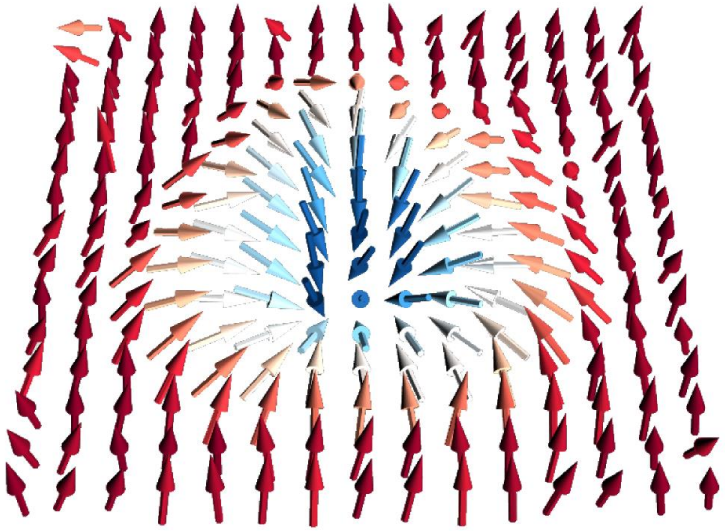
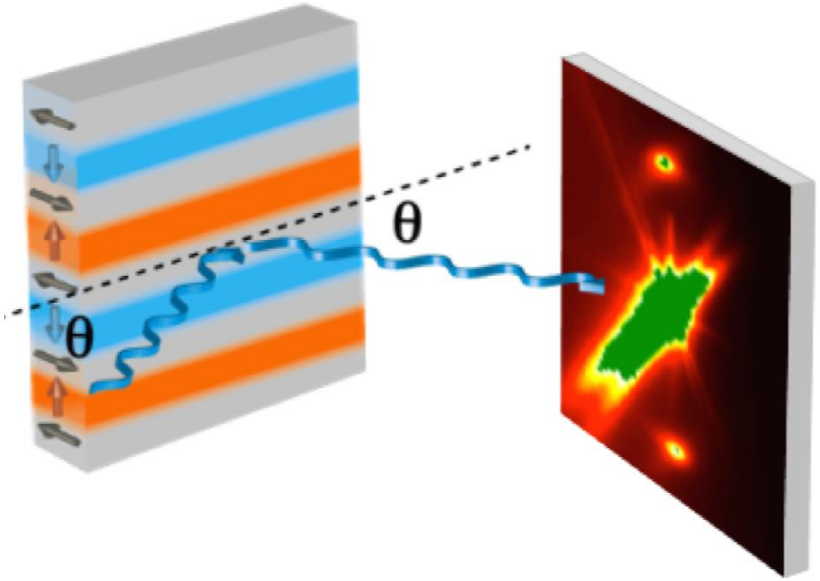
Detecting and Tailoring Chiral Spin Textures in the Presence of Interfacial DMI

Gong Chen

UC Davis



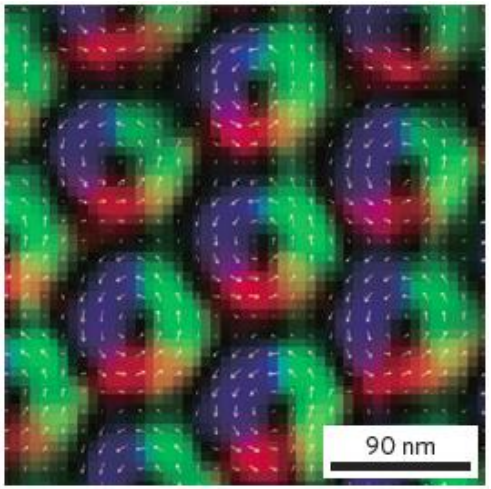


Imaging skyrmions

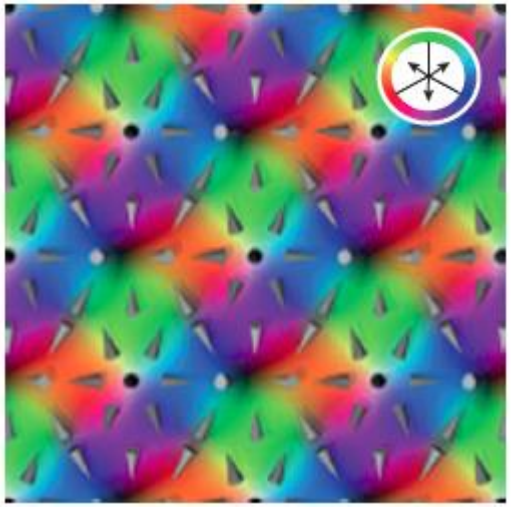
Skyrme, Nucl. Phys. 31, 556 (1962)
Röβler et al. Nature 442, 797 (2006)
Neubauer et al. PRL 102, 186602 (2009)

Mühlbauer et al. Science 323, 915 (2009)
Pappas et al. PRL 102, 197202 (2009)

Fert et al. Nature Nano. 8, 152 (2013)



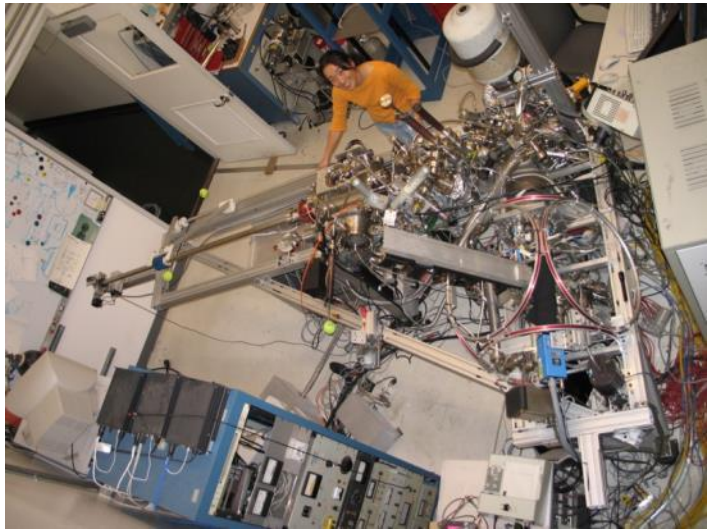
Yu et al. Nature 465, 901 (2010)

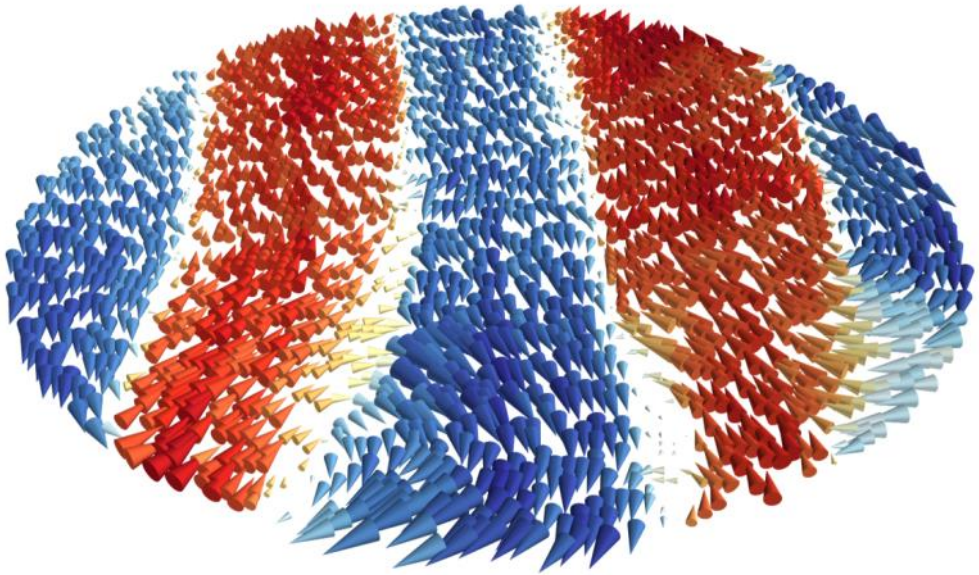


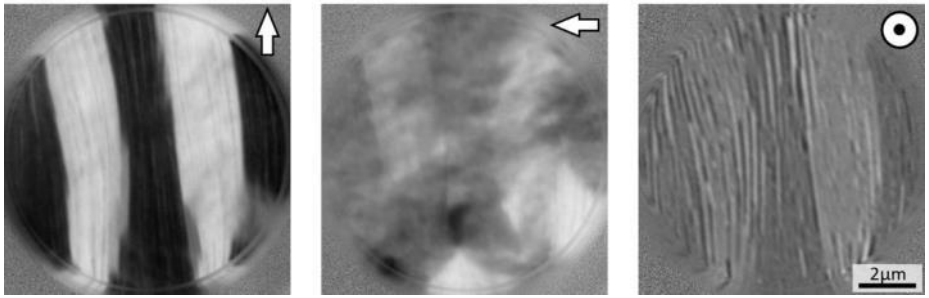
Heinze et al Nat. Phys. 7, 713 (2011)
Romming et al Science 341, 636 (2013)

Spin Polarized Low Energy Electron Microscopy (SPLEEM)

NCEM NATIONAL CENTER FOR ELECTRON MICROSCOPY

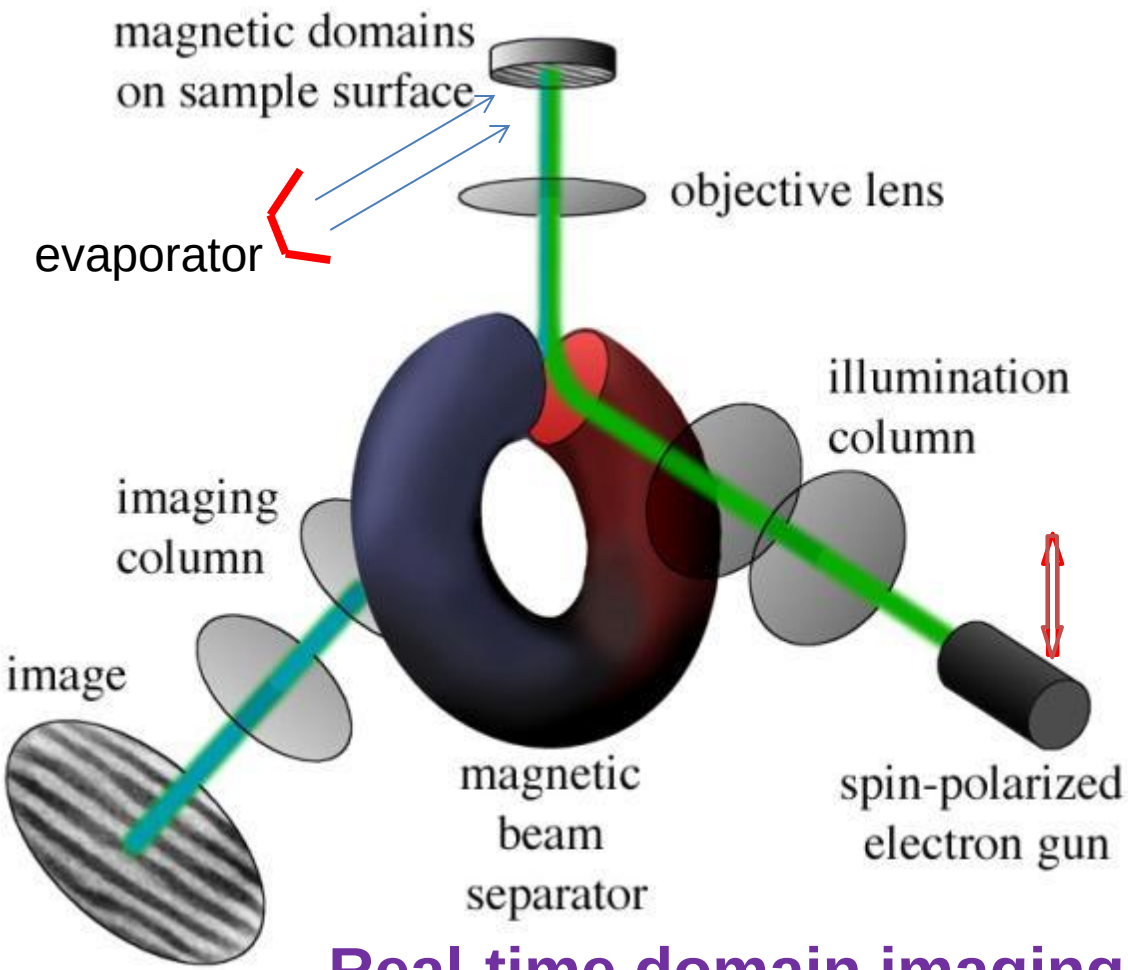


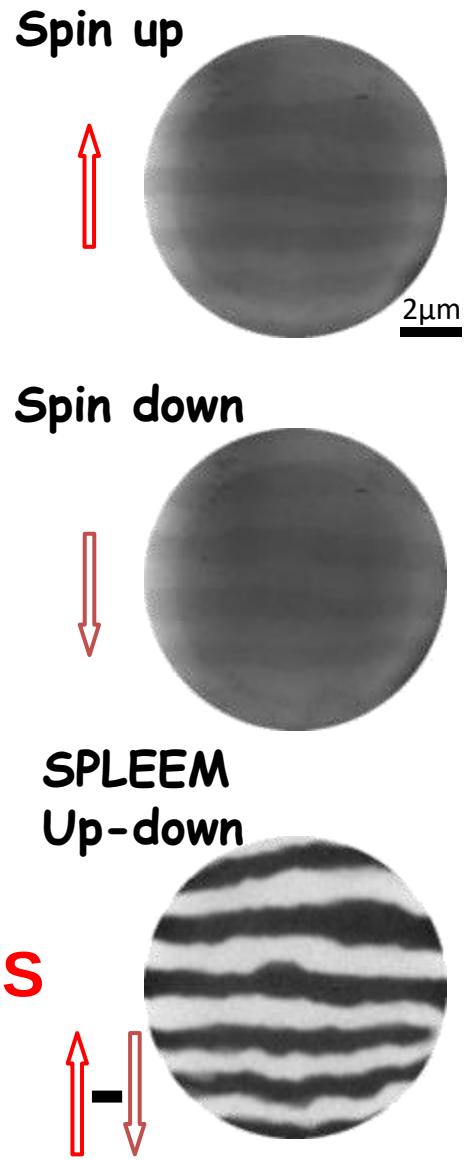




G. Chen and A.K. Schmid, *Adv. Mater.* **27**, 5738 (2015)

Spin Polarized Low Energy Electron Microscopy (SPLEEM)



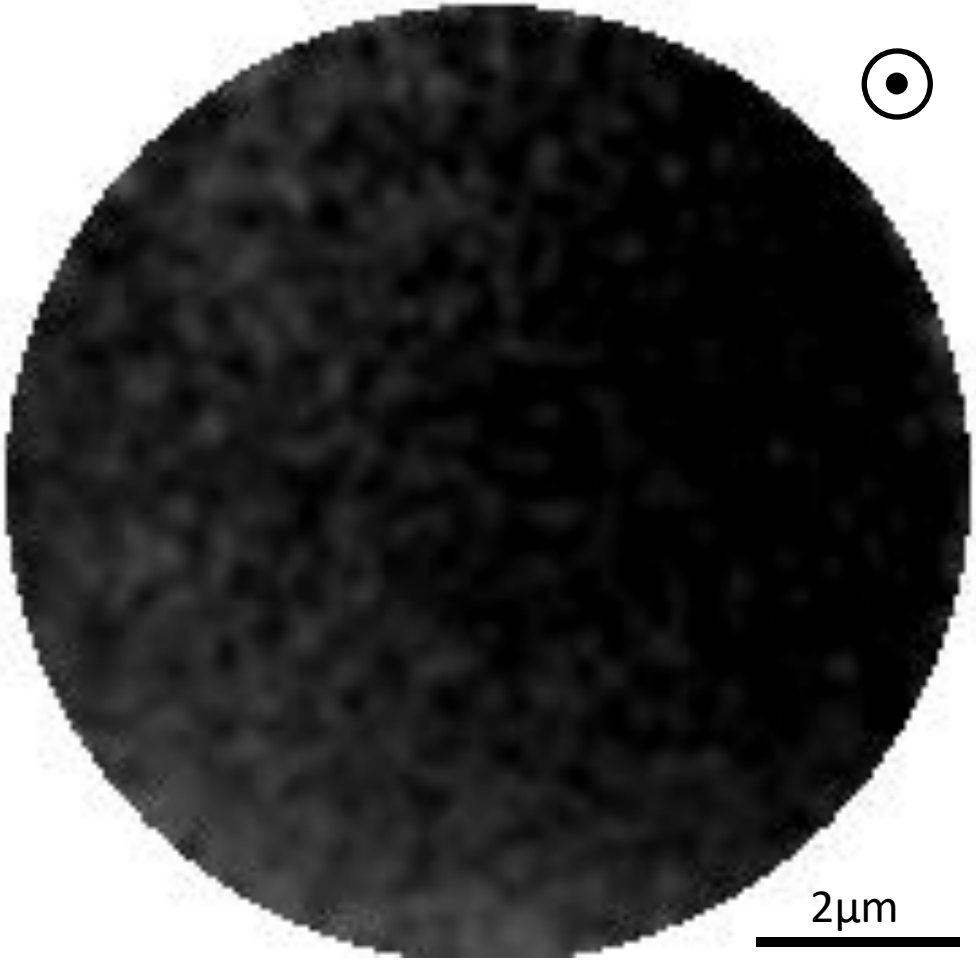


Real-time domain imaging, 0.5S

Resolution: ~10nm

Review paper: N. Rougemaille, and A.K. Schmid, Eur. Phys. J. Appl. Phys. 50, 20101 (2010)

Spin Polarized Low Energy Electron Microscopy (SPLEEM)



In-situ growth of Fe on Ni/Cu(001)

Review of skyrmions

Systems	Temperature (K)	Magnetic field (mT)	Skyrmion size (nm)	Refs
Ultrathin epitaxial films and multilayers				
1-ML Fe/Ir(111)	11	0	1	13
1-ML Fe/Ir(111)/YSZ/Si(111)	26.4	0	1	56
1-ML Pd/1-ML Fe/Ir(111)	2.2	1,500	3	12
3-ML Fe/Ir(111)	7.8	2,500	~3	34
2–3-ML Fe/2-ML Ni/ 5–15-ML Cu/15-ML Ni/Cu(001)	300	0	~400	65
Sputtered multilayers				
[Ta(5)/CoFeB(1.1) /TaO_x(3)]	300	0.5	700–2,000	72
$[Pt(3)/Co(0.9)/Ta(4)]_{15}$	300	0–2	400–500	33
$[Pt(4.5)/CoFeB(0.7)/MgO(1.4)]_{15}$	300	0–2	400–500	33
$[Ir(1)/Co(0.6)/Pt(1)]_{10}$	300	0–80	40–90	32
Nanostructured sputtered multilayers				
$[Pt(3)/Co(0.9)/Ta(4)]_{15}$	300	0–2	400–500	33
$[Ir(1)/Co(0.6)/Pt(1)]_{10}$	300	8	50–90	32
Ta(3)/Pt(3)/Co(0.5–1)/MgO_x/Ta(1)	300	0–4	70–190	76

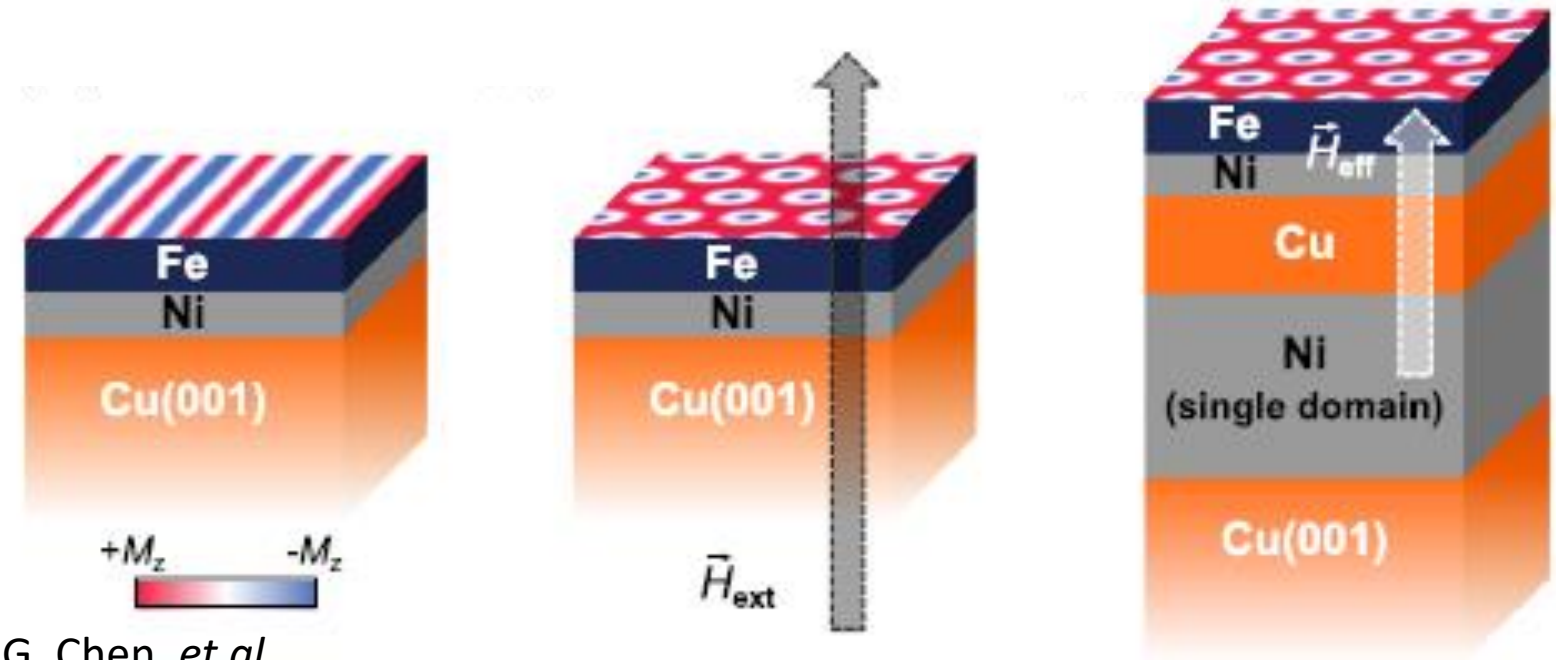
ML, monolayer; YSZ, yttria-stabilized zirconia.

Roland Wiesendanger, *Nature Reviews Materials* **1**, 16044 (2016)

Stabilizing skyrmions

Interlayer exchange coupling

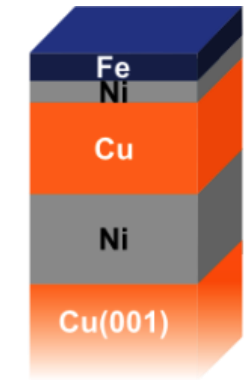
P. Grünberg, et al. Phys. Rev. Lett. 57, 2442 (1986)
G. Binasch, et al. Phys. Rev. B 39, 4828(R) (1989)
S. S. P. Parkin, et al. Phys. Rev. Lett. 64, 2304 (1990)
S. S. P. Parkin, et al. Phys. Rev. Lett. 66, 2152 (1991)



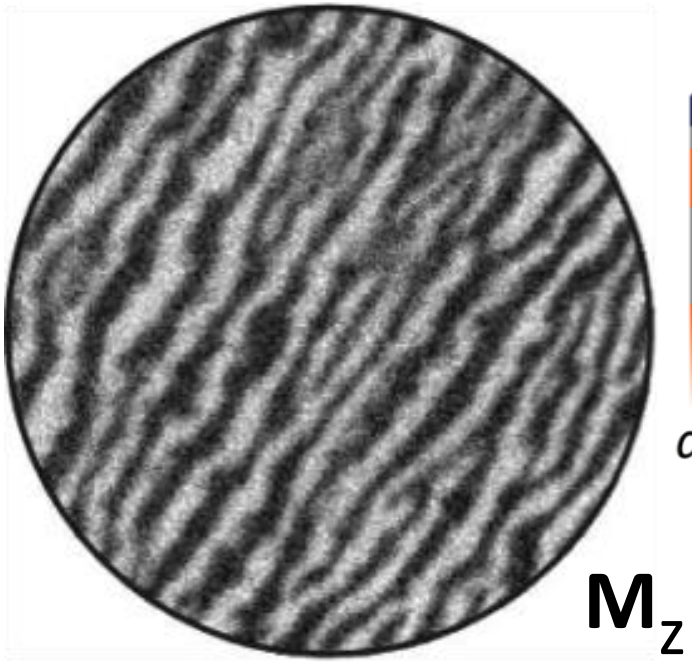
G. Chen, *et al*.
PRL **110**, 177204 (2013)

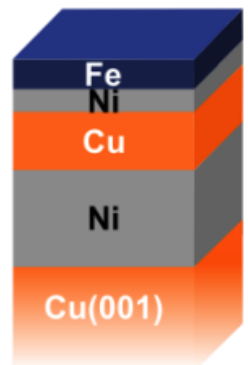
No applied external magnetic field

Stabilizing skyrmions

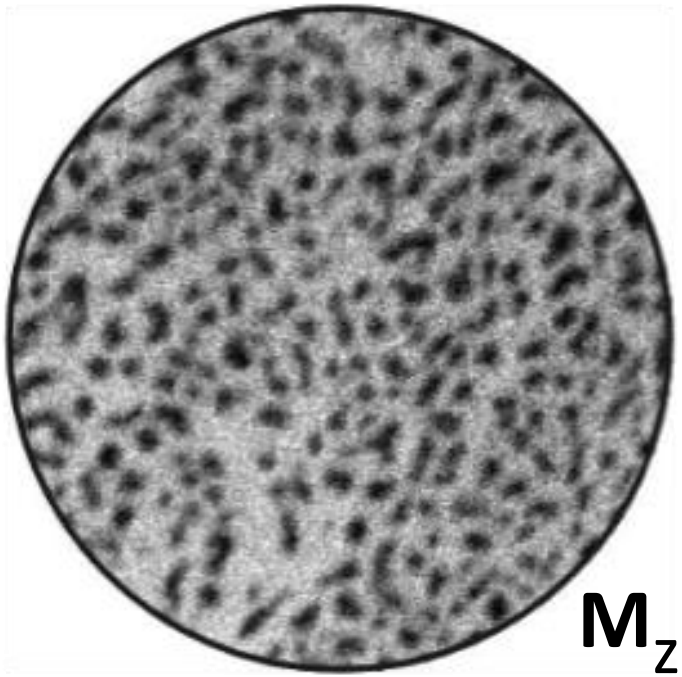


d_{Cu}=14.6 ML





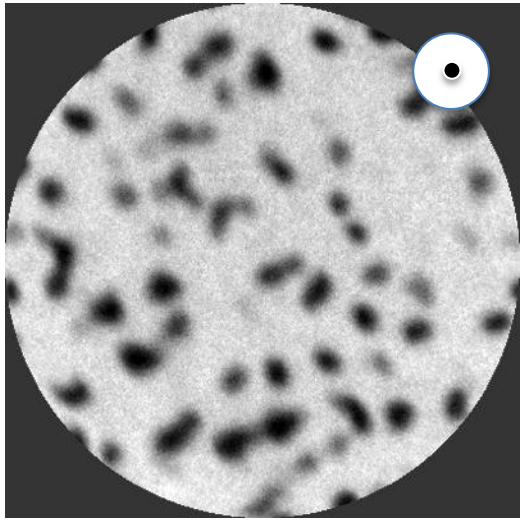
d_{Cu}=8.6 ML



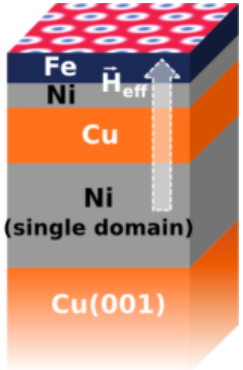
Room temperature

No applied external magnetic field

Imaging 3D structures

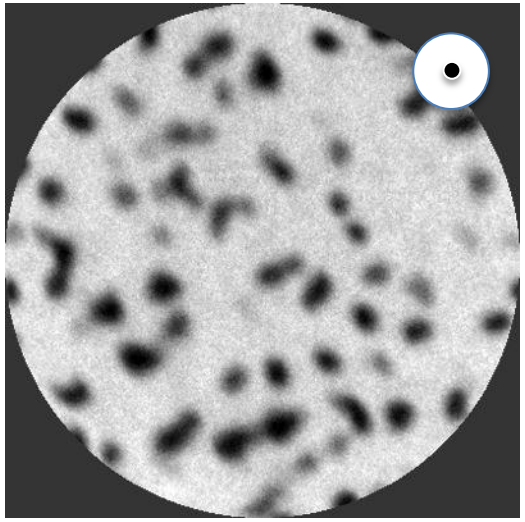


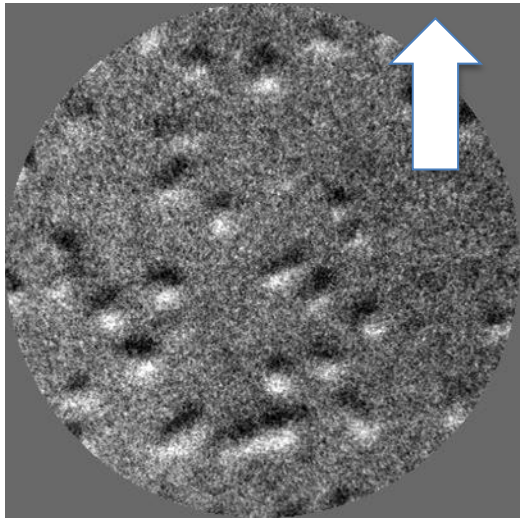
- out-of-plane magnetization component
- field of view 10um

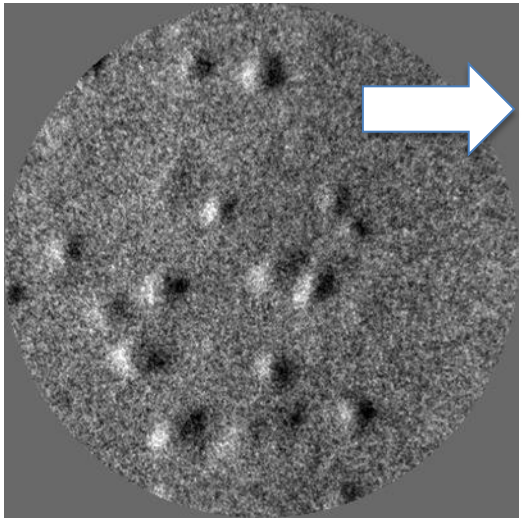


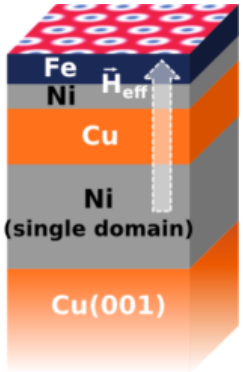
Fe/Ni/Cu/Ni/Cu(100)

Imaging 3D structures



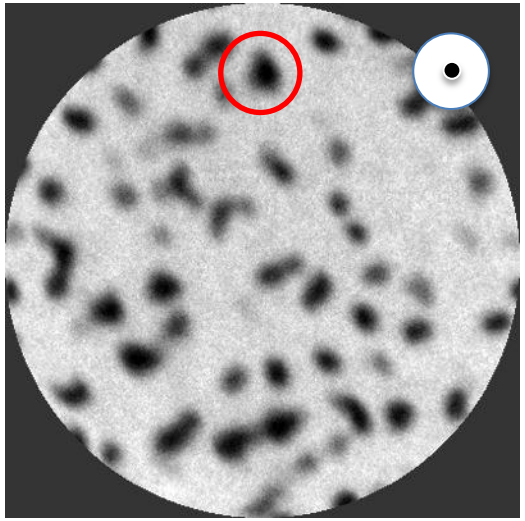


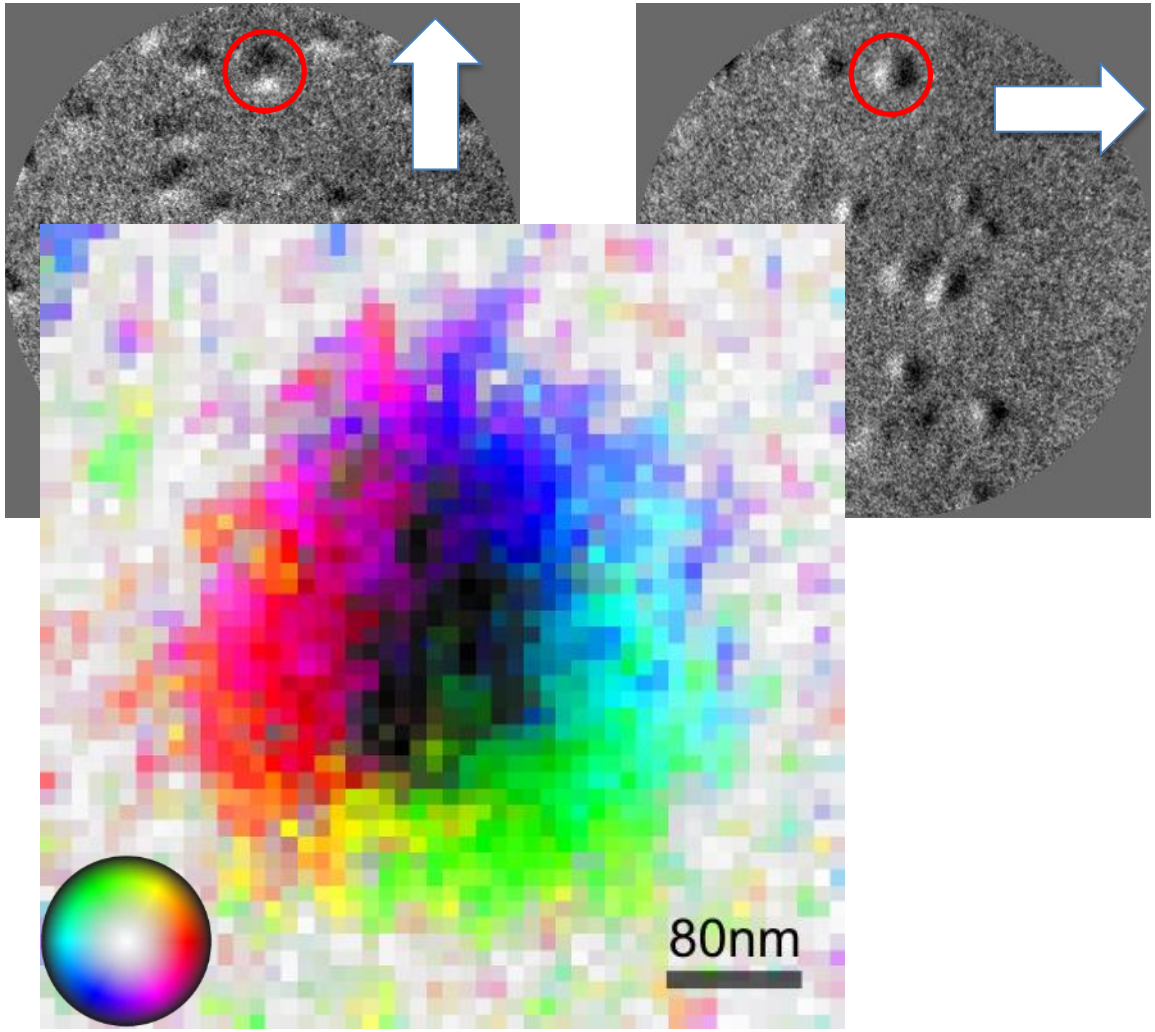


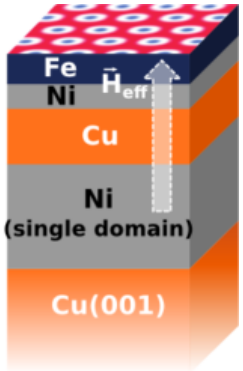


Fe/Ni/Cu/Ni/Cu(100)

Imaging 3D structures

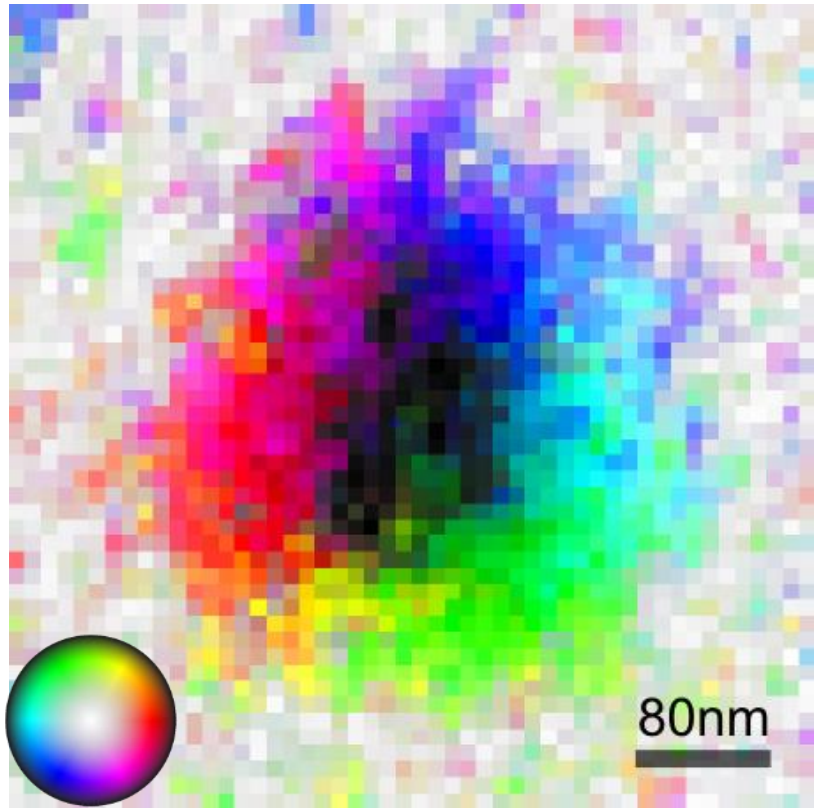


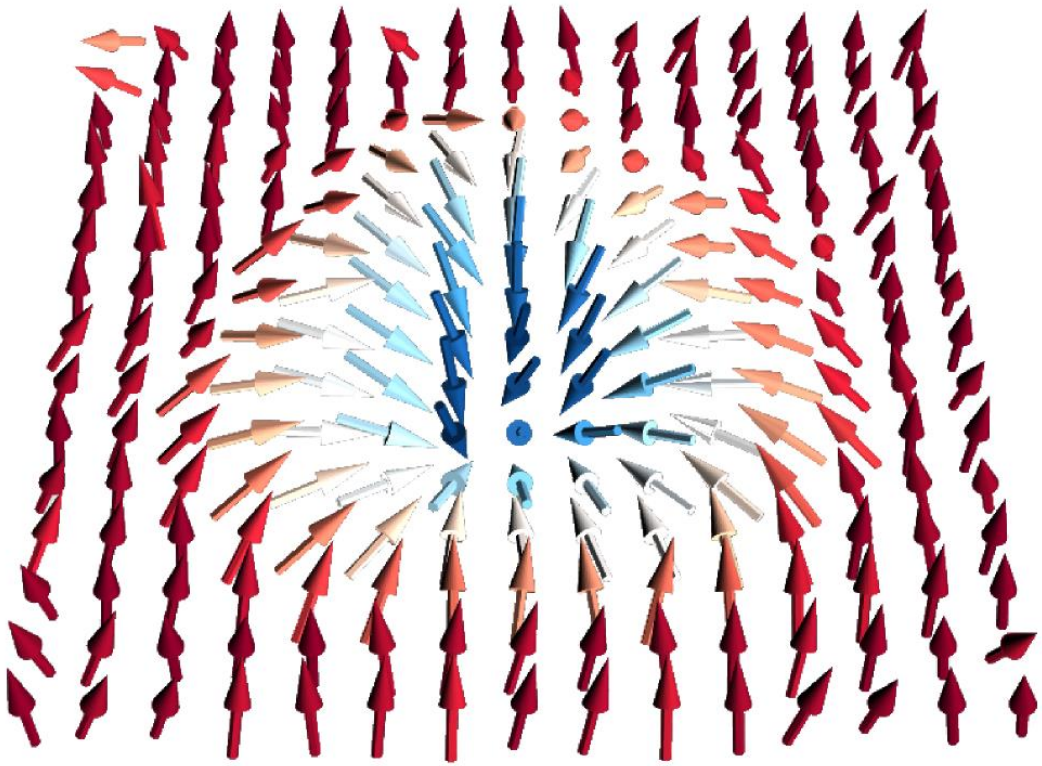




Fe/Ni/Cu/Ni/Cu(100)

Imaging 3D structures



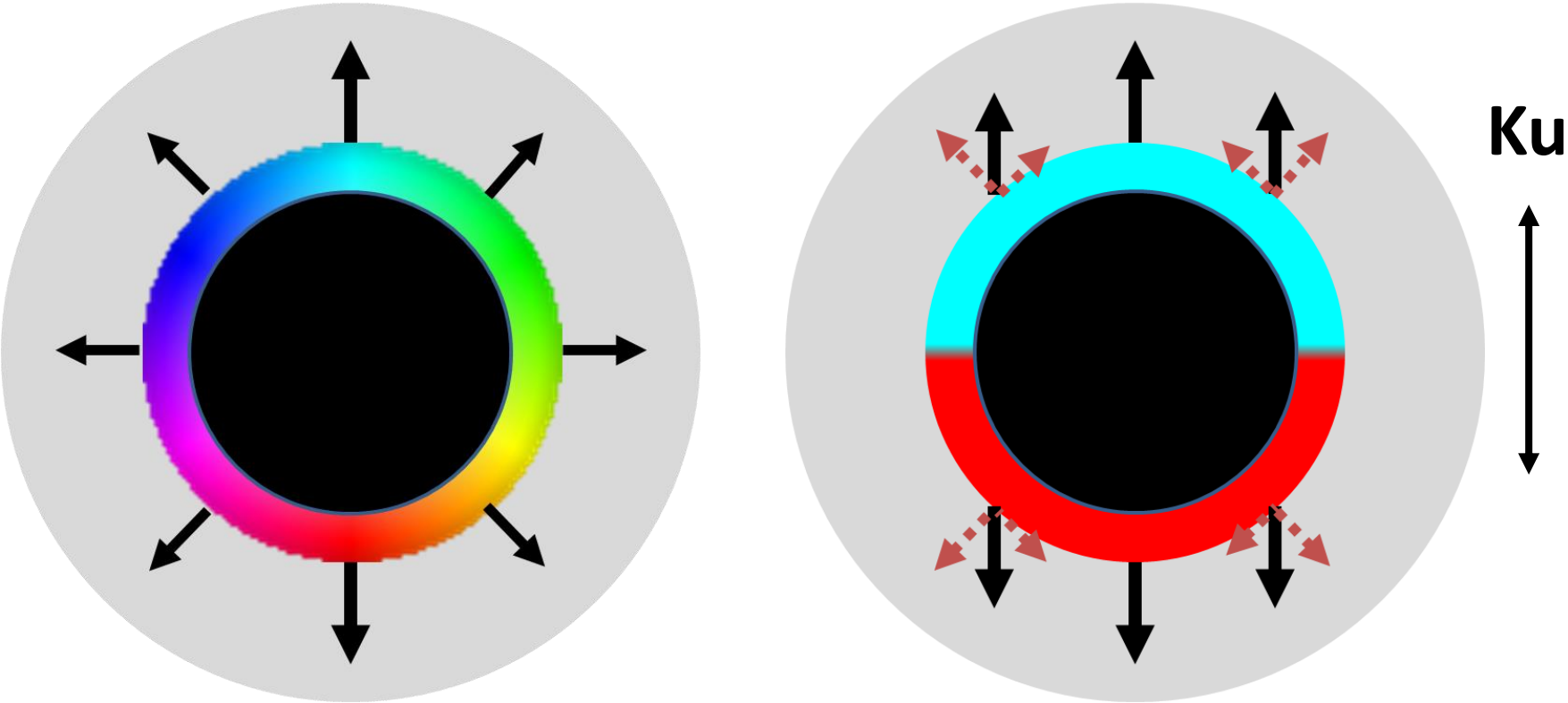


G. Chen, *et al*. Appl. Phys. Lett. **106**, 242404 (2015)

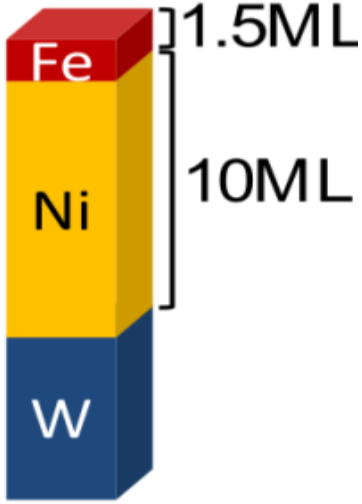
Also see First principle calculation: Nandy et al. PRL **116**, 177202 (2016)

Skyrmions at interfaces with lower symmetry

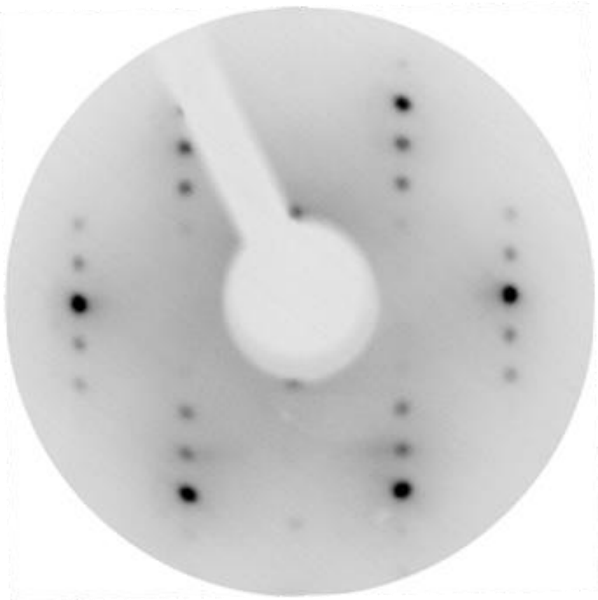
bcc(110), fcc(110) interfaces: anisotropic DMI, uniaxial K_u



Skyrmions at interfaces with lower symmetry

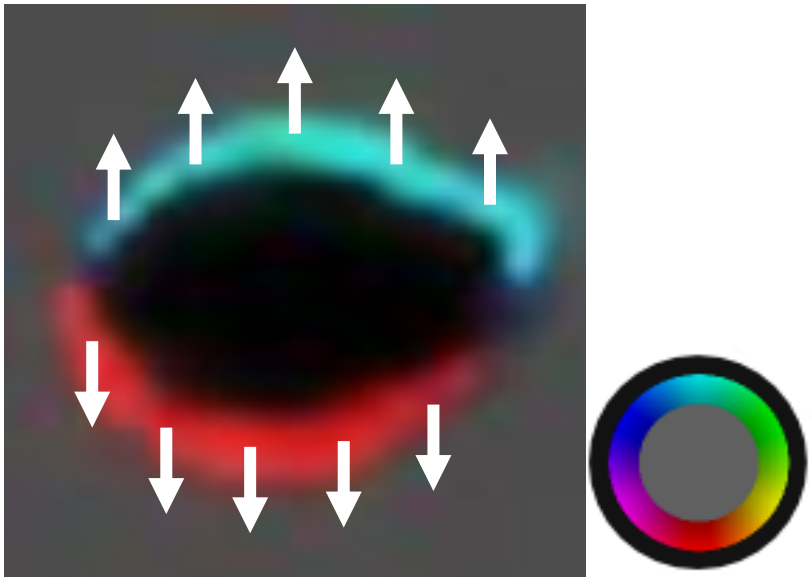


LEED



1ML Ni
132eV

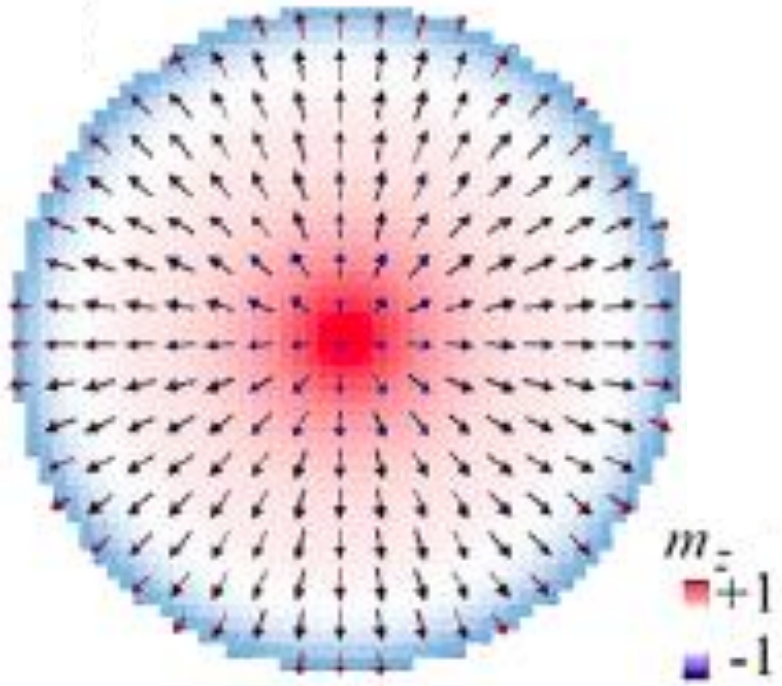
SPLEEM



G. Chen, *et al*. *Nat. Commun*. **6**, 6598 (2015)

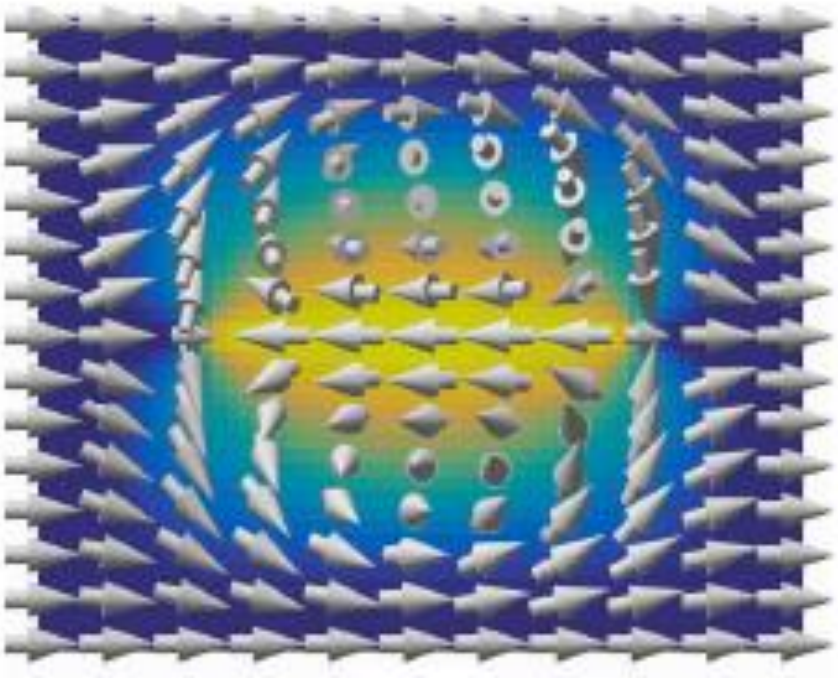
In-plane skyrmions

Talk on Monday



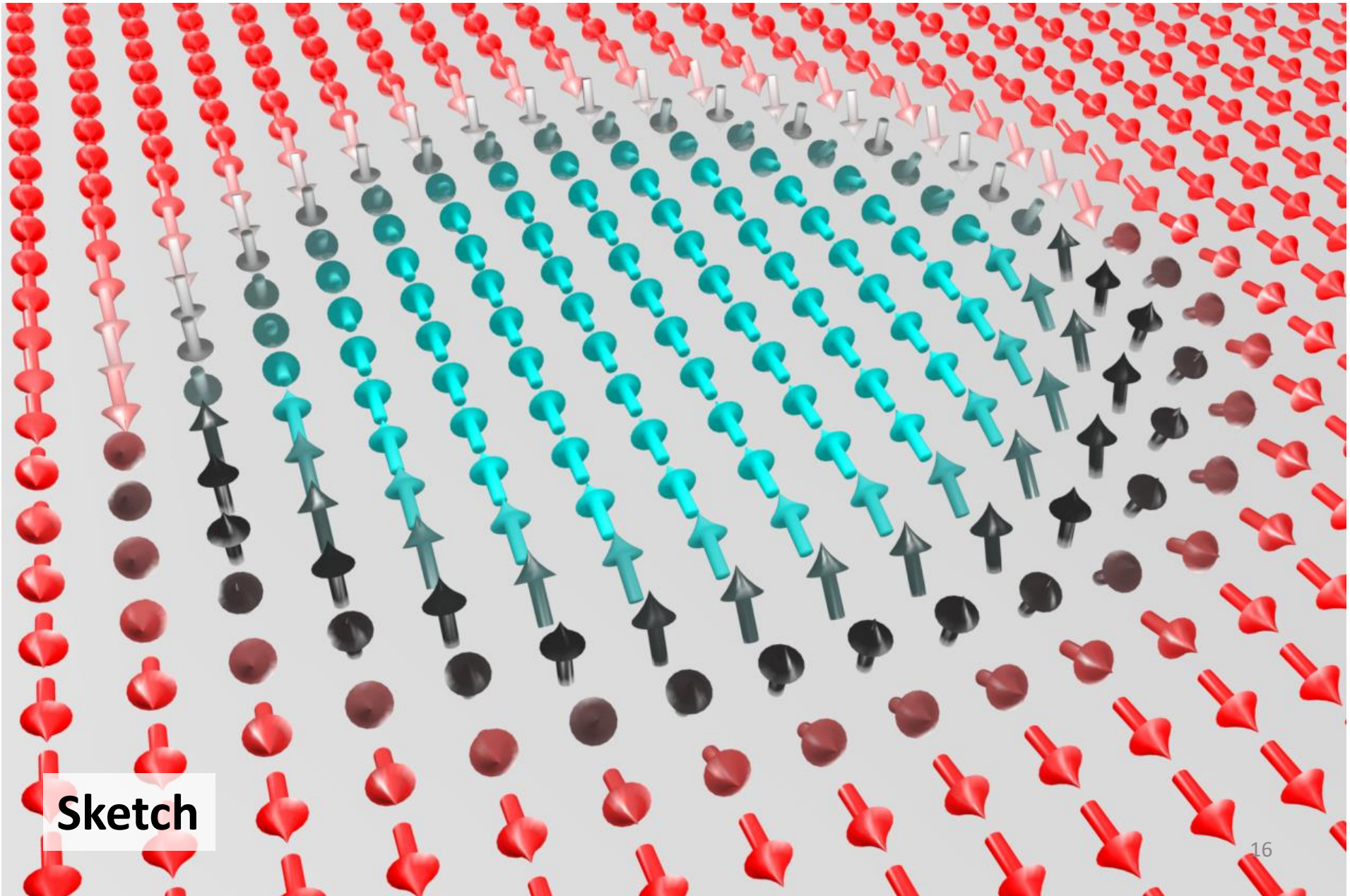
Siracusano et al. PRL 117, 087204 (2016)

Poster on Tuesday

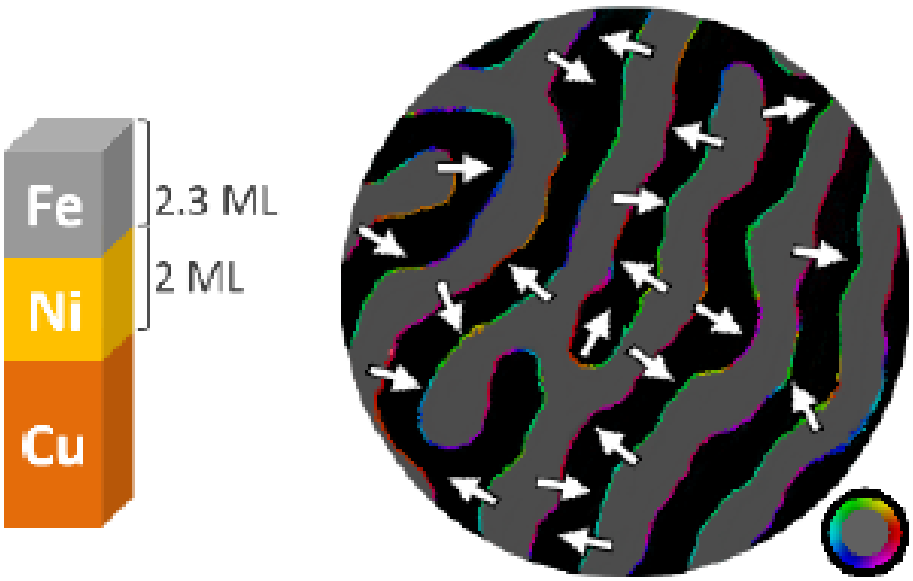


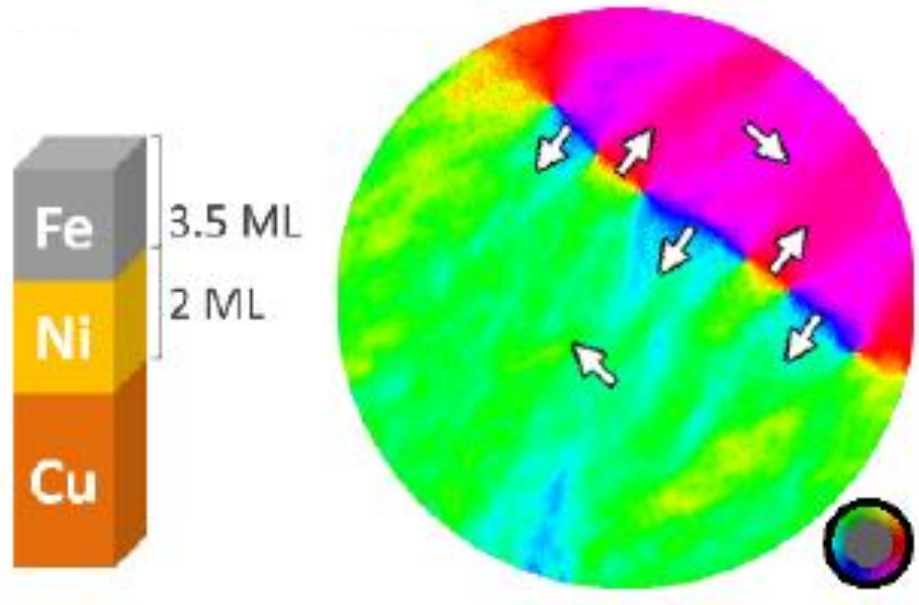
Meynell et al. PRB 96, 054402 (2017)

In-plane Néel-type skyrmions



In-plane chirality?





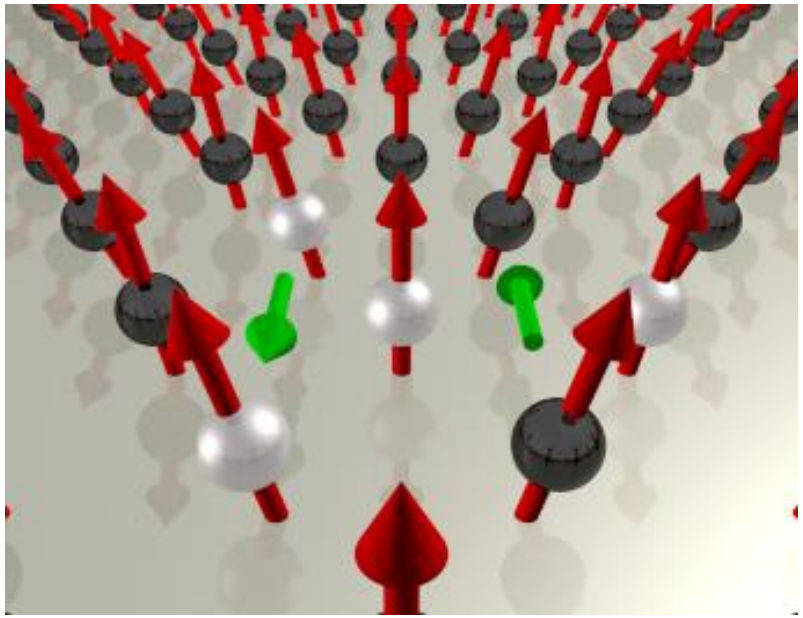
Out-of-plane system
Chiral wall

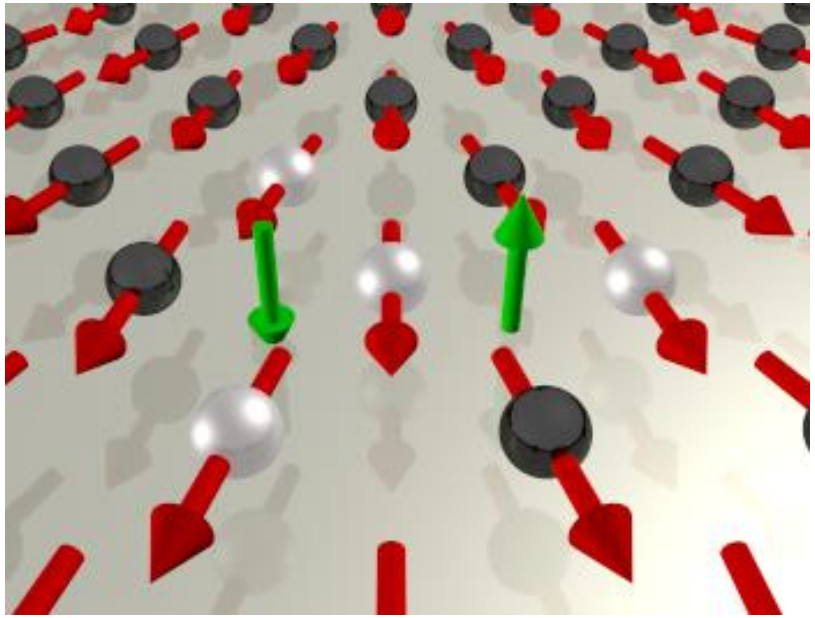
In-plane system
Achiral wall

G. Chen, et al. *unpublished*

Absence of chirality: in-plane rotation

DMI energy term $-\mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$





Out-of-plane

DMI ≠ 0

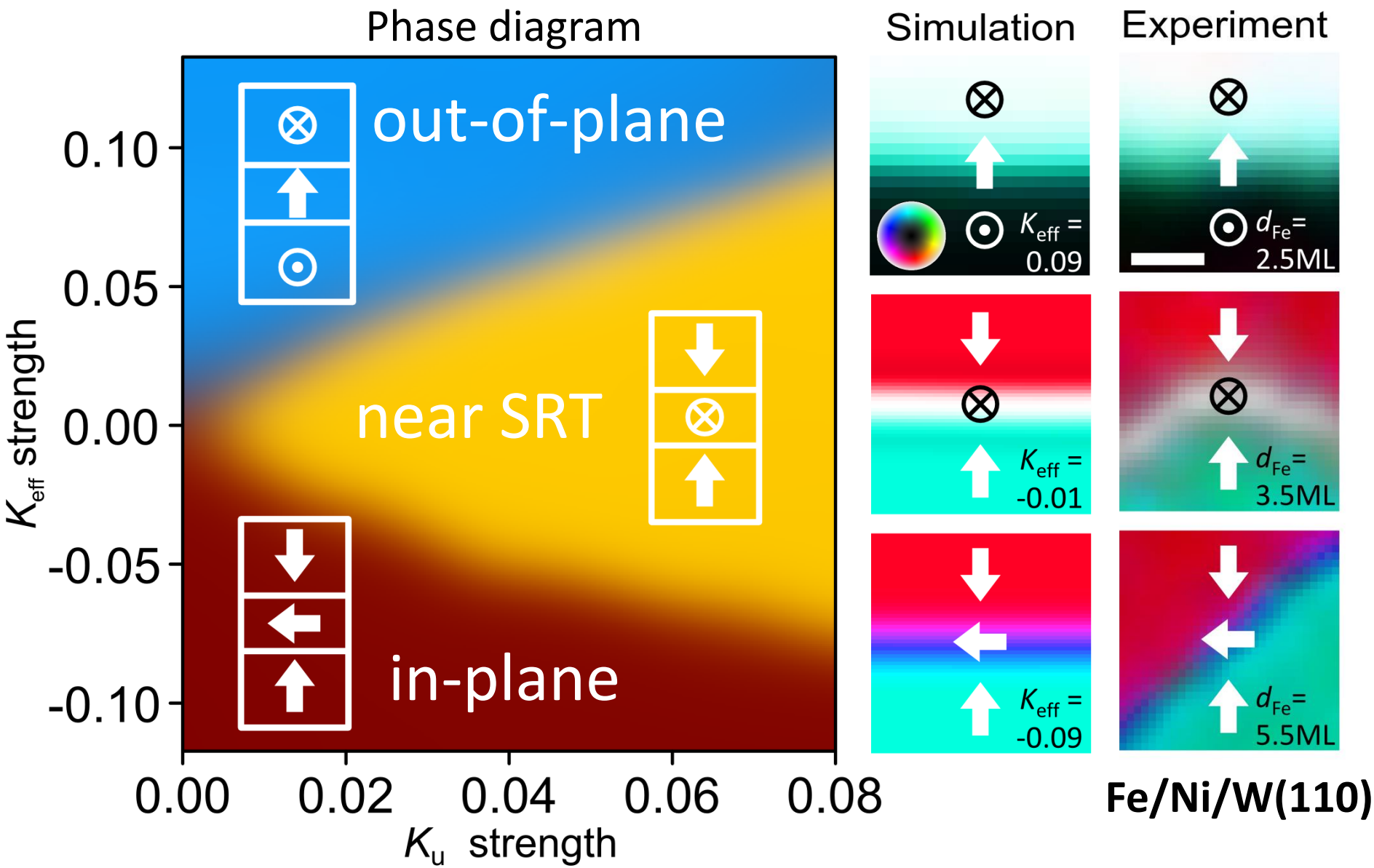
In-plane

DMI = 0

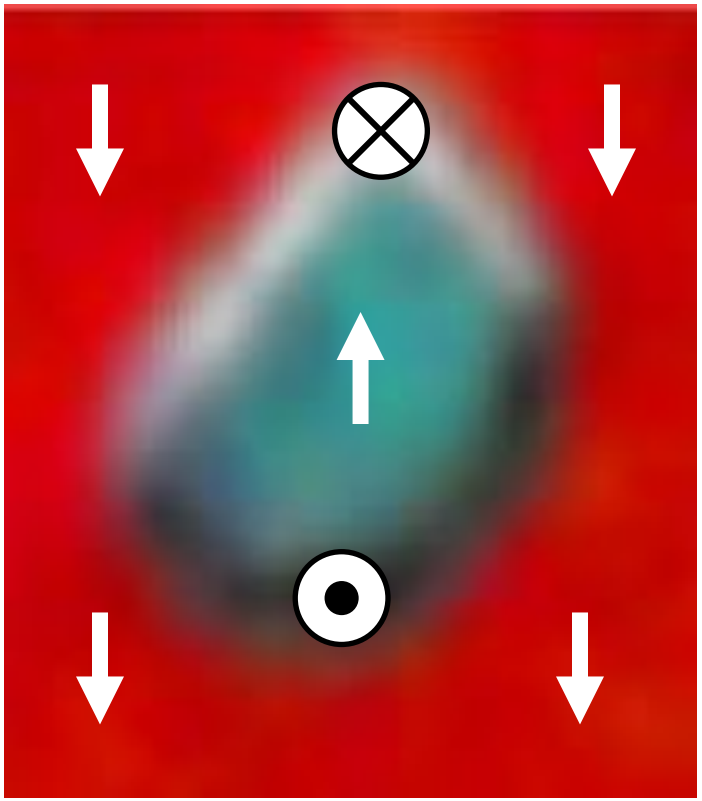
Red arrows: spin

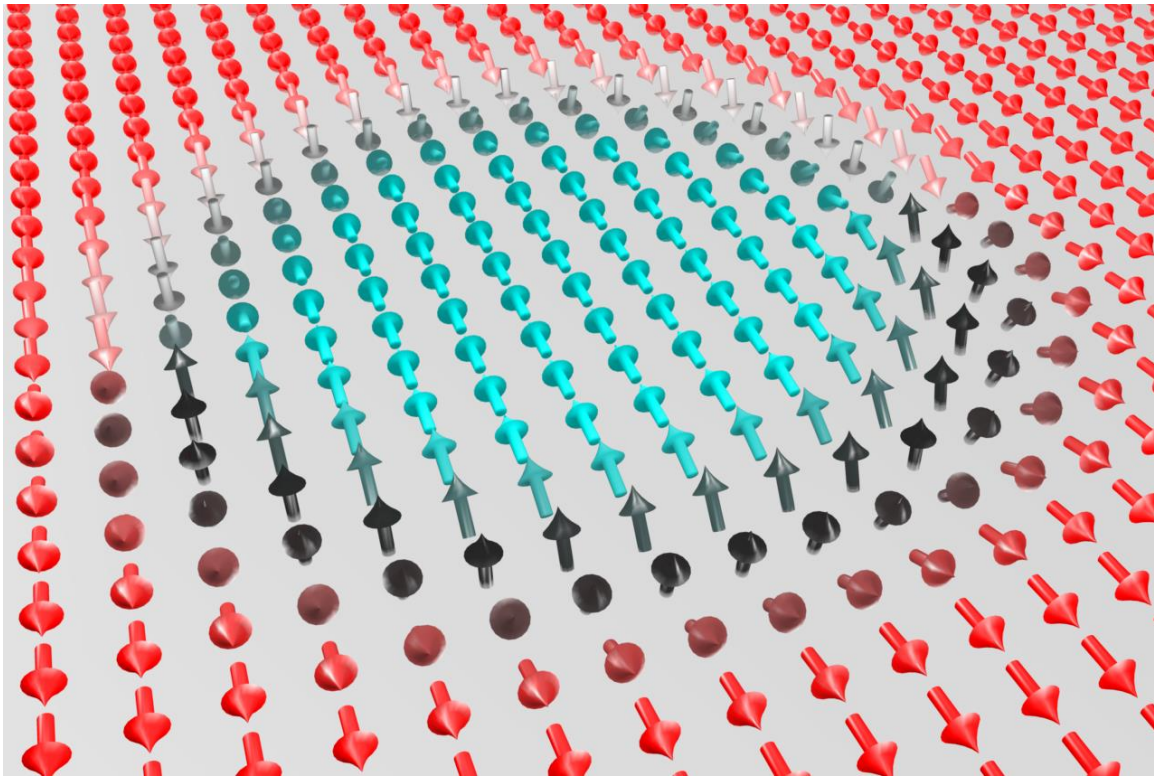
Green arrows: $\mathbf{S}_i \times \mathbf{S}_j$

Stabilizing chirality in in-plane magnet



observation of in-plane Néel-type skyrmion

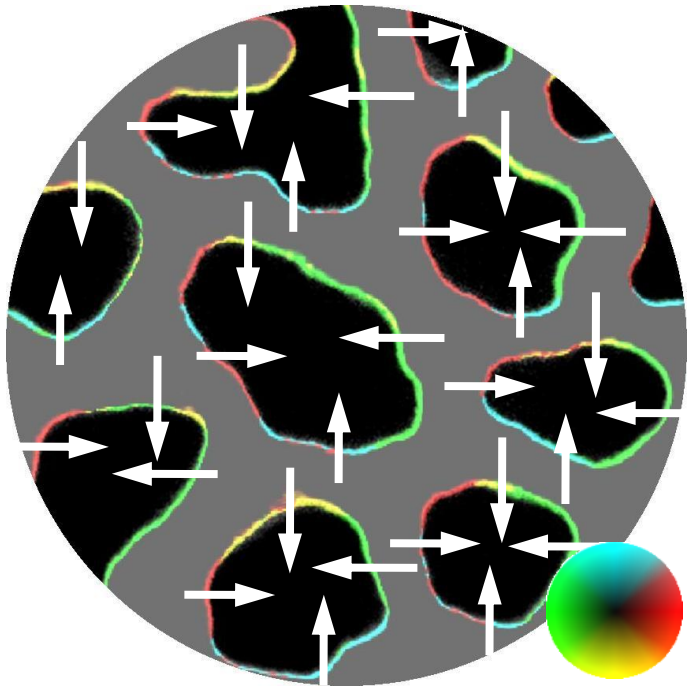




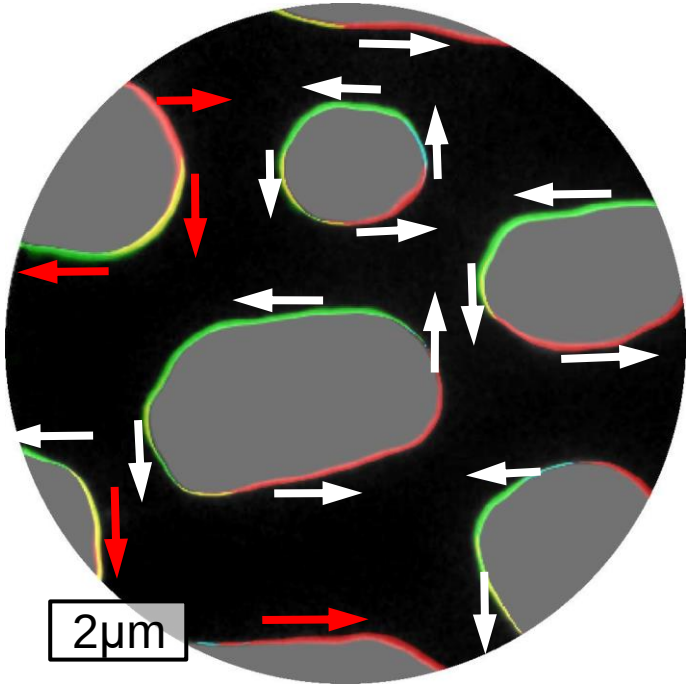
G. Chen, *et al*. *Nat. Commun*. **8**, 15302 (2017)

Is bubble always a skyrmion?

Thin Fe/Ni film



Thick Fe/Ni film



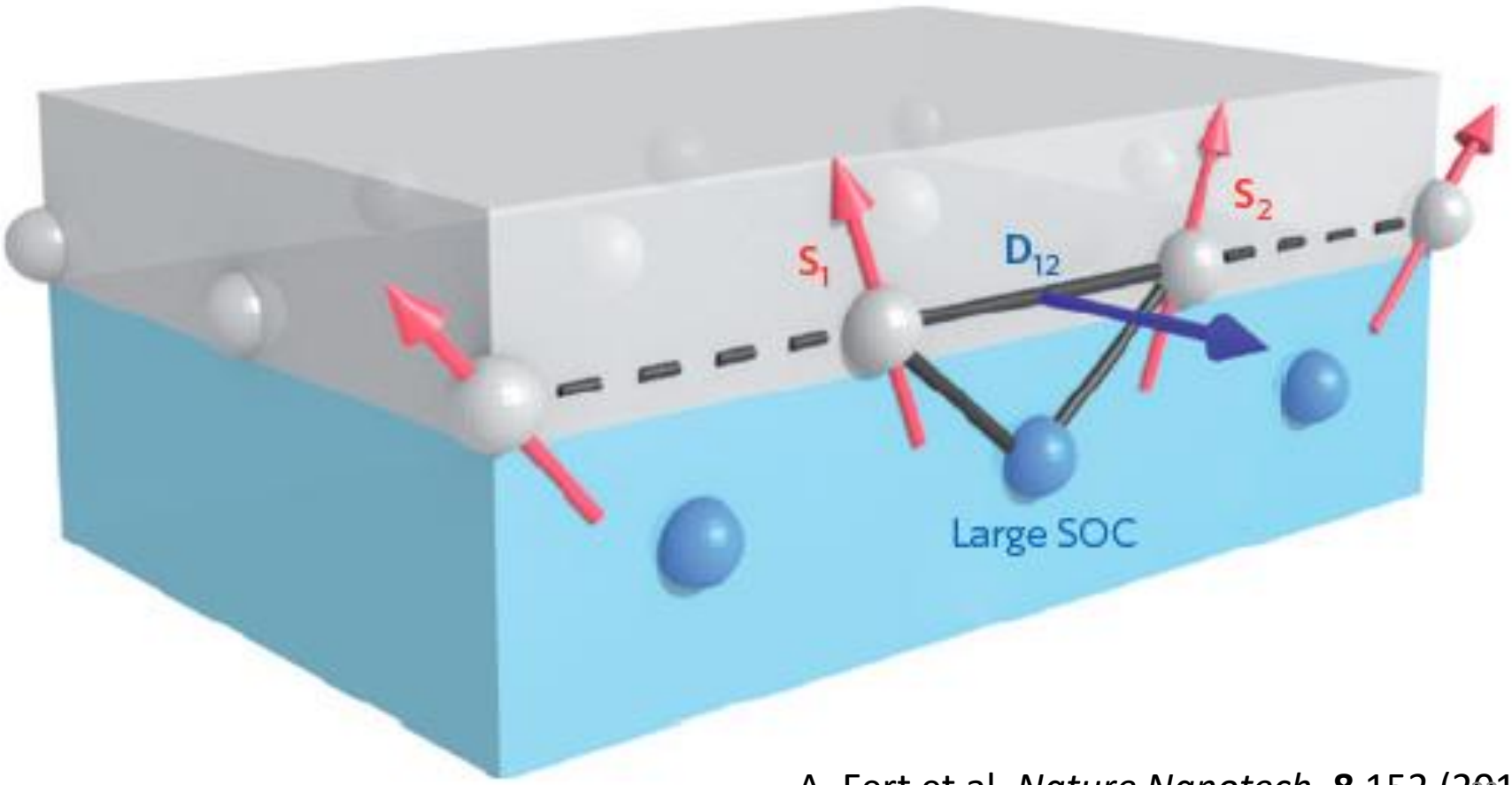
The importance of knowing and tailoring the DMI

Dzyaloshinskii-Moriya interaction

Inversion symmetry broken

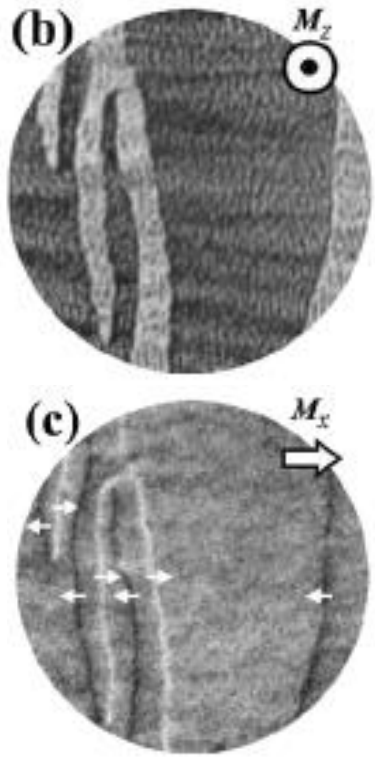
E. Dzyaloshinskii, *Sov. Phys. JETP* **5**, 1259 (1957)
T. Moriya, *Phys. Rev.* **120**, 91 (1960)

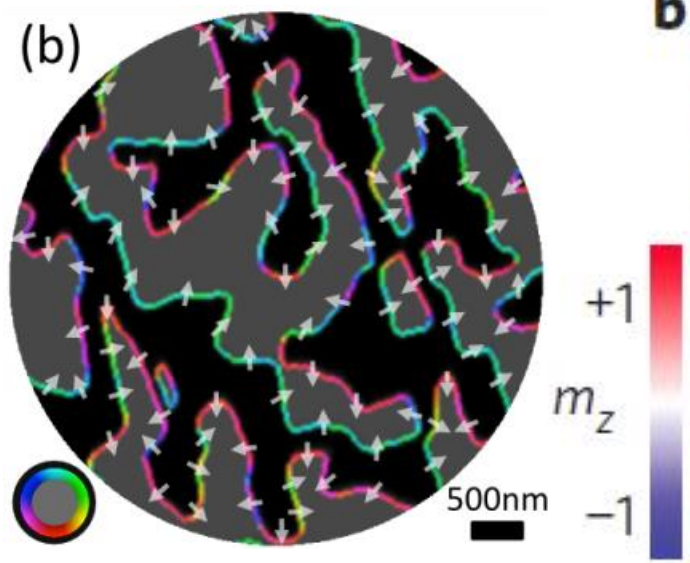
$$-\mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

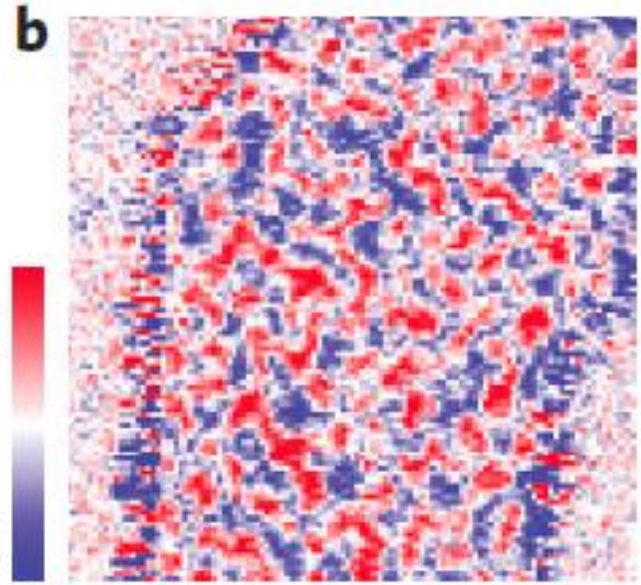


A. Fert et al. *Nature Nanotech*, **8** 152 (2013)

Ternary superlattice boosting the DMI







[Fe/Ni/Cu]$_n$

G. Chen, *et al*.
Phys. Rev. Lett.
110, 177204 (2013)

[Ir/Co/Ni]$_n$

G. Chen, *et al*.
Appl. Phys. Lett.
106, 062402 (2015)

[Ir/Co/Pt]$_n$

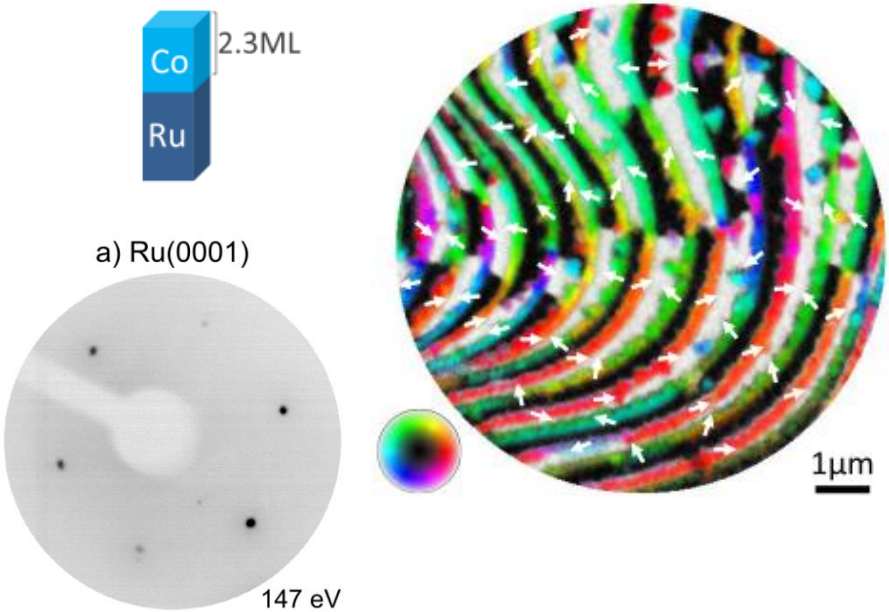
Moreau-Luchaire et al.
Nature Nano.
11, 444 (2016)

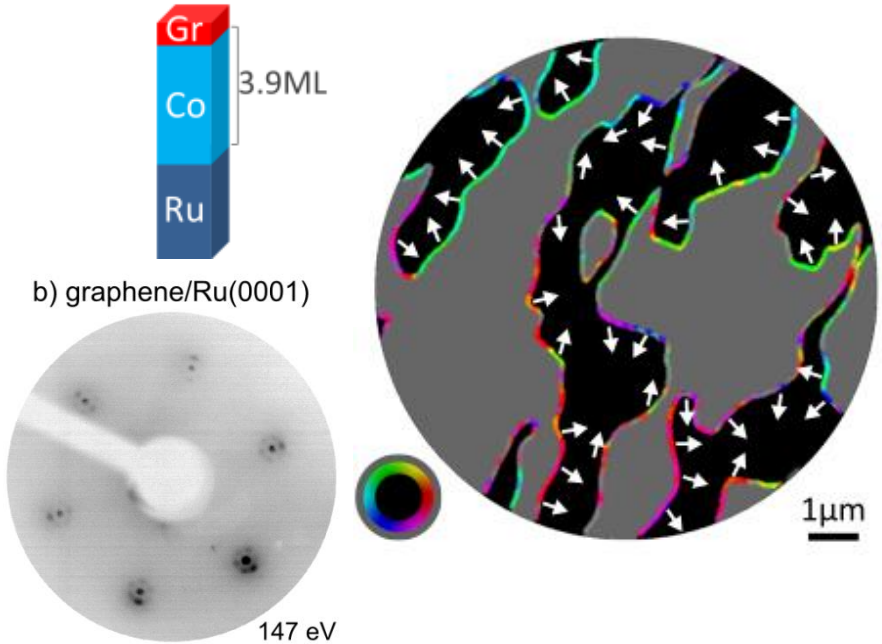
Possible iDMI in the periodic table of the elements

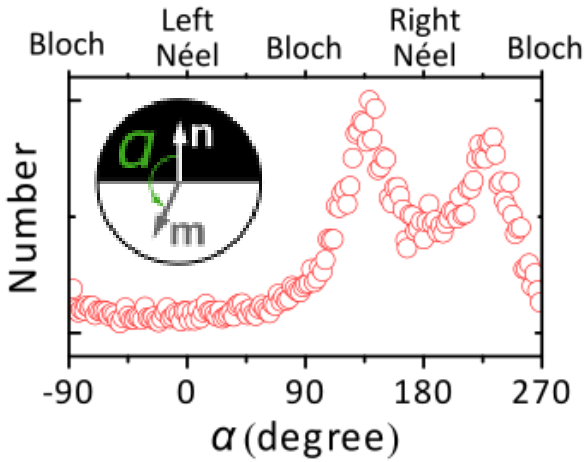
hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

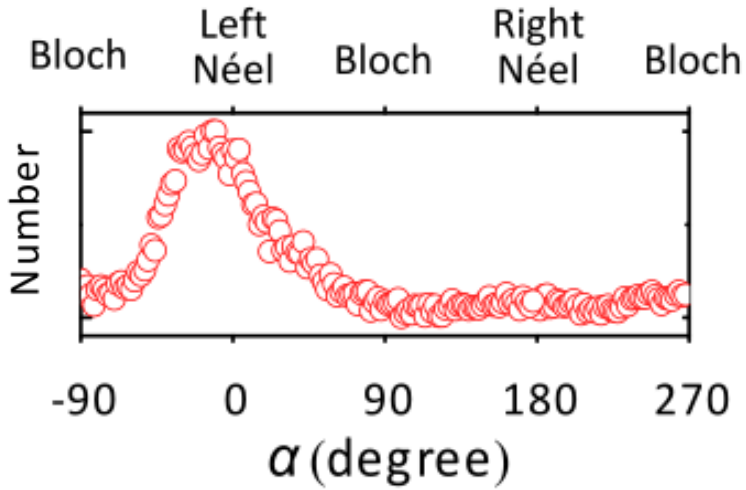
*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Significant DMI at Gr/Co interface









Right-handed Néel wall

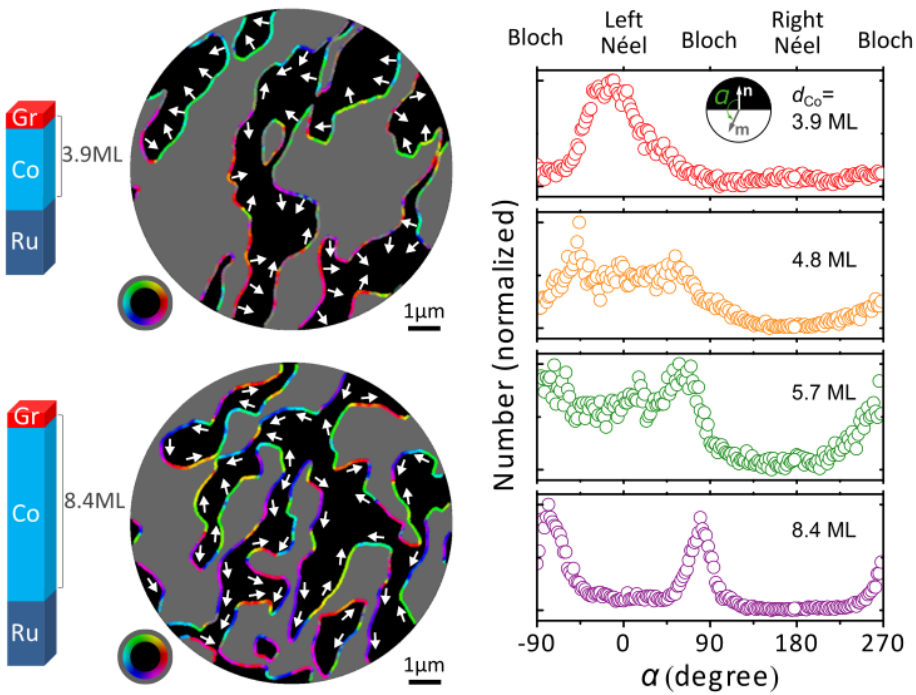
Left-handed Néel wall

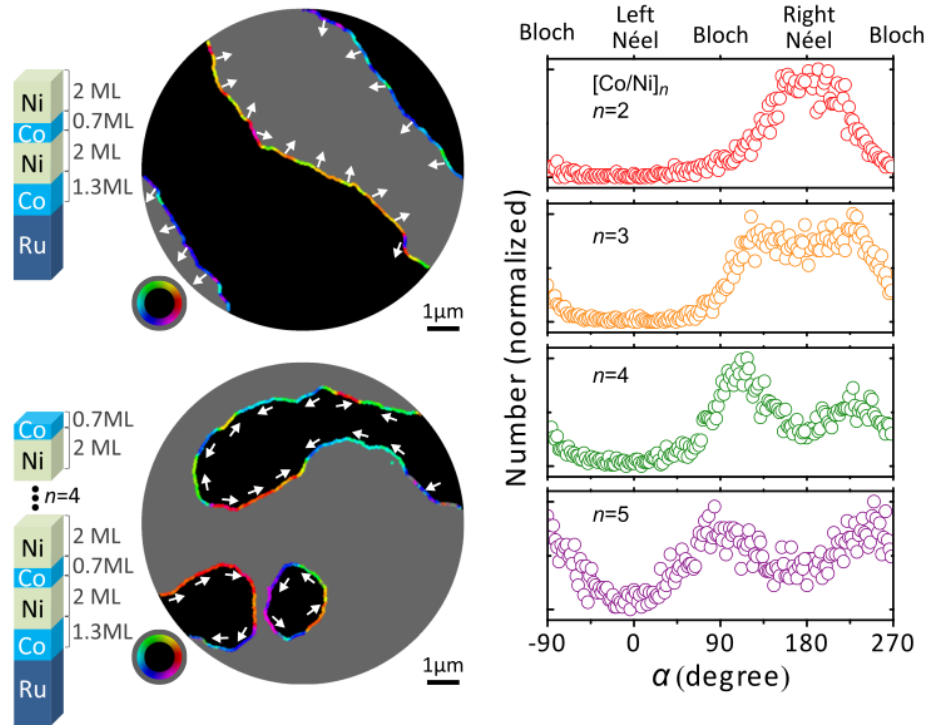
Quantifying the DMI at Gr/Co interface

Thickness dependent transition of chirality

⇨ The DMI strength and sign

G. Chen, *et al*. *PRL* **110**, 177204 (2013)
G. Chen, *et al*. *Nat. Commun*. **4**, 2671 (2013)





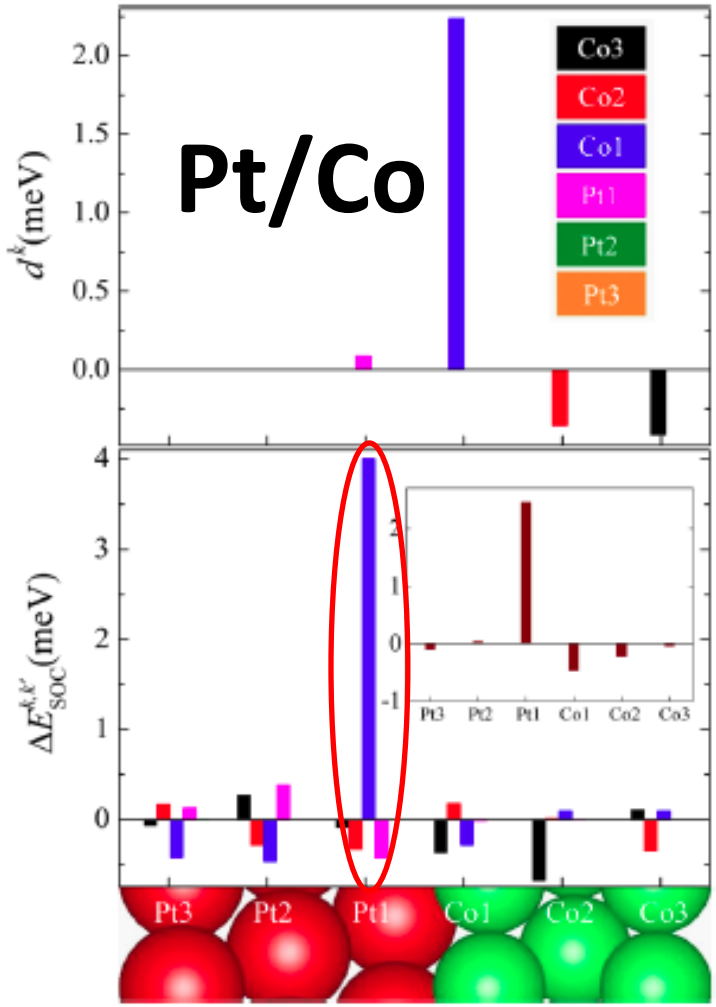
DMI in Gr/Co/Ru: 0.11±0.04 meV/atom

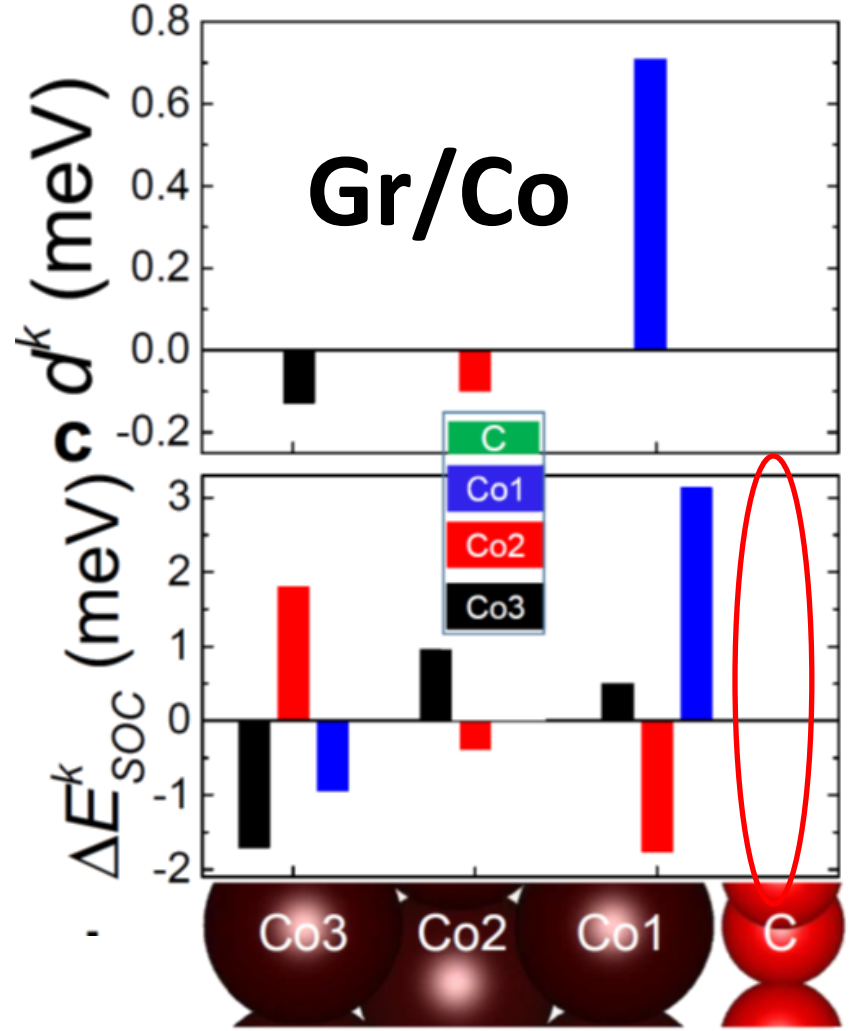
DMI at Co/Ru: -0.11±0.06 meV/atom

DMI at Gr/Co interface: 0.22±0.1 meV/atom

arXiv preprint arXiv:1704.09023

Rashba effect induced DMI





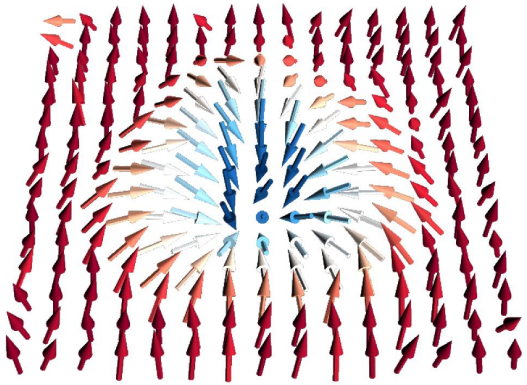
Yang et al. PRL 115, 267210 (2015)

Model: Fert, A. & Levy, P. M. PRL 44, 1538 (1980)

Rashba DMI: 0.3 meV/atom

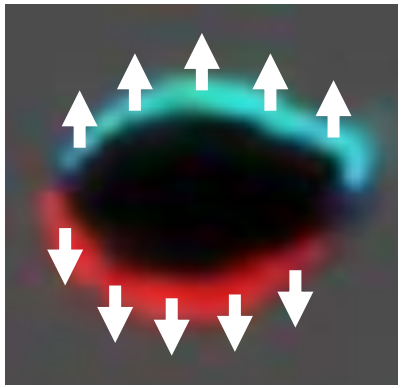
arXiv preprint arXiv:1704.09023

Summary



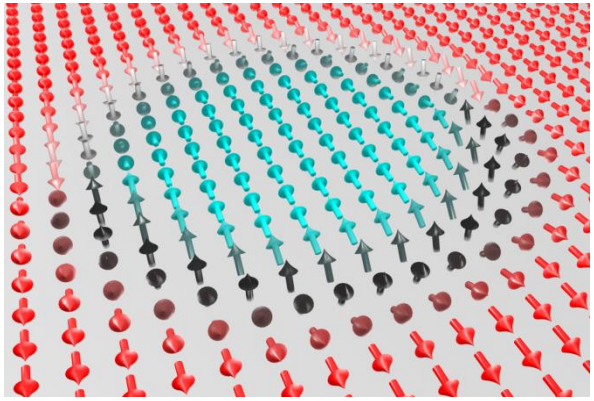
Zero-field skyrmions

Chen APL 2015



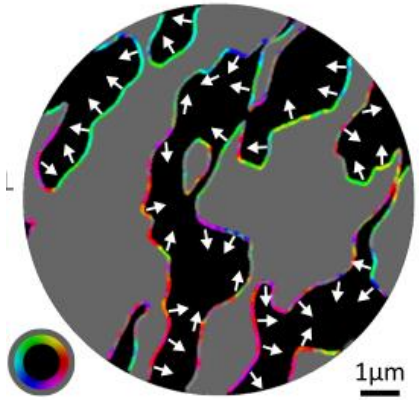
low symmetry interface

Chen Nat. Commun. 2015



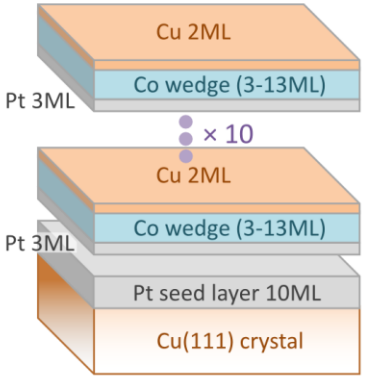
In-plane skyrmions

Chen Nat. Commun. 2017



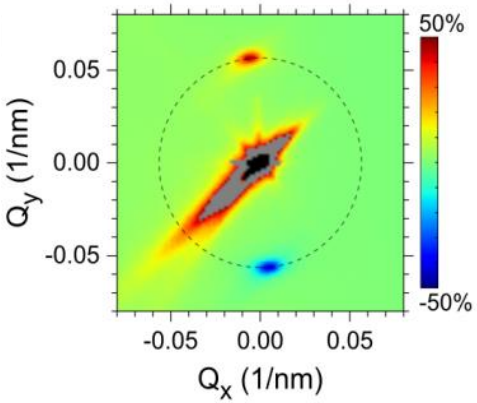
Graphene induced DMI

arXiv preprint arXiv:1704.09023



Tailoring the DMI

Chen PRL 2013, NC 2013



Chirality induced XMCD

Submitting

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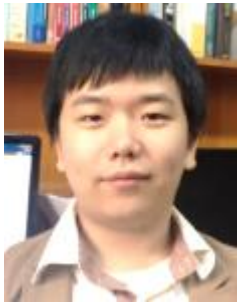

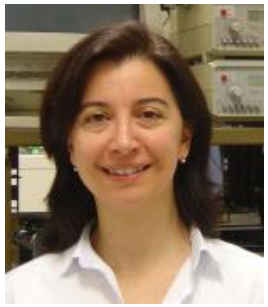
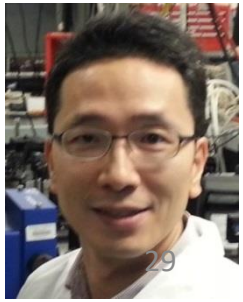

Thank you

SPLEEM – user facility

More information http://foundry.lbl.gov/

Advanced light source

More information https://als.lbl.gov/

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