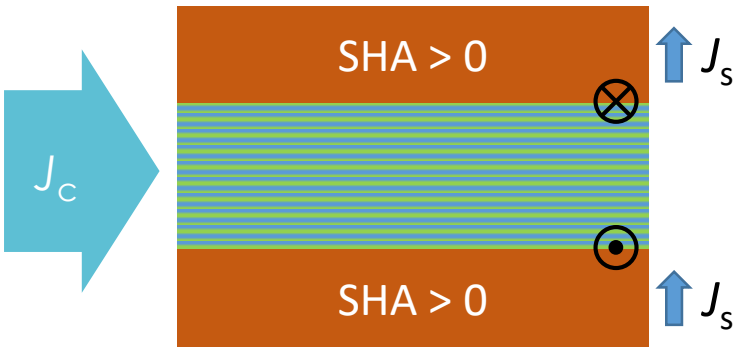
W. Legrand *et al*, *Science Adv.* **4**, eaat0415 (2018)

Torques from Buffer and Capping Layers

Opposite chirality for bottommost and topmost layer up to D_u

- Heavy metal layers with identic spin Hall angles will result in additive torques due to opposite chiralities





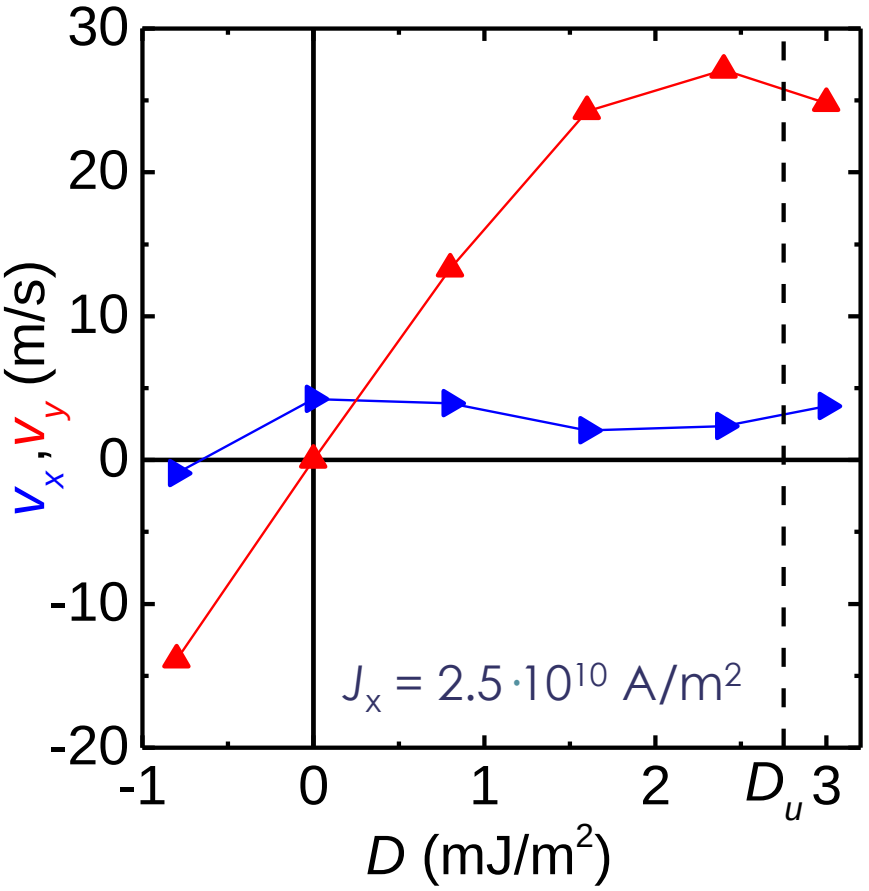
| **Pt** 8 | (**Co** 1 | **Z** 1 | **X** 1)$_{x20}$ | **Pt** 8

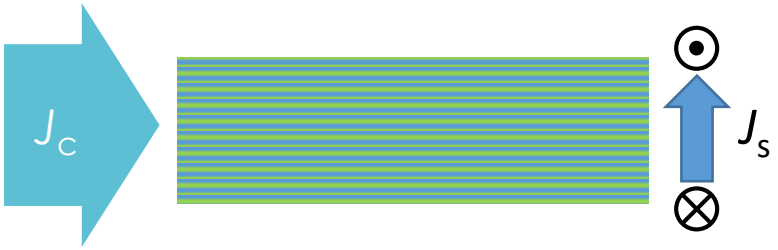
W. Legrand *et al*, *Science Adv.* **4**, eaat0415 (2018)

Torques through All Layers

Opposite chirality for bottommost and topmost layer up to D_u

- Velocity determined by the ratio of the DW chiralities



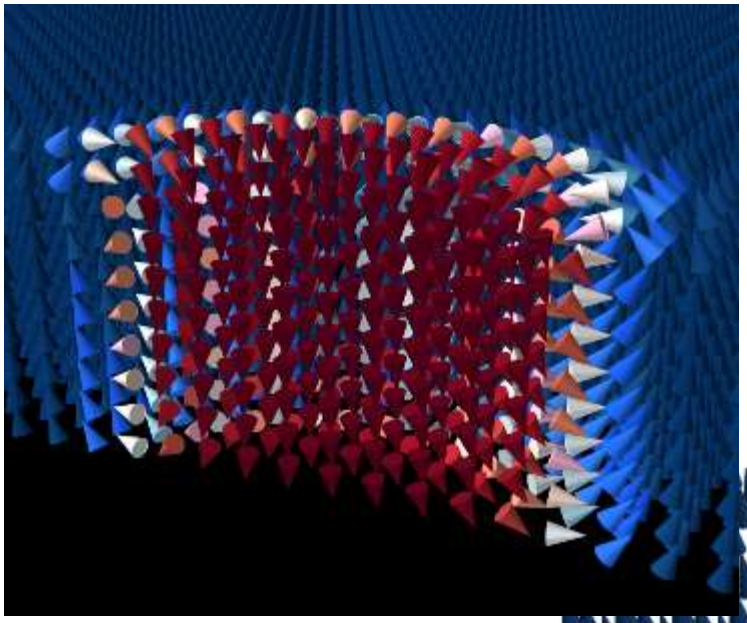


W. Legrand *et al*, *Science Adv.* **4**, eaat0415 (2018)

Question session

Conclusion

Increased complexity brings new "advantages" – still a lot to discover!



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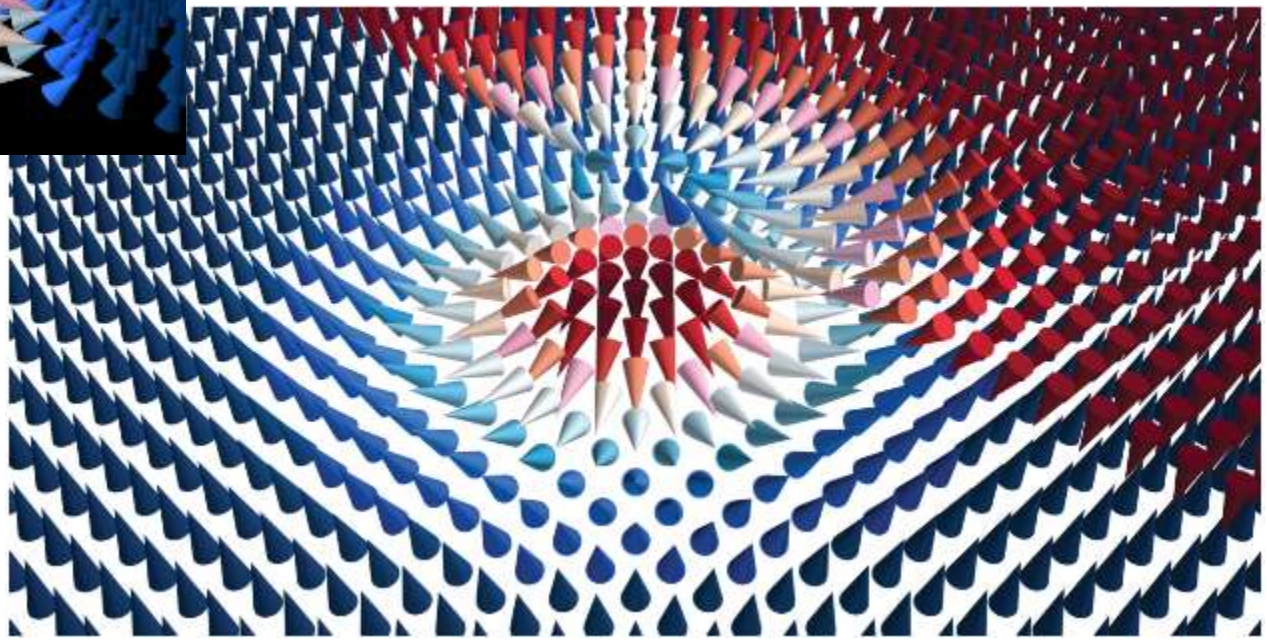
… to be continued!



Thank you for your attention!