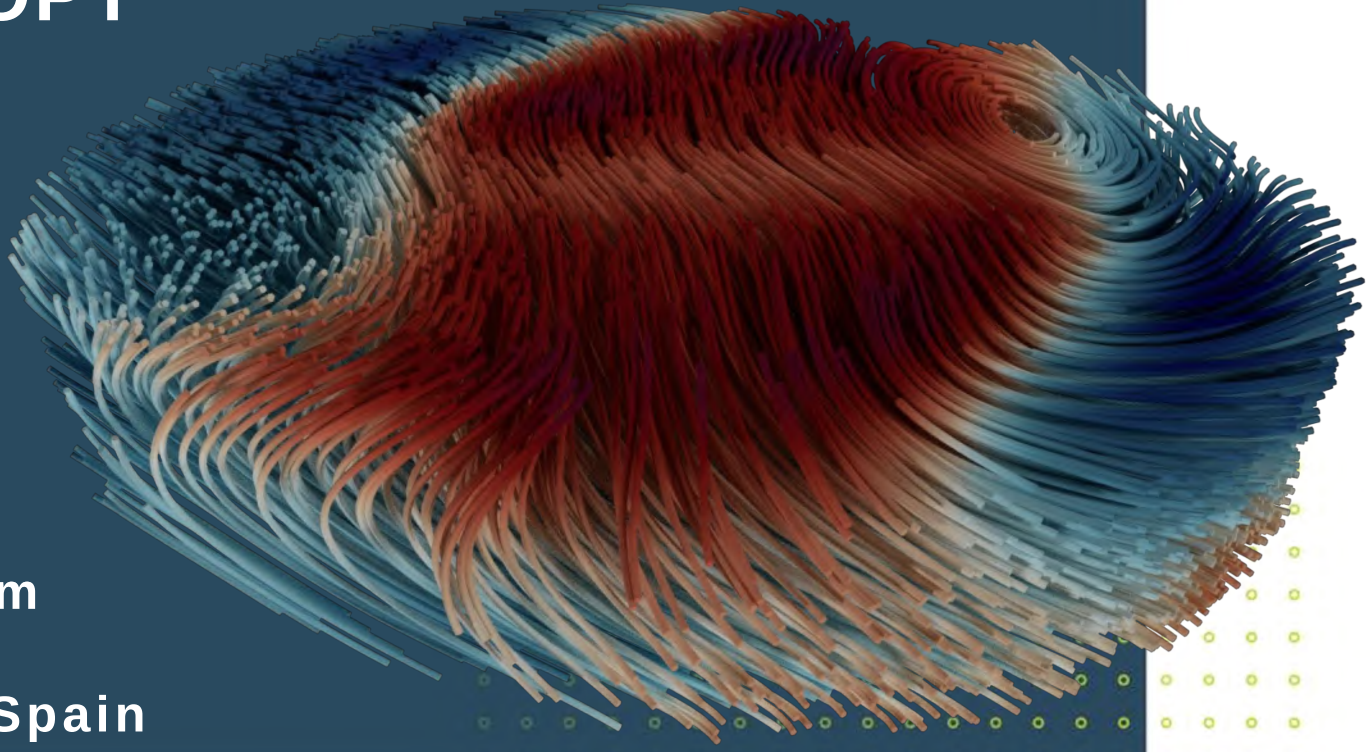
MAX PLANCK INSTITUTE
FOR CHEMICAL PHYSICS OF SOLIDS

MAGNETIC MICROSCOPY



Claire Donnelly

European School of Magnetism

7th September 2023, Madrid, Spain

QUICK INTRO TO ME ☺

Spin3D

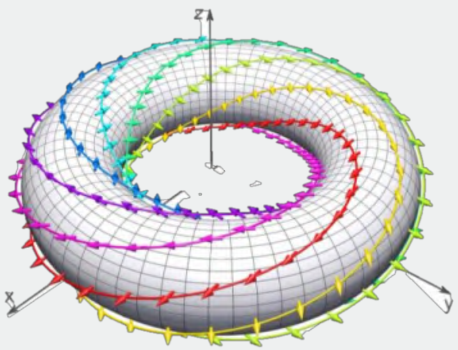
Max Planck Institute
for Chemical Physics of Solids (MPI-CPfS)

Dresden, Germany

→ Three dimensional magnetic systems

MAGNETISM: FROM 2D … TO 3D

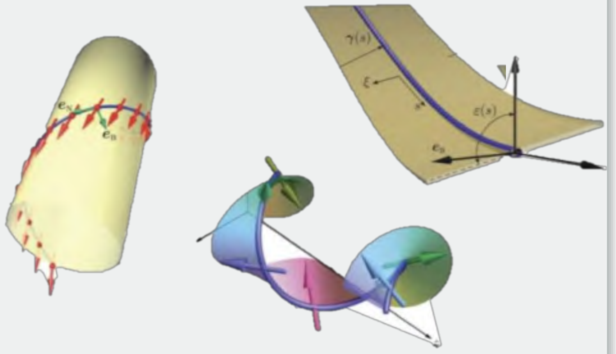
Three dimensional topological textures



Rybakov., arXiv:1904.00250

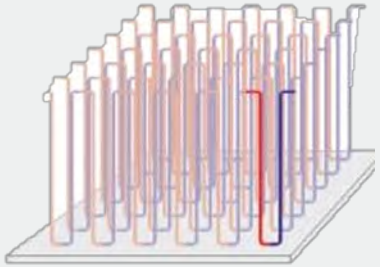
Fernandez-Pacheco et al.,
Nat. Comm. 8, 15756 (2017)

Geometrical tuning of magnetic properties



Sheka et al.,
Small **18**, 2105219, (2022)

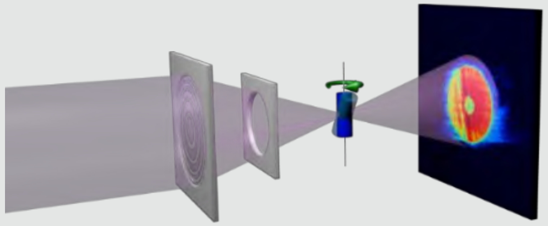
Opportunities for devices



Parkin et al.,
Science 320,190 (2008)

TOOLS FOR MAGNETIC TEXTURES

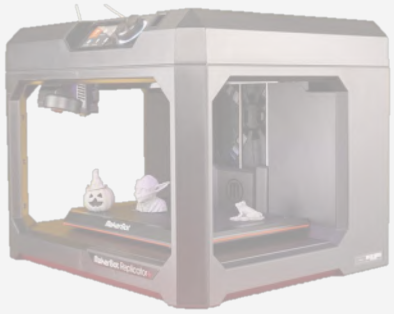
*Visualising them?**



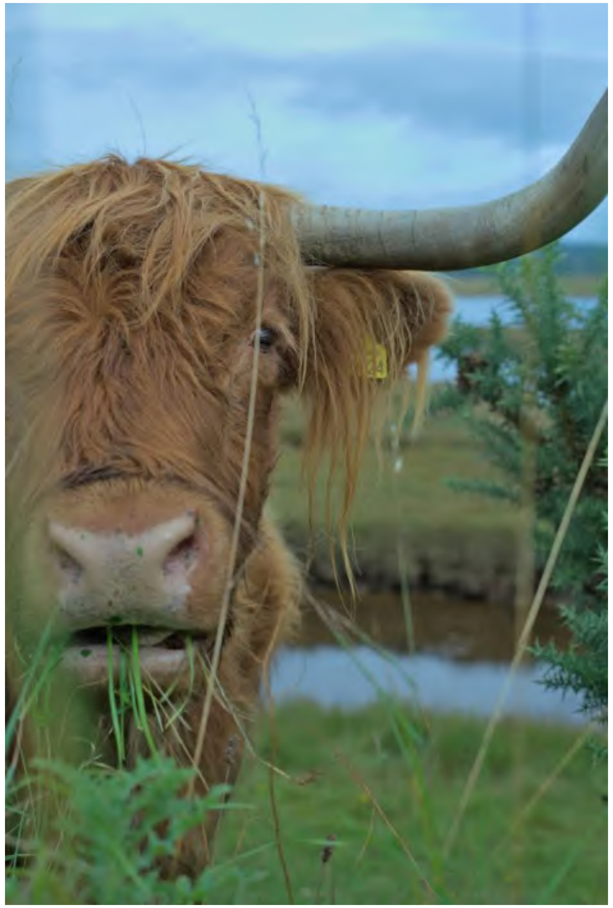
Understanding them?

*** We often make use of synchrotron X-rays!***

Fabricating them?

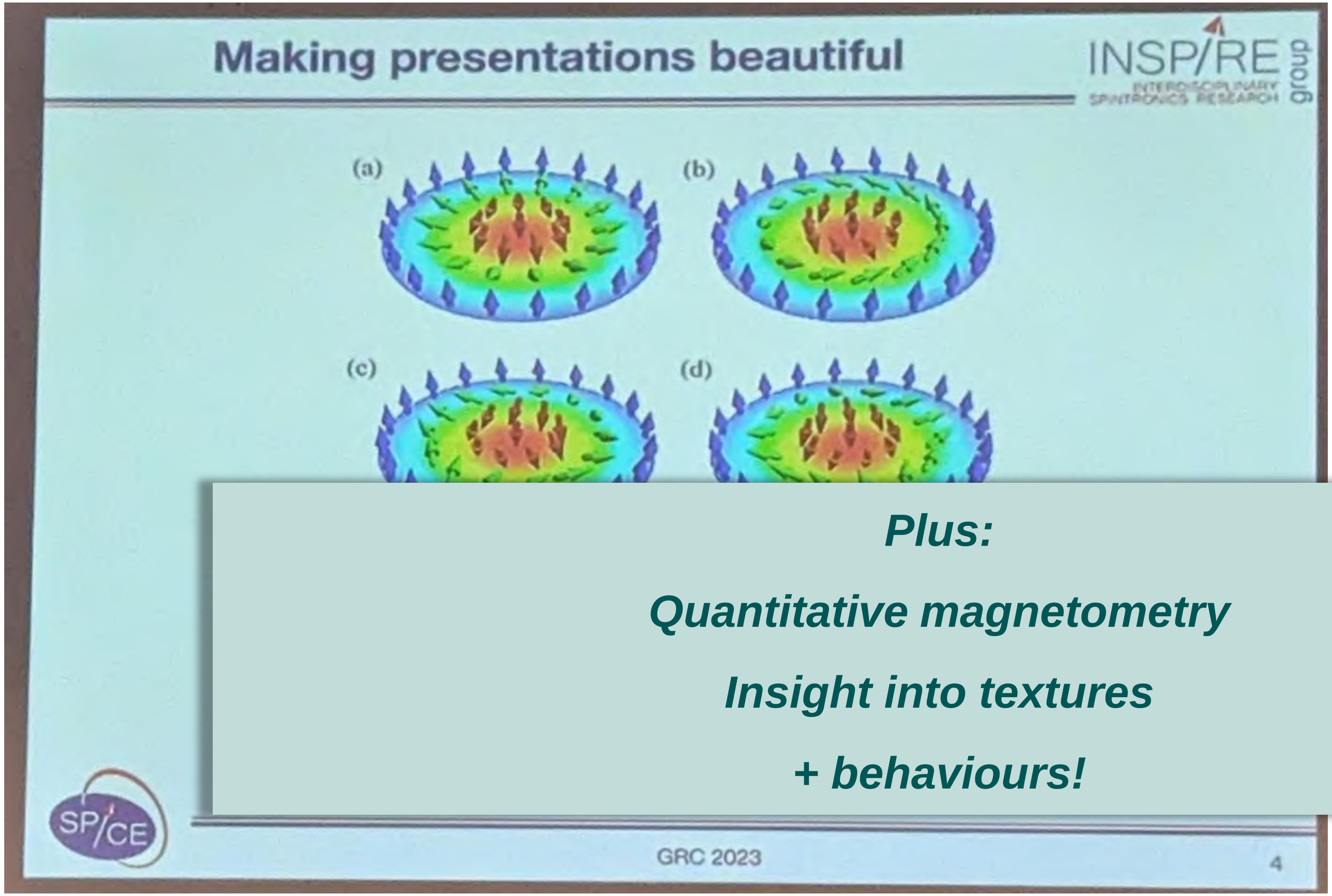


RECORDING 2D IMAGES IMPORTANT!



RECORDING 2D IMAGES IMPORTANT! → THANKS RON!

WHY MAGNETIC MICROSCOPY?



Plus:

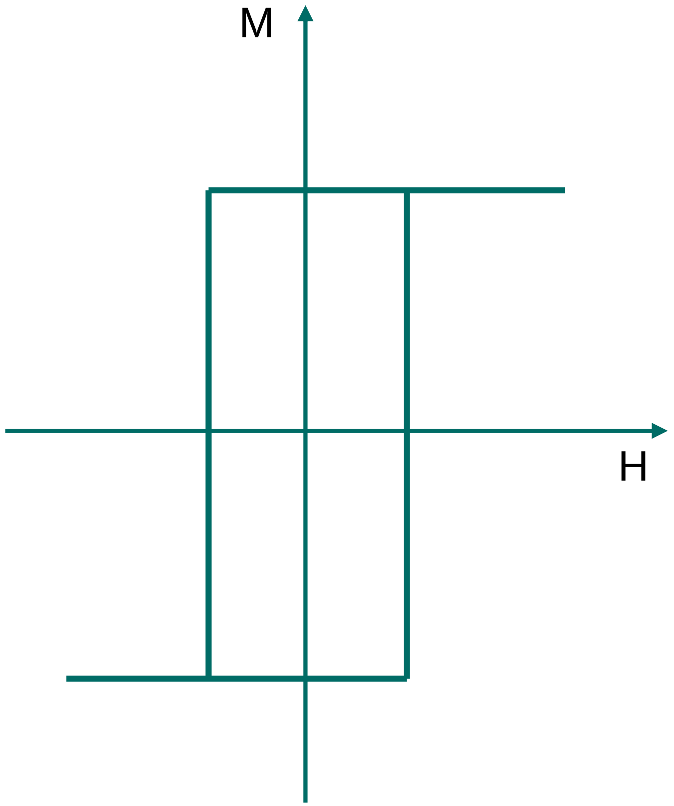
Quantitative magnetometry

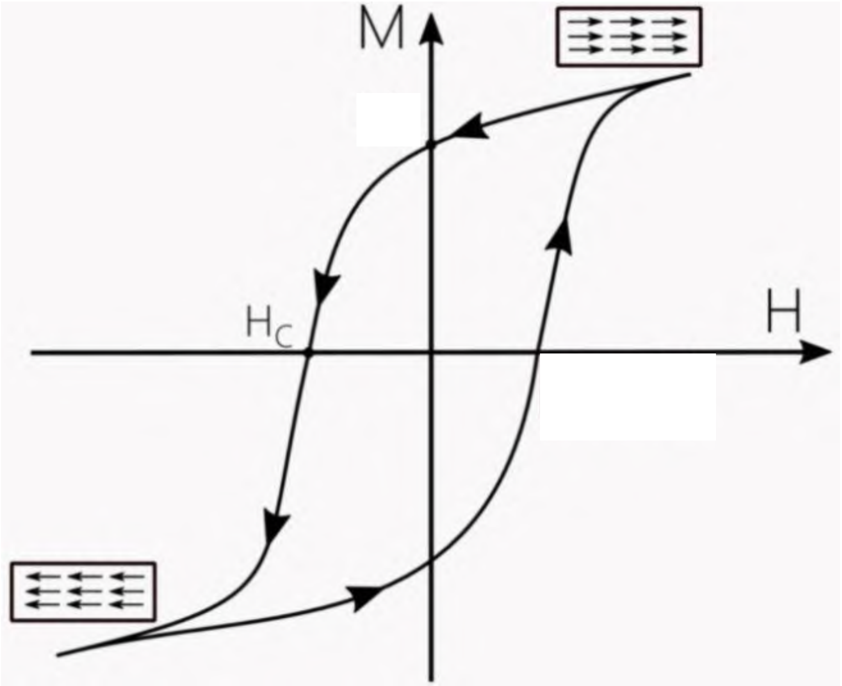
Insight into textures

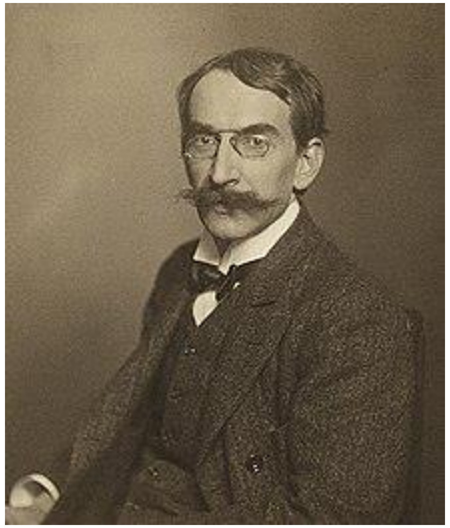
+ behaviours!

cs in Nanostructures,
ly 2023

WHAT ARE WE RECORDING IN MAGNETS?







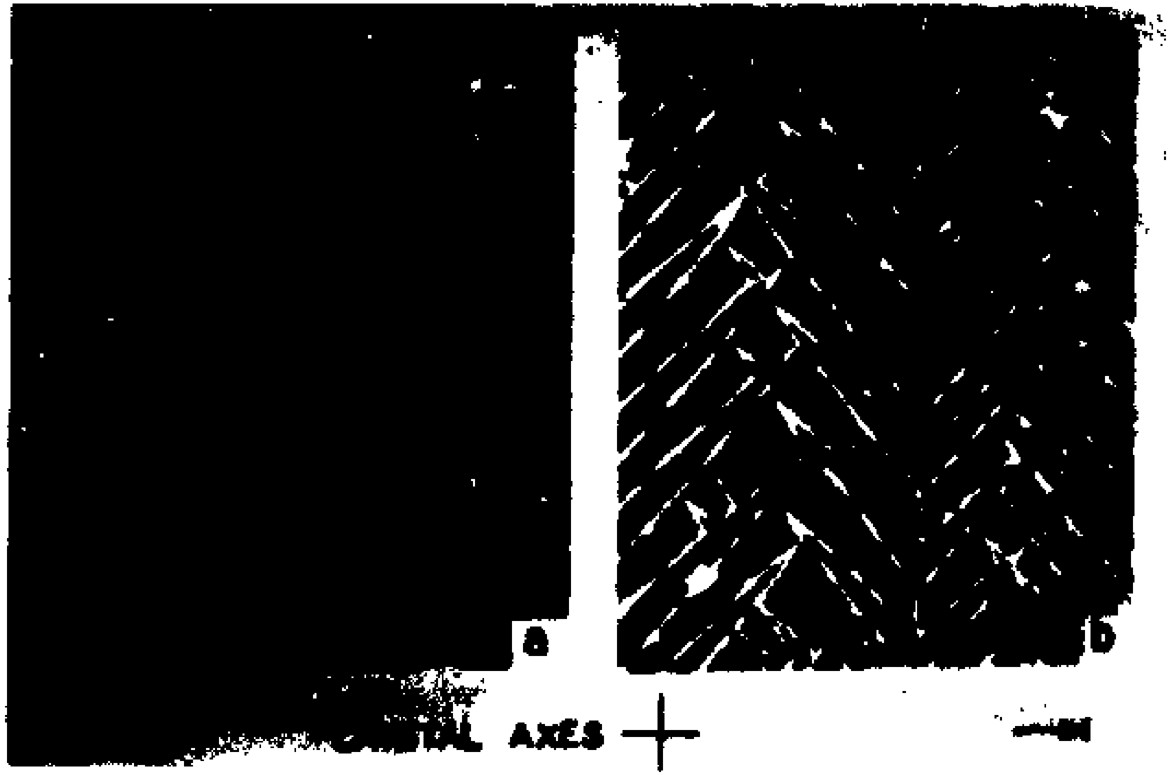
Pierre Weiss, 1907

Magnetic materials appear “non-magnetic”

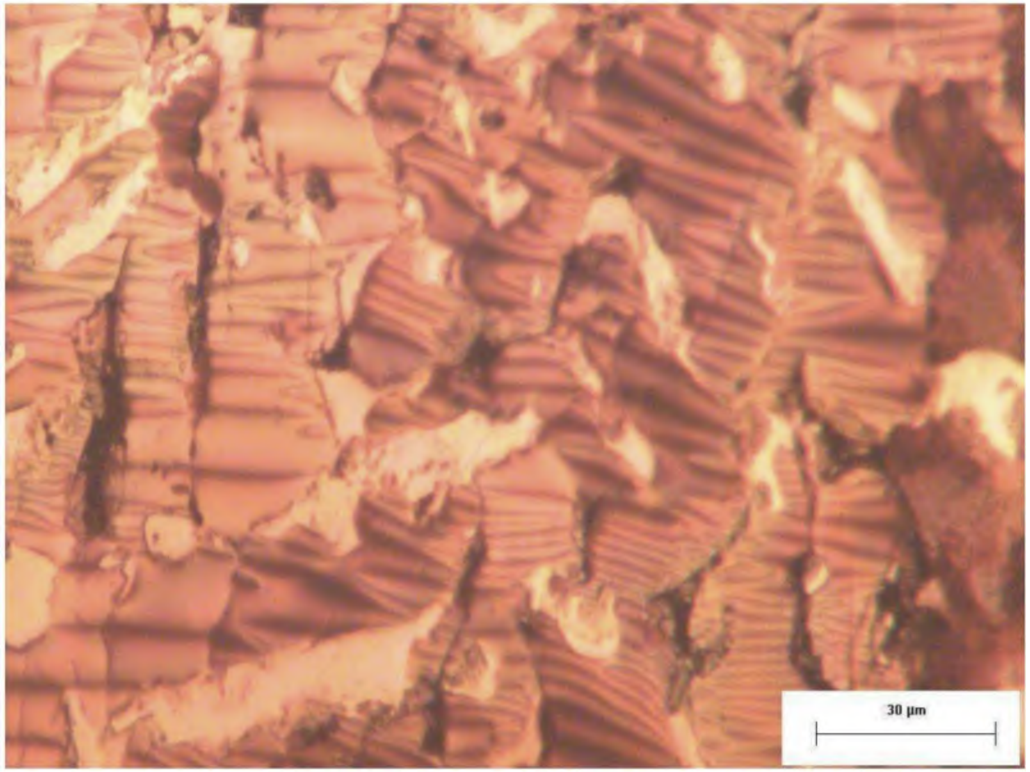
→ presence of magnetic domains

CONFIRMED WITH FIRST MAGNETIC MICROSCOPY: THE BITTER METHOD

Put ferrofluid on top of a magnet

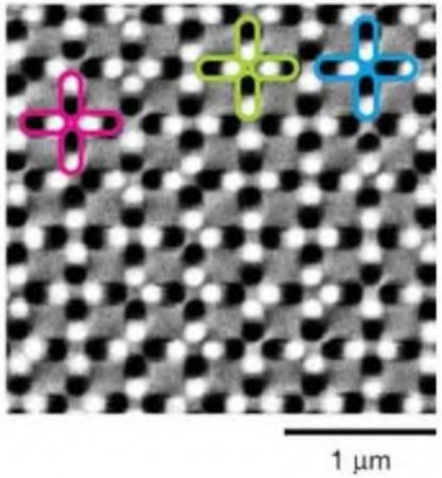


R. Patton, K. Strnat (1963)

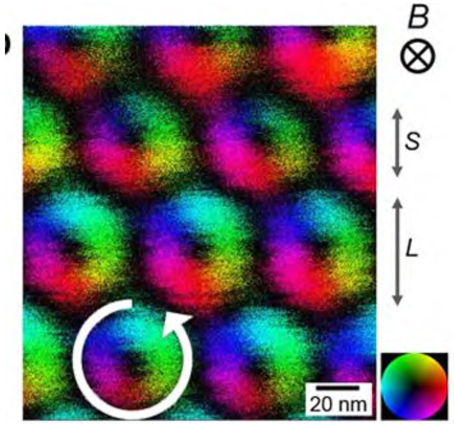


Lemos et al., Materials Science Forum Vol. 802 (2014)

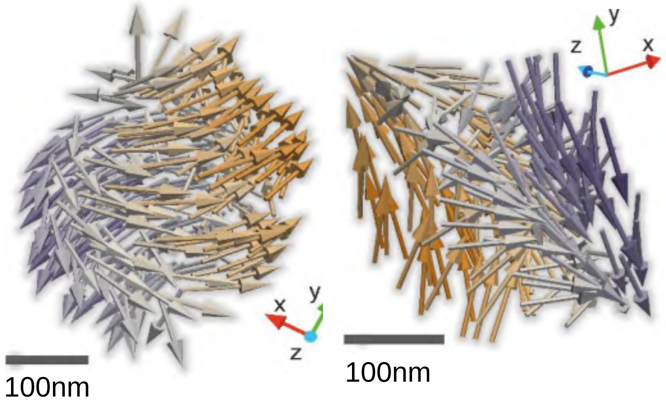
NOWADAYS…
MAGNETIC MICROSCOPY PLAYS KEY ROLE!



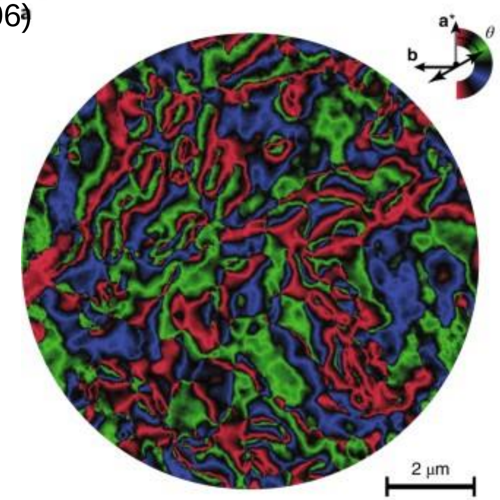
Wang et al., Nature (2006)



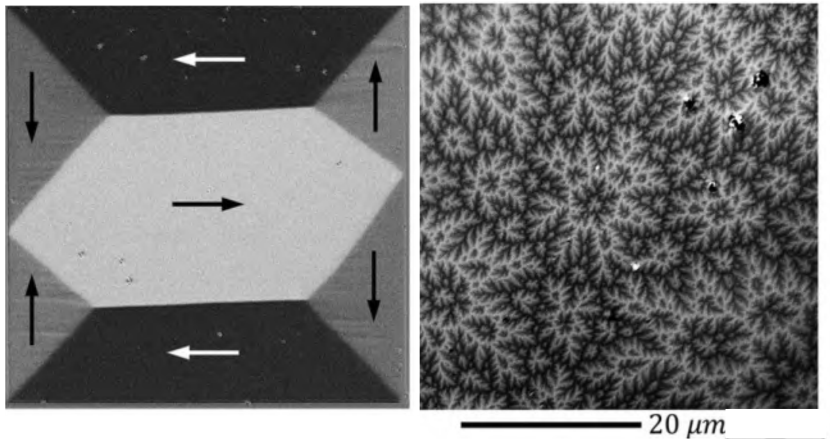
Matsumoto et al., Science Advances (2016)



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

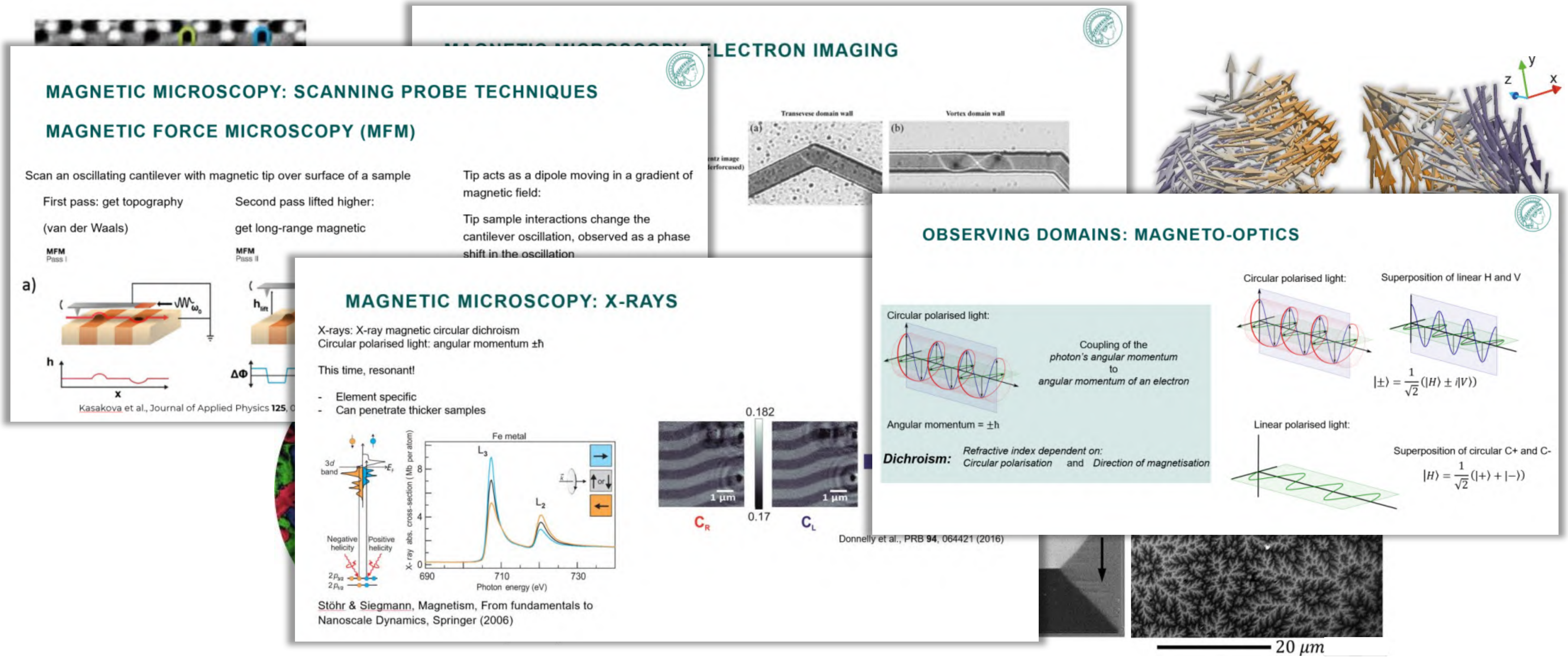


Chmiel et al., Nature Materials 17, 581 (2018)



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

MAGNETIC MICROSCOPY:
HOW DO WE CHOOSE OUR METHOD?



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

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

OUR QUESTIONS FOR THIS MORNING'S LECTURES:

What do we need to consider?

Spatial resolution

Sample environments

Time resolution

What methods are available?

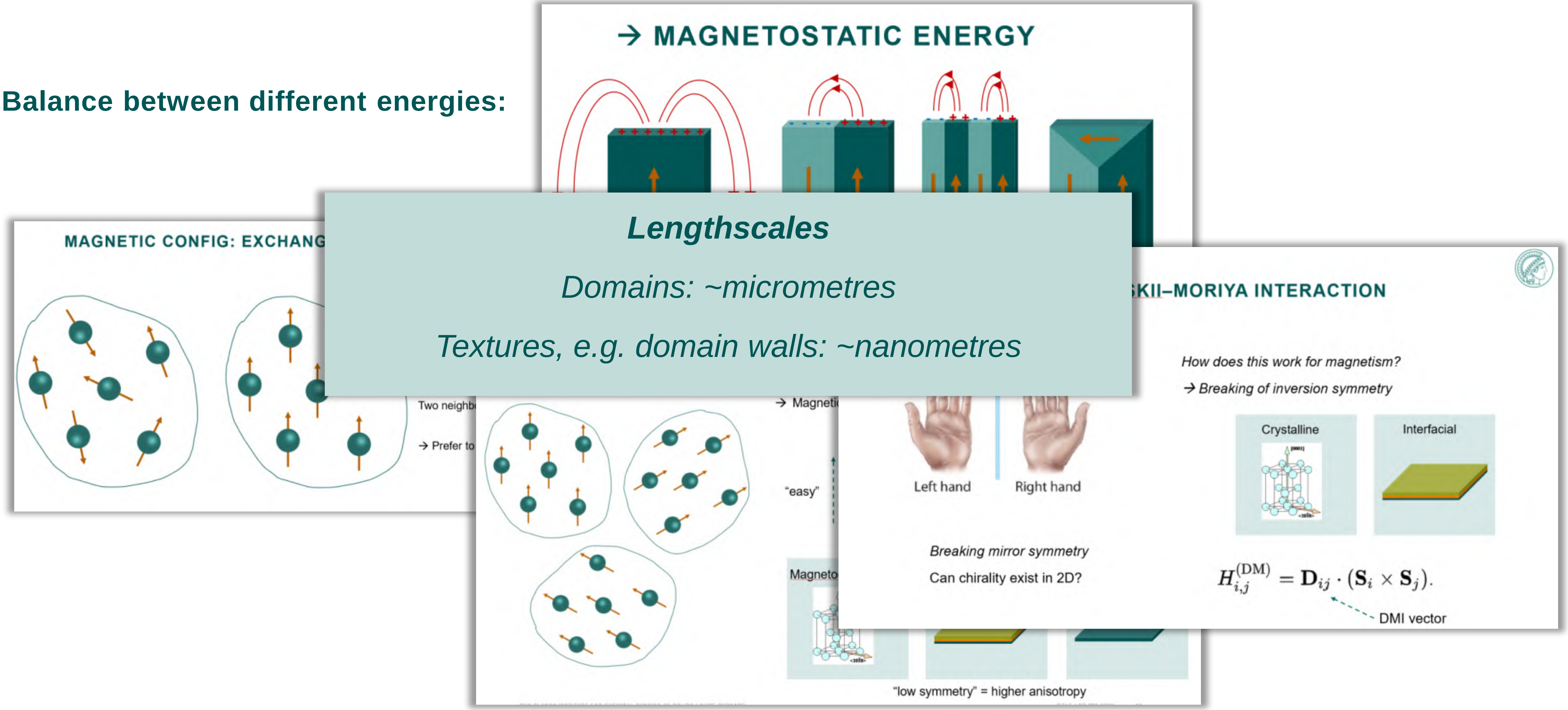
Choosing the method for me and my samples?

MAGNETIC MICROSCOPY: HOW DO WE CHOOSE OUR METHOD?

What can we see?	***Length scales → spatial resolution***
What samples can we probe?	***Type of sample? Strength of signal vs noise?***
Will our samples survive?	***Effect on sample? What can we measure?***
Magnetic behaviour?	***Time resolved, sample environments?*** → *Second lecture!*
Cost/ accessibility?	***In the lab or large scale facilities?***

SPATIAL RESOLUTION: WHAT DO WE NEED?

Balance between different energies:



Lengthscales

Domains: ~micrometres

Textures, e.g. domain walls: ~nanometres

QUICK DISCUSSION OF SPATIAL RESOLUTION...

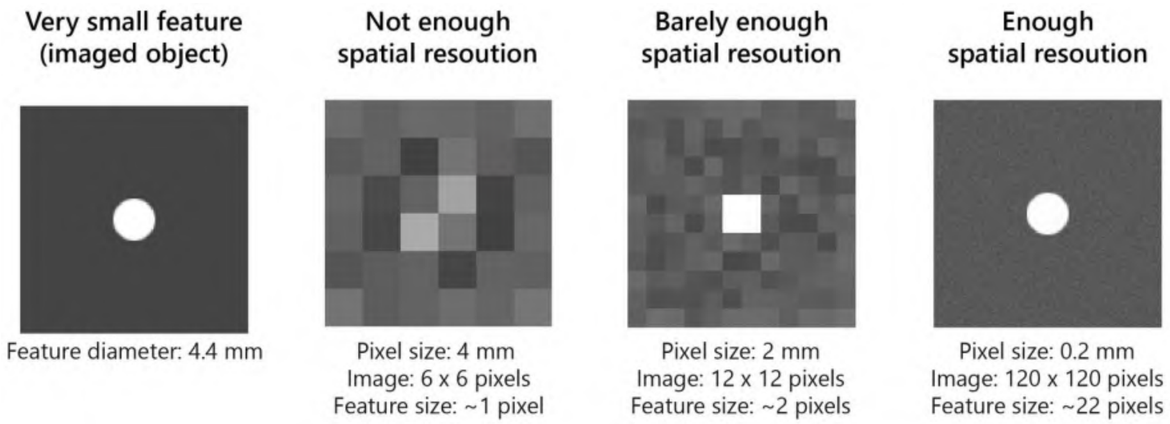
Question!

What determines our resolution?

Our pixel size? Or our lens?

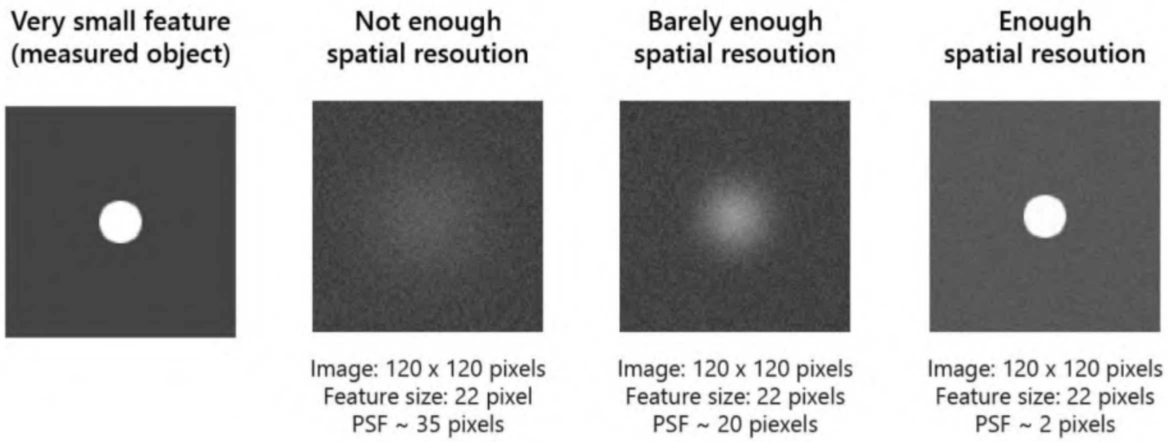
QUICK DISCUSSION OF SPATIAL RESOLUTION…

Pixel size



Nyquist sampling: pixel size < feature size/2

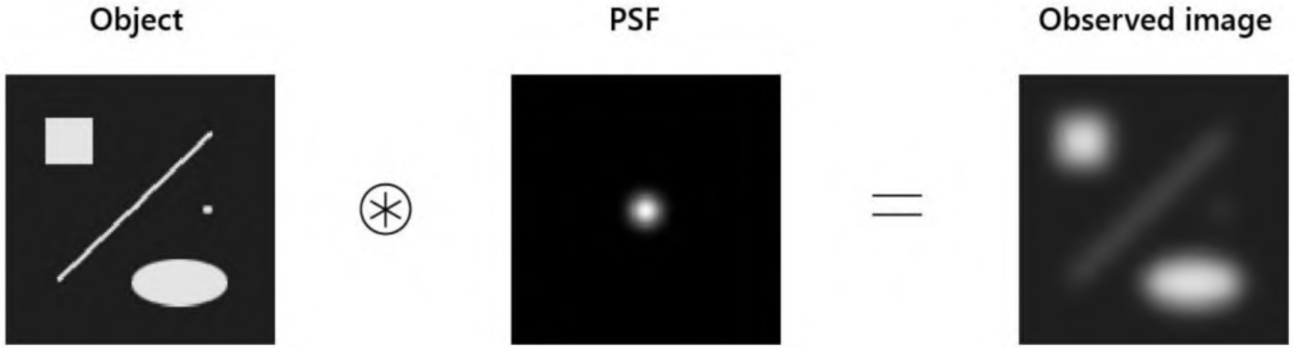
Optical resolution



We need both!

Small enough pixels

High enough optical resolution



https://imaging.rigaku.com/blog/improve-resolution-x-ray-ct-images

MEASURING SPATIAL RESOLUTION

Resolving two features

Need two features to resolve…

Nyquist sampling:

pixel size < feature size/2

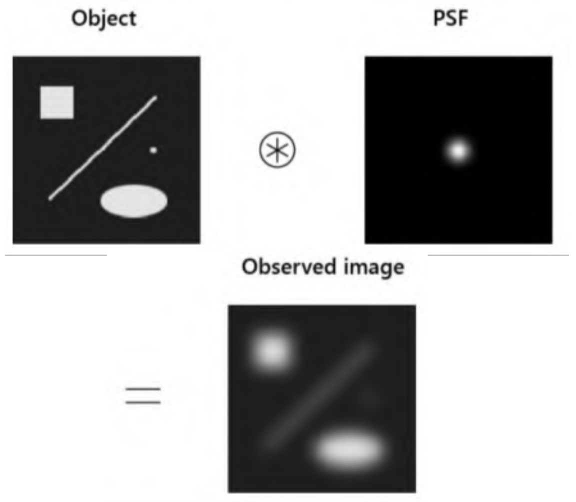
https://www.princetoninstruments.com/learn/camera-fundamentals/pixel-size-and-camera-resolution

Edge sharpness

Sharpness is a convolution of

a) the real edge width

b) the spatial resolution

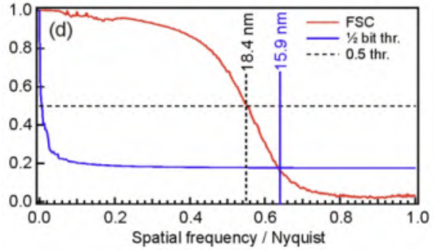


https://imaging.rigaku.com/blog/improve-resolution-x-ray-ct-images

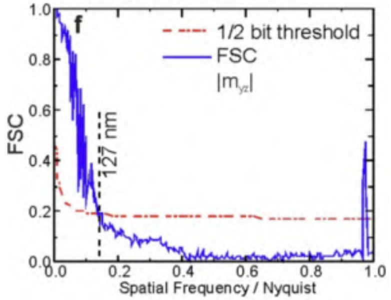
Fourier Ring Correlation

Take 2 independent images, compare cross correlation as a function of spatial frequency. Dependent on pixel size

Higher:



Lower:



Q & A:
CAN WE MEASURE EXPERIMENTALLY THE DOMAIN WIDTH WHEN IN THE NM SCALE?

Answer: It depends!

→ **Measured width = Convolution of spatial resolution & Domain wall width**

→ **Either:**

→ Know that you have sufficient resolution (and that width = N*spatial resolution)

Or

→ Know the expected domain wall width, & compare.

Domain wall width: $\Delta \sim \pi\sqrt{A/K}$

Hard: 2-3 nm → Soft: 10s to 100s nm

→ We need a spatial resolution from 10s of nm, to ~1 nm

→ **Let's keep this in mind!**

OUR QUESTIONS FOR THIS MORNING'S LECTURES:

What do we need to consider?

Spatial resolution

Sample environments

Time resolution

Second lecture!

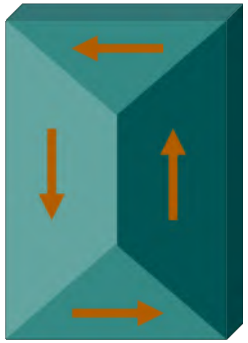
What methods are available?

Choosing the method for me and my samples?

AIM OF TODAY: WE’LL FILL OUT…

	MFM	Nitrogen vacancy	TEM	MOKE	XMCD (synchrotron)	XMLD (synchrotron)	Spin pol. STM	SEMPA
Contrast								
Spatial resolution								
Depth sensitivity								
Sample environment								
Invasive								
Sensitivity								
Cost/ accessibility								

WE CAN THINK ABOUT WHAT IS PROBED:



$B = \mu_0(M + H)$

$\boldsymbol{B}$ probes

Electrons, scanning probe, Bitter method…

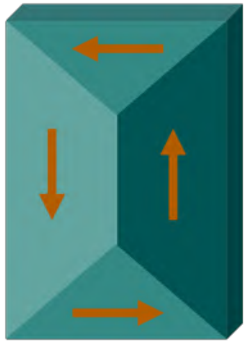
Scanning probe	***Electrons***

$\boldsymbol{M}$ probes

Magneto-optics, spin-polarised STM, SEM with polarisation analysis

Optical regime	***Electrons***	***X-rays***

B probes



M probes

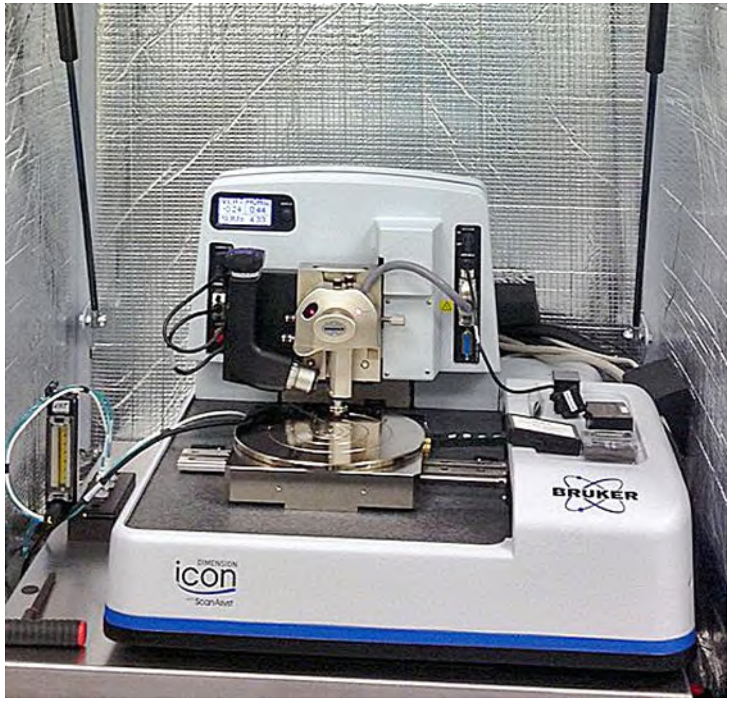
$$B = \mu_0(M + H)$$

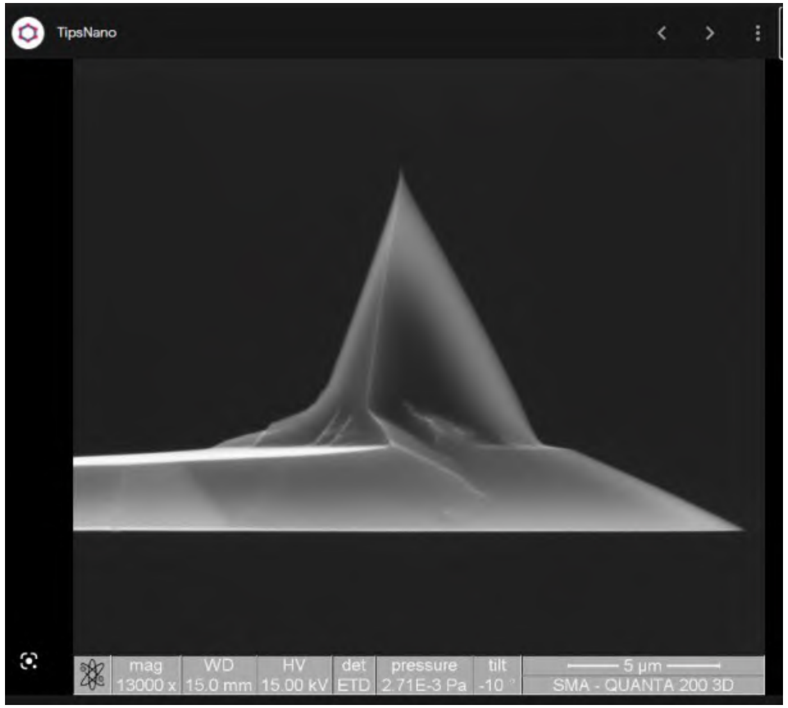
Scanning probe

Electron microscopy

SCANNING PROBES OF B:

MAGNETIC FORCE MICROSCOPY





Cantilever with magnetic tip

MAGNETIC FORCE MICROSCOPY

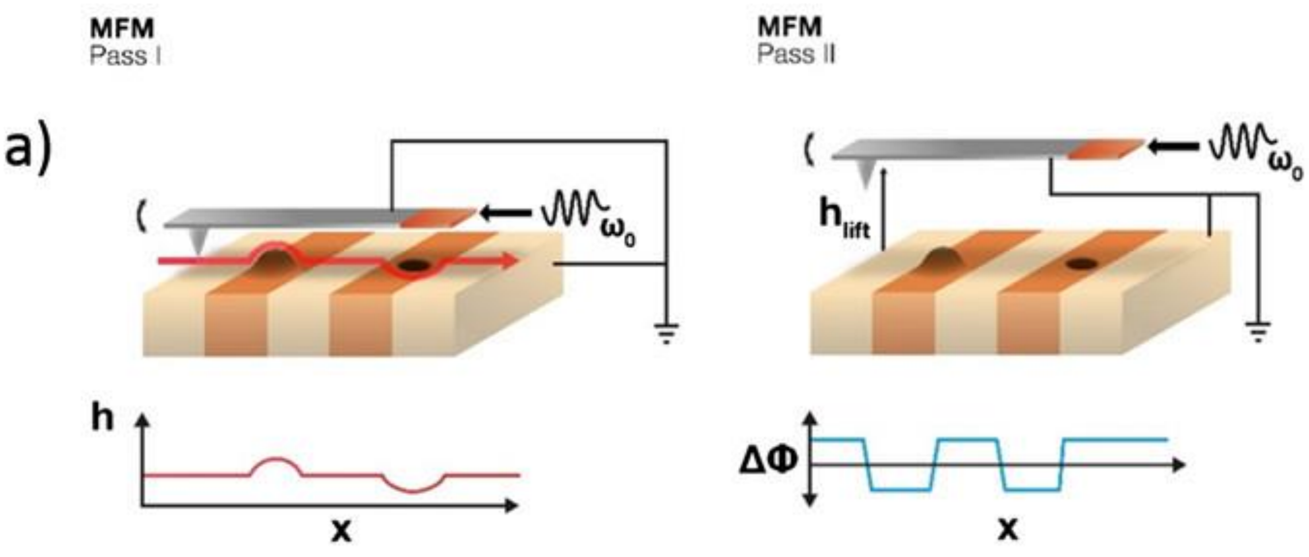
Scan an oscillating cantilever with magnetic tip over surface of a sample

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

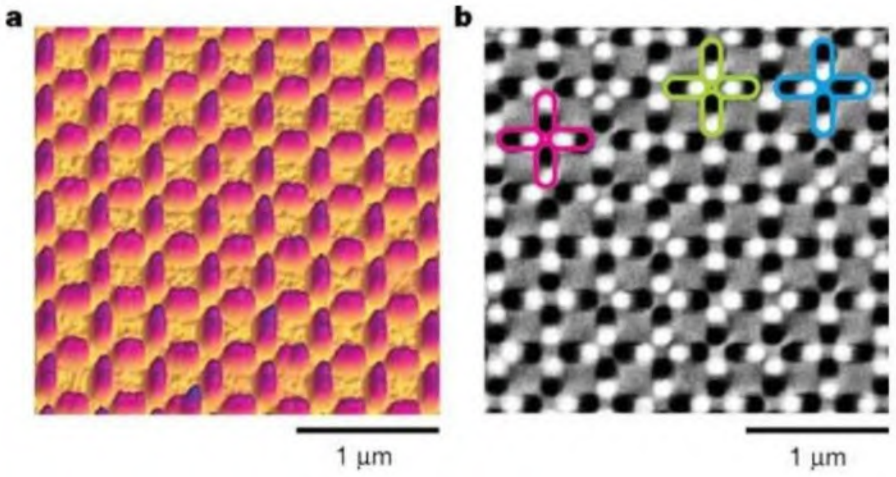
& buried configuration!

* Long range interaction

MAGNETIC FORCE MICROSCOPY

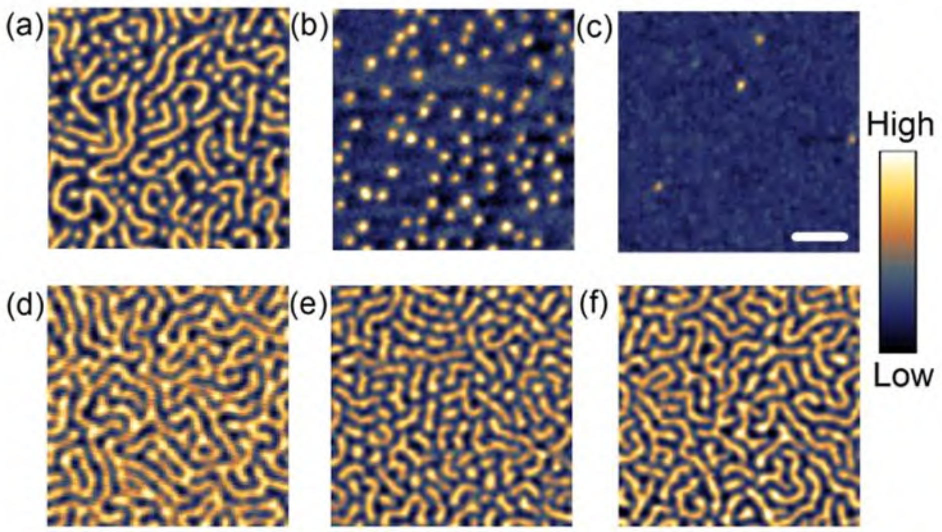
Nanomagnet arrays:

Wang et al., Nature (2006)



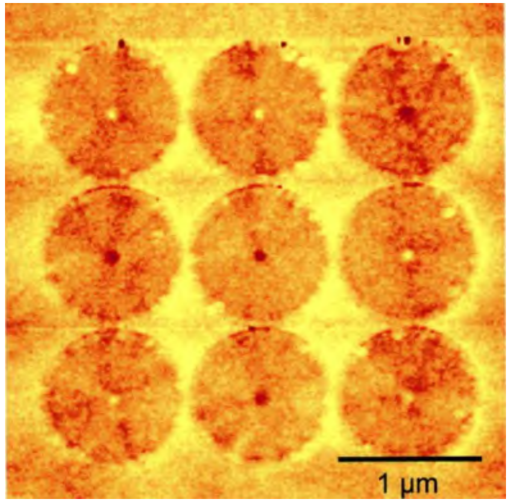
Magnetic domains, skyrmions:

Duong et al., APL (2019)



Patterned magnetic micro/nanostructures:

Magnetic vortices



Shinjo et al., Science (2000)

MAGNETIC FORCE MICROSCOPY

Take Home Messages of MFM

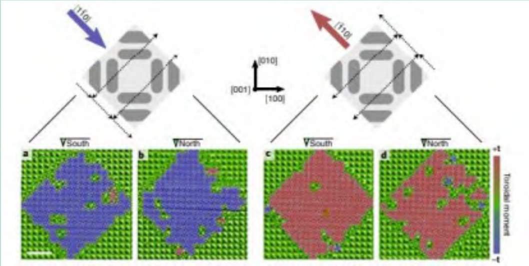
- High spatial resolution imaging of magnetic surface charges

- 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*]

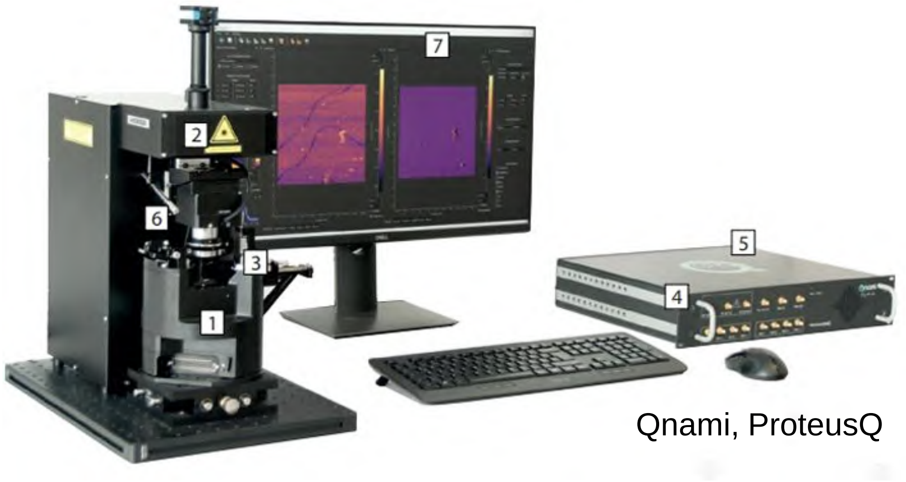


– Limited to ~flat samples – could need higher sensitivity –

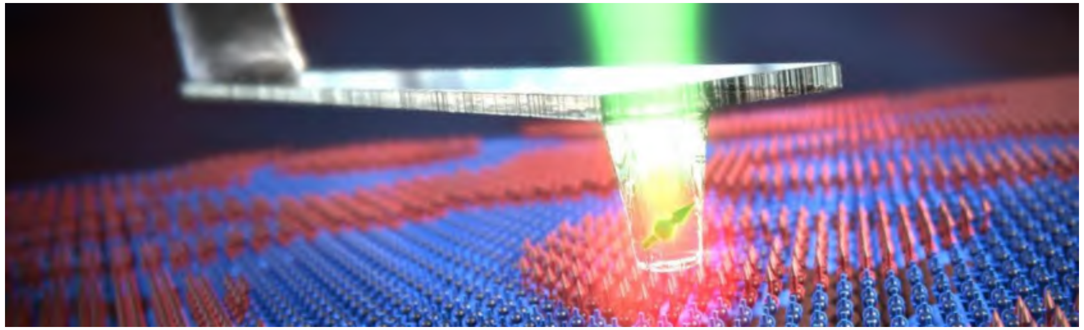
	MFM
Contrast	$\boldsymbol{H}$, surface charges
Spatial resolution	10s of nm
Depth sensitivity	Surface sensitive
Sample environment	Field, cryo, electrical contacts
Invasive	Yes
Sensitivity	Medium
Cost/ accessibility	Lab-based, accessible

SCANNING PROBES OF B:

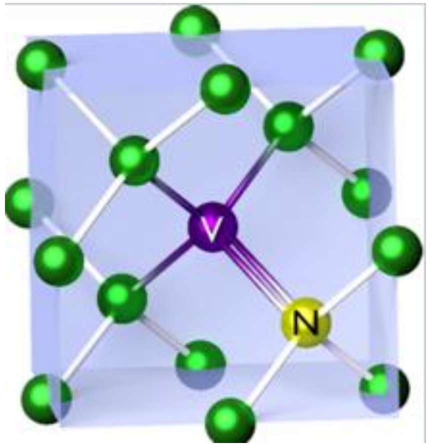
NITROGEN VACANCY MICROSCOPY



Qnami, ProteusQ

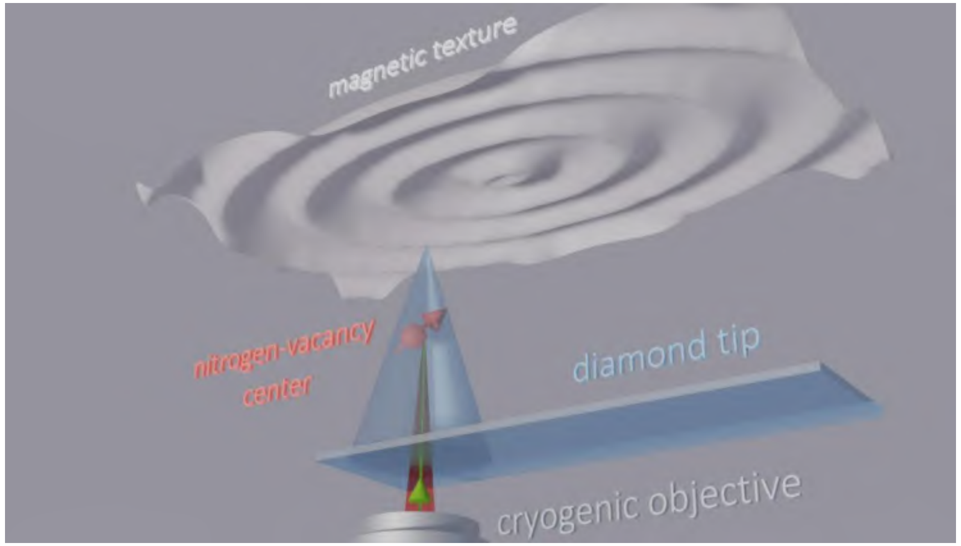


- Diamond tip, with a defect in the lattice:
- Prepare a particular quantum state, probe the field splitting of the state:
- Very sensitive: can detect a single electron spin ~nms from NV centre!
- Non-invasive



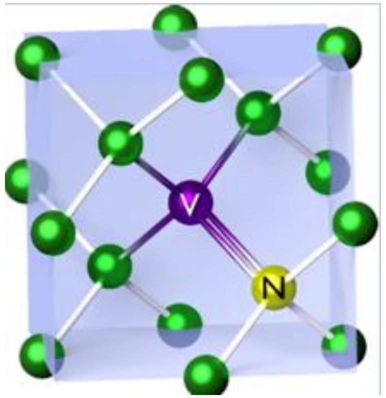
SCANNING PROBES OF B:

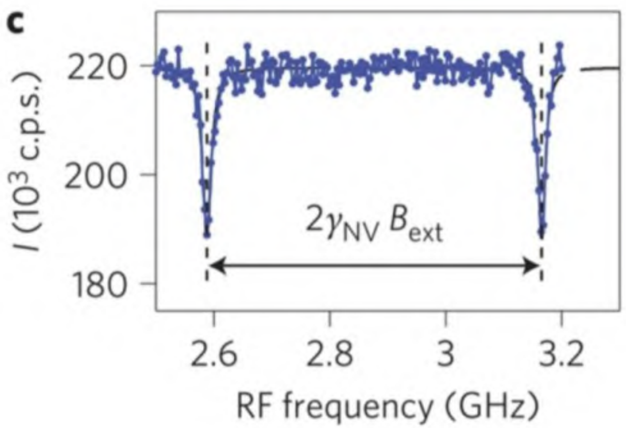
NITROGEN VACANCY MICROSCOPY



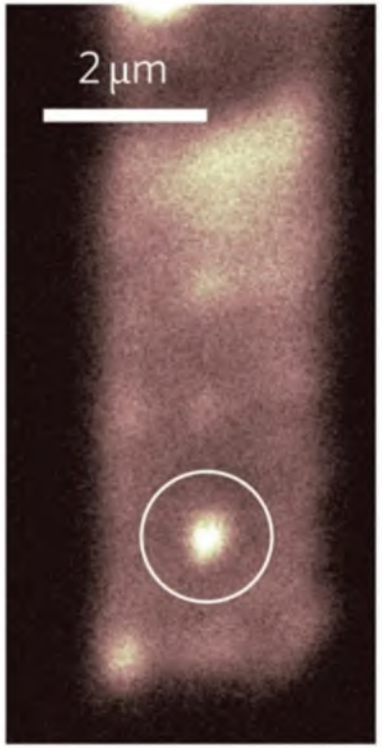
https://www.fkf.mpg.de/7721404/NV-Magnetometry

- Defect behaves as an artificial atom
- Spin triplet ground state
    - Magnetic sensitivity & long spin coherence
- Optical readout
- Zeeman splitting = sensitivity to magnetic field





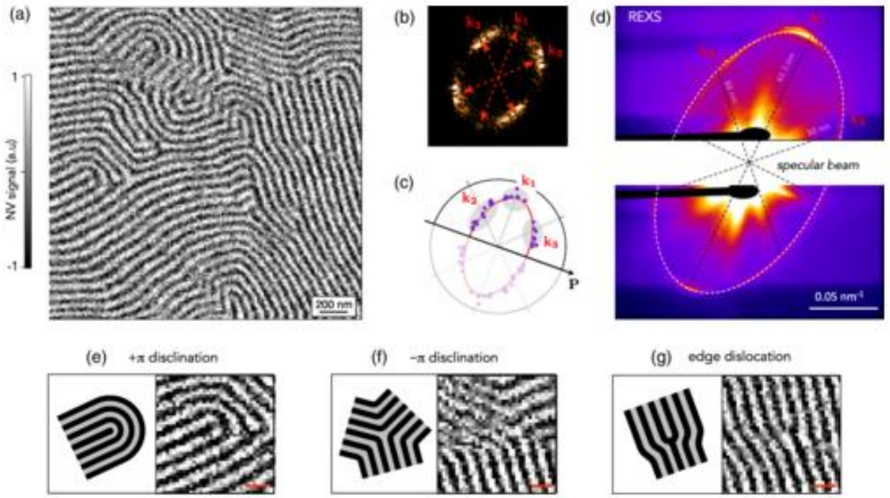
Optical image of tip:



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

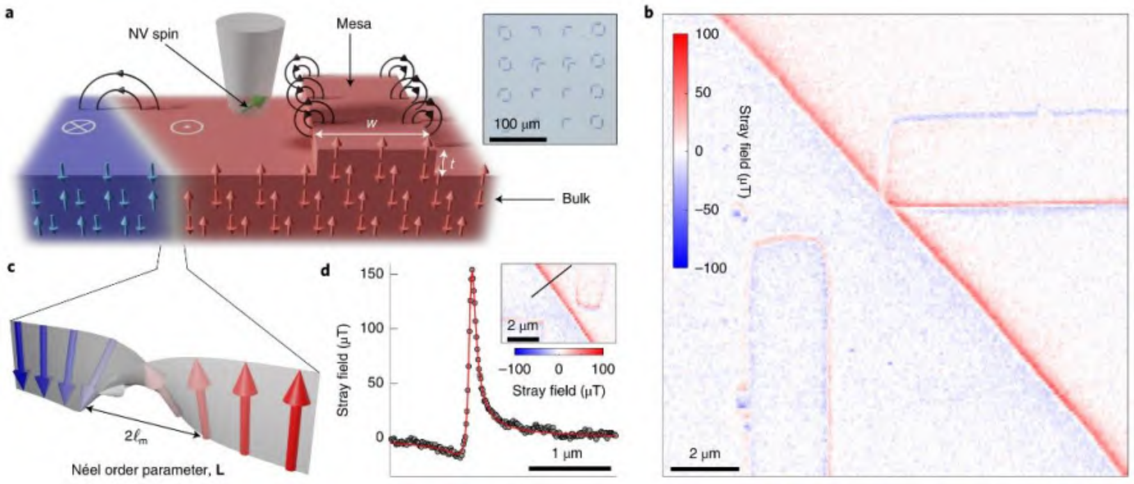
NITROGEN VACANCY MICROSCOPY

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

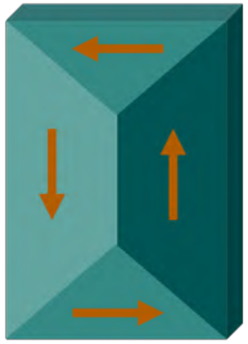
- High spatial resolution imaging of magnetic surface charges

- 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:

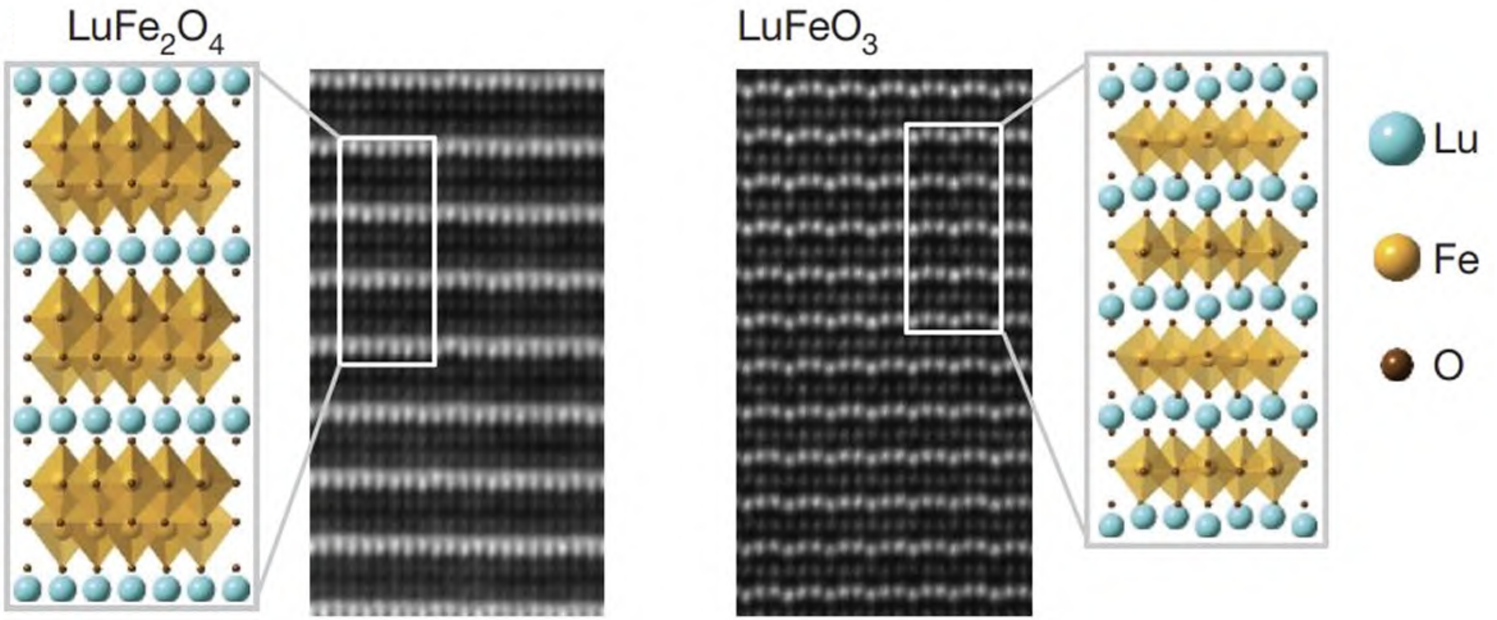
TRANSMISSION ELECTRON MICROSCOPY

JEOL ARM 200F

In dedicated labs, millions of euros

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

Question!

What determines our resolution?

Wavelength?

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

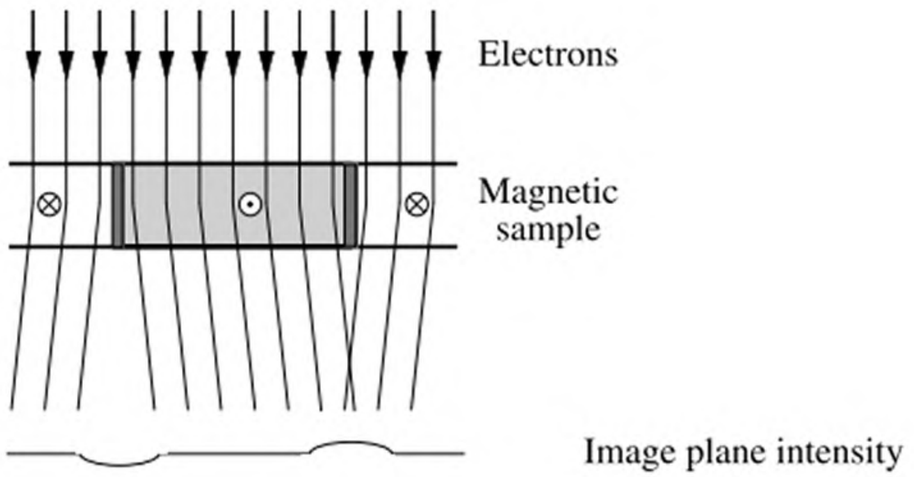
MAGNETIC TEM: LORENTZ MICROSCOPY

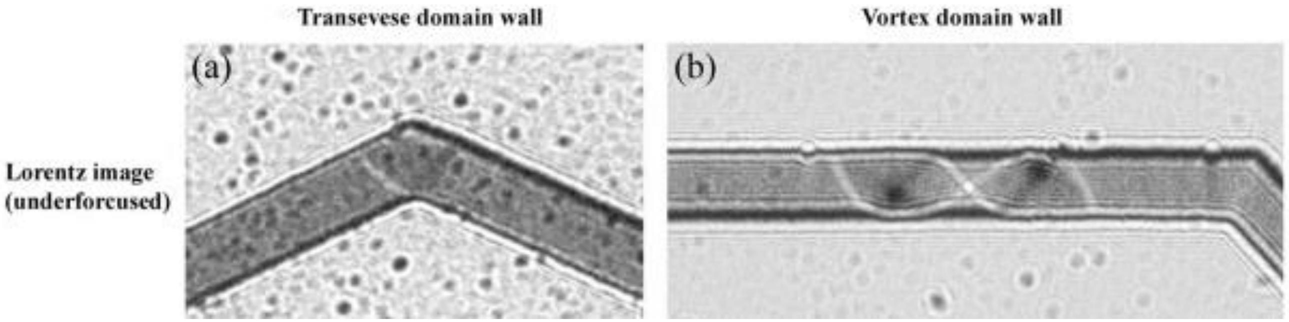
Lorentz microscopy:

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

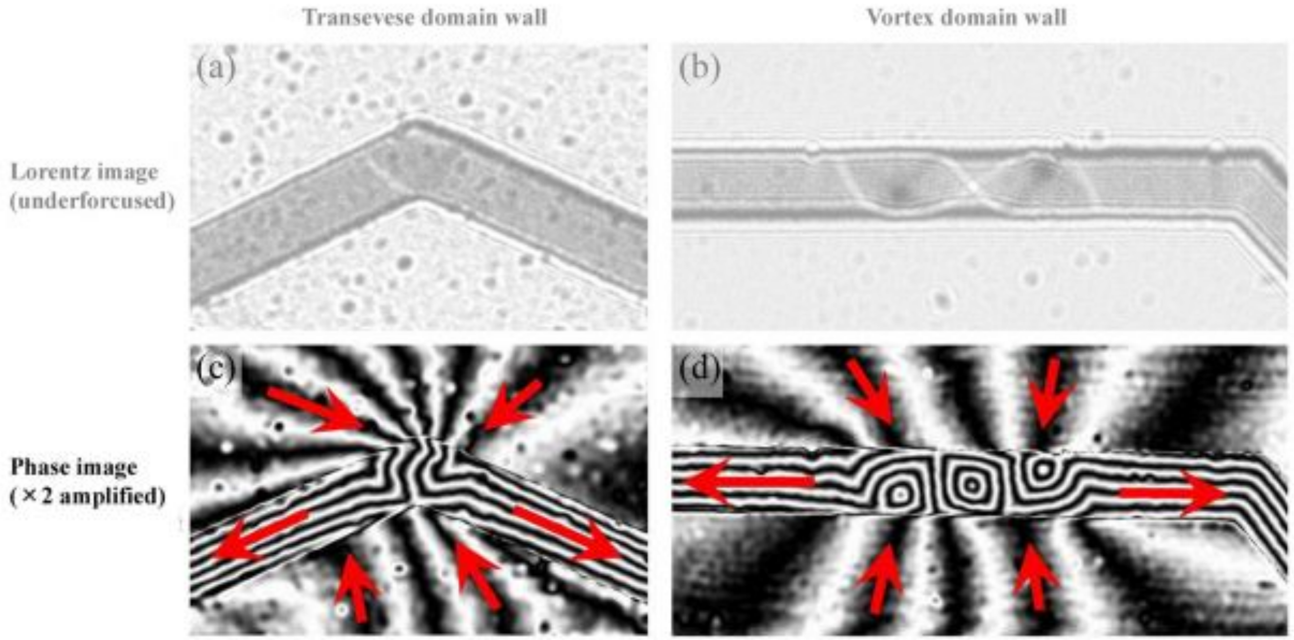
Electron holography:

Aharonov–Bohm effect:

Electrically charged particle affected by an electromagnetic potential, which leads to a change in phase of the wavefunction of the particle.

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

→ In-plane components of magnetic field B



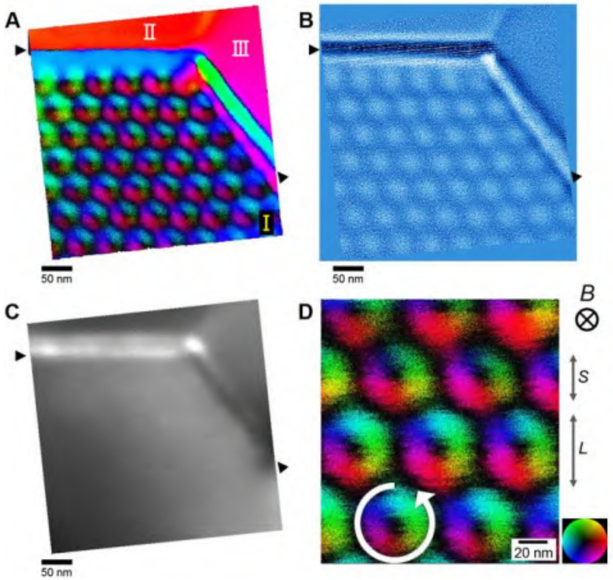
Togawa et al., Proc. SPIE 7036, Spintronics, 703617 (2008)

Spatial resolution: single digit nm

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

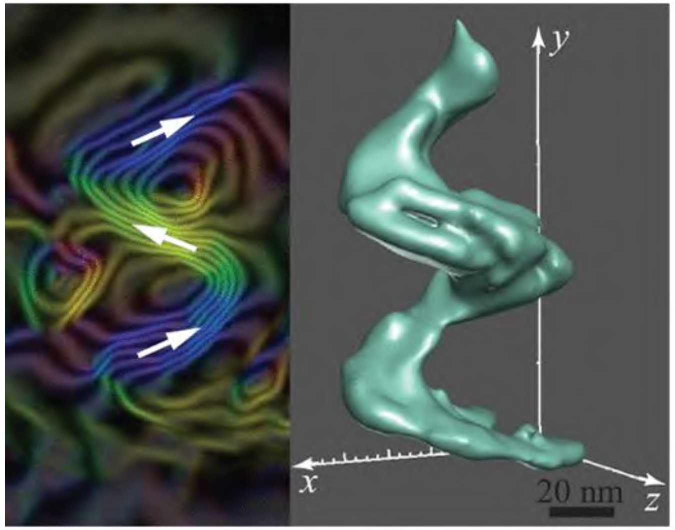
MAGNETIC TEM: ELECTRON HOLOGRAPHY

Magnetic skyrmions



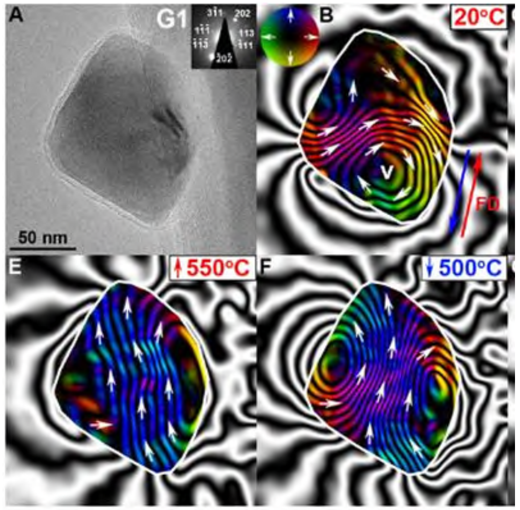
Matsumoto et al., Science Advances (2016)

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)

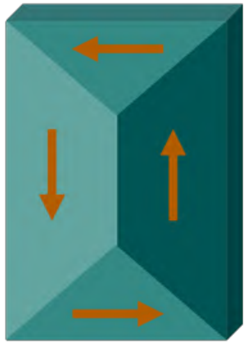
- Probe of induction perpendicular to direction of propagation of electrons

- 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	***Electron microscopy***	***X-ray microscopy***

IN THE LAB: MAGNETO-OPTICS

Durham Magneto Optics

Evico Magnetics

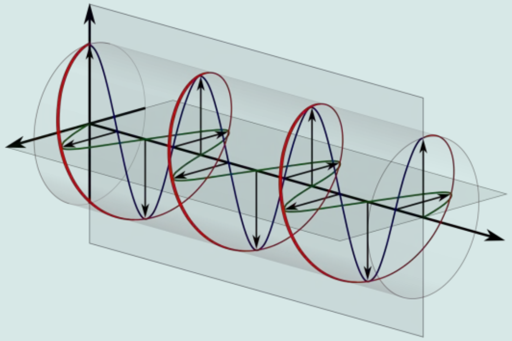
Table-top setup

Laser as source of photons

Relatively low cost, accessible

OBSERVING DOMAINS: MAGNETO-OPTICS

Circular polarised light:

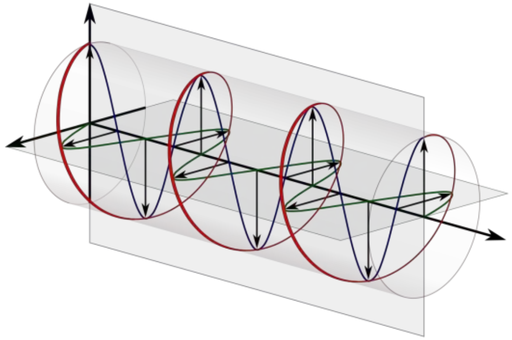


Coupling of the
photon's angular momentum
to
angular momentum of an electron

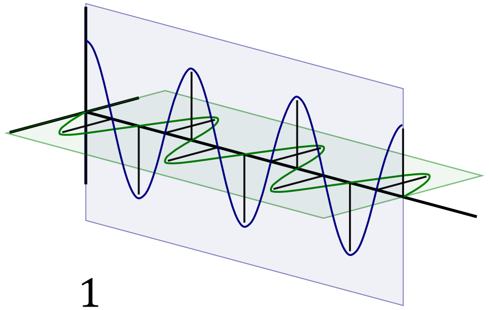
Angular momentum = $\pm\hbar$

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

Circular polarised light:

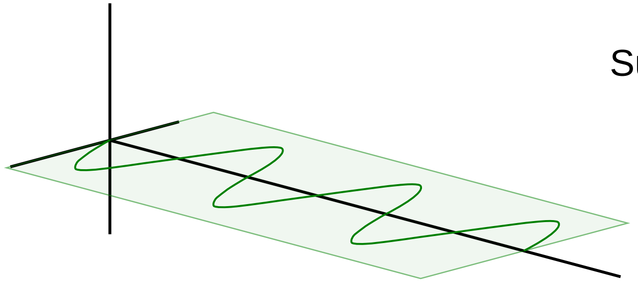


Superposition of linear H and V



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

Linear polarised light:



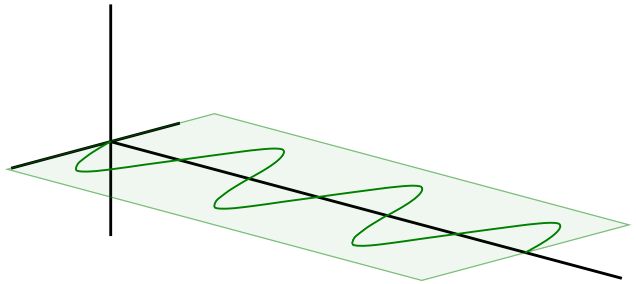
Superposition of circular C+ and C-

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

OBSERVING DOMAINS: MAGNETO-OPTICS

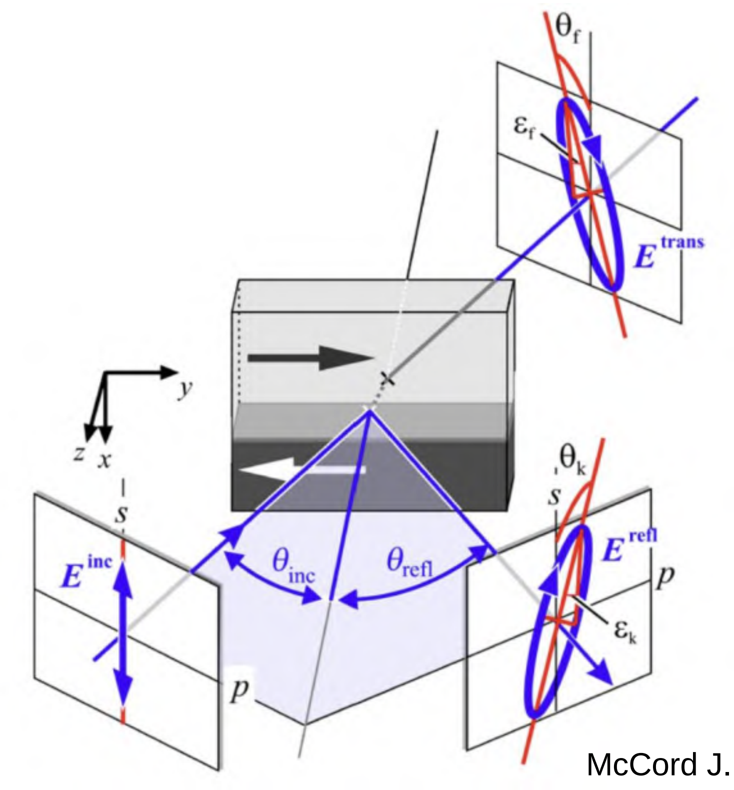
In transmission: Faraday effect

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

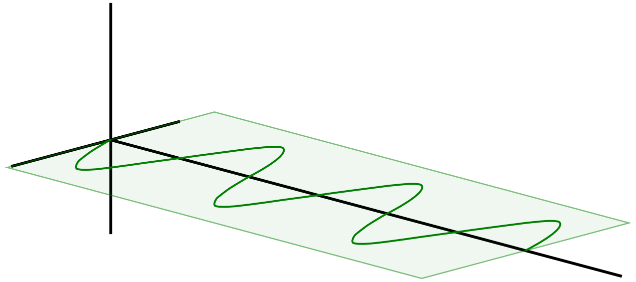
In reflection: Kerr effect

Spatial resolution:

limited by wavelength of light
~hundreds of nanometres

OBSERVING DOMAINS: MAGNETO-OPTICS

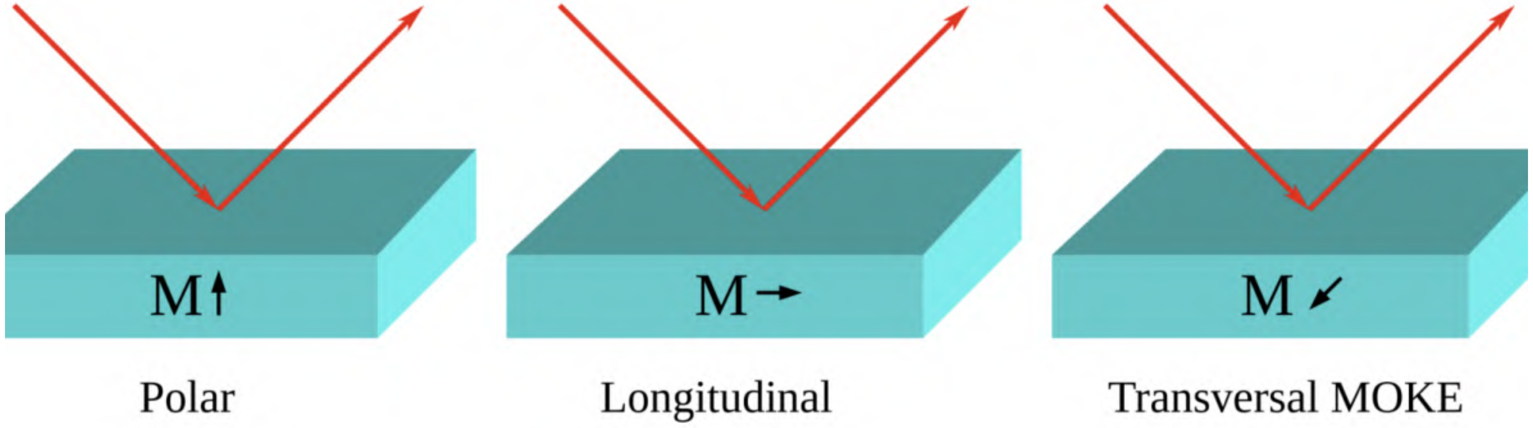
Linear polarised light incident on magnetic material:



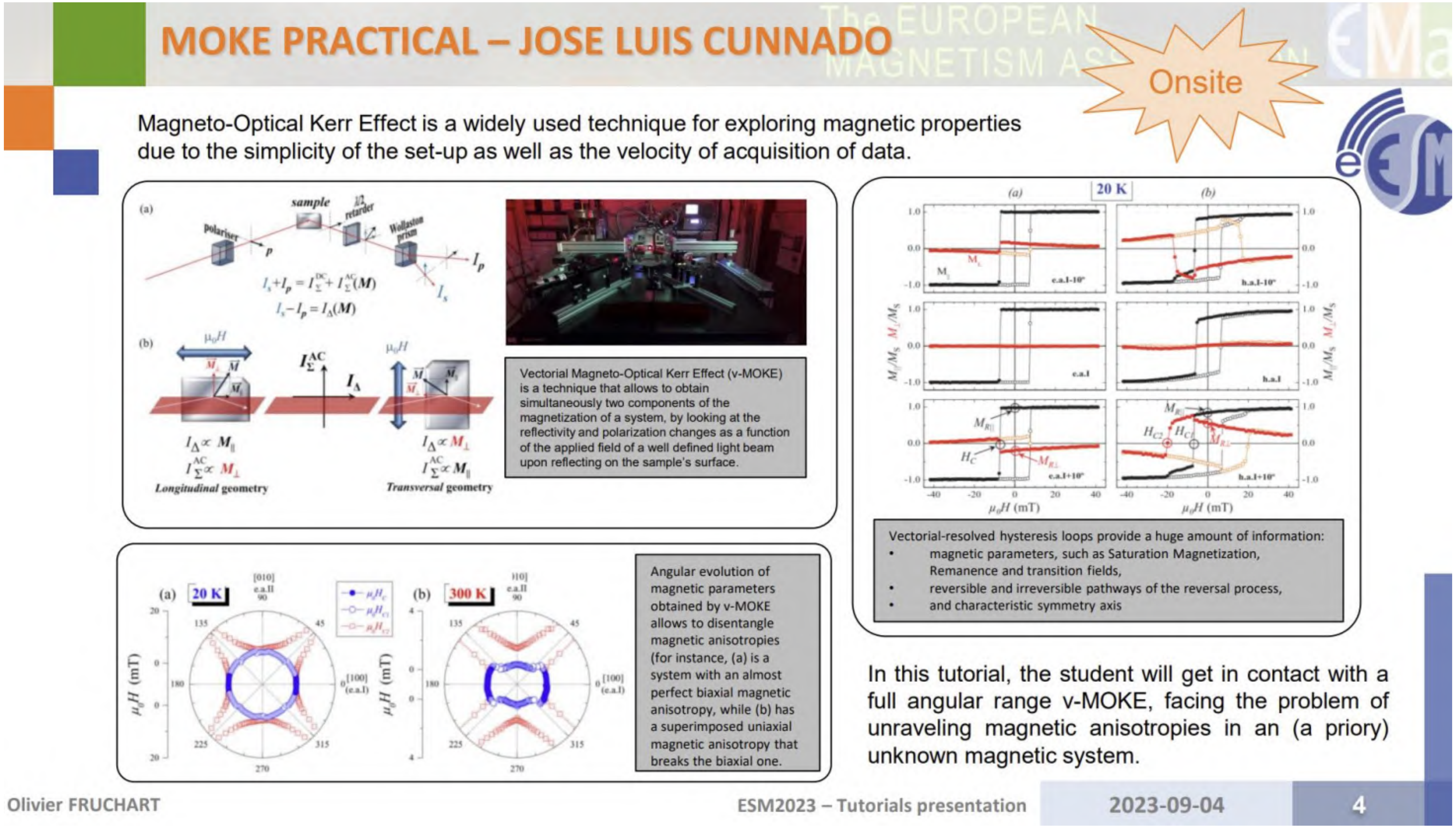
→ *Rotation* of the linear polarisation
→ Ellipticity of the light

Measure this rotation → probe the magnetisation // k

Vector information:



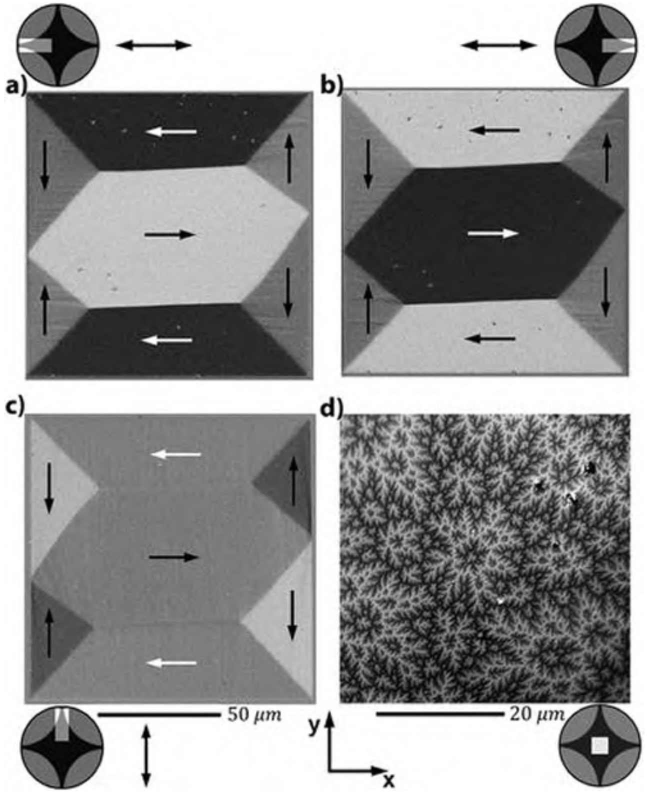
OBSERVING DOMAINS: MAGNETO-OPTICS



MOKE MICROSCOPY

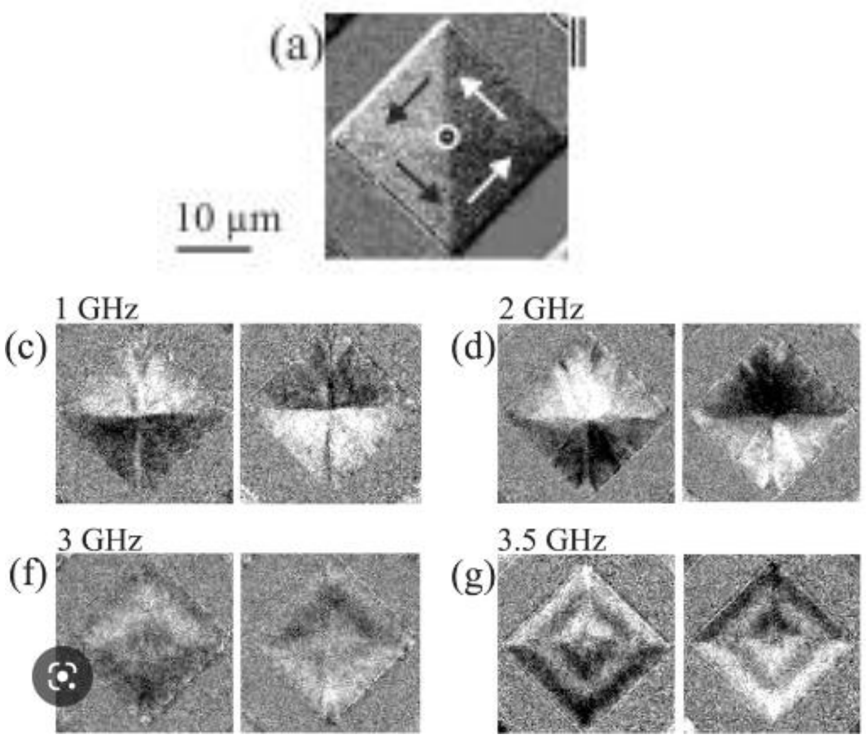
MOKE signal depends on **k**

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)

Q & A:
WHAT IS THE PENETRATION DEPTH FOR KERR.
HOW TO OBSERVE A DOMAIN WALL AT THE INTERFACE WITH A THICKER FILM, SAY, 40NM?

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

→ Can probe thin materials & multilayers

→ 40 nm: perhaps better to go for X-rays

Sensitivity limit:

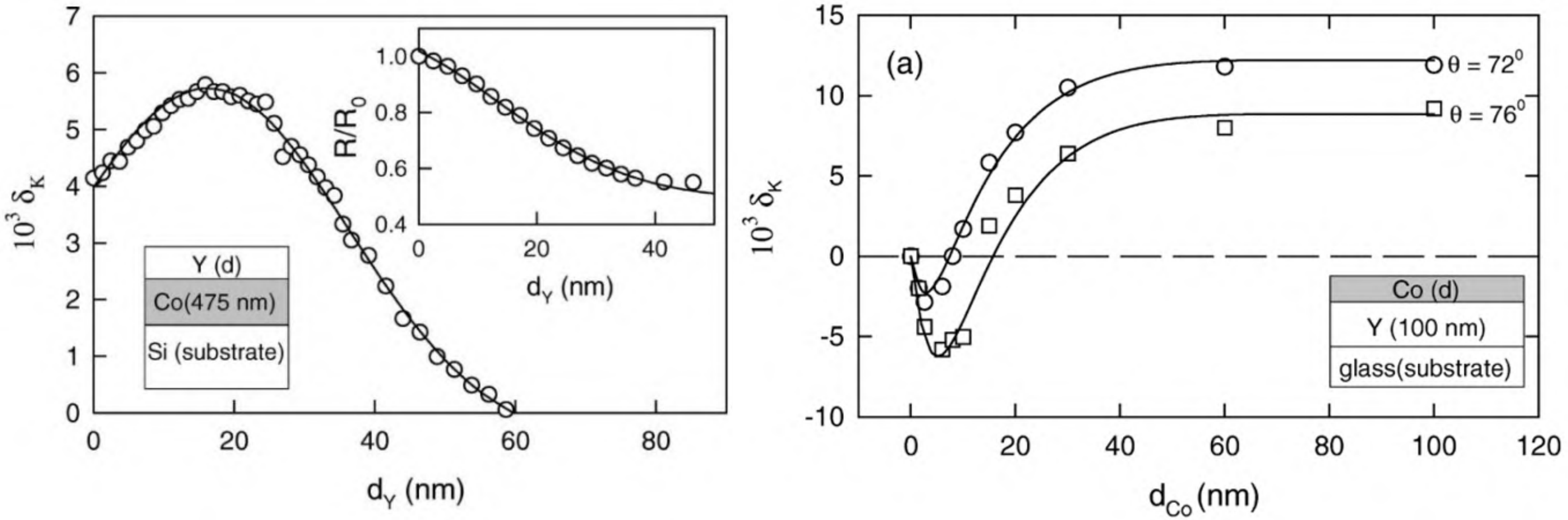
MOKE signal disappears for

> 40 nm of capping layer

MOKE signal plateaus for

> 40 nm of Co layer

Dehesa-Martinez et al., PRB 64, 024417 (2000)



MAGNETO-OPTICAL MICROSCOPY

Take Home Messages of Magneto-Optical Microscopy

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

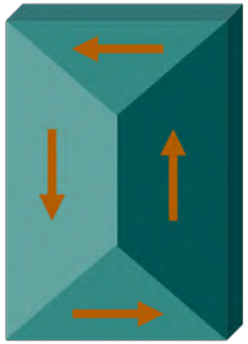
- Can distinguish orientations of the magnetisation!

- 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

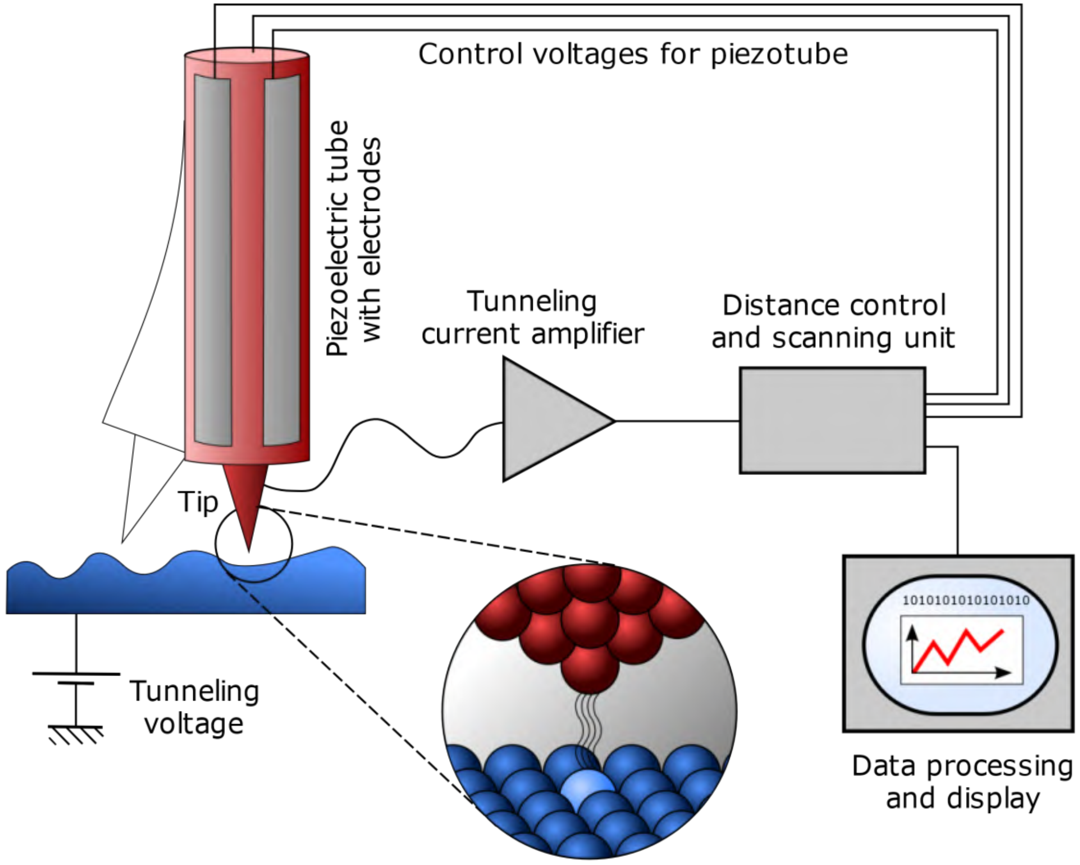
$$B = \mu_0(M + H)$$

Optical techniques

Electron microscopy

X-ray microscopy

SPIN POLARISED SCANNING TUNNELLING MICROSCOPY



https://en.wikipedia.org/wiki/Scanning_tunneling_microscope

- → Voltage applied between tip and sample
- → Electrons tunnel from tip to sample.
- → Highly sensitive to distance to tip, and material
- → Tip-sample separation: ~0.4 – 0.7 nm
- → Spatial resolution: 0.1 nm!

SPIN POLARISED SCANNING TUNNELLING MICROSCOPY

→ Voltage applied between tip and sample

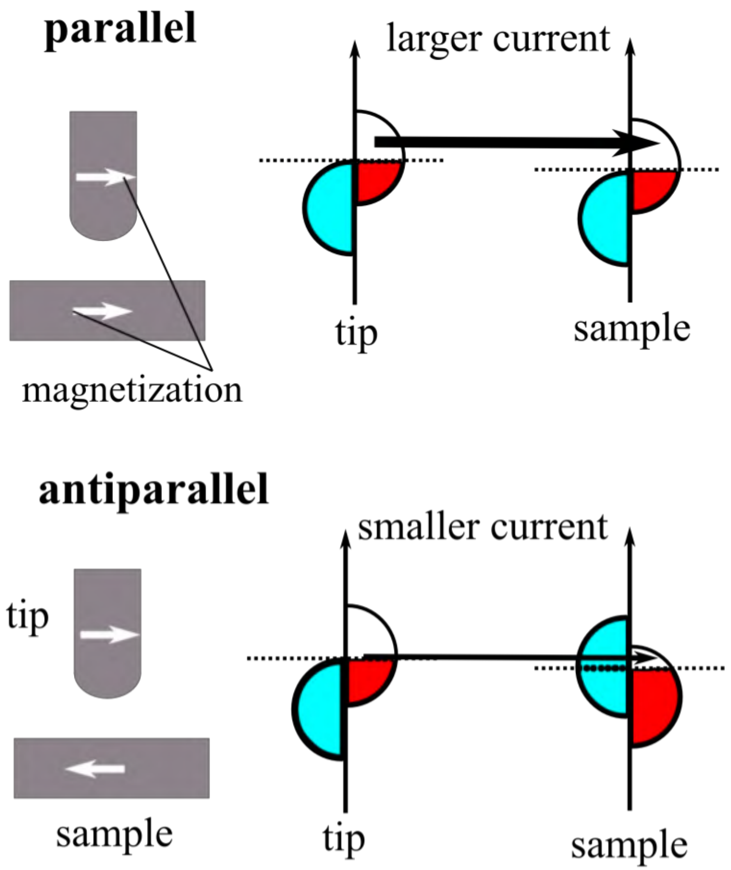
→ Electrons tunnel from tip to sample.

→ Highly sensitive to distance to tip, and material

→ Tip-sample separation: ~0.4 – 0.7 nm

→ Spatial resolution: 0.1 nm!

→ **Tunnelling probability higher if magnetisation of tip parallel to magnetisation of sample**



By ST_surf, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=70795756

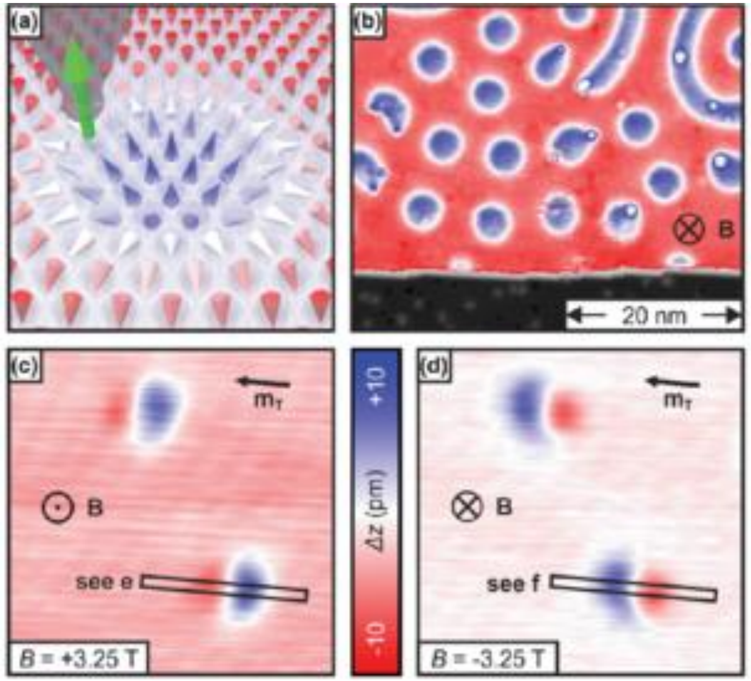
Atomic magnetic resolution requires:
- Atomically sharp, spin polarised tip
- Direction of moment well defined
- Low enough moment to not disturb sample

→ Ultra high vacuum, high stability

SPIN POLARISED STM

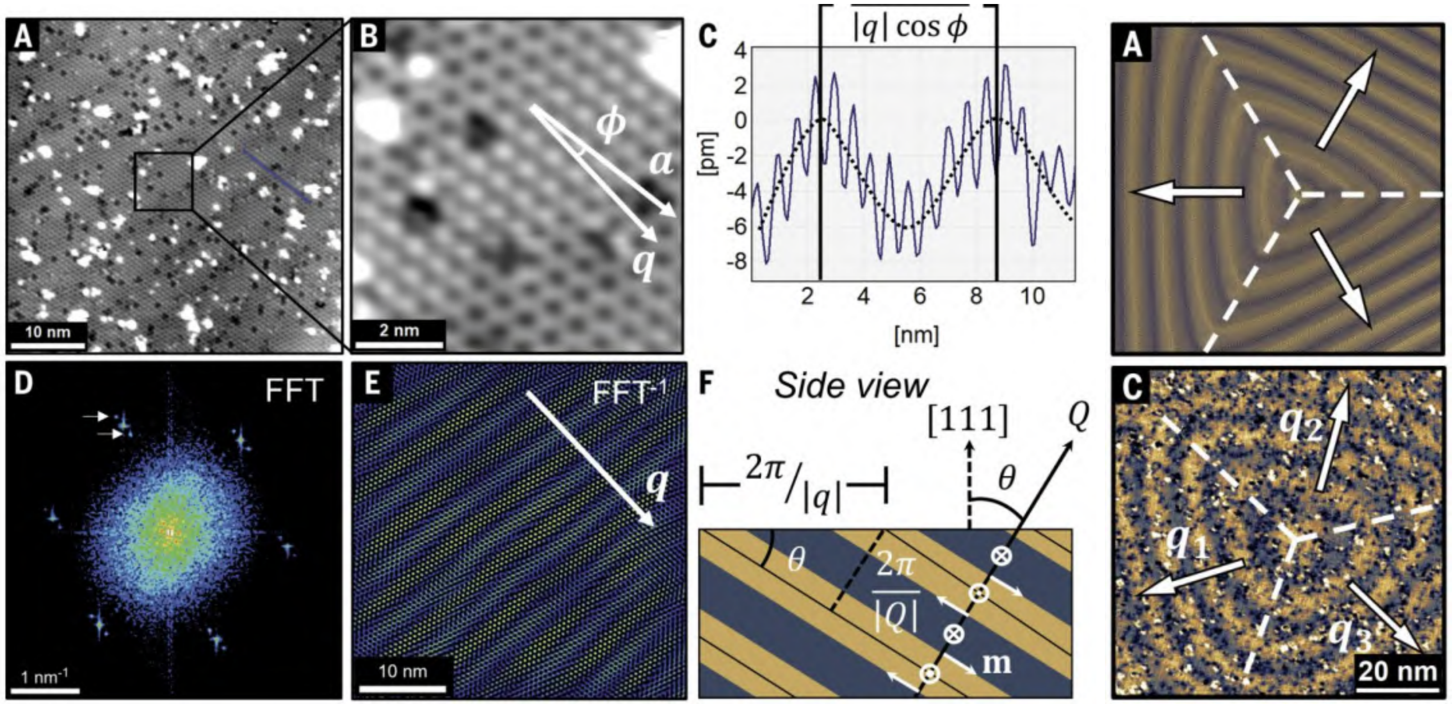
High resolution (atomic scale!) magnetic imaging of…

Skyrmions in ultra-thin PdFe/Ir(111)



Romming et al., Phys. Rev. Lett. **114**, 177203 (2015)

Helical textures in MnGe



Repicky et al., Science

SPIN POLARISED SCANNING TUNNELLING MICROSCOPY

Take Home Messages of Spin Polarised STM

- *High spatial resolution imaging of magnetisation*
- *Can resolve atomic lattice*
- *Highly surface sensitive → 0.1 nm*
- *Highly sensitive*

– Specialised, UHV equipment

	Spin Pol. STM
Contrast	$\boldsymbol{m}$
Spatial resolution	0.1 nm
Depth sensitivity	0.1 nm
Sample environment	Cryo, field
Invasive	No
Sensitivity	High
Cost/ accessibility	Lab-based, Specialised UHV equipment

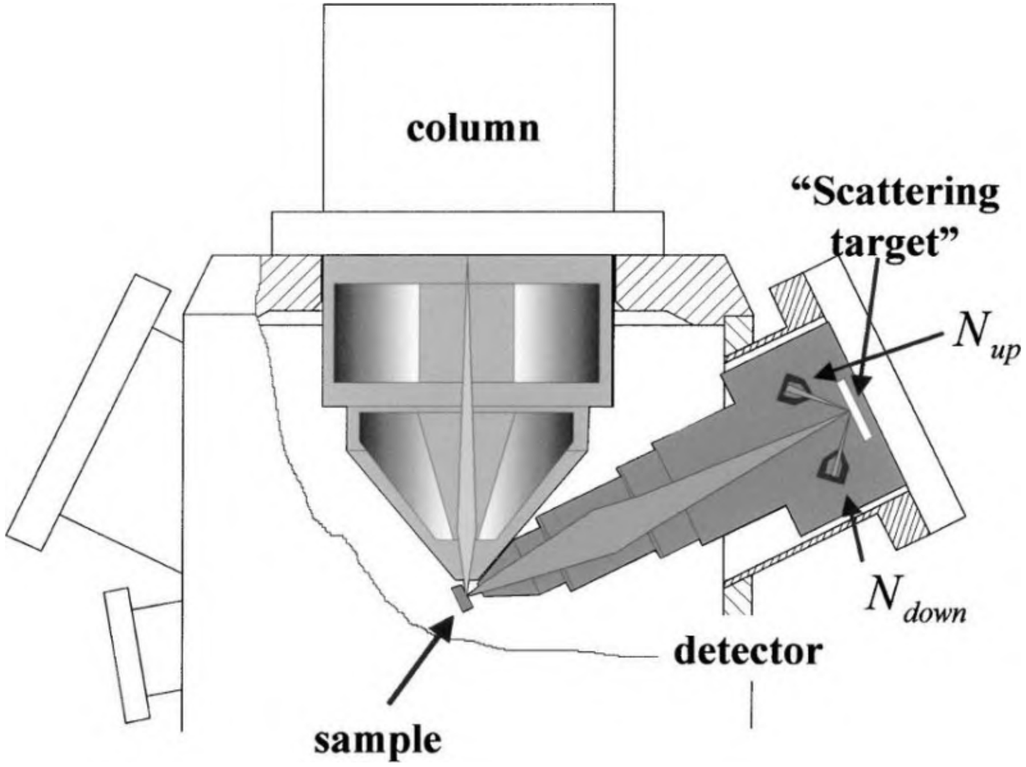
SEMPA: SCANNING ELECTRON MICROSCOPY WITH POLARISATION ANALYSIS

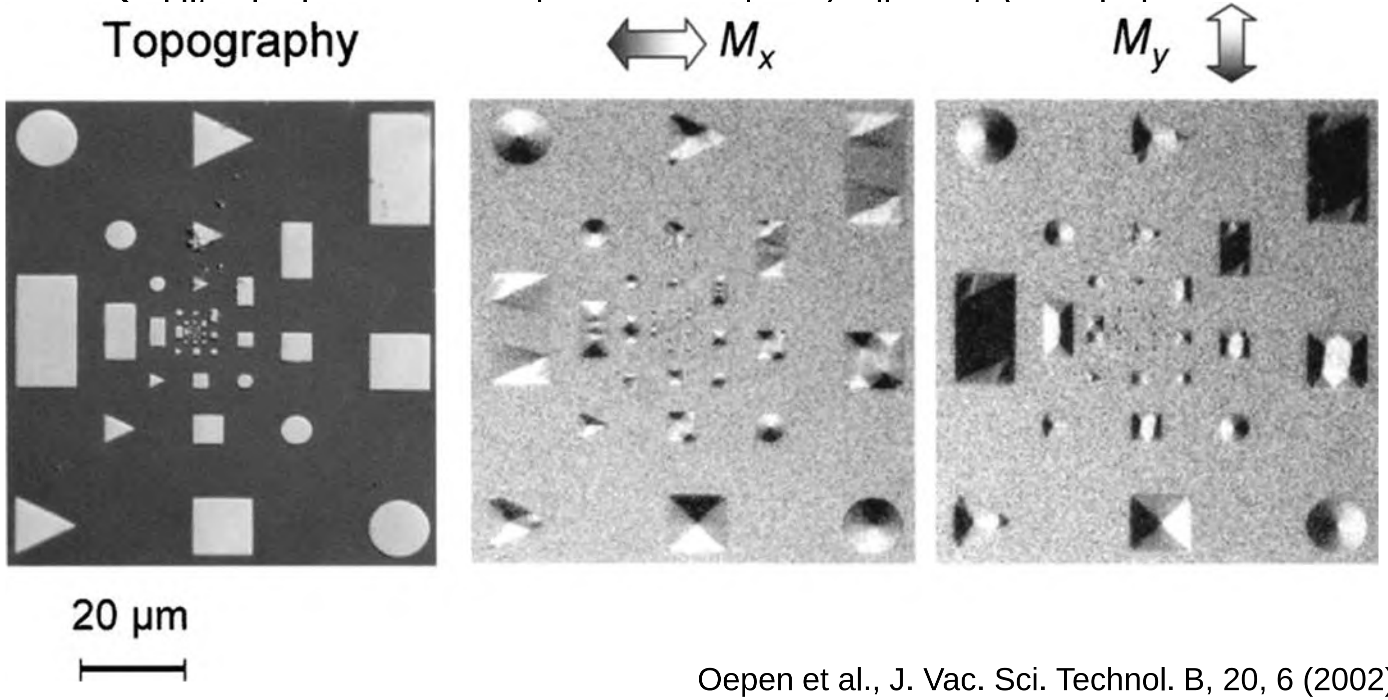
Scanning electron microscope + polarisation analyser

Polarisation of secondary electrons is related to **in-plane magnetisation of sample**

High spatial resolution: ~5 nm

Extremely surface sensitive: only top ~1 nm

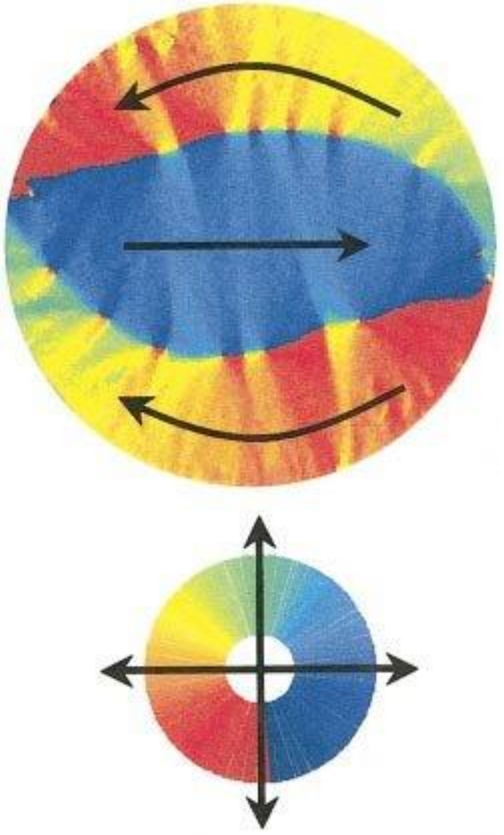




Oepen et al., J. Vac. Sci. Technol. B, 20, 6 (2002)

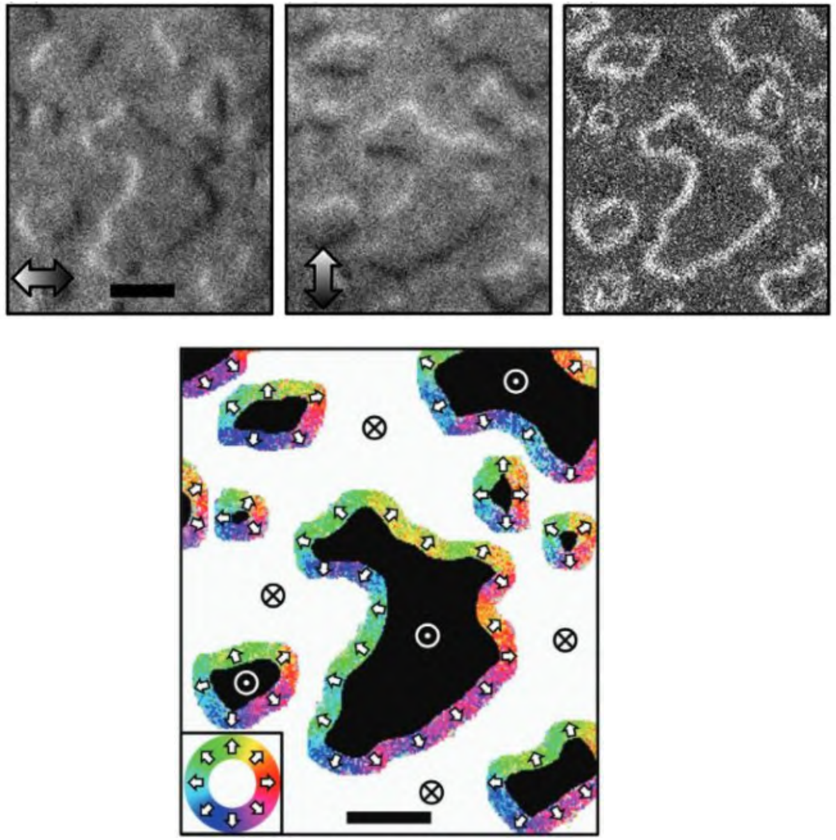
SEMPA: SCANNING ELECTRON MICROSCOPY WITH POLARISATION ANALYSIS

Cross-tie walls in microstructures



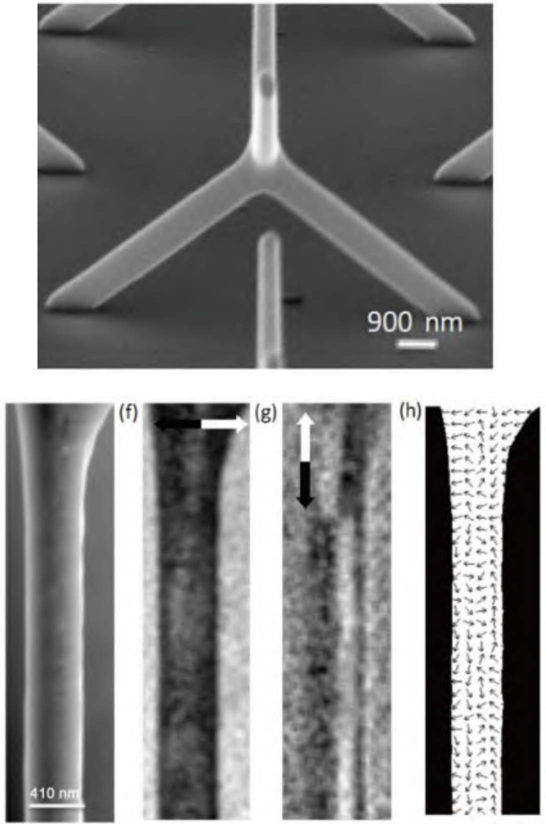
Oepen et al., J. Vac. Sci. Technol. B, 20, 6 (2002)

Mapping chiral domain walls & skyrmions



Seng et al., Adv. Funct. Mat., 31, 2102307 (2021)

Measuring 3D magnetic nanostructures



Williams et al., Nano Research 11, 845 (2018)

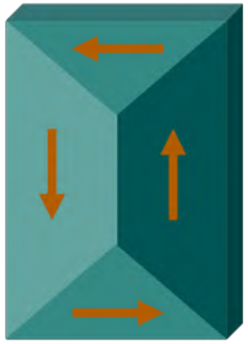
SCANNING ELECTRON MICROSCOPY WITH POLARISATION ANALYSIS

Take Home Messages of SEMPA

- *High spatial resolution imaging of magnetisation*
- *Highly surface sensitive → 1 nm*
- *Highly sensitive*
- *– Specialised, UHV equipment*

	SEMPA
Contrast	$\boldsymbol{m}$
Spatial resolution	~5 nm
Depth sensitivity	1 nm
Sample environment	Challenging, UHV & preparation required
Invasive	No
Sensitivity	High
Cost/ accessibility	Lab-based, Specialised UHV equipment

B probes



M probes

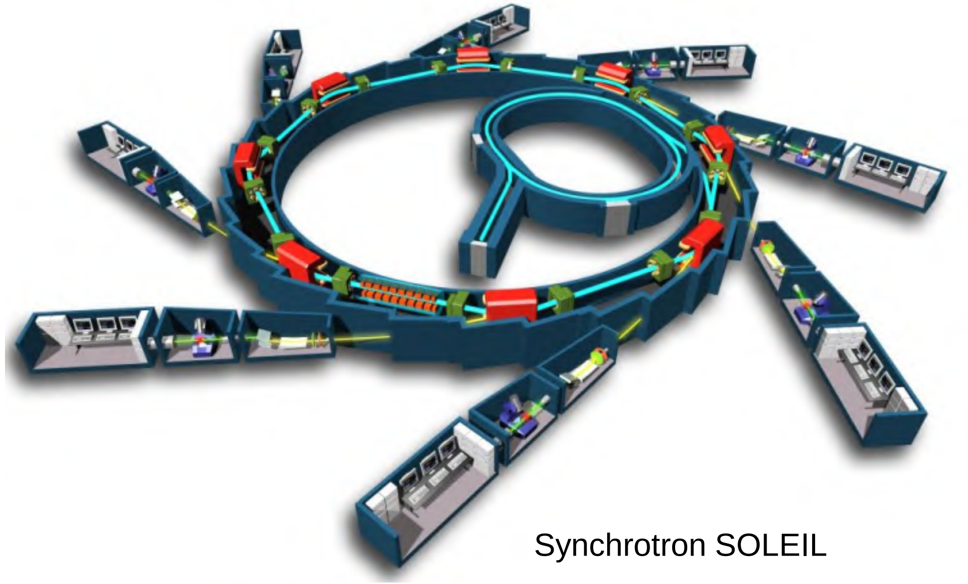
$$B = \mu_0(M + H)$$

Optical techniques	*Electron microscopy*	***X-ray microscopy***

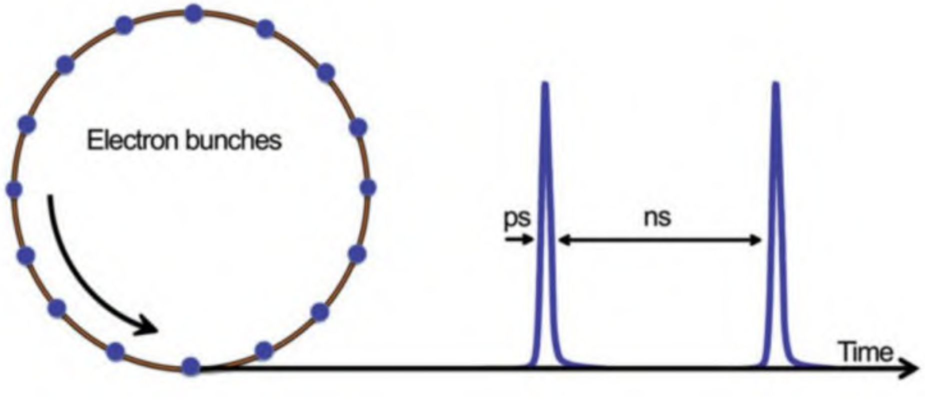
LARGE SCALE FACILITIES: SYNCHROTRON X-RAYS

Synchrotron light sources:

Swiss Light Source, PSI



Synchrotron SOLEIL



Balerna, Mobilio Intro. Synch. Rad

MAGNETIC MICROSCOPY @ SYNCHROTRONS

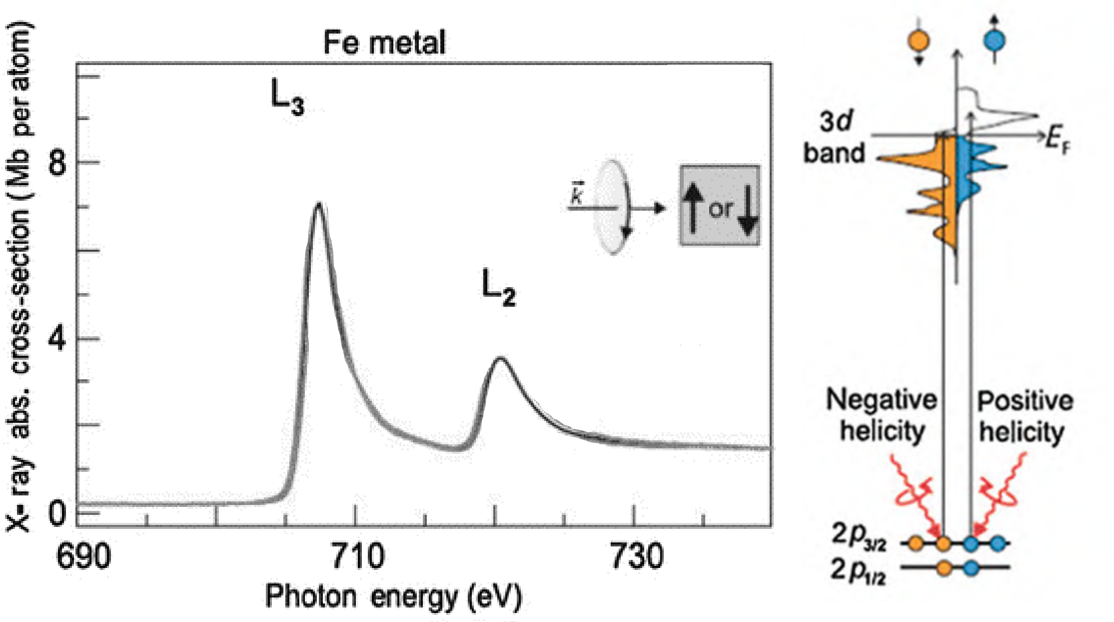
Synchrotron X-ray microscopy

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 m!

MAGNETIC MICROSCOPY: X-RAYS

Question!

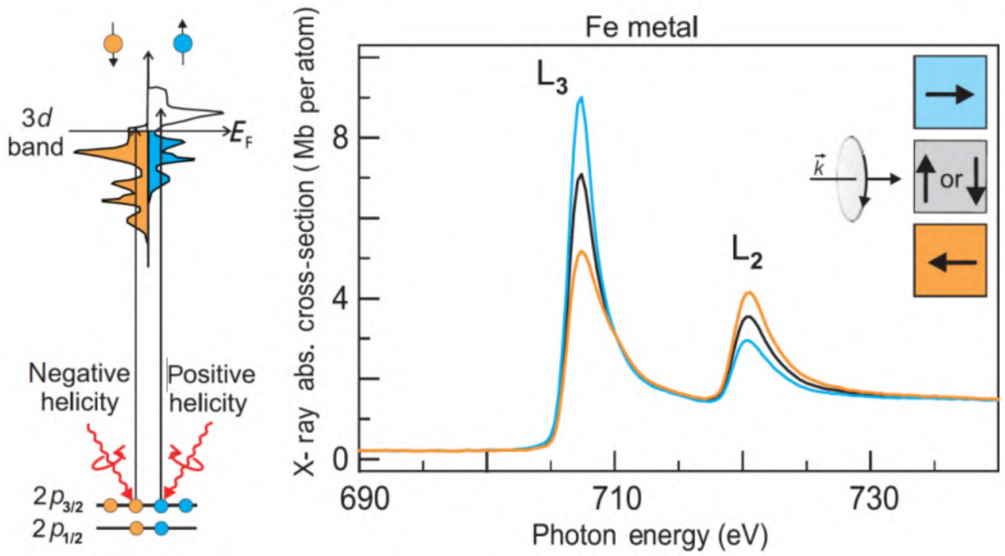
*Which direction of **m** are we sensitive to?*

MAGNETIC MICROSCOPY: X-RAYS

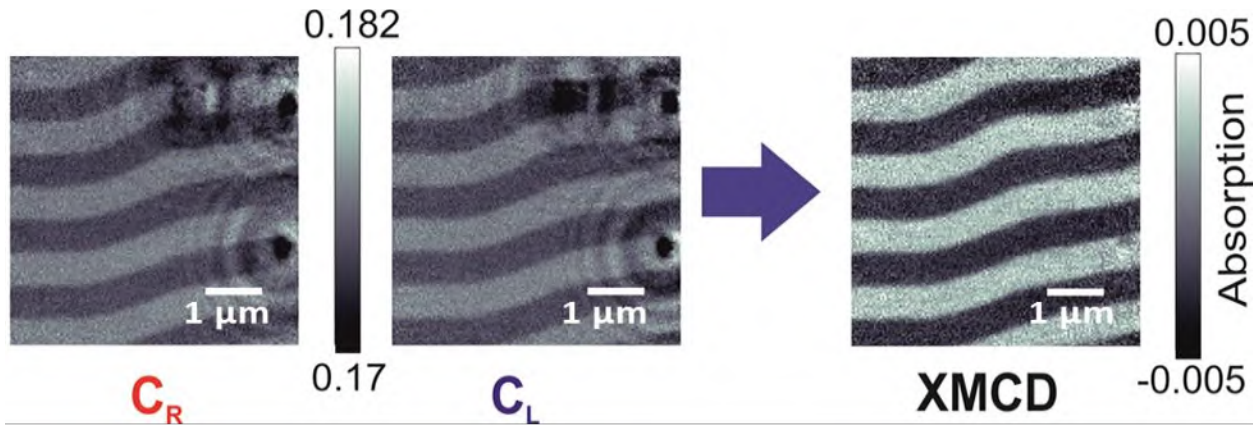
X-rays: X-ray magnetic circular dichroism
Circular polarised light: angular momentum $\pm\hbar$

This time, resonant!

- Element specific
- Can penetrate thicker samples



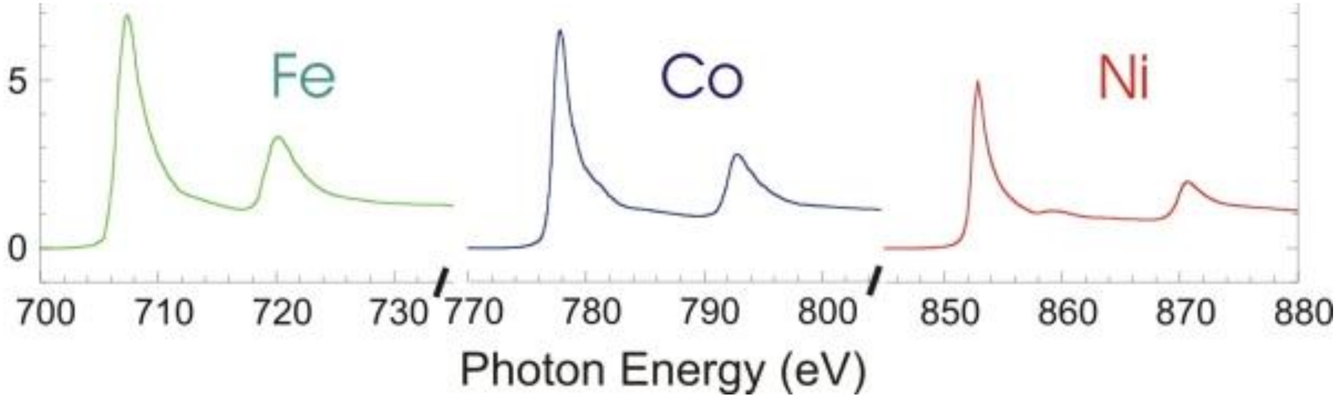
Stöhr & Siegmann, Magnetism, From fundamentals to Nanoscale Dynamics, Springer (2006)



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

X-RAY MAGNETIC CIRCULAR DICHROISM: ELEMENT SPECIFICITY

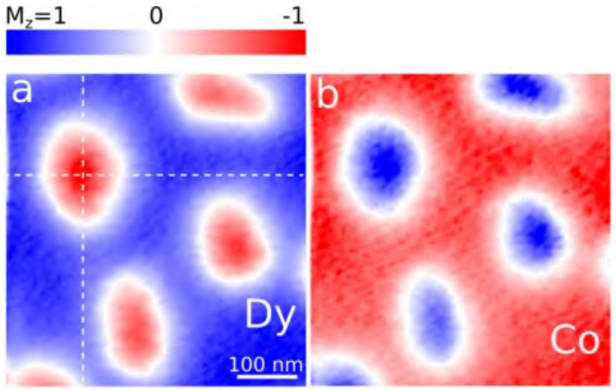
Key Advantage of X-rays: Element specificity



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

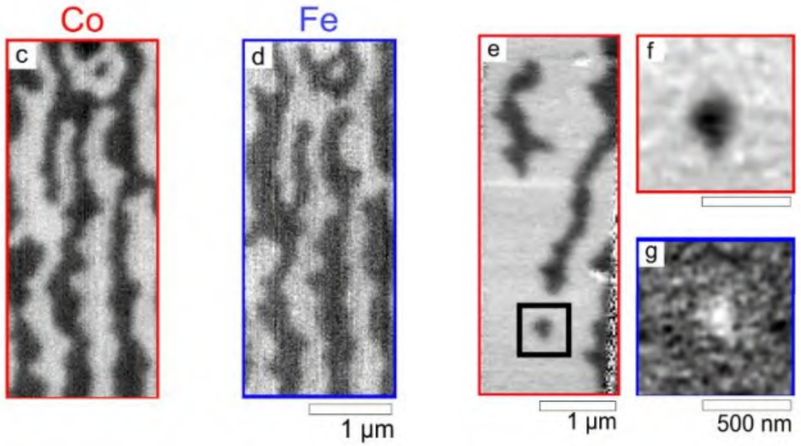
→ Different elements can be targeted separately

For ferrimagnets:
Ferrimagnetic skyrmions in DyCo_3 film



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

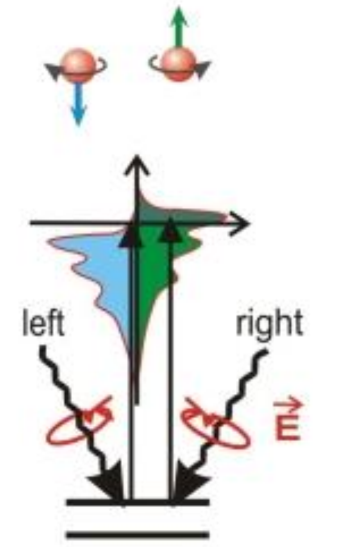
And synthetic antiferromagnets:
Synthetic antiferromagnetic skyrmion:

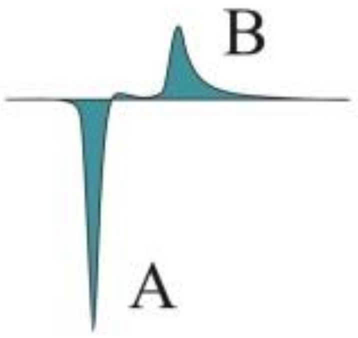


Juge et al., Nat. Comm. **13**, 4807 (2022)

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***

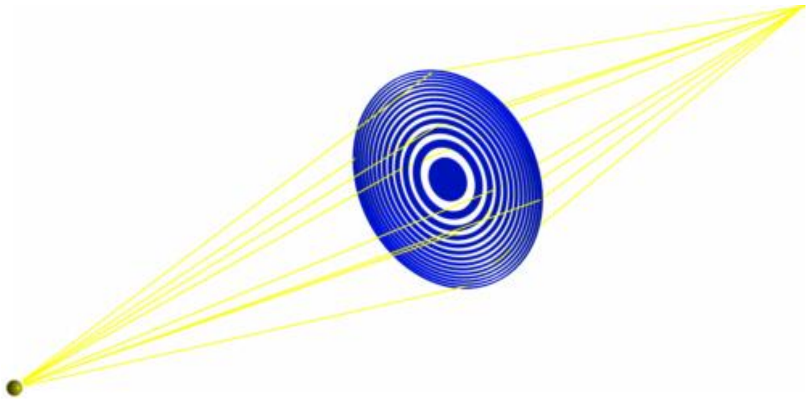
And the microscopy?

MAGNETIC MICROSCOPY: X-RAYS

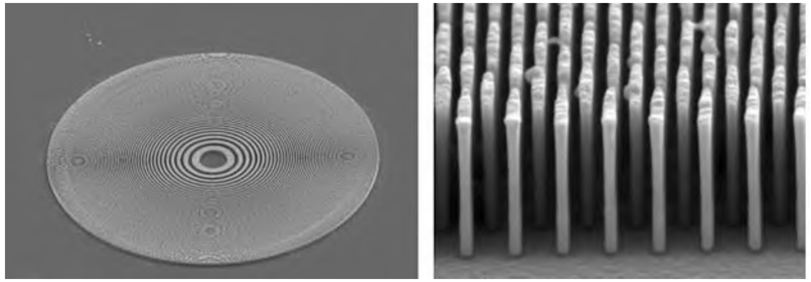
Advantage of X-rays: highly penetrating, so can look through “thick” samples

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

Fresnel Zone Plate:

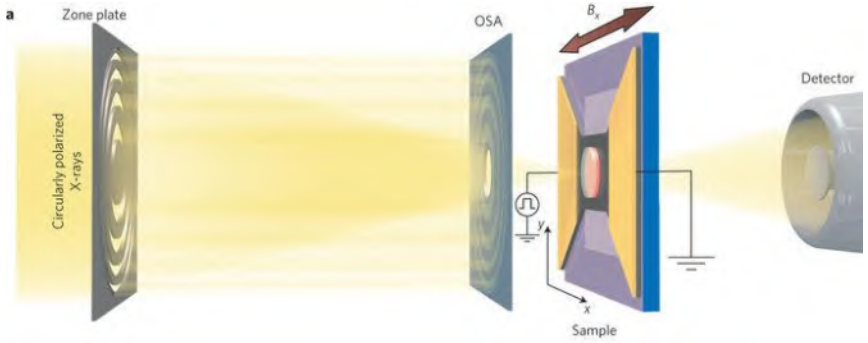


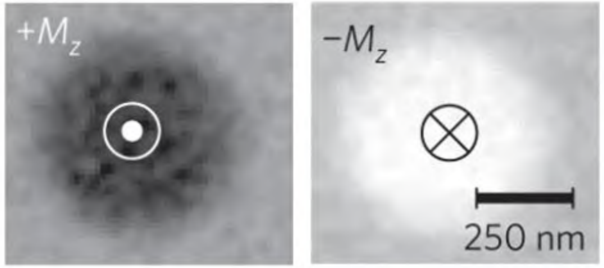
Nanofabrication determines spatial resolution



STXM

(Scanning Transmission X-ray Microscopy)



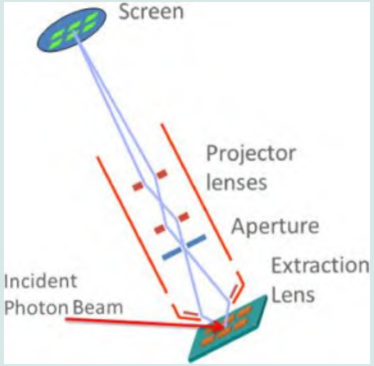


Baumgartner et al., Nat. Nano. **12**, 980 (2017)

MAGNETIC MICROSCOPY: X-RAYS

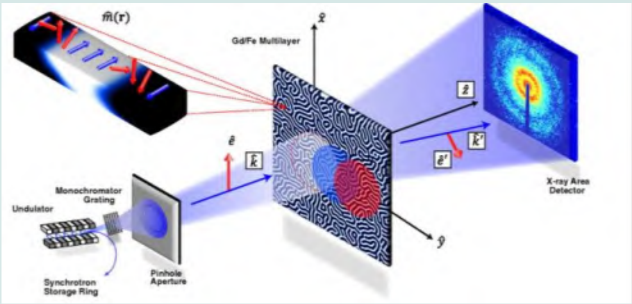
Alternative ways to obtain high resolution:

Photo emission electron microscopy



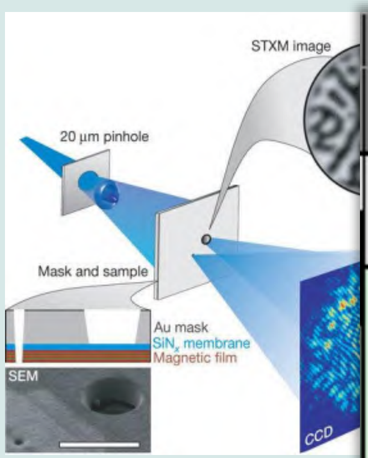
Cheng et al., Rep. Progr. Phys. **25**, 2 (2012)

Coherent diffractive imaging



Tripathi et al., PNAS **108**, 33 (2011)

Holography

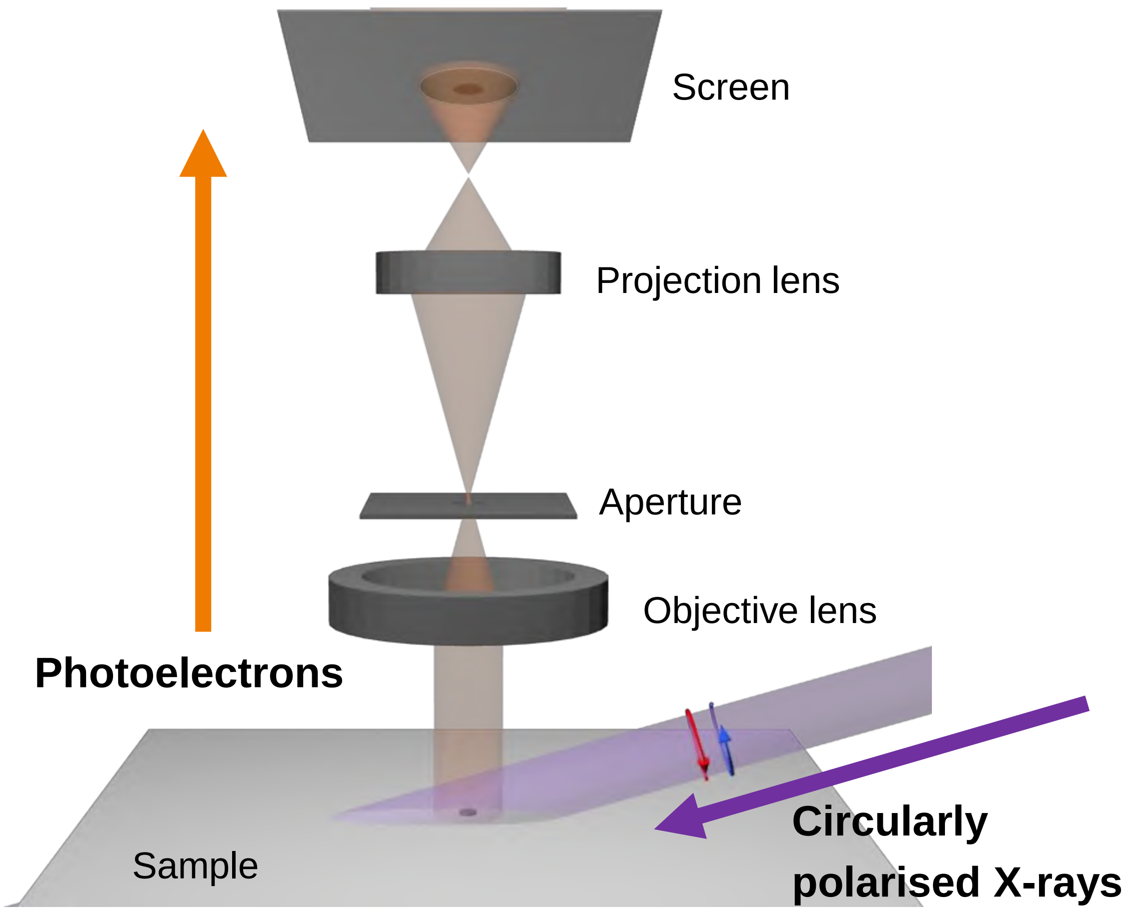


Eisebitt et al., Nature **432**, 8

Spatial resolution: not limited by wavelength! But by signal/ focusing optics, depending on techni

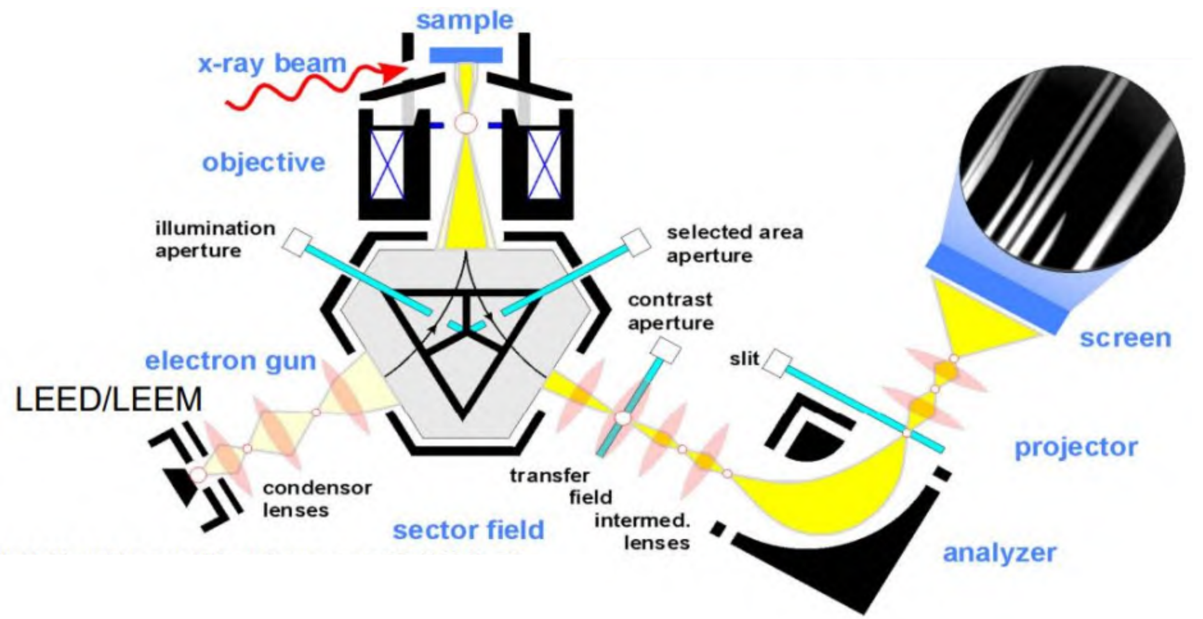
~ 20 nm routinely achievable

PEEM: PHOTO EMISSION ELECTRON MICROSCOPY



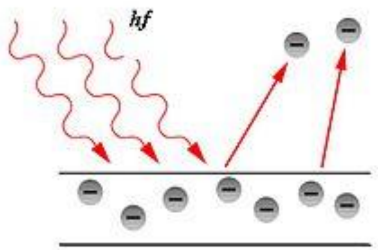
Donnelly & Scagnoli, J. Phys. D. (2020)

In reality, much more complicated…
→ ask Sandra for more details :)



E. Bauer, Surface Microscopy with Low Energy Electrons, Springer, (2014)

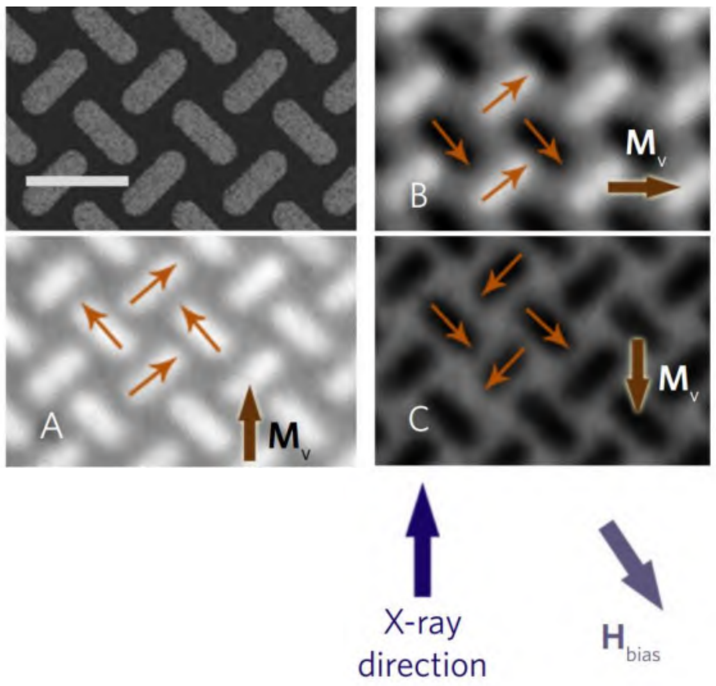
PEEM: PHOTO EMISSION ELECTRON MICROSCOPY



→ Surface sensitive technique:

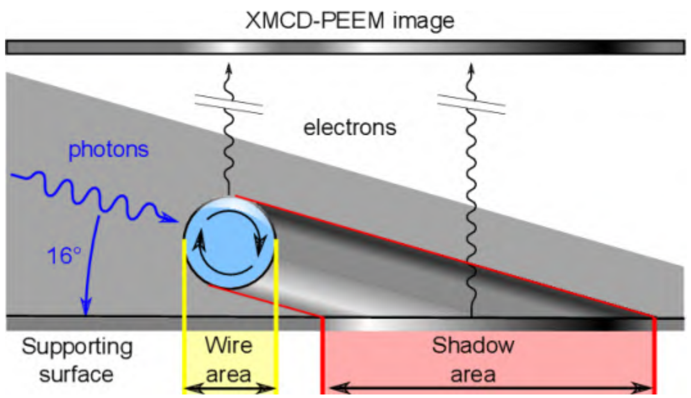
Depth determined by escape depth of electrons ~ few nm

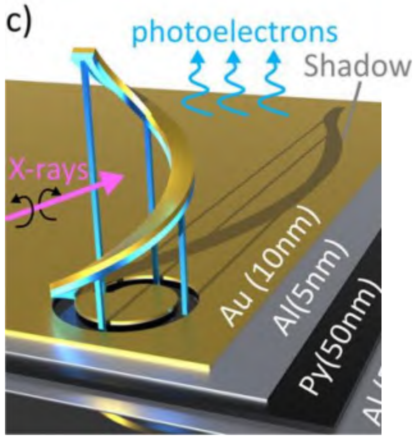
2D artificial spin ice ~2-3 nm thick:

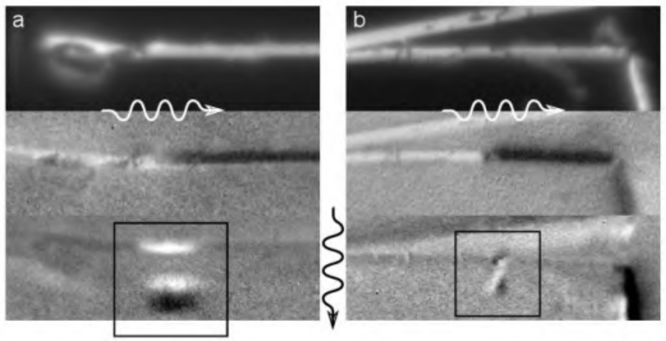


Gliga et al., Nature Materials (2017)

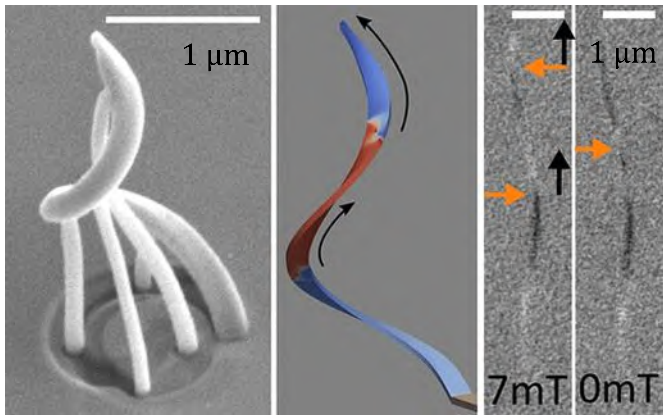
And for 3D structures – with shadow PEEM!







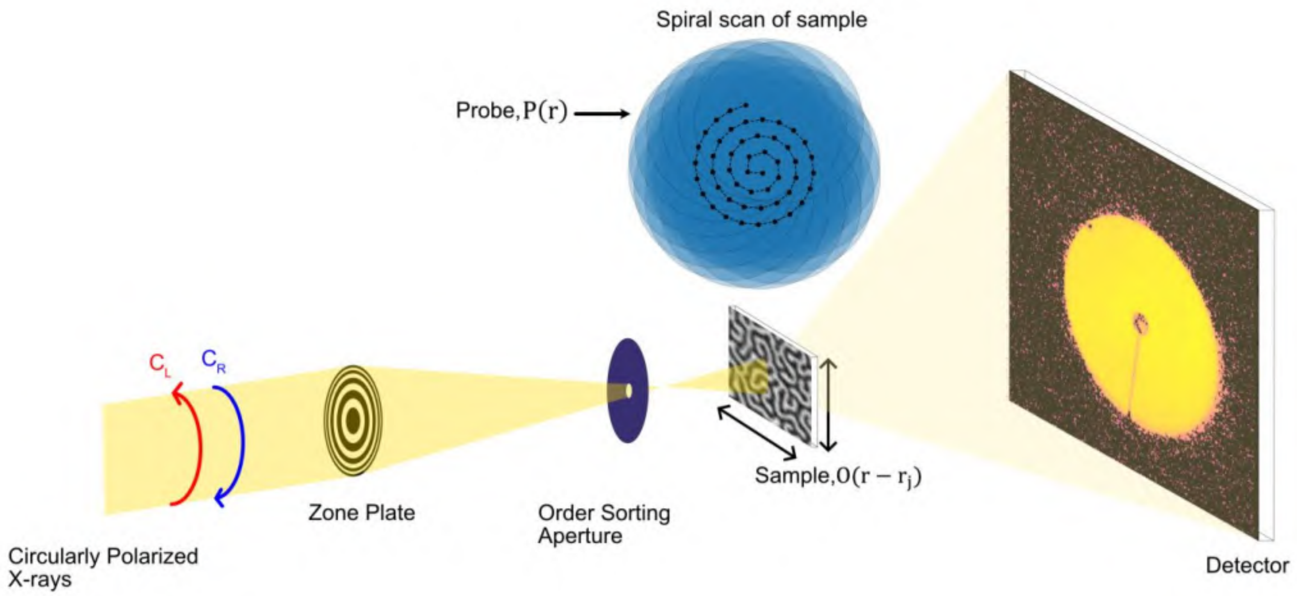
De Col et al. PRB (2013)



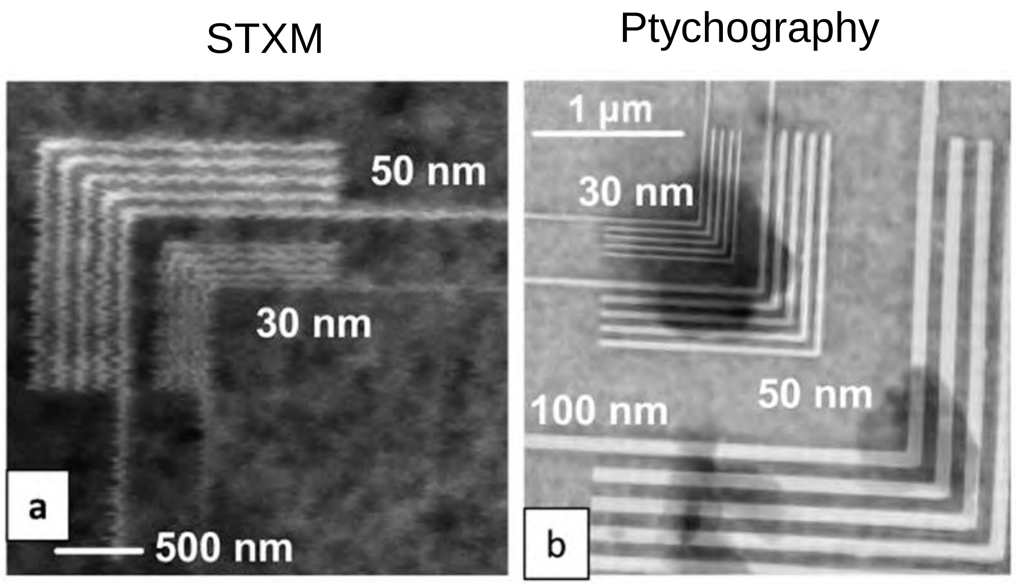
Skoric et al. ACS Nano (2022)

HIGH SPATIAL RESOLUTION: COHERENT DIFFRACTIVE IMAGING → *PTYCHOGRAPHY*

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



→ Reconstruct complex transmission function

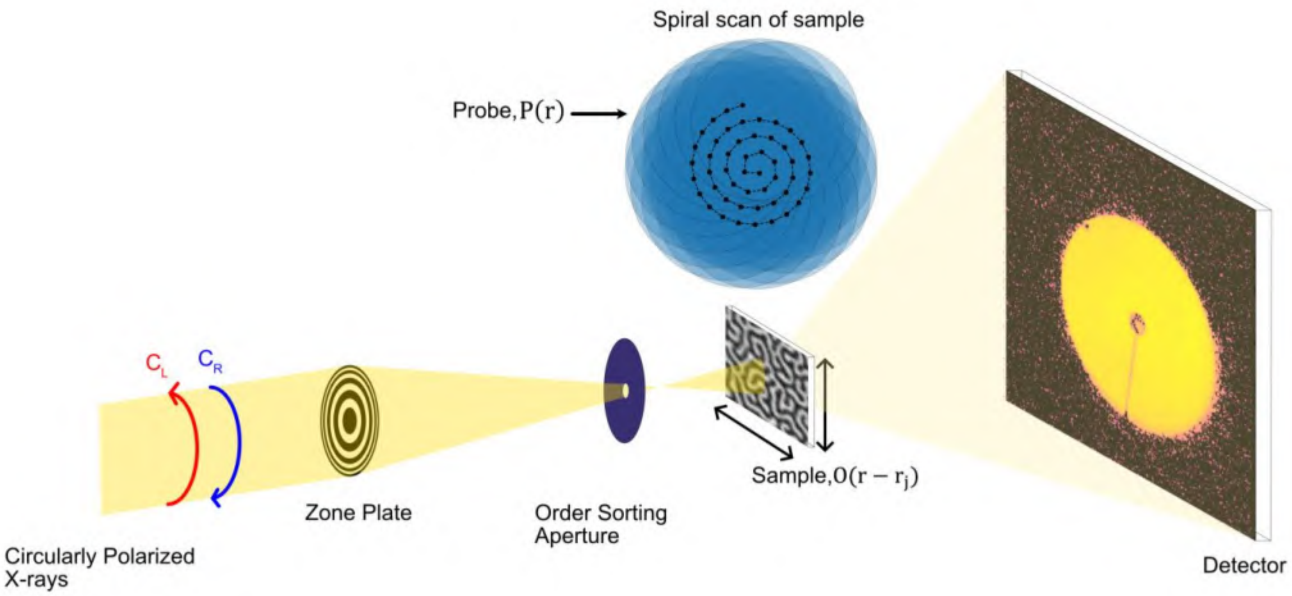


→ Significant increase in spatial resolution, sensitivity

Urqyuhart, ACS Omega 7, 11521 (2022)

DICHROIC X-RAY MAGNETIC PTYCHOGRAPHY

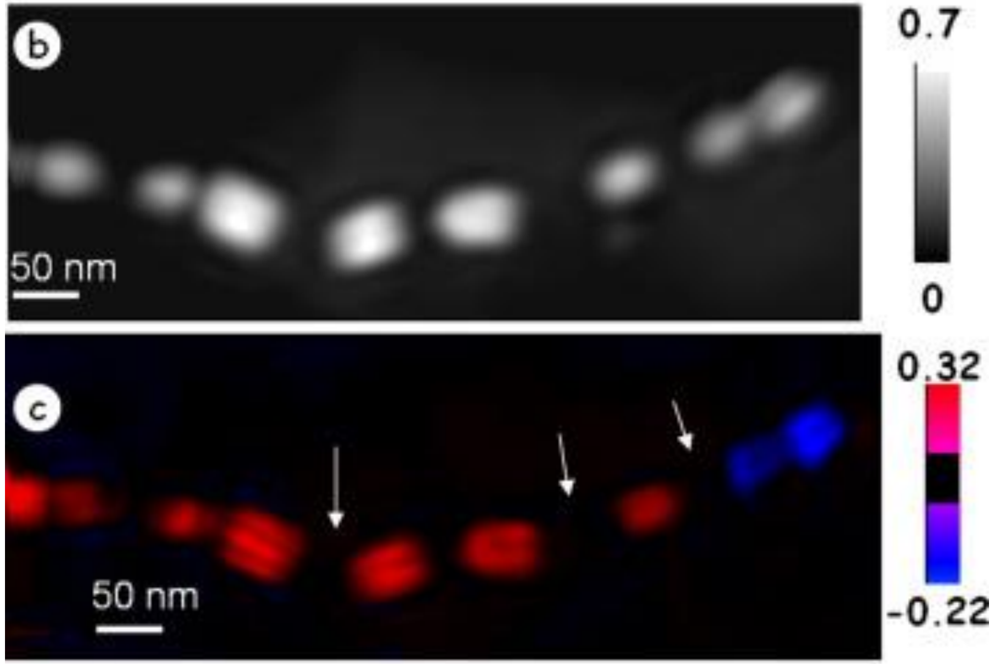
Take a large coherent beam, and measure coherent diffraction patterns for overlapping illuminations



→ Reconstruct complex transmission function

Apply to magnetic imaging:

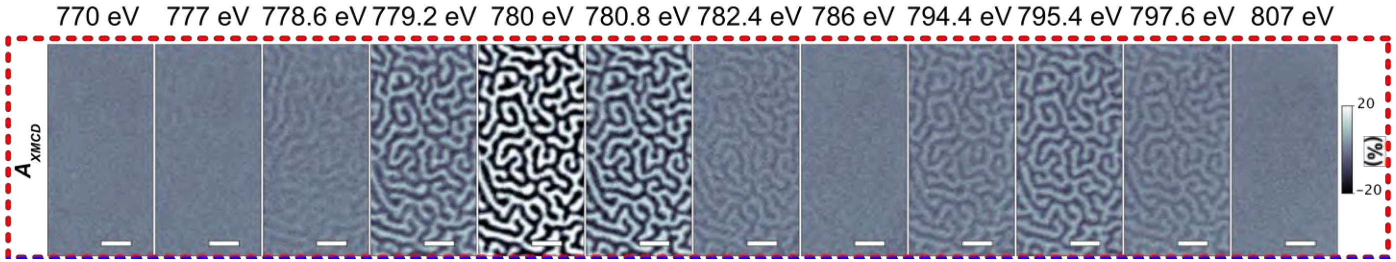
7 nm spatial resolution imaging of magnetotactic bacteria:



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

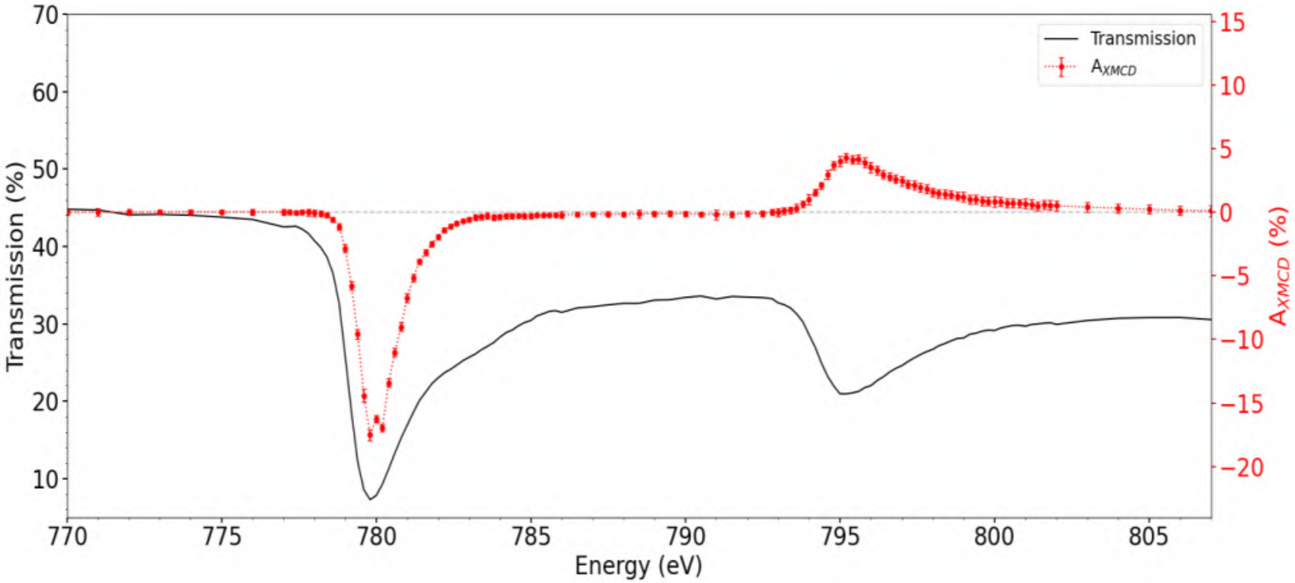
DICHROIC X-RAY MAGNETIC PTYCHOGRAPHY

Jeffrey Neethirajan



Co/Pt Multilayer
Grown by Ales Hrabec

Soft X-ray spectro-ptychography:
I08 @ Diamond



Absorption XMCD contrast
→ at maximum absorption

Complex XMCD:
Phase contrast across energy spectrum

Scherz et al., PRB **76**, 214410 (2007)
Donnelly et al., PRB **94**, 064421 (2016)
Neethirajan et al., *Submitted*

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…

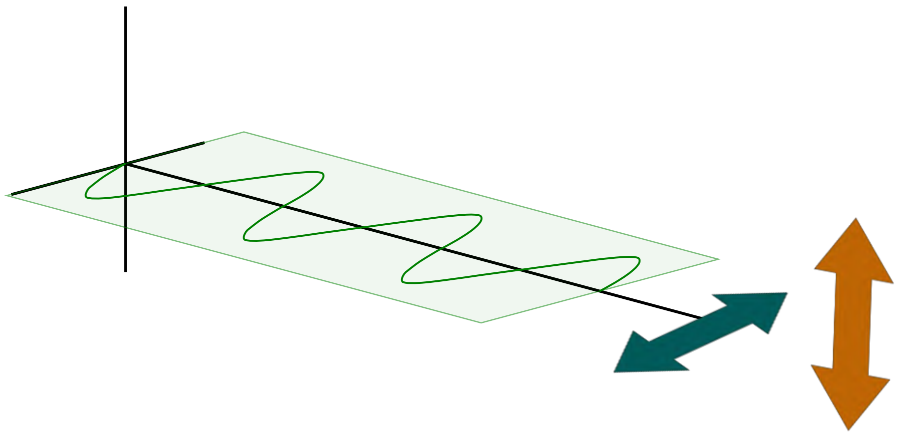
On resonance:
There exist higher order terms in the magnetic scattering factor:

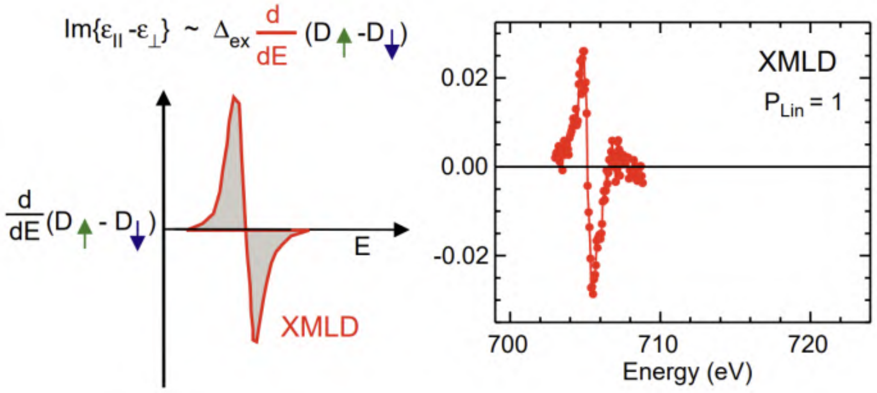
"Electronic" — XMCD: *Circular dichroism*

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

XMLD: *Linear dichroism*

Linear polarised light:

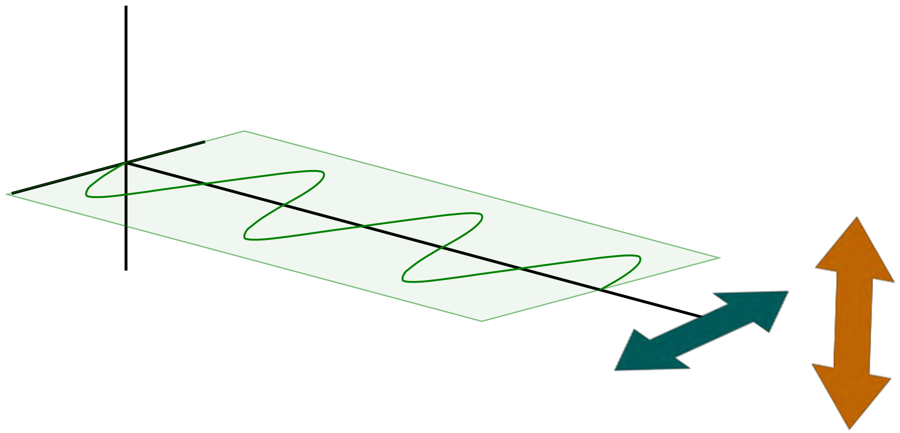




J. Kunes et al. JMMM 272, 2146 (2004)

MAGNETIC MICROSCOPY: ANTIFERROMAGNETS

XMLD-PEEM



CuMnAs:

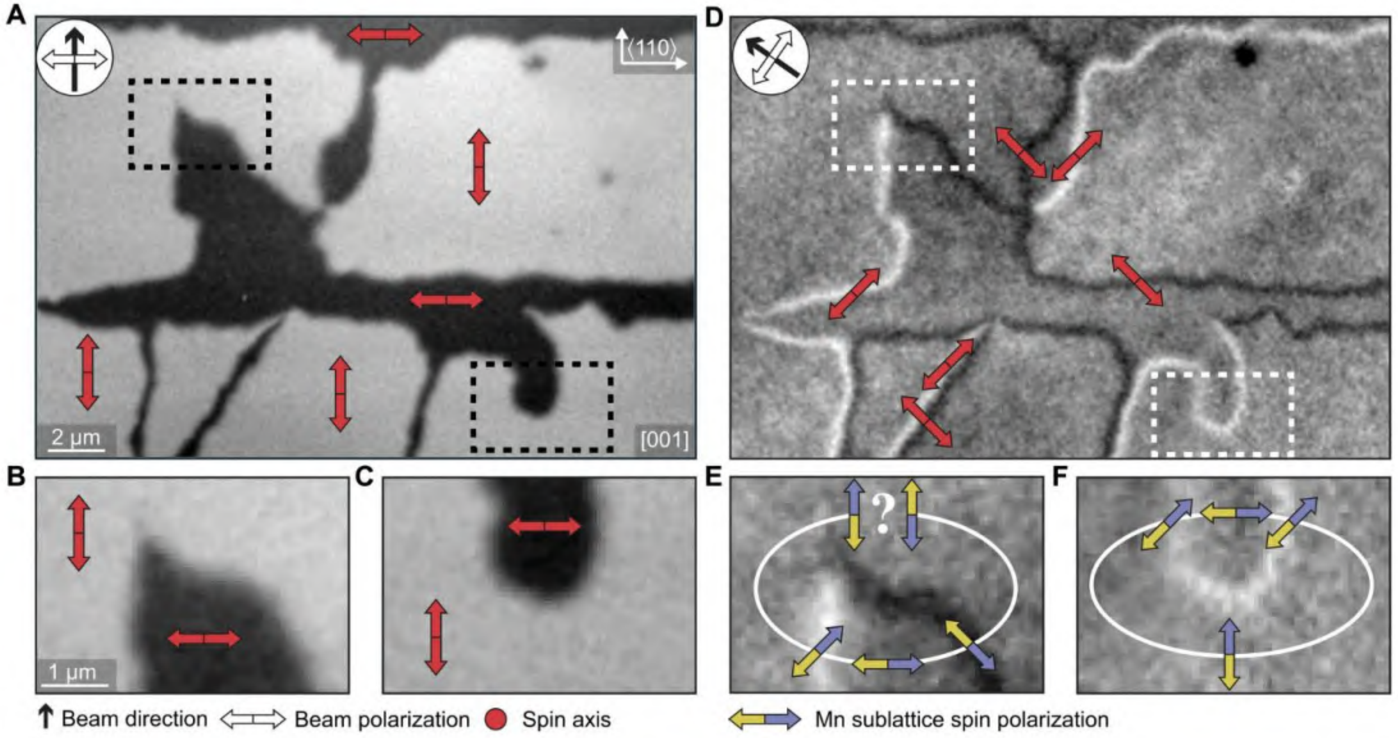
SPINTRONICS

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]

Can distinguish domains

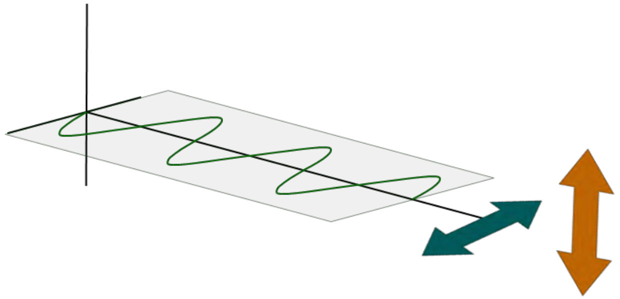
By rotating the polarisation: Can image domain walls



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

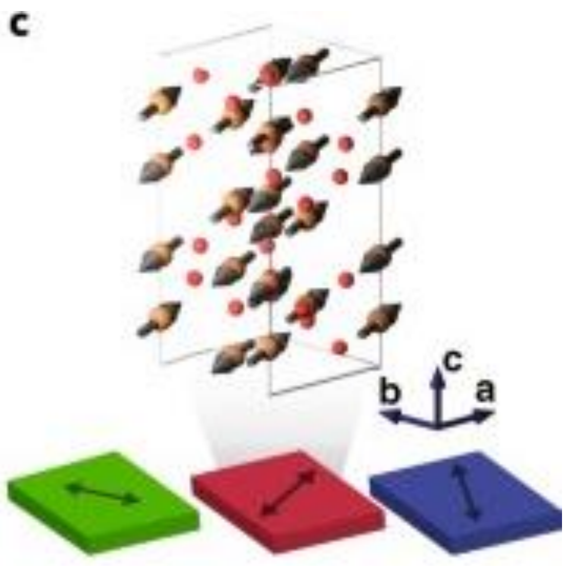
MAGNETIC MICROSCOPY: ANTIFERROMAGNETS

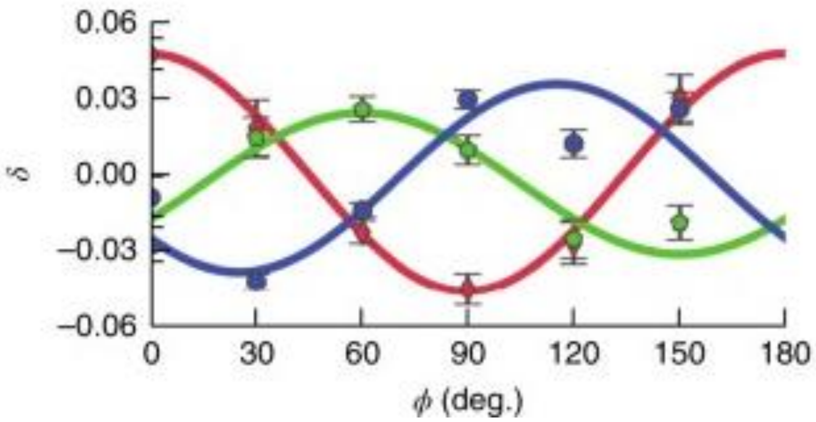
XMLD-PEEM

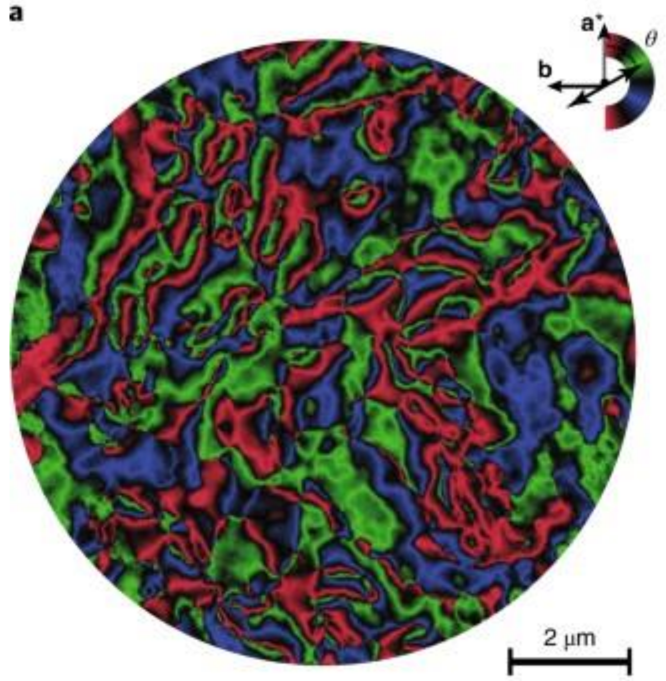


Combining with vector imaging:

→ 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	XMCD (synchrotron)	XMLD (synchrotron)	Spin pol. STM	SEMPA
Contrast	$\boldsymbol{H}$, surface charges	$\boldsymbol{H}$, surface charges	$\boldsymbol{B} \perp \boldsymbol{k}$	$\boldsymbol{m}$	$\boldsymbol{m} \parallel \boldsymbol{k}$	Néel vector ($\boldsymbol{m} \perp \boldsymbol{k}$)	$\boldsymbol{m}$	$\boldsymbol{m}$
Spatial resolution	10s of nm	10s of nm	Single digt nm (or below!)	100s nm – µms	10s nm (& below!)	10s nm	0.1 nm	~5 nm
Depth sensitivity	Surface sensitive	Surface sensitive	Thin samples ~<100 nm	Surface sensitive	nm - µms	nm - µms	0.1 nm	1 nm
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	Field, ~cryo, electrical contacts (in dev.), TR	Field, ~cryo, electrical contacts (in dev.), TR	Cryo, field	Challenging, UHV & preparation required
Invasive	Yes	No	No	No	No	No	No	No
Sensitivity	Medium	High!!	Medium	High	High, element sensitive	Medium, element sensitive, antiferromagnets!	High	High
Cost/ accessibility	Lab-based, accessible	Lab-based, recent commercial examples	Lab based, specialised equipment (10^6 €)	Lab based, accessible	Large scale user facility, **Open to all**	Large scale user facility, **Open to all**	Lab-based, Specialised UHV equipment	Lab-based, Specialised UHV equipment

Q & A:
CAN WE MEASURE EXPERIMENTALLY THE DOMAIN WIDTH WHEN IN THE NM SCALE?

Answer: It depends!

→ **Measured width = Convolution of spatial resolution & Domain wall width**

→ **Either**

→ Kno

Or

	MFM	Nitrogen vacancy	TEM	MOKE	XMCD (synchrotron)	XMLD (synchrotron)	Spin pol. STM	SEMPA
Contrast	$\boldsymbol{H}$, surface charges	$\boldsymbol{H}$, surface charges	$\boldsymbol{B} \perp \boldsymbol{k}$	$\boldsymbol{m}$	$\boldsymbol{m} \parallel \boldsymbol{k}$	Néel vector ($\boldsymbol{m} \perp \boldsymbol{k}$)	$\boldsymbol{m}$	$\boldsymbol{m}$
Spatial resolution	10s of nm	10s of nm	Single digt nm (or below!)	100s nm – µms	10s nm (& below!)	10s nm	0.1 nm	~5 nm

→ Know the expected domain wall width, & compare.

Domain wall width: $\Delta \sim \pi\sqrt{A/K}$

Hard: 2-3 nm → Soft: 10s to 100s nm

→ We need a spatial resolution from 10s of nm, to ~1 nm

→ **Let's keep this in mind!**

OUR QUESTIONS FOR THIS MORNING'S LECTURES:

What do we need to consider?

Spatial resolution

Sample environments

Time resolution

After coffee!

What methods are available?

Choosing the method for me and my samples?

	MFM	Nitrogen vacancy	TEM	MOKE	XMCD (synchrotron)	XMLD (synchrotron)	Spin pol. STM	SEMPA
Contrast	$\boldsymbol{H}$, surface charges	$\boldsymbol{H}$, surface charges	$\boldsymbol{B} \perp \boldsymbol{k}$	$\boldsymbol{m}$	$\boldsymbol{m} \parallel \boldsymbol{k}$	Néel vector ($\boldsymbol{m} \perp \boldsymbol{k}$)	$\boldsymbol{m}$	$\boldsymbol{m}$
Spatial resolution	10s of nm	10s of nm	Single digt nm (or below!)	100s nm – μms	10s nm (& below!)	10s nm (& below!)	0.1 nm	~5 nm
Depth sensitivity	Surface sensitive	Surface sensitive	Thin samples ~<100 nm	Surface sensitive	nm - μms	nm - μms	0.1 nm	1 nm
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	Field, ~cryo, electrical contacts (in dev.), TR	Field, ~cryo, electrical contacts (in dev.), TR	Cryo, field	Challenging, UHV & preparation required
Invasive	Yes	No	No	No	No	No	No	No
Sensitivity	Medium	High!!	Medium	High	High, element sensitive	Medium, element sensitive, antiferromagnets!	High	High
Cost/ accessibility	Lab-based, accessible	Lab-based, recent commercial examples	Lab based, specialised equipment (10^6 €)	Lab based, accessible	Large scale user facility, **Open to all**	Large scale user facility, **Open to all**	Lab-based, Specialised UHV equipment	Lab-based, Specialised UHV equipment