

PAUL SCHERRER INSTITUT



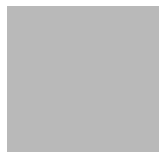
ETH zürich



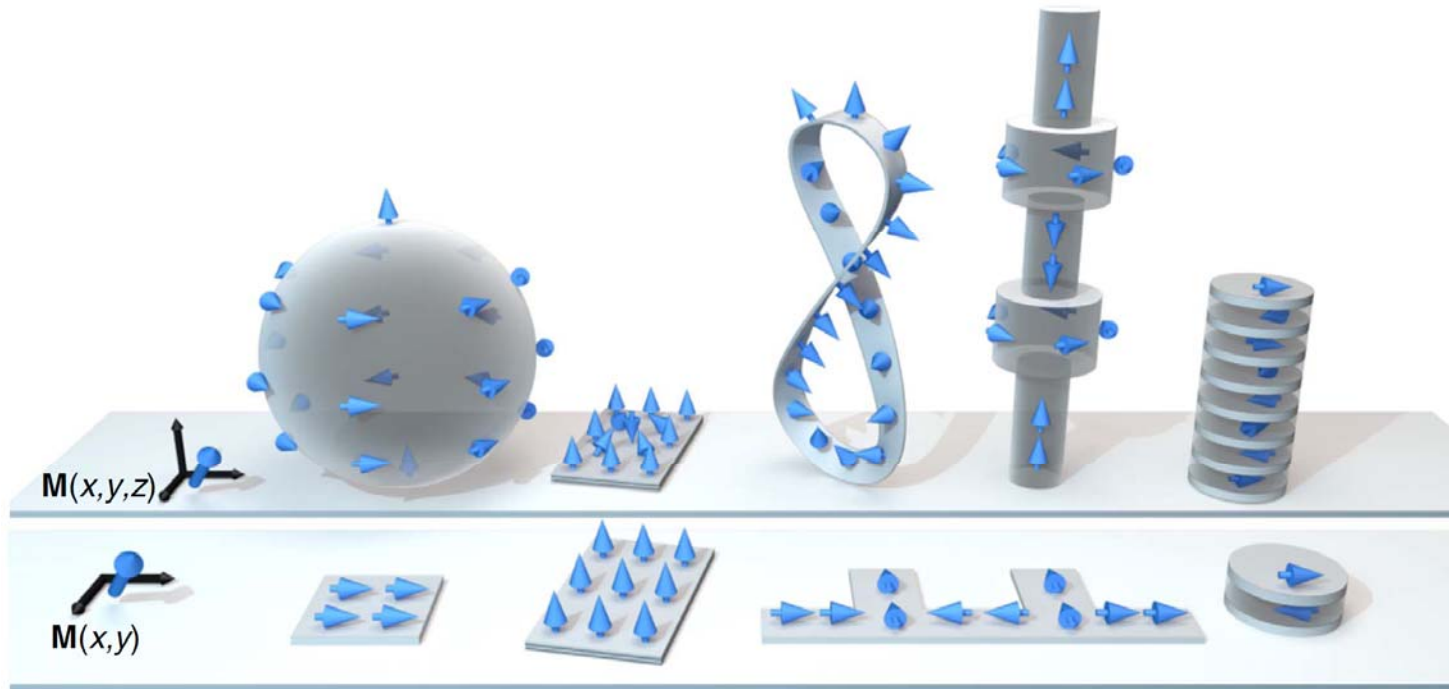
Prof. Laura Heyderman :: ETH Zurich - Paul Scherrer Institute

3D Mesoscopic Magnetic Architectures: Fabrication, Actuation & Imaging

DPG Meeting, March 2020



Mesoscopic Systems
<http://www.mesosys.mat.ethz.ch>



Three-dimensional nanomagnetism

A Fernández-Pacheco et al. Nature Communications (2017)

Magnetism in curved geometries

R Streubel et al. J Phys D (2016)

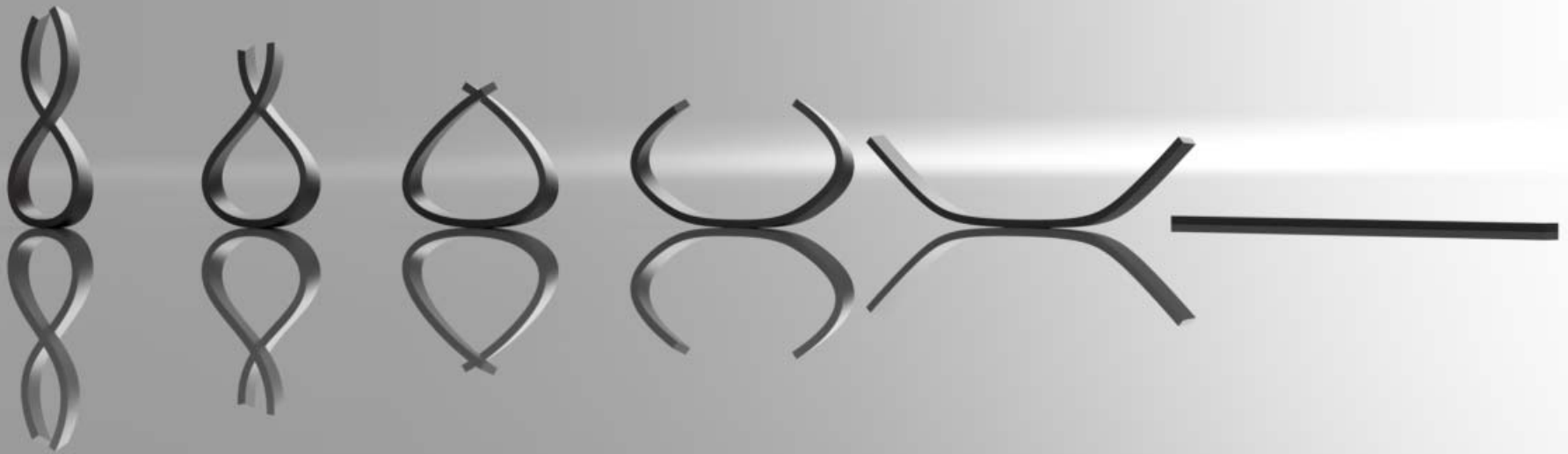
Launching a new dimension with 3D magnetic nanostructures

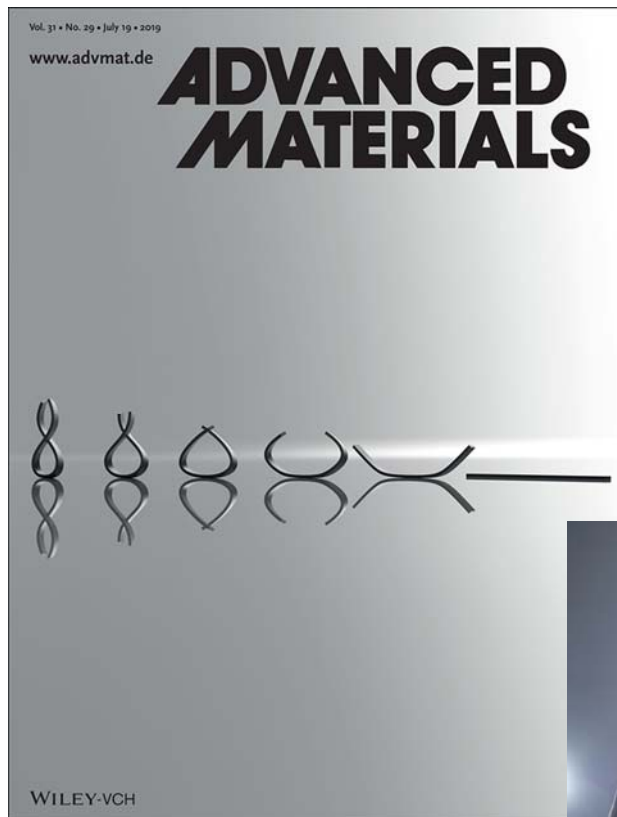
P Fischer et al. APL Materials (2020)

Imaging three-dimensional magnetic systems with X-rays

C Donnelly & V Scagnoli, J. Condens. Matter Phys. (2019)

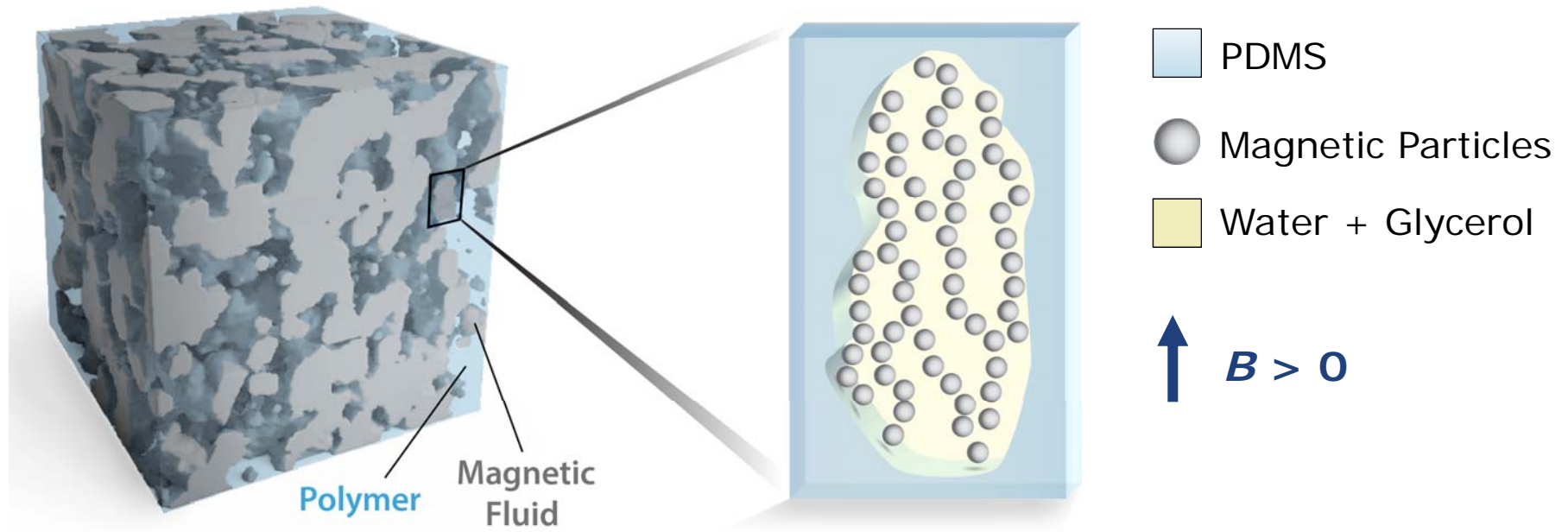
Topic 1
Magneto-mechanical Systems





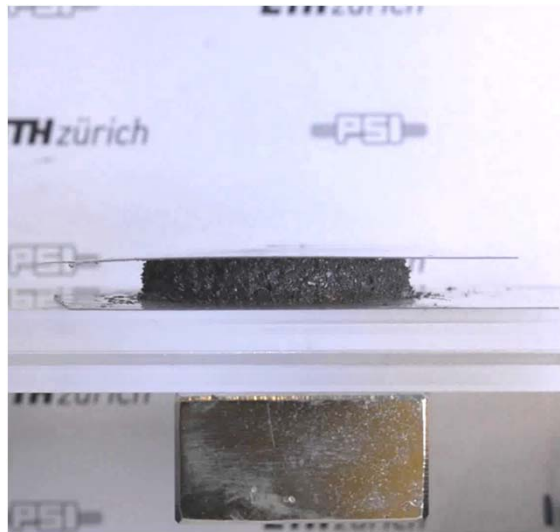
P Testa, RW Style, J Cui, C Donnelly, E Borisova, PM Derlet, ER Dufresne, LJ Heyderman
Advanced Materials (2019)

Magneto-mechanical materials



Cube edge: 390 μm
 Mean particle size: 2.5 μm

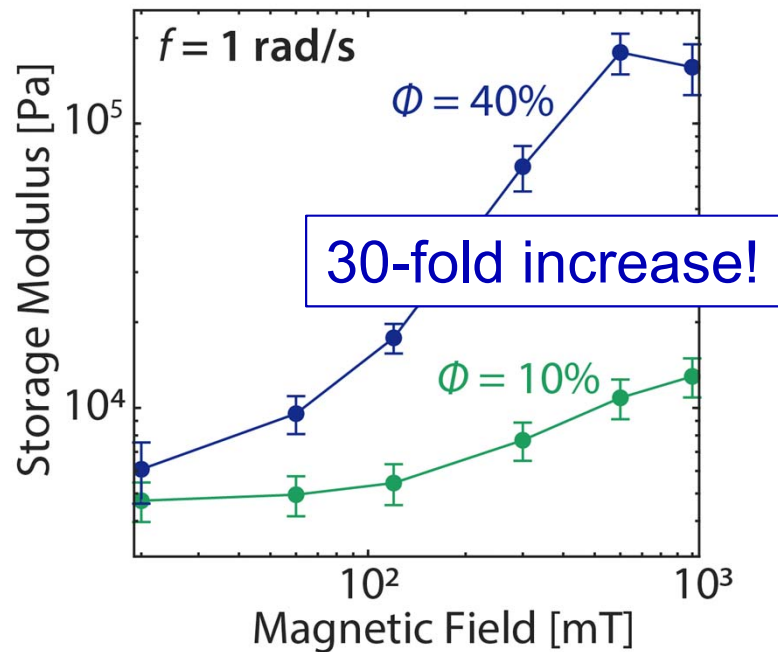
Stiffening



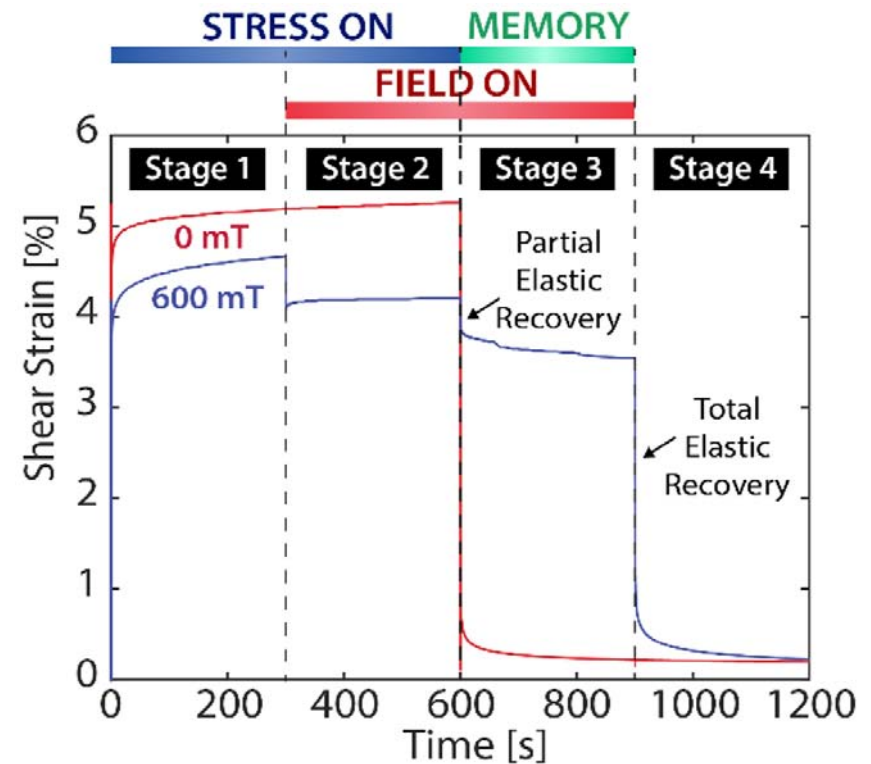
Shape-memory



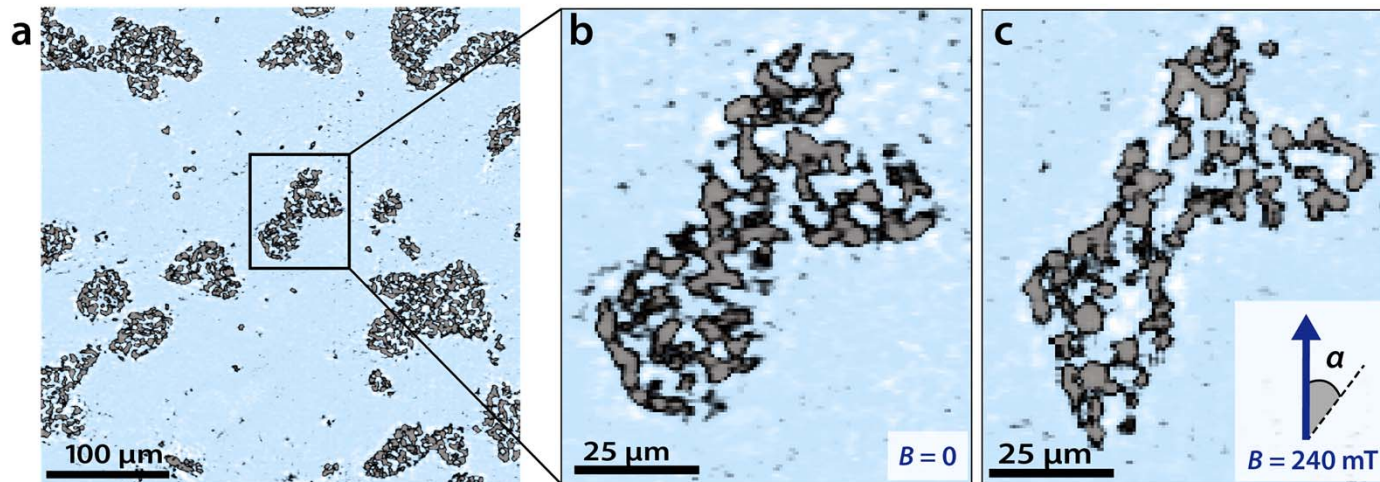
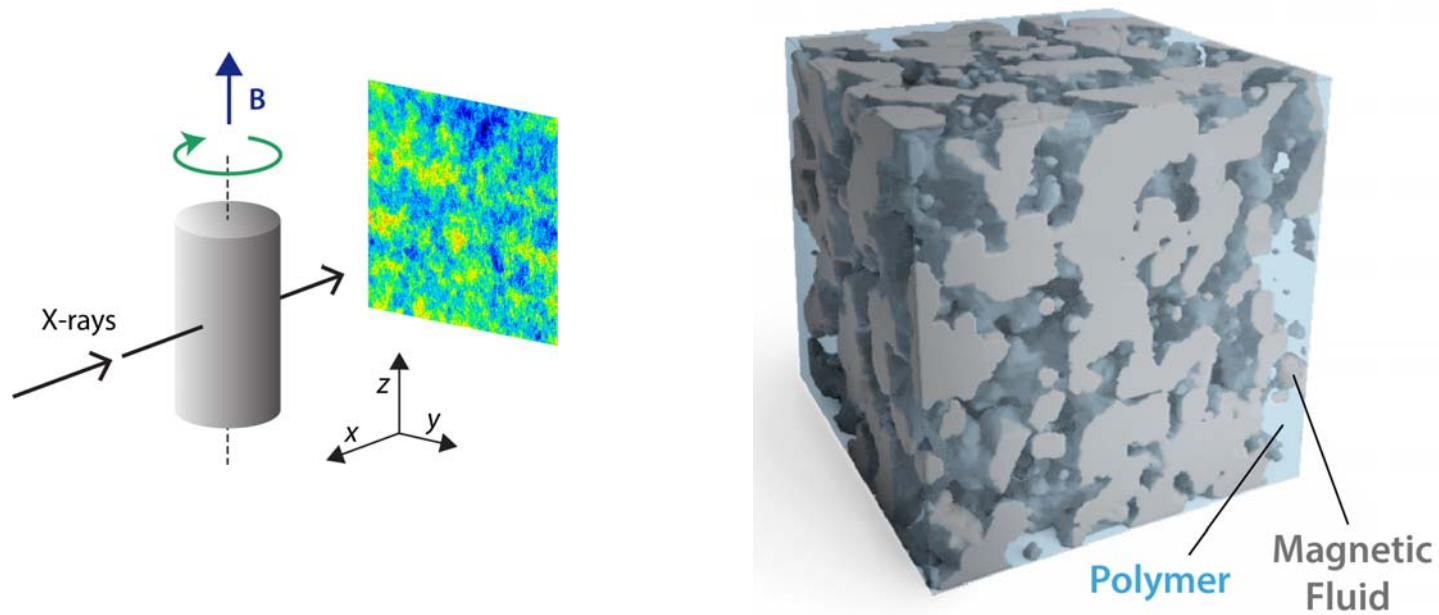
Stiffening



Shape-memory



Synchrotron X-ray Tomography



P Testa, RW Style, J Cui, C Donnelly, E Borisova, PM Derlet, ER Dufresne, LJ Heyderman
Advanced Materials (2019)

flapping wings

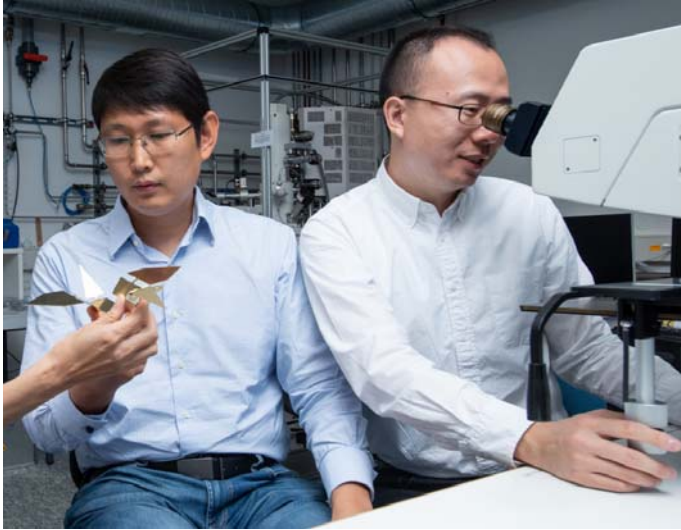
flying high

振翅
高飛

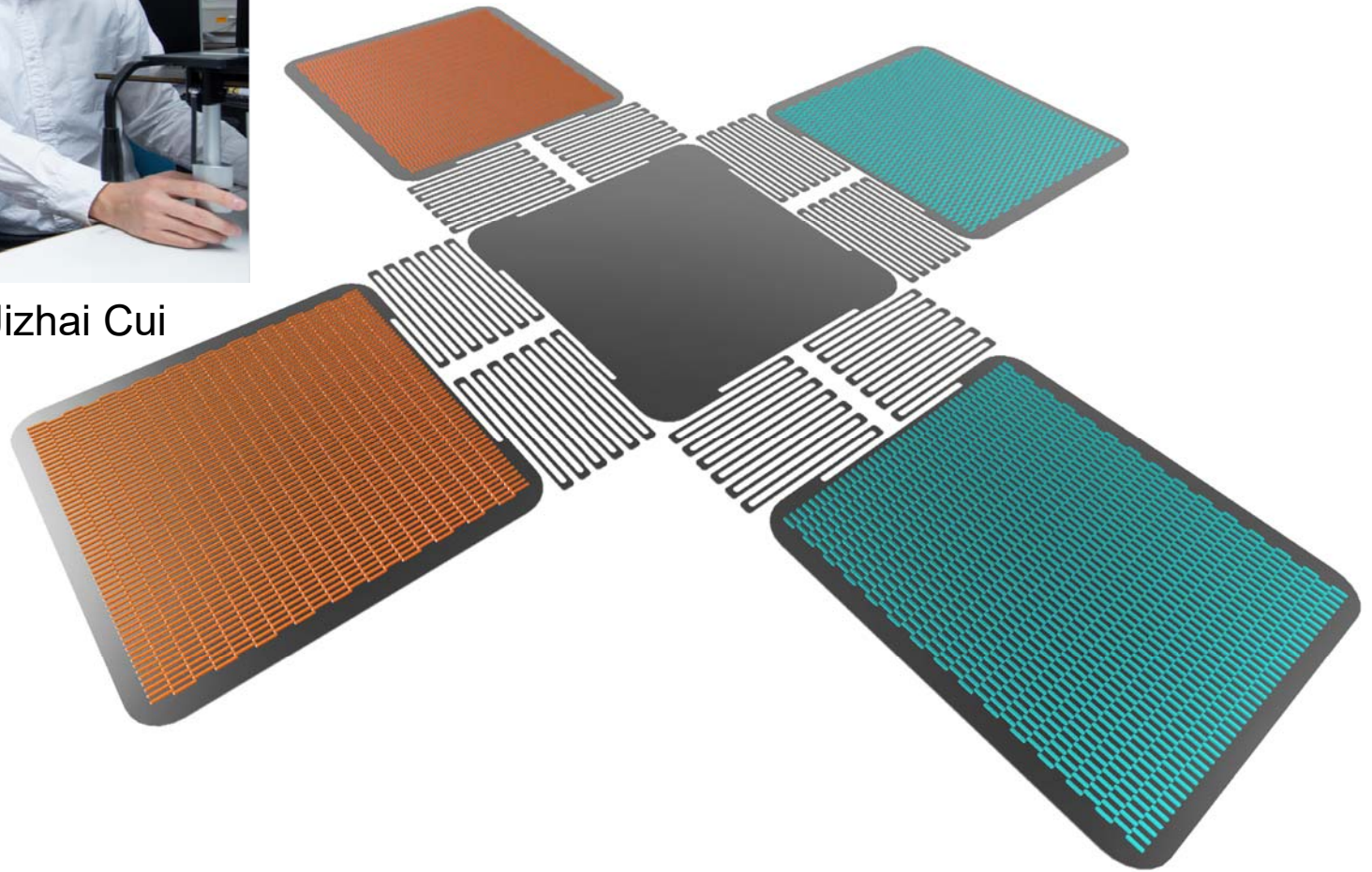
Topic 2
Origami Micromachines



Origami Micromachines

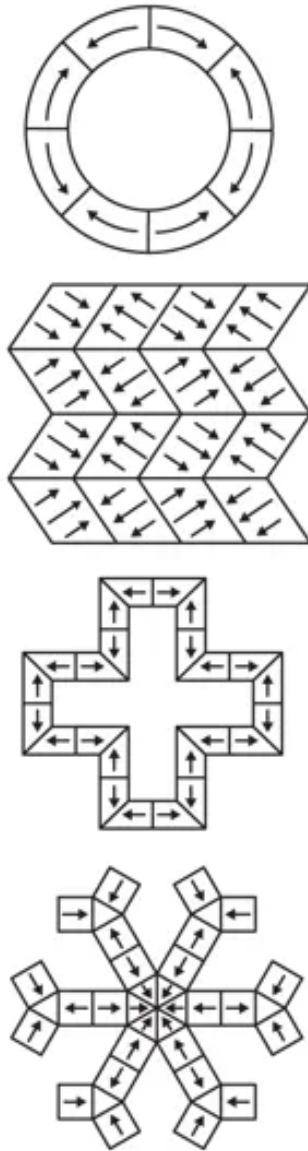


Tianyun Huang & Jizhai Cui



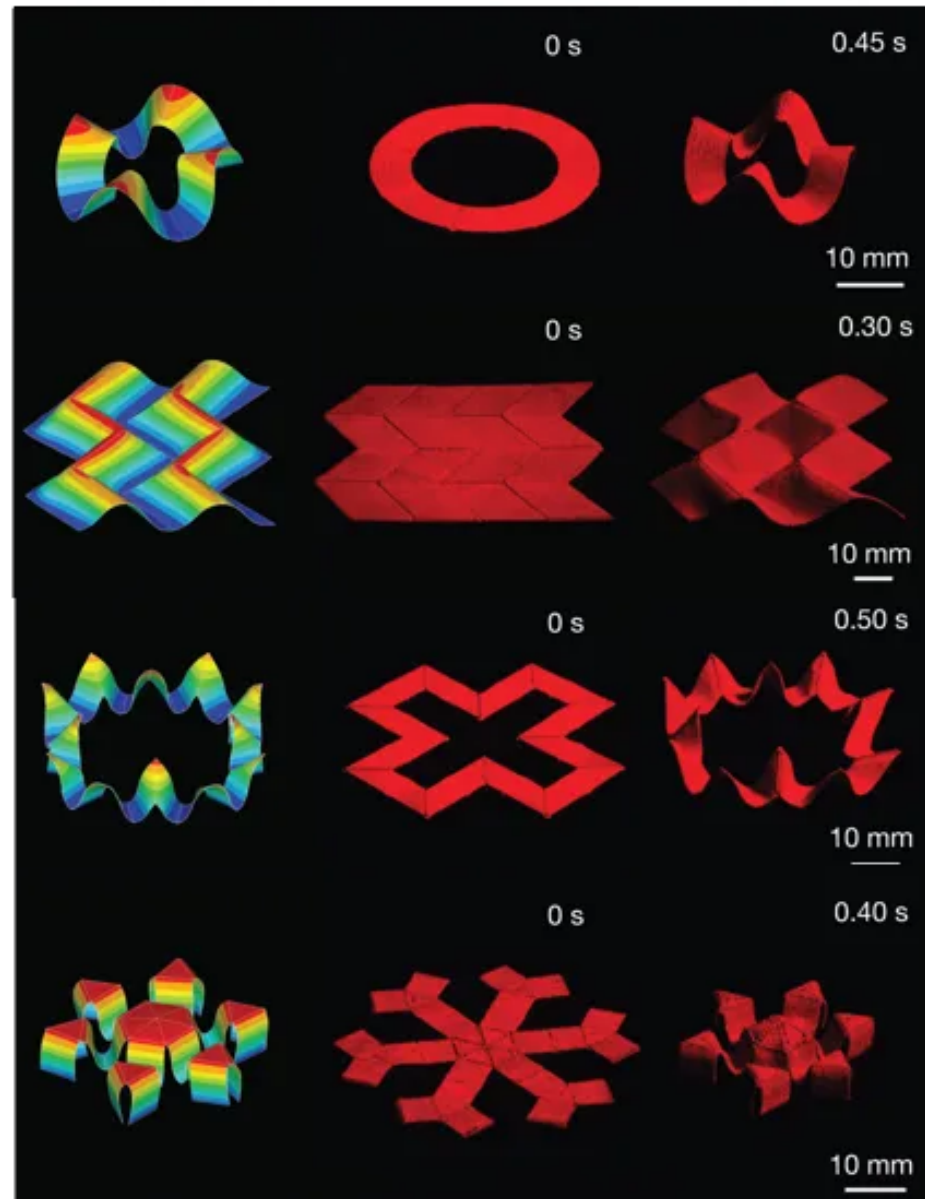
Origami Micromachines

Design



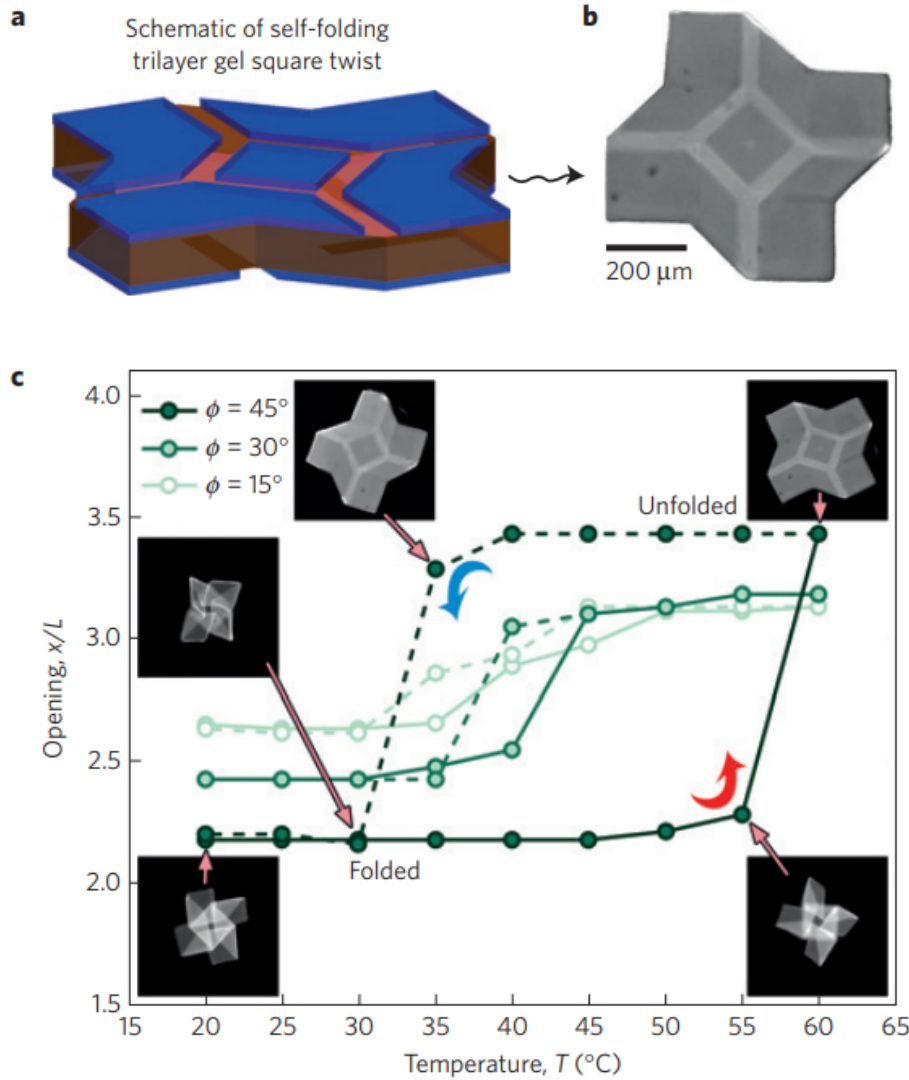
Simulation

Experiment

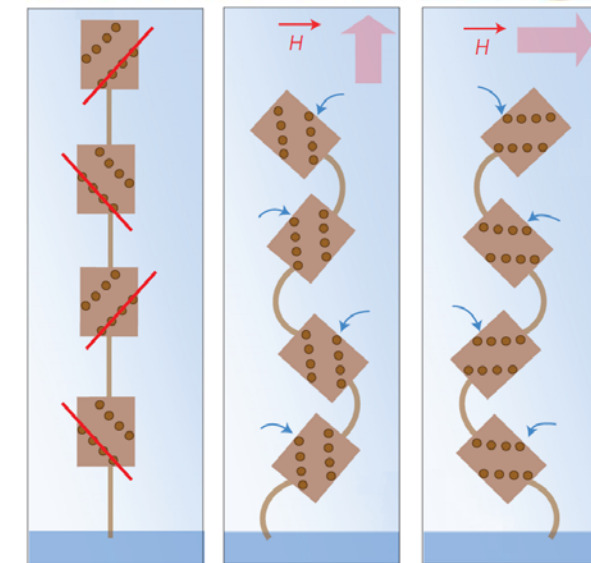
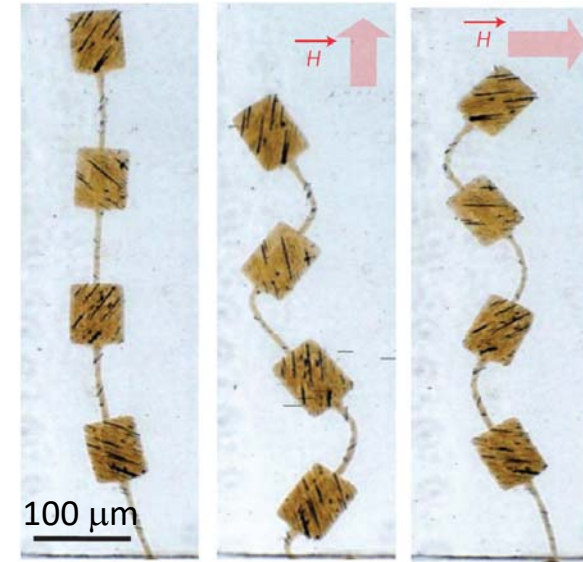


Y Kim et al. Nature (2018)

Origami Micromachines



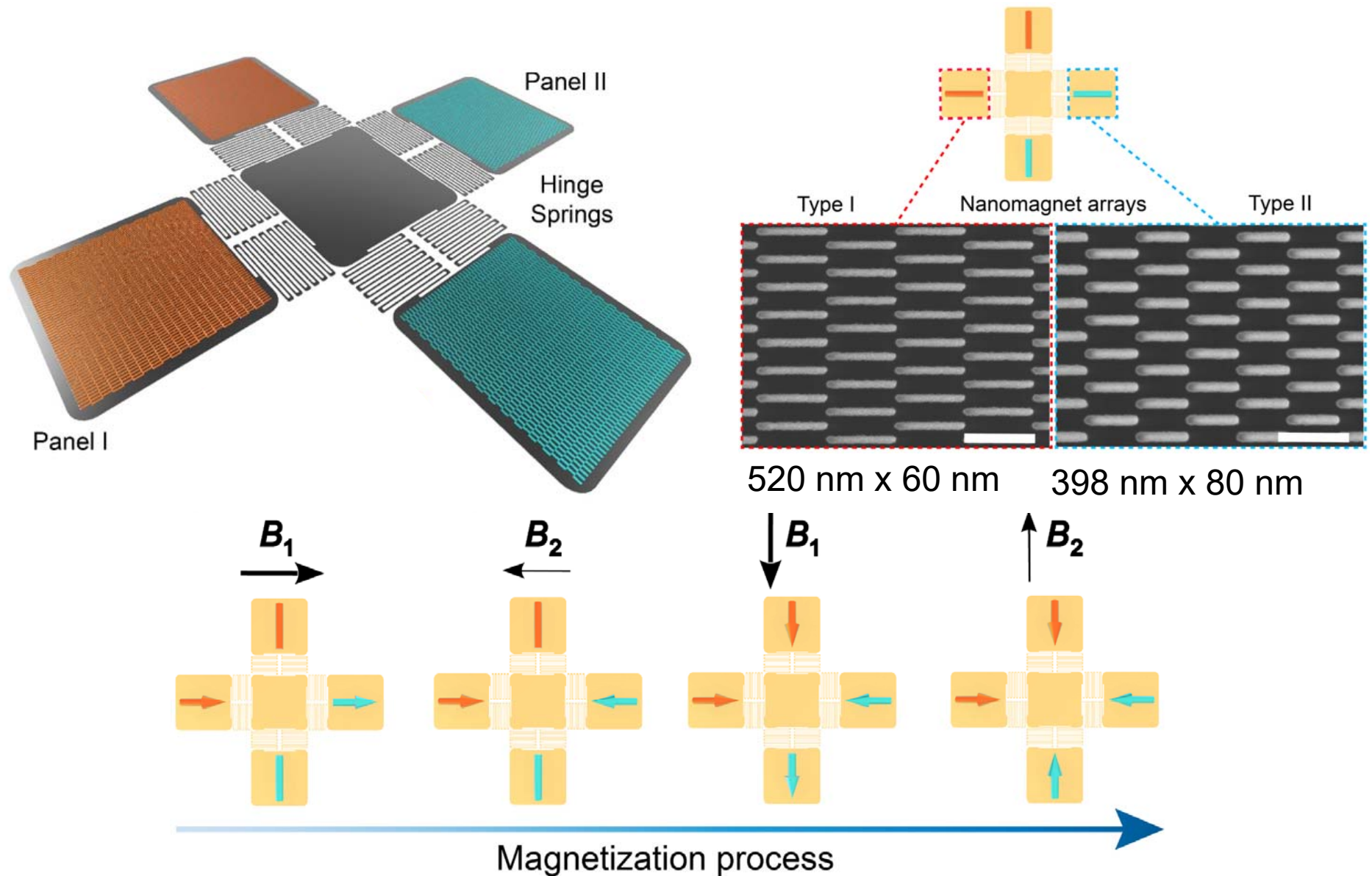
Silverberg et al. Nat Mater (2015)



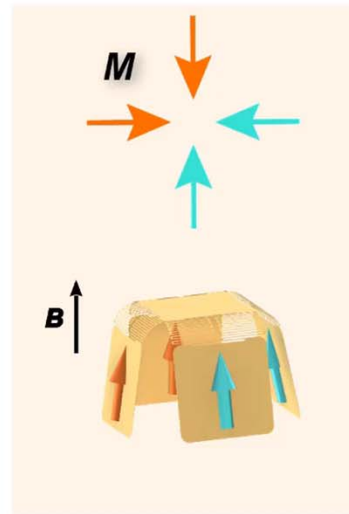
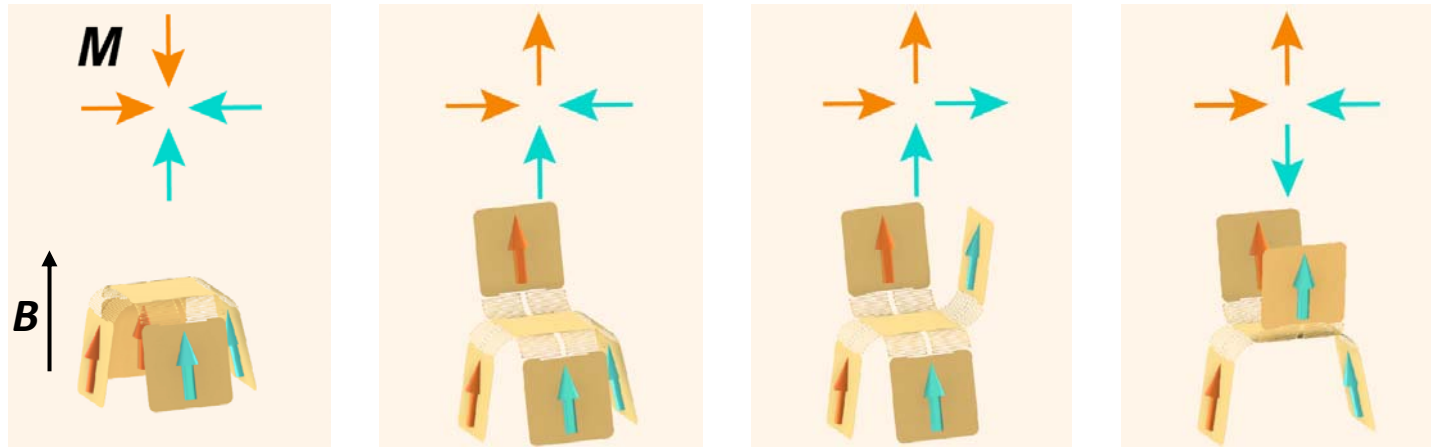
Initial State Axes rotation in a magnetic field

J Kim et al. Nat Mater (2011)

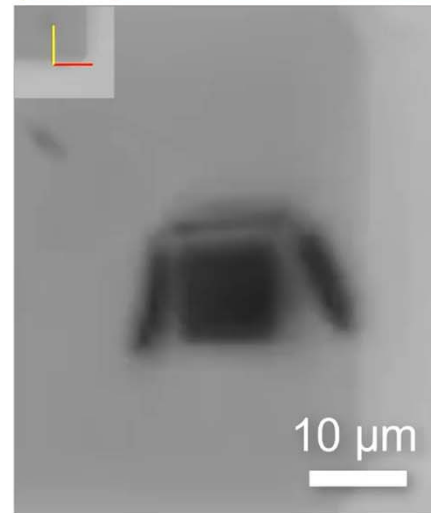
Origami Micromachines



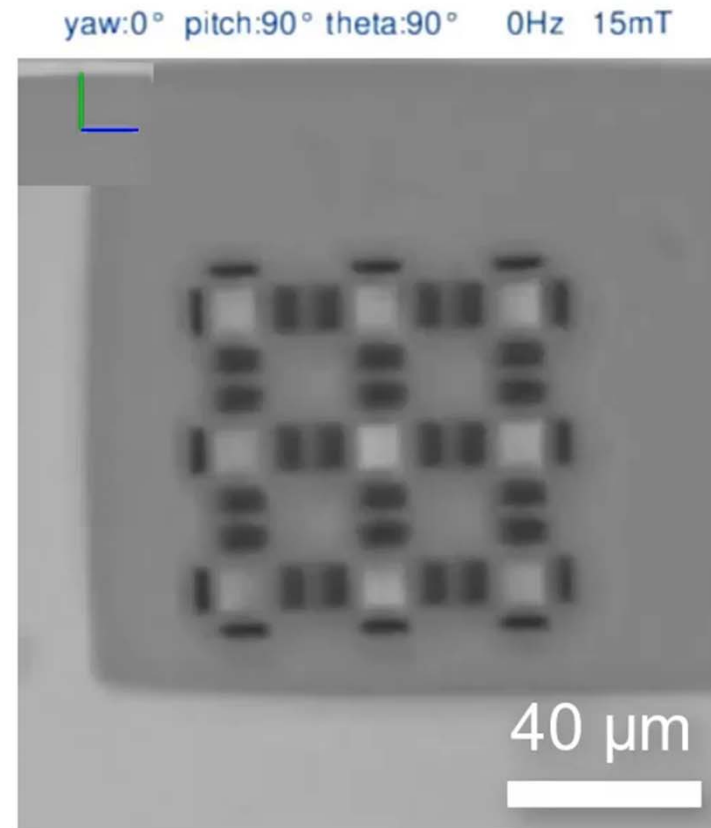
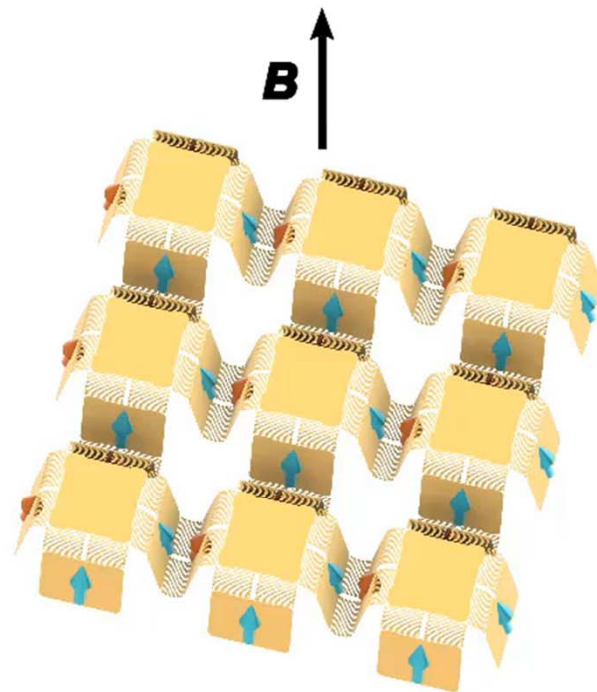
J Cui, T-Y Huang, Z Luo, P Testa, H Gu, X-Z Chen, BJ Nelson, LJ Heyderman, Nature (2019)
 X. Zhao & Y. Kim, News & Views, Nature (2019)



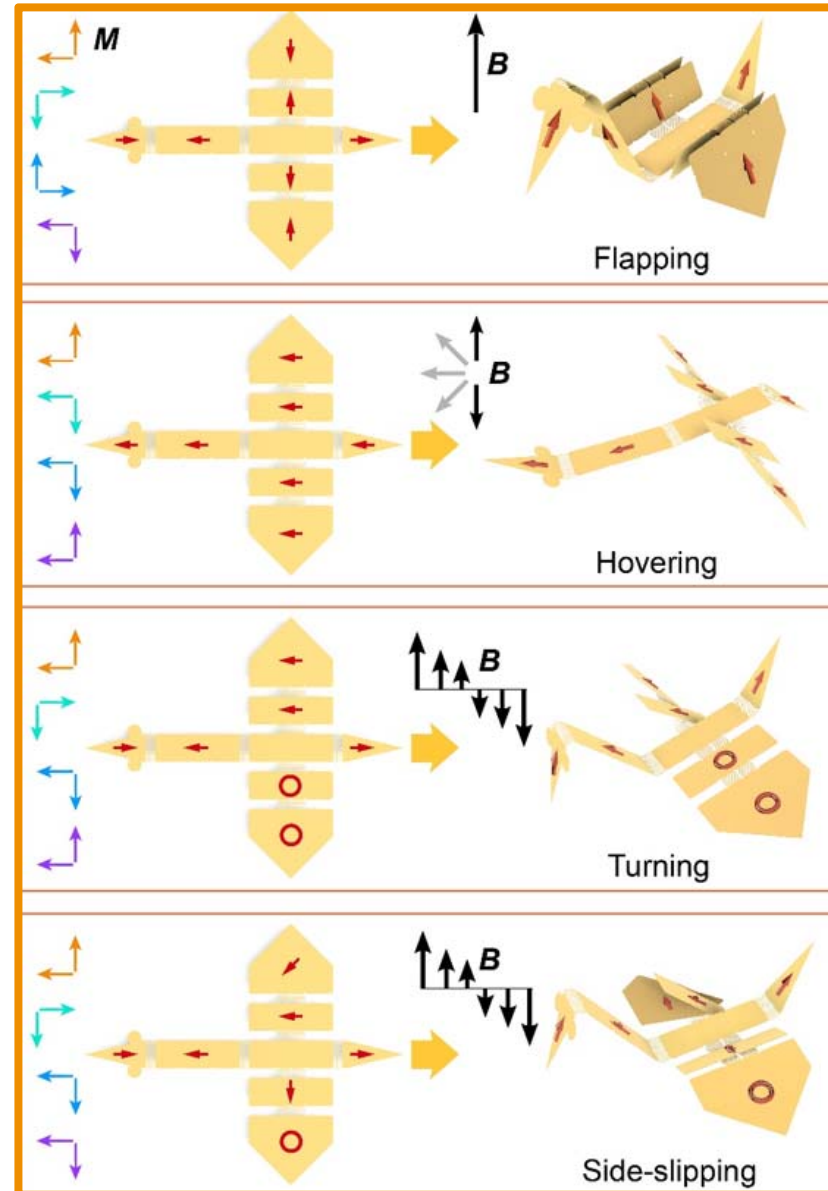
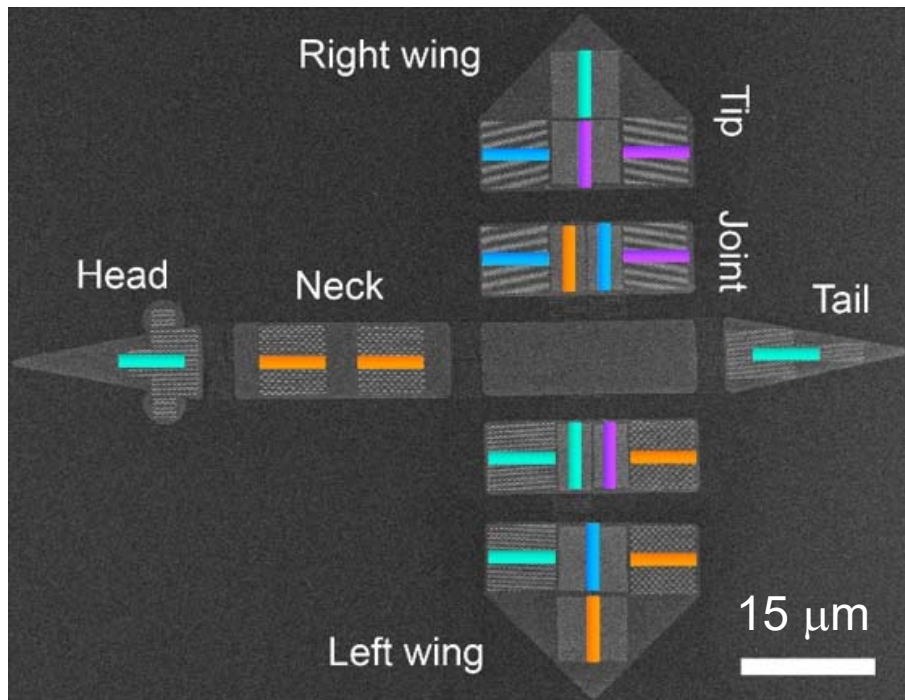
yaw:0° pitch:0° theta:0° 0Hz 4.8mT



J Cui, T-Y Huang, Z Luo, P Testa, H Gu, X-Z Chen, BJ Nelson, LJ Heyderman, Nature (2019)
 X. Zhao & Y. Kim, News & Views, Nature (2019)

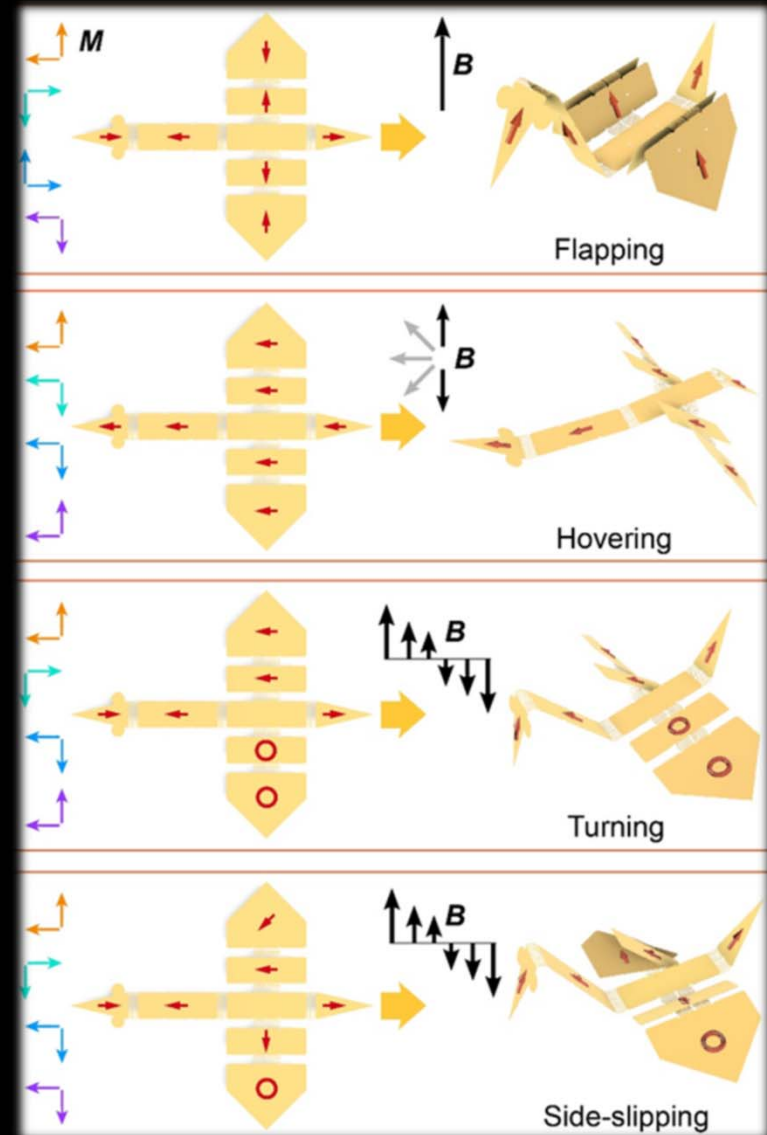
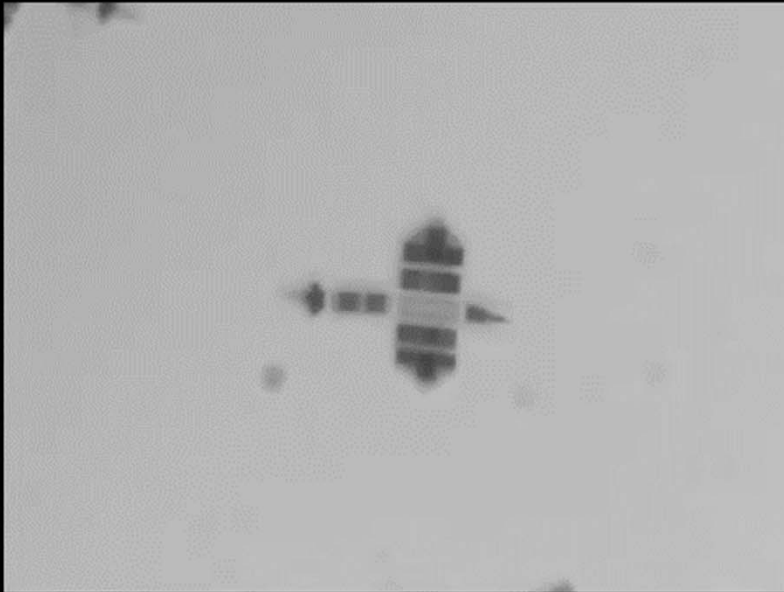


J Cui, T-Y Huang, Z Luo, P Testa, H Gu, X-Z Chen, BJ Nelson, LJ Heyderman, Nature (2019)
X. Zhao & Y. Kim, News & Views, Nature (2019)

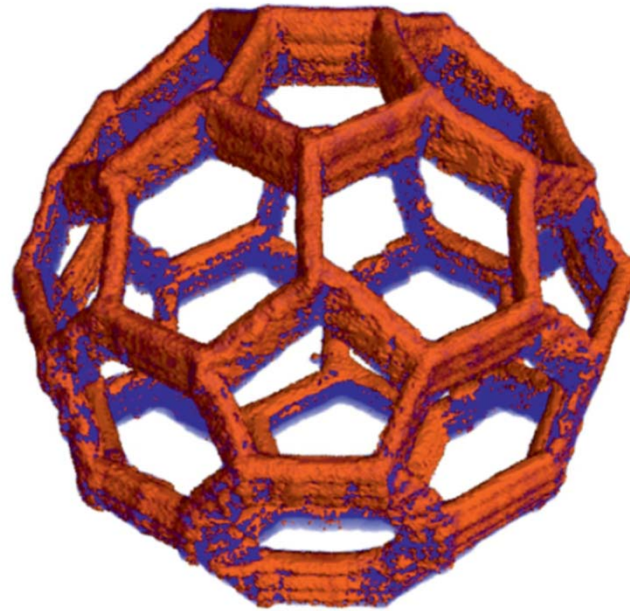


J Cui, T-Y Huang, Z Luo, P Testa, H Gu, X-Z Chen, BJ Nelson, LJ Heyderman, Nature (2019)
 X. Zhao & Y. Kim, News & Views, Nature (2019)

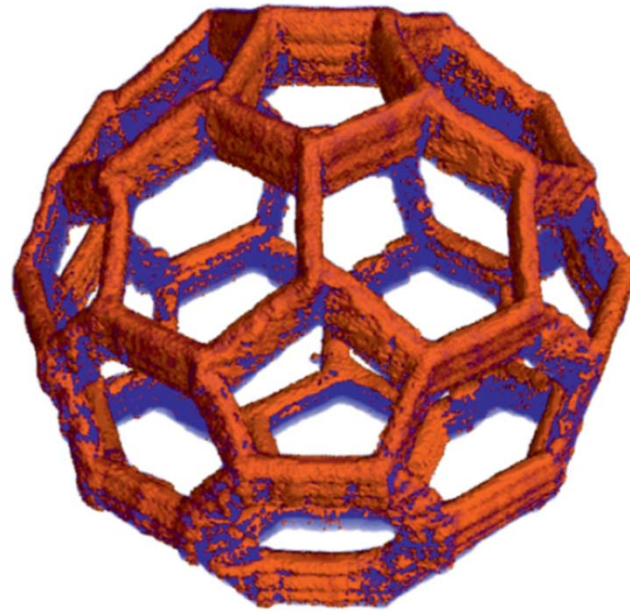
Origami Micromachines



J Cui, T-Y Huang, Z Luo, P Testa, H Gu, X-Z Chen, BJ Nelson, LJ Heyderman, Nature (2019)
X. Zhao & Y. Kim, News & Views, Nature (2019)



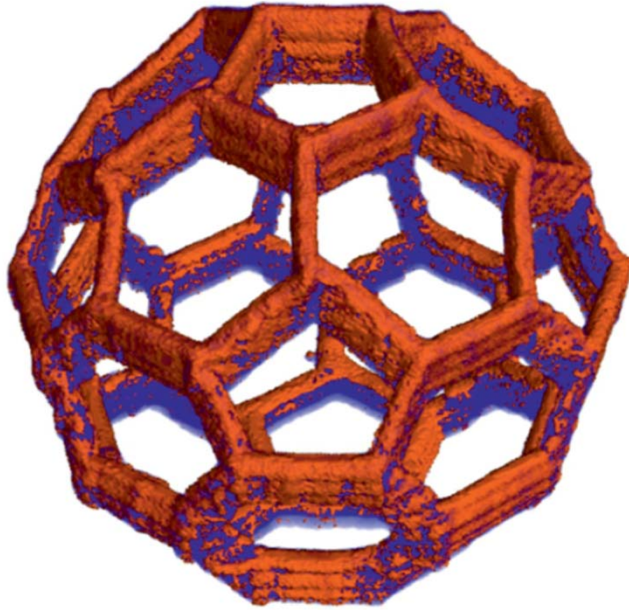
Topic 3
Two Photon Laser Lithography



6 μm Buckyball

Resonant Ptychographic Tomography

*Quantitative hard x-ray phase imaging & resonant elastic scattering
→ element-specific 3D characterization with 25 nm spatial resolution*



6 μm Buckyball



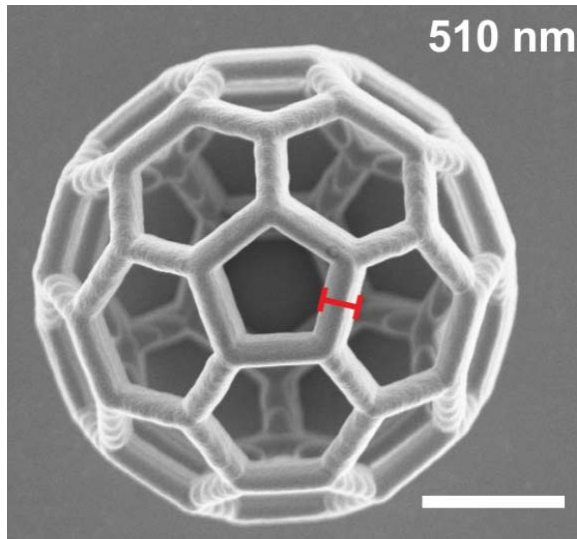
Resonant Ptychographic Tomography

*Quantitative hard x-ray phase imaging & resonant elastic scattering
→ element-specific 3D characterization with 25 nm spatial resolution*

C. Donnelly et al. PRL (2015)

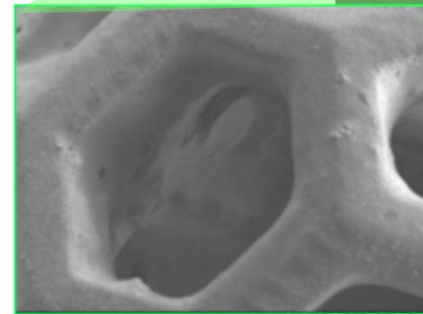
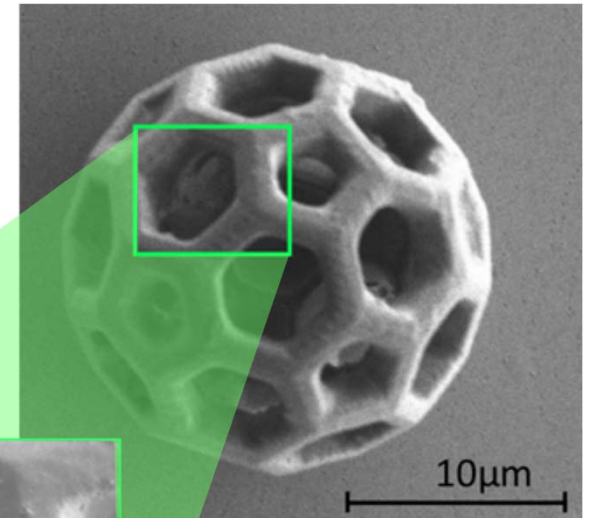
Three Dimensional Structures

**10 nm Al₂O₃/10nm Ir
grown conformally with ALD**

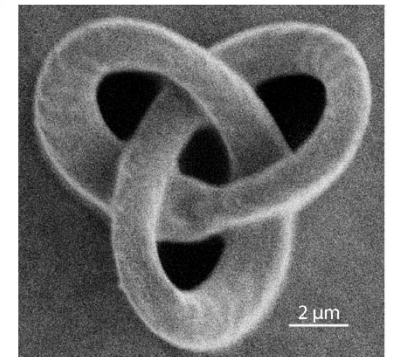
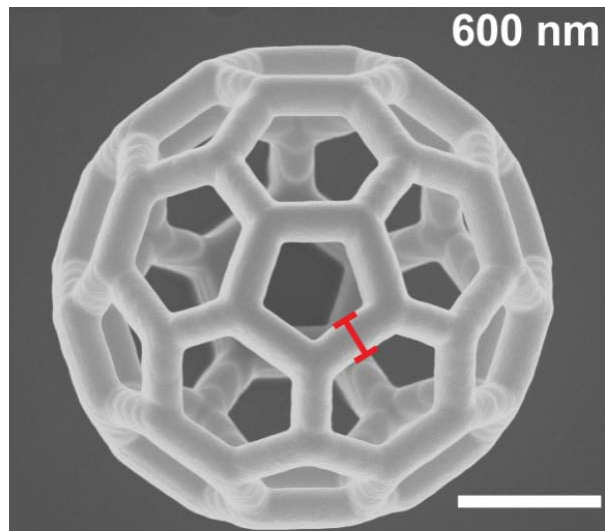


Ir: conductive layer
Al₂O₃: prevents cracking of Ir film due to expansion of polymer

Electroless Deposition



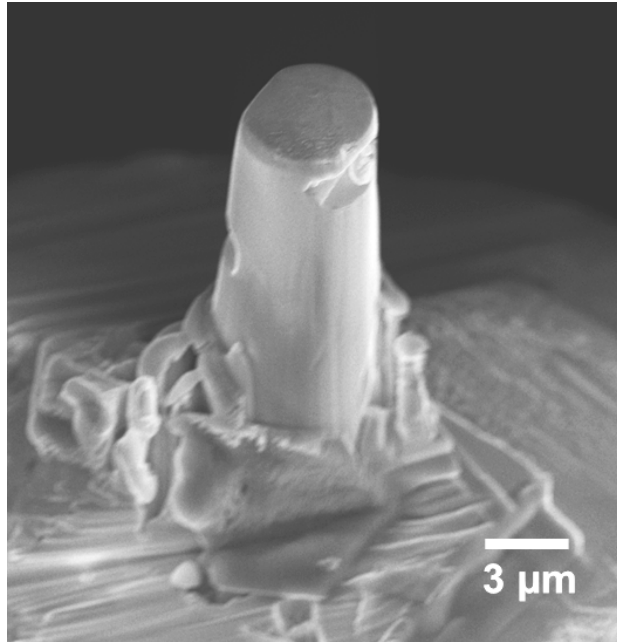
**45 nm - thick
Ni film grown
by electro-
deposition**



cf. Petai Pip & Laetitia Philippe
EMPA Thun



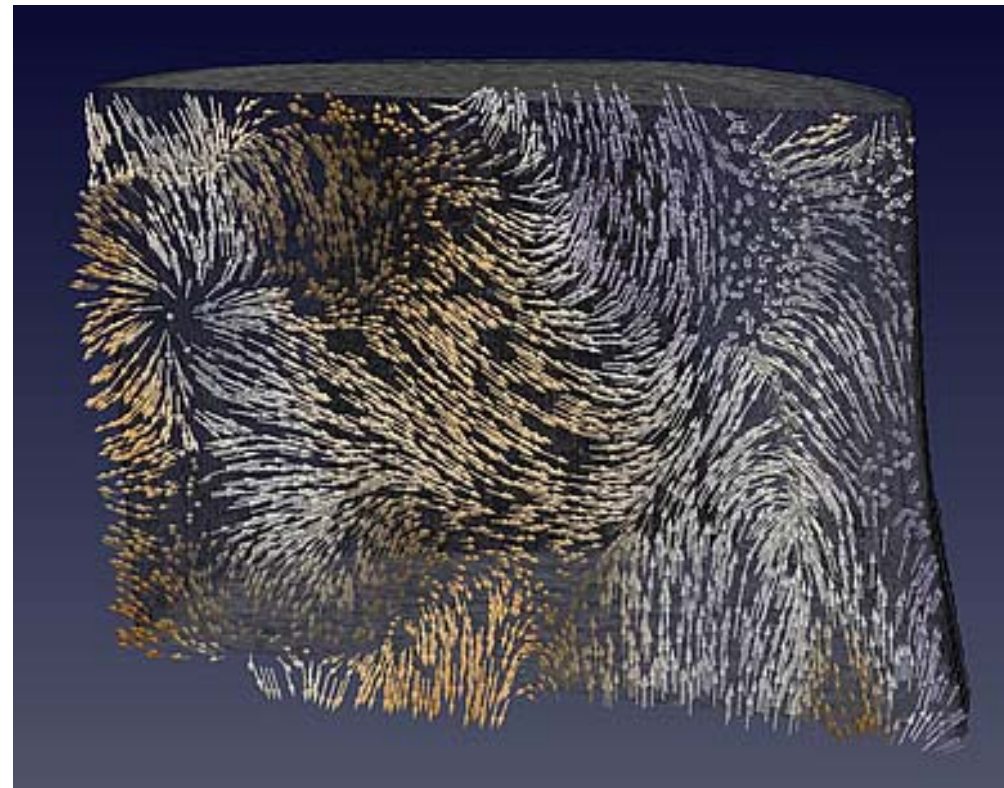
Topic 4
3D magnetic characterisation



GdCo₂ Pillar

Cut from nugget with FIB

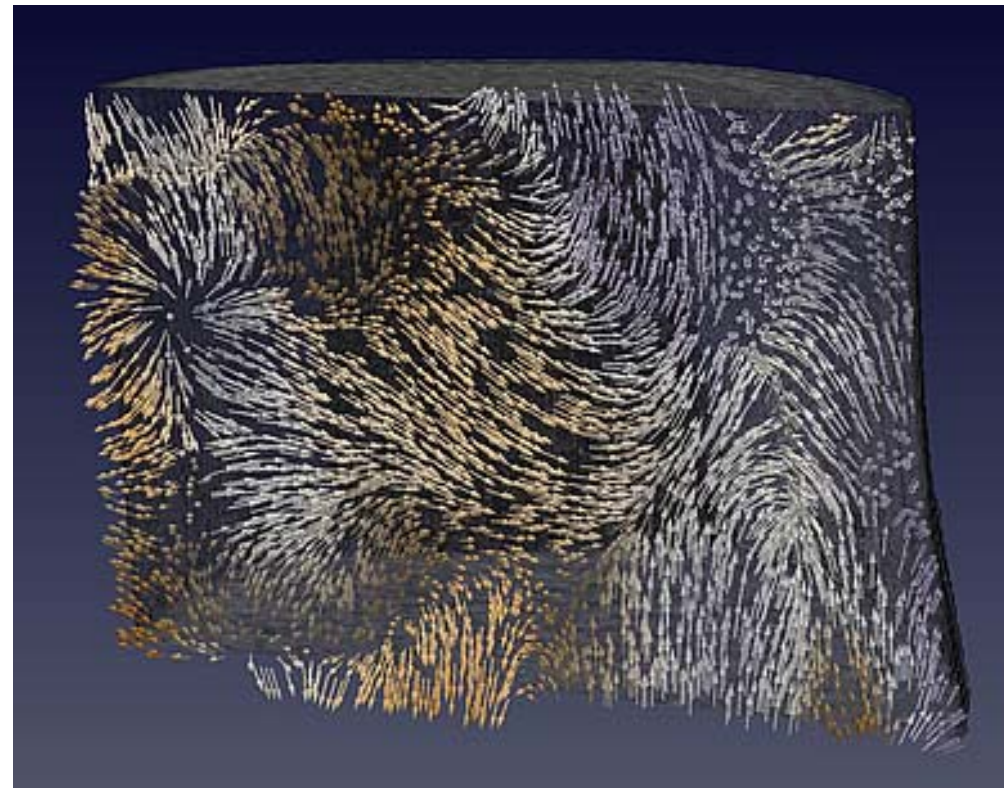
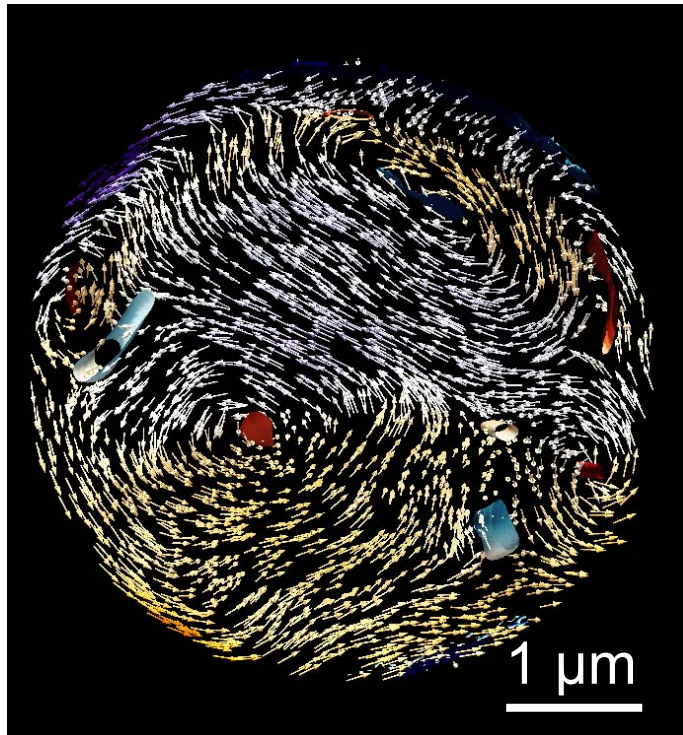
Sample from:
R. Galera, CNRS, Grenoble



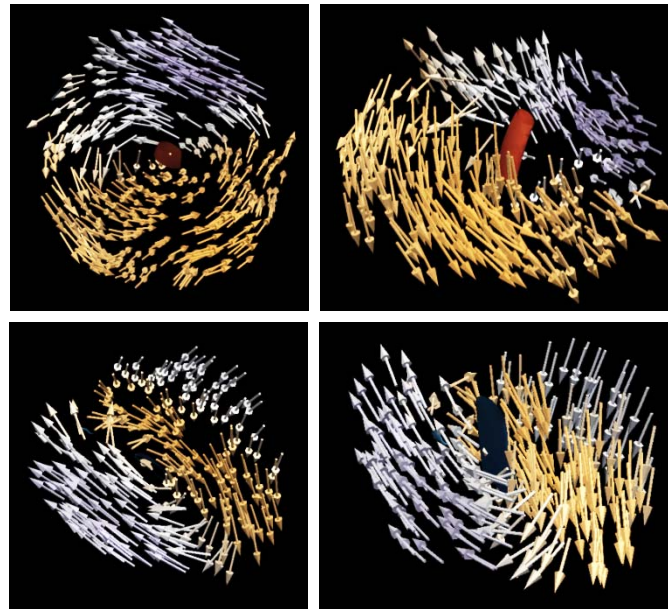
1 μm



One slice:



Vortex

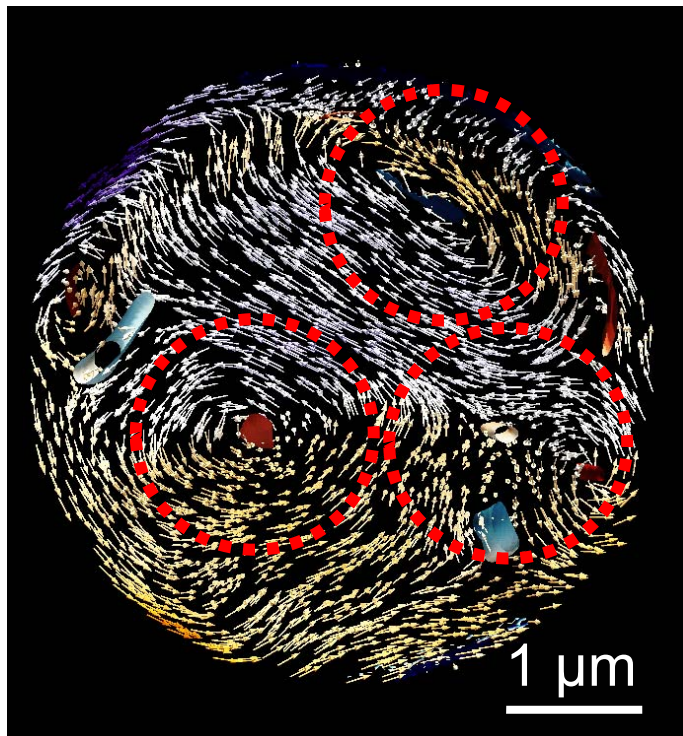
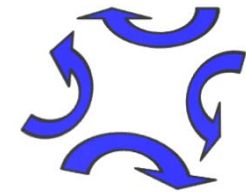
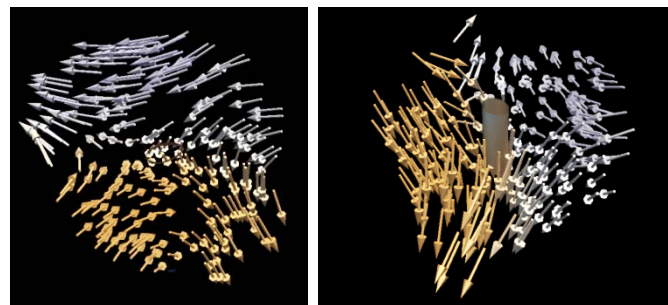


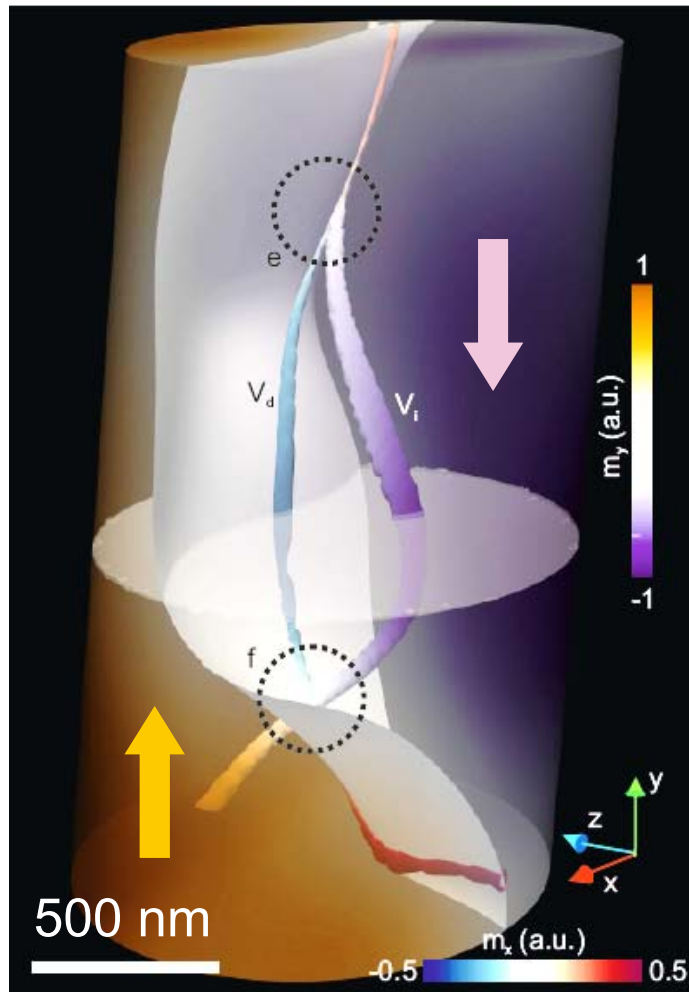
Clockwise

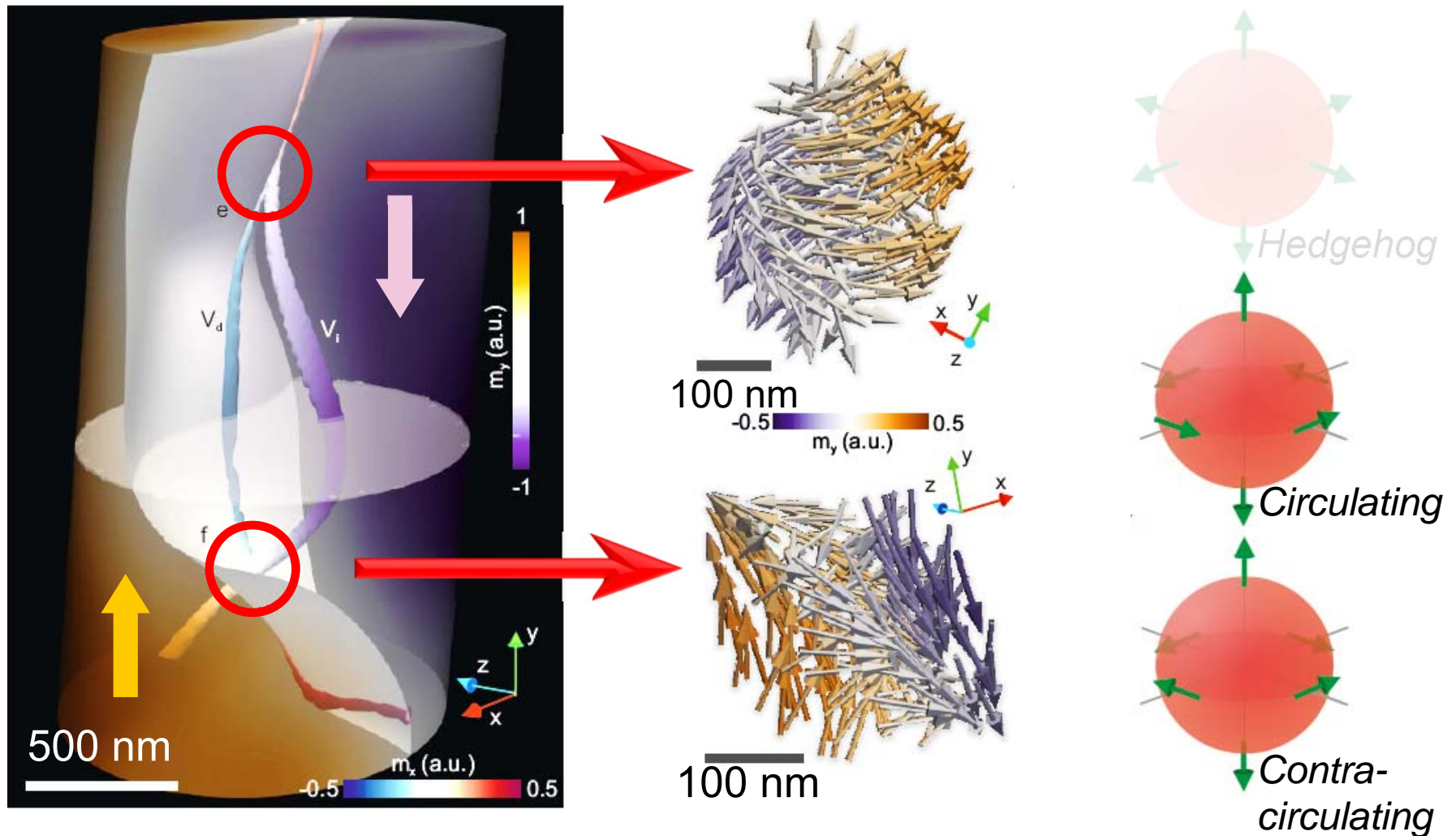


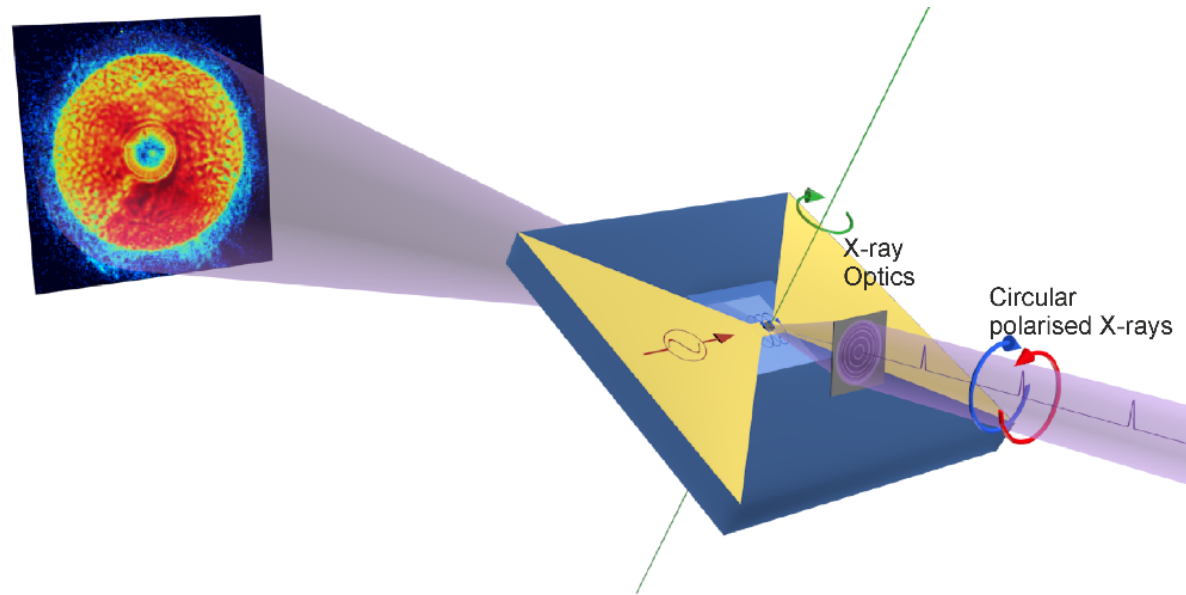
Anticlockwise

Antivortex

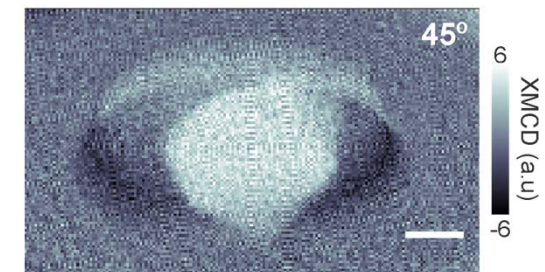
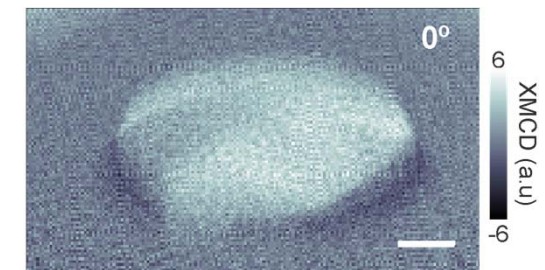
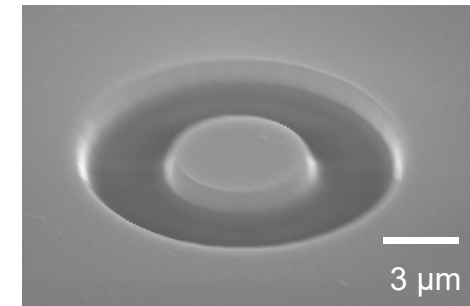






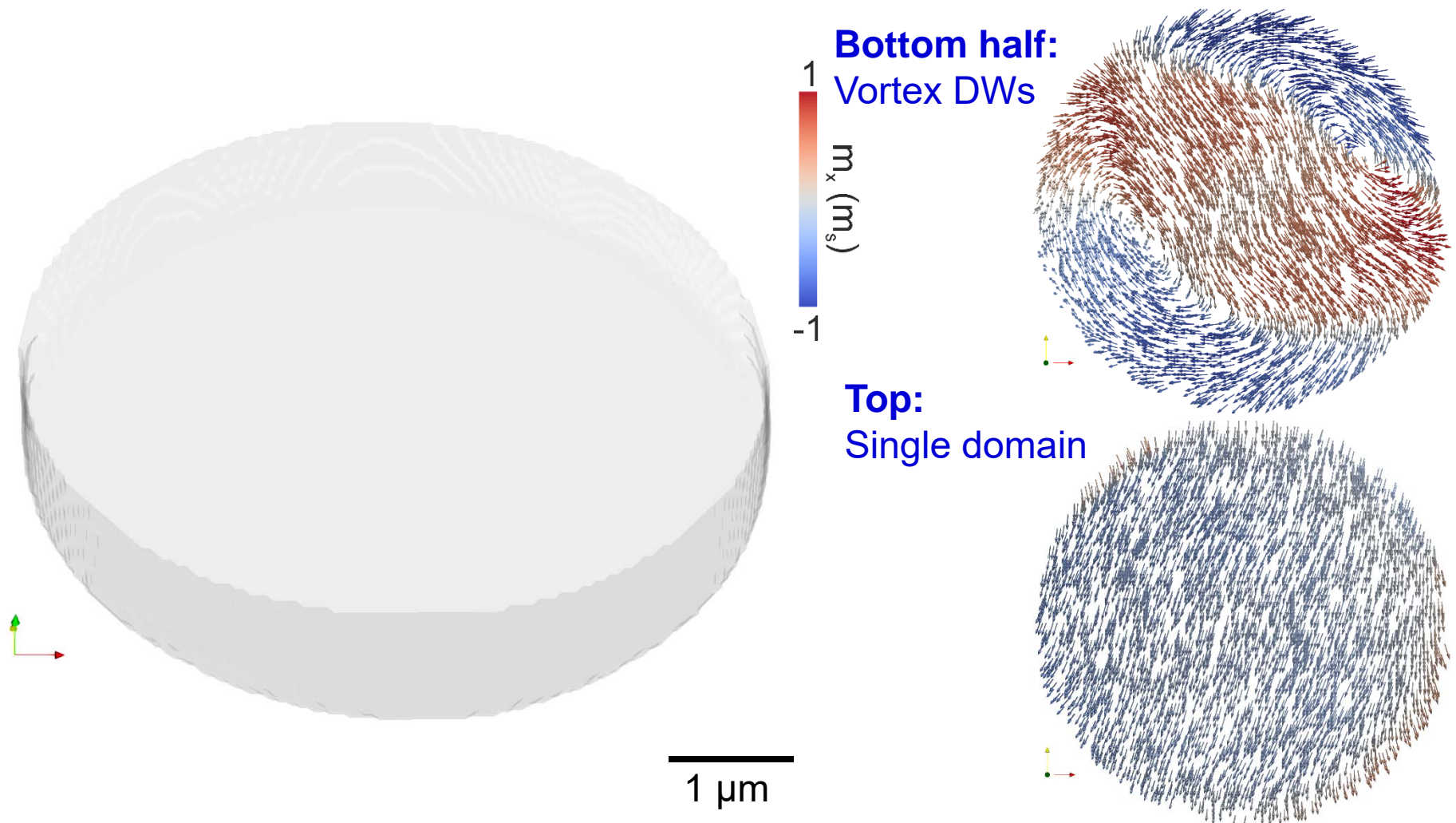


1.2 μm-thick GdCo Disc
Varying magnetic anisotropy



Hard X-ray magnetic laminography
144 XMCD projections around 360°
All 3 components probed with one rotation axis!

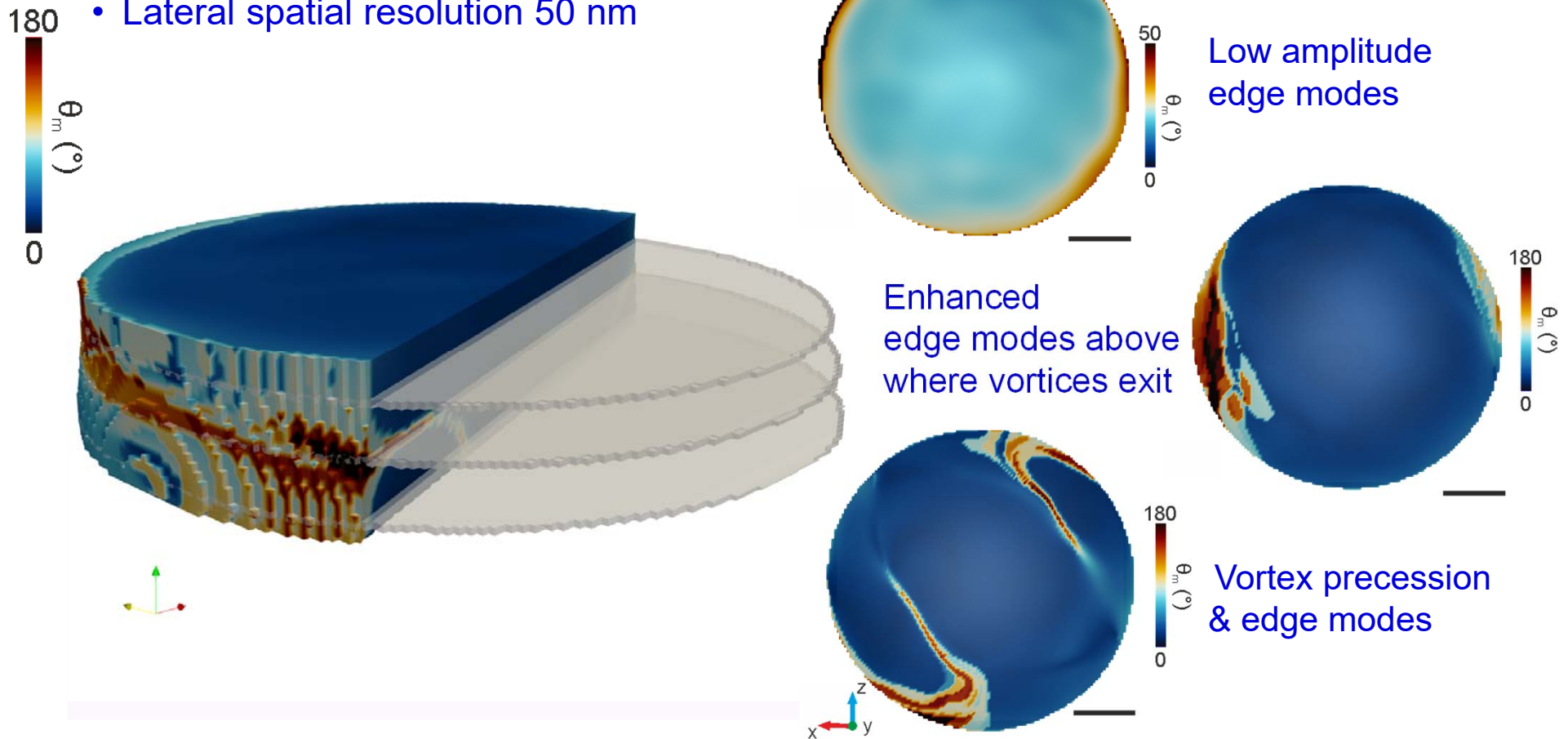
C Donnelly, S Finizio, S Gliga, M Holler, A Hrabec, M Odstrčil, S Mayr, V Scagnoli, LJ Heyderman, M Guizar-Sicairos, J Raabe, Nature Nanotechnology (2020)



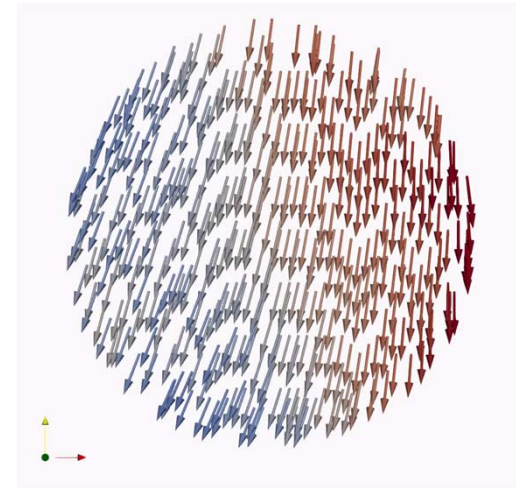
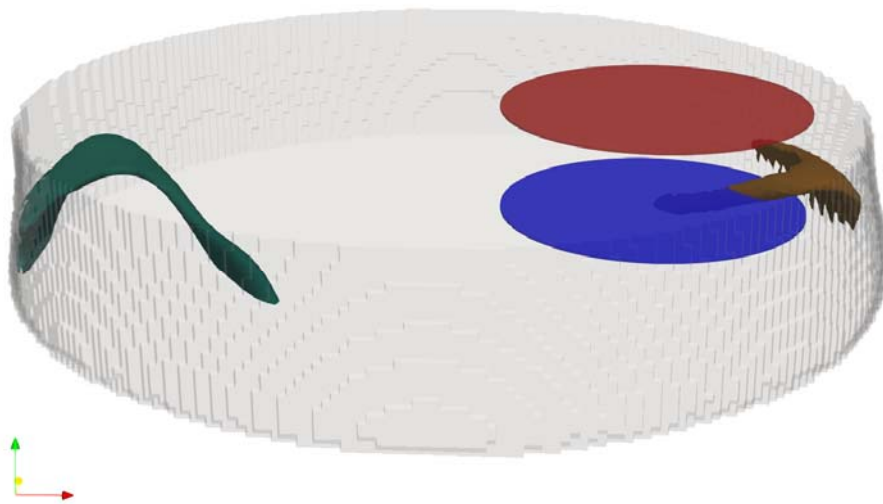
C Donnelly, S Finizio, S Gliga, M Holler, A Hrabec, M Odstrčil, S Mayr, V Scagnoli, LJ Heyderman, M Guizar-Sicairos, J Raabe, Nature Nanotechnology (2020)

→ Magnetisation dynamics closely linked to 3D magnetic structure

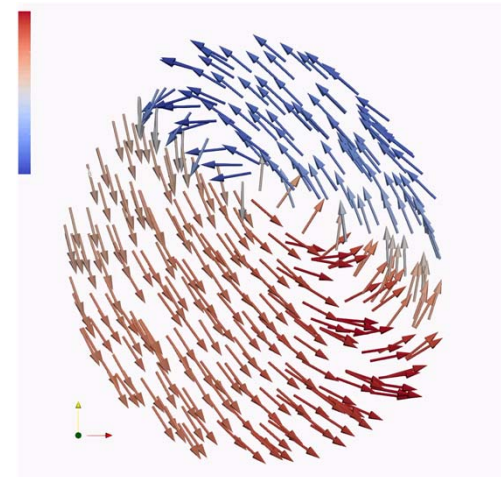
- Dynamic response to 500 MHz magnetic field
- Temporal resolution 70 ps
- Lateral spatial resolution 50 nm



C Donnelly, S Finizio, S Gliga, M Holler, A Hrabec, M Odstrčil, S Mayr, V Scagnoli, LJ Heyderman, M Guizar-Sicairos, J Raabe, Nature Nanotechnology (2020)



Rotation of magnetisation

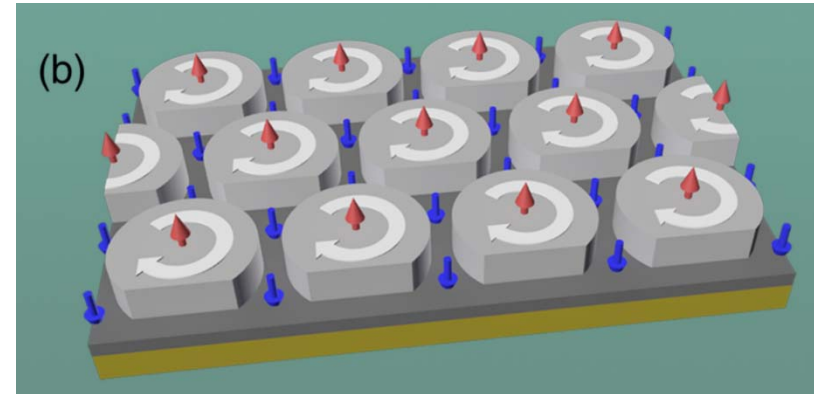
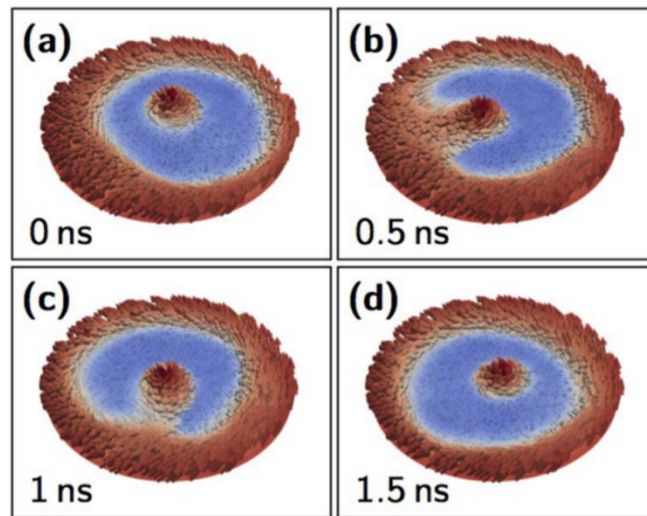


Vortex / domain wall dynamics

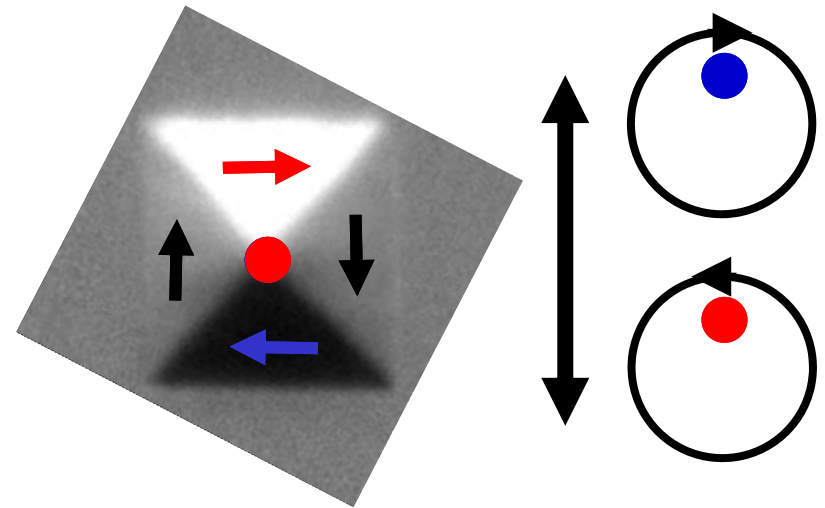
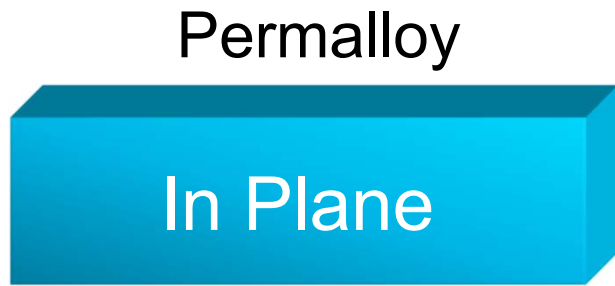
C Donnelly, S Finizio, S Gliga, M Holler, A Hrabec, M Odstrčil, S Mayr, V Scagnoli, LJ Heyderman, M Guizar-Sicairos, J Raabe, Nature Nanotechnology (2020)

*Magnetization dynamics of imprinted
non-collinear spin textures*

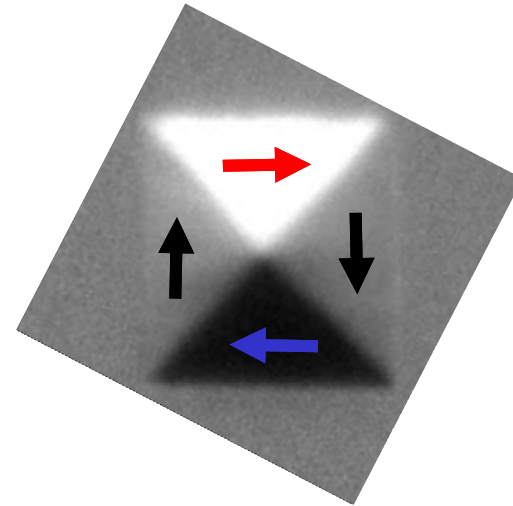
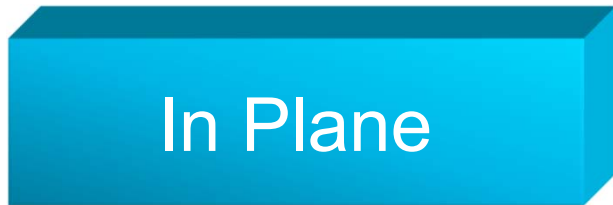
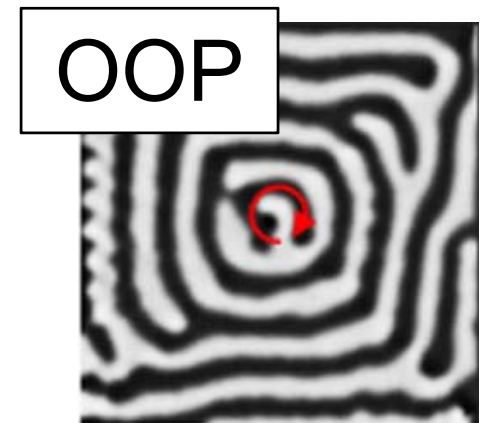
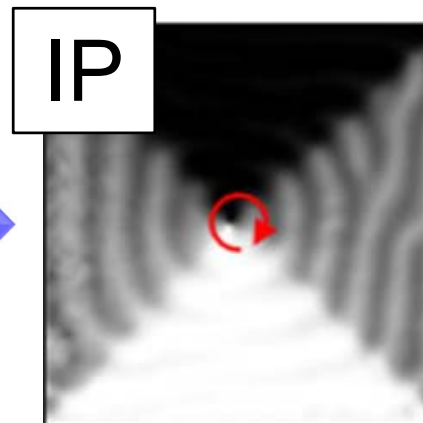
R Streubel et al. AIP Advances 2014

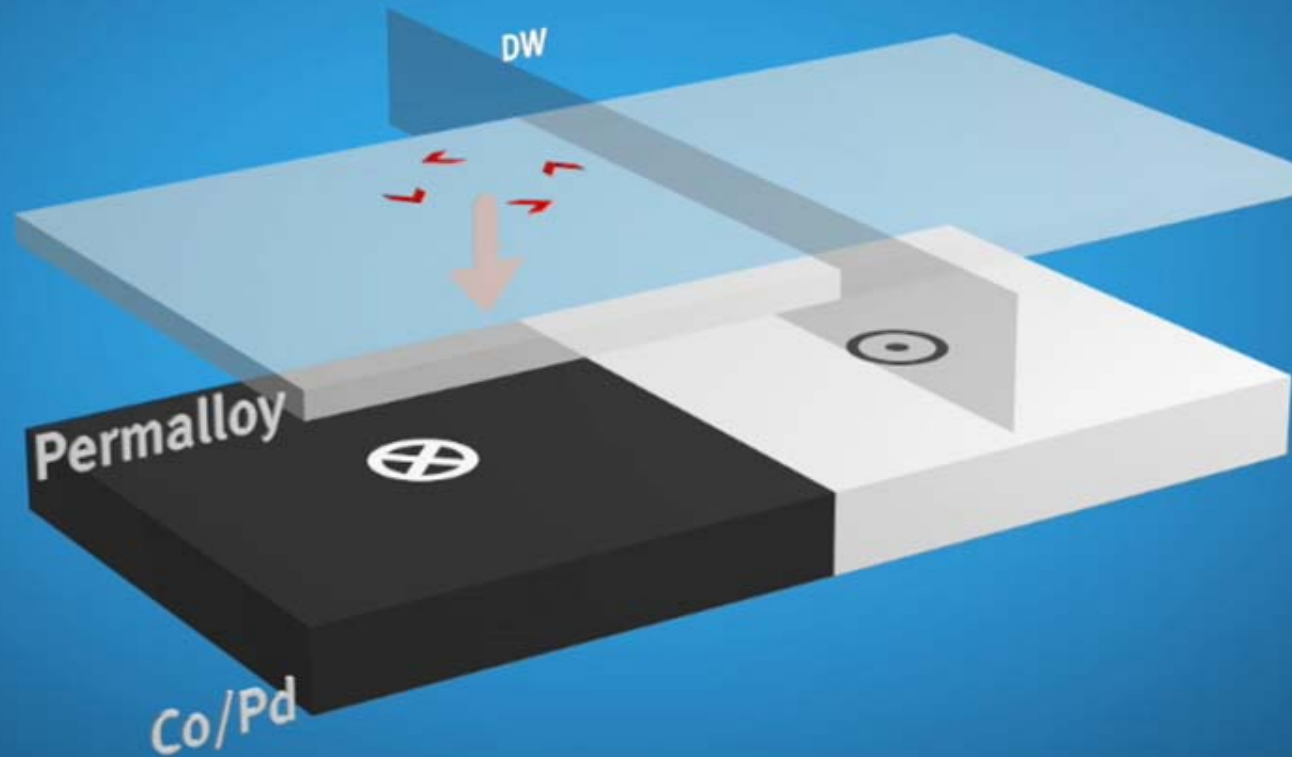


*Creating an Artificial Two-Dimensional
Skyrmion Crystal by Nanopatterning*
L Sun et al. PRL 2013



Permalloy

 $[\text{Co}(0.3 \text{ nm})/\text{Pd}(0.9 \text{ nm})]_8$ 

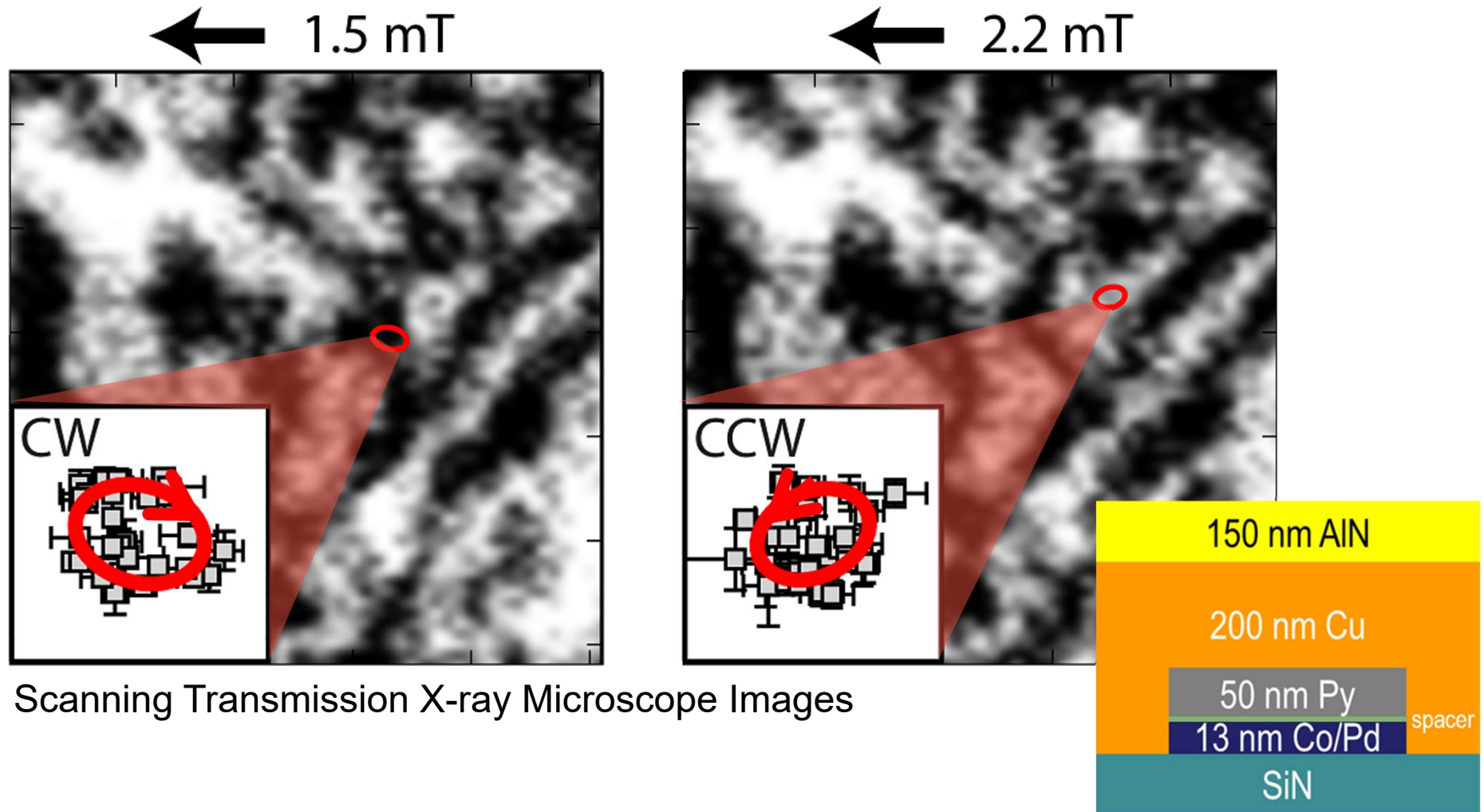


Animation: Mahir Dzambegovic/Paul Scherrer Institute

P Wohlhüter et al. Nature Communications (2015)

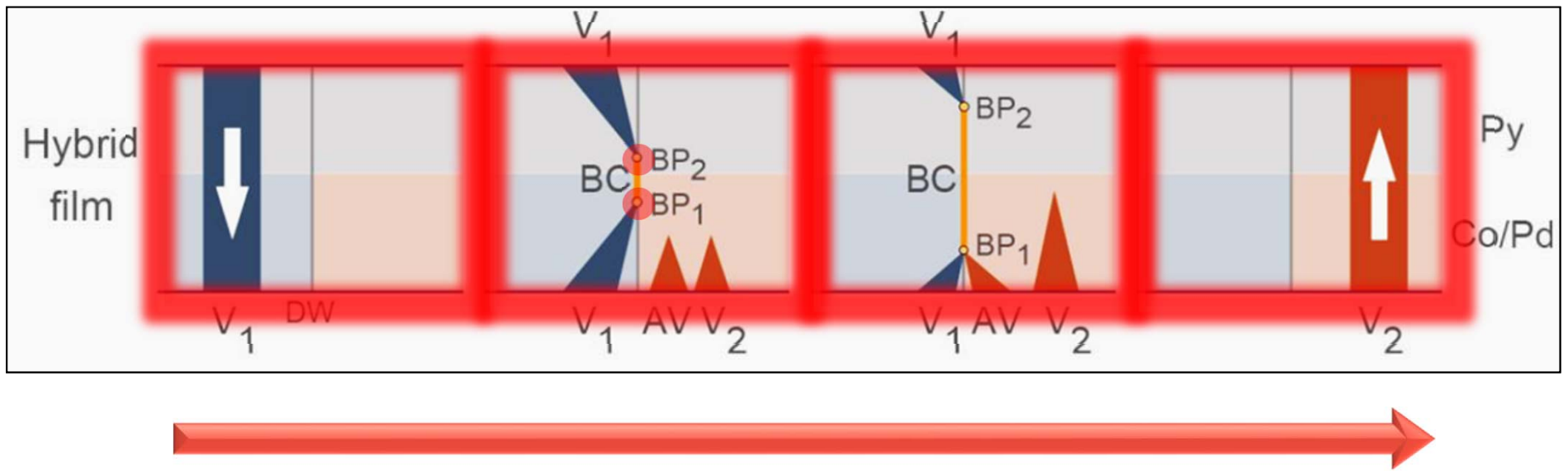
G. Heldt et al. Appl Phys Letts (2014)

Nanoscale Vortex Core Switch



P Wohlhüter, MT Bryan, P Warnicke, S Gliga, SE Stevenson, G Heldt, L Saharan, AK Suszka, C Moutafis, RV Chopdekar, J Raabe, T Thomson, G Hrkac, LJ Heyderman
 Nature Communications (2015)

Nanoscale Vortex Core Switch



P Wohlhüter, MT Bryan, P Warnicke, S Gliga, SE Stevenson, G Heldt, L Saharan, AK Suszka, C Moutafis, RV Chopdekar, J Raabe, T Thomson, G Hrkac, LJ Heyderman
 Nature Communications (2015)

Acknowledgements





**Research & Technical Staff, Paul Scherrer Institute
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- ❖ *Photoemission Electron Microscopy, SIM Beamline*
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- ❖ *Scanning Transmission X-ray Microscopy, PolLux Beamline*
Joerg Raabe, Simone Finizio
- ❖ *X-ray Scattering, SIM Beamline*
Urs Staub
- ❖ *Hard X-ray Tomography & Imaging, CSAXs Beamline*
Manuel Guizar Sicaïros, Andreas Menzel, Joerg Raabe, Mirko Holler
- ❖ *Hard X-ray Structural Tomography, Tomcat Beamline*

Condensed Matter Theory Group: Peter Derlet

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Pietro Gambardella & Group
Robert Style & Eric Dufresne
Tianyun Huang, Bradley Nelson & Group

Univ. Manitoba:

Robert Stamps

Univ. Exeter:

Gino Hrkac & Group

Univ. St Andrews:

Machiel Flokstra, Steve Lee

Univ. Cambridge:

Gunnar Möller

Univ. Manchester:

Thomas Thomson & Group

UC Dublin:

Hans-Benjamin Braun & Group

Uppsala University:

Björgvin Hjörvarsson & Group

SOLEIL Synchrotron:

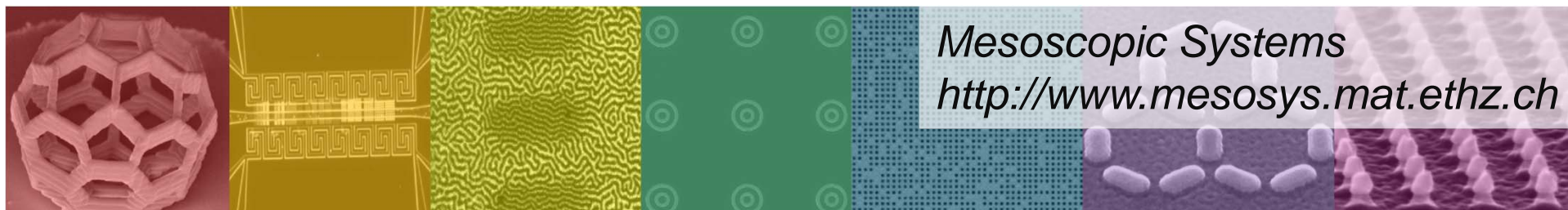
Nicolas Jaouen, Jean-Marc Tonnerre,
Jan Lüning, Maurizio Sacchi

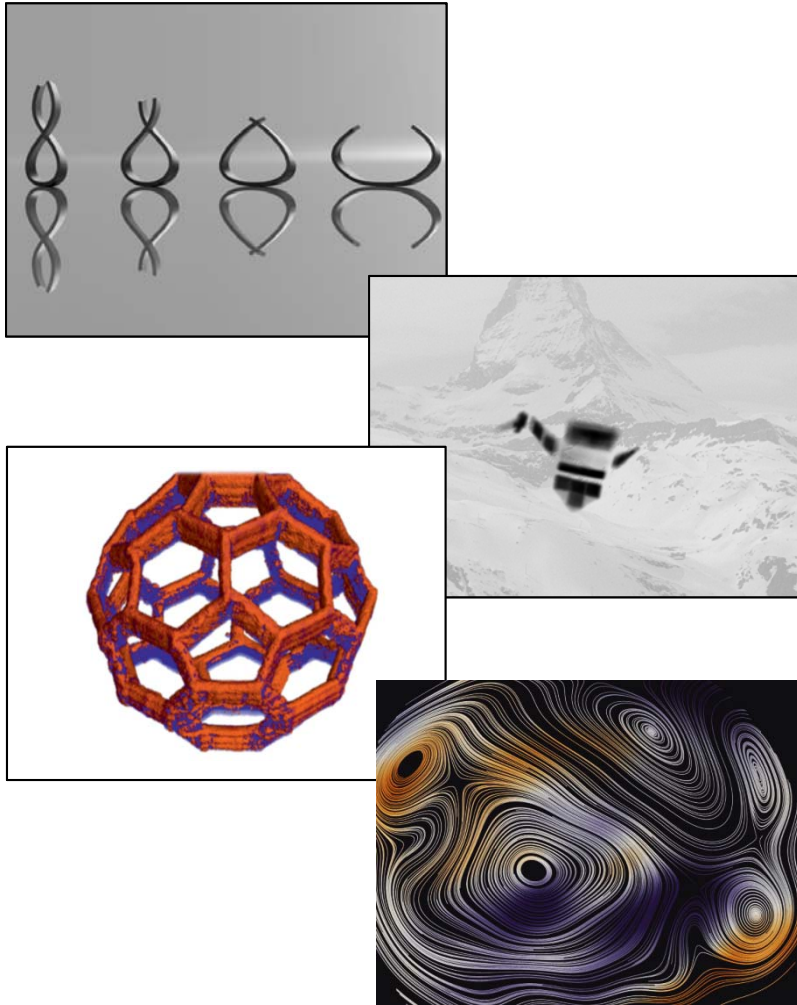
ESRF Synchrotron:

Fabrice Wilhelm, Francois Guillou,
Andrei Rogalev, Carsten Detlefs

Adv. Light Source:

Andreas Scholl, Rajesh Chopdekar & Colleagues





1. Magneto-mechanical Systems
2. Origami Micromachines
3. Two Photon Laser Lithography
4. 3D magnetic characterisation



Mesoscopic Systems

<http://www.mesosys.mat.ethz.ch>