Room temperature chiral magnetic skyrmions in ultrathin Pt/Co/MgO nanostructures

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  Micromagnetic simulation : **L. Prejbeanu**, O. Klein

  Ab-initio calculation : **H. Yang, M. Chshiev**

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Outline

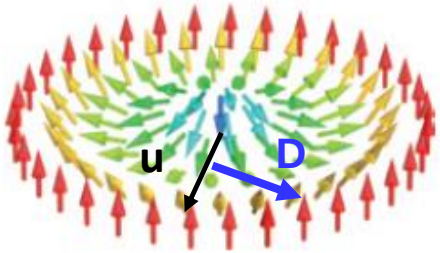
- Observation of chiral Néel domain walls by XMCD-PEEM in ultrathin Pt/Co/MgO films
- Large DMI in Pt/Co/MgO thin films
  - → BLS spin wave spectroscopy measurements
  - → Ab-initio calculations
- Room temperature chiral magnetic skyrmions in Pt/Co/MgO nanostructures
  - →Experiments
  - →Micromagnetic simulations and numerical models

Magnetic skyrmion

« Bloch - like » skyrmion

Bulk DMI **D** ~ **u**

« Néel - like» skyrmion



Interfacial DMI **D** ~ **z** x **u**

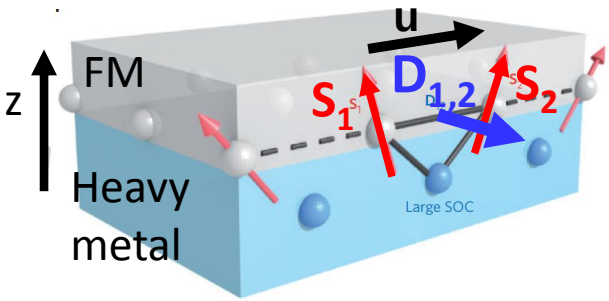
A. Fert et al., Nat Nano **8**, 152 (2013).

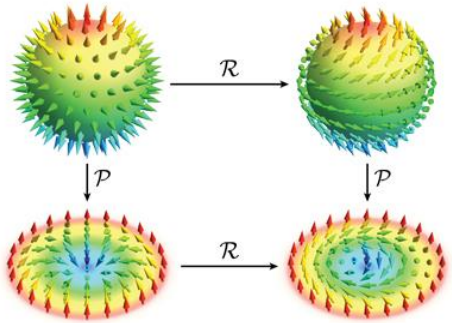
- **Nanometer scale**
- **Chiral** magnetic object driven by the Dzyaloshinskii-Moriya $H_{DMI} = -\vec{D}_{1,2}(\vec{u}).(\vec{S_1} \times \vec{S_2})$
- **Topologically protected**

$$S = \frac{1}{4\pi}\int_C \vec{m}.\left(\frac{\partial \vec{m}}{\partial x} \times \frac{\partial \vec{m}}{\partial y}\right)$$

→ |S|=1 for single skyrmion

→ S=0 for FM states

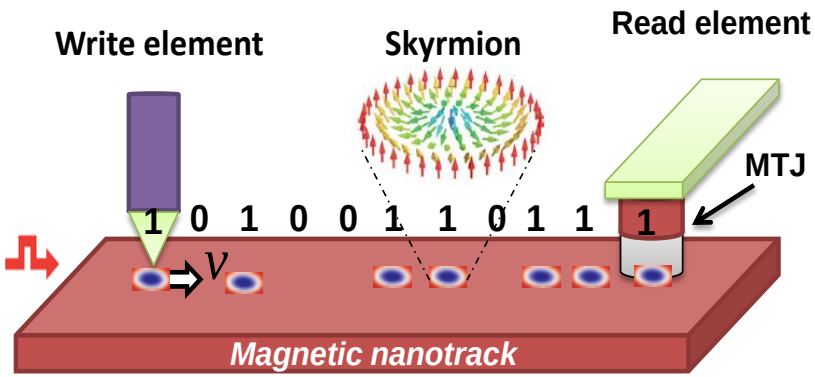




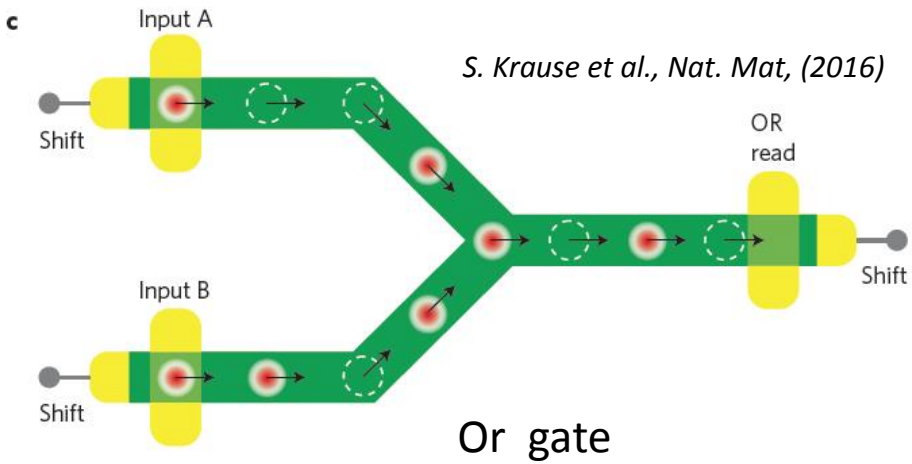
Credit Christoph Schuette

[1a] A. Fert et al., Nat Nano **8**, 152 (2013).[1b] Nagaosa, Nat.Nano, **8**,899 (2013)

Non-volatile memory and logic applications



Racetrack memory



S. Krause et al., Nat. Mat, (2016)

Or gate

- **Manipulation by current with low density**[1,2,3,4] (~10^6 A/m²)
- Need for **isolated skyrmions stable at room temperature and zero magnetic field** with 10 of nms diameter
- **chirality and |S|=1** needed for current induced motion

[1] T. Schulz et al., Nat Phys **8**, 301 (2012). [2] X.Z. Yu et al., Nat Commun **3**, 988 (2012)
[3] Jonietz, *Science* **330**, 1648 (2010) [4] Jiang et al., Science, **349**, 283 (2015)

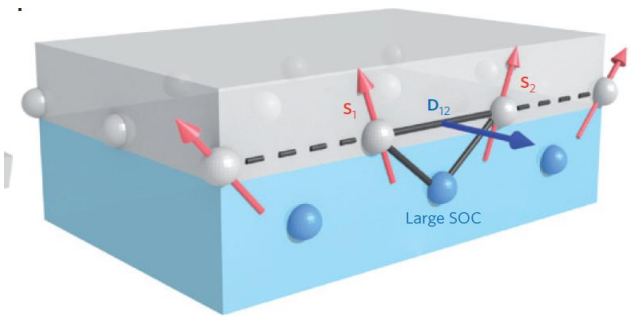
Experimental observations of chiral skyrmion structures

- **B-20 bulk or thin film chiral magnet[8] ($MnSi^3$, $Fe_{1-x}Co_xSi^4$, $FeGe^5$,…)**

100 nm

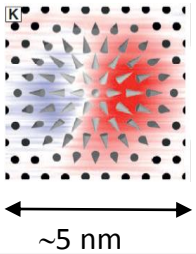
  - First experimental observations of magnetic skyrmions
  - DMI due to the bulk crystalline structure asymmetry
  - « Bloch like »skyrmion
  - Observed below room temperature + external H

- **Sputtered ultrathin FM/Heavy metal multilayers**



  - Large DMI + large spin orbit torque
  - Tunable properties (K,DMI, A) by playing on materials
  - Fast sputtering deposition
  - Compatible with spintronics devices (MTJ)

- **Ultrathin epitaxial film [6,7] (Ir(111)/Fe(1ML), Ir(111)/FePd,…)**



  - Interfacial DMI due to inversion asymmetry by the interface+ Heavy metal
  - Néel like skyrmion
  - Only stable at low temperature

[3] S. Mühlbauer et al., Science, **323**, 915 (2009).
[4] X.Z. Yu et al., Nature **465**, 901 (2010).
[5] X.Z. Yu Nat Mater **10**, 106 (2011).
[6] S. Heinze *et al.* Nat Phys **7**, 713 (2011).
[7] N. Romming *et al.*, Science **341**, 636 (2013
[8] Nagaosa et al., Nat. Nano, 8, 899 (2013)

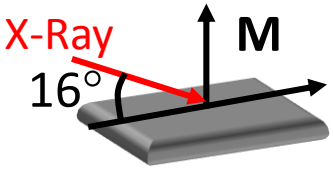
Samples and experiments

- **Samples**
  - Si/Ta/**Pt(3 nm)/Co(1 nm)/Mg-ox(2nm)/**Ta
  - annealed 1H30 @250°C
  - Perpendicularly magnetized (H_{sat}=200 mT)

- **XMCD-PEEM magnetic microscopy**

- High lateral spatial resolution (down to 25 nm)

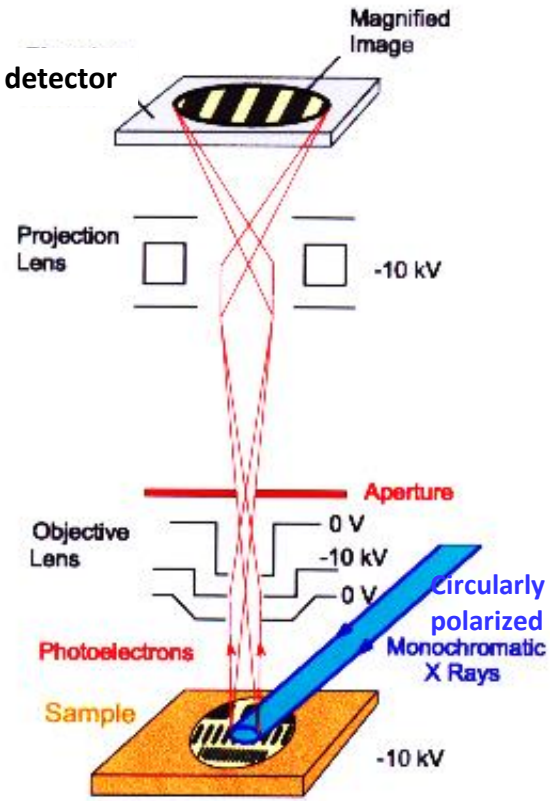
- **Magnetic contrast proportional to the projection of M on X ray beam direction**



→ contrast 3x larger for $M_{inplane}$ than $M_{out\text{-}of\text{-}plane}$

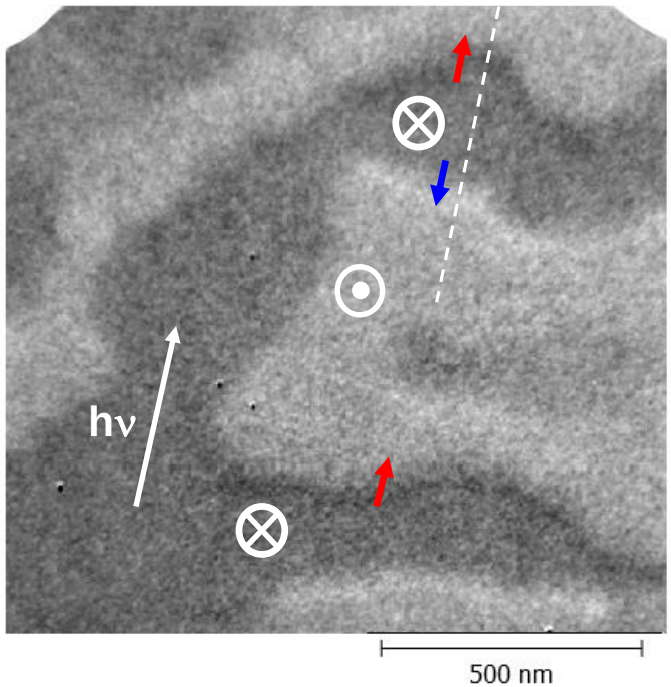
⇨ Imaging of the **internal structure** of DWs/skyrmion

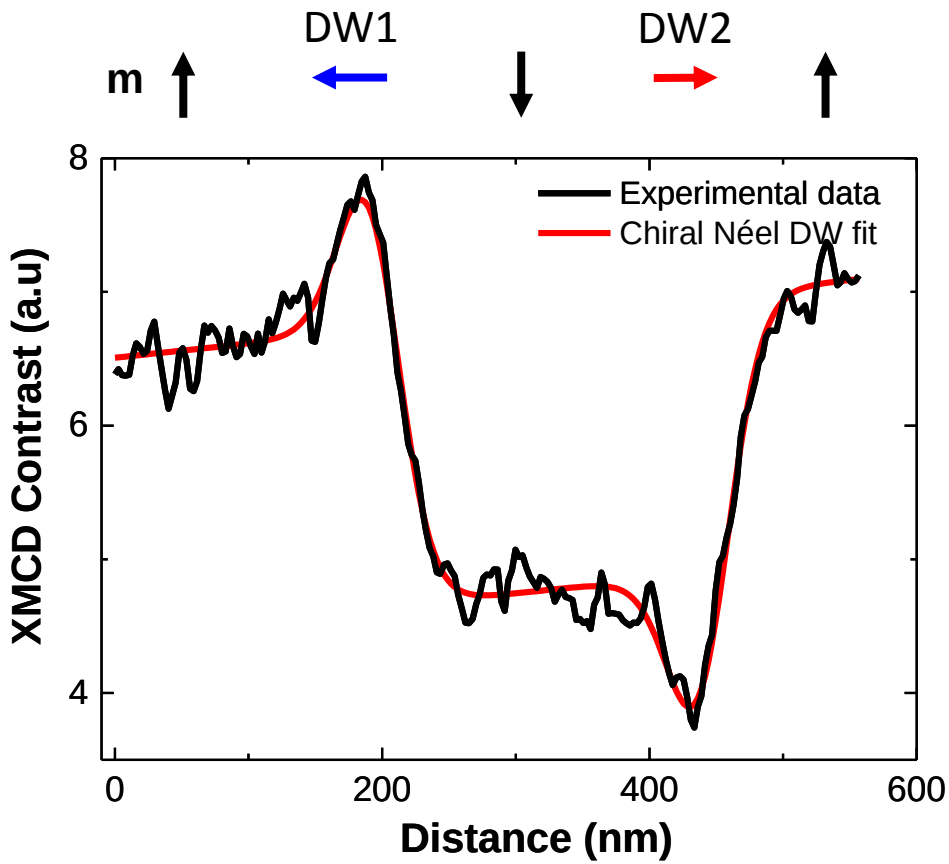
- Observation in a virgin demagnetized state at room temperature



Stöhr et al.

Chiral Néel Domain Wall





- Dark contrast for down/up DW (P to beam) and a bright contrast for up/down DW (AP to beam) → Left handed chiral Néel DW
- XMCD contrast well fitted assuming a chiral Néel DW profile with gaussian convolution → DW width ≈ 30±4 nm ($\pi\sqrt{A/K}$)

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- **Large DMI in Pt/Co/MgO thin films**
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  - → Ab-initio calculations
- Chiral magnetic skyrmions in Pt/Co/MgO nanostructures
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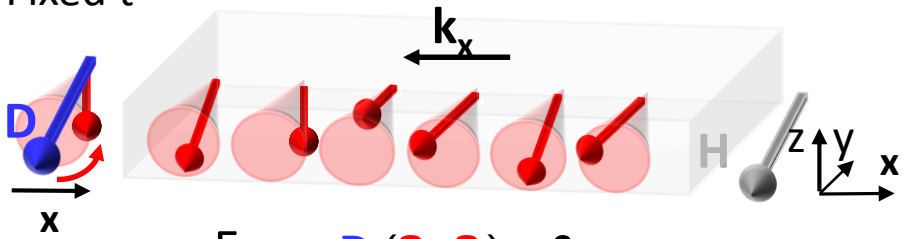
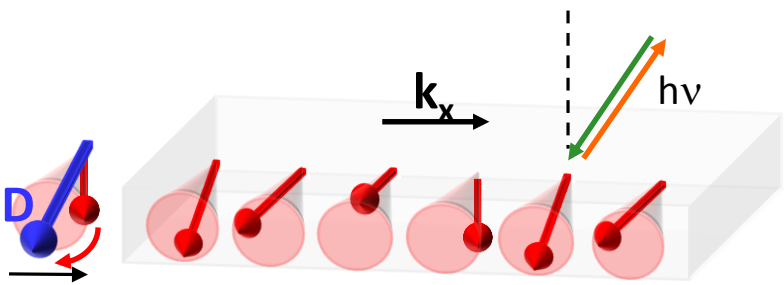
Measurement of DMI from BLS spin wave spectroscopy

Fixed t



$E_{DMI}=-D.(S_i x S_j) < 0$

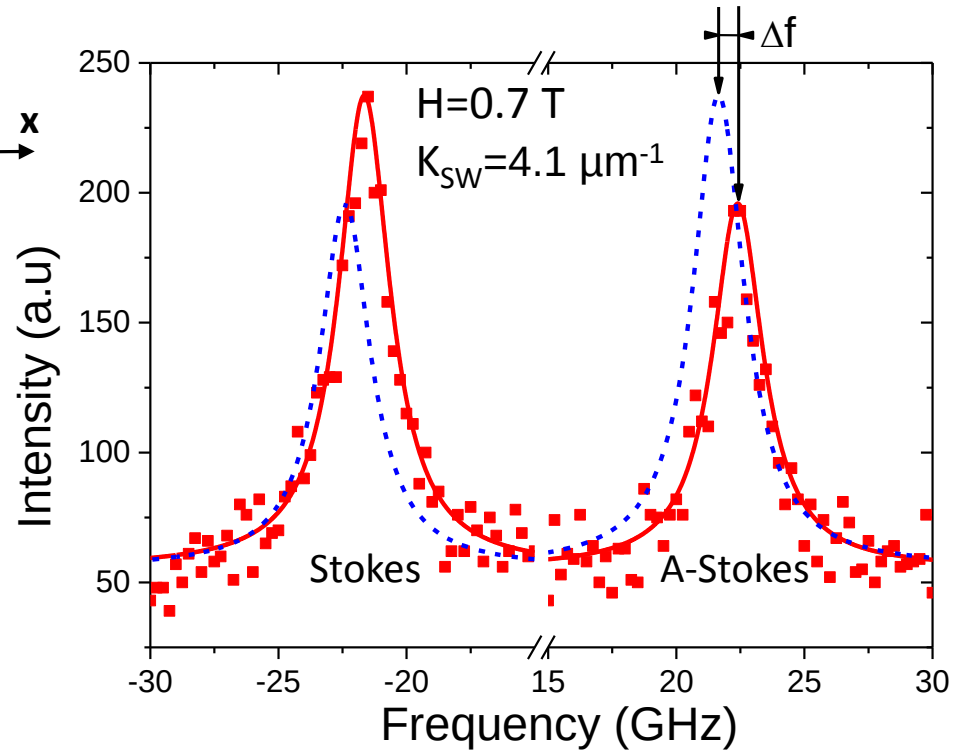


$E_{DMI}=-D.(S_i x S_j) > 0$

$$E_{DMI} = \pm 2D\hbar k_x \gamma / M_s$$

$$\Delta f(k_x) = \frac{2\gamma k_x D}{\pi M_s}$$

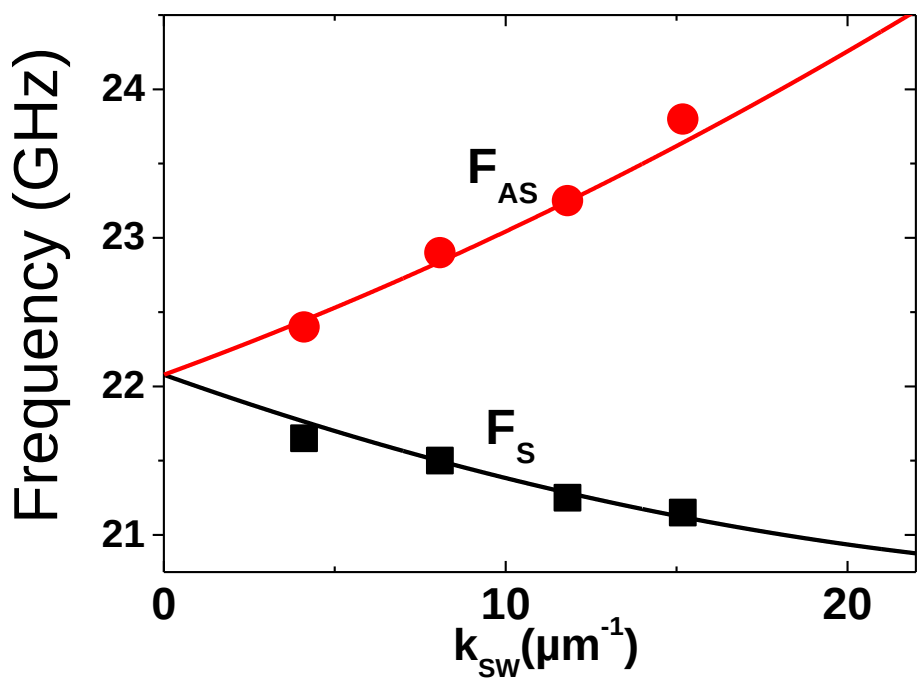
Brillouin Light Scattering experiment

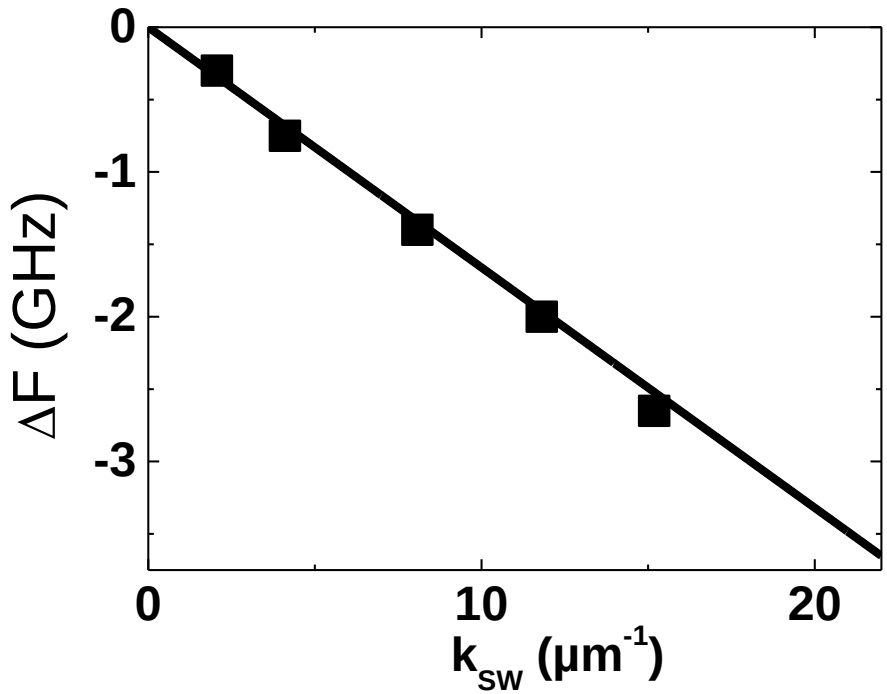


M. Belmeguenai et al., LSPM, Université Paris 13 (PRB ***91****,* 180405 (2014) *and K. Di et al., PRL* ***114****, 047201 (2015))*

- DMI leads to a shift in frequency for spin waves with opposite k vector (**k**⊥ $\mathbf{H}_{in\text{-}plane}$)
- Difference in frequency shifts between Stokes and anti-Stokes peaks in BLS measurements

Measurement of DMI from BLS spin wave spectroscopy





$$\Delta f(k) = \frac{2\gamma k D}{\pi M_s}$$ ⇨ **D=2.05±0.3** mJ/m²

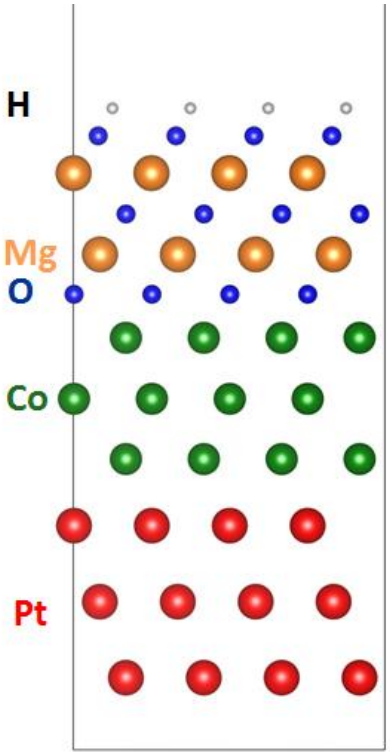
D/D$_c$ ~ 0.8 $D_c = \frac{4\sqrt{AK_{eff}}}{\pi}$

$$D = \frac{D_s}{t} \rightarrow D_s = 2.17 \pm 0.14\ pJ/m$$ (vs D_s=1.7 pJ/m in Pt/Co/AlOx)

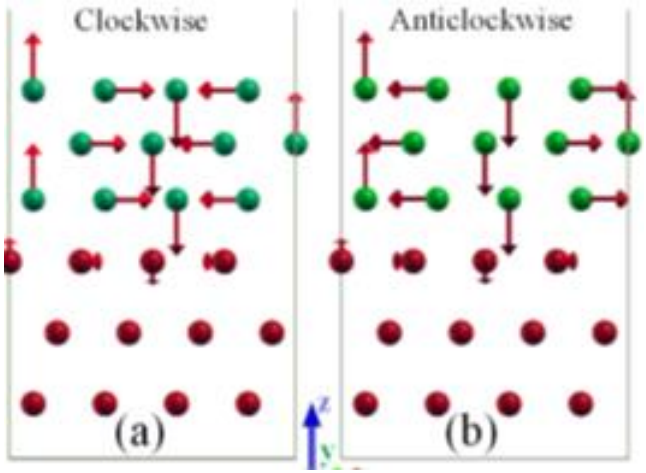
→ Largest value reported so far in sputtered magnetic thin films

Ab-initio calculations

H. Yang, M. Chshiev



Pt[3]/Co[3]/MgO

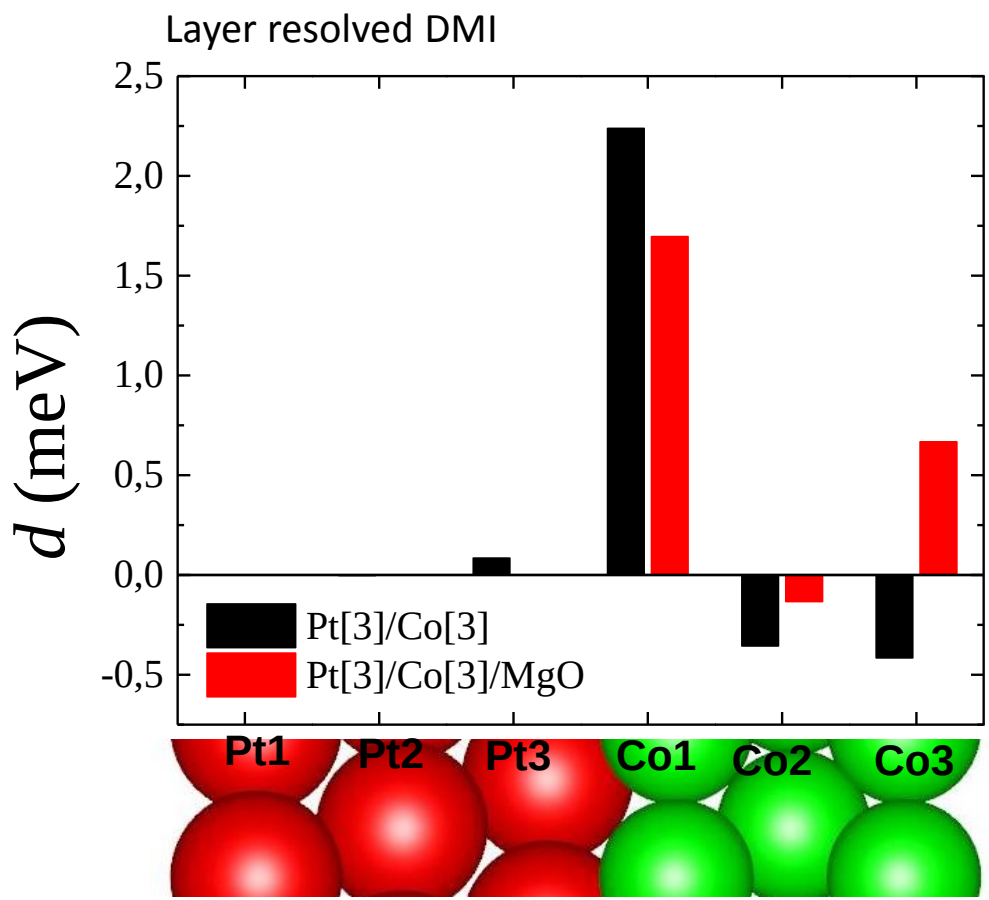


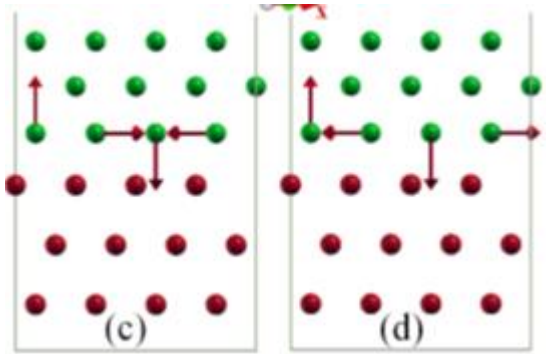
$$d = (E_{cw} - E_{ccw})/12$$

- Calculations based on density functional theory
- DMI calculated from the difference between clockwise and counter clockwise spin spiral. (H. Yang, M. Chshiev et al., **115**, 267210 (2015)

- Pt/Co 5 ML/MgO → D=2.3 mJ/m² for 5 ML (~1 nm) close to the experimental value D=2.03±0.3 mJ/m²
- Pt/Co 5 ML/vacuum → D=1.5 mJ/m²

Ab-initio calculations (2)





- Larger contribution of DMI at the Pt/Co interface
- Larger DMI in Pt/Co/MgO due to an additional contribution at the Co/MgO interface

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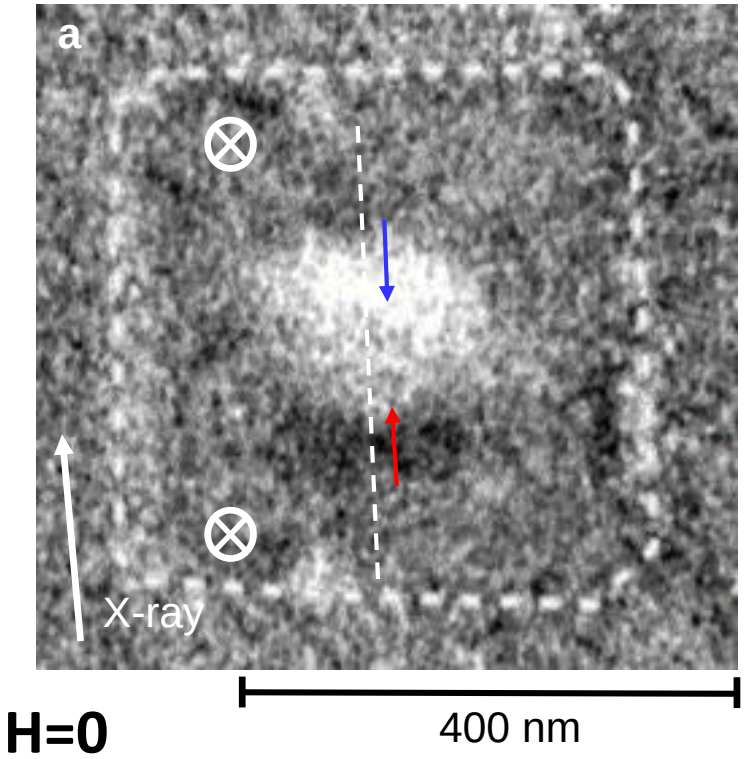
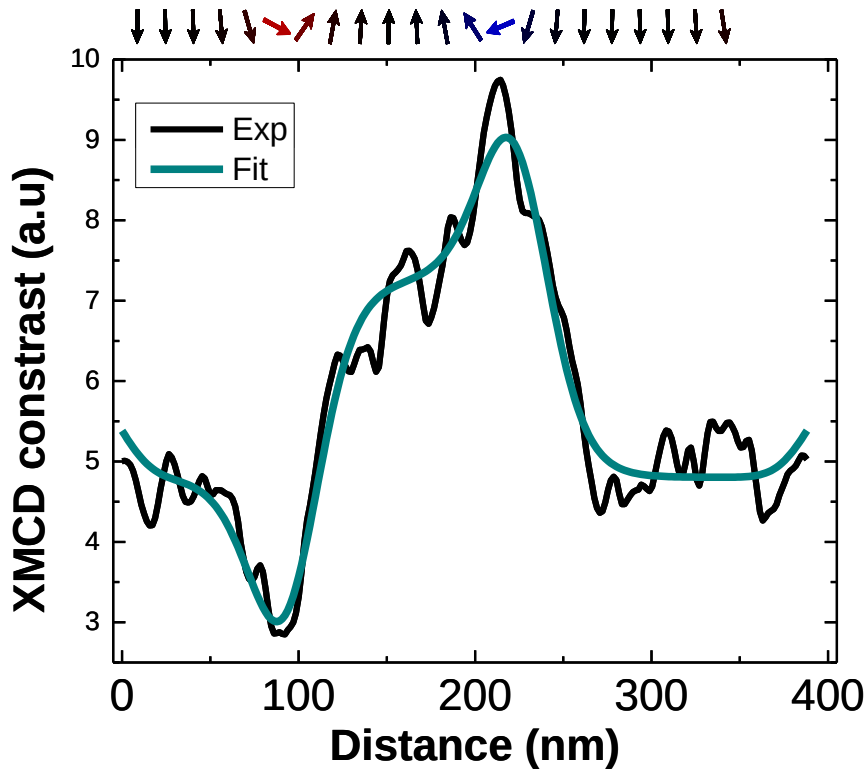
Zero field room temperature chiral Néel skyrmion



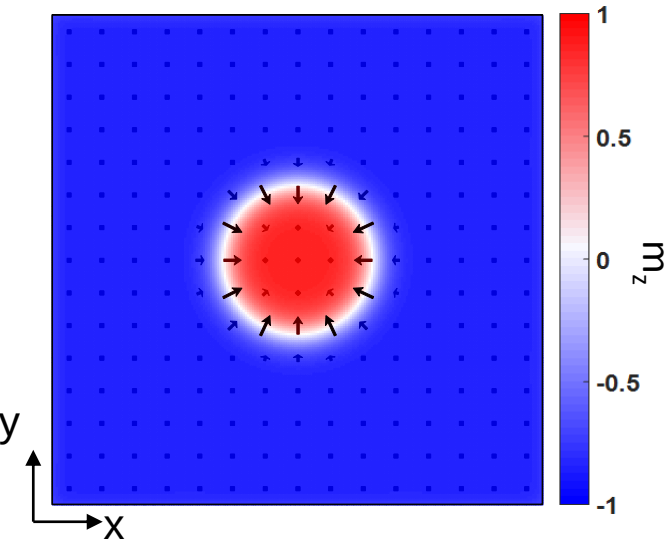


- Chiral Néel skyrmion stable room temperature at zero field in 420 nm square dots (S=1).
- Profile well fitted by two gaussian convoluted chiral Néel domain walls

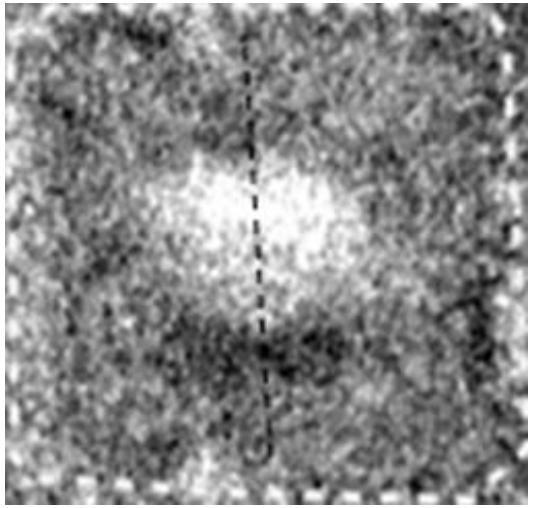
  → Skyrmion diameter = 130±3 nm

Micromagnetic simulation

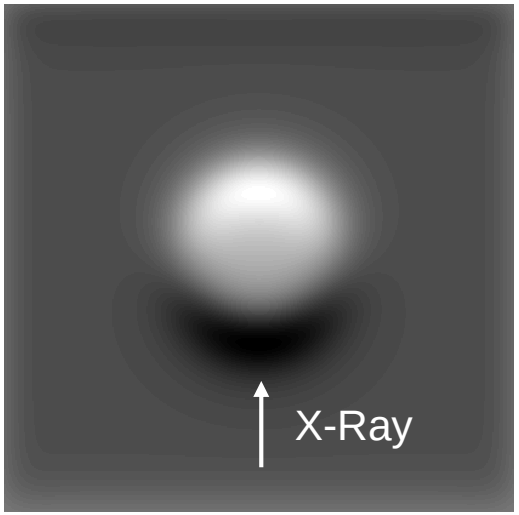
µmag simulation



Experiments

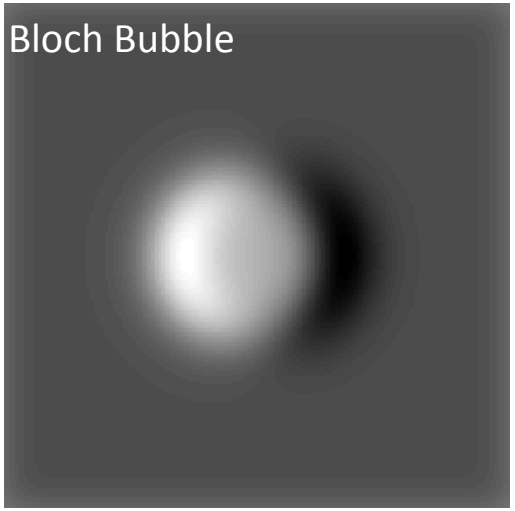


Simulated X-PEEM image



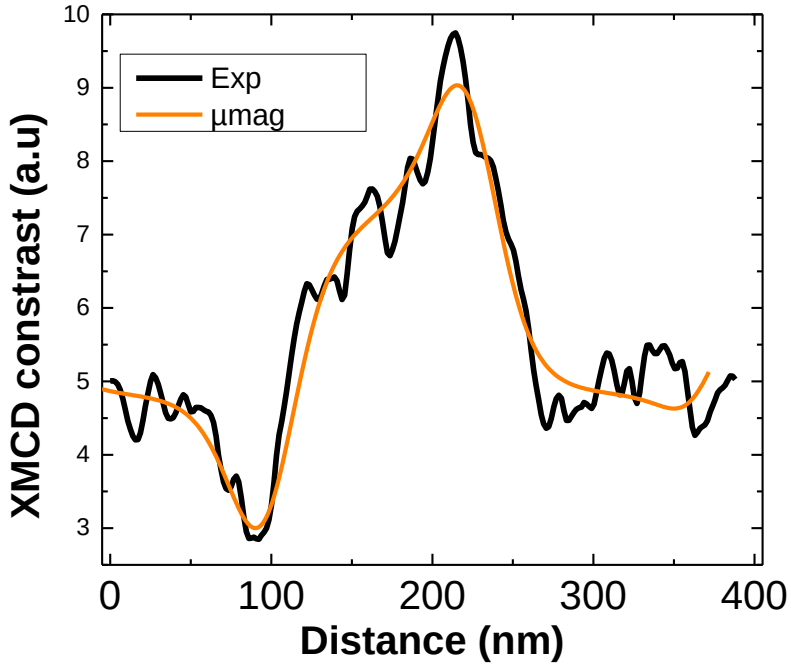
D=2.05 mJ/m², M_s=1.4x10^6 J/m^3,
A=27.5 pJ/m, K_u=1.45x10^6 J/m^3,
H=0

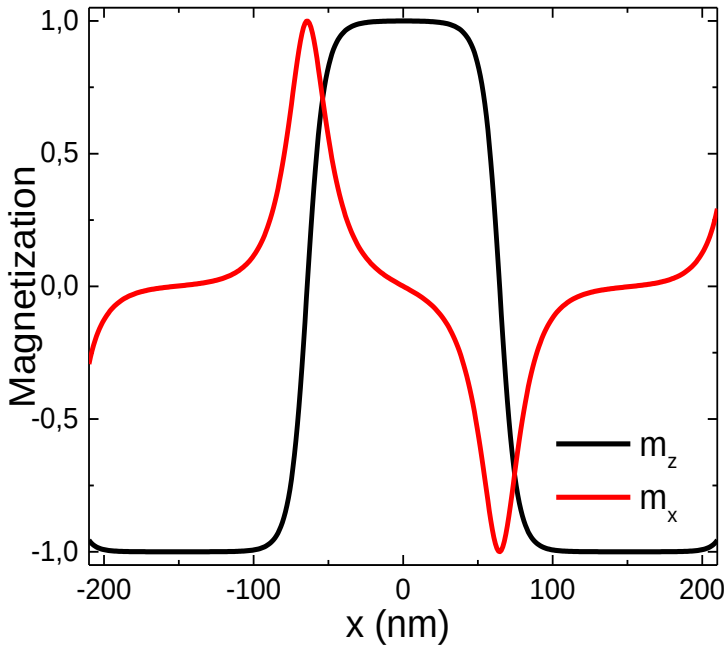
⇨ Skyrmion diameter =128 nm
DW width=37 nm



- Micromagnetic simulation well reproduce experiments.

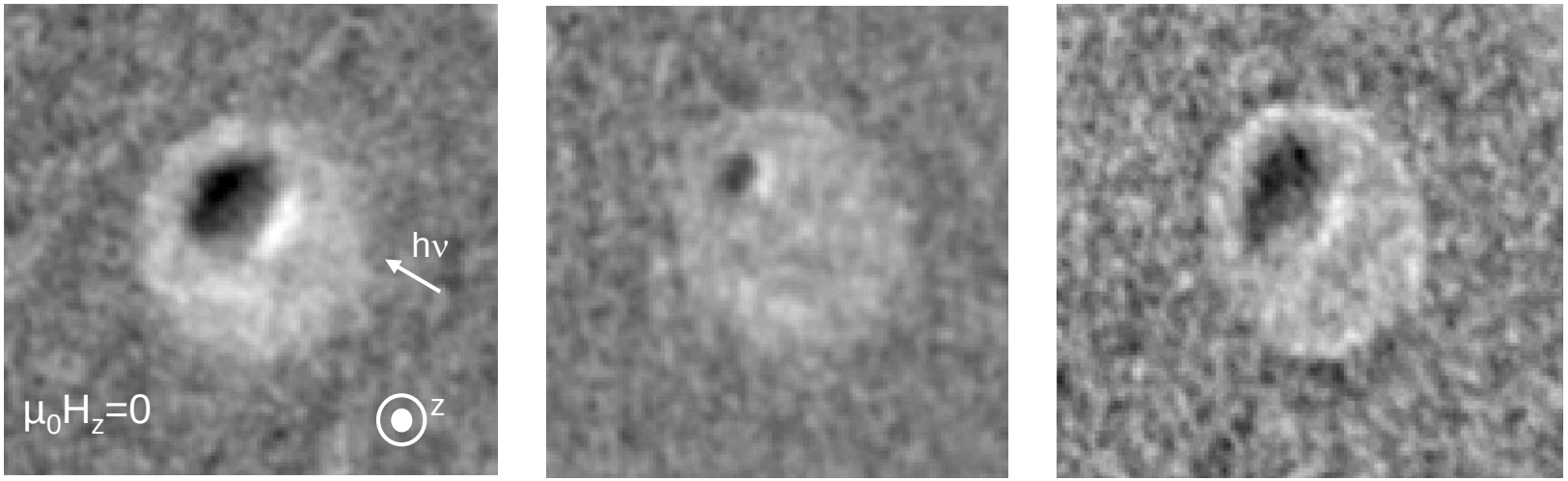
Skyrmion structure





- Skyrmion diameter (130 nm) large compared to the DW width (37 nm) → skyrmion structure closer to two independant chiral Néel DWs

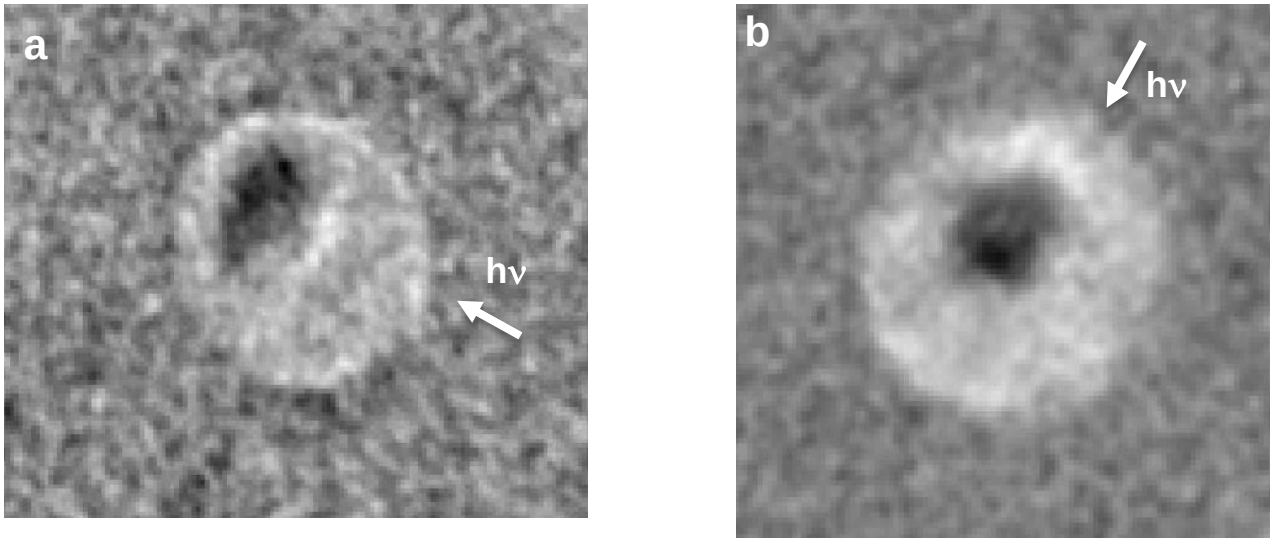
Application of a perpendicular magnetic field



$\mu_0 H_z$= 0 mT → $\mu_0 H_z$= - 4 mT → $\mu_0 H_z$=0

- Skyrmion in a 630 nm diameter disk patterned in Pt/Co(**1.1** nm)/MgO
- Larger skyrmion diameter (190 nm), which can be explained by the larger thickness
- Large decrease of the skyrmion diameter from **190** nm to **70** nm when applying a small Hz=4 mT opposite to the core
- Reversible contraction/expension of the skyrmion with H_z

Rotation of the beam direction



- Rotation of the black/white contrast when rotating the sample with respect to the X-ray beam direction

  → confirms the radial orientation of the DW in-plane spins of the skyrmion

Model

- Ansatz : $\theta(r) = \theta_{DW}(r - d/2) + \theta_{DW}(r + d/2)$

$$\theta_{DW}(r) = 2\arctan[\exp(r/\Delta)]$$

$$\boxed{E = E_\sigma + E_{mag}}$$

- E_σ = exchange, DMI, anisotropy, internal stray field (~ DW energy)

$$E_\sigma[\theta(r)] = 2\pi t \int_0^R \left\{ \underbrace{A\left[\left(\frac{d\theta}{dr}\right)^2 + \frac{\sin^2\theta}{r^2}\right]}_{\text{exchange}} \underbrace{- D\left[\frac{d\theta}{dr} + \frac{\cos\theta\sin\theta}{r}\right]}_{\text{DMI}} + \underbrace{(K_{eff}}_{\text{Anisotropy}} + \underbrace{E^s_{DW})}_{\text{DW demag energy}} \sin^2\theta \right\} r dr$$

Bogdanov et al., Sov. Phys. JETP, 85, 178 (1989)

- E_{mag} = magnetostatic energy due to the dipolar interaction between the domains

$$E_{mag}(d) = E_{mag0} - t(1 - N_{DW})\frac{\mu_0 M_s^2}{2}\int_0^R \cos^2\theta \; 2\pi r dr \;\; \text{with}$$

$$E_{mag0} = \frac{4\pi t}{R}\int_0^\infty [1 - \exp(-\beta x)] I^2(x) dx$$

$$I(x) = \int_0^1 dr' r' J_0(xr')\cos\theta(r')$$

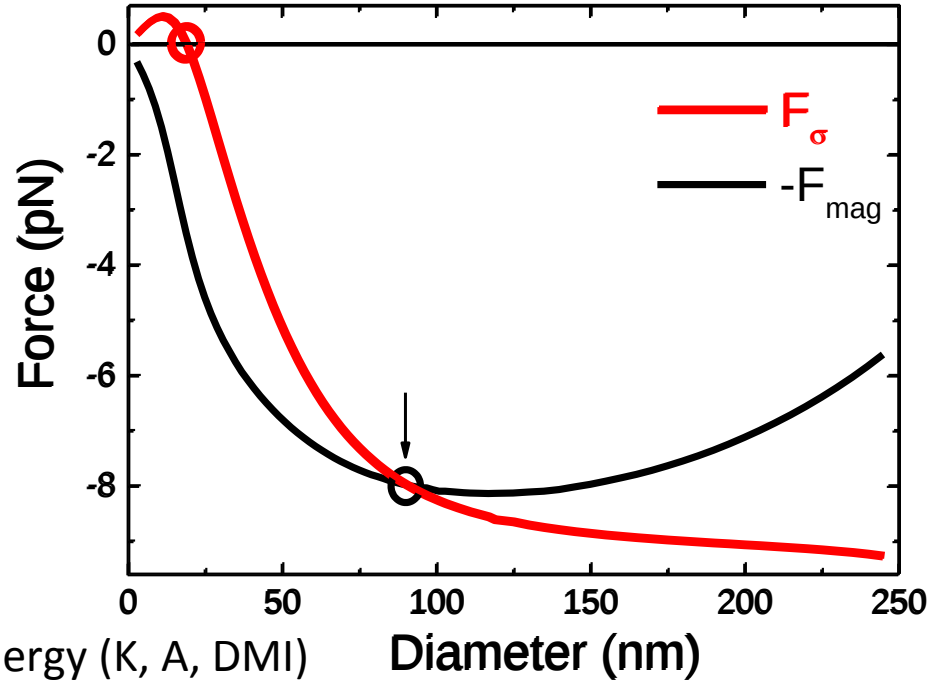
K. Guslienko, *IEEE Magn. Lett.* **6**, 1–4 (2015).

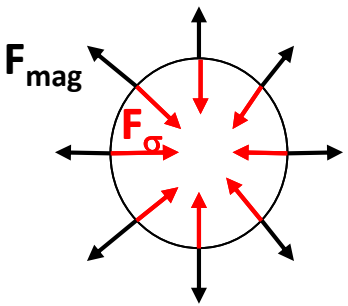
Force on the skyrmion DWs

$$F_\sigma = -\frac{\partial E_\sigma}{\partial d}$$

$$F_{mag} = -\frac{\partial E_{mag}}{\partial d}$$

Calculation for a 420 nm circular dot





- **Force F_σ** due to DW energy (K, A, DMI)

  → **F_σ**=0 for **d=20 nm** (DW energy (~d) vs curvature energy due to exchange (~1/d))

- **Force F_{mag}** due to magnetostatic interaction between domains : expands the skyrmion

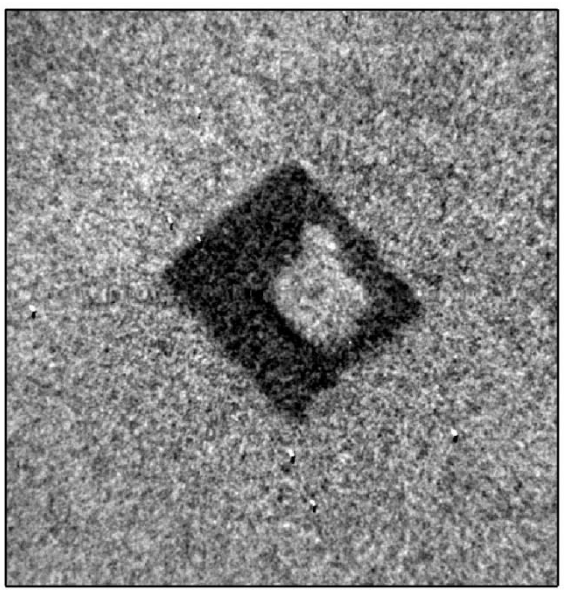
  → **F_{mag}+F_σ=0 for larger d=90 nm.**

- Magnetostatic effect important when thickness $\boldsymbol{t > l_w = \frac{\sigma}{\mu_0 M_s^2}}$ $(= E_{mag} > E_{DW})$

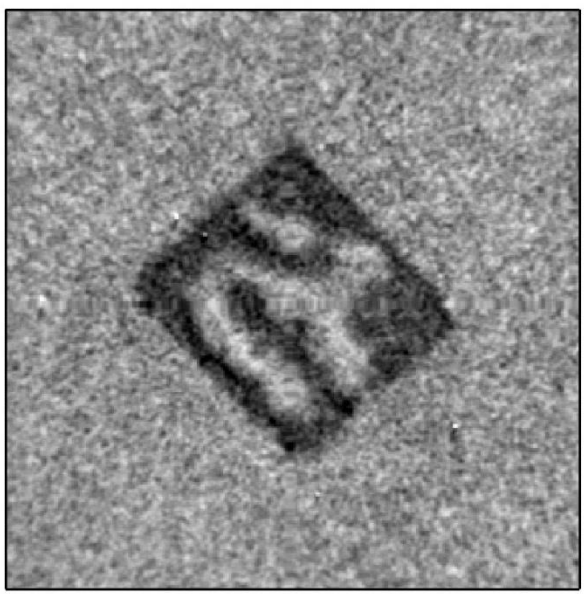
- $\boldsymbol{\sigma} = 4\sqrt{(AK)} - \boldsymbol{\pi D}$ → $\boldsymbol{l_w \sim 1\ nm \sim t}$

  →Large effect of dipolar interaction due to lowered DW energy by DMI

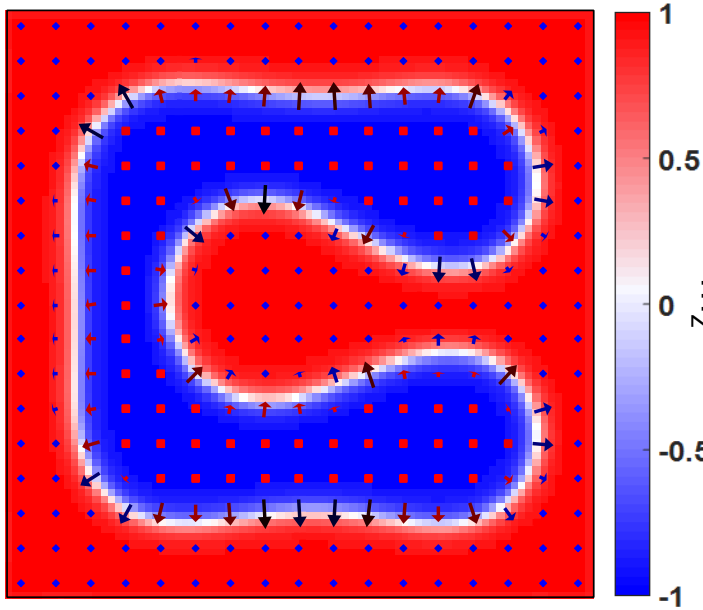
Influence of the nanostructure lateral dimensions



1 µm

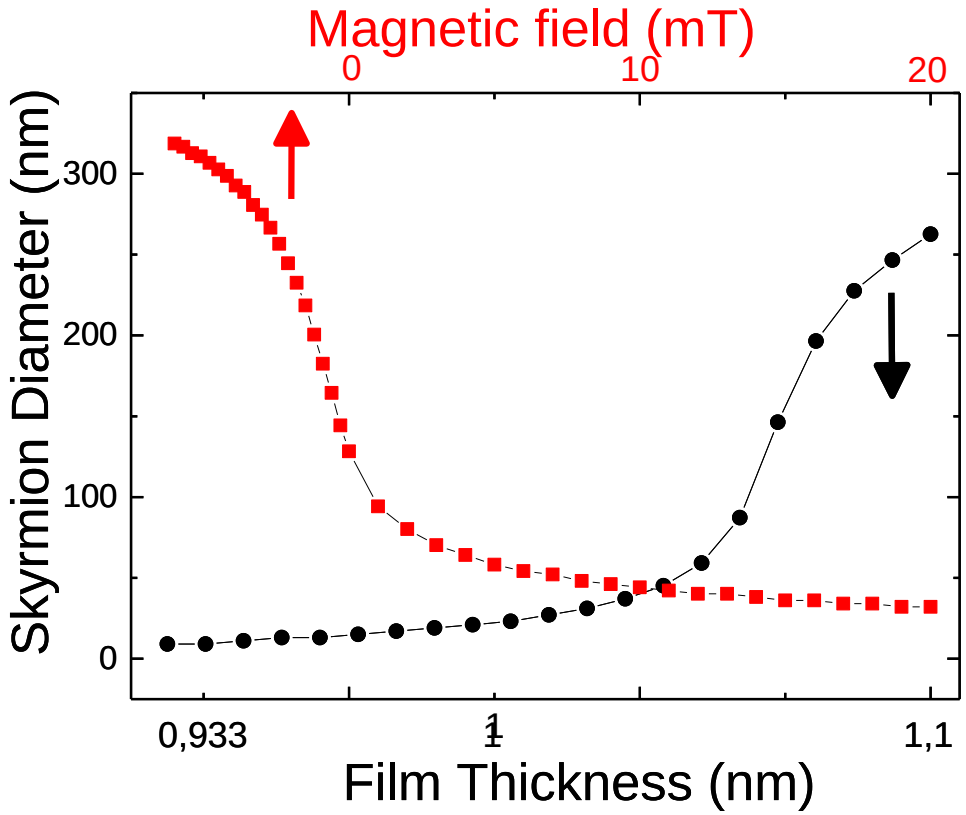


1 µm



- No skyrmion observed at zero field for skyrmions with lateral dimension>1 µm
- The magnetostatic interaction destabilizes the skyrmion for larger structure

Dependance of the skyrmion diameter on thickness and H

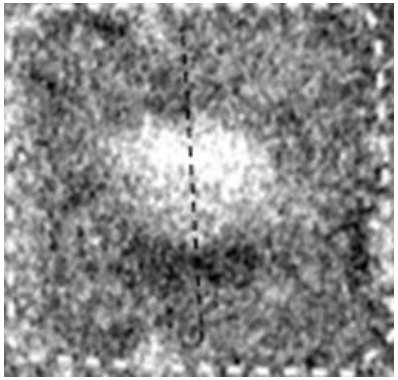


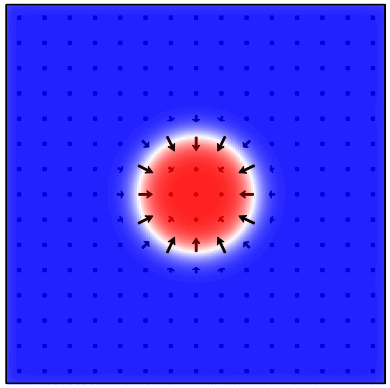
Micromagnetic simulation

- Skyrmion stable only within a narrow range of film thickness between 0.9 and 1.1 nm. Large dependance of the diameter on the film thickness
- skyrmion diameter can be tuned by small perpendicular magnetic field

Conclusion

- **Observation of isolated skyrmion and its internal chiral Néel structure** at room temperature and zero external magnetic field in Pt/Co/MgO nanostructures
- A large DMI is measured using BLS experiments. Ab-initio calculations suggest an additional DMI contribution at the Co/MgO interface.
- Experimental results are substantiated by micromagnetic simulations
- The skyrmion size and stability is the result of balance between the DW energy modulated by DMI and the domain magnetostatic interaction





Boulle et al., Nature Nanotechnology, 11, 449 (2016)