XI AUSE Conference & VI ALBA Users Meeting
03/09/2024

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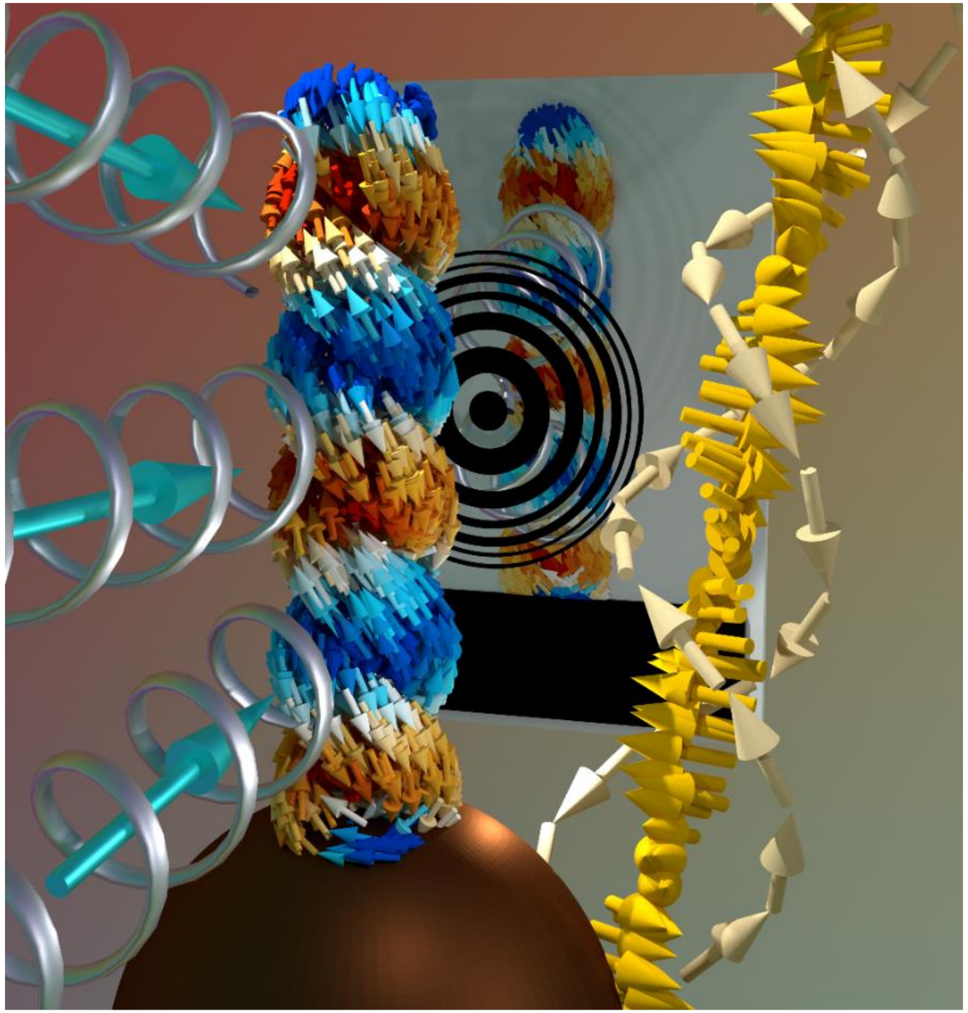
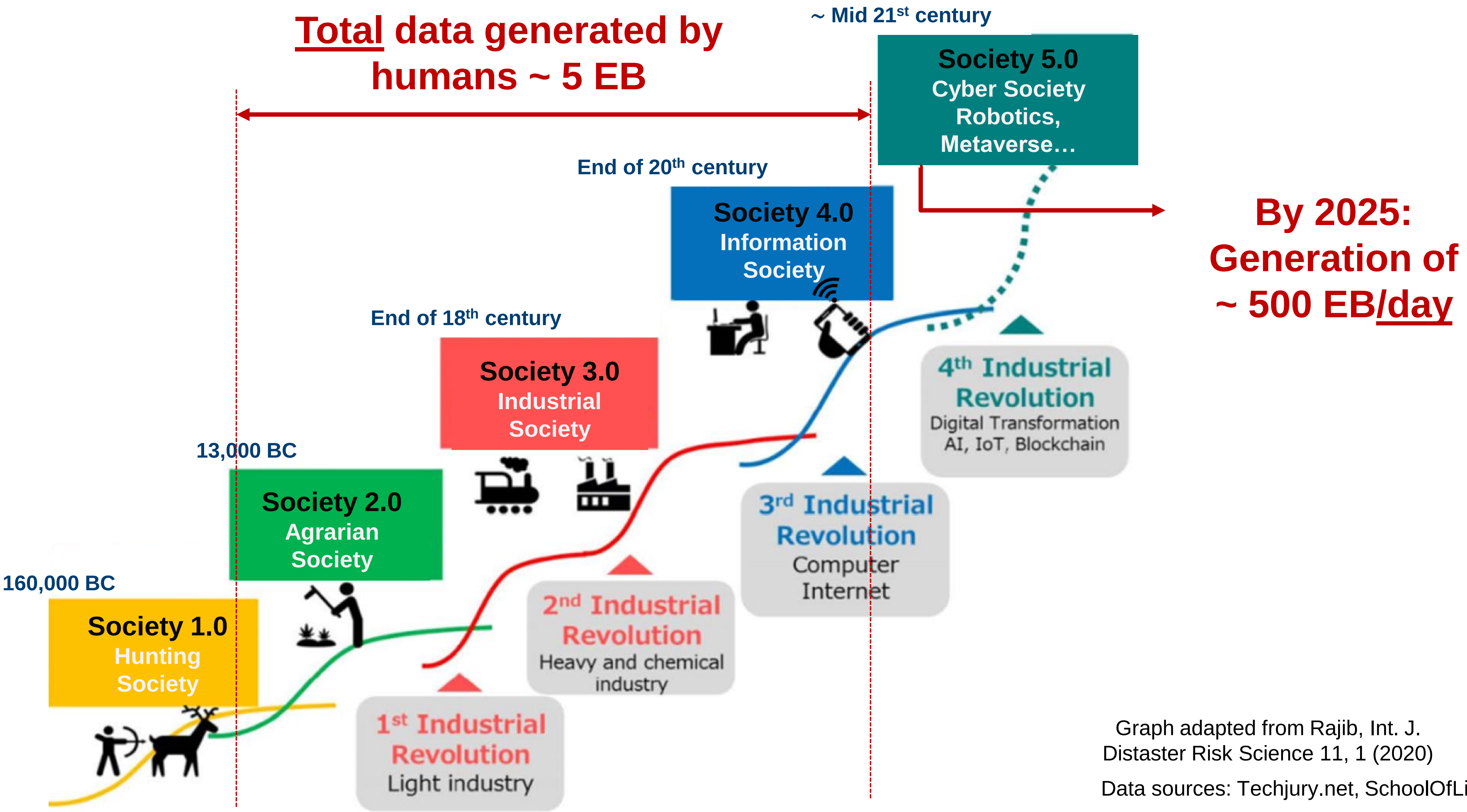
http://tuwien.at/phy/iap/3dnano

Investigations in three-dimensional nanomagnetism using XR synchrotron techniques



European Research Council
Established by the European Commission

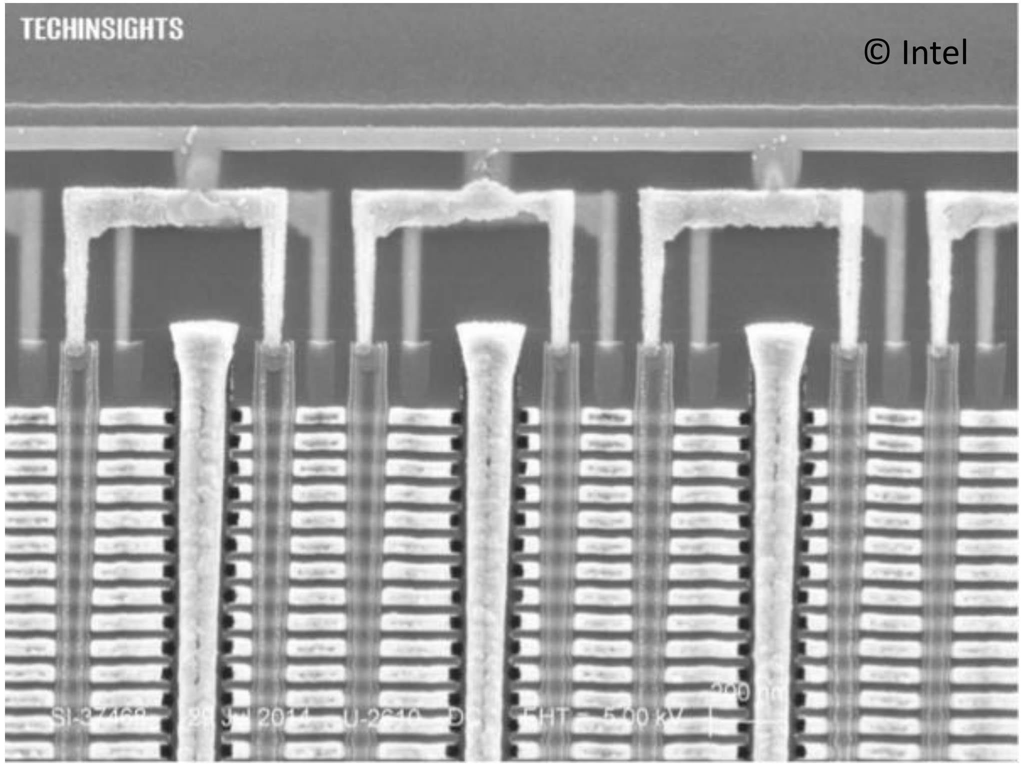
Modern society & data generation



Graph adapted from Rajib, Int. J. Distaster Risk Science 11, 1 (2020)

Data sources: Techjury.net, SchoolOfLife

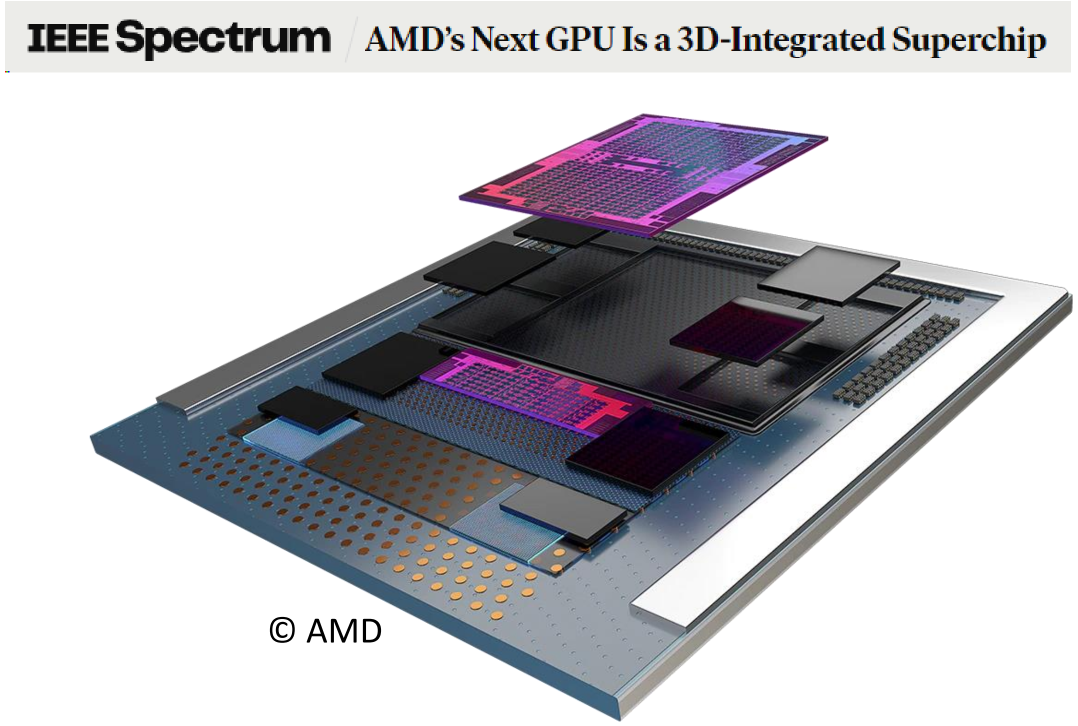
Semiconductor technologies moving towards 3D



https://www.techtarget.com/searchstorage/definition/3D-NAND-flash

Since 2013, Samsung offering Vertical NAND FLASH memory for ultra-high storage density

2.5D technology with hundreds of layers

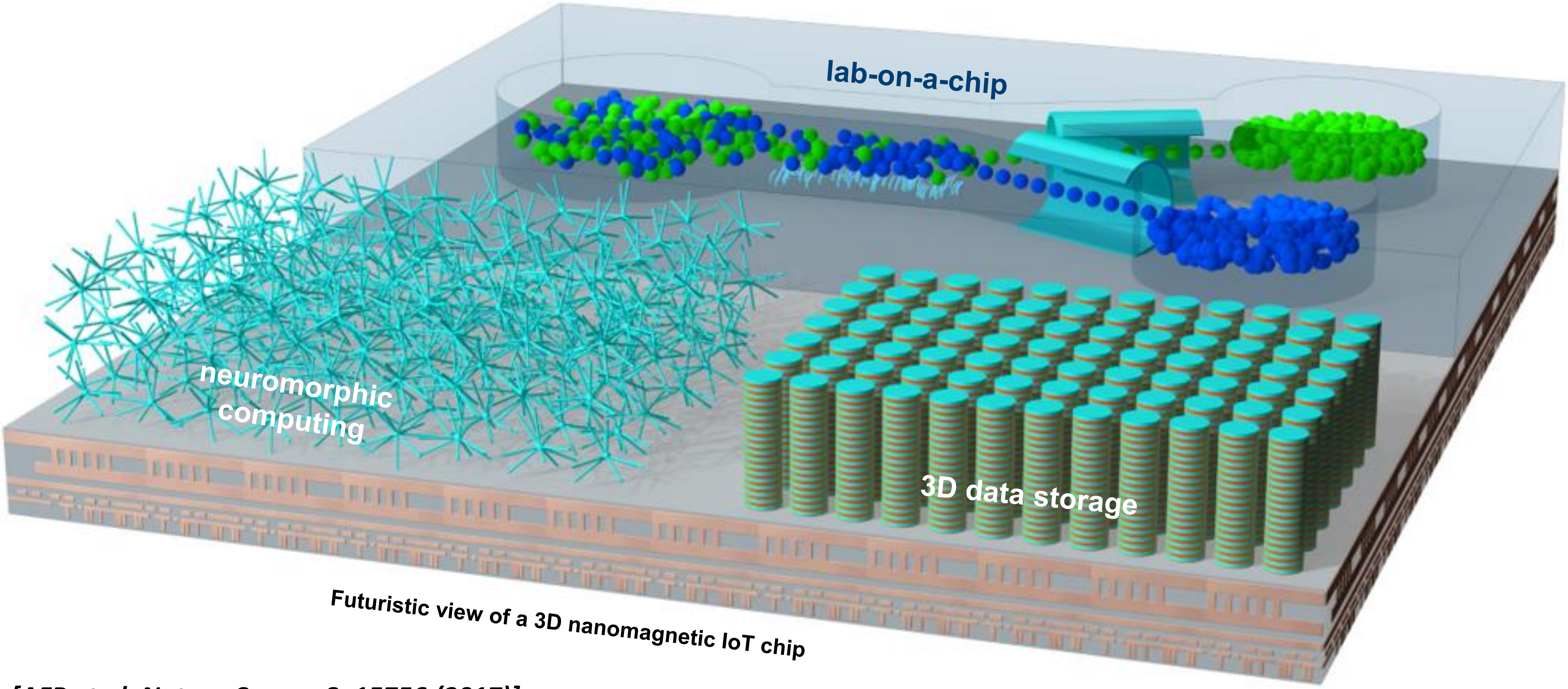


https://spectrum.ieee.org/amd-mi300

Chiplets stacking vertically GPU, CPU, communication ports

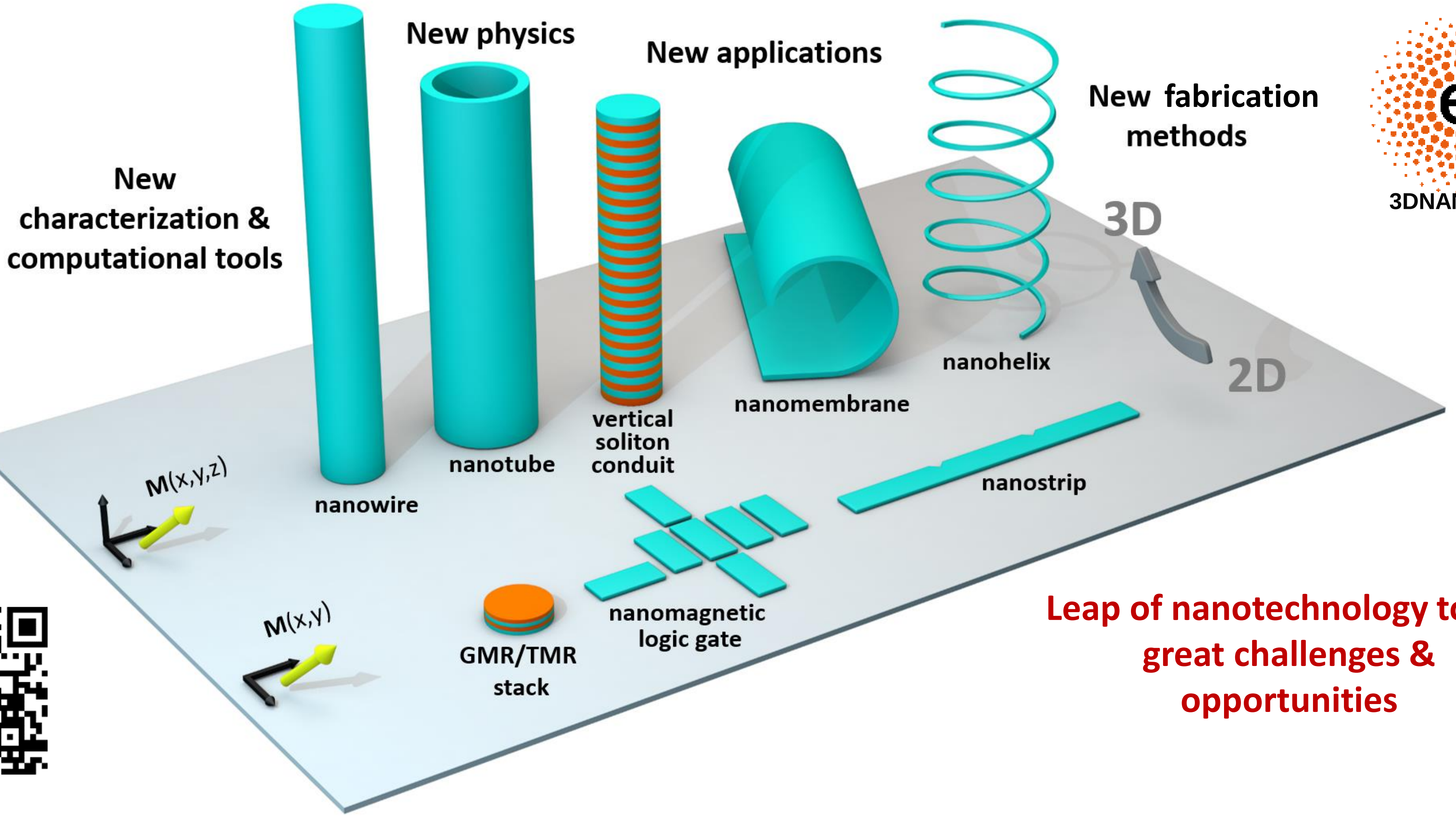
Boost of storage density & speed, improving performance for AI

3D nanomagnetism for future green technologies



[AFP et al, Nature Comm. 8, 15756 (2017)]

Three-dimensional nanomagnetism

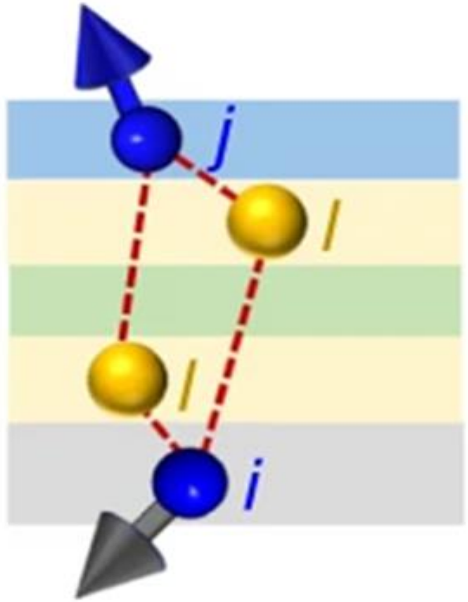


3DNANOMAG

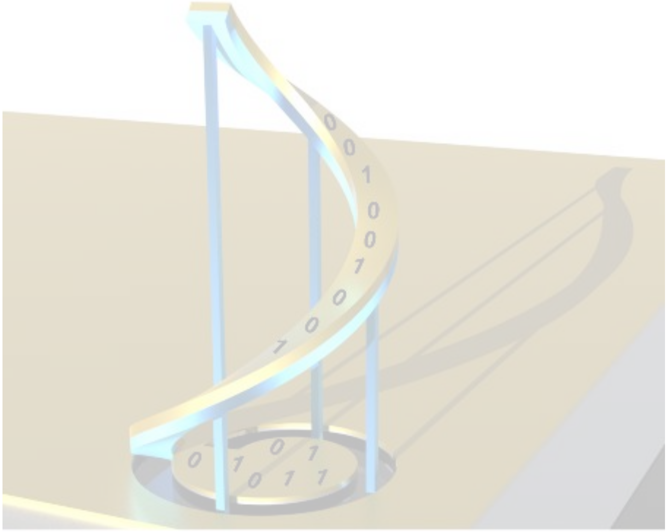
Leap of nanotechnology to 3D: great challenges & opportunities

Outline

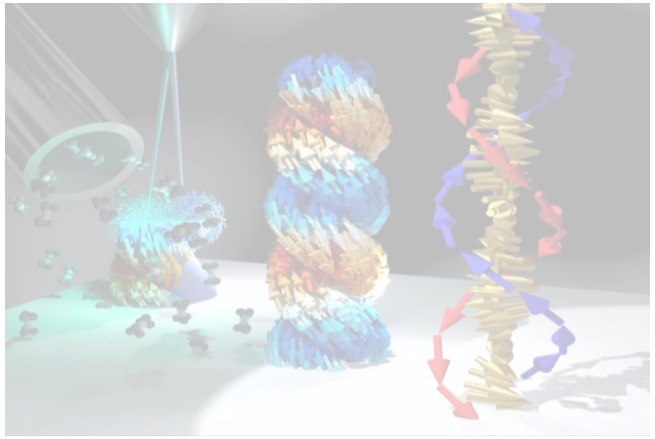
Chiral spin interactions in synthetic antiferromagnets



Domain wall motion in 3D nanomagnetic circuits

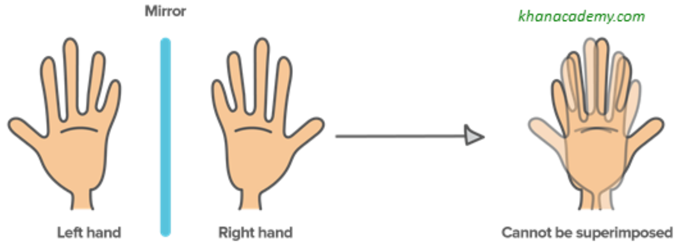


Imprinting of topological states in 3D helical nanomaterials

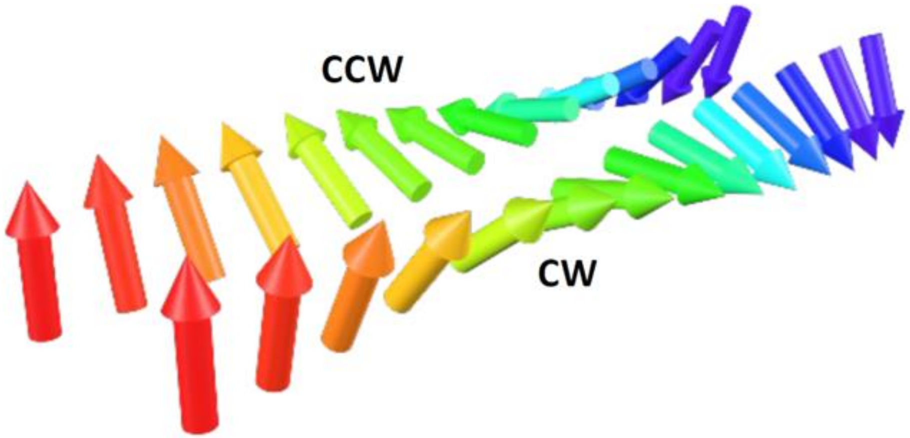


Chirality & magnetism

Chirality or handedness refers to the property structures that cannot be superimposed on their mirror image"
[Kelvin (1904), Larmor (1900) , Eddington (1946)]
Onmipresent in nature, e.g. DNA, molecules (flavour, toxicity, drug efficiency)…



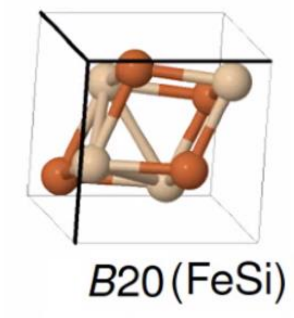
Chiral magnetism



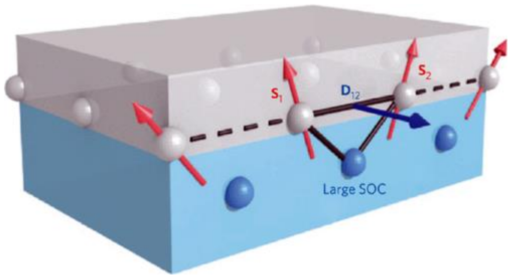
In general, magnetic textures are not chiral or both chiralities are degenerate in energy

Symmetry breaking
+
Spin-orbit coupling
=
Emergence of antisymmetric exchange (Dzyaloshinskii–Moriya interaction: DMI)
[Moriya et al, Phys. Rev. 120, 91 (1960)]

$$H^{DMI} = -\vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$$



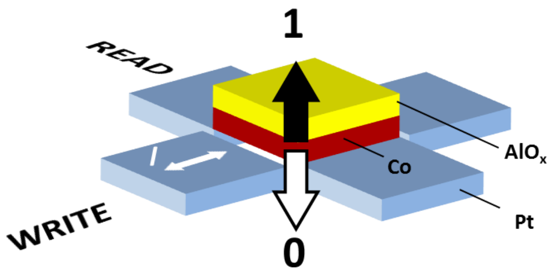
Non-centro symmetric crystal



DMI interaction in thin magnetic layer interfaced with a heavy metal

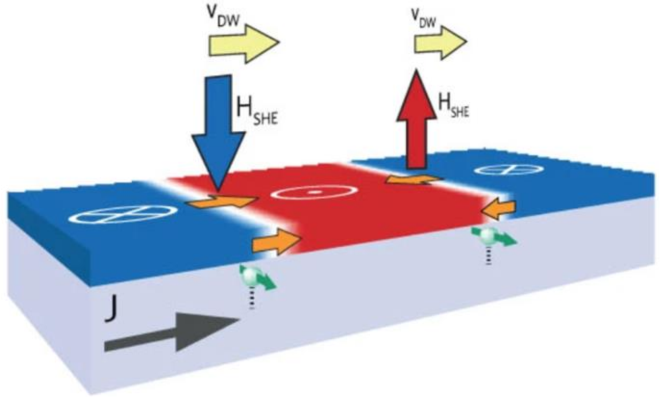
Magnetic chirality: key concept in modern spintronics

Low-power magnetic switching



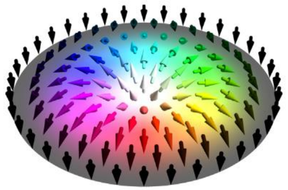
[Miron et al, Nature 476, 189–193 (2011); Liu et al, Science 336 555-558 (2012)]

Unidirectional motion of spin textures



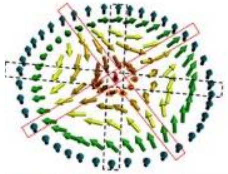
[Fert et al, Nature Nano 8, 152–156 (2013); Parkin et al, Nature Nano 10, 195 (2015)]

Formation of topological spin textures



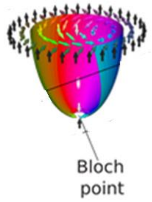
Magnetic skyrmion

[Göbel et al, Phys. Reports 895, 1 (2021)]]



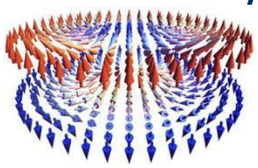
Antiskyrmions

[Nayak et al, Nature 548, 561(2017)]



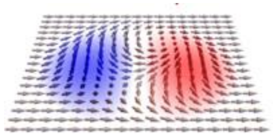
Chiral bobbers

[Zheng et al, Nature Nano 13, 451(2018)]



Antiferromagnetic skyrmions

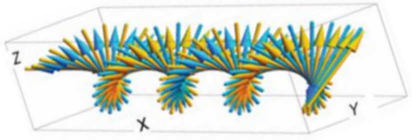
[Legrand et al, Nature Mat 19, 34 (2020)]



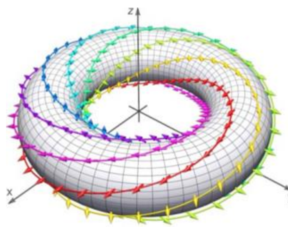
Bimerons

[Göbel et al, Phys. Rev. B 99, 060407 (2019)]

Spin spirals



[Vedmendeko et al, Phys. Rev. Lett. 112, 078206 (2014)]

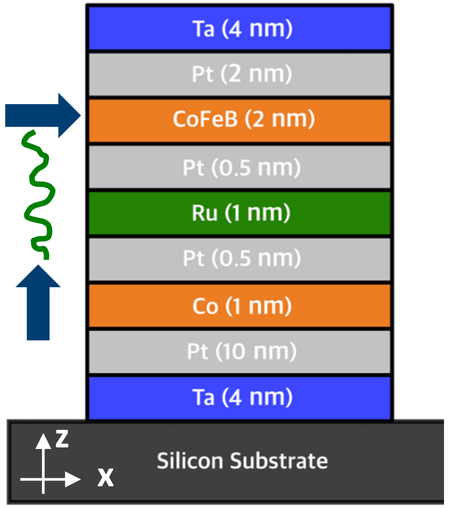


Hopfions

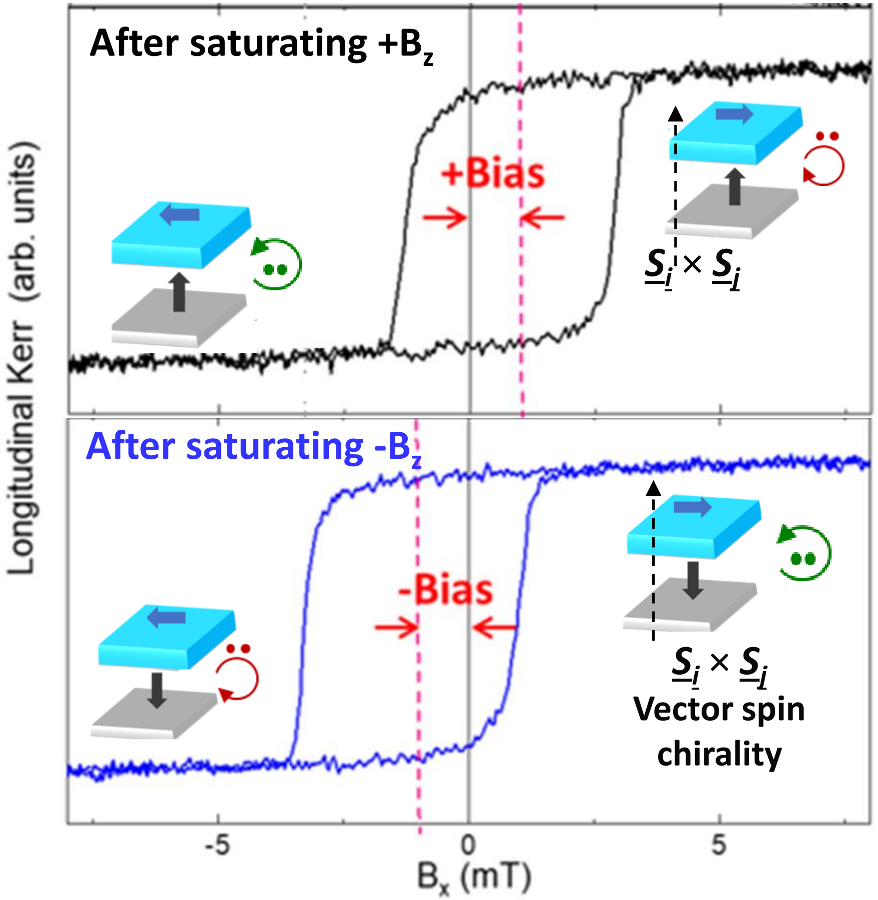
[Suttcliffe et al, Phys. Rev. Lett. 118, 247203 (2017); Zheng et al, Nature 623, 718 (2023)]

Discovery of interlayer chiral exchange interactions

T-SAF

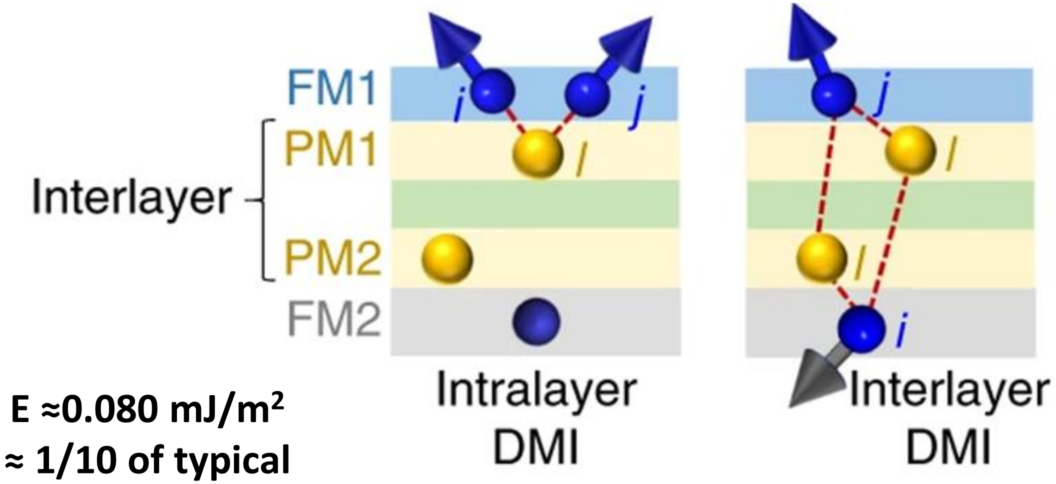


[AFP at, Nature Materials 18, 679 (2019)]



In-plane B_x minor loops:

Opposite sign of exchange bias for opposite saturating initial B_z field



E ≈0.080 mJ/m² ≈ 1/10 of typical intra-layer DMI

$$E_{ij}^{DMI} = \underline{\boldsymbol{D}}_{ij} \cdot (\underline{\boldsymbol{S}}_i \times \underline{\boldsymbol{S}}_j)$$

Theory of interlayer DMI in multilayered systems

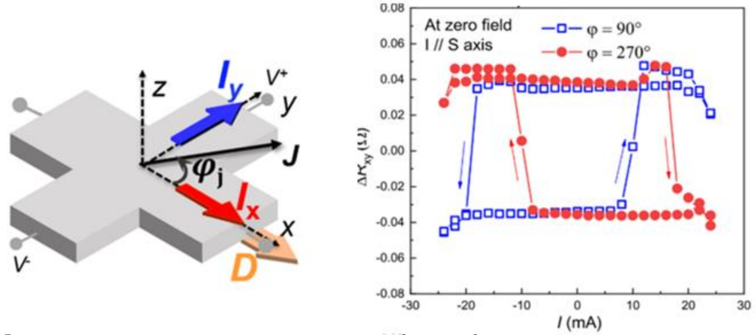
[Vedmenenko et al, PRL 122, 257202 (2019)]

Simultaneous experimental reporting of the effect

[Han et al, Nature Materials 18 703–708 (2019)]

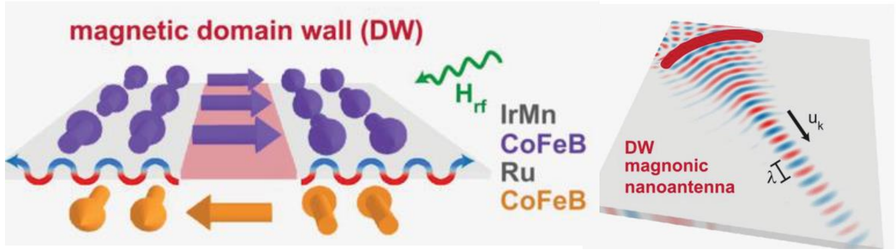
Interlayer chiral magnetic interaction: Opportunities for planar & 3D spintronics

Planar spintronics



[He et al, Nano Lett. 22, 6857 (2022)
Wang et al, Cell Rep. Phys. Sci. 4.4 (2023)
Xie et al, Adv. Mater. 35 2208275 (2023)
Li et al. Phys. Rev. Appl. 20, 024032 (2023)
Lin et al, ACS Mater. Lett. 6, 400–408 (2024)]

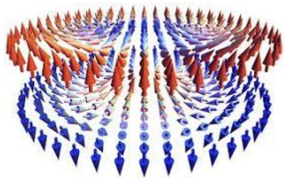
Already demonstrated: Field-Free Spin–Orbit Torque Switching



[Albisetti et al. Adv. Mater. 32 1906439 (2020)]

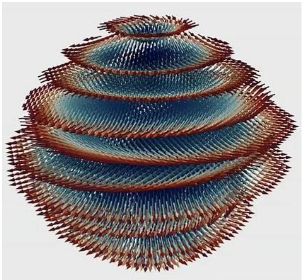
Future: Nonreciprocal effects (like intralayer DMI, but tuneable via neighbours)

3D spintronics



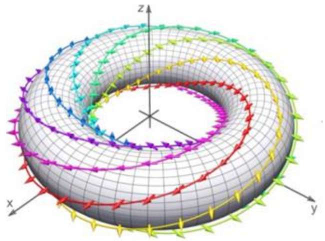
Antiferromagnetic skyrmions

[Legrand et al, Nature Mat 19, 34 (2020)]



Skyrmion cocoons

[Grelier et al, Nature Comm. 13, 6843 (2022)]

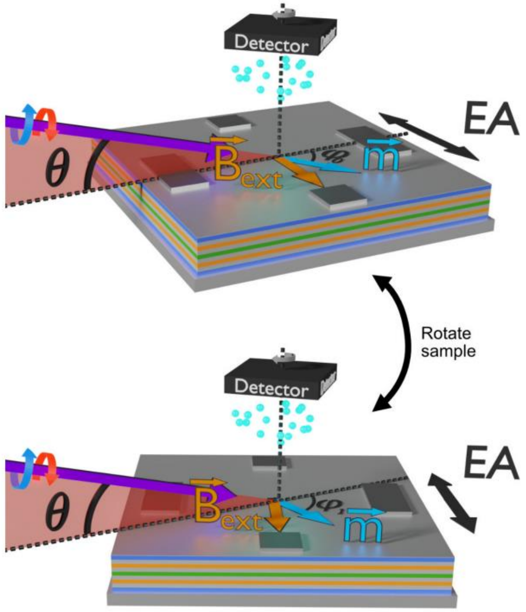


Hopfions

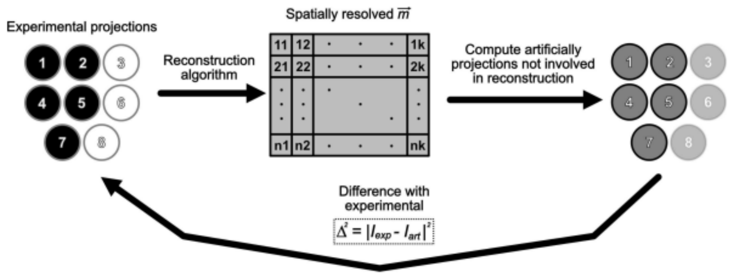
[Suttcliffe et al, Phys. Rev. Lett. 118, 247203 (2017); Kent et al, Nature Comm. 12, 1562 (2021); Zheng et al, Nature 623, 718 (2023)]

Tuneable chiral interaction to promote 3D topological spin textures

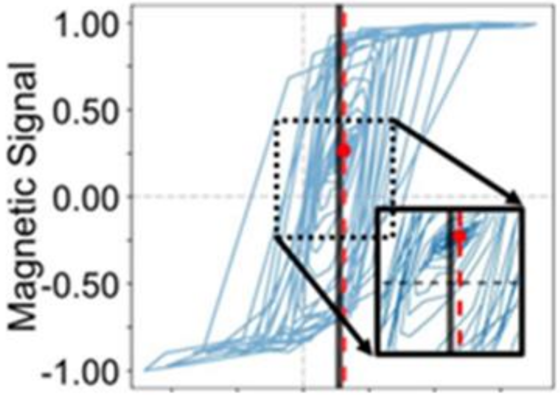
What type of spin textures does interlayer DMI promote?

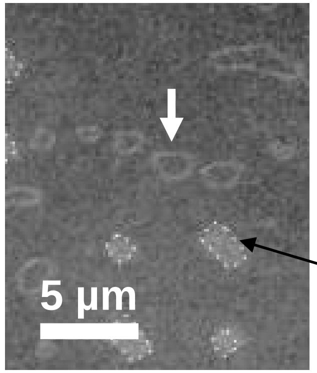


XMCD photoelectron microscopy (XMCD-PEEM):
Vector tomography at 20 nm resolution

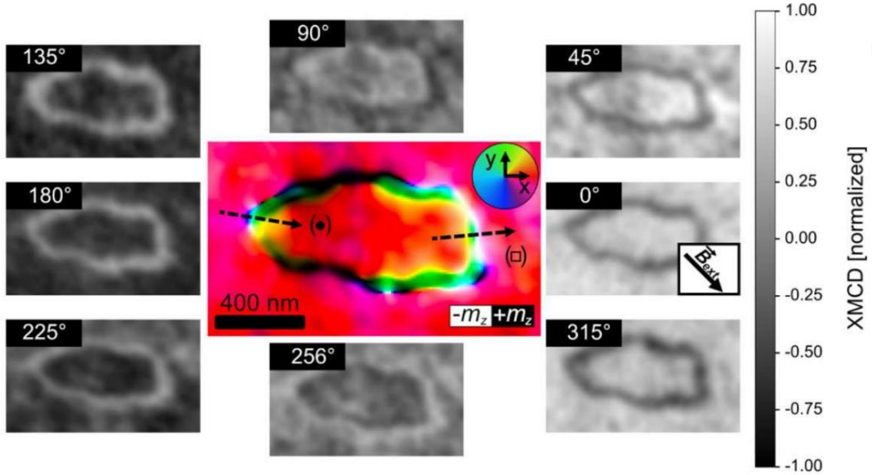


[Cascales-Sandoval, AFP et al, J. Sync. Rad. 31, 336-342 (2024)]





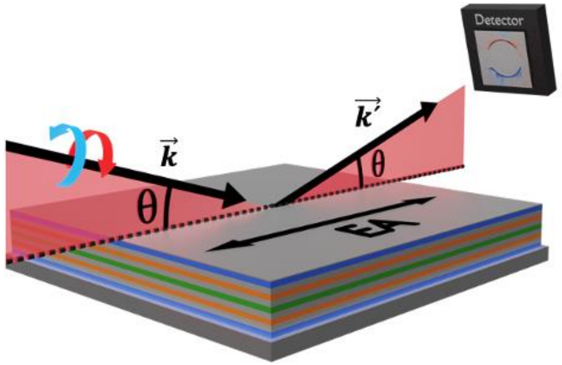
rectangular deposits: for alignment in magnetic reconstruction



Formation of 360º domain wall rings due to exchange bias

[Cascales-Sandoval, AFP et al, Appl. Phys. Lett. 123, 172407 (2023)]

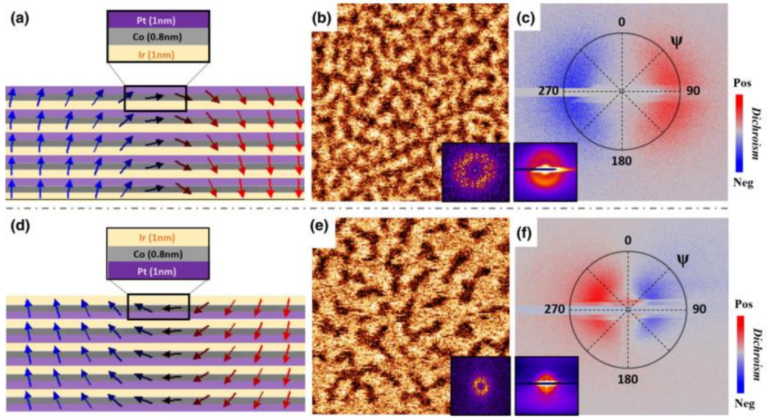
X-ray magnetic scattering: presence of chiral spin textures

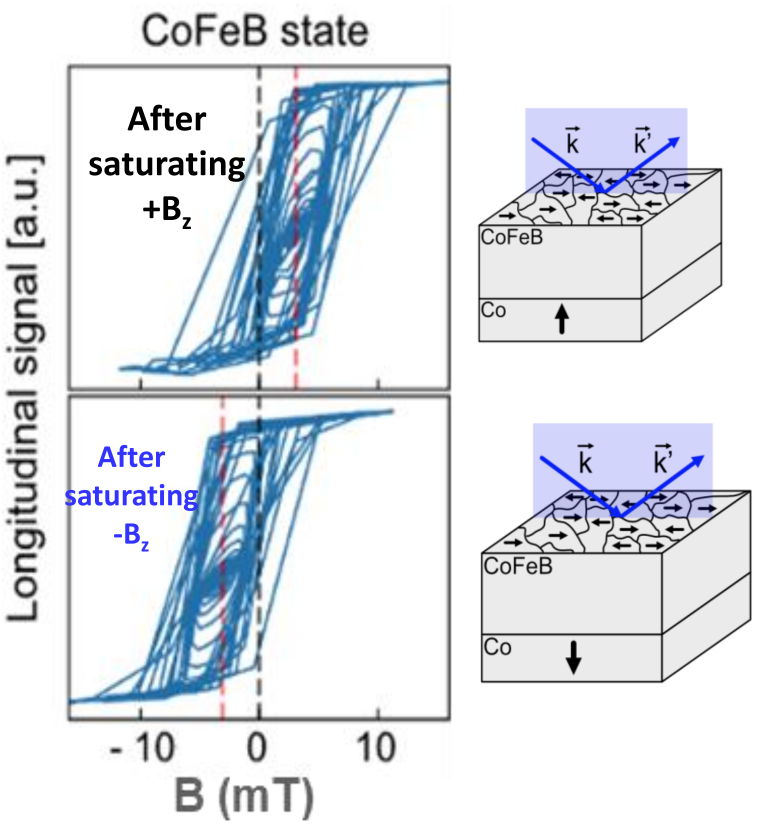


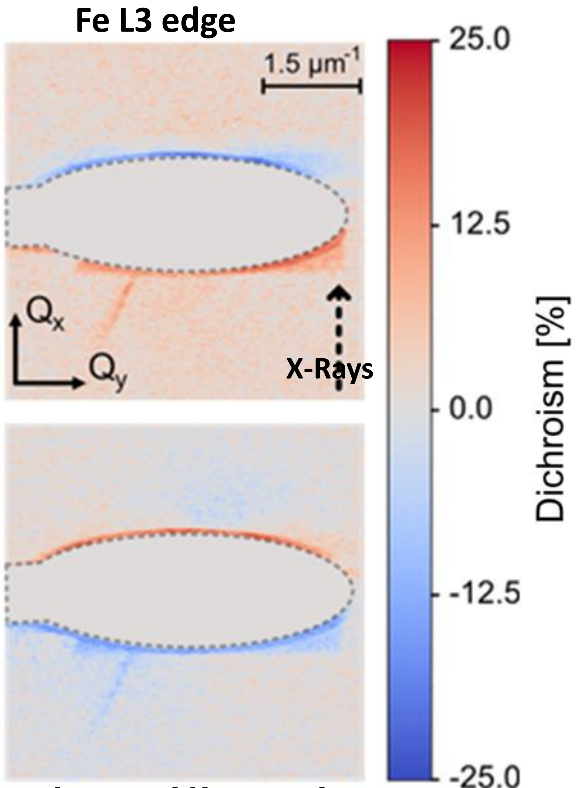
X-ray resonant magnetic scattering (XRMS)

Magnetic diffuse scattering around specular beam
Probing winding sense & lengthscales of chiral spin states

[Chauleau et al, Phys. Rev. Lett. 120, 037202 (2018)]







$(I_{CL}-I_{CR})/(I_{CL}+I_{CR})$

Specular reflection blocked by beam stopper

Chiral spin states - micron-size in-plane domains in CoFeB layer

XRMS asymmetry changes sign when Co layer is reversed!!

[Cascales-Sandoval, AFP et al, arXiv 2404.07637]

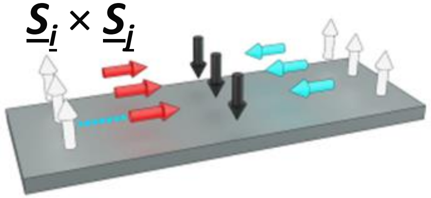
Conservation of net interlayer scalar spin chirality

Intralayer DMI

Chiral domain wall:

Conservation of vector spin chirality

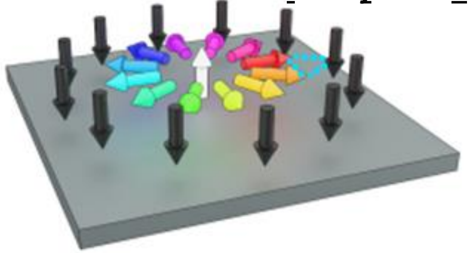
$\underline{S}_i \times \underline{S}_j$

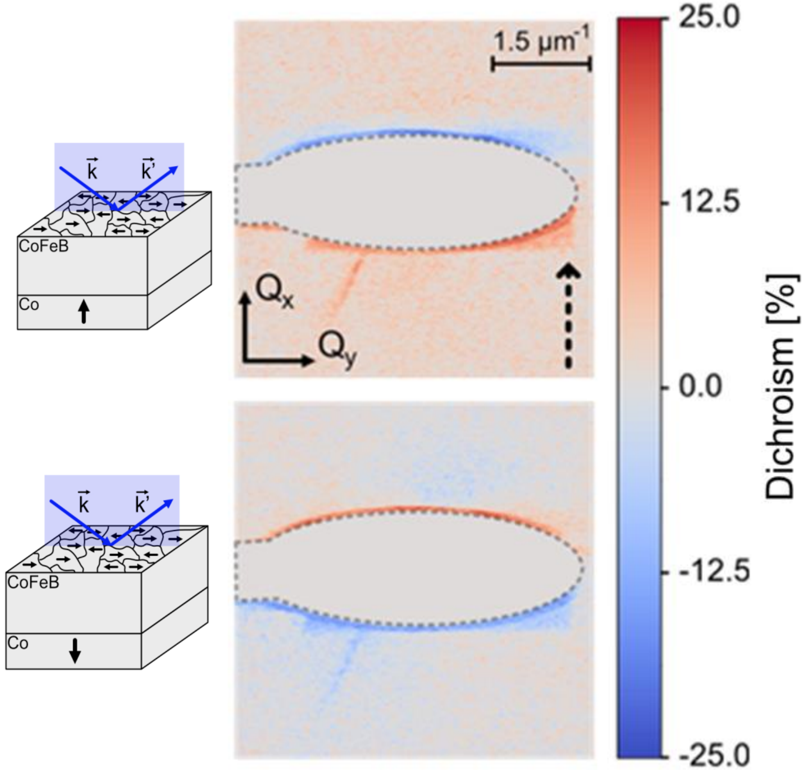


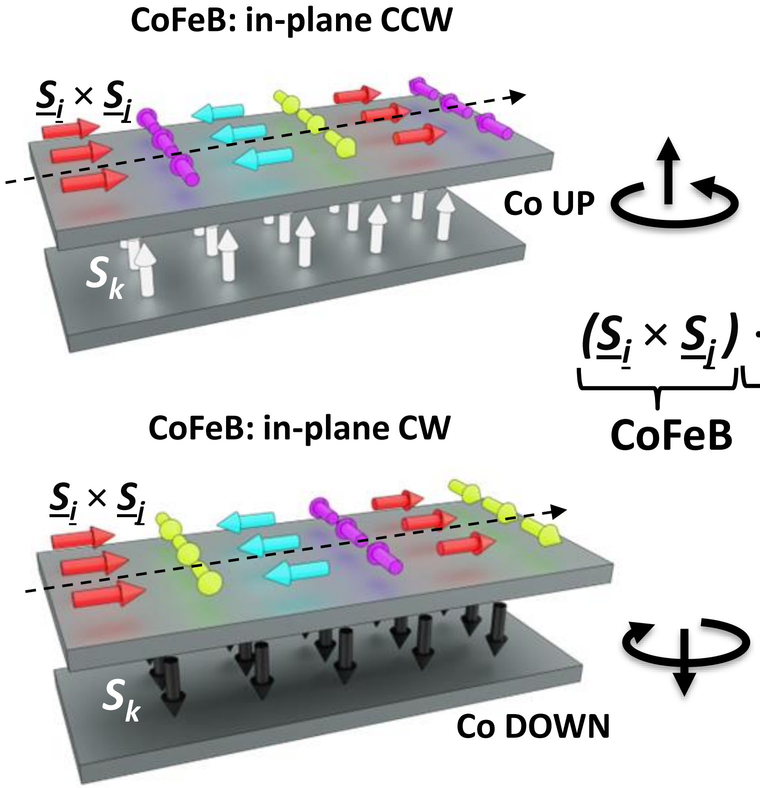
Skyrmion:

Conservation of scalar spin chirality

$(\underline{S}_i \times \underline{S}_j) \cdot \underline{S}_k$







$$\underbrace{(\underline{S}_i \times \underline{S}_j)}_{\text{CoFeB}} \cdot \underbrace{\underline{S}_k}_{\text{Co}}$$

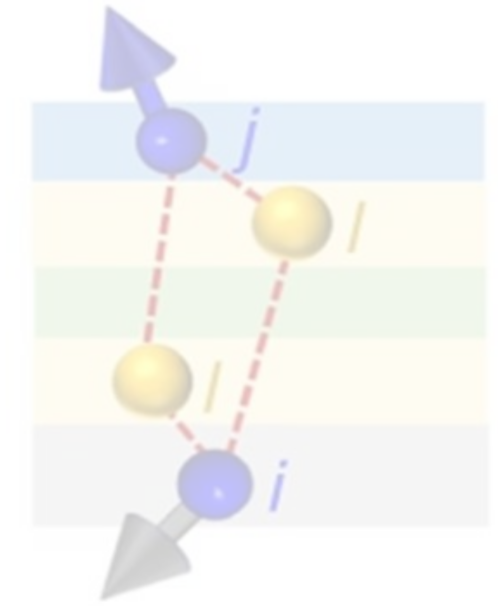
Remote control of vector spin chirality in CoFeB layer by direction of Co

Net conservation of interlayer scalar spin chirality within the multilayer

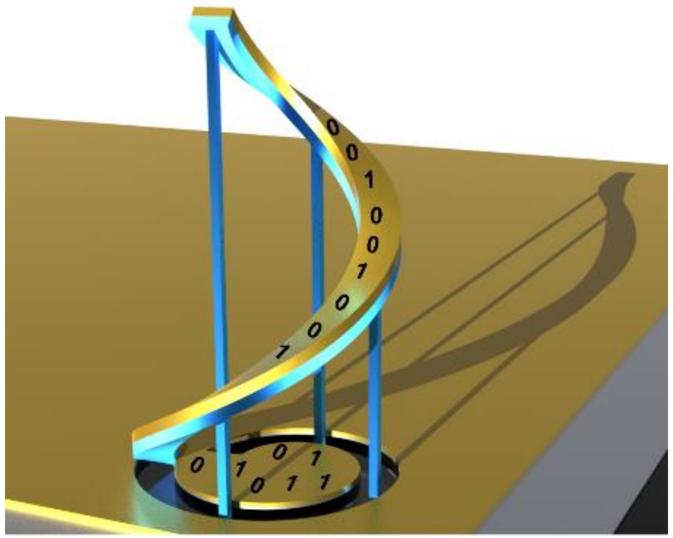
[Cascales-Sandoval, AFP et al, arXiv 2404.07637]

Outline

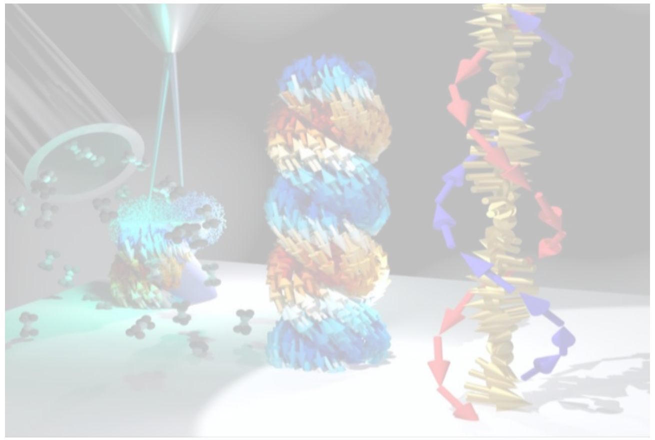
Chiral spin interactions in synthetic antiferromagnets



Domain wall motion in 3D nanomagnetic circuits



Imprinting of topological states in 3D helical nanomaterials

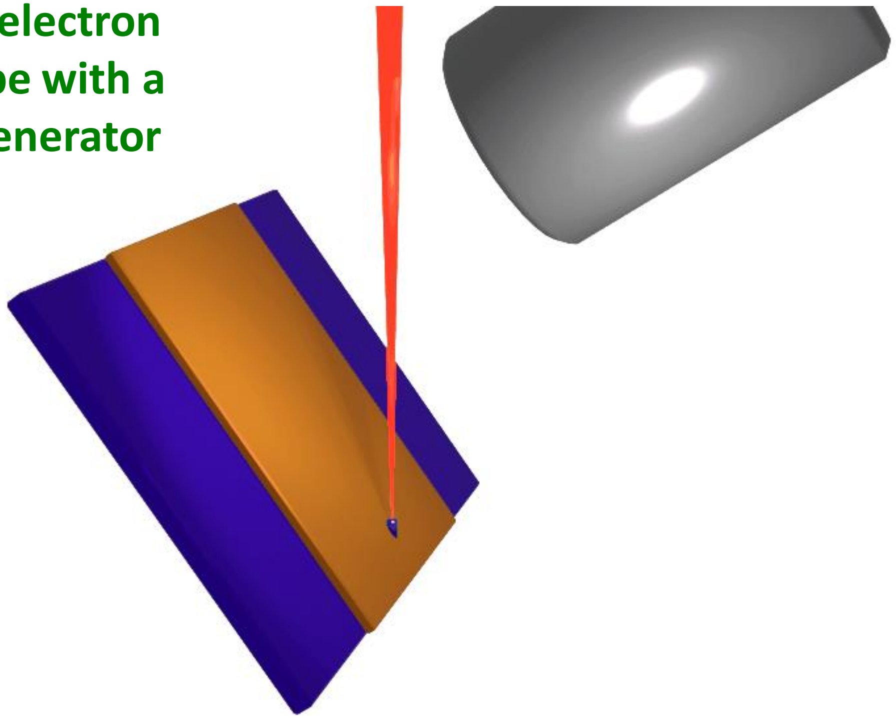


New 3D nanofab tool: Focused electron beam induced deposition (FEBID)

Scanning electron microscope with a pattern generator

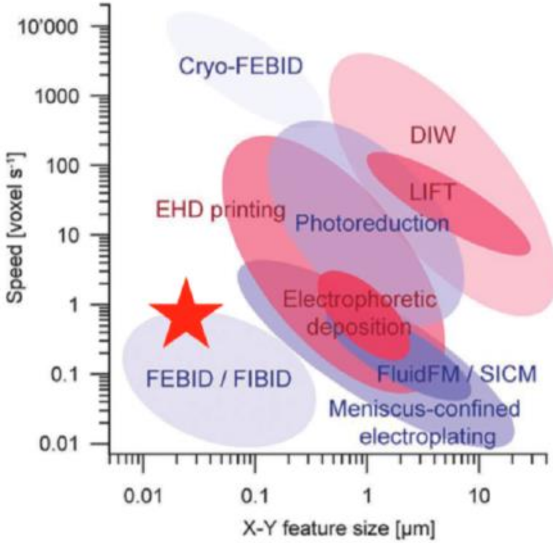
Focused beam of electrons

Gas injector system



FEBID: Local Chemical Vapor Deposition induced by a focused beam of electrons

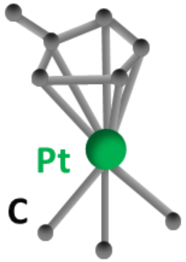
[Utke et al, J. Vac. Sci. Technol, 26, 1197 (2008)]



Unique tool for nano-prototyping & low-throughput 3D nanolithography

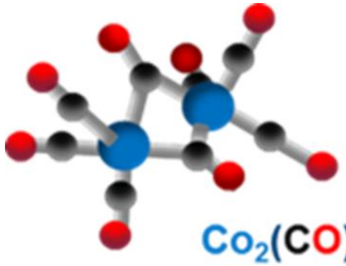
[Hirt et al, Adv. Mater. 29, 1604211 (2017)]

Gases & resulting materials



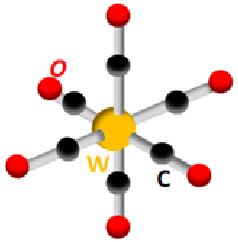
$(CH_3)_3Pt(CpCH_3)$

carbonaceous



$Co_2(CO)_8$

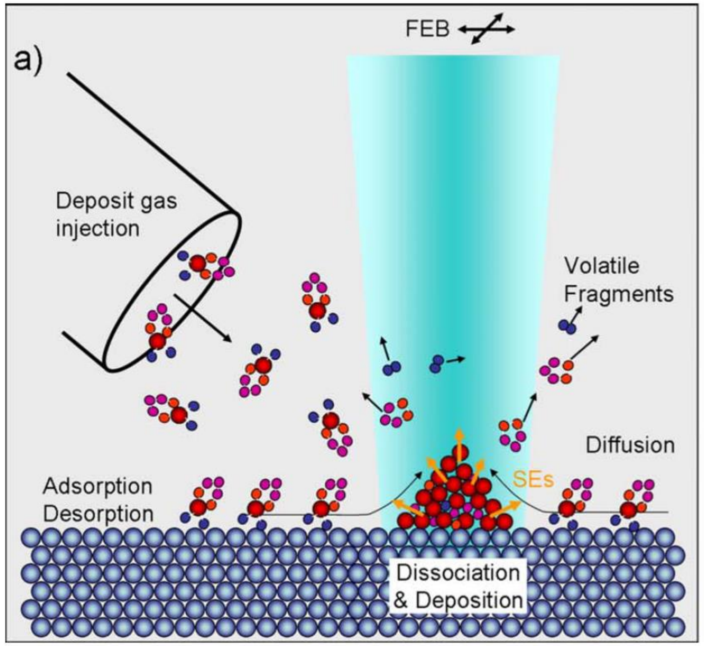
ferromagnets



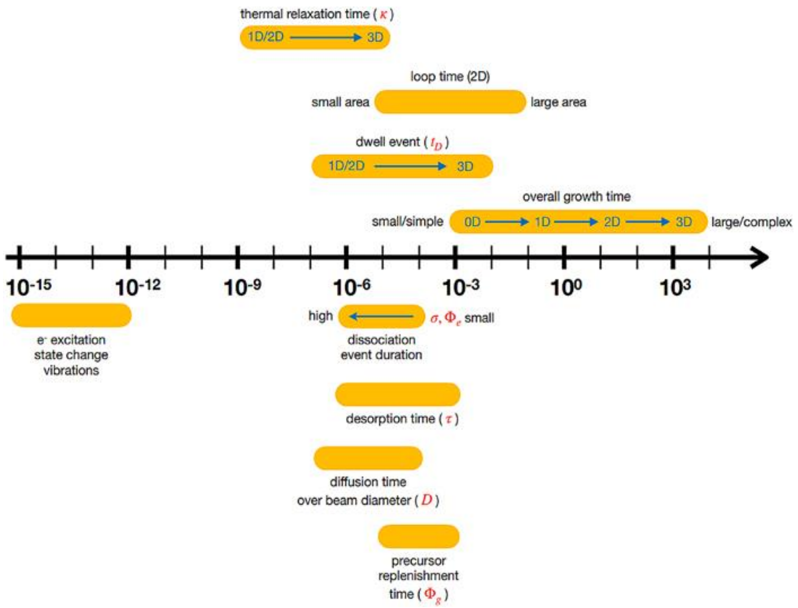
$W(CO)_6$

superconductors

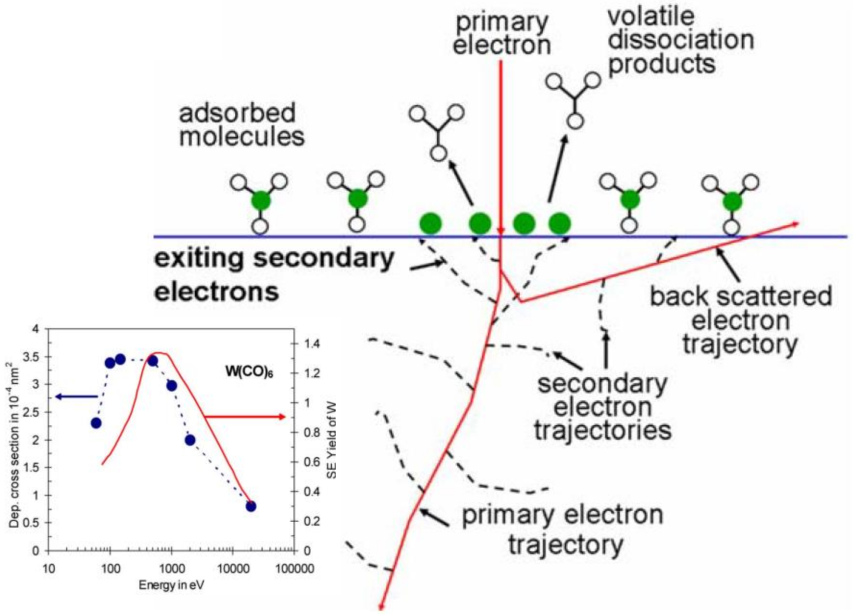
FEBID is a complex process



Many competing processes



Multiple timescales



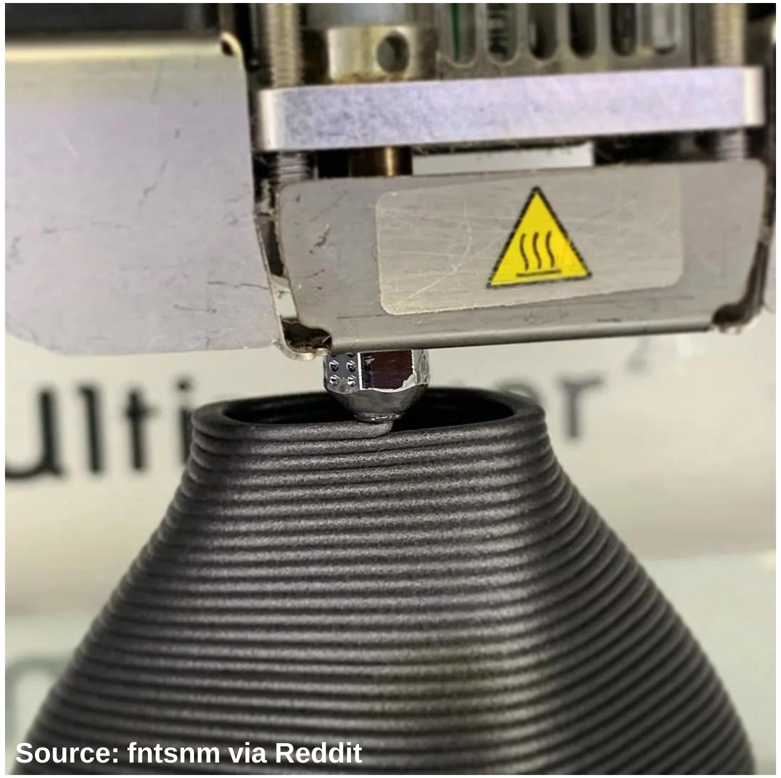
Complex interaction of electrons with matter in solid & gas phases

3D geometry, material composition, electrical, mechanical, thermal… properties critically depending on many parameters: Current, voltage, dwell times, overlap, base & growth pressure, pattern strategy, GIS geometry…

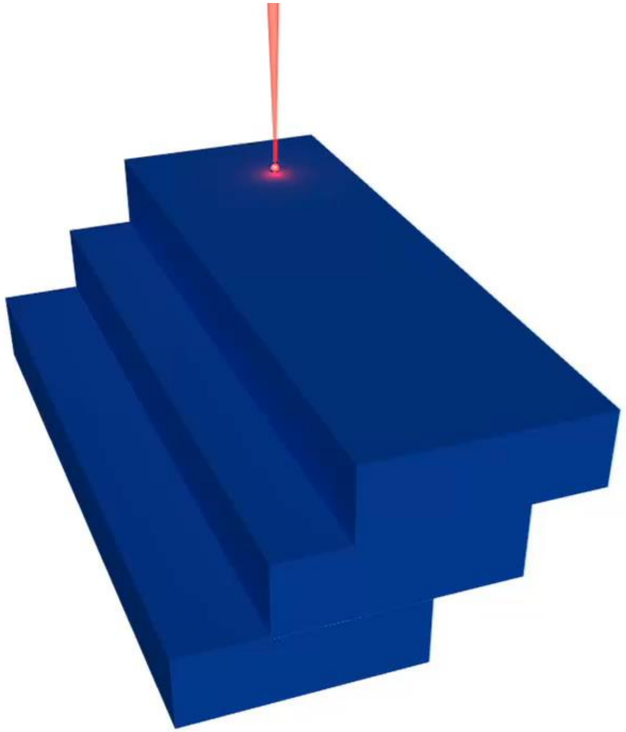
[Utke et al, J. Vac. Sci. Technol, 26, 1197 (2008); Huth et al, J. Appl. Phys. 130, 170901 (2021)]

Layer-by-layer 3D nano-printing by FEBID

[Skoric et al, Nano Lett. 20, 184 (2020)]



Standard 3D printer extruder: Macro/microscale



FEBID: Nanoscale

f3ast

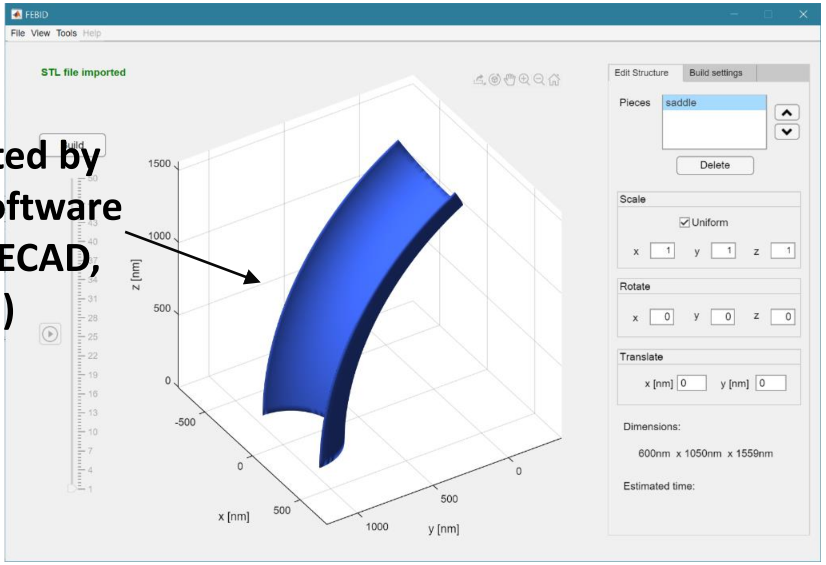
FEBID 3D Algorithm for STream file generation

First FEBID code able to 3D print arbitrary nano-geometries

f3ast 3D printing algorithm in a nutshell

[Skoric et al, Nano Lett. 20, 184 (2020)]

3D object created by standard CAD software (AutoCAD, FREECAD, Inventor…)

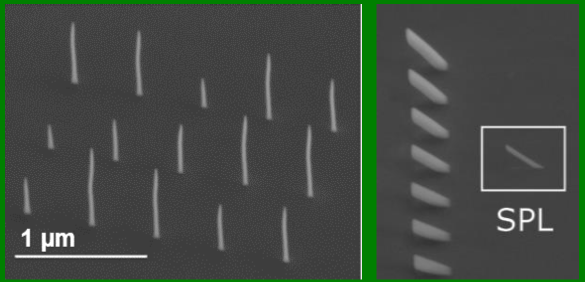


corrections

Feed the model

growth rate (+ heating)

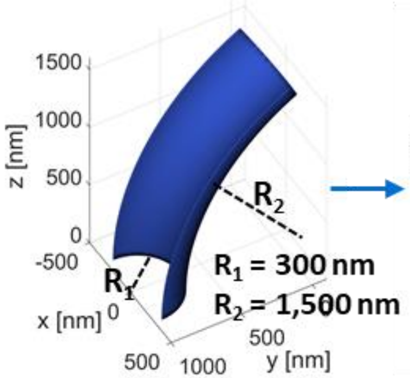
interaction volume



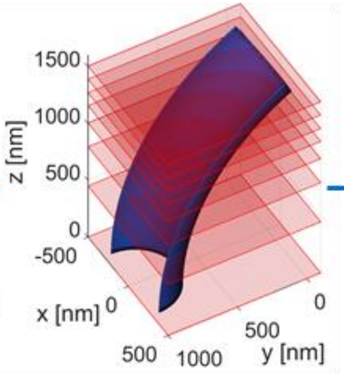
2-step calibration

FEBID modelling

3D design (.stl file)

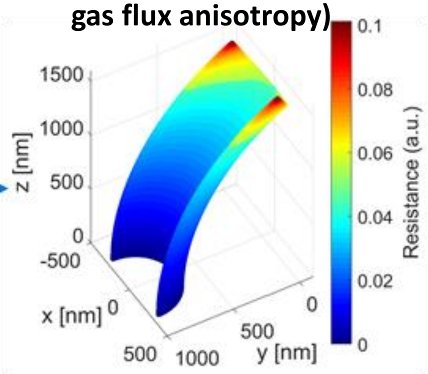


Design slicing

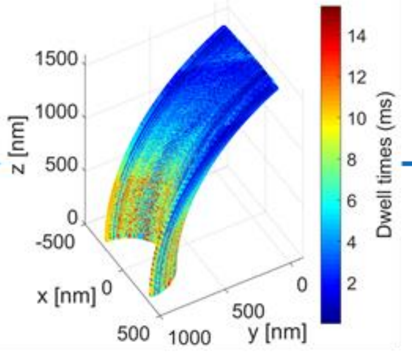


Additional effects

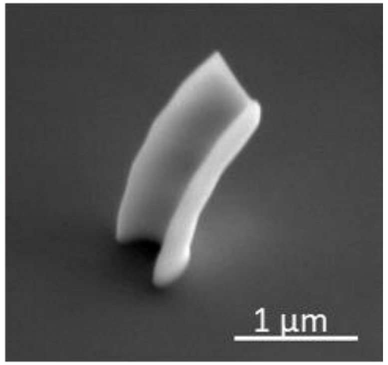
(beam heating, defocusing, gas flux anisotropy)



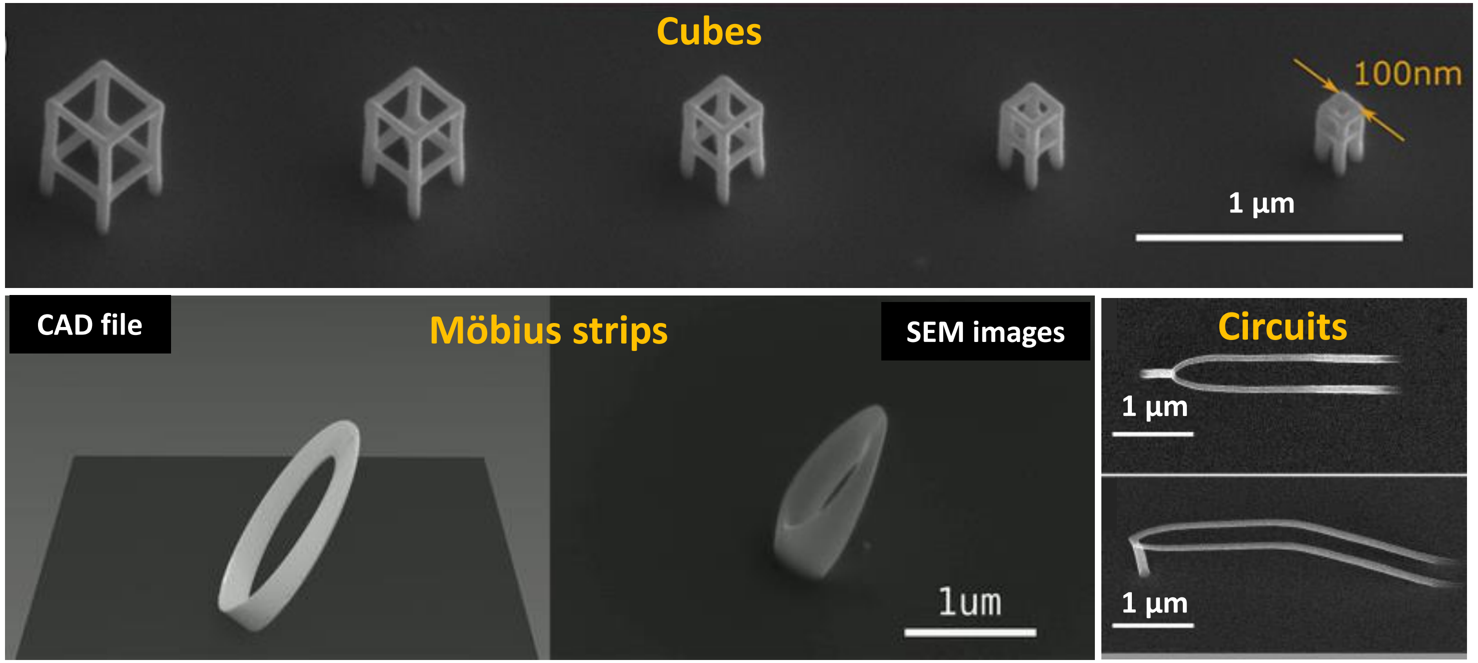
Dwell time calculation

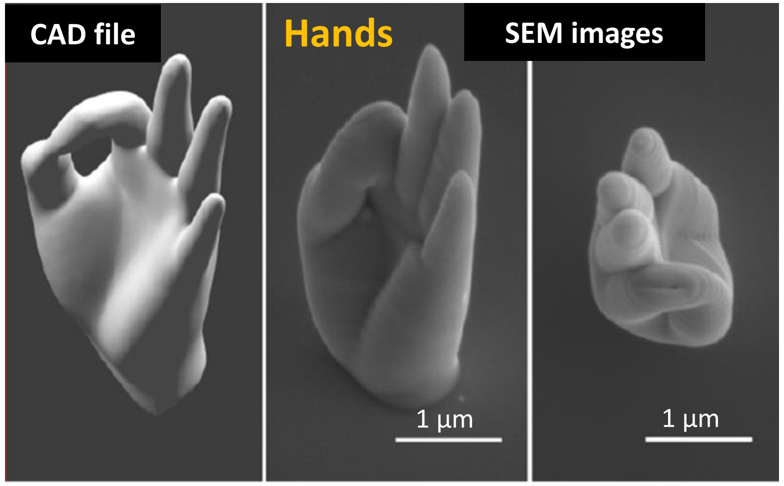


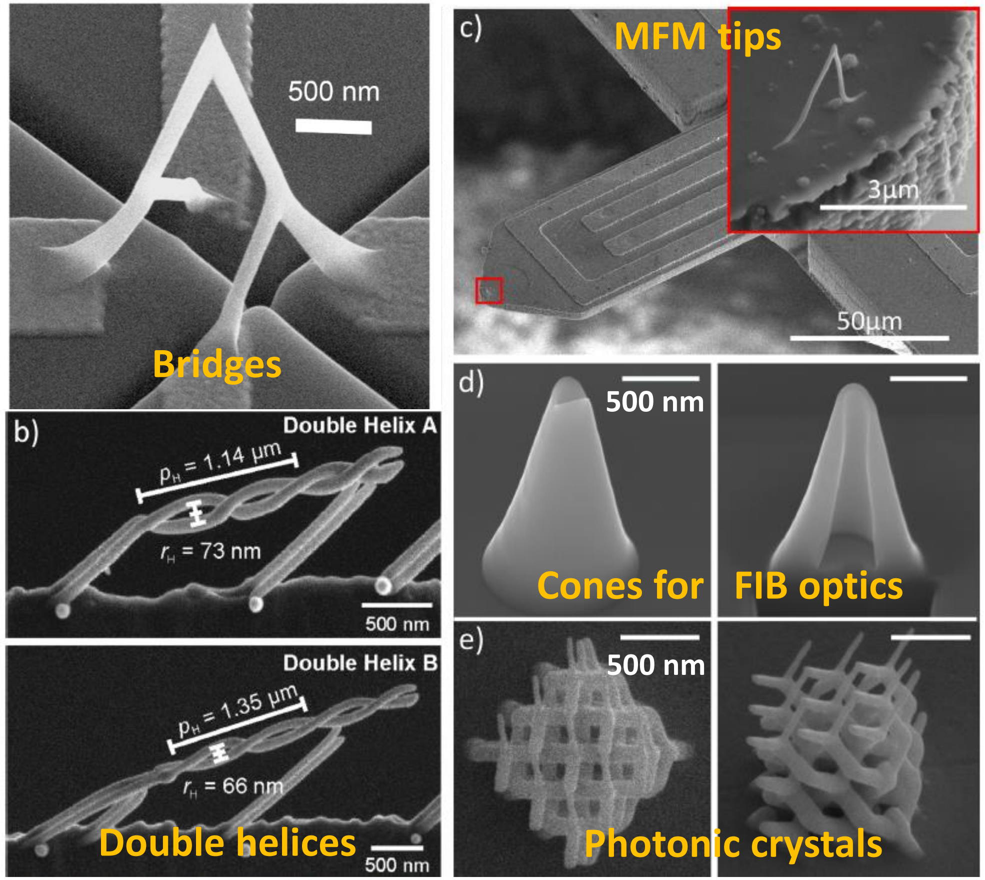
SEM image of 3D object



3D printing of complex 3D nano-geometries by f3ast







3D printing of arbitrary geometries (nanowire-based, surfaces & volumes) at sub-100 nm resolutions

[Skoric PhD thesis, St. John's College Cambridge (2021)]

[Skoric et al, Nano Lett. 20, 184 (2020)]

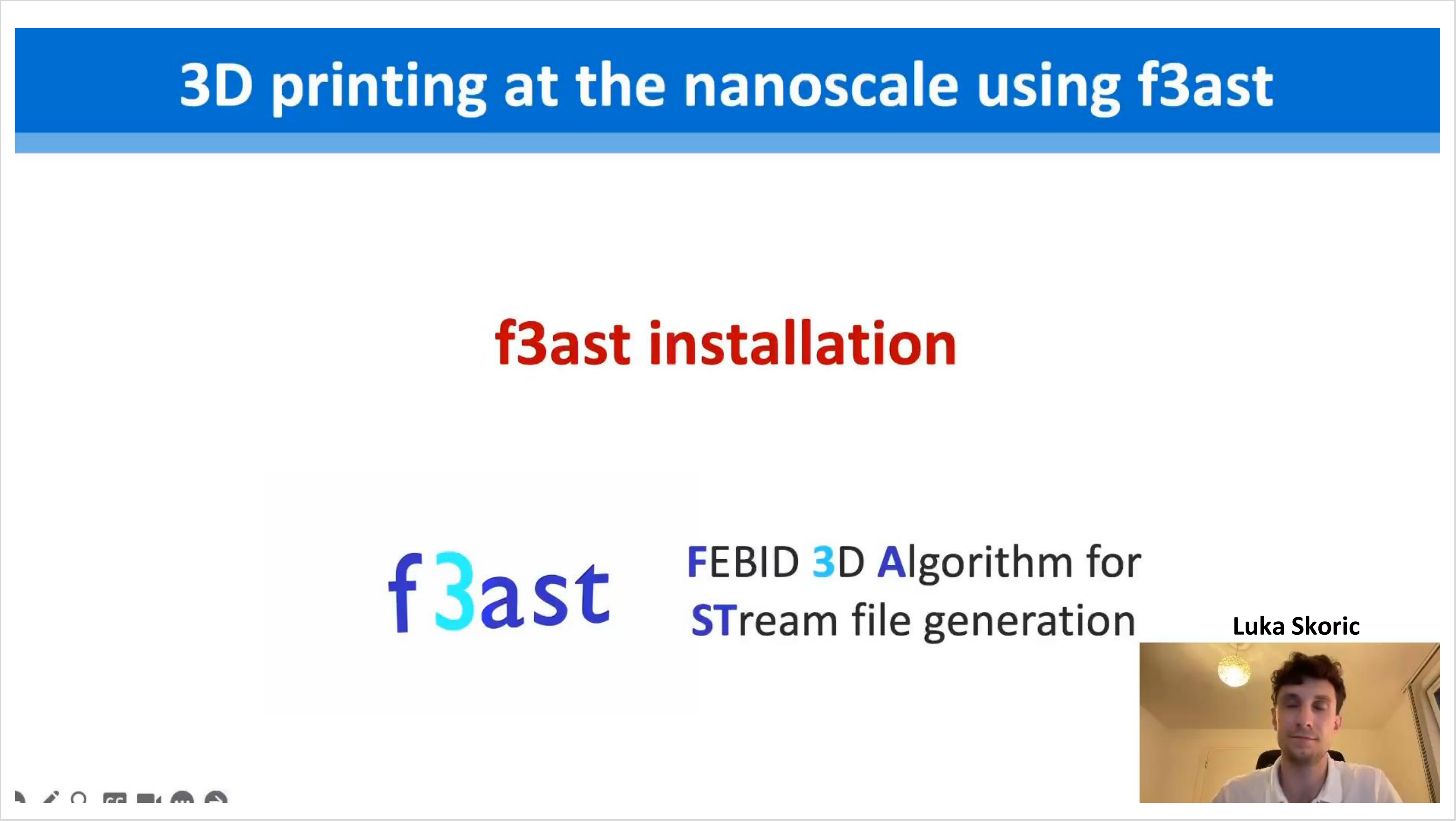
f3ast software open to the community

Open access since 2022: https://github.com/Skoricius/f3ast

YouTube channel launched recently: www.youtube.com/@f3ast-nanofab

Tutorial videos:

How to install & navigate through the software; how to perform 3D printing experiments, fundamentals of the algorithm… and a few surprises!



3D magnetic nanocircuits: new opportunities

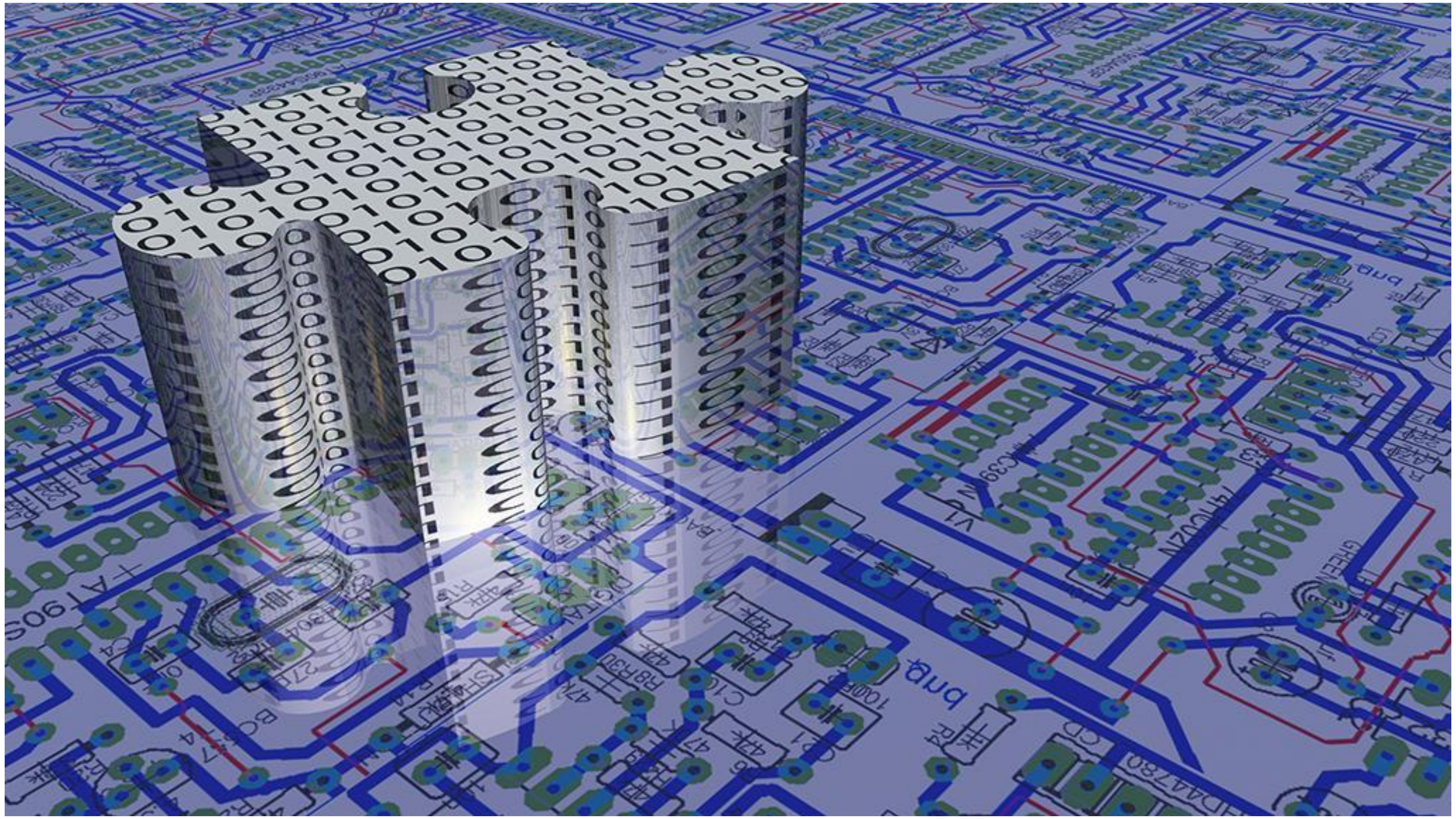


Image: Shutterstock

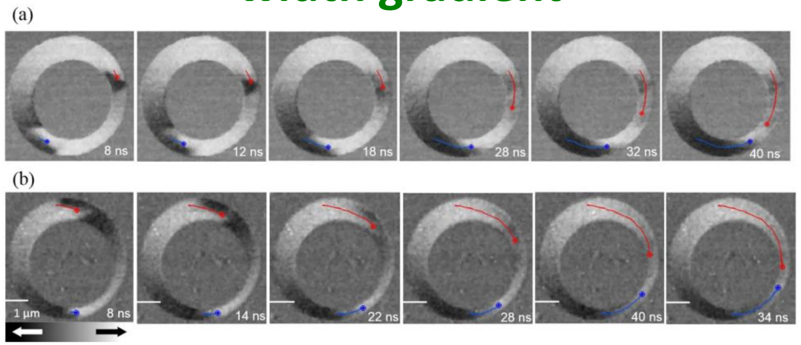
What mechanisms are most suitable for transmission of magnetic information between planes?

Magnetic fields, spin transfer-torque, spin orbit torque…
→ Low heat dissipation, multiple spin-to-charge conversion
[Park et al, IEEE J. Solid-State Circuits 50, 204213 (2015)]

Automotion of domain walls in nanowires

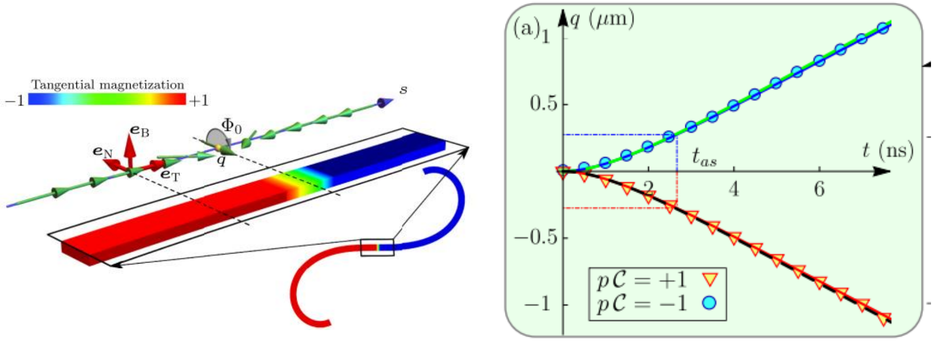
Geometrical gradient in 2D nanowires: width, curvature….
leads to automotion (no stimuli needed) of domain walls

width gradient



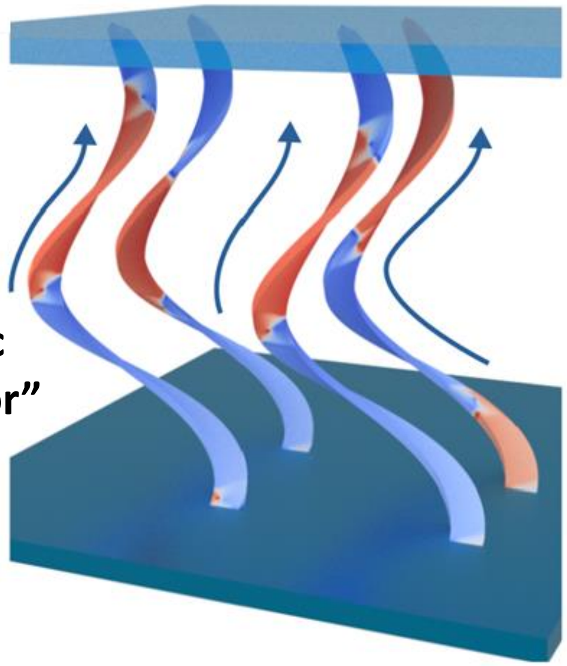
Mawass et al, Phys. Rev. Appl. 7, 044009 (2017)

curvature gradient



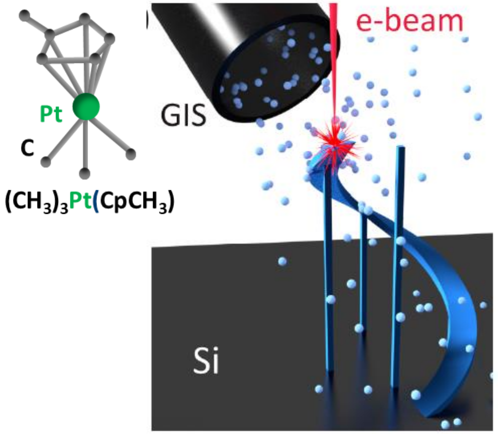
Yershov et al, Phys. Rev. B 98, 060409 (2018)

Our proposal: Exploit geometrical effects for **3D automotion** of magnetic information

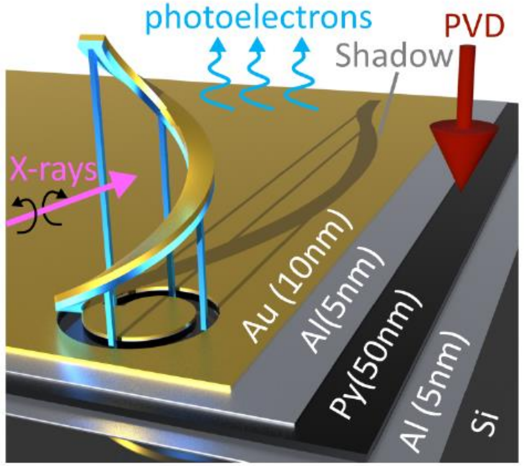


Efficient way to transport information in between magnetic planes

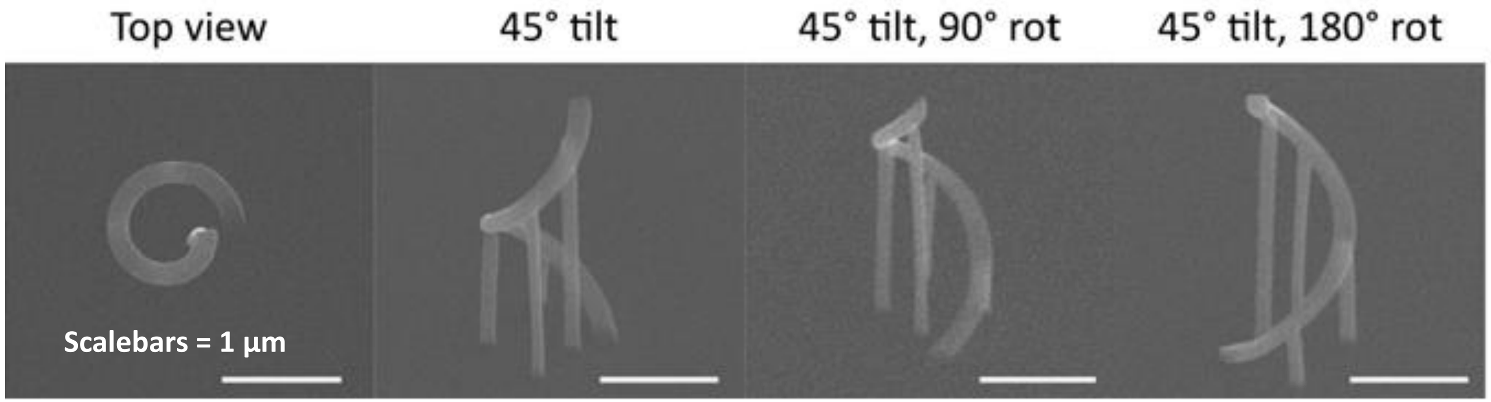
Experimental realisation of 3D spiral nano-interconnectors



(1) 3D non-magnetic scaffold (FEBID)



(2) Thin films integration including 50nm NiFe (evaporation)

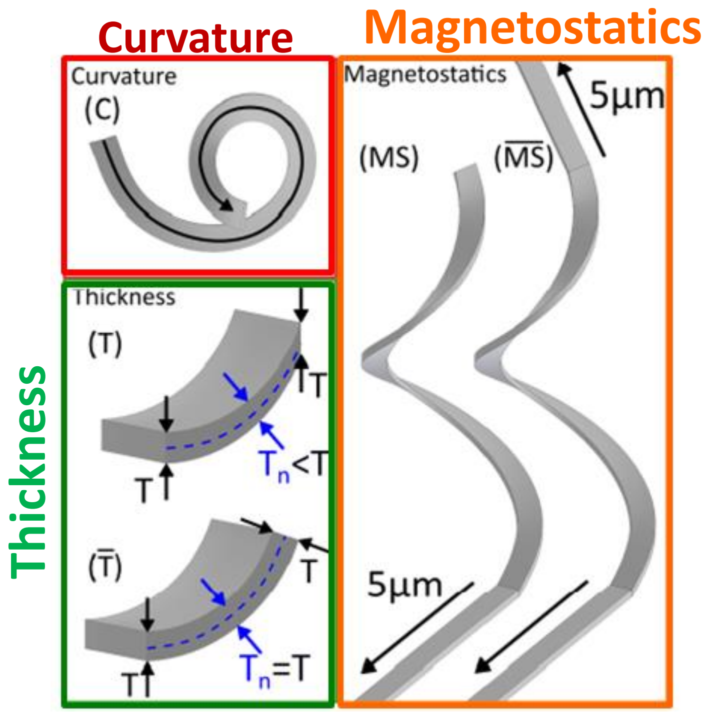


[Skoric, AFP et al, ACS Nano 16, 8860 (2022)]

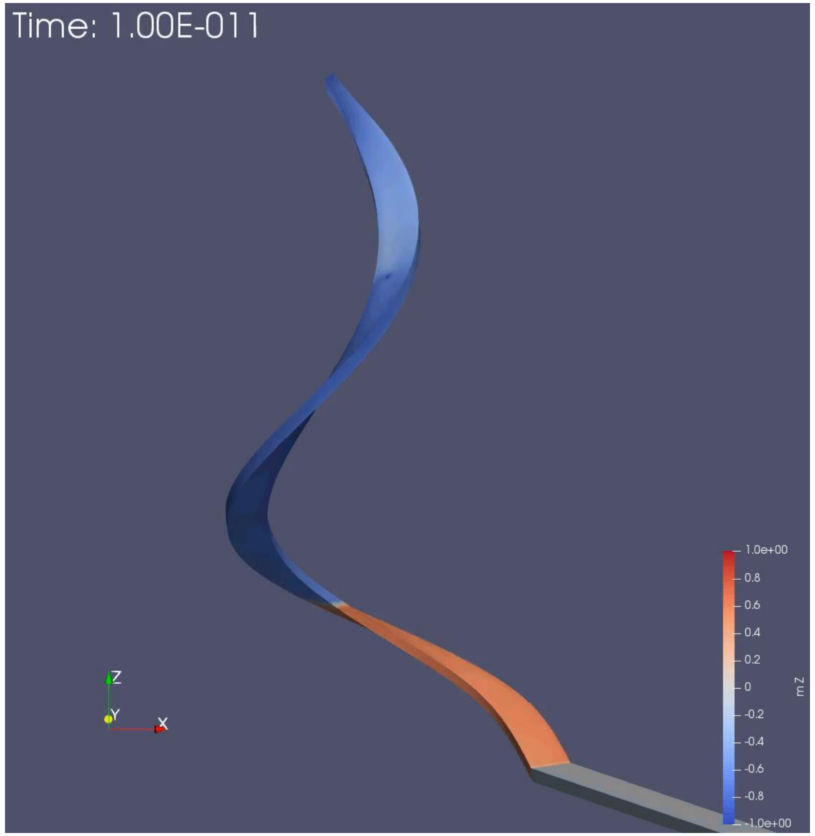
Mechanisms for 3D automotion of domain walls in spirals

[Skoric, AFP et al, ACS Nano 16, 8860 (2022)]

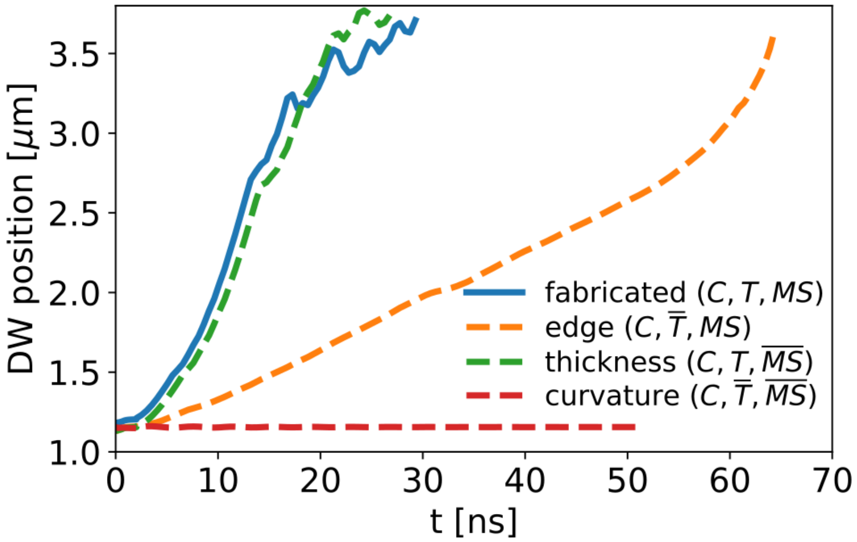
Possible automotion mechanisms:



- Curvature gradient (C) = 0.09 μm^{-2}
- Thickness gradient = -5.3 nm/µm
- Magnetostatic interactions (MS)



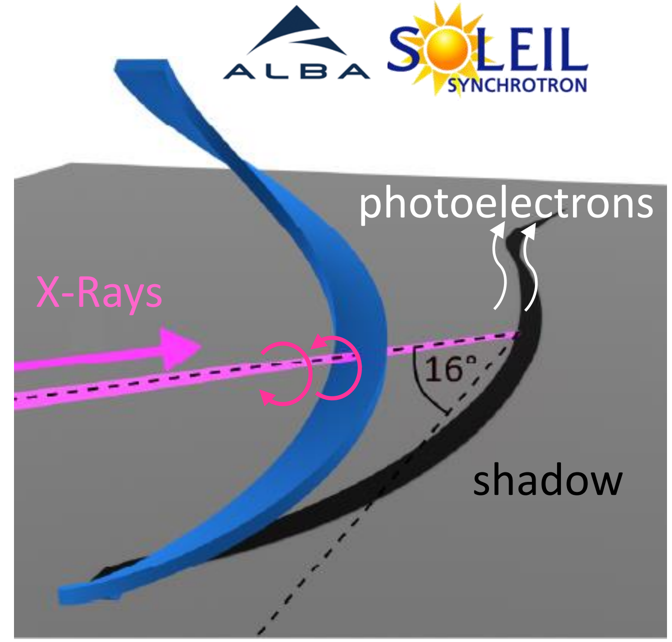
FEM micromagnetic simulations (Magnum.Fe @ University of Vienna)

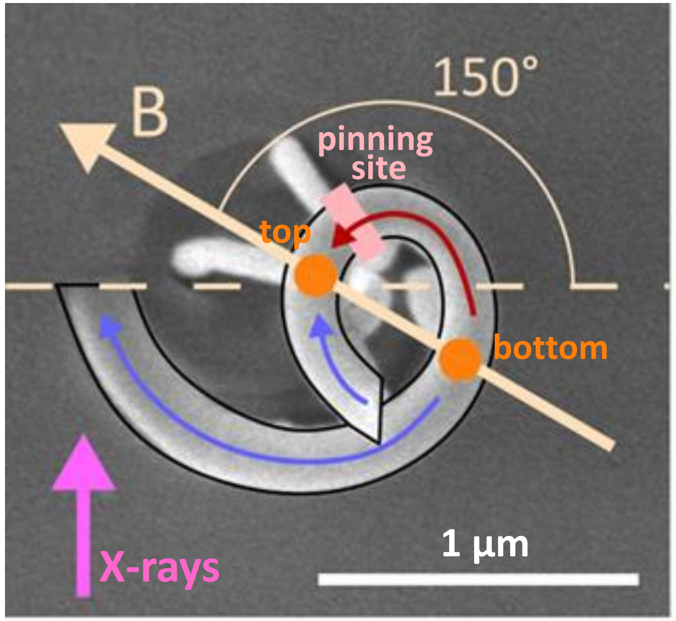


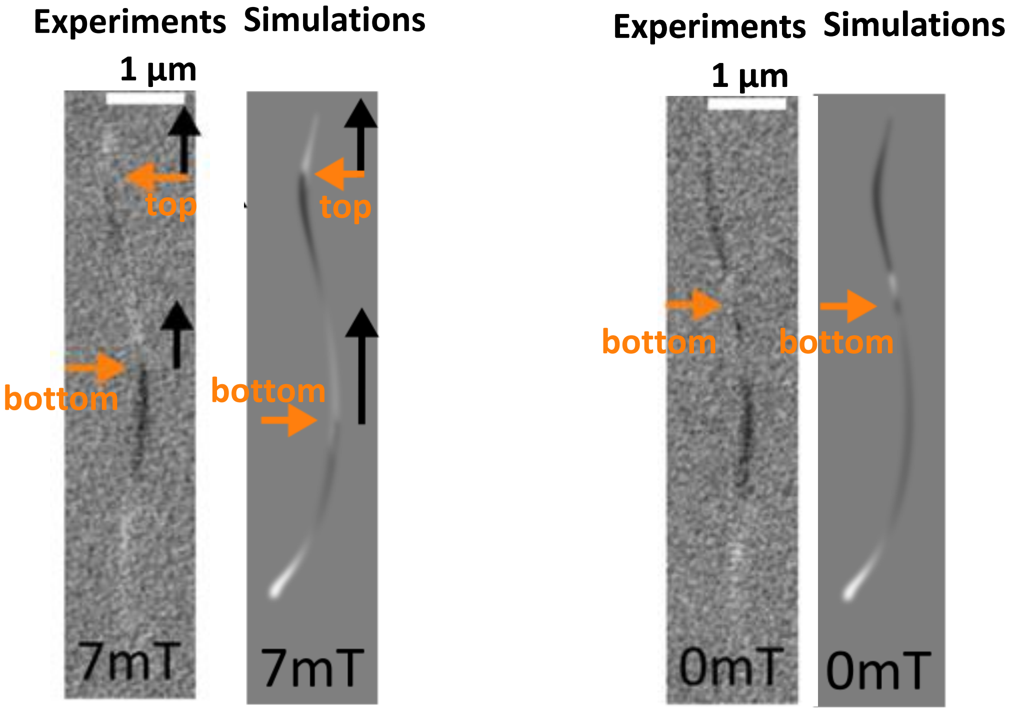
Thickness gradient dominant → Fast & robust motion of domain walls

$E_{DW} \propto$ NW cross section

Domain wall 3D automotion observed experimentally







Shadow XMCD PEEM for the imaging of 3D magnetic nanostructures at ≈ 15 nm resolution

[Kimling et al, Phys. Rev. B 84, 174406 (2011)]

(1) High (B = 70 mT) applied at 150º to nucleate two domains
(2) Each domain at different position with respect to pinning site
(3) Image magnetic state at lower B values (7mT, 0 mT)

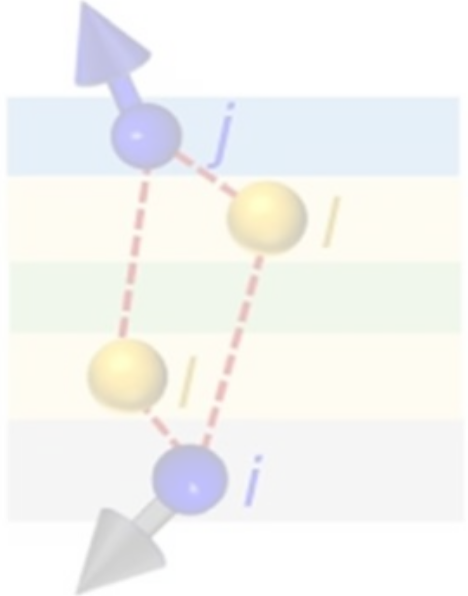
Two walls located at both sides of the pinning site

Top wall gone, bottom one at pinning site

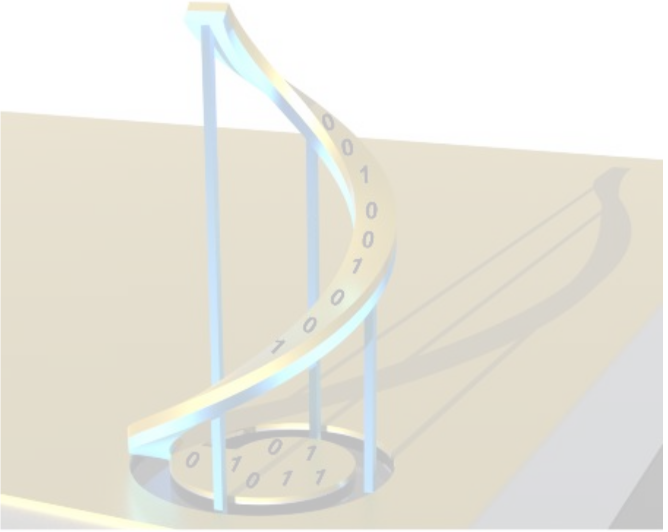
Robust mechanism for domain wall motion in 3D nanocircuits

Outline

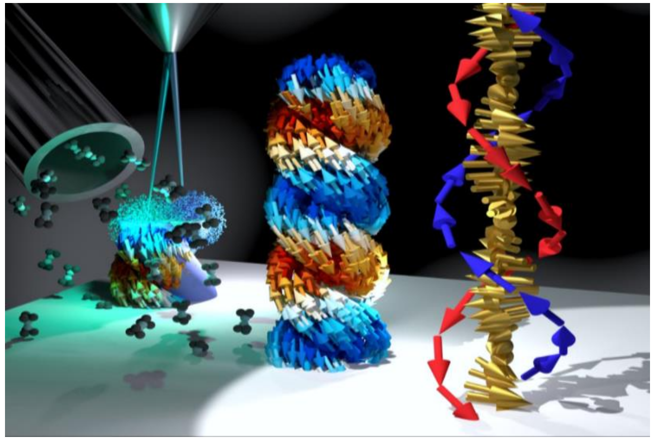
Chiral spin interactions in synthetic antiferromagnets



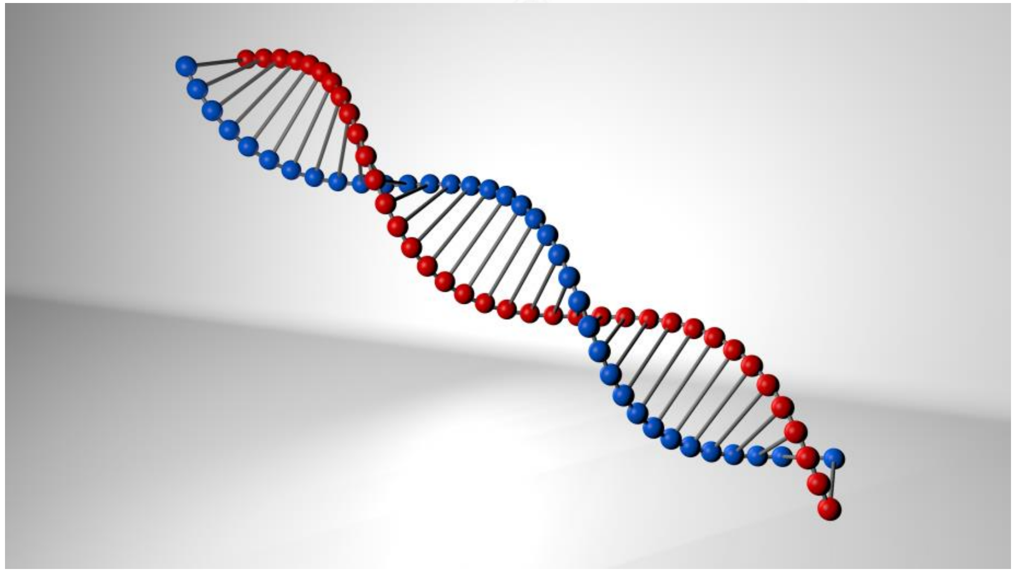
Domain wall motion in 3D nanomagnetic circuits



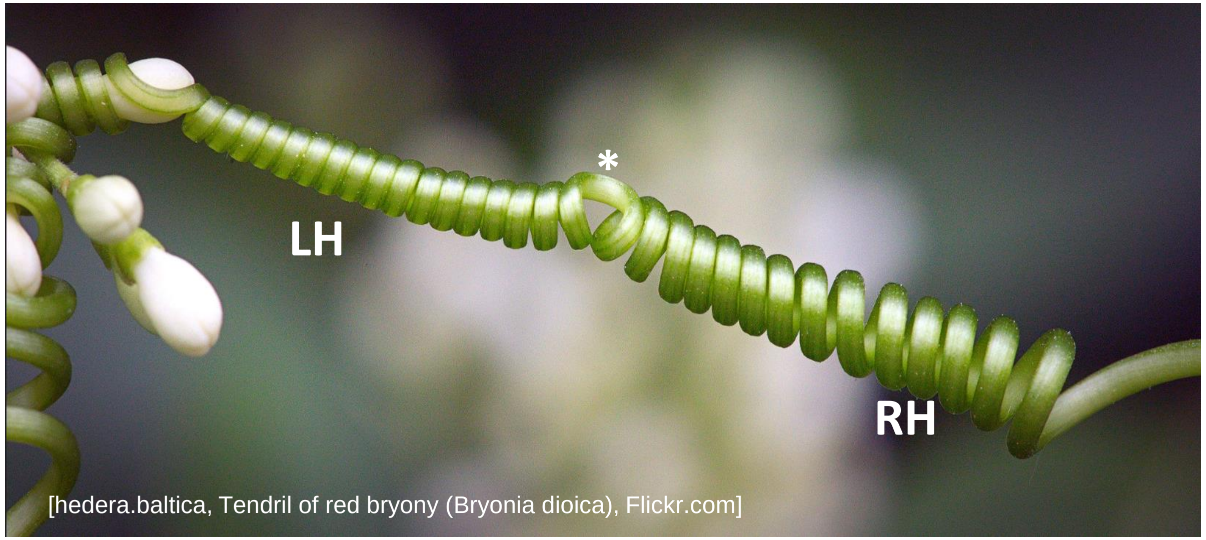
Imprinting of topological states in 3D helical nanomaterials



Chirality in nature: helical geometries

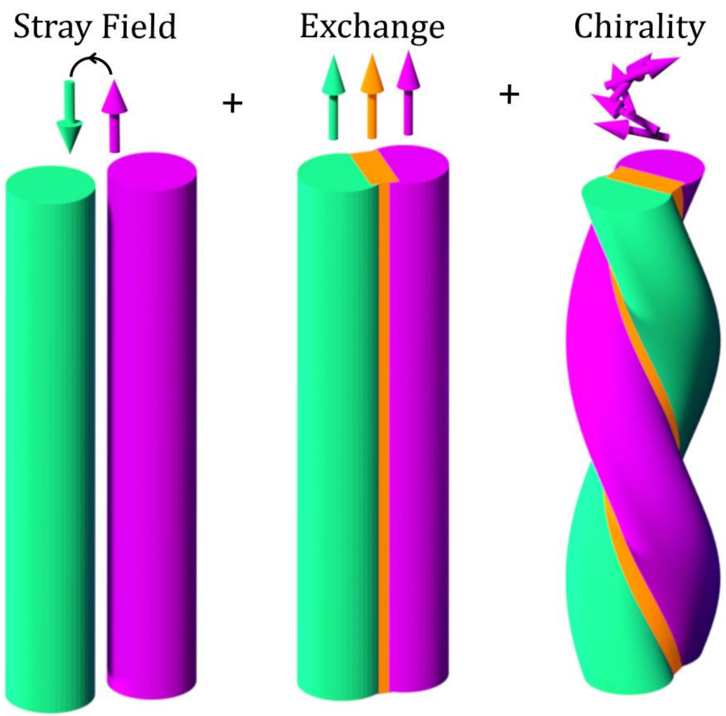


Double strand
structure in DNA



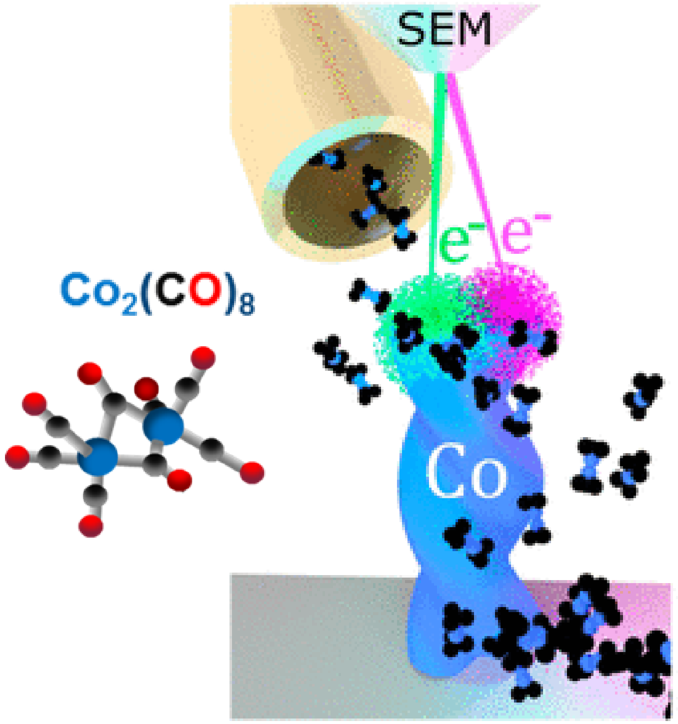
Reversal of chirality via a topological defect (tendril perversion)

Double nano-helix for geometrical control of magnetic chirality



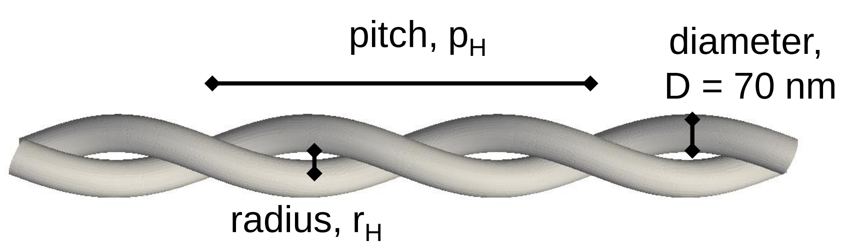
Multi-strand helical nanostructures:
geometrical control of magnetic chirality + competing interactions = imprinting of topological magnetisation states

[Sanz-Hernández, AFP et al, ACS Nano 14, 8084 (2020)]
[Fullerton, AFP et al Nanotechnology 34, 125301 (2023)]

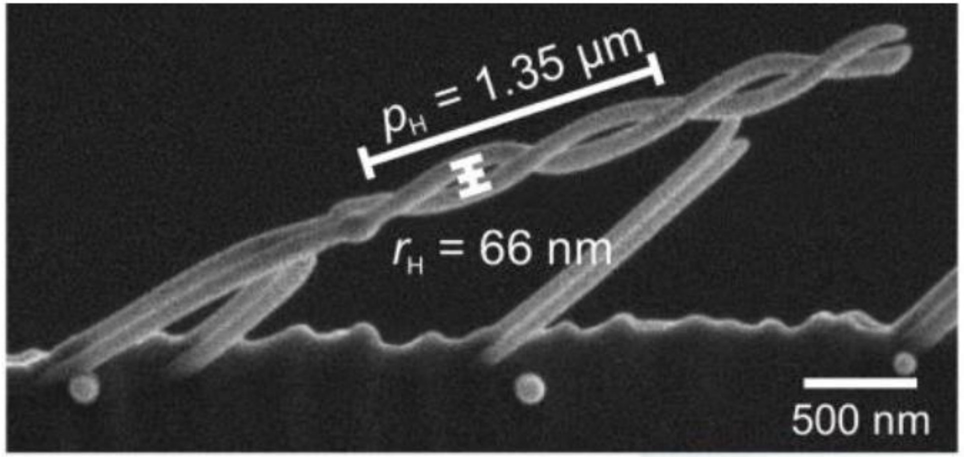


FEBID 3D printed nanomagnetic double helix with controlled inter-strand distance

Double helix nanostructures with non-overlapped strands

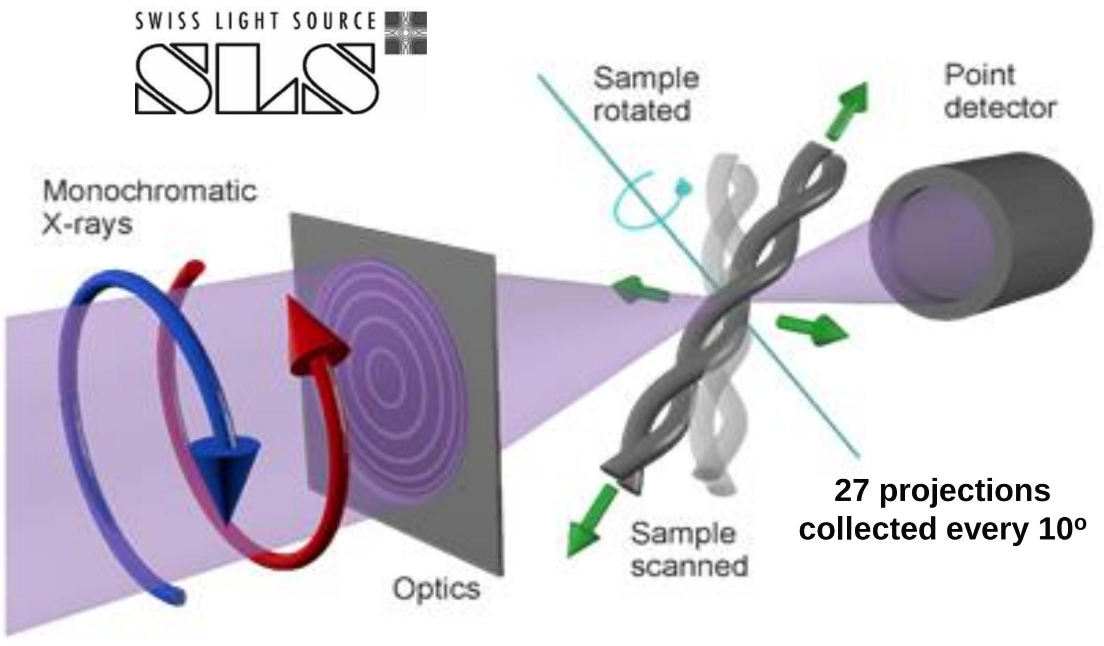


CAD design for 3D nano-printing



SEM image of one double helix structure

[Donnelly, AFP et al, Nature Nanotechnology 17, 136 (2022)]



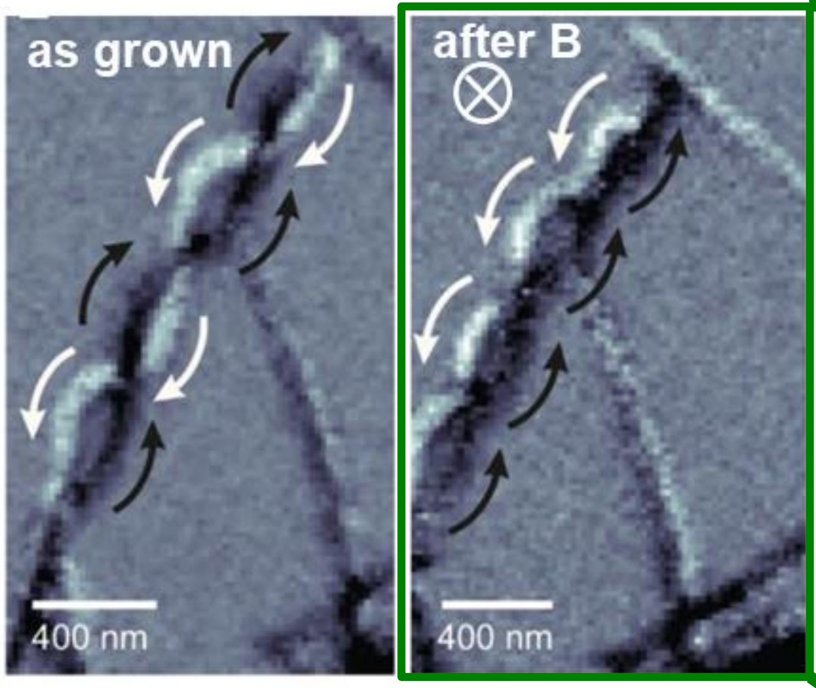
[Witte et al, Nano Lett. 20, 1305 (2020)]

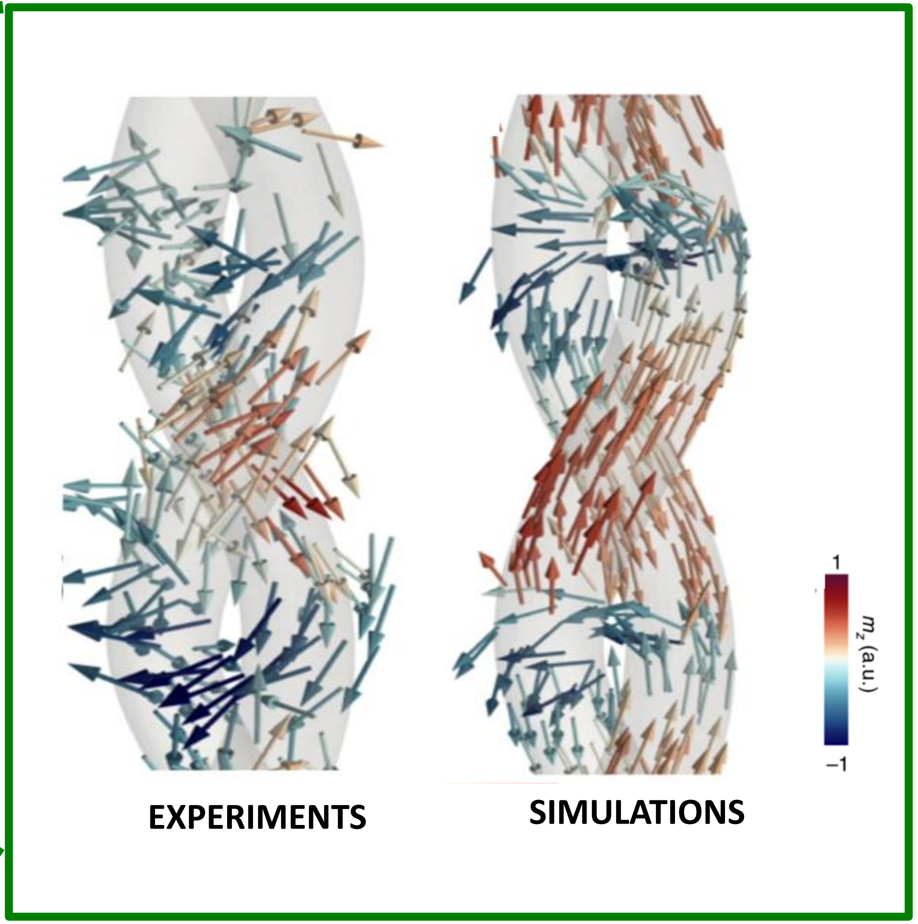
Tomographic laminography using scanning transmission X-ray magnetic microscopy (STXM)

Formation of strongly coupled “locked” domain walls

antiparallel

“locked” domain walls



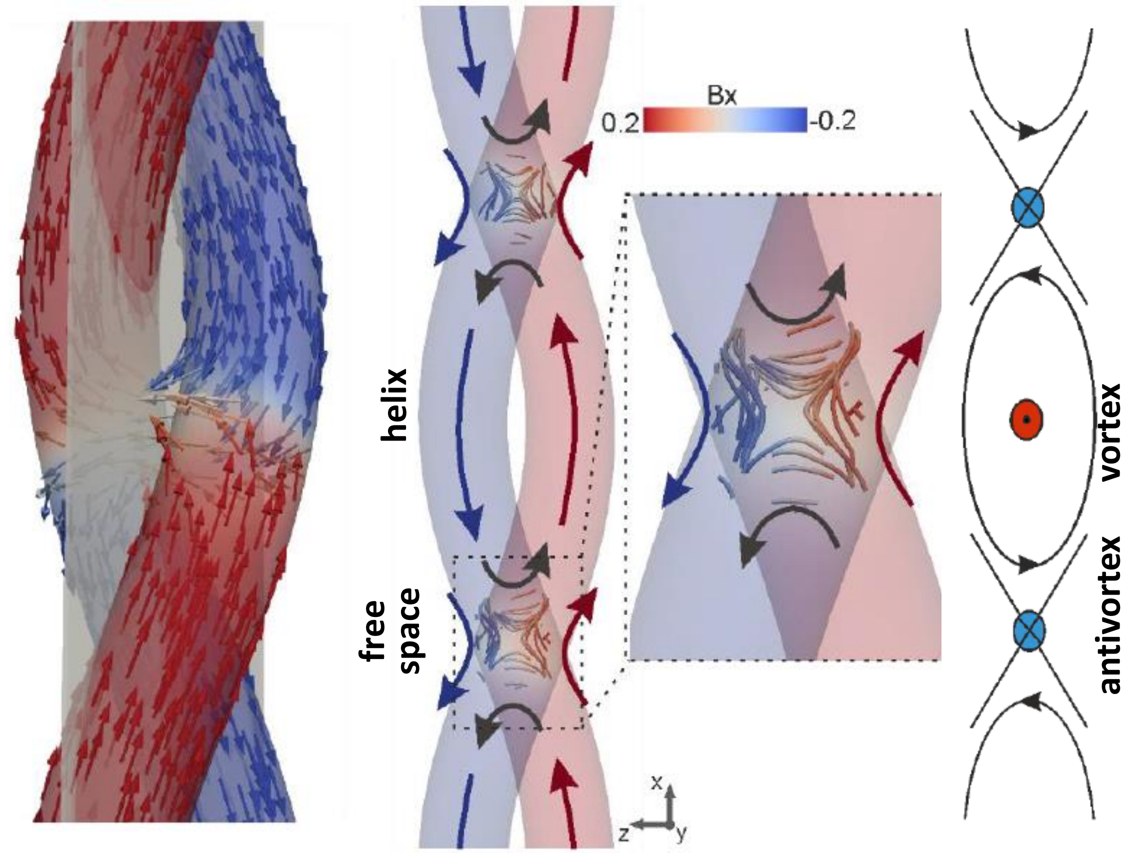


STXM images at zero field for one projection, two different magnetic configurations

3D reconstruction of magnetisation vector

[Donnelly, AFP et al, Nature Nanotechnology 17, 136 (2022)]

Locked wall pairs lead to nanoscale stray fields with topological features

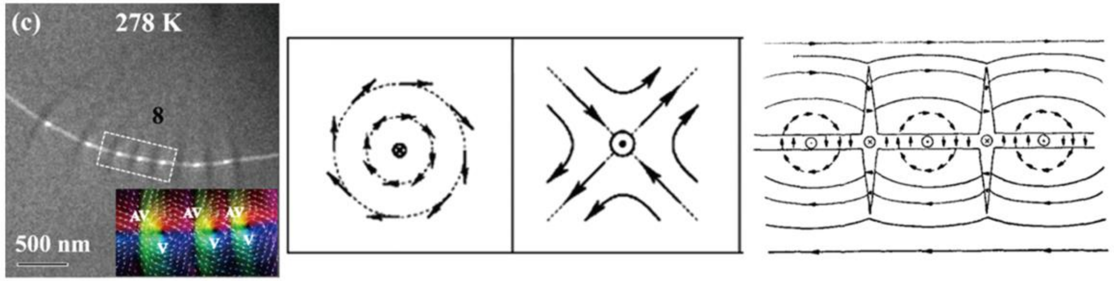


Antivortex formed in free-space stray magnetic field: large magnetic field gradients on the nanoscale

[Donnelly, AFP et al, Nature Nanotechnology 17, 136 (2022)]

- Vortex of *M* in the helices
- Antivortex of *H* in the free space

→ "Cross-tie"-like wall in *B*: 3D nanopatterning for topological textures in *B* across whole space



Cross-tie domain wall in M measured by Lorentz microscopy

[Zhang et al. Acta Mater. 140, 465 (2017)]

Conclusions

amalio.fernandez-pacheco@tuwien.ac.at
http://tuwien.at/phy/iap/3dnano

Towards multilayers with 3D functionality

- Synthetic antiferromagnets with chiral exchange bias: interlayer DMI
- Evidence of conservation of interlayer spin chirality

New tools for 3D nanomagnetism

- f3ast software for nanoscale 3D printing by FEBID
- XR magnetic techniques: XMCD-PEEM tomography, software development for XR magnetic techniques

3D nanowire circuits

- Domain wall automotion in 3D helical interconnectors
- Geometrical control of magnetic chirality: imprinting of topological spin states

Synchrotron techniques: Key for investigations in 3D nanomagnetism

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3DNANOMAG

f3ast

www.youtube.com/@f3ast-nanofab

Funded by the European Union
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3DMAG 2026. July 13-17, Vienna (Austria)

https://www.tuwien.at/en/phy/iap/conferences/3dmag-2026

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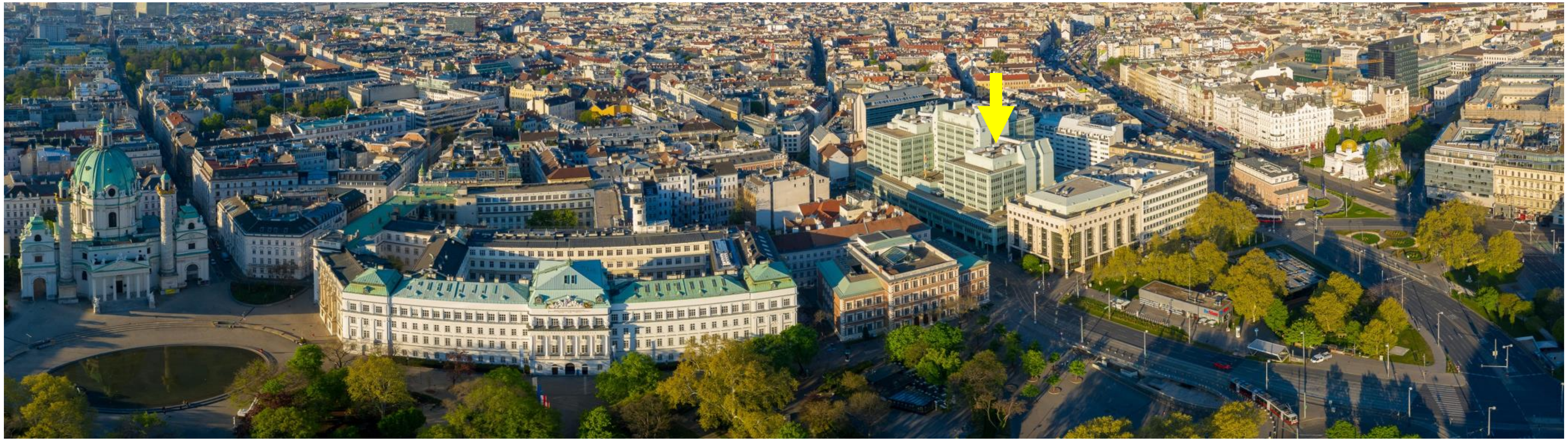
1st International Symposium on Three-Dimensional Nanomagnetism



Thank you. Questions?

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