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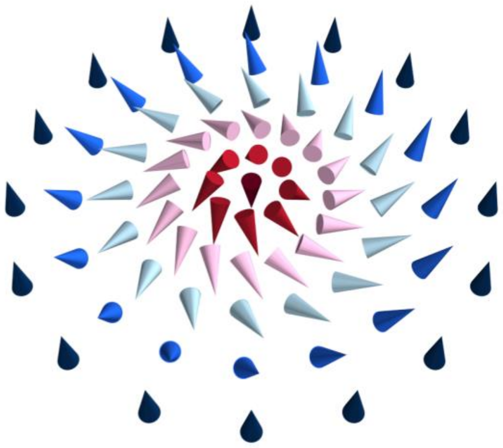
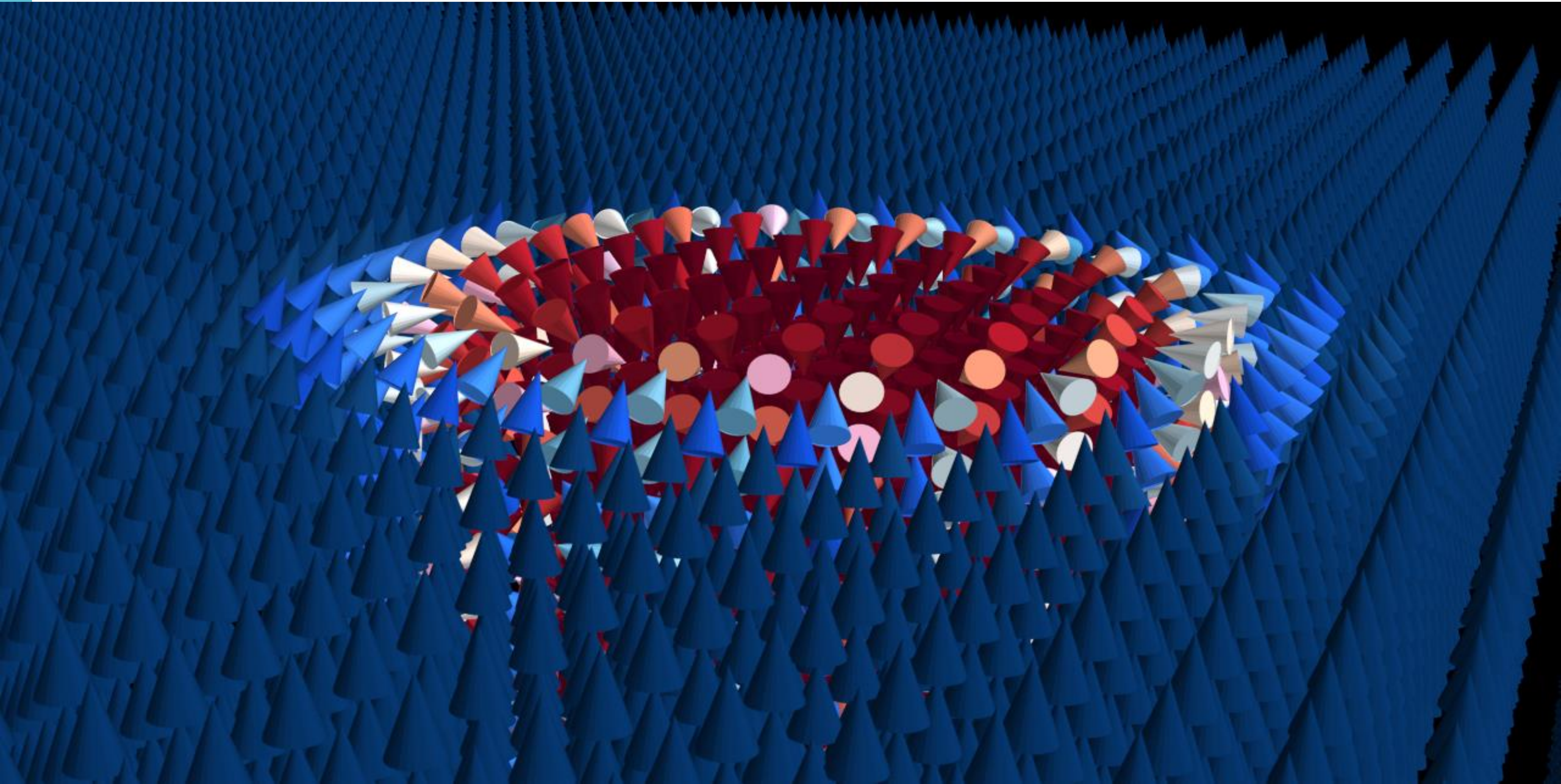
Crafting magnetic skyrmions at room temperature: size, stability and dynamics in multilayers

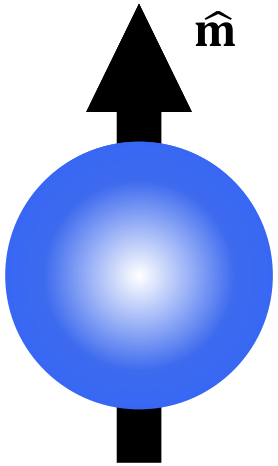
RJP 2021

Unité mixte de physique CNRS/Thales, Palaiseau
Supervisors: Vincent Cros & Nicolas Reyren



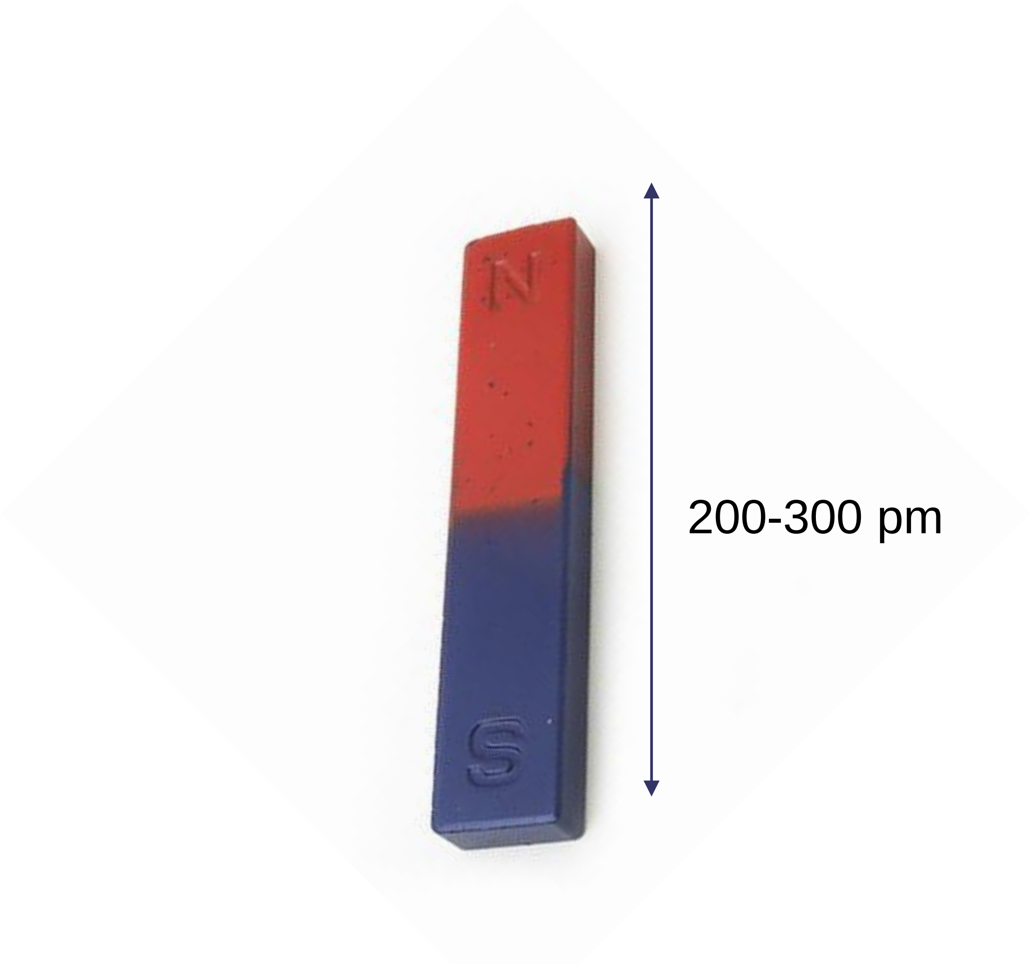
A skyrmion





magnetic atom

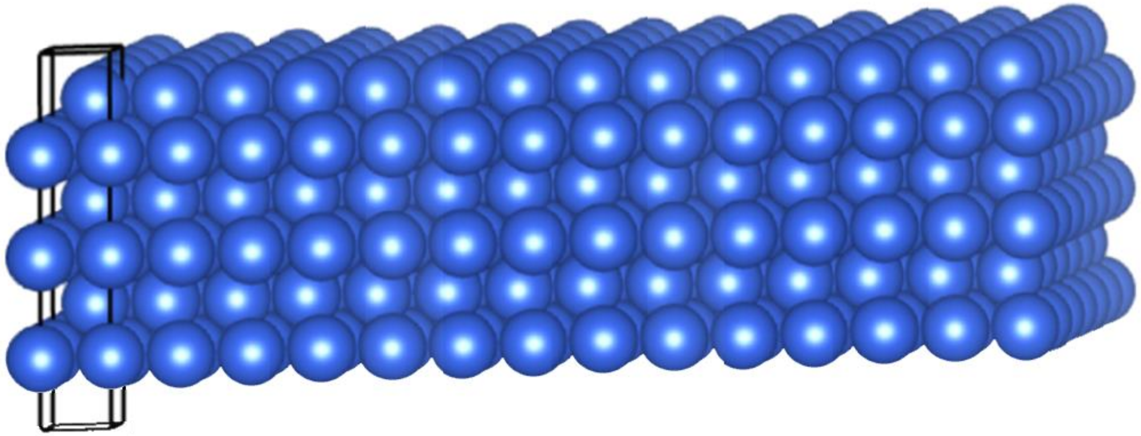
=



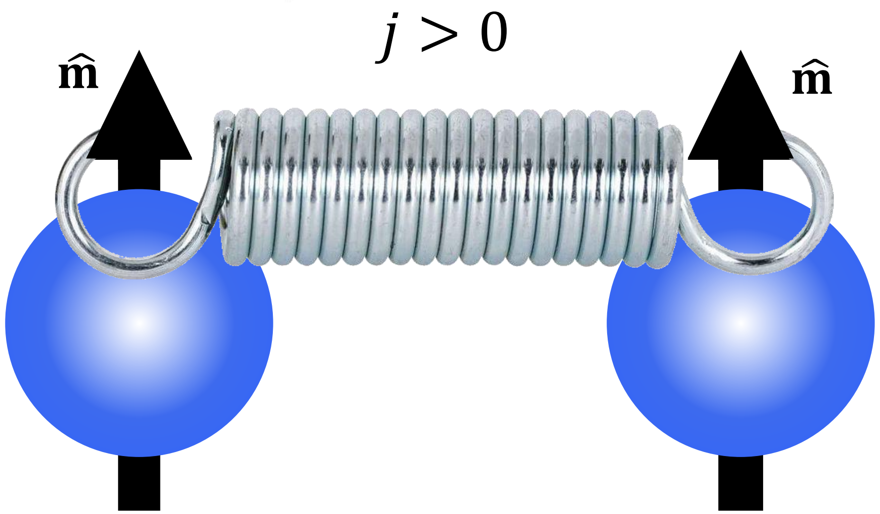
a magnet

Interactions in ferromagnets: symmetric exchange

Heisenberg exchange

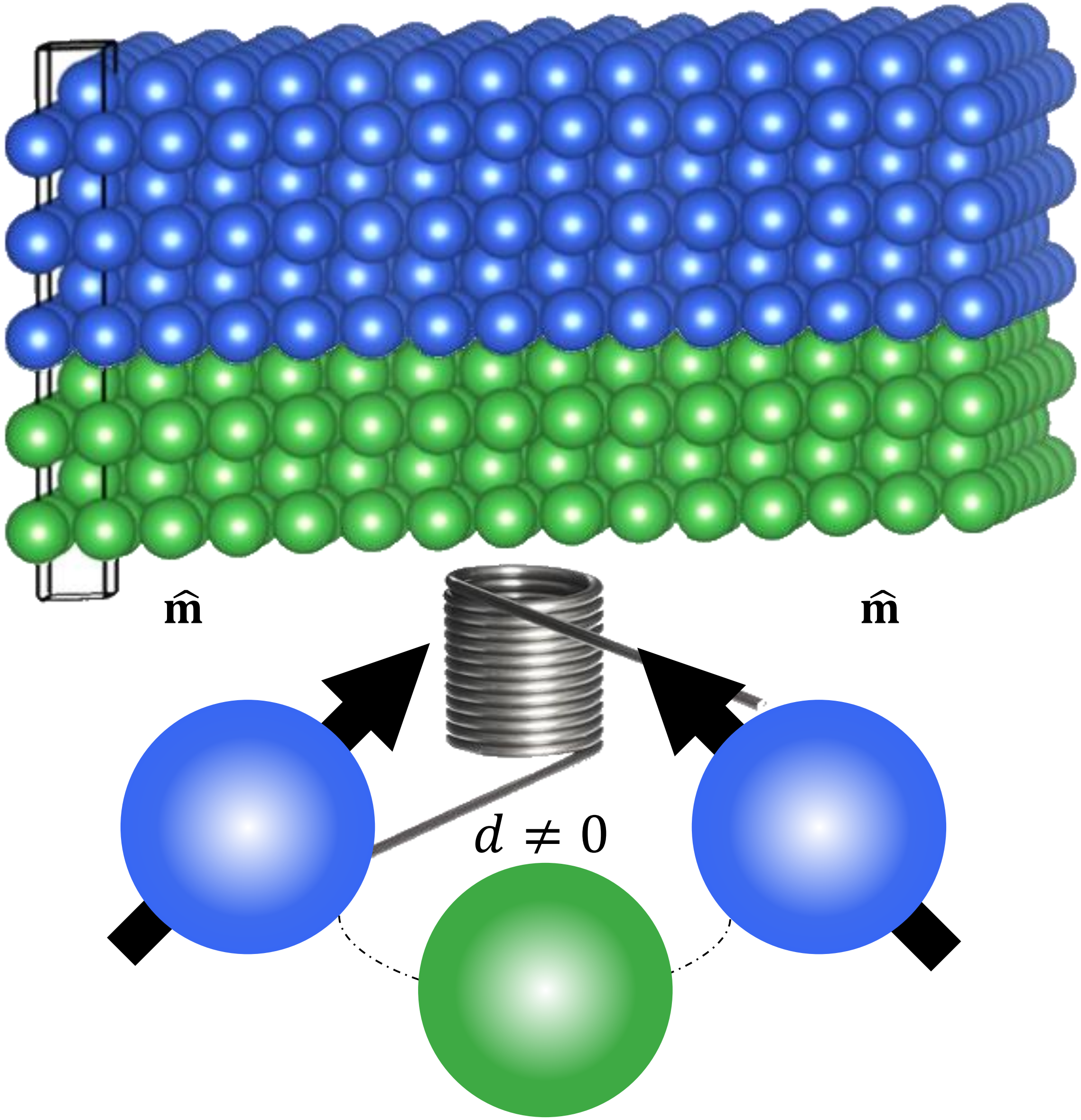


FM material, for ex : Co



Interactions in ferromagnets: antisymmetric exchange

Dzyaloshinskii-Moriya interaction (DMI)

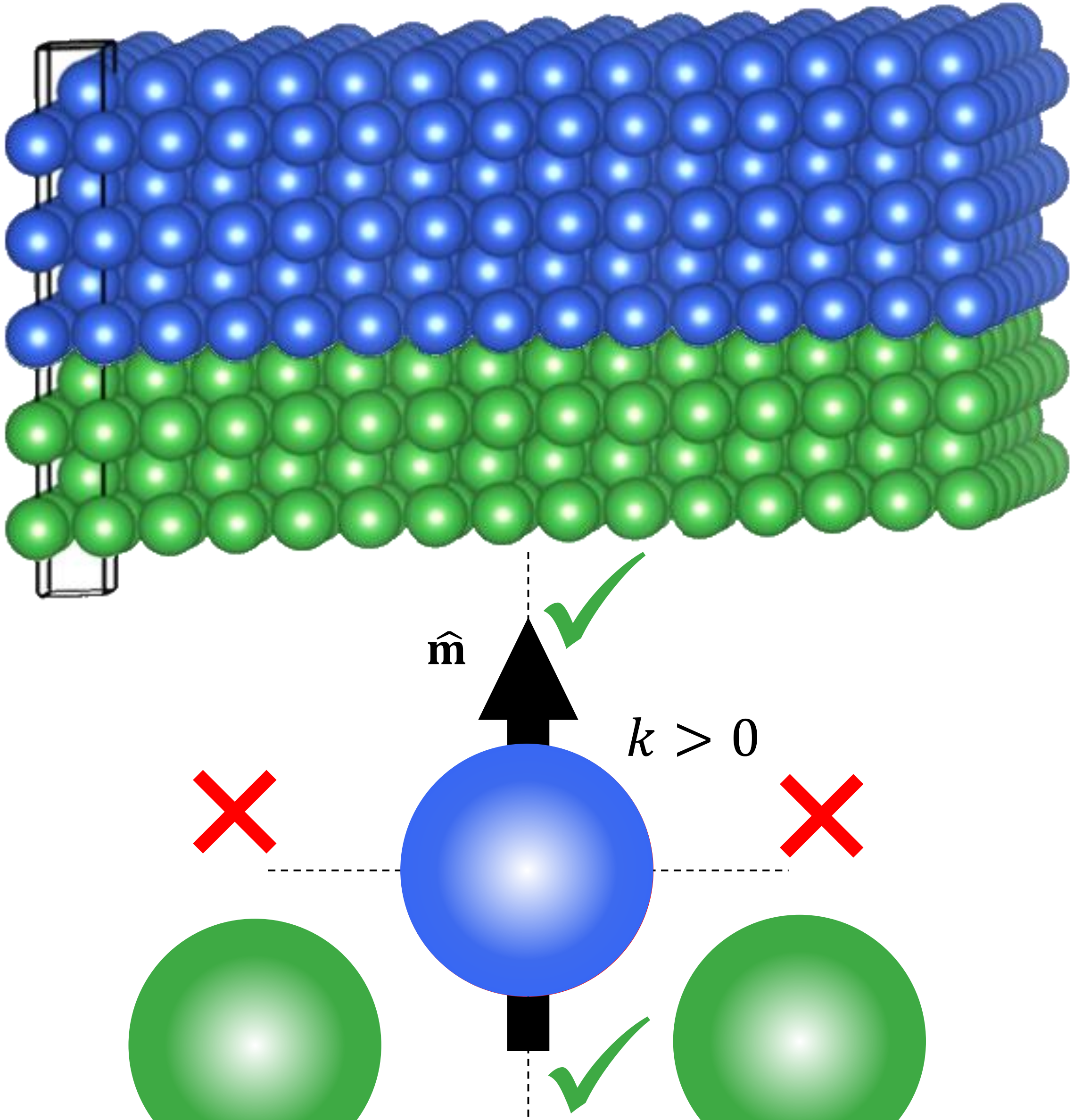


FM material, for ex : Co

HM material, for ex : Pt
Spin-orbit coupling

Interactions in ferromagnets: perpendicular magnetic anisotropy

Anisotropy

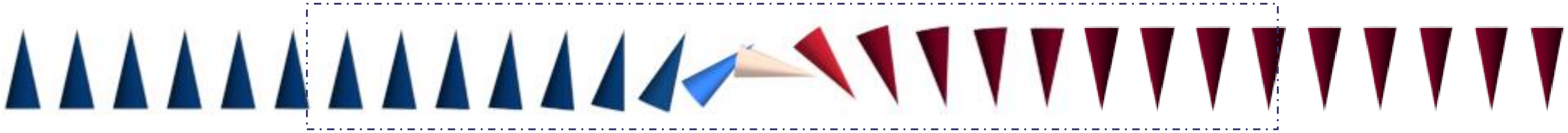


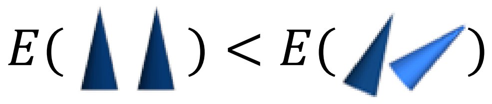
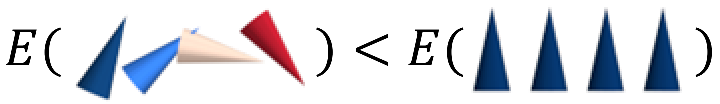
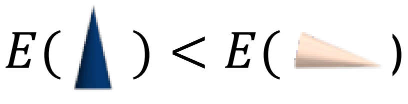
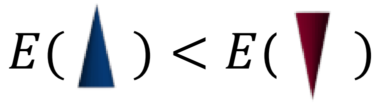
FM material, for ex : Co

HM material, for ex : Pt
Spin-orbit coupling

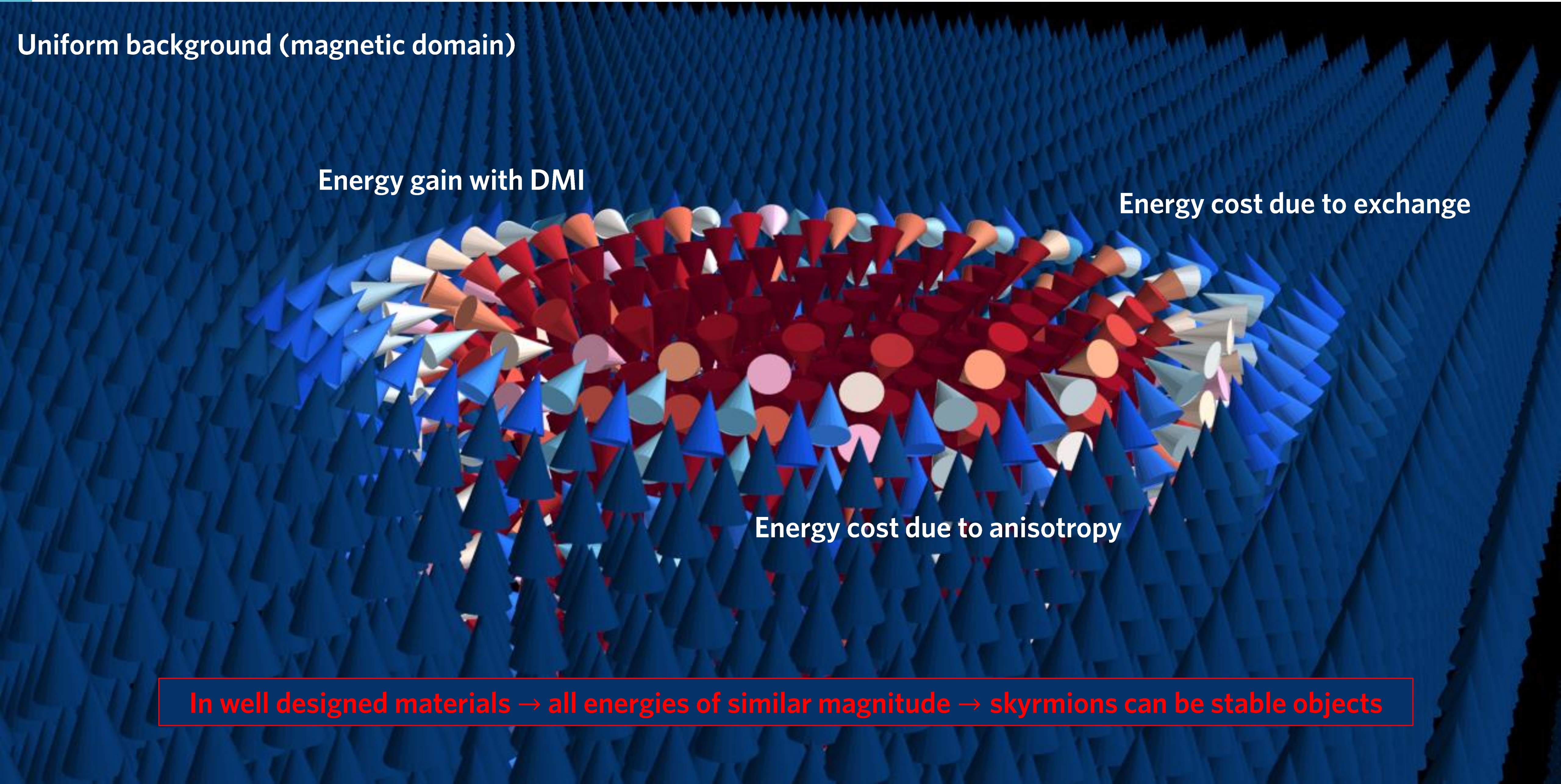
What is a ferromagnet ?

$\hat{\mathbf{m}}$ is almost continuous in space

$\hat{\mathbf{m}}$ 

	Heisenberg exchange	Dzyaloshinskii-Moriya interaction	Perp. anisotropy	Zeeman
Energy density (J m^{-3})	$E_A = A\left(\frac{\partial m_i}{\partial x_j}\right)^2$	$E_D = D(m_z \operatorname{div} \hat{\mathbf{m}} - (\hat{\mathbf{m}} \cdot \boldsymbol{\nabla})m_z)$	$E_K = -K_u(m_z)^2$	$E_z = -\mu_0 \widehat{H} \cdot \widehat{M_s}$
				

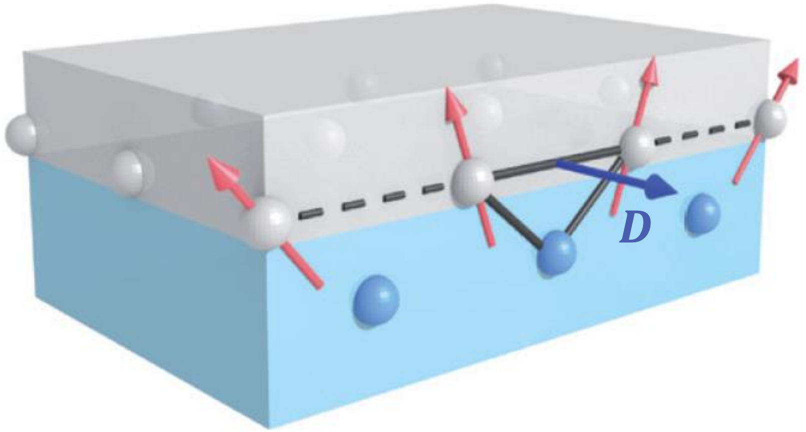
Stabilisation of skyrmions – balance of energies



In well designed materials → all energies of similar magnitude → skyrmions can be stable objects

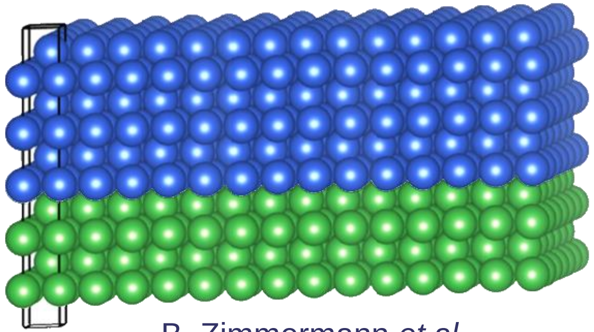
Two types of skyrmion systems

Interfacial DMI



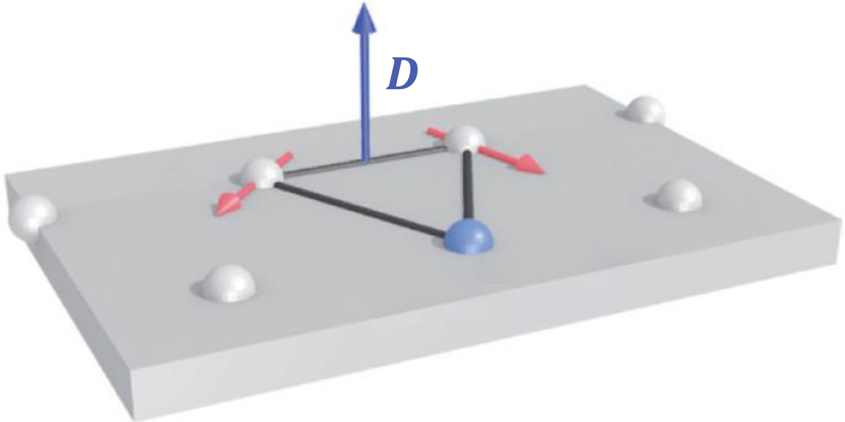
Néel skyrmions

- nm-thick films and multilayers
- Ir/PdFe, Pt/Co/Ir, Ta/CoFeB/Pt, etc.

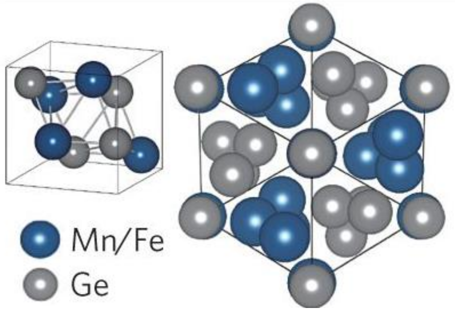


B. Zimmermann *et al*, *Appl. Phys. Lett.* **113**, 232403 (2018)

Bulk DMI



- thin slabs of a single crystal
- MnSi, $Fe_{0.5}Co_{0.5}Si$, FeGe, MnGe, etc.

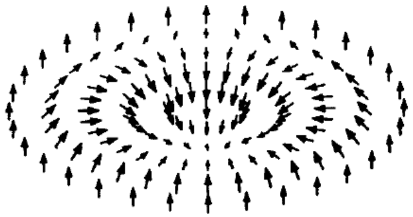


K. Shibata *et al*, *Nat. Nanotech.* **8**, 723-728 (2013)

Bloch skyrmions

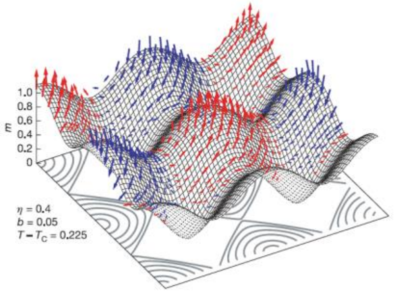
Previous milestones

1989-1994	2006	2009	2010
First concept	Prediction in thin films	First detection of skyrmions	First imaging of bulk skyrmions

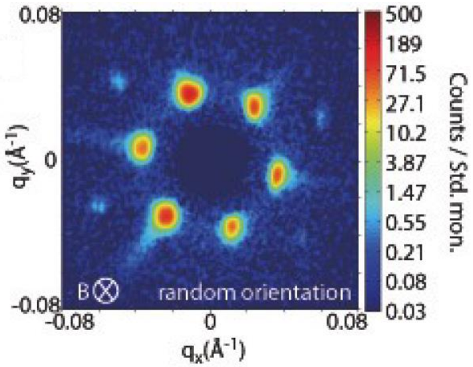


A. N. Bogdanov and D. A. Yalonskii, *JETP Lett.* **68**, 101 (1989)

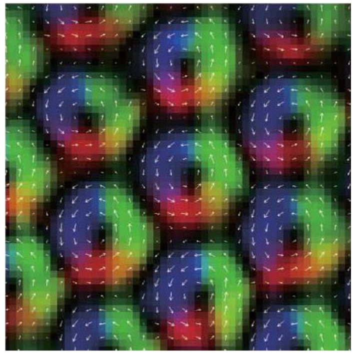
A. Bogdanov and A. Hubert, *Phys. Stat. Sol. B* **186**, 527 (1994)



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



S. Mühlbauer *et al, Science* **323**, 915 (2009)

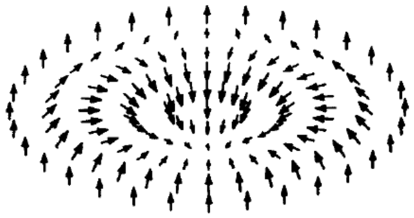


X. Z. Yu *et al, Nature* **465**, 901 (2010)

Previous milestones

1989-1994

First concept

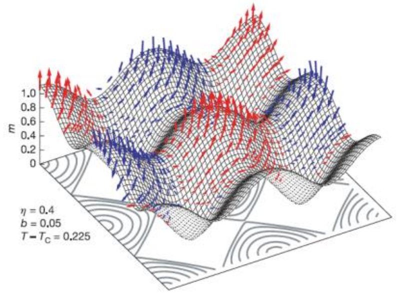


A. N. Bogdanov and D. A. Yalonskii, *JETP Lett.* **68**, 101 (1989)

A. Bogdanov and A. Hubert, *Phys. Stat. Sol. B* **186**, 527 (1994)

2006

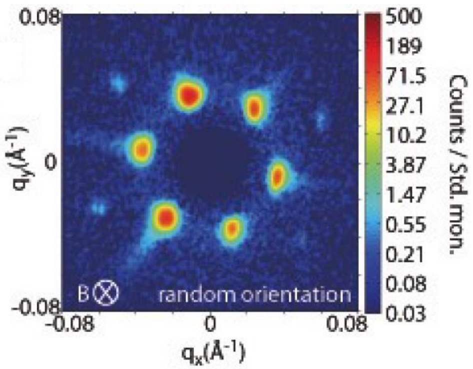
Prediction in thin films



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

2009

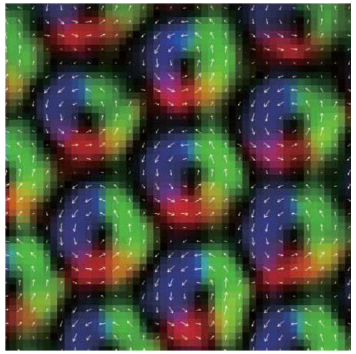
First detection of skyrmions



S. Mühlbauer *et al*, *Science* **323**, 915 (2009)

2010

First imaging of bulk skyrmions



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

Previous milestones

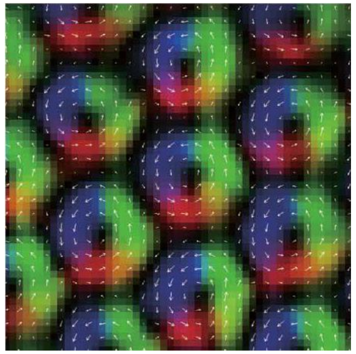
2010

Bulk sk.

2012

2015

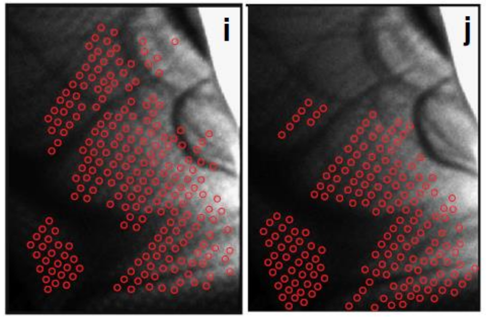
First imaging of bulk skyrmions



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

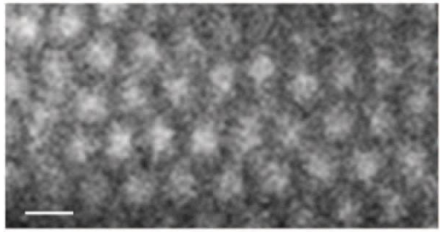
Interface sk.

Motion at ultralow currents



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

RT stabilisation in Co-Zn-Mn alloys



Y. Tokunaga *et al*, *Nat. Commun.* **6**, 7638 (2015)

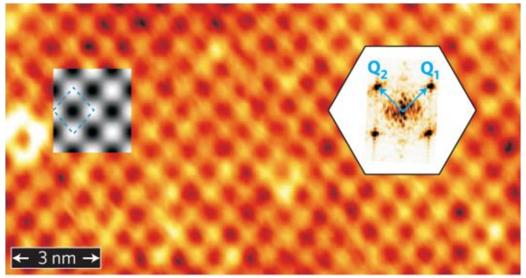
2011

2015

2016

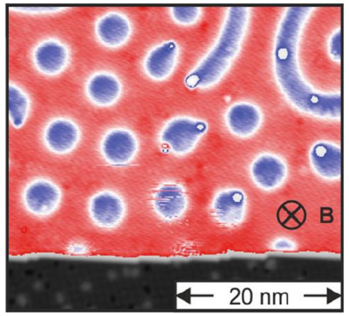
This work

First imaging of interfacial skyrmions



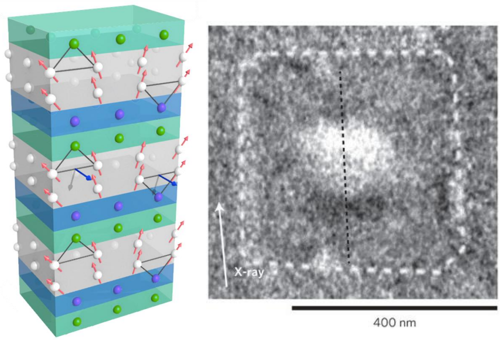
S. Heinze *et al*, *Nat. Phys.* **7**, 713 (2011)

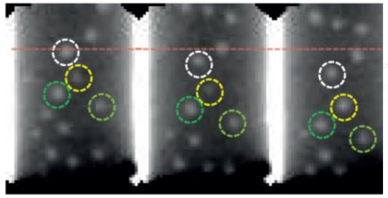
Isolated skyrmions

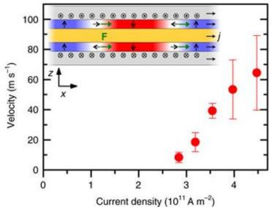


N. Romming *et al*, *Phys. Rev. Lett.* **114**, 177203 (2015)

RT stabilisation in multilayers and current-induced motion







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

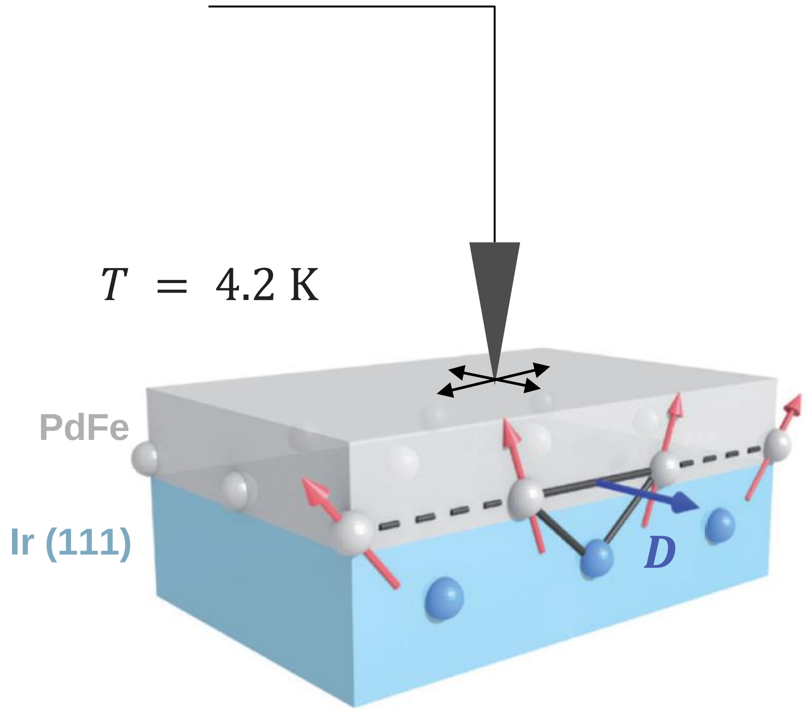
A. Hrabec *et al*, *Nat. Commun.* **8**, 15765 (2017)

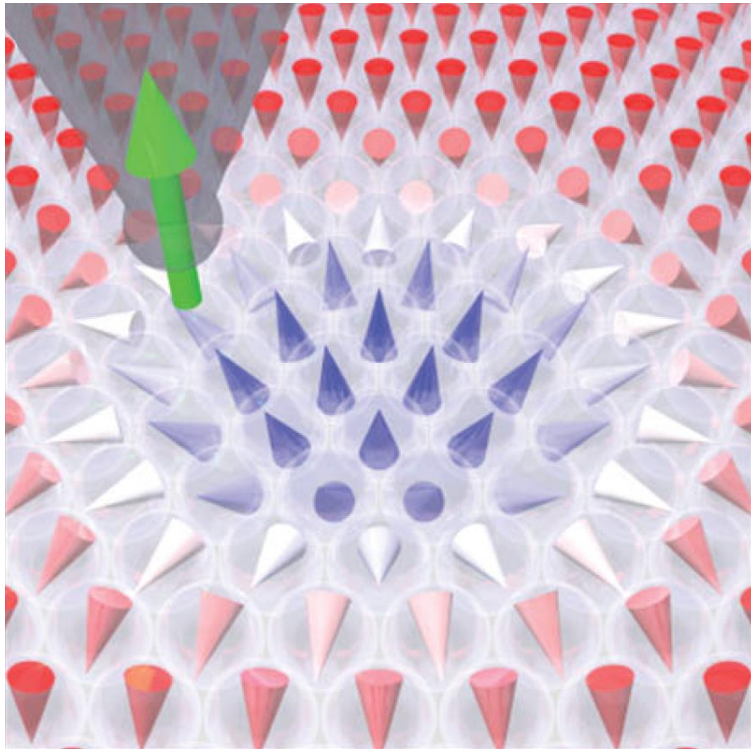
C. Moreau-Luchaire *et al*, *Nat. Nanotech.* **11**, 444 (2016)

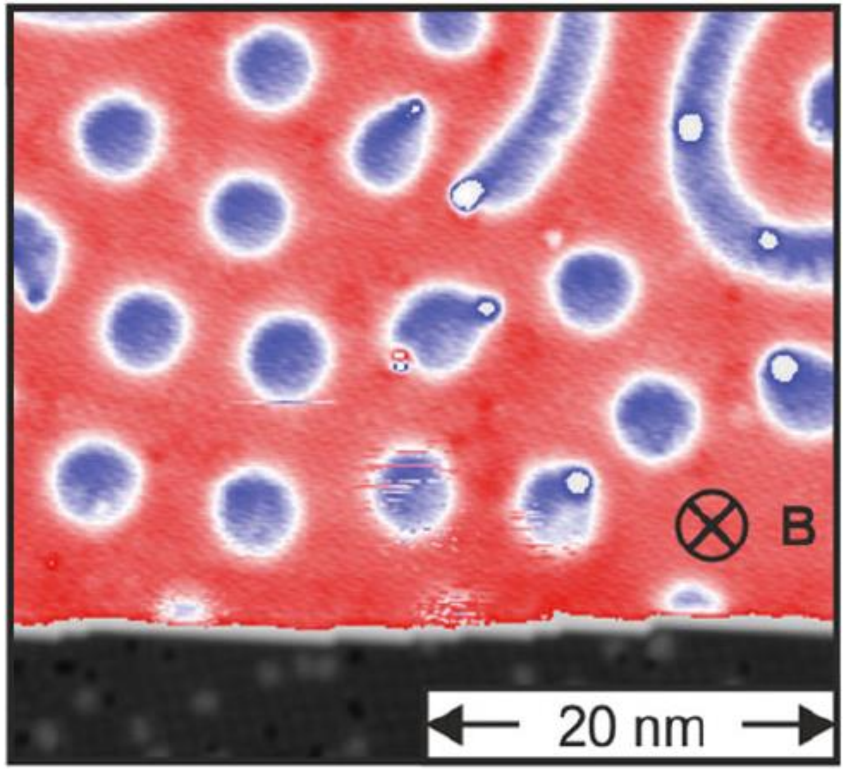
O. Boulle *et al*, *Nat. Nanotech.* **11**, 449 (2016)

Isolated skyrmion observation

SP-STM at low temperatures



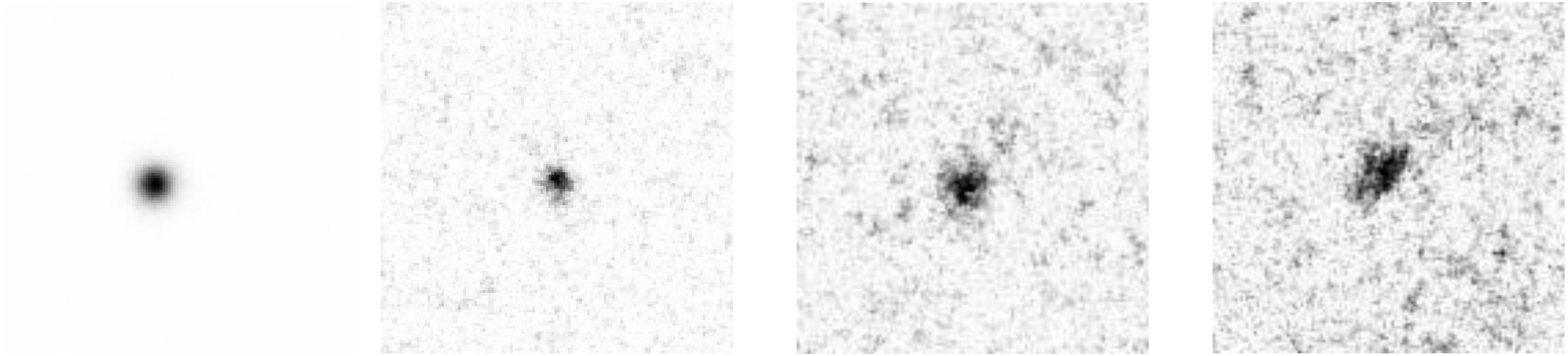




N. Romming *et al*, *Phys. Rev. Lett.* **114**, 177203 (2015)

Temperature shaking

Simulations: m_z *component of the magnetisation, 1 frame = 200 ps*



$T = 4$ K　　$T = 100$ K　　$T = 200$ K　　$T = 300$ K

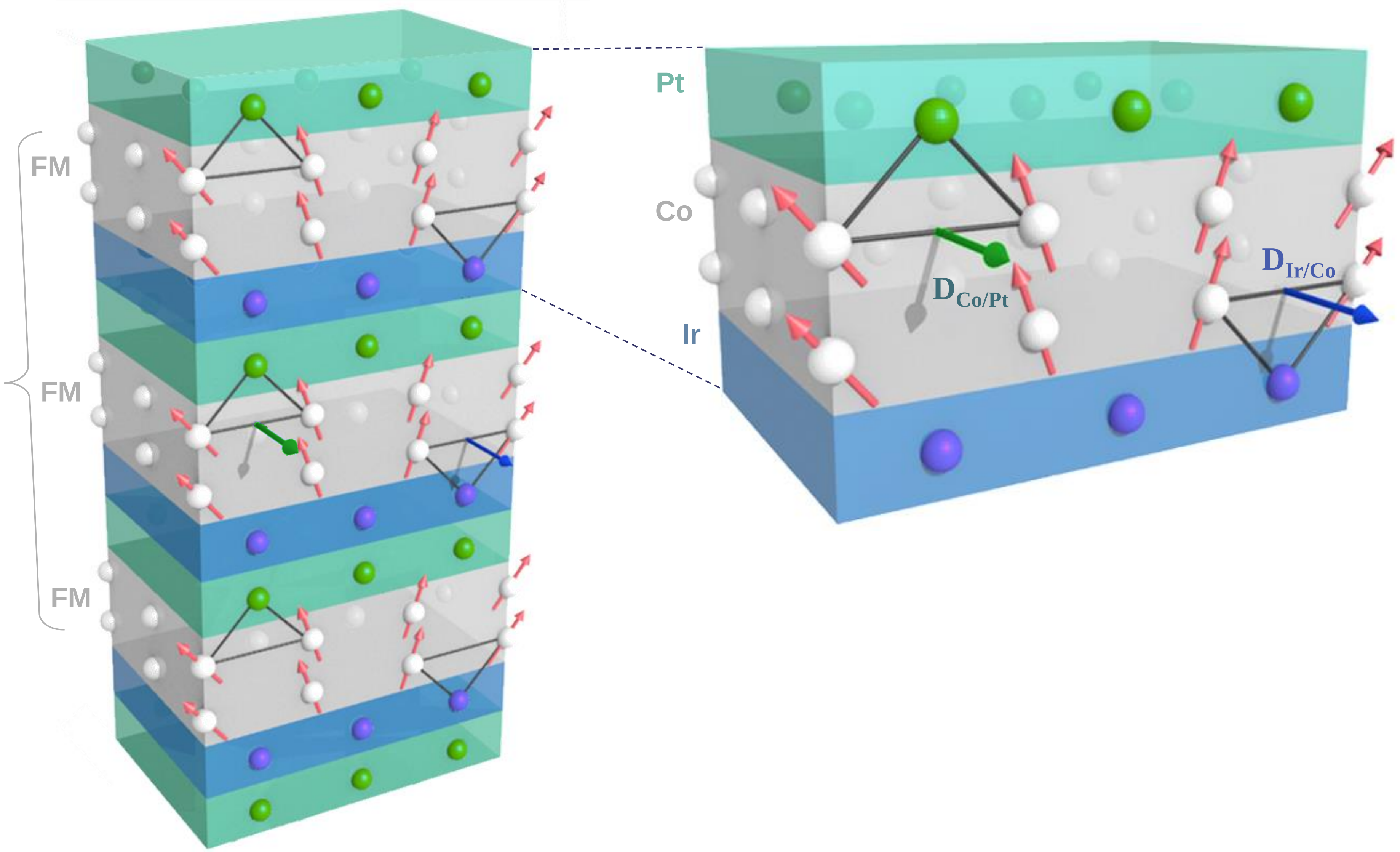
1 magnetic layer of 0.6 nm

Strategy to obtain room-temperature stability

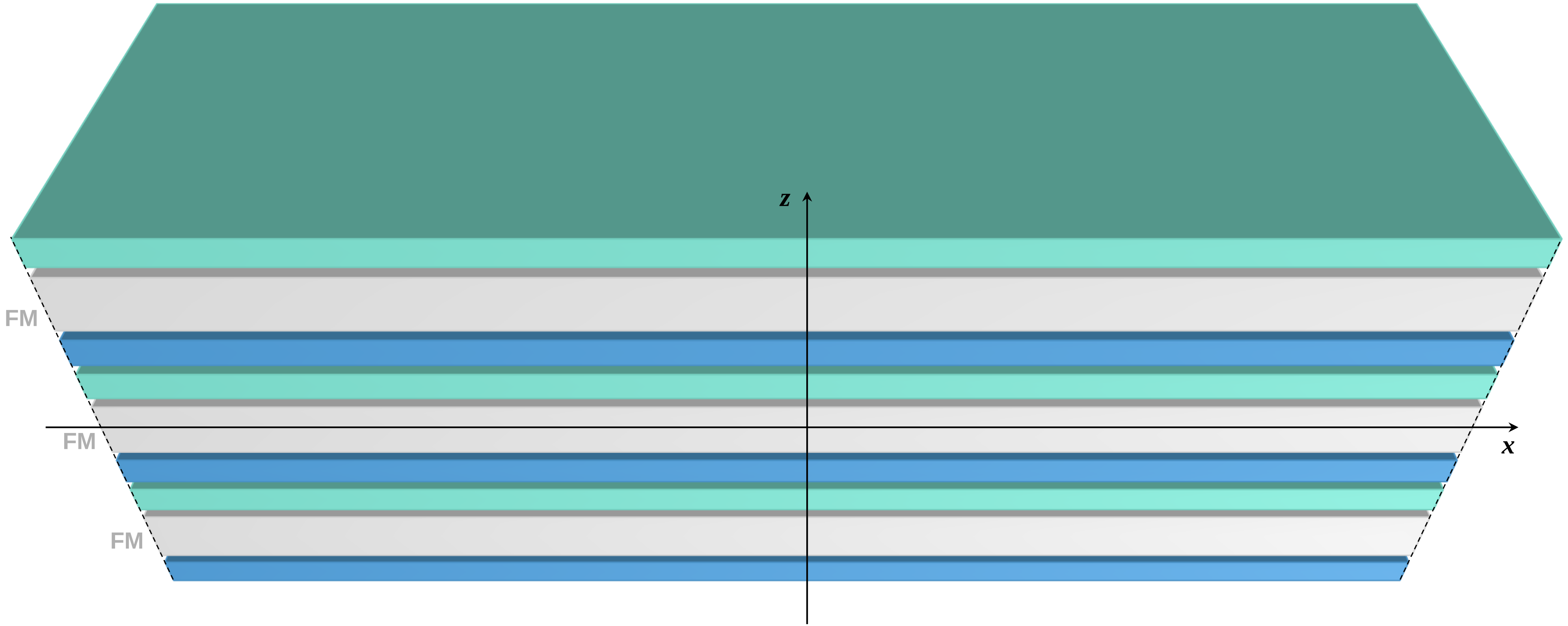
C. Moreau-Luchaire *et al, Nat. Nanotech.* **11**, 444 (2016)

Magnetic multilayers

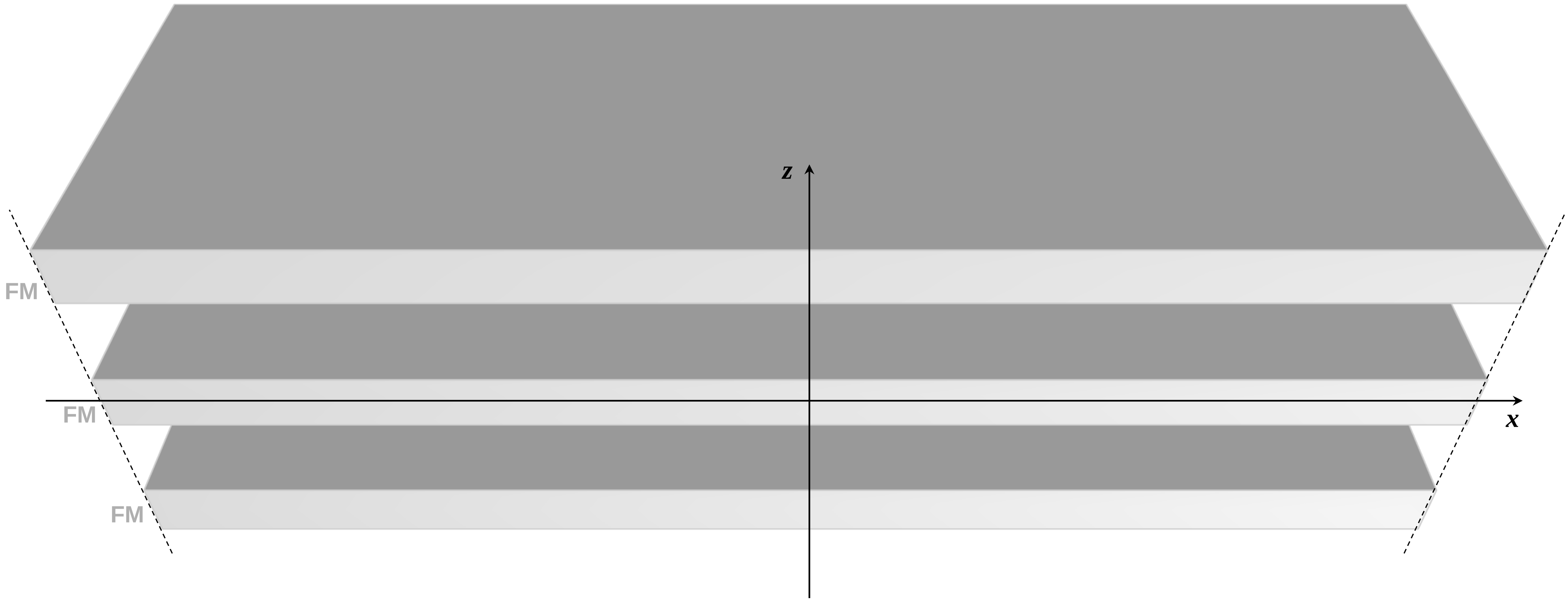
L: number of FM layers



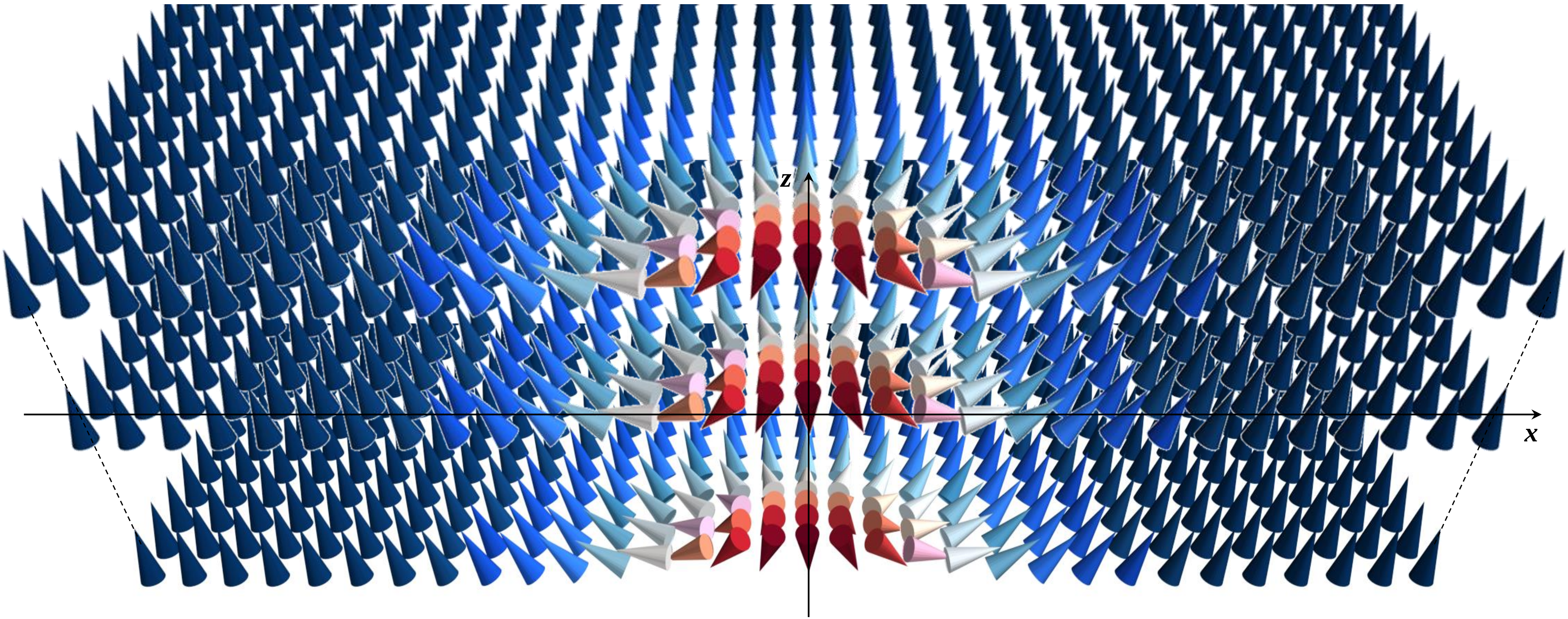
Multilayered skyrmion



Multilayered skyrmion

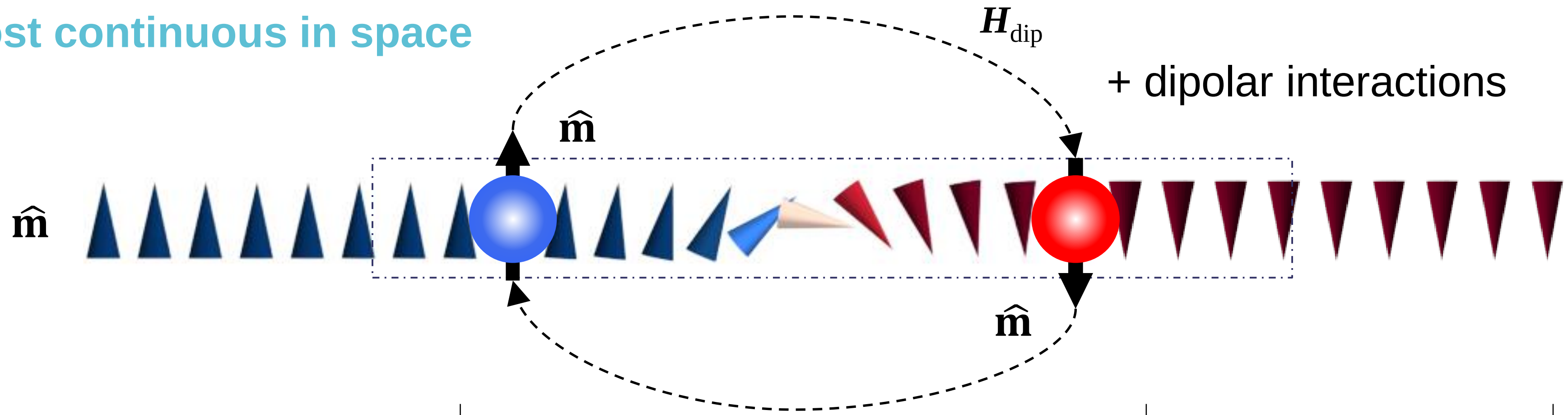


Multilayered skyrmion

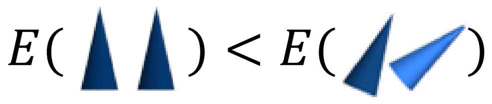
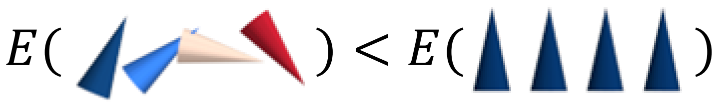
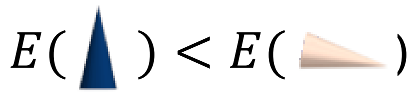
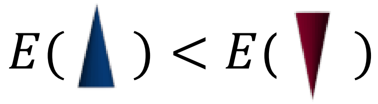


Importance of dipolar interactions

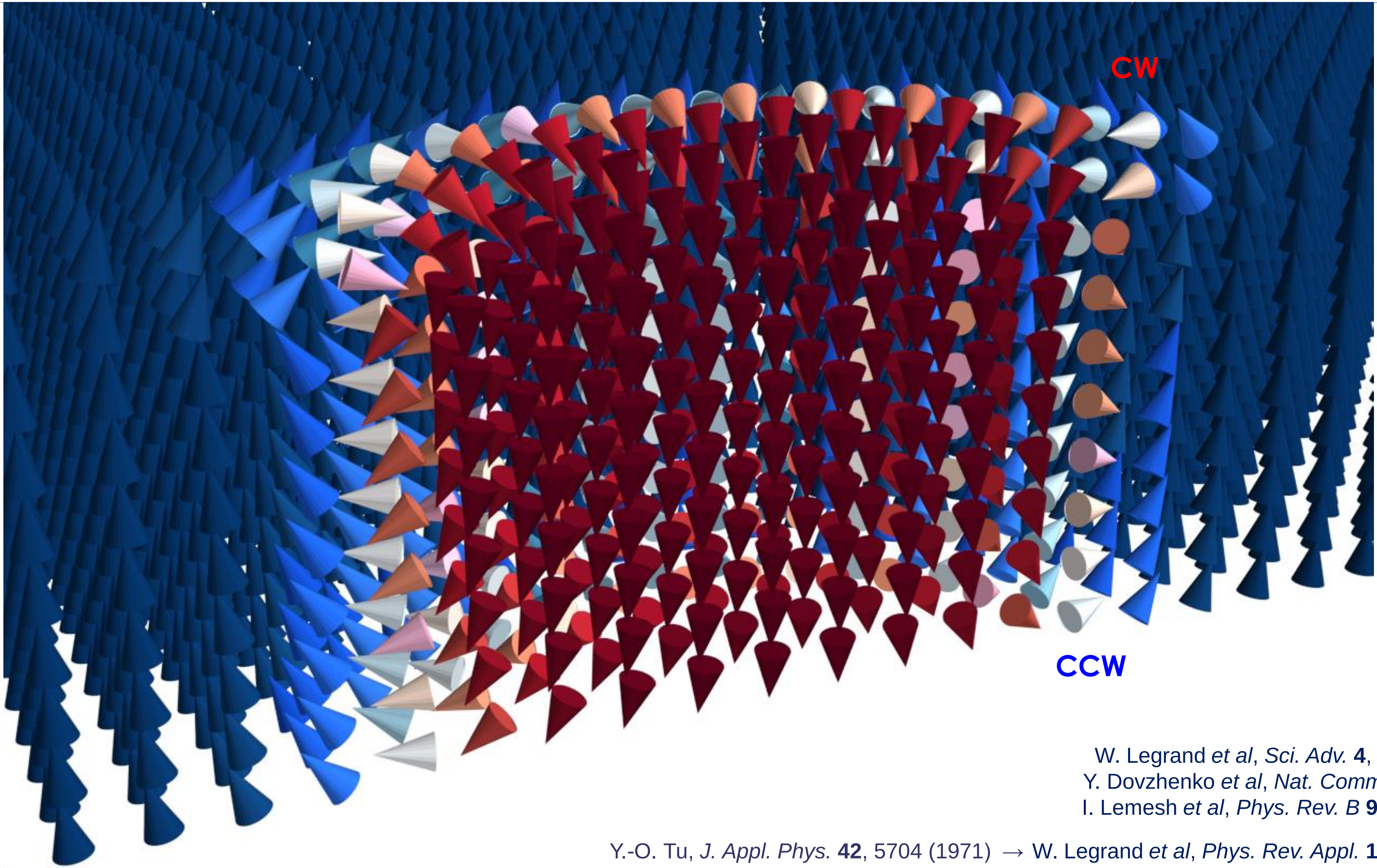
$\hat{\mathbf{m}}$ is almost continuous in space



+ dipolar interactions

	Heisenberg exchange	Dzyaloshinskii-Moriya interaction	Perp. anisotropy	Zeeman
Energy density (J m^{-3})	$E_A = A\left(\frac{\partial m_i}{\partial x_j}\right)^2$	$E_D = D(m_z \operatorname{div} \hat{\mathbf{m}} - (\hat{\mathbf{m}} \cdot \boldsymbol{\nabla}) m_z)$	$E_K = -K_u (m_z)^2$	$E_z = -\mu_0 \hat{H} \cdot \widehat{M_s}$
				

Hybrid chiral skyrmions

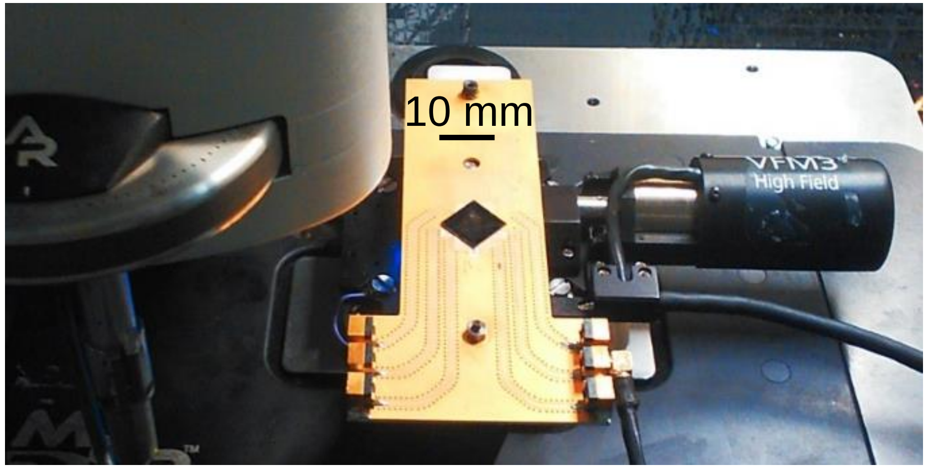


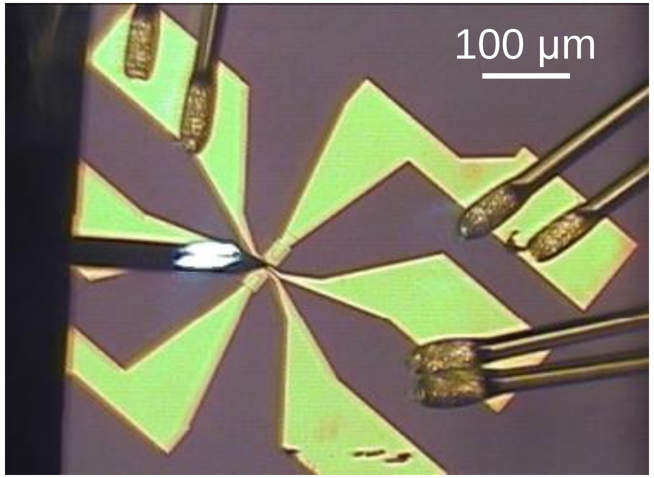
W. Legrand *et al*, *Sci. Adv.* **4**, eaat0415 (2018);
Y. Dovzhenko *et al*, *Nat. Comm.* **9**, 2712 (2018);
I. Lemesh *et al*, *Phys. Rev. B* **98**, 104402 (2018)

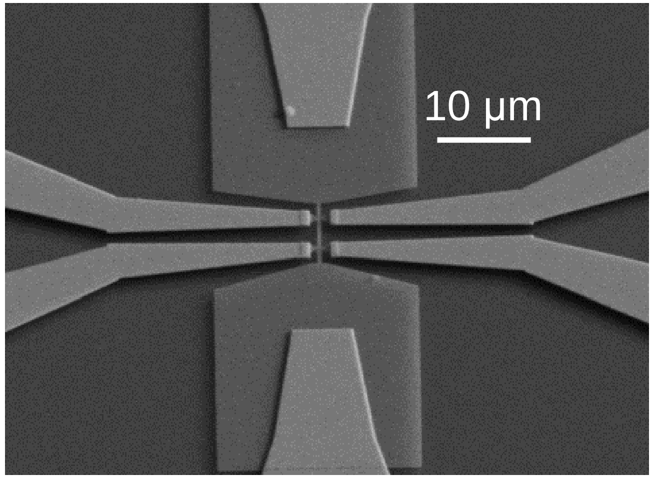
Y.-O. Tu, *J. Appl. Phys.* **42**, 5704 (1971) → W. Legrand *et al*, *Phys. Rev. Appl.* **10**, 064042 (2018)

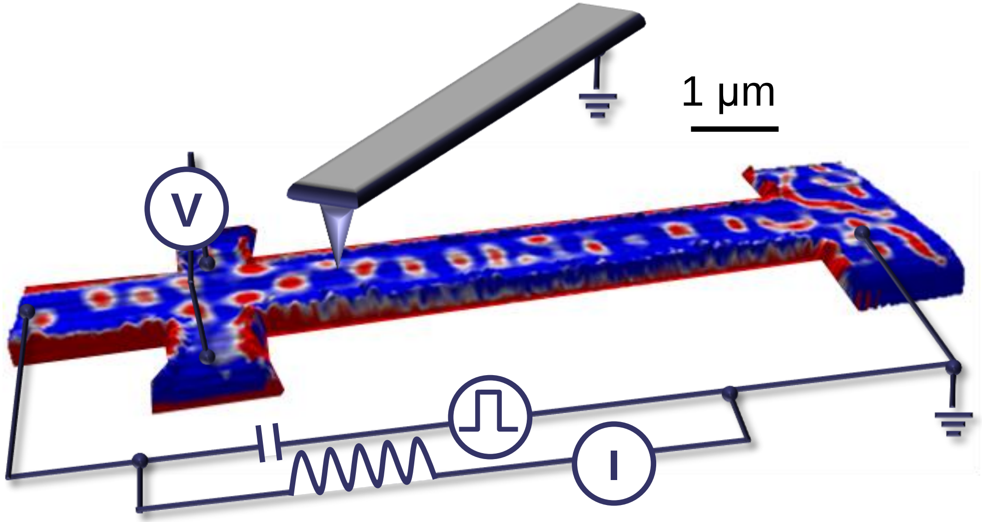
Multilayer & device measurements

Magnetic Force Microscopy





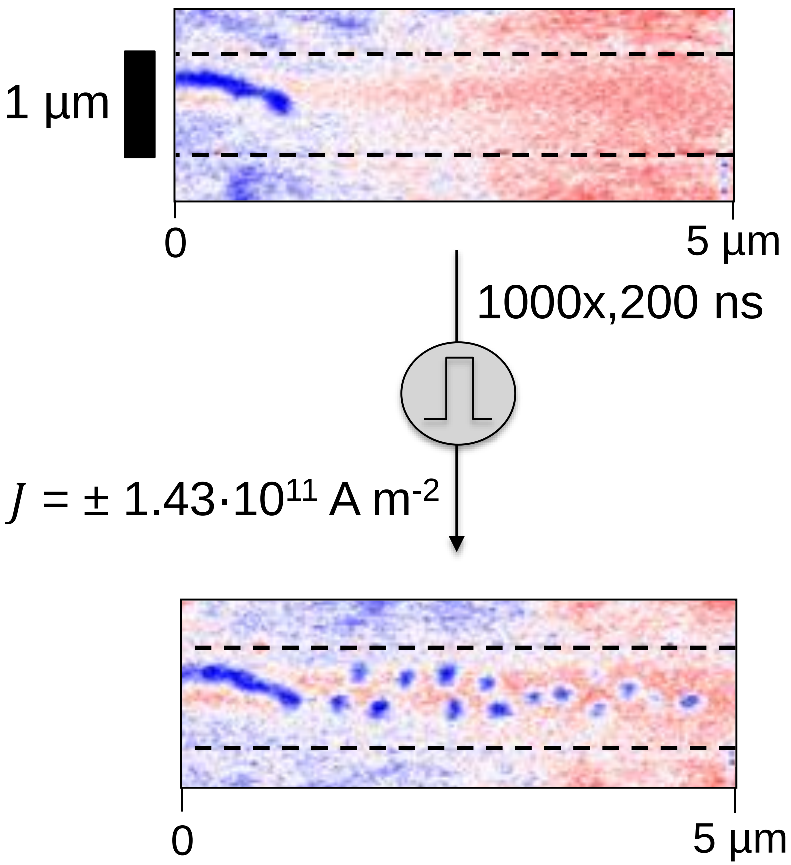




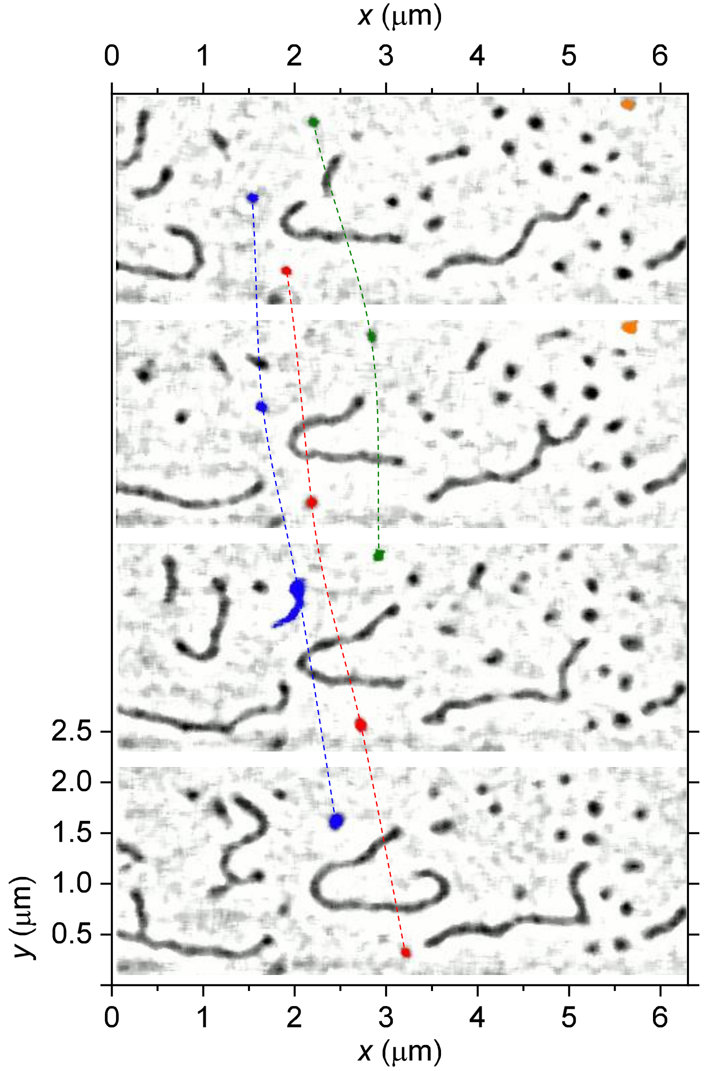
Skyrmion manipulation by current

At T = 300K

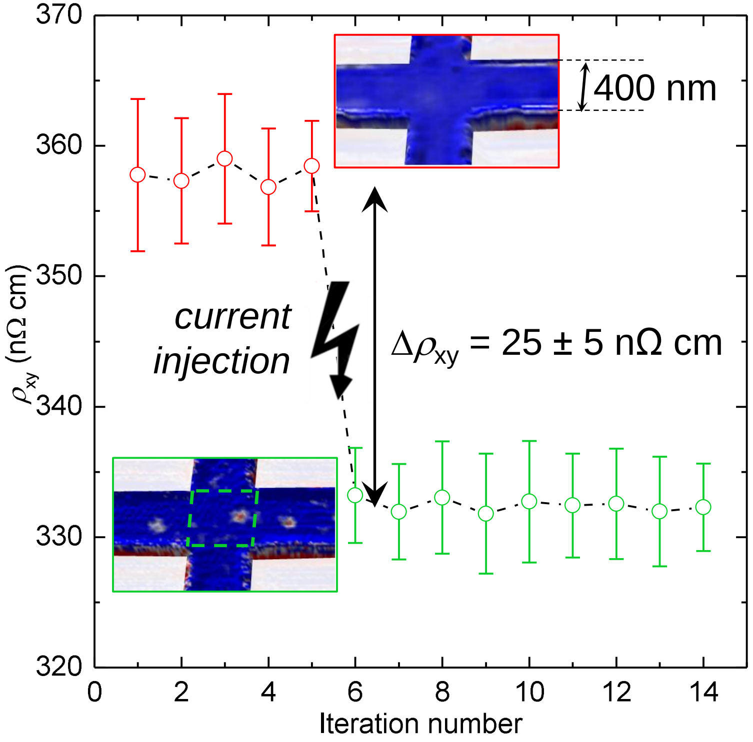
Nucleation



Motion

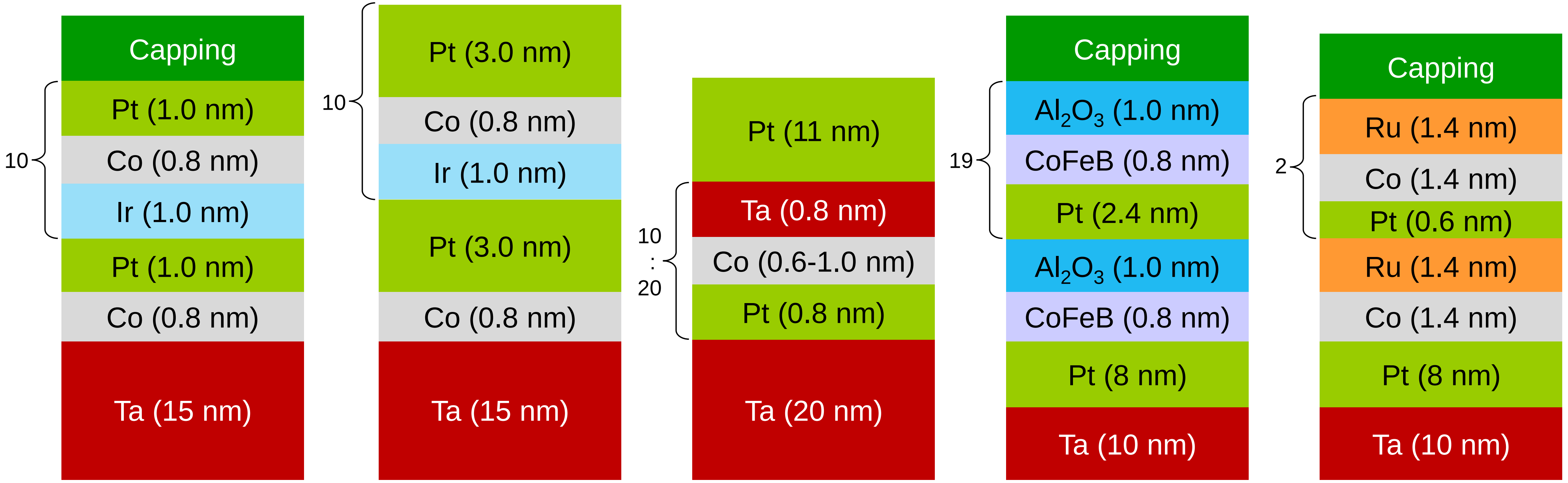


Detection



W. Legrand *et al*, *Nano Lett.* **17,** 2703 (2017); D. Maccariello, WL *et al, Nat. Nanotech.* **13**, 233 (2018)

Example structures studied



v_{sk} **(m s^{-1})**	0.5	2	–	6	**37**
J **(TA m^{-2})**	0.29	0.21	–	**0.15**	0.77

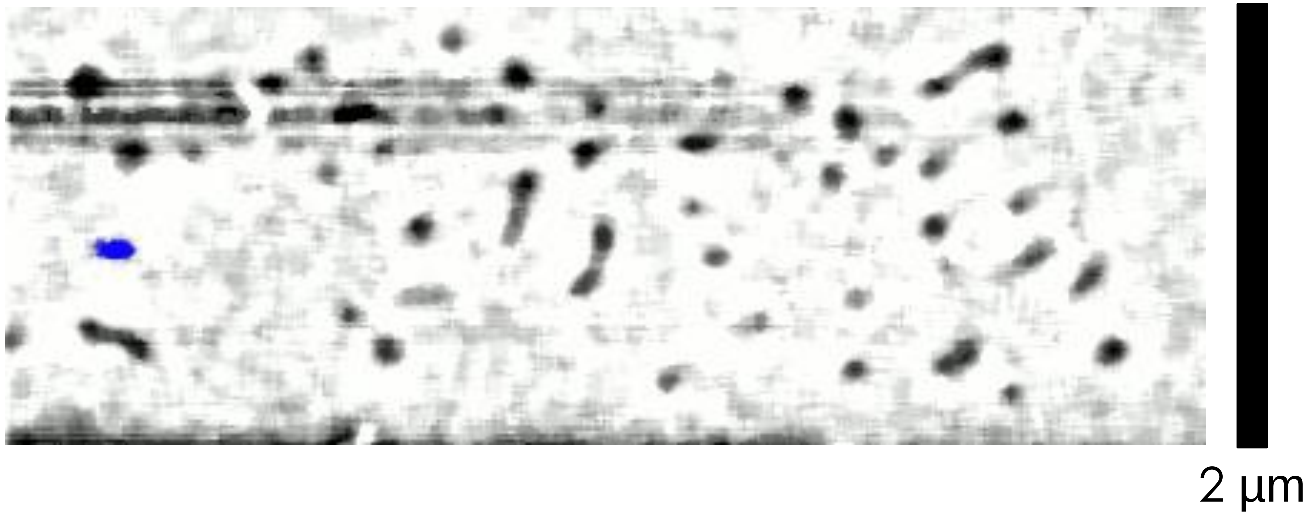
see *Ph.D. thesis*

Motion at larger efficiencies

Multilayer: Pt 8/(Pt 1/Co 1.4/Ru 1.4)$_{x3}$/Pt 3

J = 8.2 10^{11} A m^{-2}

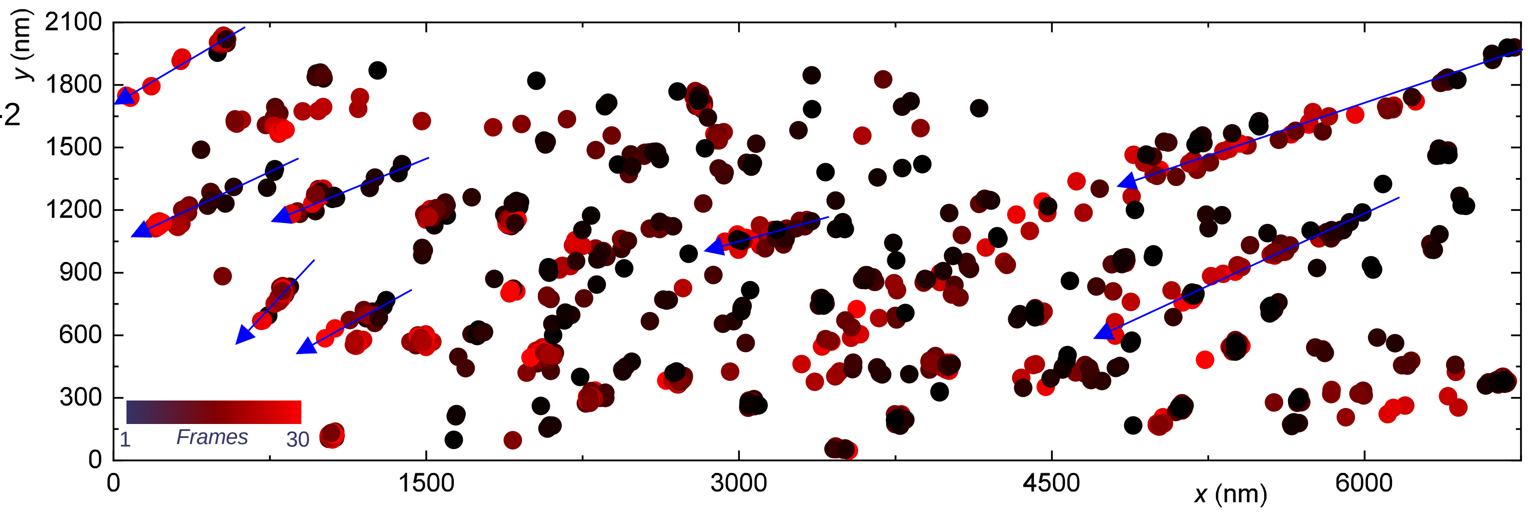
1x,10 ns



v_{sk} = 35-40 m/s

J = -7.7 10^{11} A m^{-2}

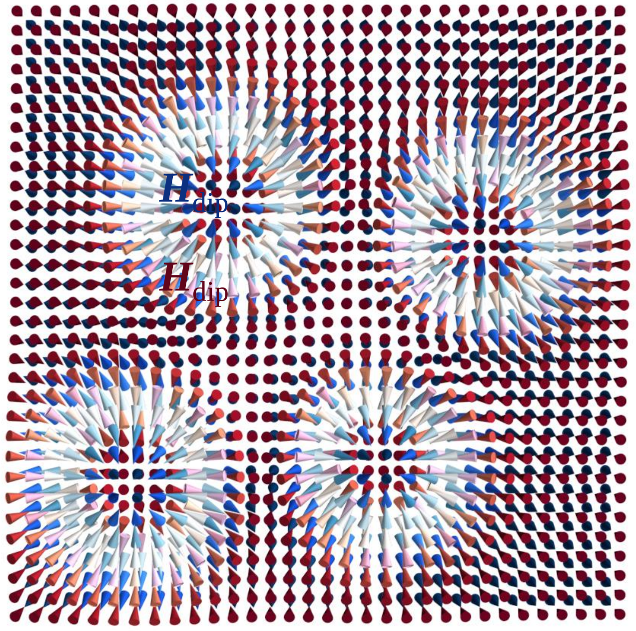
1x,12 ns

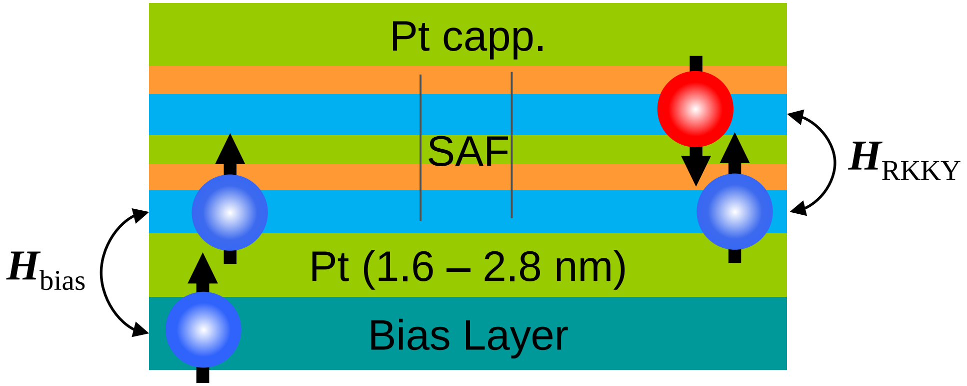


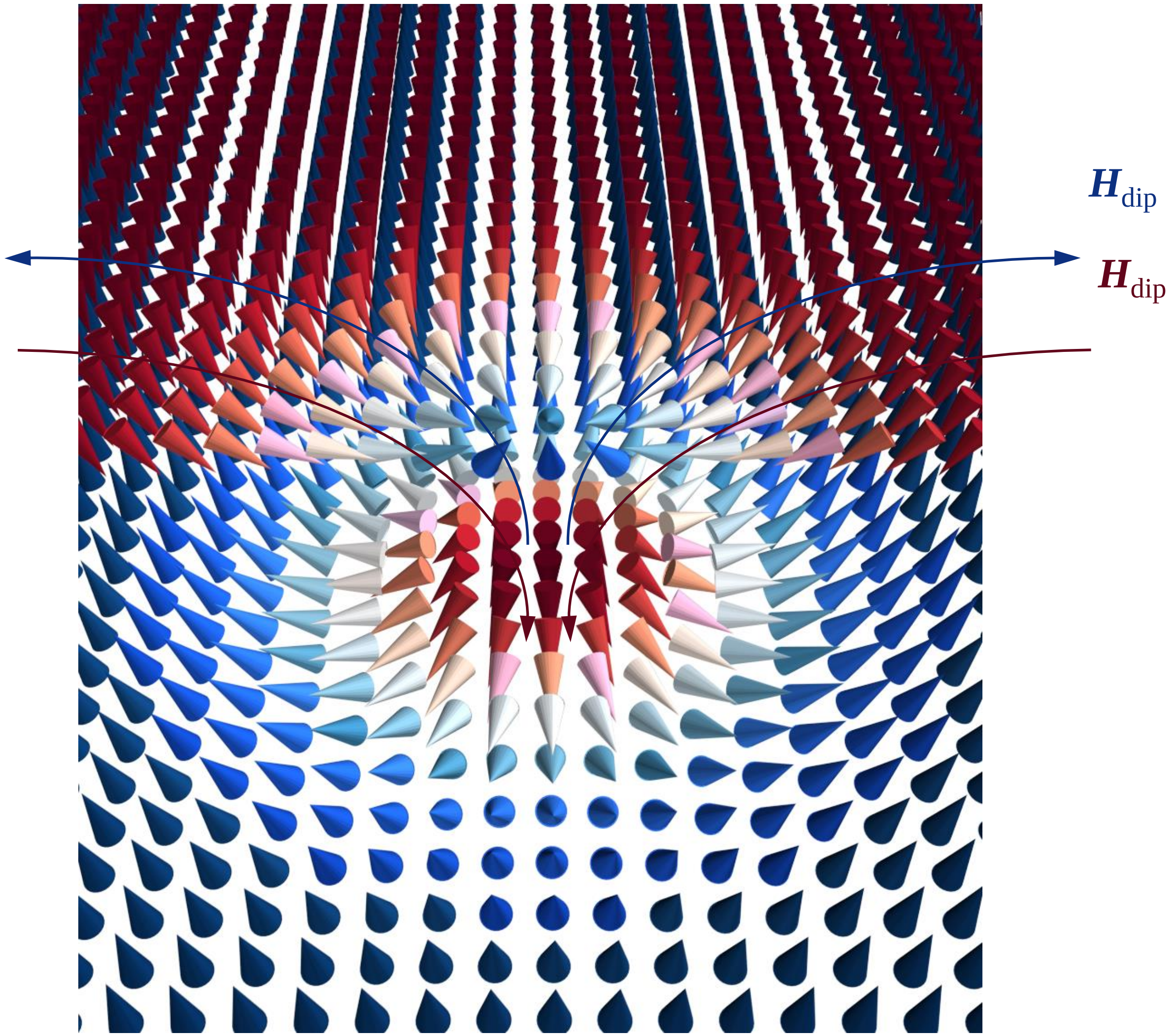
Θ_{sk} = 15-25°

see *Ph.D. thesis*

Stabilizing antiferromagnetic skyrmions

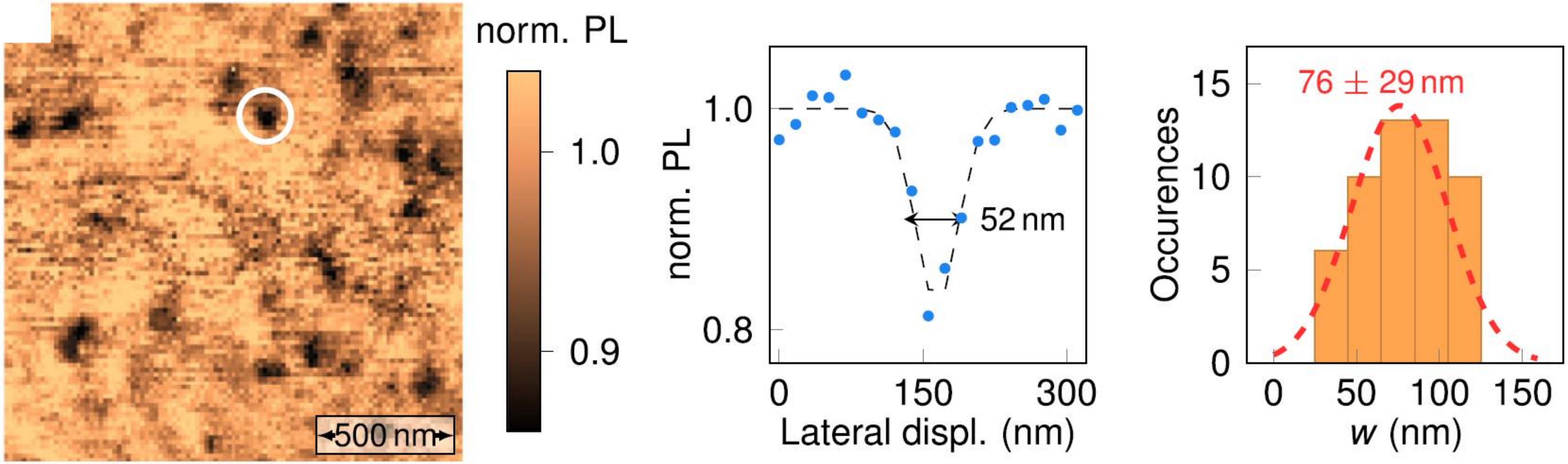


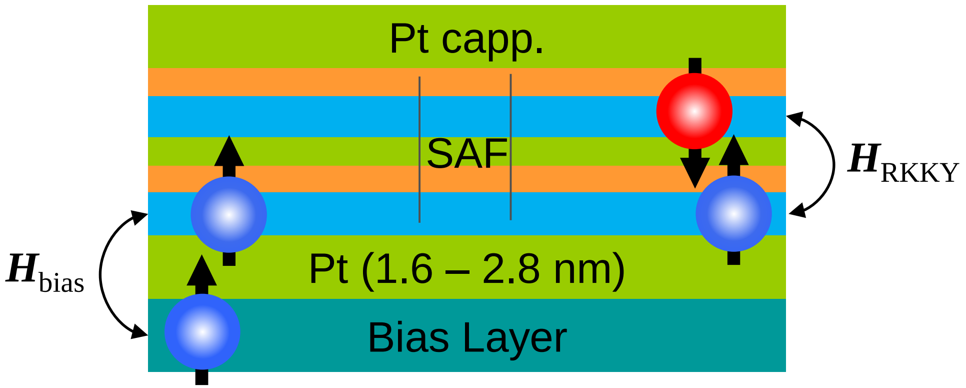




W. Legrand *et al*, *Nat. Mater.* **19**, 34-42 (2020)

NV observation of SAF skyrmions

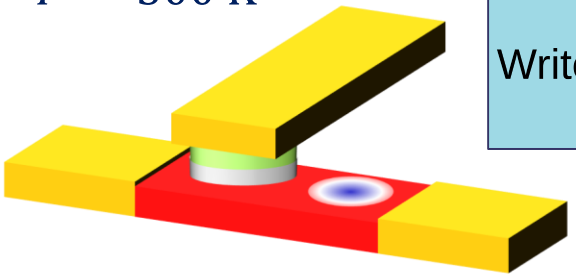


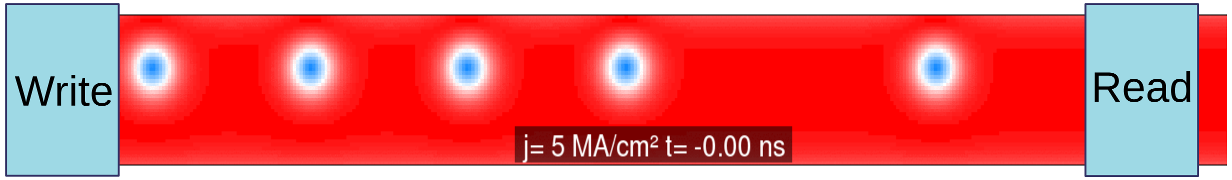


Reduced size
Observed radius 50-100 nm
Actual radius ~ 25-35 nm

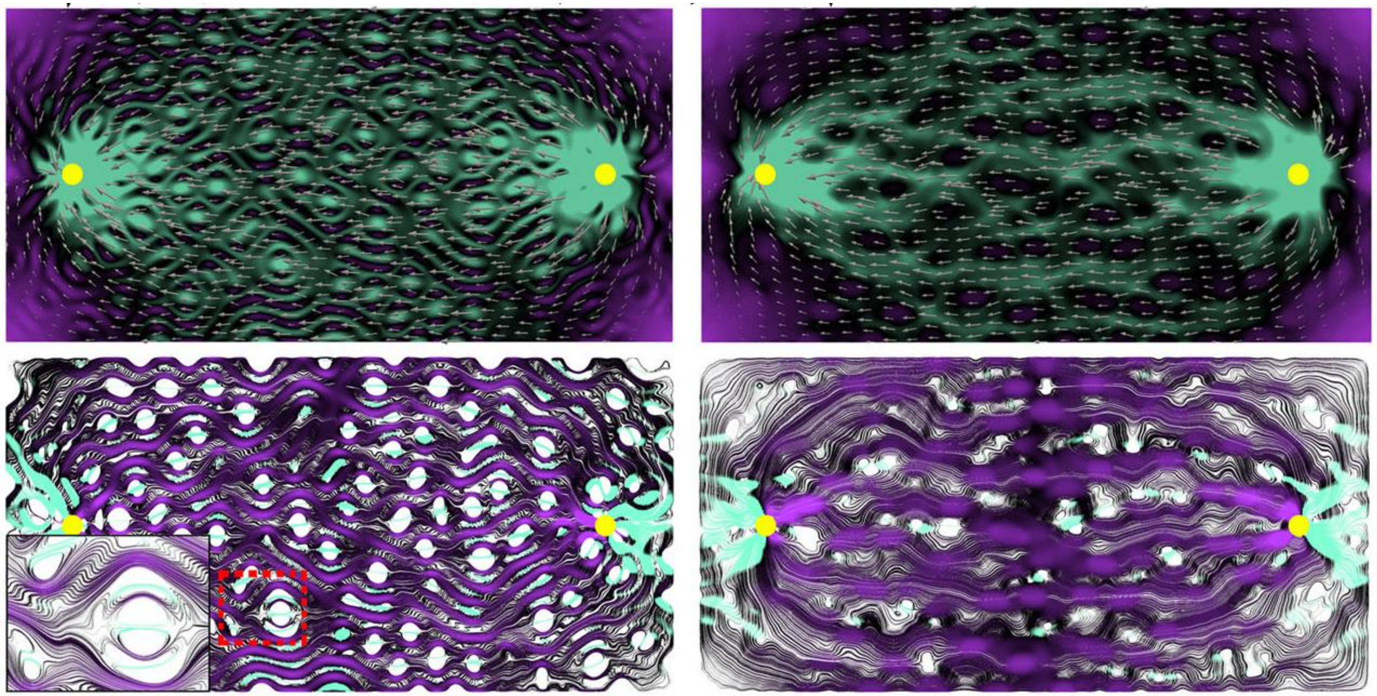
A. Finco *et al*, *Nat. Comm.* **12**, 767 (2021)

Foreseen applications

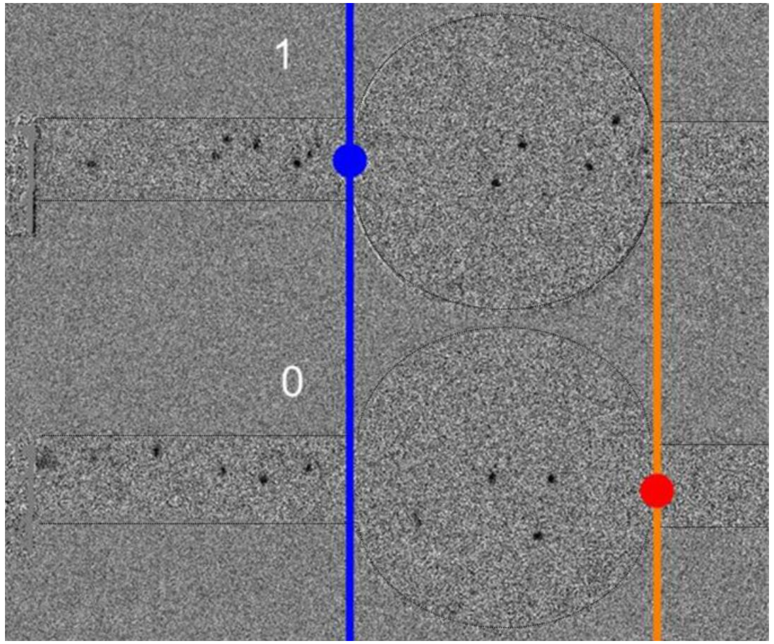




A. Fert *et al*, *Nat. Nanotech.* **8**, 152 (2013) ; A. Fert *et al*, *Nat. Rev. Mat.* **2**, 17031 (2017)



G. Bourianoff *et al*, *AIP Adv.* **8**, 055602 (2018)



D. Pinna *et al*, *Phys. Rev. Appl.* **9**, 064018 (2018)
J. Zazvorka *et al*, arXiv:1805.05924 (2018)

Outlook

Antiferromagnetic skyrmions in SAF: more layers/other FM

- Have potential to be reduced in size below 10 nm
- Possibility of motion without topology-related deflection
- More efficient motion mechanism ?
- Electrical detection + Topological Hall effect

Skyrmion lattices

- Motion at lower current densities
- Interesting reciprocal space properties
- Use for topological supraconductivity experiments

Rare-earth multilayers rather than alloys

- Reduction of magnetisation
- Efficient dynamics
- Bulk perpendicular magnetisation