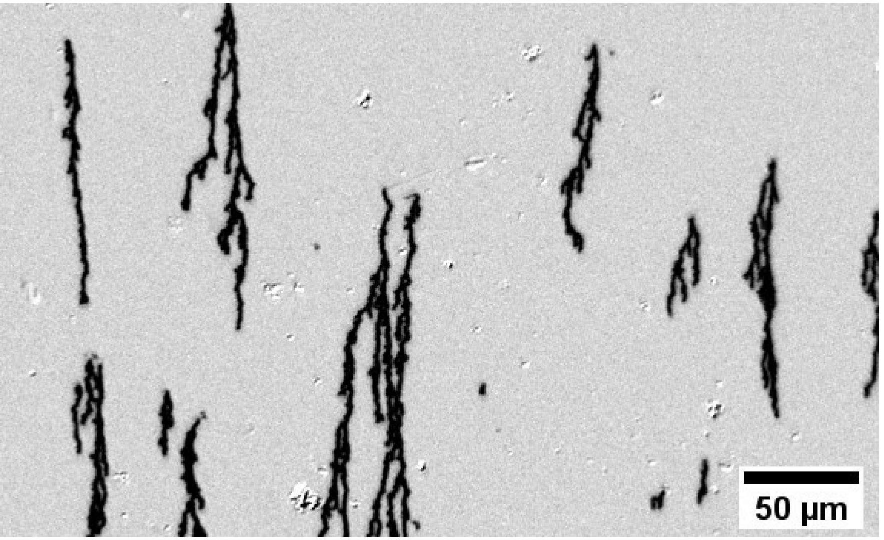
Stripe domain phases in chiral magnetic systems with perpendicular anisotropy

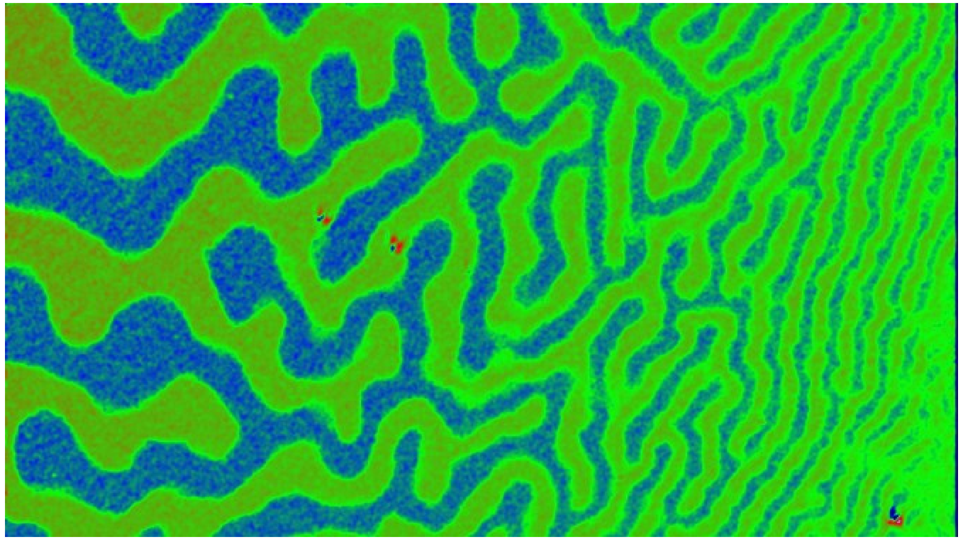
J.A. Brock, R. Saatjian, S. Montoya, …. and E.E. Fullerton

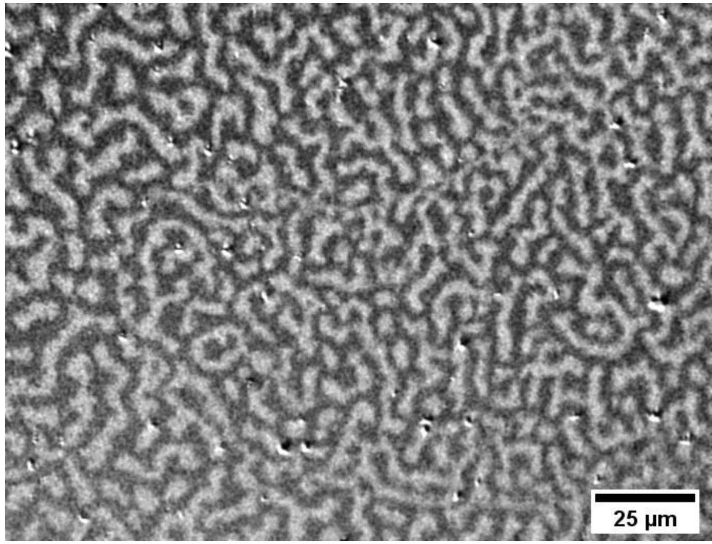
Introduction to stripe phases and role of DMI

Symmetries of magnetic reversal



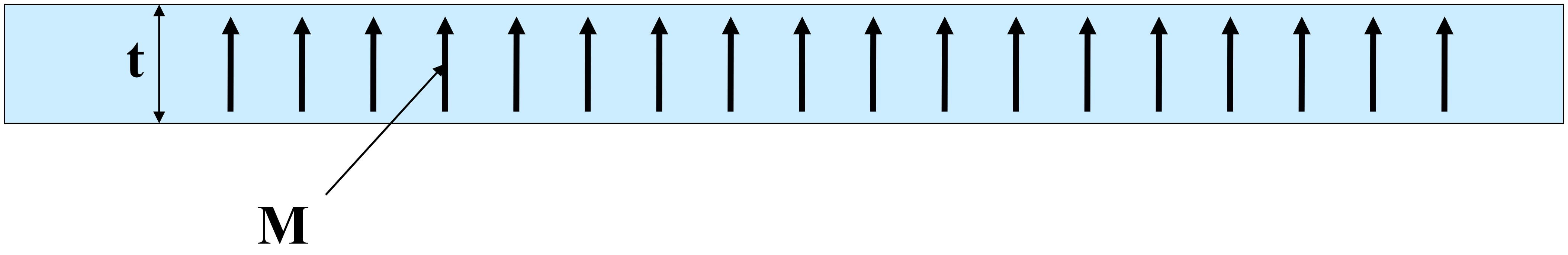
Stripe phases in low exchange materials





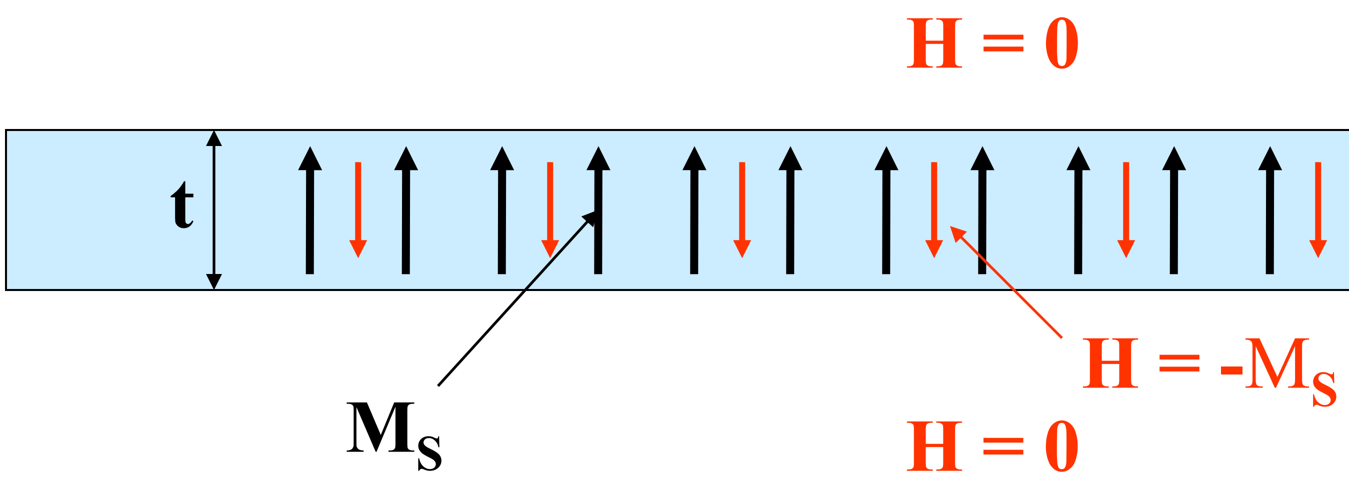
CMRR
Center for Memory and Recording Research
UC San Diego

Domains in a perpendicular film



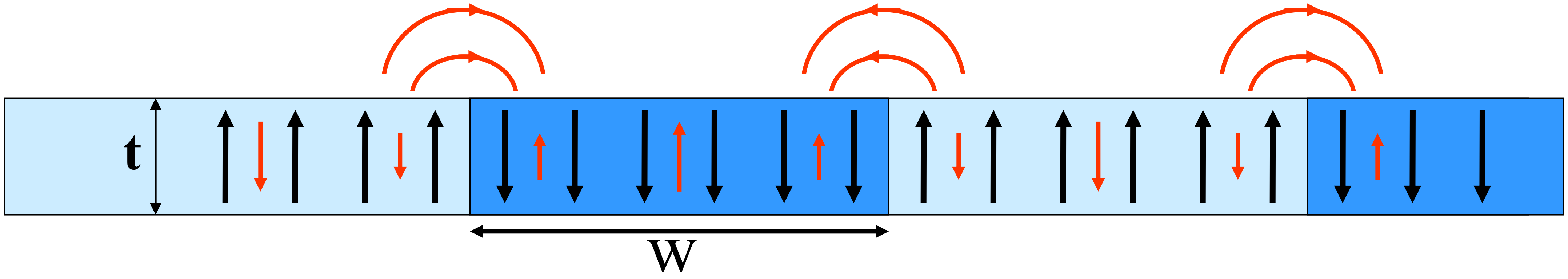
What are the fields?

Domains in a perpendicular film



$$Energy = -\frac{1}{2}\,\mu_0\,\vec{H}\cdot\vec{M} = \frac{1}{2}\,\mu_0 M_s^2$$

Domains in a perpendicular film



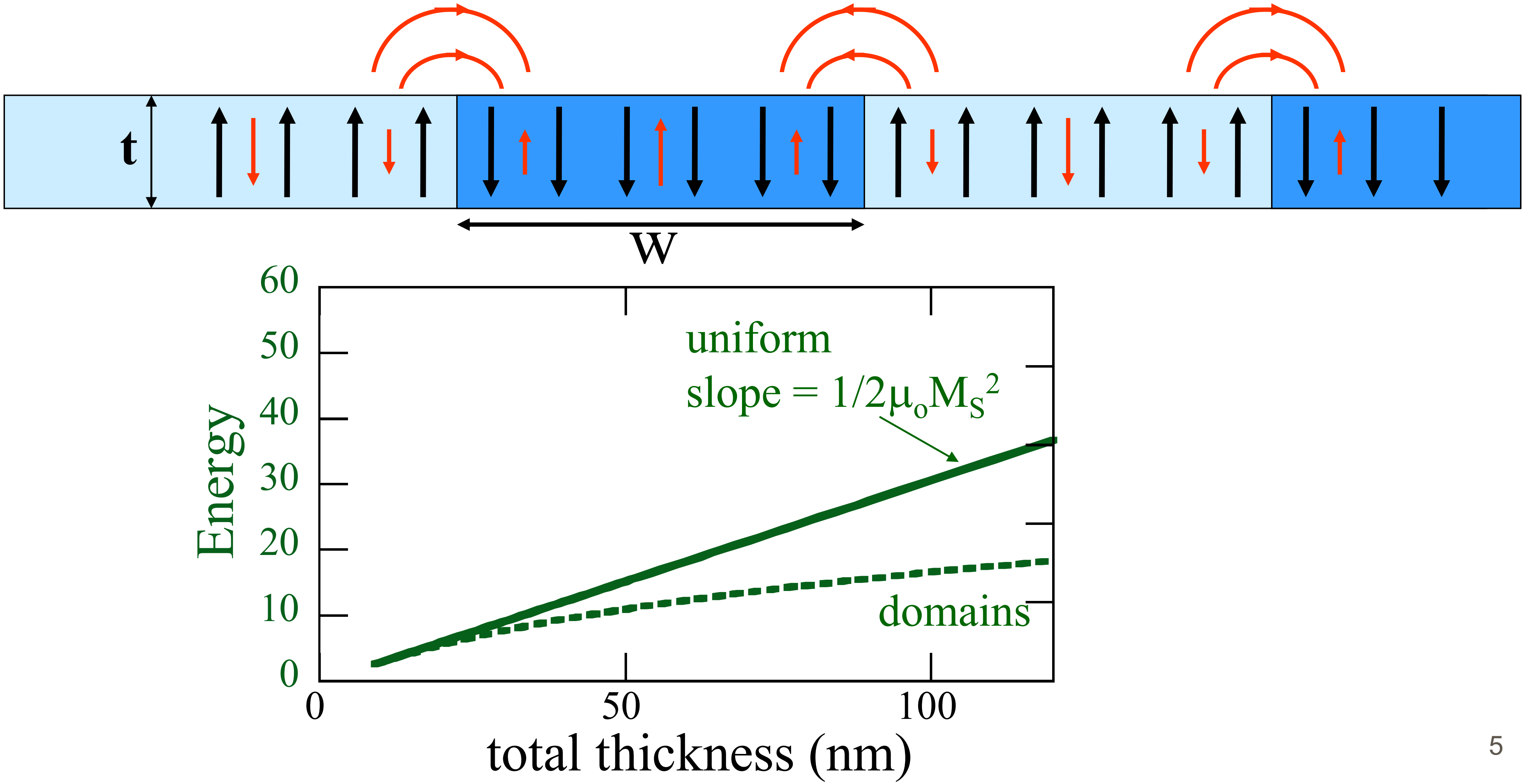
dipolar energy *vs.* **domain wall energy**

$$E_{dipole} \approx \frac{16 M_S^2 w}{\pi^2} \sum_n^{odd} \frac{1}{n^3}\left[1-\exp(-n\pi t / w)\right] \quad \leftrightarrow \quad \sigma\, t / w$$

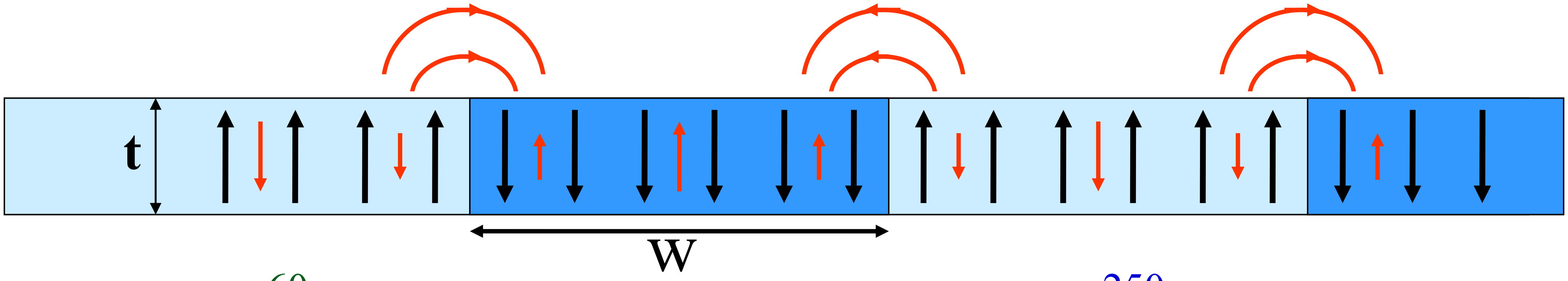
C. Kittel
Rev. mod. Phys. 21 (1949) 541.

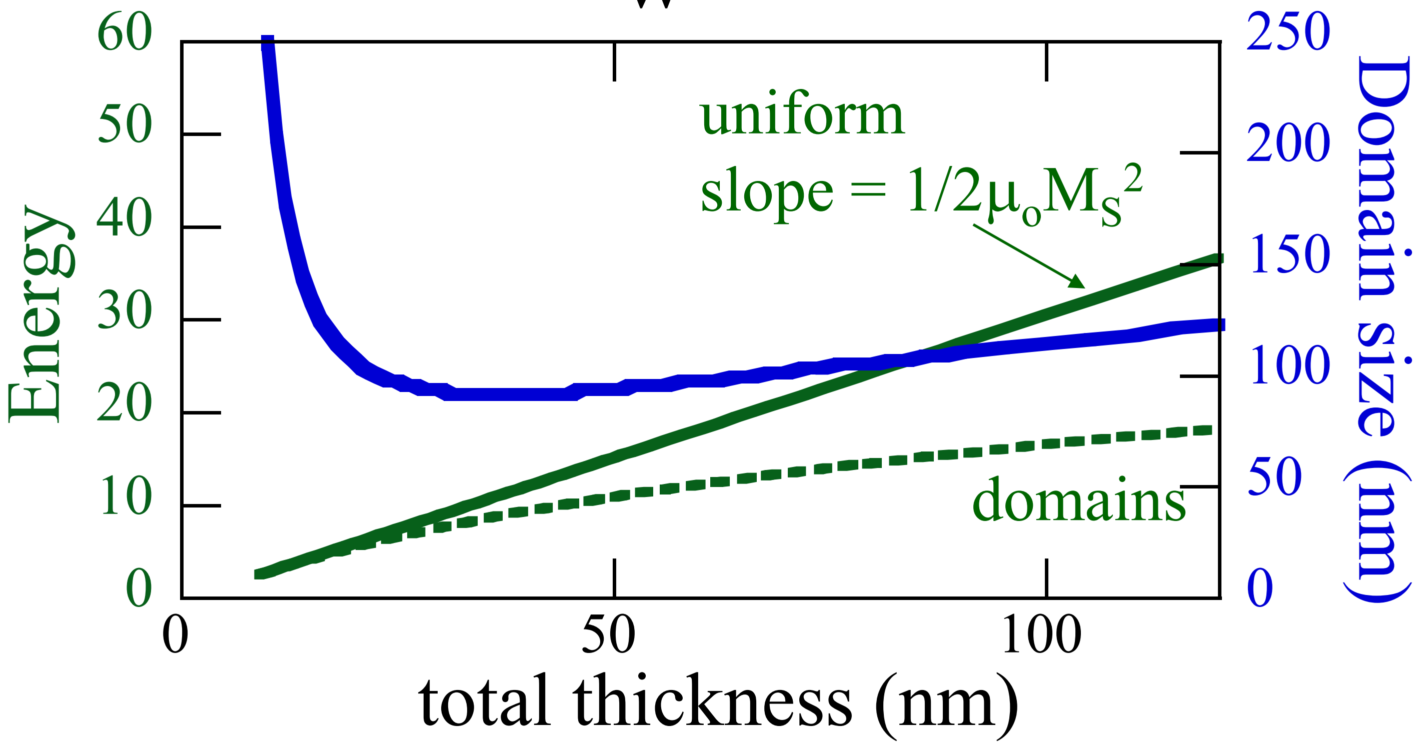
C. Kooy and U. Enz
Philips Res. Repts 15 (1960) 7.

Domains in a perpendicular film

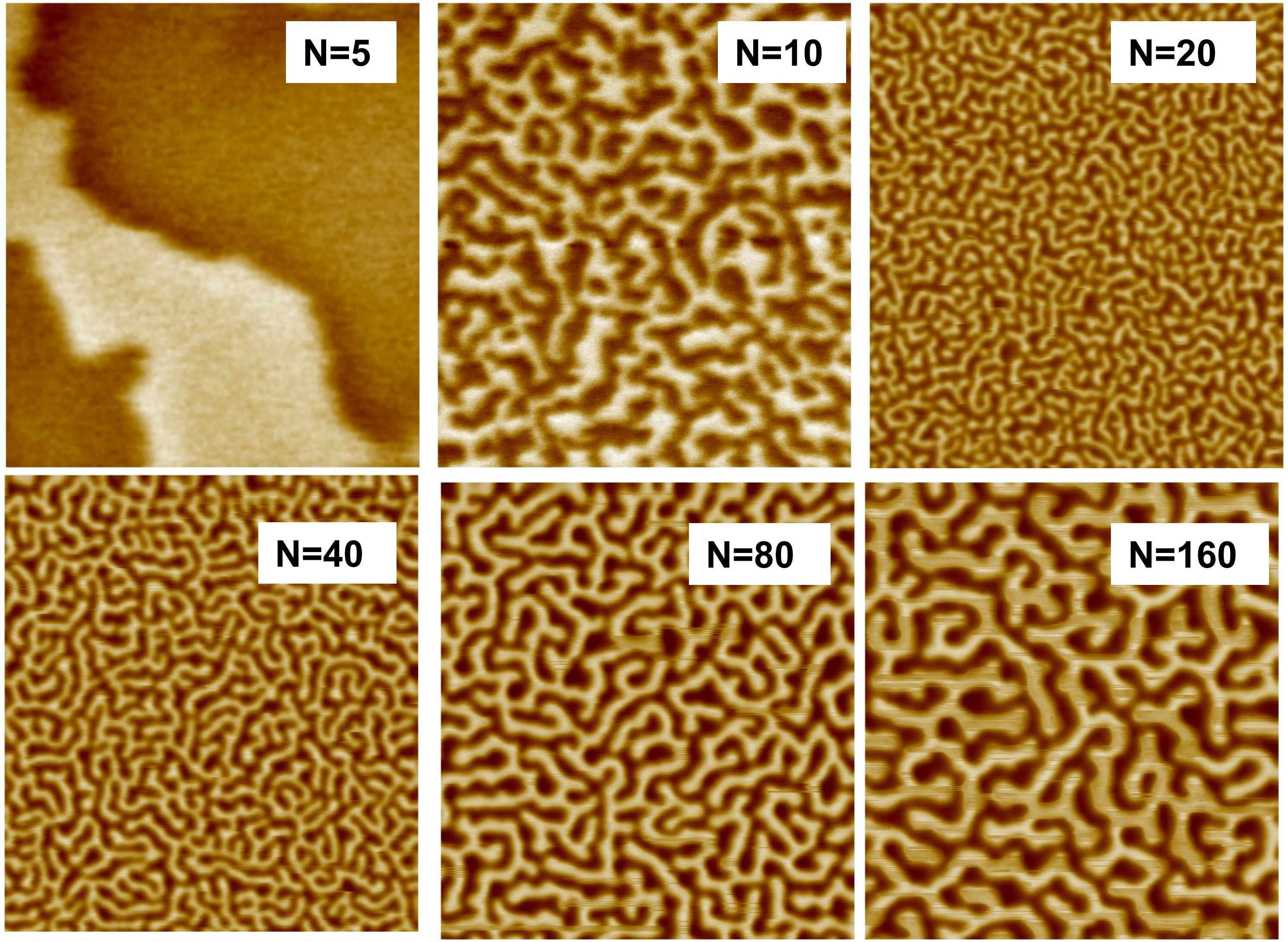


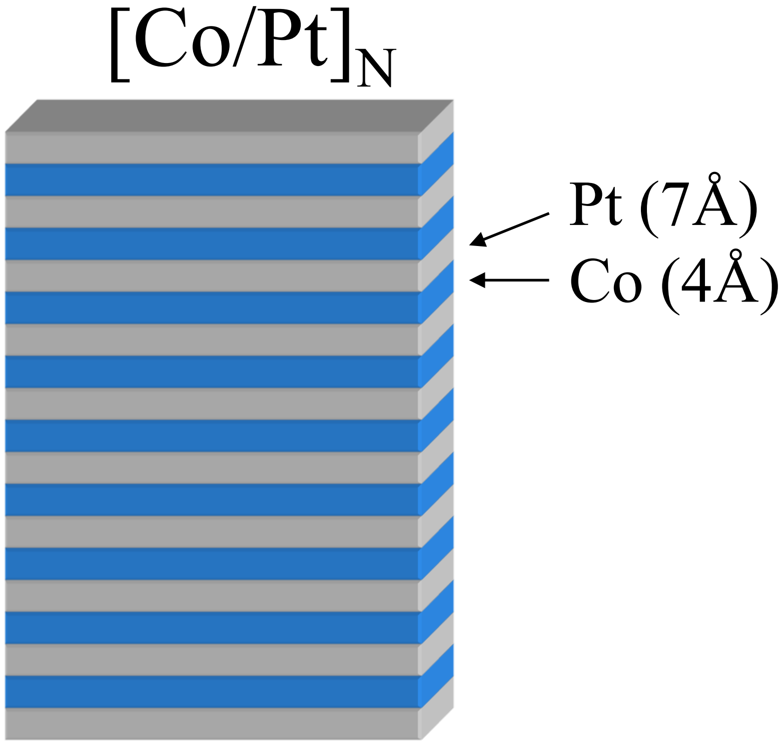
Domains in a perpendicular film





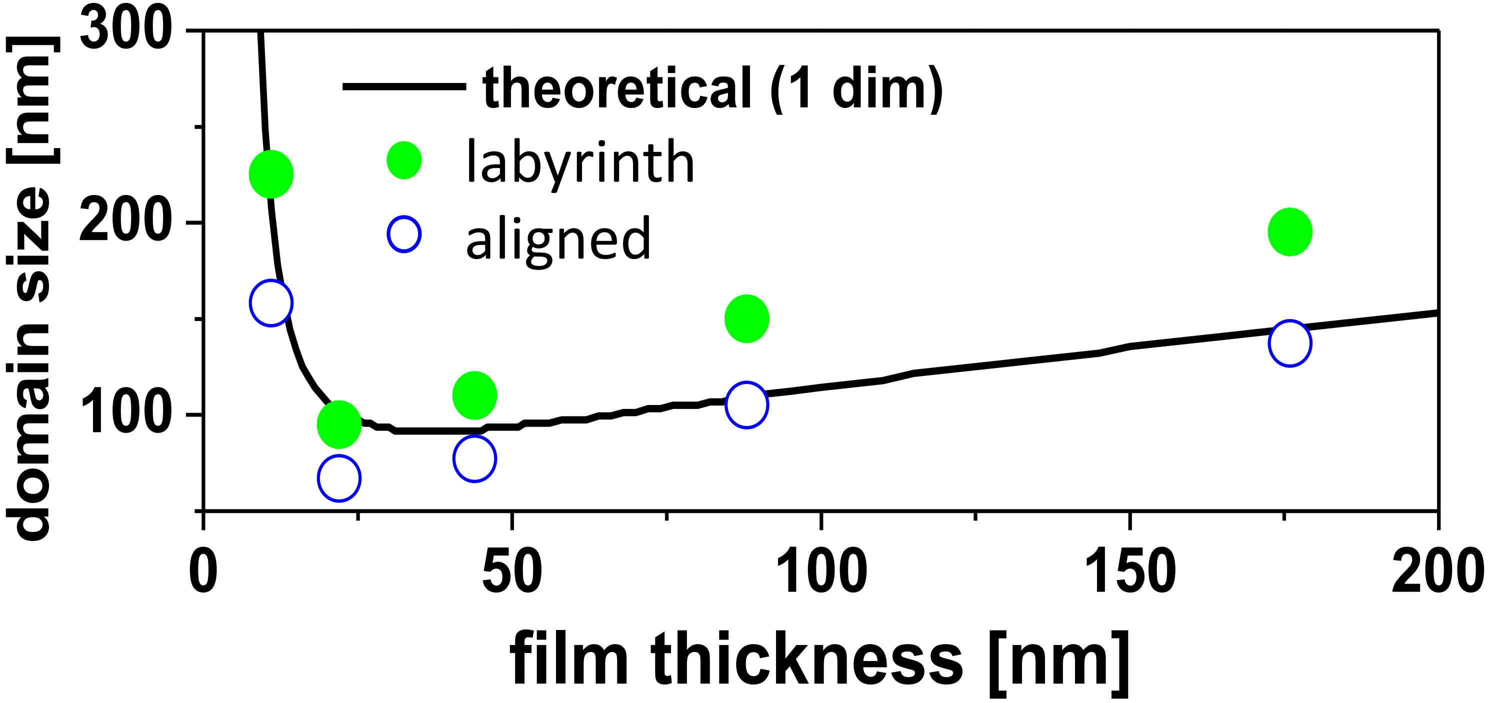
Co/Pt multilayers

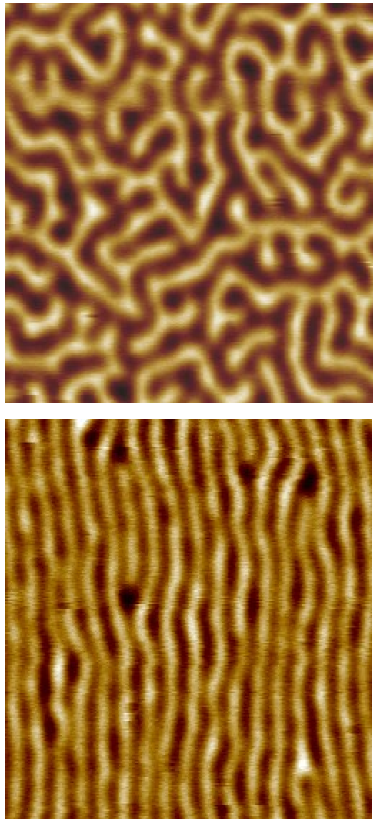




Hellwig et al., *JMMM* ***319****, 13-55 (2007)*

Co/Pt multilayers





N=50

Parameters:

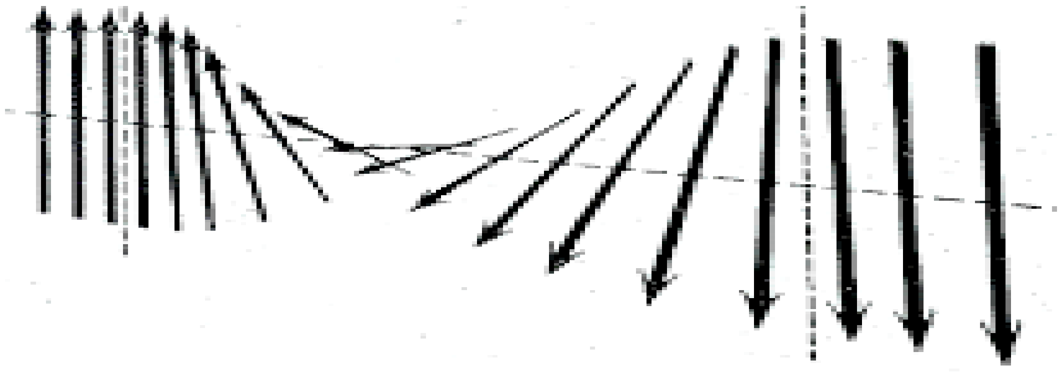
$M_s = 700$ kA/m , $K_u = 5x10^5$ J/m^3, $A = 10^{-11}$ J/m

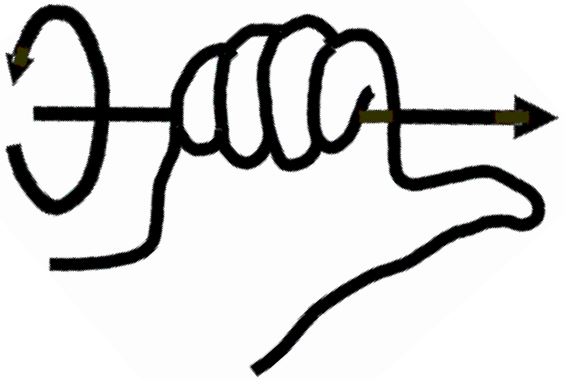
$M_s = 700$ emu/cm^3 , $K_u = 5x10^6$ ergs/cm^3, $A = 10^{-6}$ ergs/cm

Hellwig et al., *JMMM **319**, 13-55 (2007)*

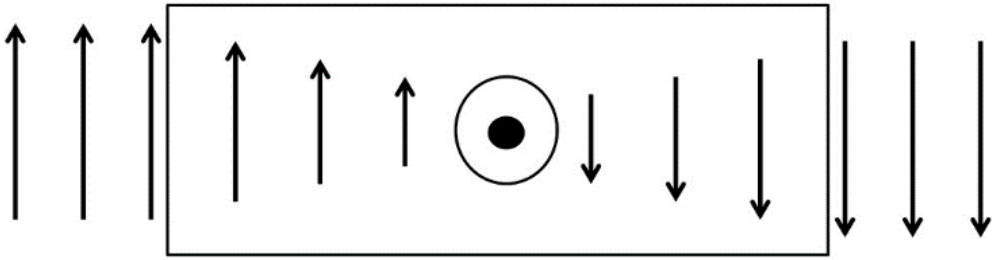
Chiral magnetic domain walls

Bloch domain wall

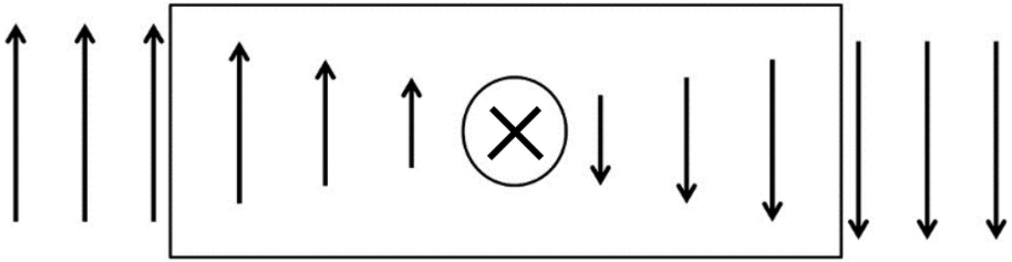




Right handed



Left handed



Often referred to as **achiral** because these are energetically equivalent

Chirality Control

Heisenberg exchange

$$E_{Heisenberg} = -J\, \boldsymbol{S_1} \cdot \boldsymbol{S_2}$$

Dzyaloshinskii-Moriya interaction (DMI)

$$E_{DMI} = -\boldsymbol{D} \cdot (\boldsymbol{S_1} \times \boldsymbol{S_2})$$

I. Dzyaloshinsky, *J. Phys. Chem. Solids* **4**, 241 (1958).

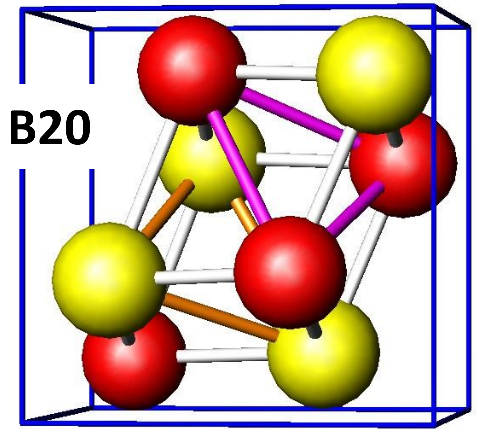
T. Moriya, *Phys Rev.* **120**, 91 (1960).

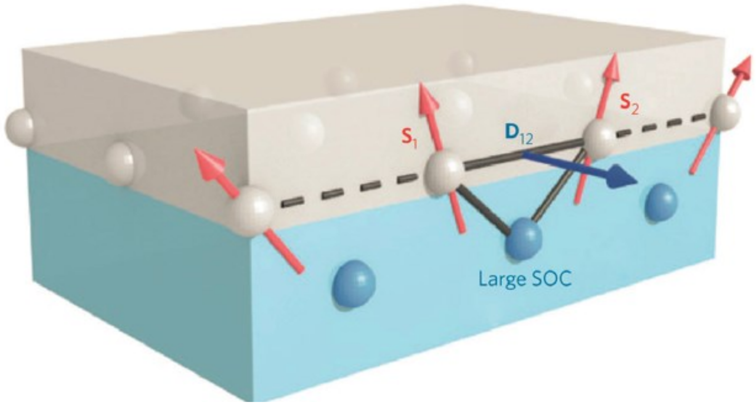
Handedness is set by the sign of *D*

Domain wall energy $\sigma_{DW} \sim 4\sqrt{AK_{eff}} - \pi|D|$

non-centro-symmetric materials

MnSi

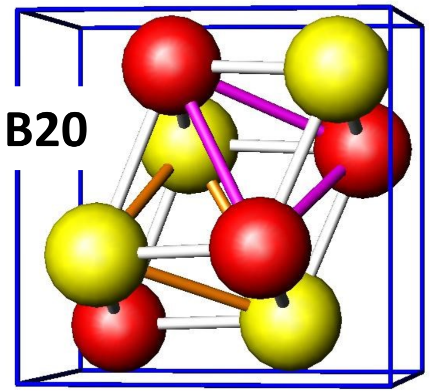




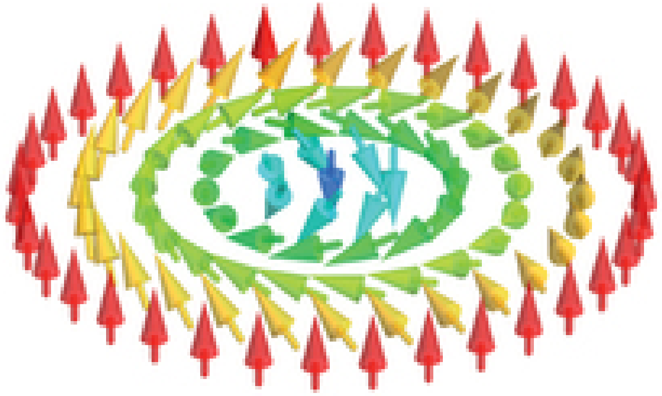
A. Fert, *Mat. Sci. For.* **1990**, *59-60*, 439

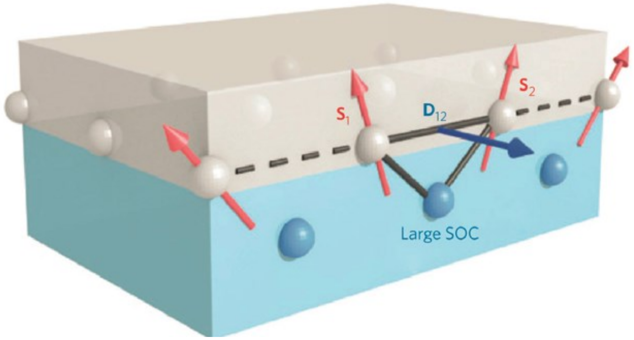
DMI and skyrmions

MnSi

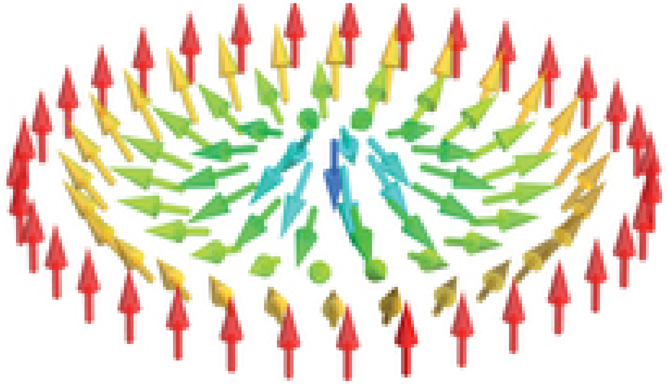


Bulk-like DMI
Chiral Bloch walls





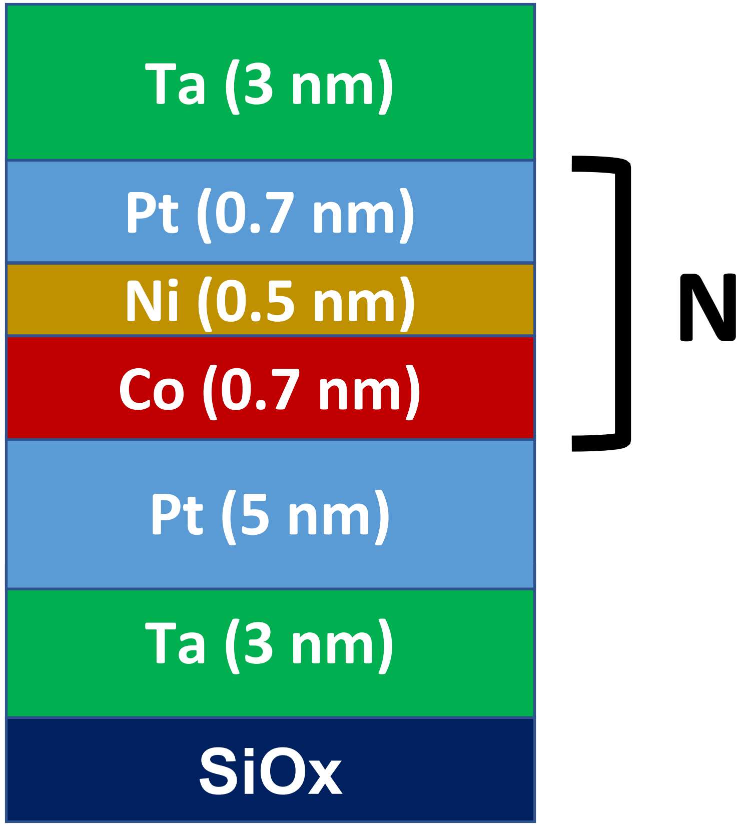
Interfacial DMI
Chiral Néel walls

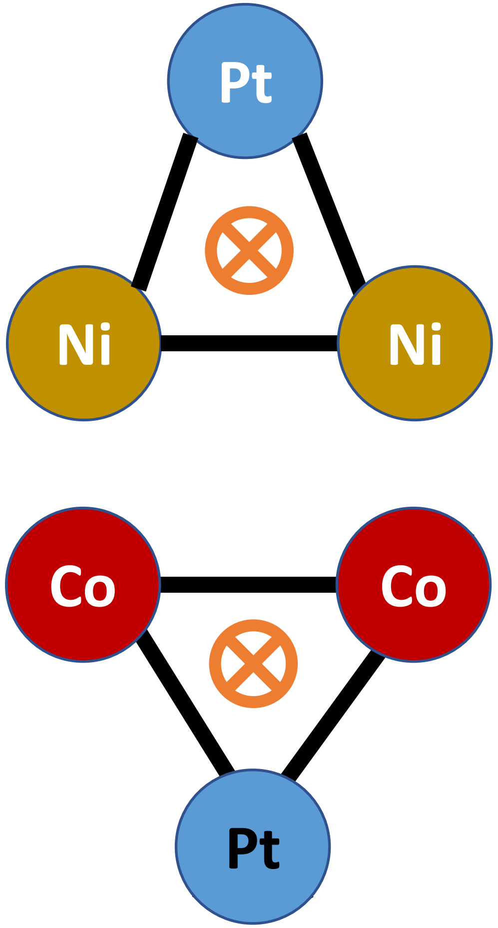


Competition between chiral Néel and achiral Bloch walls

Review Articles: Fert, *et al.*, Nature Rev. Mater. **2**, 17031 (2017)
Jiang, *et al*. Phys. Rep. **704**, 1-49 (2017)
Hellman et al., Rev. Mod. Phys. **89**, 025006 (2017)

Interfacial DMI: Pt/Co/Ni/Pt

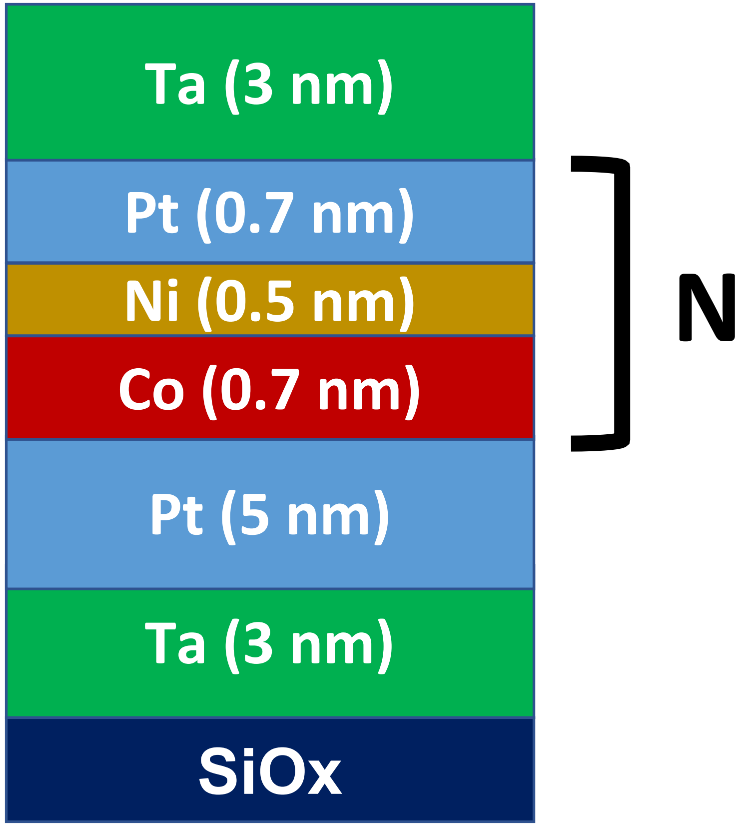




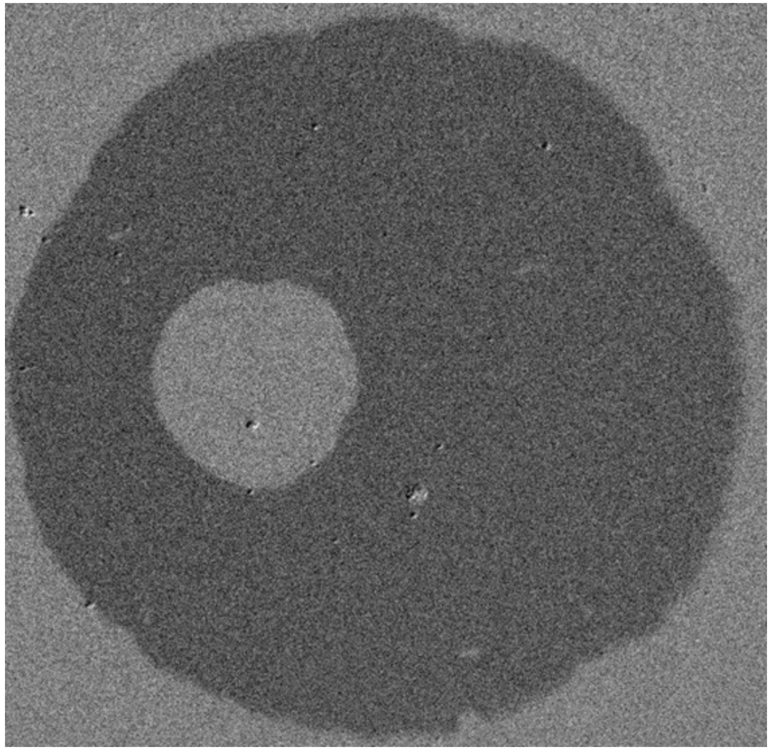
A. Hrabec *et al.*, PRB 90, 020402R (2016)
C. Moreau-Luchaire *et al.*, Nat. Nanotech. 11, 444 (2016)
R. Lavrigsen *et al.*, PRB 91, 104414 (2015)
G. Chen *et al.*, Nat. Comm. 4, 2671 (2013)
Soumyanarayanan *et al.*, Nat. Mat. 16, 898 (2017)
P. Jadaun *et al.*, npj Comp. Mater. 6, 88 (2020)

Interfacial DMI: Pt/Co/Ni/Pt

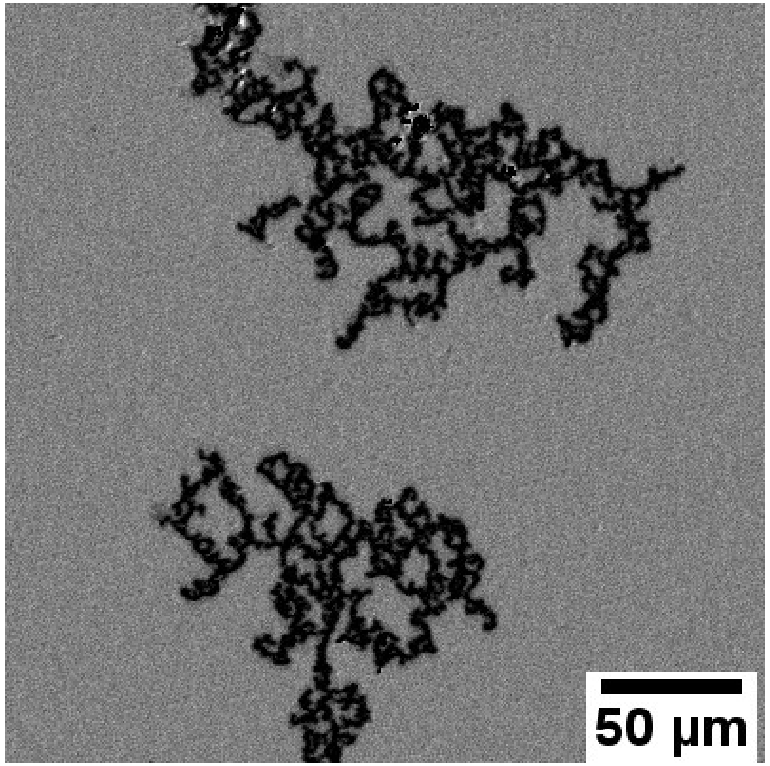
Domain wall energy $\sigma_{DW} \sim 4\sqrt{AK_{eff}} - \pi|D|$



N = 2

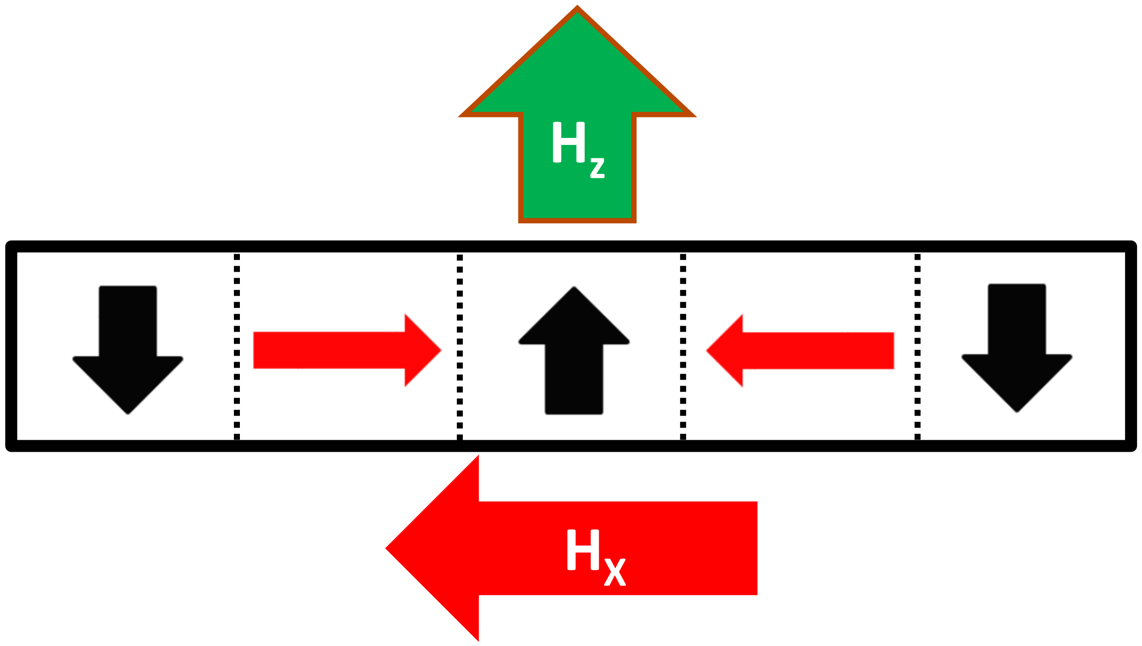


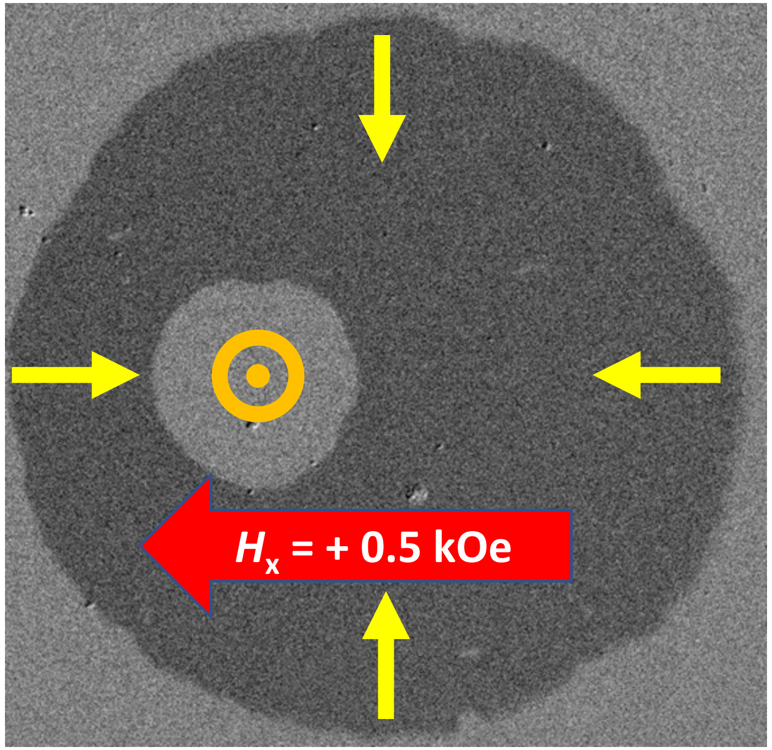
N = 3



- **Dendritic stripes the reversal mechanism**
- **Consistent with the presence of iDMI**

Impact of chirality on magnetic reversal



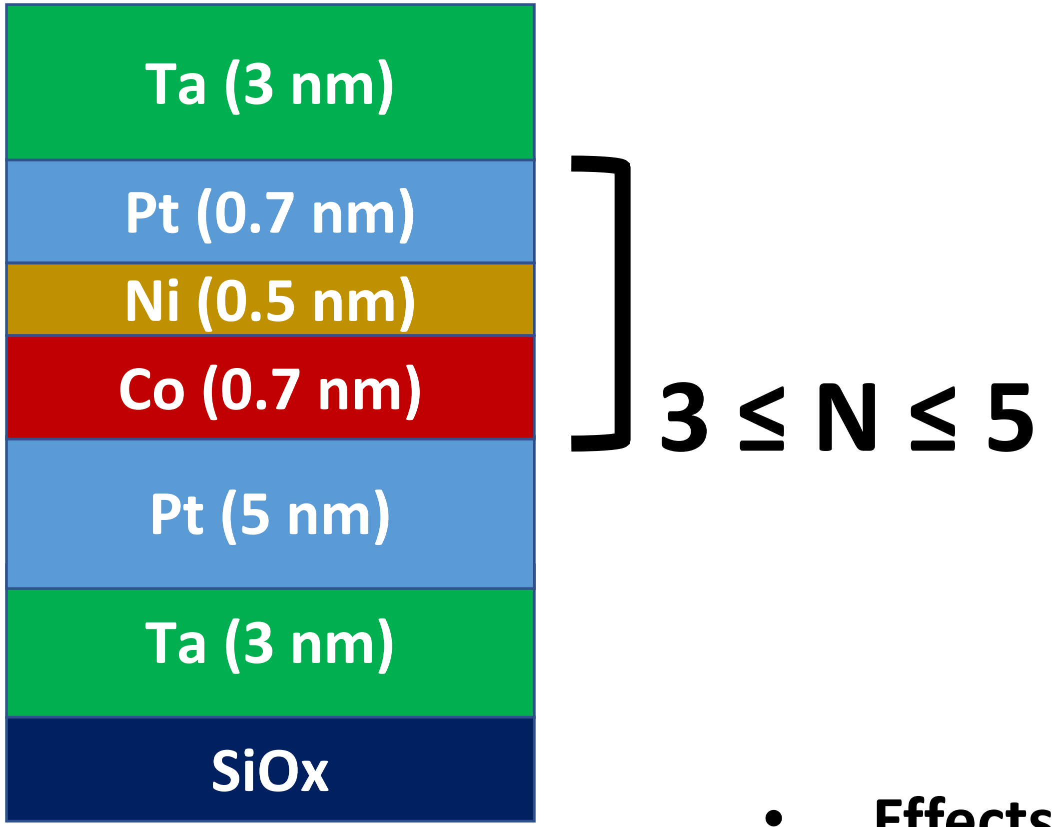


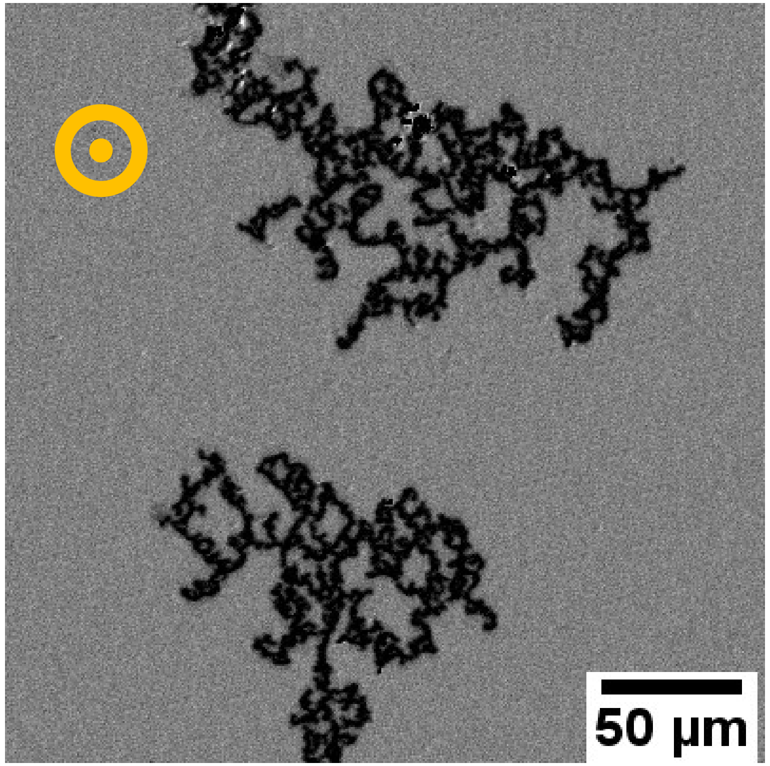
J. P. Pellegren *et al.*, PRL 119, 027203 (2017)
S.-G. Je *et al.*, PRB 88, 214401(2013)

- Expected left/right growth asymmetry
- D = -0.63 mJ/m^2 (confirmed by BLS)
- Néel walls confirmed by LTEM for N ≤ 5

Brock, *et al.*, Adv. Mater. **33**, 2101524 (2021)

Impact of chirality on magnetic reversal

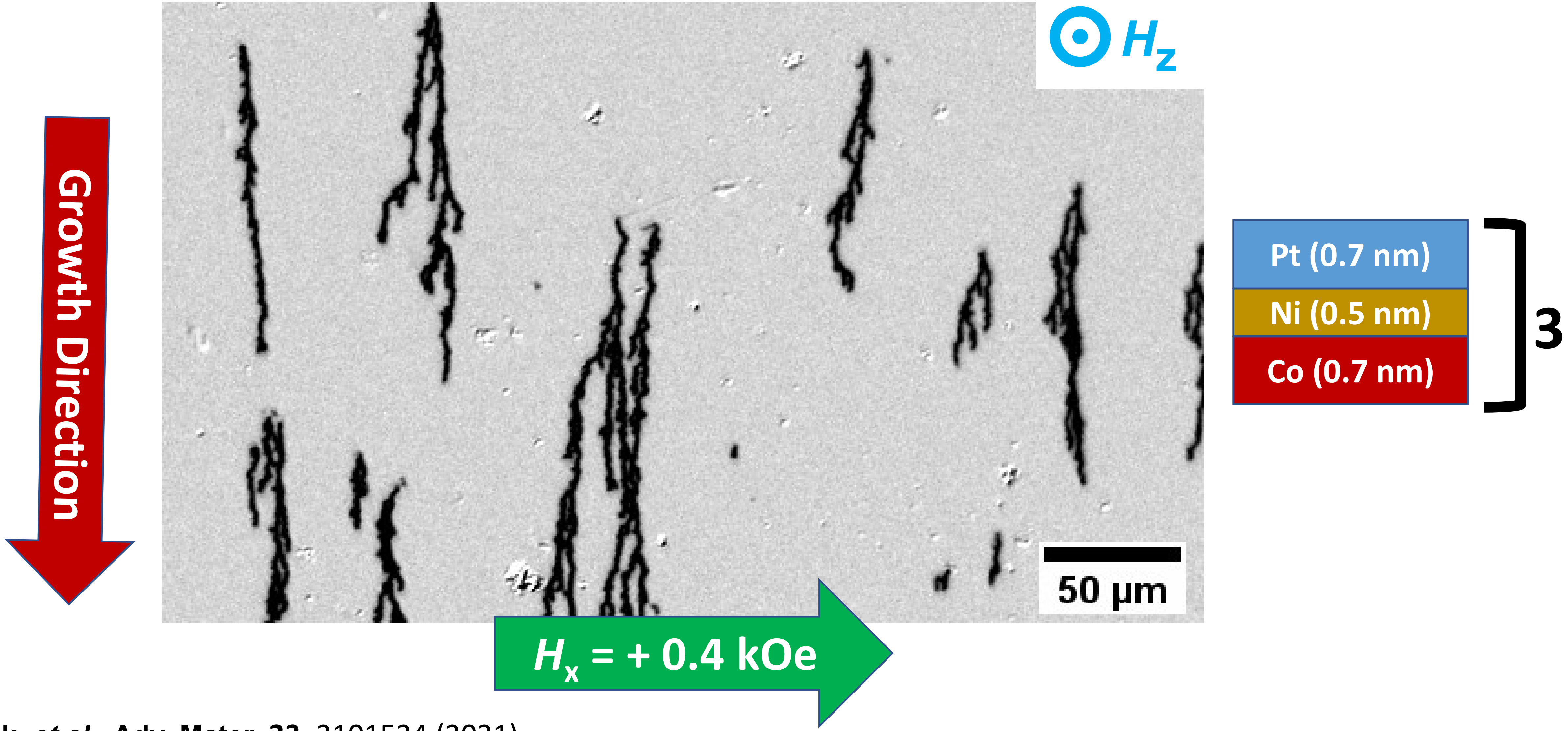




- **Effects of symmetry-breaking in-plane fields?**

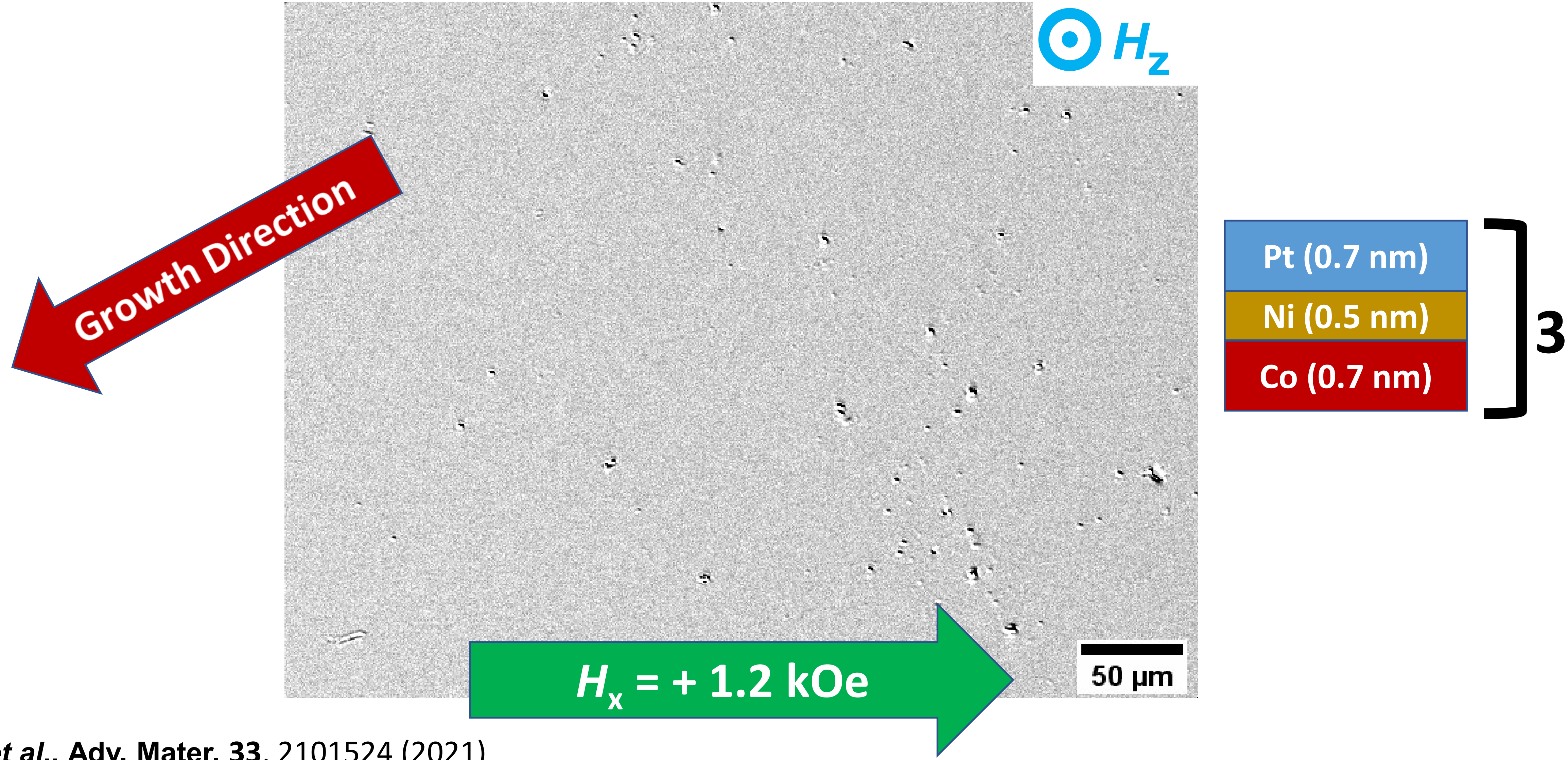
Brock, ***et al.*****, Adv. Mater. 33**, 2101524 (2021)

Impact of chirality on magnetic reversal



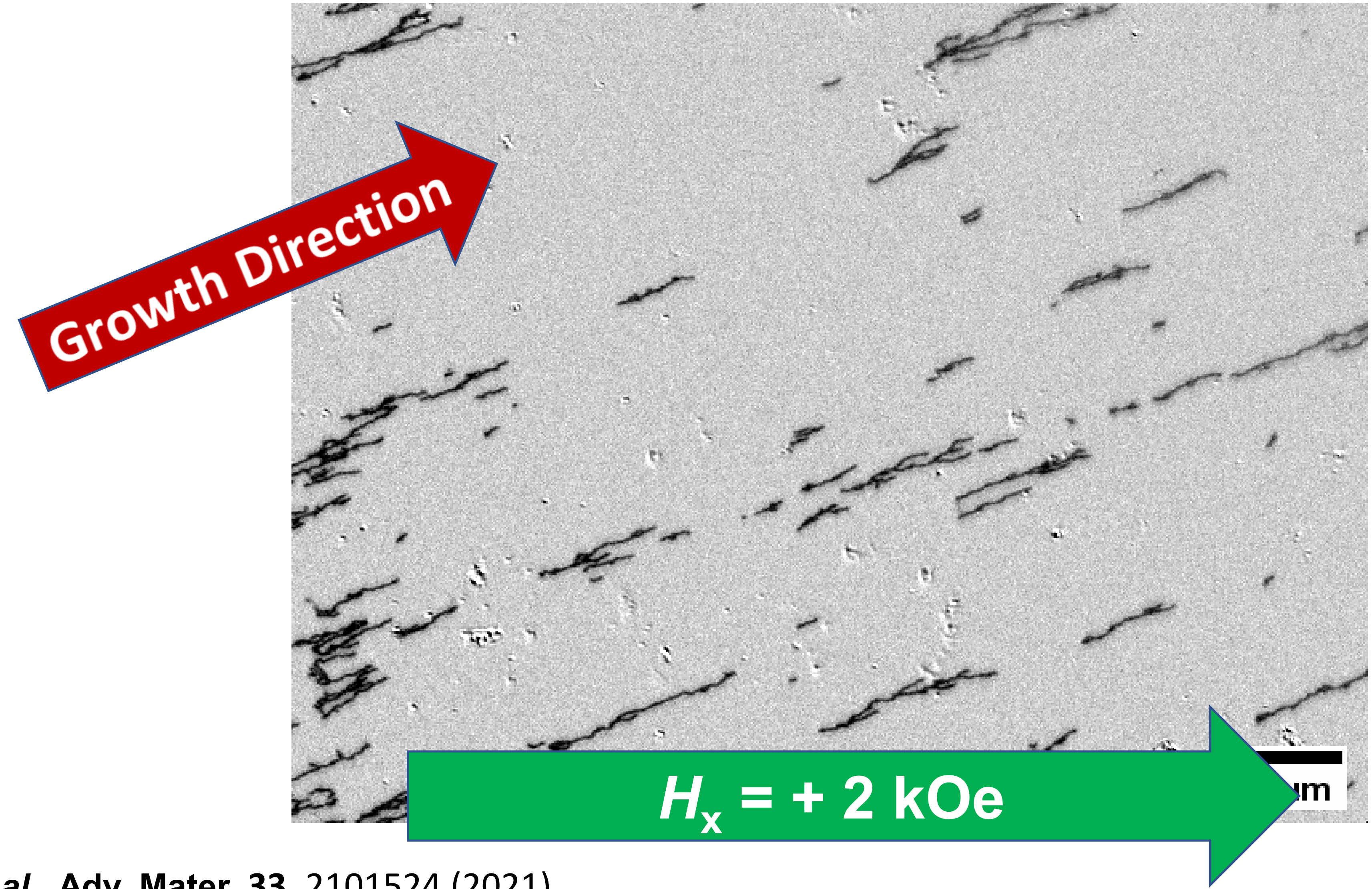
Brock, *et al.*, Adv. Mater. 33, 2101524 (2021)

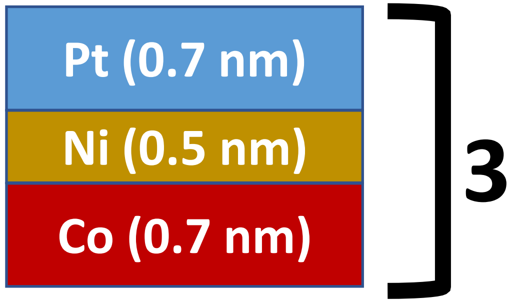
Impact of chirality on magnetic reversal



Brock, *et al.*, Adv. Mater. 33, 2101524 (2021)

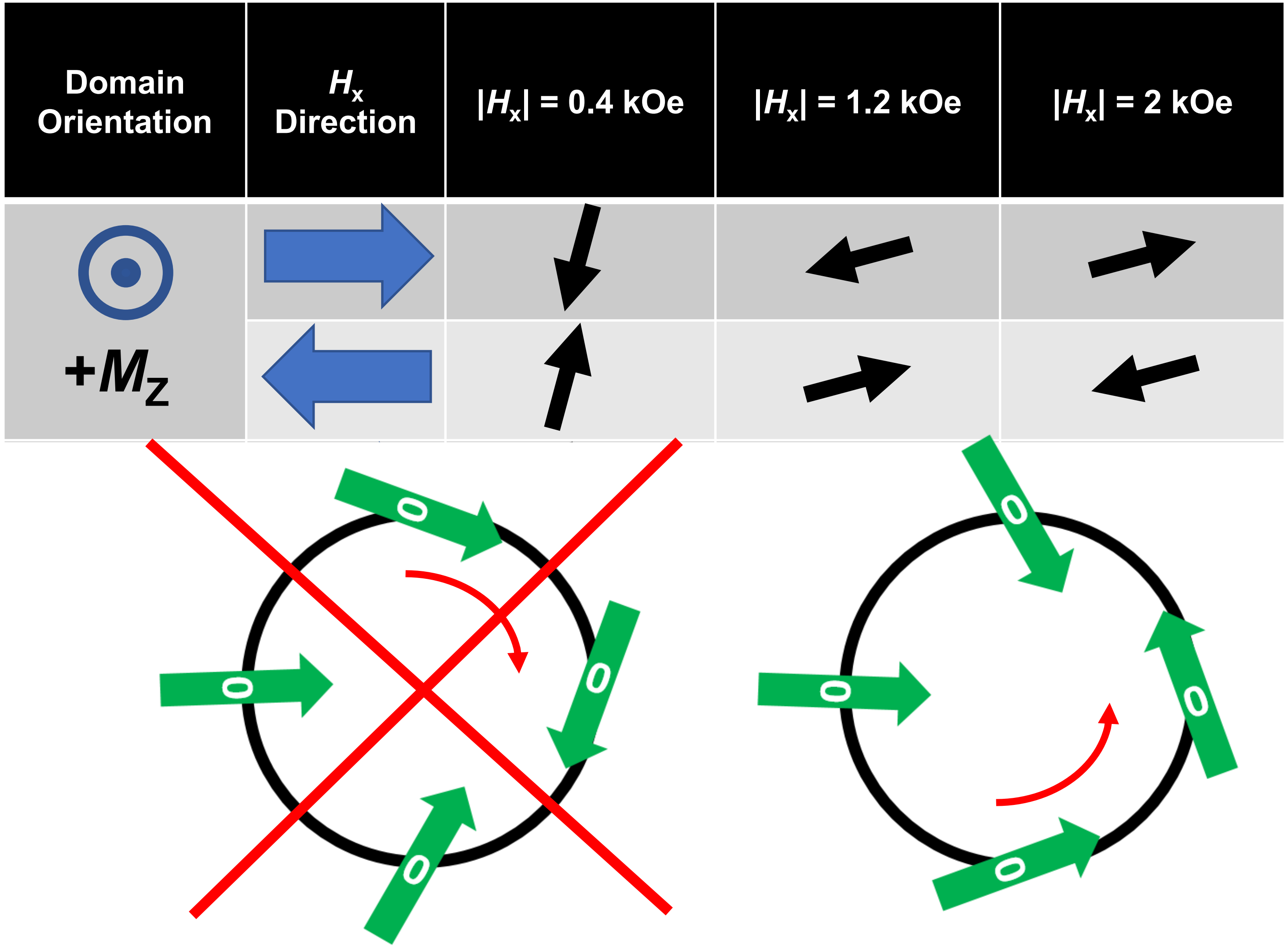
Impact of chirality on magnetic reversal



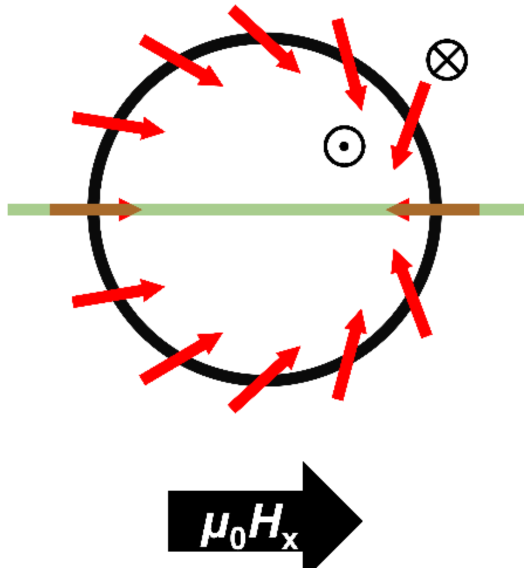


Brock, *et al.*, Adv. Mater. **33**, 2101524 (2021)

Symmetries of magnetic reversal



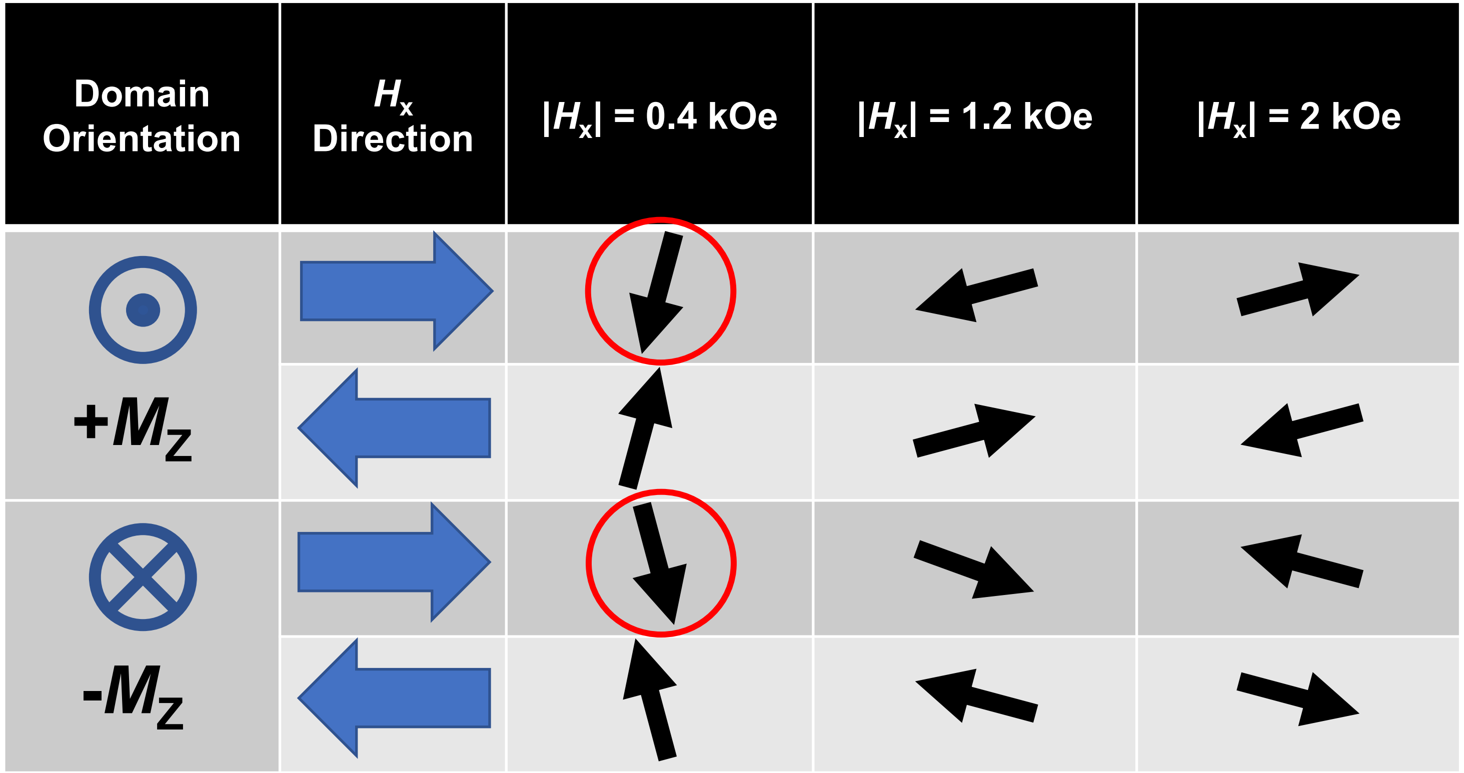
Standard Treatment of iDMI



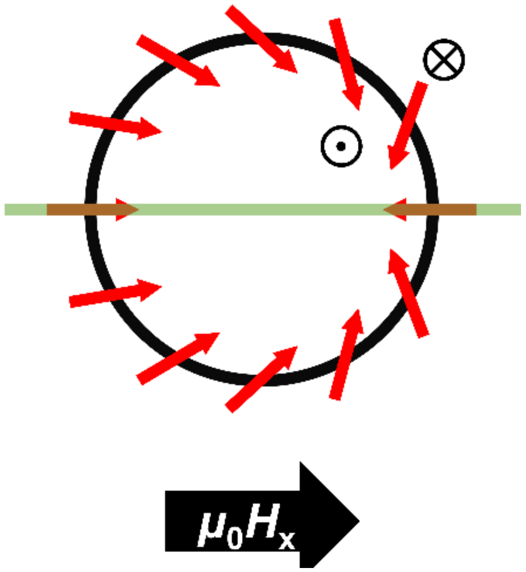
- Top/bottom should be of equivalent energy
- Is there a presence of a "bulk-like" DMI?

Brock, *et al.*, Adv. Mater. 33, 2101524 (2021)

Symmetries of magnetic reversal



Standard Treatment of iDMI

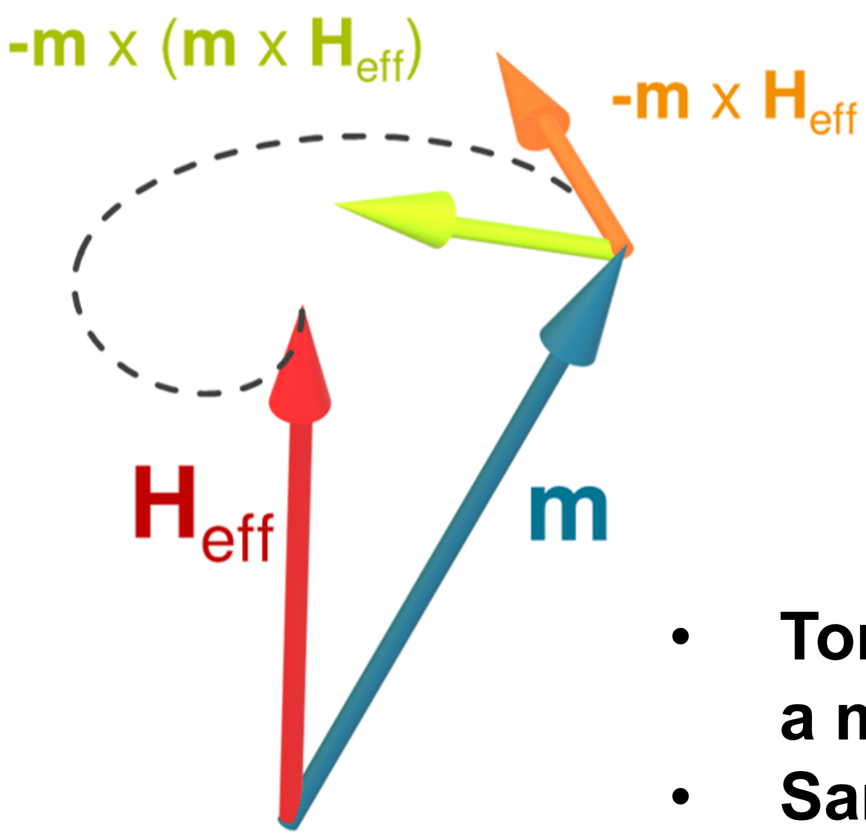


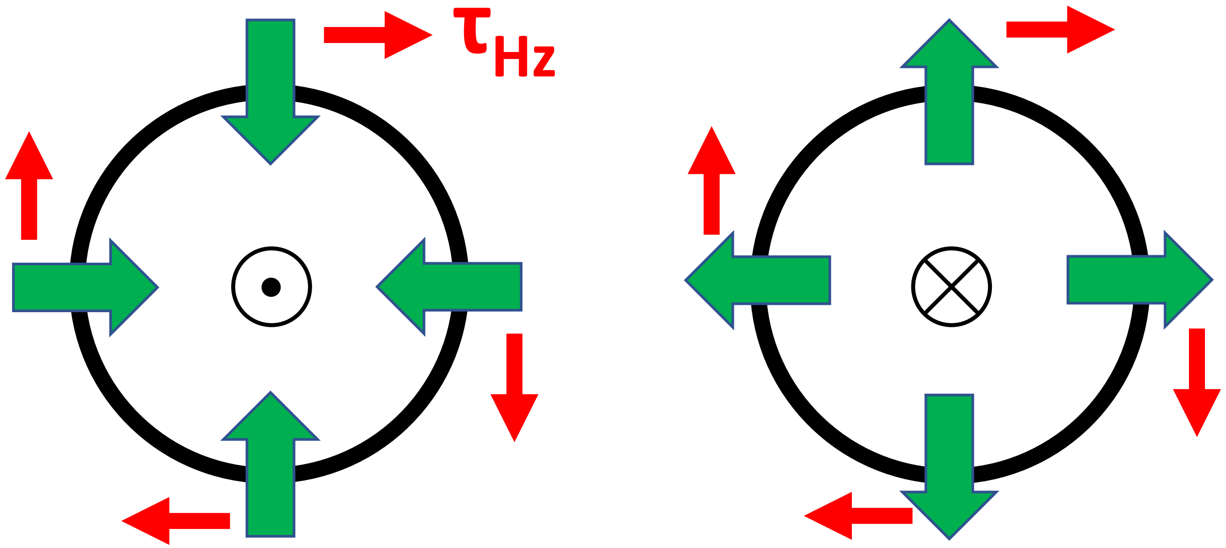
- **Top/bottom should be of equivalent energy**

- **Left-right symmetries consistent with iDMI**
- **Up-down symmetries not consistent with a structural symmetry breaking**

Brock, *et al.*, Adv. Mater. **33**, 2101524 (2021)

Dynamic symmetry breaking

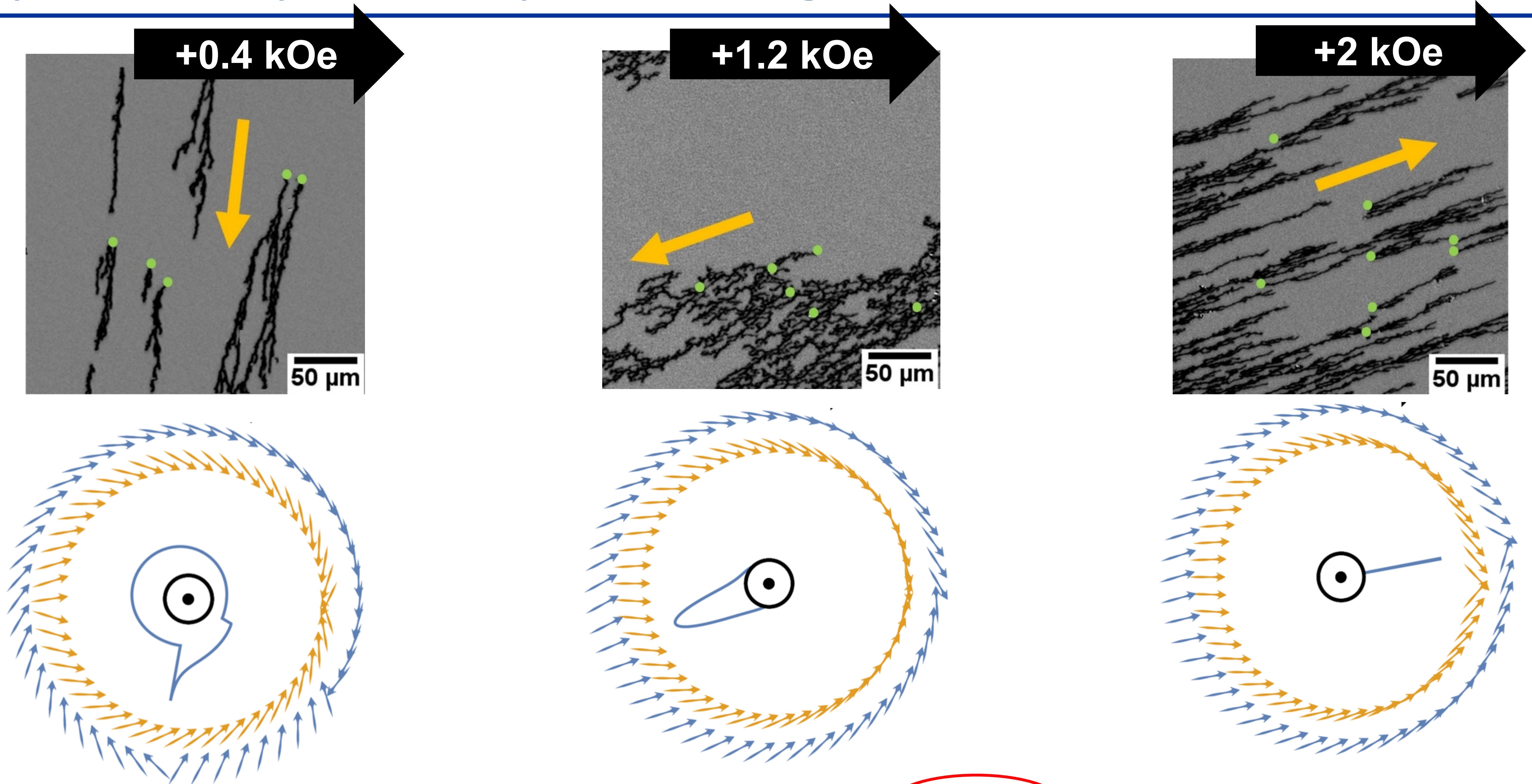




- **Torque from H_z gives a "Bloch-like" twisting for a moving domain**
- **Same rotation for both domain polarities**
- **Generally not considered in circular domains**

N. I. Schreyer & L. R. Walker, JAP 45, 5406 (1974)
L. Sanchez-Tejeria *et al.*, JMMM 423, 217 (2017)

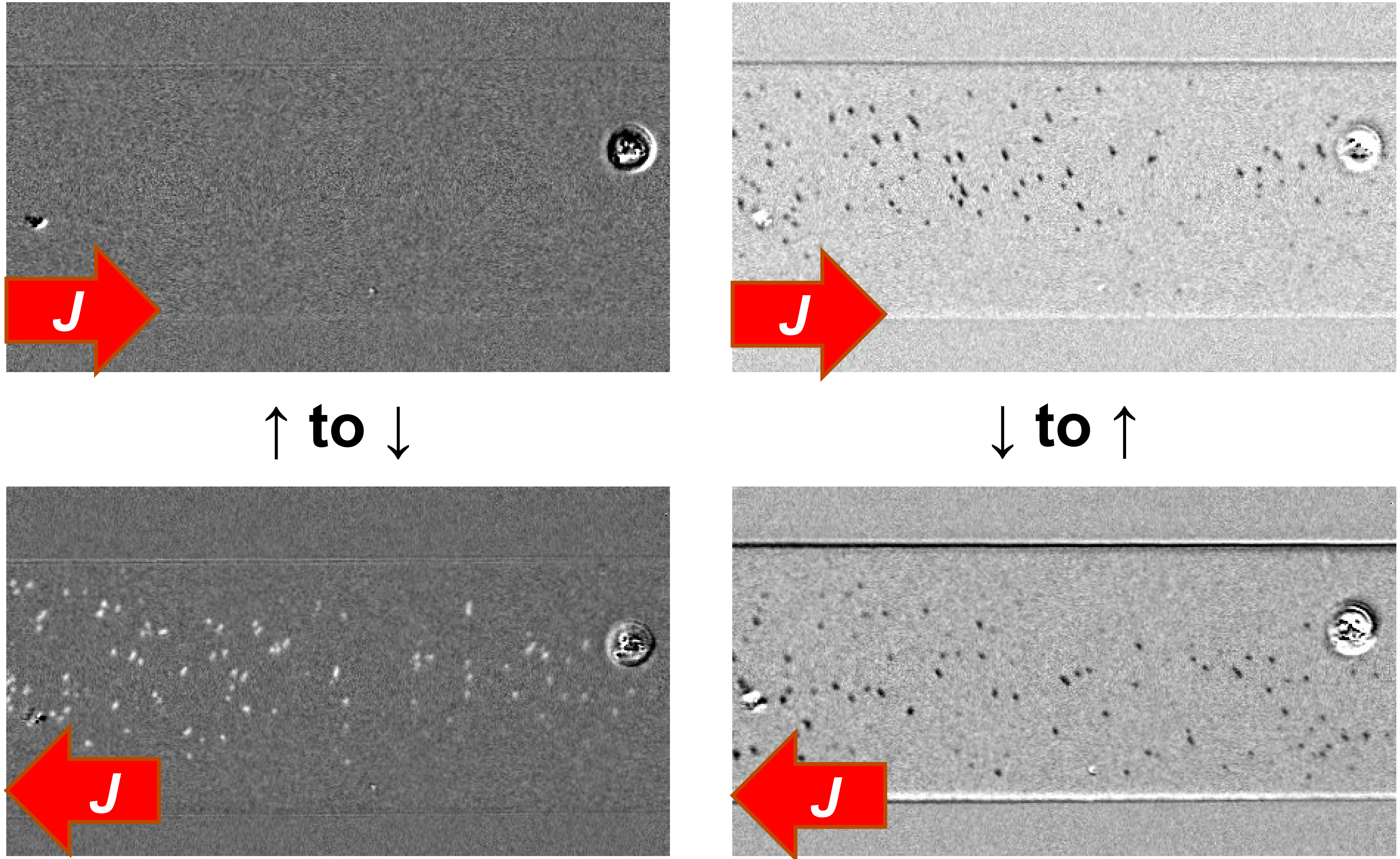
Dynamic symmetry breaking



Sokalski group, CMU PRL **119**, 027203 (17).

Brock, Kitcher, *et al.*, Adv. Mater. 33, 2101524 (2021)

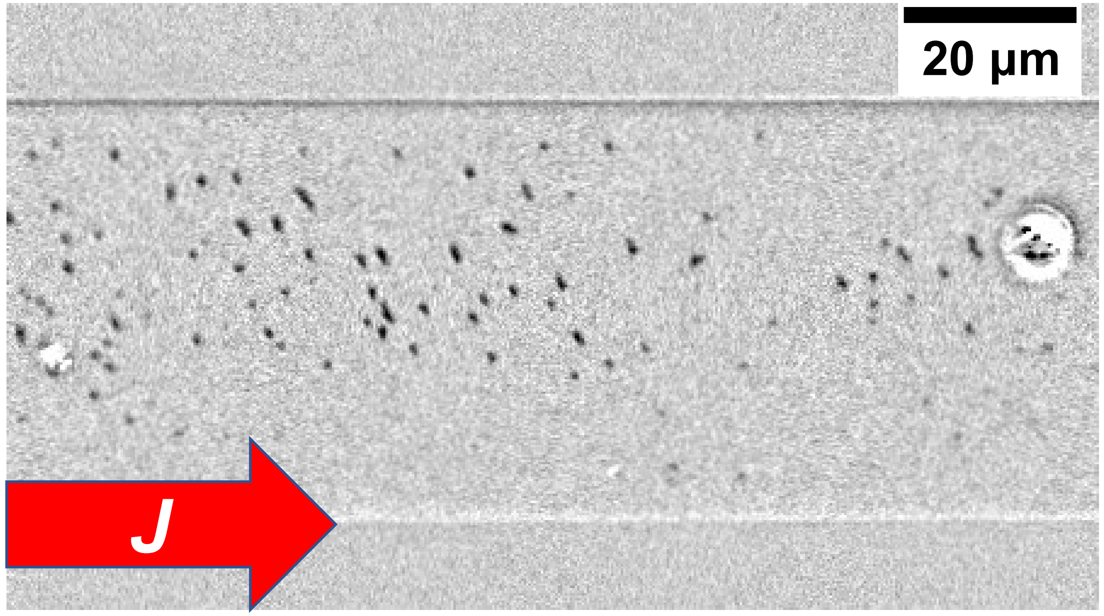
SOT switching

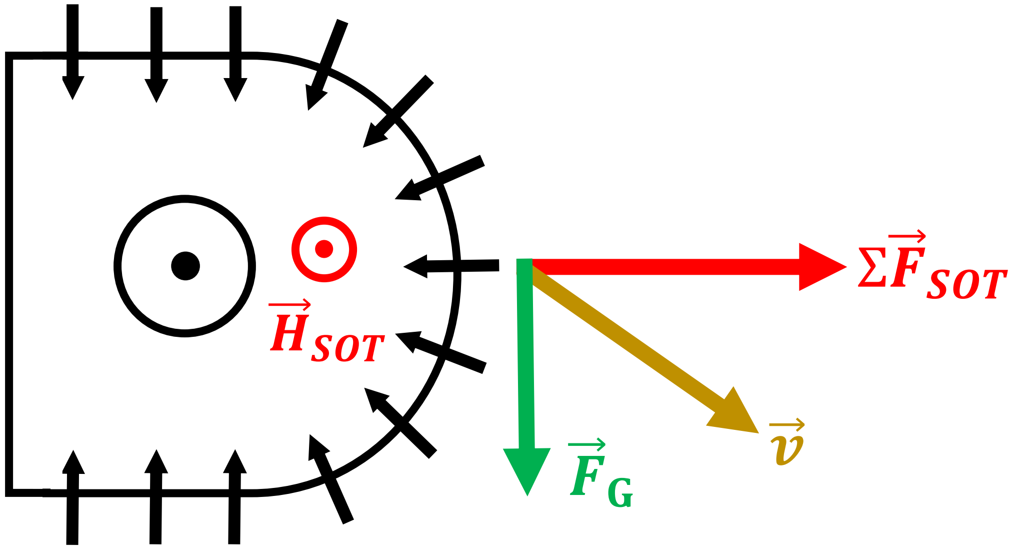


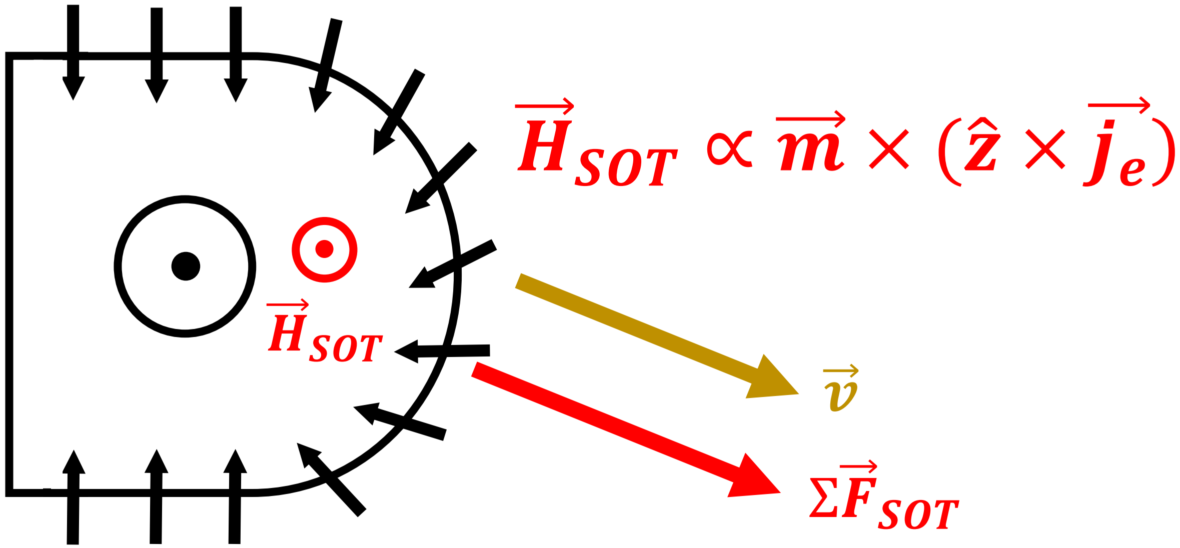
j_{pulse} = 1.8 x 10^{11} A/m^2
t_{pulse} = 15 ms

Growth angle:
48.6° ± 1.3°

SOT switching



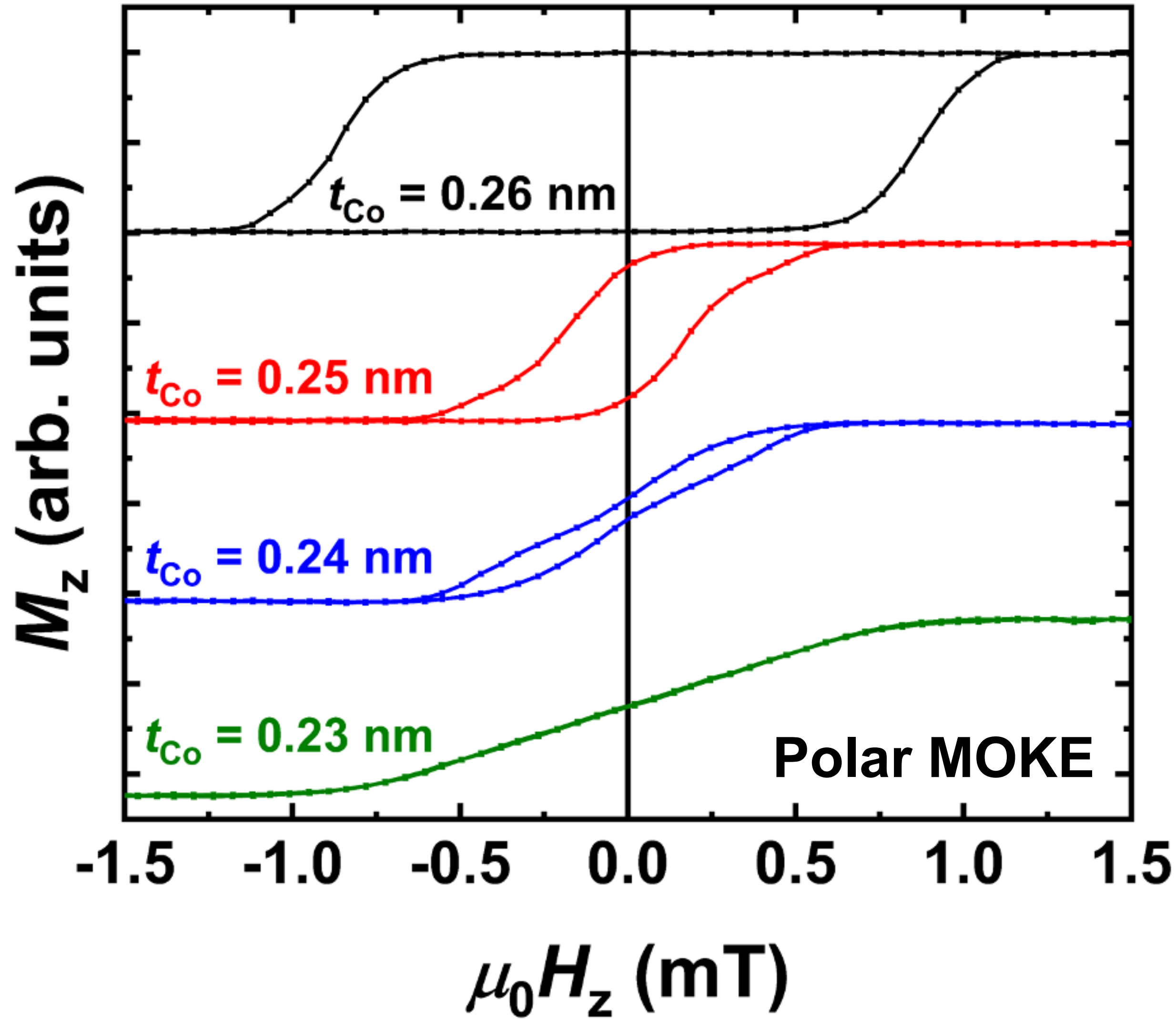


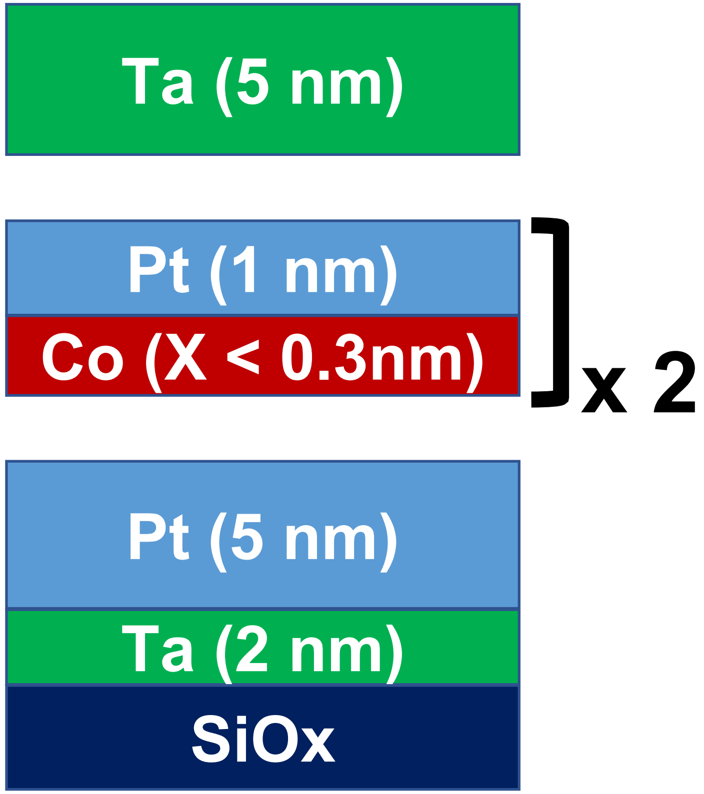


- **Stripes grow at an angle relative to *J***
  - **Interpreted as skyrmion Hall effect**

Y. Hirata *et al.*, Nature Nanotech. 14, 232 (2019)
S. Zhang *et al.*, SciAdv 6, 1876 (2020)
S. Yang, *et al.*, Adv. Quant. Tech. 4, 2000060 (2021)

Low exchange: thin Co layers

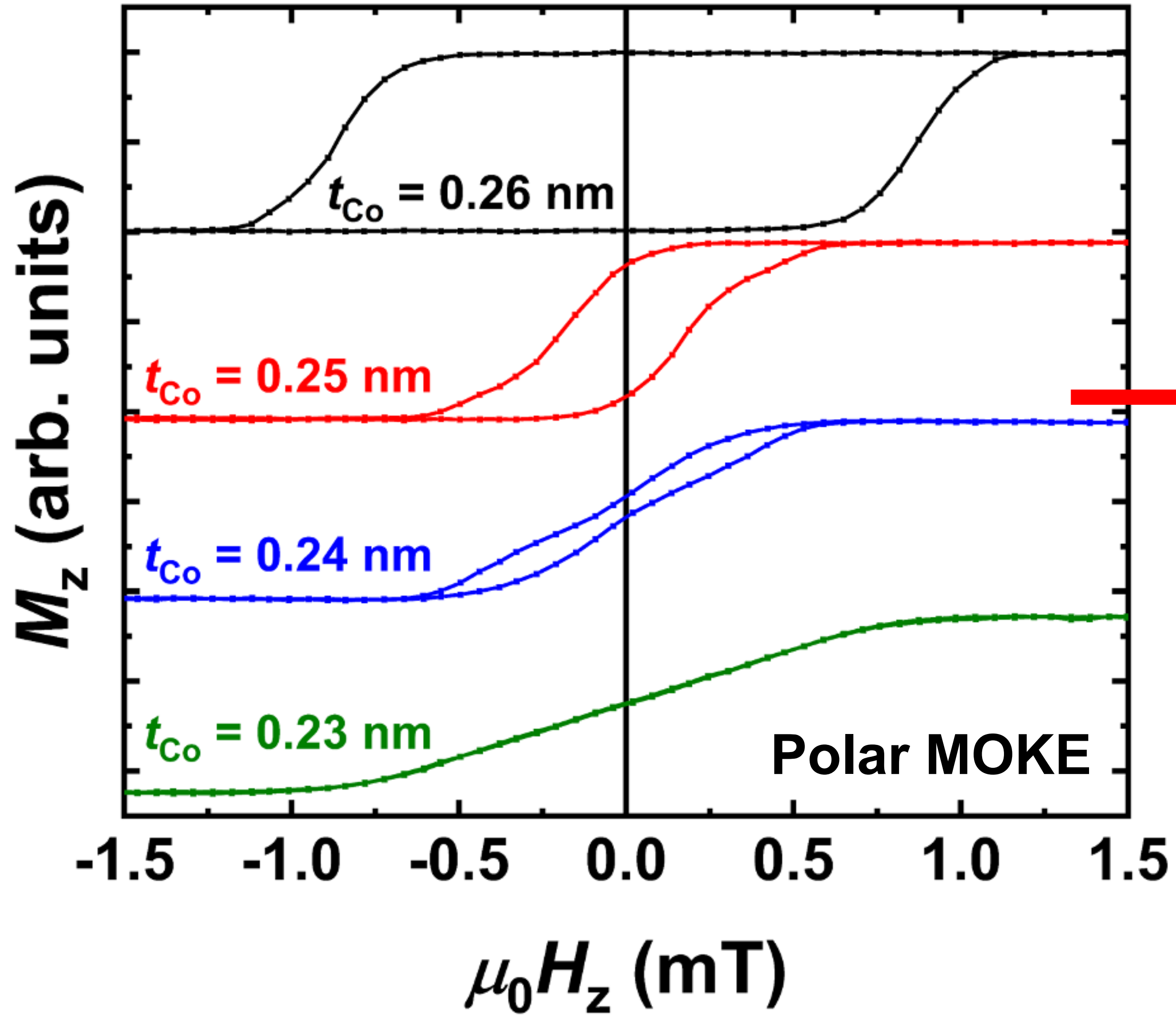


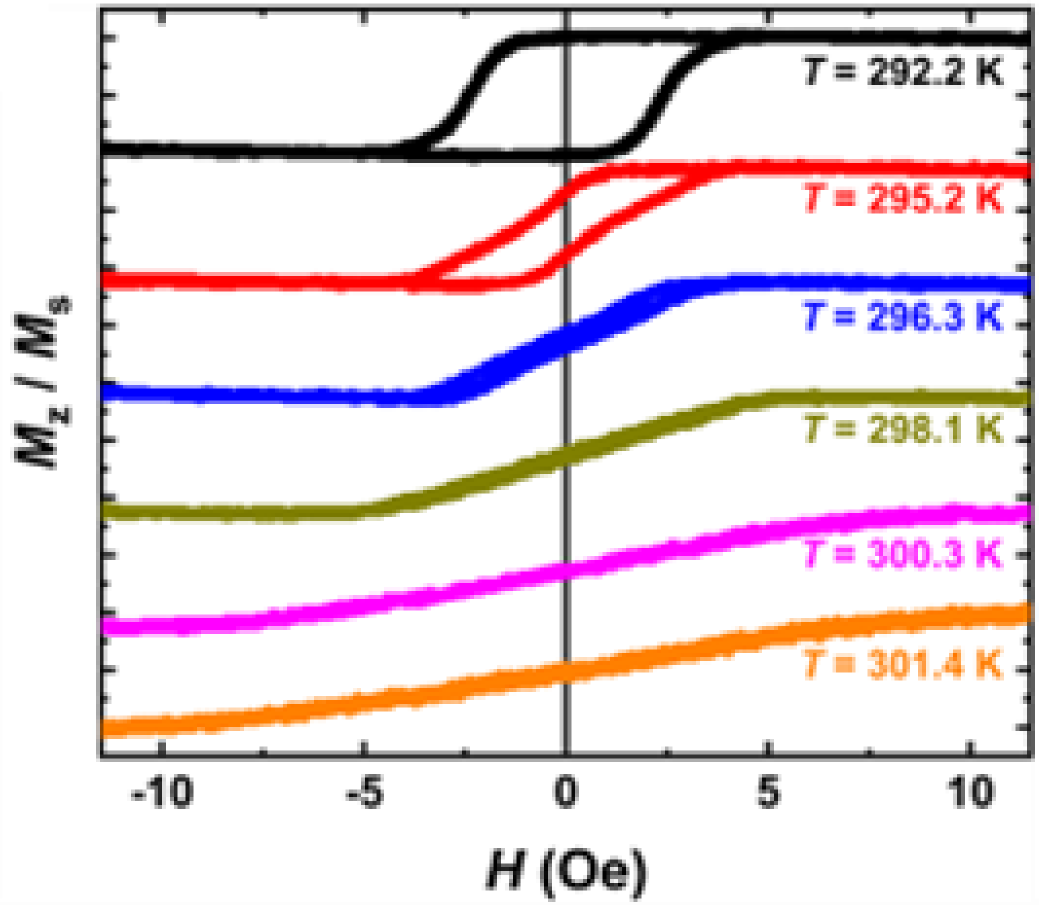


Modest DMI D = -0.14 mJ/m²

Brock & Fullerton, *Advanced Materials Interfaces* **9**, 2101708 (2022).

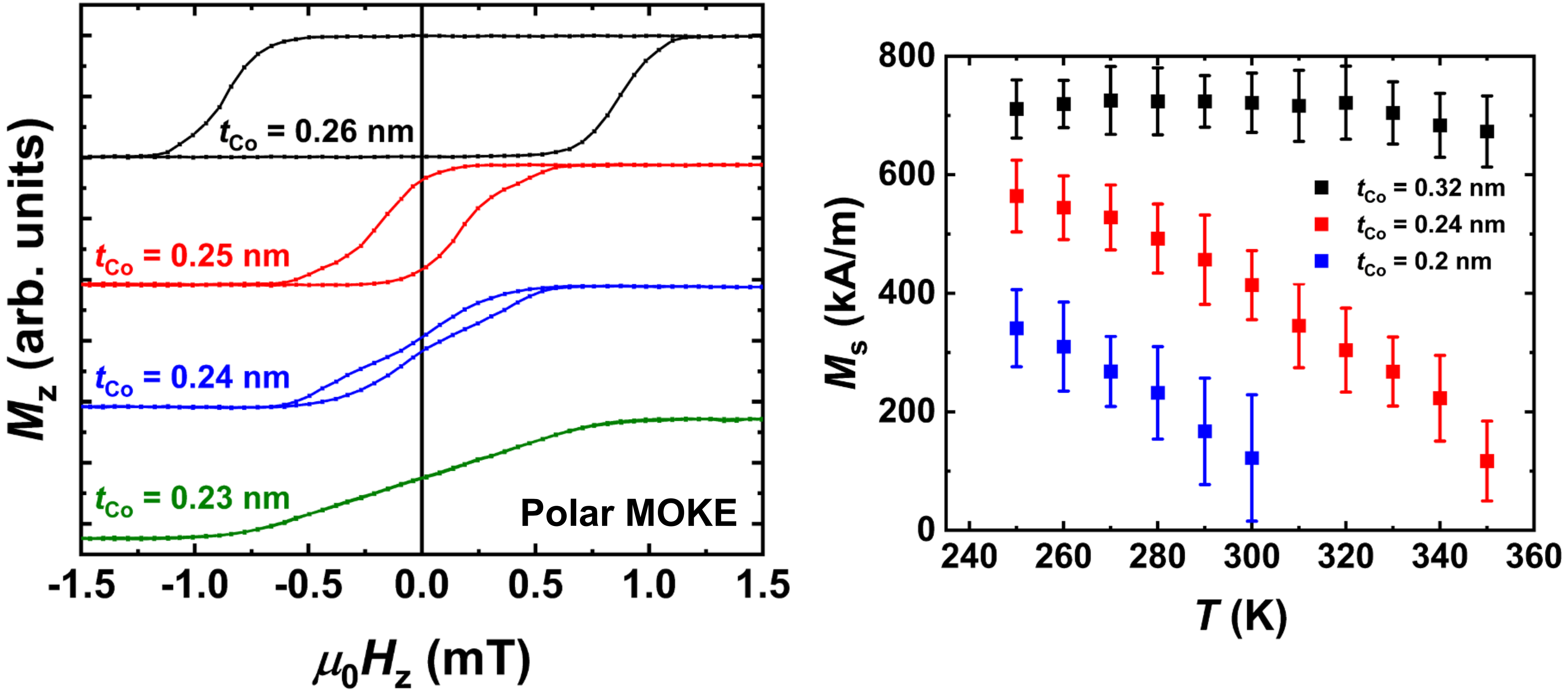
Thin Co layers





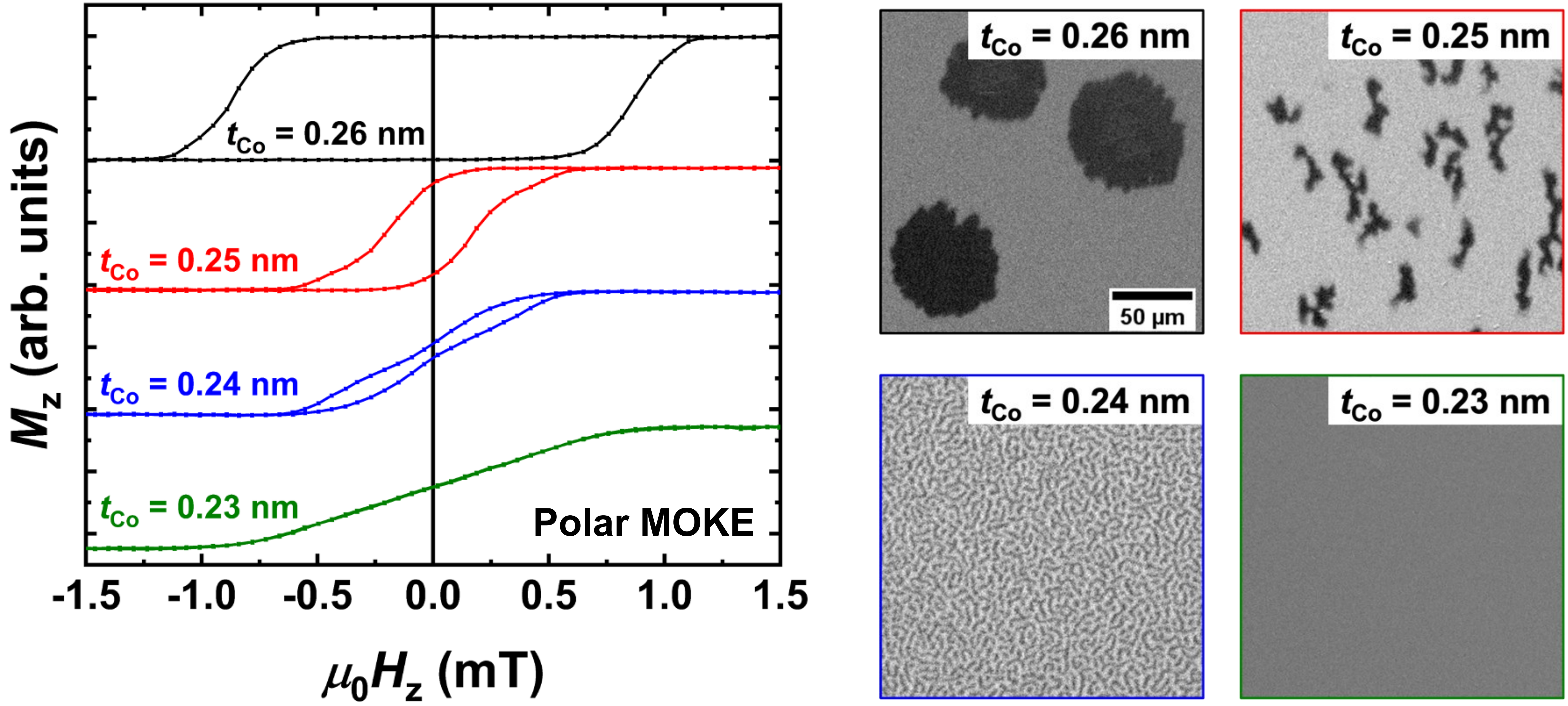
Brock & Fullerton, *Advanced Materials Interfaces* **9**, 2101708 (2022).

Thin Co layers



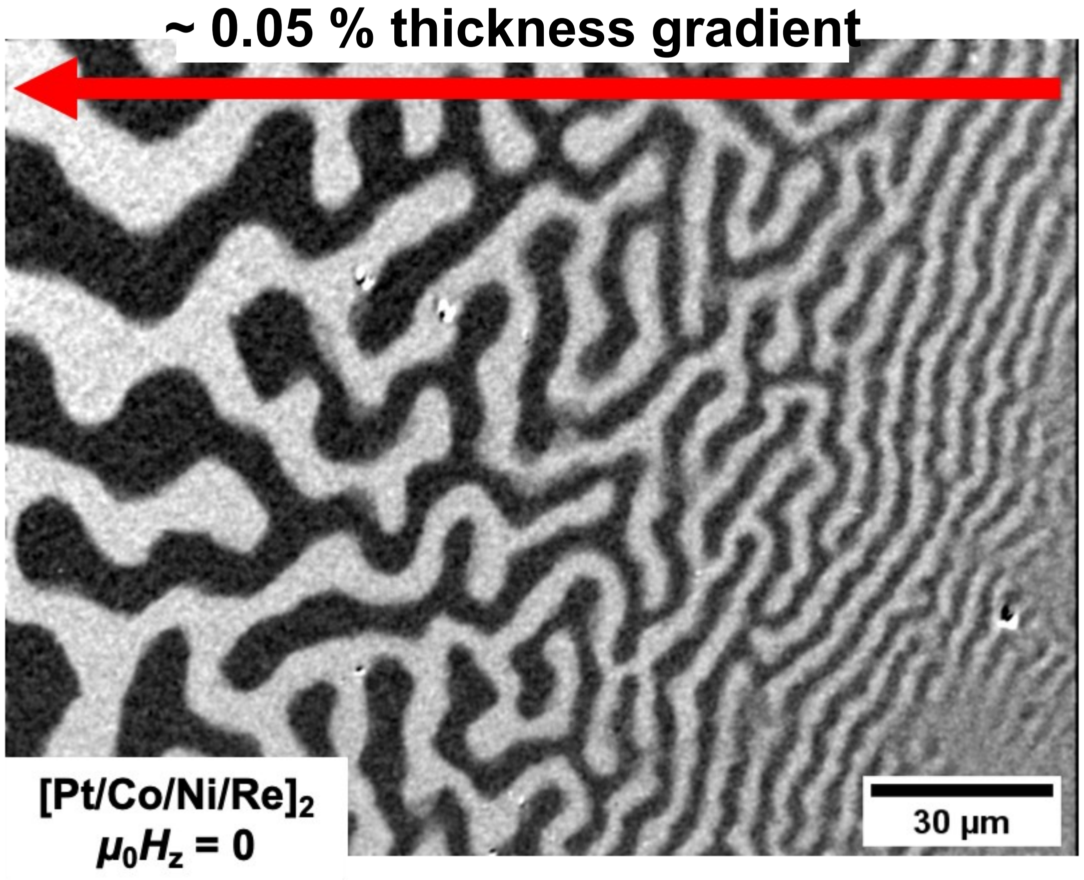
Brock & Fullerton, *Advanced Materials Interfaces* **9**, 2101708 (2022).

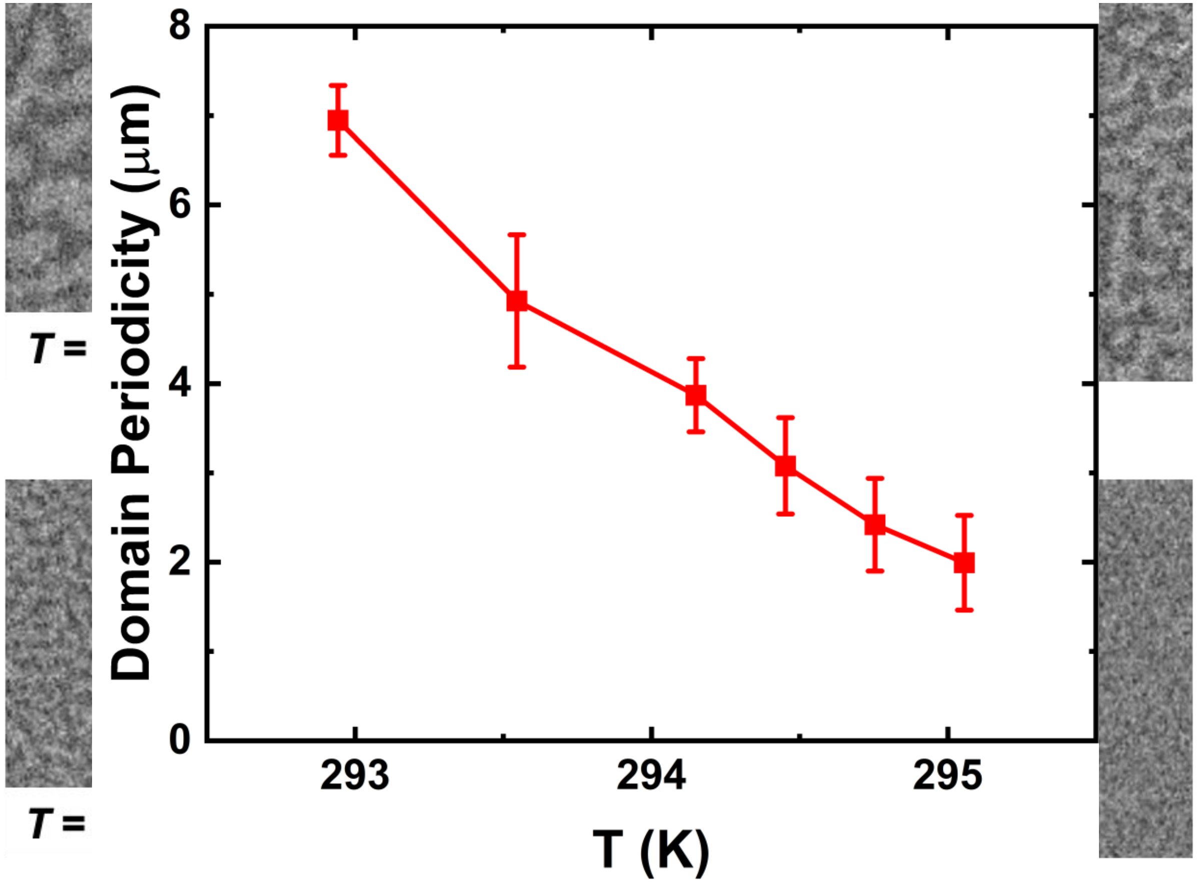
Thin Co layers



Brock & Fullerton, *Advanced Materials Interfaces* **9**, 2101708 (2022).

Domain size evolution





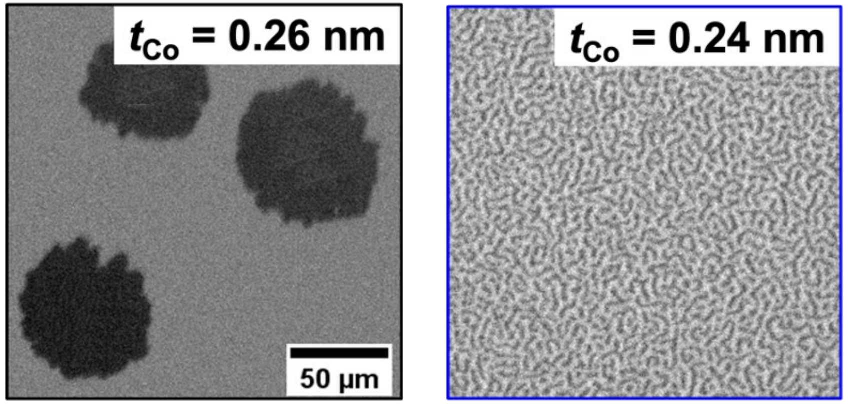
Domain size scales with FM thickness

Domain size decreases with temperature

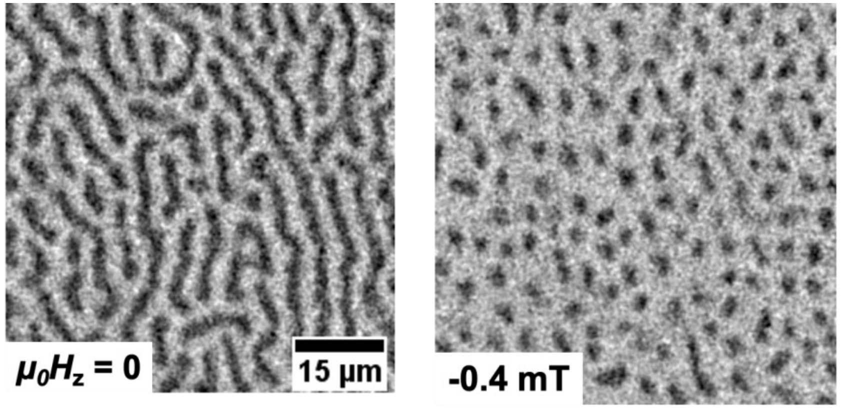
Equivalence b/t changing thickness and changing temperature

Nature of the transition

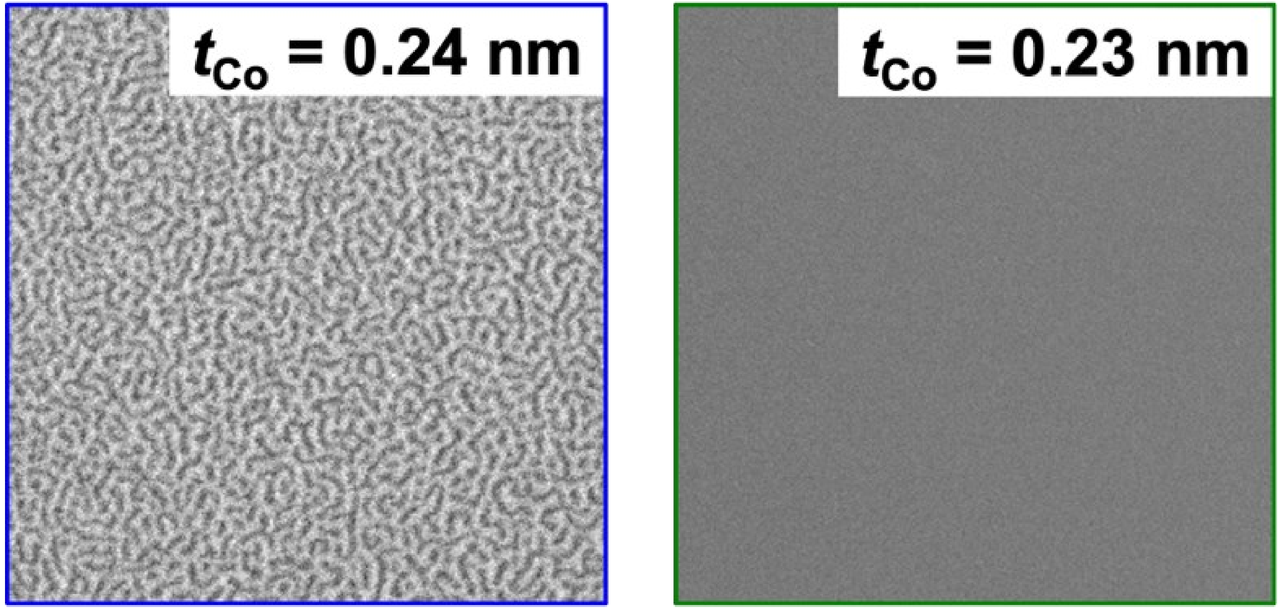
Bubbles to Labyrinthine Stripes ✓



Labyrinthine Stripes to Skyrmions ✓



Labyrinthine Stripes to ?



Similar results in Pt/Co/Os/Pt structures
Tolley *et al.*, Phys. Rev. Mater. 2, 044404 (2018)

Spin reorientation transition

SRT occurs when

$$K_{eff} = K_{\perp} - \frac{1}{2}\mu_0 M_s^2 \sim 0$$

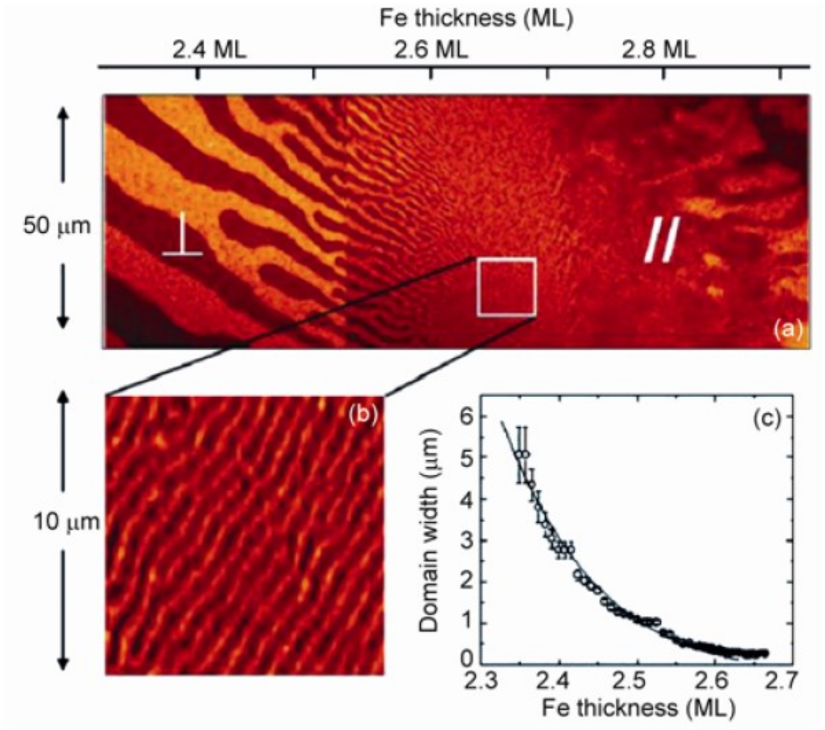
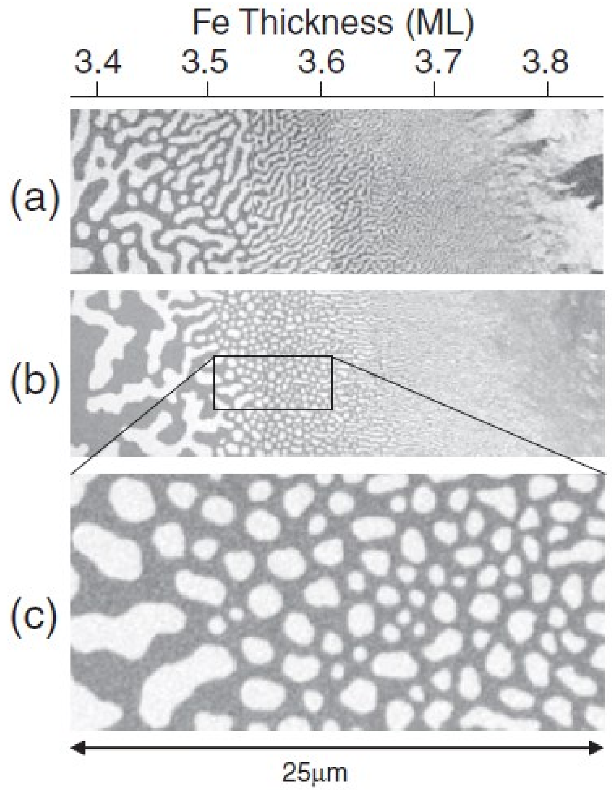


Figure 11 (a) PEEM image of the magnetic domains of Fe/Ni(5 ML)/Cu(001). The stripe domain width decreases as the Fe thickness increases towards to the SRT point at $t_{Fe} \approx 2.7$ ML. (b) A zoom-in image of the magnetic stripes in the box of (a). (c) Stripe domain width versus Fe film thickness. The solid line depicts the theoretical fitting. Taken from Wu et al. [55]. Reprinted with permission from APS.

PRL **98**, 207205 (2007) PHYSICAL REVIEW LETTERS

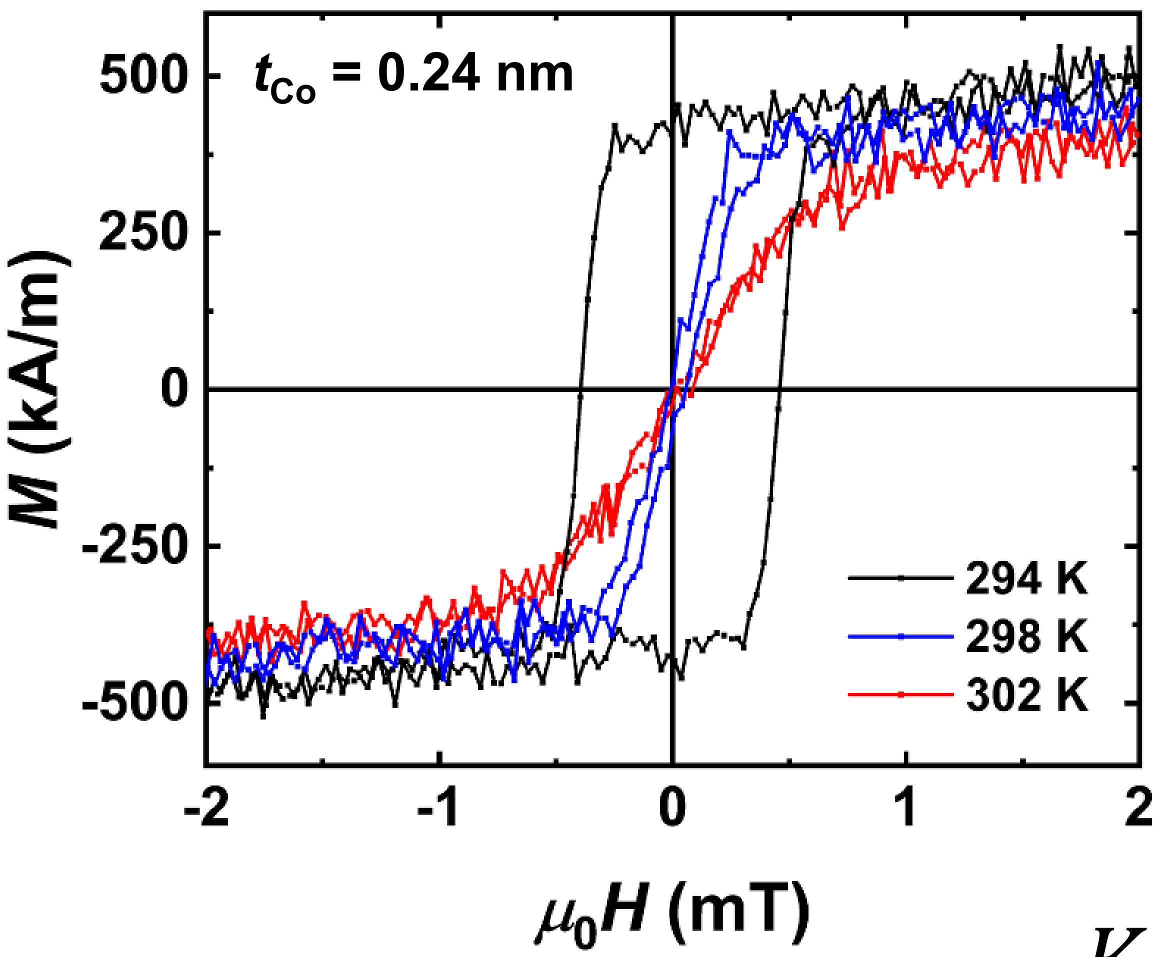
Magnetic Bubble Domain Phase at the Spin Reorientation Transition of Ultrathin Fe/Ni/Cu(001) Film

J. Choi,[1] J. Wu,[1] C. Won,[1,2] Y. Z. Wu,[1,3] A. Scholl,[4] A. Doran,[4] T. Owens,[1] and Z. Q. Qiu[1]

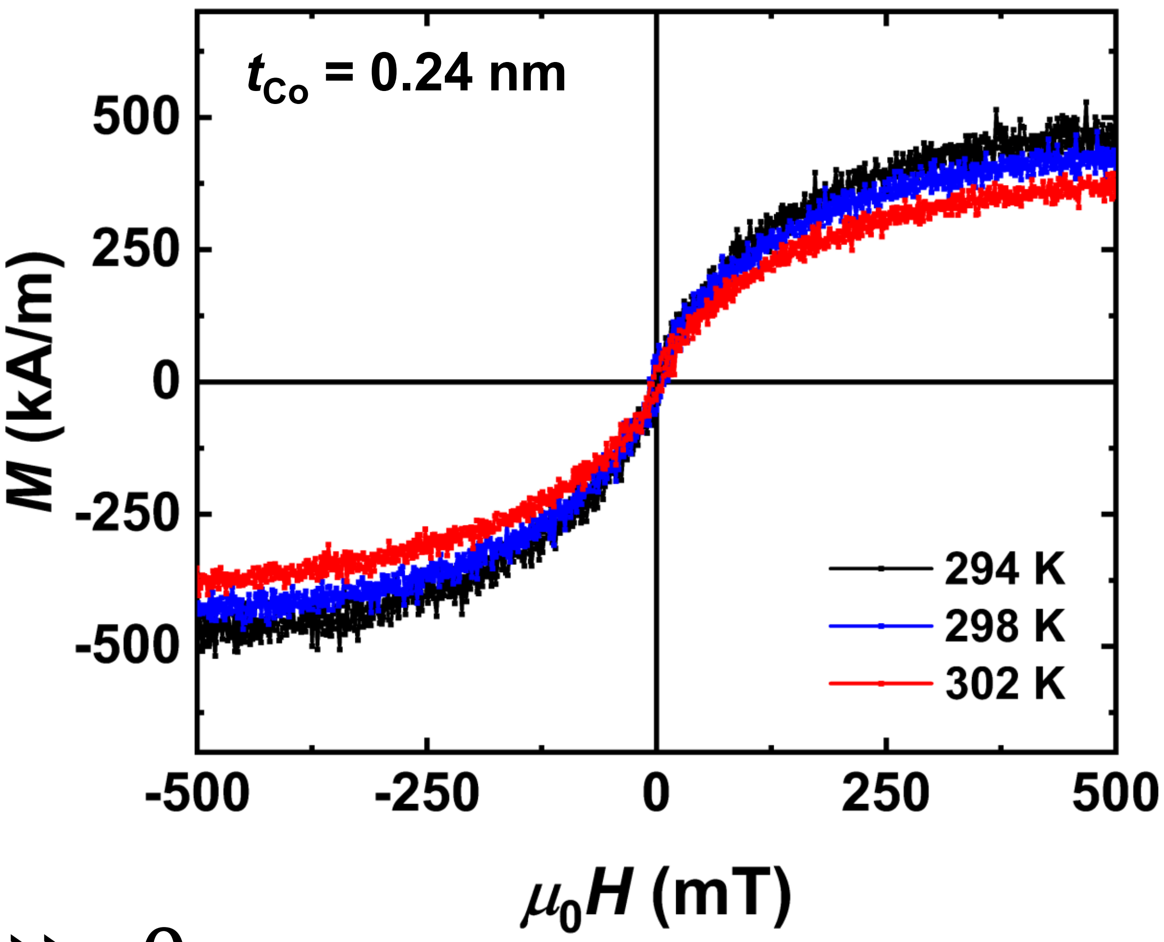


Is this a spin-reorientation transition?

Out-of-Plane



In-Plane

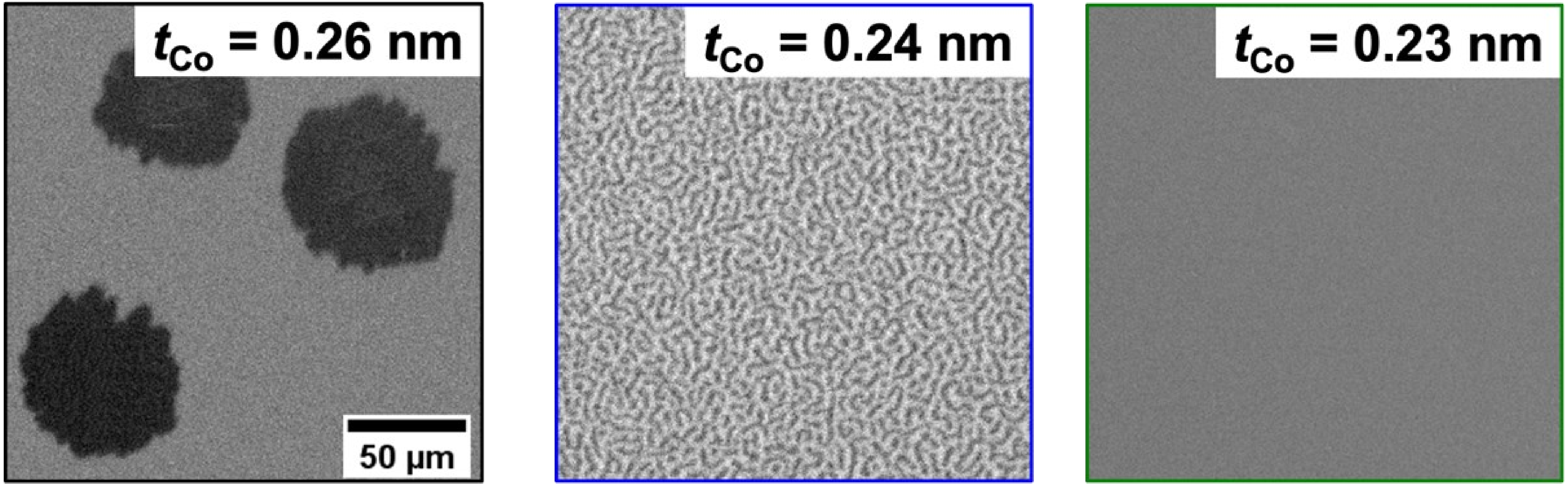


$$K_{eff} \gg 0$$

Nature of the transition

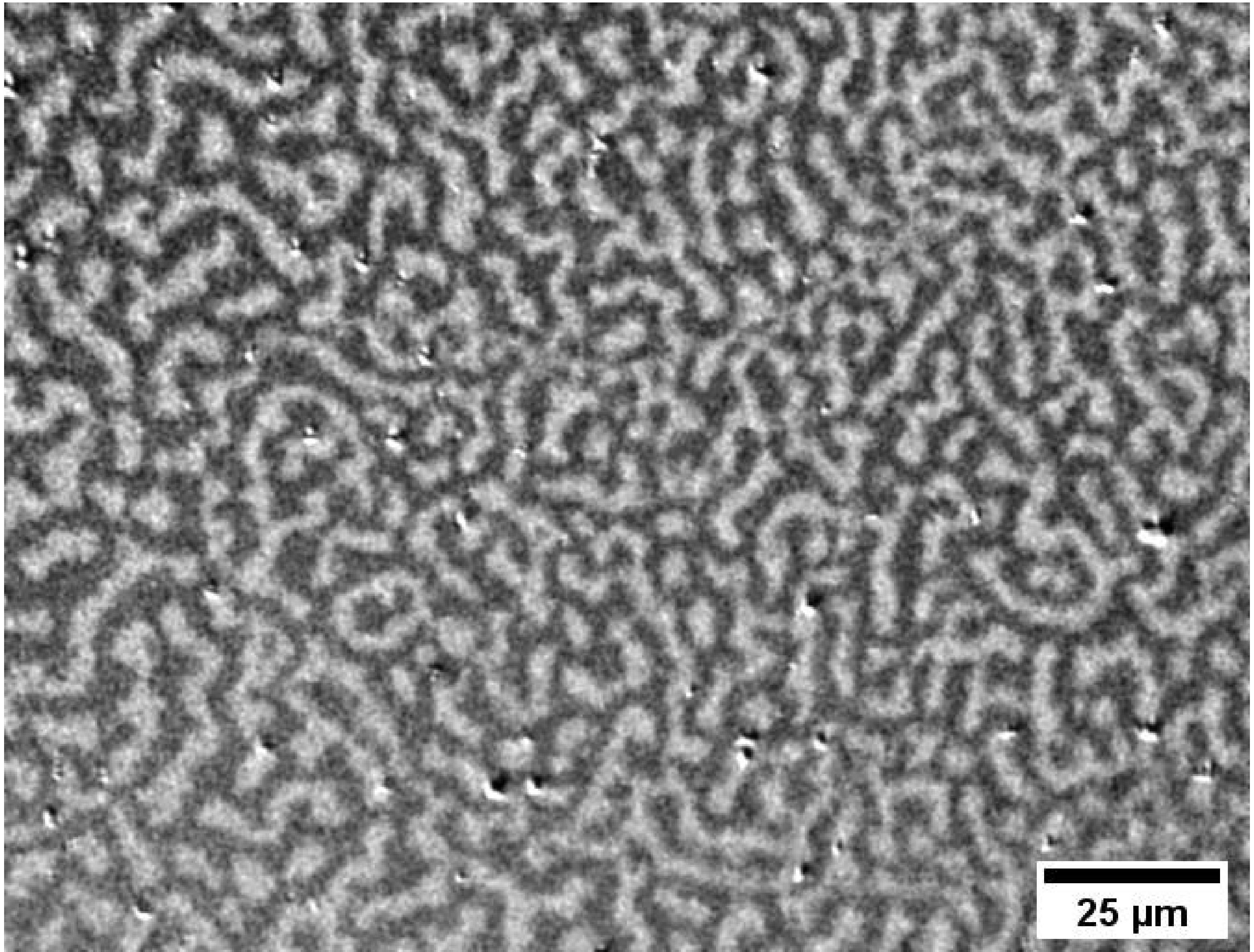
$$\sigma_{DW} = 4\sqrt{A_{ex}K_{eff}} - \pi|D| \qquad \sigma_{DW} \rightarrow 0 \text{ or neg.}$$

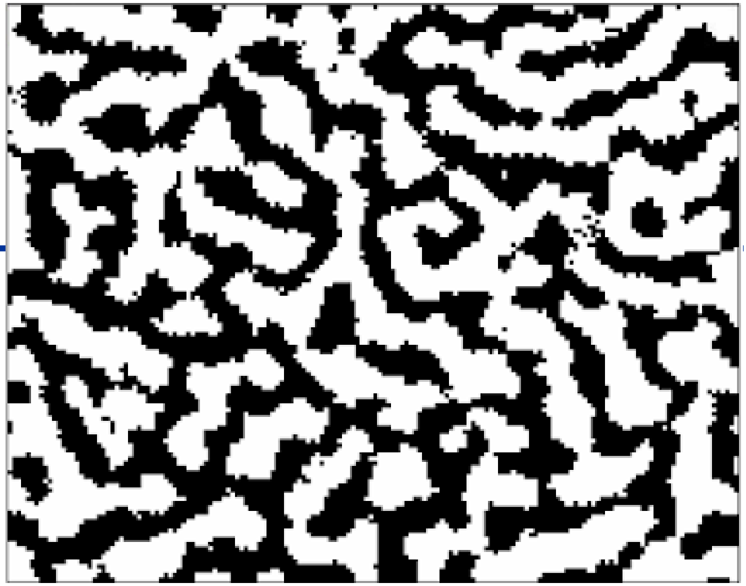
Small large modest

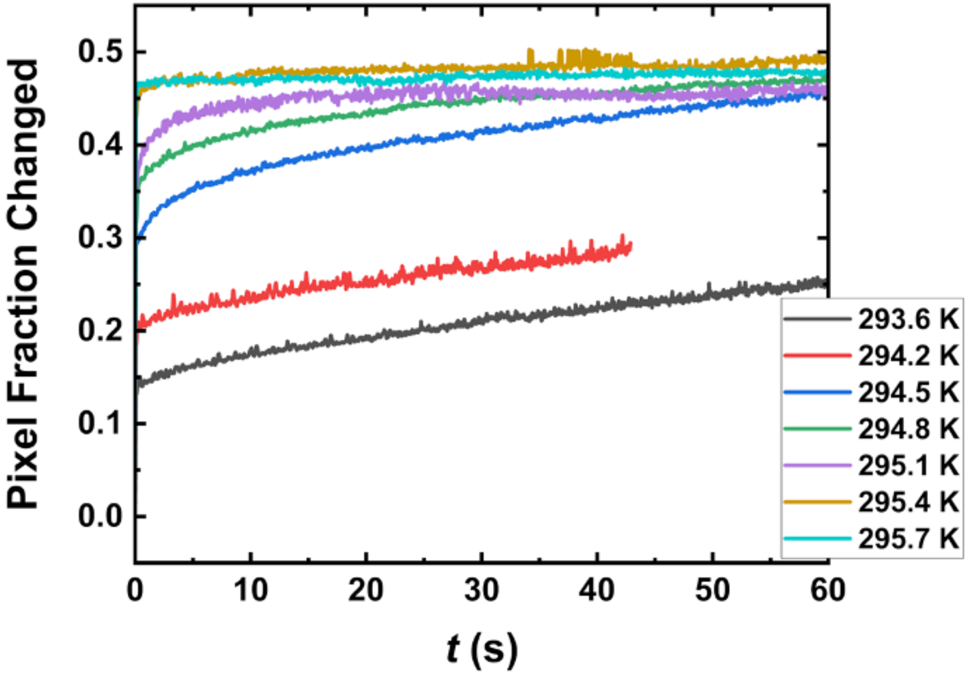


Brock & Fullerton, *Advanced Materials Interfaces* **9**, 2101708 (2022).

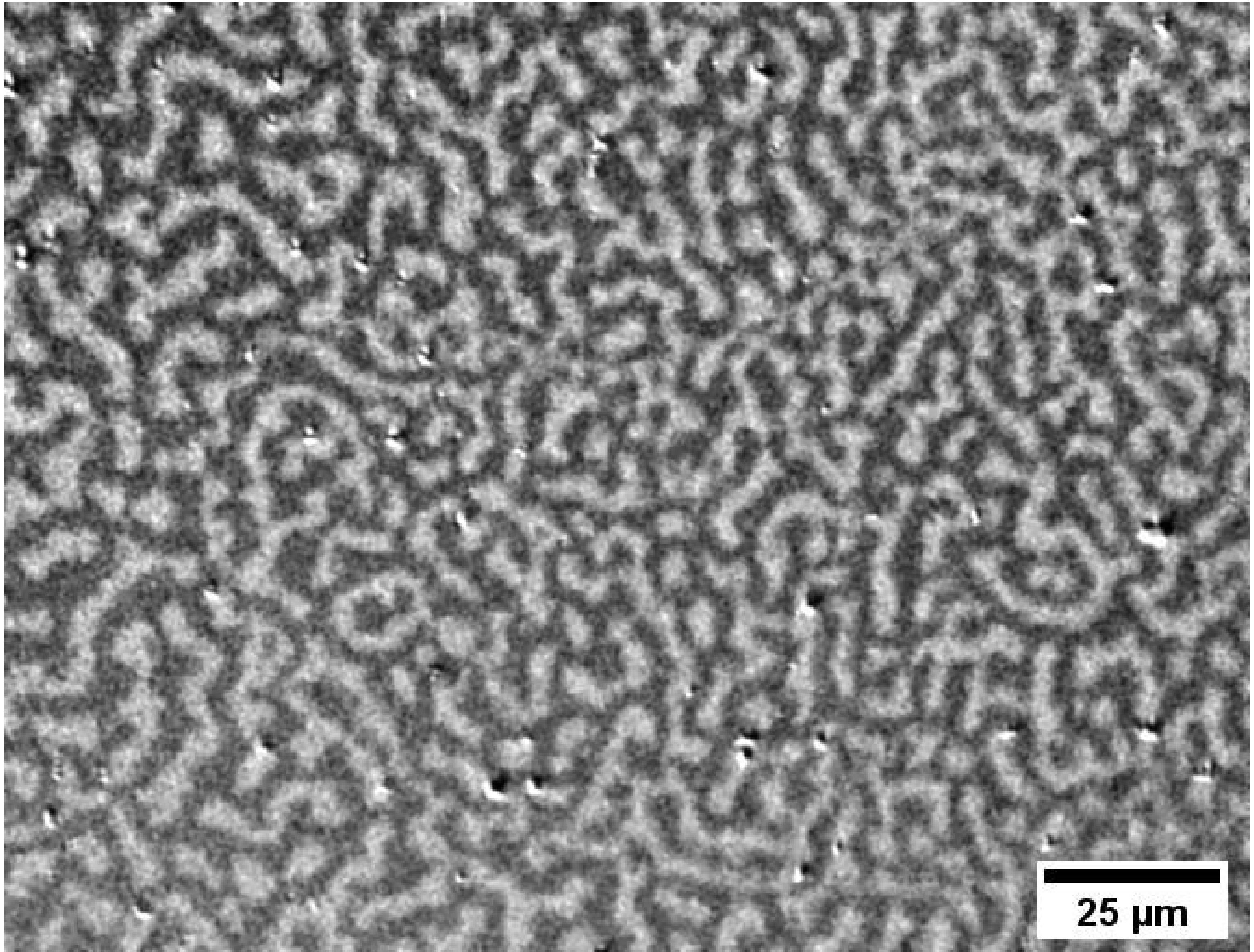
Domain fluctuations

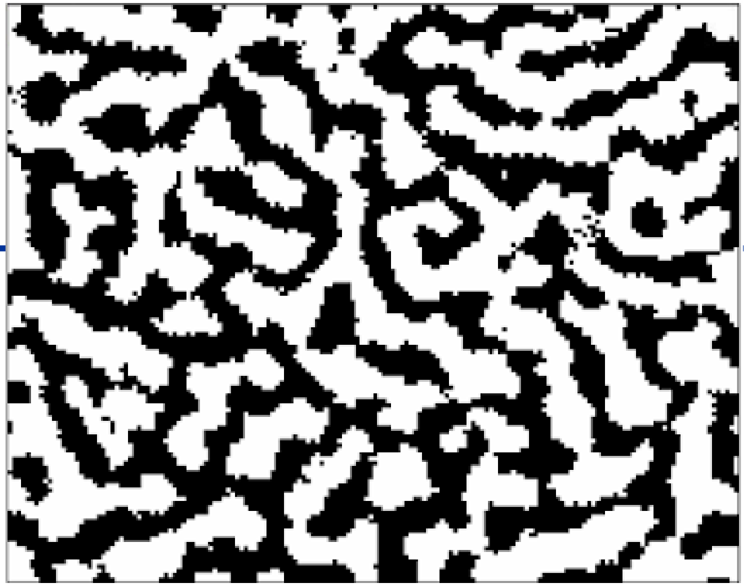


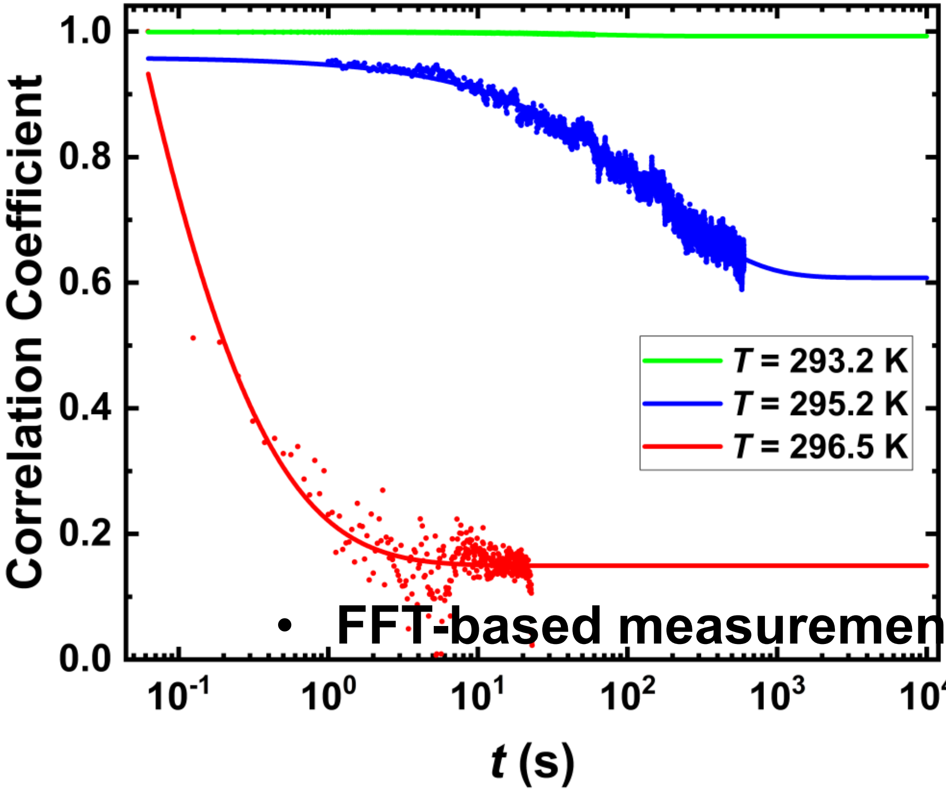




Domain fluctuations

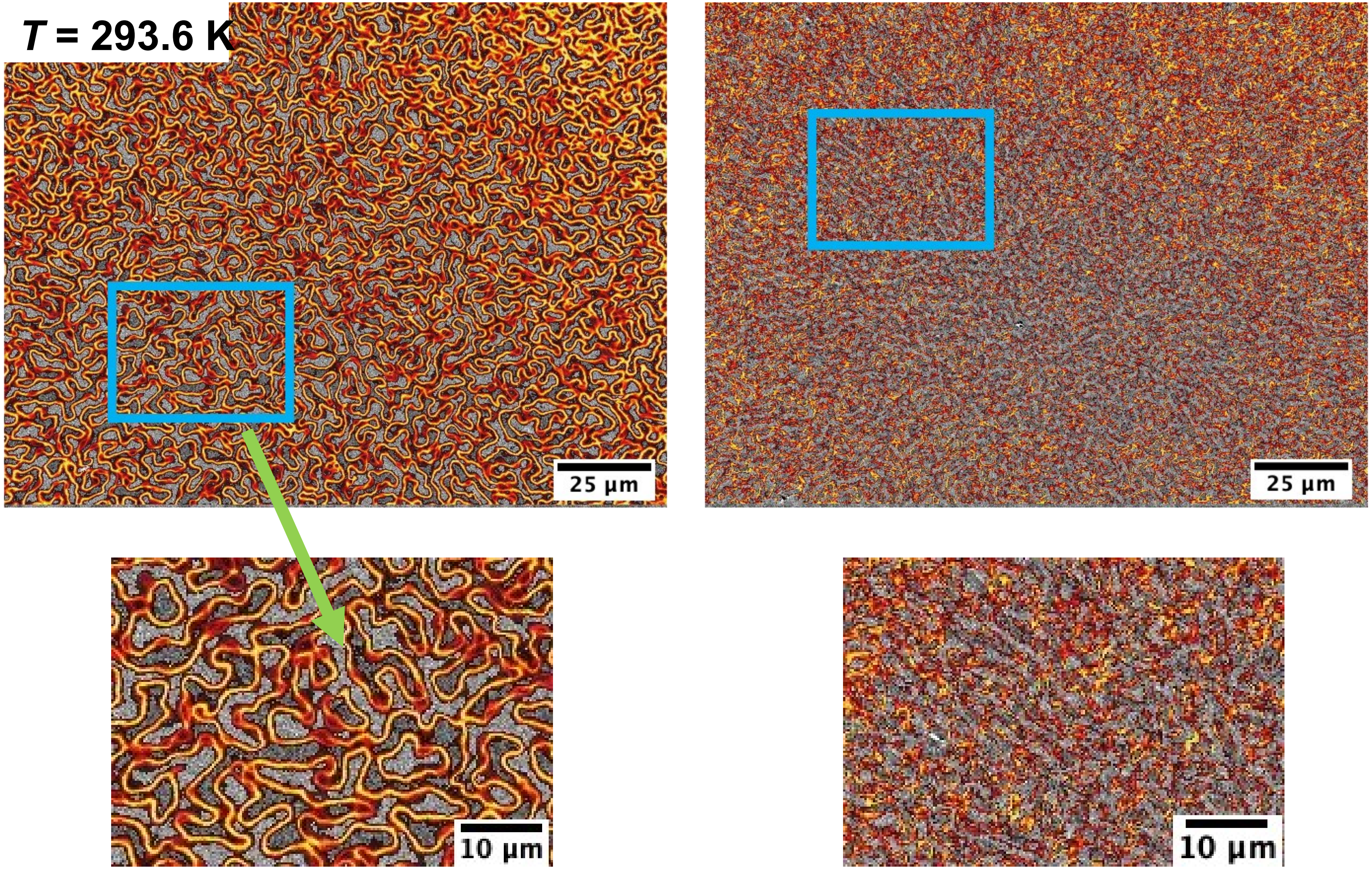






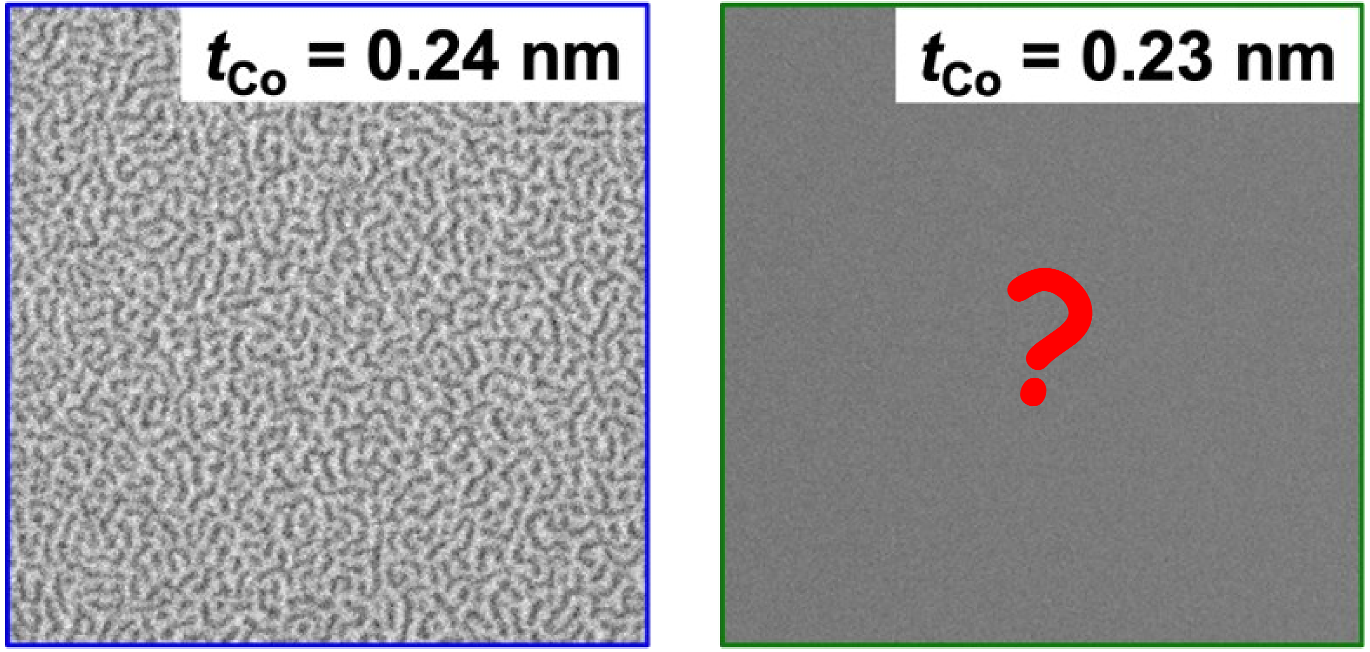
- FFT-based measuremen

Domain fluctuations: heat maps



- **Fluctuation localized to DW**
- **Larger fraction of sample is DWs at higher temperature**
  - **Domain size**

Domain state



- **Stripe domains that are:**
  - **below our spatial resolution**
  - **Fluctuating faster than our temporal resolution**
- **Stripe domain liquid?**
- **Probe the domain fluctuation dynamics?**

PHYSICAL REVIEW B **106**, 054413 (2022)

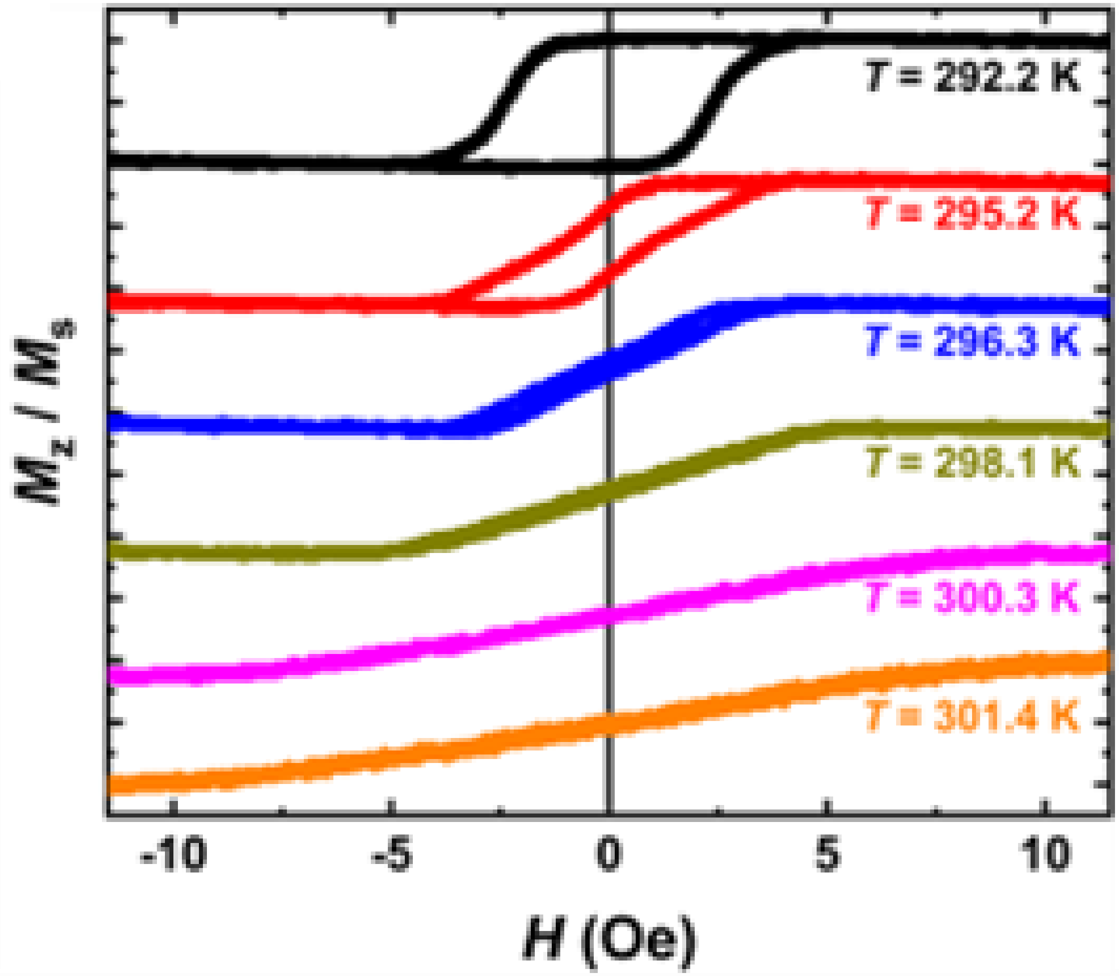
Weakly pinned skyrmion liquid in a magnetic heterostructure

Rhodri Mansell,[1,*] Yifan Zhou,[1] Kassius Kohvakka,[1] See-Chen Ying,[2] Ken R. Elder,[3] Enzo Granato,[4] Tapio Ala-Nissila,[5,6] and Sebastiaan van Dijken[1]

AC susceptibility

- **Anomalous Hall effect**
  - **AC field and lock in the Hall voltage**

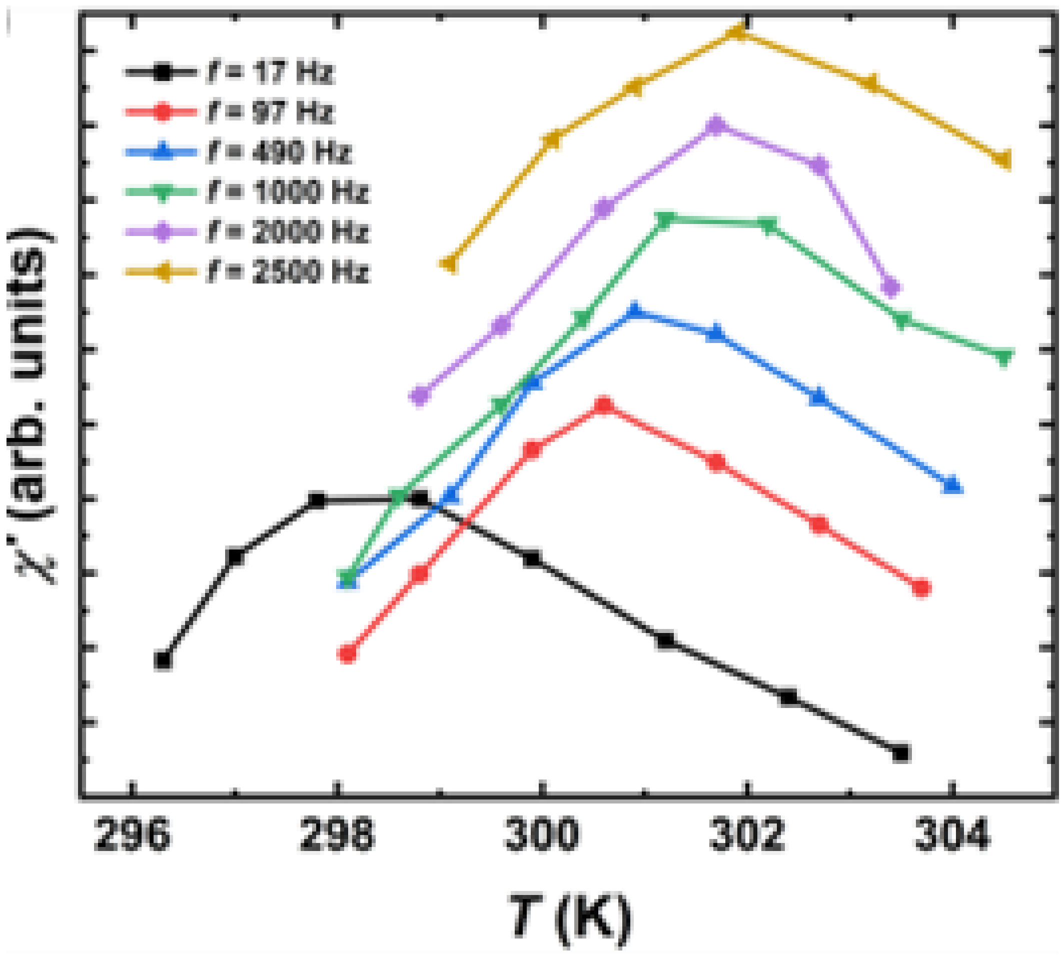
$$\tau = \tau_0 e^{E_B / k_B T}$$



AC susceptibility

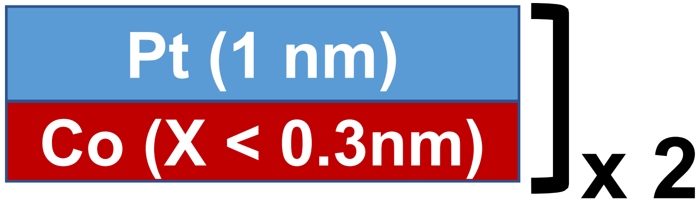
- **Anomalous Hall effect**
  - **AC field and lock in the Hall voltage**

$$\tau = \tau_0 e^{E_B/k_B T}$$



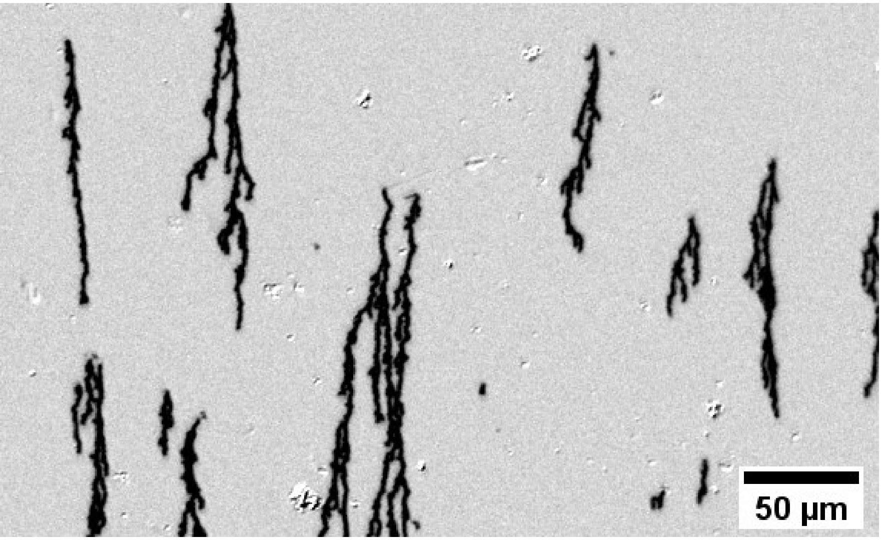
Conclusion

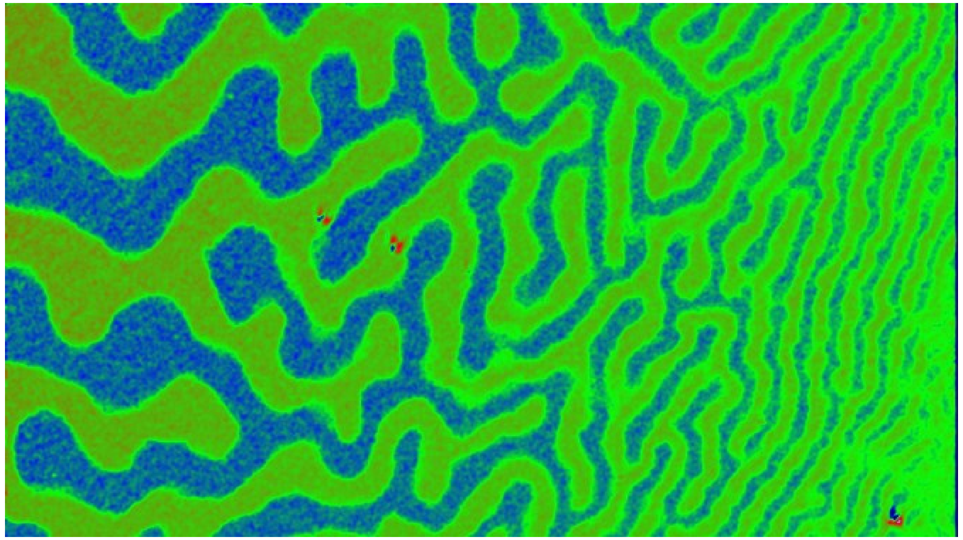
- **Directional growth of stripe domains**
- **Combined effect of iDMI and dynamics**

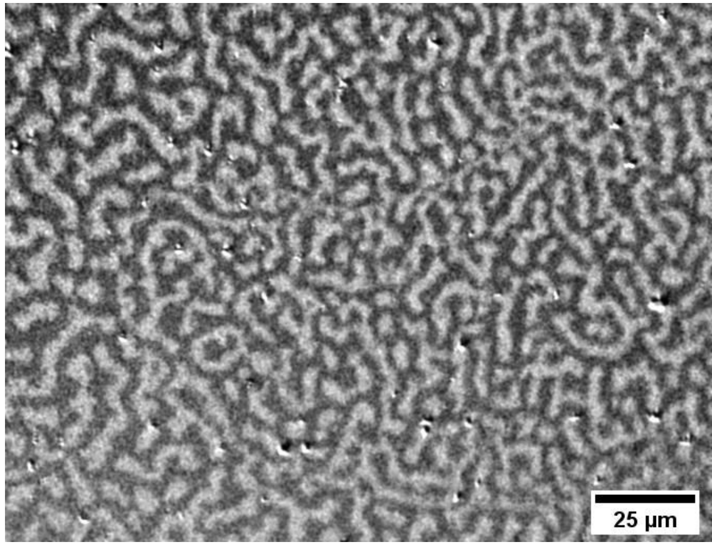


- **Low A_{ex}**
- **Substantial K_{eff}**
- **Moderate D**

$$\sigma_{DW} = 4\sqrt{A_{ex}K_{eff}} - \pi|D| \rightarrow 0$$







Thank you