Chiral asymmetry in nanomagnetism

Laszlo Szunyogh & Laszlo Udvardi

Department of Theoretical Physics

Budapest University of Technology and Economics, Hungary

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Coworkers:

K. Palotás, A. Antal, E. Simon, L. Balogh, A. Deák, L. Rózsa

Budapest University of Technology and Economics, Hungary

B. Újfalussy, B. Lazarovits

Research Institute for Solid State Physics, Hungary

U. Nowak, J. Jackson, R. Yanes, G. Hasselberg, D. Hinzke

University of Konstanz, Germany

Outline of the talk

Spin Hamiltonians and Dzyaloshinskii-Moriya interaction (DMI)

Effects in magnetic nanostructures induced by DMI:

- *Magnetic pattern formation in ultrathin films*
  - *Spin-spirals*
  - *Magnetic skyrmions & skyrmion lattices*
- *Asymmetry of the spin-wave spectra*
- *Perpendicular exchange bias*

Introduction

Effects of spin-orbit coupling in nanomagnetism:

Magneto-crystalline anisotropy

Spin-reorientation phase transitions

Superparamagnetism

Magneto-optics: Faraday effect, Kerr effect

Spintronics:

- Bychkov-Rashba effect
- Transverse transport phenomena (AHE, SHE)

...

Classical spin Hamiltonian

$$H = \frac{1}{2}\sum_{i\neq j} \vec{e}_i \, \mathbf{J}_{ij} \, \vec{e}_j + \frac{1}{2}\sum_{i\neq j} \vec{e}_i \, \mathbf{M}_{ij} \, \vec{e}_j + \sum_{i} \vec{e}_i \, \mathbf{K}_i \, \vec{e}_i$$

exchange interaction | **magnetic dipole-dipole interaction** | **on-site anisotropy**

Tensorial exchange interaction

$$\mathbf{J}_{ij} = J_{ij}\,\mathbf{I} + \mathbf{J}_{ij}^{S} + \mathbf{J}_{ij}^{A}$$

$$J_{ij} = \frac{1}{3} Tr \mathbf{J}_{ij} \qquad \mathbf{J}_{ij}^{S} = \frac{1}{2}\left(\mathbf{J}_{ij} + \mathbf{J}_{ij}^{t}\right) - J_{ij}\,\mathbf{I} \qquad \mathbf{J}_{ij}^{A} = \frac{1}{2}\left(\mathbf{J}_{ij} - \mathbf{J}_{ij}^{t}\right)$$

isotropic | anisotropic symmetric | antisymmetric

anisotropic symmetric → relativistic (spin-orbit) effects ← antisymmetric

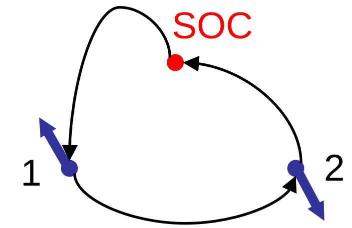
relativistic (spin-orbit) effects

Dzyaloshinskii-Moriya interaction (DMI)

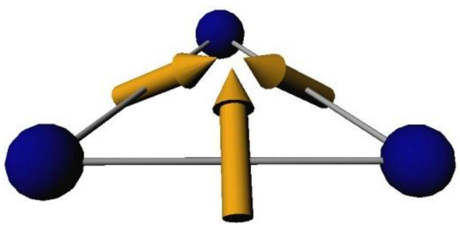
I. E. Dzyaloshinskii, Sov. Phys. JETP 5, 1259–1262 (1957)
T. Moriya, Phys. Rev. 120, 91–98 (1960)

$$E_{DM} = \overrightarrow{e}_i \, \mathbf{J}_{ij}^{A} \, \overrightarrow{e}_j = \overrightarrow{D}_{ij} \left(\overrightarrow{e}_i \times \overrightarrow{e}_j \right) \quad \Rightarrow \quad D_{ij}^{\alpha} = \frac{1}{2} \varepsilon_{\alpha\beta\gamma} J_{ij}^{\beta\gamma}$$

Asymmetric exchange (RKKY) interaction:
DMI scales with the strength of SOC
A. Fert and P. M. Levy, Phys. Rev. Lett. 44, 1538 (1980)

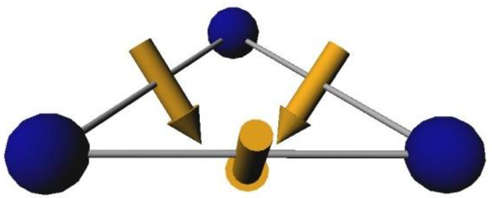


Equilateral Cr trimer on top of Au(111) A. Antal *et al.*, Phys. Rev. B **77**, 174429 (2008)

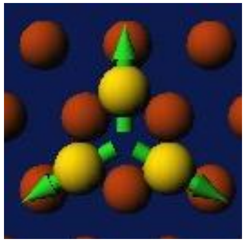


$D_z > 0$

DM vectors



$D_z < 0$

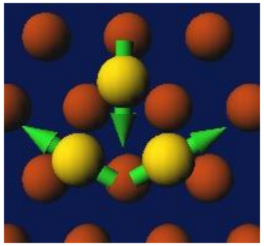


$\kappa_z = -1$

Chirality

$$\vec{\kappa} = \frac{2}{3\sqrt{3}} \sum_{(ij)} \left(\vec{\sigma}_i \times \vec{\sigma}_j \right)$$

$$E_{DM} = \frac{3\sqrt{3}}{2} D_z \, \kappa_z$$



$\kappa_z = 1$

Ab initio methods to calculate tensorial exchange interactions & anisotropy parameters

- Relativistic torque method

A.I. Liechtenstein *et al.,* JMMM 67, 65 (1987)

L. Udvardi *et al.,* PRB 68 104436 (2003)

H. Ebert and S. Mankovsky, PRB 79, 045209 (2009)

Based on zero temperature ordered (ferromagnetic) state

- Spin-cluster expansion

R. Drautz and M. Fähnle, PRB 69, 104404 (2004), PRB 72, 212405 (2005)

L. Szunyogh *et al*., PRB 83, 024401 (2011)

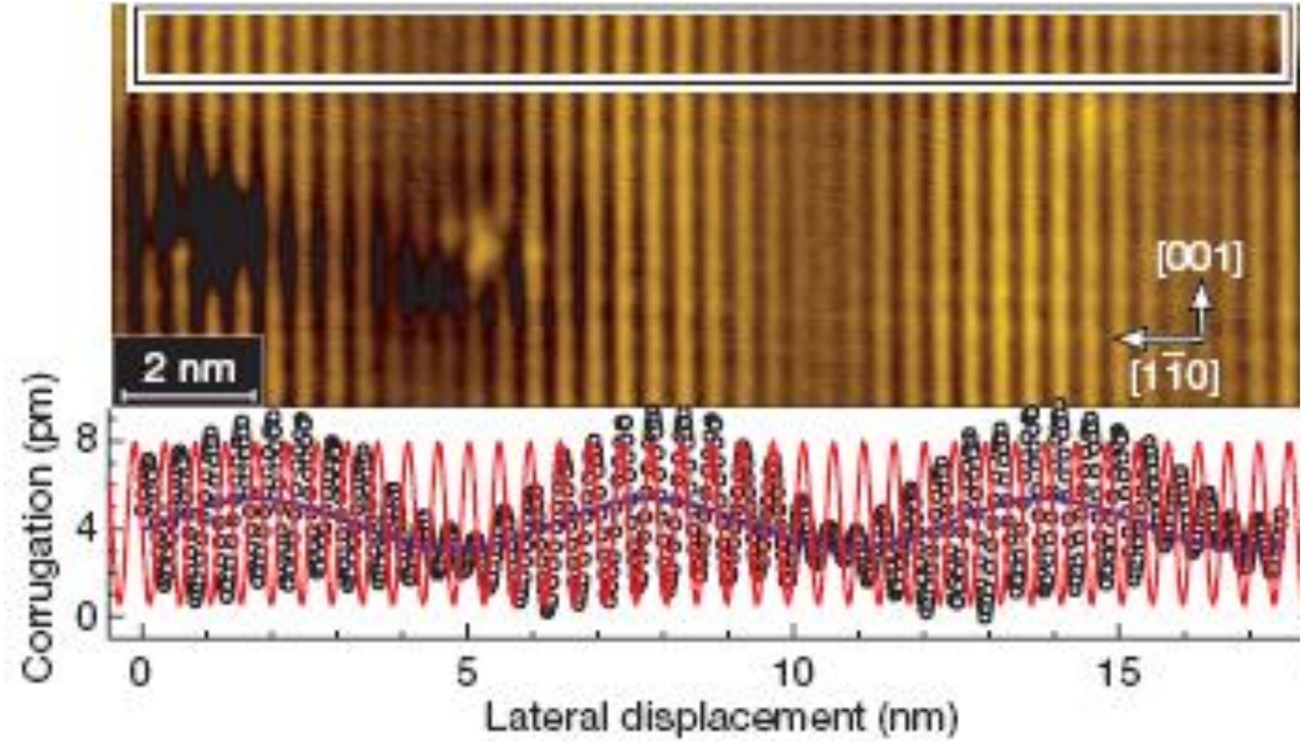
A. Deák *et al*., PRB 84, 224413 (2011)

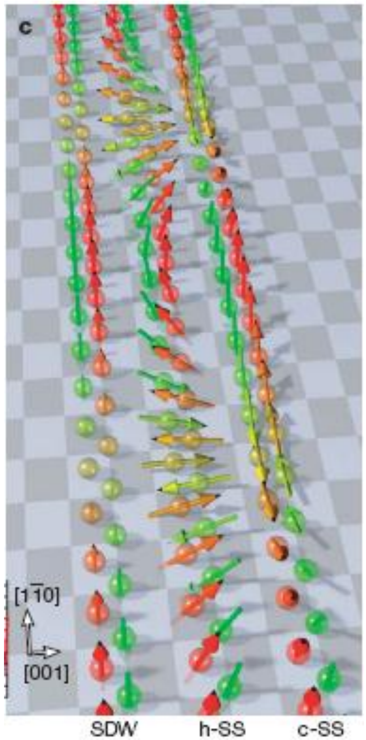
Based on high temperature paramagnetic (Disordered Local Moment) state

Effects of DM interactions in thin magnetic films: Formation of spin-spirals

Mn monolayer on W(110) M. Bode et al., Nature 447, 193 (2007)

Constant current SP-STM image



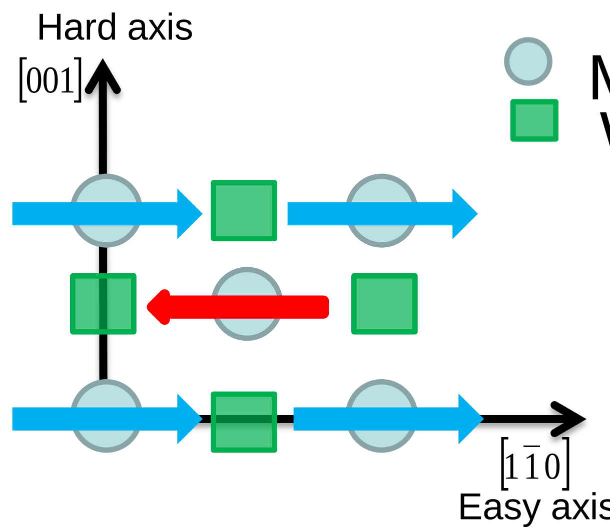


- row-by-row AF structure with a long-wavelength (12 nm) modulation
- cycloidal spin-spiral (CSS) → spins rotate around the (001) axis
- ab initio calculations confirmed DMI as origin of CSS

Formation of spin-spirals: spin-model for Mn/W(110)

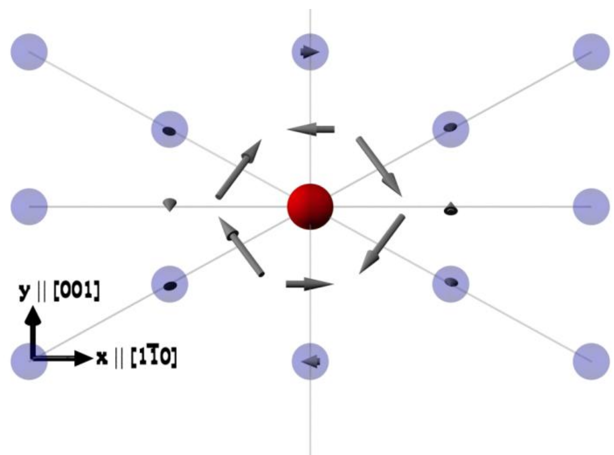
L. Udvardi *et al.*, Physica B 403, 402-404 (2008) rel. torque method

G. Hasselberg *et al.* (2013) to be submitted spin-cluster expansion

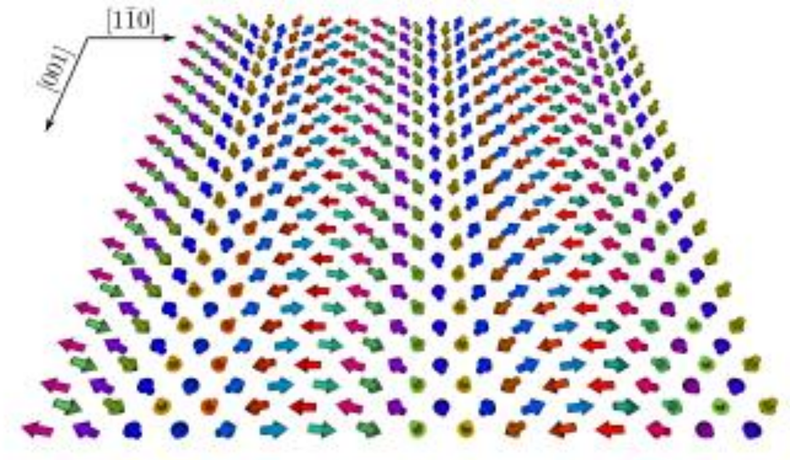


in-plane AFM

DM vectors



Formation of spin-spirals: spin-model for Mn/W(110)



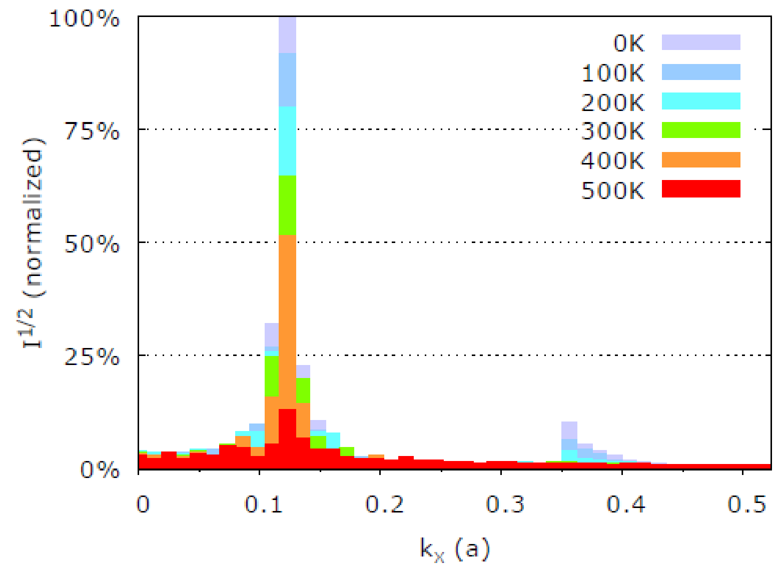
CSS ground state obtained by simulating a cooling-down process until T=0 K

Wave length λ=12 nm in good agreement with experiment.

Temperature dependence of λ

P. Sessi *et. al.*, Phys. Rev. Lett. 103, 167201 (2009)

Square root of the intensity of the Fourier transform of z-component of the magnetization plotted over k_x for different temperatures

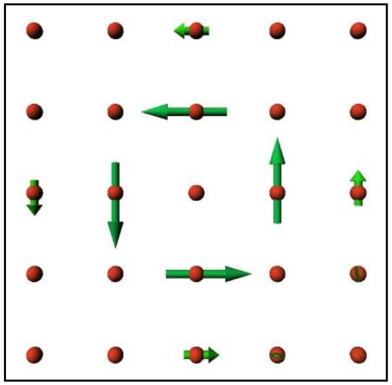


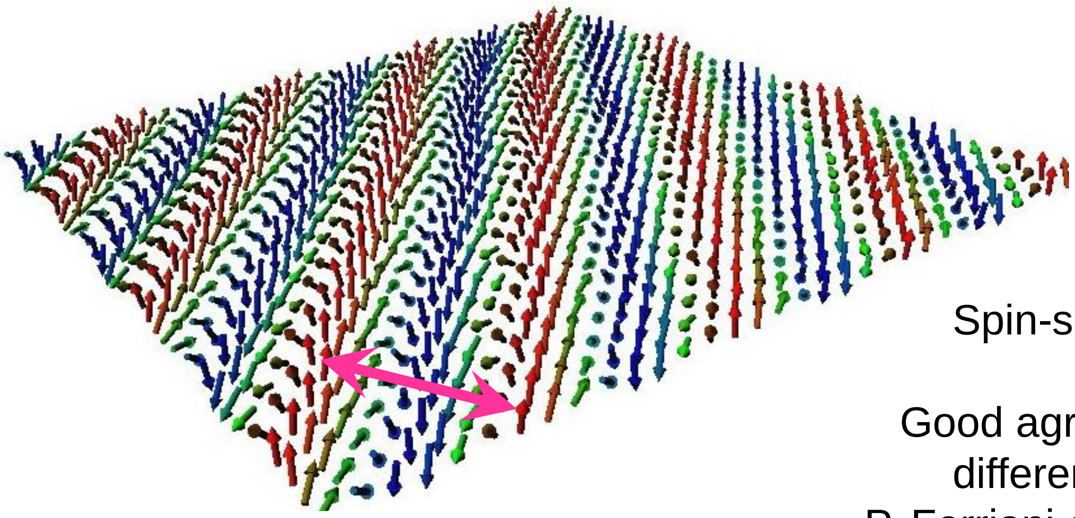
Formation of spin-spirals in Mn/W(100)

L. Udvardi *et al.*, Physica B 403, 402-404 (2008) rel. torque method

Calculated isotropic exchange interactions
and length of DM vectors (all data in mRyd)

NN	1	2	3
J_{ij}	-3.91	1.10	0.12
D_{ij}	0.57	0.04	0.24





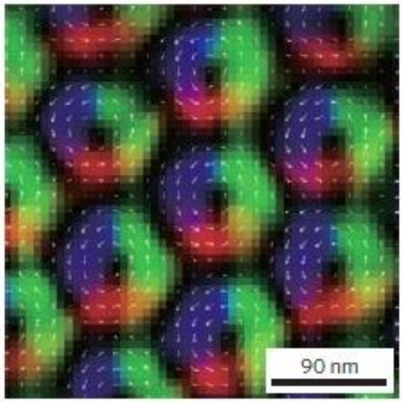
Spin-spiral wavelength ~ 2.2 nm

Good agreement with experiment and
different theoretical approach by
P. Ferriani et al., PRL **101,** 027201 (2008)

Magnetic skyrmions & skyrmion lattices

Topologically protected whirling spin-configurations $S = \frac{1}{4\pi}\int \mathbf{n}\cdot\left(\frac{\partial \mathbf{n}}{\partial x}\times\frac{\partial \mathbf{n}}{\partial y}\right)dx\,dy \rightarrow 0, \pm 1$

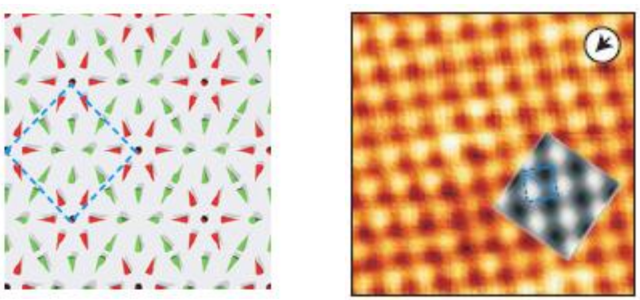
Bulk MnSi, FeCoSi, …



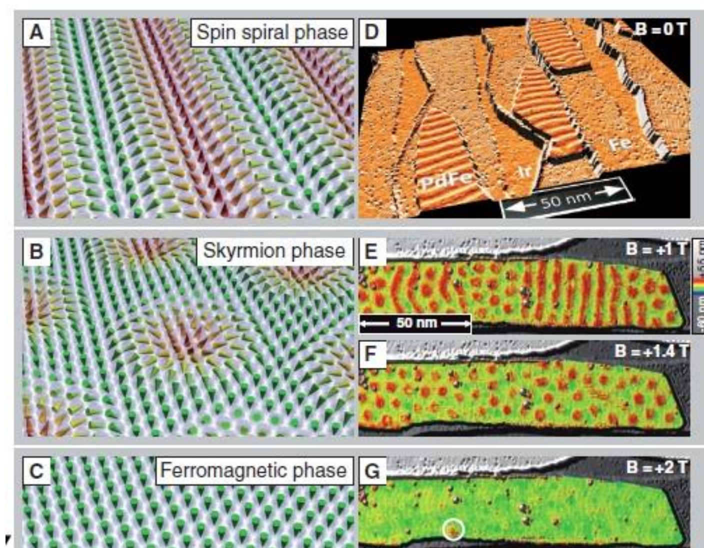
Surface skyrmions

A. Fert *et al*., Nature Nanotech. 8, 152 (2013): promise for ultradense memory and logic devices

S. Heinze et al., Nature Phys. 7, 713 (2011)
nanoskyrmions in Fe/Ir(1111)

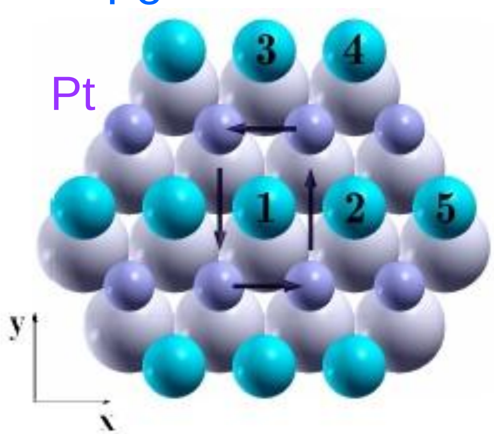


N. Romming *et al.,* Science 341, 636 (2013)
skyrmions in a PdFe bilayer on Ir(111)



Magnetic skyrmions & skyrmion lattices

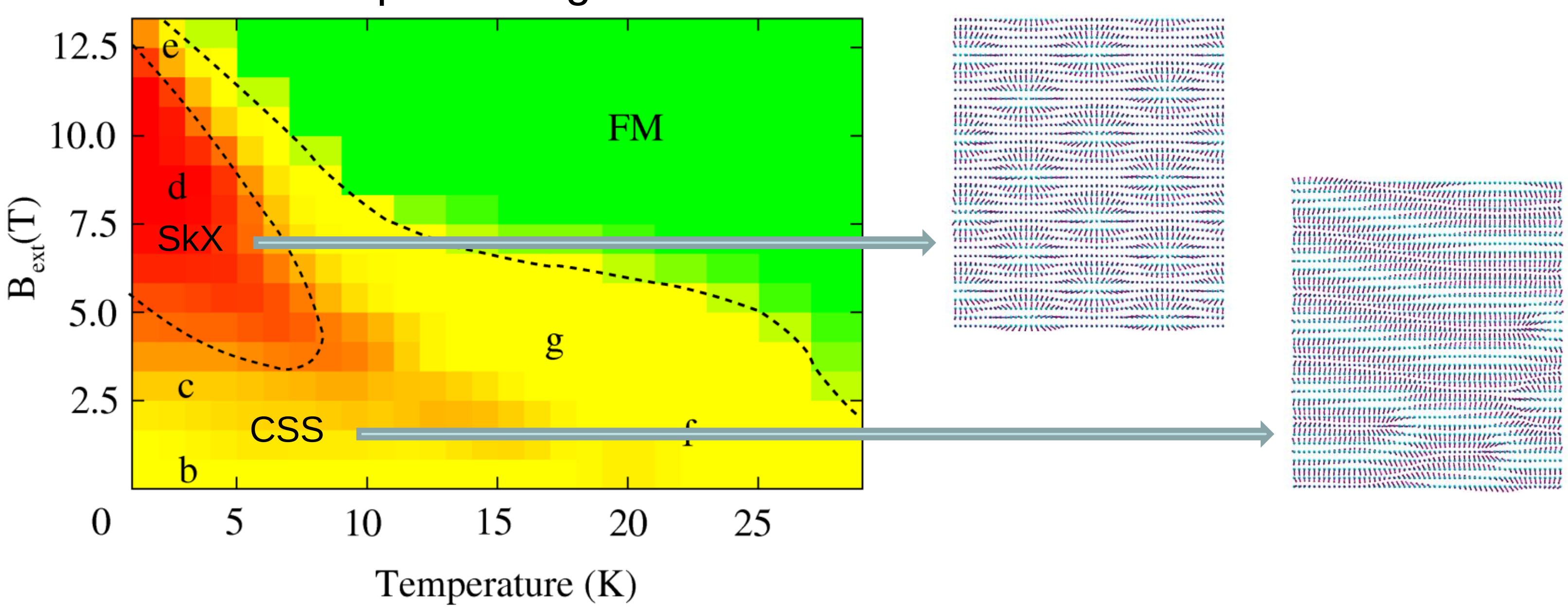
S. Polesya et al., arxiv:1310.5681 ab initio spin-model (RTM) & Monte-Carlo study of an FePt monolayer on Pt(111)



DM and isotropic exchange interactions

i-j	R_{ij}	D^x_{ij}	D^y_{ij}	D^z_{ij}	J_{ij}
1-2	0.707	0.00	2.44	0.39	23.90
1-3	1.225	-2.47	0.00	0.00	4.59
1-4	1.414	-0.31	0.50	-0.69	-0.56
1-5	1.414	0.00	0.39	-0.17	-1.07

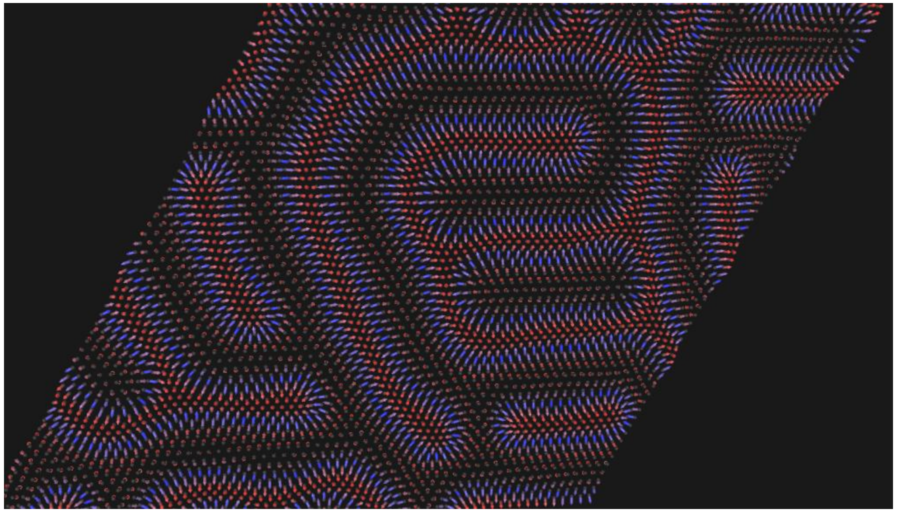
B-T phasediagram



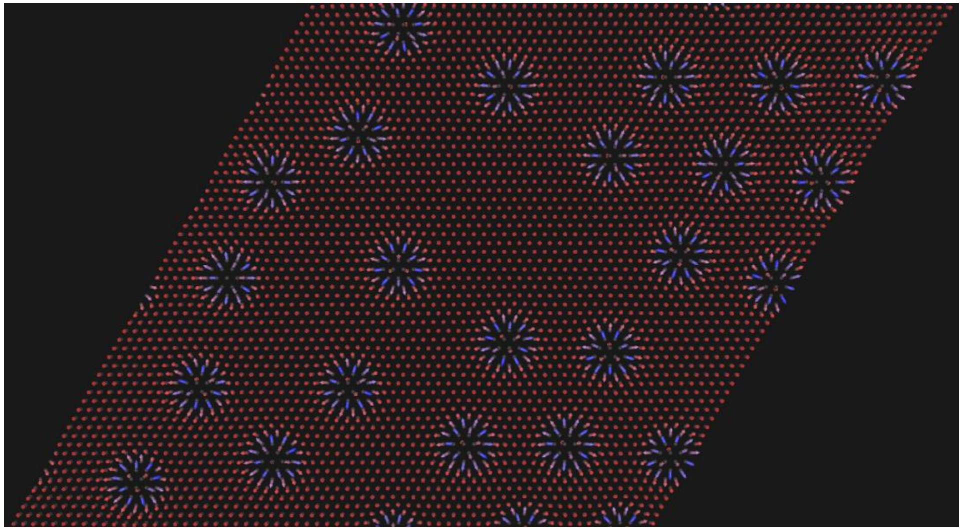
Magnetic skyrmions & skyrmion lattices

E. Simon et al. (unpublished) PdFe bilayer on Pt(111), SCE spin-model
(T = 0 K)

B = 0 T $\rightarrow$ CSS with $\lambda \approx 2.2$ nm

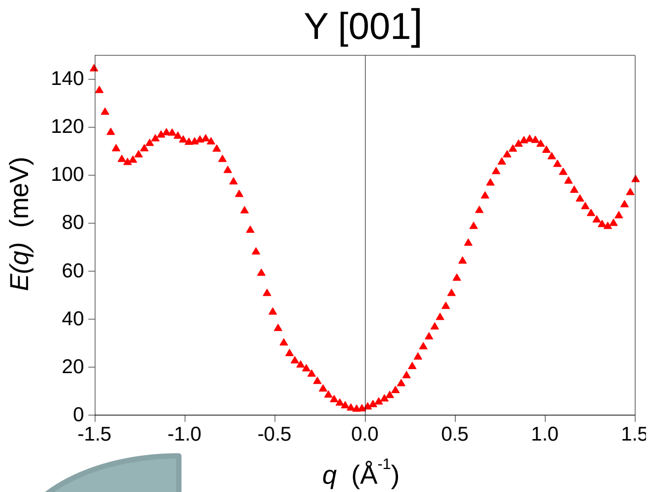


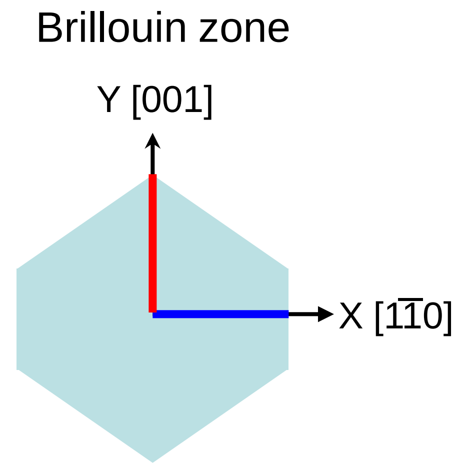
B $\approx$ 100 T (???) $\rightarrow$ SkX

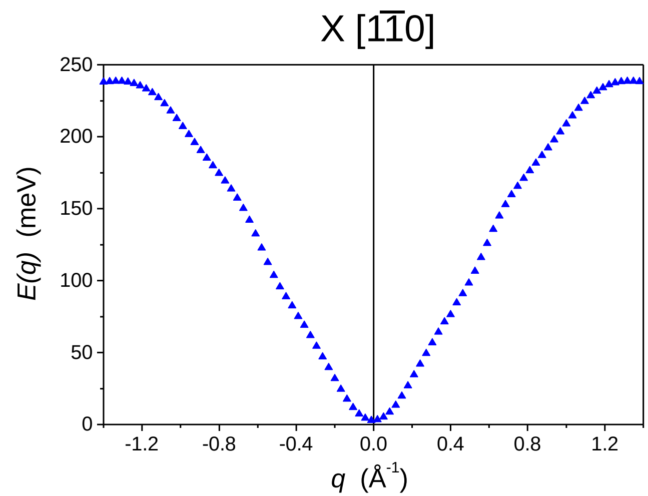


Chiral asymmetry of the spin-wave spectrum

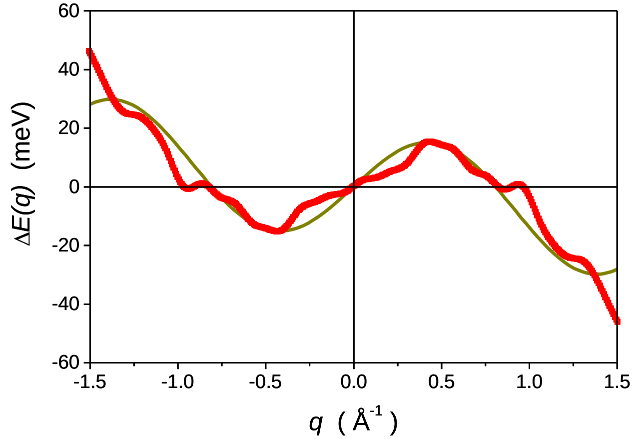
Spin-waves in Fe_1/W(110) L. Udvardi and L.Szunyogh, PRL 102, 207204 (2009)

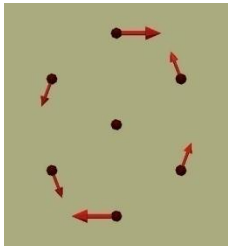






Asymmetry





DM vectors

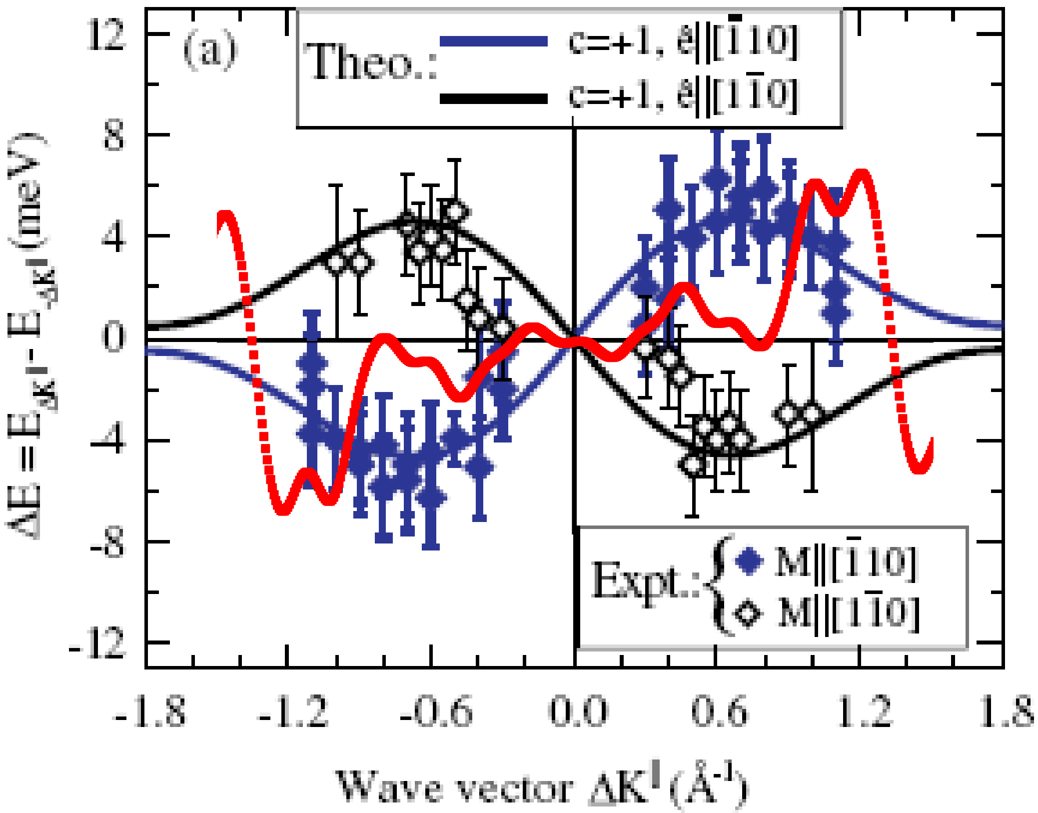
$$\Delta E(q) = \frac{16\mu_B}{M_0} D_1^x \sin(\frac{1}{2}qa) - \frac{8\mu_B}{M_0} D_2^x \sin(qa)$$

Possibility for a direct measurement of the DM interactions!

Chiral asymmetry of the spin-wave spectrum

Experiment: Fe_2/W(110)

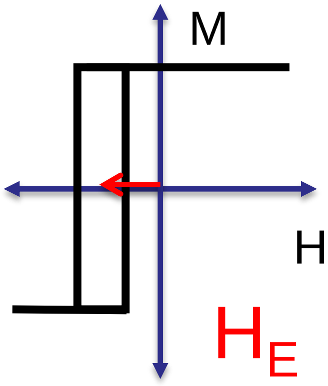
Kh. Zakeri et al. PRL 104, 137203 (2010)



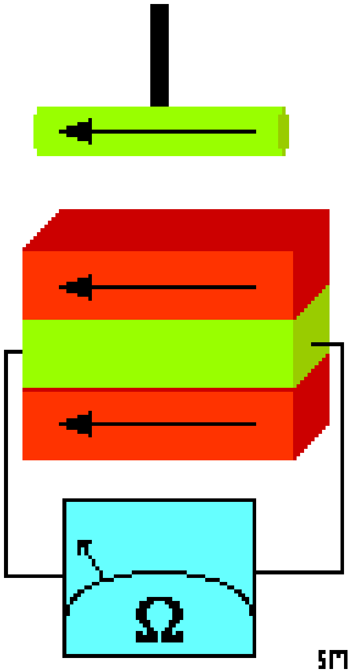
L.U. & L.S. (unpublished)
SCE spin-model

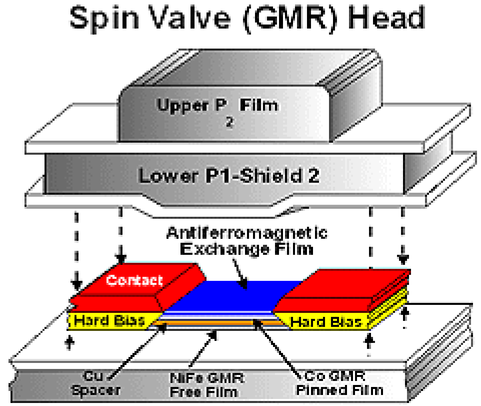
Exchange bias

Effective unidirectional anisotropy at an FM/AFM interface → Shift in the hysteresis loop



W.H. Meiklejohn *et.al.,* Phys. Rev. 105, 904 (1957)
A.P. Malozemoff ,J. Appl. Phys. 63,3874 (1988)
T.C. Schulthess and W.H. Butler, Phys. Rev. Lett. 81,4516 (1998)
P. Miltényi *et.al.* ,Phys. Rev. Lett, 84, 4224 (2000)



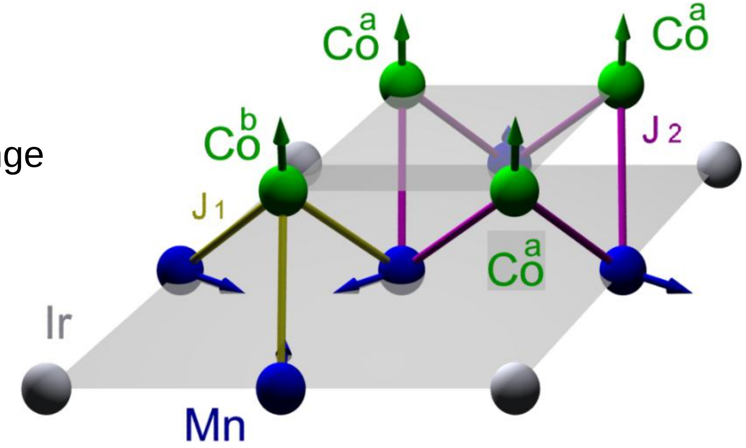


HITACHI

Perpendicular exchange bias (PEB) at an $IrMn_3$/Co interface

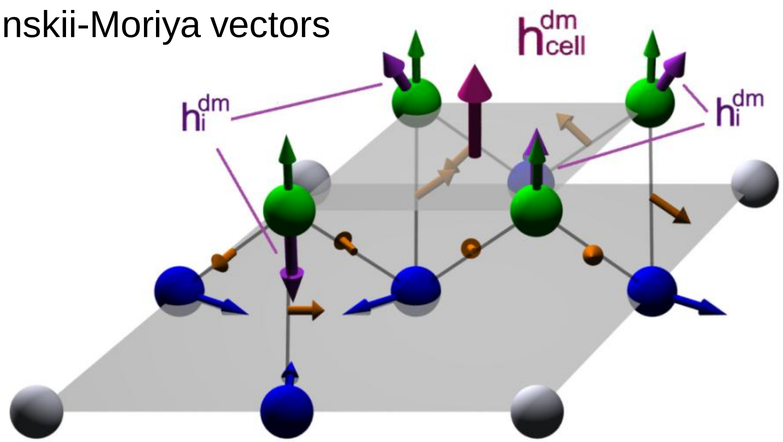
L. Szunyogh *et al*., Phys. Rev. B 79, 020403(R) (2009)
L. Szunyogh *et al*., Phys. Rev. B 83, 024401 (2011)
R. Yanes *et al*., Phys. Rev. Lett. in print (2013)

Isotropic exchange



J_1= -6.15 meV (AFM)
J_2= 1.2 meV (FM)

Dzyaloshinskii-Moriya vectors



$DM_{Co\text{-}Mn}$ vectors are in-plane

⇩

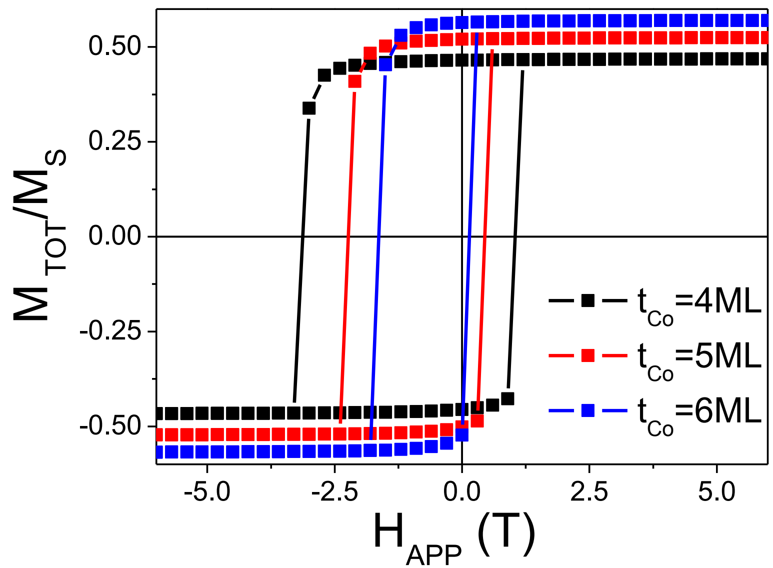
Effective DM field acting on the Co moments::

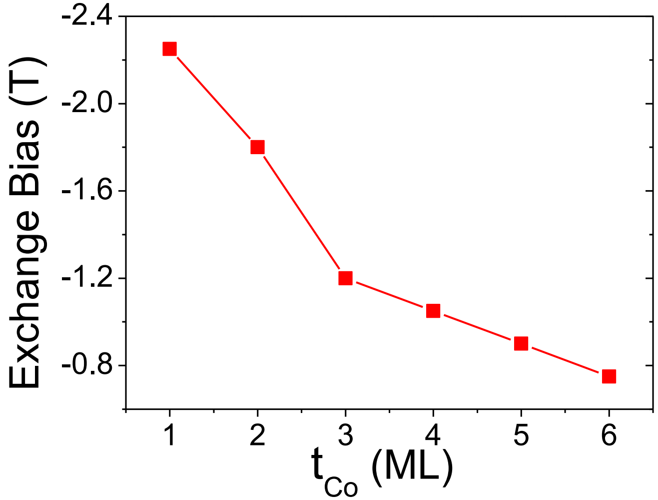
$$\vec{h}^{\text{dm}}_{\text{cell}} = \sum_{i=1}^{4} \sum_{j}' (\vec{m}_j \times \vec{D}_{ij}) \approx 1.05\hat{k}\,\text{meV}$$

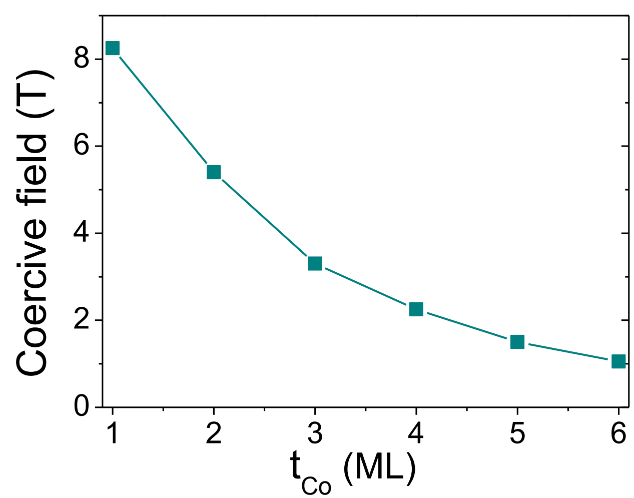
perpendicular to the interface

Perpendicular exchange bias (PEB) at $IrMn_3$/Co interface

Hysteresis loops as a function of t_{Co}



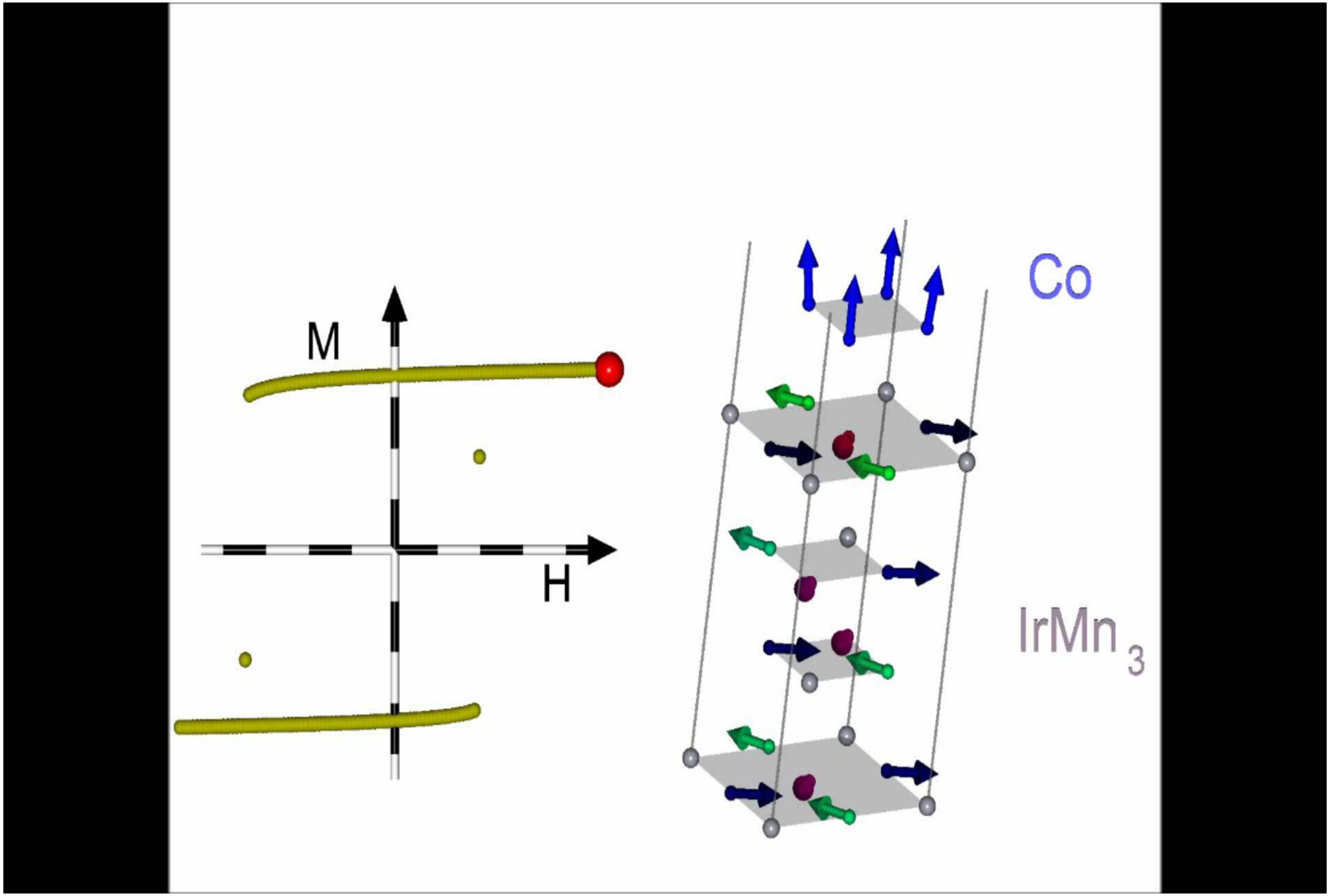




Perpendicular exchange bias (PEB) at $IrMn_3$/Co interface

The switching process: spin-flop coupling

[T.C. Schulthess and W.H. Butler, Phys. Rev. Lett. 81,4516 (1998)]



Conclusions

- Relativistic (spin-orbit) effects play a pronounced role in nanomagnetism
- Dzyaloshinskii-Moriya interactions give rise to
  - spin-spirals
  - magnetic skyrmions
  - asymmetry of the spin-wave spectra
  - perpendicular exchange bias
  - *homochirality of domain walls, SS's, SK's*
  - *effects in finite magnetic nanoparticles …*
- Spin-models are often useful, however, they (mostly) fail in the presence of induced moments $\rightarrow$ constrained DFT; RDLM at finite temperature

Thank you for attention!