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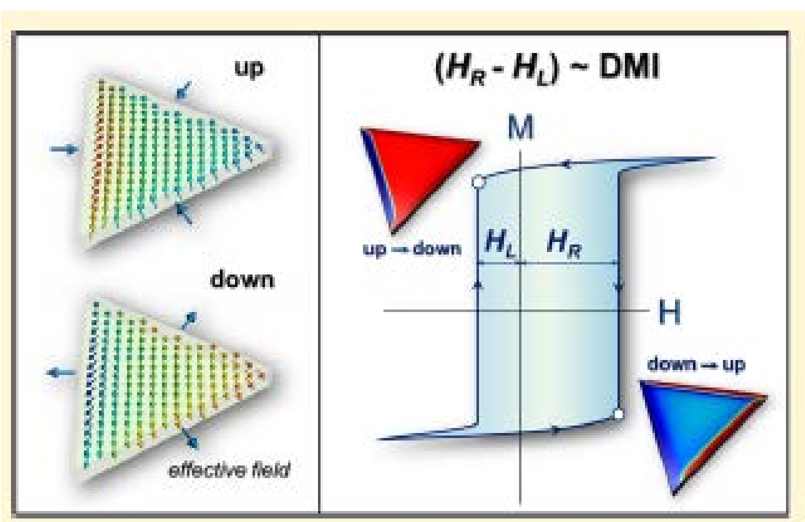
# Shift of Magnetic Hysteresis Loop by Dzyaloshinskii Moriya Interaction in Laterally Asymmetric Microstructure




**24 Nov. 2016**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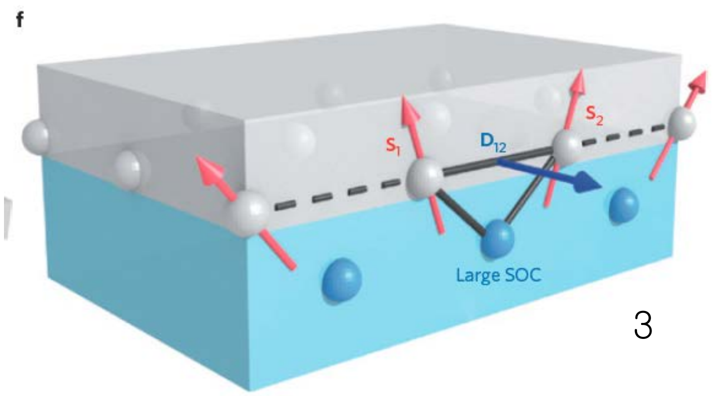
Mathias Klaui

# Contents

- Introduction of DMI
- Measurement technique of DMI
  - Brillouin Light Scattering (BLS)
  - Asymmetric Domain Wall Motion
  - Spin Wave Velocity
- Asymmetric Hysteresis for Probing DMI (*Static Measurement*)

Han, CY *et al*. Nano Lett. **16**, 4438 (2016)

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Spin Phenomena for Information Nano-devices

# DMI (Dzyaloshinskii-Moriya Interaction)

- Most general expression for two sites exchange energy

$$E_{ex} = \sum_{i \neq j} \vec{S}_i^{+} \overleftrightarrow{A}_{ij} \vec{S}_j$$

$$\overleftrightarrow{A}_{ij}^{S} = \frac{1}{2}\left(\overleftrightarrow{A}_{ij} + \overleftrightarrow{A}_{ij}^{+}\right)$$

$$\overleftrightarrow{A}_{ij} = J_{ij}\overleftrightarrow{I} + \overleftrightarrow{A}_{ij}^{S} + \overleftrightarrow{A}_{ij}^{A}$$

$$\overleftrightarrow{A}_{ij}^{A} = \frac{1}{2}\left(\overleftrightarrow{A}_{ij} - \overleftrightarrow{A}_{ij}^{+}\right)$$

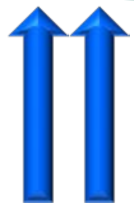
- Antisymmetric exchange interaction (DMI)

$$E_{ex}^{A} = \sum_{i \neq j} \vec{S}_i^{+} \overleftrightarrow{A}_{ij}^{A} \vec{S}_j = -\sum_{i \neq j} \vec{D}_{ij} \cdot \left(\vec{S}_i \times \vec{S}_j\right)$$

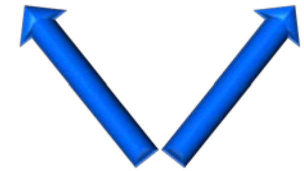
  - Dzyaloshinskii (1958): purely symmetry
  - Moriya (1960) : microscopic mechanism

# What's the role of DMI?

$$E_{ex} = -\sum_{i \neq j} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



$$E_{DMI} = -\sum_{i \neq j} \vec{D}_{ij} \cdot \left( \vec{S}_i \times \vec{S}_j \right)$$



- EC (exchange coupling) prefers aligned spins
- DMI prefers perpendicular spin configurations
  - They compete each other, spiral spin configuration!
- Domain walls (DW) with different chirality have different energies due to the DMI
  - Walker breakdown is suppressed
- Formation of *Skyrmion* (small, stable, and easy to move)

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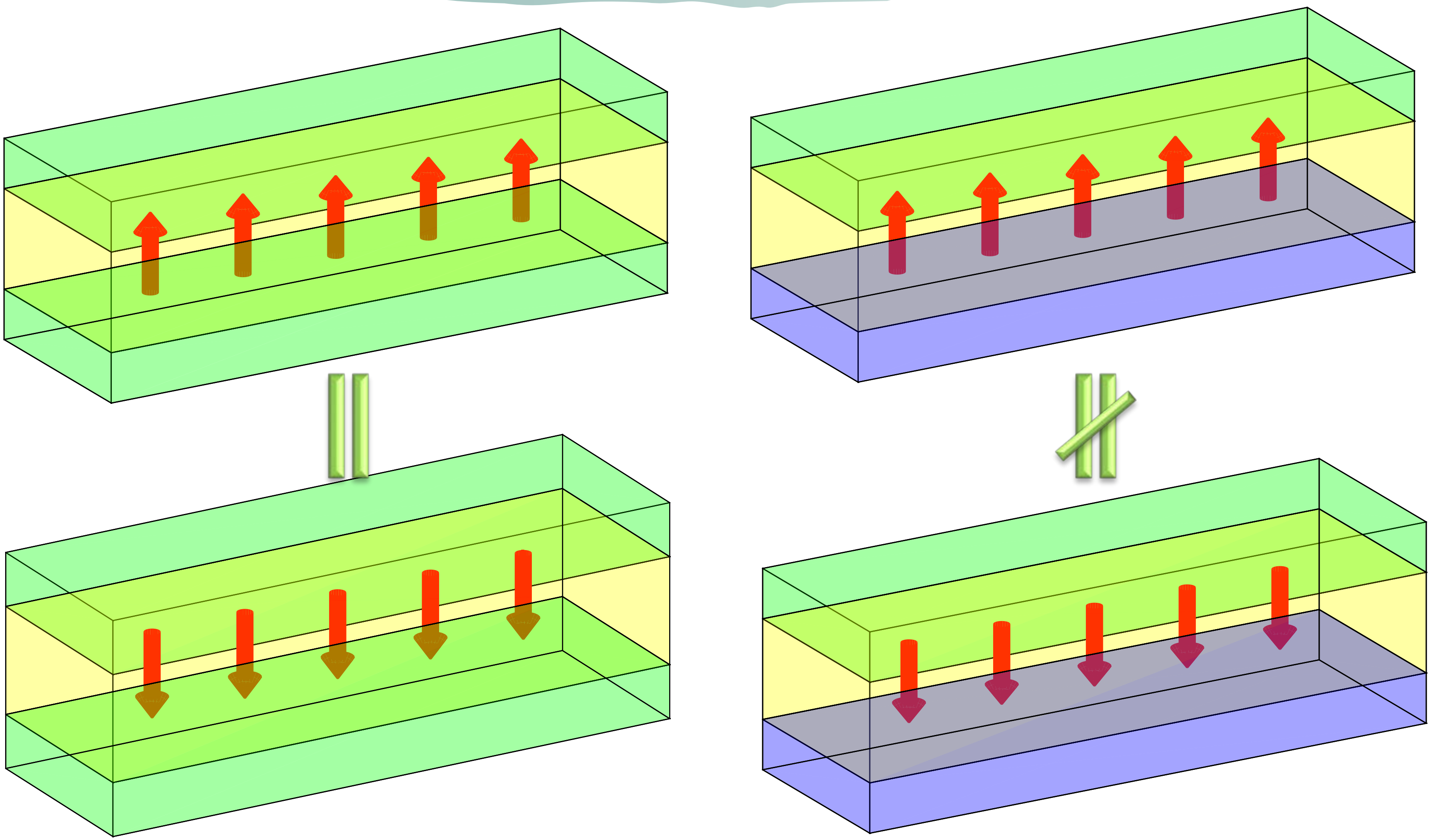
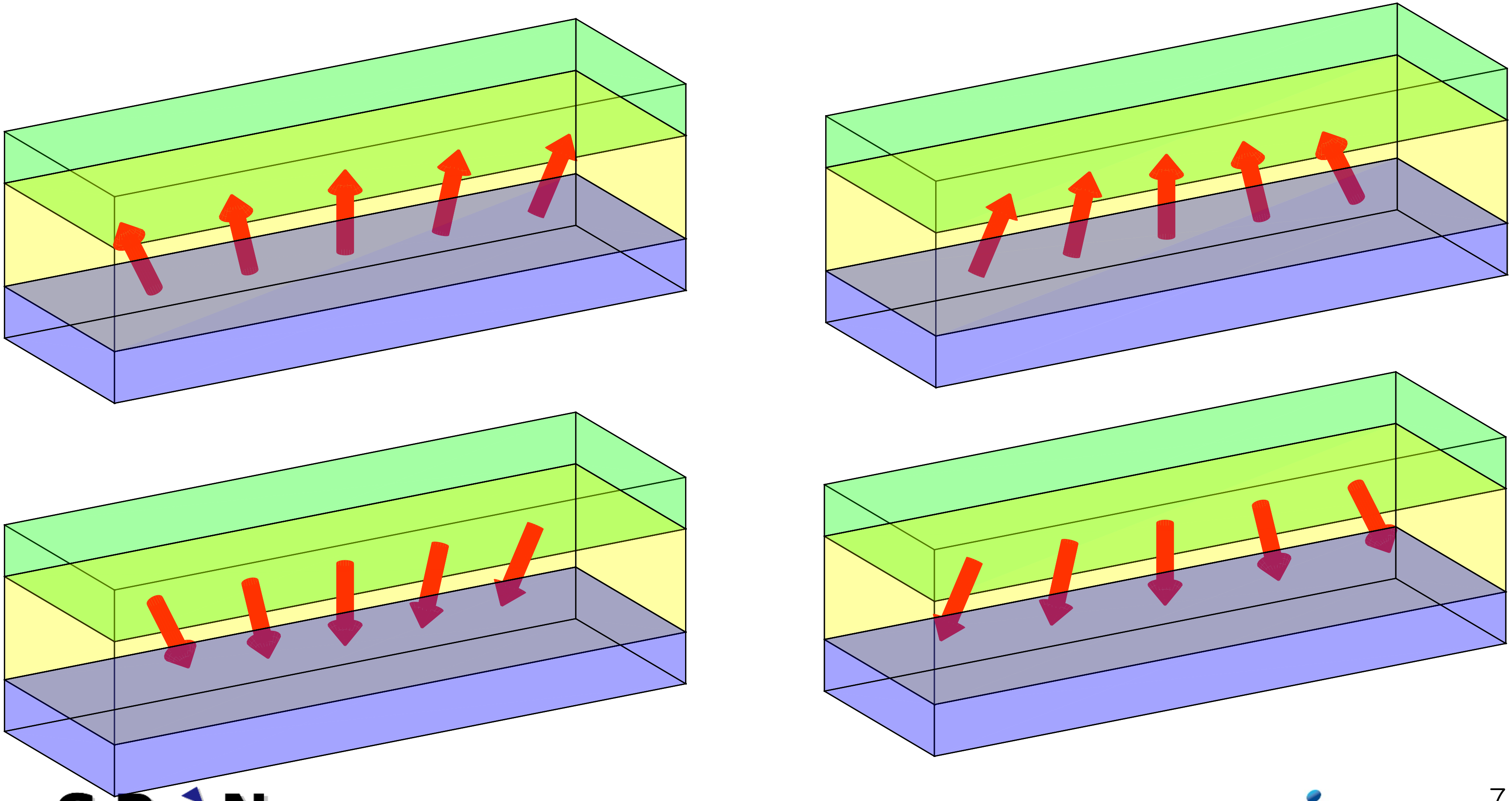
# Inversion Symmetry Breaking



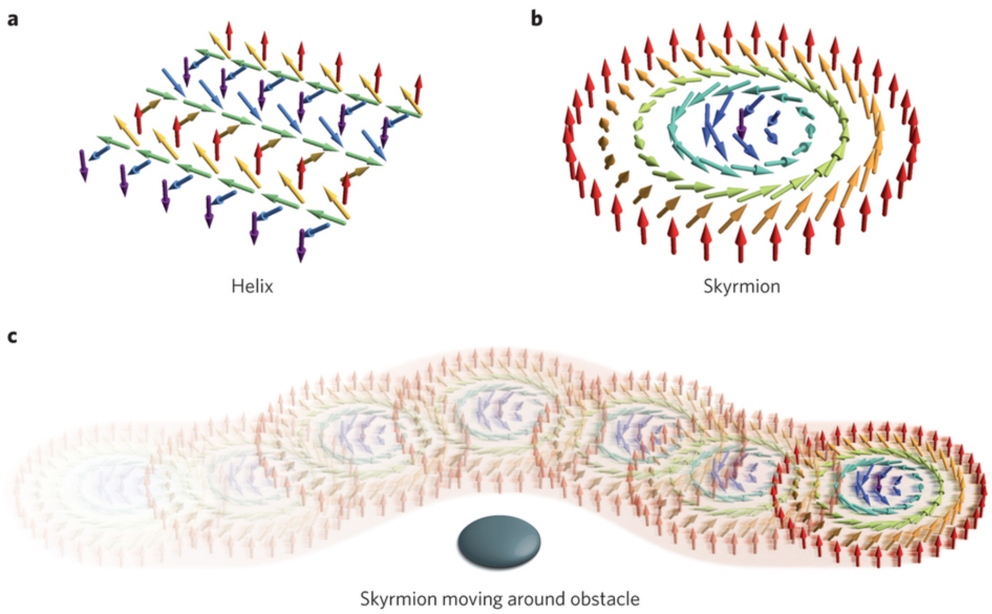
# Dzyaloshinskii-Moriya Interaction

$$E_{DMI} = -\sum_{i \neq j} \vec{D}_{ij} \cdot \left( \vec{S}_i \times \vec{S}_j \right)$$

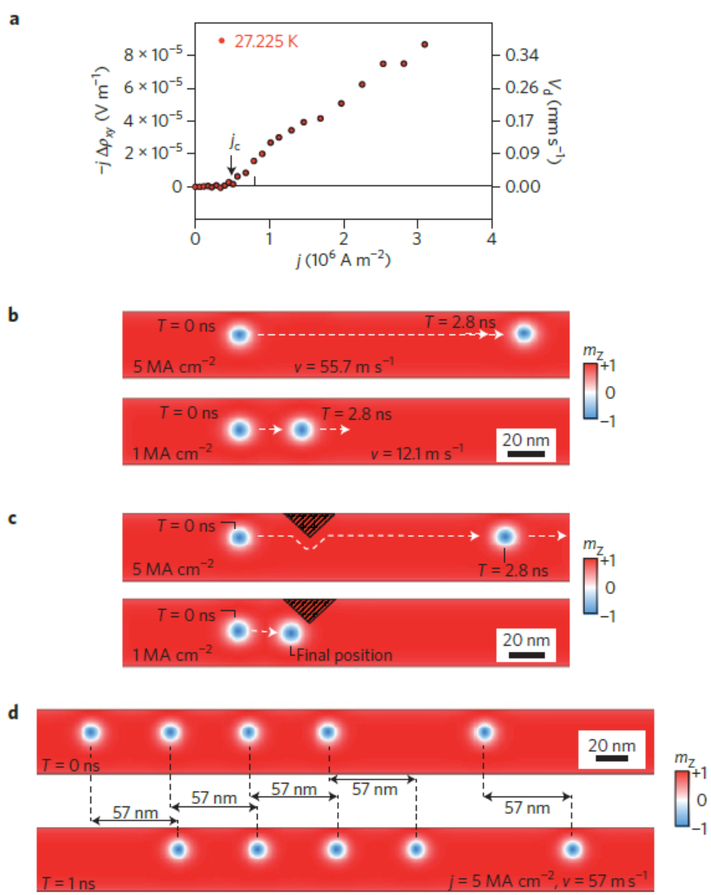


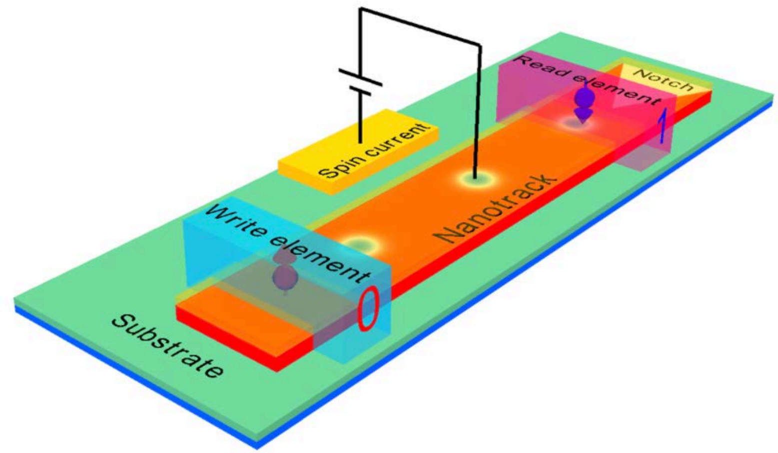
# Skyrmion for future memory/logic devices

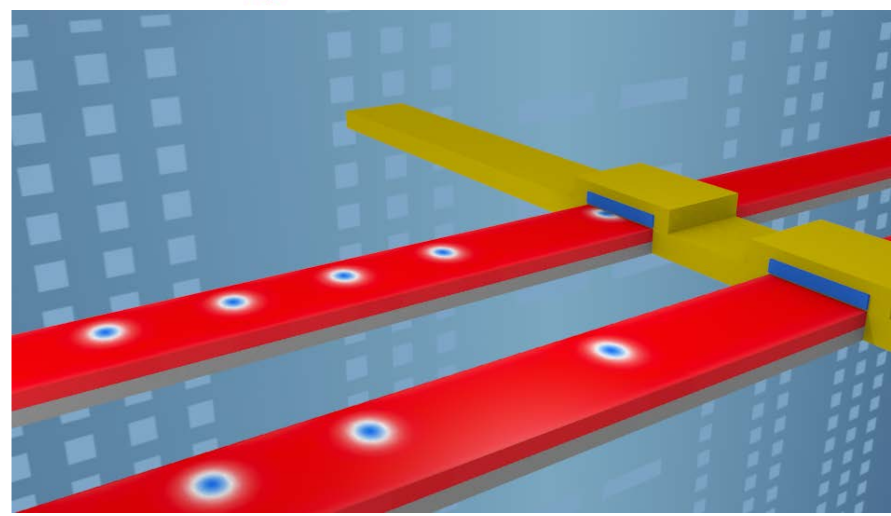
- Skyrmion is topologically stable and small object
- Easily moving with small field or current
- Broad ground state energy of skyrmions



# Skyrmion-ics

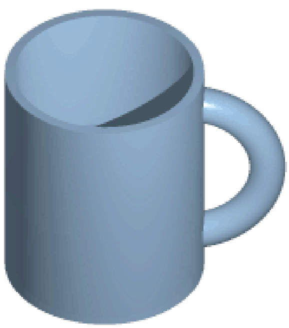


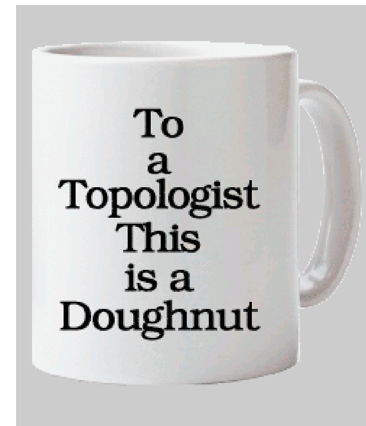



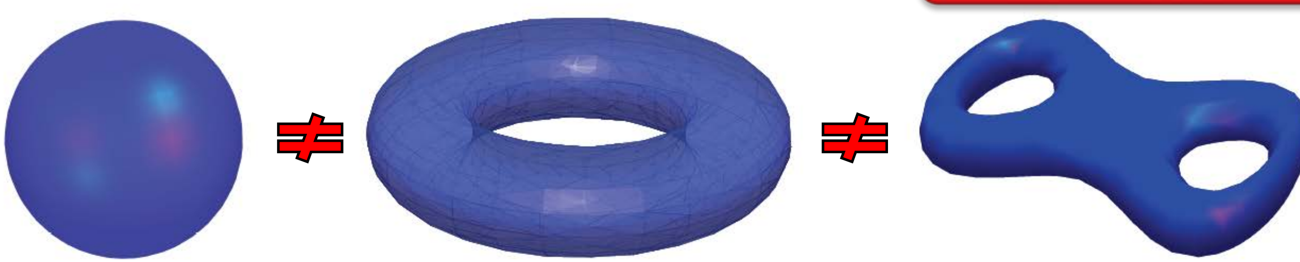
# Topologically protected Skyrmion

- Topologically same objects, easily deformed



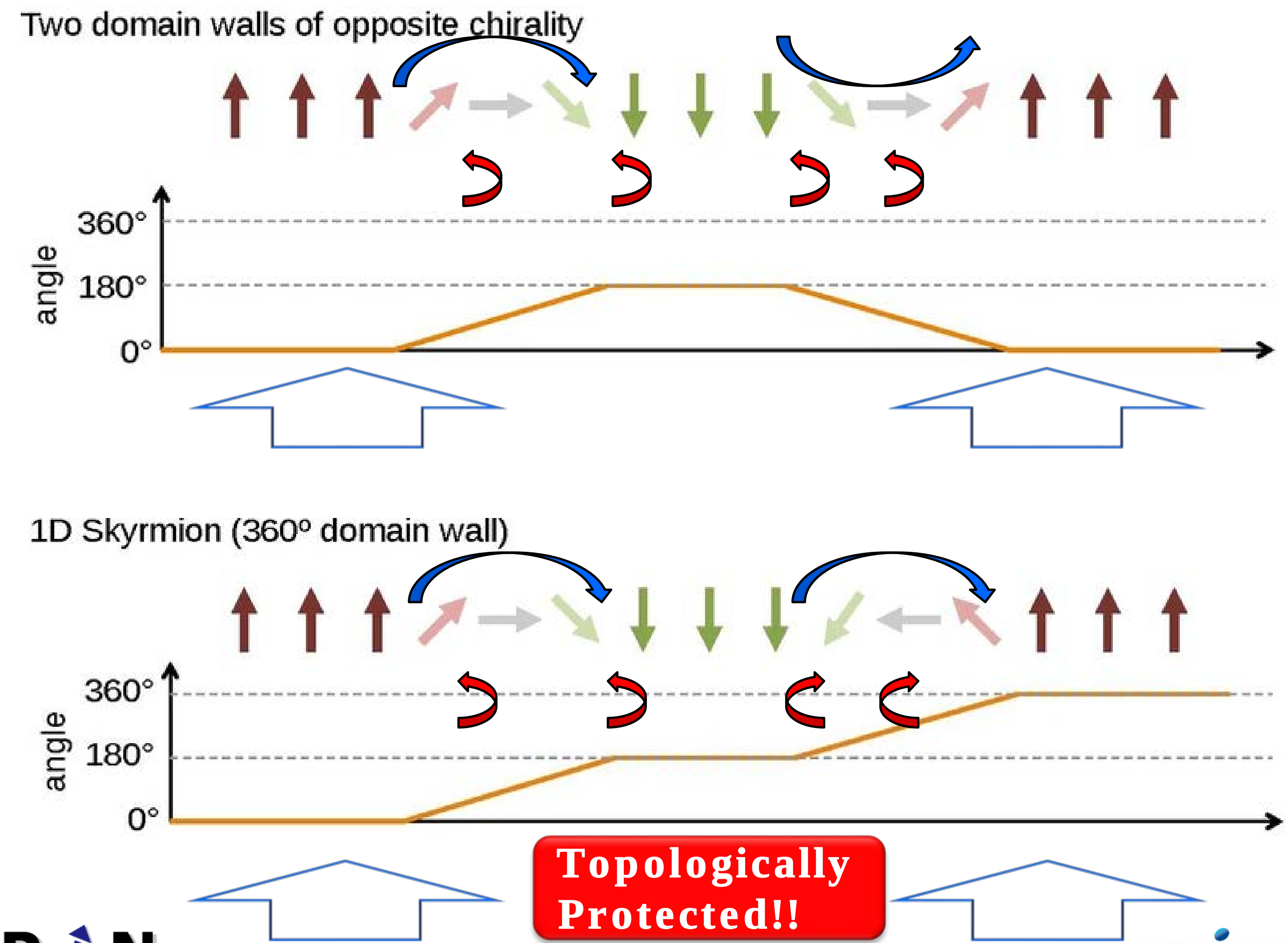



**Topologically different objects**



(a) sphere (b) torus (c) 2-torus

# Topologically Protected 1D Skyrmion




**Topologically Protected!!**

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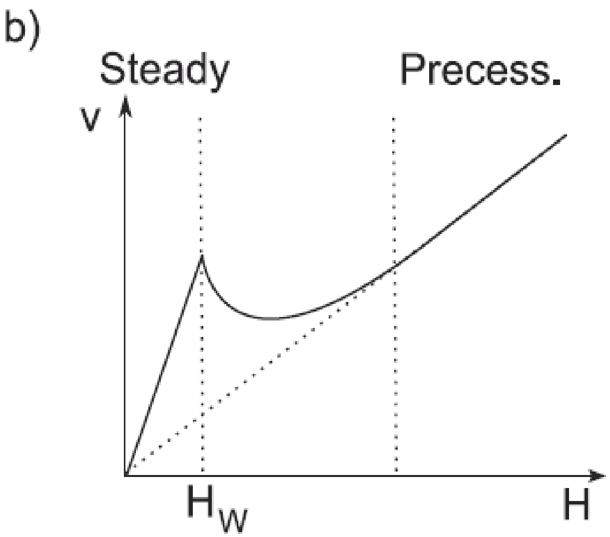
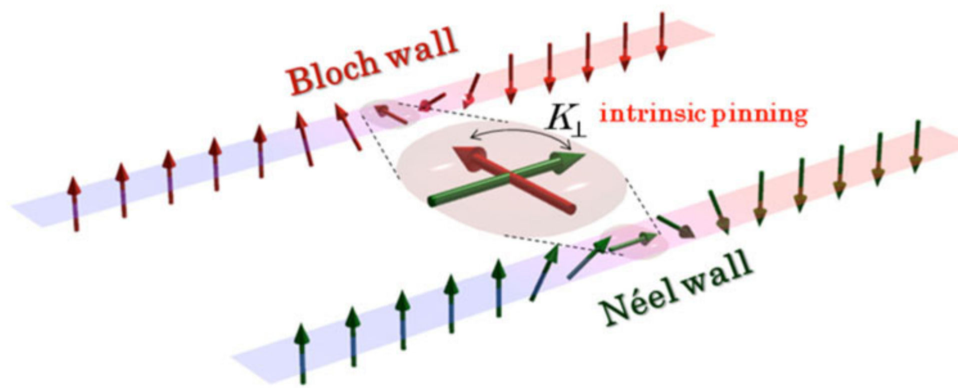
# DW motion & Walker Breakdown




- After Walker breakdown, DW precesses & energy loss

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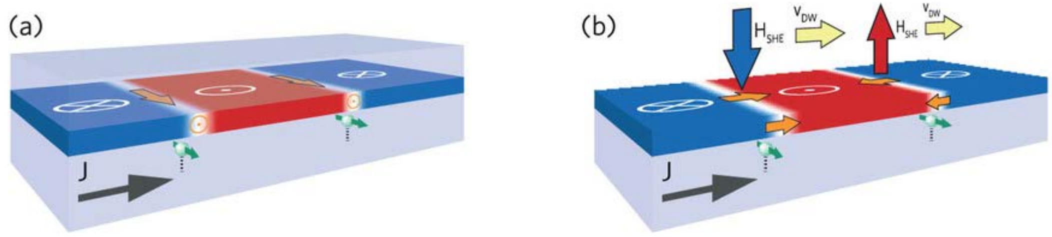
# DMI acts as effective field in DW

- Eq. of motion of DW [S. Emori, Nat. Mat. 12, 611 (2013)]

$$\left(1+\alpha^2\right)\frac{dX}{dt}=\alpha\gamma_0\lambda H_z+\left(1+\alpha\beta\right)b_J-\frac{\gamma_0\lambda H_K}{2}\sin\left(2\Phi\right)$$
$$+\frac{\gamma_0\lambda\pi}{2}\left[\alpha H_{SHE}-H_y\right]\cos\left(\Phi\right)+\frac{\gamma_0\lambda\pi}{2}\left[H_{DMI}+H_x\right]\sin\left(\Phi\right)$$

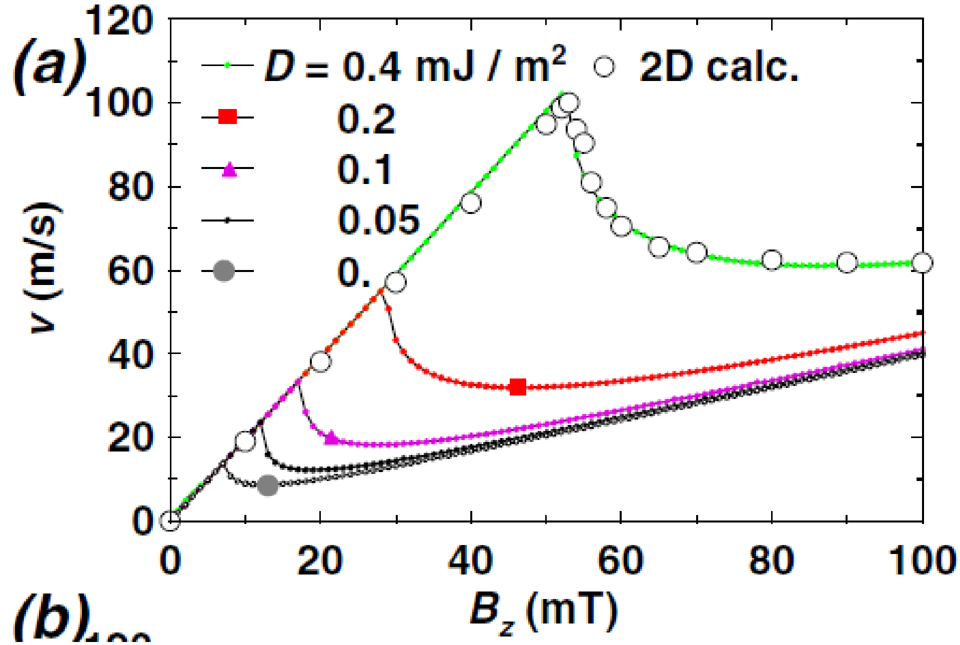
$$\left(1+\alpha^2\right)\lambda\frac{d\Phi}{dt}=\gamma_0\lambda H_z+\left(\beta-\alpha\right)b_J-\frac{\alpha\gamma_0\lambda H_K}{2}\sin\left(2\Phi\right)$$
$$+\frac{\gamma_0\lambda\pi}{2}\left[H_{SHE}+\alpha H_y\right]\cos\left(\Phi\right)-\frac{\alpha\gamma_0\lambda\pi}{2}\left[H_{DMI}+H_x\right]\sin\left(\Phi\right)$$

- DMI prefers Neel wall



# DW motion with DMI

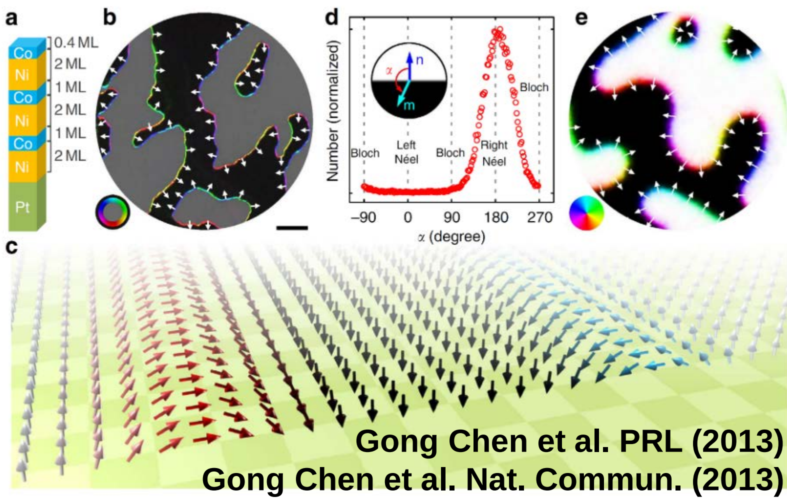
- DMI plays crucial role in the DW dynamics
- DMI prefers Neel type DW
- Walker breakdown is suppressed
- High DW velocity




A. Thiaville *et al*. EPL **100**, 57002 (2012)

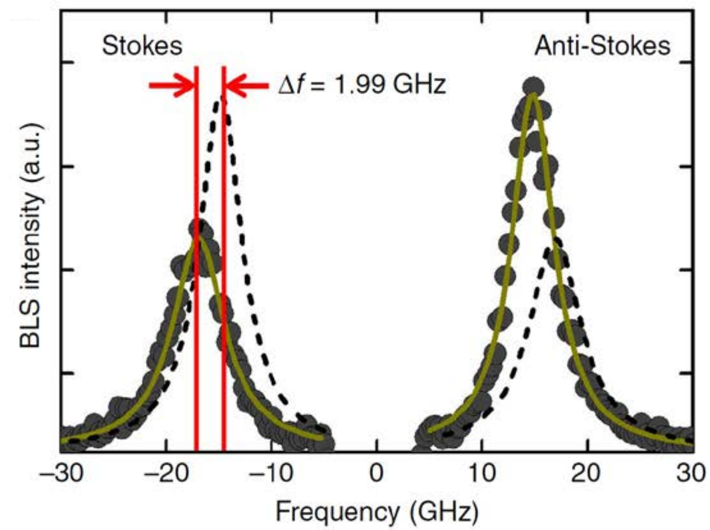
# How to measure DMI ?

## Imaging magnetic configuration



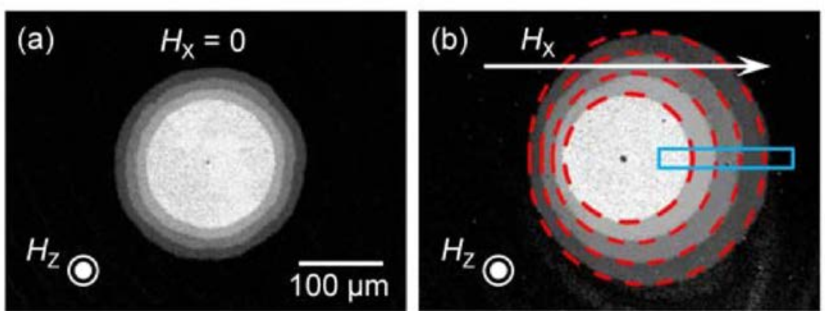

Gong Chen et al. PRL (2013)
Gong Chen et al. Nat. Commun. (2013)

## Asymmetric SW's dispersion relation




J. Cho et al., Nat. Commun (2015)
M. Belmeguenai et al., PRB (2015)
K Di et al., PRL (2015)
H.T. Nembachet al., Nat. Phys. (2015)
J. M. Lee et al., Nano Lett. (2015)
H. S. Körner et al., PRB (2015)
⋮

## Asymmetric magnetic DWM




S. Je *et al.*, PRB (2013)
A. Hrabec *et al.*, PRB (2014)
R. Lavrijsen et al., PRB (2015)

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# Measurement methods of DMI

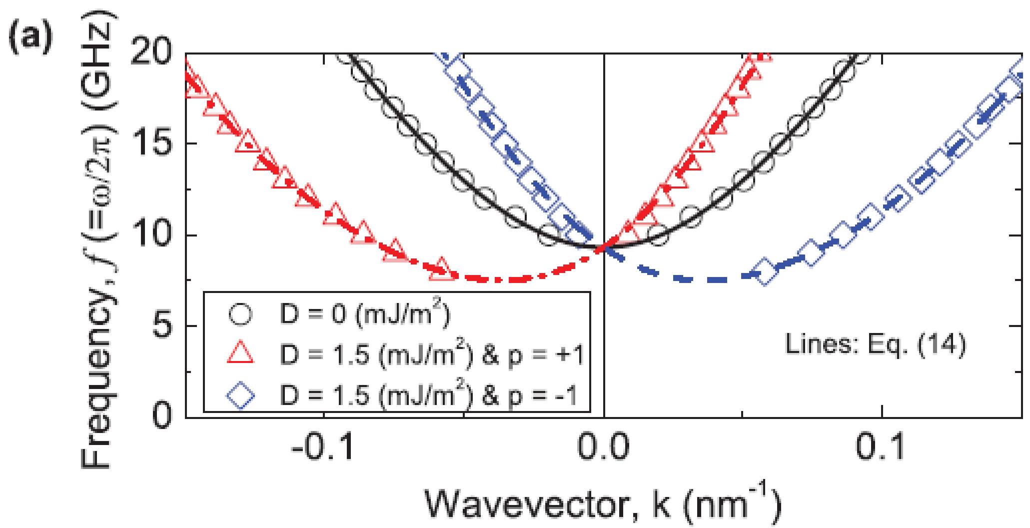
- BLS (Brillouin Light Scattering):
  Inha U.(DGIST) + TU/e, Singapore NU, NIST, etc.
- SPEELS (Spin polarized electron energy loss spectroscopy): J. Kirschner, Max-Planck
- FMR with antenna: Osaka, KIST
- DW motion: Seoul Nat. Univ., TU/e, Univ. of Leeds
- New method: DGIST+ Inha + TU/e + Mainz
  - Relatively simple, less sample limitation, quick & dirty method

J. H. Moon *et al.* PRB **88**, 184404 (2013).

# Non-Reciprocal Spin Wave dispersion with DMI

$$\frac{\omega}{\gamma\mu_0} = \sqrt{(H + M_s/4 + Jk^2)(H + 3M_s/4 + Jk^2) - \frac{e^{-4|k|d}M_s^2}{16}(1 + 2e^{2|k|d})} + pD^*k$$

$$\Lambda_\pm = \frac{1}{\alpha\omega}\left(2\gamma\mu_0 J|k_\pm| + \frac{\gamma\mu_0 M_s^2 d e^{-4|k_\pm|d}(1 + e^{2|k_\pm|d})/8 \pm pD^*(\omega \mp \gamma\mu_0 pD^*|k_\pm|)}{H + M_s/2 + Jk_\pm^2}\right),$$



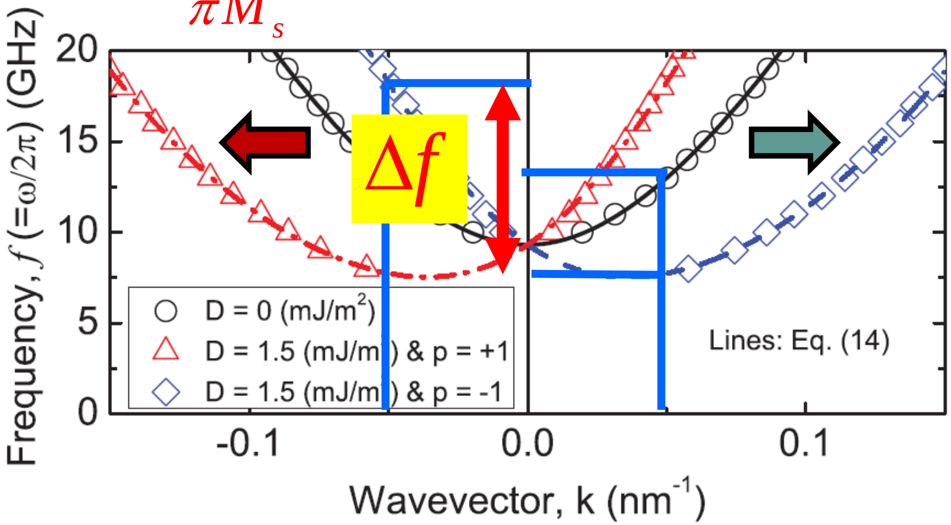

- DMI add extra linear term in SW dispersion relations
- Shift of SWD
- Different SW velocity for $\pm k$

# Theory for spin waves with iDM interaction

$$f_{DE} = f_0\left(M_s, H_{ext}, K_U, A_{ex}, k_x\right) + p\frac{\gamma D}{\pi M_s}k_x$$

$$\Delta f = \left| f_{DE}\left(+k_x\right) - f_{DE}\left(-k_x\right) \right| = \frac{2\gamma D}{\pi M_s}k_x$$

$f_0 + \frac{\gamma D}{\pi M_s}k_x$ $\qquad$ $f_0 - \frac{\gamma D}{\pi M_s}k_x$

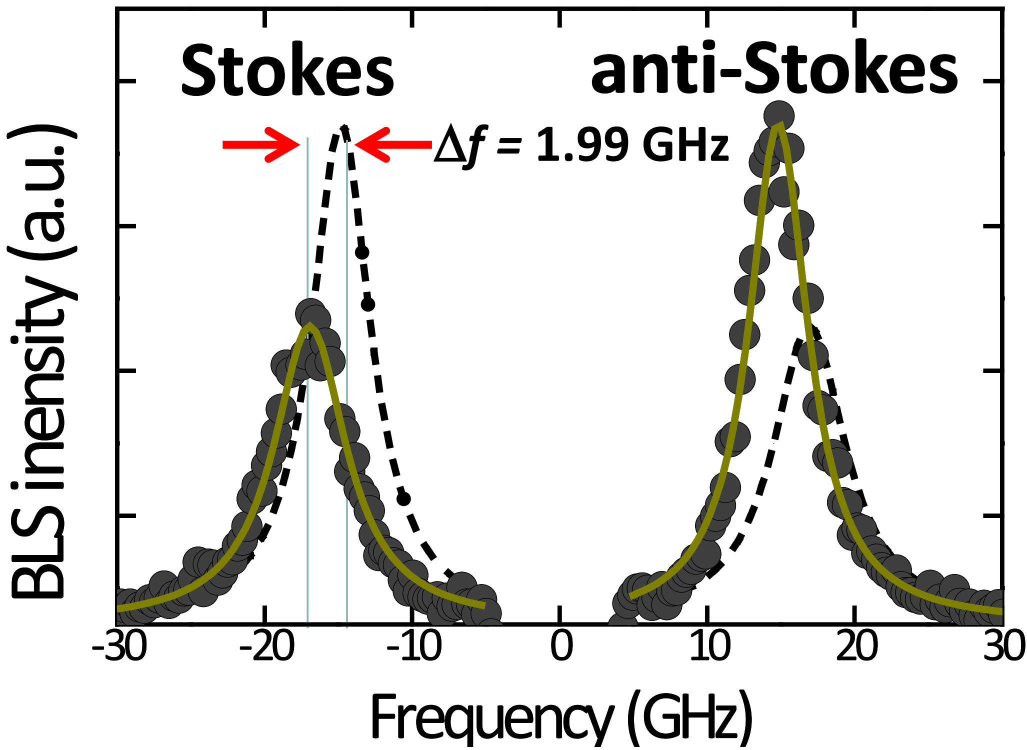



$M_s$ :saturated magnetization
$H_{ext}$ : applied magnetic field
$K_u$ :anisotropy energy
$A_{ex}$ :exchange stiffness constant
$k_x$ :wavenumber of spin waves
$\gamma$ : gyromagnetic ratio
$D$ :DM energy density
$p$ :polarity of DM energy density

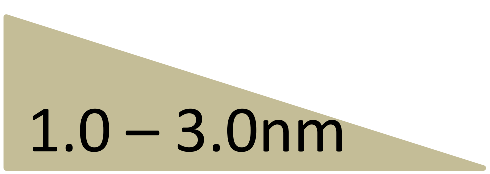
# BLS schematic and spectrum

**Sample structure**

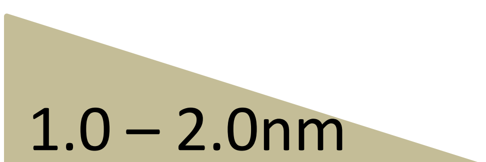
- AlOx cap 2 nm
- CoFeB (Co) wedge
- Pt 4 nm
- $SiO_2$ substrate




**$Co_{48}Fe_{32}B_{20}$ Wedge shape**

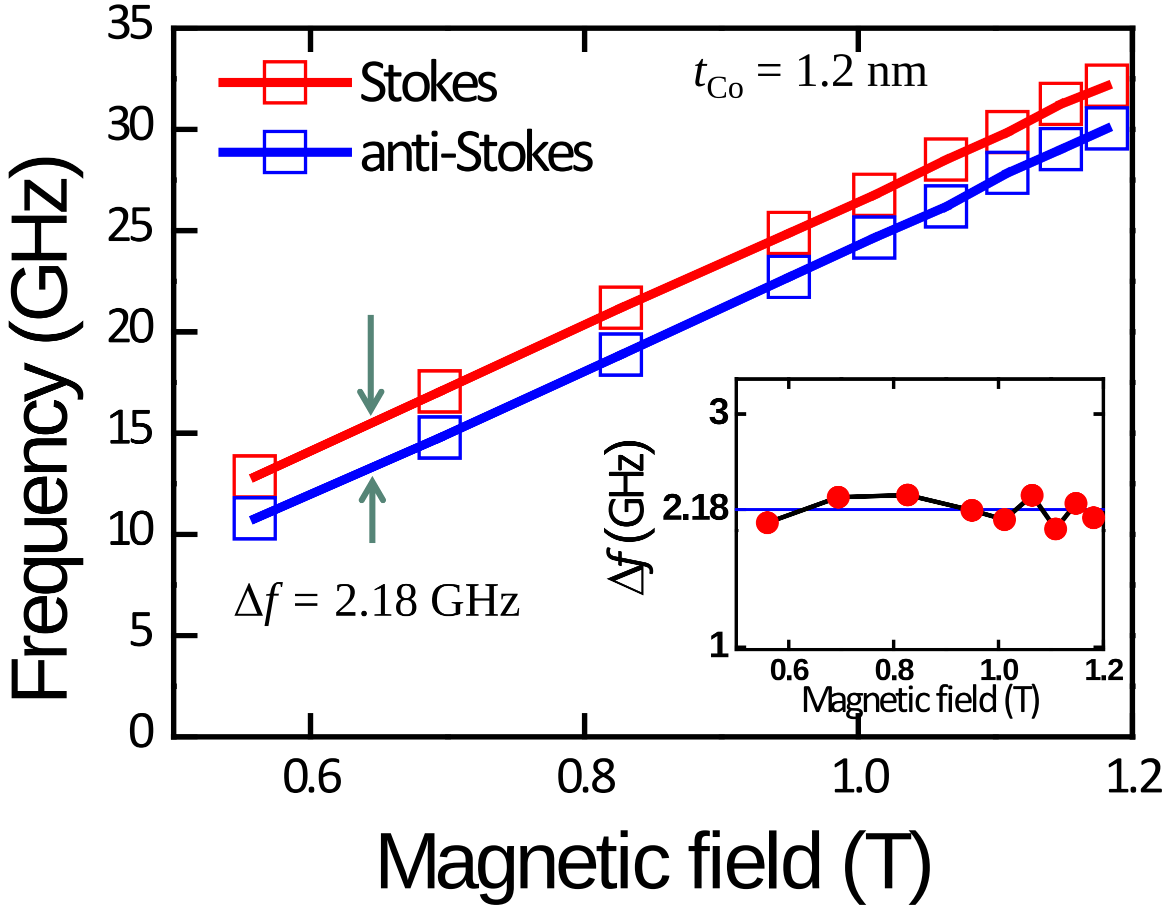



**Co Wedge shape**




**Strong Point of BLS!!!**

# Result of the Field dependence




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

$\gamma = 2.37 \times 10^5\ \mathrm{m/(A \cdot s)}$

$k_x = 0.0167 \times \mathrm{nm}^{-1}$

$M_s = 1100\ \mathrm{kAm}$

$D = 1.13\ \mathrm{mJ/m^2}$

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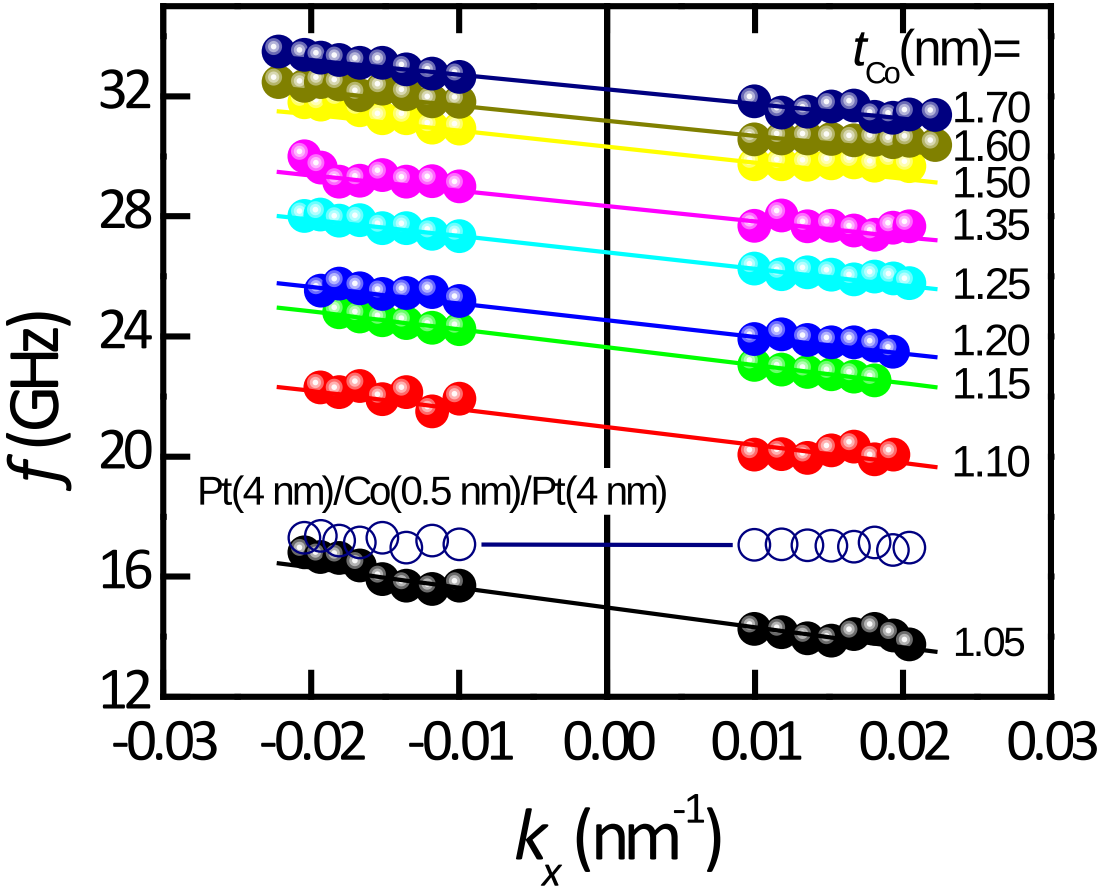
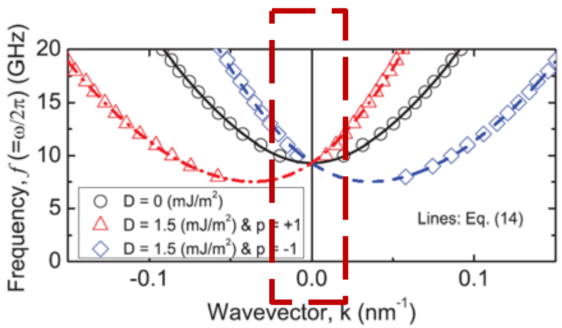
# Result of SW Dispersion relations

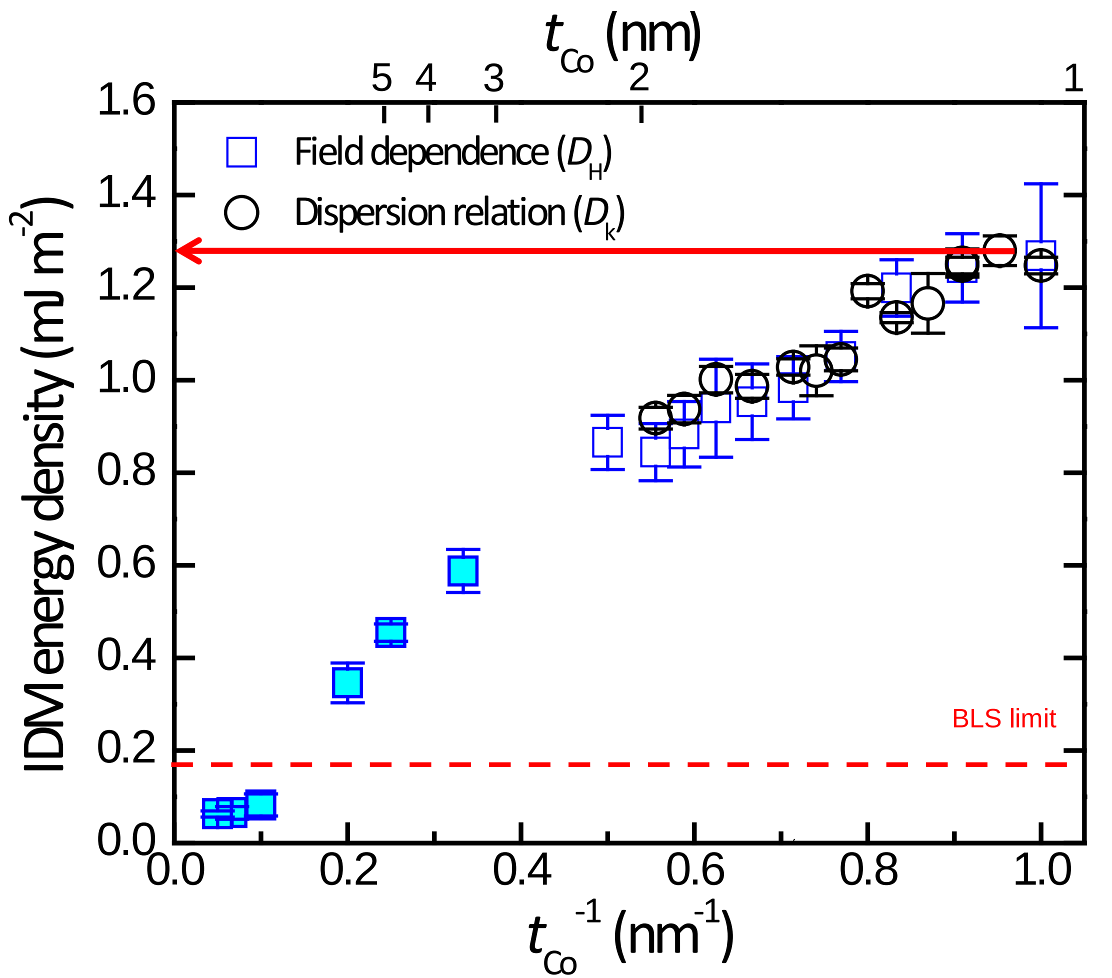



$$f_{DE} = f_0 + p\frac{\gamma D}{\pi M_s}k_x$$



Cho, CY, *et al.* Nat. Comm. **6**, 7635 (2015)

# iDM energy density of Pt/Co/$AlO_x$

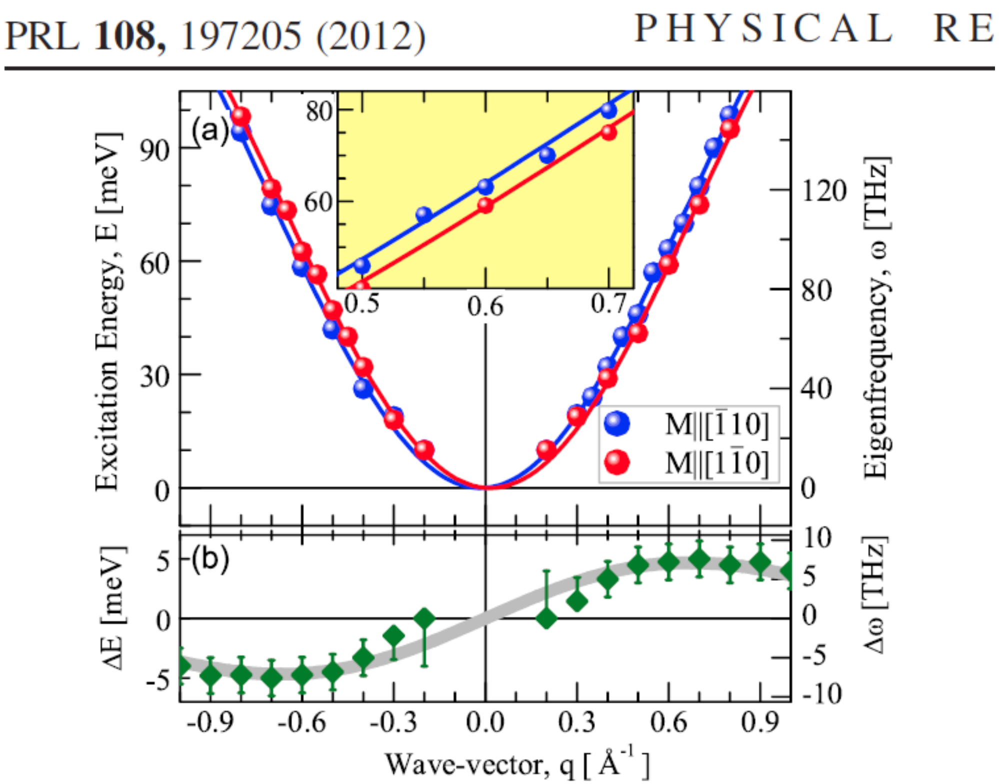



$$D = \frac{\pi \Delta f \cdot M_s}{2\gamma \cdot k_x}$$

$D_{max} = 1.24$ mJ/m$^2$

@ $t_{Co}$ = 1.0 nm

# SPEELS (Spin polarized electron energy loss spectroscopy)




- $q$~ 1 nm$^{-1}$
- Zero-magnetic field
- High quality samples

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PHYSICAL REVIEW B 88, 214401 (2013)

# Asymmetric magnetic domain-wall motion by the Dzyaloshinskii-Moriya interaction

Soong-Geun Je,[1] Duck-Ho Kim,[1] Sang-Cheol Yoo,[1,2] Byoung-Chul Min,[2] Kyung-Jin Lee,[3,4] and Sug-Bong Choe[1,*]

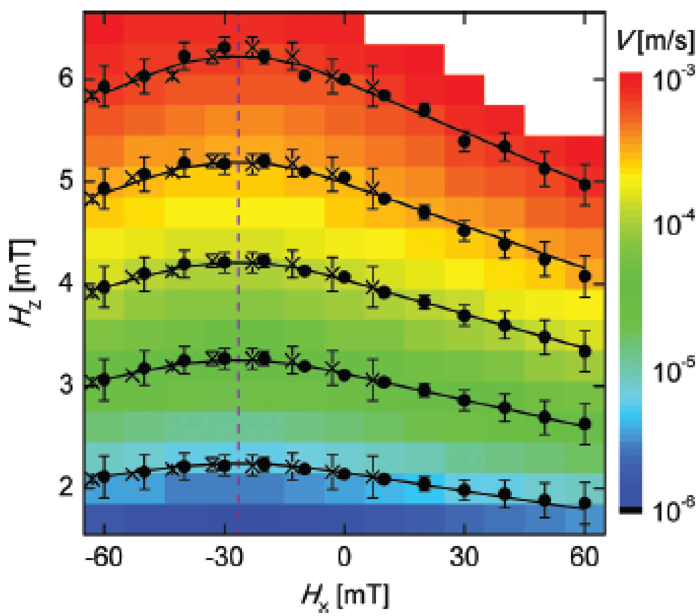
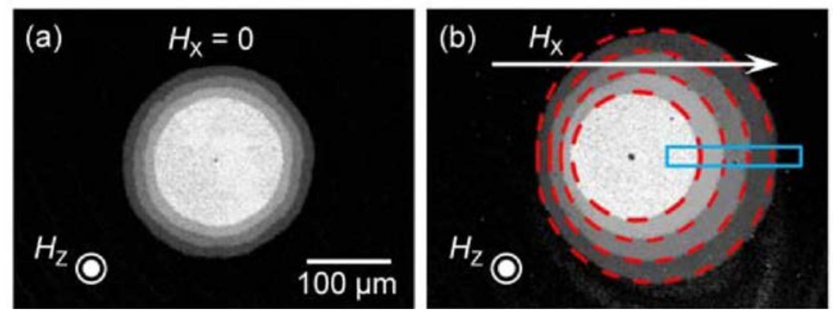


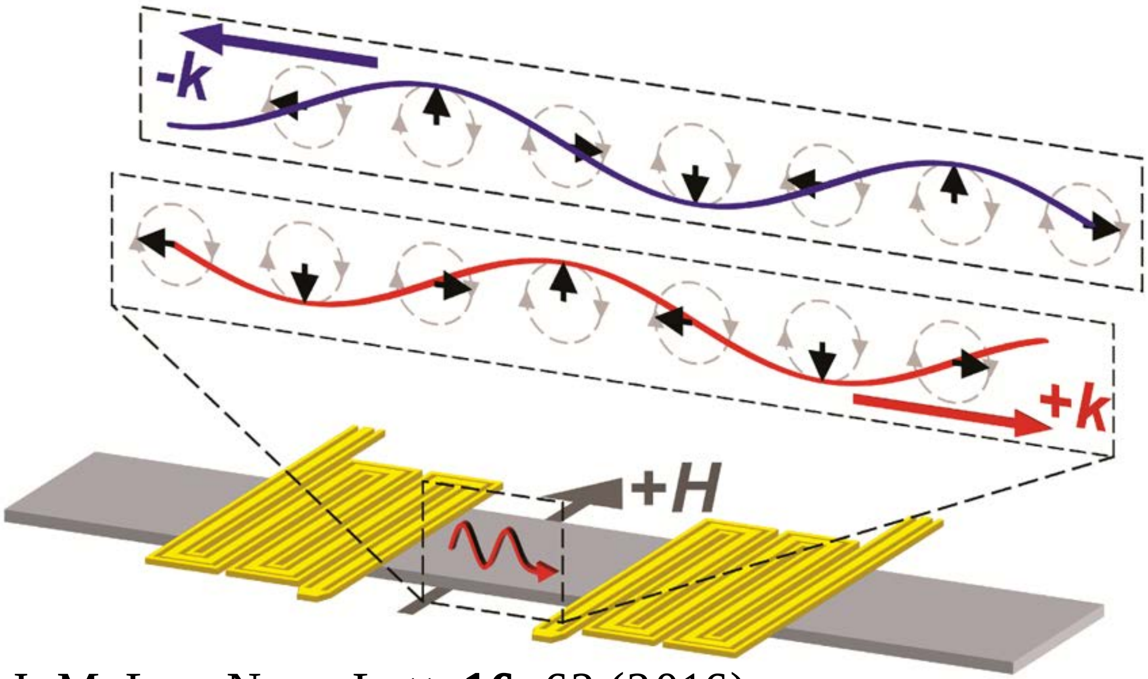

FIG. 2. (Color online) Two-dimensional equi-speed contour map of $V$ as a function of $H_x$ and $H_z$. The color corresponds to the magnitude of $V$ with the scale on the right. The symbols with error bars show the measured positions $(H_x, H_z)$ on several equi-speed contours. The black solid lines show the best fit using Eq. (2). The purple line indicates the symmetric axis $H_x = H_0$ for inversion.




**S. Je *et al.*, PRB (2013)**
**A. Hrabec *et al.*, PRB (2014)**
**R. Lavrijsen et al., PRB (2015)**

$$D = \frac{2\mu_0 M_S H_{DMI}}{\pi} \lambda$$

# Non-reciprocity of Spin Waves




J. M. Lee, Nano Lett. **16**, 62 (2016).

- Propagating SW velocity for left ≠ right due to DMI in real space

# FMR with antenna

- Complicate pattern, rather poor signal for thin FM
- Better frequency resolution
- Osaka, Korea Univ., KIST, etc.

D. S. Kim, JKPS (2015)

Magnetostatic Spin Wave in a Very Thin CoFeB Film Grown ··· – Dongseok KIM *et al.*

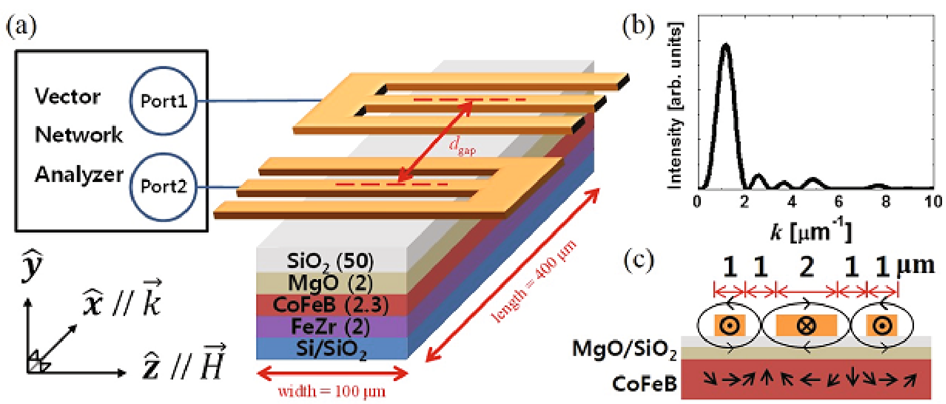



Fig. 1. (Color online) (a) Schematics of the sample structure and antenna geometry. $d_{gap}$ is the distance betwee of the two antennas. (b) The Fourier transform of the in-plane magnetic field underneath the antennas. The maxin is at $k = 1.2\ \mu m^{-1}$. (c) A side view of the sample and the antennas. An antenna is composed of three lines, and a different current direction. Spin waves are induced by the antennas and have a wavelength of 5.2 $\mu$m.

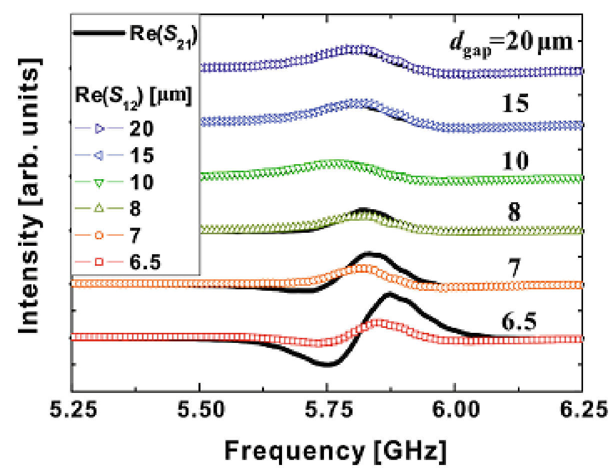



Fig. 3. (Color online) (a) Comparison of $S_{21}$ (solid lines) and $S_{12}$ (colored open symbols) spectra for different distances between antennas. The asymmetry between $S_{12}$ and $S_{21}$ weakens and finally disappears for $d_{gap} > 10\ \mu m$.

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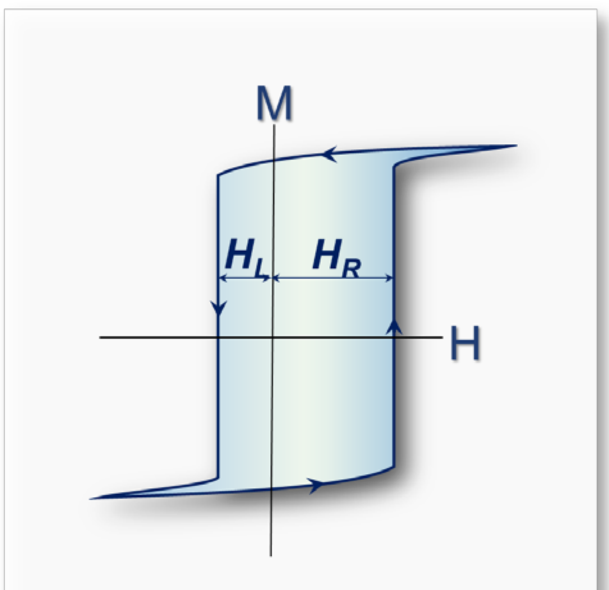
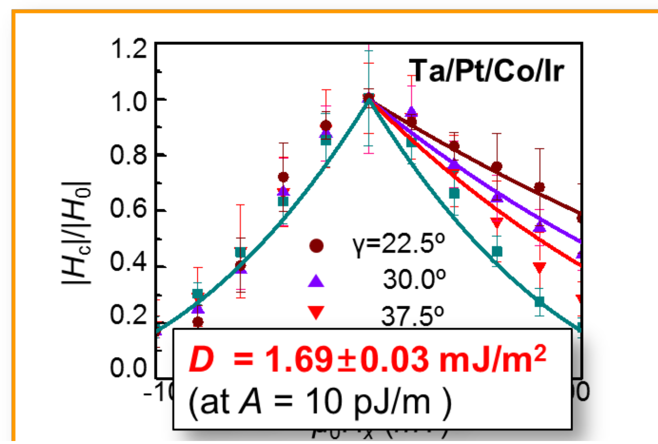
# Asymmetric Hysteresis for Probing Dzyaloshinskii−Moriya Interaction




D. Han, CY *et al*. Nano Lett. **16**, 4438 (2016).

# Asymmetric Nucleation due to DMI

PRL **113,** 047203 (2014) PHYSICAL RE

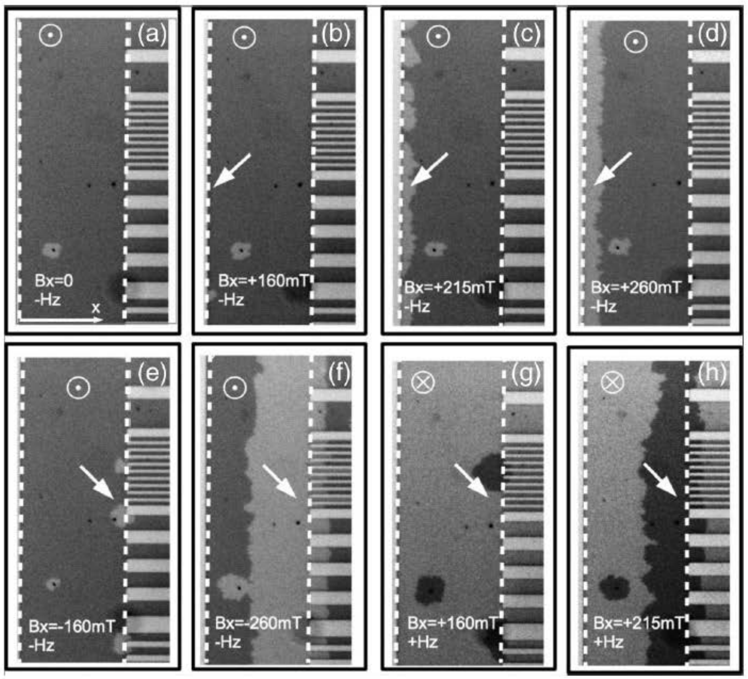



FIG. 1. Kerr images showing the chiral nucleation of domains at one edge of the pad of the Pt/Co/$AlO_x$ microstructure, by application of an out-of-plane field pulse. (a)–(d) Magnetization is initially saturated ↑ and $B_x = 0$, +160, +215, and +260 mT, (e)—(f) magnetization is initially saturated ↑ and $B_x = -160$ and −260 mT, (g)–(h) magnetization is initially saturated ↓ and $B_x$ is +160 and +260 mT. The width of the pad is 70 $\mu$m. The dotted lines highlight the left and right edges of the pad and the arrows show the side of the sample where nucleation takes place.

PRL **113,** 047203 (2014) PHYSICAL RE

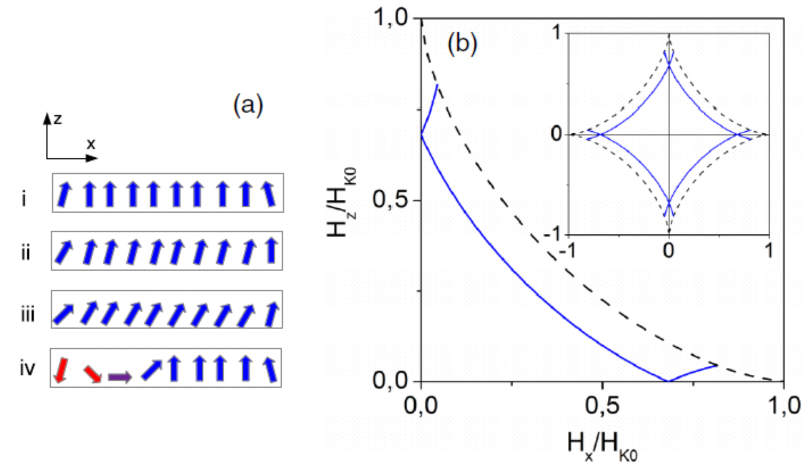
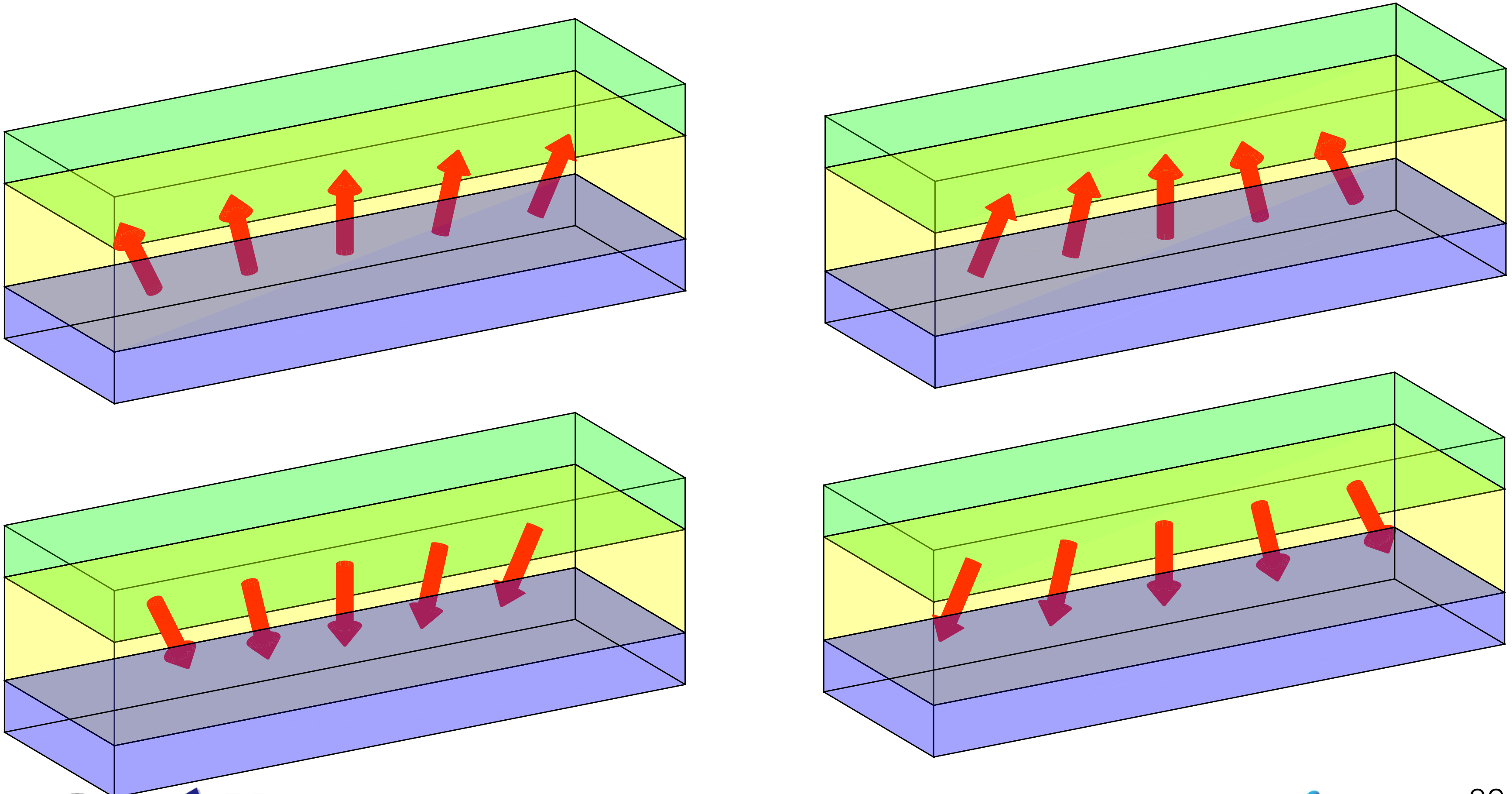



FIG. 3 (color online). (a) Sketch of the micromagnetic configuration within a microstructure with the DMI in zero applied field (i), under an $x$ field (ii), under an additional negative $z$ field (iii), and after reversal, with a domain wall of magnetization parallel to the $x$ field (iv). (b) results of a 1D calculation showing the reversal field for $D/D_{c0} = 0$ (dashes) and 0.5 (lines). For $D \neq 0$ an easy and a hard branch develop, corresponding to the reversal at the two edges of the microstructure. Inset: complete astroids.

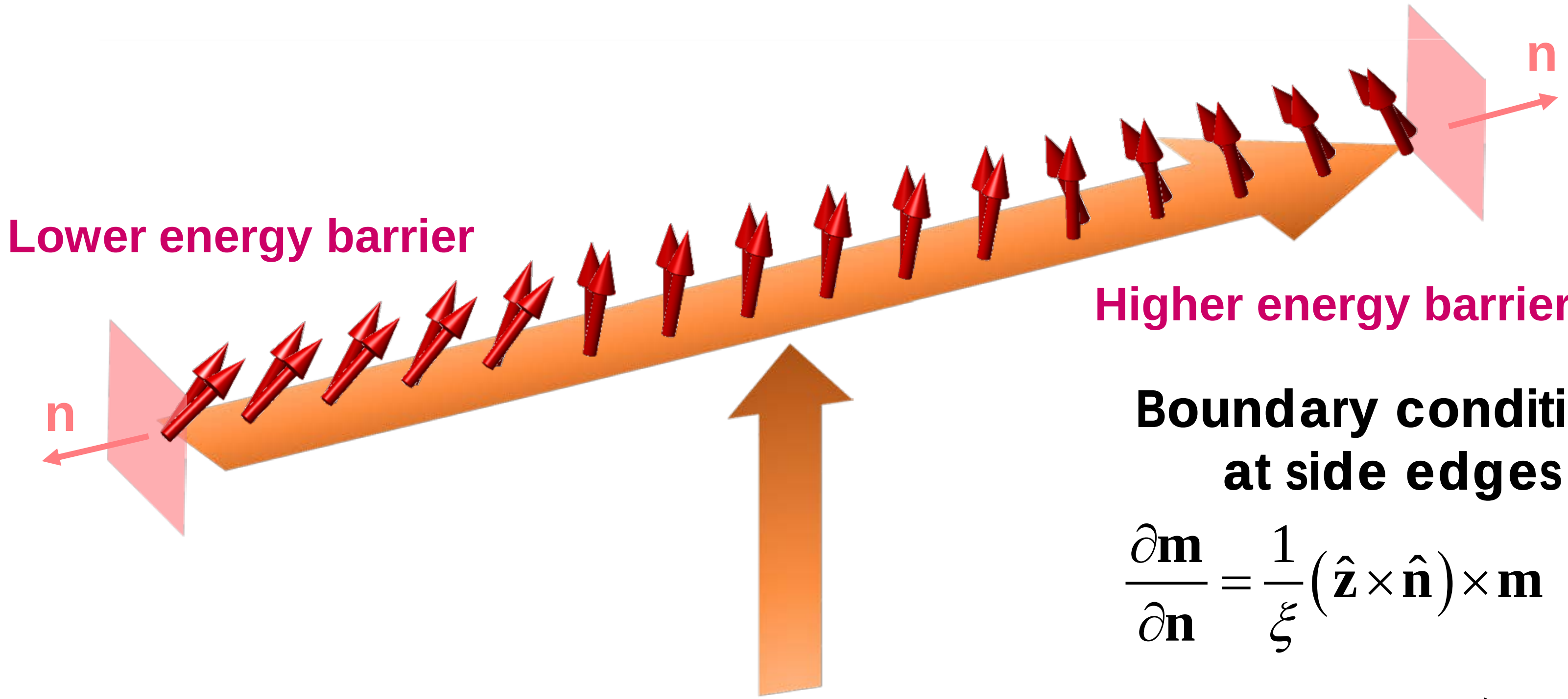
# Dzyaloshinskii-Moriya Interaction

$$E_{DMI} = -\sum_{i \neq j} \vec{D}_{ij} \cdot \left( \vec{S}_i \times \vec{S}_j \right)$$



# Chirality-induced asymmetric switching

***Interfacial DMI + Boundary: Chiral tilting***



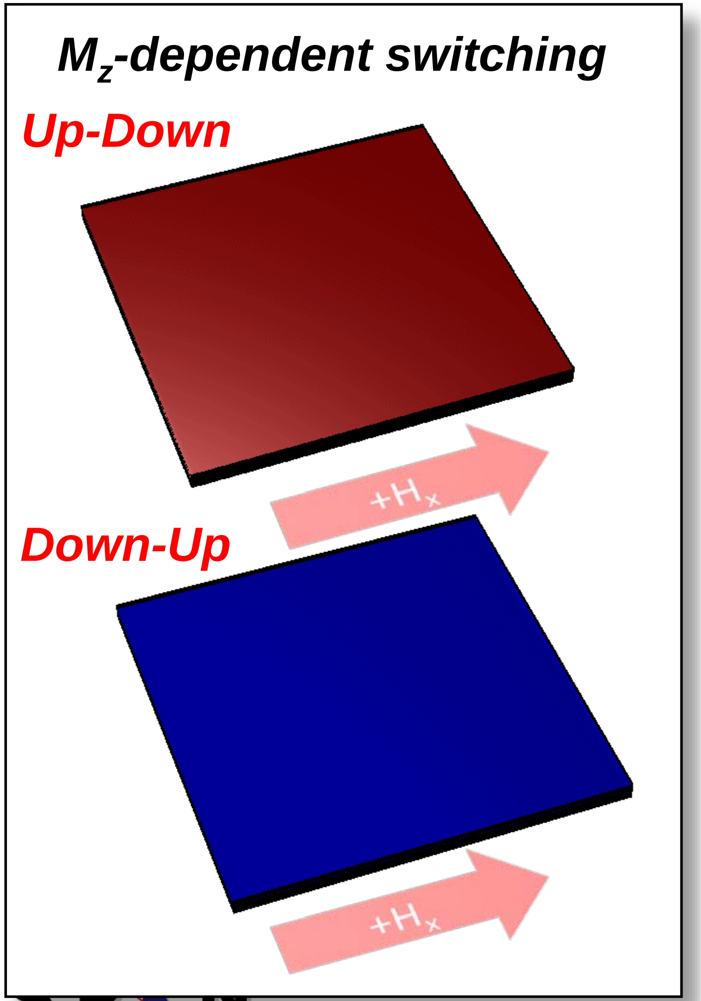

**Boundary condition at side edges**

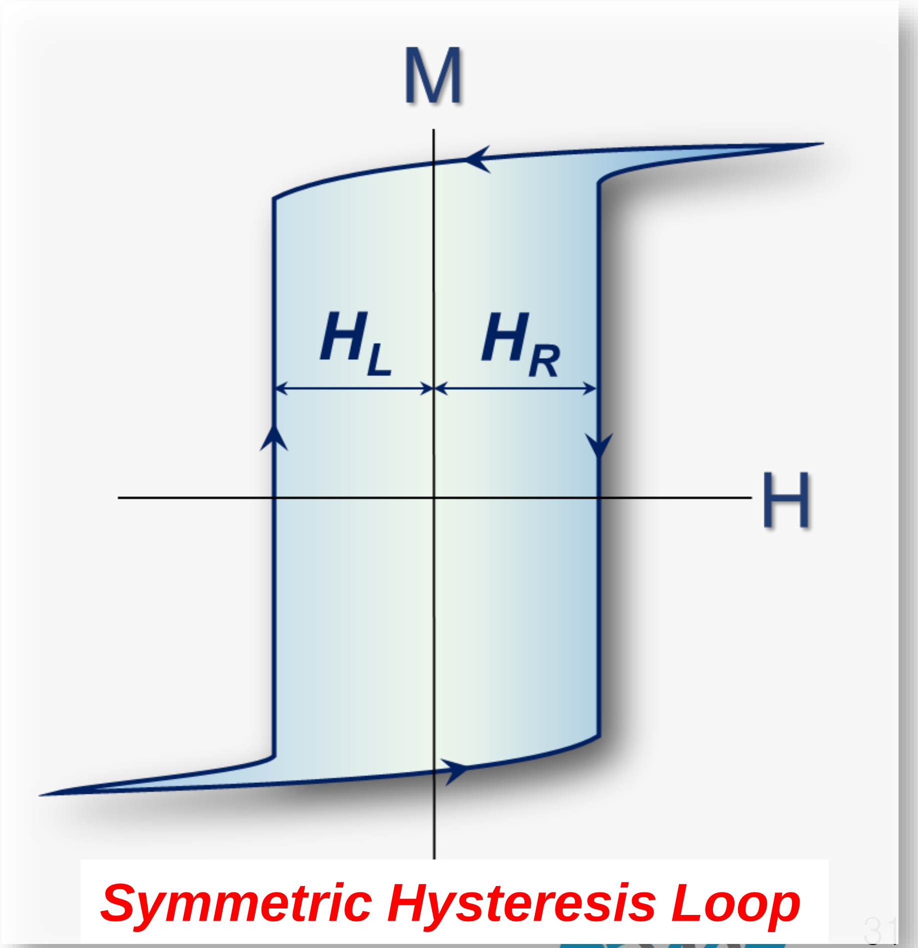
$$\frac{\partial \mathbf{m}}{\partial \mathbf{n}} = \frac{1}{\xi}(\hat{\mathbf{z}} \times \hat{\mathbf{n}}) \times \mathbf{m}$$

$$\text{where } \xi = 2A/D$$

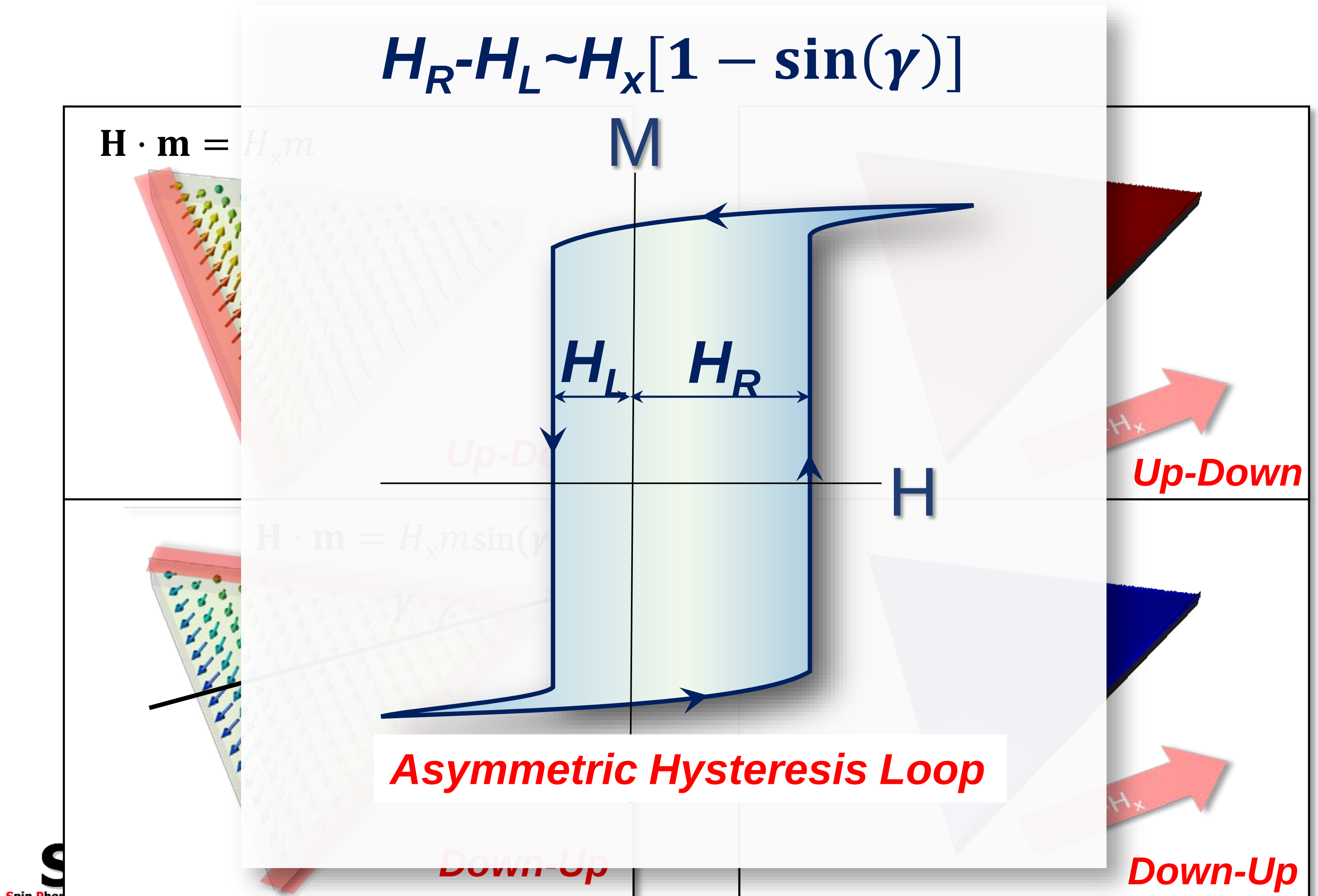
Phys. Rev. B **88**, 184422 (2013).
Phys. Rev. B **89**, 224408 (2014).

# Edge dominant reversal in M-H loop



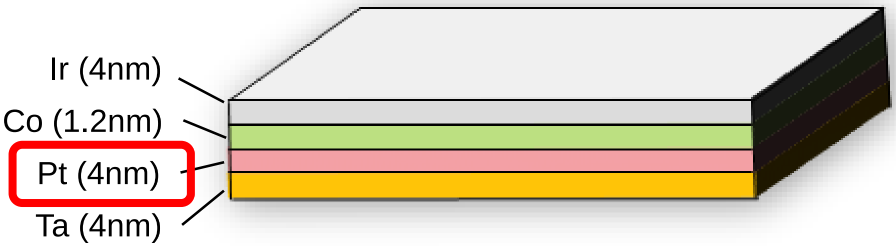



# Breaking the Lateral Symmetry !!

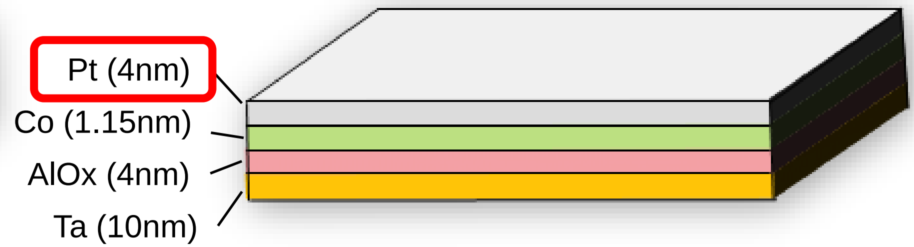


# Measurement principle : asymmetric hysteresis

**Ta/Pt/Co/Ir**

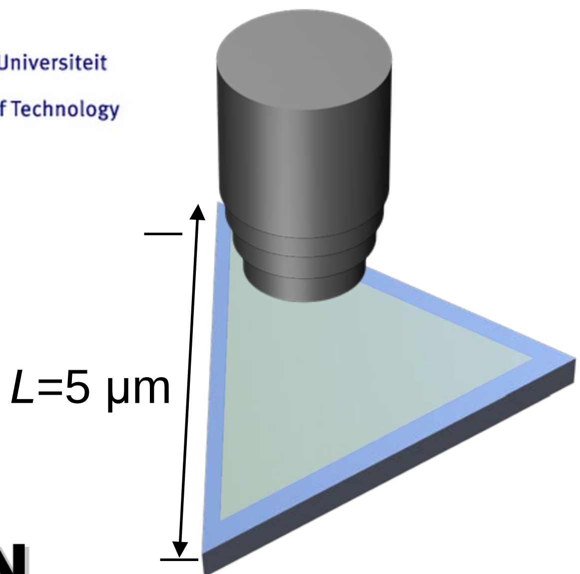



**Ta/AlOx/Co/Pt**




**Inverted sign ?**

Technische Universiteit Eindhoven University of Technology




**Kerr Microscope (EVICO)**

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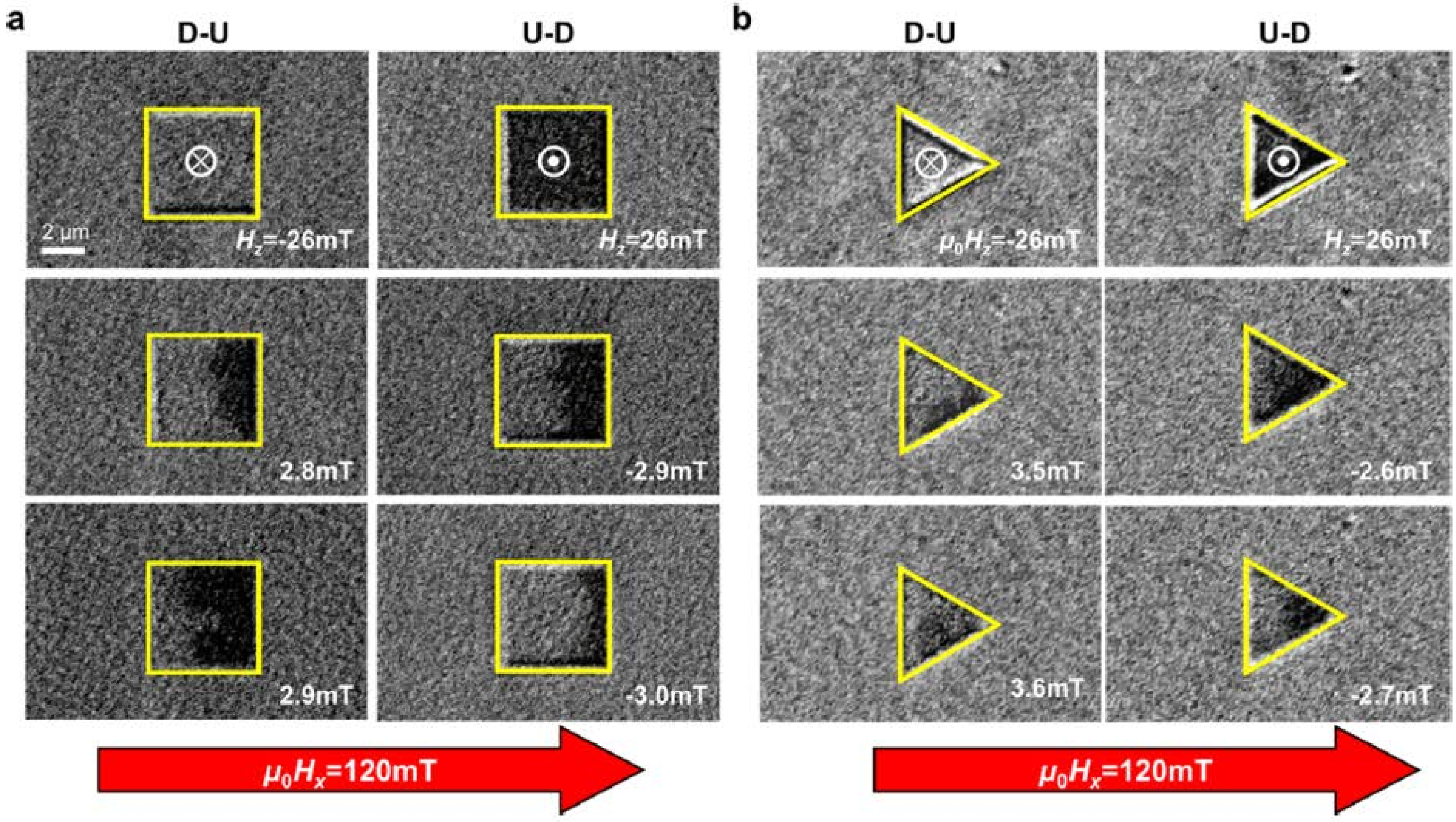
# MOKE Images Pt/Co/Ir

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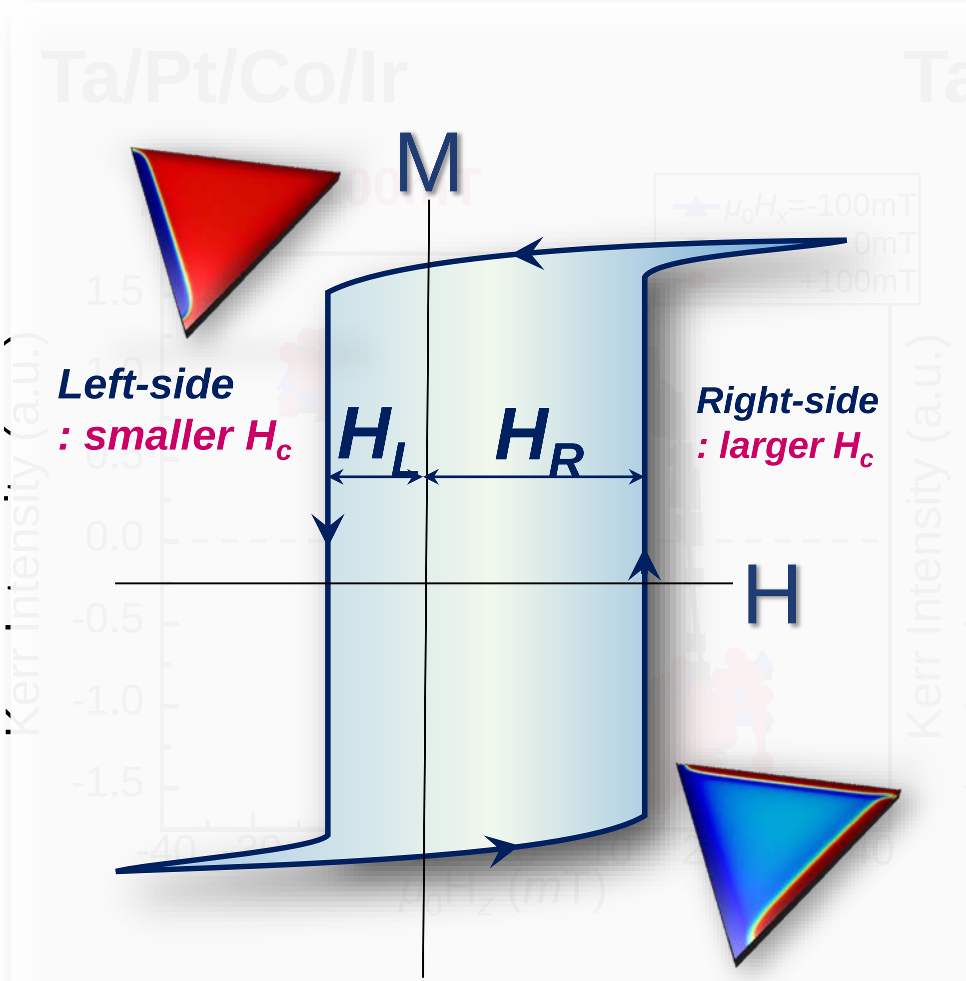
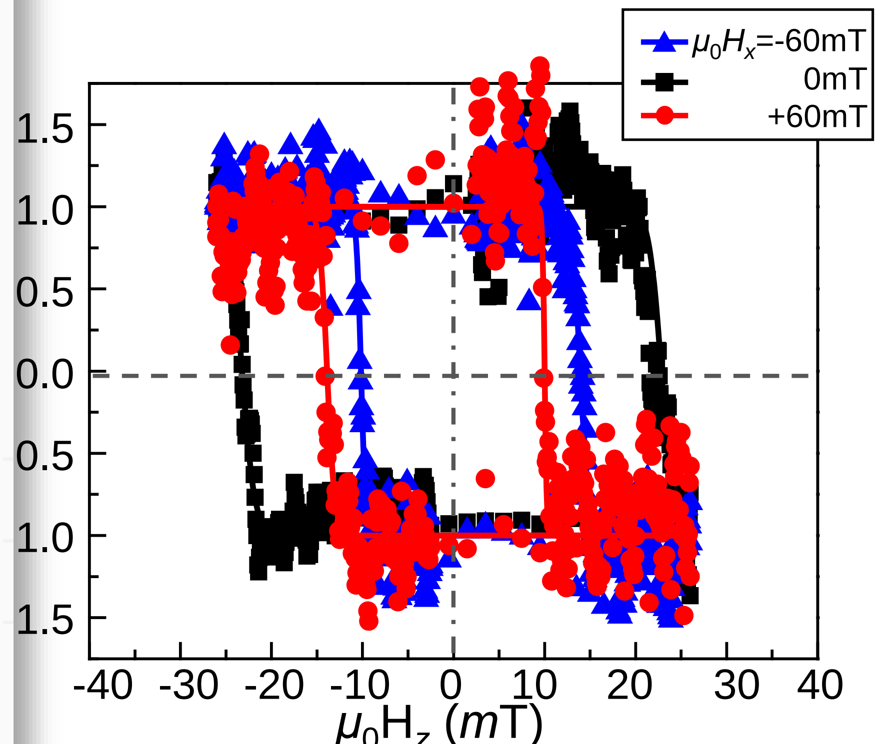
DGIST

# Easy Determination of DMI Sign




**Left-handed chirality**

## Ta/AlOx/Co/Pt




**Right-handed chirality**

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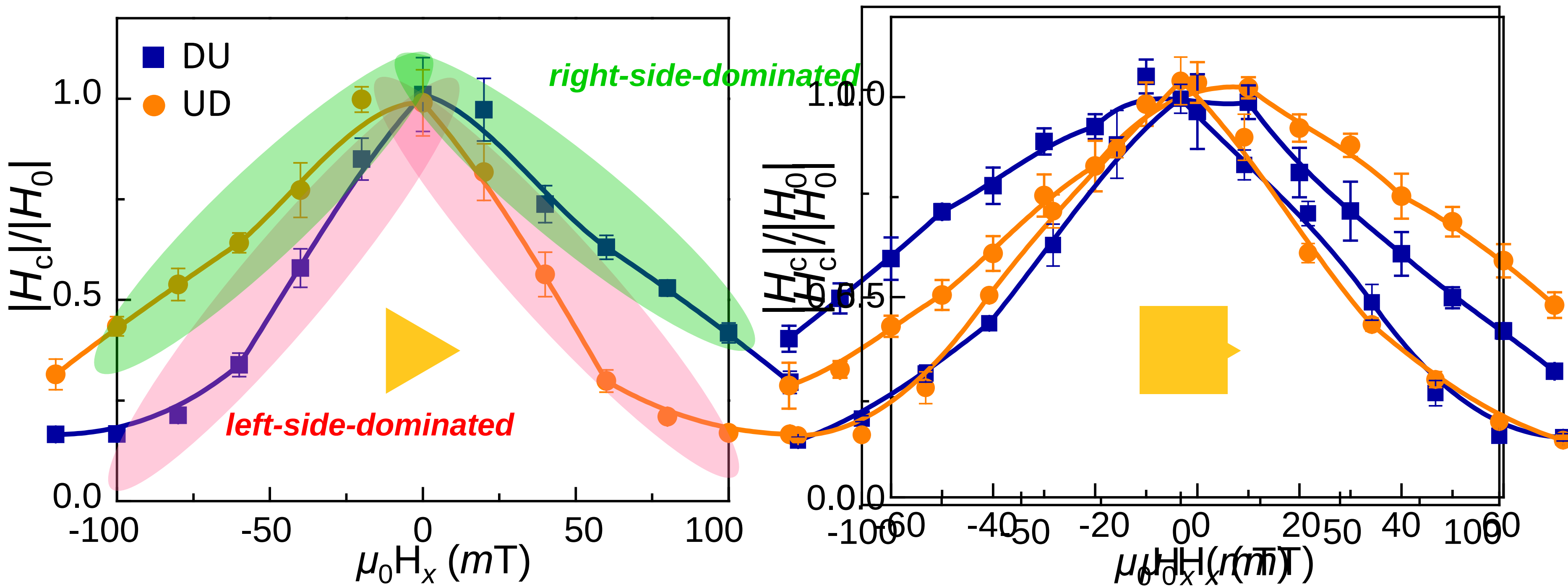
# Asymmetric Hysteresis Loops

**Ta/Pt/Co/Ir** **Ta/AlOx/Co/Pt**




$$H_R\text{-}H_L \sim H_x[1-\sin(\gamma)]$$

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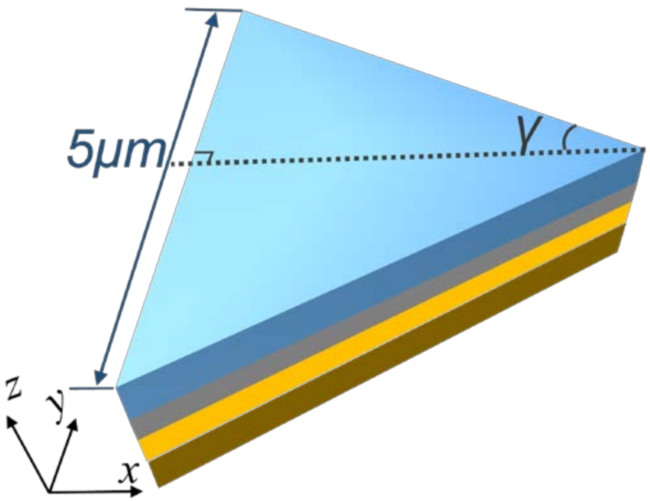
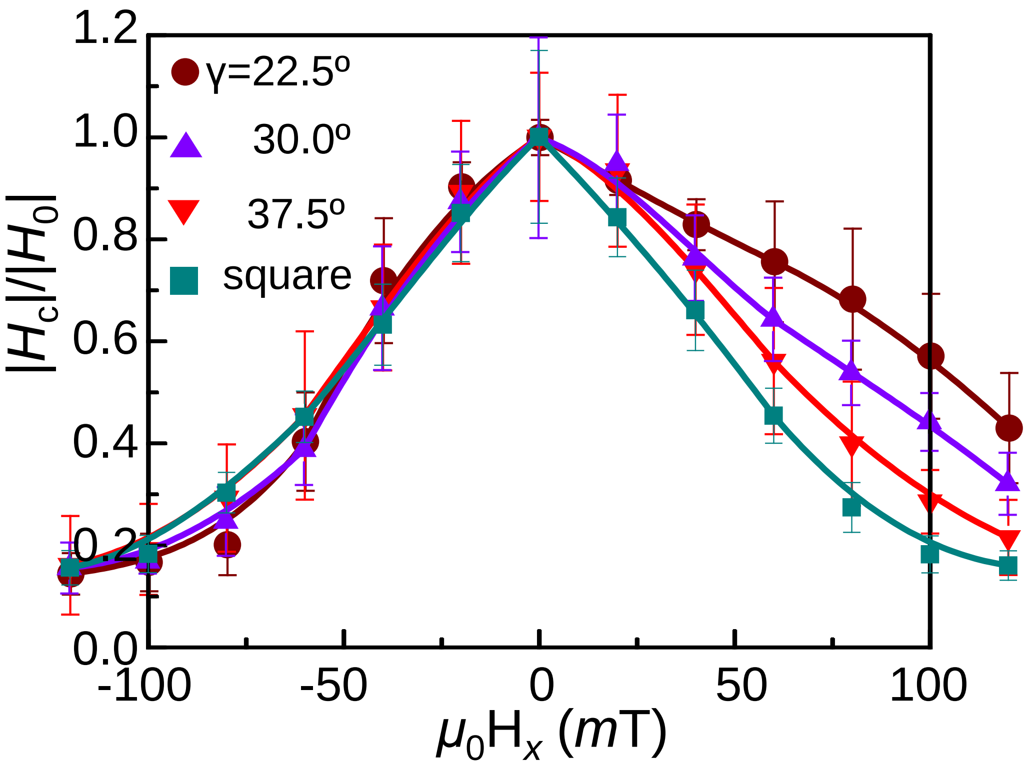
# Edge Angle Dependence




***Object asymmetry***
***~ $H_x$(1-sinγ)***

**Ta/Pt/Co/Ir**

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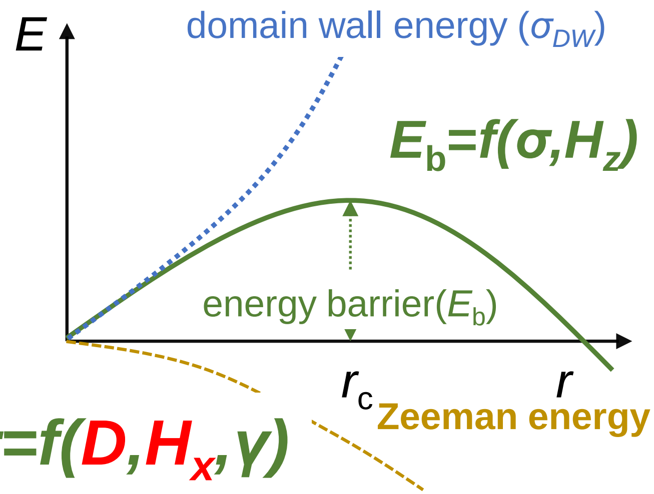
# Droplet Model

## *A droplet model*


S Pizzini et al., PRL (2014)
J. Vogel et al., Comptes Rendus Physique (2006)




$\sigma=f(D,H_x,\gamma)$

**DW energy : DMI + in-plane field**

$$\Delta E = \pi R t \sigma_{DW} - \pi R^2 t \mu_0 M_s \left( \sqrt{1-\left(H_{in}/\left(H_K+H_z\right)\right)^2} H_z \right)$$

$$\sigma_{DW} = \sigma_0 \left( \sqrt{1-\left(H_{in}\cos\varphi/H_K\right)^2} + \left( H_{in}\cos\varphi/H_K + \frac{2D}{\sigma_0} \right) \left( \arccos\left(H_{in}\cos\varphi/H_K\right) \right) \right) \qquad \sigma_0 = 4\sqrt{A K_{eff}}$$

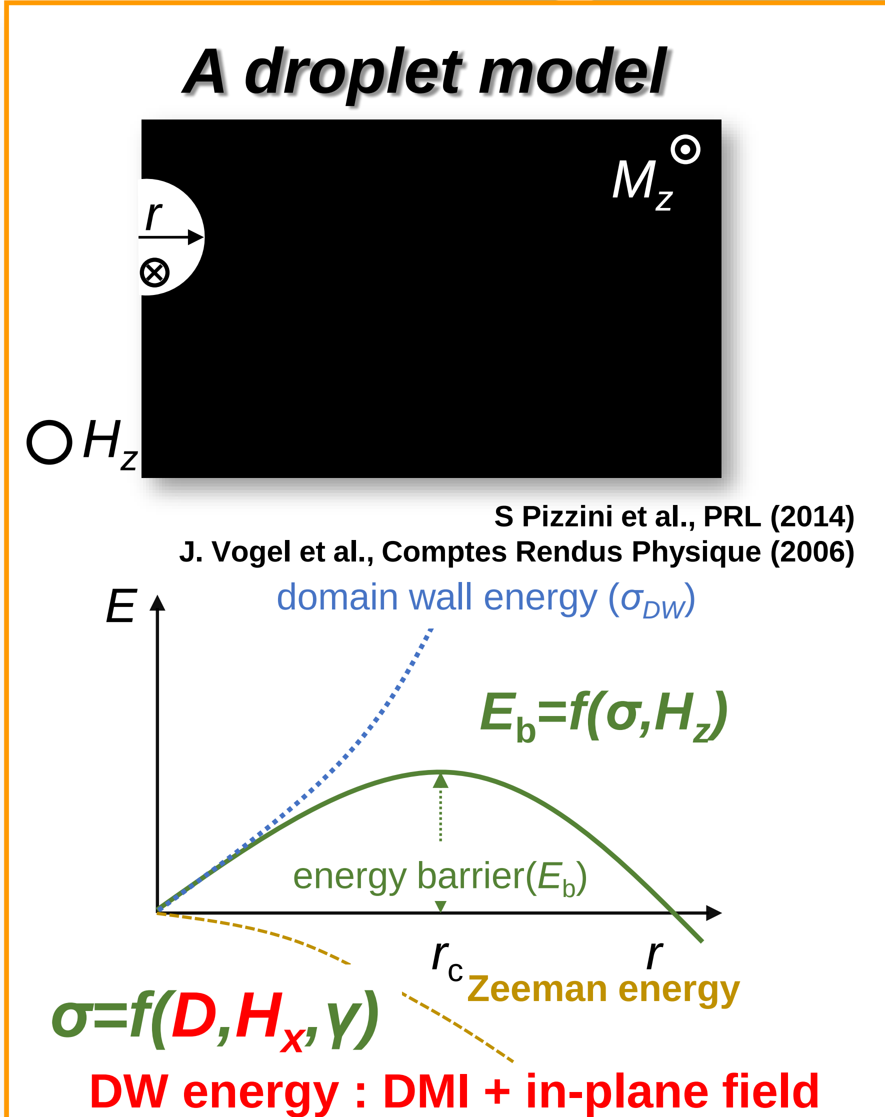
$$E_B = \frac{\pi\left(\sigma_{DW,\gamma}\right)^2 t}{4\mu_0 M_s \sqrt{1-\left(H_{in}/\left(H_K+H_z\right)\right)^2} H_z}$$

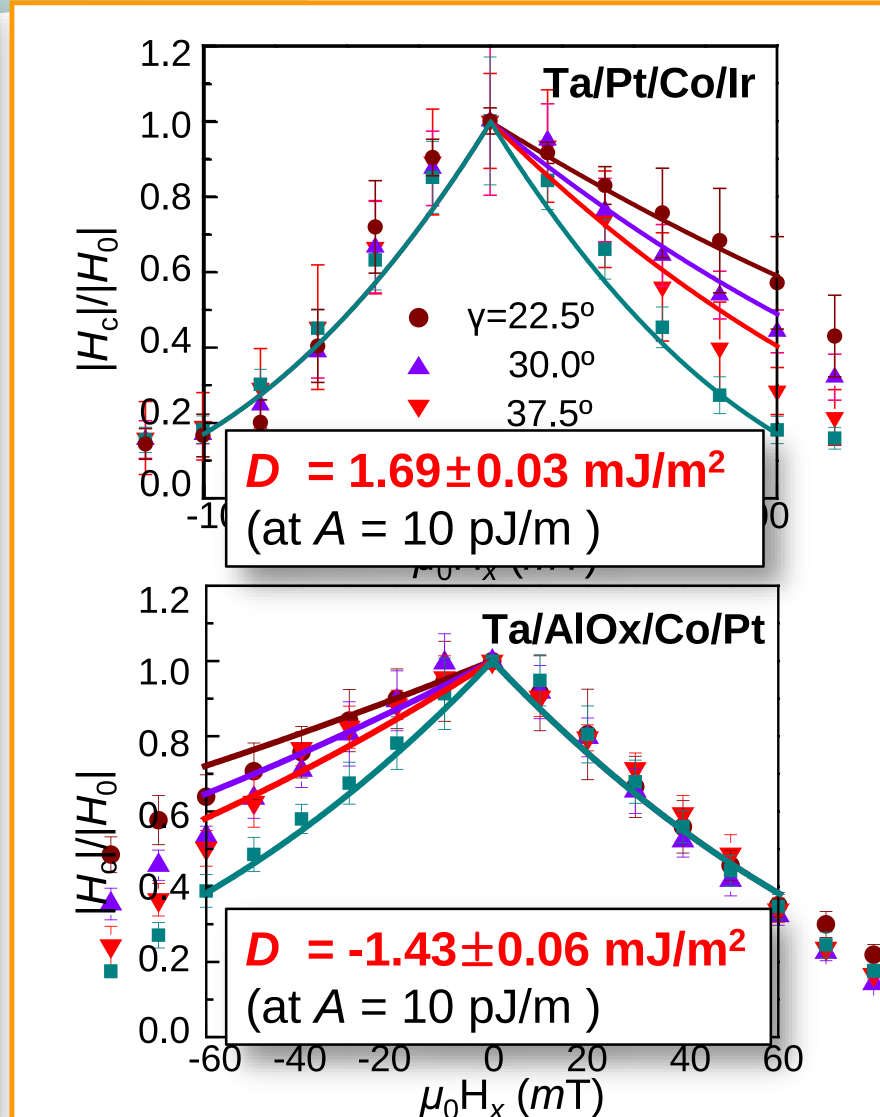
Arrhenius equation $\tau = \tau_0 \exp\left(\frac{-E_B}{k_B T}\right)$

$$H_{C,L} = \frac{\pi t\left(\sigma_{DW}\right)^2}{4\mu_0 M_s p k_B T \sqrt{1-\left(H_{in}/H_K\right)^2}}, \qquad p = E_B/k_B T$$

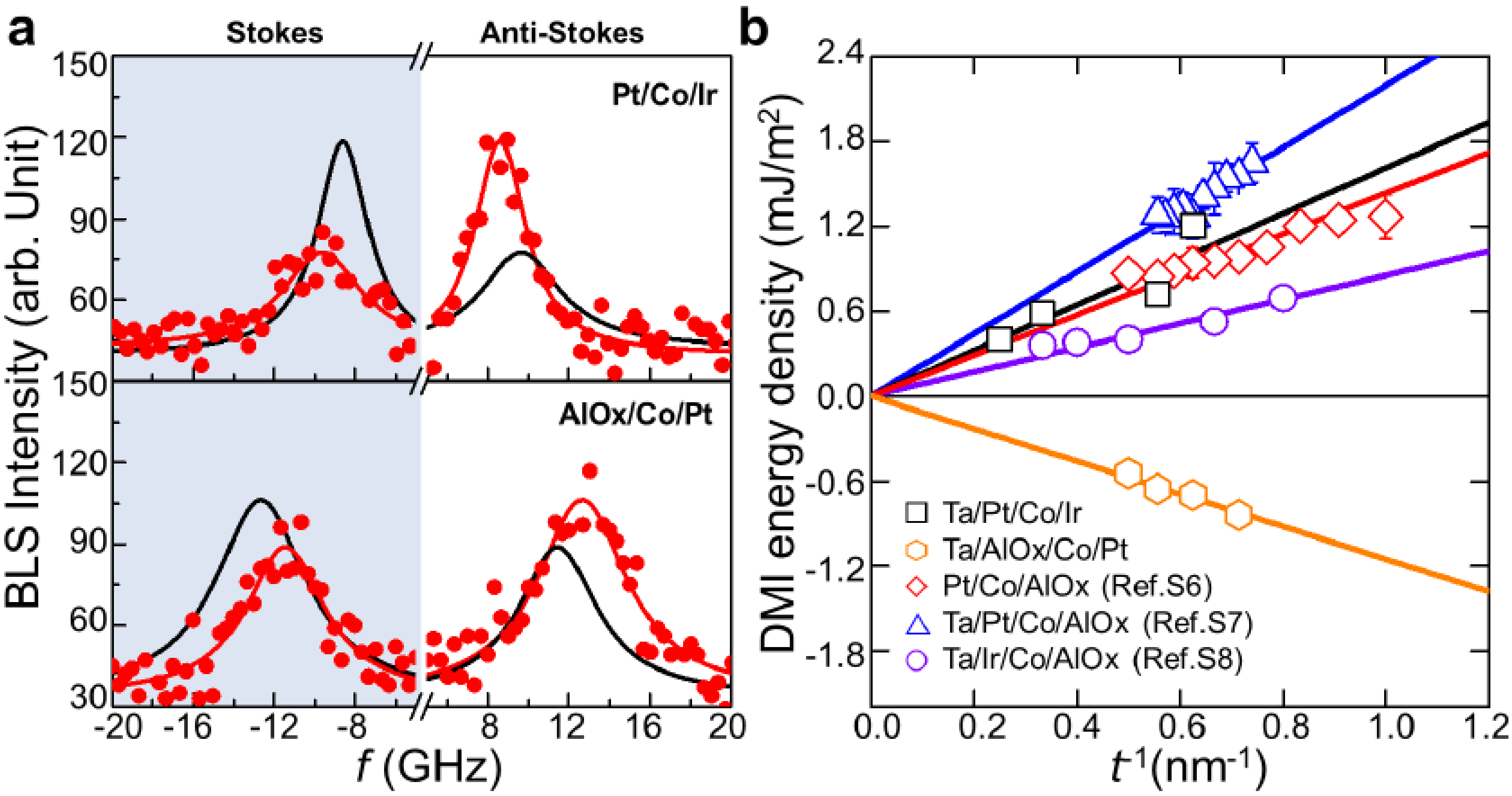
$$H_{C,R} = \frac{\pi t\left(\sigma_{DW,\gamma}\right)^2}{4\mu_0 M_s p k_B T \sqrt{1-\left(H_{in}/H_K\right)^2}},$$

# Droplet Model + Angle-Resolved Data



# BLS measurements

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# Comparison with BLS

***Asymmetric hysteresis***

**Ta/Pt/Co/Ir : $1.69 \pm 0.03$ mJ/m$^2$**

**Ta/AlOx/Co/Pt : $-1.43 \pm 0.06$ mJ/m$^2$**

***BLS measurement***

**Ta/Pt/Co/Ir : $1.34 \pm 0.12$ mJ/m$^2$**

**Ta/AlOx/Co/Pt : $-1.00 \pm 0.05$ mJ/m$^2$**

- With the nominally same samples
- Most serious error came from DW width (energy)

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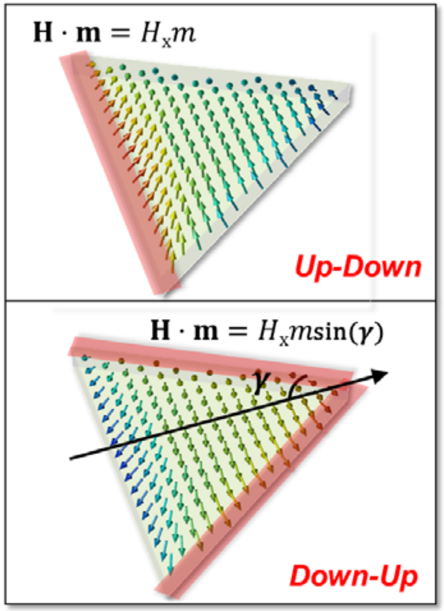
# Conclusions

- Asymmetric Hysteresis Loop measurement
  - Relatively easy, simple, & quick
  - In principle, it is applicable to any kind of MH-loop (static, AHE, MR, VSM, …)
  - Qualitatively and/or Quantitatively



# Thank You

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