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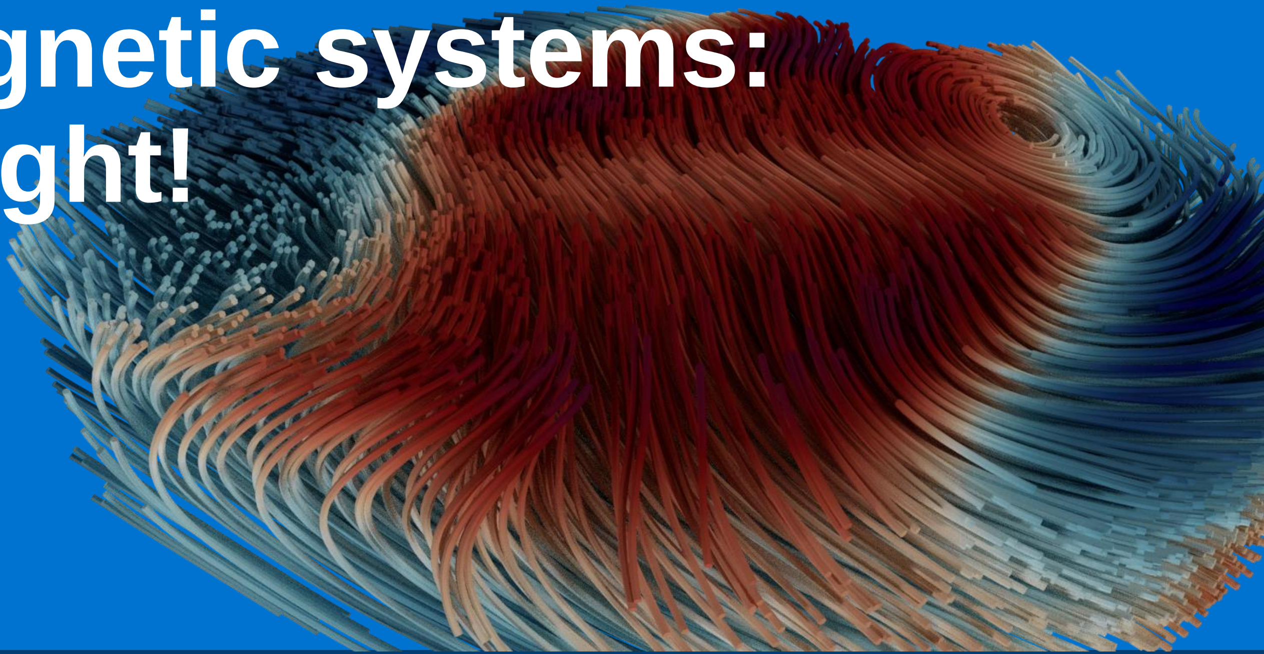
PAUL SCHERRER INSTITUT PSI

ETH zürich

Three-dimensional magnetic systems: the future is bright!



Claire Donnelly

SPICE-SPIN+X Seminar – 25th November 2020

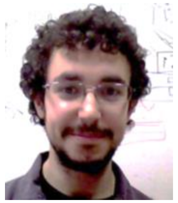
Thank you!

University of Cambridge
Dedalo Sanz-Hernandez
Luka Skorič
Fanfan Meng
Russell Cowburn
Nigel Cooper





University of Glasgow
Amalio Fernandez-Pacheco
Aurelio Hierro-Rodriguez
Billy Smith
Sam McFadzean

University of Vienna
Dieter Süss
Claas Abert

Donetsk Institute for Physics and Technology
Konstantin Metlov

Mesoscopic Systems, PSI/ETH
Laura Heyderman
Valerio Scagnoli
Eugenie Kirk
Ales Hrabec
Petai Pip



Swiss Light Source
Manuel Guizar-Sicairos
Mirko Holler
Jörg Raabe
Simone Finizio
Katharina Witte
Sina Mayr





Paul Scherrer Institut
Elisabeth Müller
Sebastian Gliga

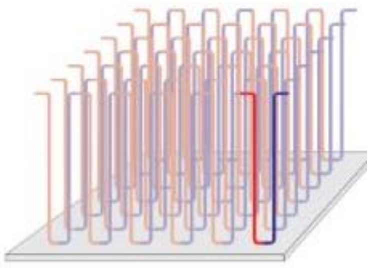
LEVERHULME TRUST

Isaac Newton Trust

For Women in Science
FONDATION L'ORÉAL

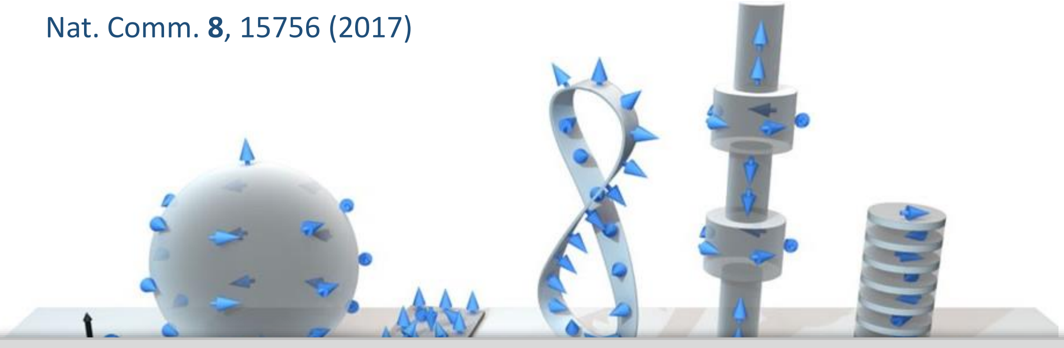
Magnetism: from 2D … to 3D

High density memory

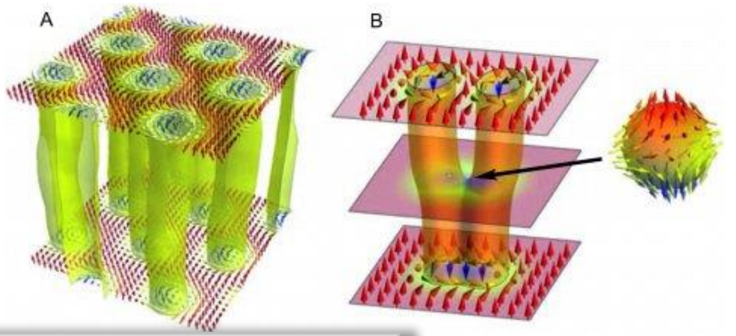


Parkin et al.,
Science 320,190 (2008)

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

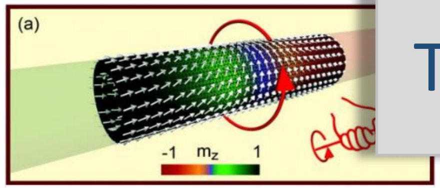


Buried topological transformations



40, 6136, (2013).

Promising domain wall dynamics

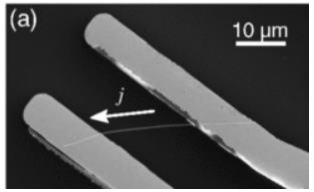


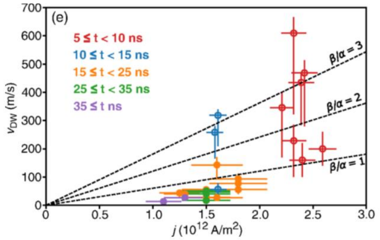
To study these experimentally, new methods are needed!

ures:

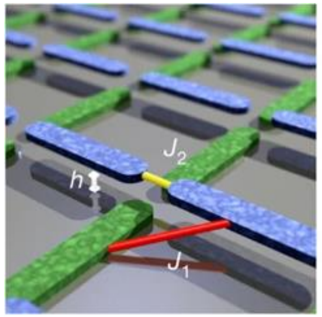
Hopfions

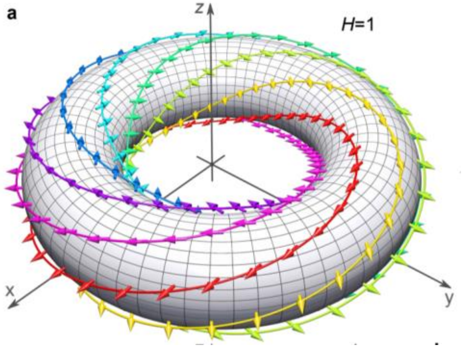
Yan *et al.*, APL **100**, 252401 (2012)
Yan *et al.*, APL. **99**, 122505 (2011)





Extensive degeneracy in 3D artificial spin ice





Schöbitz et al., PRL **123**, 217201 (2019)

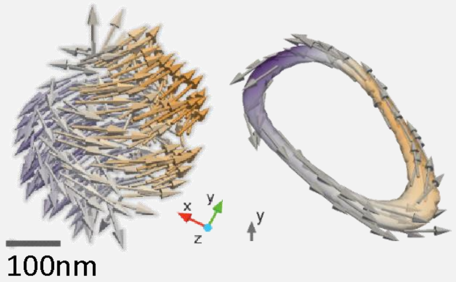
Perrin et al., Nature 540, 410–413 (2016)

Rybakov., arXiv:1904.00250 [cond-mat.str-el]

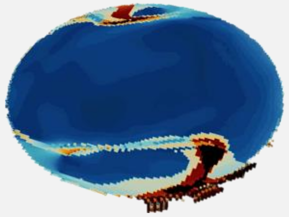
Reviews on 3D magnetism:
Streubel et al., J. Phys. D. **49**, 36 (2016)
Donnelly & Scagnoli, J. Phys. D. **32**, 213001 (2020)
Fernandez-Pacheco et al., Nat. Comm. **8**, 15756 (2017)
Fischer et al., APL Materials **8**, 010701 (2020)

Experimental 3D nanomagnetism:

In the bulk:

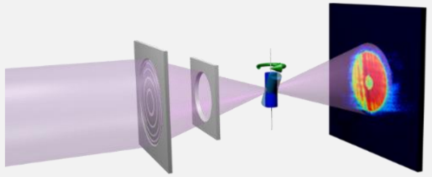


Observe 3D magnetic configurations

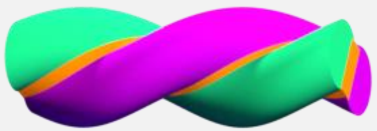


And their 3D magnetisation dynamics!

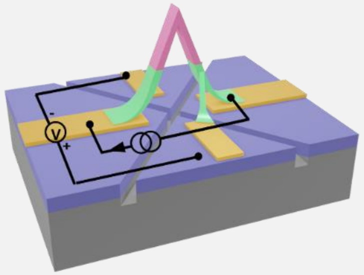
→ ***3D imaging techniques***



In patterned 3D structures:

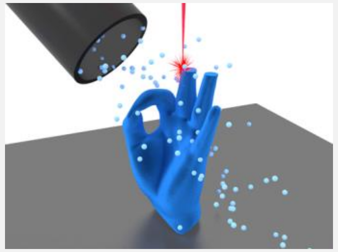


Introduce geometric effects such as chirality



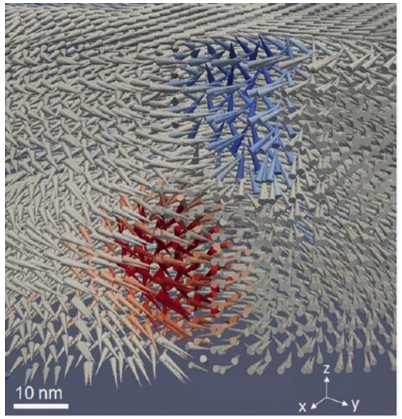
Realise 3D spintronics!

→ ***3D nanofabrication***



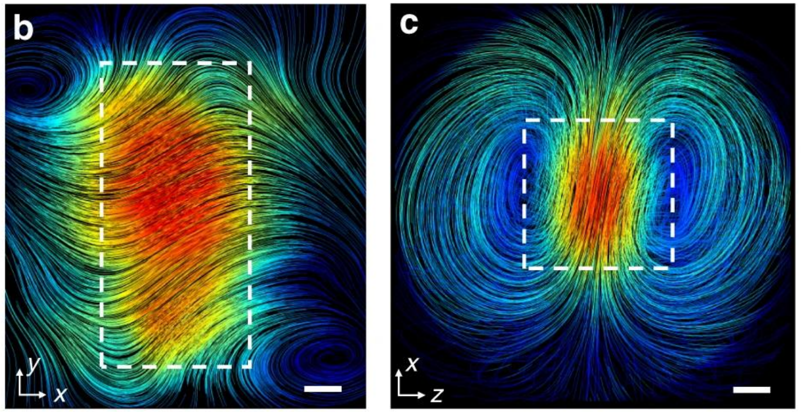
Magnetic imaging in 3D

With electrons:



Tanigaki et al., Nano. Lett. **15**, 1309 (2015)
Wolf et al. Chem. Mater. **27**, 6771 (2015)
Wolf et al., Comm. Phys. **2**, 87 (2019)

… neutrons:



Hilger et al., Nat. Comm. **9**, 4023 (2018)
Manke et al., Nat. Comm. **1**, 125 (2010)
Kardjilov et al., Nat. Phys. **4**, 399 (2008)

… & X-rays:

Streubel et al., Nat. Comm. (2015)
Blanco-Roldan et al, Nat Comm. (2015)
Donnelly et al., Nature **547**, 328 (2017)
Suzuki et al., Appl.Phys. Expr. **11**, 036601 (2018)
Hierro-Rodriguez et al., arXiv (2019)
Donnelly et al., Nat. Nano. **15**, 356 (2020)
Witte et al., Nano Lett. **20**, 1305 (2020)

Spatial Resolution:
< 10 nm

Sample thickness:
< 200 nm

Spatial Resolution:
~10-100 µm

Sample thickness:
up to mms

Spatial Resolution:
~10 -100 of nm

Sample thickness:
Up to 10s of µm

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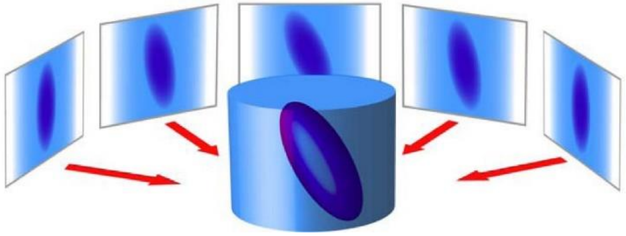
Review on 3D magnetic imaging:
Donnelly & Scagnoli, J. Phys. D. **32**, 213001 (2020)

Characterisation of 3D systems: developing 3D magnetic imaging

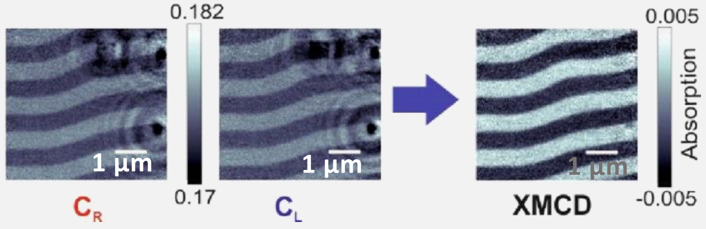
Magnetic tomography



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

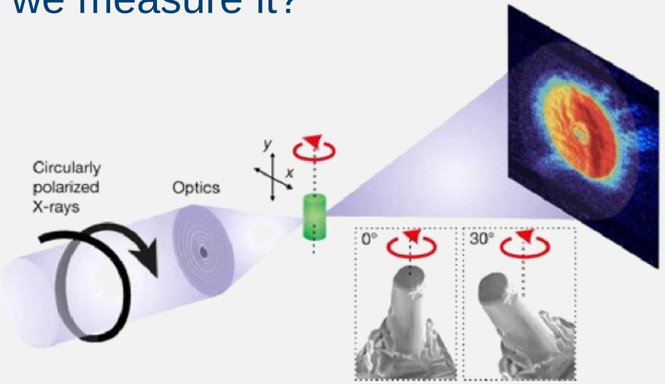
2D Hard X-ray magnetic imaging

Overcome weak magnetic signals with highly sensitive **Coherent Diffractive Imaging**



Donnelly et al., Phys. Rev. B 94, 064421 (2016)
XMCD: Schütz et al., PRL. 58, 737 (1987)

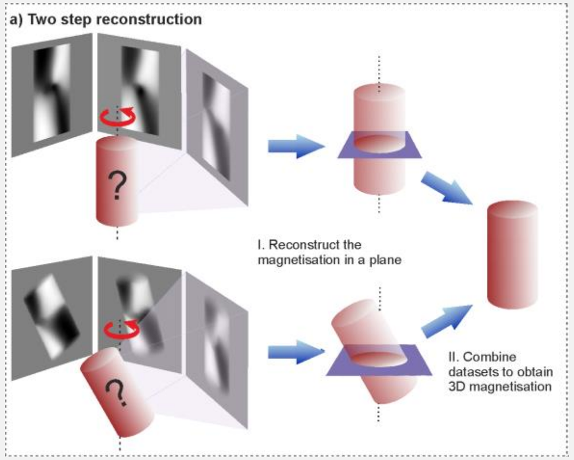
What data do we need, and how do we measure it?



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

New reconstruction algorithm

…to reconstruct the three-dimensional magnetisation vector field…



Donnelly et al., NJP 20 083009 (2018)

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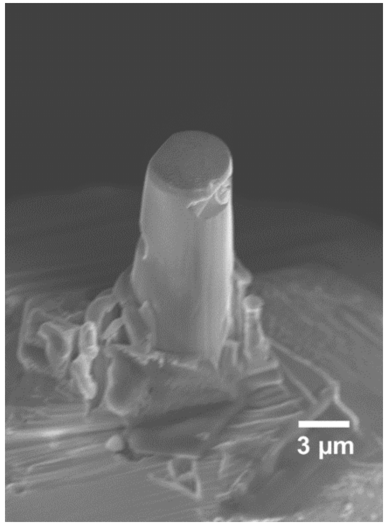
Review on 3D magnetic imaging:
Donnelly & Scagnoli, J. Phys. D. **32**, 213001 (2020)

X-ray magnetic tomography

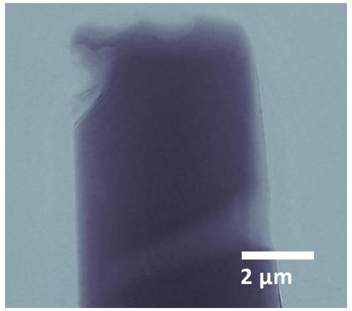
$GdCo_2$ Pillar
Cut from a nugget with FIB



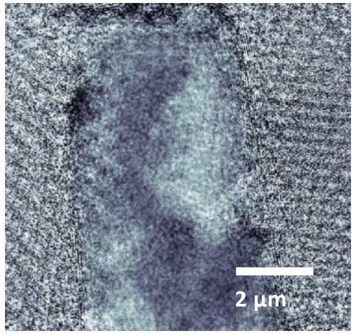
Unknown magnetic configuration

Sample: R. Galera, CNRS, Grenoble

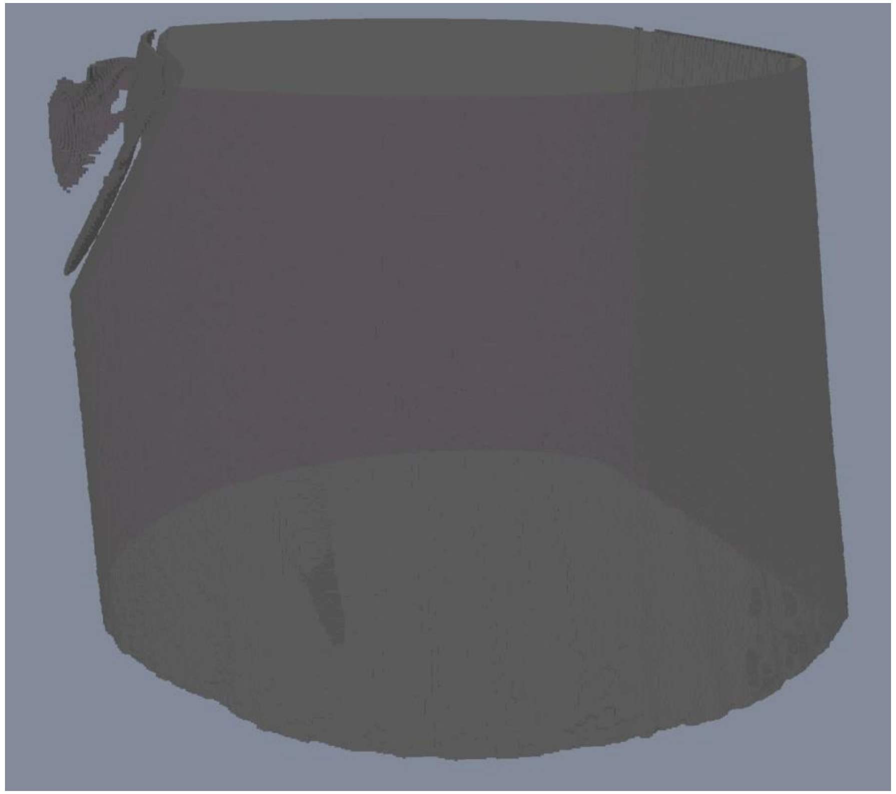
Absorption image (C_L)



XMCD image (C_L-C_R)



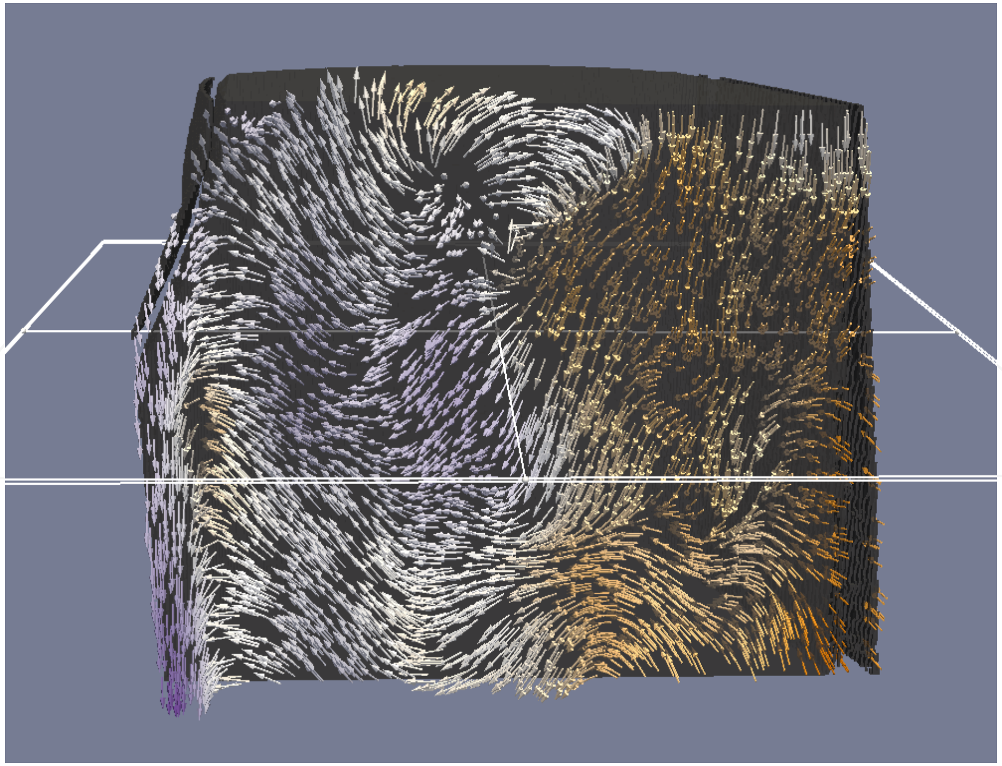
Reconstruct with 100 nm spatial resolution



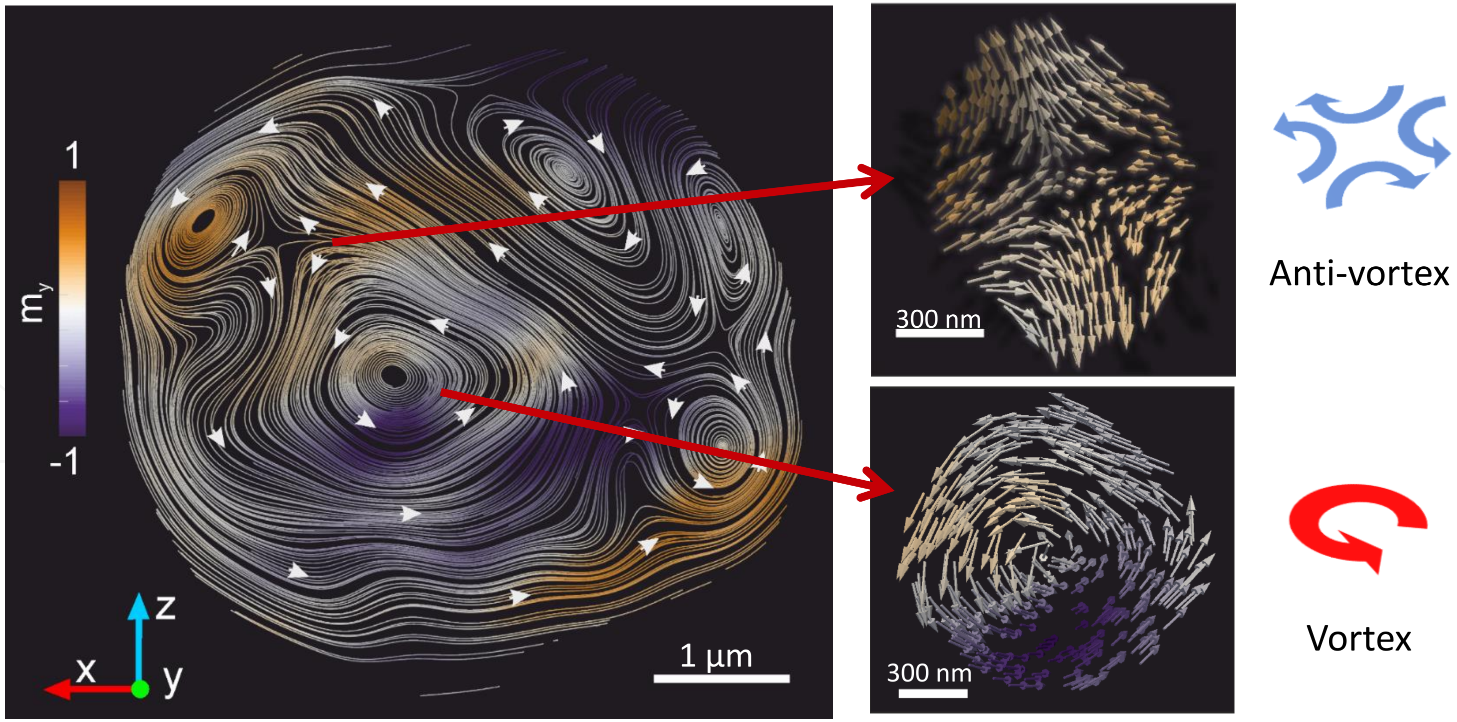
5 µm

Donnelly, Guizar-Sicairos, Scagnoli, Gliga, Holler, Raabe & Heyderman Nature **547**, 328 (2017)

X-ray magnetic tomography: a slice

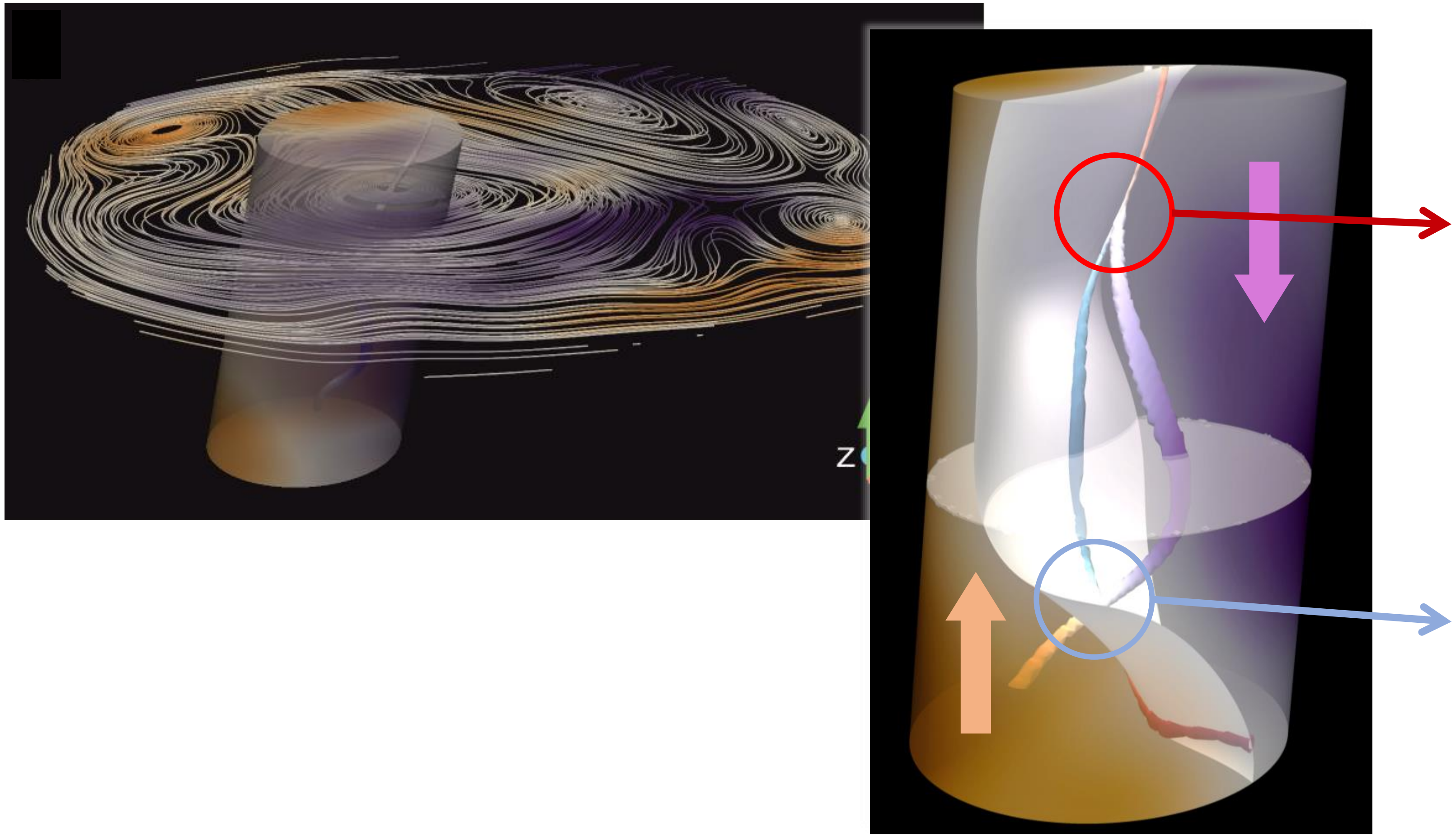


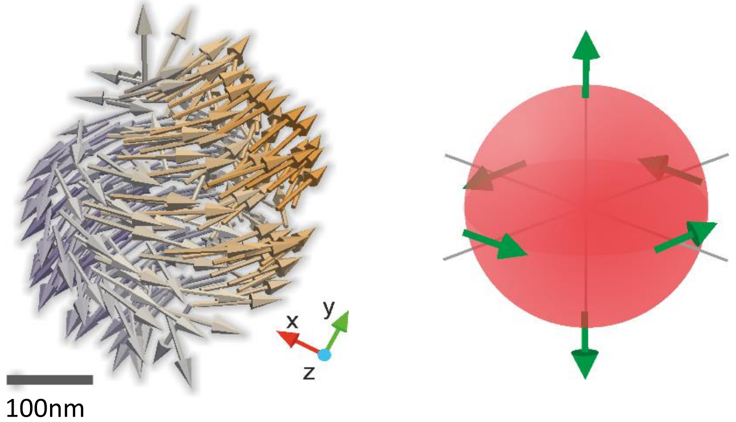
5 µm



Donnelly, Guizar-Sicairos, Scagnoli, Gliga, Holler, Raabe & Heyderman Nature **547**, 328 (2017)

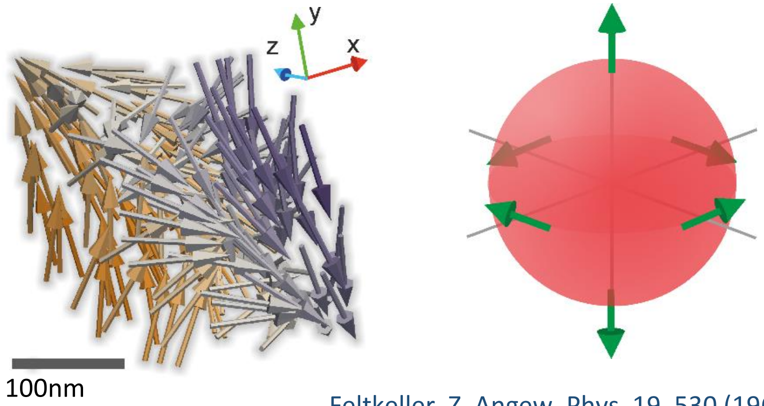
X-ray magnetic tomography: Complex 3D magnetic structure





Magnetisation Singularities

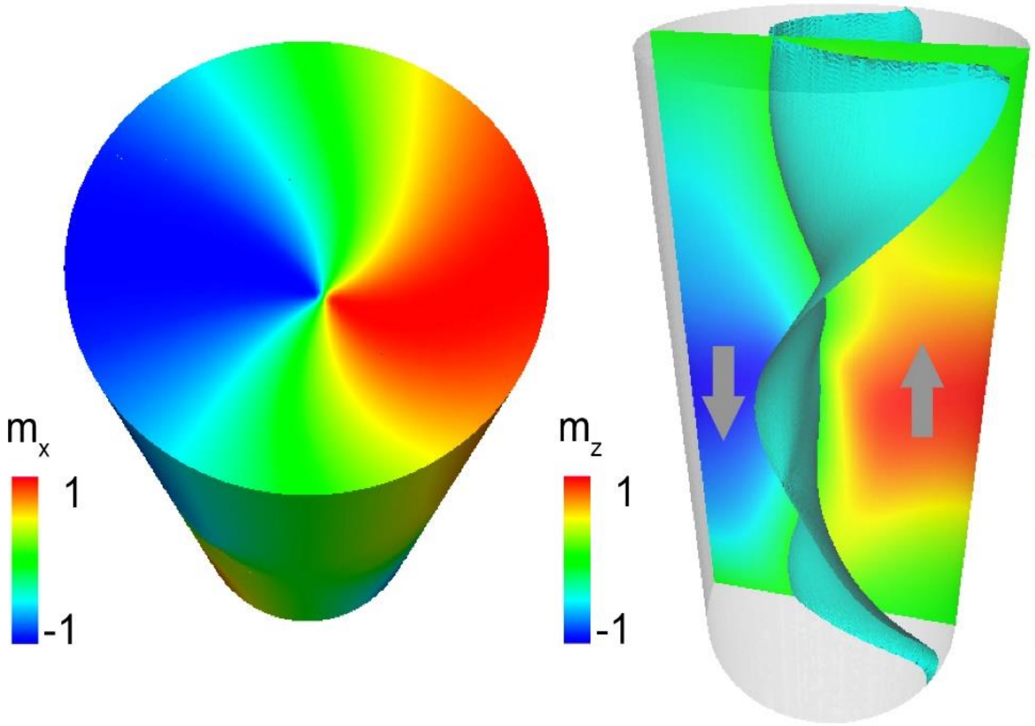
Bloch points



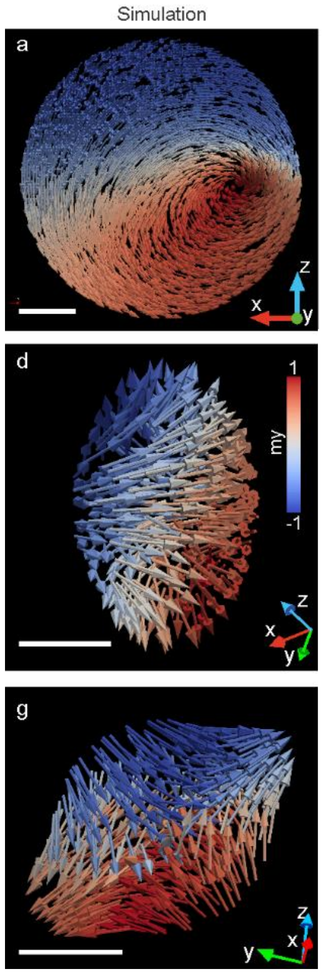
Feltkeller, Z. Angew. Phys. 19, 530 (1965)

Donnelly, Guizar-Sicairos, Scagnoli, Gliga, Holler, Raabe & Heyderman Nature **547**, 328 (2017)

Validating the magnetic reconstruction with simulations



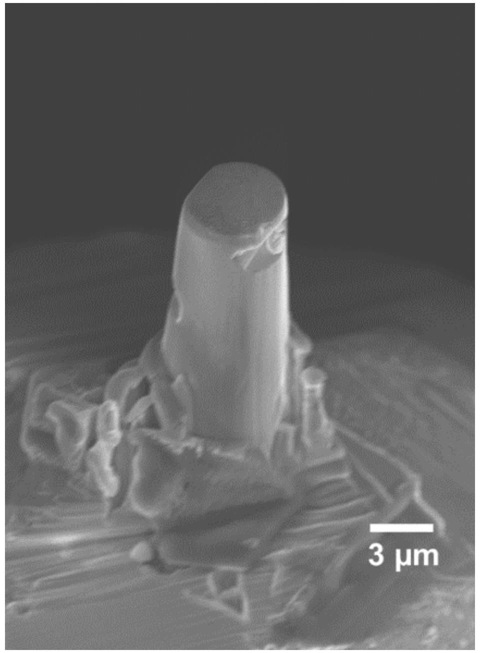
Finite element micromagnetic simulations by Sebastian Gliga, PSI
Magnetic structure contains vortices and Bloch points

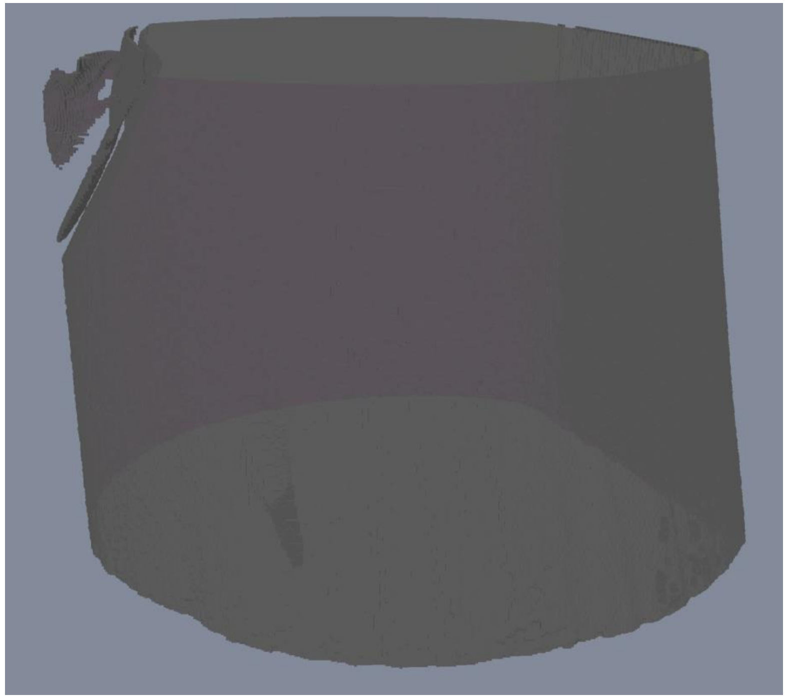


95% of vectors have <2% error in $|\boldsymbol{m}|$ & <15° error in θ_m

Donnelly, Gliga, Scagnoli, Holler, Raabe, Heyderman & Guizar-Sicairos, New Journal of Physics **20**, 083009 (2018)

Beyond magnetic tomography…





One main challenge:

how to analyse & identify complex 3D structures?

Donnelly, Guizar-Sicairos, Scagnoli, Gliga, Holler, Raabe & Heyderman Nature **547**, 328 (2017)
Donnelly, Metlov, Scagnoli, Guizar-Sicairos, Holler, Bingham, Raabe, Heyderman, Cooper & Gliga, Nature Physics (2020)

Interpreting 3D magnetic configurations

One main challenge:
how to analyse & identify complex 3D structures?

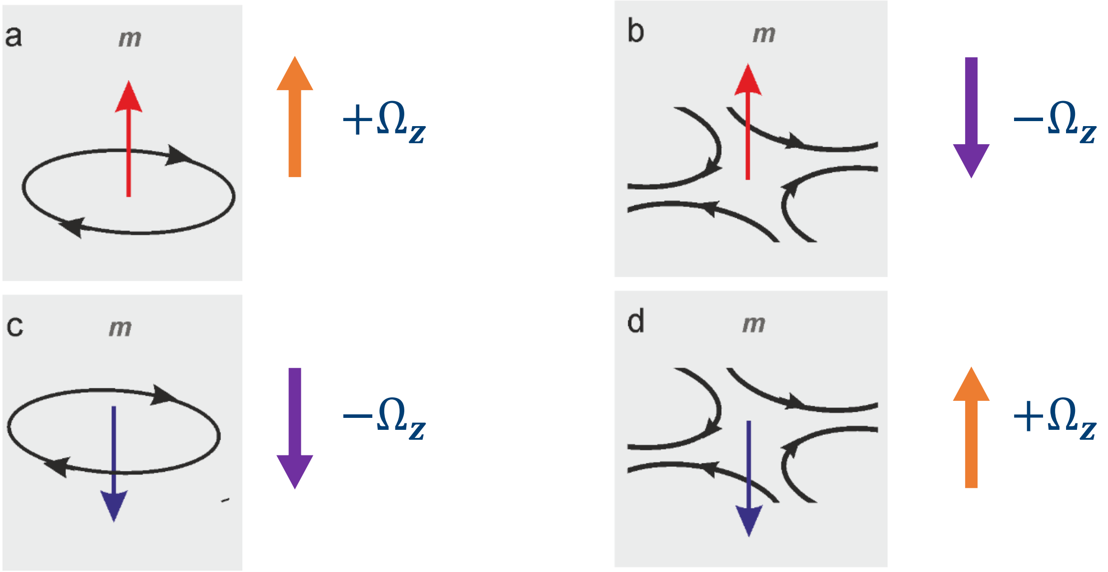
Through calculations of the ***magnetic vorticity Ω****:*

$$\Omega_\alpha = \frac{1}{8\pi}\varepsilon_{ijk}\varepsilon_{\alpha\beta\gamma}n_i\partial_\beta n_j\partial_\gamma n_k$$

(n_i= unit vector)

N. Papanicolaou, NATO ASI Series C404, 151-158 (1993).
Cooper, PRL 82 1554 (1999)

Vortices: ***Antivortices:***



Magnetic vorticity Ω = ***flux*** *of Skyrmion number density*

Donnelly, Guizar-Sicairos, Scagnoli, Gliga, Holler, Raabe & Heyderman Nature **547**, 328 (2017)
Donnelly, Metlov, Scagnoli, Guizar-Sicairos, Holler, Bingham, Raabe, Heyderman, Cooper & Gliga, Nature Physics (2020)

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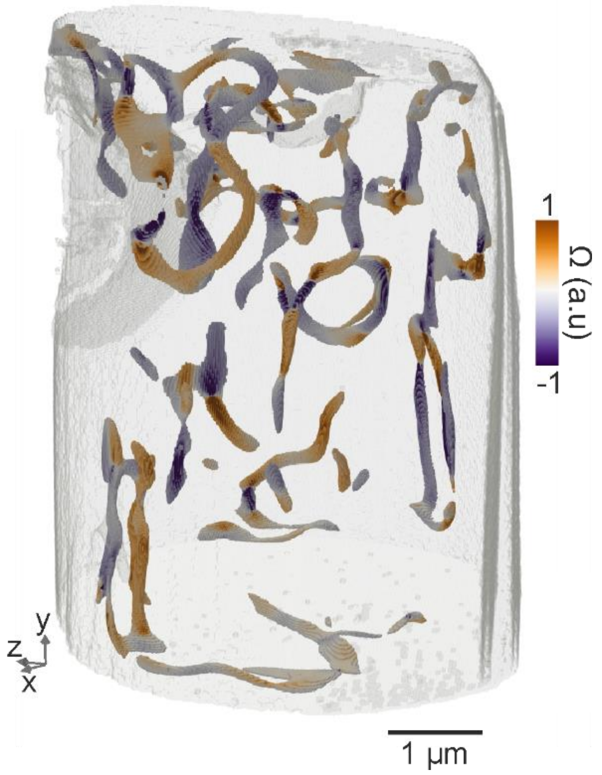
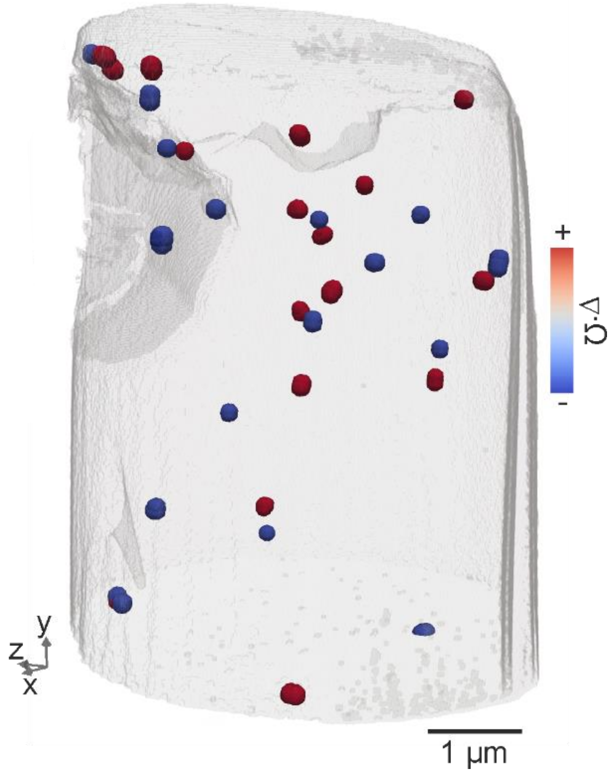
Cooper, PRL 82 1554 (1999)



Identify & understand 3D structures

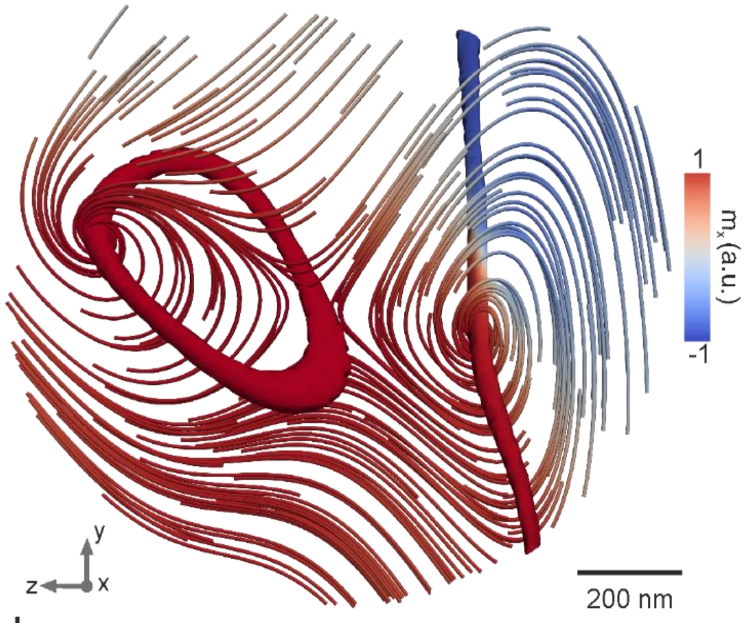


Locate singularities within the bulk

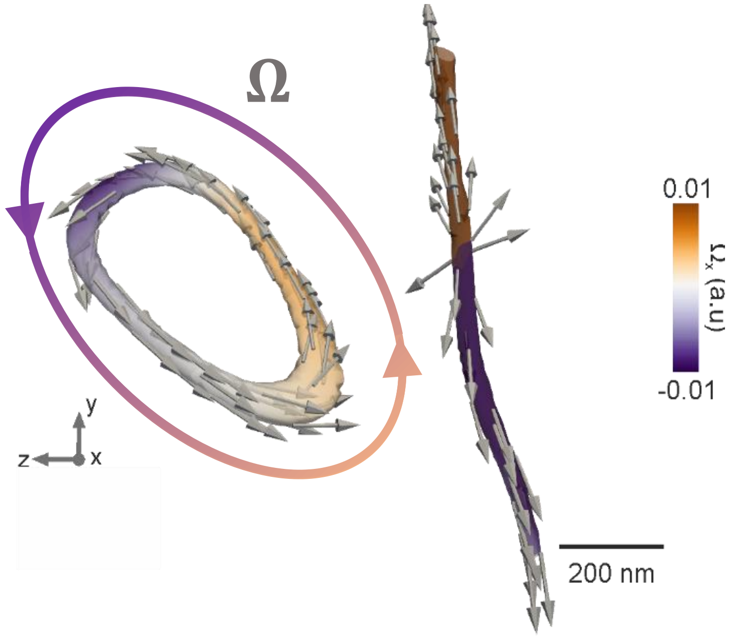
Donnelly, Guizar-Sicairos, Scagnoli, Gliga, Holler, Raabe & Heyderman Nature **547**, 328 (2017)
Donnelly, Metlov, Scagnoli, Guizar-Sicairos, Holler, Bingham, Raabe, Heyderman, Cooper & Gliga, Nature Physics (2020)

We can use this to understand new 3D textures:

In this way, we observe unexpected stable 3D structures such as loops of vortex-antivortex pairs :



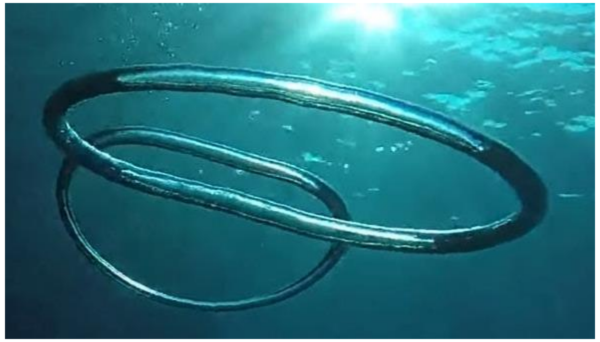
That have circulating vorticity:



→ *Magnetic vortex rings*

N. Papanicolaou, NATO ASI Series C404, 151-158 (1993).
Cooper, PRL 82 1554 (1999)

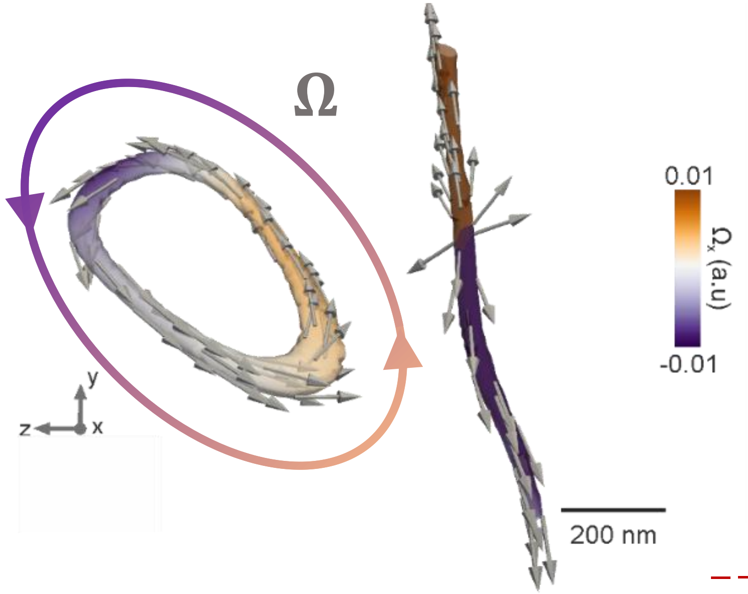
Analogous to hydrodynamic vortex rings:



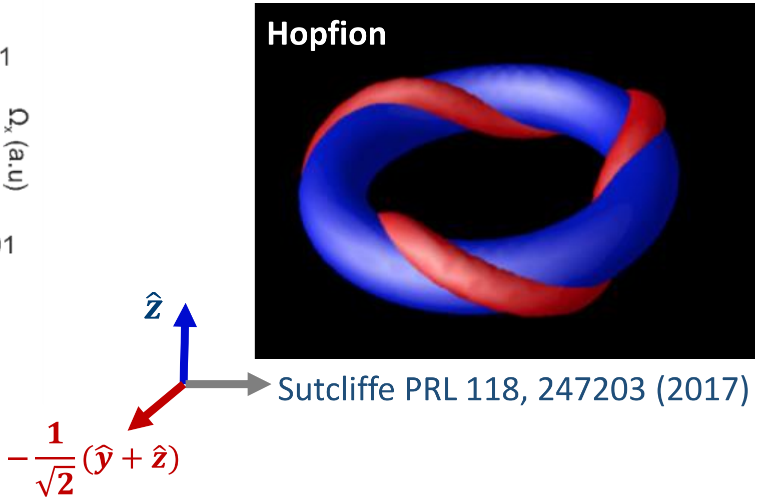
Donnelly, Metlov, Scagnoli, Guizar-Sicairos, Holler, Bingham, Raabe, Heyderman, Cooper & Gliga, Nature Physics (2020)

But why are these stable?

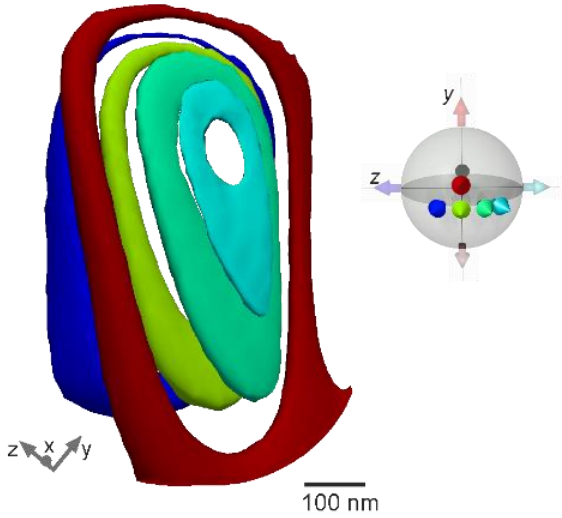
Could it be the topology of the vortex ring?



By plotting "pre-images" in 3D:



Sutcliffe PRL 118, 247203 (2017)

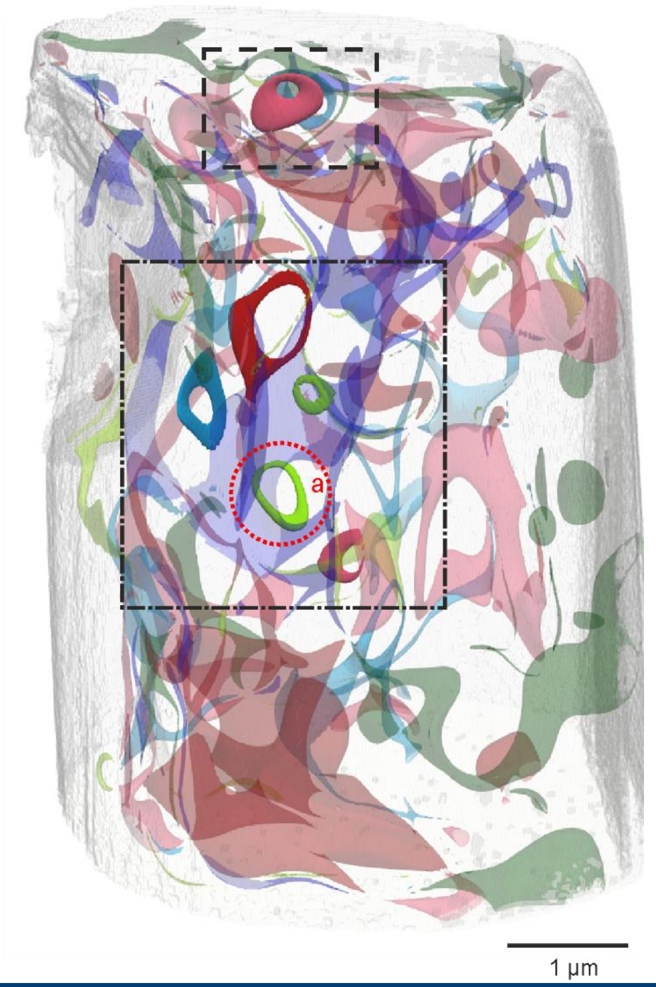


Pre-images link 3 times
→Hopf Index H=3

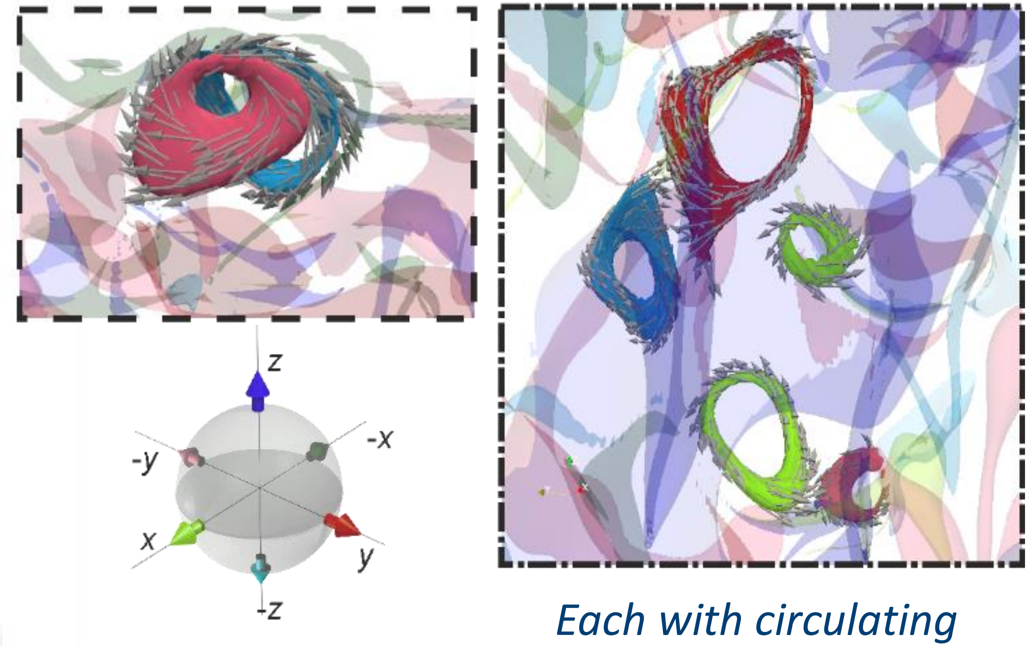
Pre-images don't link
→Hopf Index H=0

Donnelly, Metlov, Scagnoli, Guizar-Sicairos, Holler, Bingham, Raabe, Heyderman, Cooper & Gliga, Nature Physics (2020)

3D magnetic vortex loops:



We find a variety of vortex rings



Each with circulating vorticity!

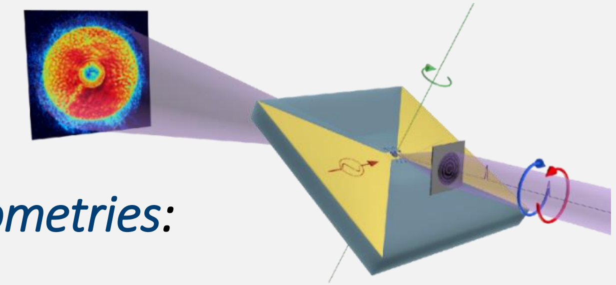
Observations of size and surroundings
&
Modelling of bulk textures

→ ***Magnetostatics key in 3D!***

Donnelly, Metlov, Scagnoli, Guizar-Sicairos, Holler, Bingham, Raabe, Heyderman, Cooper & Gliga, Nature Physics (2020)

Beyond magnetic tomography…

More flexible experimental geometries:



To the 4th dimension:

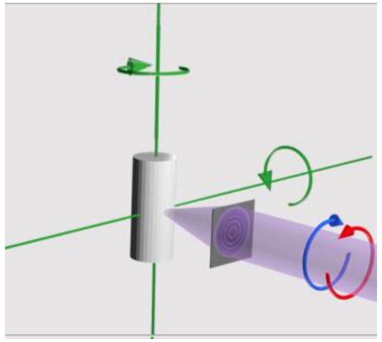
Higher spatial resolutions & sensitivity for nanoscale 3D structures

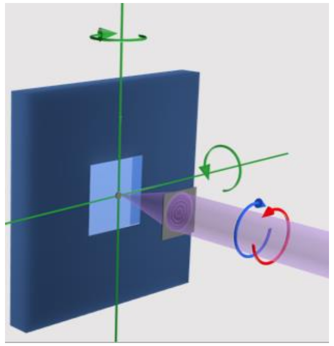
Tomography:

a non-destructive 3D imaging method

Sample ideally cylindrical

Problematic for flat, extended samples



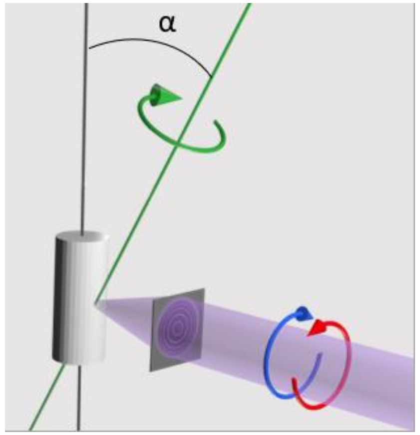


Laminography:

Rotation axis tilted towards the beam

Ideal for flat, extended samples

Consistent amount of material for different orientations



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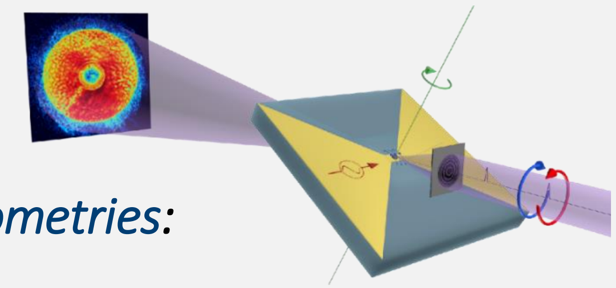
Review on 3D magnetic imaging:
Donnelly & Scagnoli, J. Phys. D. **32**, 213001 (2020)

Beyond magnetic tomography…

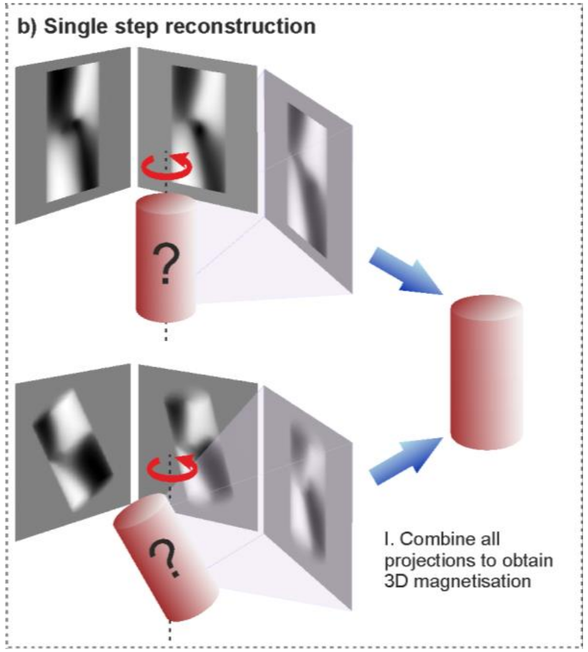
More flexible experimental geometries:



To the 4th dimension:

Higher spatial resolutions & sensitivity for nanoscale 3D structures

First, need to generalise reconstruction algorithm to arbitrary geometries:

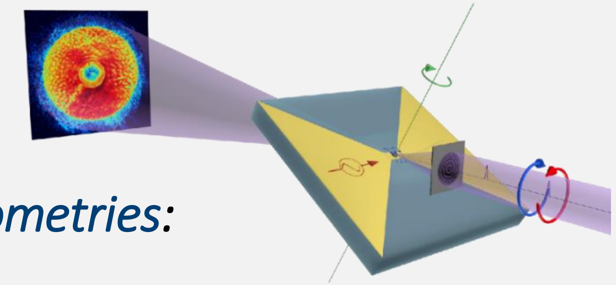


Reconstruction algorithm available open access at: 10.5281/zenodo.1324335

Donnelly, Gliga, Scagnoli, Holler, Raabe, Heyderman & Guizar-Sicairos, New Journal of Physics **20**, 083009 (2018)

Beyond magnetic tomography…

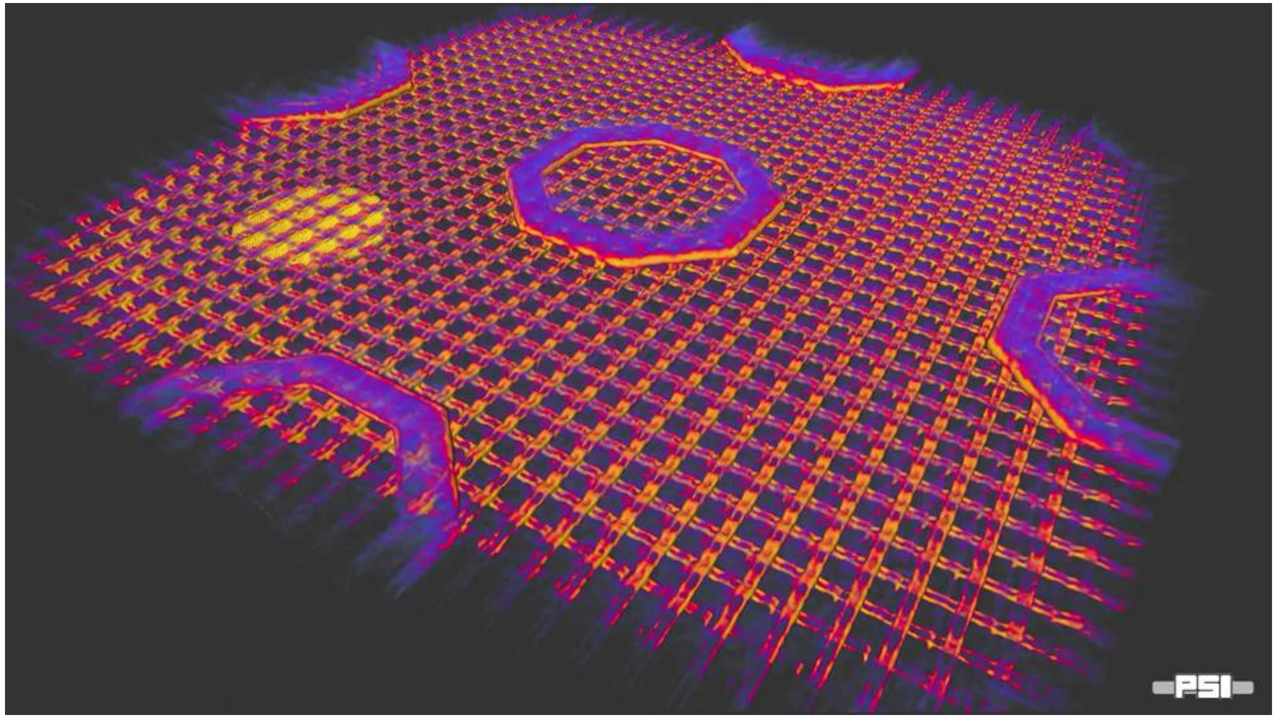
More flexible experimental geometries:



To the 4th dimension:

Higher spatial resolutions & sensitivity for nanoscale 3D structures

Then, we need a high resolution experimental setup: cSAXS beamline, SLS

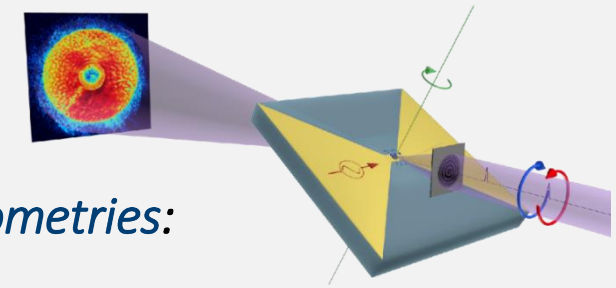


Mulit-scale hard X-ray laminography of an integrated circuit
Spatial resolution: <20 nm

Holler, Odstrcil, Guizar-Sicairos, Lebugle, Müller, Finizio, Tinti, David, Zusman, Unglaub, Bunk, Raabe, Levi, Aeppli Nat. Elec. (2019)

Beyond magnetic tomography…

More flexible experimental geometries:

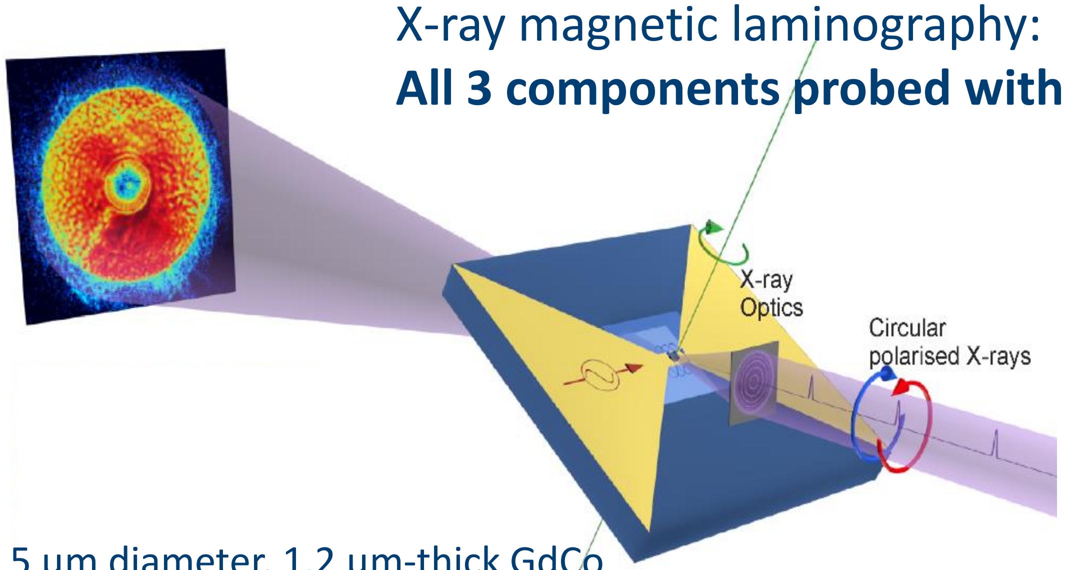


To the 4th dimension:

Higher spatial resolutions & sensitivity for nanoscale 3D structures

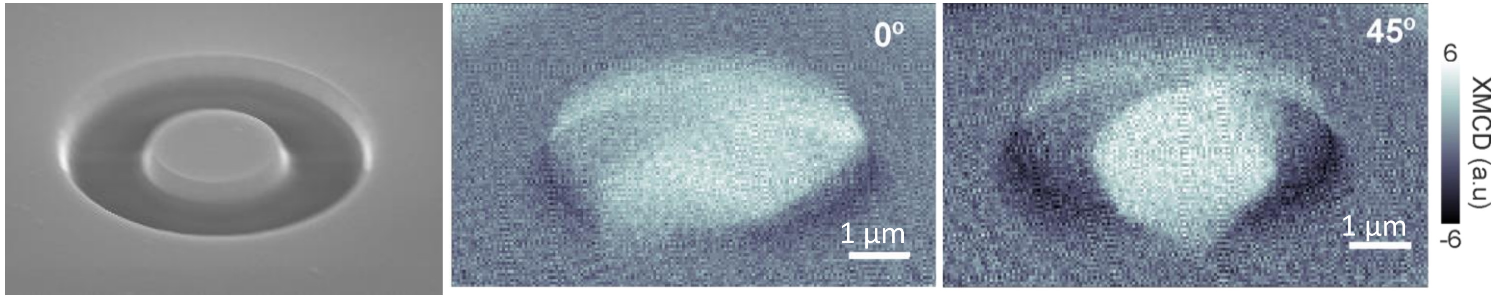
X-ray magnetic laminography:

All 3 components probed with one rotation axis!



5 µm diameter, 1.2 µm-thick GdCo

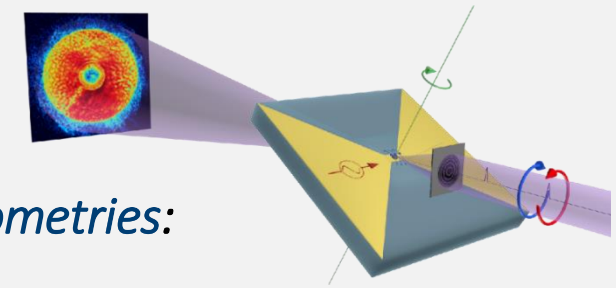
Varying magnetic anisotropy



Donnelly, Finizio, Gliga, Holler, Hrabec, Odstrčil, Mayr, Scagnoli, Heyderman, Guizar-Sicairos & Raabe, Nature Nanotechnology **15** 356 (2020)

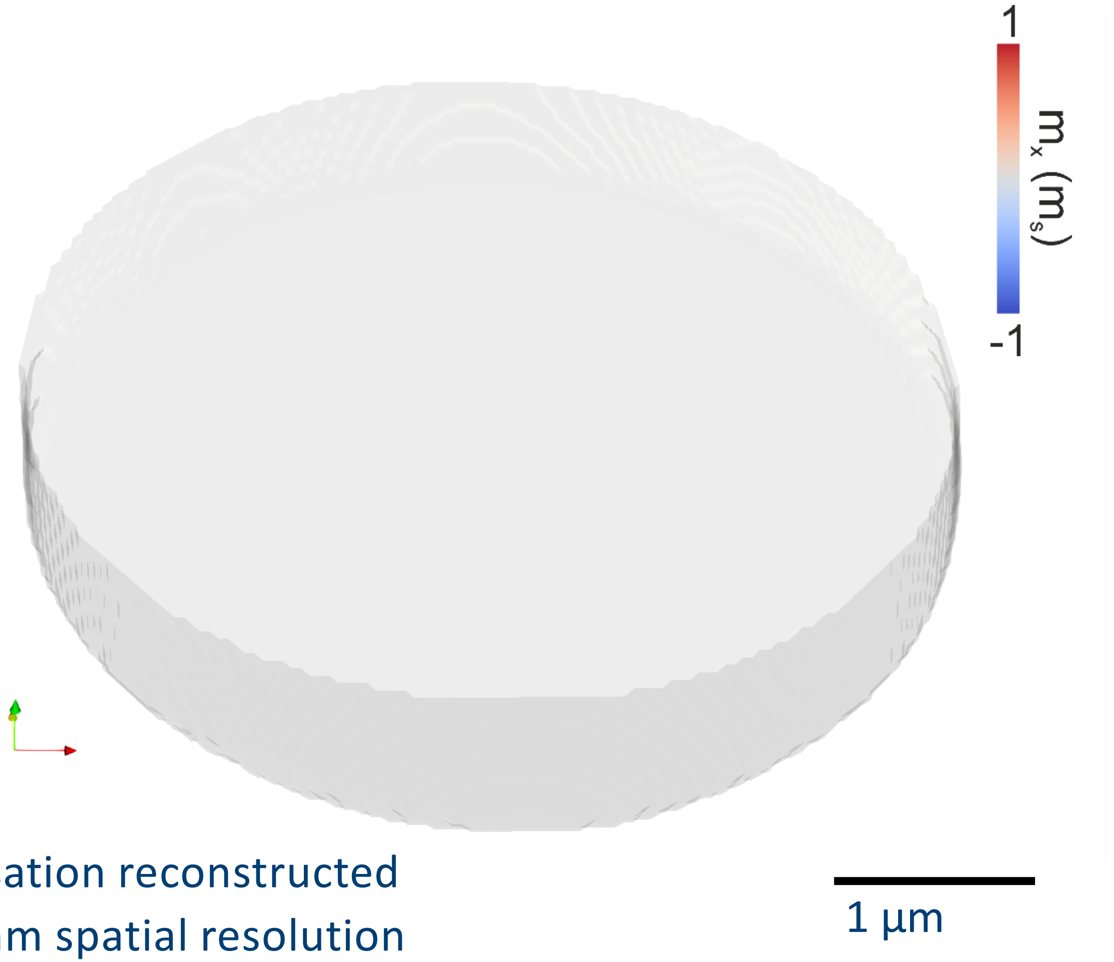
Beyond magnetic tomography…

More flexible experimental geometries:



To the 4th dimension:

Higher spatial resolutions & sensitivity for nanoscale 3D structures



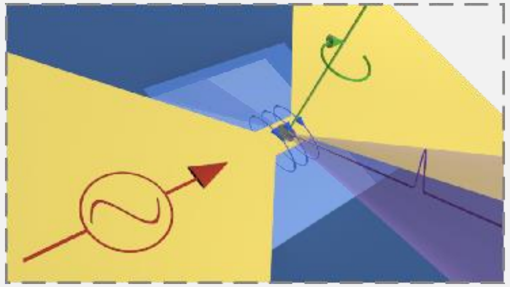
Magnetisation reconstructed with 50 nm spatial resolution

Donnelly, Finizio, Gliga, Holler, Hrabec, Odstrčil, Mayr, Scagnoli, Heyderman, Guizar-Sicairos & Raabe, Nature Nanotechnology **15** 356 (2020)

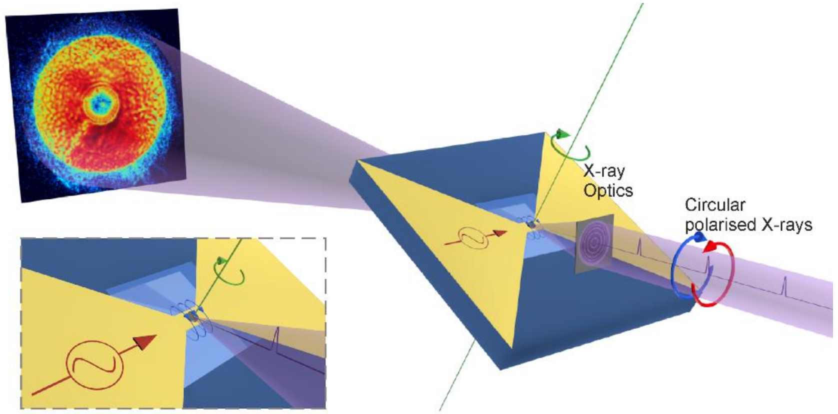
Beyond magnetic tomography…

More flexible experimental geometries:

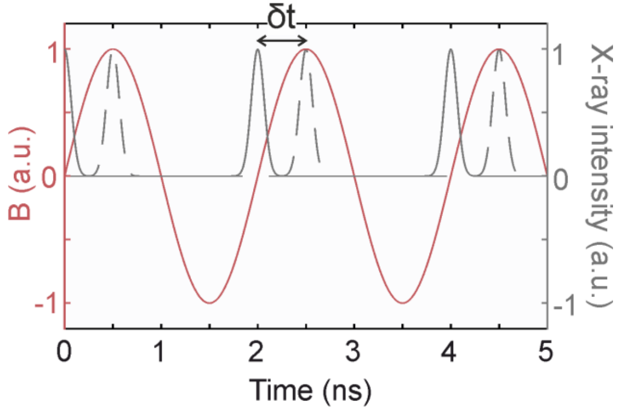
To the 4th dimension:



Higher spatial resolutions & sensitivity for nanoscale 3D structures



- Exploit pulsed waveform of synchrotron @ 500 MHz with 70 ps resolution
- Pass frequency & phase-matched excitation through stripline to create AC magnetic field



At multiple time-steps, measure 3D laminography dataset

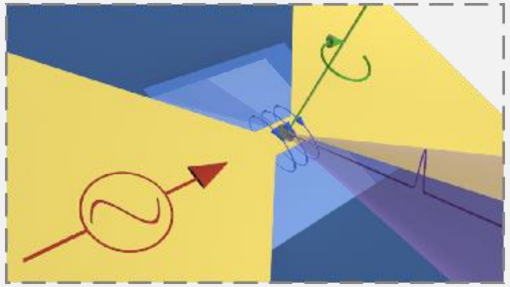
→ *Four-dimensional magnetic information*

Donnelly, Finizio, Gliga, Holler, Hrabec, Odstrčil, Mayr, Scagnoli, Heyderman, Guizar-Sicairos & Raabe, Nature Nanotechnology **15** 356 (2020)

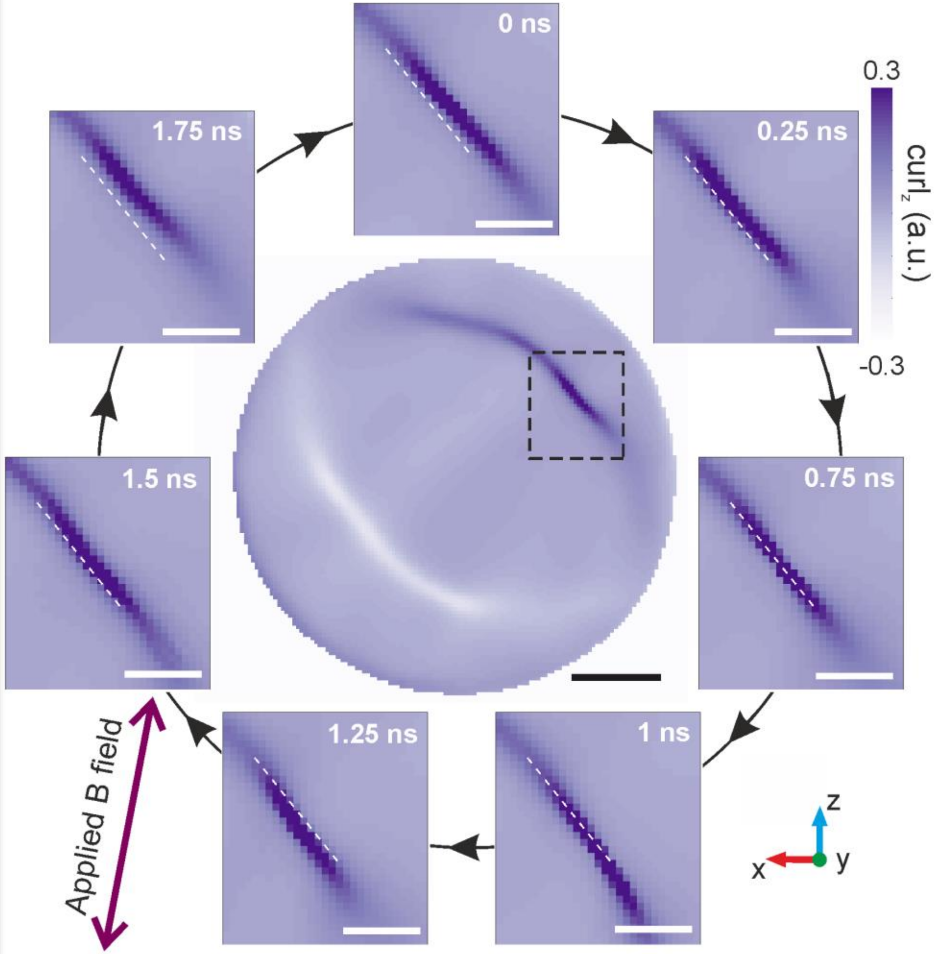
3D magnetisation dynamics

More flexible experimental geometries:

To the 4th dimension:



Higher spatial resolutions & sensitivity for nanoscale 3D structures



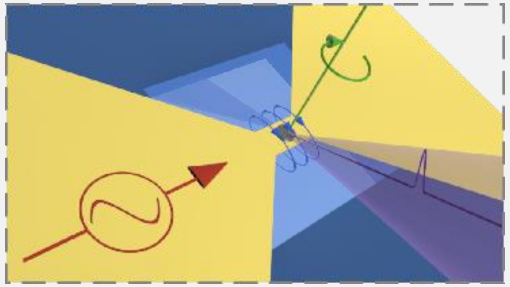
Track fast motion
(200 m/s)
of topological structures
– *domain walls* –
with high accuracy

Donnelly, Finizio, Gliga, Holler, Hrabec, Odstrčil, Mayr, Scagnoli, Heyderman, Guizar-Sicairos & Raabe, Nature Nanotechnology **15** 356 (2020)

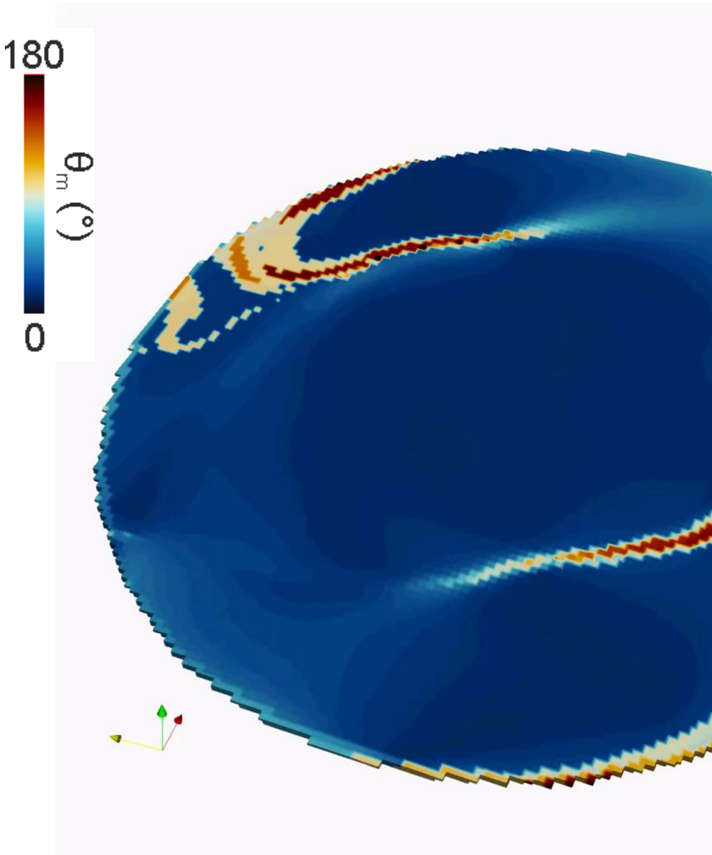
3D magnetisation dynamics

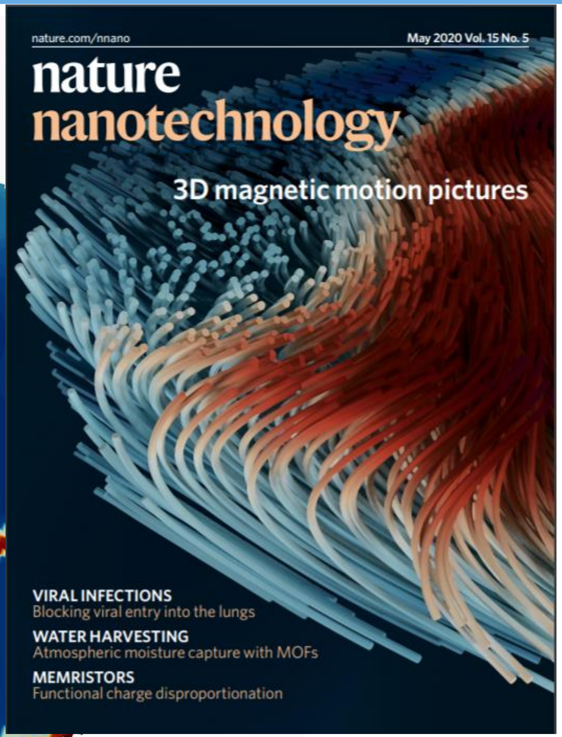
More flexible experimental geometries:

To the 4th dimension:



Higher spatial resolutions & sensitivity for nanoscale 3D structures





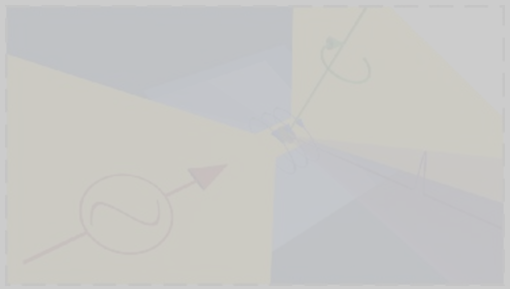
→ Map the modes of the magnetisation dynamics Which are closely linked to 3D magnetic structure

Donnelly, Finizio, Gliga, Holler, Hrabec, Odstrčil, Mayr, Scagnoli, Heyderman, Guizar-Sicairos & Raabe, Nature Nanotechnology **15** 356 (2020)

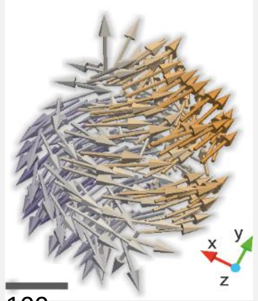
3D magnetisation dynamics

More flexible experimental geometries:

To the 4th dimension:



Higher spatial resolutions & sensitivity for nanoscale 3D structures



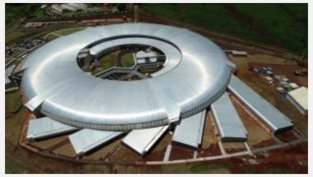
Smaller length scales → higher signal to noise ratio!

Higher coherent flux:

Upgrades of 3rd generation:

ESRF-II   SLS 2.0   Diamond II

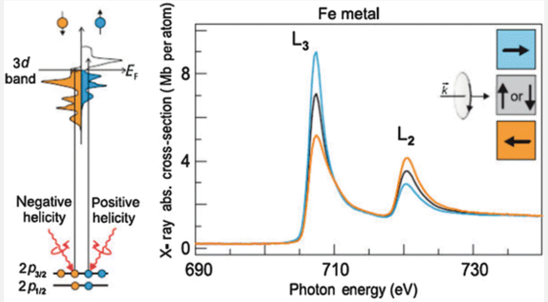
And the next generation!



Providing up to 10^3 more flux in coming years

Stronger signals:

→ soft X-rays

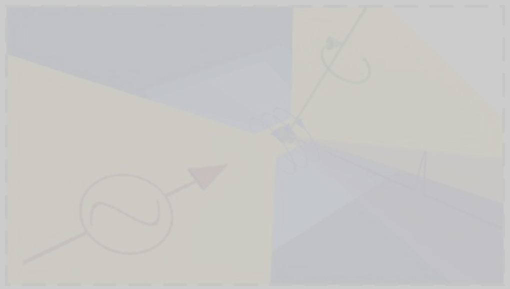


XMCD of transition metals: Up to 100% of absorption

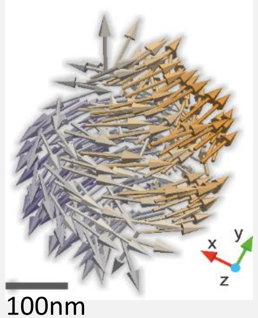
3D magnetisation dynamics

More flexible experimental geometries:

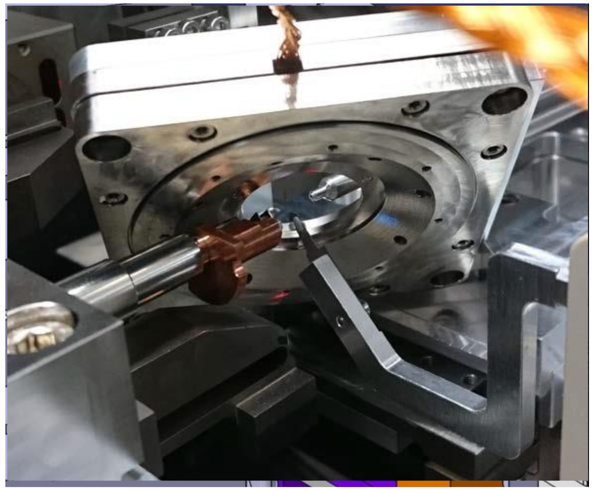
To the 4^{th} dimension:



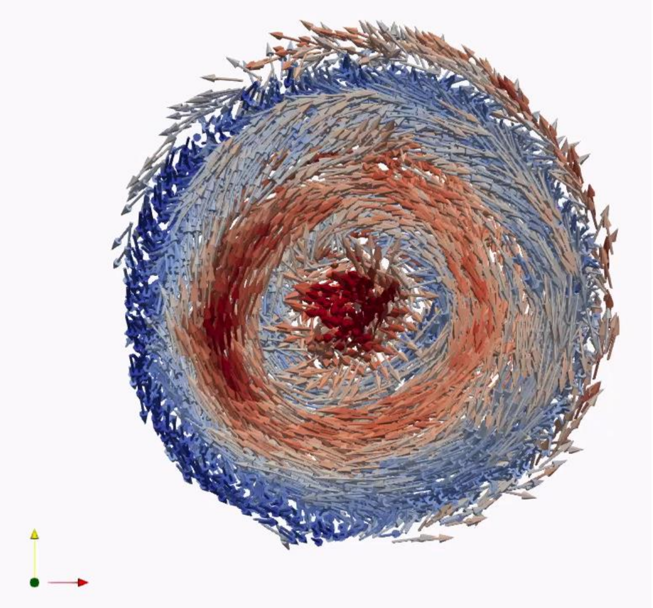
Higher spatial resolutions & sensitivity for nanoscale 3D structures



Soft X-ray STXM Laminography @ PolLux, SLS



Setup implemented by Katharina Witte, PSI.



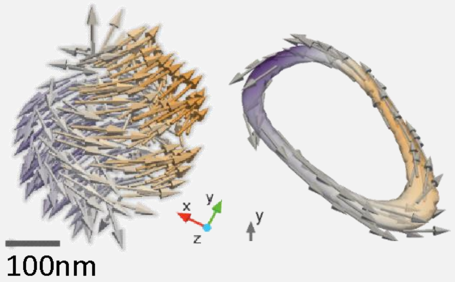
Magnetic laminography of "target skyrmion"

Higher sensitivity of soft X-rays make probing nanostructures possible

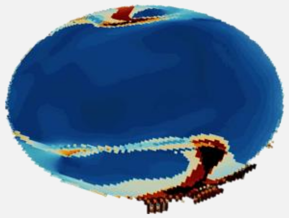
Witte, Späth, Finizio, Donnelly, Watts, Sarafimov, Odstrcil, Guizar-Sicairos, Holler, Fink & Raabe, Nano Letters **20** 1305 (2020)
J. Raabe et al., Rev Sci Instrum. 79 113704, (2008)

Experimental 3D nanomagnetism:

In the bulk:

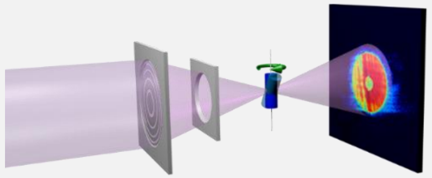


Observe 3D magnetic configurations

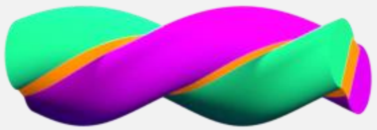


And their 3D magnetisation dynamics!

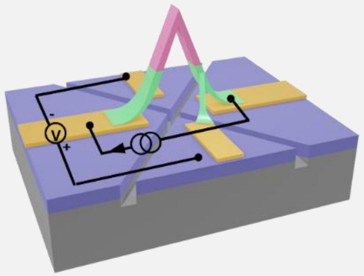
→ ***3D imaging techniques***



In patterned 3D structures:

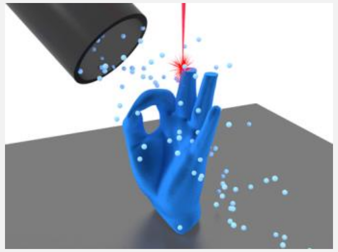


Introduce geometric effects such as chirality



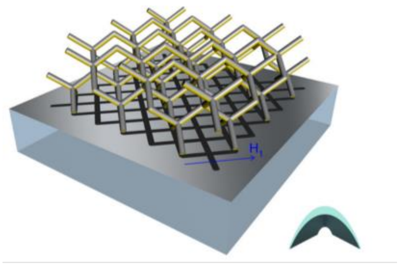
Realise 3D spintronics!

→ ***3D nanofabrication***

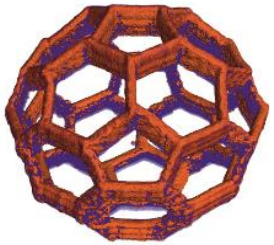


Fabrication of 3D magnetic nanostructures?

Coated 3D scaffolds (2-photon lithography):



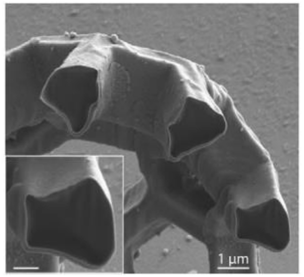
May et al., Comm. Phys. 2, 13 (2019)



Donnelly et al., PRL (2015)

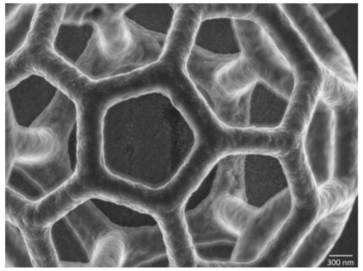
With new ways to achieve homogeneous deposition:

Electroless deposition:



Pip et al., Small (2020)

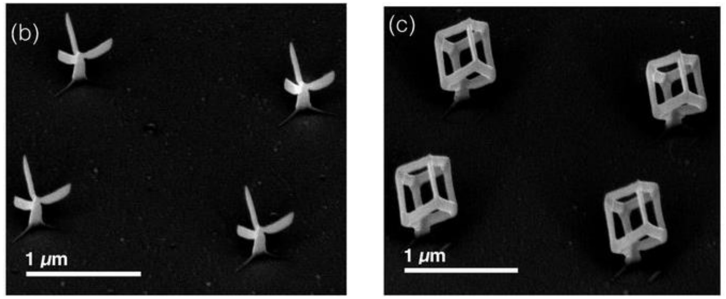
ALD + Electrodeposition:



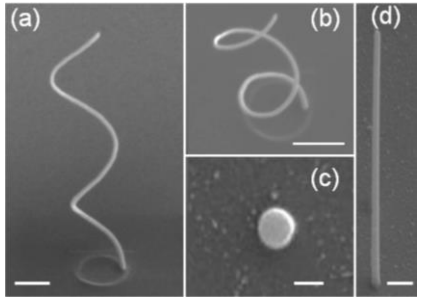
Gliga et al., Materials Today 26, 100 (2019)

Direct-write printing of magnetic materials (FEBID):

Nanowire-based structures & lattices:



Keller, et al., Sci. Rep. **8**, 6160 (2018)

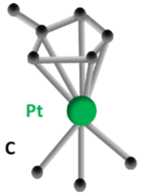


Fernandez-Pacheco et al., Sci. Rep. **3**, 1492 (2013)

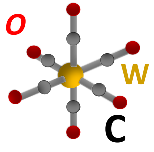
Beyond nanowires?

3D printing of magnetic materials

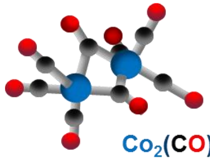
Combining focused electron-induced deposition (FEBID):



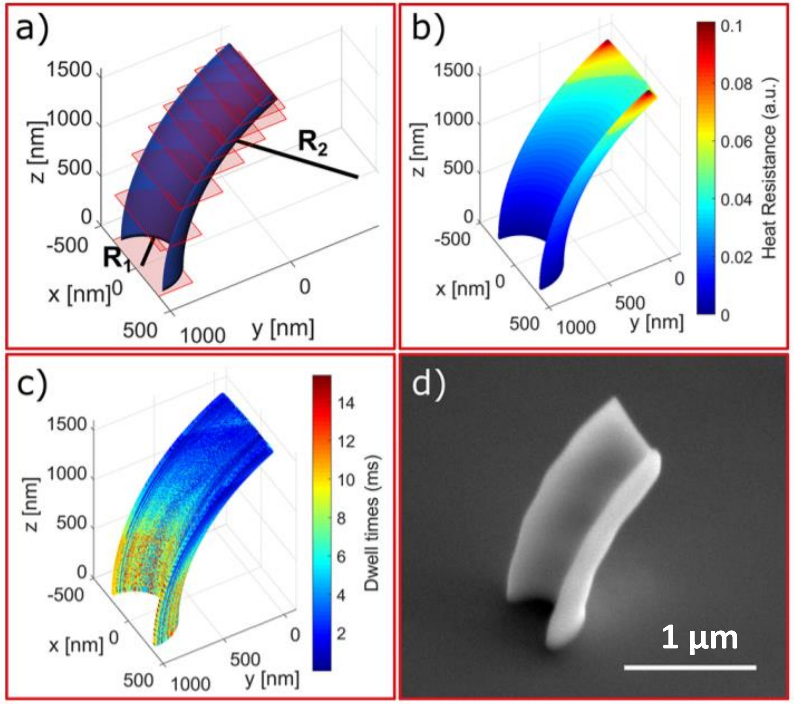
$(CH_3)_3Pt(CpCH_3)$



$W(CO)_6$


$Co_2(CO)_8$

With CAD designs and a growth model:



Luka Skoric
Uni. Cambridge

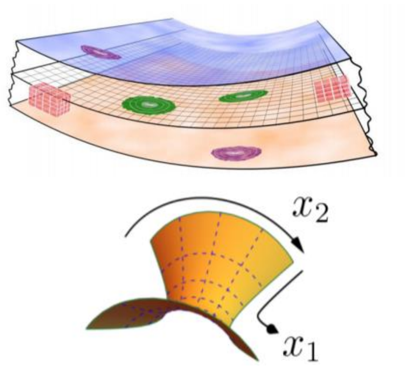
UNIVERSITY OF CAMBRIDGE

Reviews on FEBID:
A. Fernández-Pacheco et al., Materials. 13, 3774 (2020).
R. Winkler et al., Jour. Appl. Phy. 125, 210901 (2019).
J. M. D. Teresa et al., J. Phys. D: Appl. Phys. 49, 243003 (2016).

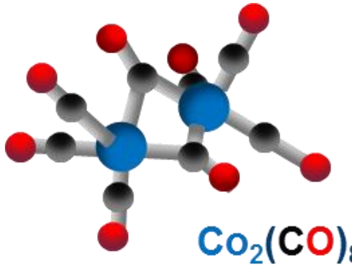
Skoric, Sanz-Hernandez, Meng, Donnelly, Merino-Aceituno, Fernandez-Pacheco, Nano Lett. **20**, 184 (2020)

Opening the door to…

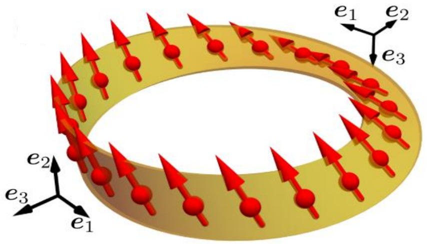
Curved surfaces



Sheka et al., Comm. Phys. **3**, 1 (2020).

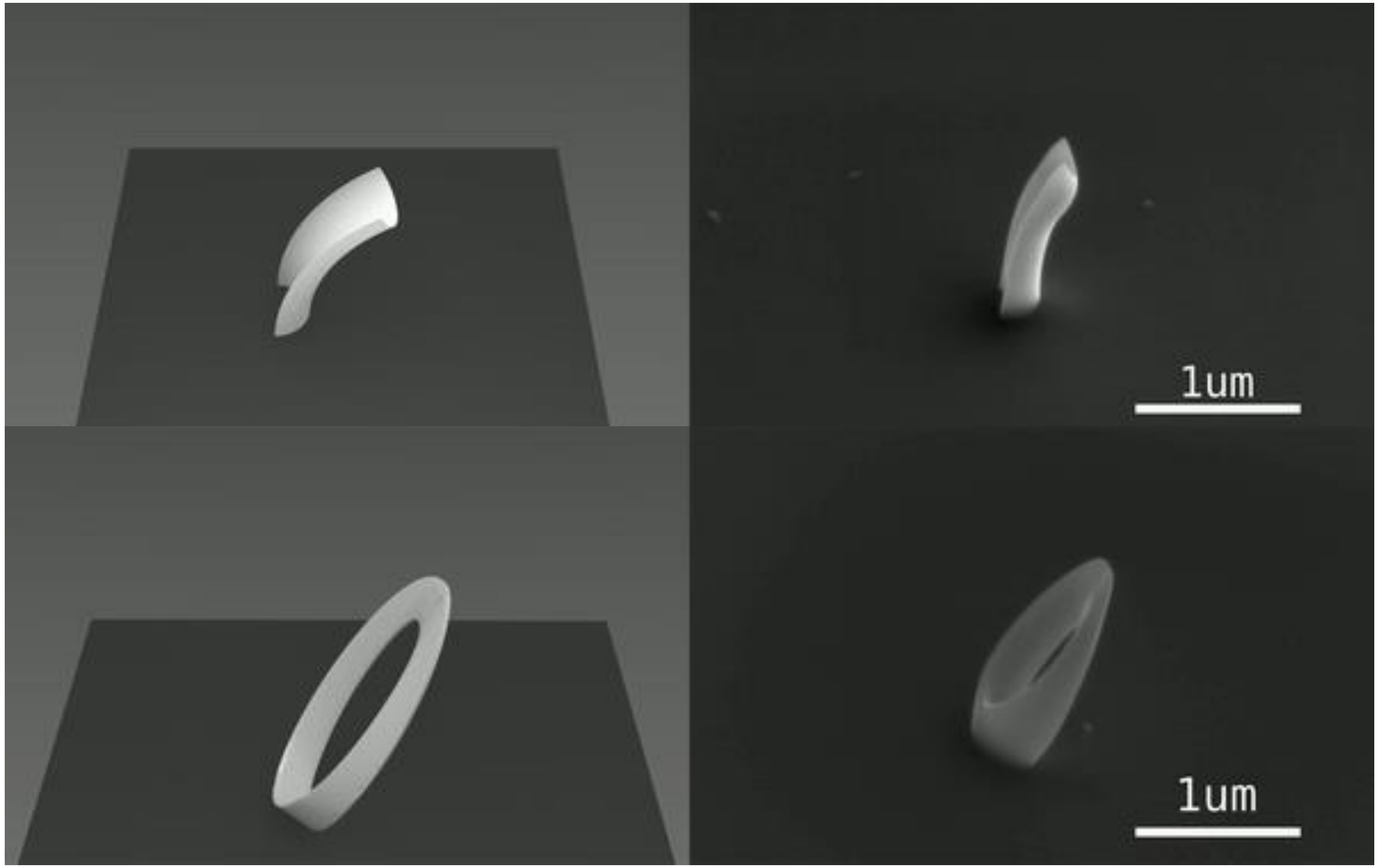


Topological objects



Gaididei et al., J. Phys. A: Math. Theor. **50**, 385401 (2017).

3D model ***Fabricated structure***

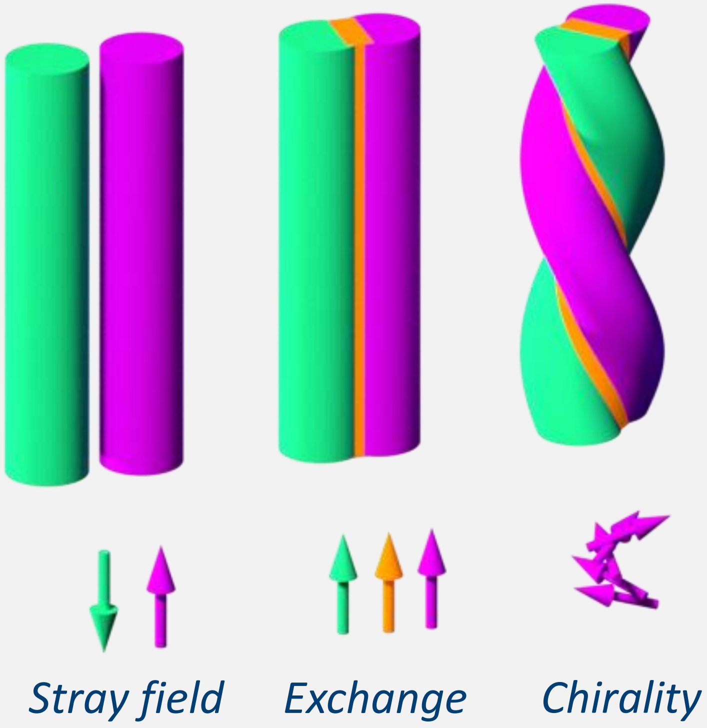


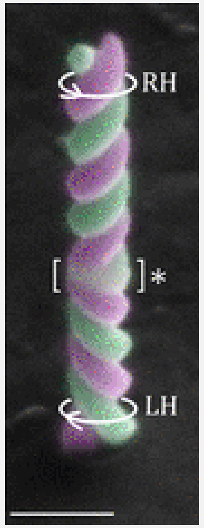
Skoric, Sanz-Hernandez, Meng, Donnelly, Merino-Aceituno, Fernandez-Pacheco, Nano Lett. **20**, 184 (2020)

And with these new capabilities we can achieve:

Geometry-induced magnetochirality

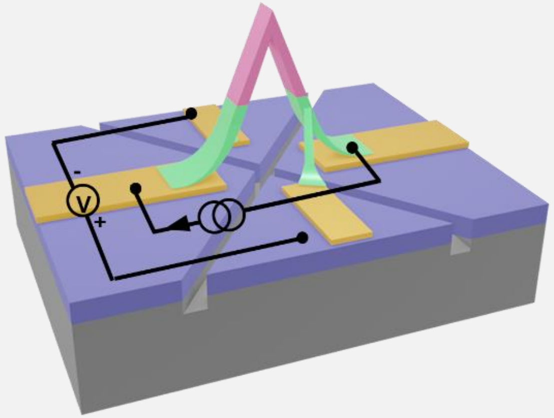
Dedalo Sanz-Hernandez
Uni. Cambridge
(Now CNRS Thales)

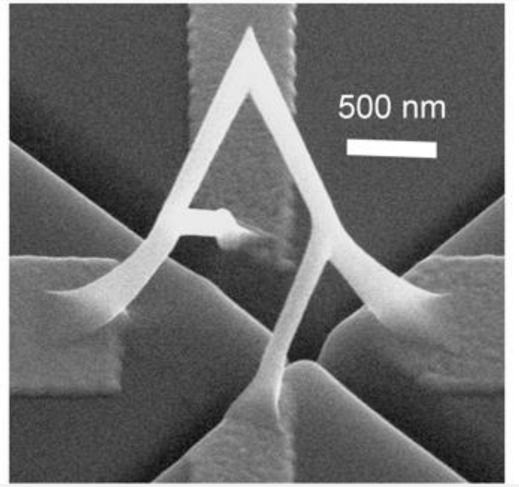




Bringing spintronics to 3D

Fanfan Meng
Uni. Cambridge





Sanz-Hernández, Hierro-Rodriguez, Donnelly, Pablo-Navarro, Sorrentino, Pereiro, Magén, McVitie, de Teresa, Ferrer, Fischer, Fernández-Pacheco ACS Nano **14**, 8084 (2020)

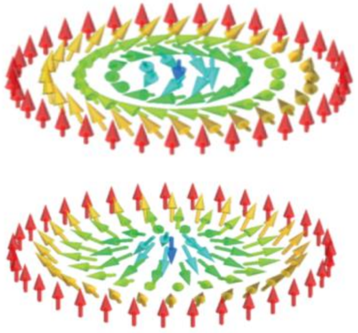
Meng, Donnelly, Abert, Skoric, Holmes, Xiao, Liao, Newton, Barnes, Sanz-Hernandez, Hierro-Rodriguez, Suess, Cowburn, Fernandez-Pacheco, *Submitted,* arXiv:2011.09199 [cond-mat.mes-hall]

Geometry-induced chirality

Chirality: *DMI*

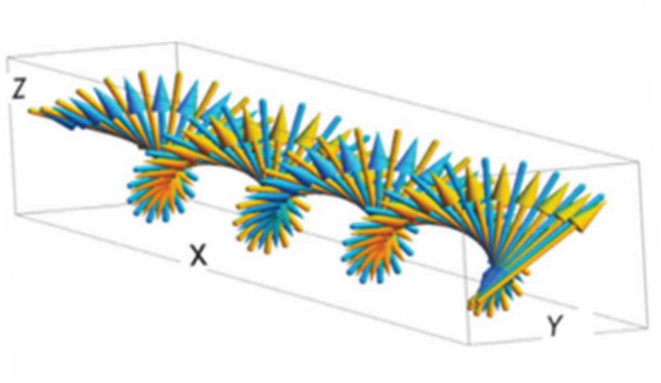
Results in exotic chiral states:

Skyrmions



Fert, et.al. Nat Rev Mat 2017

Spin Spirals

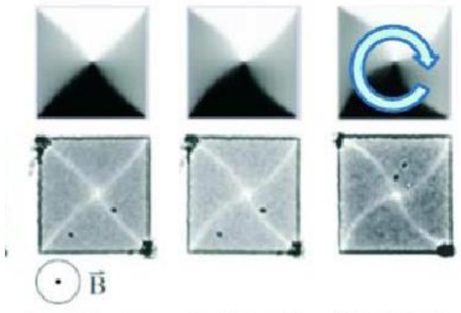


Vedmendeko et al, Phys. Rev. Lett., 2014

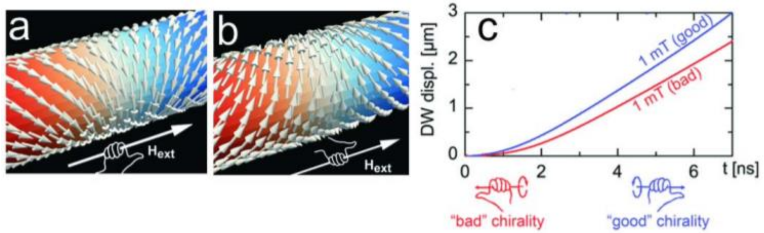
Until now, mostly required **specific** materials & interfaces

But…

Chirality can also be induced via *curvature*:

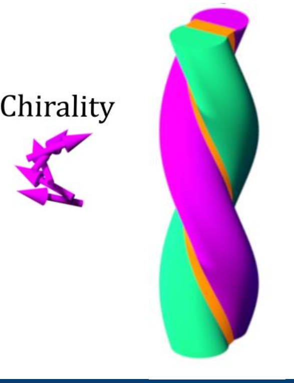


Dietrich et al., PRB **77** 174427 (2008)



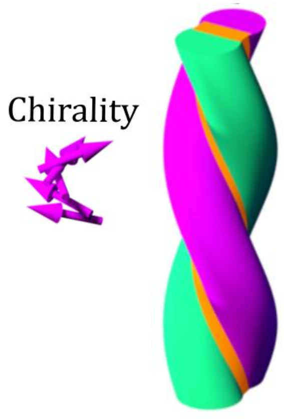
Hertel, Spin **3** 1340009 (2013)

And *chiral geometries*:



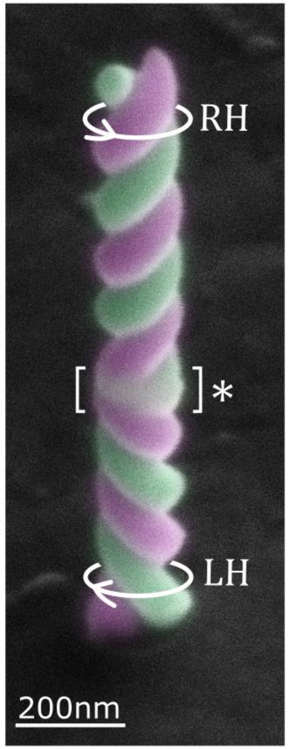
Sanz-Hernández, Hierro-Rodriguez, Donnelly, Pablo-Navarro, Sorrentino, Pereiro, Magén, McVitie, de Teresa, Ferrer, Fischer, Fernández-Pacheco
ACS Nano **14**, 8084 (2020)

Artificial double helix

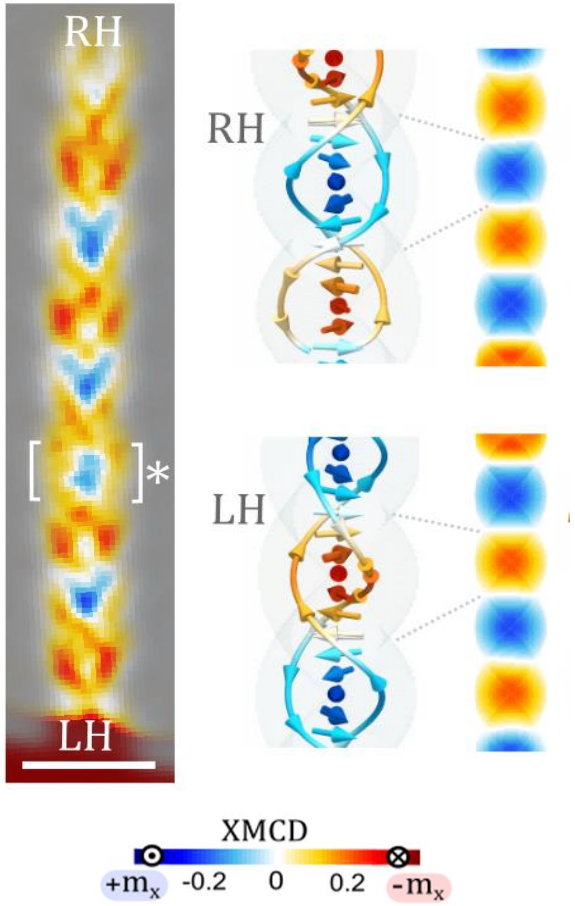


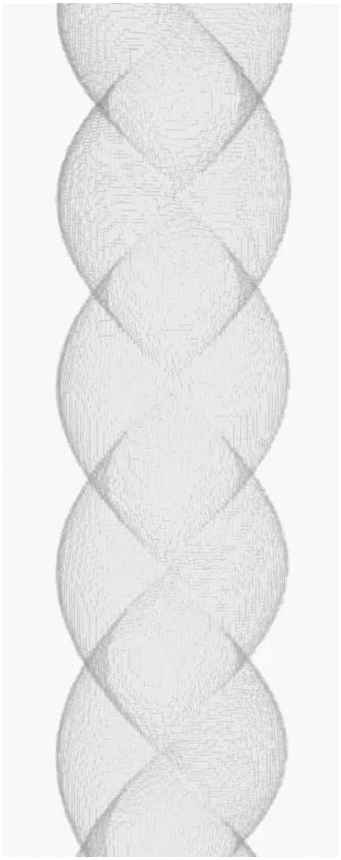
→

with FEBID



XMCD **Simulation**



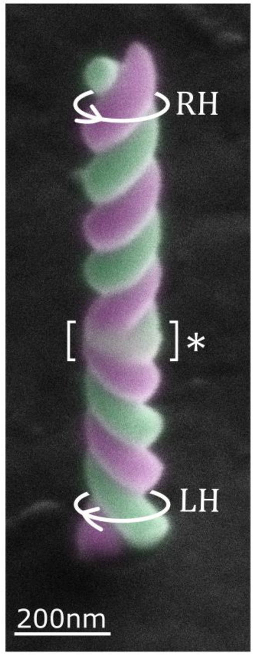


Helical Bloch domain-wall (Spin Spiral)

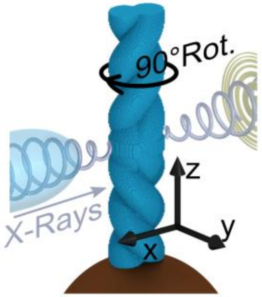
→ *Chiral domain wall!*

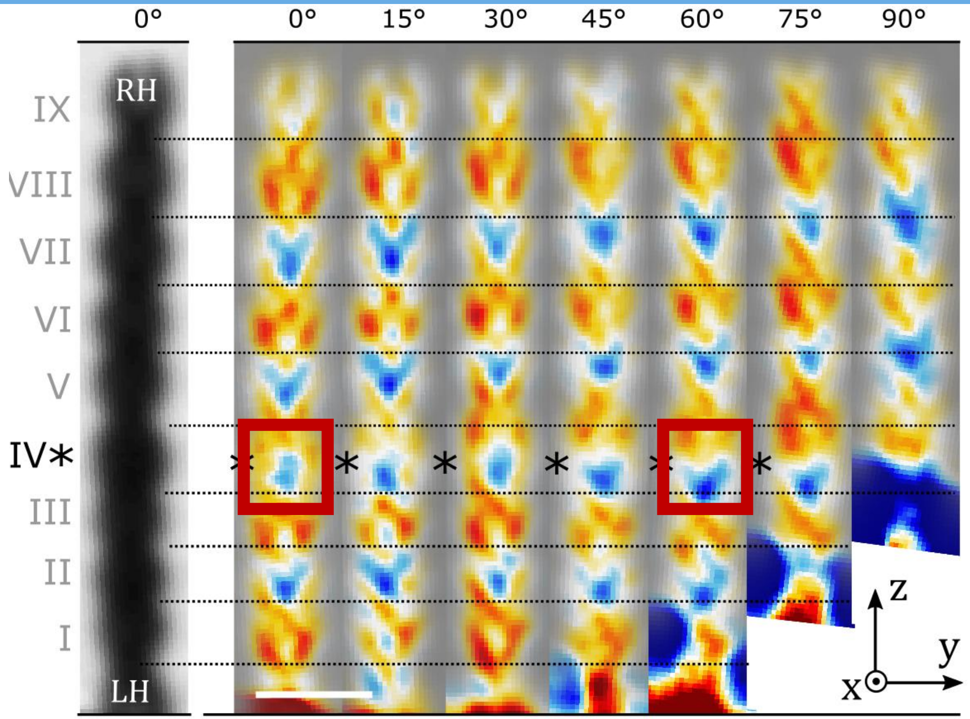
Sanz-Hernández, Hierro-Rodriguez, Donnelly, Pablo-Navarro, Sorrentino, Pereiro, Magén, McVitie, de Teresa, Ferrer, Fischer, Fernández-Pacheco
ACS Nano **14**, 8084 (2020)

Artificial double helix

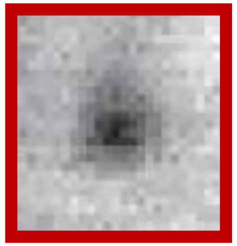


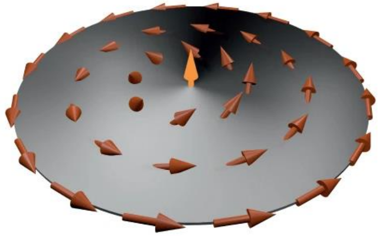
Tendril of red bryony
(Bryonia dioica), Flickr.com



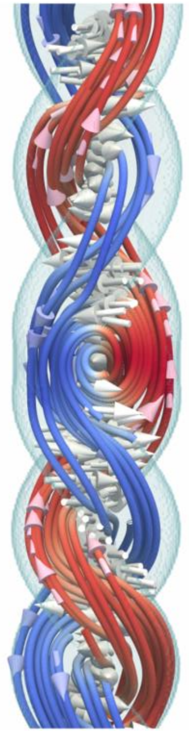


What happens at the threshold?





Wintz et al., Nat. Nano. **11**, 948 (2016)



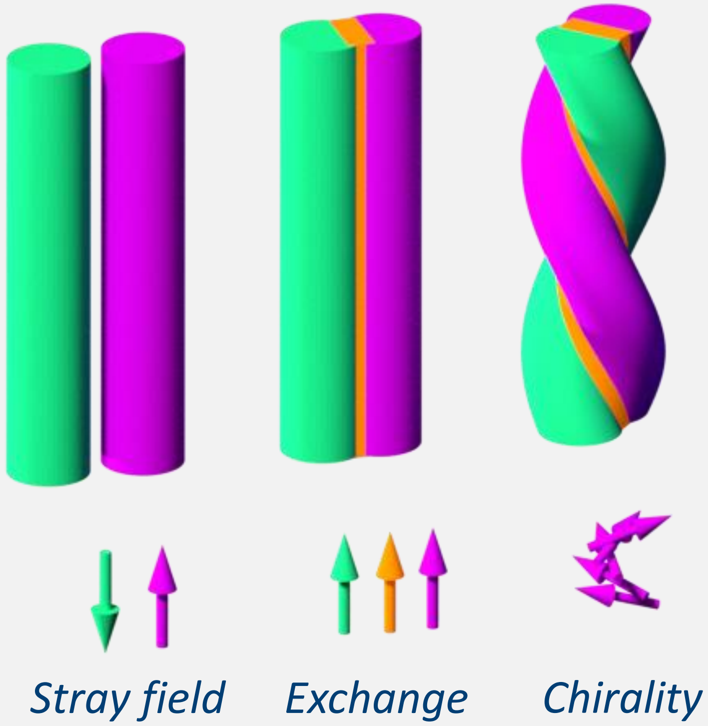
Topological defect
– vortex! –
at chirality threshold

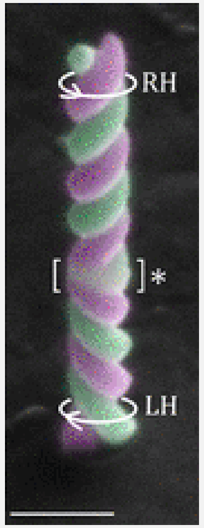
Sanz-Hernández, Hierro-Rodriguez, Donnelly, Pablo-Navarro, Sorrentino, Pereiro, Magén, McVitie, de Teresa, Ferrer, Fischer, Fernández-Pacheco
ACS Nano **14**, 8084 (2020)

And with these new capabilities we can achieve:

Geometry-induced magnetochirality

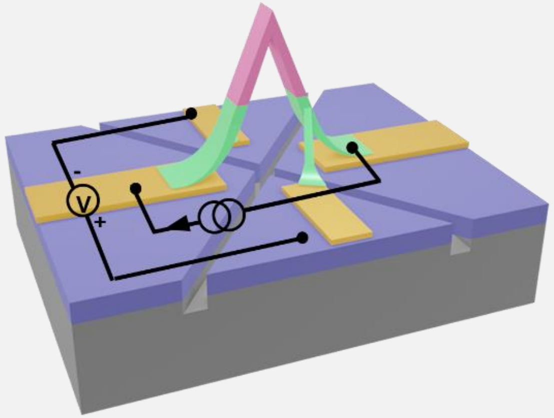
Dedalo Sanz-Hernandez
Uni. Cambridge
(Now CNRS Thales)

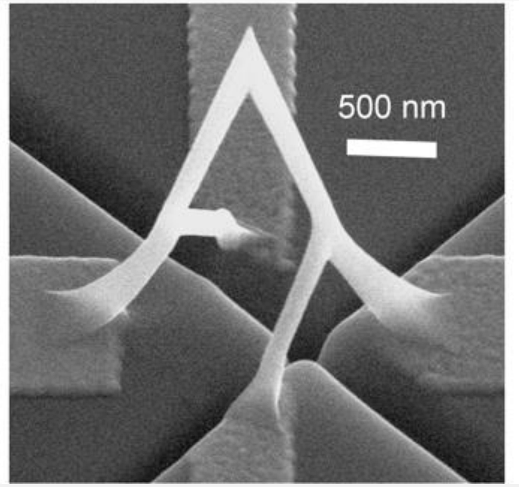




Bringing spintronics to 3D

Fanfan Meng
Uni. Cambridge



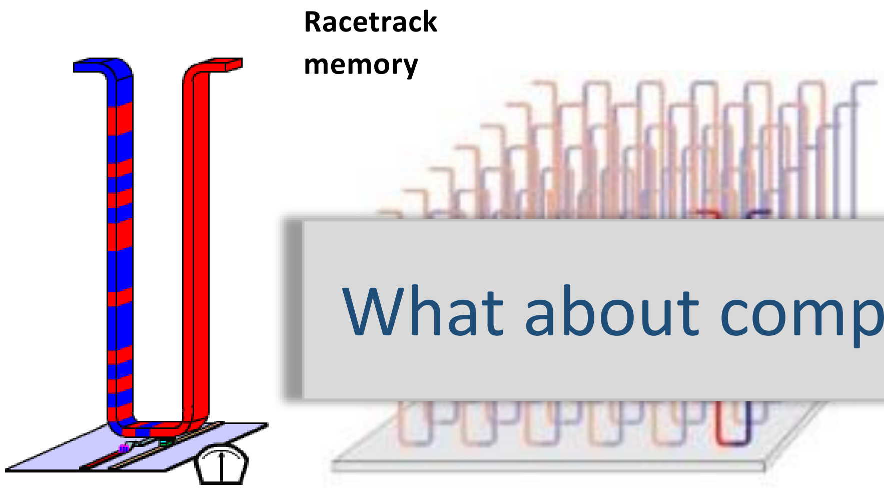


Sanz-Hernández, Hierro-Rodriguez, Donnelly, Pablo-Navarro, Sorrentino, Pereiro, Magén, McVitie, de Teresa, Ferrer, Fischer, Fernández-Pacheco ACS Nano **14**, 8084 (2020)

Meng, Donnelly, Abert, Skoric, Holmes, Xiao, Liao, Newton, Barnes, Sanz-Hernandez, Hierro-Rodriguez, Suess, Cowburn, Fernandez-Pacheco, *Submitted,* arXiv:2011.09199 [cond-mat.mes-hall]

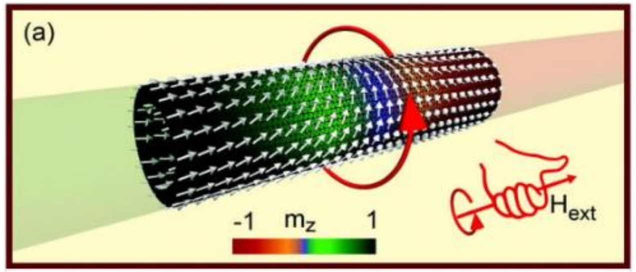
3D spintronics promises…

High memory densities:



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

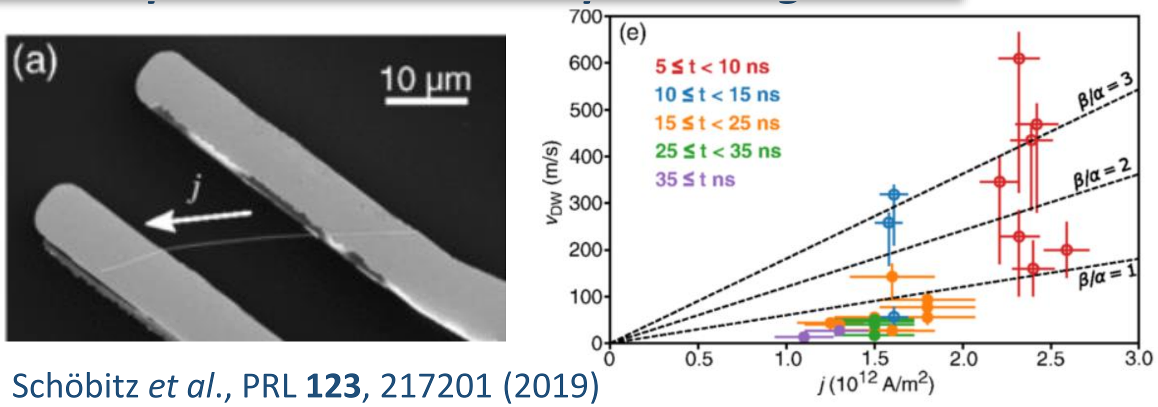
Fast, chiral, domain wall motion



Yan *et al.*, APL **100**, 252401 (2012)

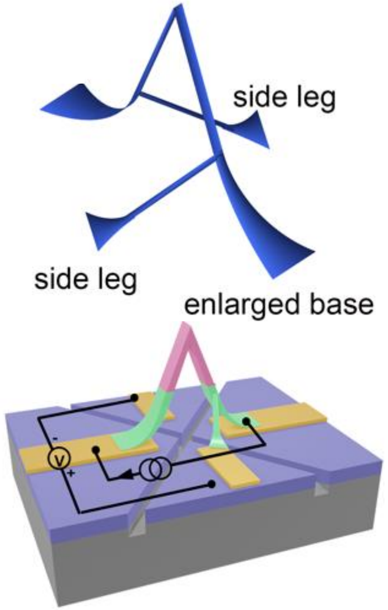
What about complex three-dimensional spintronics devices?

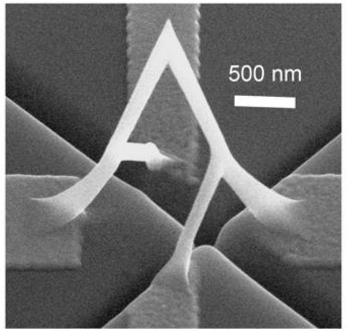
…ties!



Schöbitz *et al.*, PRL **123**, 217201 (2019)

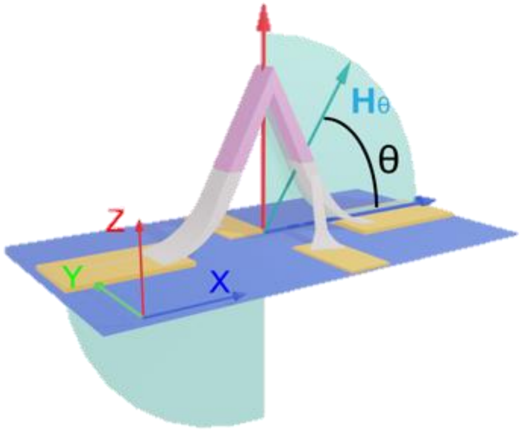
Our 3D device: a cobalt nanobridge



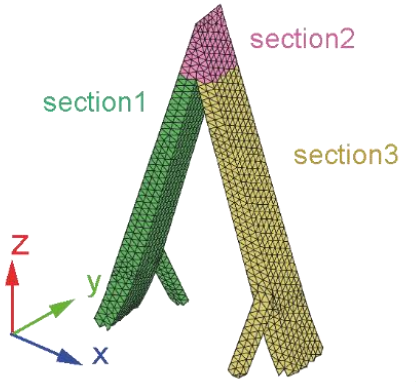


To understand the magnetotransport in 3D:

We combine:



Angular dependence of the magnetotransport

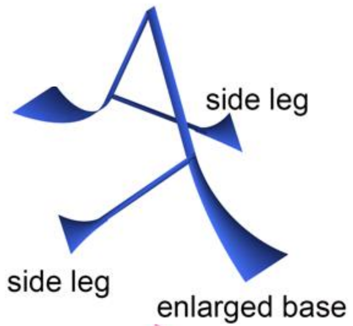


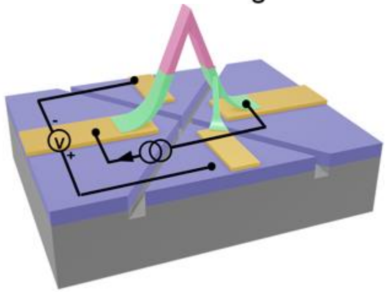
Finite element and macrospin simulations

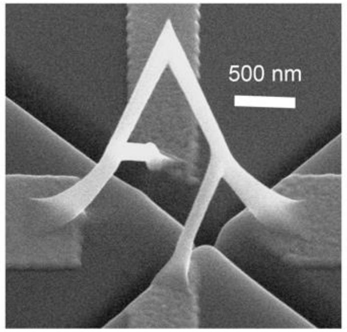
→ Characterise magnetoelectrical properties

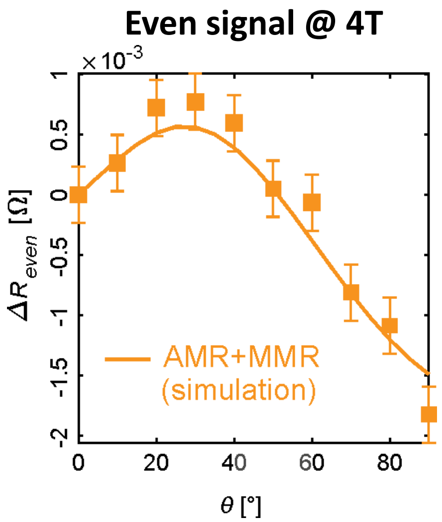
Meng, Donnelly, Abert, Skoric, Holmes, Xiao, Liao, Newton, Barnes, Sanz-Hernandez, Hierro-Rodriguez, Suess, Cowburn, Fernandez-Pacheco, *Submitted,* arXiv:2011.09199 [cond-mat.mes-hall]

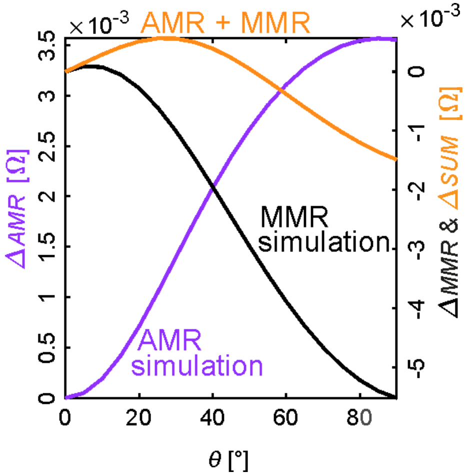
Our 3D device: a cobalt nanobridge



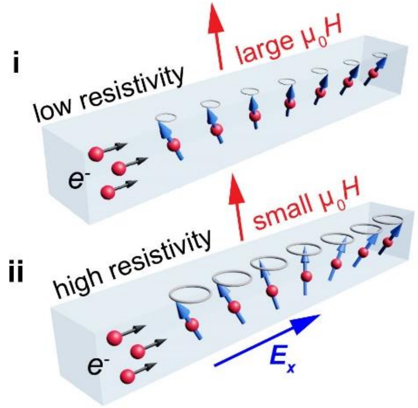


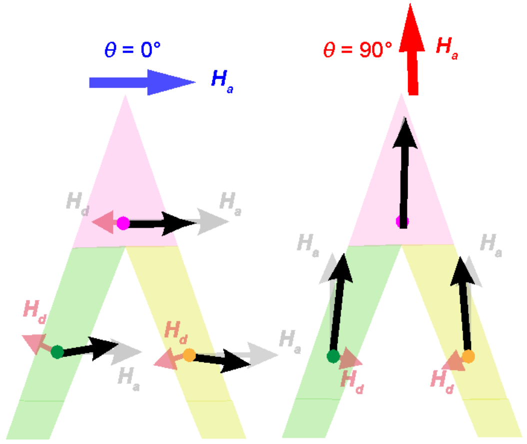






Magnon Magnetoresistance (MMR)





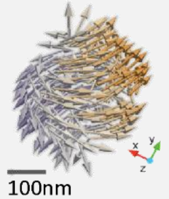
→ *Magnon magnetoresistance: strongly influences the transport*

→ *Due to importance of magnetostatics in 3D*

Nanoprototyping method → extendable to wide variety of geometries!

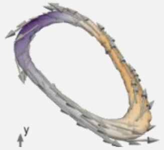
Meng, Donnelly, Abert, Skoric, Holmes, Xiao, Liao, Newton, Barnes, Sanz-Hernandez, Hierro-Rodriguez, Suess, Cowburn, Fernandez-Pacheco, *Submitted,* arXiv:2011.09199 [cond-mat.mes-hall]

Conclusions



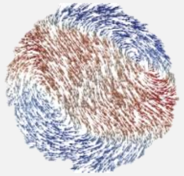
Magnetic tomography: Bloch points

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



Observation of magnetic vortex rings

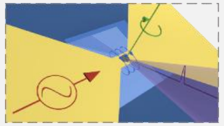
Donnelly et al., Nature Physics (Accepted)



Hard & soft magnetic laminography

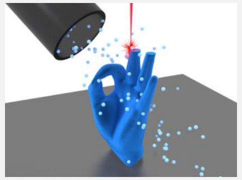
Donnelly et al., Nature Nanotechnology **15** 356 (2020)

Witte et al., Nano Letters **20** 1305 (2020)



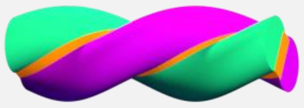
Magnetisation dynamics in 3D

Donnelly et al., Nature Nanotechnology **15** 356 (2020)



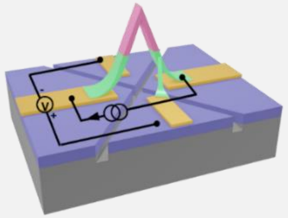
3D printing of magnetic nanostructures

Skoric et al., Nano Letters **20**, 184 (2020)



Chiral magnetic nanostructures

Sanz-Hernandez et al., ACS Nano **14**, 8084 (2020)



Towards 3D spintronics…

Meng et al., *arXiv:2011.09199 [cond-mat.mes-hall]*

& Outlook…

Higher spatial resolution with next generation + upgrades

Statics and dynamics of 3D magnetic systems!

Topologically non-trivial 3D structures!

UNIVERSITY OF CAMBRIDGE

Next year: New group @ MPI-CPfS in Dresden

For PhD & postdoc positions in 3D magnetism: *Contact **cd691@cam.ac.uk***