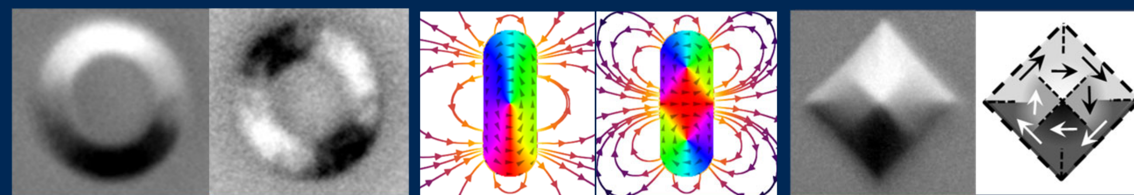

Tailoring Magnetic Spin Textures in $La_{0.7}Sr_{0.3}MnO_3$-based Micromagnets

Prof. Yayoi Takamura
Department of Materials Science and Engineering
University of California, Davis

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Min-Fu Hsieh, Guenter Reiss, Yayoi Takamura

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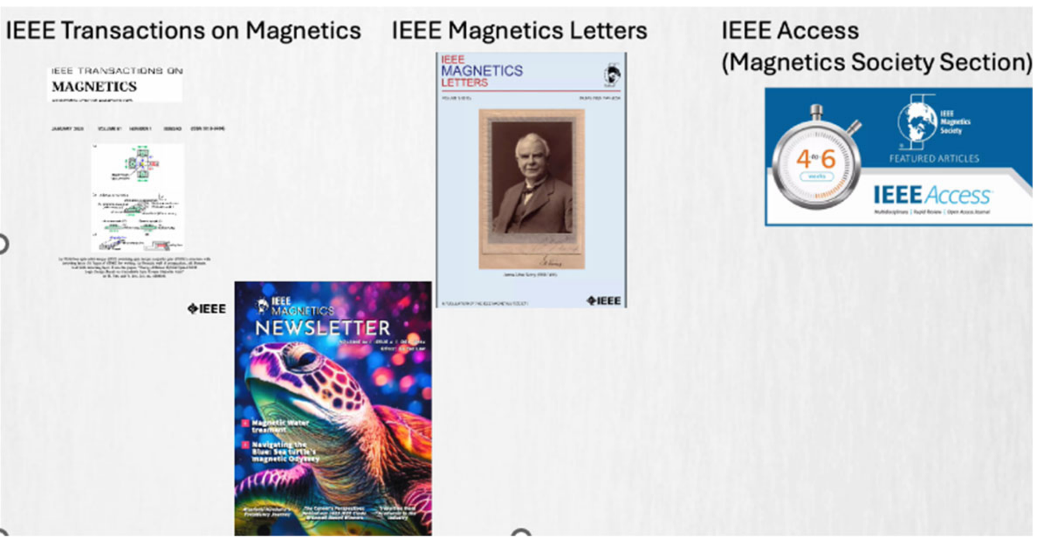

- Professional Activities
- Travel and Professional Awards
- Networking

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Acknowledgements

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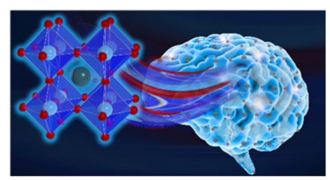
Takamura Research Group: pictured from left to right: Varun Rao, Nathan Tsui, **Dr. Dayne Sasaki** (now at ALS), Yayoi Takamura, Matthew Frame, Hudson Shih, Izoah Snowden, Ishmam Nihal (not pictured Tanaya Sahoo, **Dr. Michael Lee** (now at Niron), **Dr. Rajesh Chopdekar** (now at WD), Ethan Teanu, Steve Ho)

UC Davis: Prof. Jeremy Mason

ALS: Andreas Scholl, Barat Achinuq

ORNL: Scott Retterer

ALS

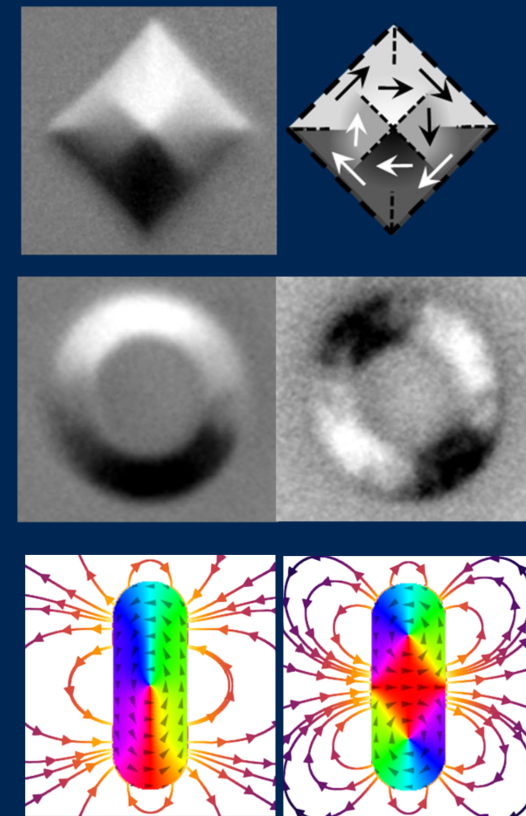


DE-SC0019273

UNIVERSITY OF CALIFORNIA
National Laboratory Research Program

Outline

- Motivation
- Imaging magnetic spin textures
- Two short stories on tailoring magnetic spin textures
    1. $La_{0.7}Sr_{0.3}MnO_3$ micromagnets
    2. $La_{0.7}Sr_{0.3}MnO_3$ artificial spin ice structures
- Summary



Complex Oxides

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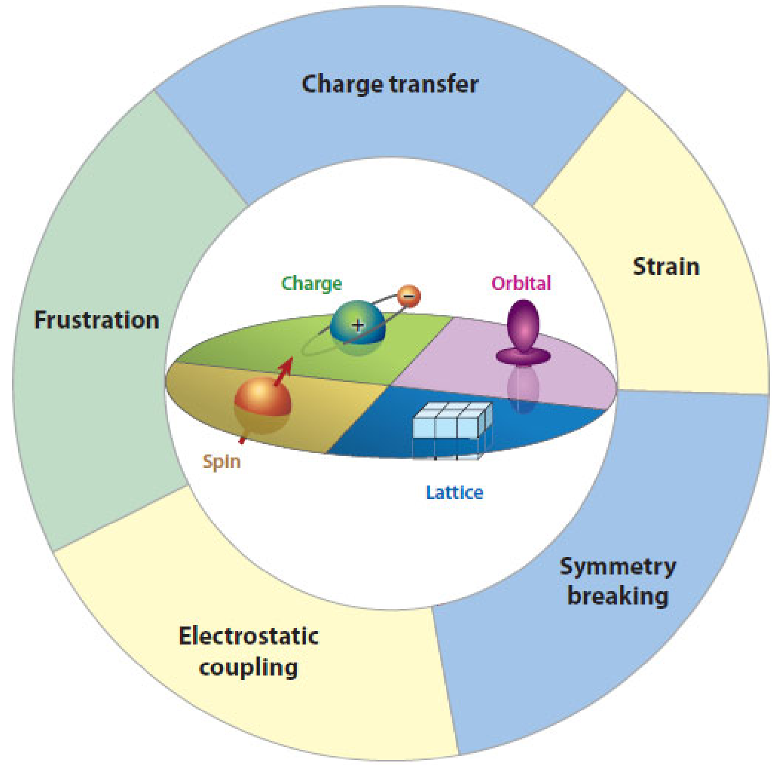
- Strong interaction among the lattice, charge, spin, orbital degrees of freedom
  - Stimulus-sensitive functional properties
- Wide range of functional properties
  - Ferromagnetism, ferroelectricity, superconductivity, etc…
- Applications in spintronics, neuromorphic computer, magneto-ionics, and solid oxide fuel cells



Zubco *et al., Annu. Rev. Condens. Matter Phys.*, **2**, 141 (2011)

ABO$_3$ Perovskite Oxides

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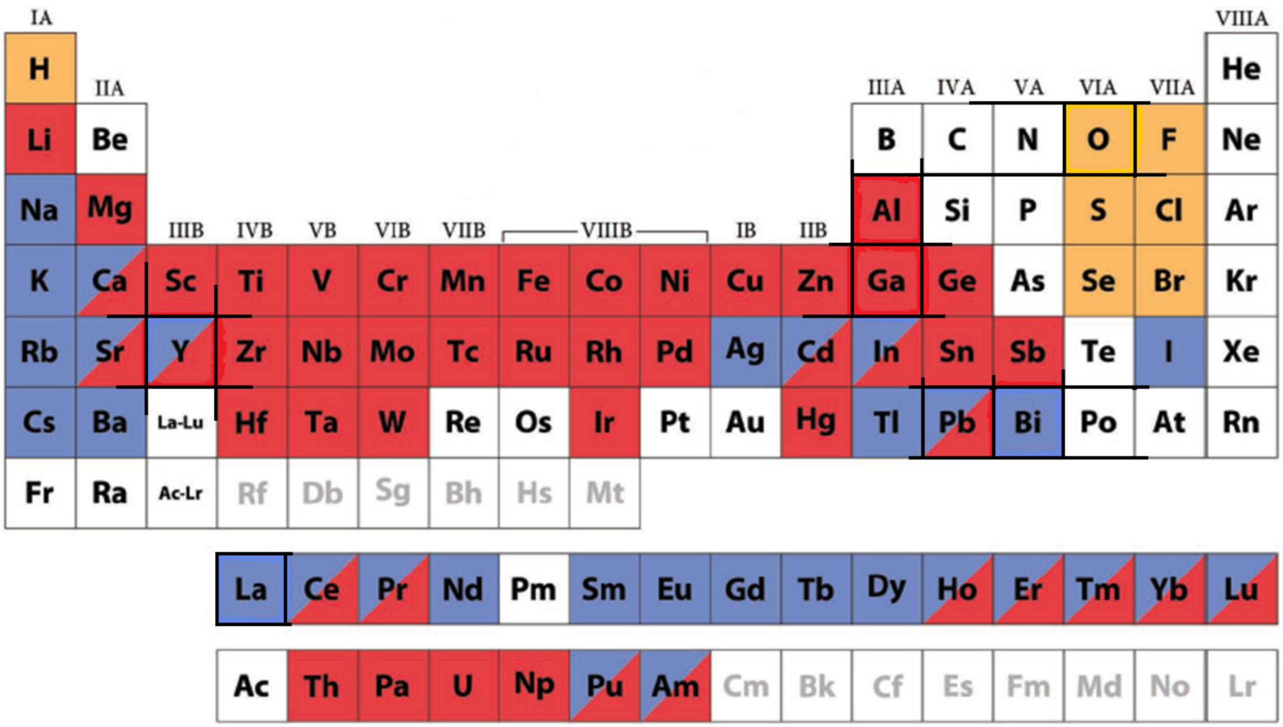
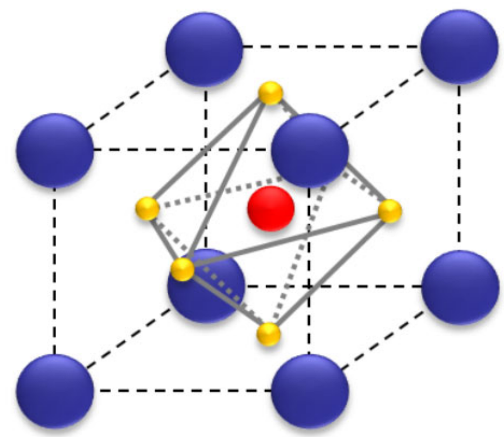
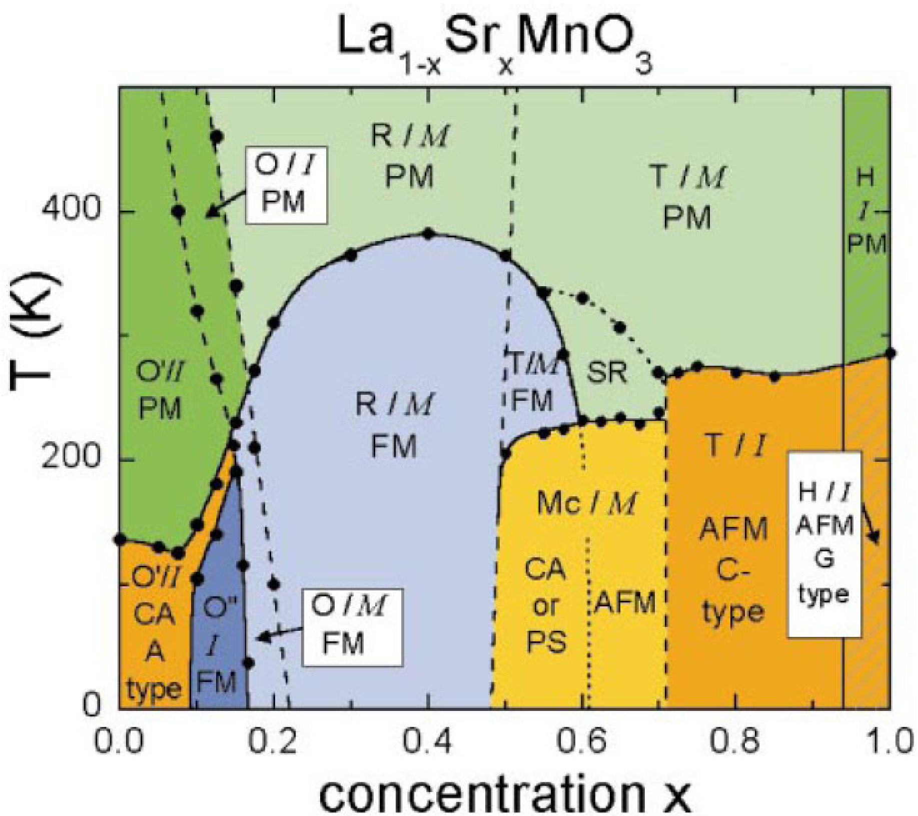


Rondinelli and Fennie, *Adv. Mater.*, **24**, 1962 (2012)



- Compatible with many different elements leading to a wide range of functional properties

Magnetic Perovskite Oxides



- $La_{0.67}Sr_{0.33}MnO_3$ (LSMO):
  - Ferromagnetic (FM) metal < T_C = 360 K, half metal, colossal magnetoresistance

Hemberger *et al.*, *PRB*, **66**, 094410 (2002)

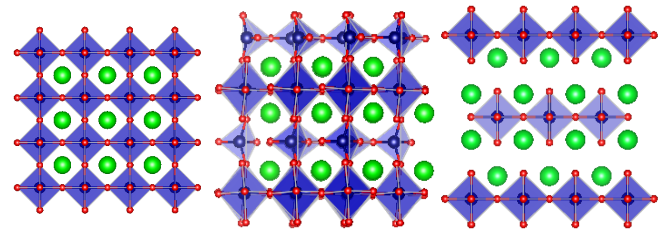
Research Highlights

Magneto-ionics

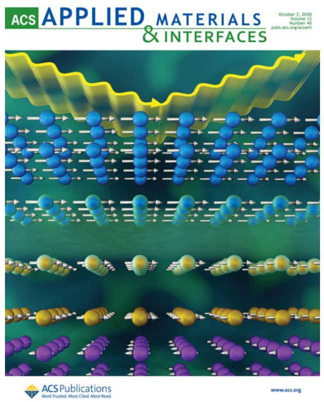
Controlling Spin Textures

Voltage-controlled Magnetism

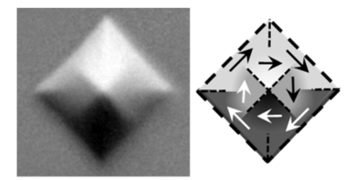
Interfacial Phenomena

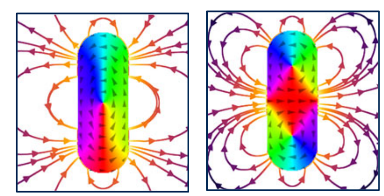


I.T. Chiu, *et al., PRM*, ***5***, 064416 (2021)
M. Feng, *et al., J. Phys. Chem. C*, **128**, 17124 (2024)

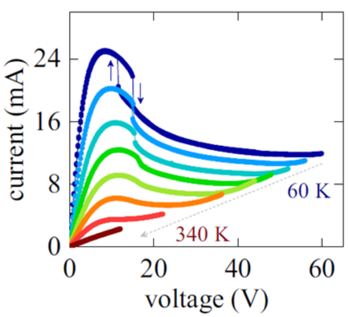


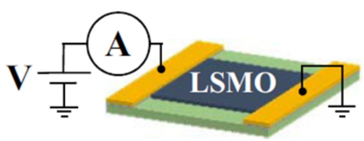
A.M. Kane *et al., ACS Appl. Mater. & Int.*, **12**, 45437 (2020)
I. Nihal *et al., PRB*, **110,** 014411 (2024)





M.S. Lee, *et al., ACS Nano*, **10**, 8545 (2016)
D. Sasaki, *et al., PR Applied*, **17,** 064057 (2022)



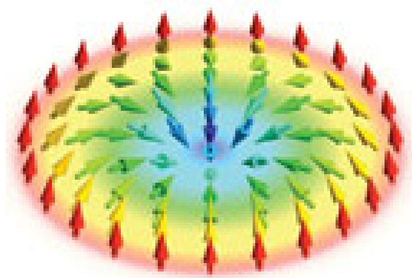


P. Salev et al., *Nat. Comm.*, **12,** 5499 (2021)

Spin Textures

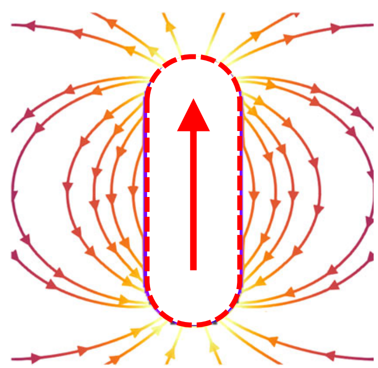
- Spatial variation of the local magnetization in a material/object

Skyrmions

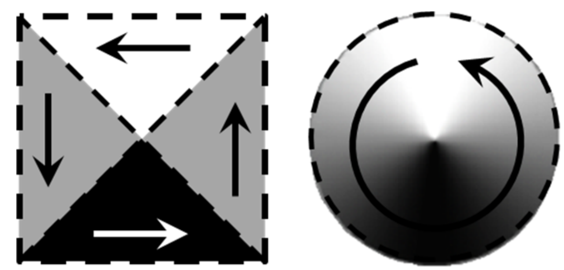


www.christophschuette.com

Single Domain



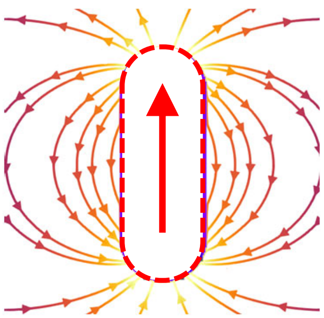
Landau/Vortex States



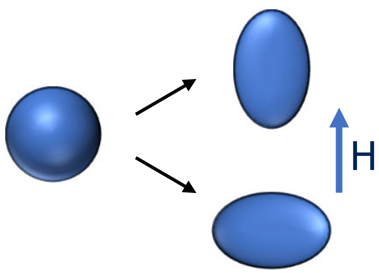
Increasing dimensions

Spin Texture Energy Terms

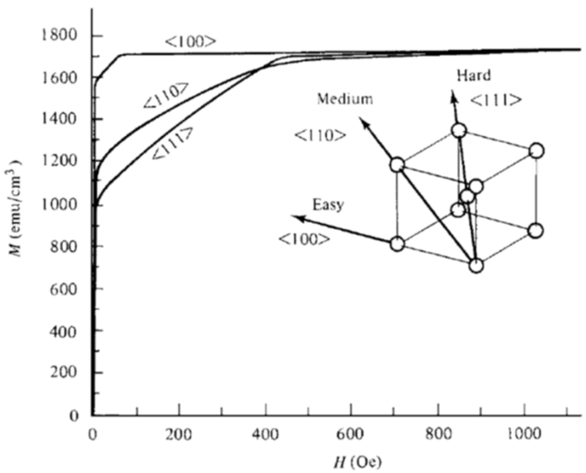
Magnetostatic Energy



Magnetoelastic Energy

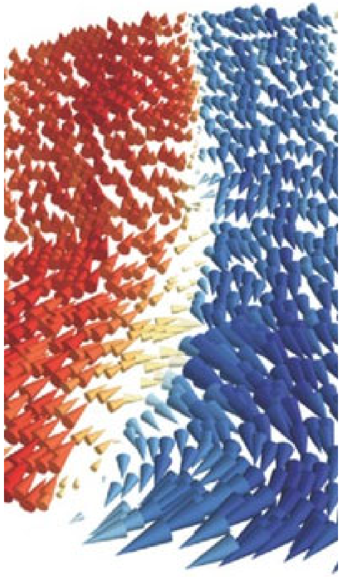


Magnetocrystalline Anisotropy Energy



Cullity and Graham, *Introduction to Magnetic Materials*, 2nd edition

Domain Wall Energy



G. Chen & A.K. Schmid*, Adv. Mater.*, 27, 5738

Spin Texture Energy Terms

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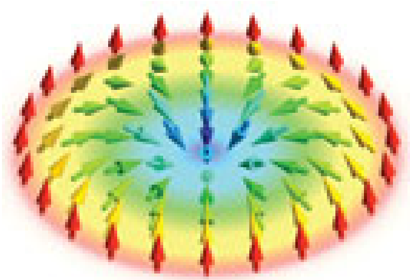
Skyrmions



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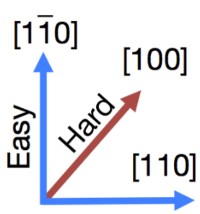
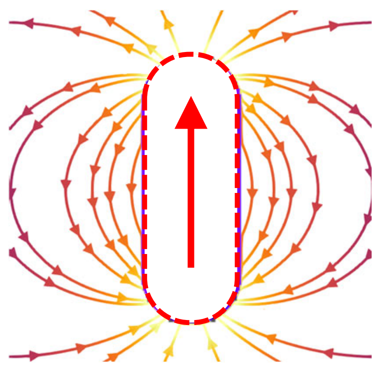
Magnetocrystalline Anisotropy Energy

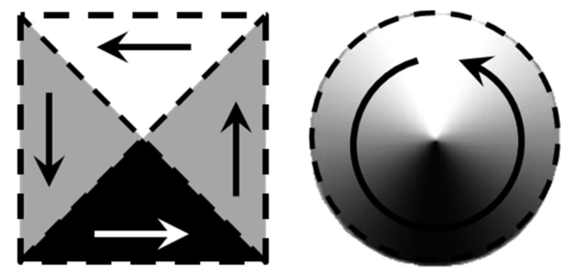


Single Domain



Magnetostatic Energy
Magnetoelastic Energy

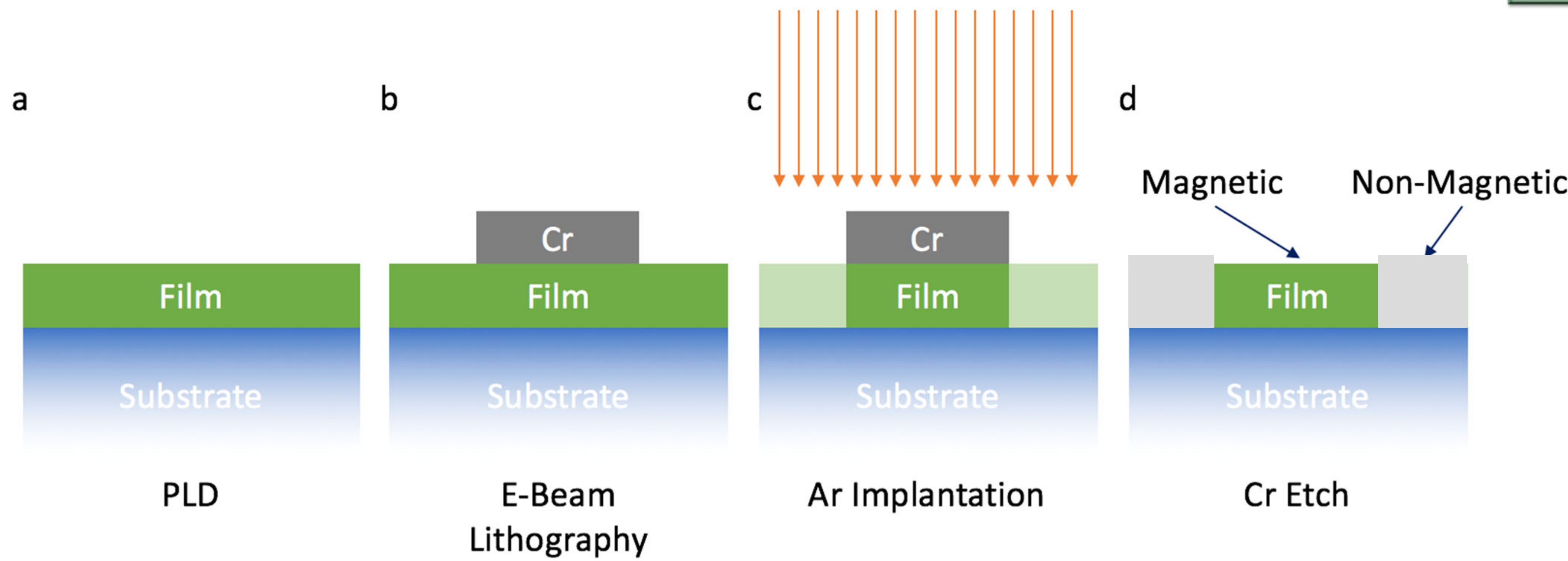
Landau/Vortex States



Domain Wall Energy (squares)
Magnetoelastic Energy (squares)

Magnetocrystalline Anisotropy Energy (circles)

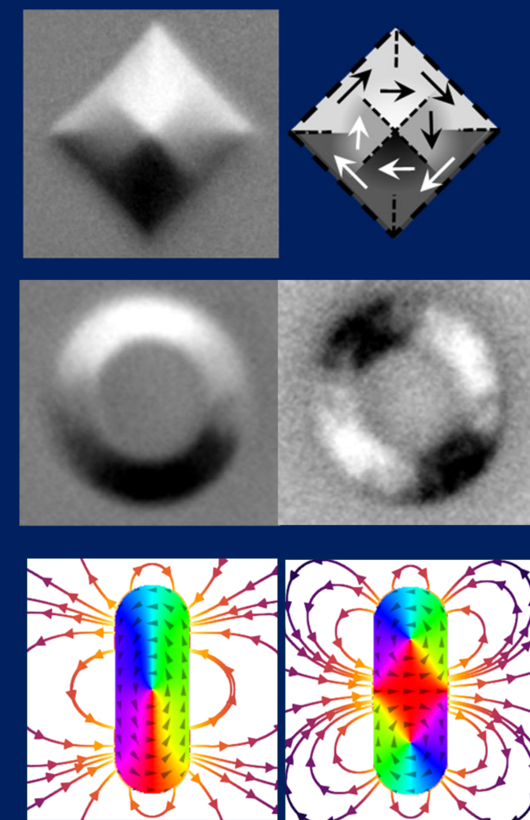
Ion Implantation-based Patterning



- Magnetic islands embedded in a non-magnetic matrix

Outline

- Motivation
- Imaging magnetic spin textures
    - X-ray photoemission electron microscopy
- Two short stories on tailoring magnetic spin textures
    1. $La_{0.7}Sr_{0.3}MnO_3$ micromagnets
    2. $La_{0.7}Sr_{0.3}MnO_3$ artificial spin ice structures
- Summary



X-ray Absorption (XA) Spectroscopy

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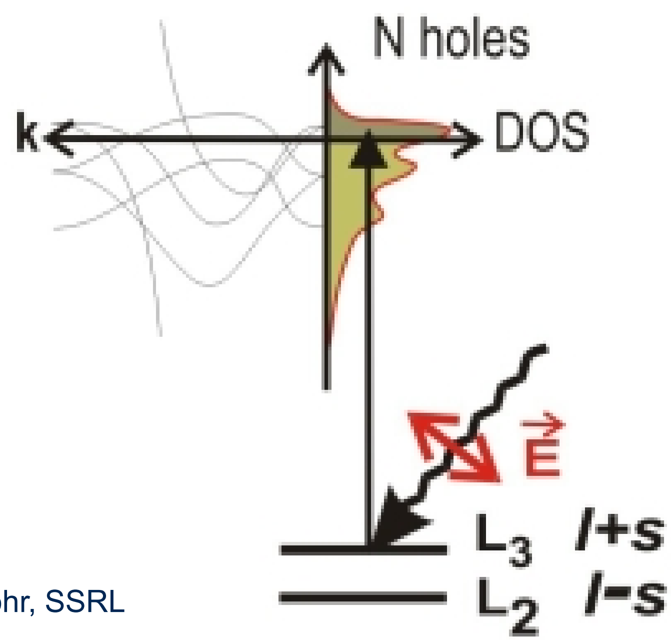
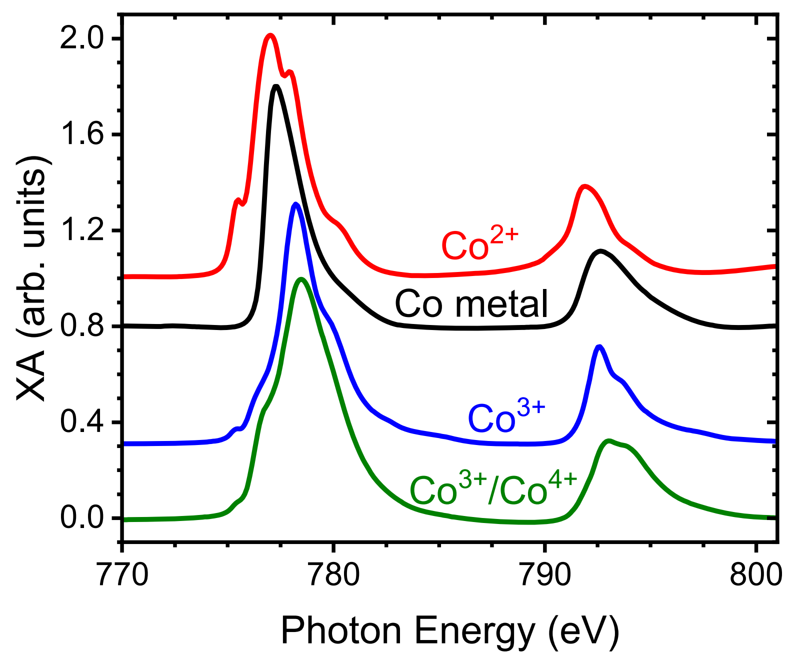
- Sensitive to valence states (e.g., Co^{2+} vs. Co^{3+} vs. Co^{4+} ions) and bonding configurations (e.g., octahedral vs. tetrahedral coordination)



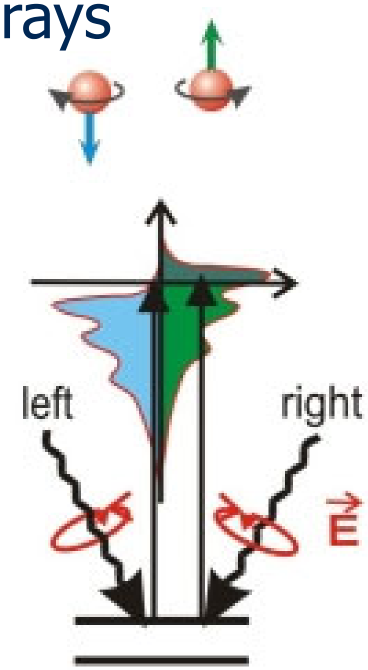
J. Stohr, SSRL



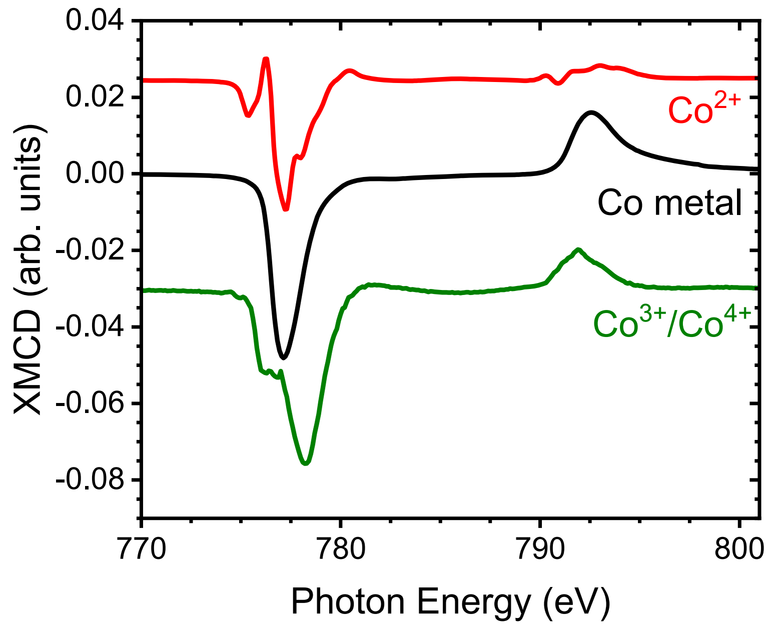
ALS

X-ray Magnetic Circular Dichroism (XMCD)

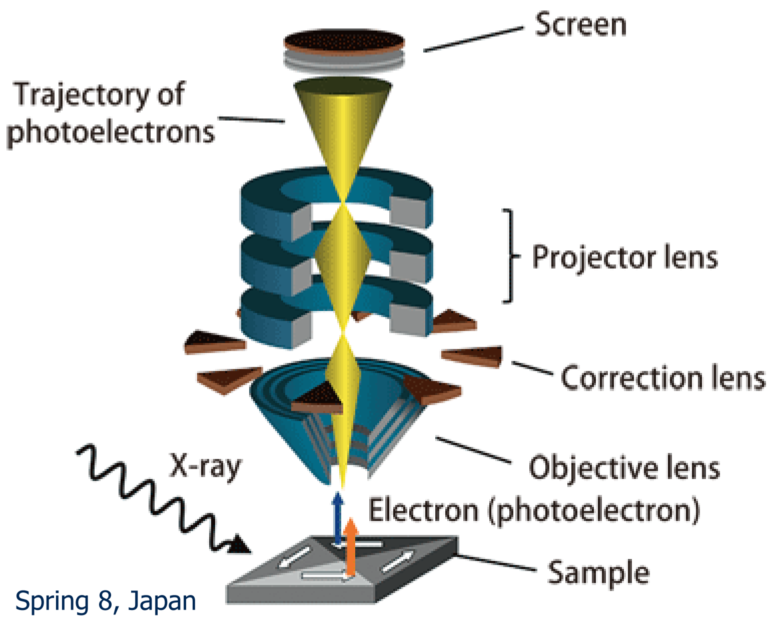
- Sensitive to ferromagnetically active ions
- Difference between XA spectra acquired with right/left circularly polarized x-rays



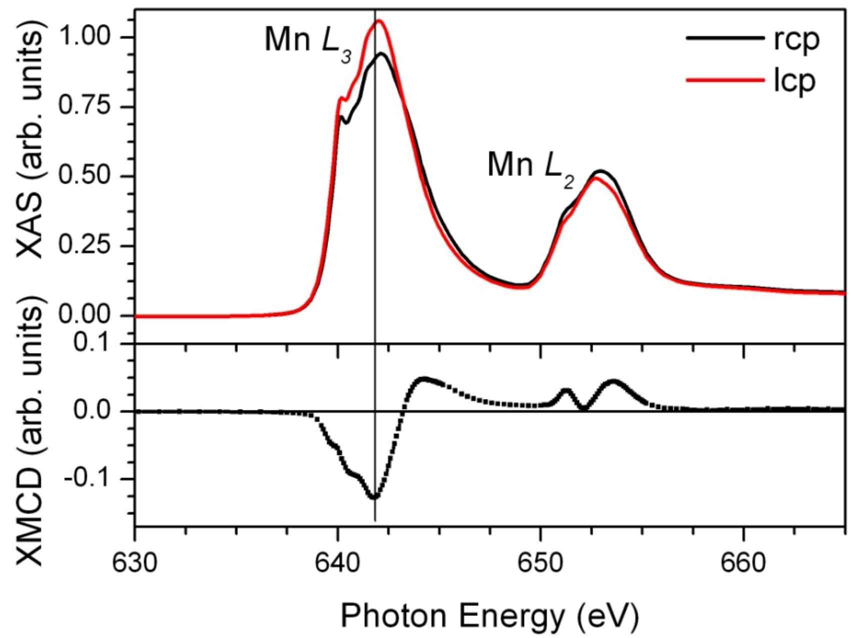
J. Stohr, SSRL



Photoemission Electron Microscopy (PEEM)



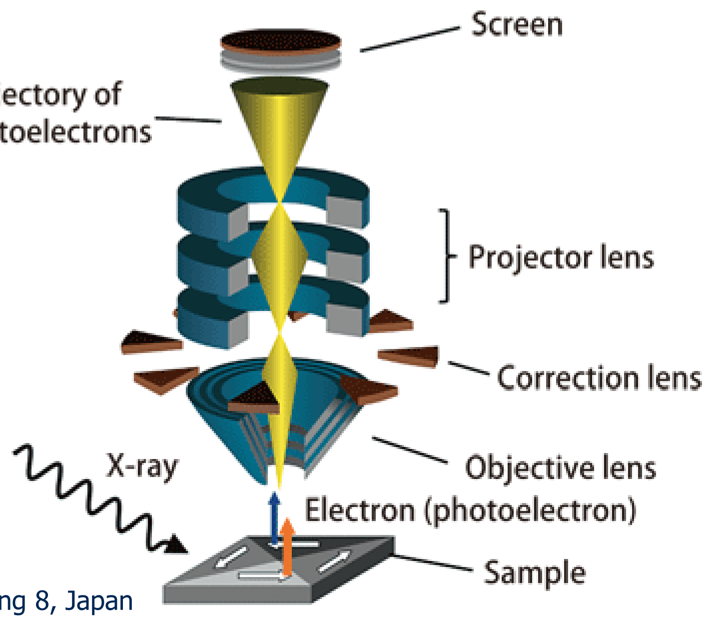
Spring 8, Japan



Performed using the PEEM-3 Microscope

$$Asymmetry = \frac{rcp - lcp}{rcp + lcp}$$

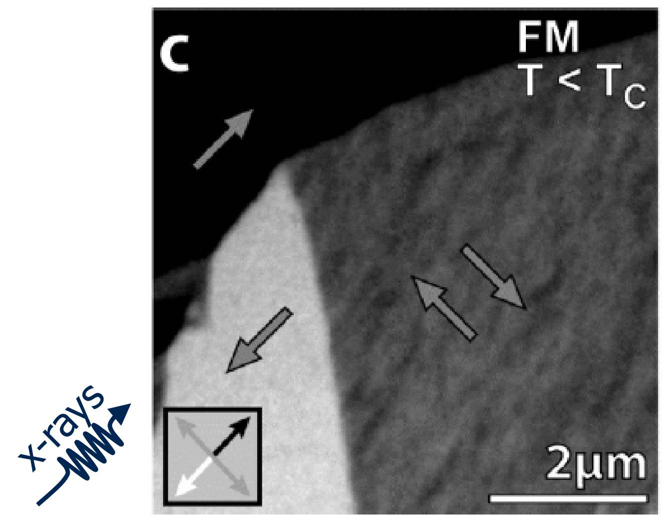
Photoemission Electron Microscopy (PEEM)



Spring 8, Japan

Performed using the PEEM-3 Microscope

- XMCD ~ ***M*** *cos (θ); θ* = angle between x-ray helicity and magnetization, ***M***

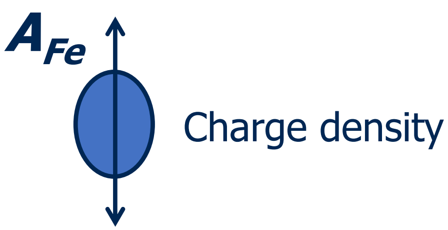


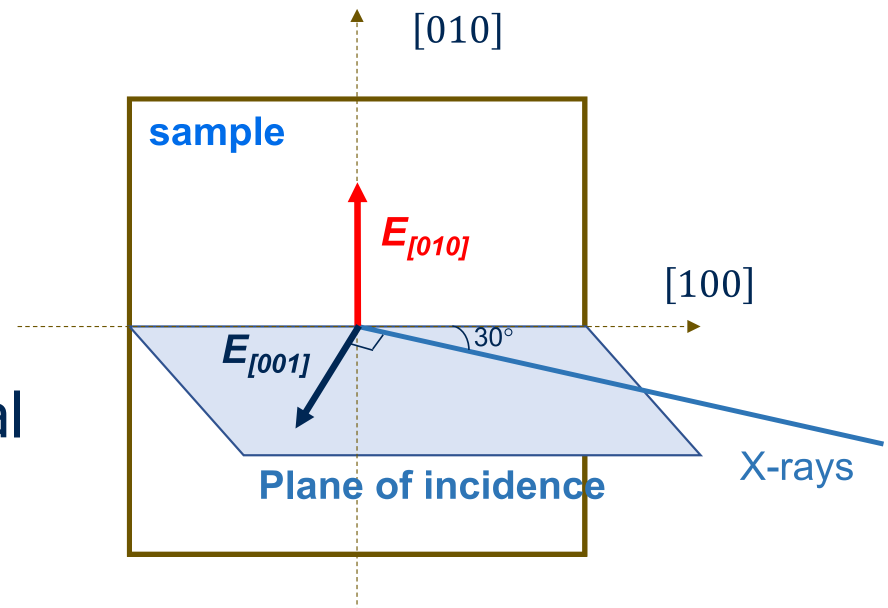
White/black/grey = antiparallel/parallel/perpendicular alignment

ALS

X-ray Magnetic Linear Dichroism (XMLD)

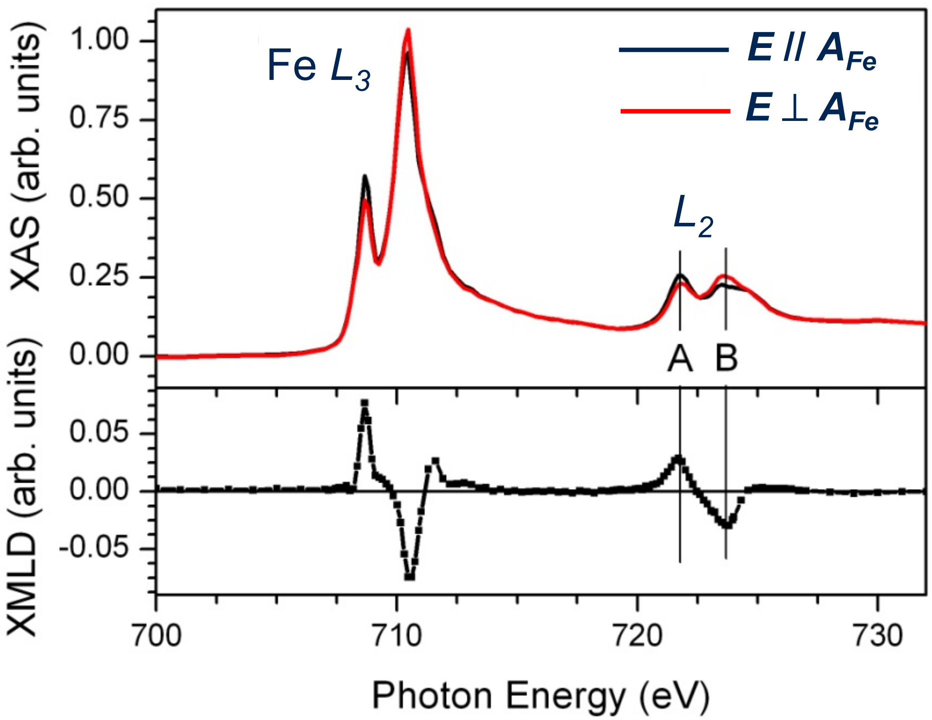
- Sensitive to *asymmetry* in the system
  - Orbital occupancy
  - Crystallographic directions/asymmetry
  - AFM spin axis
- Requires carefully designed experimental geometry

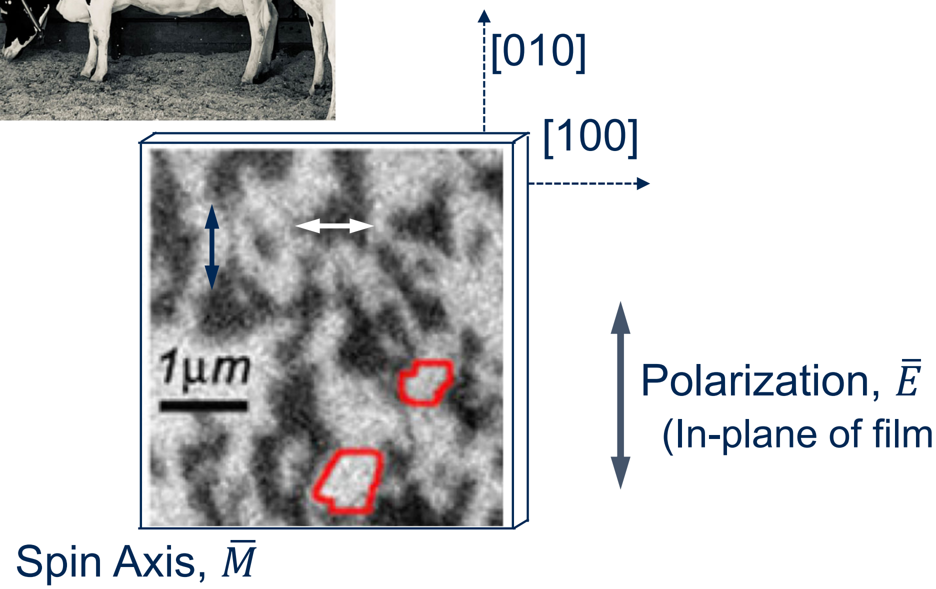




$$I_{XLD} = I_{XA}(\boldsymbol{E}_{100}) - I_{XA}(\boldsymbol{E}_{190})$$

XMLD-PEEM

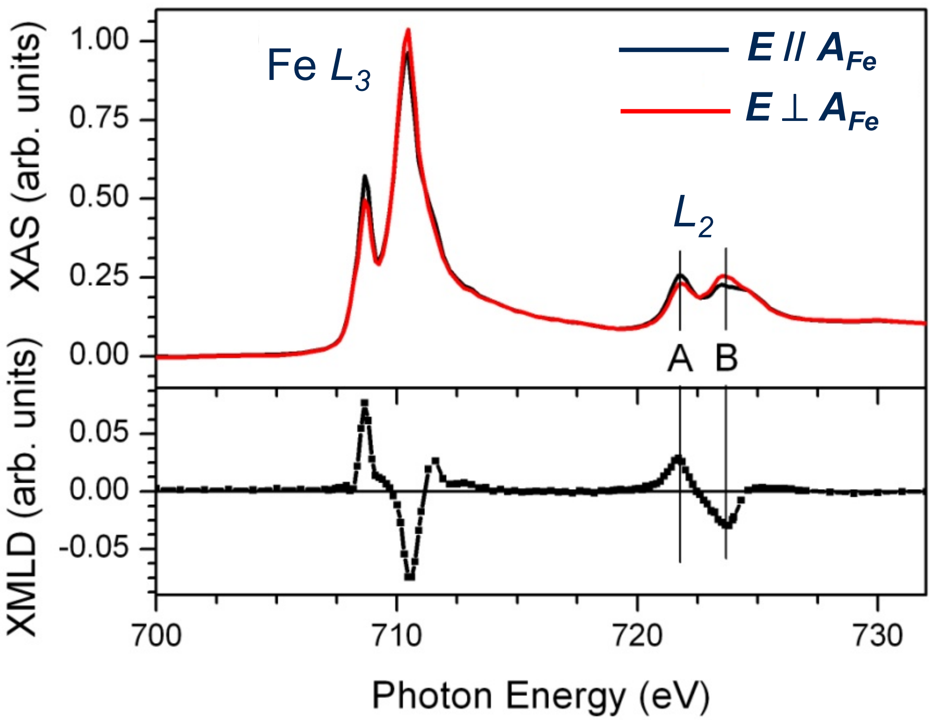


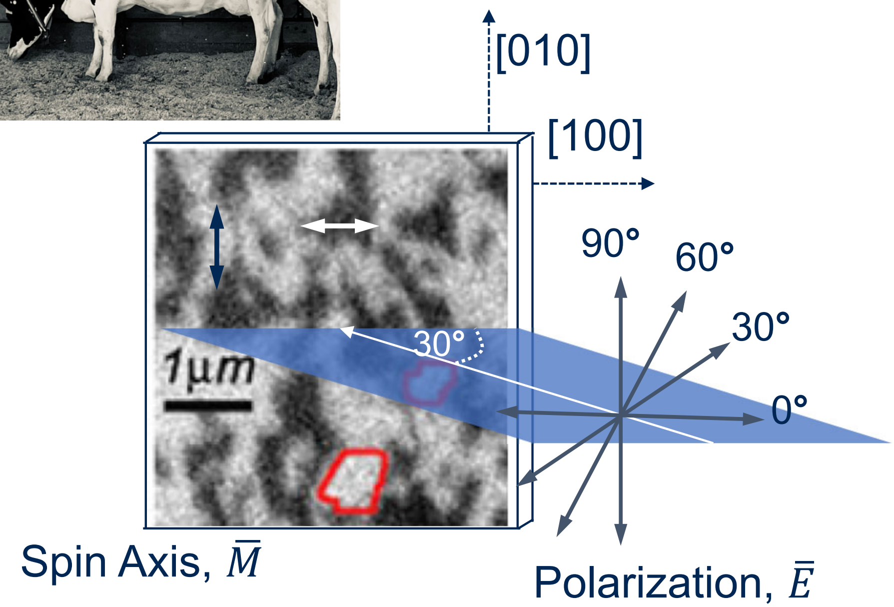


$$I(\omega, T) = a + b(3cos^2\omega - 1)\langle A^2\rangle_T$$

ω = angle between $\bar{E}$ and magnetic spin axis, $\bar{A}$

XMLD-PEEM





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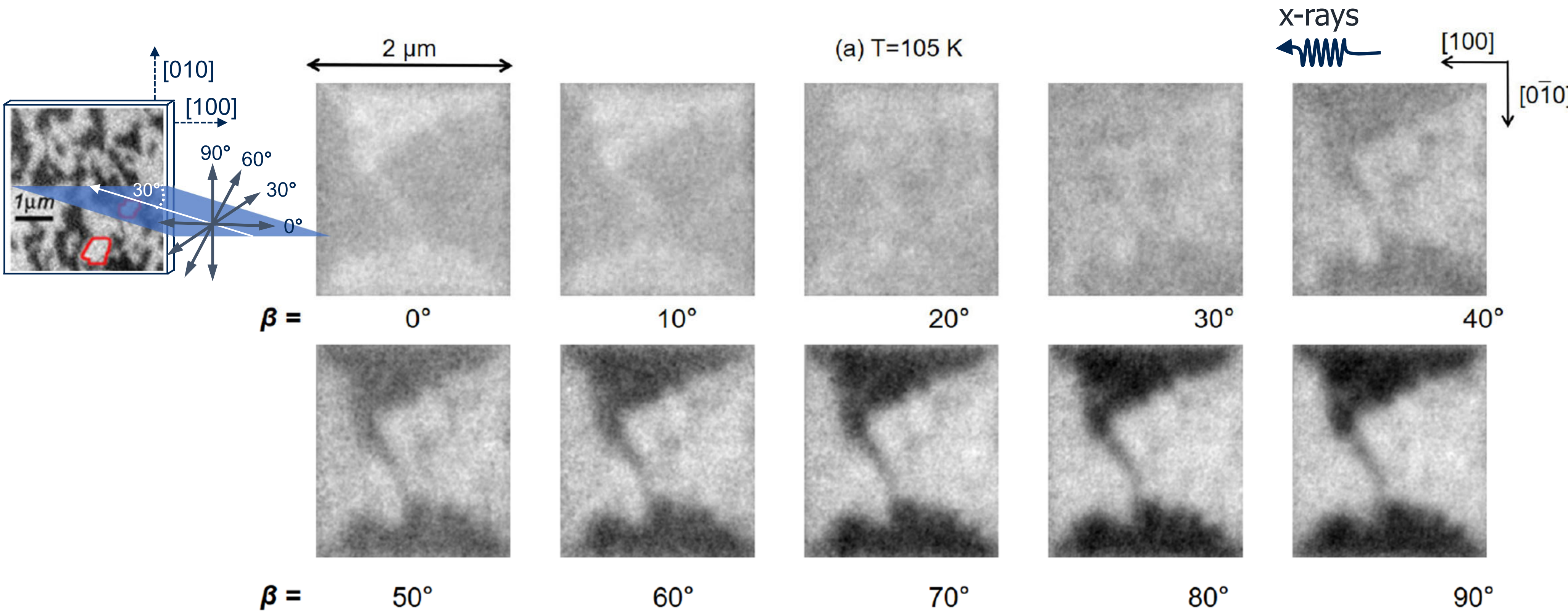
ω = angle between $\bar{E}$ and magnetic spin axis, $\bar{A}$

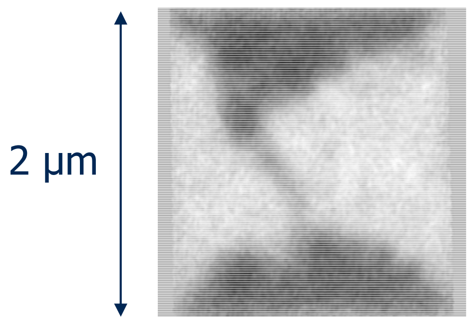
XMLD-PEEM

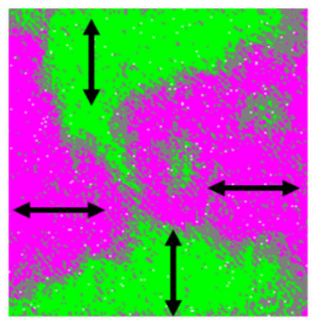


M.S. Lee, Y. Takamura *et al., JAP,* **127**, 203901 (2020)

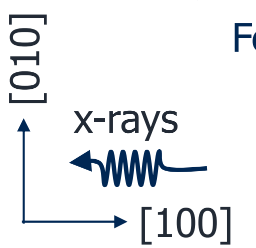
XMLD-PEEM

Square <100> edges

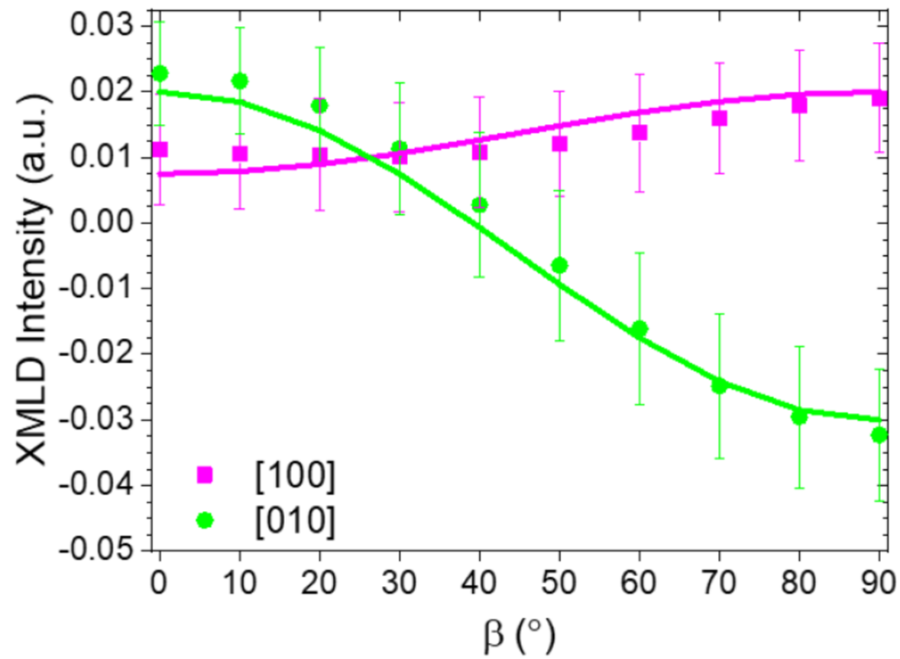




Fe XMLD, β = 90°



6 u.c. $La_{0.7}Sr_{0.3}FeO_3$



- AFM spins lie *in-plane* along the <100> directions

M.S. Lee, Y. Takamura *et al., JAP,* **127**, 203901 (2020)

Outline

- Motivation
- Imaging magnetic spin textures
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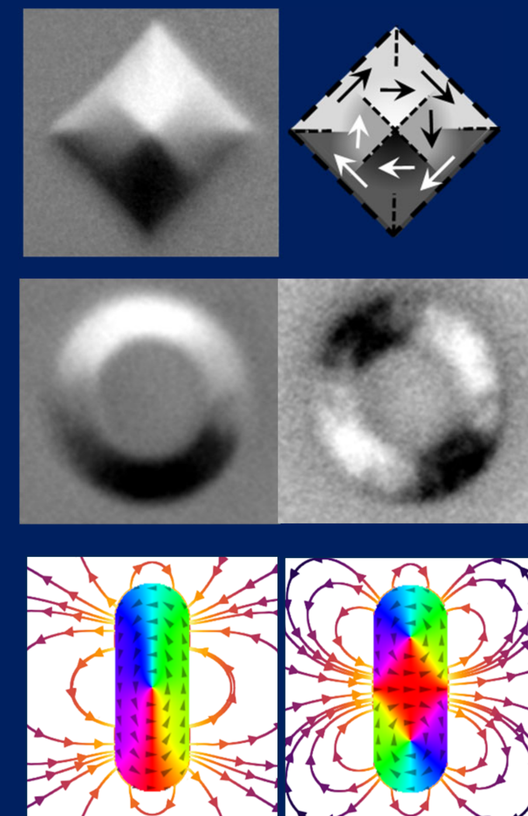
- Summary



LSMO Micromagnets

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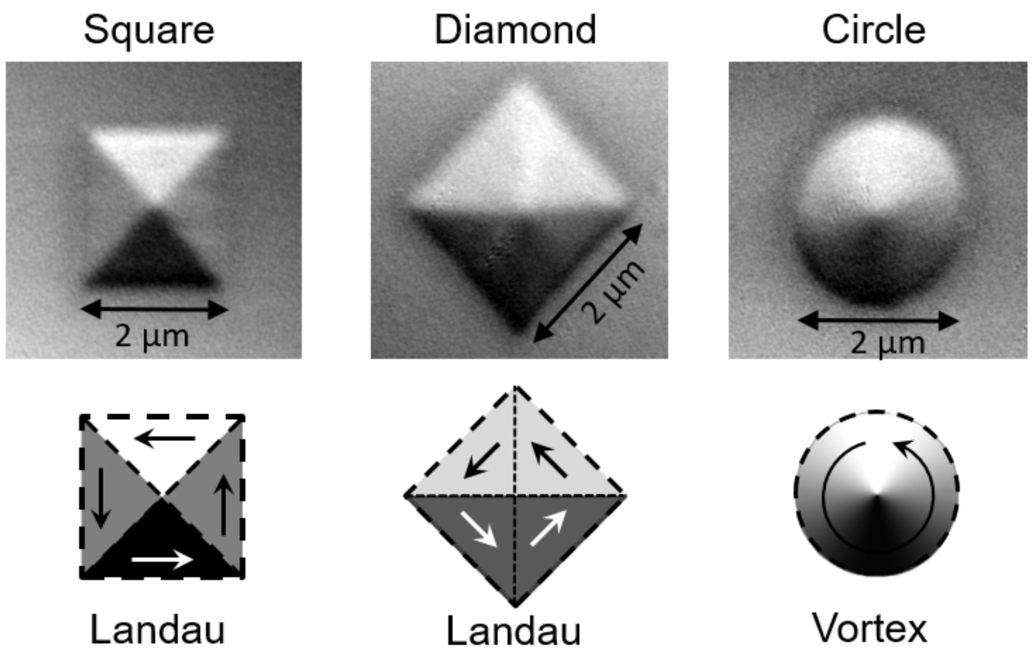
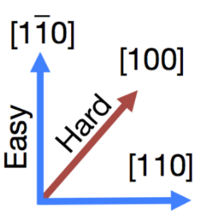




T = 230 K

100 u.c. LSMO

M.S. Lee, Y. Takamura *et al.*, *ACS Nano*, **10**, 8545 (2016)

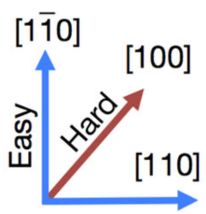
➢Domain patterns determined by *shape anisotropy*

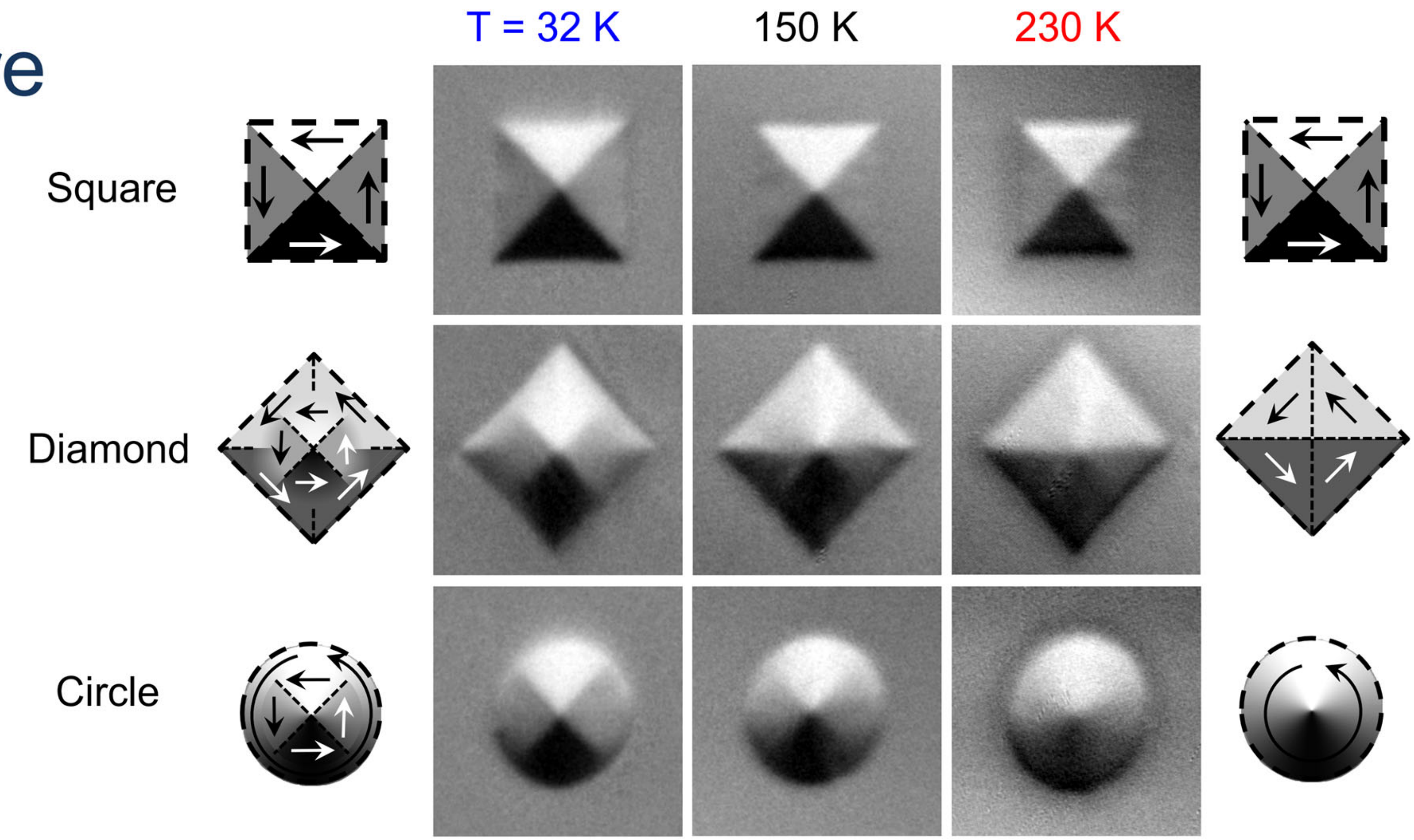
Temperature Evolution

100 u.c. LSMO

M.S. Lee, Y. Takamura *et al.*, *ACS Nano*, **10**, 8545 (2016)

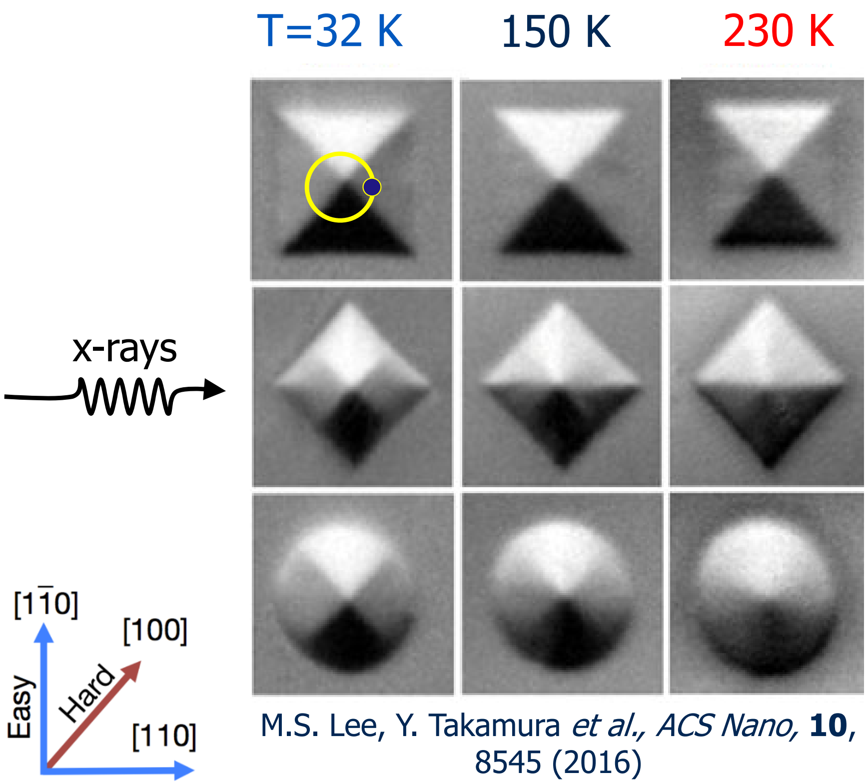
Magnetic easy axes





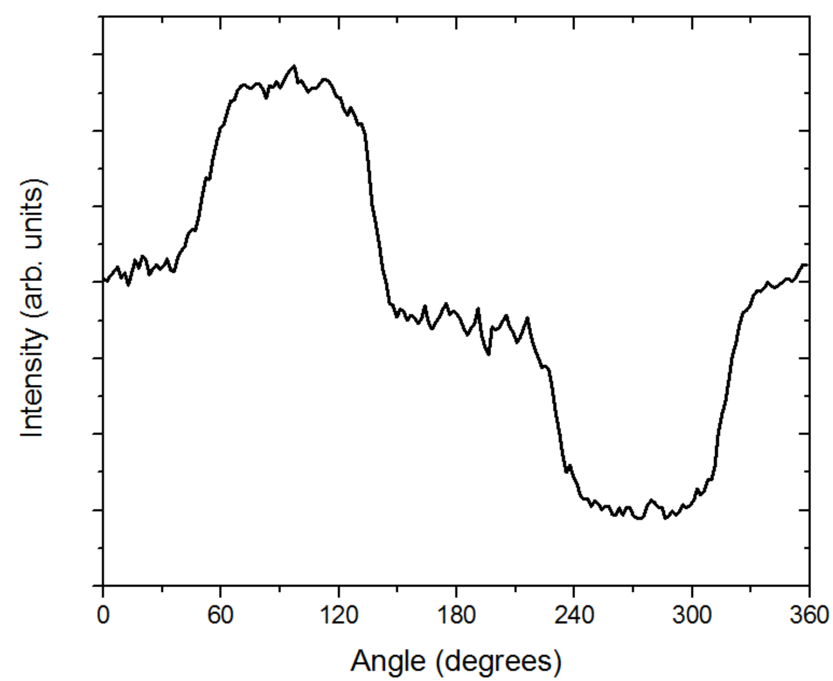
➢ Magnetocrystalline anisotropy dominates at low temperatures

Contrast Analysis

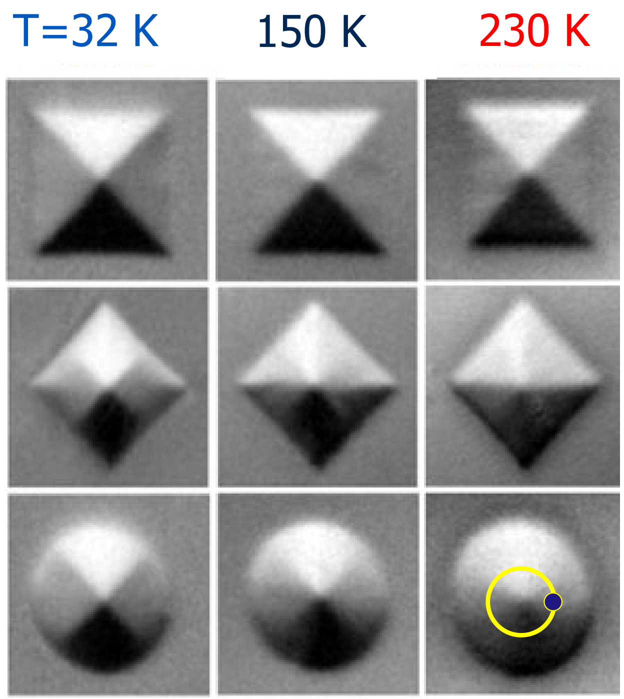


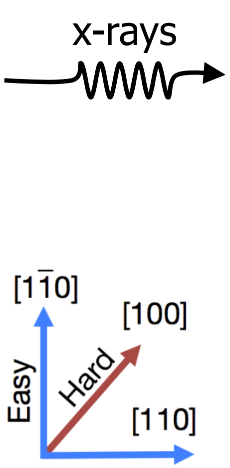
M.S. Lee, Y. Takamura *et al., ACS Nano,* **10**, 8545 (2016)

Square at 32 K

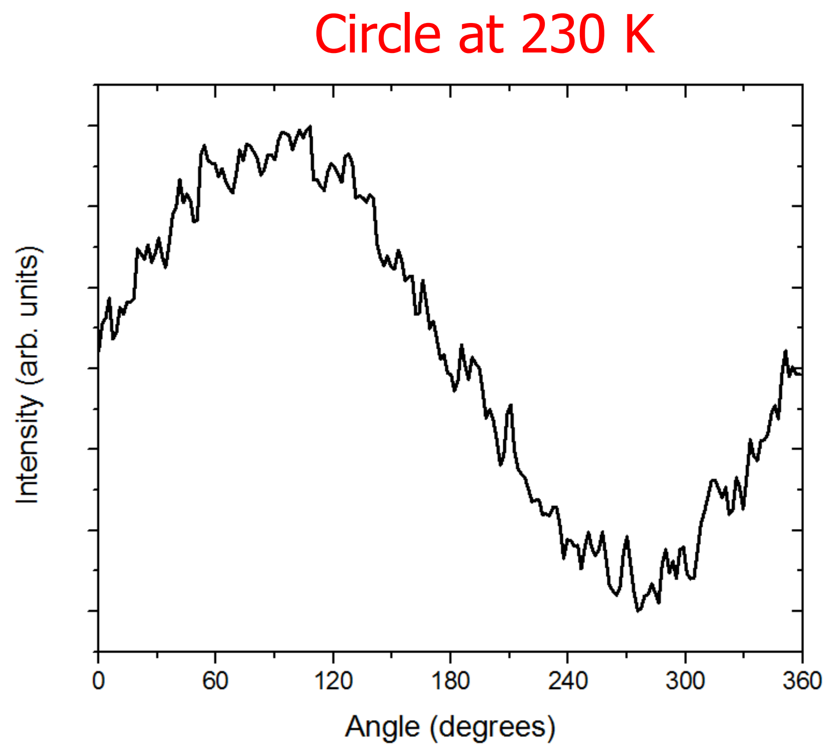


Contrast Analysis

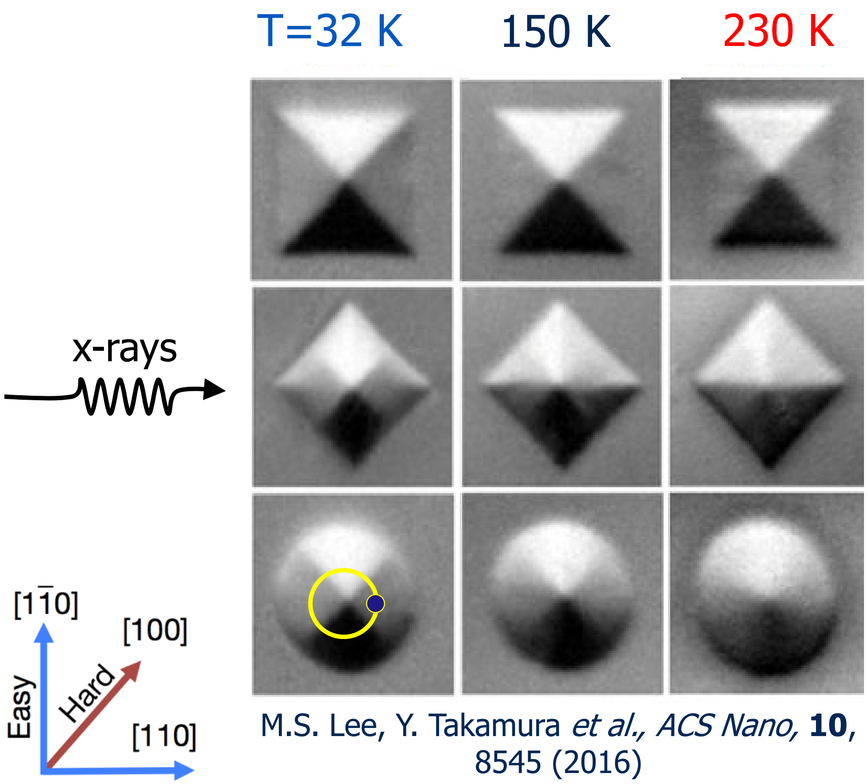




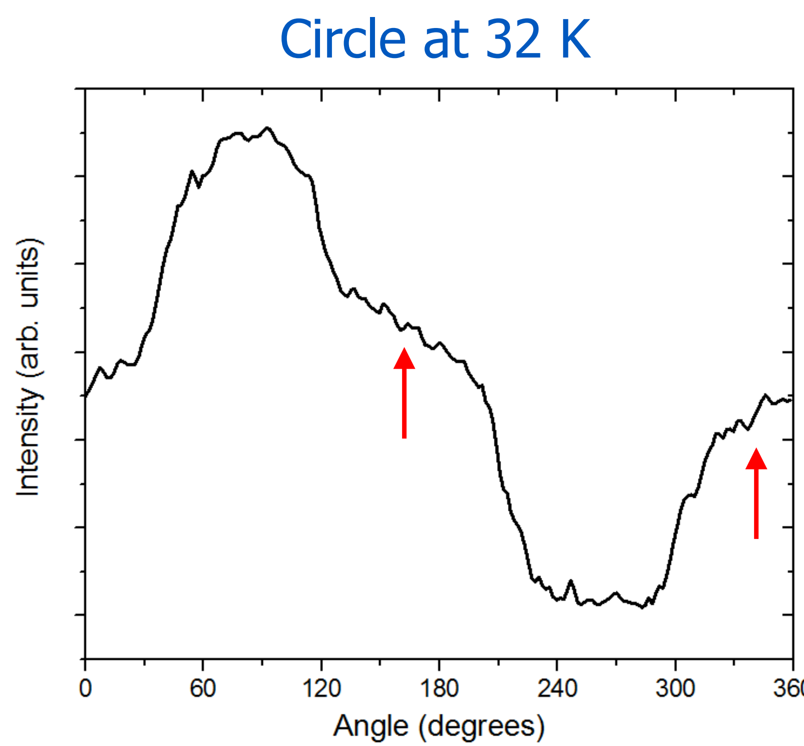
M.S. Lee, Y. Takamura *et al., ACS Nano,* **10**, 8545 (2016)



Contrast Analysis



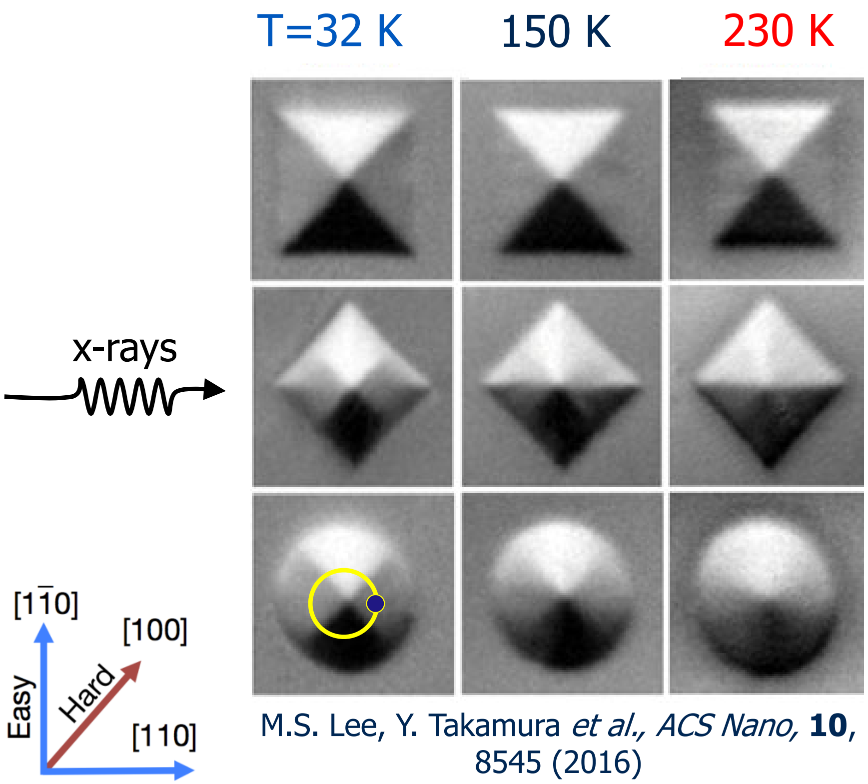
M.S. Lee, Y. Takamura *et al., ACS Nano,* **10**, 8545 (2016)



Contrast Analysis

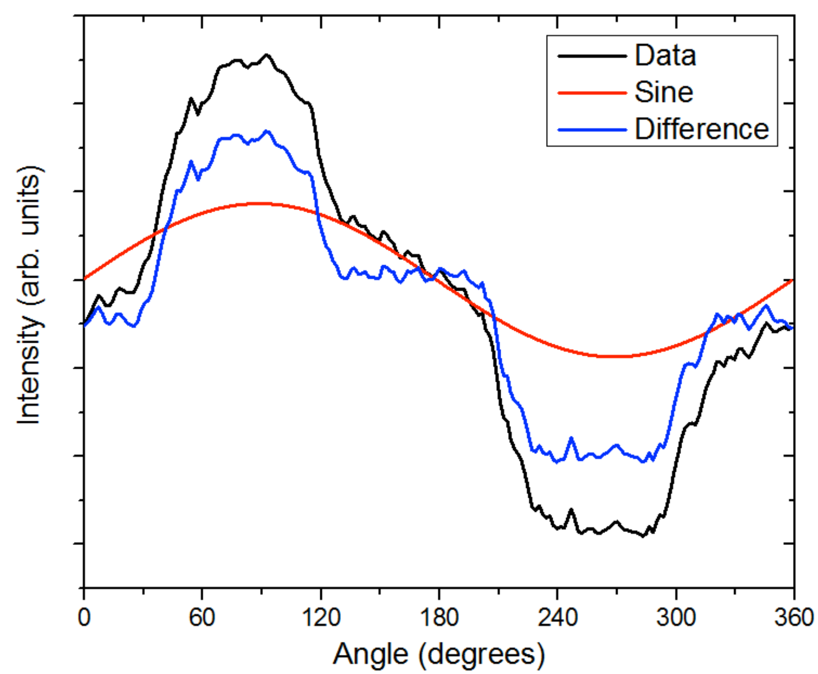
Vortex Fraction (VF)

$$VF = \frac{A_{Sine\ Func}}{A_{Sine\ Func} + A_{Step\ Func}}$$

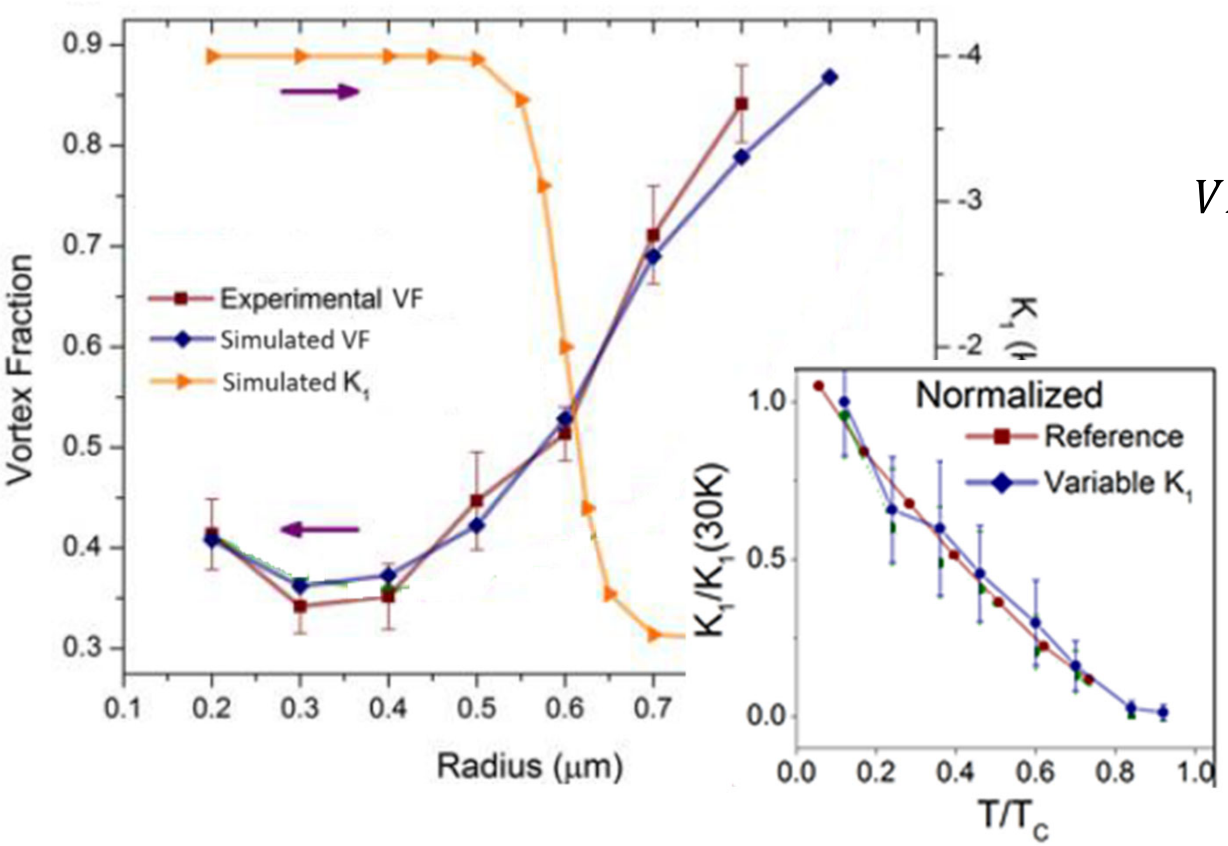


M.S. Lee, Y. Takamura *et al., ACS Nano,* **10**, 8545 (2016)

Circles at 32 K



Magnetocrystalline Anisotropy



Vortex Fraction (VF)

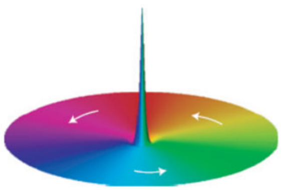
$$VF = \frac{A_{Sine\ Func}}{A_{Sine\ Func} + A_{Step\ Func}}$$

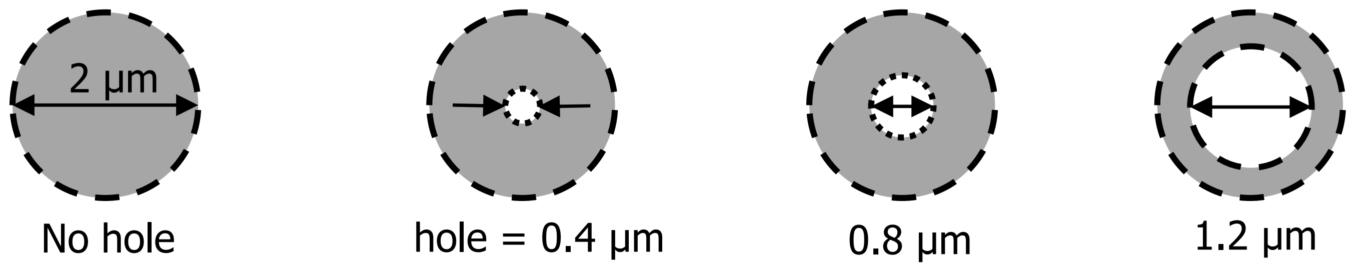
- Comparison to MuMax[3] micromagnetic simulations to extract *local* magneto-crystalline anisotropy constant (K_1) values as a function of temperature

M.S. Lee, Y. Takamura *et al., ACS Nano,* **10**, 8545 (2016)

LSMO Micromagnetic Donuts

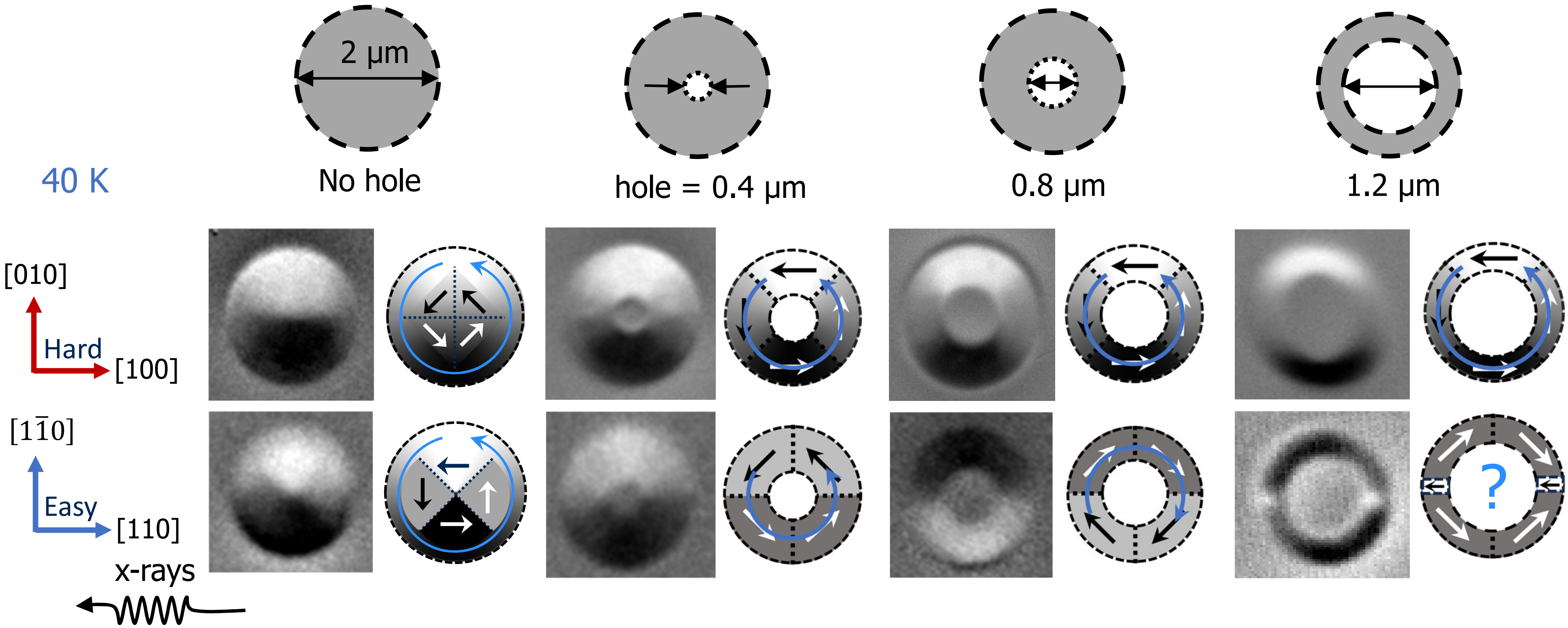
Vortex Core



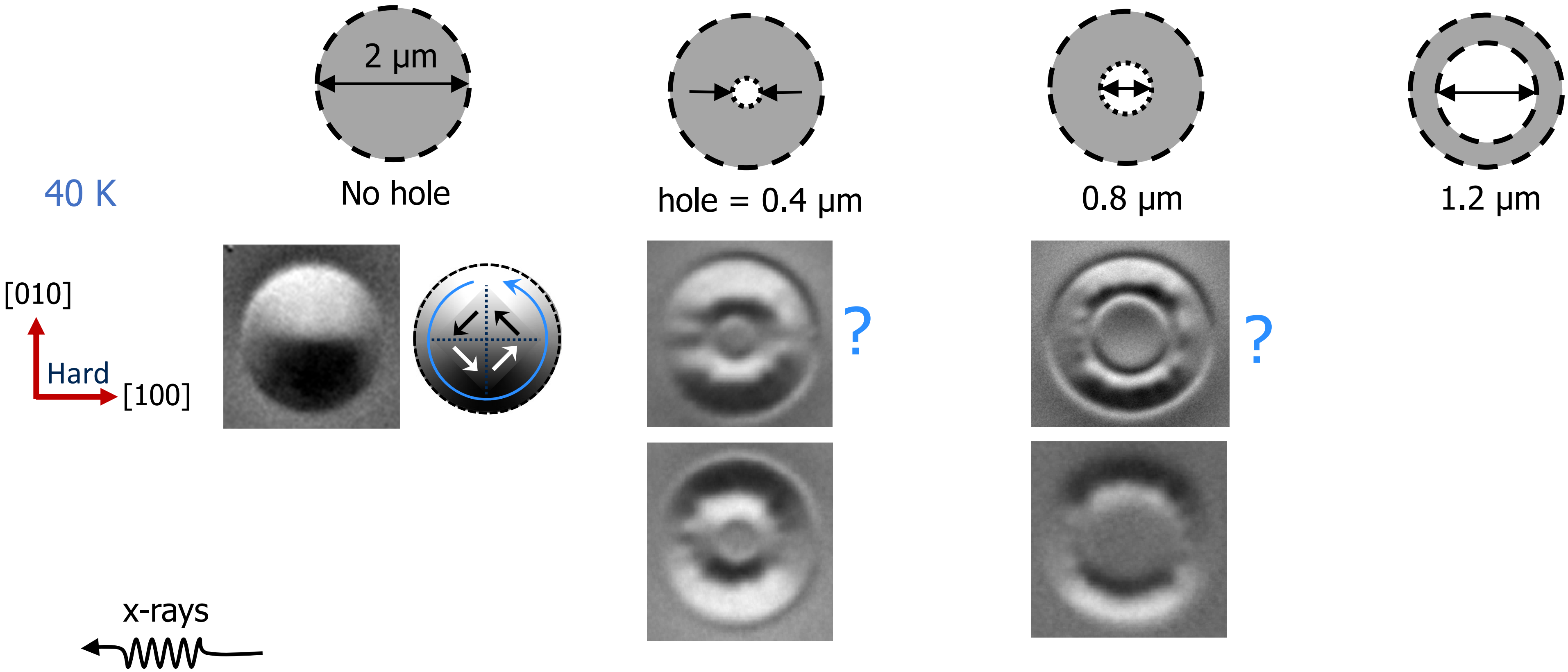


x-rays

LSMO Micromagnetic Donuts



LSMO Micromagnetic Donuts



LSMO Micromagnetic Donuts

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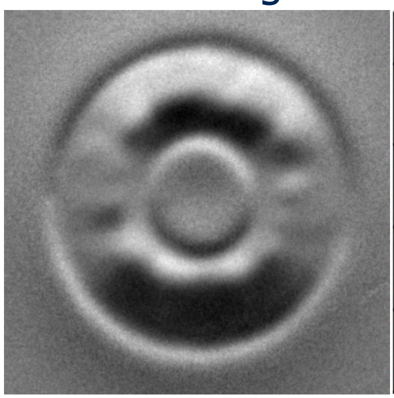
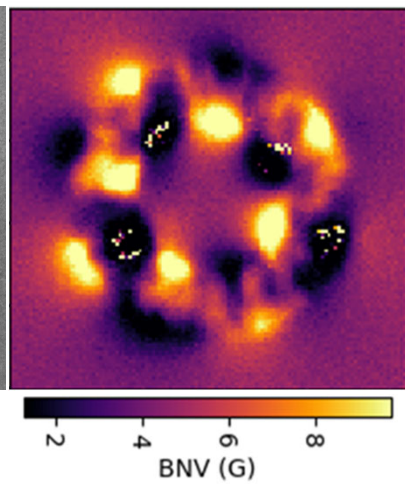
PEEM image



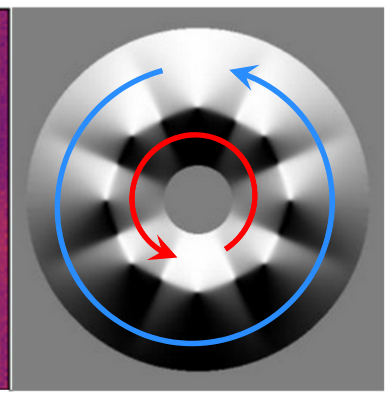
SNVM image
Sensitive to domain walls



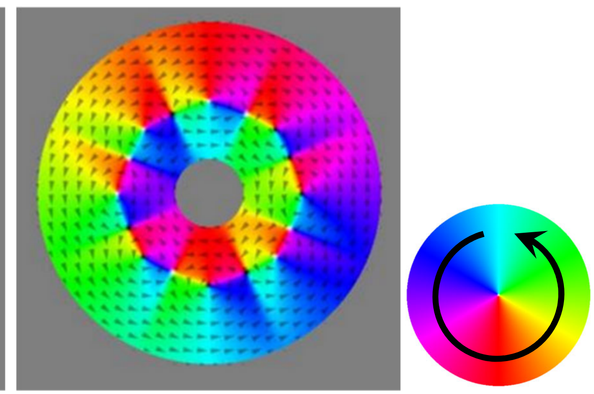
nami

MuMax^3 simulations

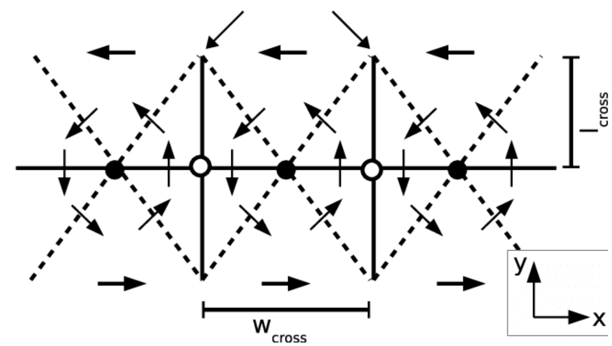
XMCD



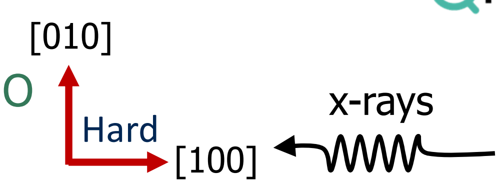
m vector field



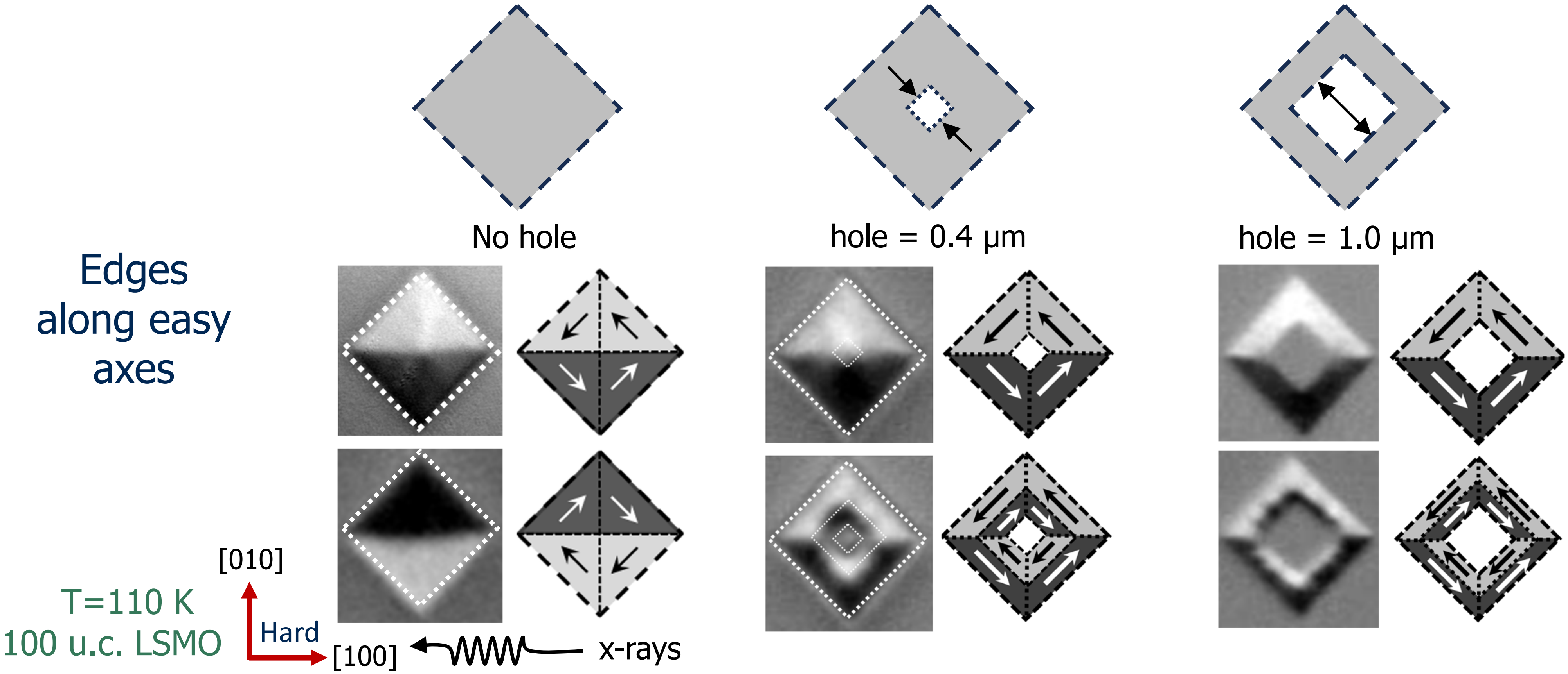
Cross-tie domains



100 u.c. LSMO

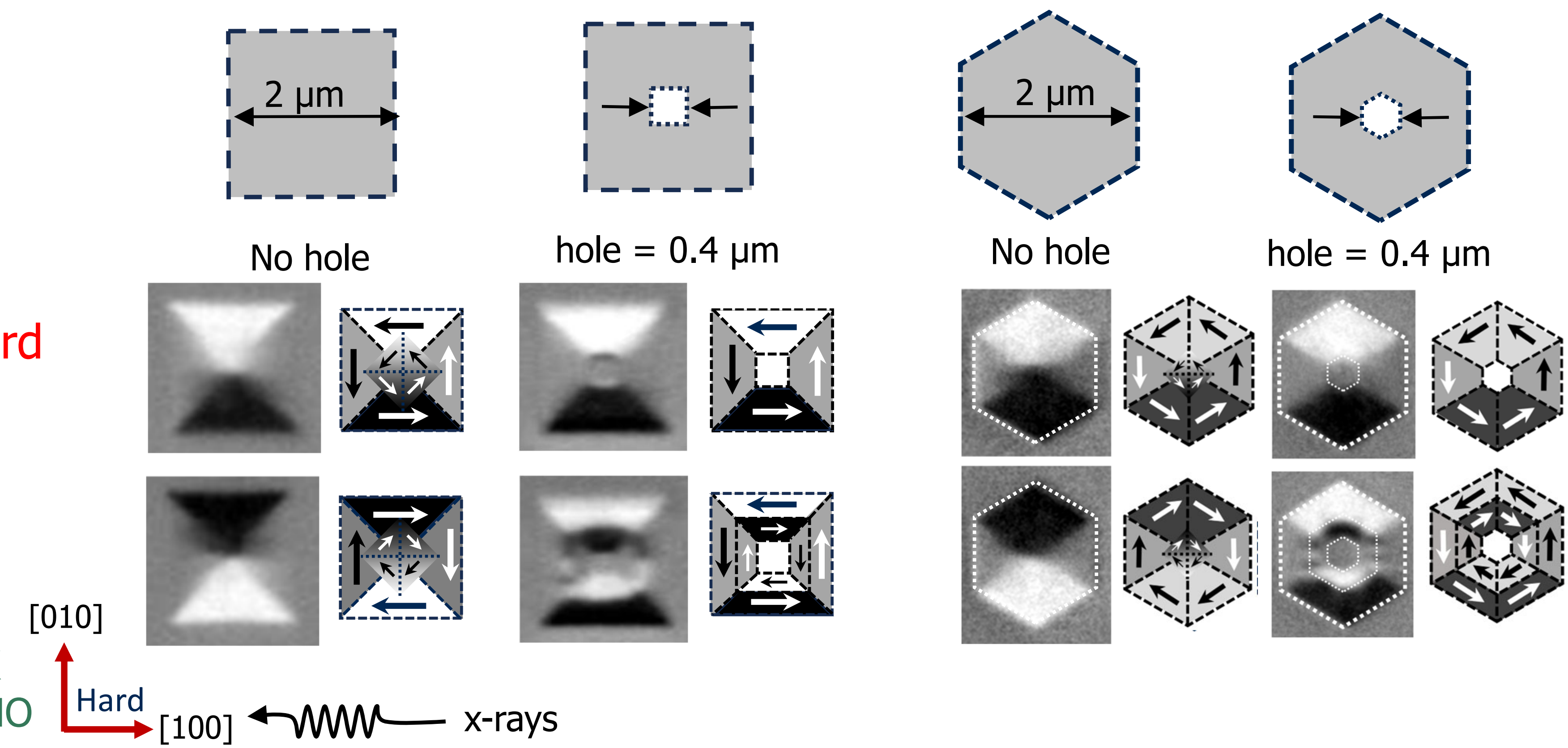


LSMO Micromagnetic Donuts



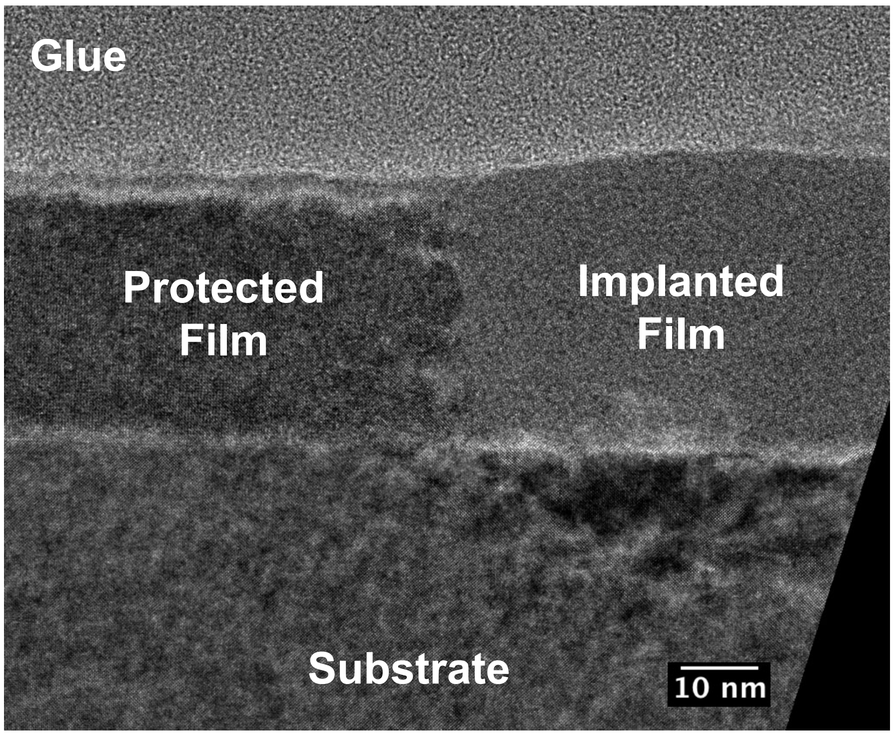
LSMO Micromagnetic Donuts

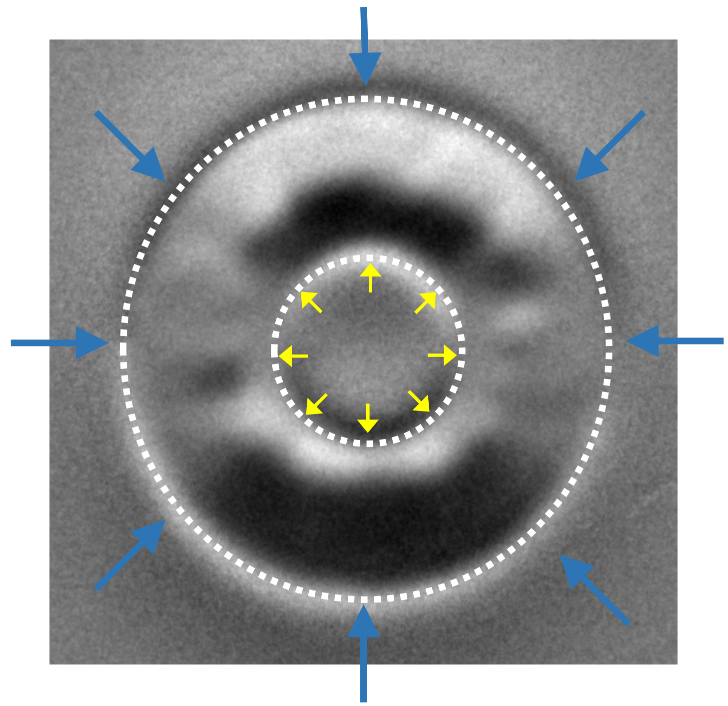
Edges along hard axes

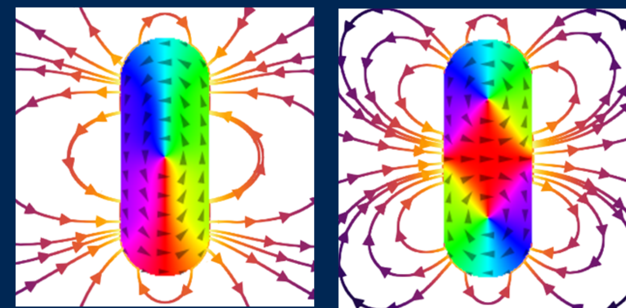


T=110 K
100 u.c. LSMO

Matrix Strain Effects







2. $La_{0.7}Sr_{0.3}MnO_3$ Artificial Spin Ice Structures

R.V. Chopdekar, Y. Takamura *et al., PR Materials,* **1**, 024401 (2017)
D.Y. Sasaki, Y. Takamura *et al., PR Applied,* **17,** 064057 (2022)
D.Y. Sasaki, Y. Takamura *et al., under review*

Artificial Spin Ice Structures

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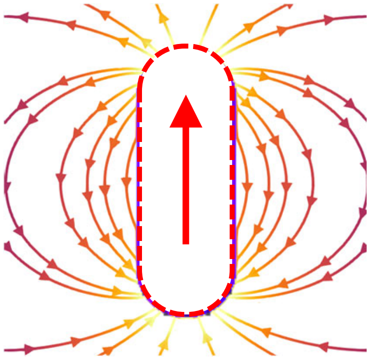
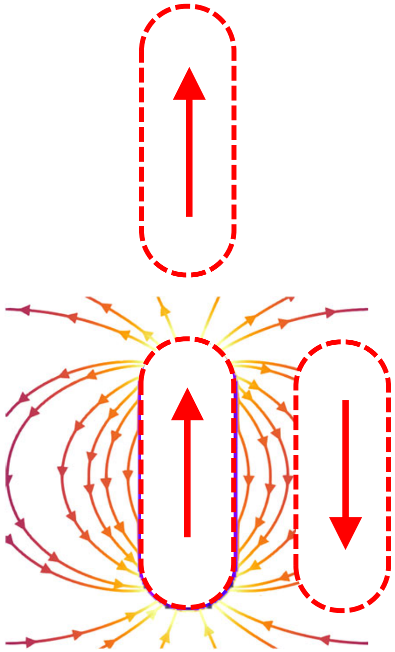
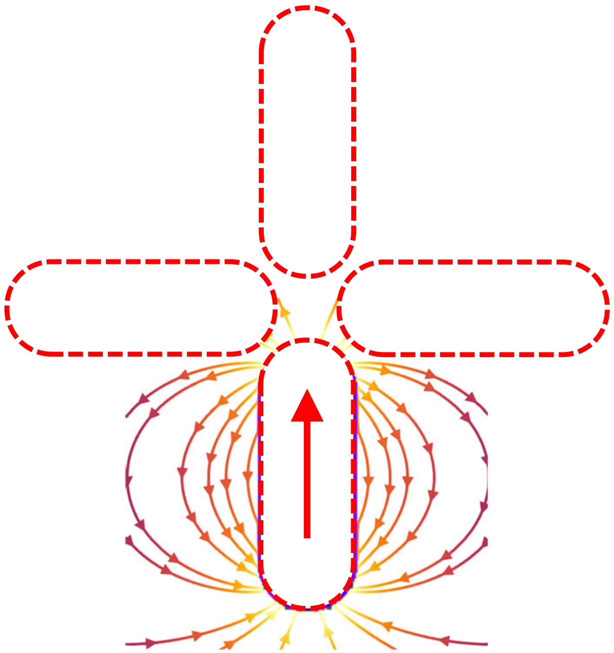


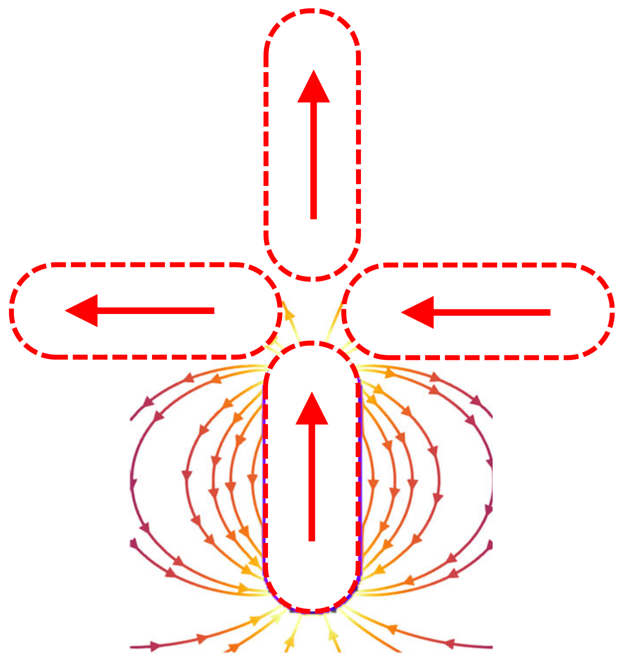
Artificial Spin Ice Structures



Artificial Spin Ice Structures



Artificial Spin Ice Structures



Artificial Spin Ice Structures

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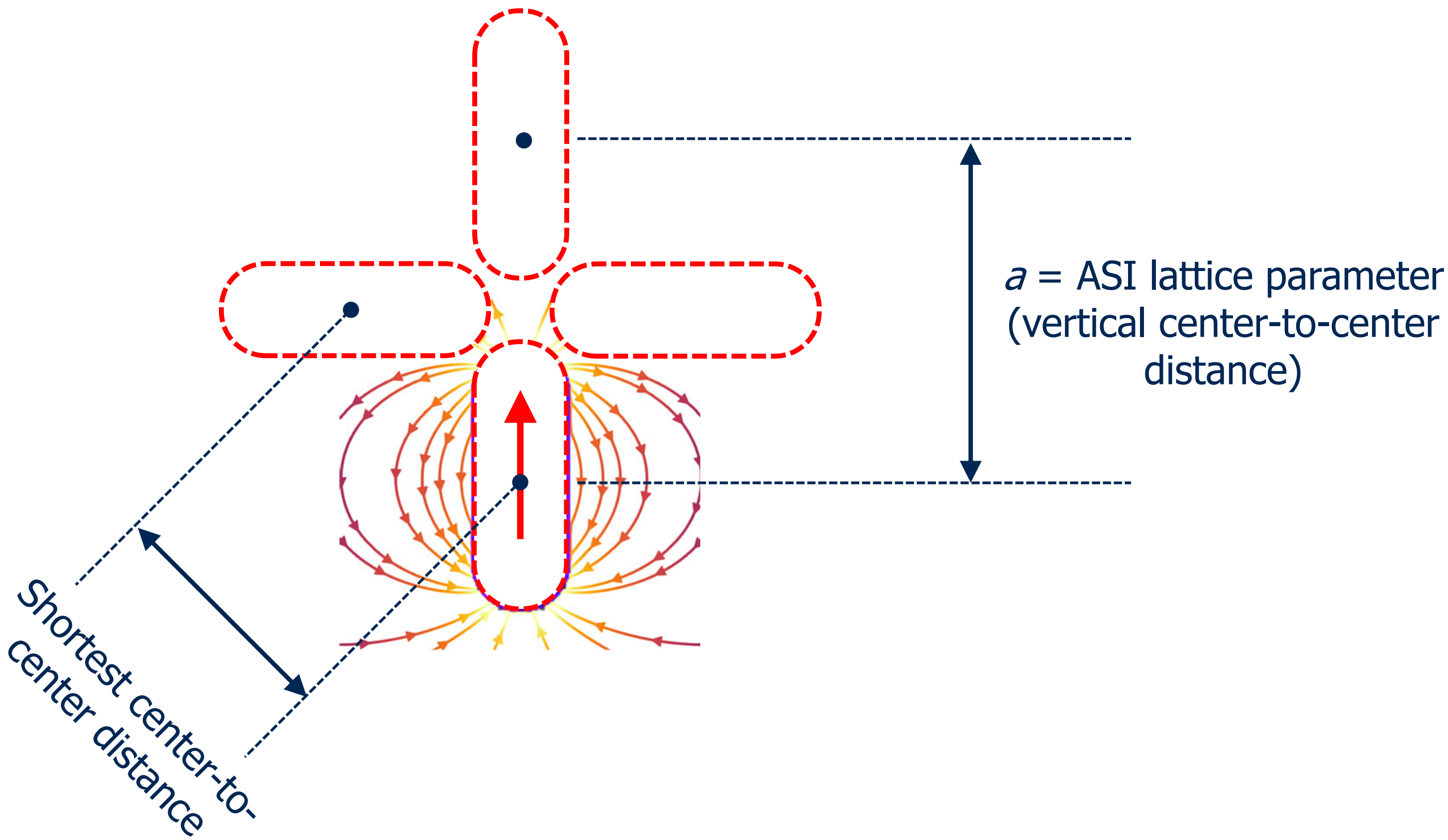
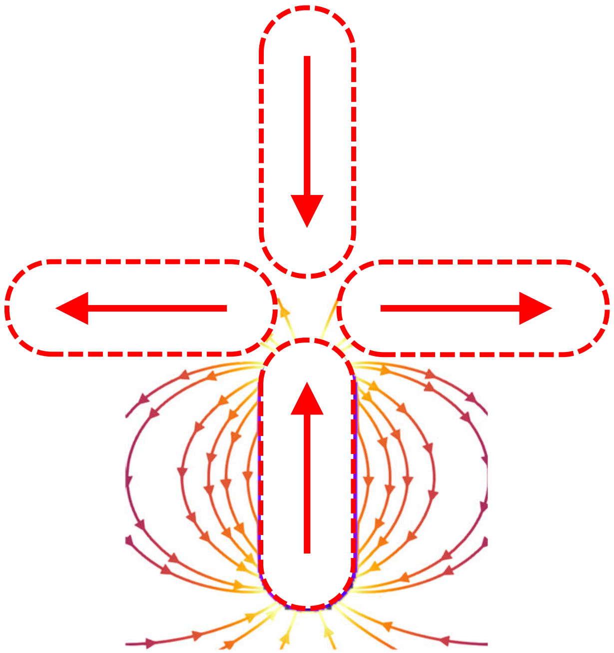
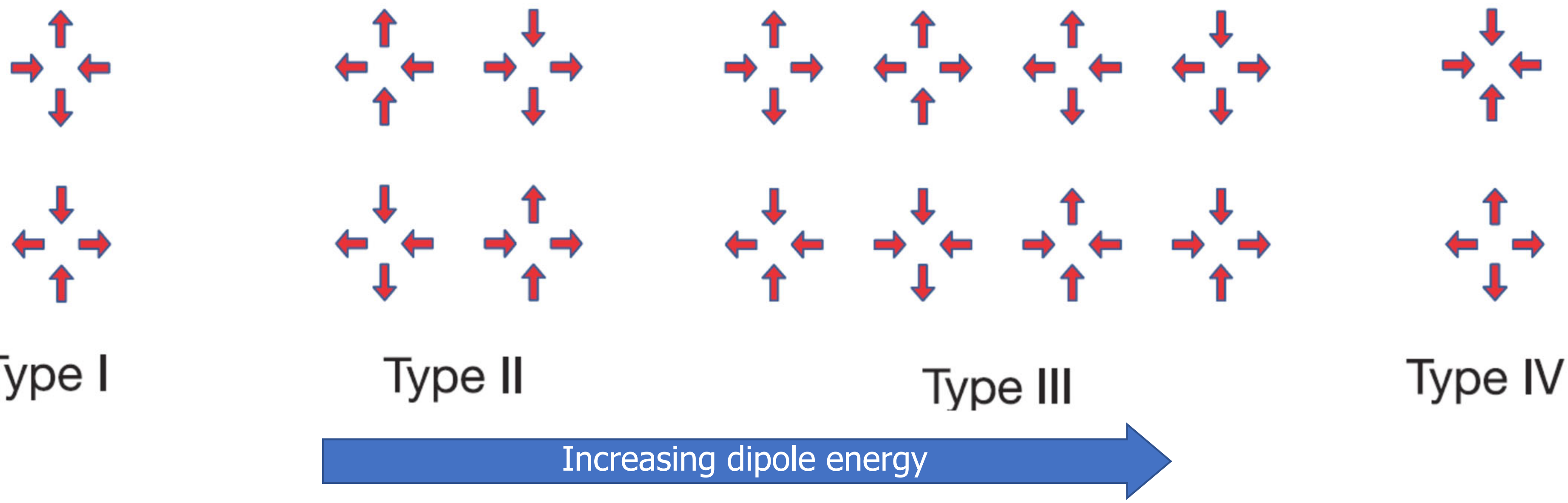


Artificial Spin Ice Structures



Lowest energy configuration

Artificial Spin Ice Structures



- Magnetic nanoisland arrays with configurations where all magnetic interactions cannot be satisfied simultaneously

Wang *et al.*, *Nature*, **439**, 303 (2006)

Brickwork Arrays

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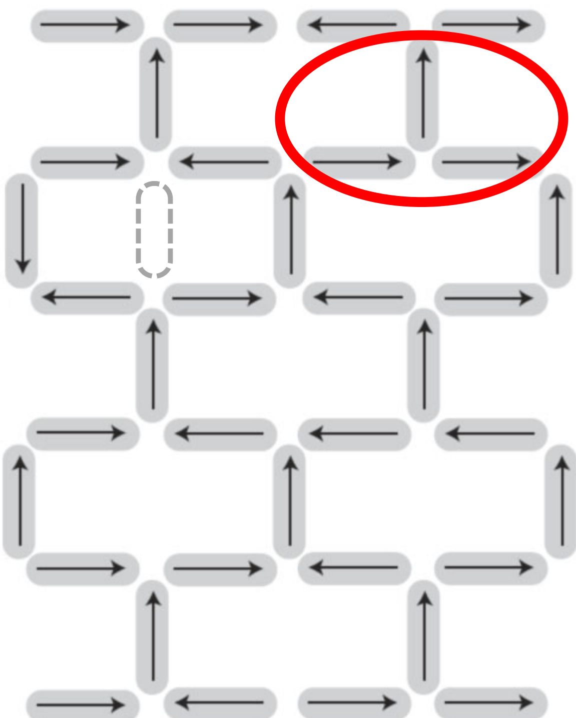
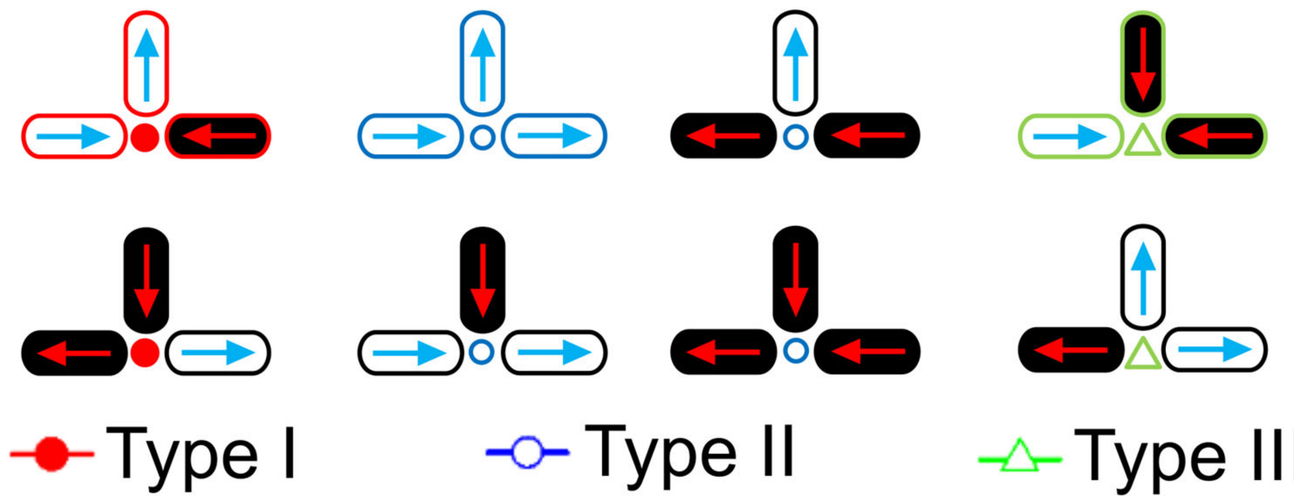
3-island vertices





Increasing dipole energy

$$Coupling\ strength, J = \frac{m^2}{a^3}$$

$m = nanoisland\ moment$

$a = ASI\ lattice\ parameter$

Effect of Coupling Strength

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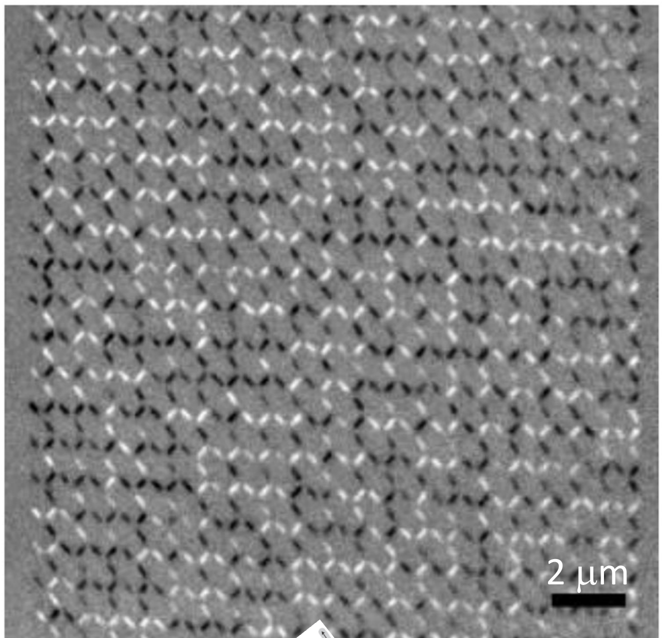
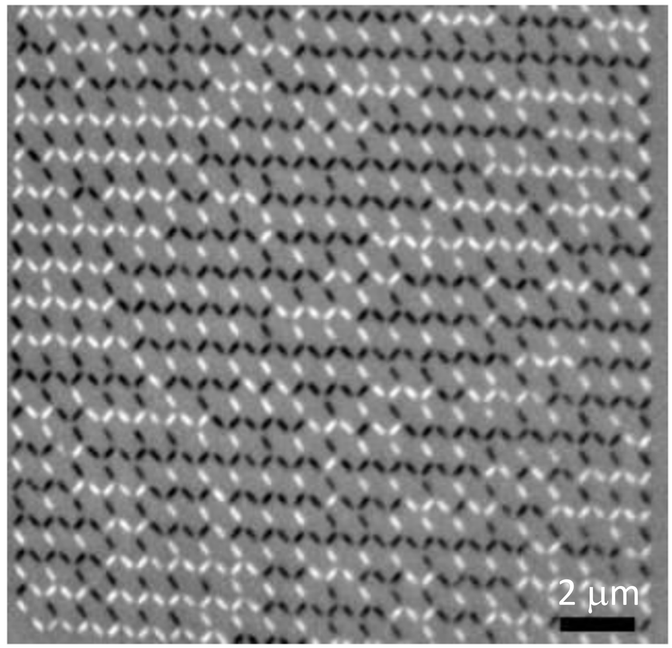
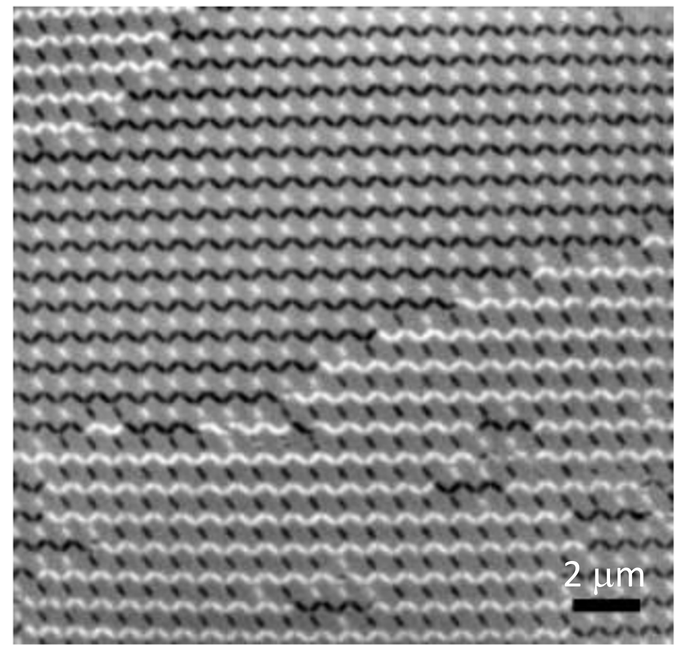
Random

Ordered patches



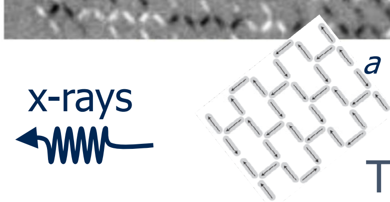




a = 650 nm, *W*=100 nm

a = 650 nm, *W*=150 nm

a = 600 nm, *W*=175 nm
L = 470 nm



Increasing *J*

T=110 K

Effect of Coupling Strength

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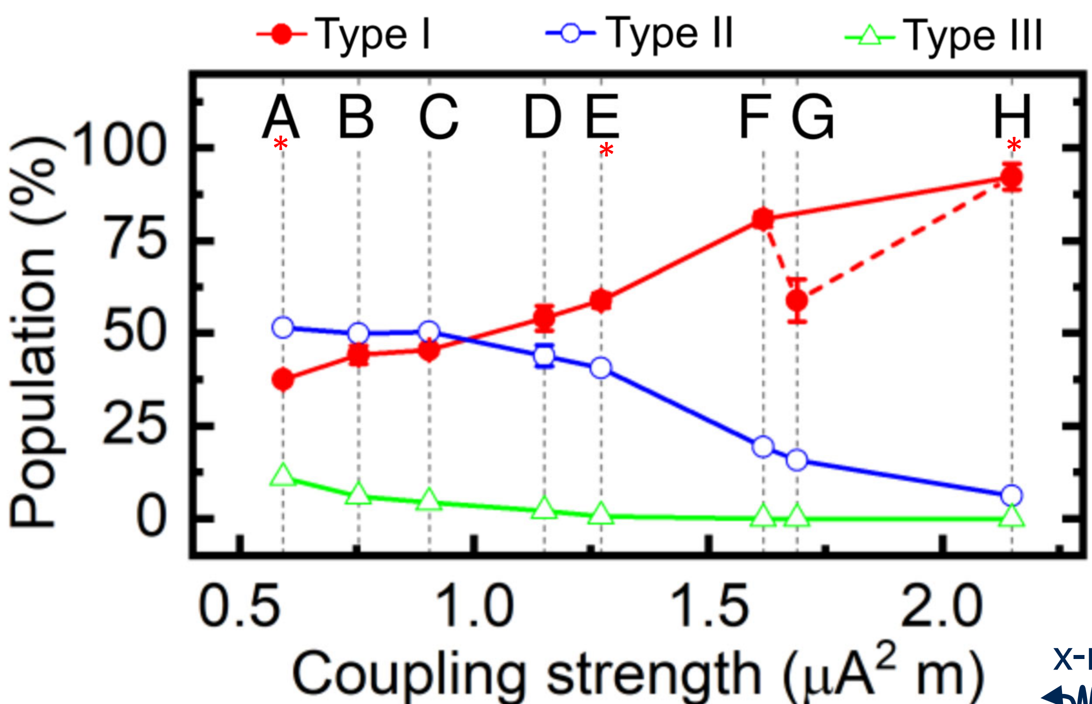
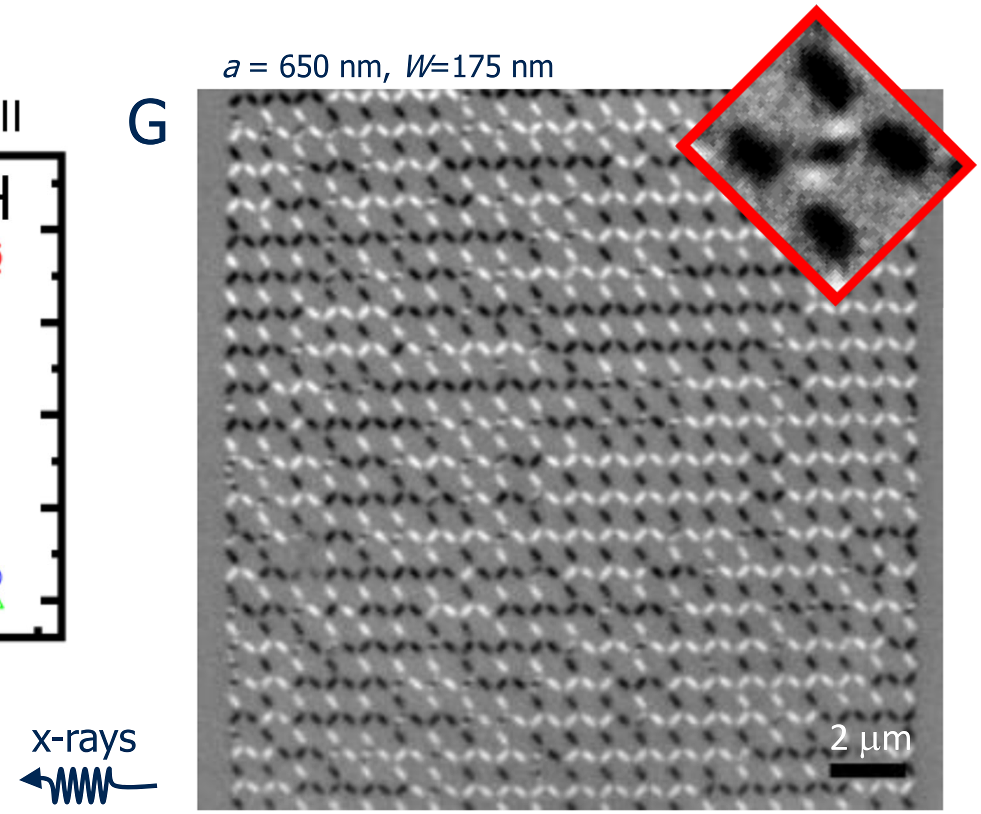


a = 650 nm, *W*=175 nm

G



T=110 K

D. Sasaki, Y. Takamura *et al.*, *PR Applied,* **17,** 064057 (2022)

Complex Spin Textures (CSTs)

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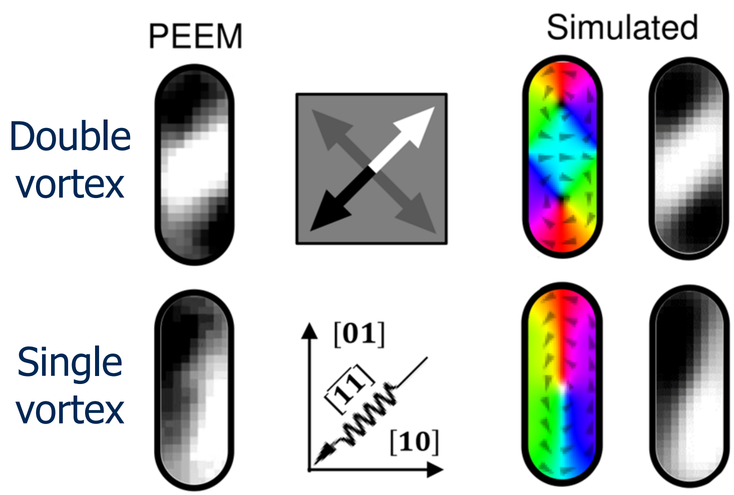

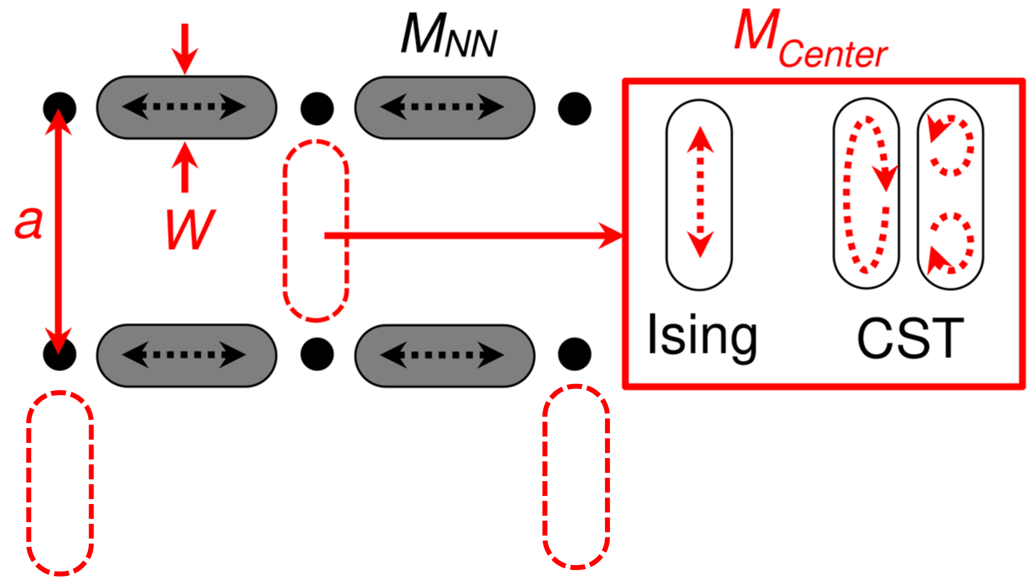

- 95% of observed CSTs occur in vertical nanoislands

D. Sasaki, Y. Takamura *et al.*, *PR Applied,* **17,** 064057 (2022)

Energetics of CSTs

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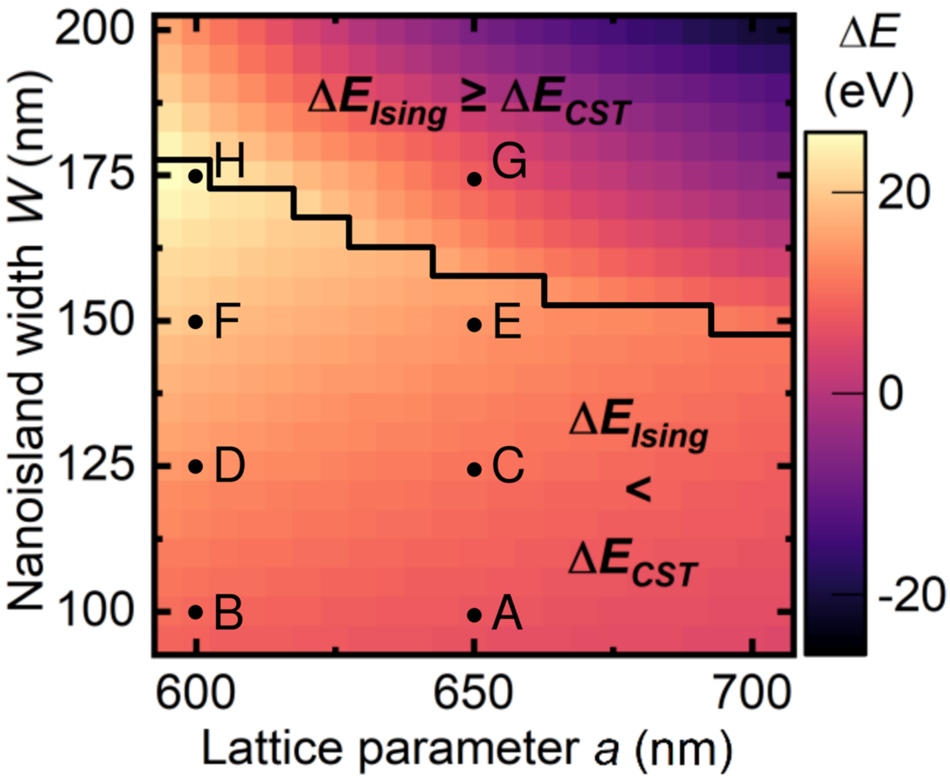
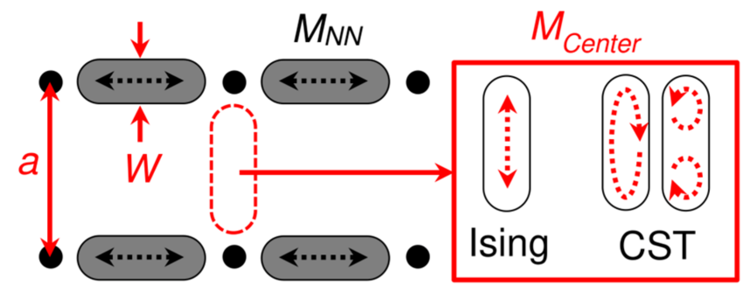


MuMax^3 simulations

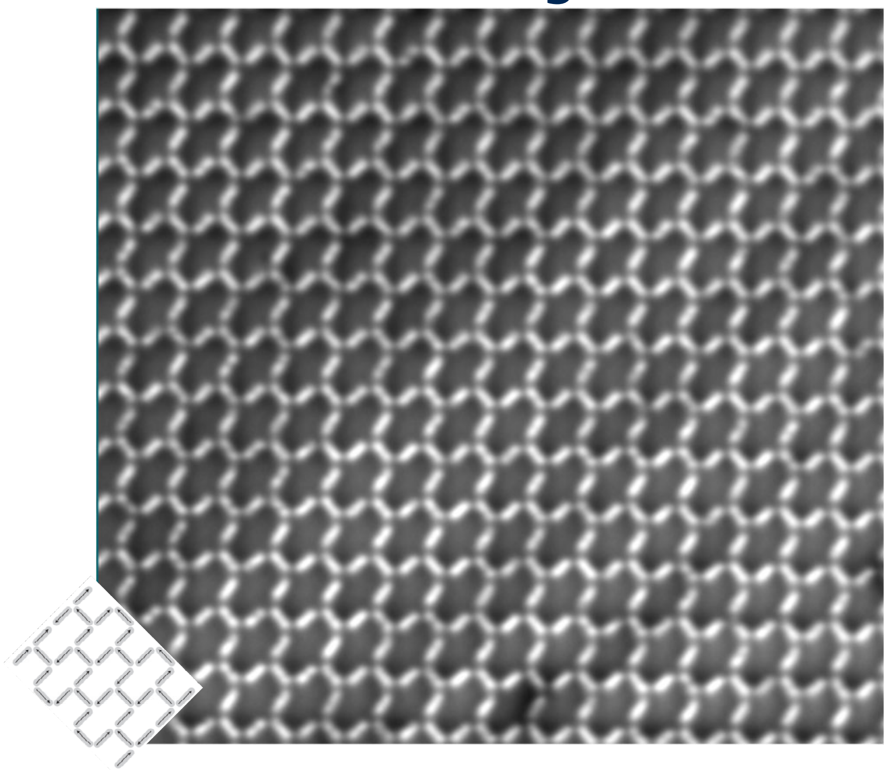


- Prevalence of CSTs controlled by ASI geometric parameters (*W* and *a*) and LSMO magnetic parameters

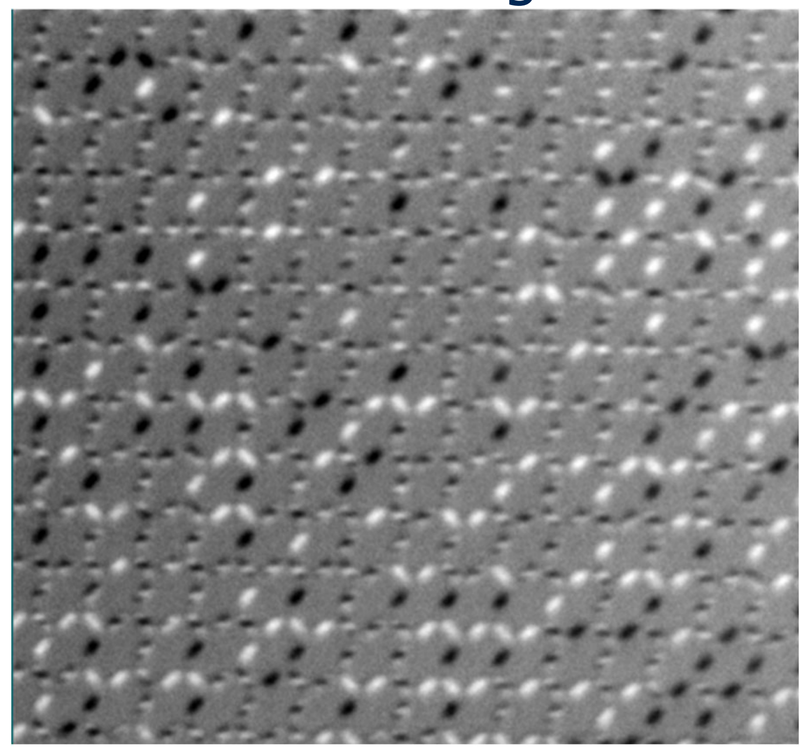
D. Sasaki, Y. Takamura *et al.*, *PR Applied,* **17,** 064057 (2022)

Prevalence of CSTs

XA image



XMCD image

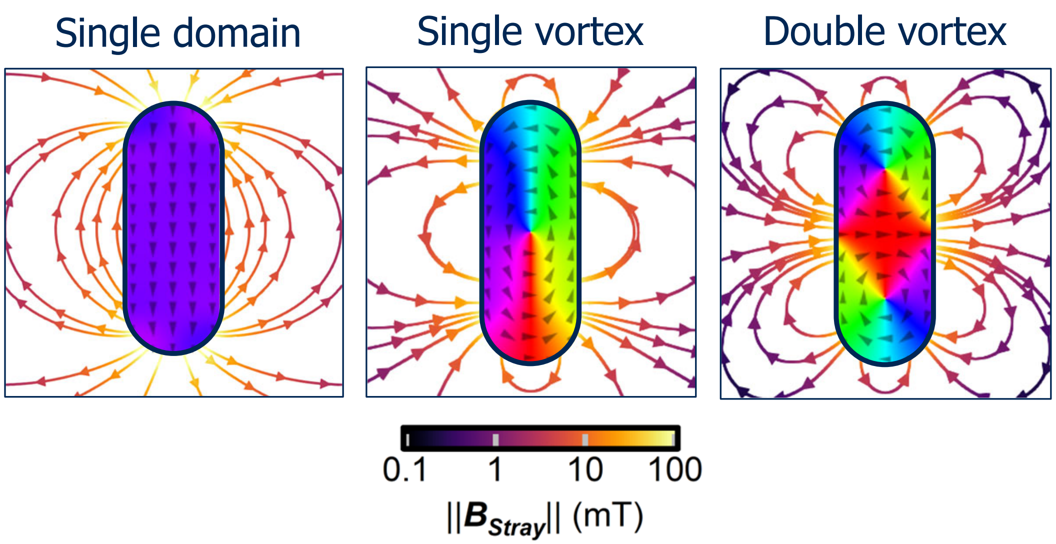


T=110 K

x-rays

a = 675 nm, W=175 nm
L = 470 nm

ASI Structures Designed for CSTs



- Balance between *intra*-island shape anisotropy and *inter*-island dipolar interactions
- Modified stray field patterns provide opportunities for new ASI structures or exotic phase transitions in existing ASI structures

Pinwheel Structures

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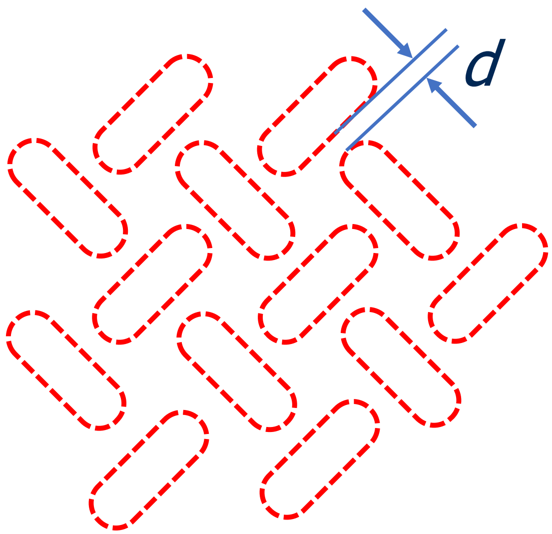
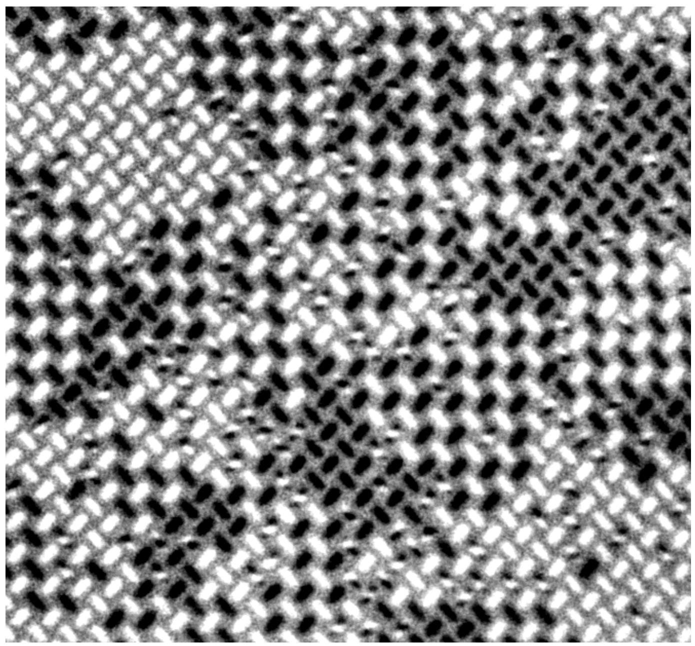
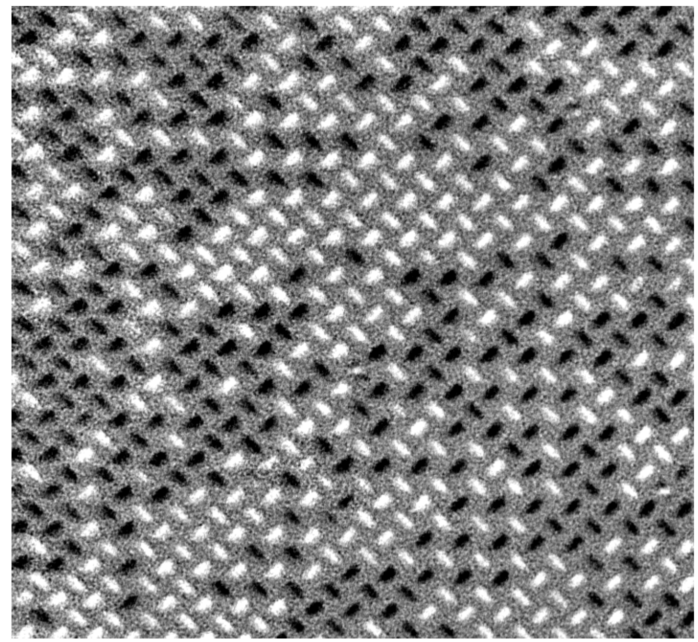


W = 175 nm
L=470 nm

d = 25 nm

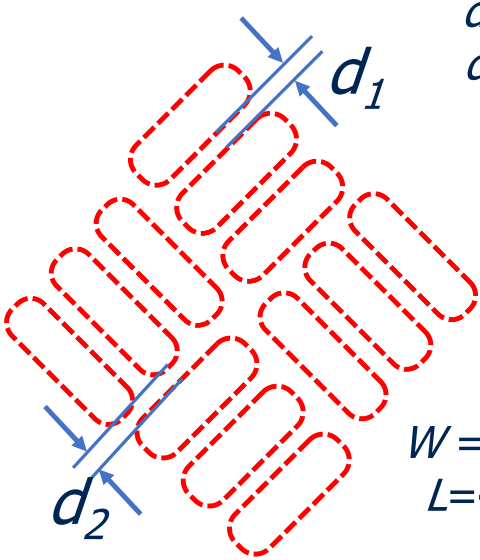


d = 150 nm



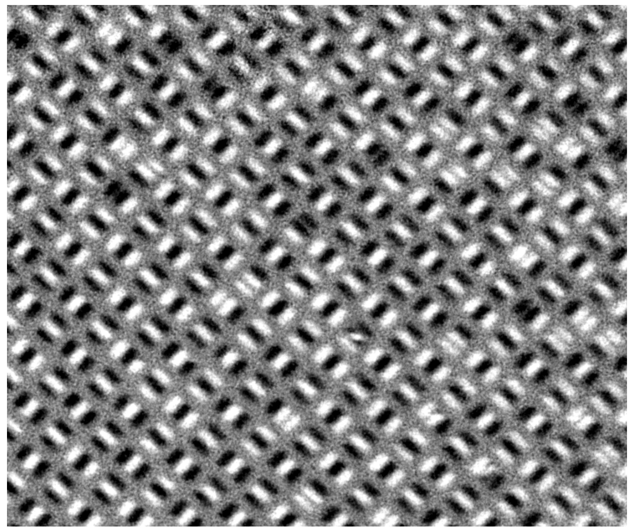
- Decreasing *d* results in increased CST formation

Trident Structures



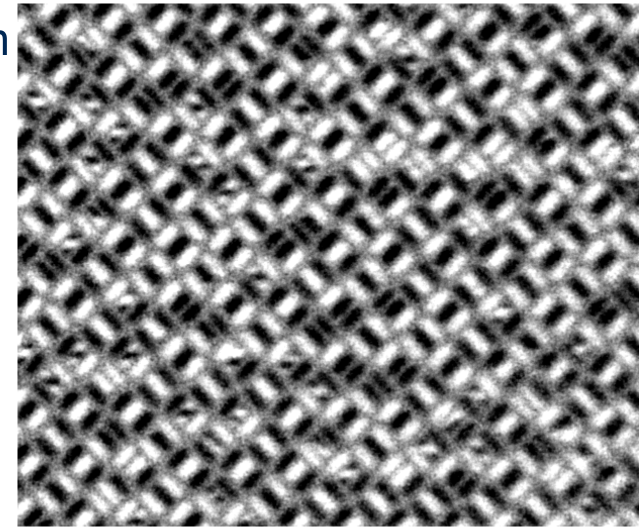
W = 175 nm
L=470 nm

d_1 = 25 nm
d_2=100 nm

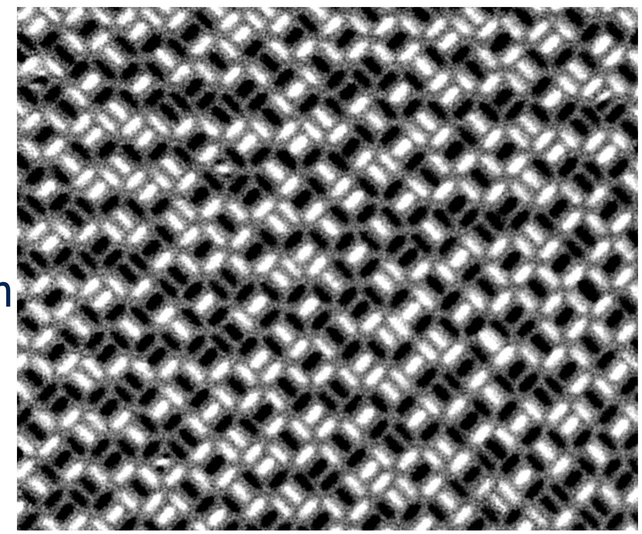


d_1 = 25 nm
d_2=25 nm

x-rays

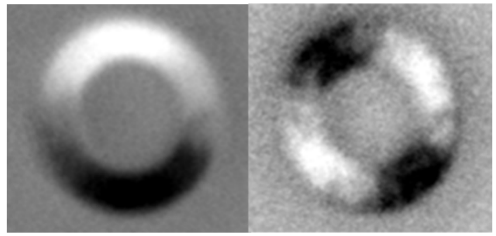
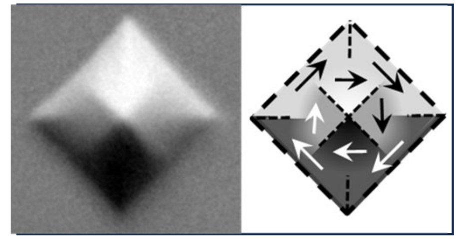
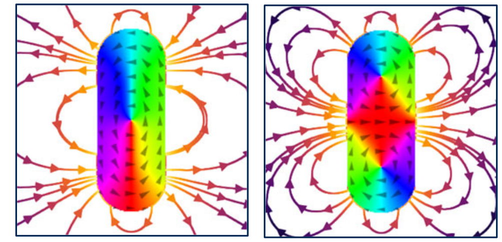


d_1 = 100 nm
d_2=25 nm



- CST formation depends and d_1 and d_2 and predominantly in center nanoisland

Summary

- Complex oxide heterostructures and micro-/nanostructures offer a rich materials playground where structural, chemical, magnetic, and electronic interactions offer fine control of functionality.
- Patterning of LSMO microstructures allows for:
  - Manipulation of a rich variety of FM (and AFM) spin textures
  - Complex competition between shape anisotropy, magnetocrystalline anisotropy, exchange coupling, and magnetoelastic energy.
- LSMO magnetic parameters enable formation of CSTs under specific ASI geometries.
  - Stray field patterns modify magnetic interactions between magnetic nanoislands

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