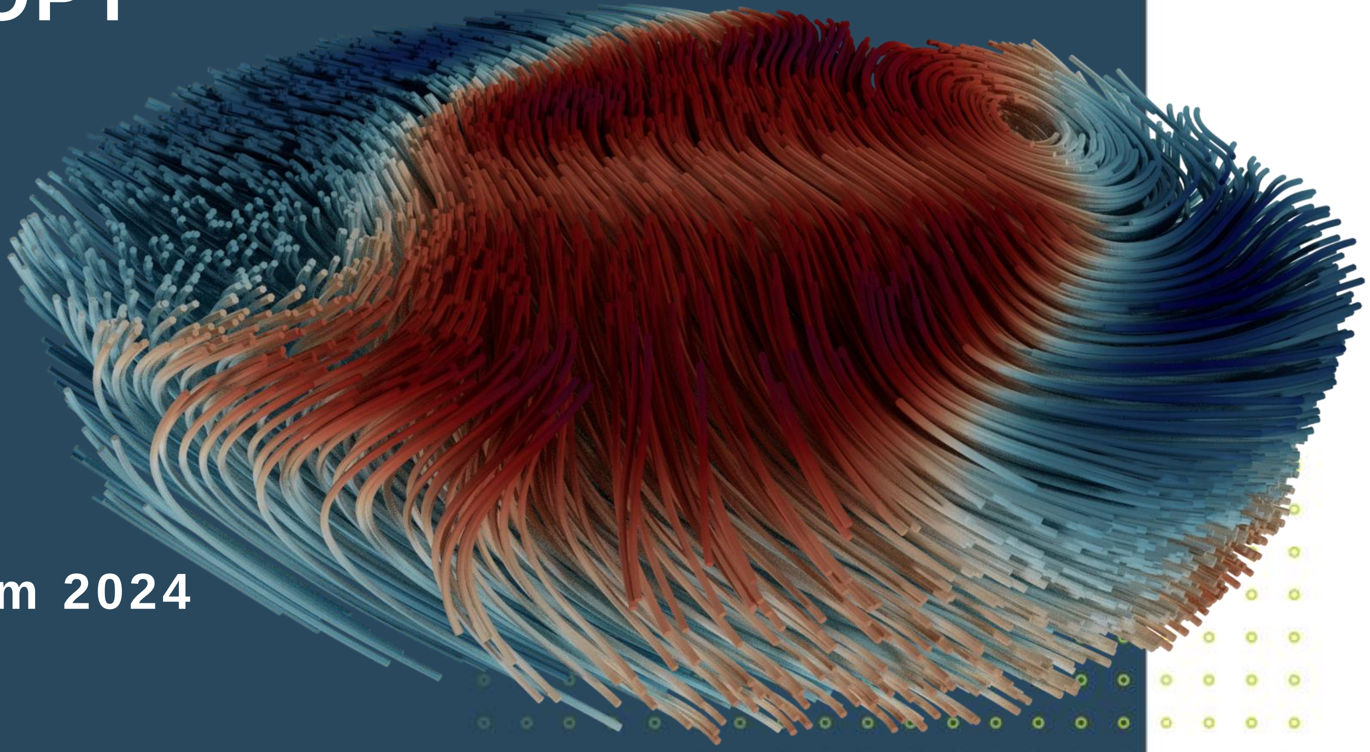
MAX PLANCK INSTITUTE
FOR CHEMICAL PHYSICS OF SOLIDS

MAGNETIC MICROSCOPY



Claire Donnelly

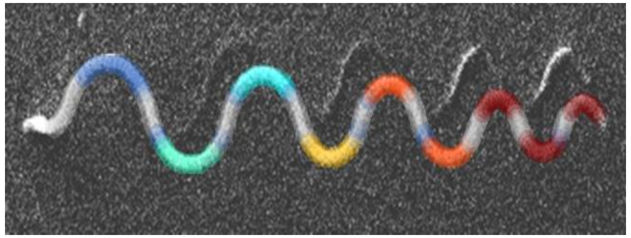
European School of Magnetism 2024

4th September 2024, York, UK

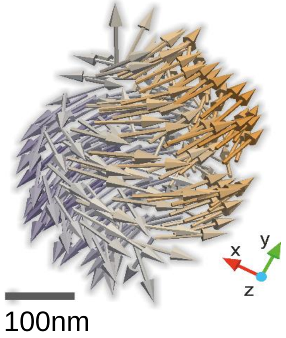
IN MY GROUP:

Spin3D

→ Three dimensional magnetism

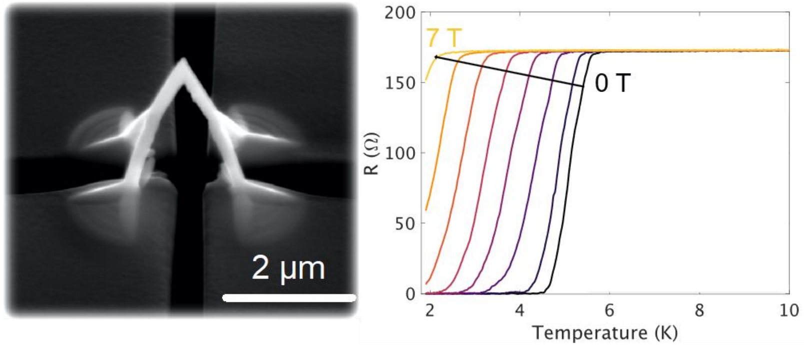


Curvilinear magnetism



3D topological textures

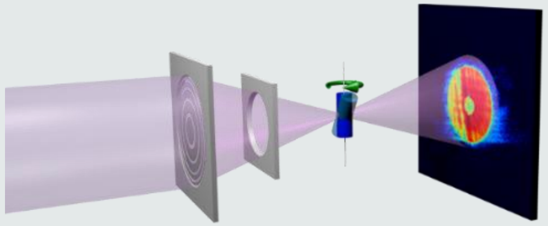
And alternative material systems...



3D nanosuperconductors

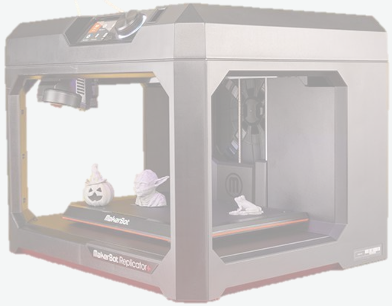
TOOLS FOR NANOMAGNETISM

Visualising them?*

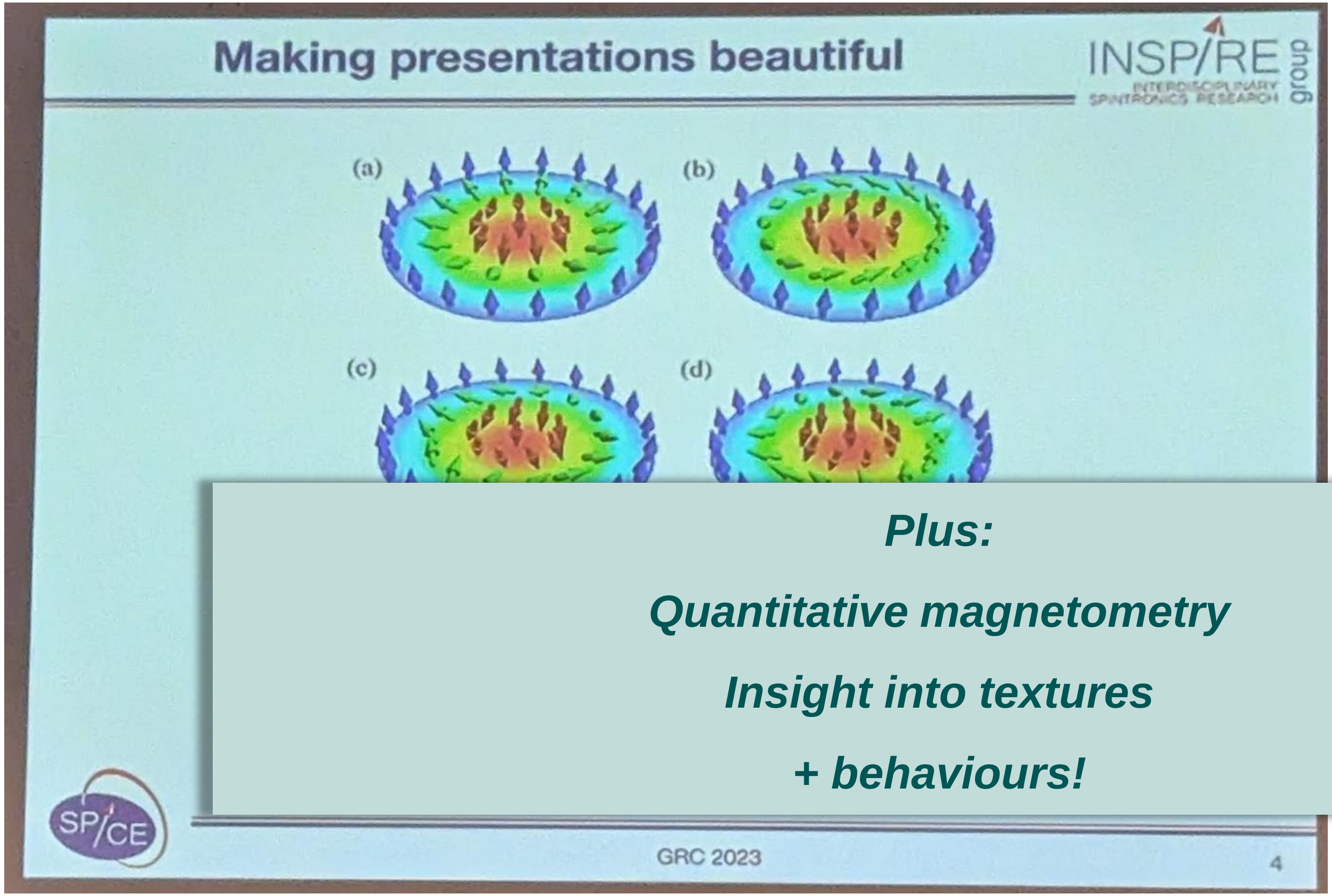


Understanding them?

Fabricating them?



WHY MAGNETIC MICROSCOPY?



Plus:

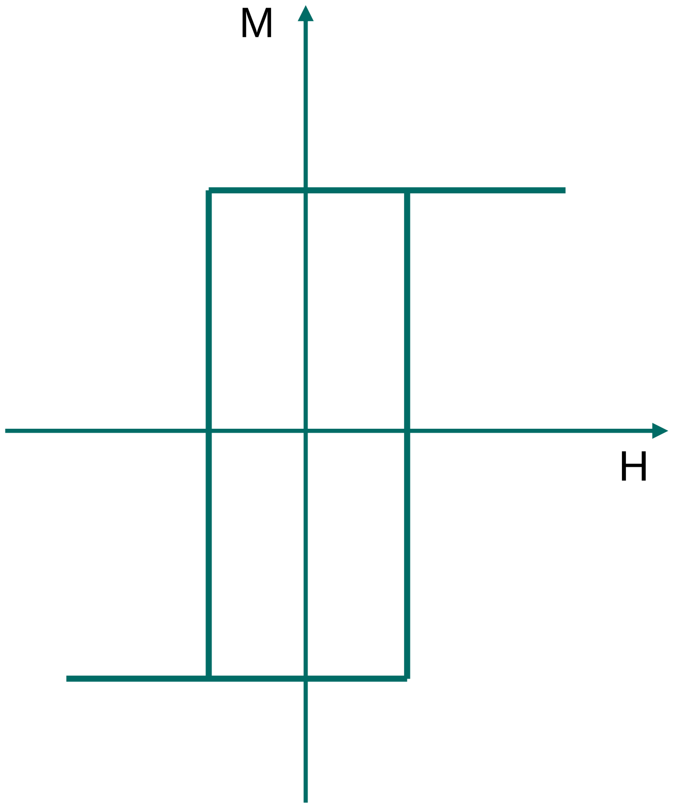
Quantitative magnetometry

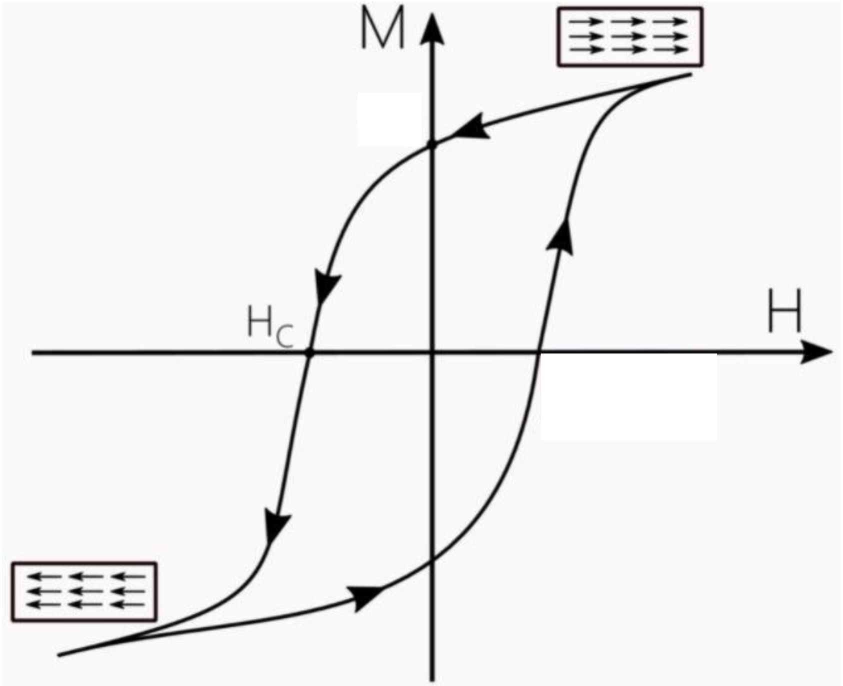
Insight into textures

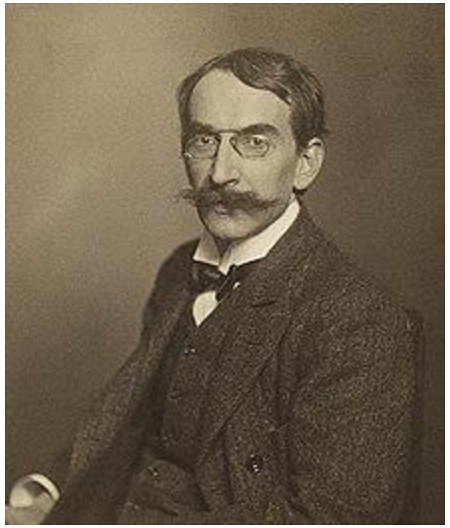
+ behaviours!

cs in Nanostructures,
ly 2023

WHAT ARE WE IMAGING IN MAGNETS?







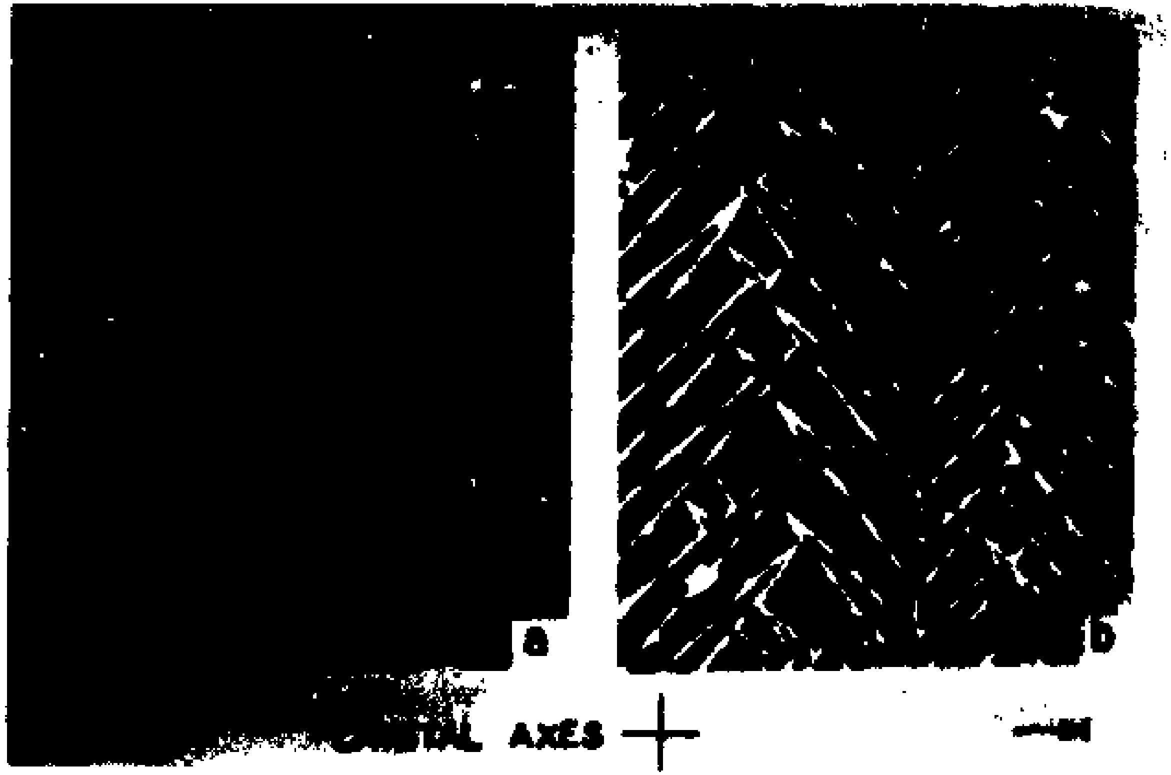
Pierre Weiss, 1907

Magnetic materials appear “non-magnetic”

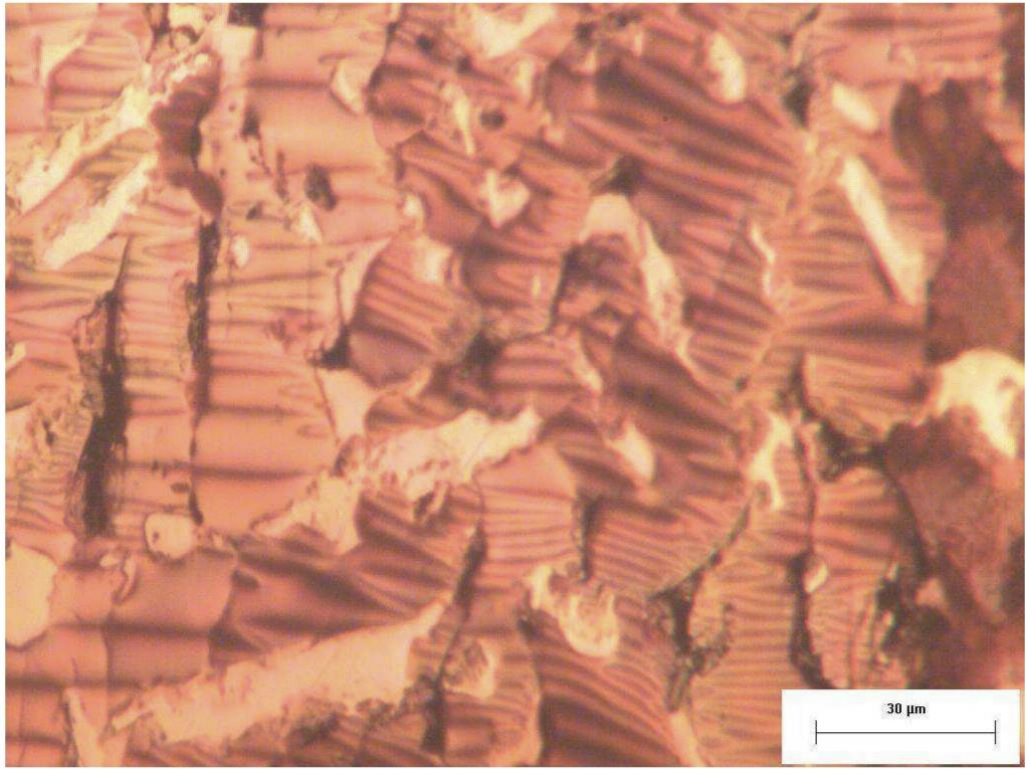
→ presence of magnetic domains

CONFIRMED WITH FIRST MAGNETIC MICROSCOPY: THE BITTER METHOD

Put ferrofluid on top of a magnet

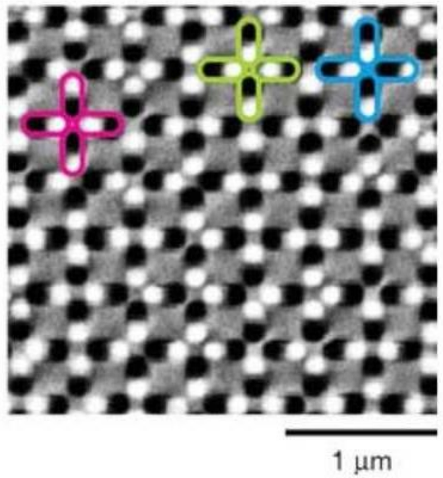


R. Patton, K. Strnat (1963)

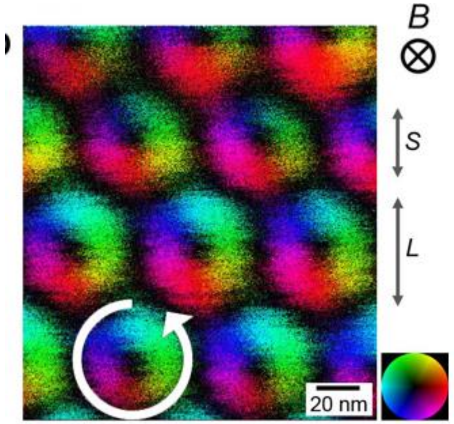


Lemos et al., Materials Science Forum Vol. 802 (2014)

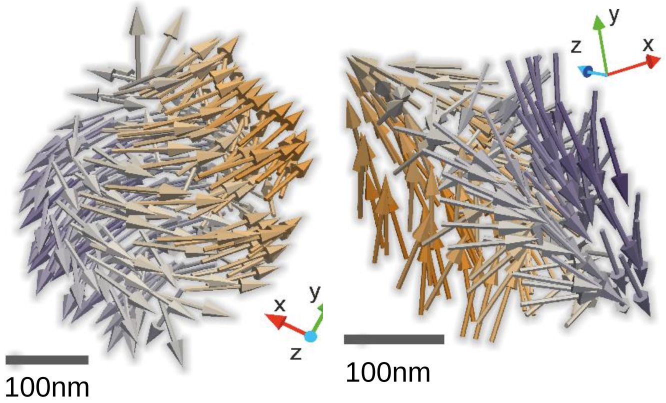
NOWADAYS…
MAGNETIC MICROSCOPY PLAYS KEY ROLE!



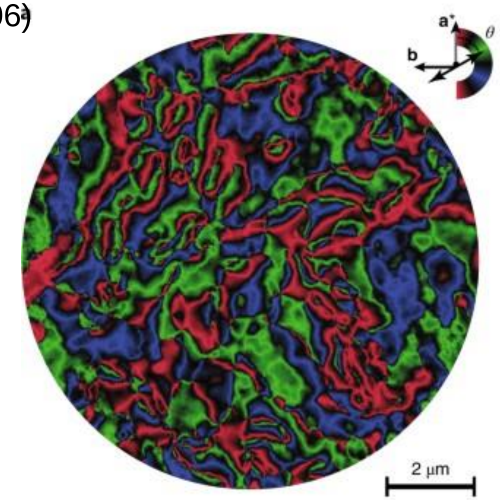
Wang et al., Nature (2006)



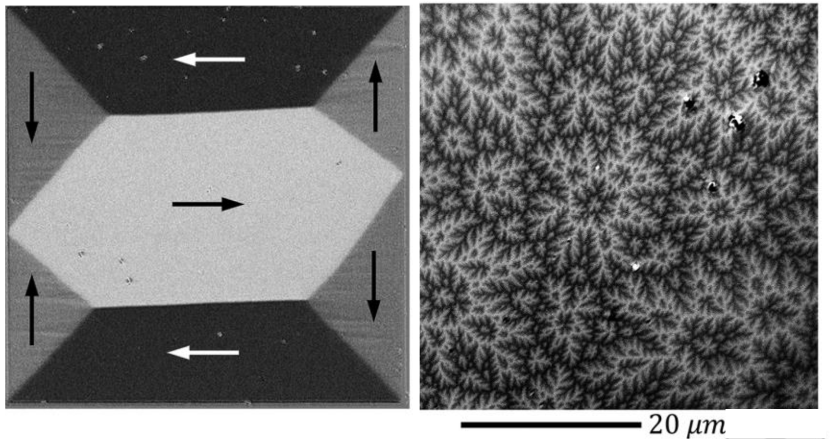
Matsumoto et al., Science Advances (2016)



Donnelly et al., Nature 547, 328 (2017)



Chmiel et al., Nature Materials 17, 581 (2018)

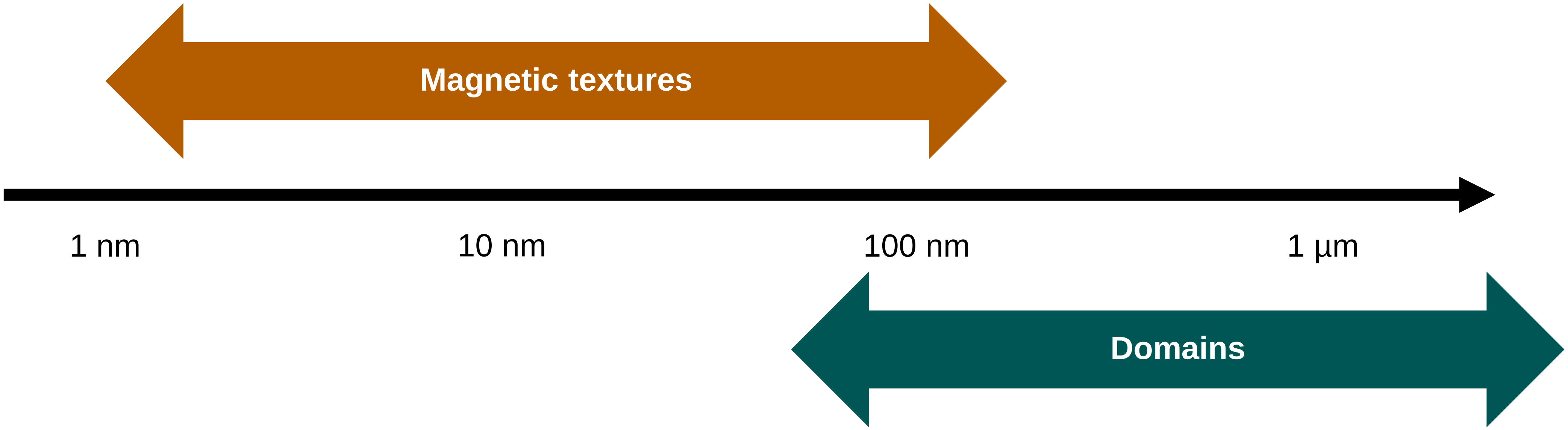


Soldatov & Schäfer, Rev. Sci. Instrum. (2017)

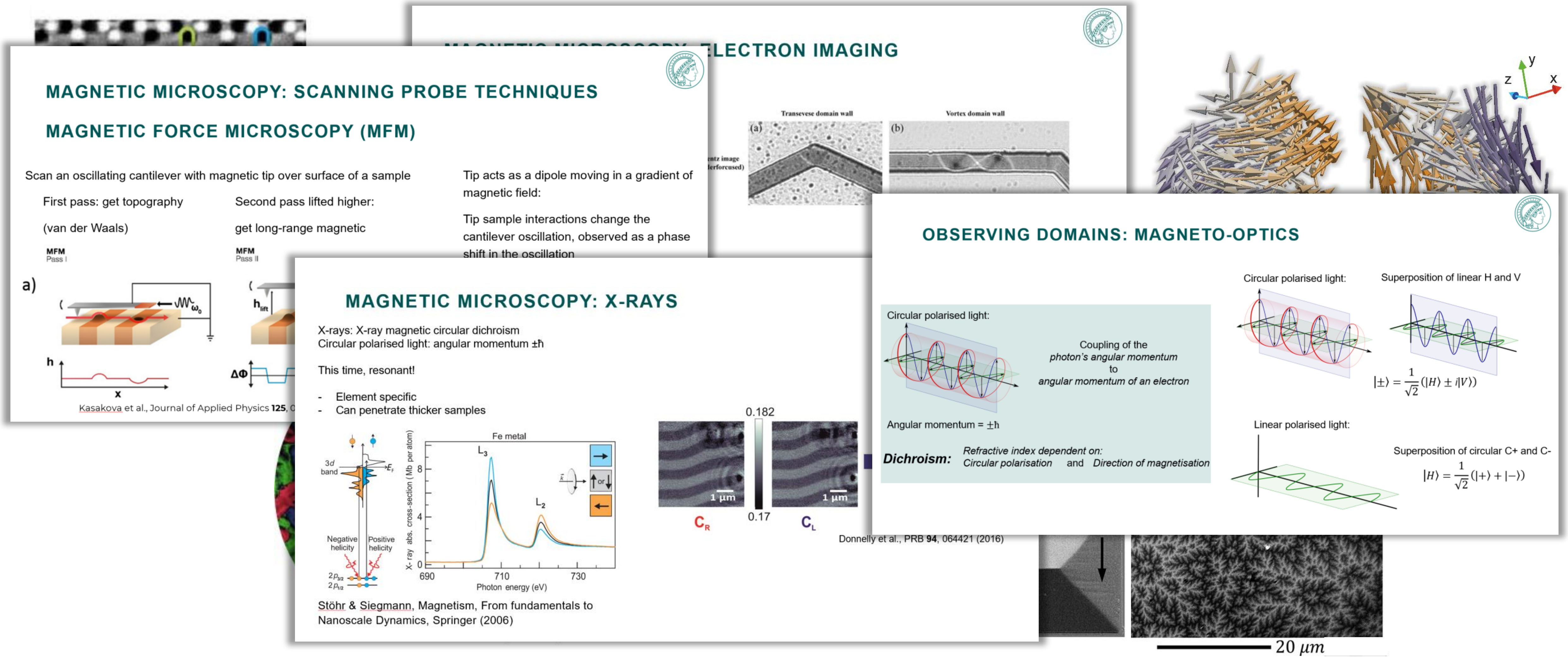
RELEVANT LENGTHSCALES

→ **We know these are on the order of nanometres to micrometres**

→ **So we need spatial resolution of our microscope to be on that order**



MAGNETIC MICROSCOPY:
HOW DO WE CHOOSE OUR METHOD?



Chmiel et al., Nature Materials 17, 581 (2018)

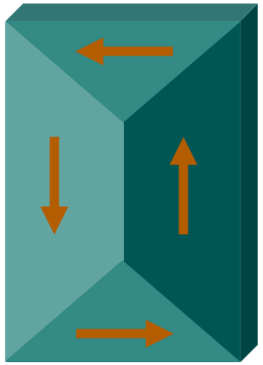
Soldatov & Schäfer, Rev. Sci. Instrum. (2017)

AIM OF TODAY: WE'LL FILL OUT…

	Probing B			Probing m		+
	MFM	Nitrogen vacancy	TEM	MOKE	XMCD (synchrotron)	XMLD (synchrotron)
Contrast						
Spatial resolution						
Depth sensitivity						
Sample environment						
Invasive						
Sensitivity						
Cost/ accessibility						

WE CAN THINK ABOUT WHAT IS PROBED:

Magnetic induction (B) probes



$$B = \mu_0(M + H)$$

Magnetisation (M) probes

Electrons, scanning probe, Bitter method…

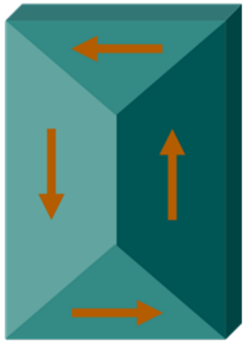
Scanning probe	Electrons

Magneto-optics, spin-polarised STM,

SEM with polarisation analysis

Optical regime	Electrons	X-rays

***B* probes**



***M* probes**

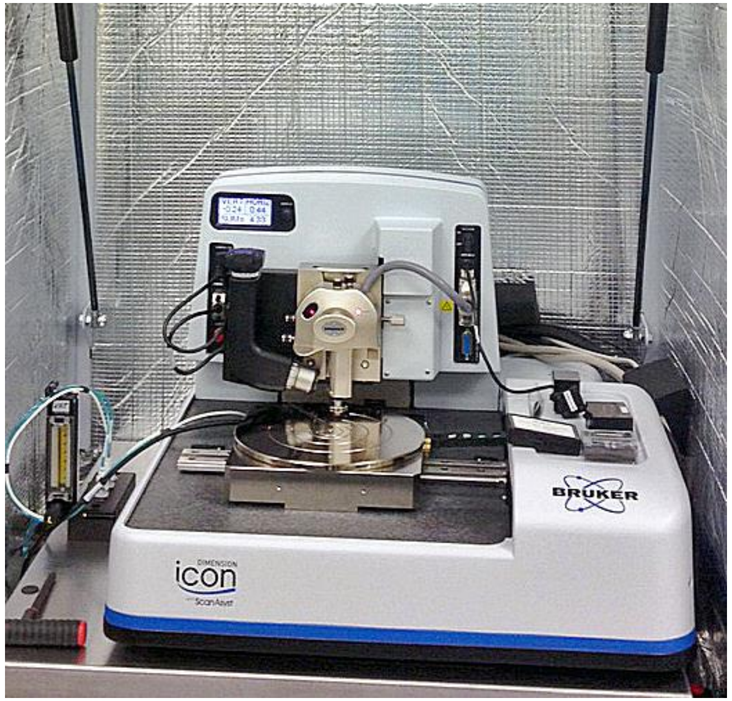
$$B = \mu_0(M + H)$$

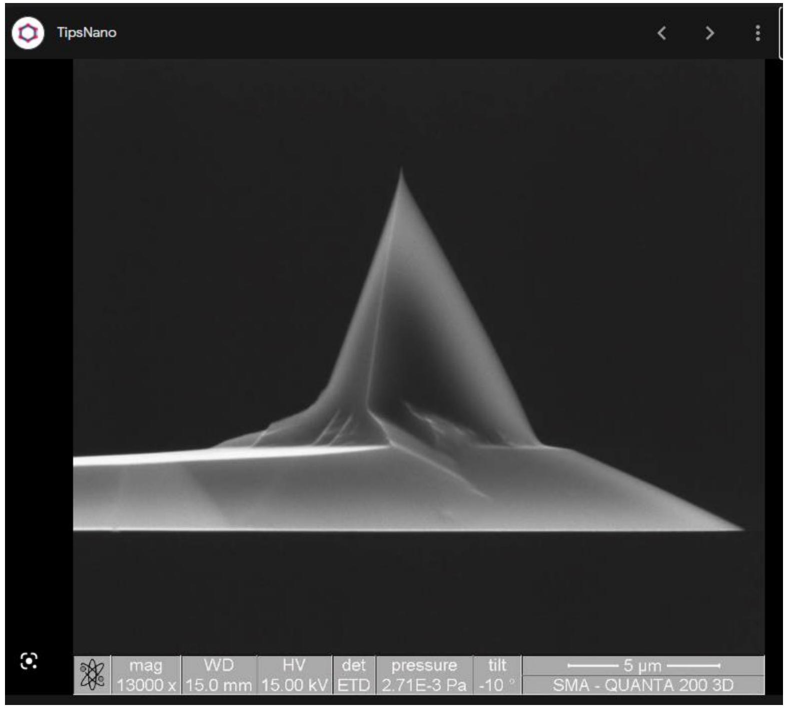
Scanning probe

Electron microscopy

SCANNING PROBES OF B:

MAGNETIC FORCE MICROSCOPY

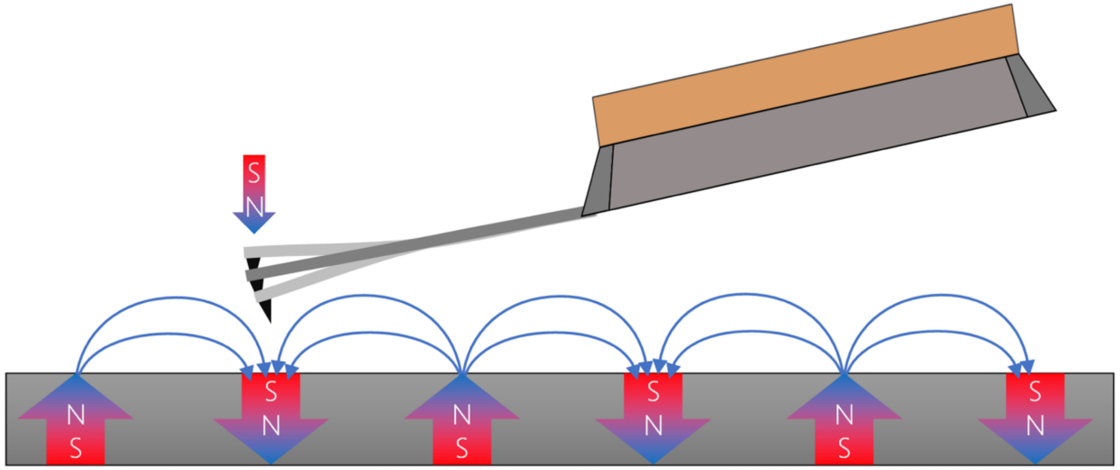




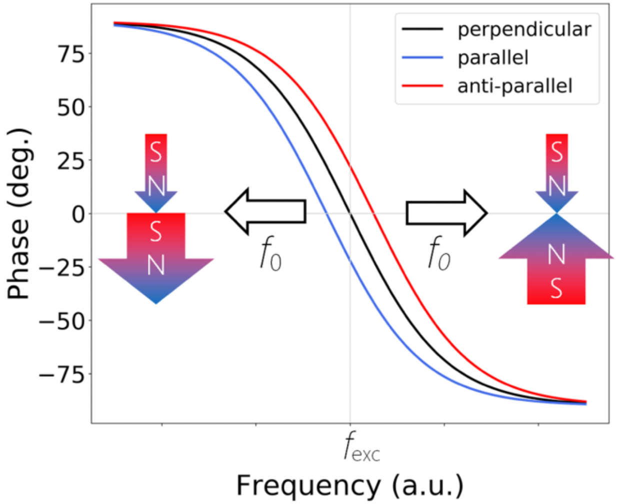
Cantilever with magnetic tip

MAGNETIC FORCE MICROSCOPY:

What are we measuring? Magnetic field above the sample!



sample with magnetic domains



Credit: Nanosurf AG

MAGNETIC FORCE MICROSCOPY

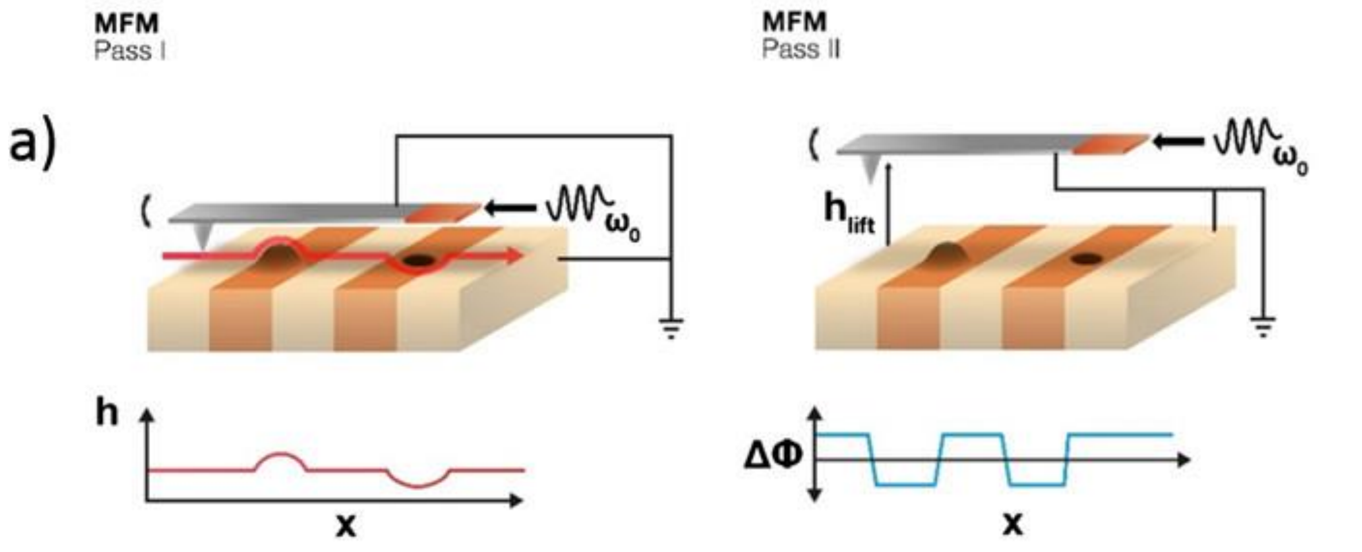
Scan an oscillating cantilever with magnetic tip over surface of a sample

First pass: get topography

(van der Waals)

Second pass lifted higher:

get long-range magnetic



Kasakova et al., Journal of Applied Physics **125**, 060901 (2019)

Tip: **dipole moving in a gradient of magnetic field**

Tip - sample interactions change the cantilever oscillation, observed as a phase shift in the oscillation

Spatial resolution: determined by tip. Roughly 50 nm (down to ~10 nm)

Measure surface charges

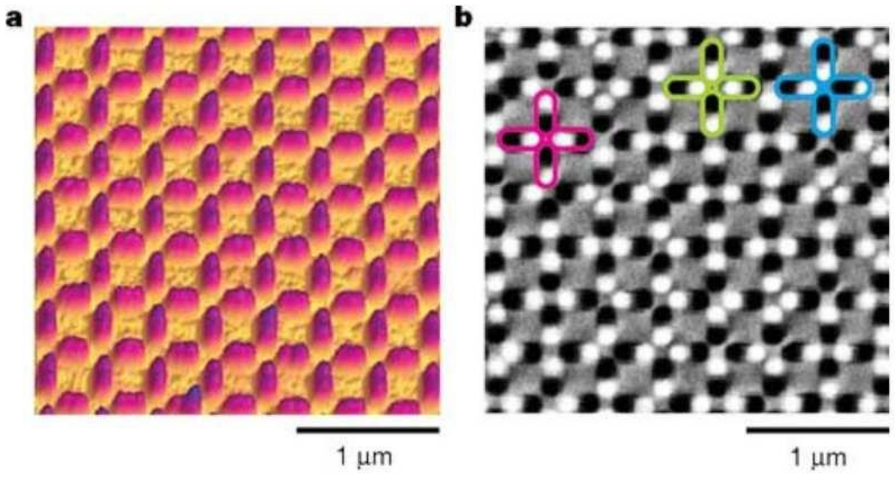
& buried configuration!

* Long range interaction

MAGNETIC FORCE MICROSCOPY

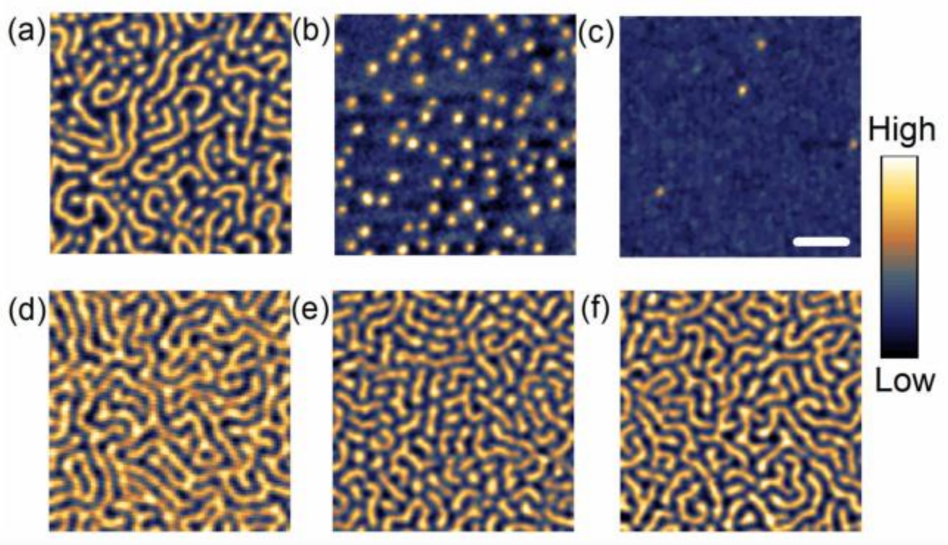
Nanomagnet arrays:

Wang et al., Nature (2006)



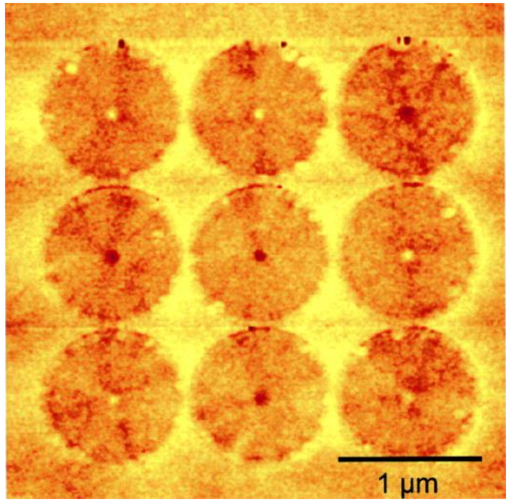
Magnetic domains, skyrmions:

Duong et al., APL (2019)



Patterned magnetic micro/nanostructures:

Magnetic vortices



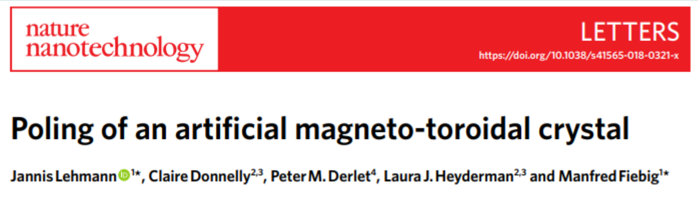
Shinjo et al., Science (2000)

MAGNETIC FORCE MICROSCOPY

Take Home Messages of MFM

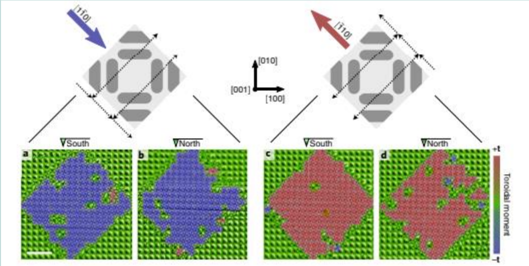
- High spatial resolution imaging of magnetic surface charges

- Tip can interact with sample surface – change state, control sample!


nature nanotechnology
LETTERS
https://doi.org/10.1038/s41565-018-0321-x

Poling of an artificial magneto-toroidal crystal

Jannis Lehmann[1*], Claire Donnelly[2,3], Peter M. Derlet[4], Laura J. Heyderman[2,3] and Manfred Fiebig[1*]

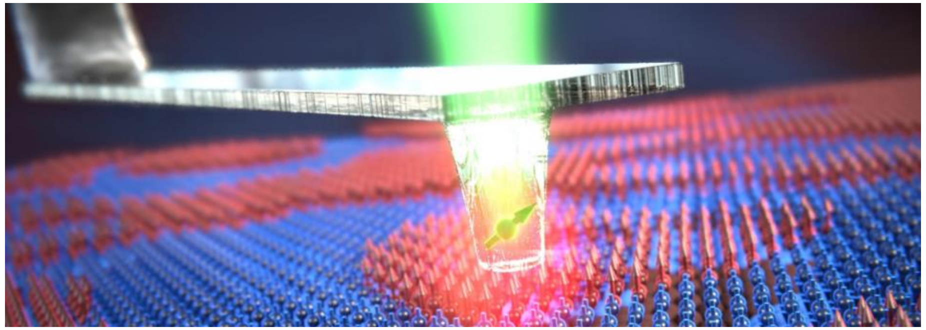


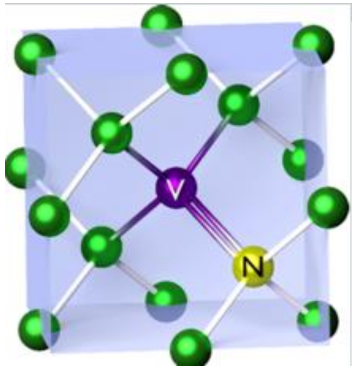
– Limited to ~flat samples – could need higher sensitivity –

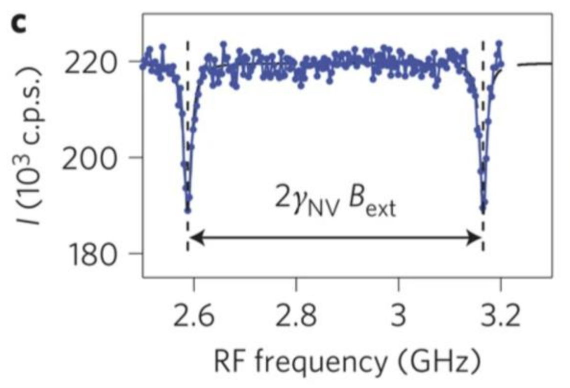
	MFM
Contrast	$\boldsymbol{H}$, surface charges
Spatial resolution	10s of nm
Depth sensitivity	Surface sensitive
Sample environment	Field, cryo, electrical contacts
Invasive	Yes
Sensitivity	Medium
Cost/ accessibility	Lab-based, accessible

SCANNING PROBES OF B:

NITROGEN VACANCY MICROSCOPY







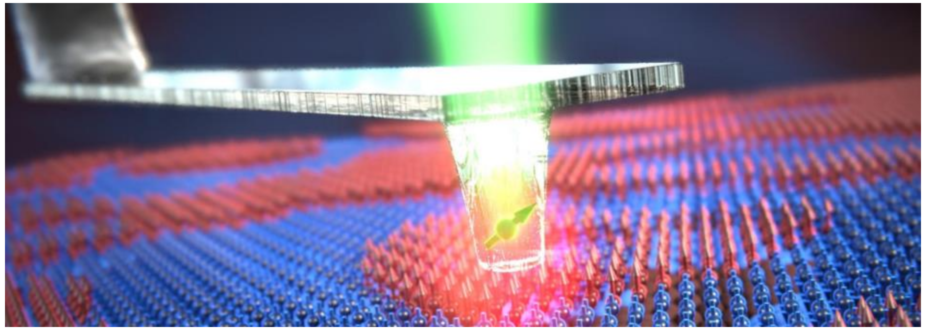
Maletinsky et al., Nat. Nano., 7, 320 (2012)

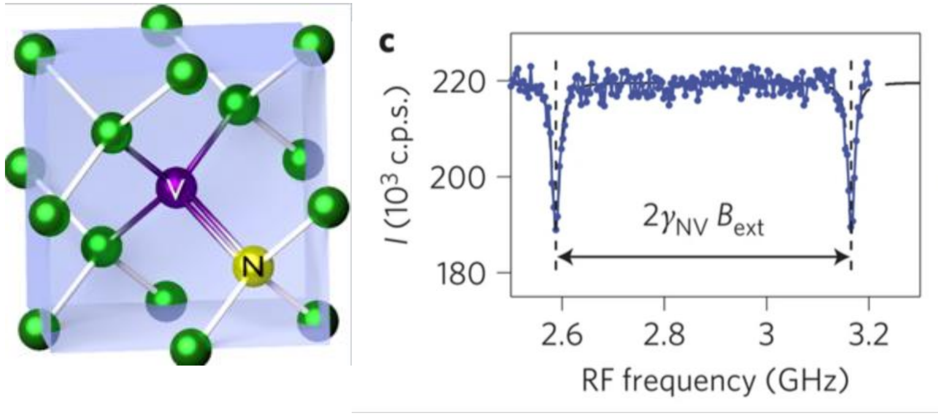
- Diamond tip, with a defect in the lattice:
- Defect behaves as an artificial atom
- Spin triplet ground state
  - Magnetic sensitivity & long spin coherence
- Optical readout

- Zeeman splitting = sensitivity to magnetic field
- Very sensitive: can detect a single electron spin ~nms from NV centre!
- Non-invasive

SCANNING PROBES OF B:

NITROGEN VACANCY MICROSCOPY

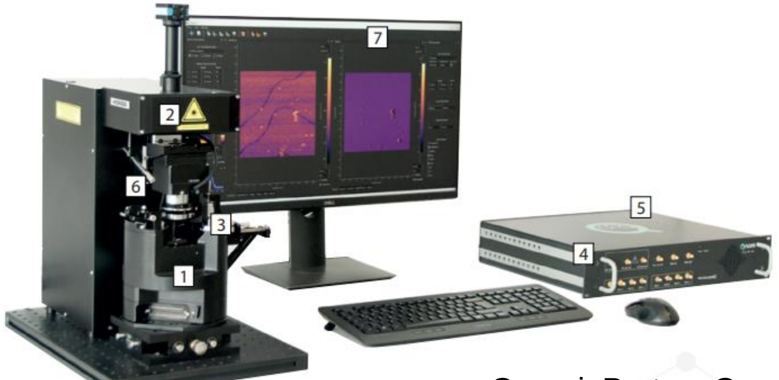




Maletinsky et al., Nat. Nano., 7, 320 (2012)

And now:

Commercial setups available:

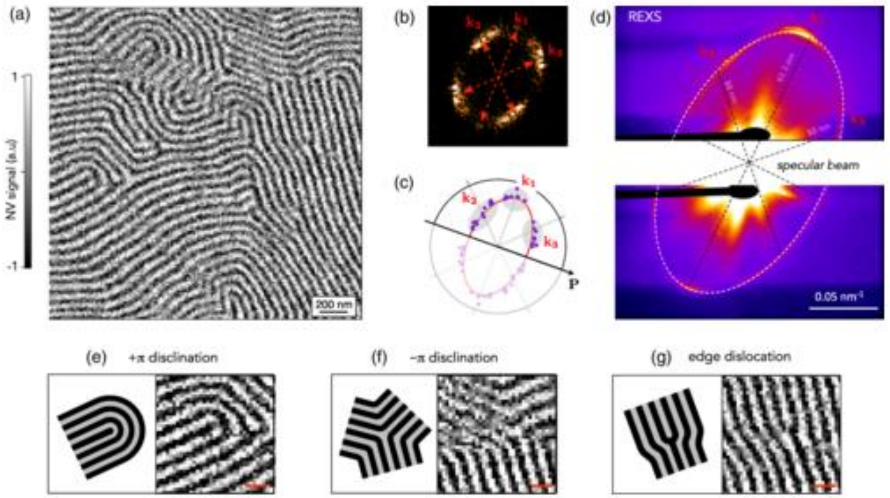


Qnami, ProteusQ

Qzabre, QSM

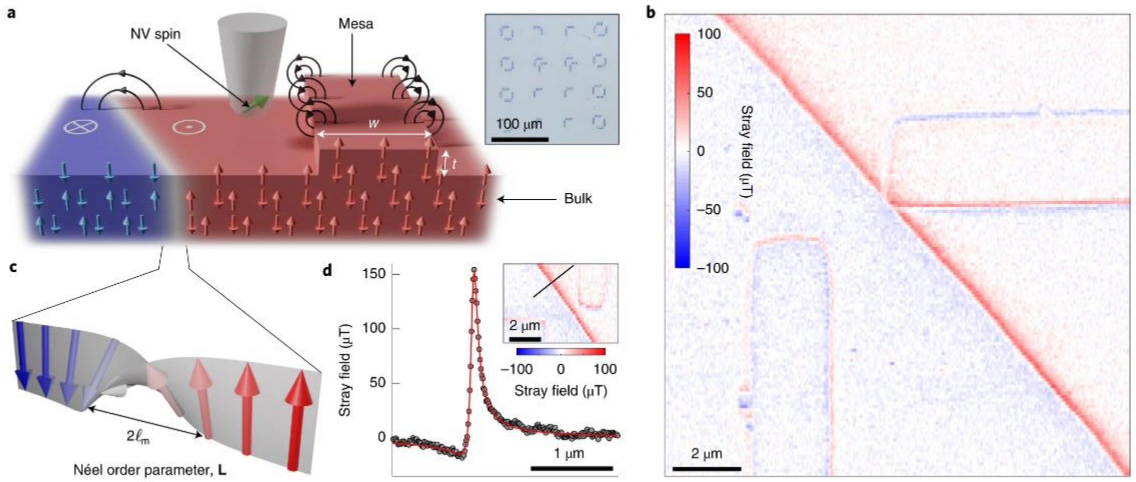
NITROGEN VACANCY MICROSCOPY

Ferromagnetic domain imaging:



Finco et al., PRL (2022)

Anti-ferromagnetic domains & domain walls:



Hedrich et al., Nature Physics (2021)

Spatial resolution: determined by tip (distance to NV centre). Roughly 50 nm (down to ~10 nm)

High sensitivity

NITROGEN VACANCY MICROSCOPY

Take Home Messages of NV Magnetometry

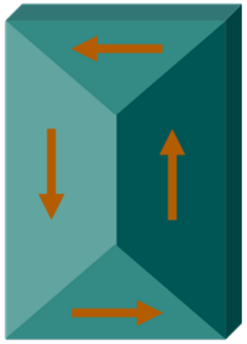
- High spatial resolution imaging of magnetic surface charges

- Highly sensitive – can even measure antiferromagnetic domain walls!

– Limited to ~flat samples – new technique, continuous development –

	NV Microscopy
Contrast	$\boldsymbol{H}$, surface charges
Spatial resolution	10s of nm
Depth sensitivity	Surface sensitive
Sample environment	Field, ~cryo, electrical contacts (in dev.)
Invasive	No
Sensitivity	High!!
Cost/ accessibility	Lab-based, recent commercial examples

B probes



M probes

$$B = \mu_0(M + H)$$

Scanning probe

Electron microscopy

ELECTRON MICROSCOPY OF B:

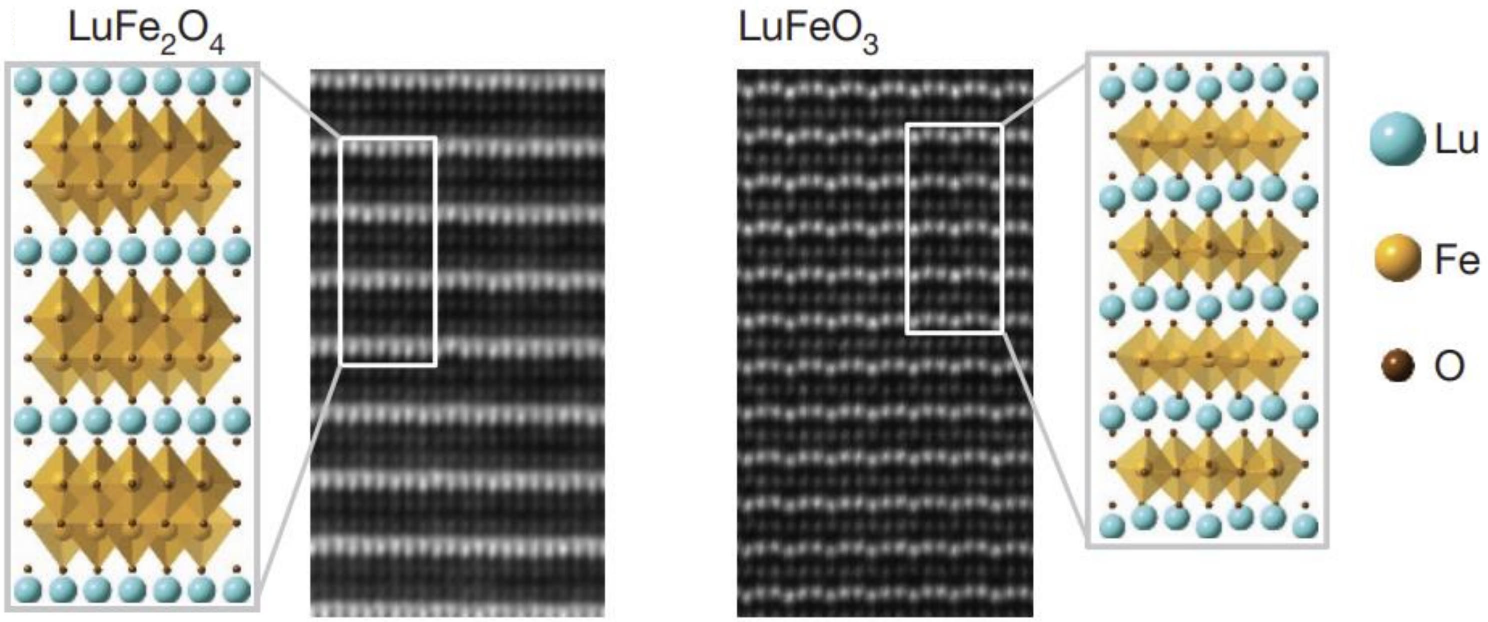
TRANSMISSION ELECTRON MICROSCOPY

JEOL ARM 200F

In dedicated labs

Highly intense source of electrons

Capable of (non-magnetic) resolution with sub-atomic resolution



Mundy et al., Nature 537, 523 (2016)

ELECTRON MICROSCOPY OF B:

TRANSMISSION ELECTRON MICROSCOPY

JEOL ARM 200F

In dedicated labs, millions of euros

Highly intense source of electrons

Capable of (non-magnetic) resolution with sub-atomic resolution

Lorentz

Electron holography

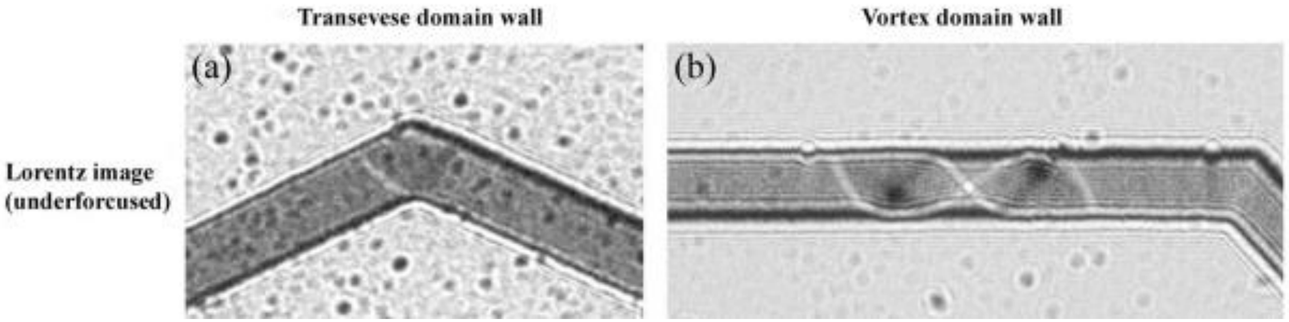
MAGNETIC TEM: LORENTZ MICROSCOPY

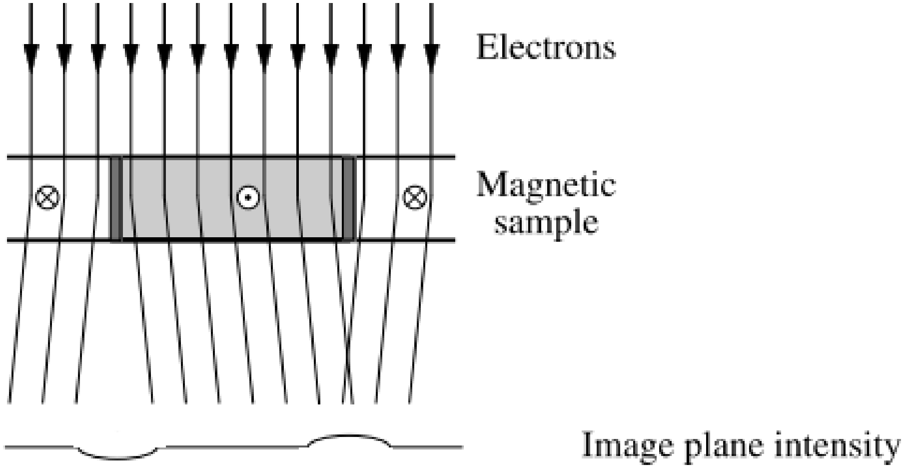
Lorentz microscopy:

Transmission electron microscopy:

Electrons deflected by Lorentz force:

$$\boldsymbol{F}_{Lorentz} = q(\boldsymbol{v} \times \boldsymbol{B})$$





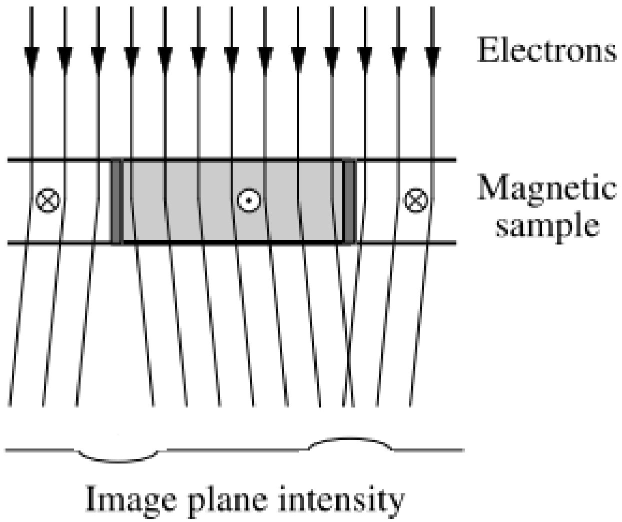
Togawa et al., Proc. SPIE 7036, Spintronics, 703617 (2008)

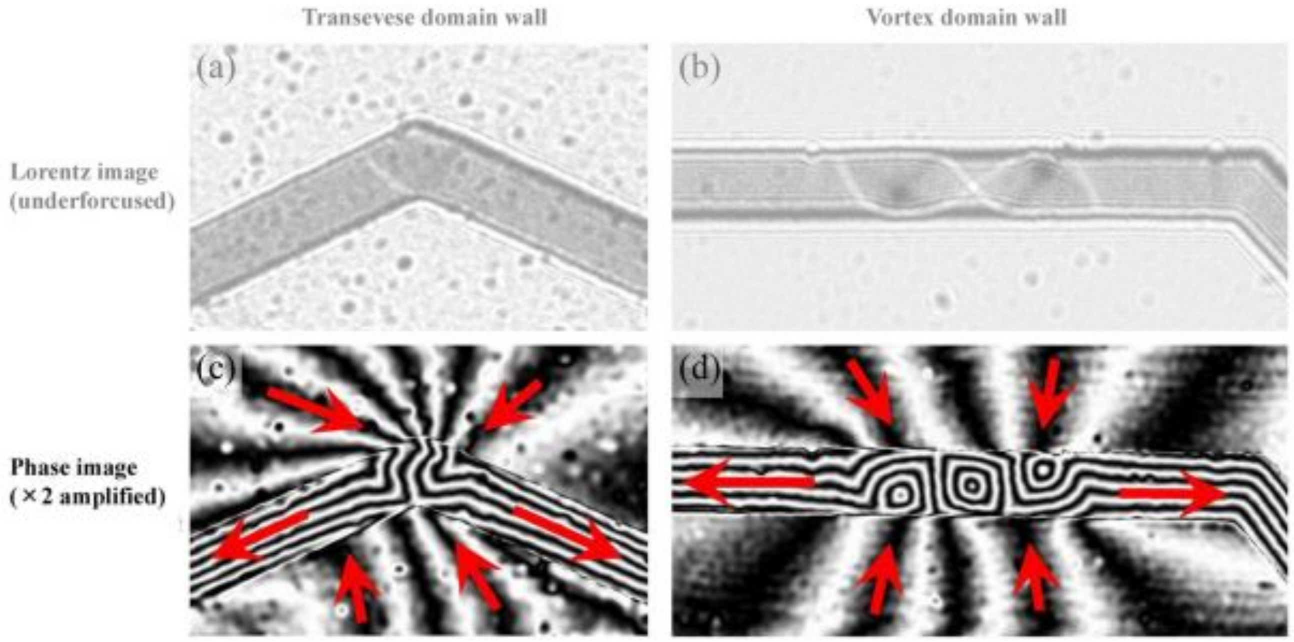
MAGNETIC TEM: ELECTRON HOLOGRAPHY

Electron holography:

Aharonov-

Electrically electroma change in particle.





Togawa et al., Proc. SPIE 7036, Spintronics, 703617 (2008)

→ If you can reconstruct the phase of an electron, you can directly reconstruct the magnetic vector potential

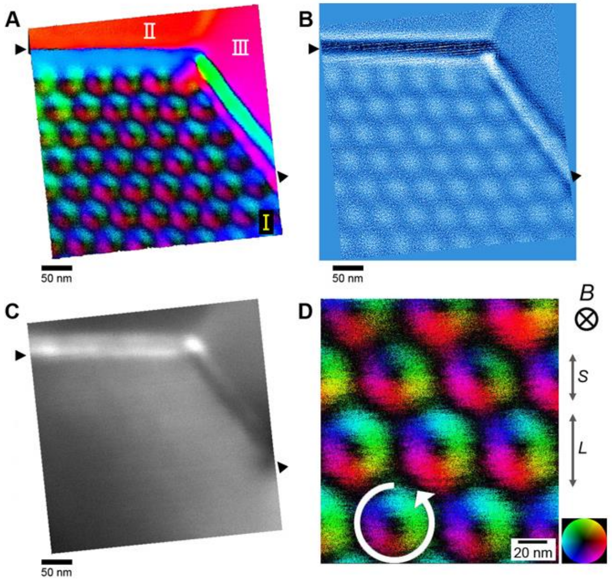
→ In-plane components of magnetic field B

Spatial resolution: single digit nm

Wavelength of an electron ~ pm. Not the limiting factor!

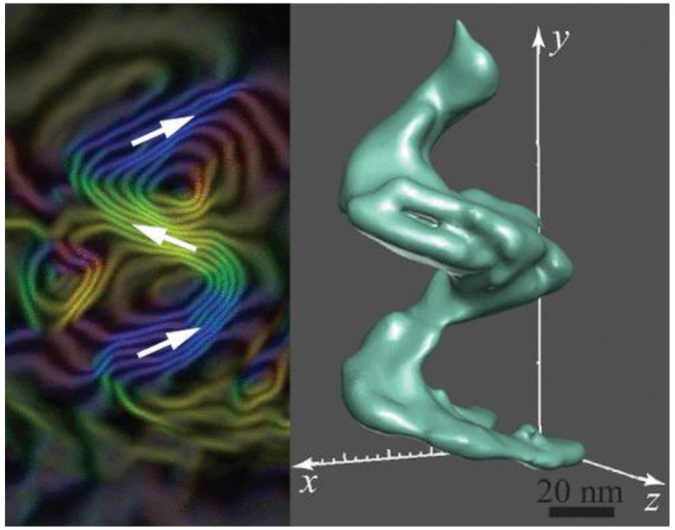
MAGNETIC TEM: ELECTRON HOLOGRAPHY

Magnetic skyrmions



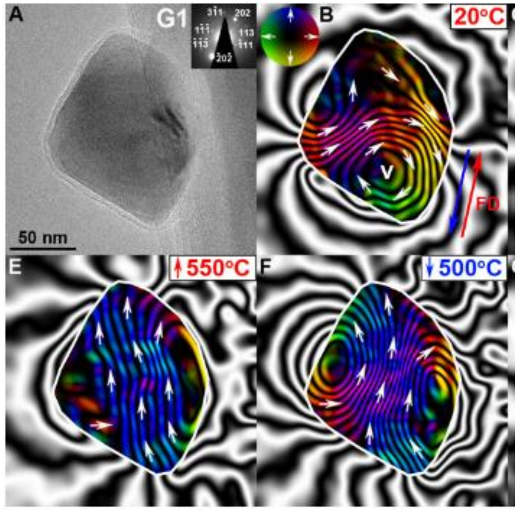
Matsumoto et al., Science Advances (2016)

Cobalt nanospirals



Phatak et al., Nano Letters (2014)

Magnetic nanoparticles



Almeida et al., Science Advances (2016)

TRANSMISSION ELECTRON MICROSCOPY

Take Home Messages of Transmission Electron Microscopy

- ***Very** high spatial resolution imaging of magnetic induction*

(single digit nm)

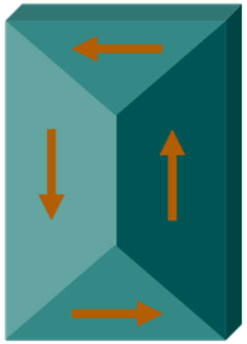
- Probe of induction perpendicular to direction of propagation of electrons

- Can also provide high resolution imaging of atomic lattice

– Limited to 100nm thick samples – Application of in situ fields difficult –

	TEM
Contrast	$\boldsymbol{B} \perp \boldsymbol{k}$
Spatial resolution	Single digt nm (or below!)
Depth sensitivity	Thin samples ~<100 nm
Sample environment	~cryo, electrical contacts (in dev.). Fields challenging
Invasive	No
Sensitivity	Medium
Cost/ accessibility	Lab based, specialised equipment (10^6 €)

B probes



M probes

$$B = \mu_0(M + H)$$

Optical techniques

X-ray microscopy

IN THE LAB: MAGNETO-OPTICS

Durham Magneto Optics

Evico Magnetics

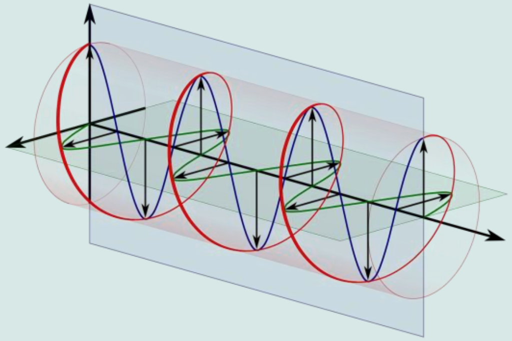
Table-top setup

Laser as source of photons

Relatively low cost, accessible

OBSERVING DOMAINS: MAGNETO-OPTICS

Circular polarised light:

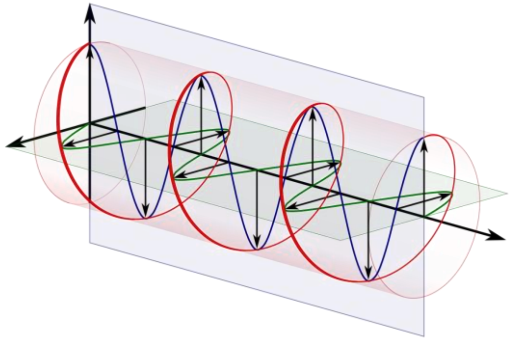


Coupling of the
photon's angular momentum
to
angular momentum of an electron

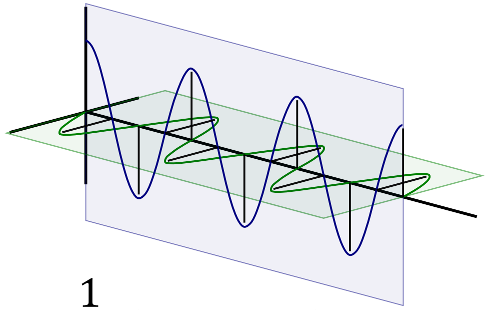
Angular momentum = $\pm\hbar$

Dichroism: *Refractive index dependent on:*
Circular polarisation and *Direction of magnetisation*

Circular polarised light:

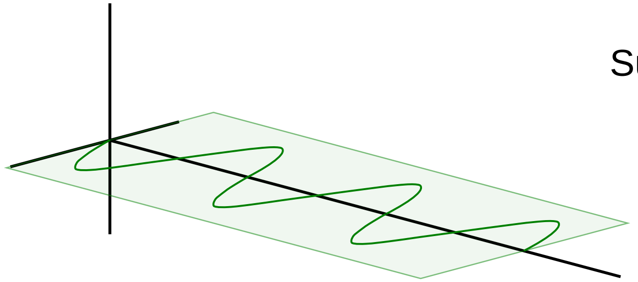


Superposition of linear H and V



$$|\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm i|V\rangle)$$

Linear polarised light:



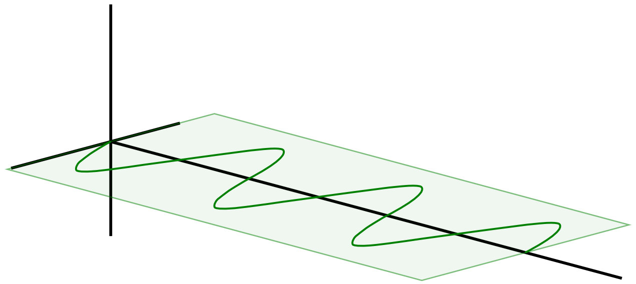
Superposition of circular C+ and C-

$$|H\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)$$

OBSERVING DOMAINS: MAGNETO-OPTICS

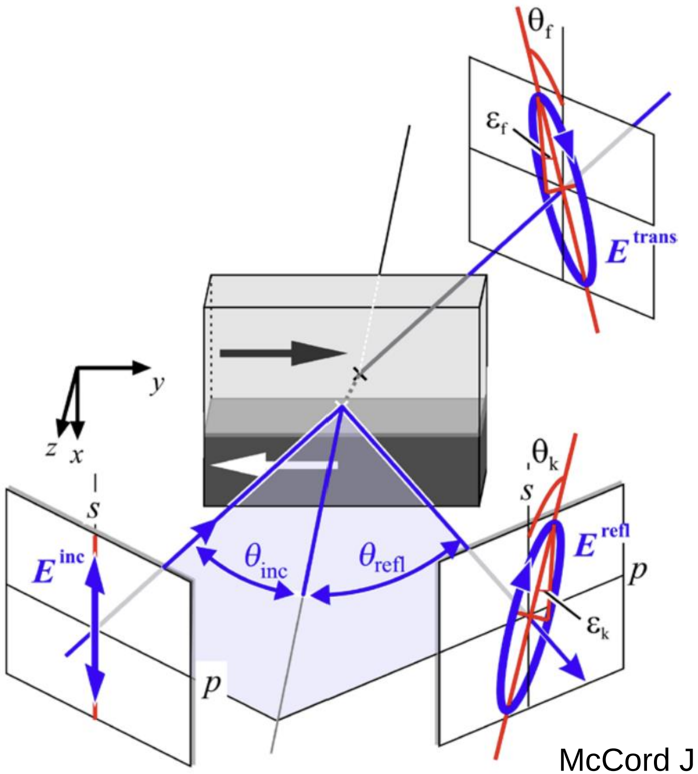
***In transmission*: Faraday effect**

Linear polarised light incident on magnetic material:



→ *Rotation* of the linear polarisation
→ Ellipticity of the light

Measure this rotation → probe the magnetisation // k



McCord J. Phys. D: Appl. Phys. 48 (2015) 333001

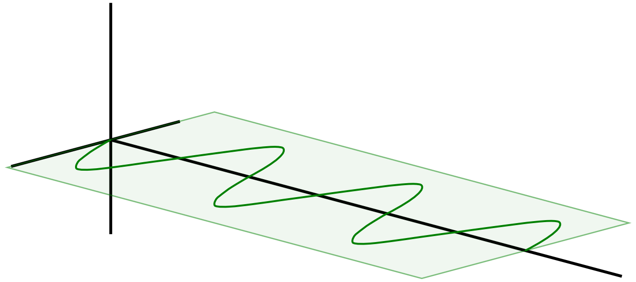
***In reflection:* Kerr effect**

Spatial resolution:

limited by wavelength of light
~hundreds of nanometres

OBSERVING DOMAINS: MAGNETO-OPTICS

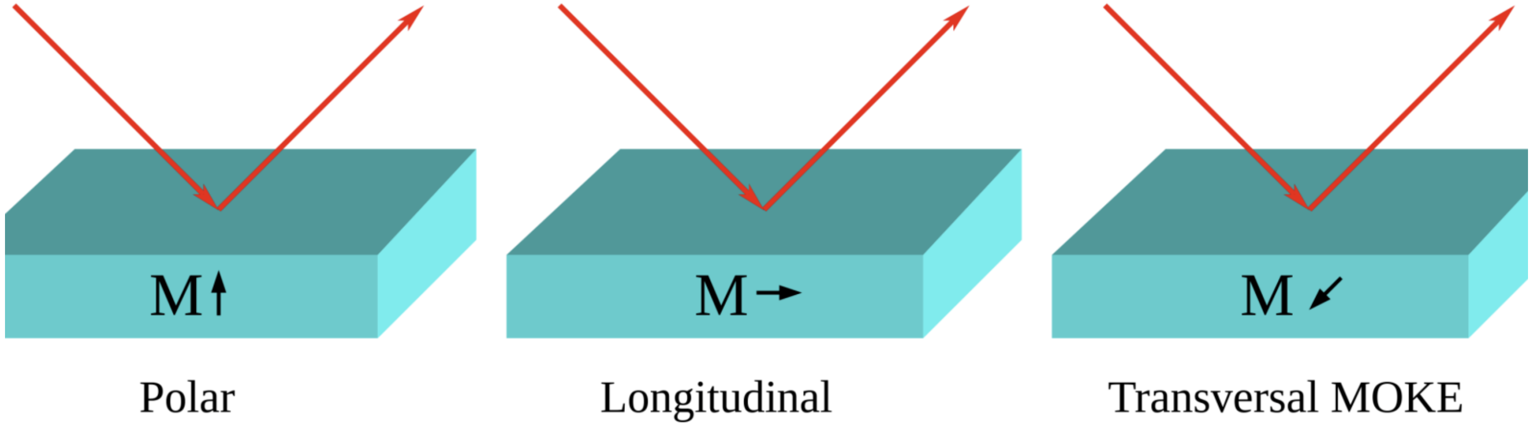
Linear polarised light incident on magnetic material:



→ *Rotation* of the linear polarisation
→ Ellipticity of the light

Measure this rotation → probe the magnetisation // k

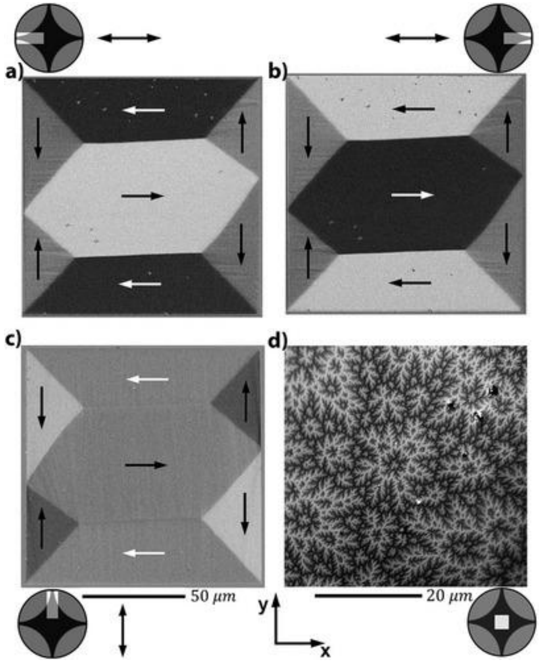
Vector information:



MOKE MICROSCOPY

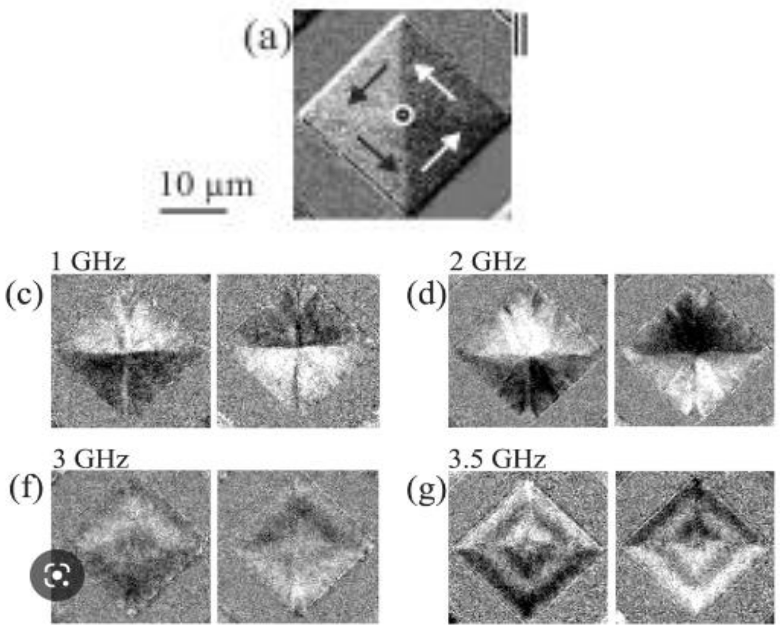
MOKE signal depends on **k**

In-plane and out of plane domains



Soldatov & Schaefer, Review of Scientific Instruments 88, 073701 (2017)

Dynamic imaging of microstructures



Urs et al., AIP Advances (2016)

* Penetration depth of MOKE is approximately 10-20 nm for metals
→ Surface sensitive

MAGNETO-OPTICAL MICROSCOPY

Take Home Messages of Magneto-Optical Microscopy

- ~100s nm – um spatial resolution imaging of surface magnetisation

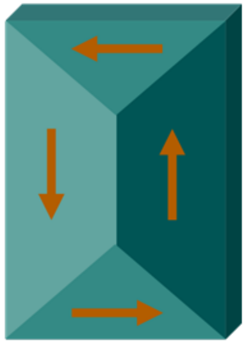
- Can distinguish orientations of the magnetisation!

- Can be combined with time-resolved imaging to probe dynamics, can combine with different sample environments

– Limited to ~flat samples – can't resolve nm textures –

	Magneto optics
Contrast	$\boldsymbol{m}$
Spatial resolution	100s nm – µms
Depth sensitivity	Surface sensitive
Sample environment	Field, ~cryo, electrical contacts (in dev.), TR
Invasive	No
Sensitivity	High
Cost/ accessibility	Lab based, accessible

B probes



***M* probes**

$$B = \mu_0(M + H)$$

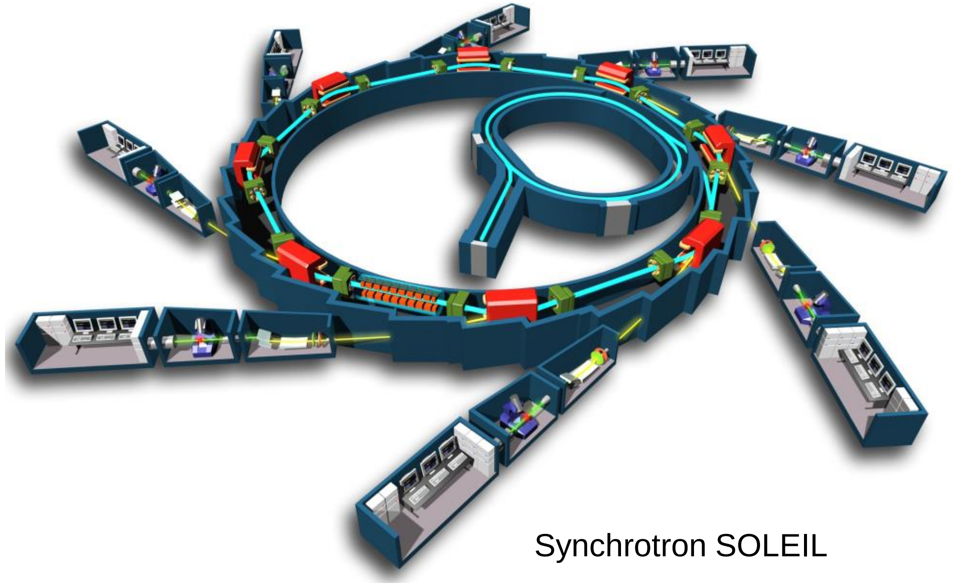
Optical techniques

X-ray microscopy

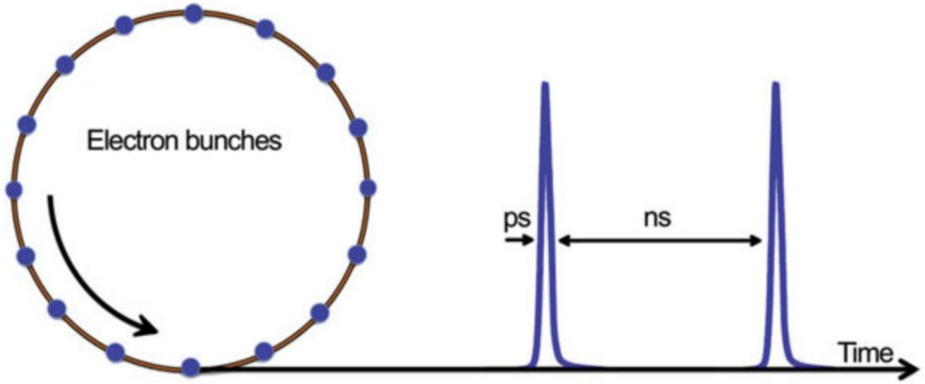
LARGE SCALE FACILITIES: SYNCHROTRON X-RAYS

Synchrotron light sources:

Swiss Light Source, PSI



Synchrotron SOLEIL



Balerna, Mobilio Intro. Synch. Rad

MAGNETIC MICROSCOPY @ SYNCHROTRONS

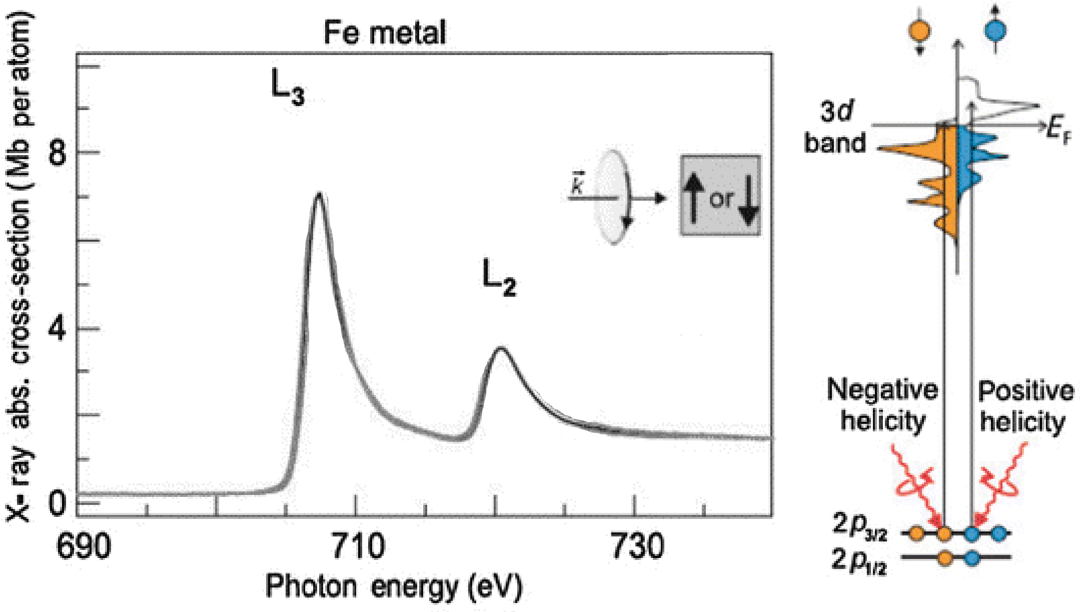
Synchrotron X-ray microscopy

e.g. Swiss Light Source

MAGNETIC MICROSCOPY: X-RAYS

X-rays: X-ray magnetic circular dichroism
Circular polarised light: angular momentum ±ħ

This time, resonant!



Stöhr & Siegmann, Magnetism, From fundamentals to Nanoscale Dynamics, Springer (2006)

"Electronic" "Magnetic"

$$f = f_c\left(\boldsymbol{\epsilon}_f^* \cdot \boldsymbol{\epsilon}_i\right)$$

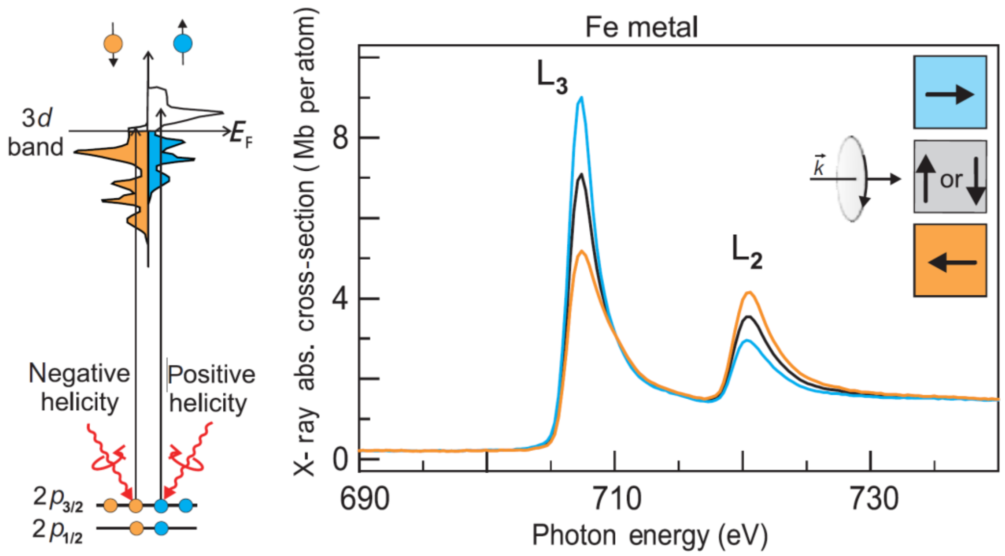
On resonance:
scattering factor dependent on polarisation and $\mathbf{m}$!

MAGNETIC MICROSCOPY: X-RAYS

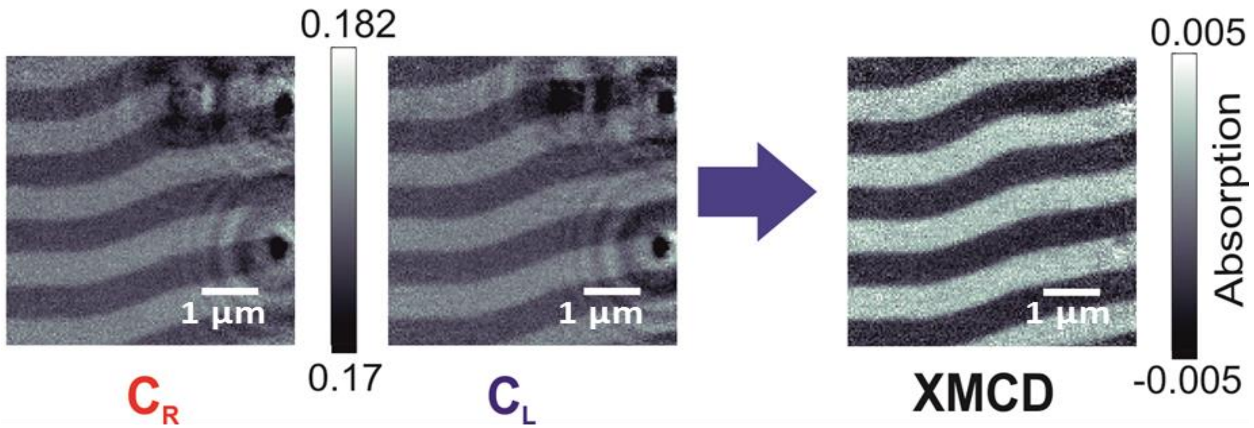
X-rays: X-ray magnetic circular dichroism
Circular polarised light: angular momentum ±ħ

This time, resonant!

- Element specific
- Can penetrate thicker samples



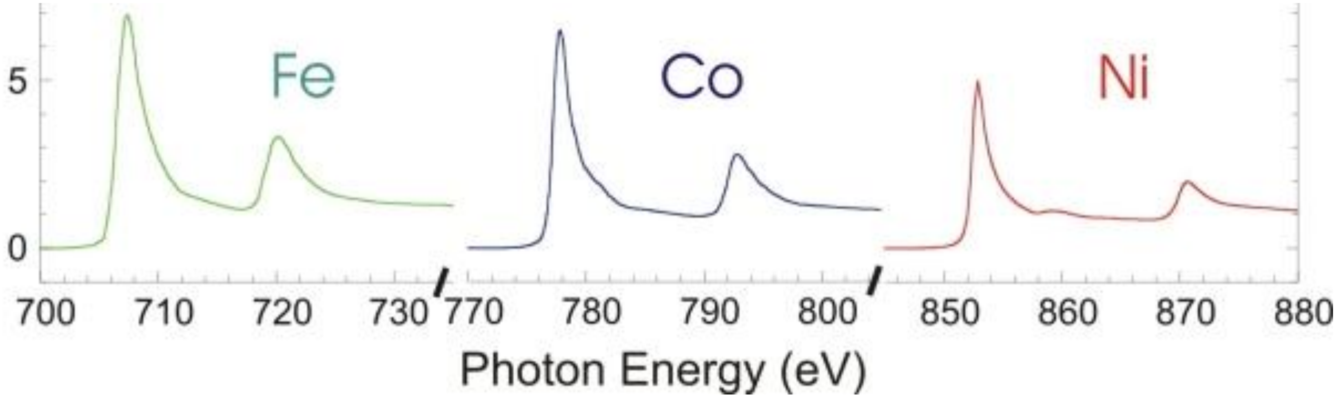
Stöhr & Siegmann, Magnetism, From fundamentals to Nanoscale Dynamics, Springer (2006)



Donnelly et al., PRB **94**, 064421 (2016)

X-RAY MAGNETIC CIRCULAR DICHROISM: ELEMENT SPECIFICITY

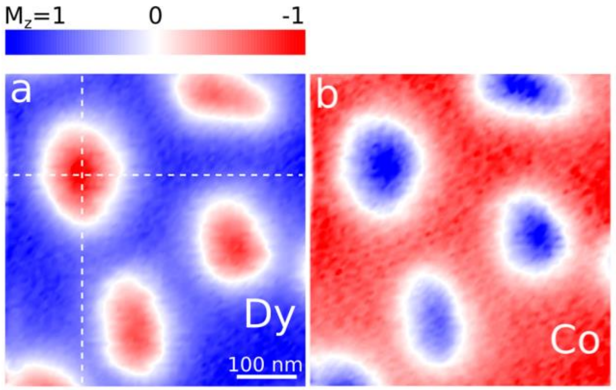
Key Advantage of X-rays: Element specificity



https://www-ssrl.slac.stanford.edu/stohr/xmcd.htm

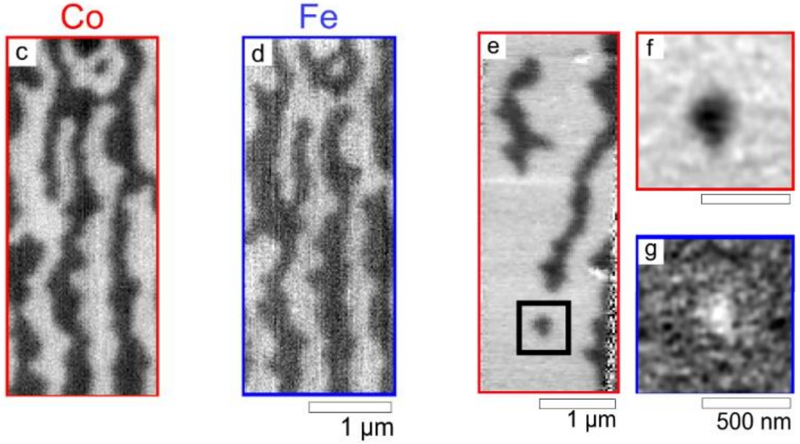
→ Different elements can be targeted separately

For ferrimagnets:
Ferrimagnetic skyrmions in DyCo_3 film



Luo et al., Comm. Phys. **6**, 218 (2023)

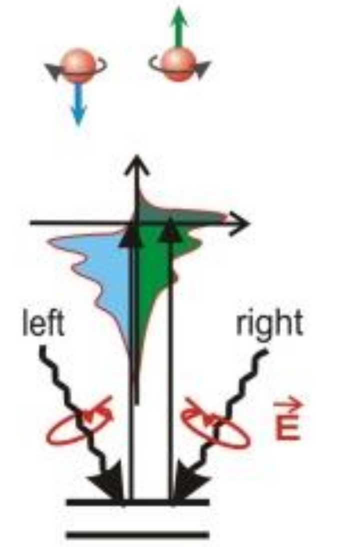
And synthetic antiferromagnets:
Synthetic antiferromagnetic skyrmion:

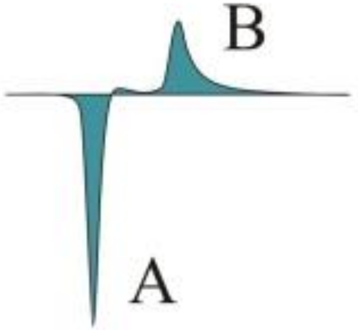


Juge et al., Nat. Comm. **13**, 4807 (2022)

X-RAY MAGNETIC CIRCULAR DICHROISM: SPIN & ORBITAL

As well as measuring something proportional to m, it provides a quantitative measure of the magnetic moment!





L3 edge $p_{3/2}$: $l + s$

→ ***+ve Photon angular momentum***

→ ***spin "up"***

→ ***orbital "up"***

L2 edge $p_{1/2}$: $l - s$

→ ***+ve Photon angular momentum***

→ ***spin "down"***

→ ***orbital "up"***

By combining L_2 and L_3, can isolate spin and orbital moments

VOLUME 68, NUMBER 12 PHYSICAL REVIEW LETTERS 23 MARCH 1992

X-Ray Circular Dichroism as a Probe of Orbital Magnetization

B. T. Thole,[1] Paolo Carra,[2] F. Sette,[2] and G. van der Laan[3]

[1] *Department of Chemical Physics, Materials Science Centre, University of Groningen, Nijenborgh 16, 9747 AG Groningen, The Netherlands*

[2] *European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble CEDEX, France*

[3] *Daresbury Laboratory, Science and Engineering Research Council, Warrington, WA4 4AD, United Kingdom*

(Received 2 December 1991)

Relevant for new opportunities in orbitronics

Perspective

Orbitronics: Orbital currents in solids

DONGWOOK GO[1,2(a)], DAEGEUN JO[3], HYUN-WOO LEE[3], MATHIAS KLÄUI[2,4,5] and YURIY MOKROUSOV[1,2]

NEWS AND VIEWS | 05 July 2023

First light on orbitronics as a viable alternative to electronics

An effect that transfers information using the rotational motion of electrons has been detected with light, forging a path towards technologies that are cheaper – and less harmful to the environment – than existing electronics.

Tatiana G. Rappoport

X-RAY MAGNETIC CIRCULAR DICHROISM:

CONTRAST ✓

Magnetisation	*Element specificity*	*Spin & Orbital moments*

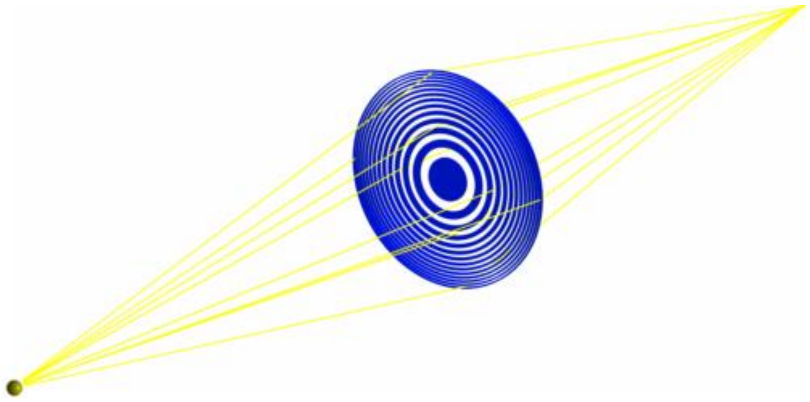
And the microscopy?

MAGNETIC MICROSCOPY: X-RAYS

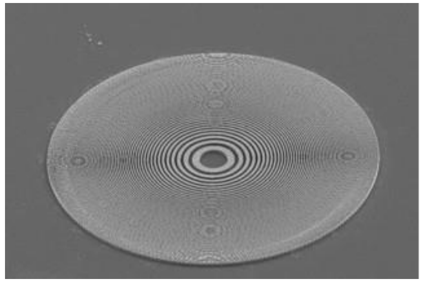
Advantage of X-rays: highly penetrating, so can look through "thick" samples

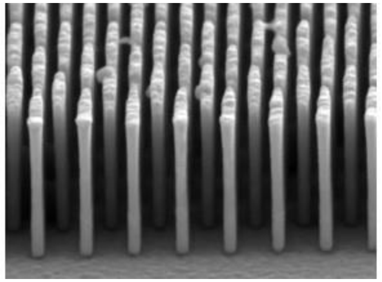
Also disadvantage: small refractive index means hard to create optics!

Fresnel Zone Plate:

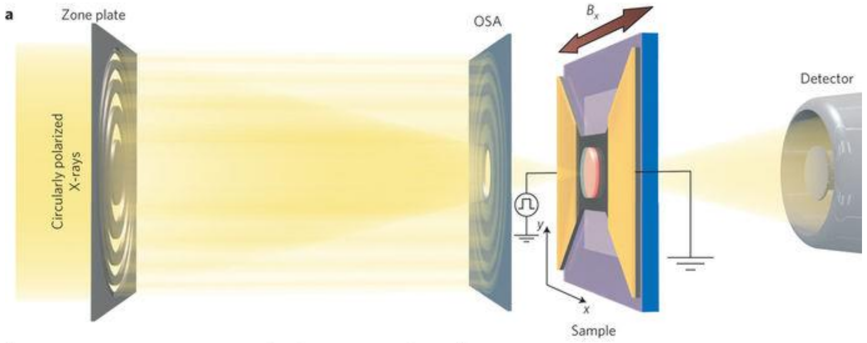


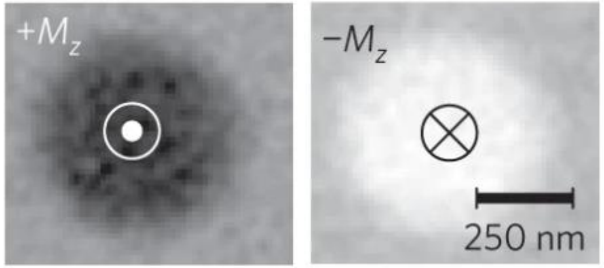
Nanofabrication determines spatial resolution





STXM
(Scanning Transmission X-ray Microscopy)

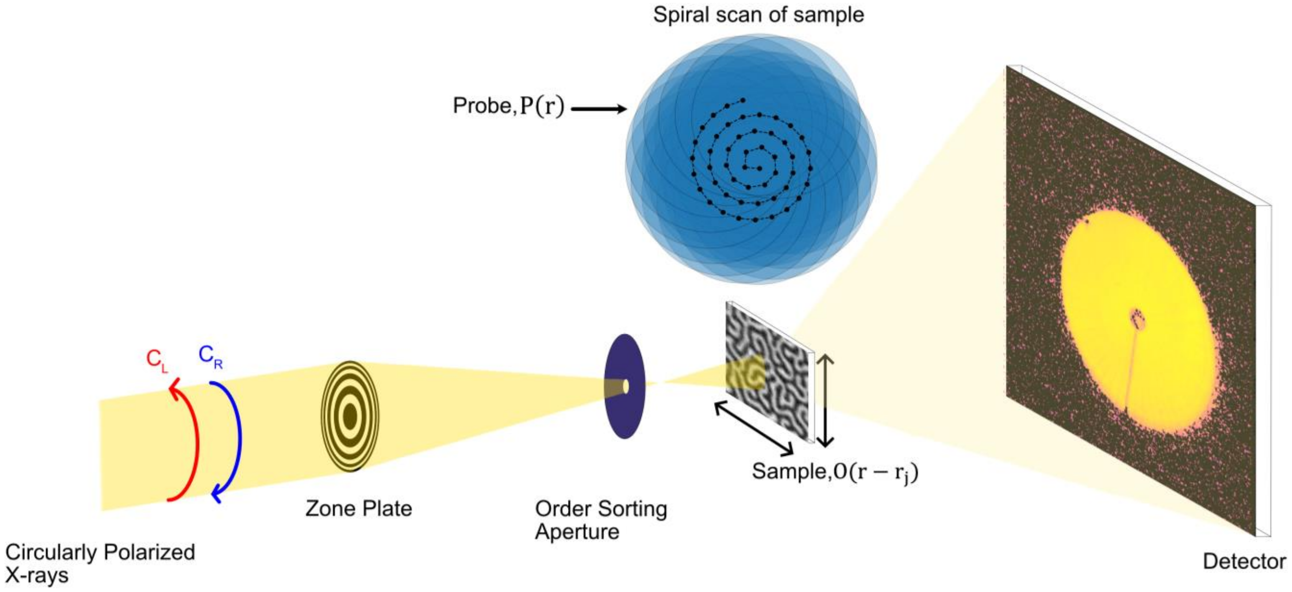




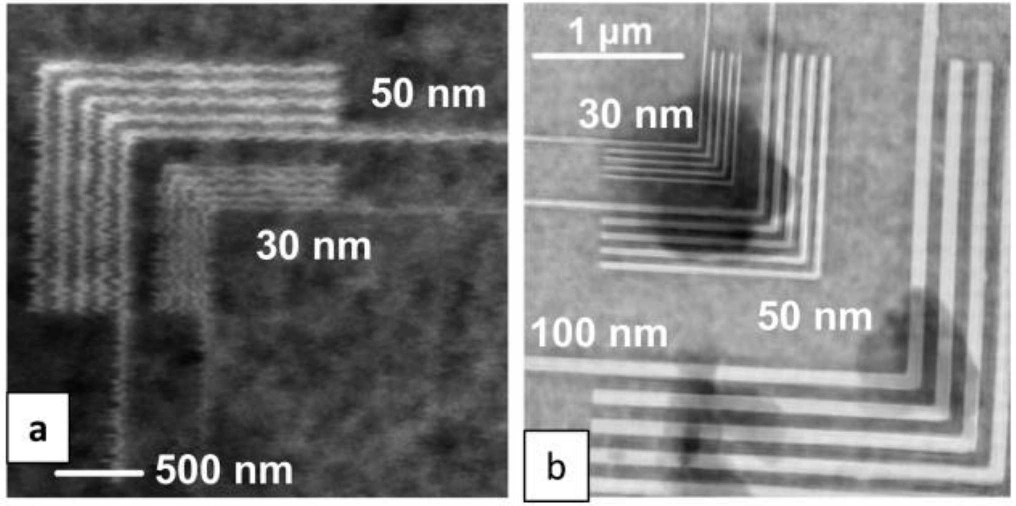
Baumgartner et al., Nat. Nano. **12**, 980 (2017)

HIGH SPATIAL RESOLUTION: COHERENT DIFFRACTIVE IMAGING → *PTYCHOGRAPHY*

Take a large coherent beam, and measure coherent diffraction patterns for overlapping illuminations



STXM | Ptychography



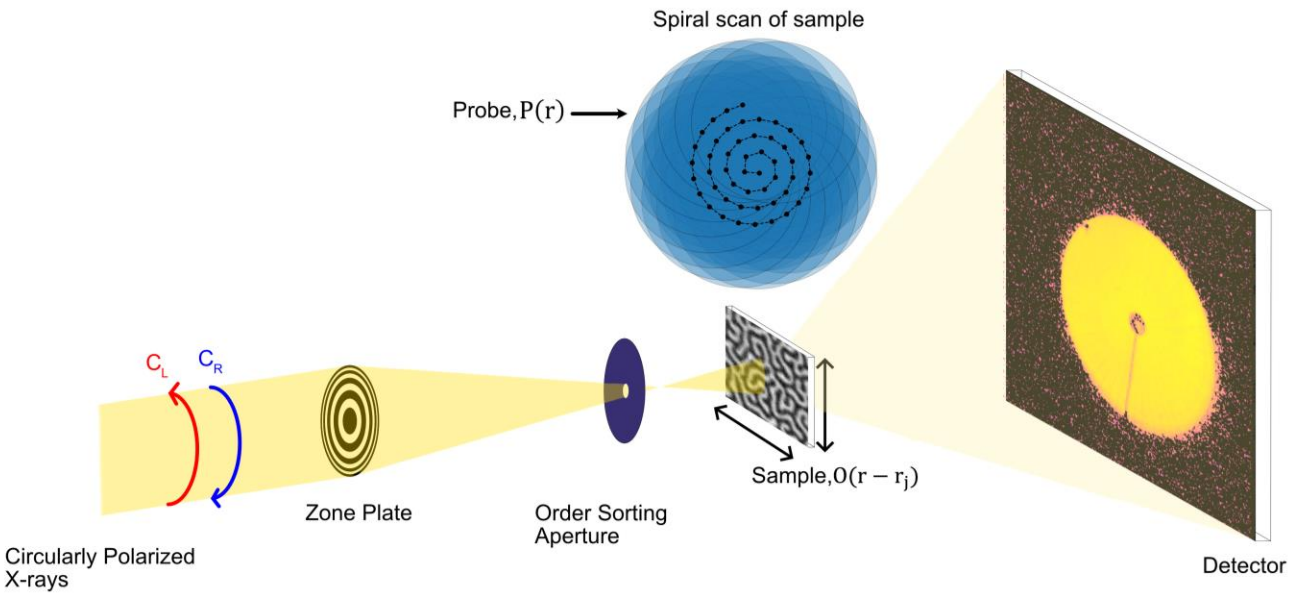
→ Significant increase in spatial resolution, sensitivity

→ Reconstruct complex transmission function

Urqyuhart, ACS Omega 7, 11521 (2022)

DICHROIC X-RAY MAGNETIC PTYCHOGRAPHY

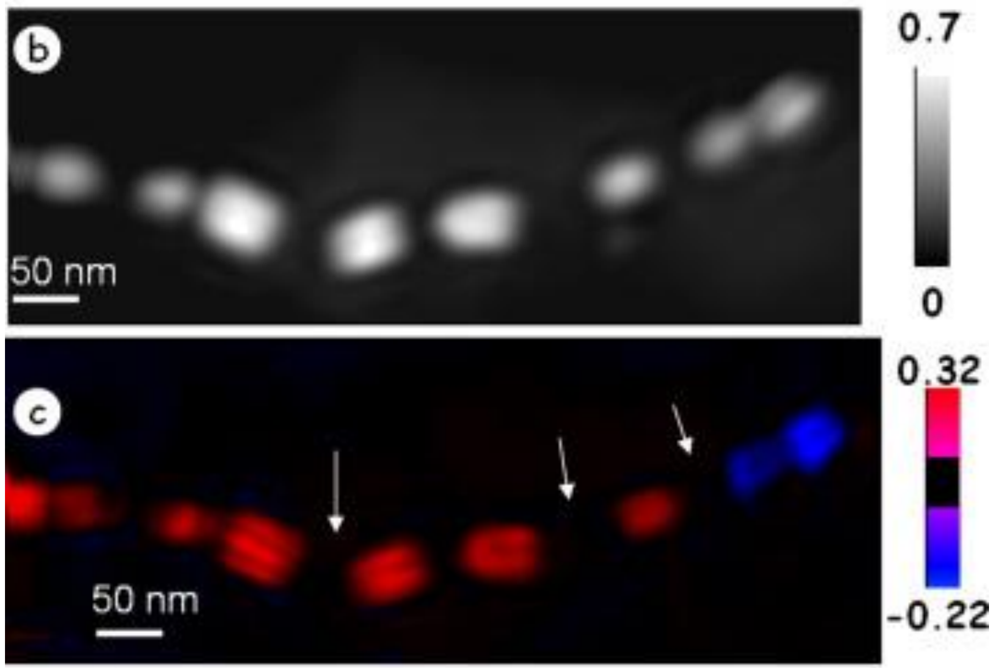
Take a large coherent beam, and measure coherent diffraction patterns for overlapping illuminations



→ Reconstruct complex transmission function

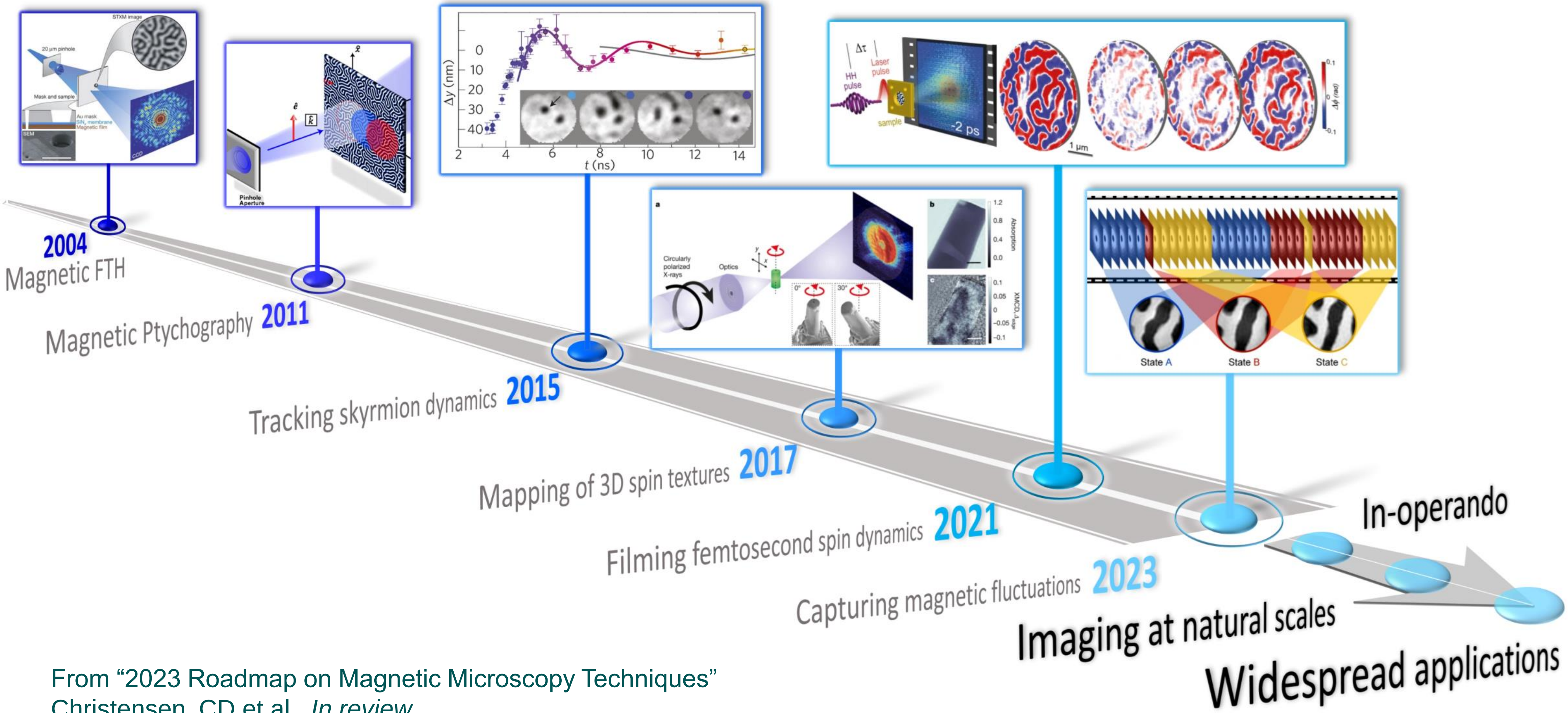
Apply to magnetic imaging:

7 nm spatial resolution imaging of magnetotactic bacteria:



Hitchcock, Journal of Electron Spectroscopy and Related Phenomena 200, 49 (2015)

COHERENT IMAGING: EXCITING THINGS TO COME!



From “2023 Roadmap on Magnetic Microscopy Techniques”
Christensen, CD et al., *In review*

X-RAY MAGNETIC MICROSCOPY: XMCD

Take Home Messages of Synchrotron X-ray microscopy: XMCD

- *High spatial resolution imaging of magnetisation*
- *Element-specific – can target different elements in a sample*
- *Can penetrate through thick samples, up to micrometres*
- *Can combine with time-resolution to probe picosecond dynamics*

– Requires submission of beamtime proposal for user beamtime –

	X-ray magnetic circular dichroism
Contrast	$\boldsymbol{m} \parallel \boldsymbol{k}$
Spatial resolution	10s nm (& below!)
Depth sensitivity	nm - µms
Sample environment	Field, ~cryo, electrical contacts (in dev.), TR
Invasive	No
Sensitivity	High, element sensitive
Cost/ accessibility	Large scale user facility, **Open to all**

MAGNETIC MICROSCOPY: X-RAYS BEYOND M…

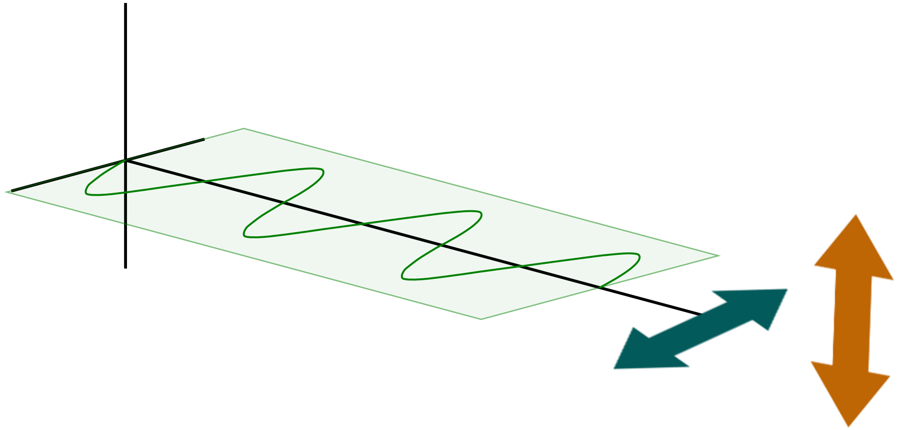
On resonance:
There exist higher order terms in the magnetic scattering factor:

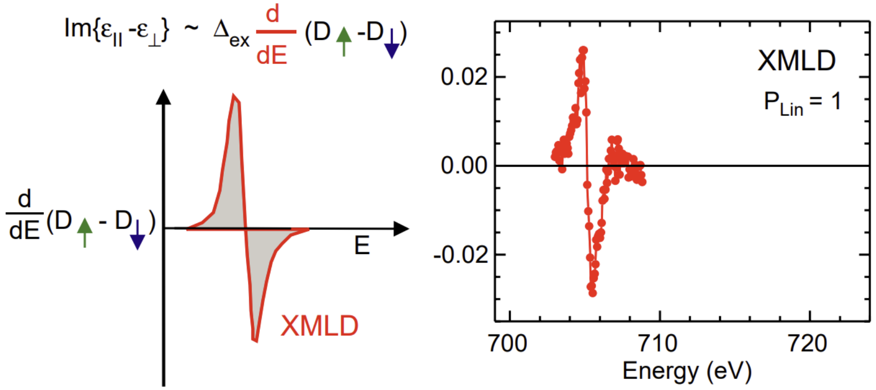
“Electronic” — **XMCD: *Circular dichroism***

$$f = f_c\left(\boldsymbol{\epsilon}_f^* \cdot \boldsymbol{\epsilon}_i\right) - i f_m^{(1)}\left(\boldsymbol{\epsilon}_f^* \times \boldsymbol{\epsilon}_i\right) \cdot \mathbf{m}(\mathbf{r})$$
$$+ f_m^{(2)}\left(\boldsymbol{\epsilon}_f^* \cdot \mathbf{m}(\mathbf{r})\right)\left(\boldsymbol{\epsilon}_i \cdot \mathbf{m}(\mathbf{r})\right)$$

XMLD: *Linear dichroism*

Linear polarised light:

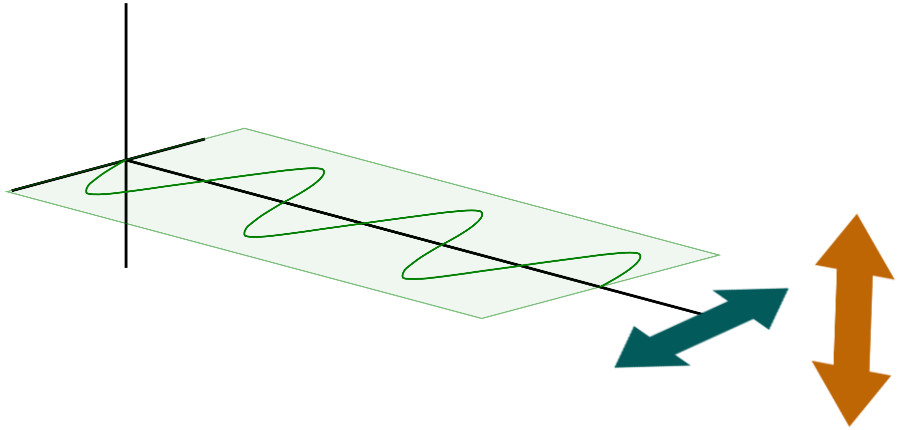




J. Kunes et al. JMMM 272, 2146 (2004)

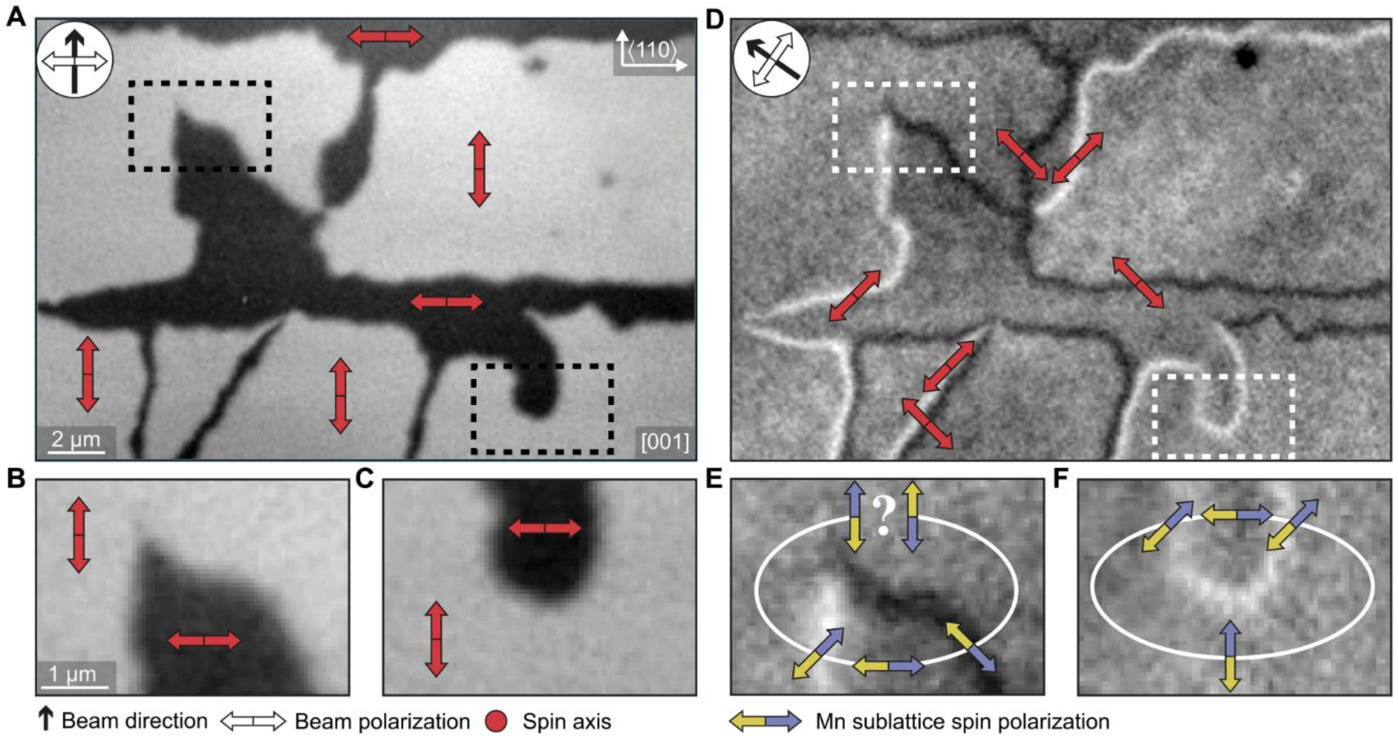
MAGNETIC MICROSCOPY: ANTIFERROMAGNETS

XMLD-PEEM



Can distinguish domains

By rotating the polarisation:
Can image domain walls



CuMnAs:

SPINTRONICS

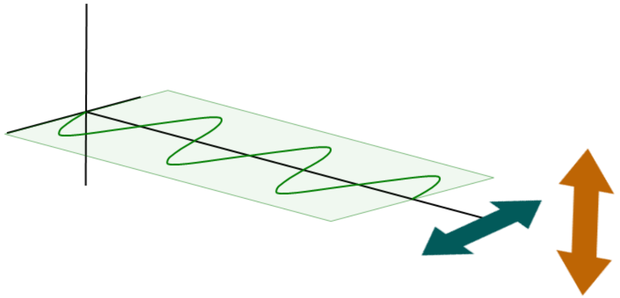
Electrical switching of an antiferromagnet

P. Wadley,[1*†] B. Howells,[1*] J. Železný,[2,3] C. Andrews,[1] V. Hills,[1] R. P. Campion,[1] V. Novák,[2] K. Olejník,[2] F. Maccherozzi,[4] S. S. Dhesi,[4] S. Y. Martin,[5] T. Wagner,[5,6] J. Wunderlich,[2,5] F. Freimuth,[7] Y. Mokrousov,[7] J. Kuneš,[8] J. S. Chauhan,[1] M. J. Grzybowski,[1,9] A. W. Rushforth,[1] K. W. Edmonds,[1] B. L. Gallagher,[1] T. Jungwirth[2,1]

Krizek et al., Science Advances, 8, 13 (2022)

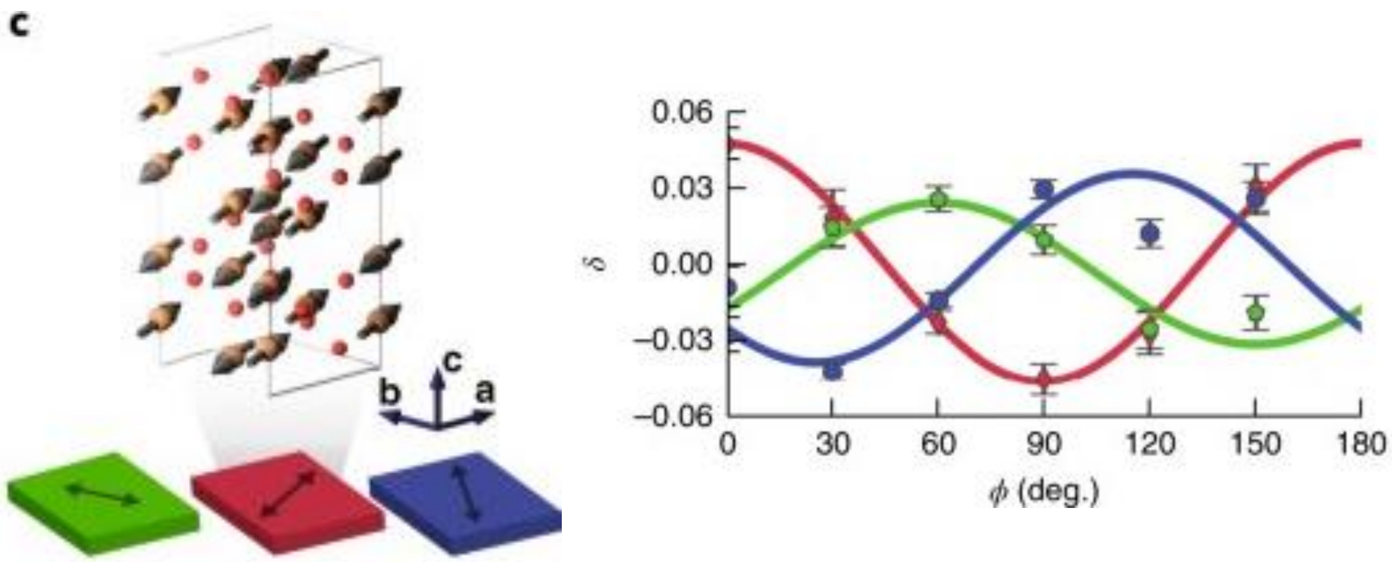
MAGNETIC MICROSCOPY: ANTIFERROMAGNETS

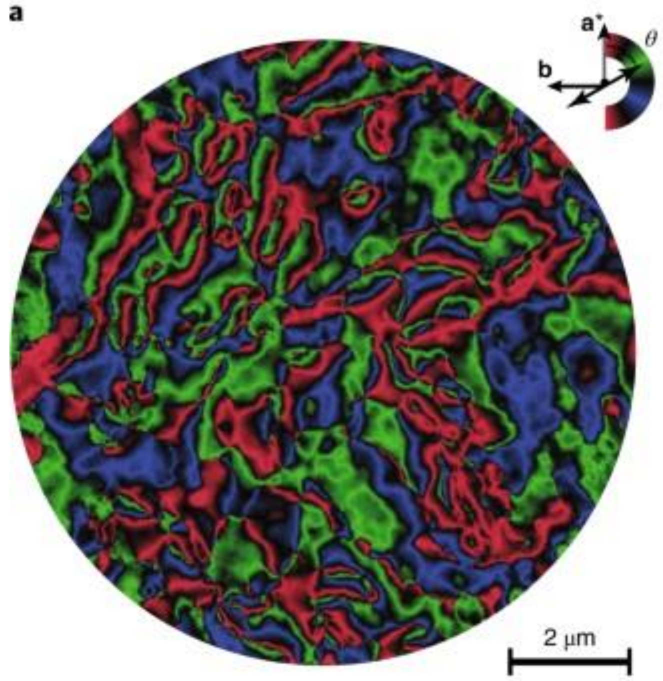
XMLD-PEEM



Combining with vector imaging:

→ Vector map of Neel vector
→ Identify topological defects in hematite





Chmiel et al., Nature Materials 17, 581 (2018)

X-RAY MAGNETIC MICROSCOPY: XMLD

Take Home Messages of Synchrotron X-ray microscopy: XMLD

- *High spatial resolution imaging of Néel vector*
- *Element-specific – can target different elements in a sample*
- *Can combine with time-resolution to probe picosecond dynamics*

– Requires submission of beamtime proposal for user beamtime –

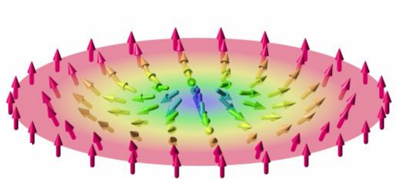
	X-ray Magnetic Linear Dichroism
Contrast	Néel vector $(\boldsymbol{m} \perp \boldsymbol{k})$
Spatial resolution	10s nm
Depth sensitivity	nm - µms
Sample environment	Field, ~cryo, electrical contacts (in dev.), TR
Invasive	No
Sensitivity	Medium, element sensitive, antiferromagnets!
Cost/ accessibility	Large scale user facility, **Open to all**

OVERVIEW OF (A SELECTION OF) AVAILABLE METHODS

	MFM	Nitrogen vacancy	TEM	MOKE	Spin pol. STM	XMCD (synchrotron)	XMLD (synchrotron)
Contrast	$\boldsymbol{H}$, surface charges	$\boldsymbol{H}$, surface charges	$\boldsymbol{B} \perp \boldsymbol{k}$	$\boldsymbol{m}$	$\boldsymbol{m}$	$\boldsymbol{m} \parallel \boldsymbol{k}$	Néel vector ($\boldsymbol{m} \perp \boldsymbol{k}$)
Spatial resolution	10s of nm	10s of nm	Single digt nm (or below!)	100s nm – µms	0.1 nm	10s nm (& below!)	10s nm
Depth sensitivity	Surface sensitive	Surface sensitive	Thin samples ~<100 nm	Surface sensitive	0.1 nm	nm - µms	nm - µms
Sample environment	Field, cryo, electrical contacts	Field, ~cryo, electrical contacts (in dev.)	~cryo, electrical contacts (in dev.). Fields challenging	Field, ~cryo, electrical contacts (in dev.), TR	Cryo, field	Field, ~cryo, electrical contacts (in dev.), TR	Field, ~cryo, electrical contacts (in dev.), TR
Invasive	Yes	No	No	No	No	No	No
Sensitivity	Medium	High!!	Medium	High	High	High, element sensitive	Medium, element sensitive, antiferromagnets!
Cost/ accessibility	Lab-based, accessible	Lab-based, recent commercial examples	Lab based, specialised equipment (10^6 €)	Lab based, accessible	Lab-based, Specialised UHV equipment	Large scale user facility, **Open to all**	Large scale user facility, **Open to all**

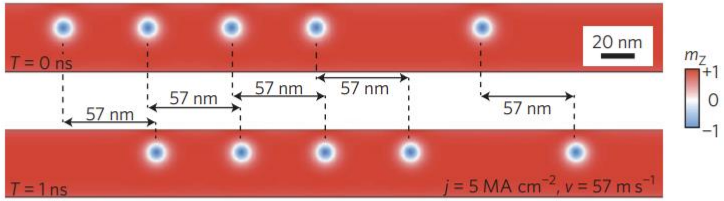
CHALLENGE: WHEN 2D IMAGING IS NOT ENOUGH…

Skyrmions:



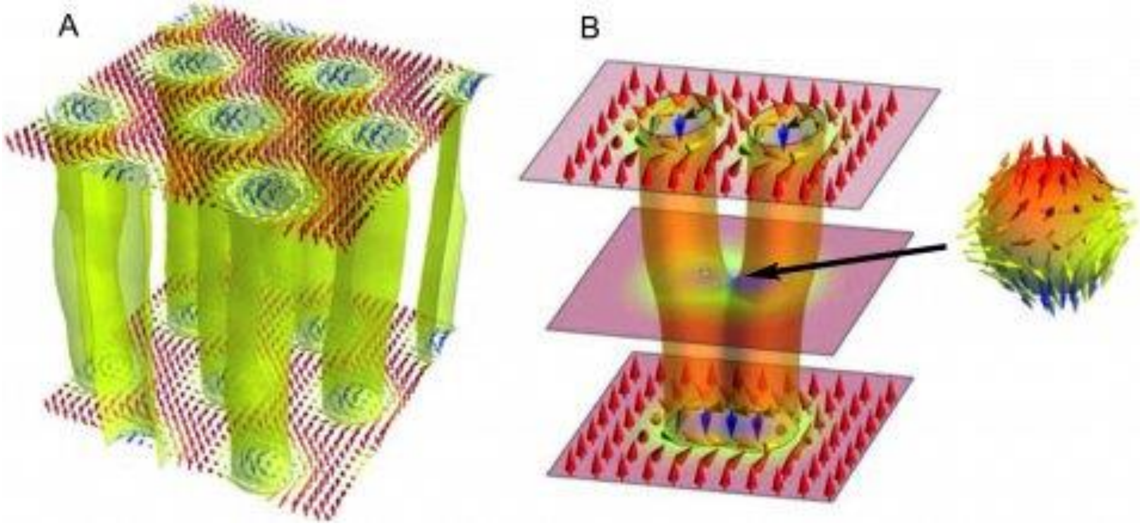
P. Milde et al., Science 340, 6136, (2013).

Well established
Typically found in chiral systems



Fert at al., Nature Nanotechnology 8, 154 (2013)

Proposed racetrack devices

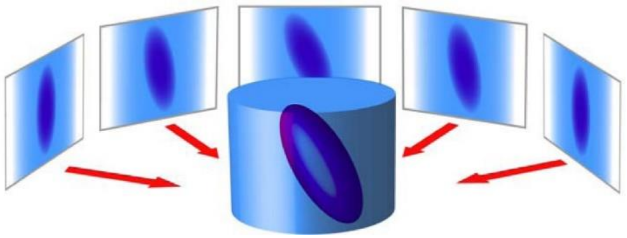


P. Milde et al., Science 340, 6136, (2013).

In 3D:
Prospect for complex 3D structure
& topological transformations

DEVELOPING 3D MAGNETIC IMAGING

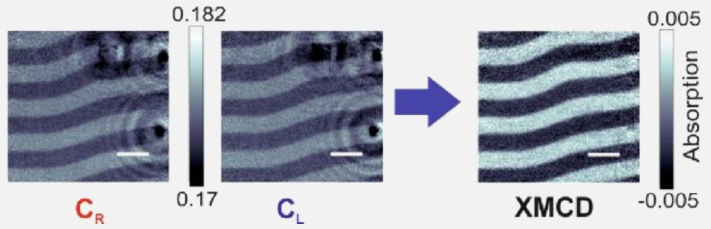
3D imaging: tomography



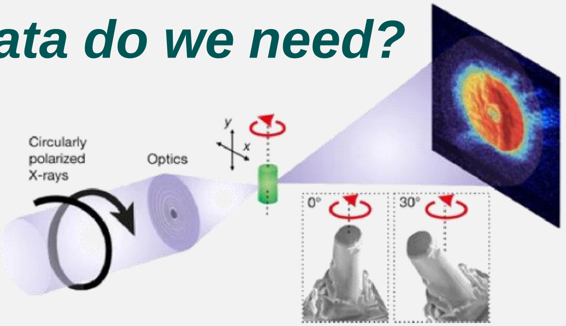
Guizar-Sicairos et al. Optics Express 19, 21345 (2011)

Ingredients of magnetic tomography?

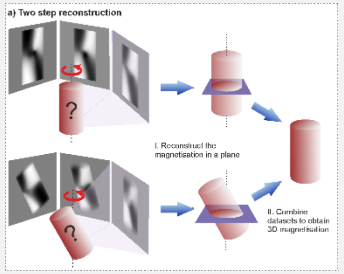
2D X-ray magnetic imaging



What data do we need?



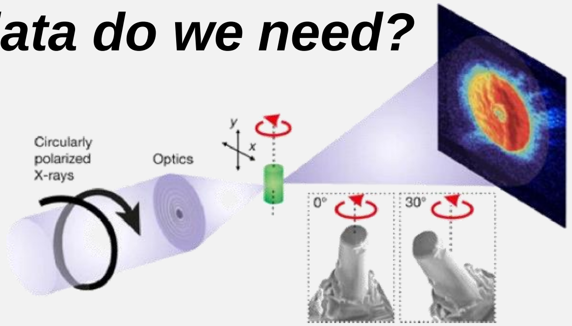
New reconstruction algorithm



DEVELOPING 3D MAGNETIC IMAGING

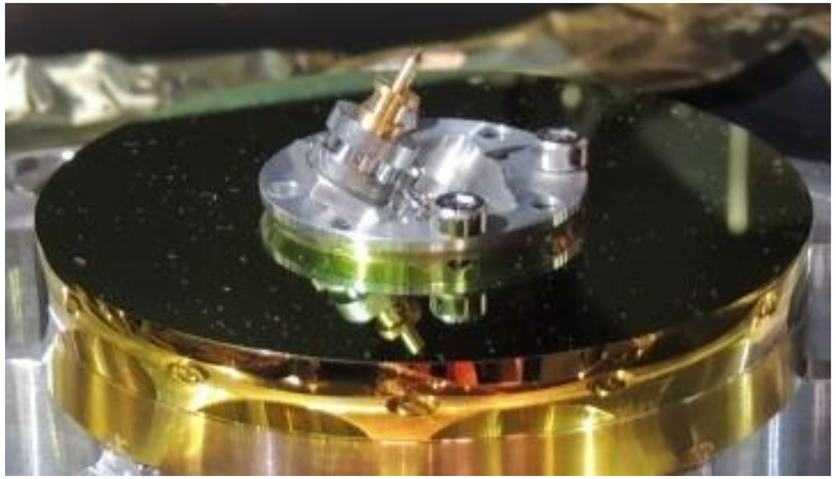
2D X-ray magnetic imaging

What data do we need?



New reconstruction algorithm

To be sensitive to the **y** component, we tilt the sample and remeasure:

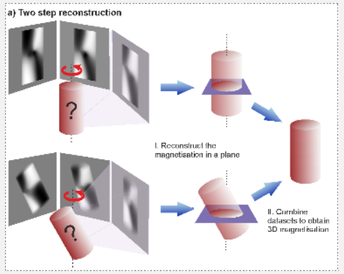


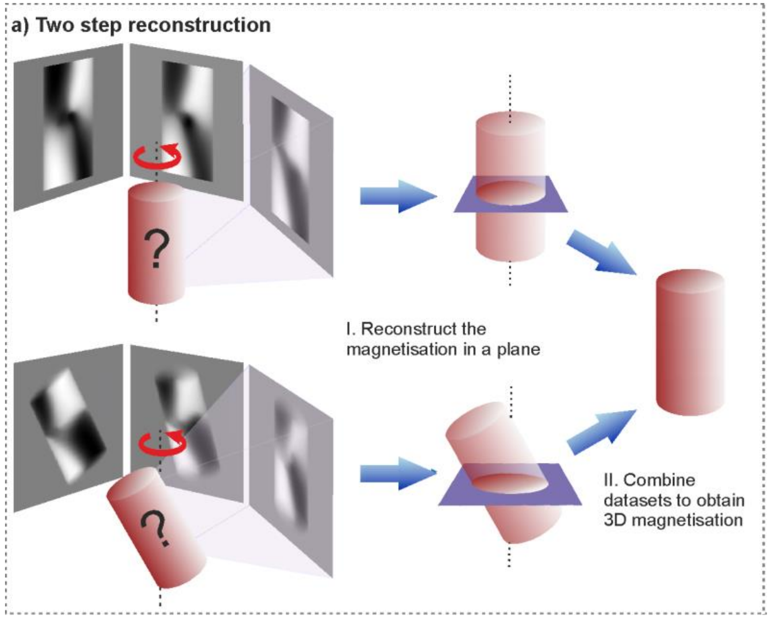
DEVELOPING 3D MAGNETIC IMAGING

2D X-ray magnetic imaging

What data do we need?

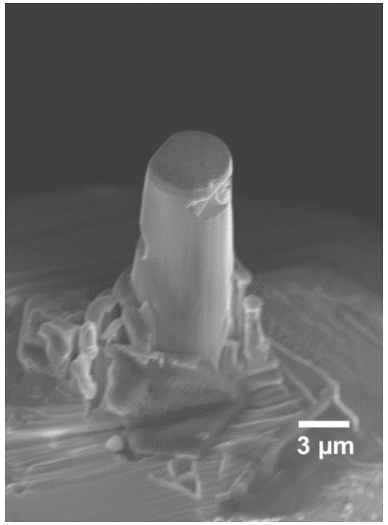
New reconstruction algorithm



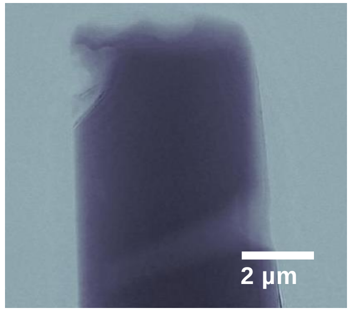


Gradient-based iterative reconstruction algorithm

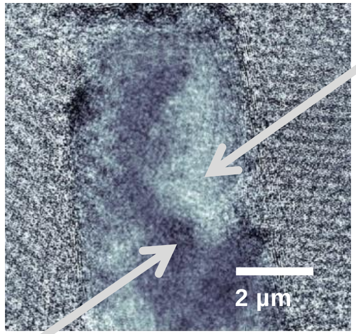
X-RAY MAGNETIC TOMOGRAPHY



Absorption image (C_L)



XMCD image (C_L-C_R)



Pointing away from us

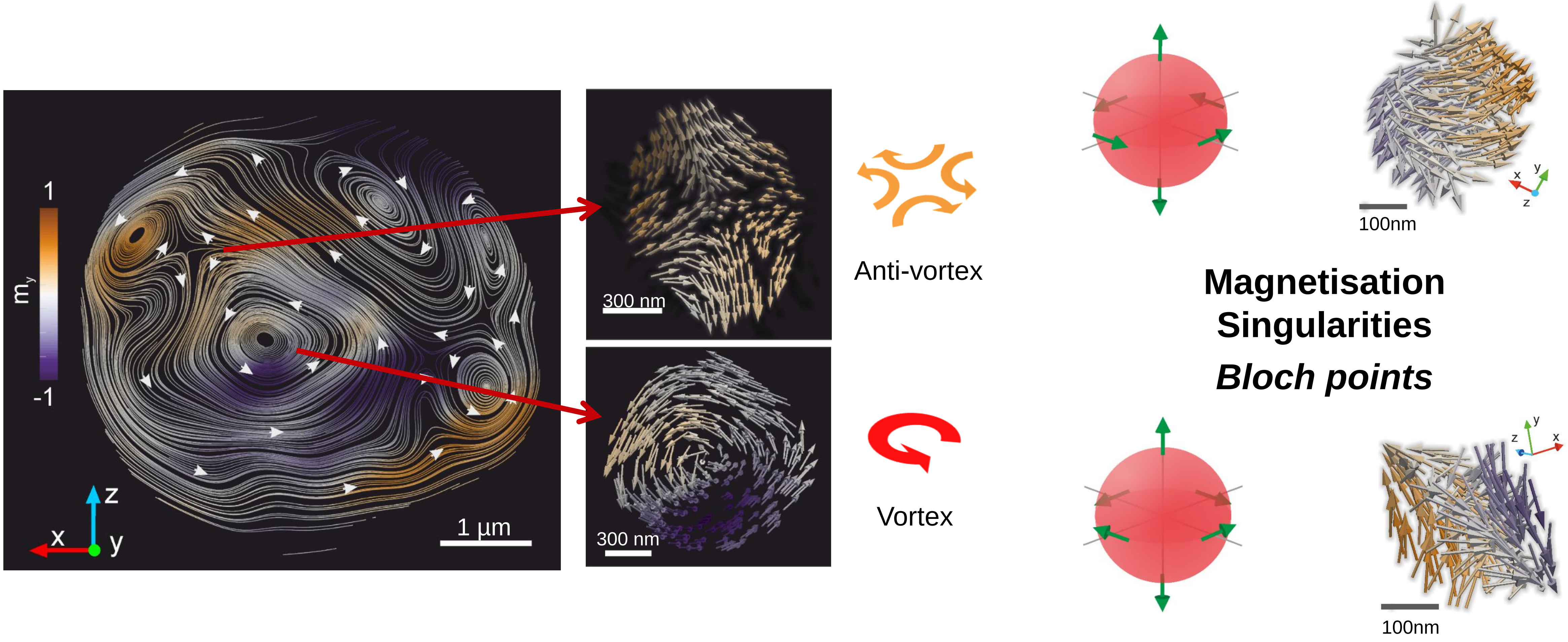
Pointing towards us

Reconstruct with 100 nm spatial resolution

5 µm

Donnelly et al., Nature **547**, 328 (2017)

X-RAY MAGNETIC TOMOGRAPHY



Donnelly et al., Nature **547**, 328 (2017)