PAUL SCHERRER INSTITUT

PSI

ETH zürich

Tutorial Talk

1. Feel free to ask questions at any time
2. If anything is under/misrepresented – please let me know !

→ A review on 3D artificial spin ice, partly based on this presentation, was submitted in July 2024.
L Berchialla, GM Macauley and LJ Heyderman (2024)

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

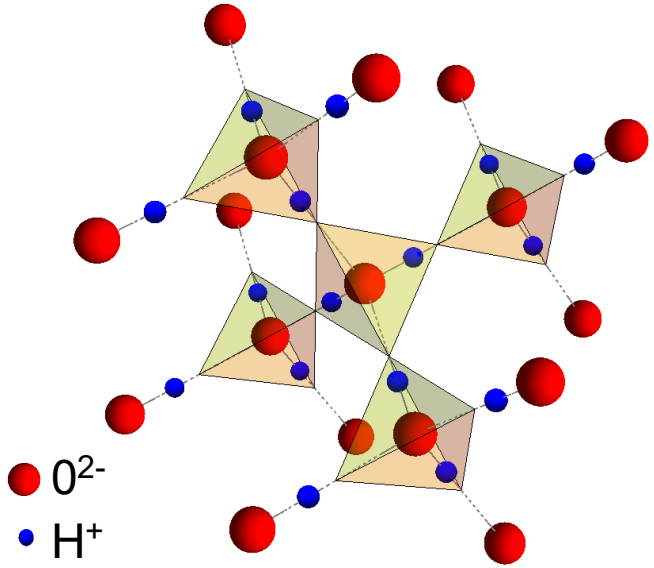
Three Dimensional Artificial Spin Ice

SPICE Workshop on Nanomagnetism in 3D, April/May 2024

MESO SYS

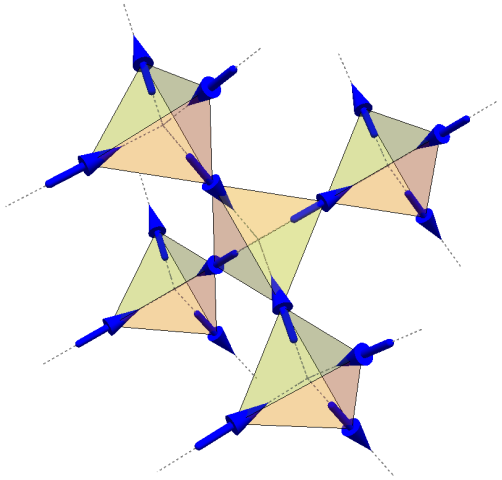
Mesoscopic Systems
http://www.mesosys.mat.ethz.ch

From Water Ice to Artificial Spin Ice



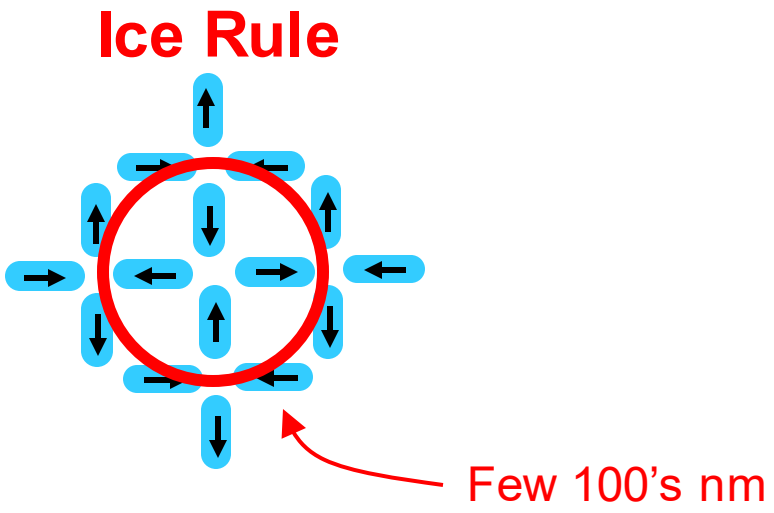
Water Ice

L Pauling
JACS (1935)



Spin Ice

MJ Harris *et al.*
PRL (1997)



Artificial Spin Ice

RF Wang *et al.*
Nature (2006)

LJ Heyderman & RL Stamps J Phys: Condens Matter (2013)
SH Skjærvø, CH Marrows, RL Stamps, LJ Heyderman, Nature Reviews Physics (2020)

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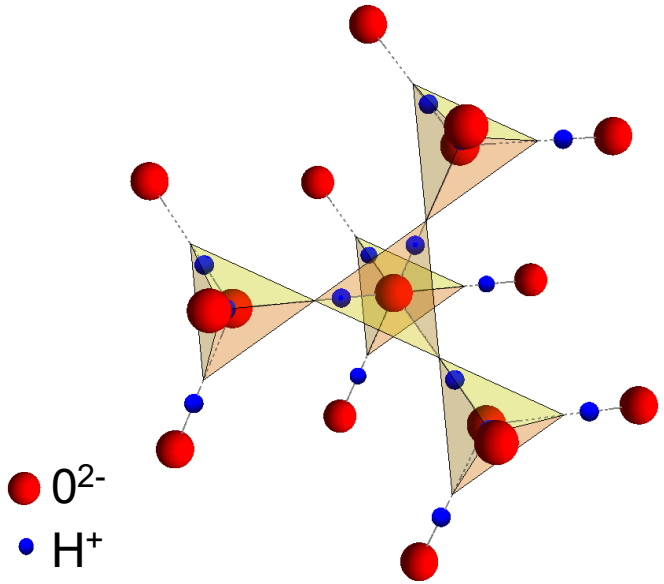

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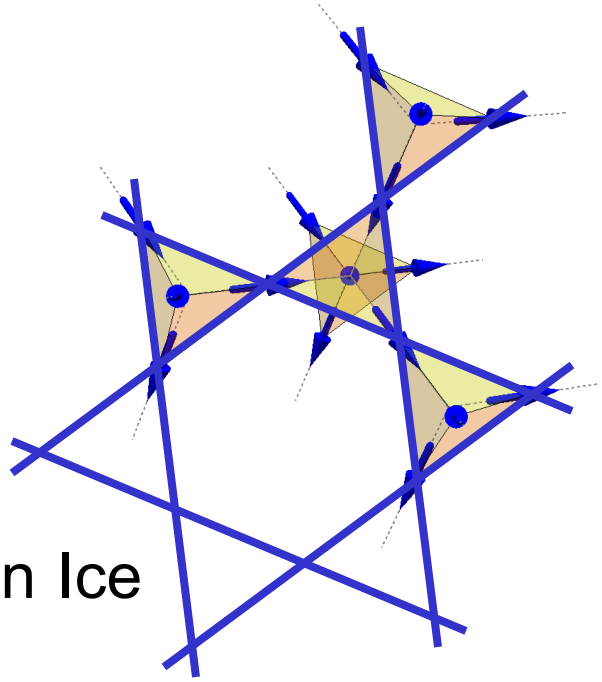

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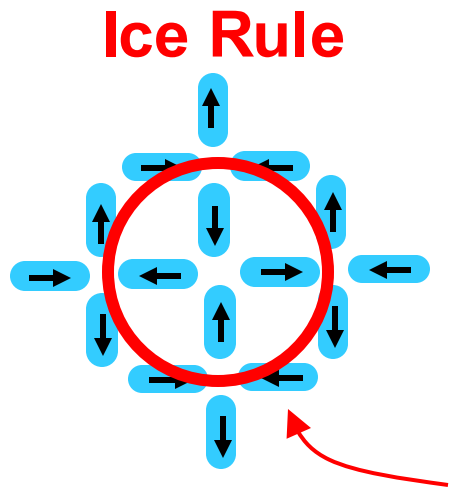

Artificial Spin Ice

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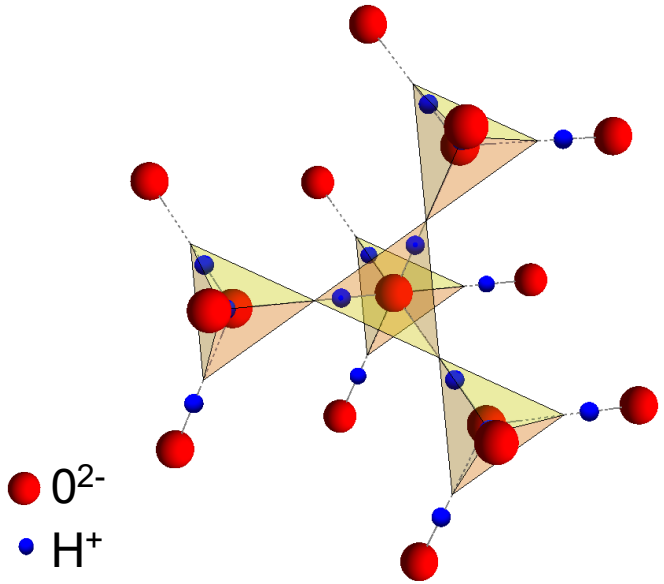

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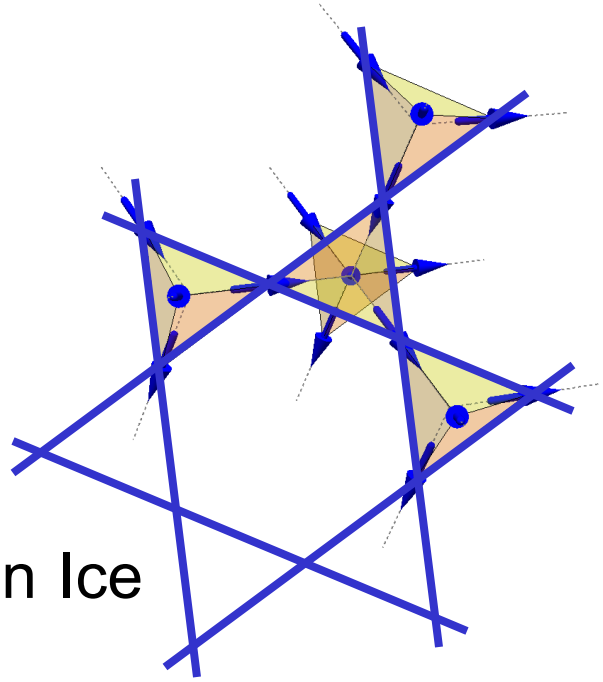
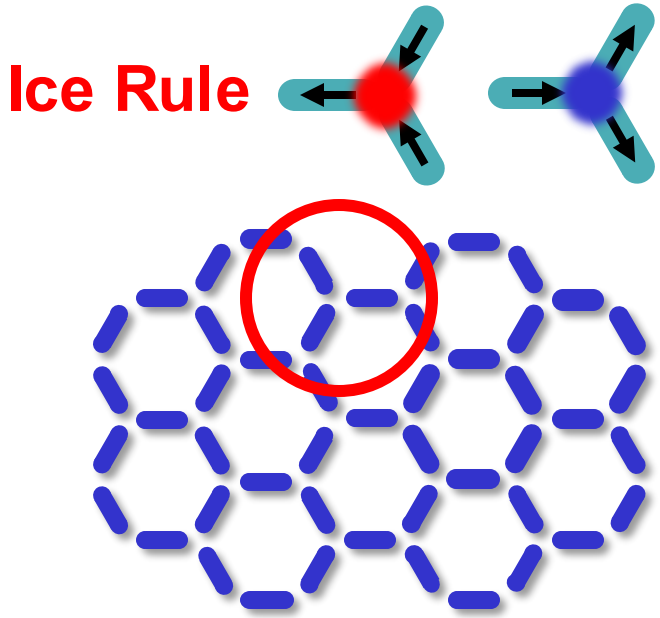


Spin Ice

MJ Harris *et al.*
PRL (1997)

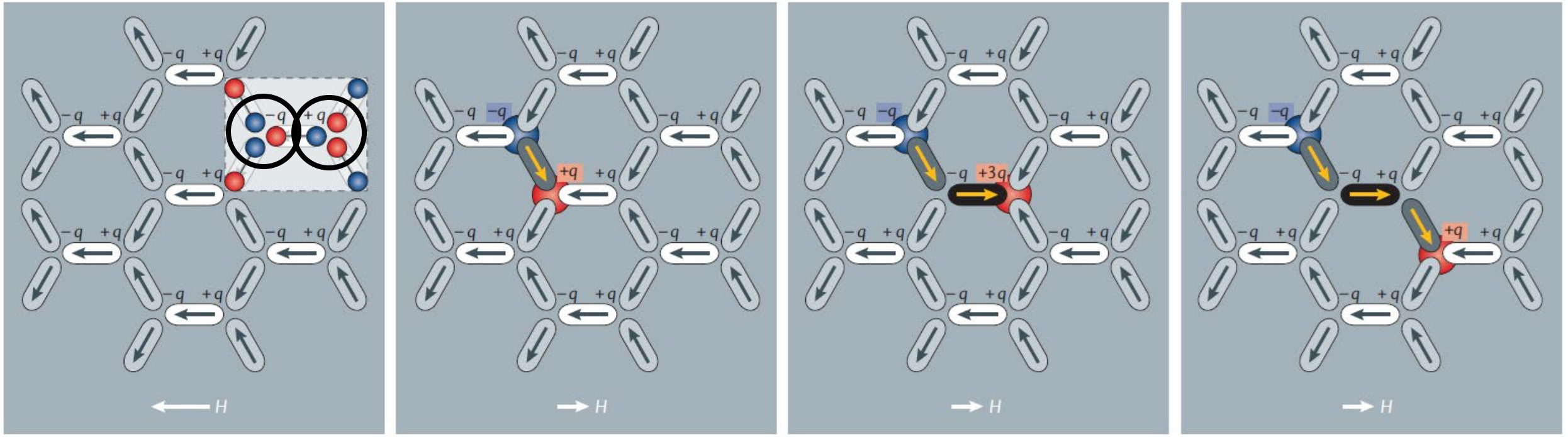


Artificial Kagome Spin Ice

AS Wills *et al.*
Phys. Rev. B (2002)

LJ Heyderman & RL Stamps J Phys: Condens Matter (2013)
SH Skjærvø, CH Marrows, RL Stamps, LJ Heyderman, Nature Reviews Physics (2020)

Artificial Spin Ice



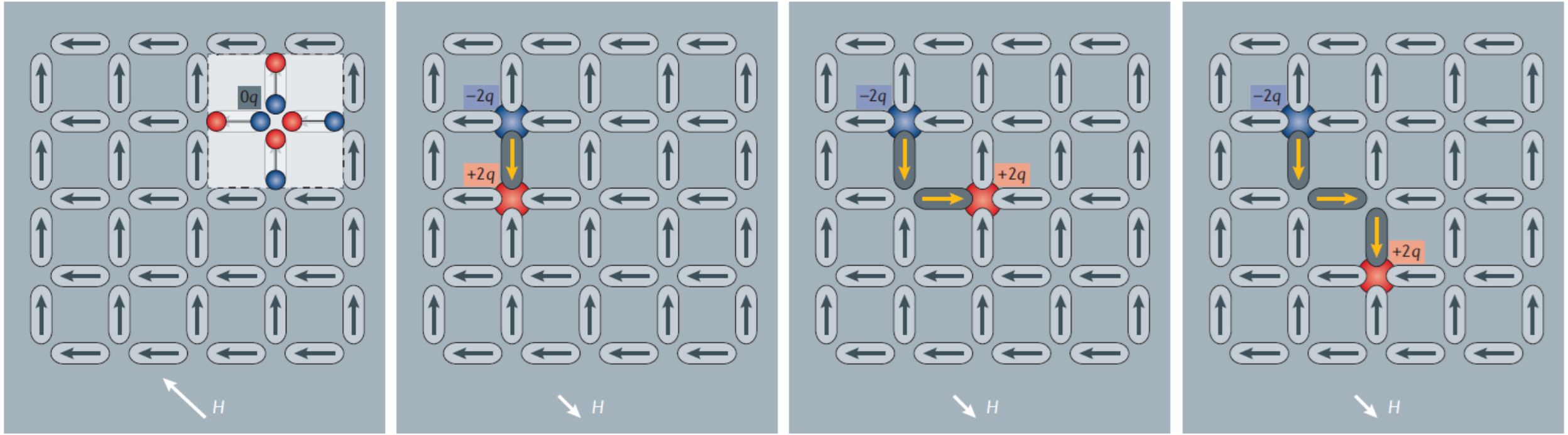
$\Delta Q = \pm 2q$

(as long as population is dilute)

LJ Heyderman & RL Stamps J Phys: Condens Matter (2013)

SH Skjærvø, CH Marrows, RL Stamps, LJ Heyderman, Nature Reviews Physics (2020)

Artificial Spin Ice



$\Delta Q = Q = \pm 2q$

The potential ($E_{Excited} - E_{GS}$): $V(R) = q/R + bX(R) + c$

Coulombic-type term — monopole pair creation

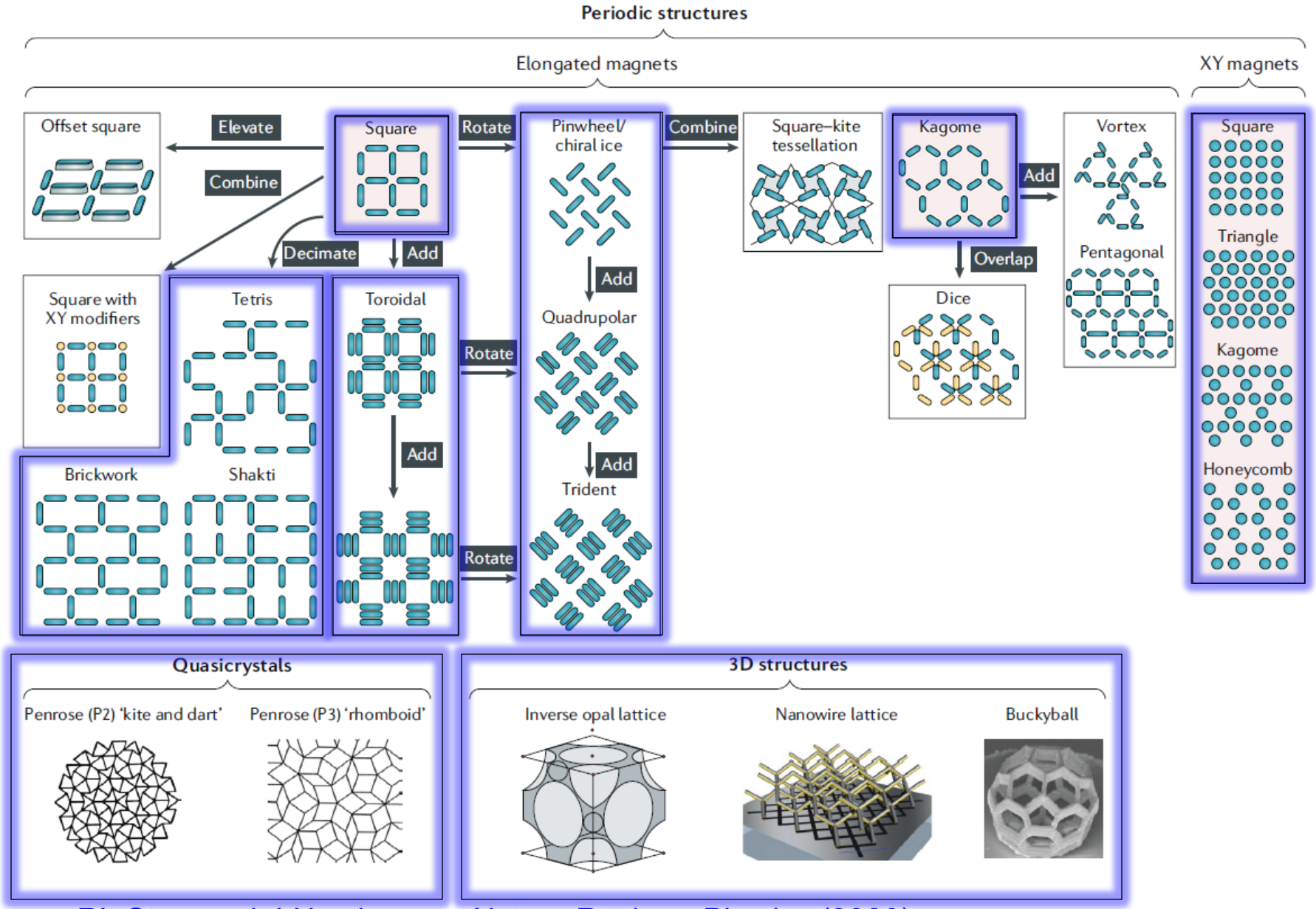
stringlike excitations that bind the monopoles

LA Mól et al. JAP (2009)

LJ Heyderman & RL Stamps J Phys: Condens Matter (2013)

SH Skjærvø, CH Marrows, RL Stamps, LJ Heyderman, Nature Reviews Physics (2020)

Artificial Spin Ice Geometries

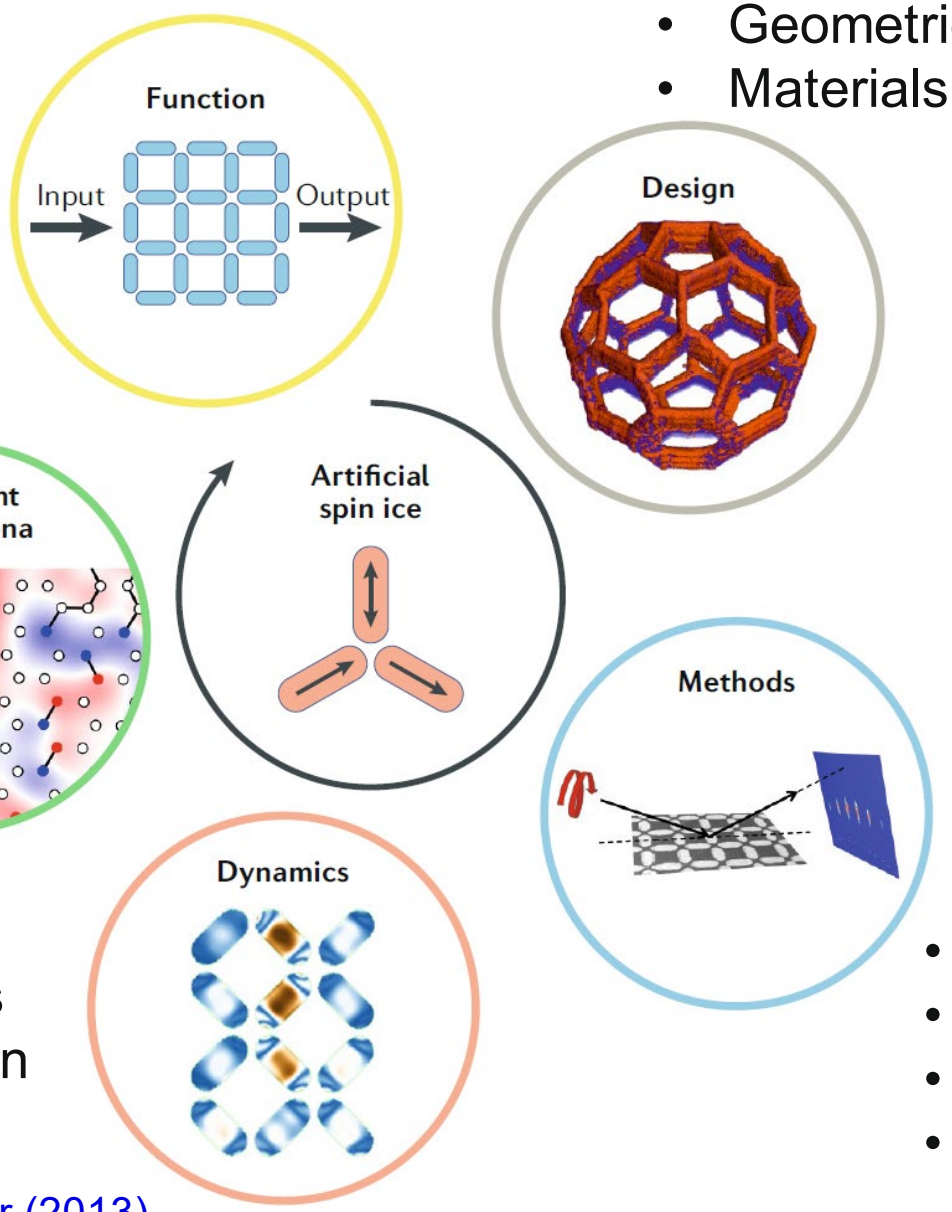


SH Skjærvø, CH Marrows, RL Stamps, LJ Heyderman, Nature Reviews Physics (2020)

Artificial Spin Ice Activities

- Computation
- Magnonics
- Hybrid systems

- Geometries
- Materials



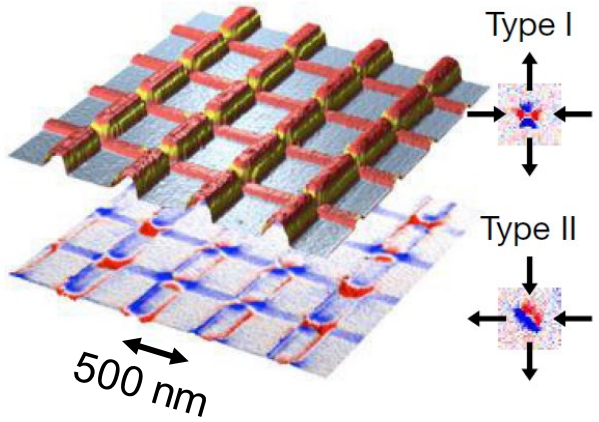
- Magnetic monopoles
- Phases transitions
- Vertex frustration
- Chirality

- Driven processes
- Thermal relaxation

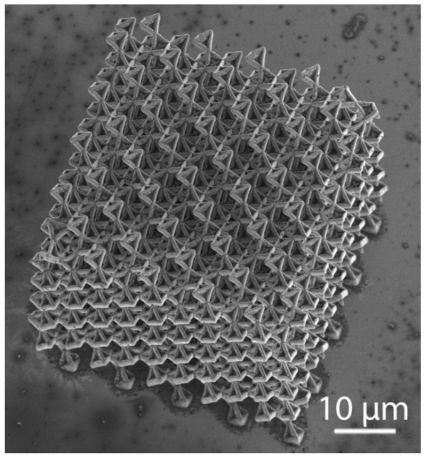
- Fabrication
- Characterization
- Manipulation
- Theory & Simulations

LJ Heyderman & RL Stamps J Phys: Condens Matter (2013)
SH Skjærvø, CH Marrows, RL Stamps, LJ Heyderman, Nature Reviews Physics (2020)

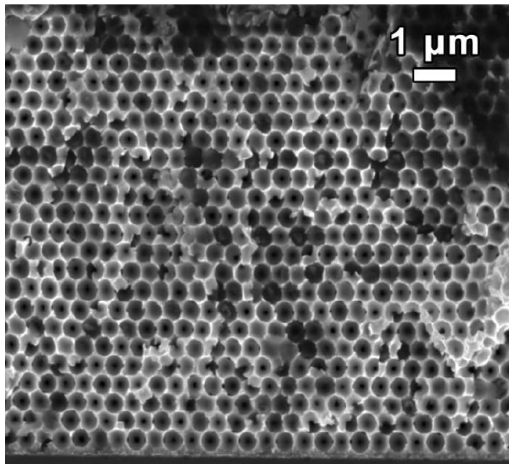
3D Artificial Spin Ice



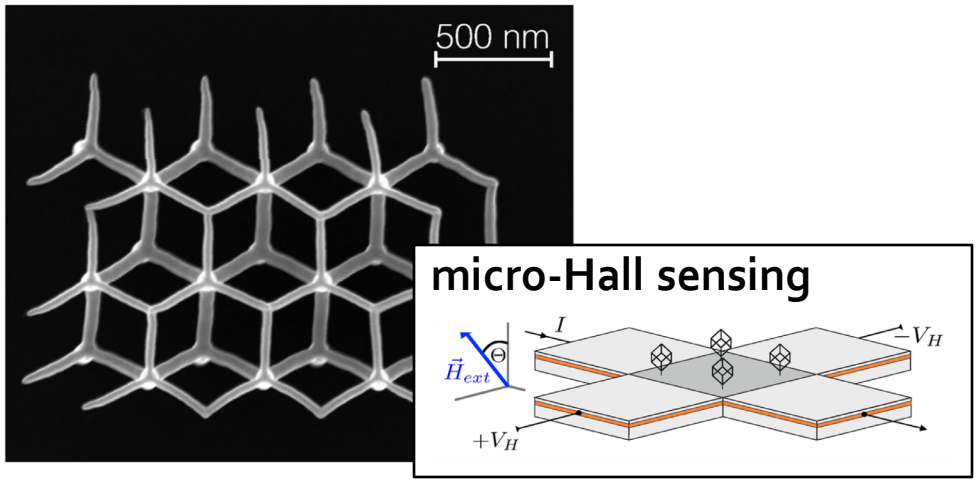
Electron Beam Lithography
Y Perrin et al. Nature 2016



Two Photon Laser Lithography
P Pip et al. Small 2020



Self-Assembly Methods
Inverse Opal-Like Structures (IOLS) & Gyroids
AA Mistonov et al. JMMM 2019



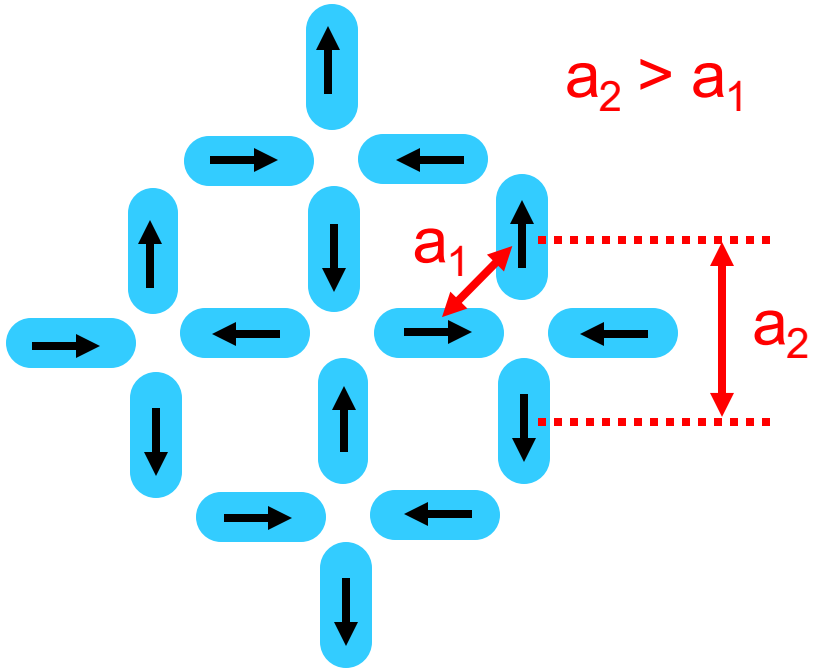
Focused electron beam induced deposition
L Keller et al. Sci Rep 2018
C Schröder et al Cond Mat ArXiv 2024

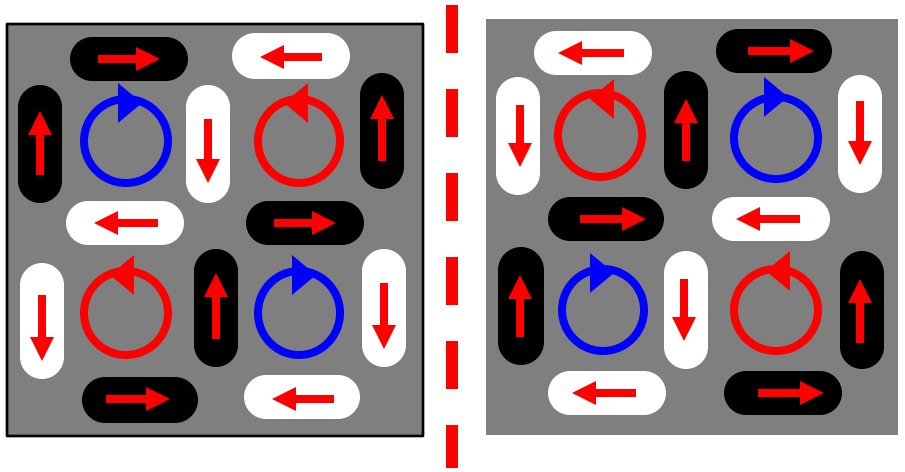
Electron Beam Lithography

- Layered Structures
- 2.5 D

Elena Mengotti working at Vistec EPBG Electron Beam Writer

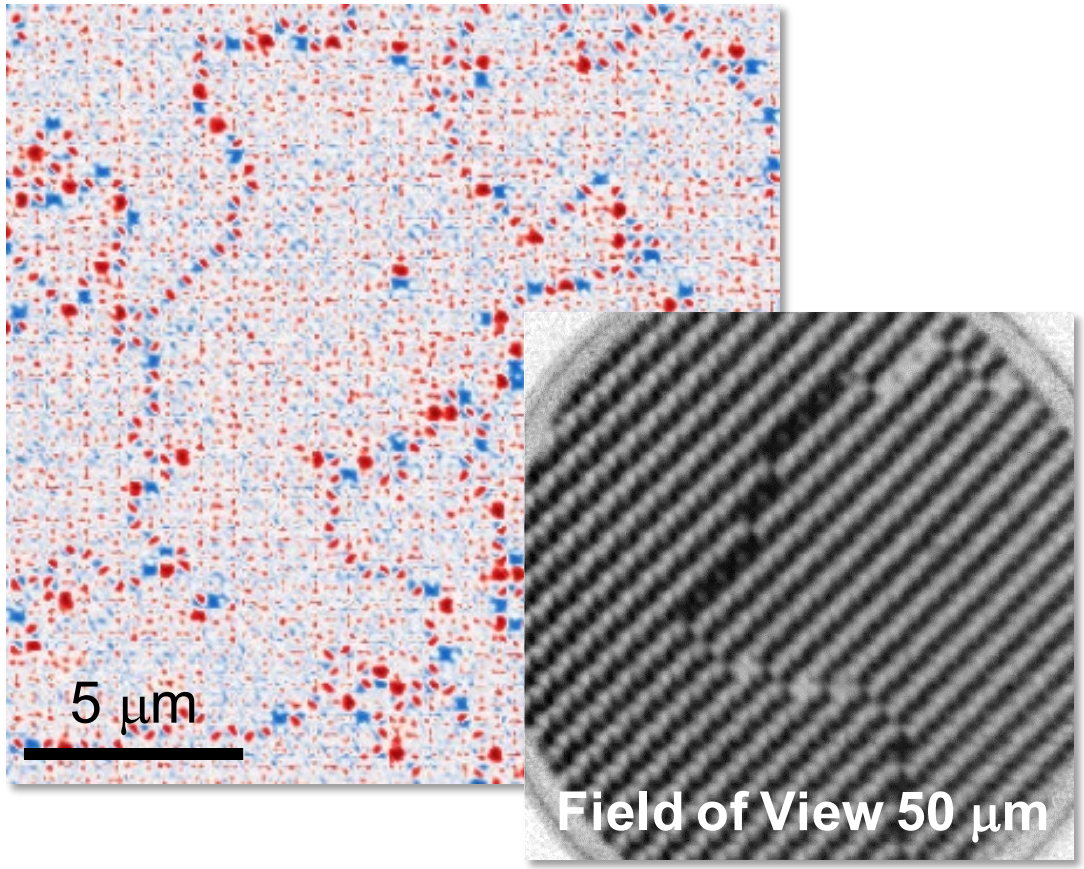
Artificial Square Ice



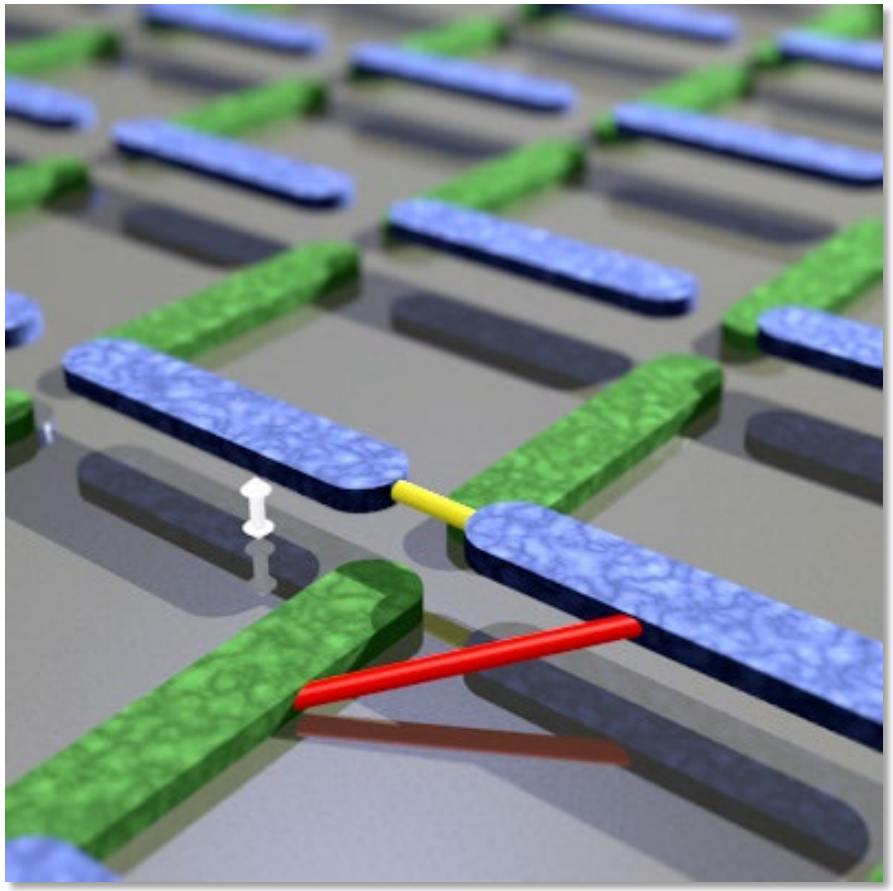


LJ Heyderman & RL Stamps J Phys: Condens Matter (2013)
SH Skjærvø, CH Marrows, RL Stamps, LJ Heyderman, Nature Reviews Physics (2020)

Raising a Sub-Lattice

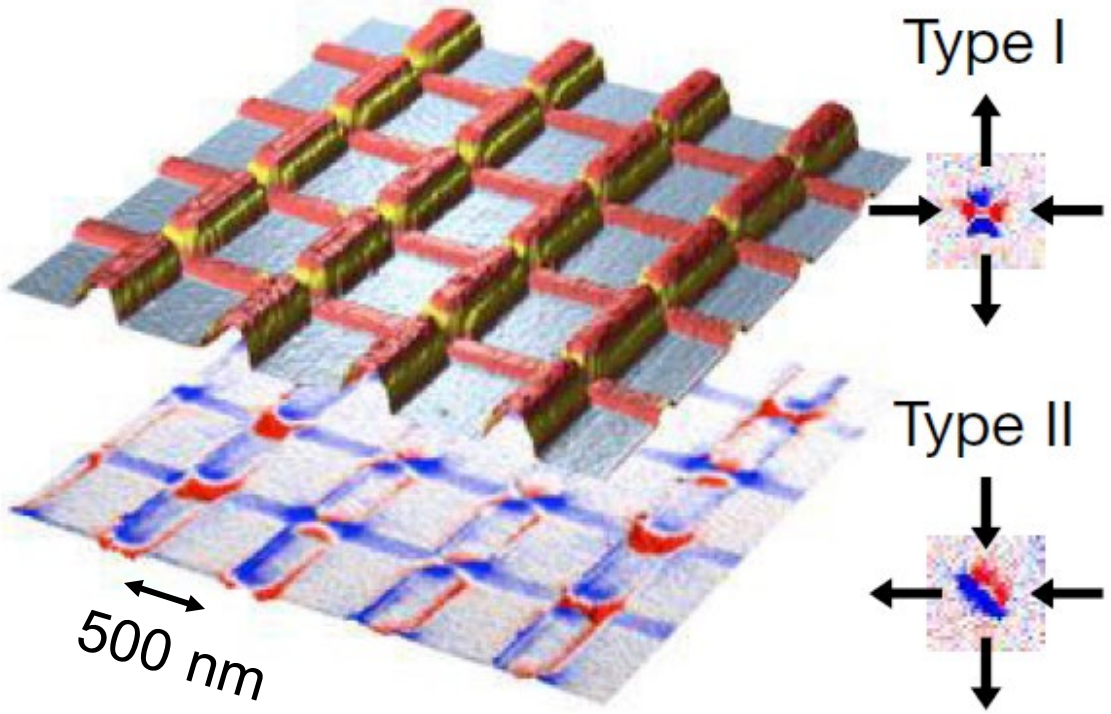


J Morgan et al. Nature Physics (2011)
JM Porro et al. NJP (2013)
S Zhang et al. Nature (2013)
A Farhan et al. PRL (2013)



G Moller & R Moessner PRL (2006)
G-W Chern et al. APL (2014)
Y Perrin et al. Nature (2016)
A Farhan et al. Science Advances (2019)

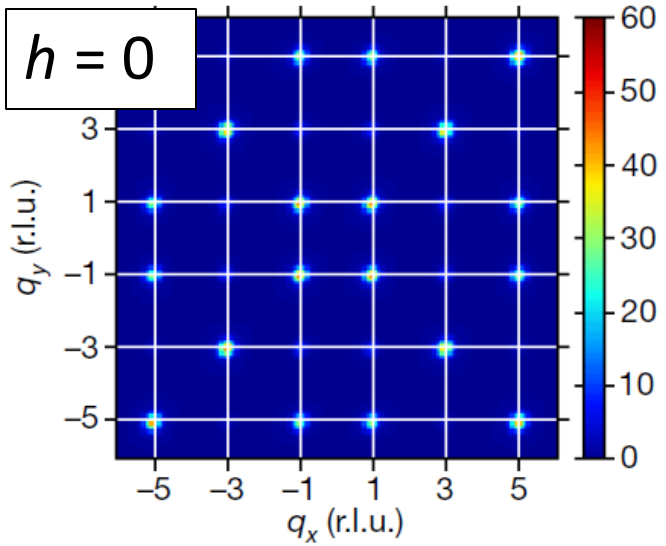
Raising a Sub-Lattice

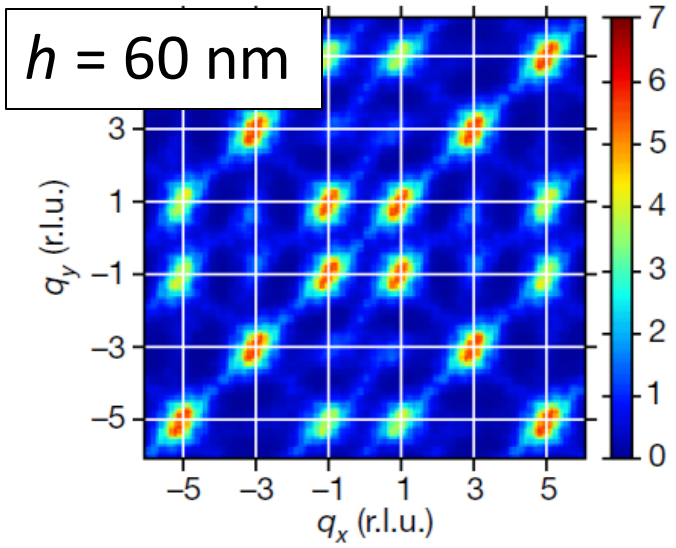


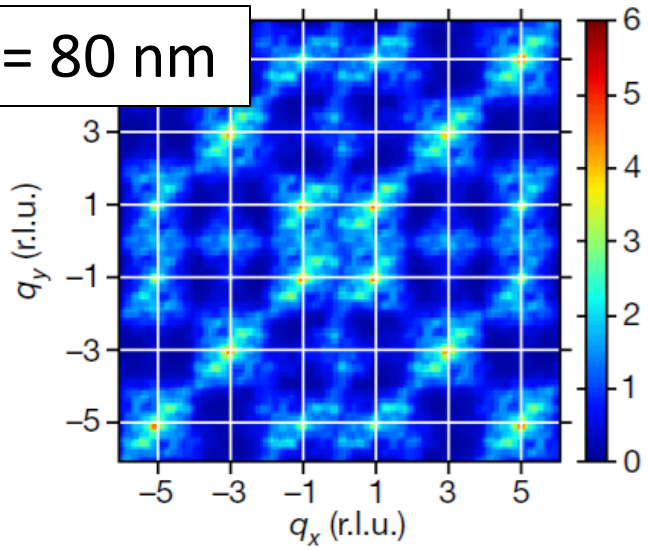
Height offset:
titanium bases with
gold capping layer

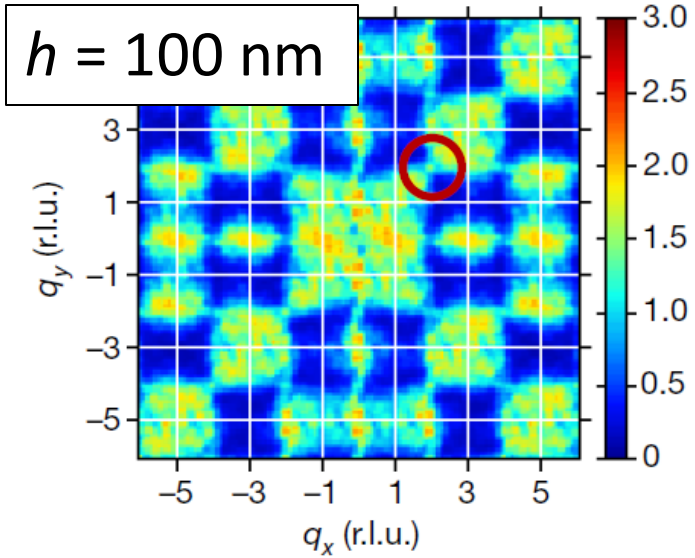
Y Perrin et al. Nature (2016)
A Farhan et al. Science Advances (2019)

Magnetic Structure Factors







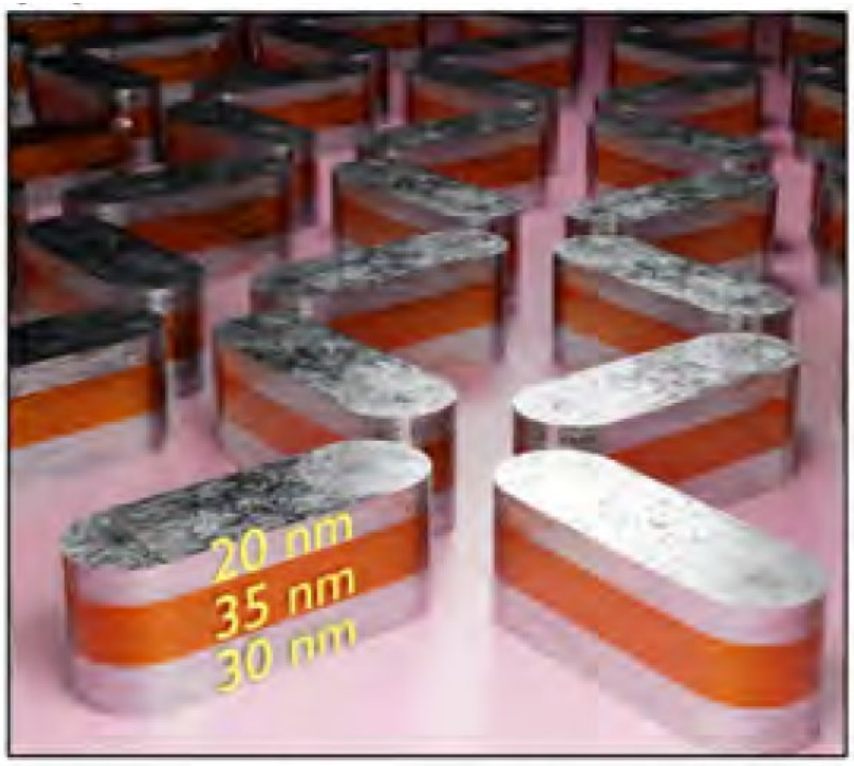


"…finite density of classical monopoles within a Coulomb phase."
Y Perrin et al. Nature (2016)

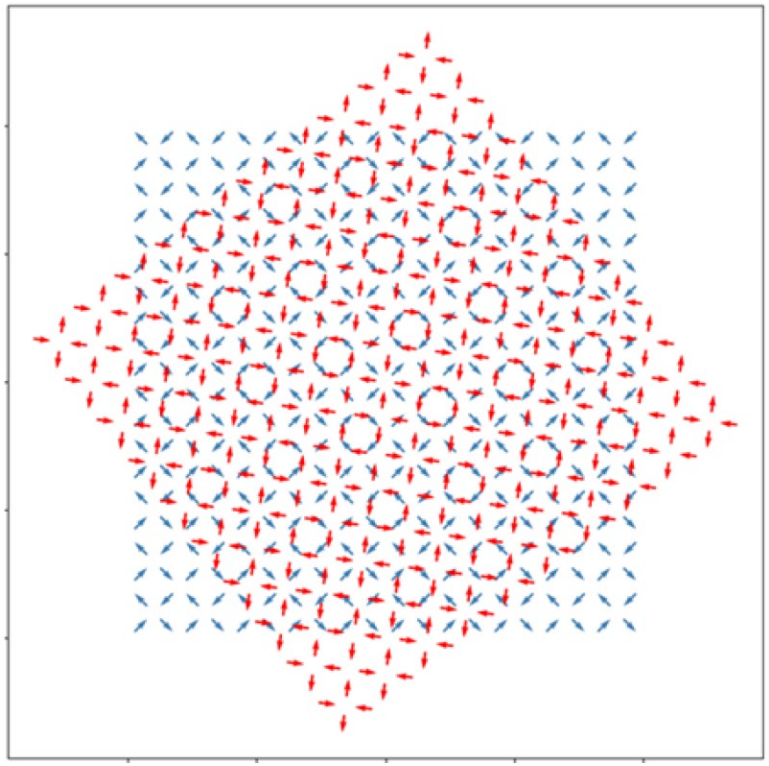
"Debye-Hückel theory - topological defects act like a plasma of Coulomb-type magnetic charges"
A Farhan et al. Science Advances (2019)

→ Christopher L. Henley, Annu. Rev. Condens. Matter Phys. 2010
The "Coulomb phase": local constraints that can be mapped to a divergence-free "flux." Defects at which the local constraint is violated behave as effective charges with Coulomb interactions.

Multilayers

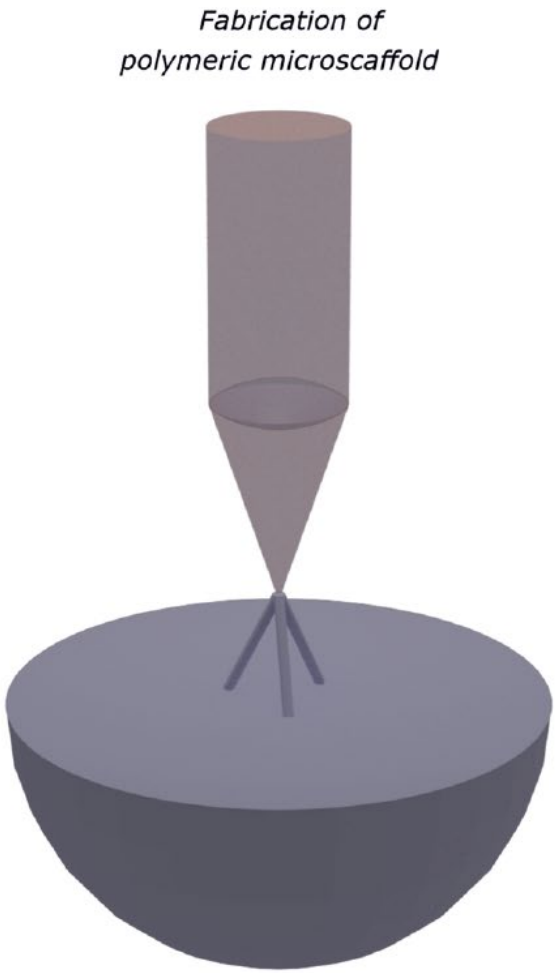


Ultrastrong Magnon-Magnon Coupling and Chiral Symmetry Breaking
T Dion et al. Cond Mat ArXiv (2023)
Nanomagnet length: 550 nm



Numerical simulations of twisted bilayer artificial spin ice
RB Popy et al. JAP 2022

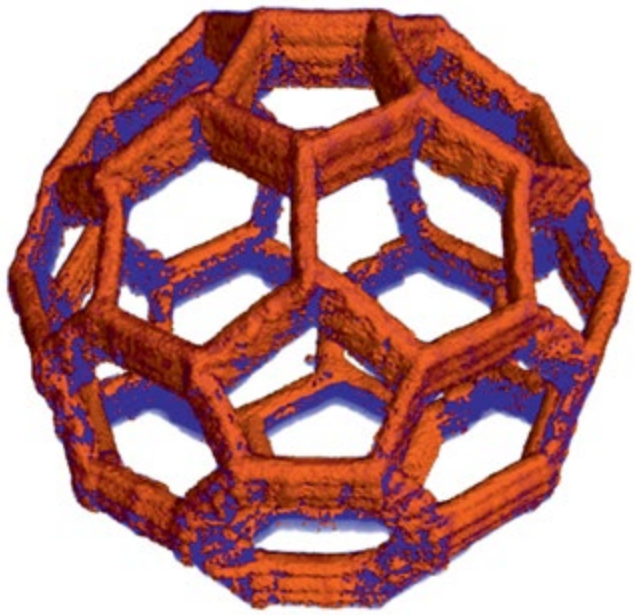
Two Photon Laser Lithography



- Nanoscribe Photonic Professional GT 2 Laser Direct Writing System
- Infra-red laser with λ = 780 nm
- UV sensitive photoresist
- Laser is focused by an optical lens
- At focal point: two-photon absorption (λ_{eff} = 390 nm) and polymerisation
- Development in propylene glycol methyl ether acetate (PGMEA)

P Pip et al. APL Materials (2022)

Three Dimensional Structures



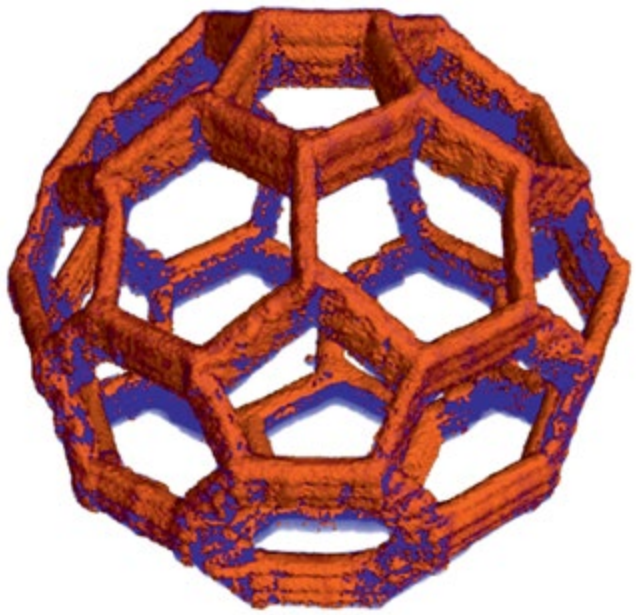
6 μm Buckyball
30 nm Co/6 nm Au with UHV sputtering

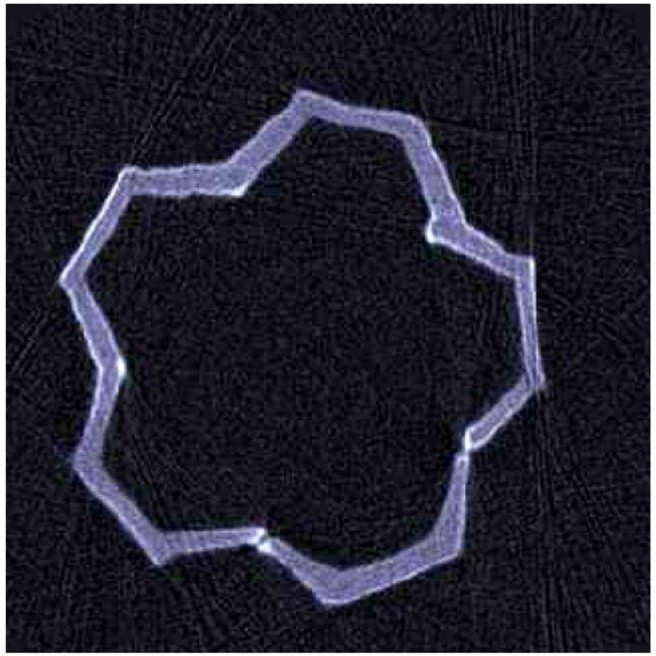
Resonant Ptychographic Tomography

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

C Donnelly et al. PRL (2015)

Three Dimensional Structures





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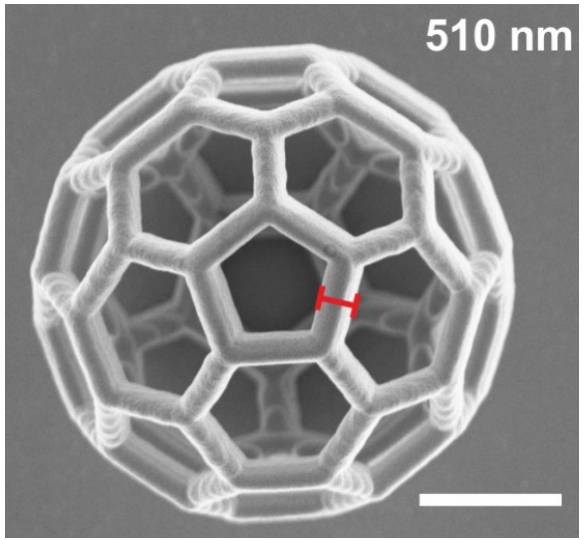
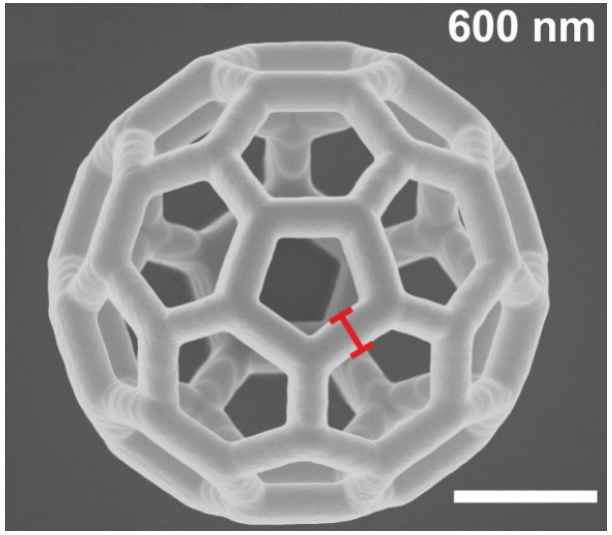
Three Dimensional Structures

10 nm Al_2O_3/10nm Ir grown conformally with ALD



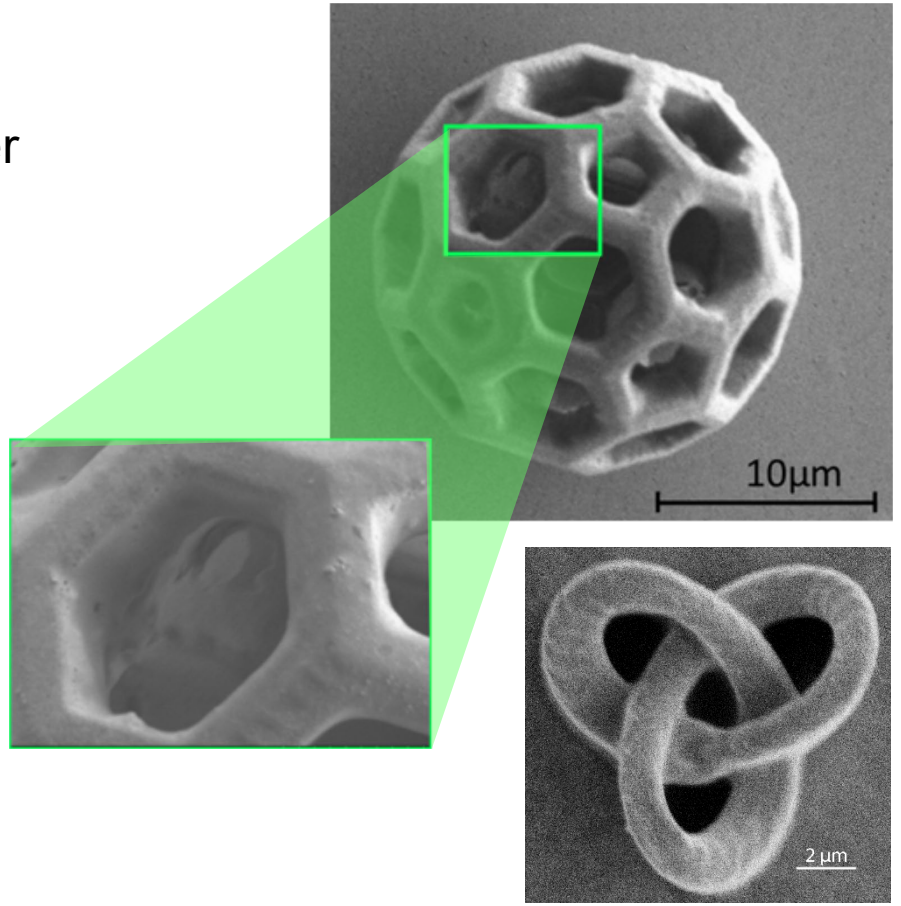
Ir: conductive layer
Al_2O_3: prevents cracking of Ir film due to expansion of polymer
Scale bars: 2 μm

45 nm-thick electrodeposited Ni film



C Donnelly PhD Thesis ETH Zurich (2017)

Electroless Deposition of NiFe(B)



cf. Petai Pip & Laetitia Philippe, EMPA Thun
P Pip PhD Thesis ETH Zurich 2021
P Pip et al. Small (2020)

Three Dimensional Structures

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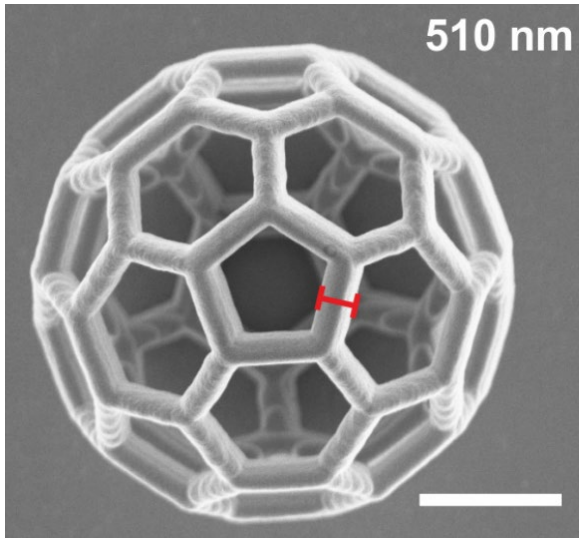

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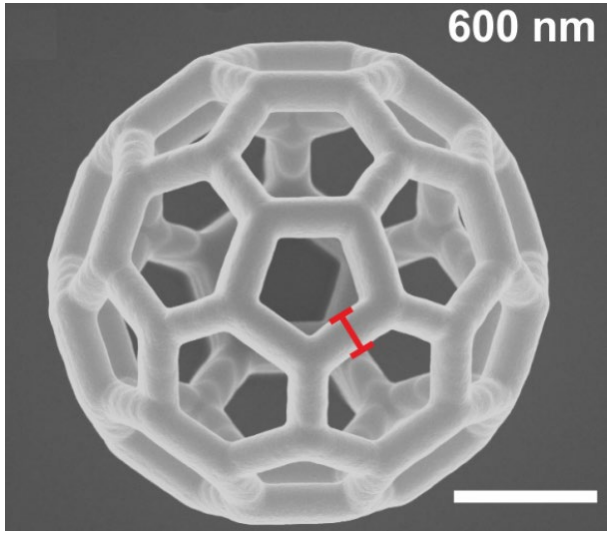

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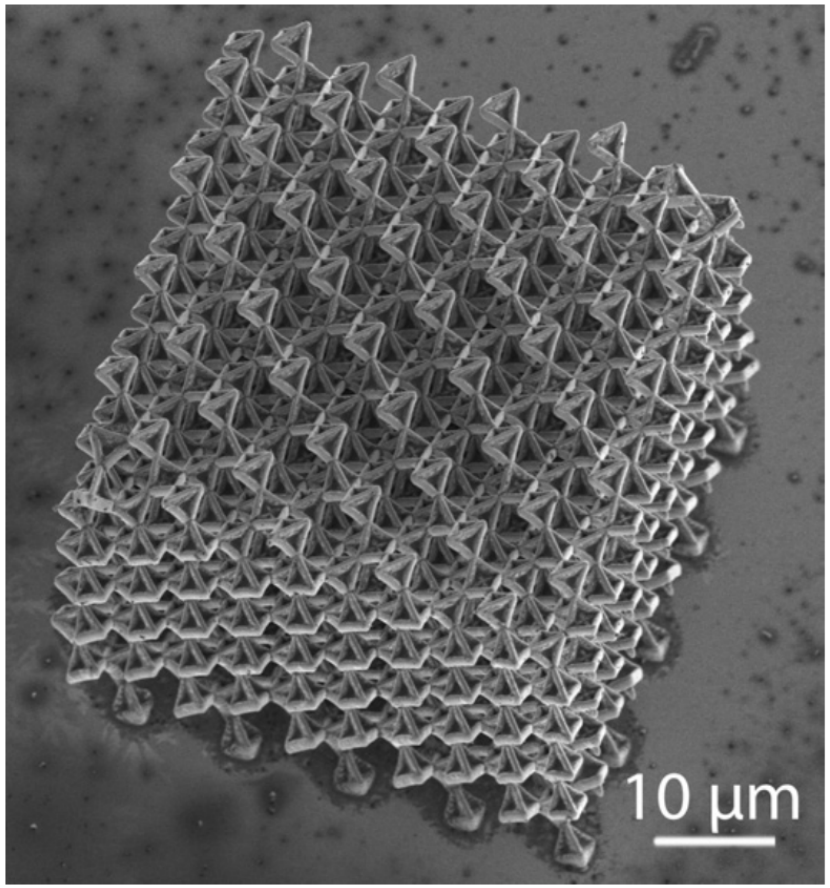
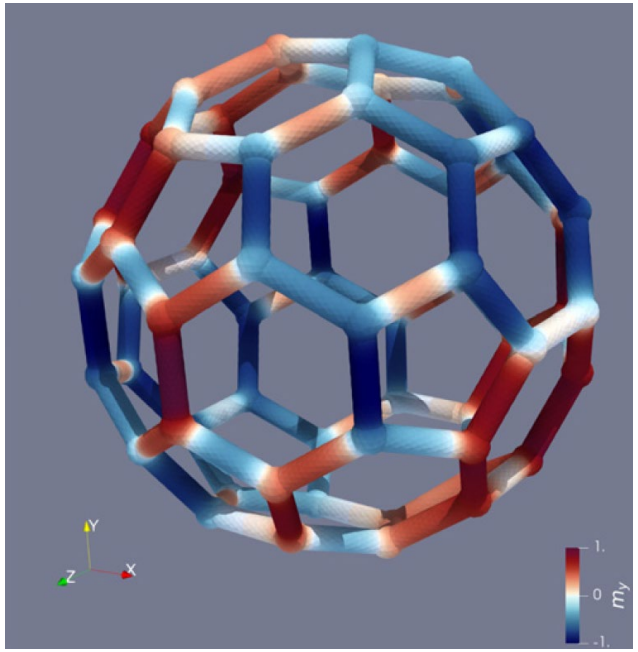
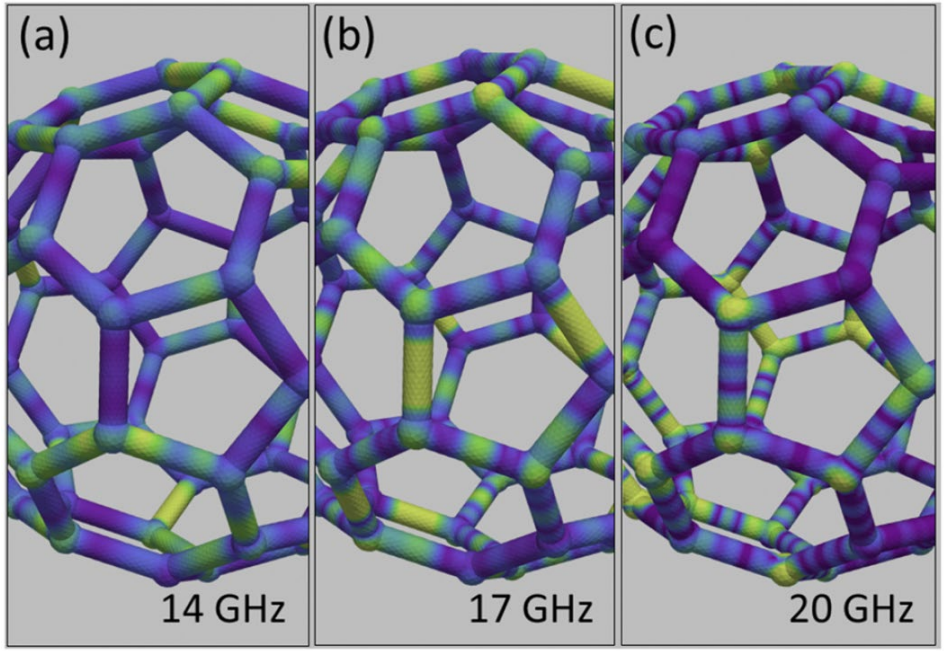


cf. Petai Pip & Laetitia Philippe, EMPA Thun
P Pip PhD Thesis ETH Zurich 2021
P Pip et al. Small (2020)

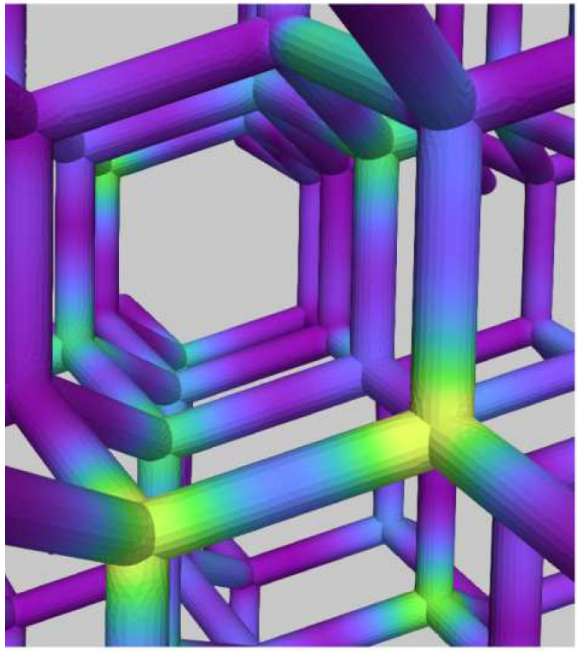
Buckyball Simulations



Switching in a buckyball
R Cheenikundil et al. APL (2021)
Nanowire Length 100 nm

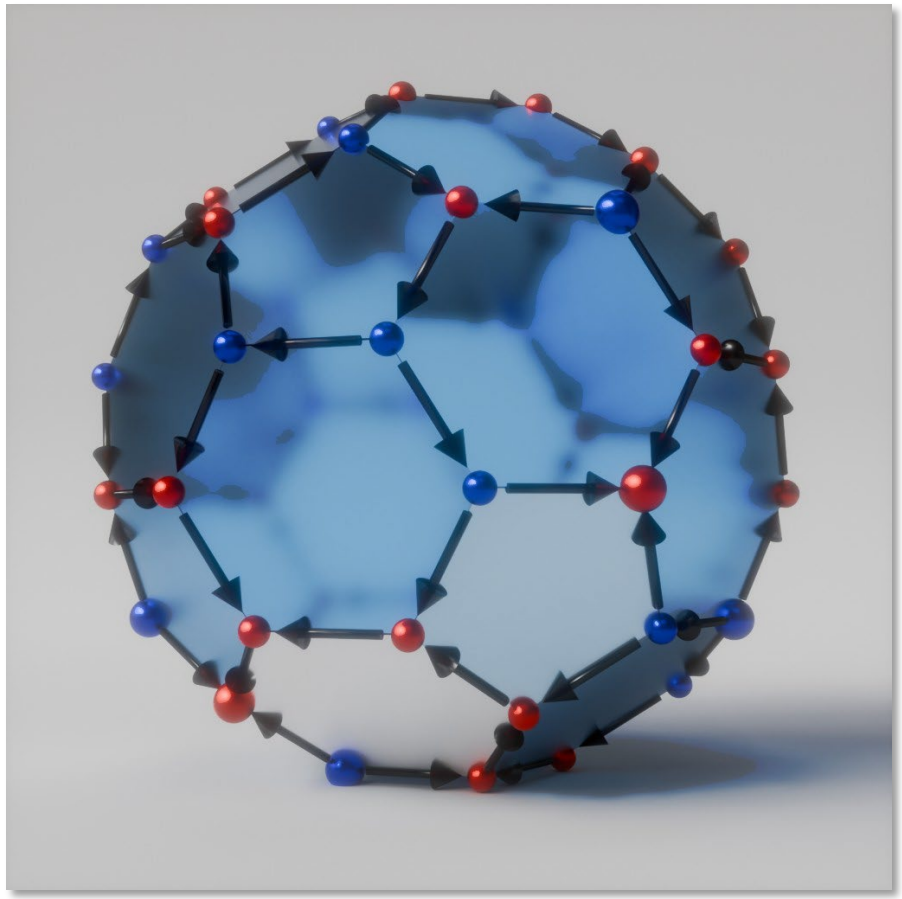


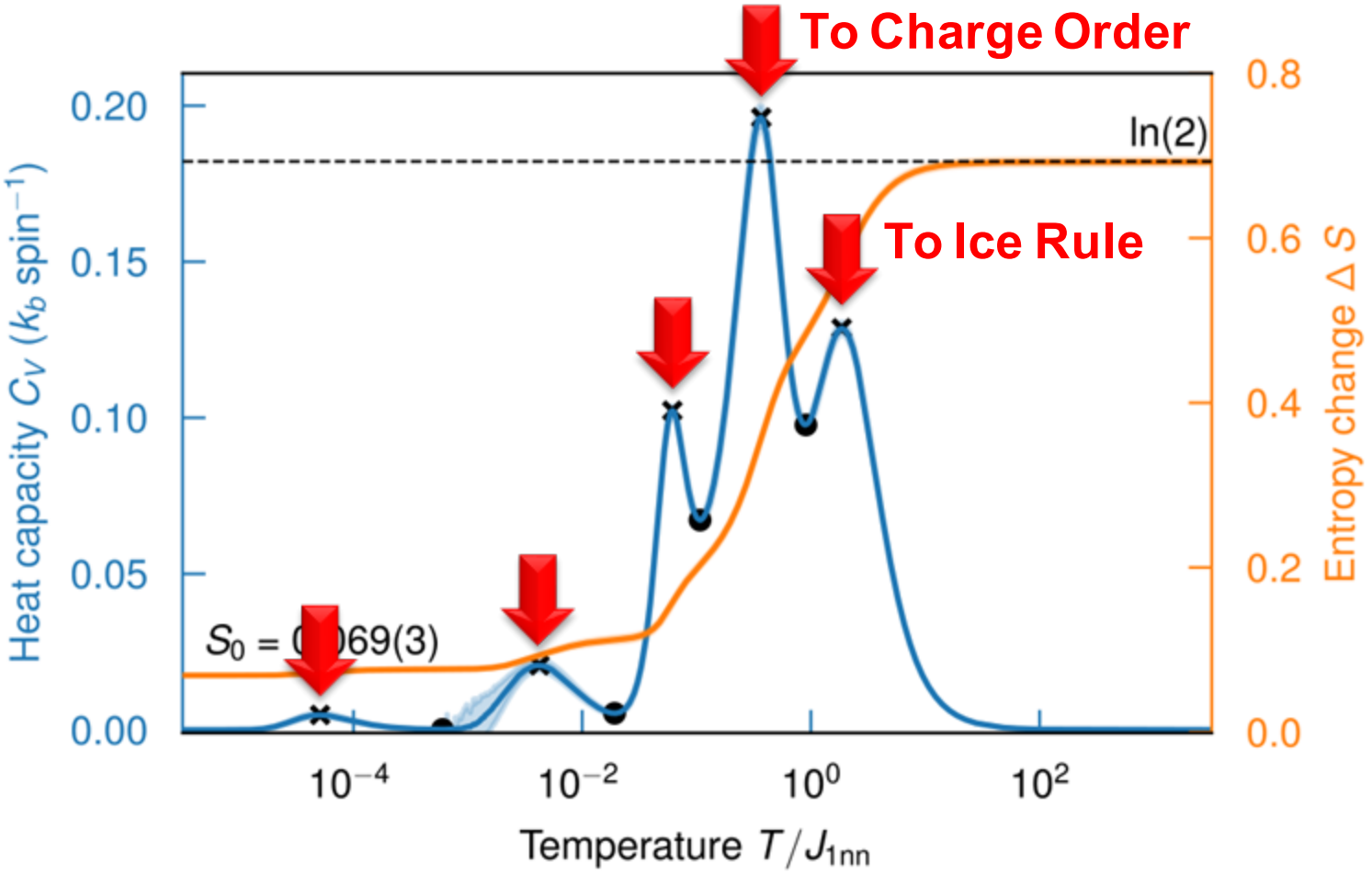
High-frequency modes in a buckyball
R Cheenikundil et al. APL Materials (2022)
Nanowire Length 100 nm



Defect-sensitive High-freq. modes in 3D ASI
R Hertel et al. hal-03850245 (2022)
Nanowire Length 70 nm

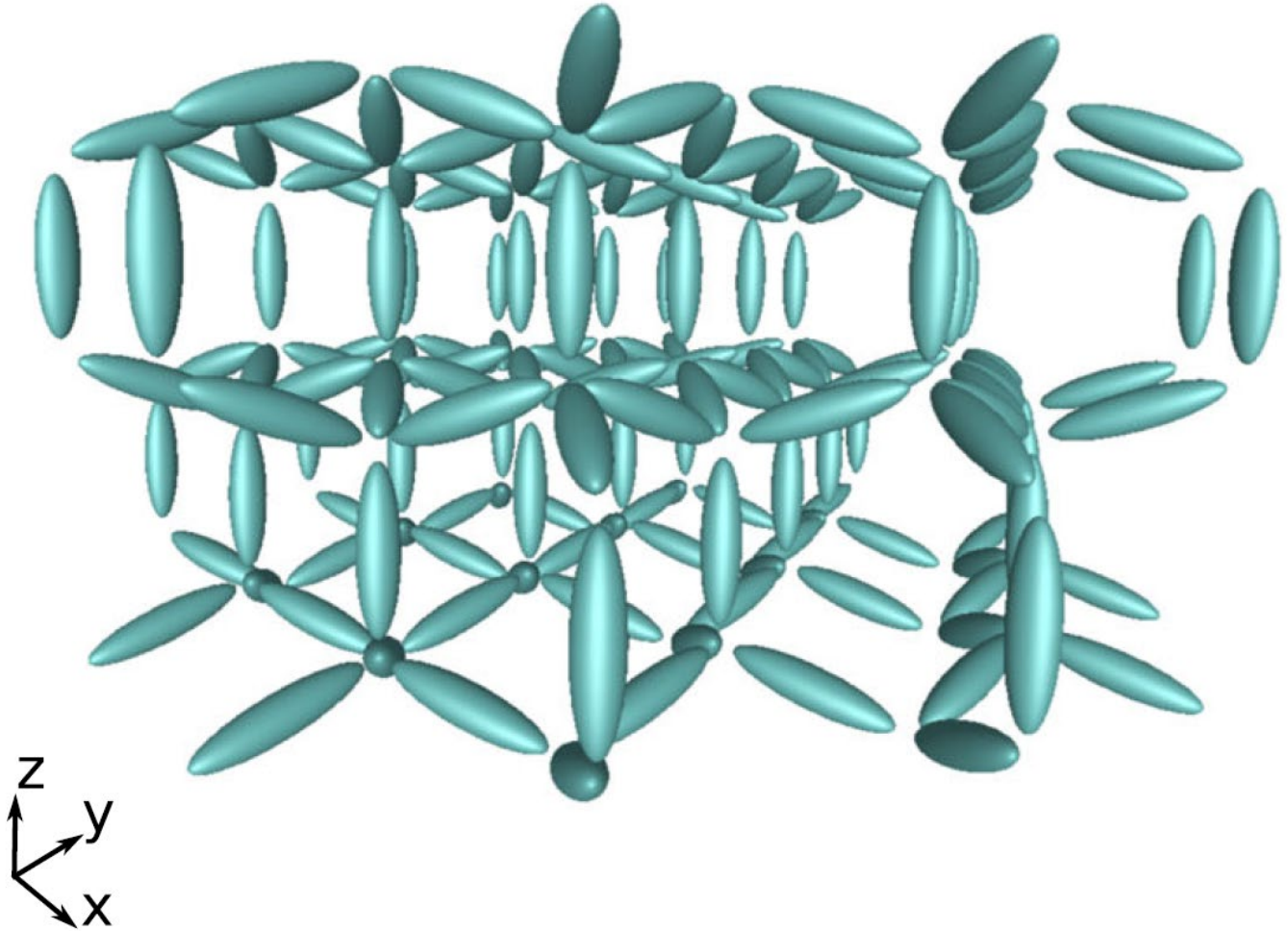
Thermodynamics in a Buckyball





GM Macauley, L Berchialla, PM Derlet and LJ Heyderman In Preparation (2024)

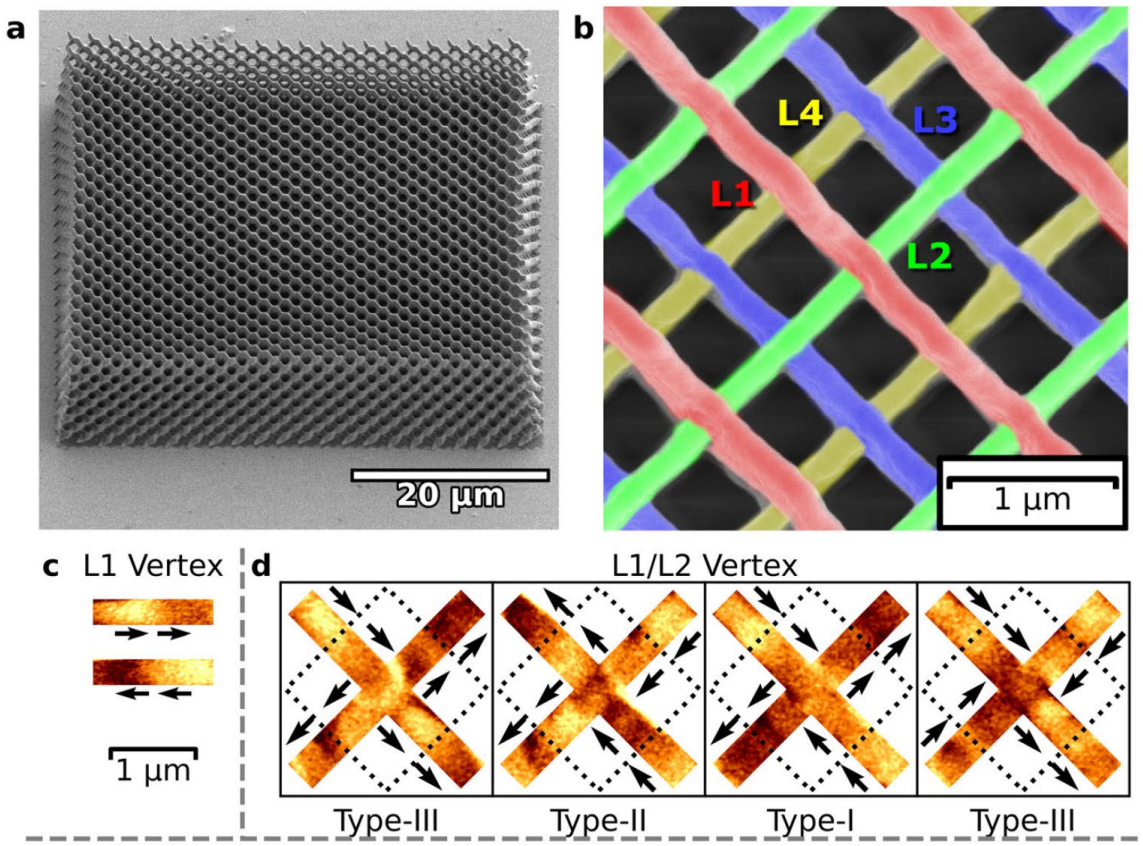
Micromagnetic Simulations



Tension-free Dirac strings and steered magnetic charges
S Koraltan et al. NPJ Comp Matls 2021
Ellipsoid Length 100 nm

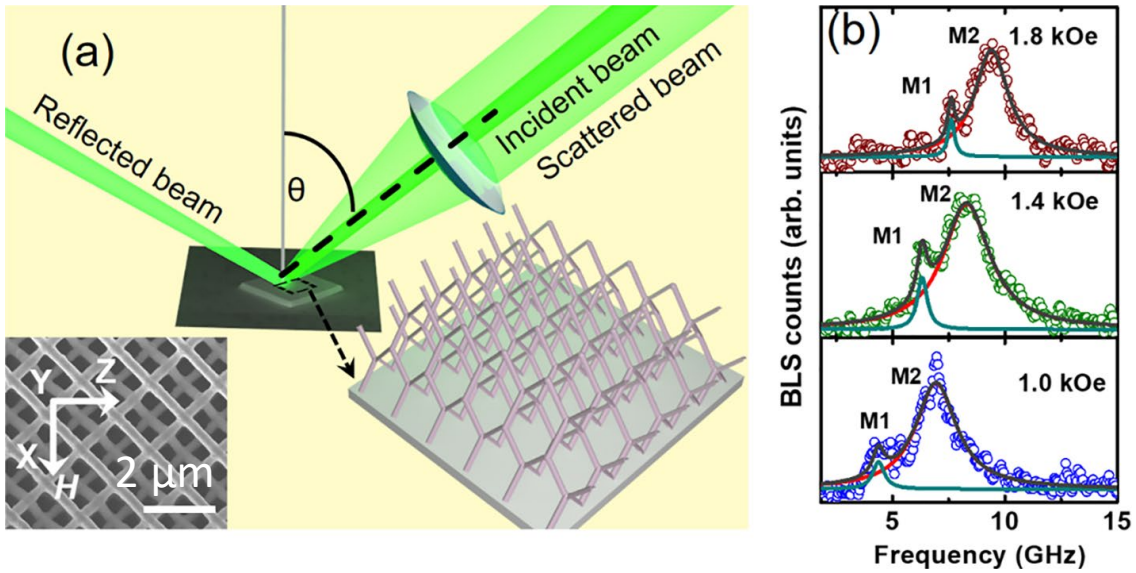
Two Photon Laser Lithography

Magnetic Force Microscopy (MFM)

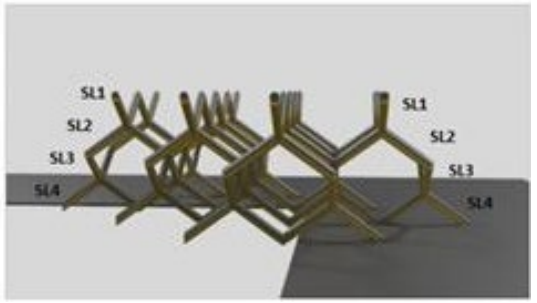


A May et al. Realisation Comm Phys 2019
A May et al. Charge Propagation Nat. Comm. 2021
M Saccone et al. ASI Phases Commun. Phys. 2023

Brillouin Light Scattering (BLS) Spectroscopy

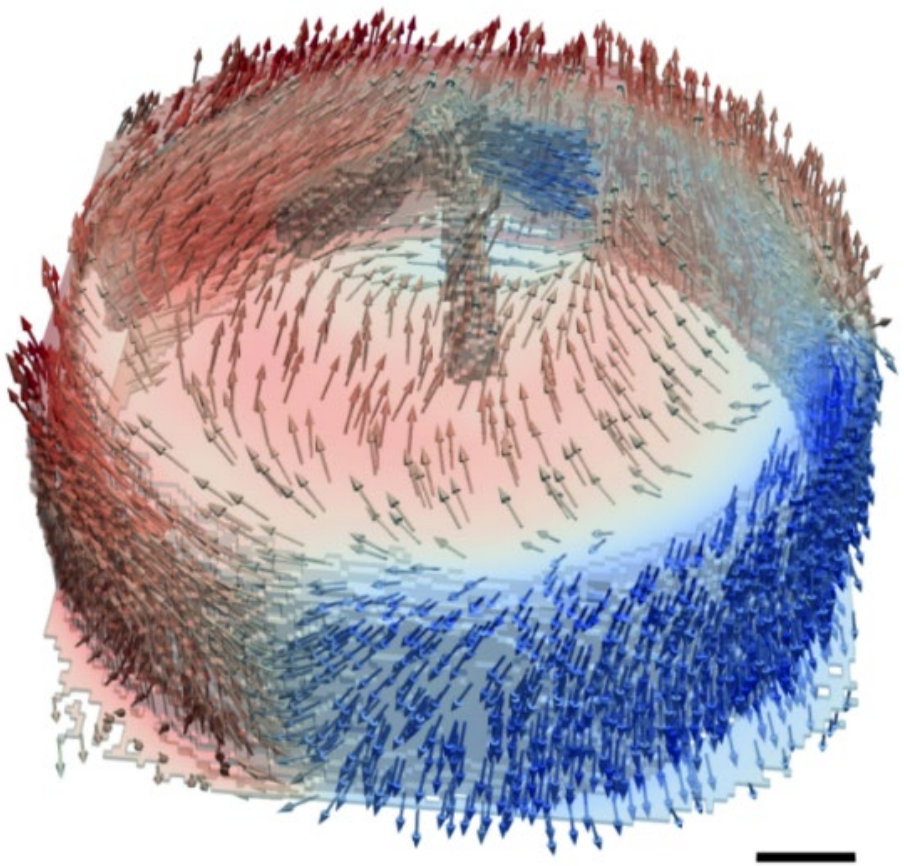


S Sahoo et al. Coherent Spin Waves Nano Lett 2021
S Sahoo et al. Ultrafast dynamics in a tetrapod with time-resolved MOKE microscopy Nanoscale 2018
H Guo et al. Bulk & surface modes in a woodpile structure Adv Mater 2023

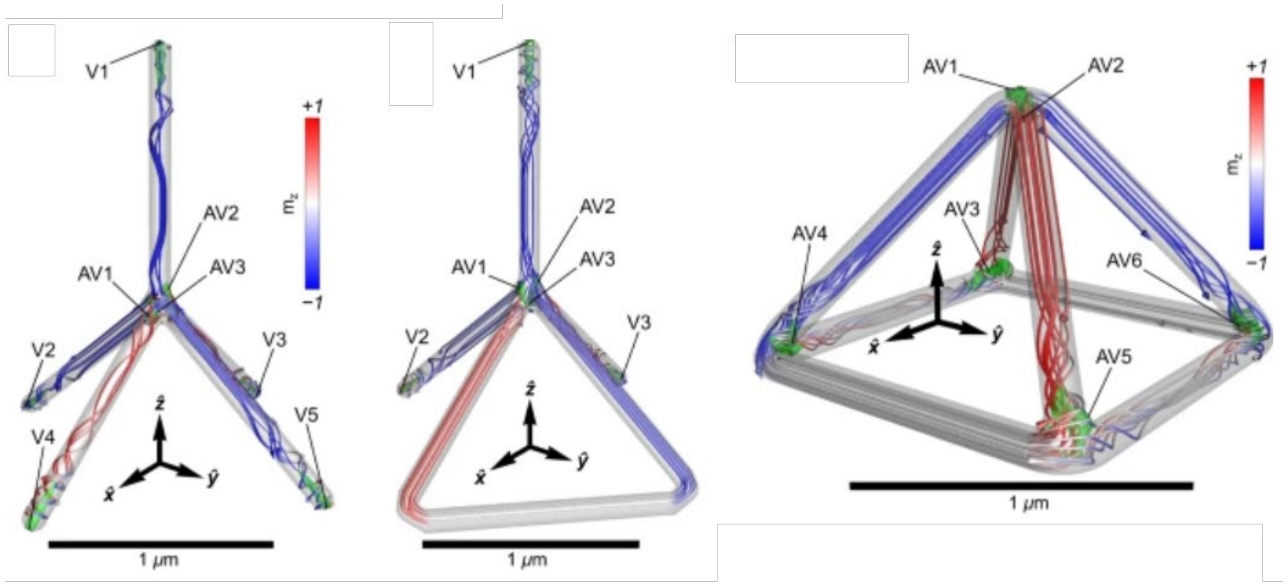


E Harding et al. APL Mater. 2024
Nanowire Length 1 µm

Artificial Spin Ice Building Block



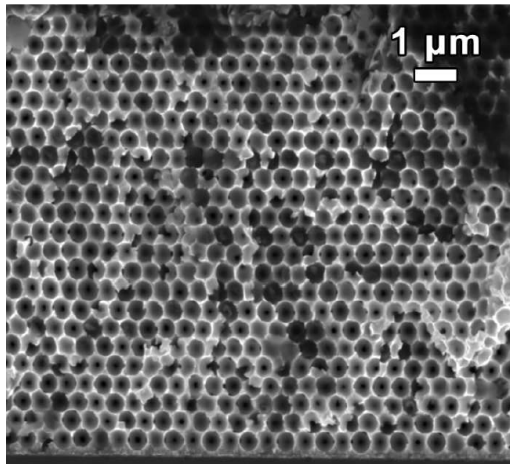
500 nm

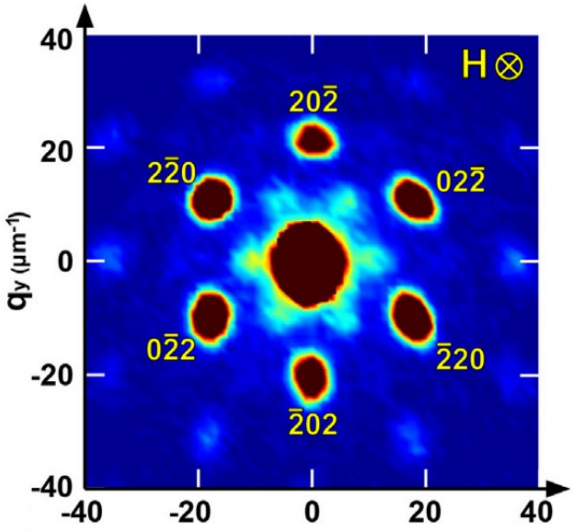


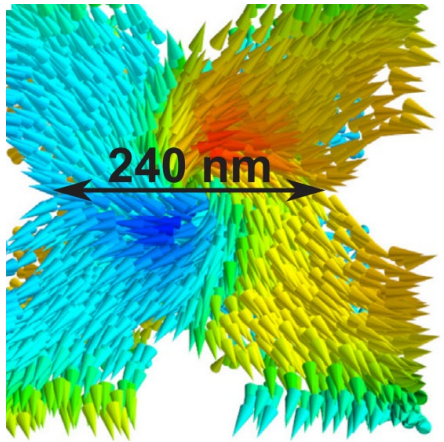
Topological magnetization textures with high-order vorticity in wireframes & FEBID
OM Volkov et al. Nature Commun 2024
Scalebar: 1 μm

Soft x-ray magnetic laminography
P Pip et al. APL Materials (2022)
In-plane reconstruction spatial resolution of < 100nm

IOLS & Gyroids

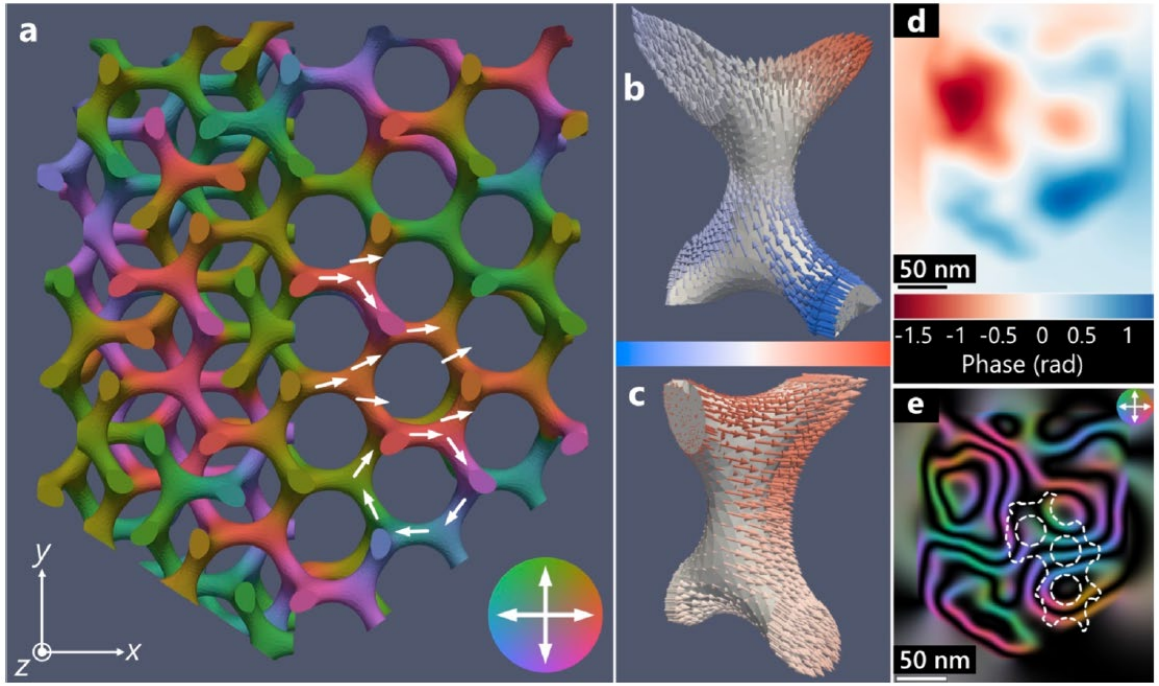






(i) Artificial opal:
Electric-field-assisted assembly of polystyrene microspheres
D = 620 nm; RSD < 10%

(ii) Si(100) substrate with 200 nm thick Au:
Co Electrodeposition in voids



Map of magnetic induction

(i) Thermal annealing of a block copolymer template

(ii) Selective dissolution of the minority block

(iii) Electrodeposition

→ NiFe double-gyroids: 42 nm unit cell & chiral triple junctions

Inverse Opal-Like Structures (IOLS)

IS Dubitskiy et al. Micromagnetic Simulations JMMM 2017
AA Mistonov et al. SANS & Micromagnetics JMMM 2019
AA Mistonov et al. 3D ASI PRB 2013
IR Shishkin et al. Geometric scaling of coercivity PRB 2016

Gyroids

J Llandro et al. 3D Nanoscale Gyroid Nanolett 2020
AS Koshikawa et al. Magnetic Order PRB 2023

Nanomagnet Robots

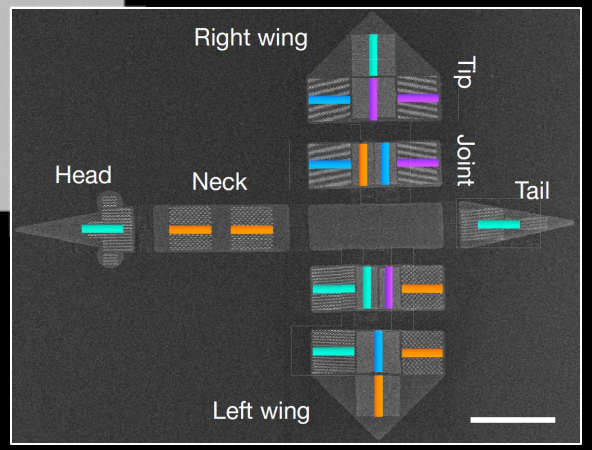
Magnetic Micromachines

Jizhai Cui (with Bradley Nelson, Tian-Yun Huang & further group members)

Origami Bird

J Cui et al. Nature (2019)

- Arrays of 60 nm thick Co nanomagnets
- 50 nm thick low-stress SiN Membrane panels
- Released in an organic liquid (PGMEA)
- Activated in a magnetic field:
  B ~ 1-10 mT at 0-25 Hz

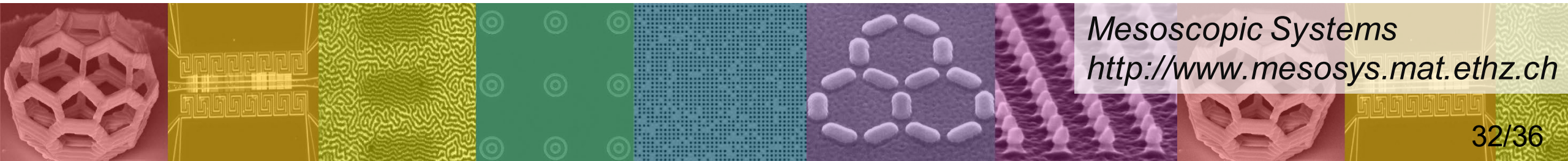


→ **3D Structures**

→ **Movement**

→ **Actuation & Robotics**
https://marss-conference.org
“Manipulation, automation and robotics at small scales”

Acknowledgements



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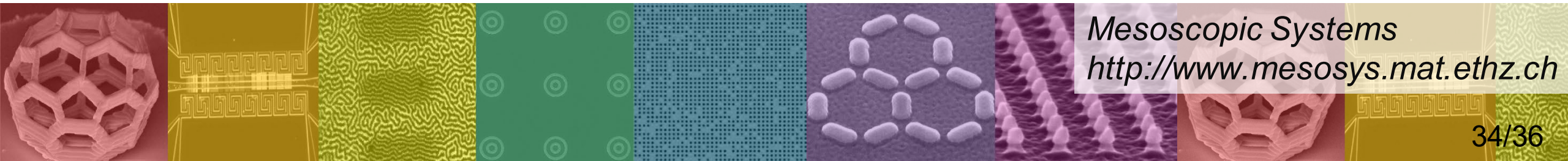
Swiss Light Source

- *Photoemission Electron Microscopy, SIM Beamline*
  Armin Kleibert, Carlos Vaz
- *Scanning Transmission X-ray Microscopy, PolLux Beamline*
  Joerg Raabe, Simone Finizio
- *X-ray Scattering, SIM Beamline*
  Urs Staub
- *X-ray Tomography and Laminography, cSAXs & PolLux Beamlines*
  Manuel Guizar Scicairos, Mirko Holler, Simone Finizio, Joerg Raabe

Laboratory for Muon Spin Spectroscopy: Hubertus Luetkens

Condensed Matter Theory Group: Peter Derlet



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Adv. Light Source:	Andreas Scholl & Colleagues

Spin ENGINE

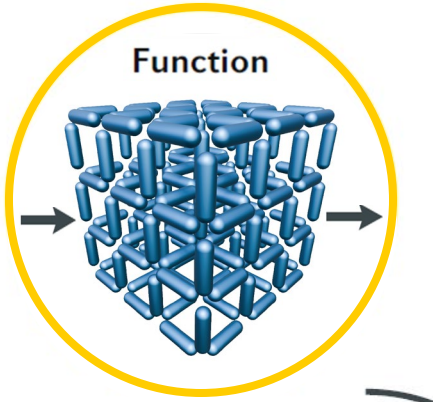
https://spinengine.eu

Swiss National Science Foundation

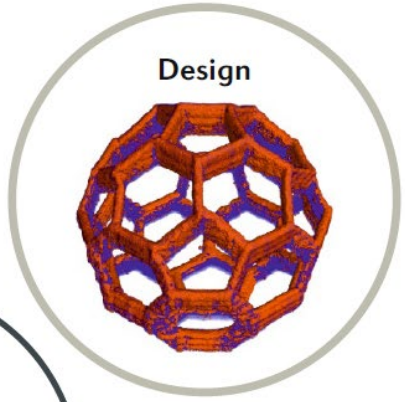
Artificial Spin Ice Activities in Three Dimensions

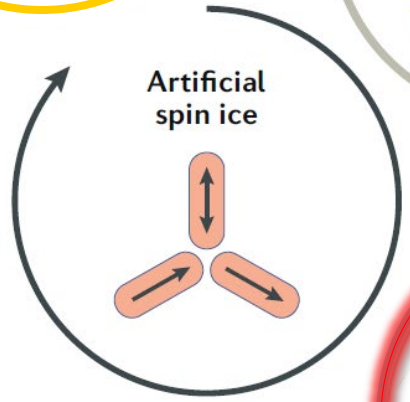
- Computation
- Magnonics
- Hybrid systems

2D: 2^{24} ~2×10^{7}
3D: 2^{144}~2×10^{43}

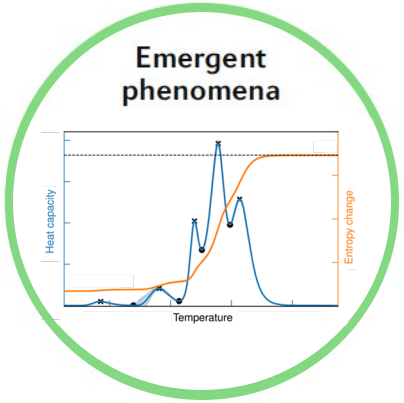


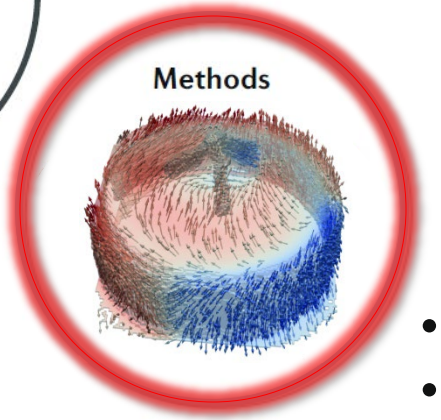
- Geometries
- Materials

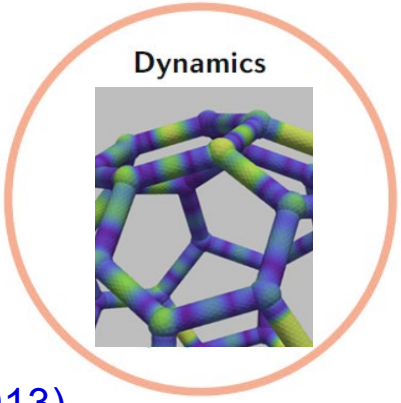




- Magnetic monopoles
- Phases transitions
- Vertex frustration
- Chirality







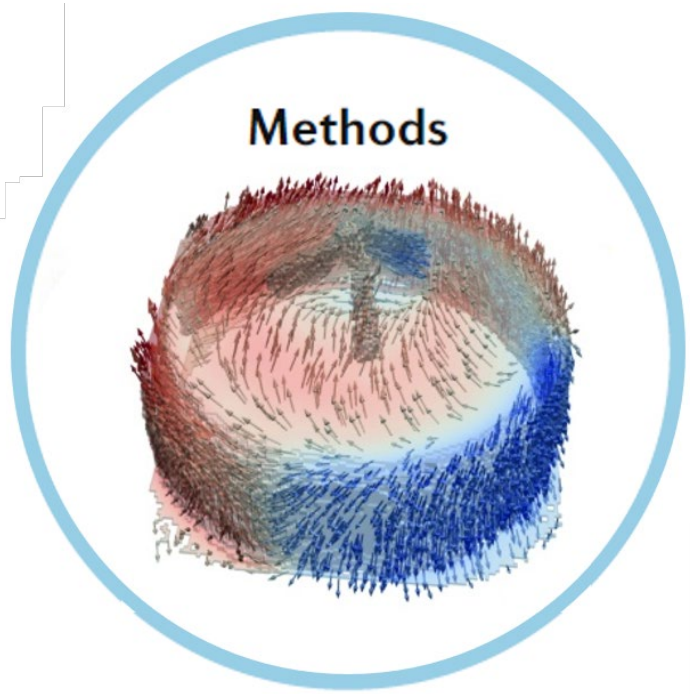
- Driven processes
- Thermal relaxation

Enabling Technologies

- Fabrication
- Characterization
- Manipulation
- Theory & Simulations

LJ Heyderman & RL Stamps J Phys: Condens Matter (2013)
SH Skjærvø, CH Marrows, RL Stamps, LJ Heyderman, Nature Reviews Physics (2020)

Artificial Spin Ice Activities in Three Dimensions



Enabling Technologies

"3D is exciting, but we have to make it feasible"

I. Fabrication

- Control of feature sizes & geometries, large volumes
- Electrodeposition & FEBID of high-quality magnetic materials

II. Characterization

- **Imaging**
  - → Large penetration depths
  - → High spatial & temporal resolution
  - → Synchrotron X-rays
  - → Electron microscopy
  - → Lab Based Methods: MFM & Kerr Microscopy
- **Magnetic Properties:** MOKE, SQUID VSM, Heat Capacity
- **Transport:** read & write magnetic states
- **Magnetization Dynamics**

III. Theory & Simulations

- Dynamics & Thermodynamics: phases & phase diagrams
- Multiscale Materials Modelling: atoms – microstructure – properties