PAUL SCHERRER INSTITUT

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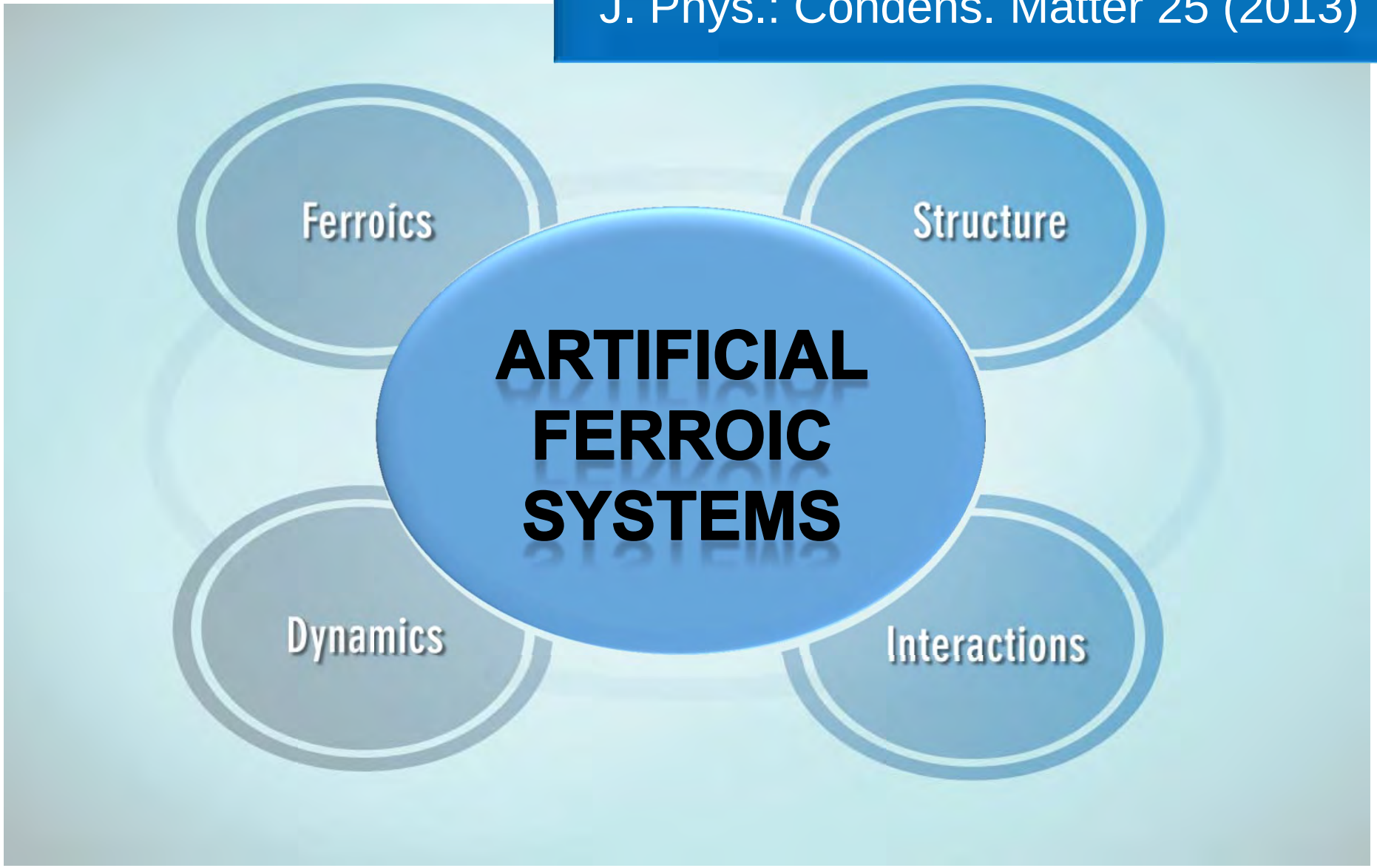
ETH zürich

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

Artificial Ferroic Systems: from hybrid systems to magnetic metamaterials

Topology Matters, July 25th-28th, 2017
JGU MITP/SPICE, Mainz, Germany

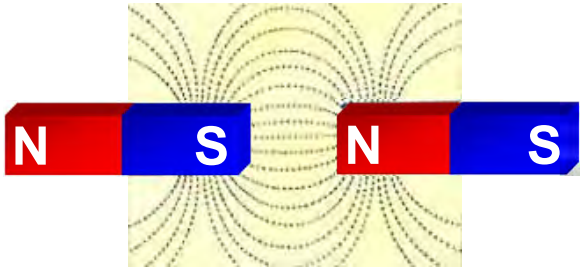
L J Heyderman & R L Stamps
J. Phys.: Condens. Matter 25 (2013)



Artificial Ferroic Systems

Hybrid or Composite Systems

Artificial Spin Systems



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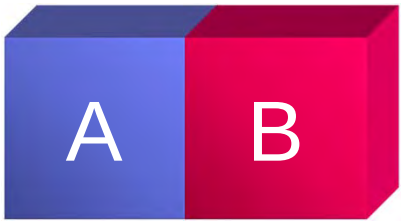
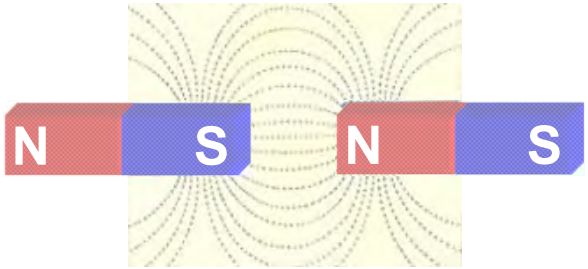
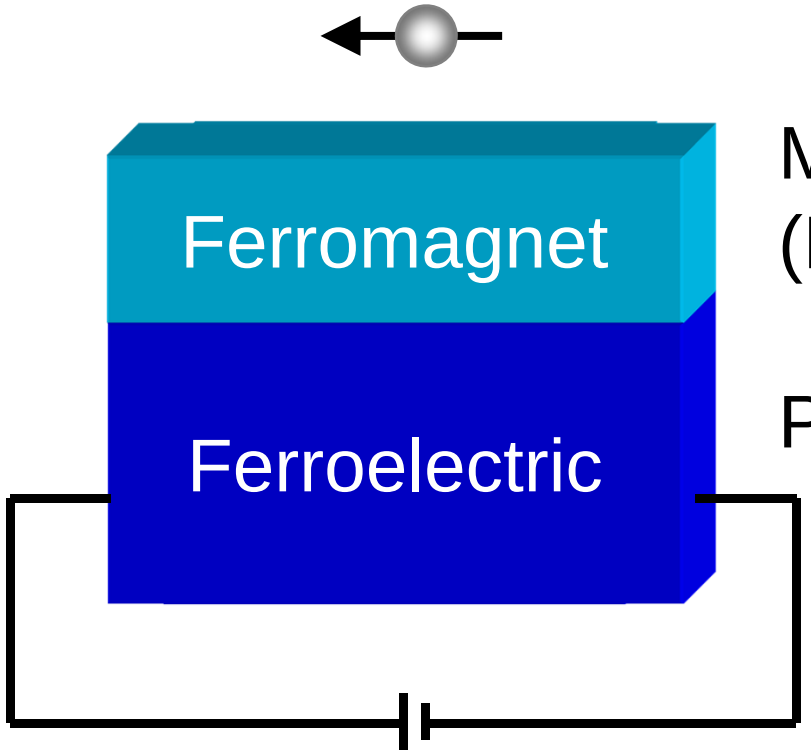




L J Heyderman & R L Stamps
J. Phys.: Condens. Matter (2013)

Multiferroic Composite/Artificial Multiferroic

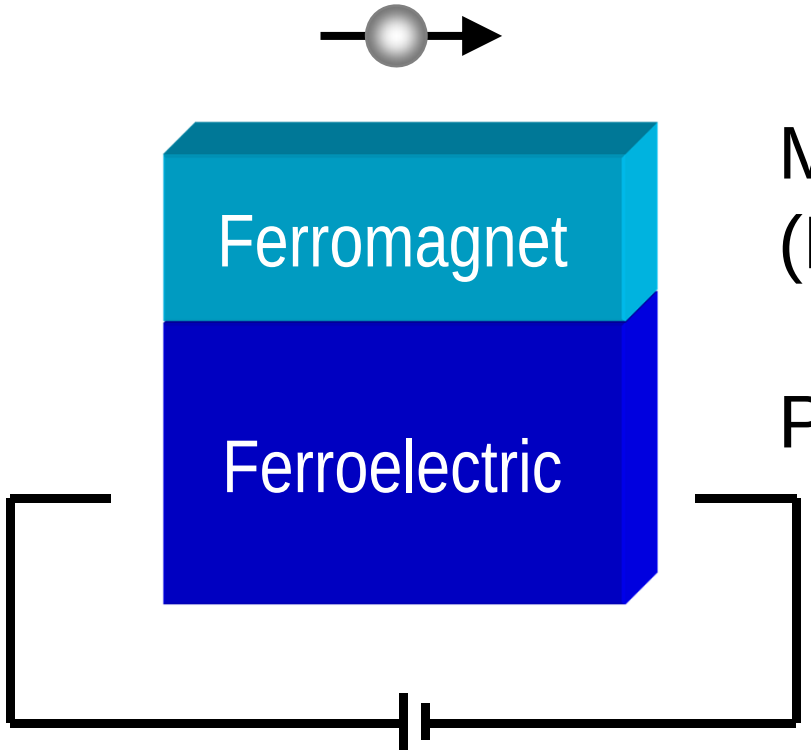


Magnetostrictive: $CoFe_2O_4$
(Ferrimagnetic Spinel)

Piezoelectric: $BaTiO_3$

→ Coupling via strain

Multiferroic Composite/Artificial Multiferroic



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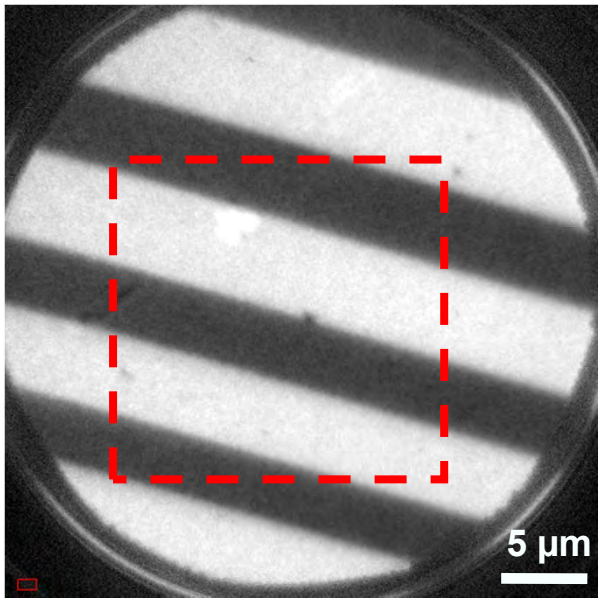
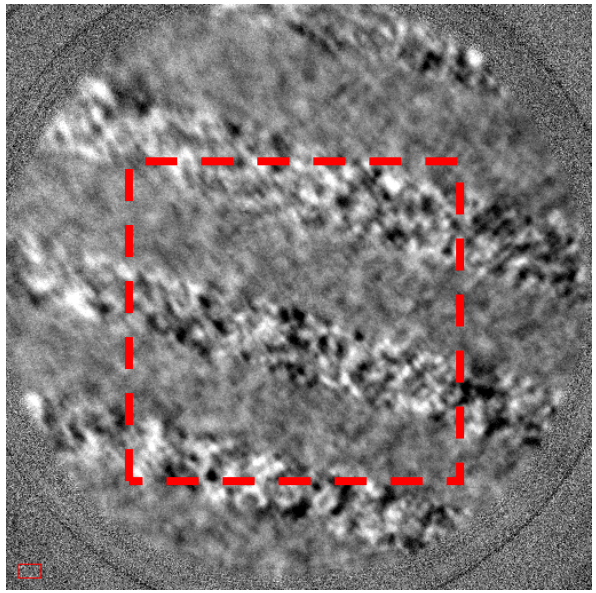
→ Coupling via strain

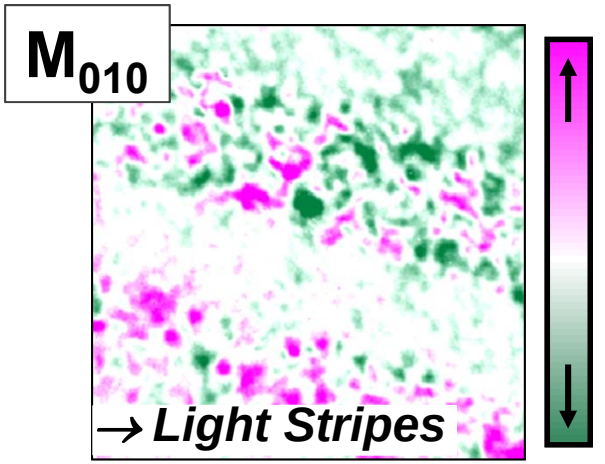
Strain and Magnetic Domains

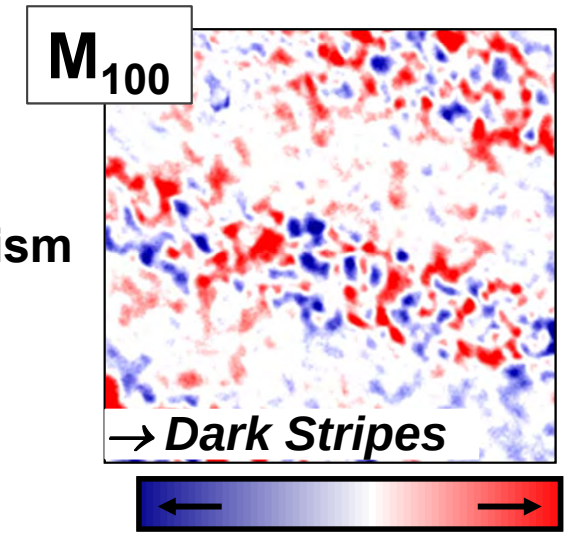


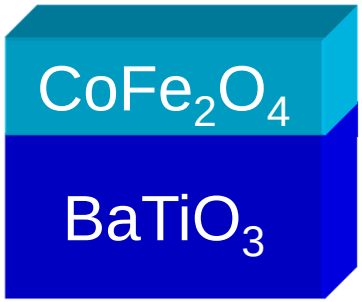
Fe X-ray Linear Dichroism



Fe X-ray Magnetic Circular Dichroism







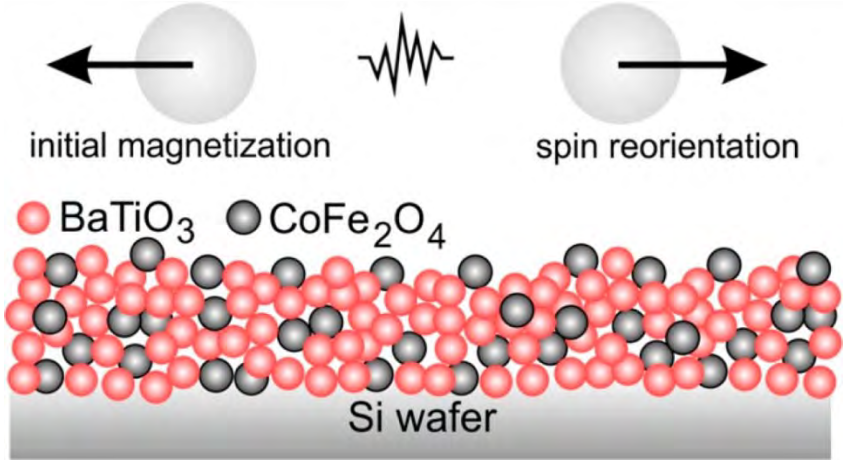
- Fe XLD: strain domains
- Fe XMCD: magnetic domains
- Substrate-induced strain modifies magnetic anisotropy

→ **Strain Imprints Magnetic States**

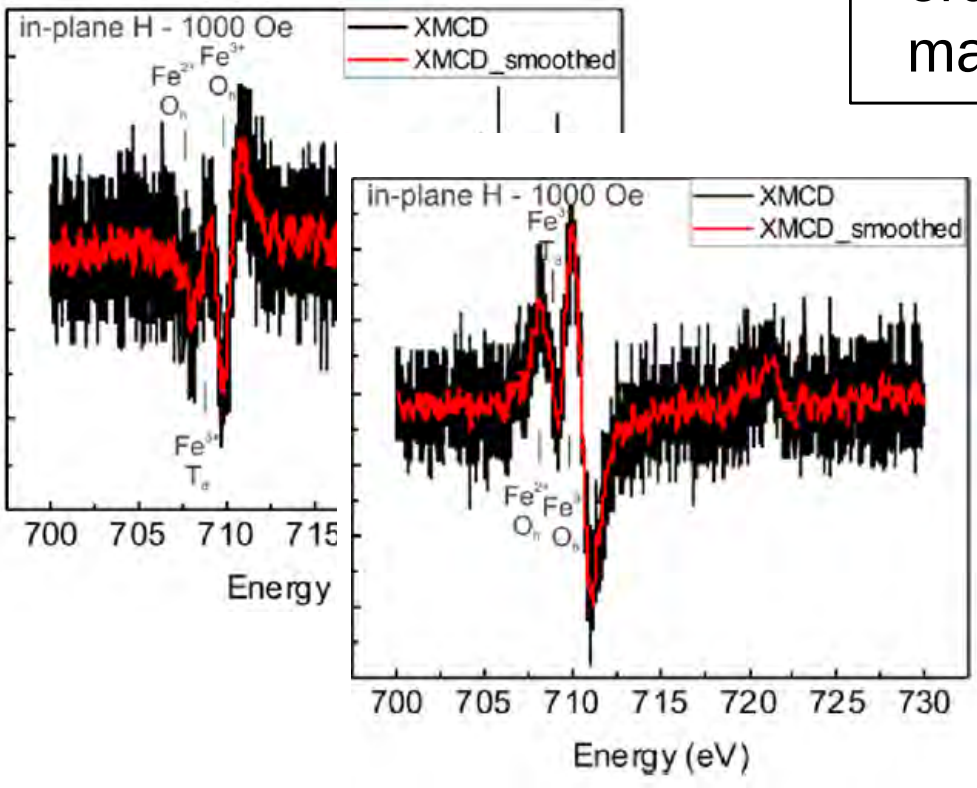
$M_{001} \sim 0$

RV Chopdekar et al. Phys. Rev. B (2012)

Multiferroic Composite Thin Films



- Spin-coated nanoparticle dispersions of $BaTiO_3$ & $CoFe_2O_4$
- Electrical & magnetic studies → both ferroelectric & ferromagnetic order
- Demonstrated coupling between orders with voltage control of magnetism

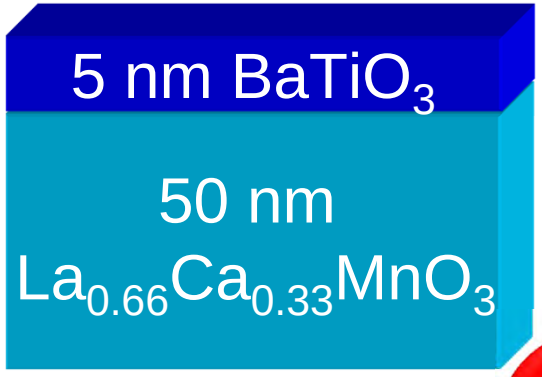


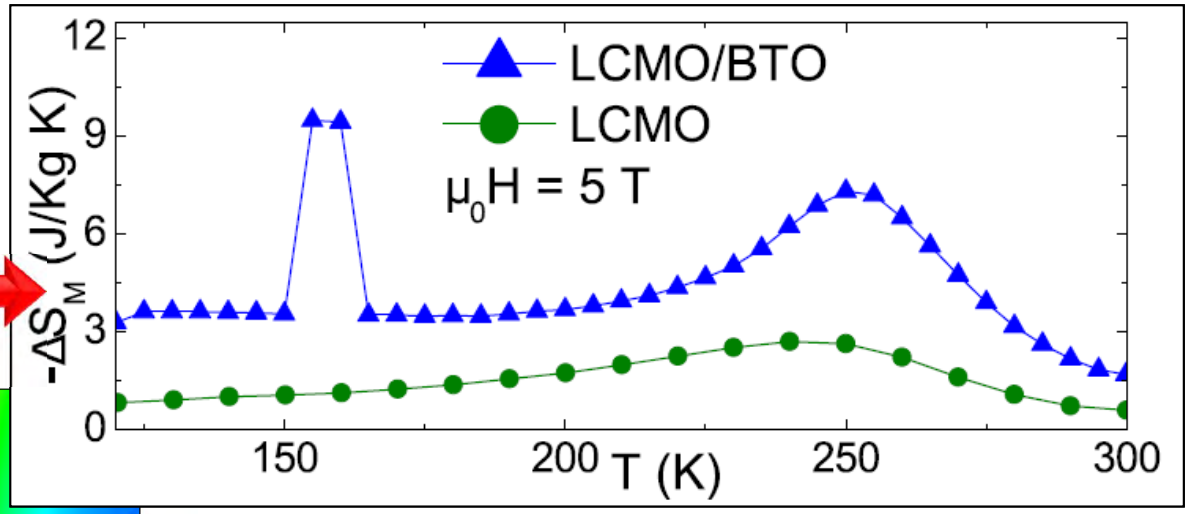
XMCD Spectra
$BaTiO_3$ – 5 wt % $CoFe_2O_4$ sample
magnetization reversal after 40 V DC electrical poling

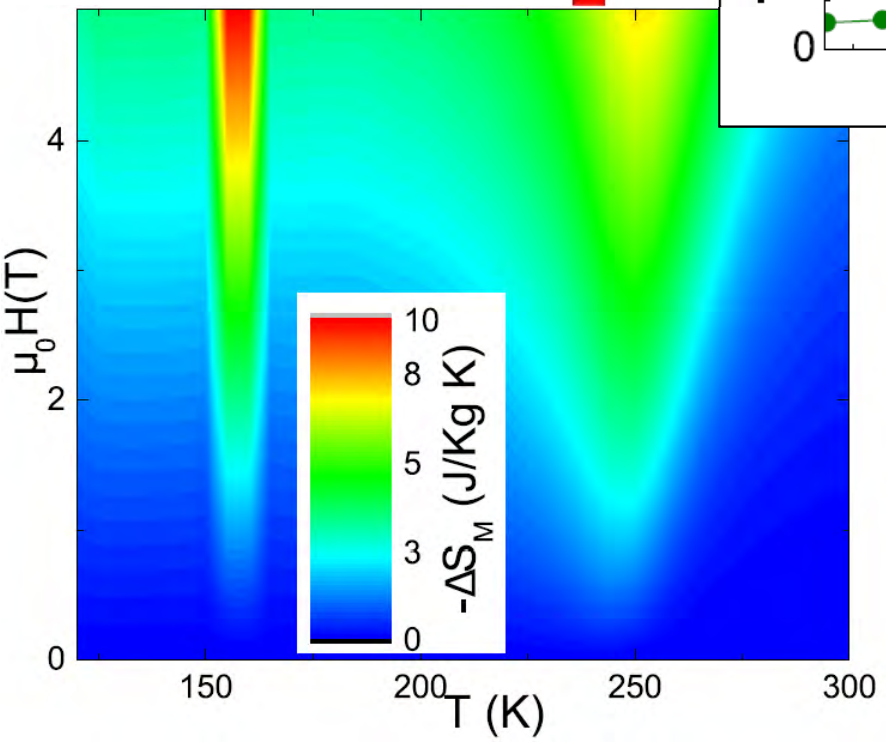
D. Erdem, N.S. Bingham, F.J. Heiligtag, N. Pilet, P. Warnicke, C.A.F. Vaz, Y. Shi, M. Buzzi, J.L.M. Rupp, L.J. Heyderman, M. Niederberger, ACS Nano (2016)

D. Erdem et al., Adv Func Matls (2015)

Strain-induced Enhancement of Magnetocaloric Effect



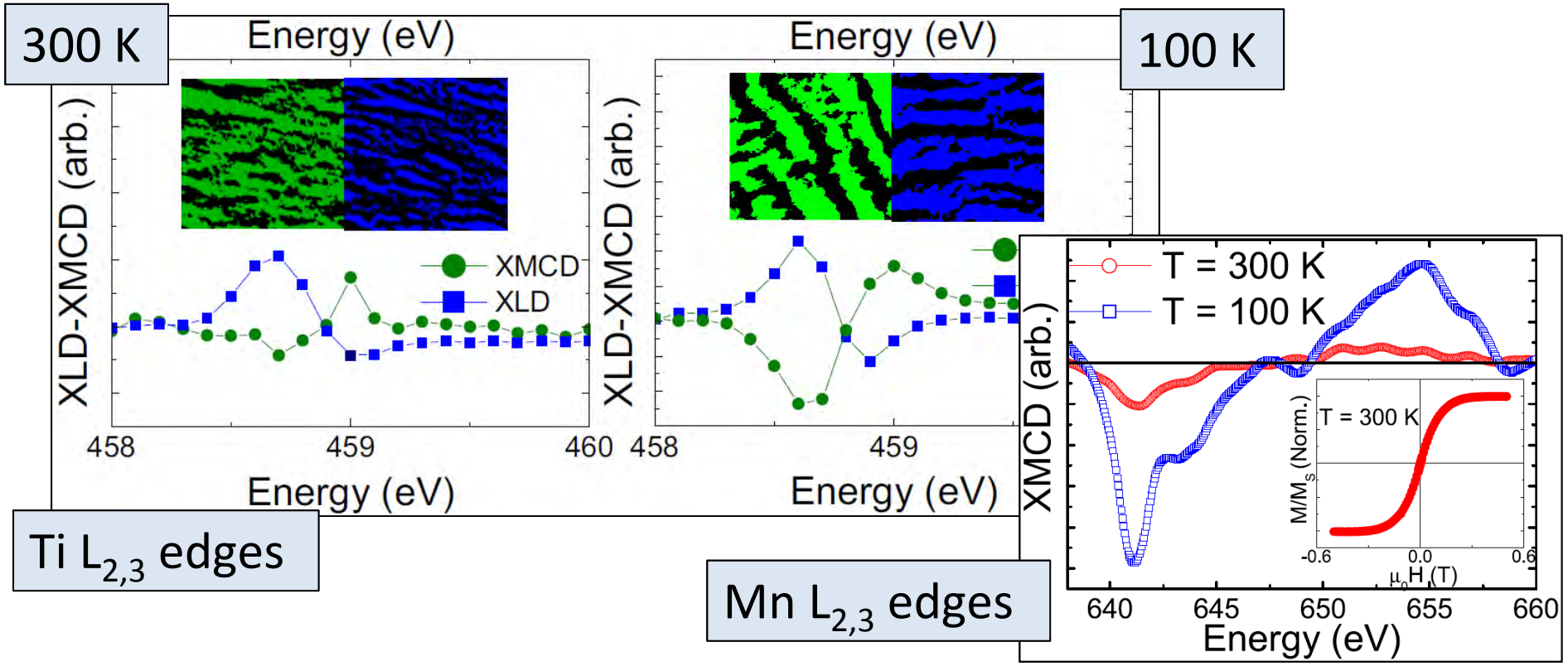




- Large MCE at 150 K
- Enhancement of MCE at 250 K
- Due to structural phase transitions in BTO:
  - orthorhombic-rhombohedral (150 K)
  - orthorhombic-tetragonal (250 K)

NS Bingham, AK Suszka, CAF Vaz, H Kim, and LJ Heyderman PRB (2017)

Room Temperature Ferromagnetism



X-ray absorption spectroscopy measurements:

→ Room temperature ferromagnetism at interface due to electronic reconfiguration of LCMO and BTO

→ Indication that charge carrier transfer results from hybridization of $Mn^{3+/4+}$ and Ti^{4+} to give $Mn^{2+/3+}$ and Ti^{3+}

NS Bingham, AK Suszka, CAF Vaz, H Kim, and LJ Heyderman PRB (2017)

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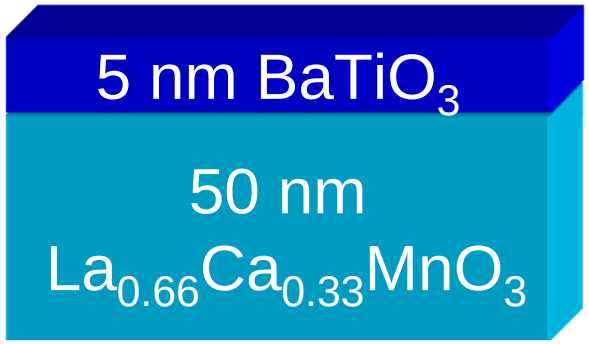
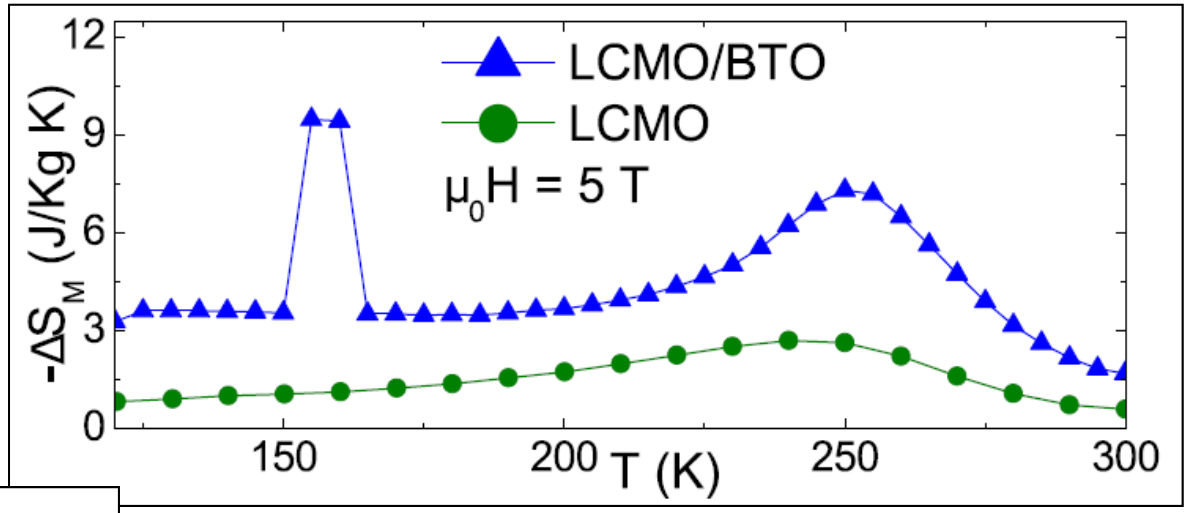
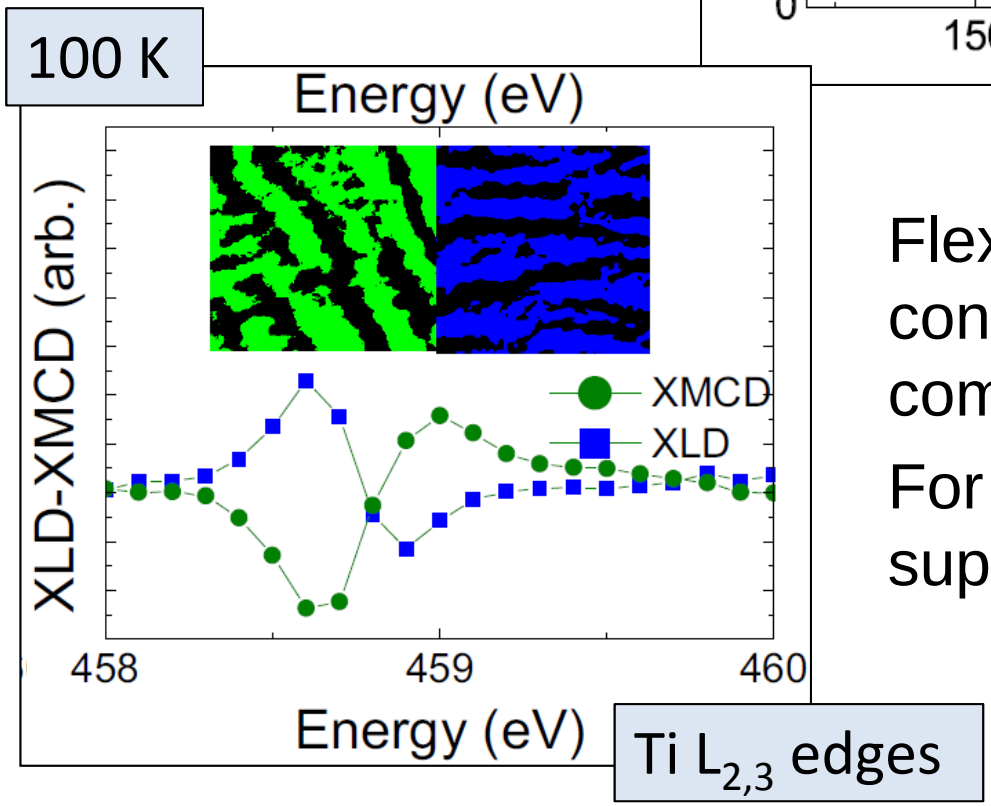






Ti $L_{2,3}$ edges

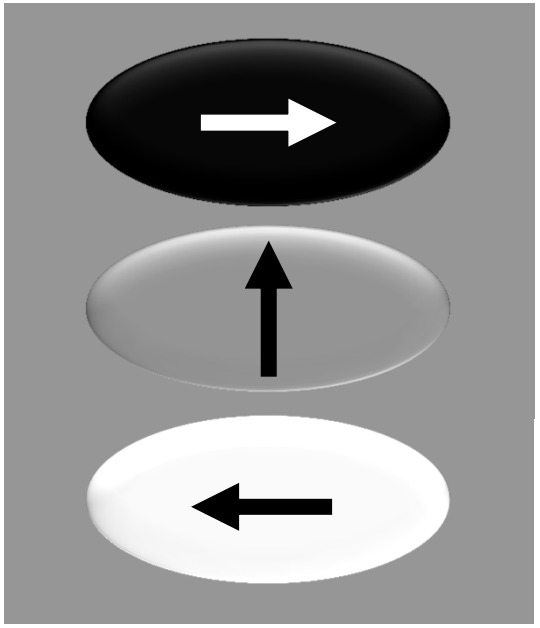
Flexible approach to enhance & control further phenomena in complex oxide heterostructures

For example: superconductivity & multiferroicity

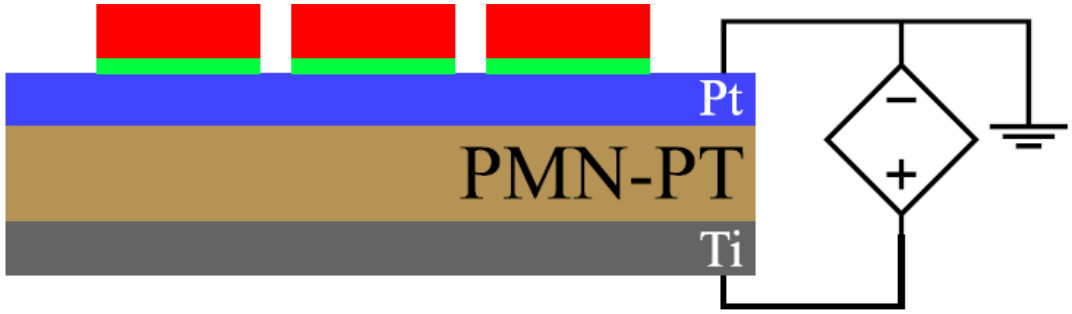
NS Bingham, AK Suszka, CAF Vaz, H Kim, and LJ Heyderman PRB (2017)

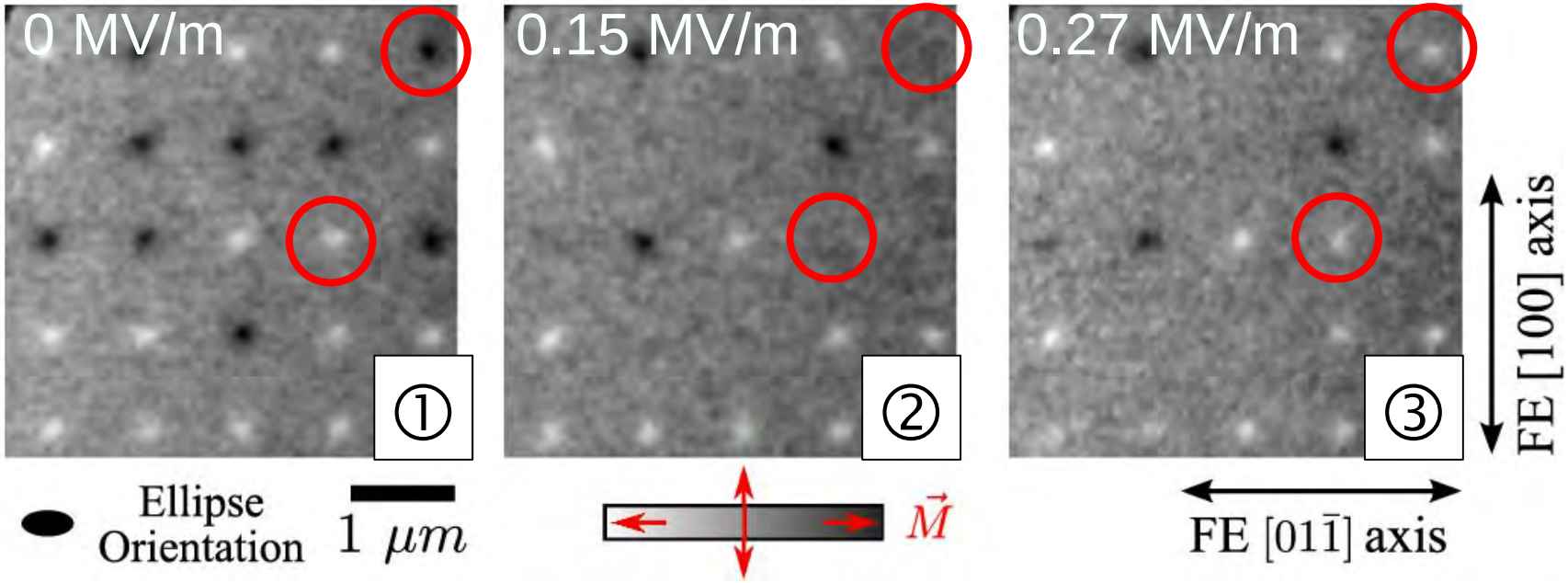
Manipulation via Electric Fields

M. Buzzi, R.V. Chopdekar, J. L. Hockel,
A. Bur, T. Wu, N. Pilet, P. Warnicke, G. P. Carman
L. J. Heyderman, and F. Nolting PRL 2013



Nickel Nanoislands

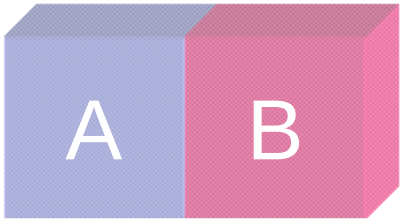


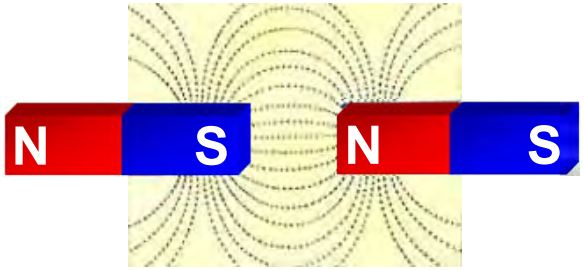


Artificial Ferroic Systems

Hybrid or Composite Systems

Artificial Spin Systems





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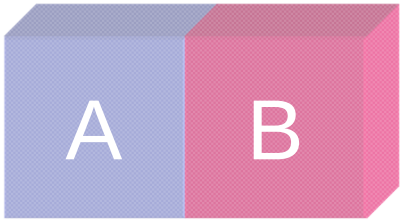
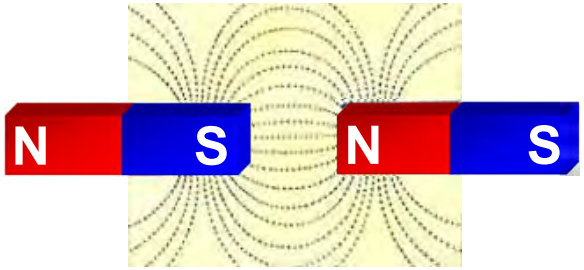


Artificial Spin Ice



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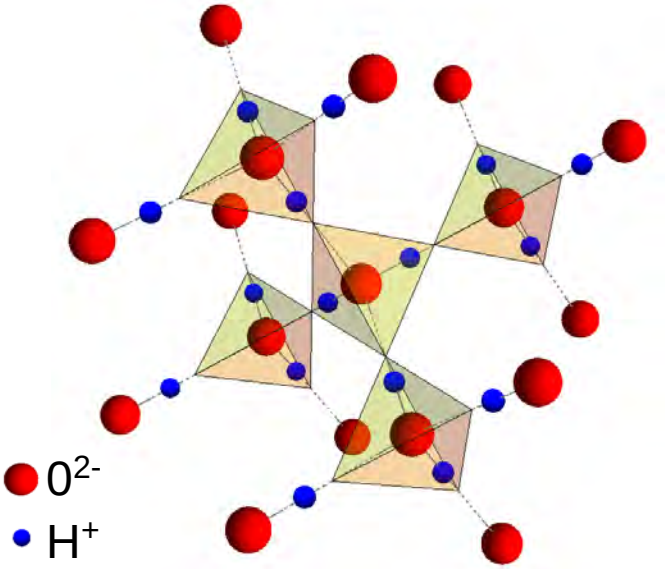
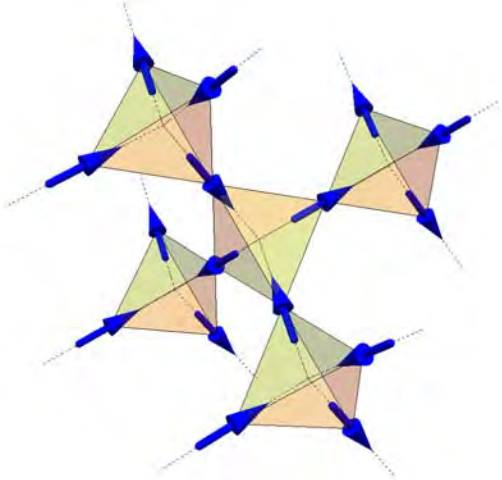
From Water Ice to Artificial Spin Ice

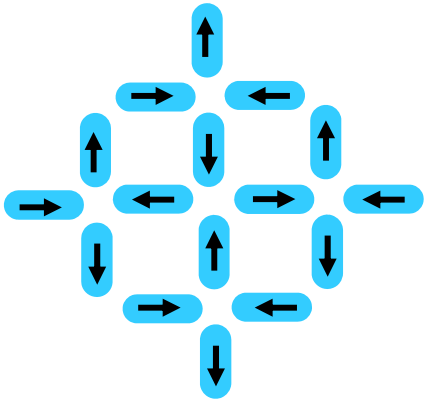


Water Ice



Spin Ice

MJ Harris *et al.*
PRL (1997)



Artificial Spin Ice

RF Wang *et al.*
Nature (2006)

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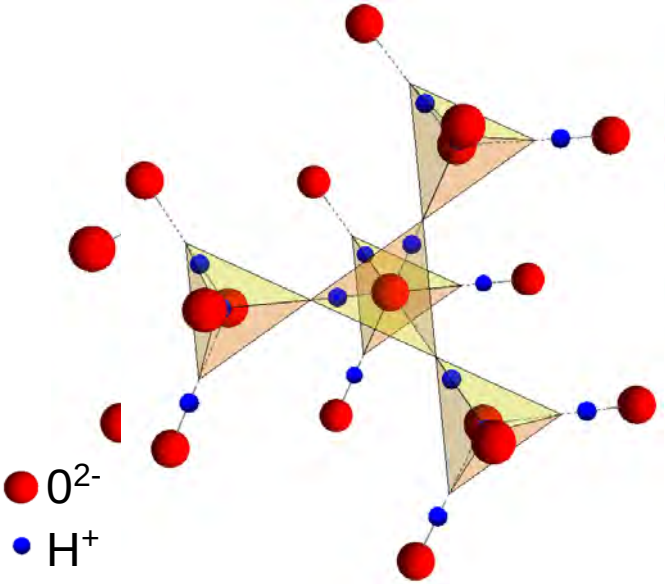

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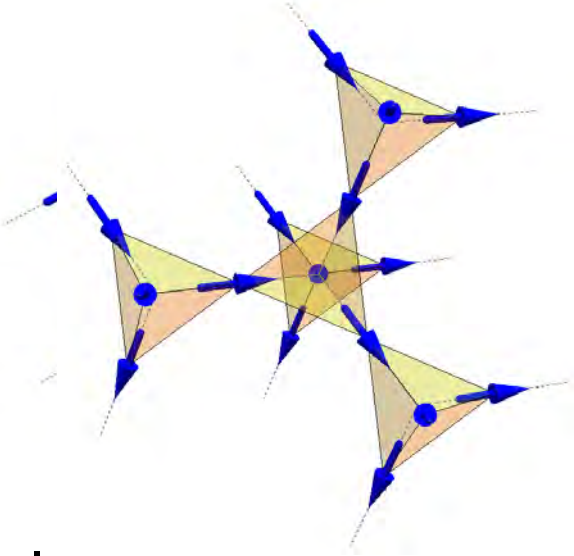

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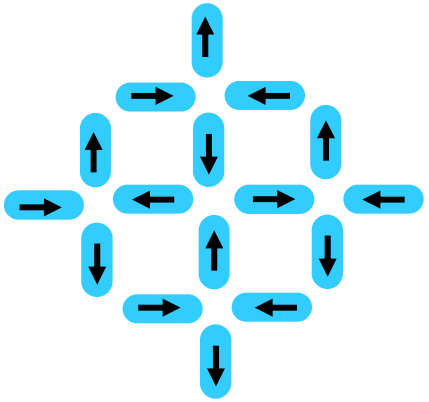

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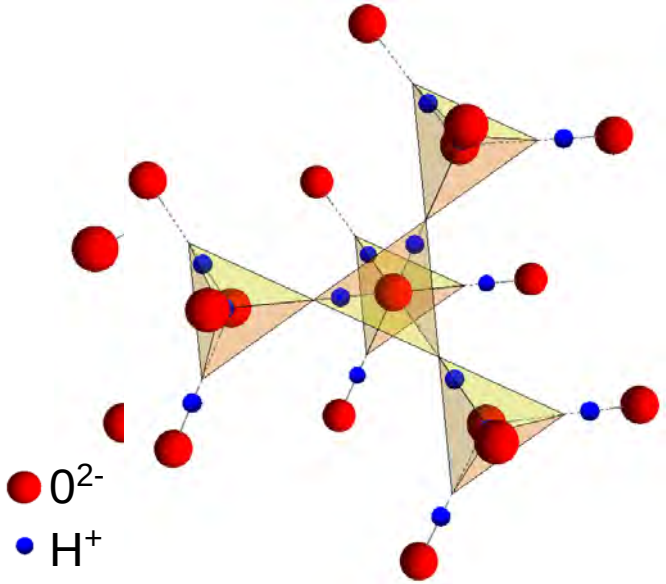
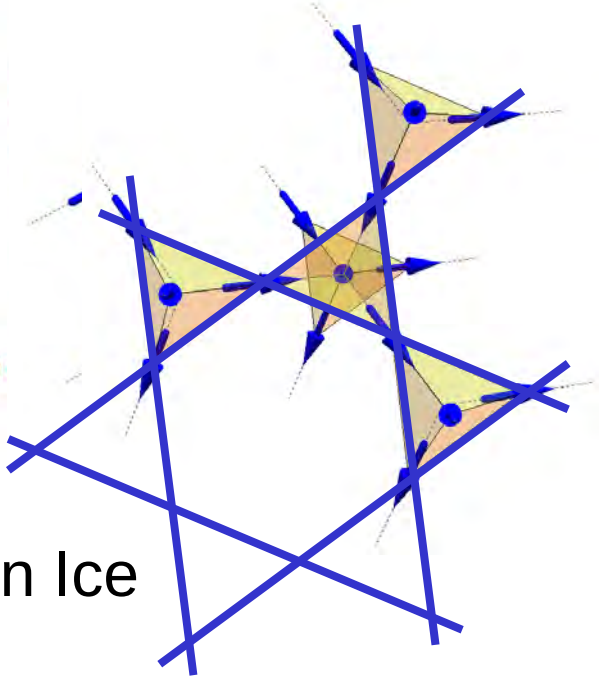


Water Ice



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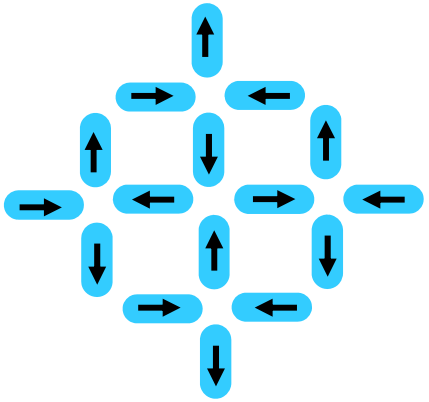
PRL (1997)



Artificial Spin Ice

RF Wang *et al.*
Nature (2006)

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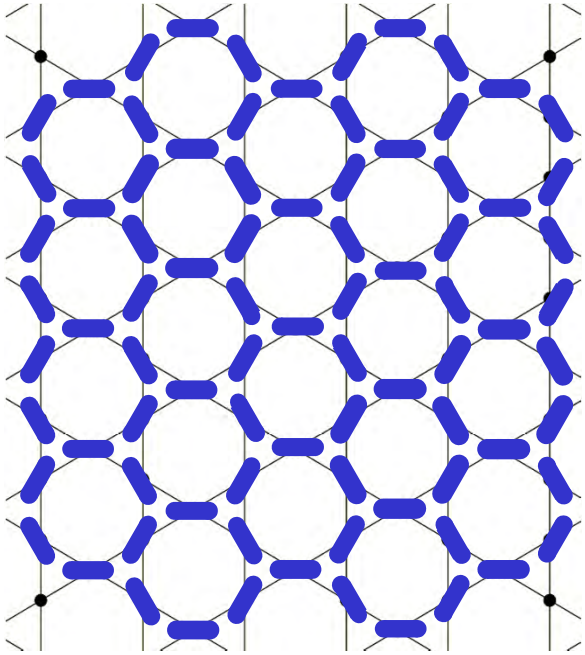
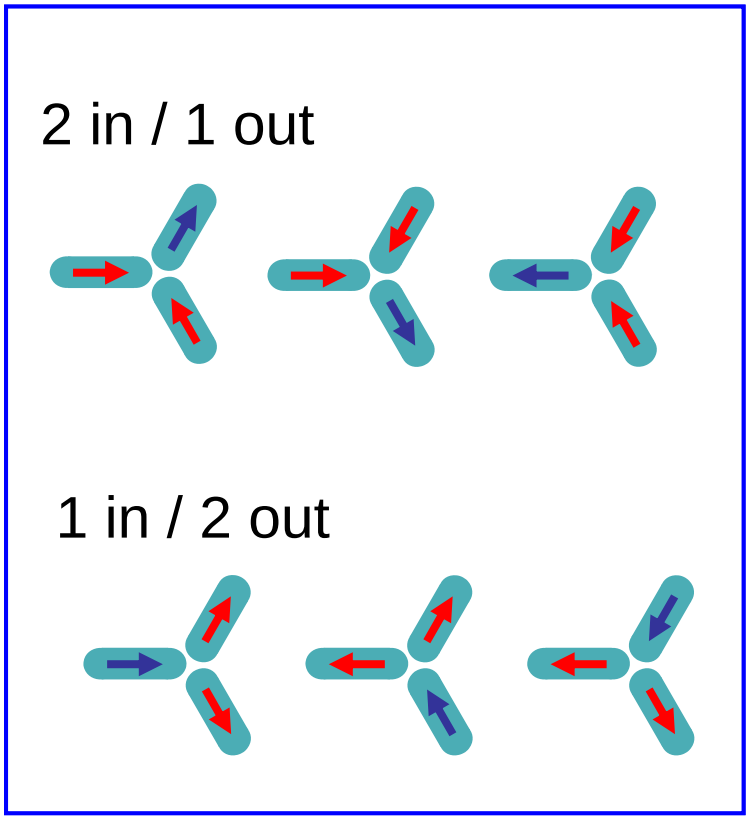
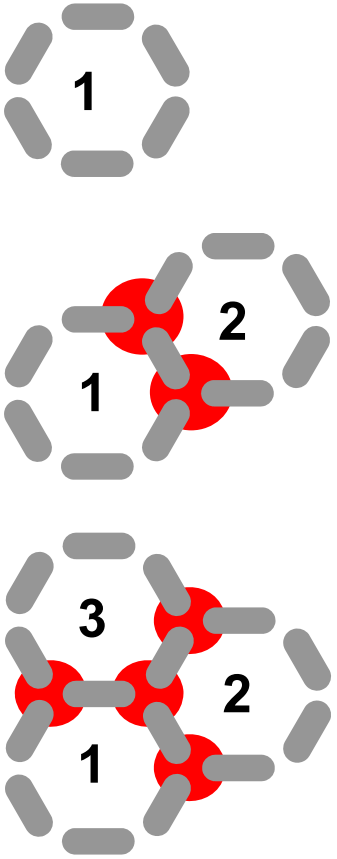
Artificial Kagome Spin Ice



Kagome lattice



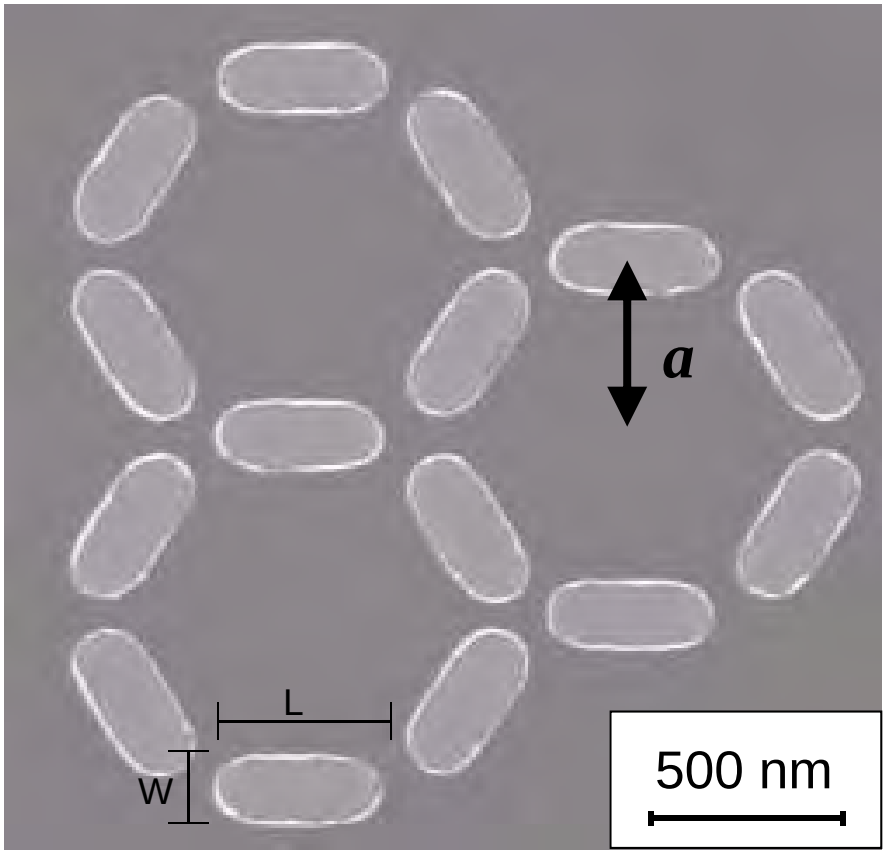
Ice rule



Building Blocks

E. Mengotti et al. Phys. Rev. B (2008)

Fabrication



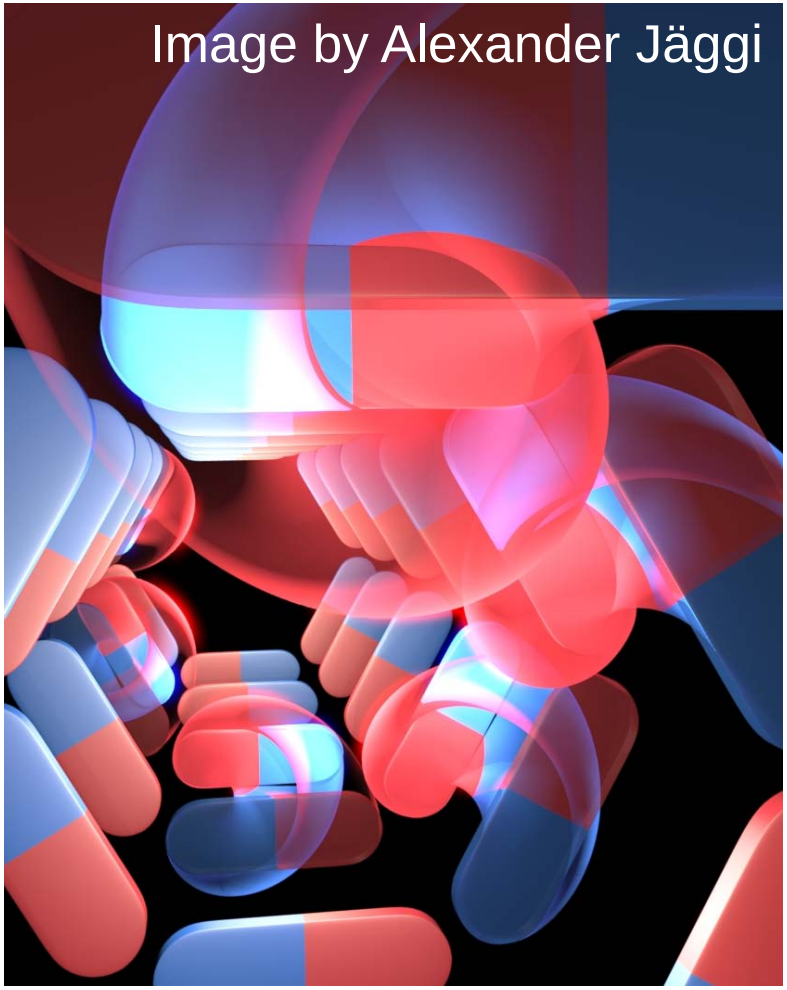
Electron Beam Lithography

- Elongated ferromagnetic islands: e.g. Permalloy or Cobalt
- Aluminum capping layer
- Vary island size & lattice parameter

Width	= 170 nm
Length	= 470 nm
Smallest *a*	= 500 nm
Thickness	= 3-40 nm

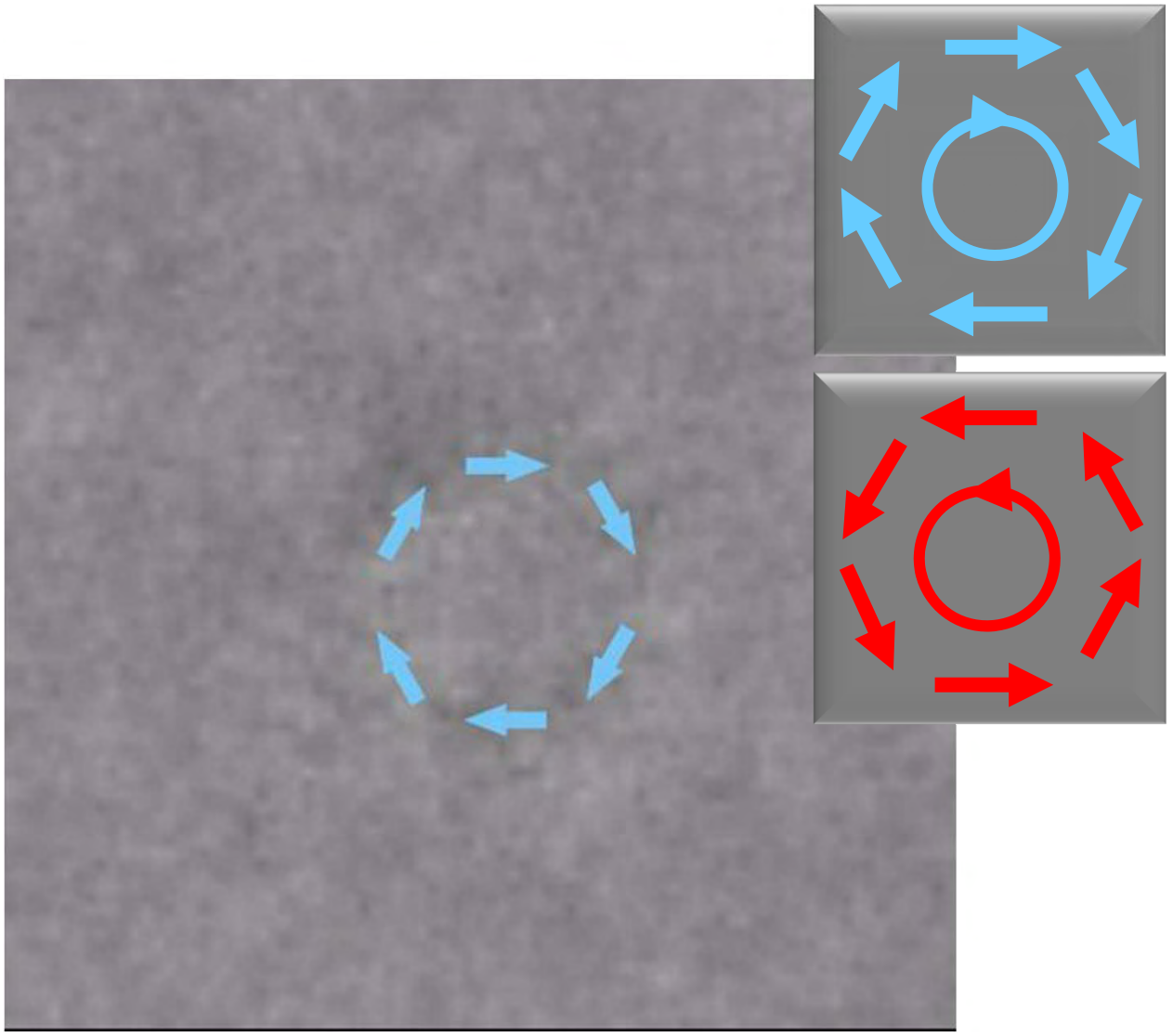
E. Mengotti et al. Phys. Rev. B (2008)
A. Trabesinger, News & Views, Nature Physics (2008)

Thermal Behaviour



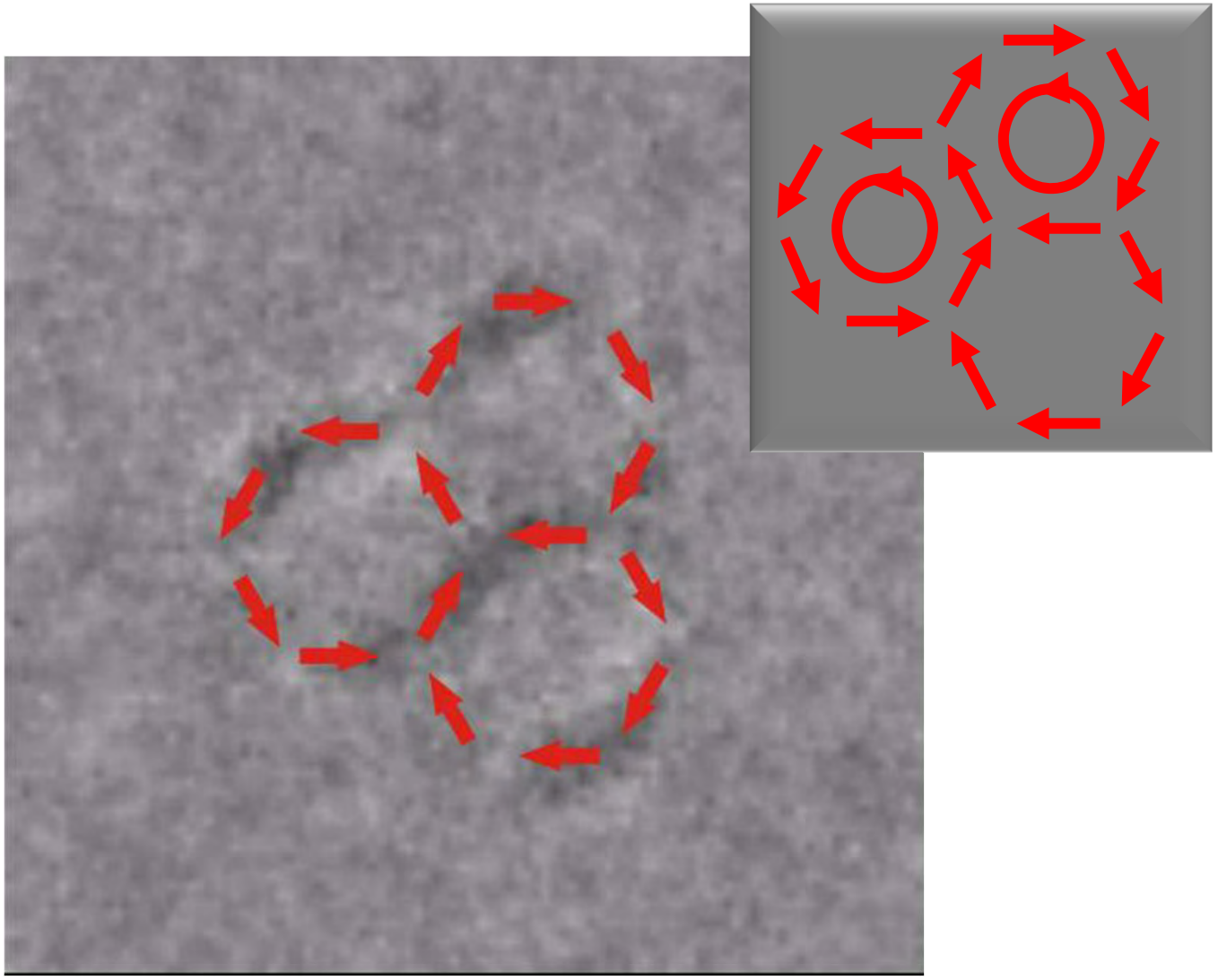
L. Heyderman, *News & Views*,
Nature Nanotechnology (2013)

Temporal Behaviour



Photoemission Electron Microscopy
Supplementary Movie from A. Farhan et al. Nature Physics (2013)

Temporal Behaviour



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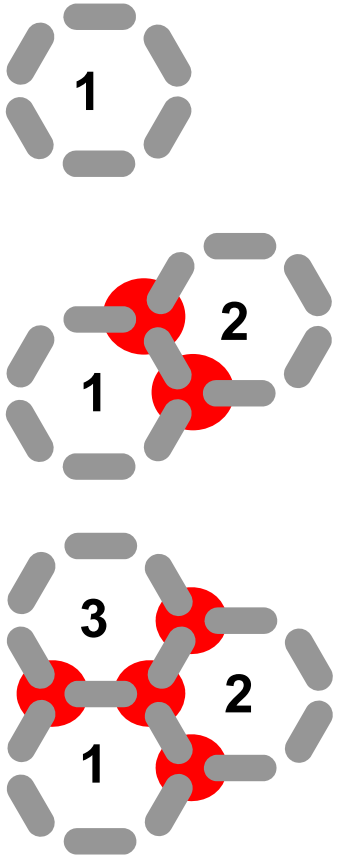
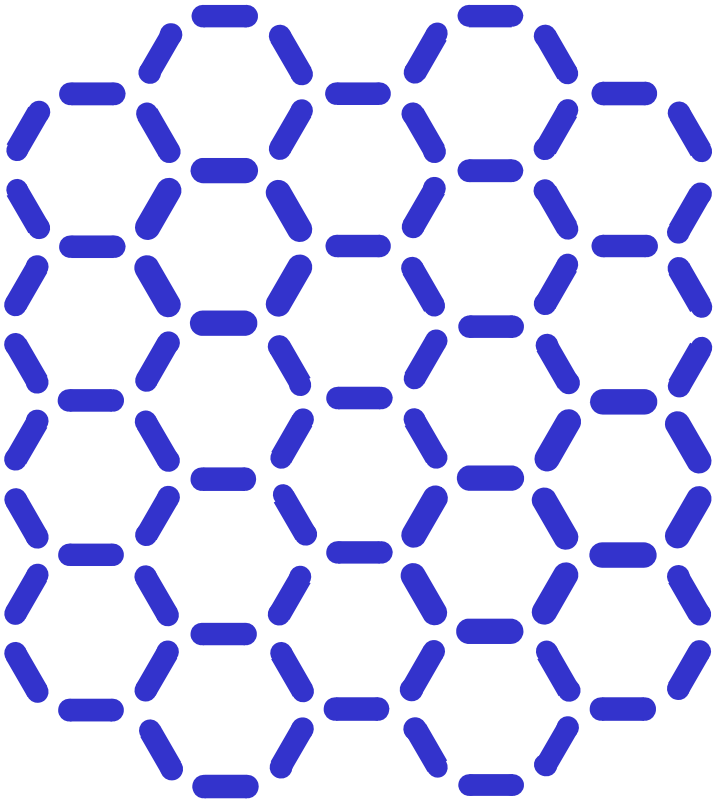
Artificial Kagome Spin Ice

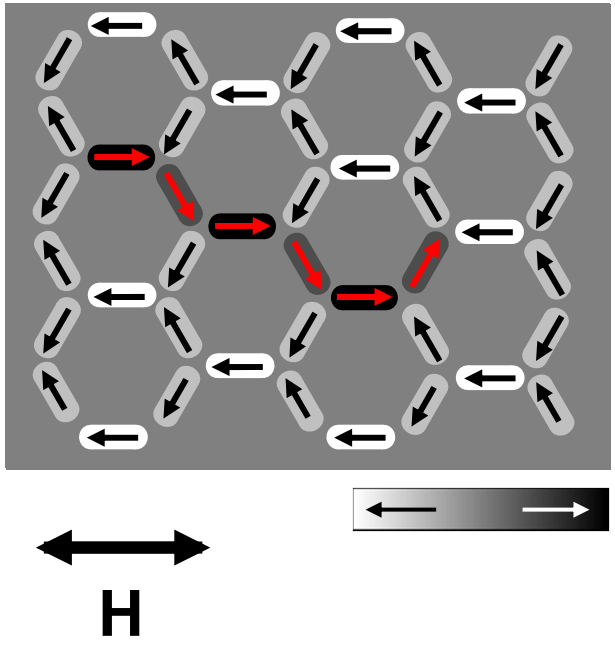


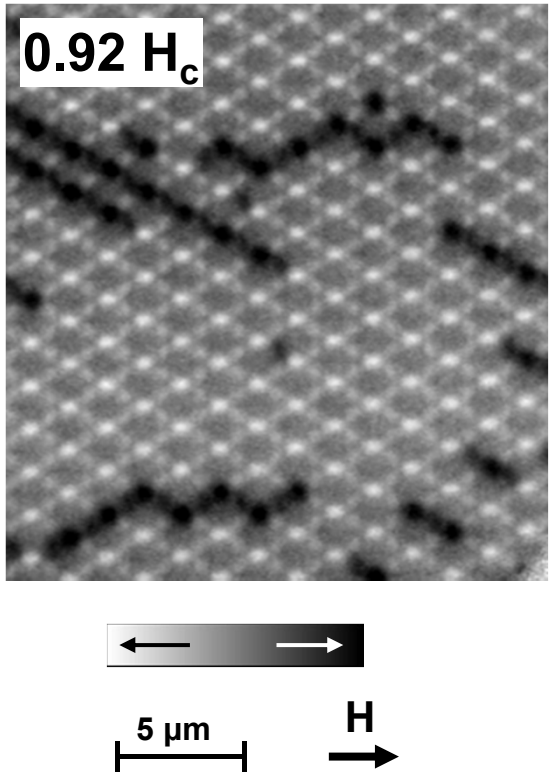


Building Blocks

Extended Arrays

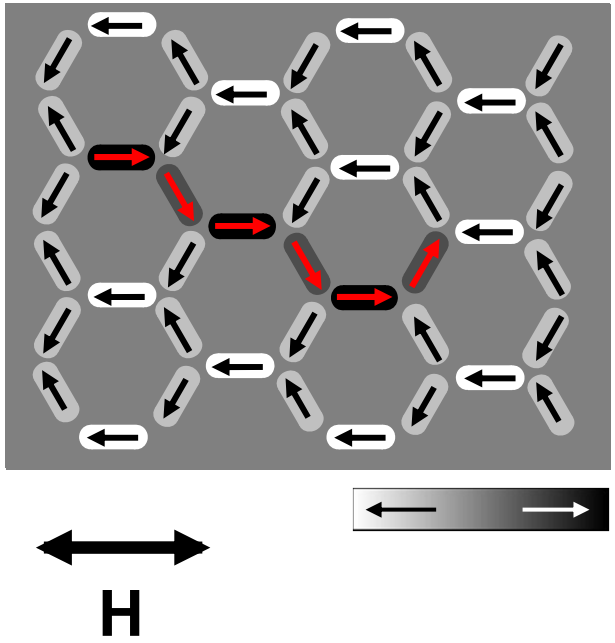
Emergent Magnetic Monopoles & Dirac Strings

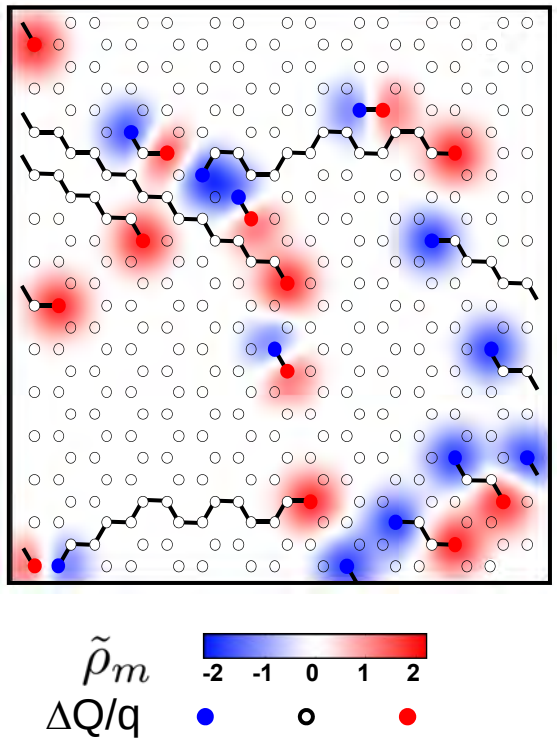




E. Mengotti, L. J. Heyderman, A. Fraile Rodríguez, F. Nolting, R.V. Hügli, H. B. Braun
Nature Physics (2011)

Emergent Magnetic Monopoles & Dirac Strings





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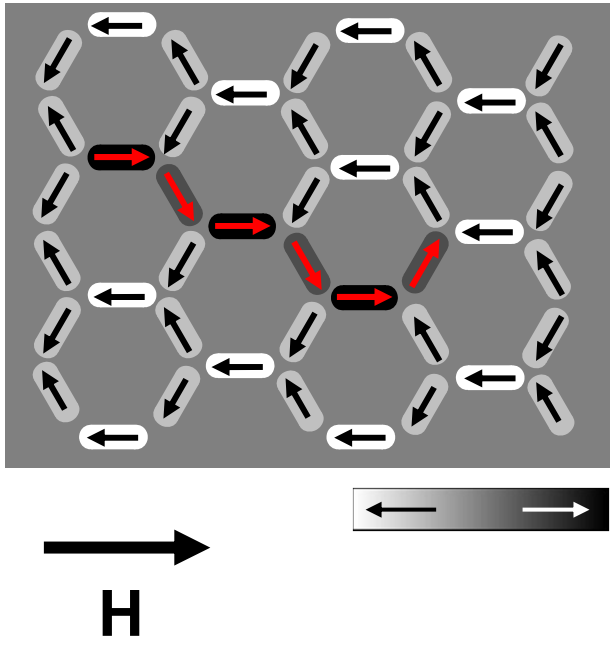
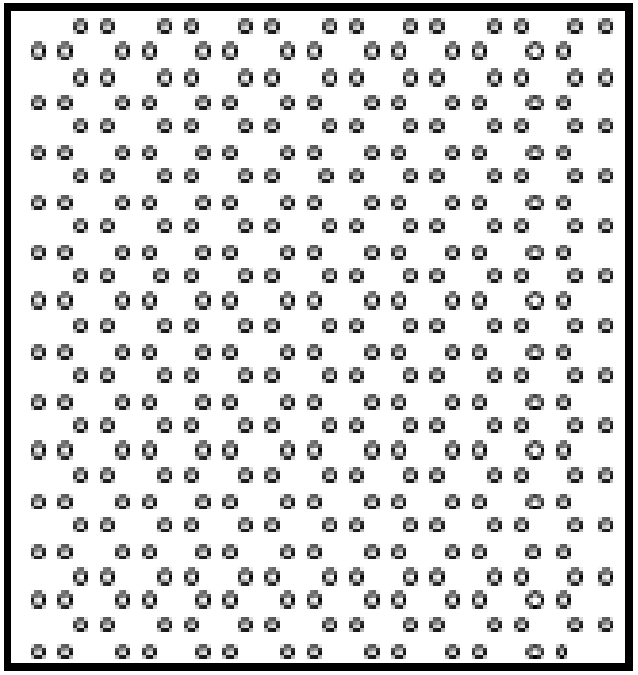
Nature Physics (2011)

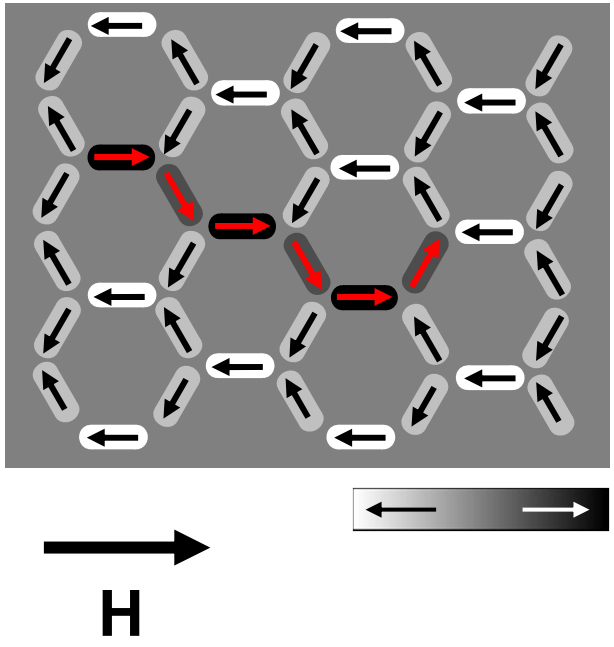
Emergent Magnetic Monopoles & Dirac Strings

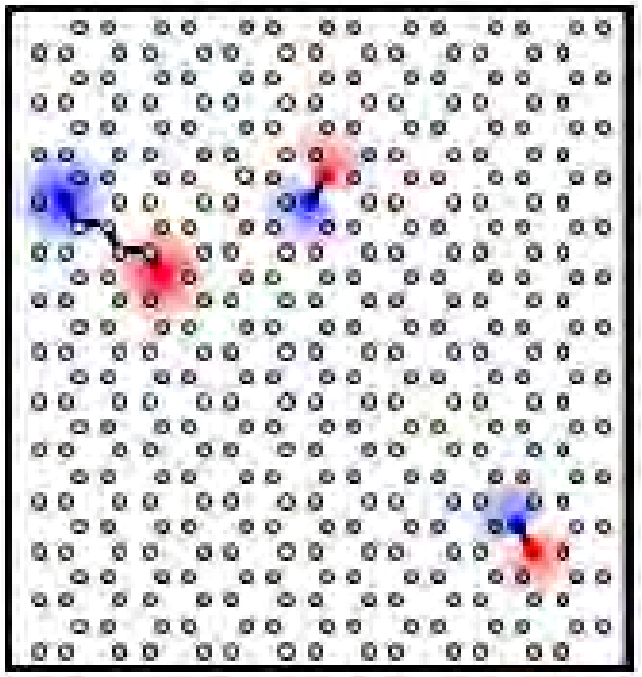




E. Mengotti, L. J. Heyderman, A. Fraile Rodríguez, F. Nolting, R.V. Hügli, H. B. Braun
Nature Physics (2011)

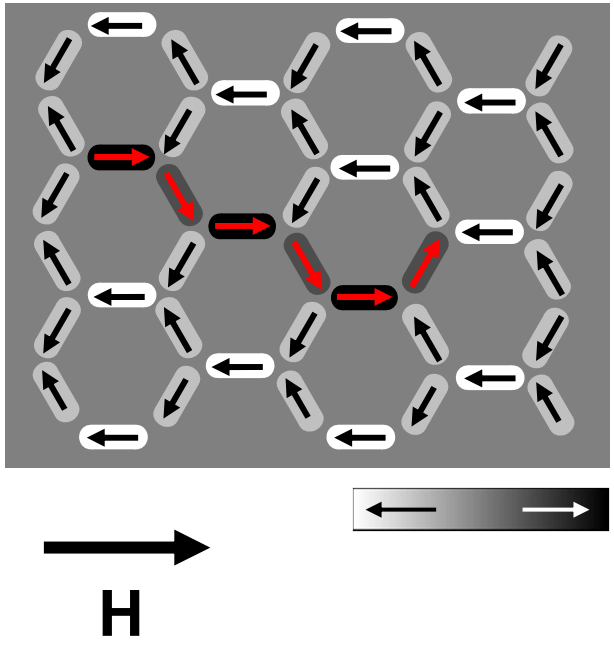
Emergent Magnetic Monopoles & Dirac Strings

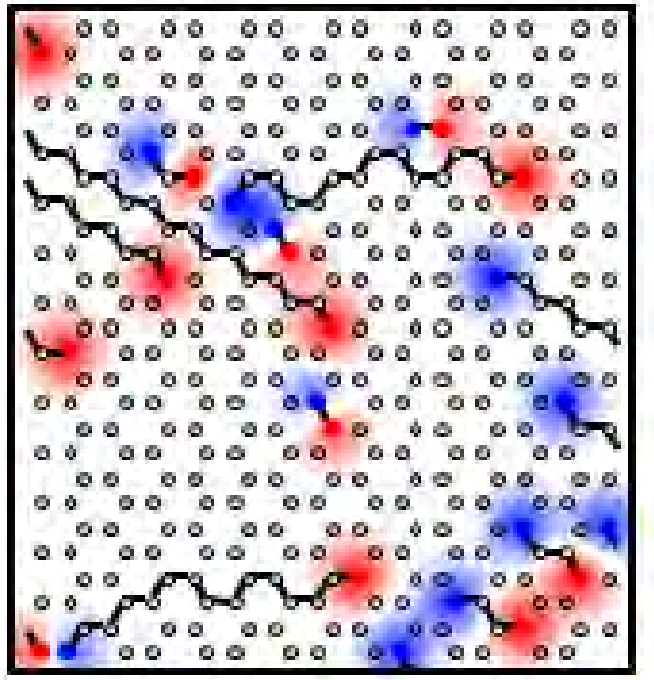




E. Mengotti, L. J. Heyderman, A. Fraile Rodríguez, F. Nolting, R.V. Hügli, H. B. Braun
Nature Physics (2011)

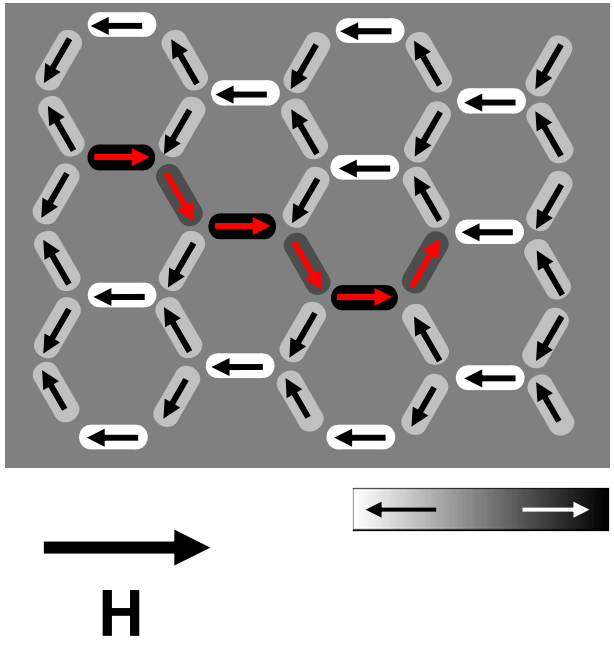
Emergent Magnetic Monopoles & Dirac Strings

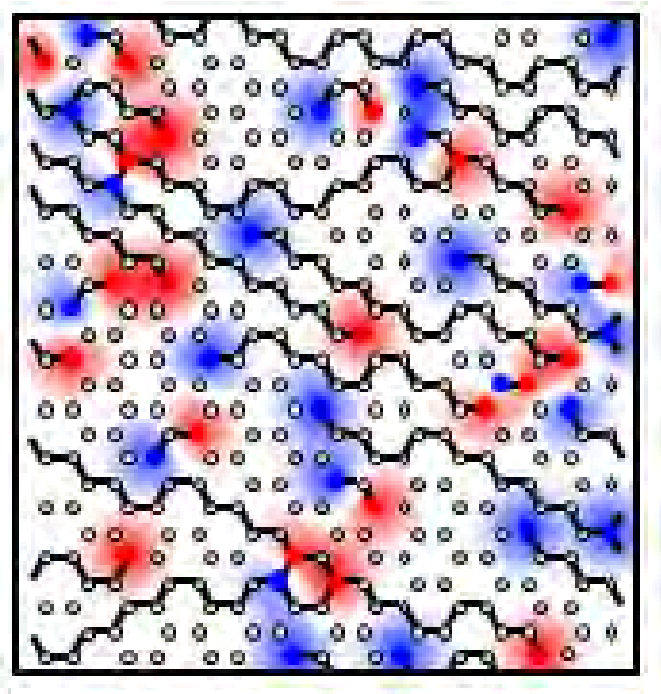




E. Mengotti, L. J. Heyderman, A. Fraile Rodríguez, F. Nolting, R.V. Hügli, H. B. Braun
Nature Physics (2011)

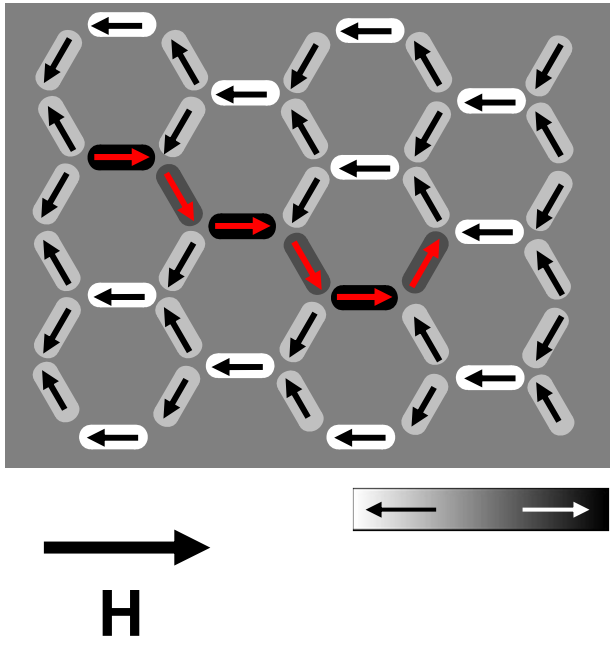
Emergent Magnetic Monopoles & Dirac Strings

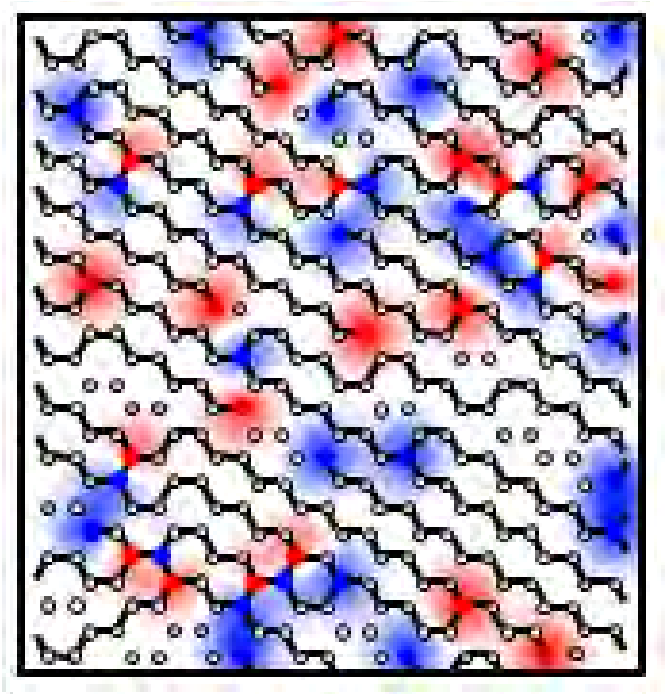




E. Mengotti, L. J. Heyderman, A. Fraile Rodríguez, F. Nolting, R.V. Hügli, H. B. Braun
Nature Physics (2011)

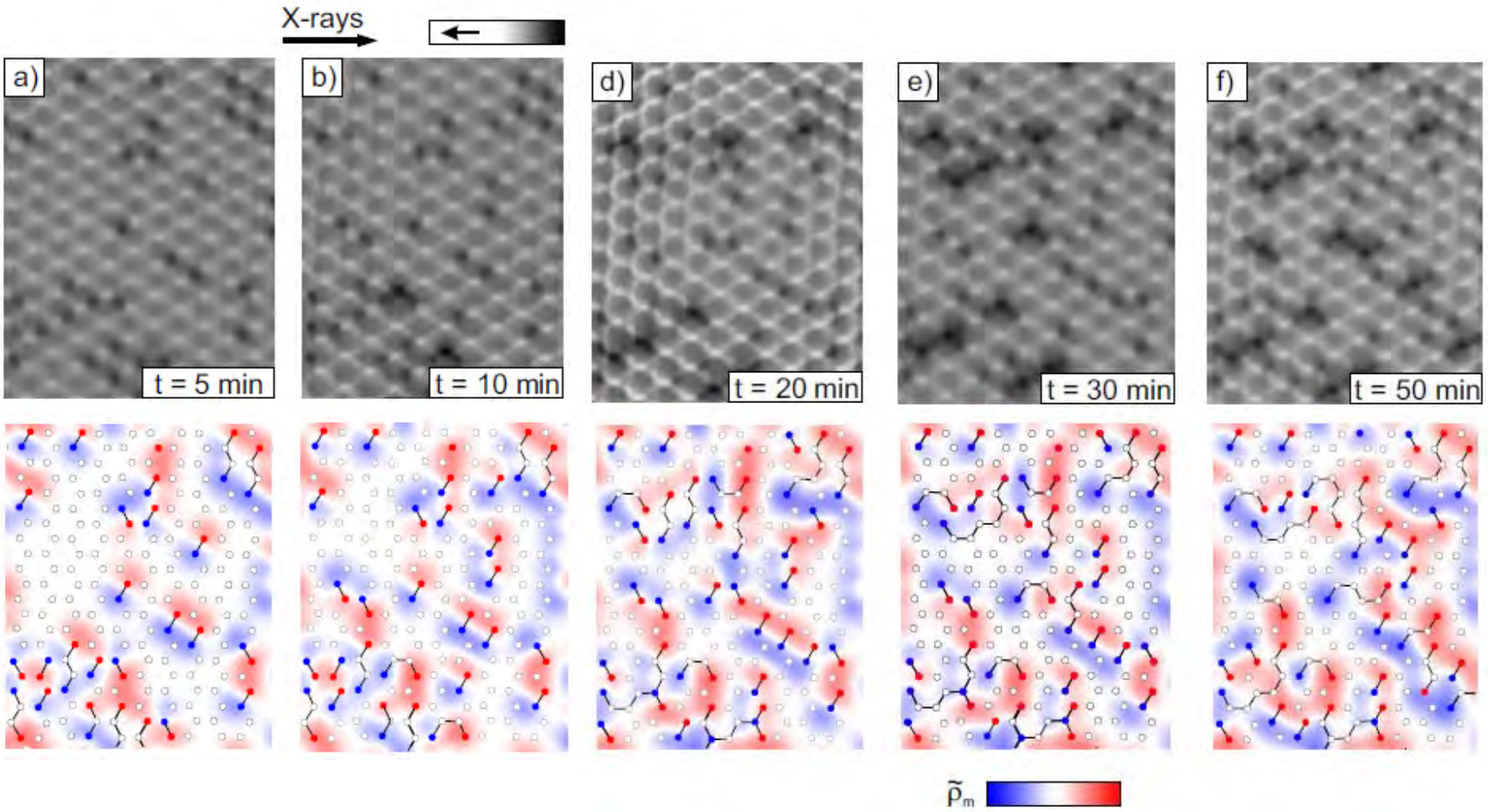
Emergent Magnetic Monopoles & Dirac Strings





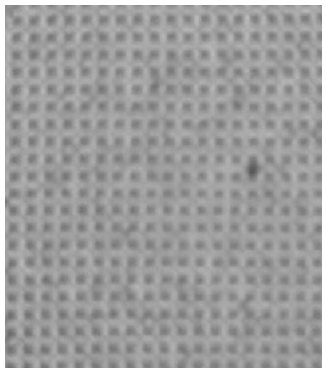
E. Mengotti, L. J. Heyderman, A. Fraile Rodríguez, F. Nolting, R.V. Hügli, H. B. Braun
Nature Physics (2011)

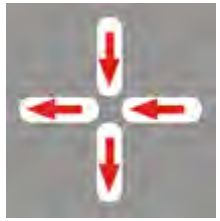
Thermally Active Artificial Kagome Ice



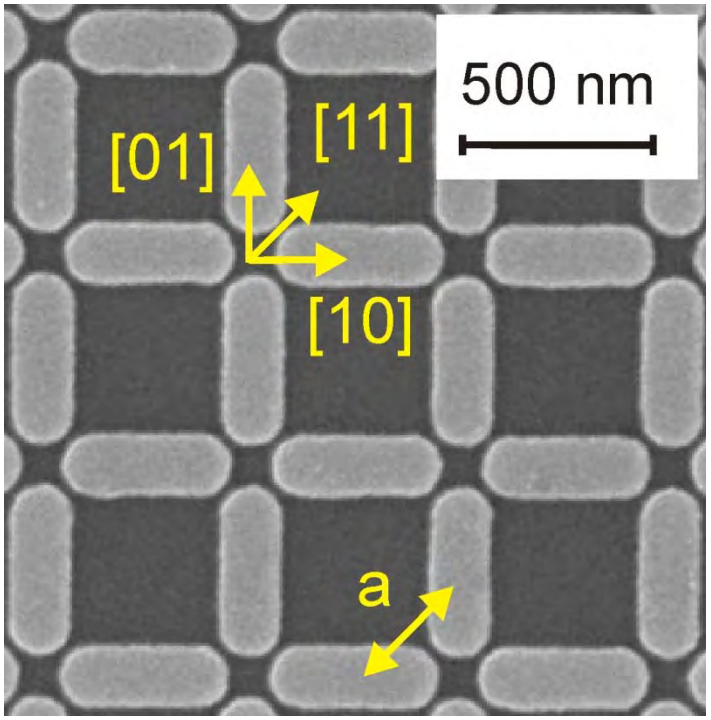
A Farhan, PM Derlet, L Anghinolfi, A Kleibert and LJ Heyderman PRB Accepted (2017)

Thermal Artificial Square Ice





H_A

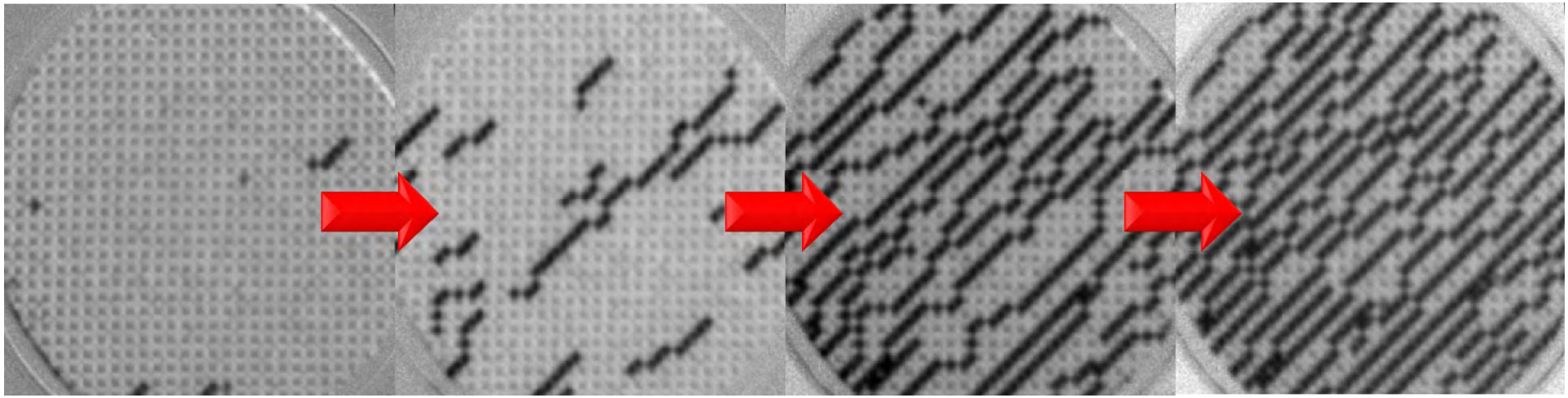


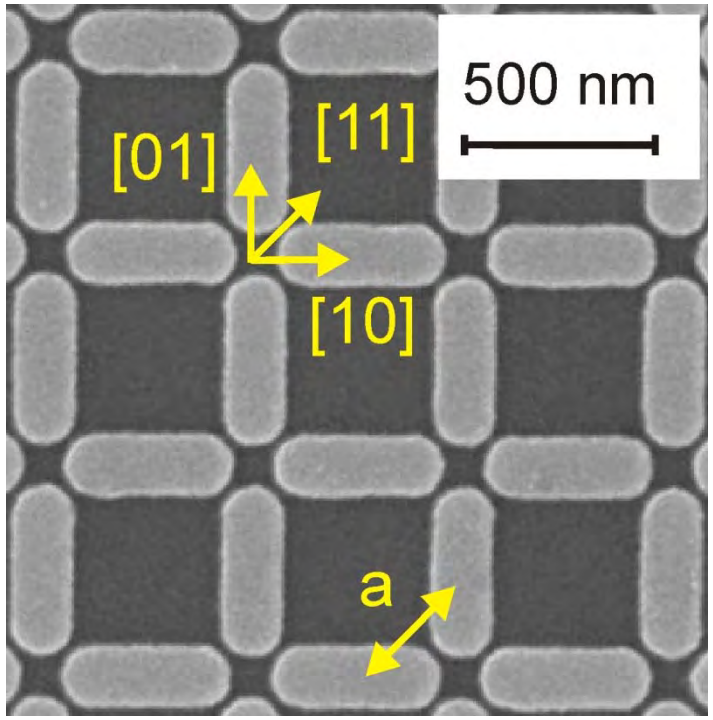
"String Regime"

Farhan et al. PRL (2013)
V. Kapaklis et al. Nature Nanotech. (2014)

Thermal Artificial Square Ice

Field of View 20 μm



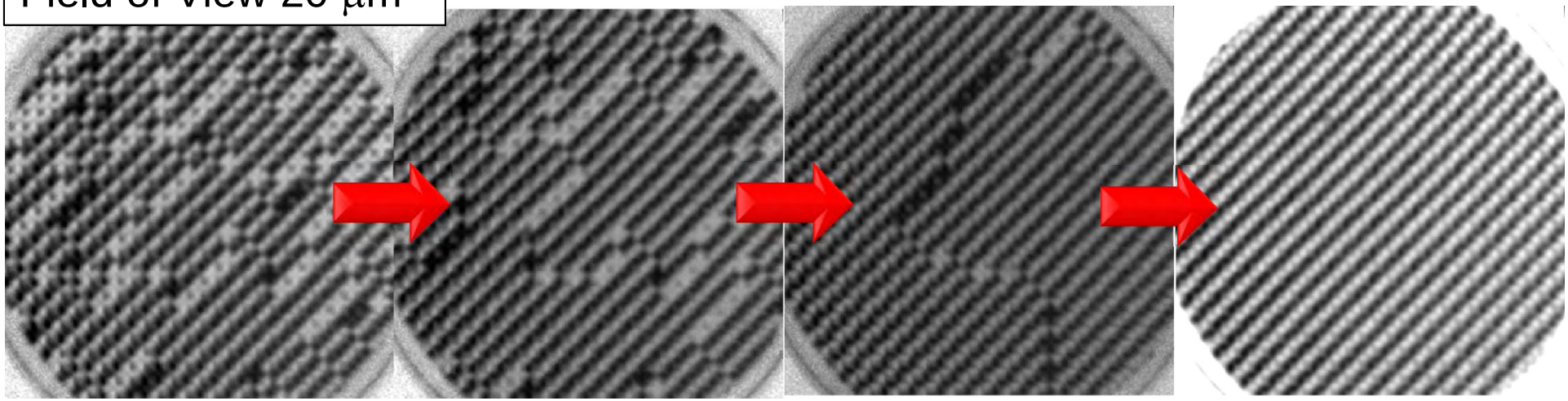


"String Regime"

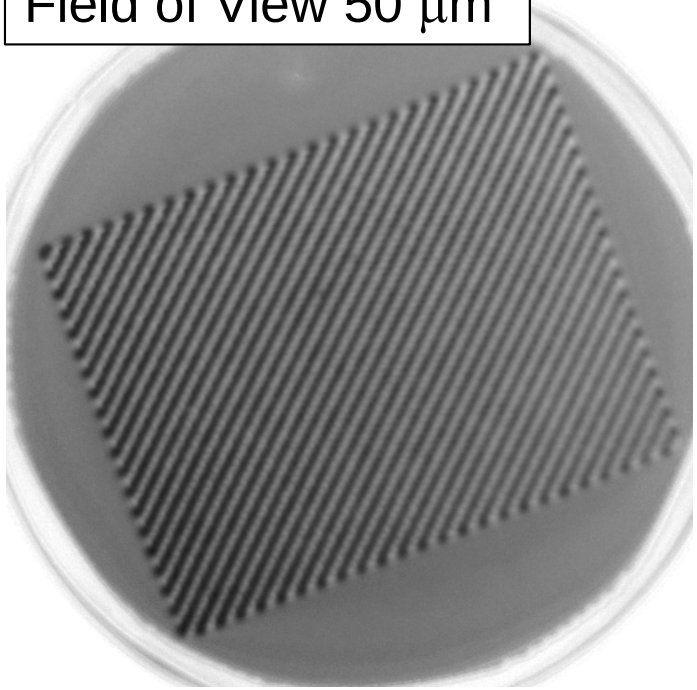
Farhan et al. PRL (2013)
V. Kapaklis et al. Nature Nanotech. (2014)

Thermal Artificial Square Ice

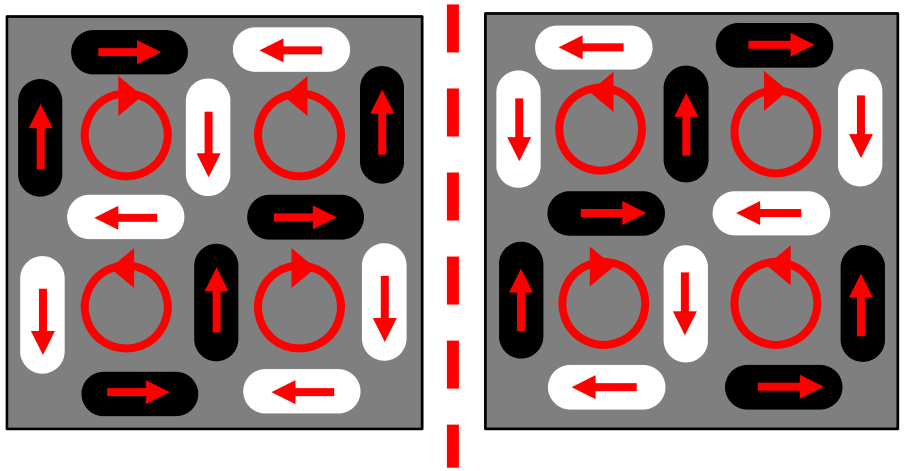
Field of View 20 μm



Field of View 50 μm



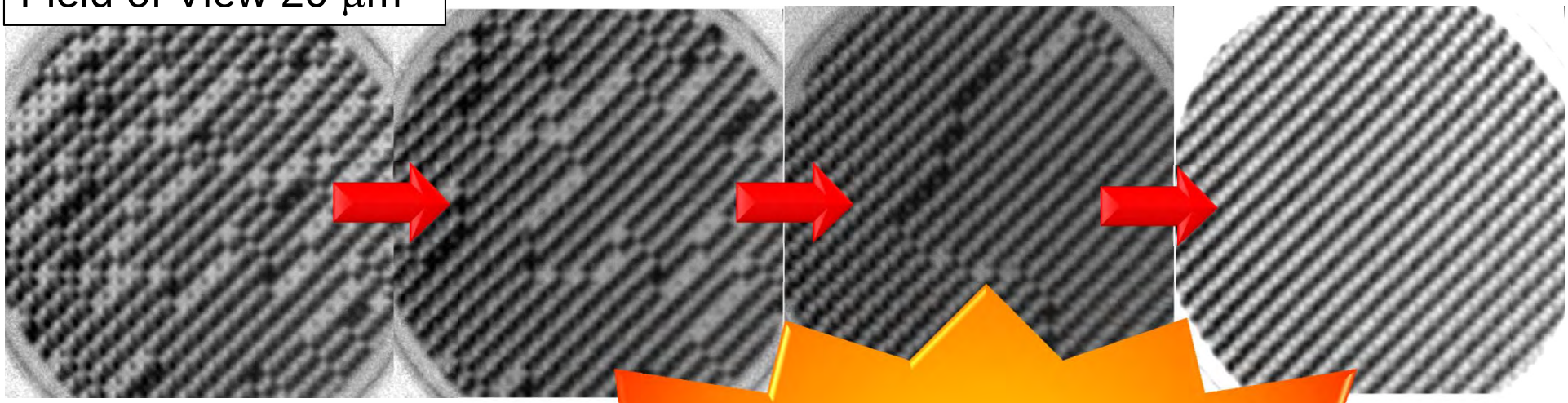
“Domain Regime”



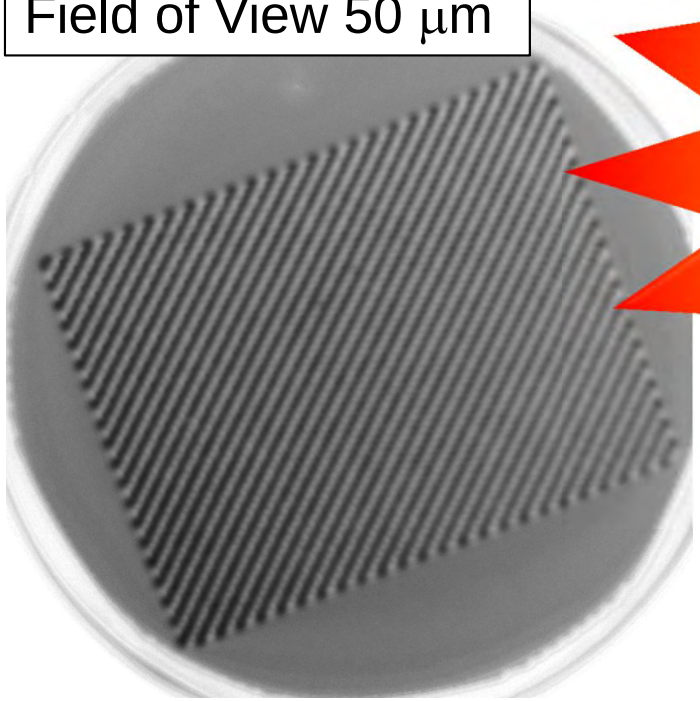
Farhan et al. PRL (2013)
V. Kapaklis et al. Nature Nanotech. (2014)

Thermal Artificial Square Ice

Field of View 20 μm



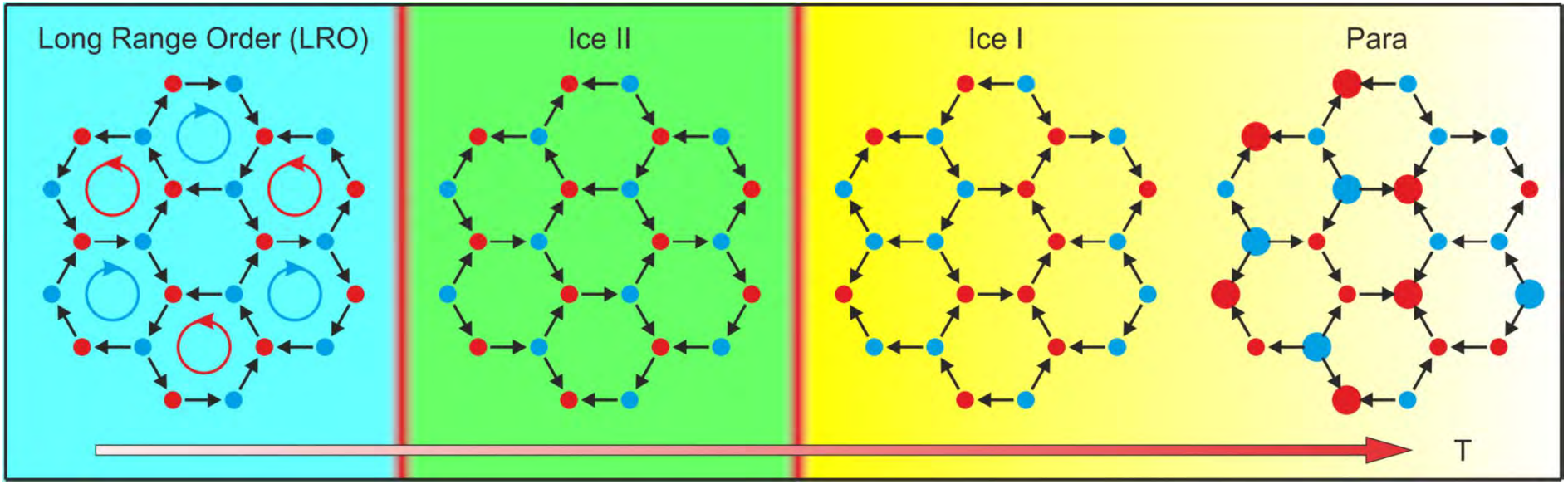
Field of View 50 μm



Thermally active systems provide a route to the ground state…..

Farhan et al. PRL (2013)
V. Kapaklis et al. Nature Nanotech. (2014)

Kagome Spin Ice Phases

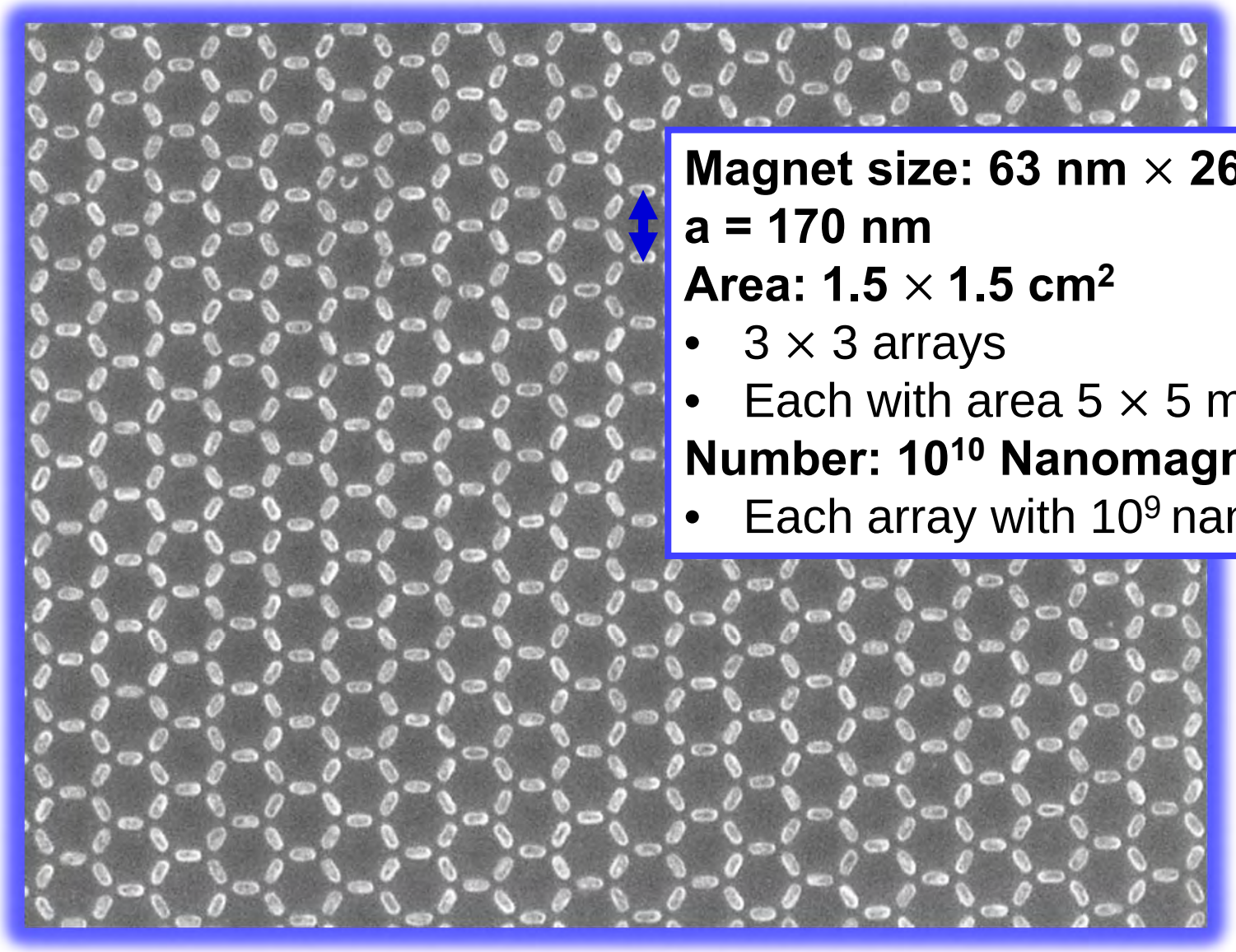


G Moller, R Moessner
Magnetic multipole analysis of kagome and artificial spin-ice dipolar arrays
Phys Rev B (2009)

GW Chern, P Mellado, O Tchernyshyov
Two-Stage Ordering of Spins in Dipolar Spin Ice on the Kagome Lattice
Phys Rev Lett (2011)

L. Anghinolfi et al. Nature Communications (2015)

Artificial Kagome Spin Ice



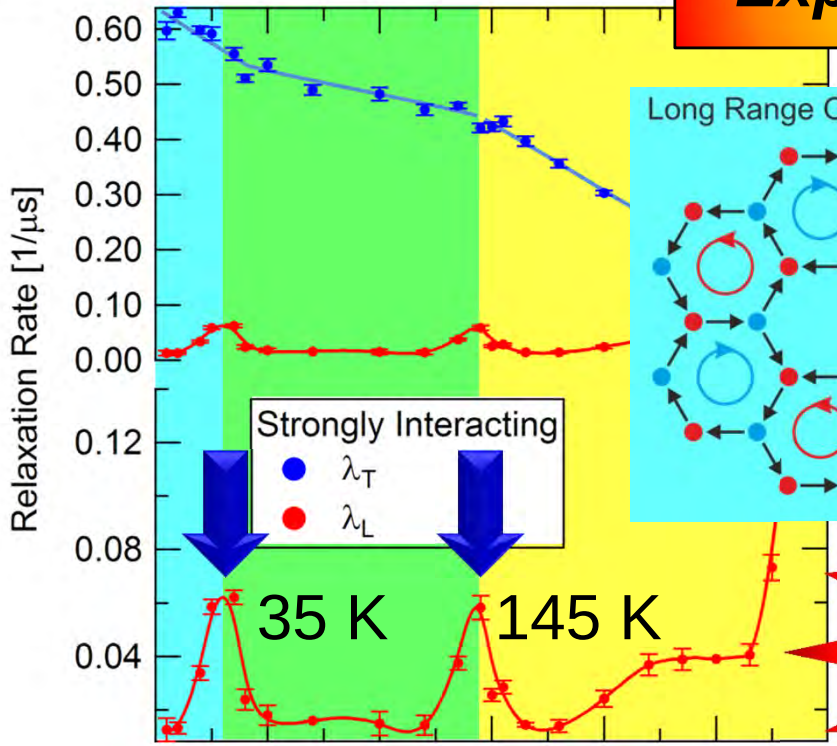
Magnet size: 63 nm × 26 nm × 6 nm
a = 170 nm
Area: 1.5 × 1.5 cm²
- 3 × 3 arrays
- Each with area 5 × 5 mm²

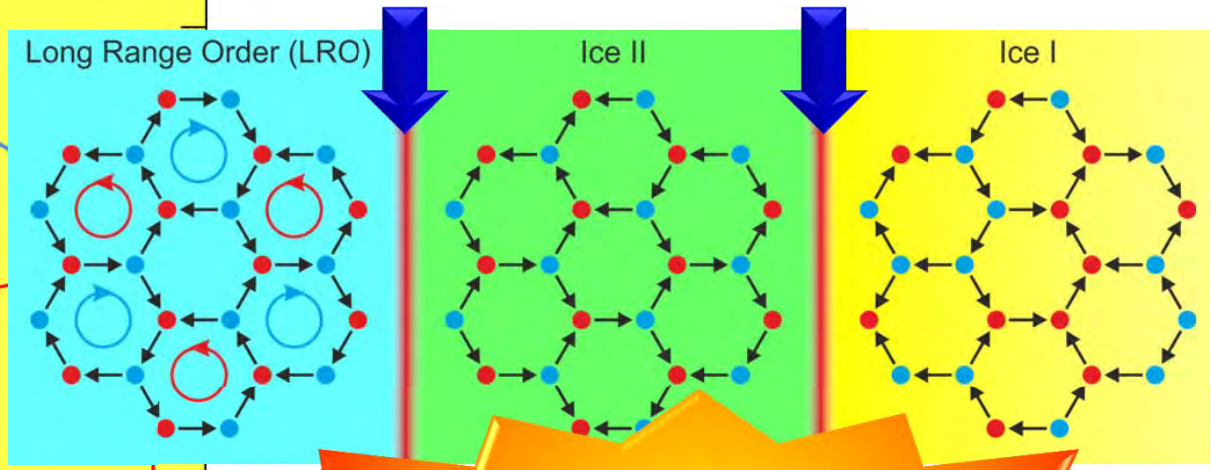
Number: 10^{10} Nanomagnets
- Each array with 10^9 nanomagnets

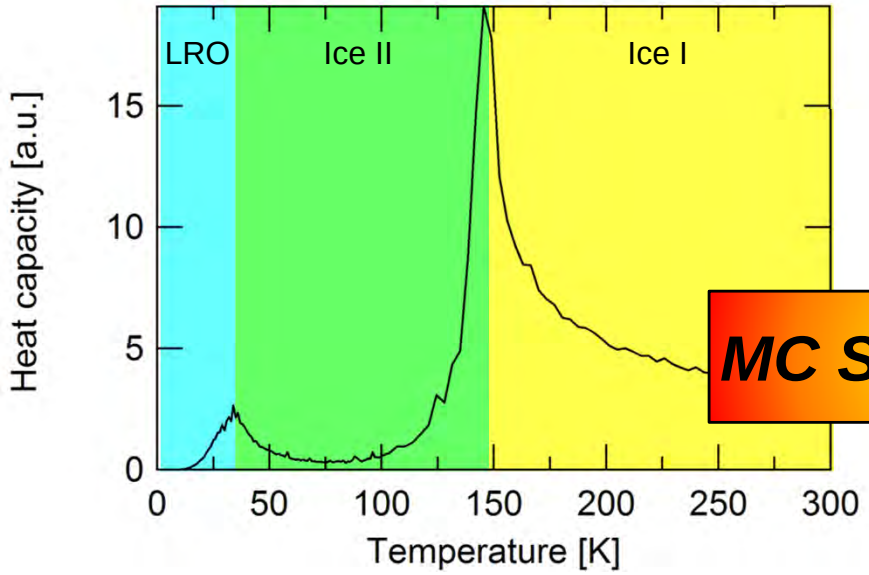
L. Anghinolfi et al. Nature Communications (2015)

ETH PSI

Experiment







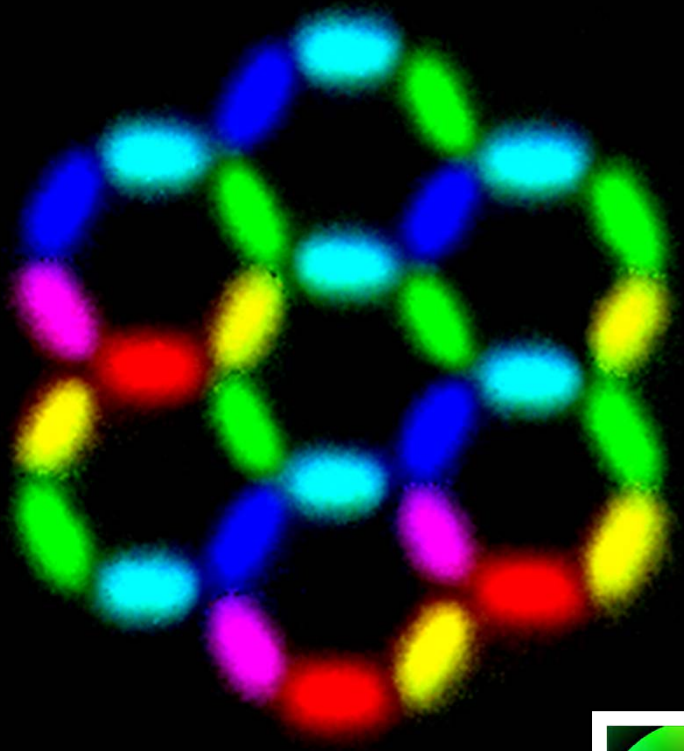
Frustrated Magnetic Metamaterial

- Thermal equilibrium
- Phase transitions

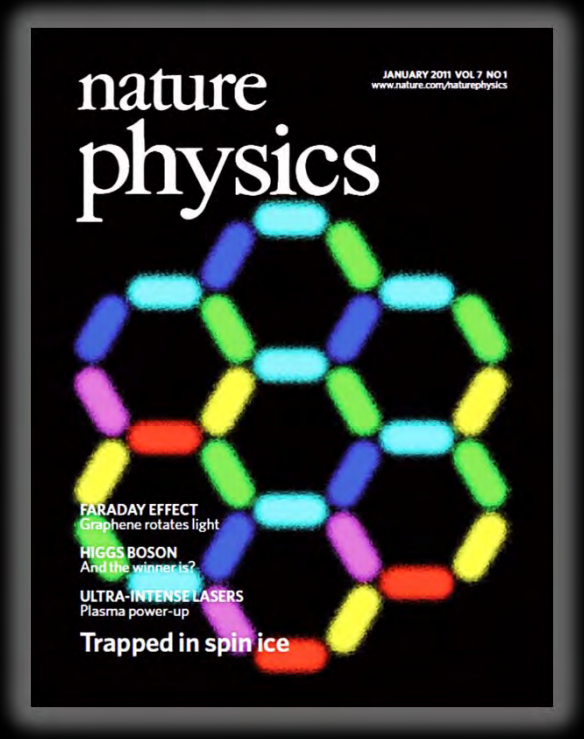
MC Simulations

L. Anghinolfi et al.
Nature Communications (2015)

Artificial Spin Ice

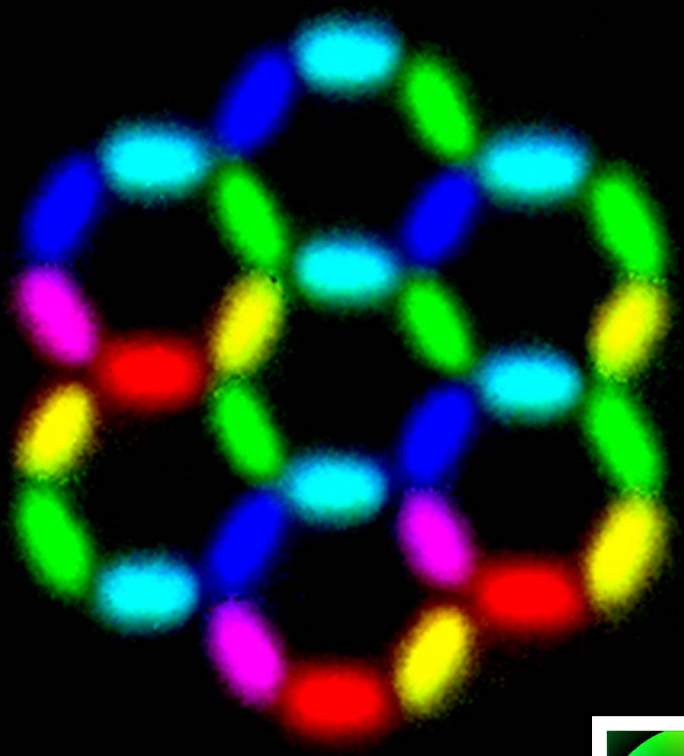


500 nm



L J Heyderman & R L Stamps, **Artificial Ferroic Systems**, J. Phys. Cond. Mat. (2013)

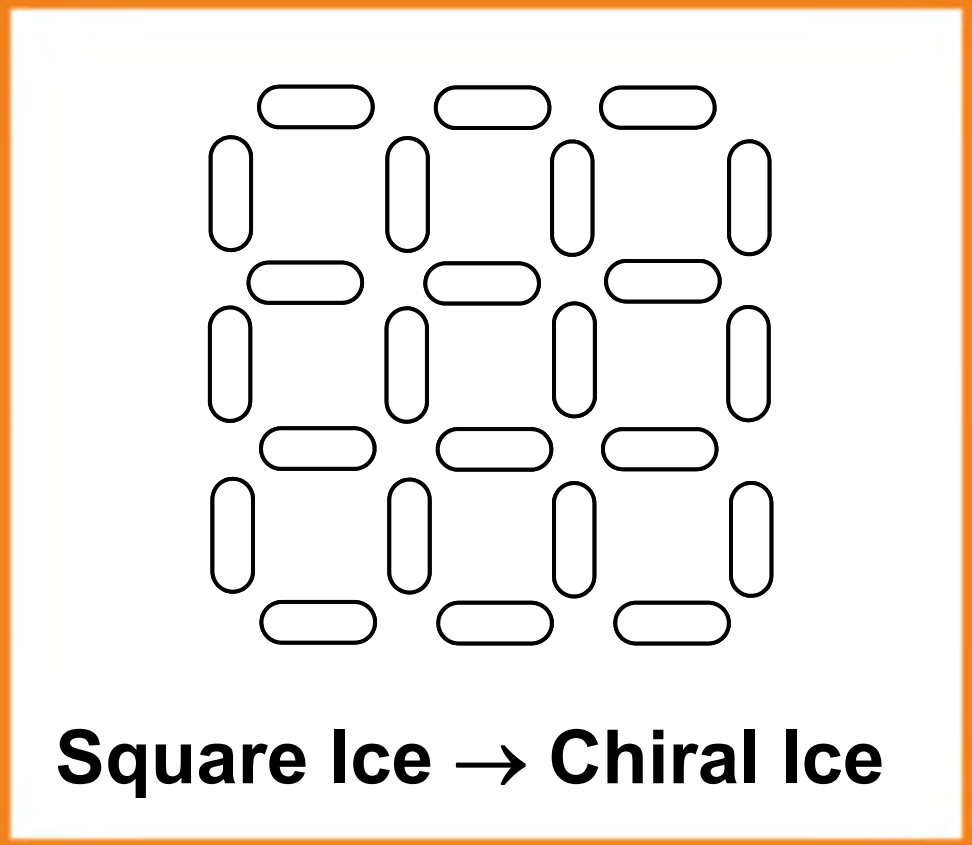
Artificial Spin Ice



- Devices
- Materials
- Geometries
- Timescales
- Techniques

L J Heyderman & R L Stamps, **Artificial Ferroic Systems**, J. Phys. Cond. Mat. (2013)

Chiral Ice



Square Ice → Chiral Ice

Devices

Materials

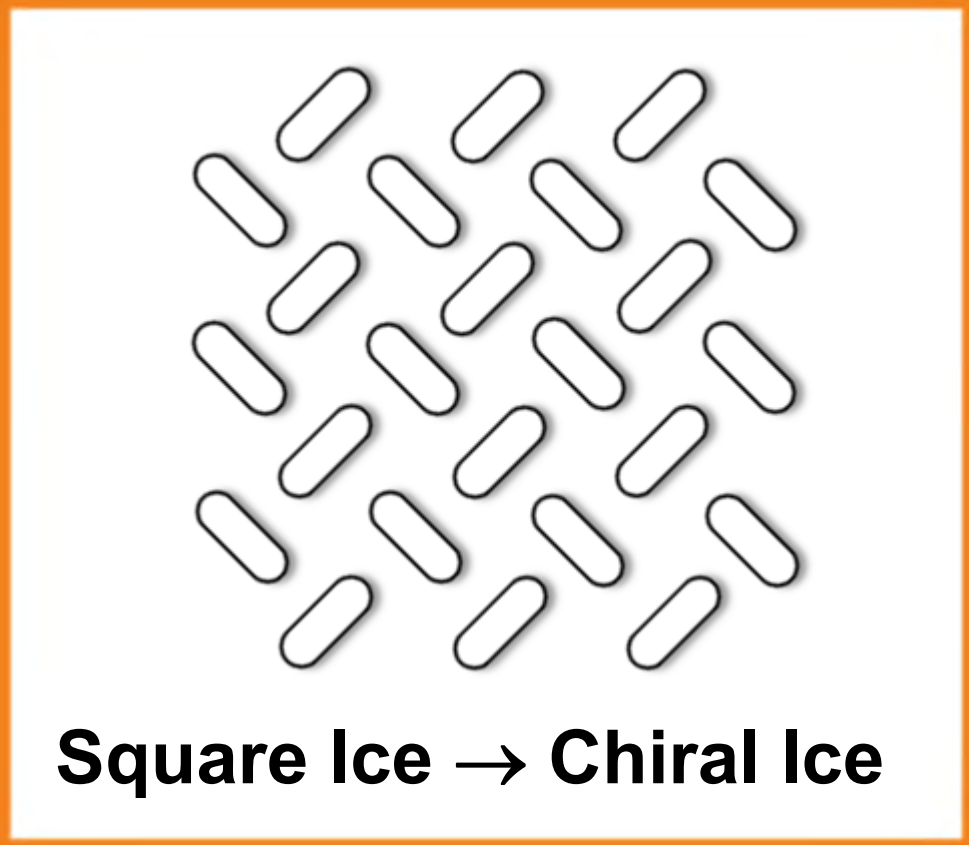
Geometries

Timescales

Techniques

S Gliga, G Hrkac, C Donnelly, J Büchi, A Kleibert, J Cui, A Farhan, E Kirk, R Chopdekar, Y Masaki, NS Bingham, A Scholl, RL Stamps, LJ Heyderman In Review (2017)

Chiral Ice



Square Ice → Chiral Ice

Devices

Materials

Geometries

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Techniques

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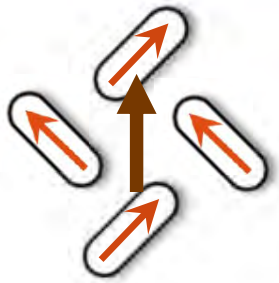
Chiral Ice



Square Ice → Chiral Ice

Devices

Materials

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S Gliga, G Hrkac, C Donnelly, J Büchi, A Kleibert, J Cui, A Farhan, E Kirk, R Chopdekar, Y Masaki, NS Bingham, A Scholl, RL Stamps, LJ Heyderman In Review (2017)

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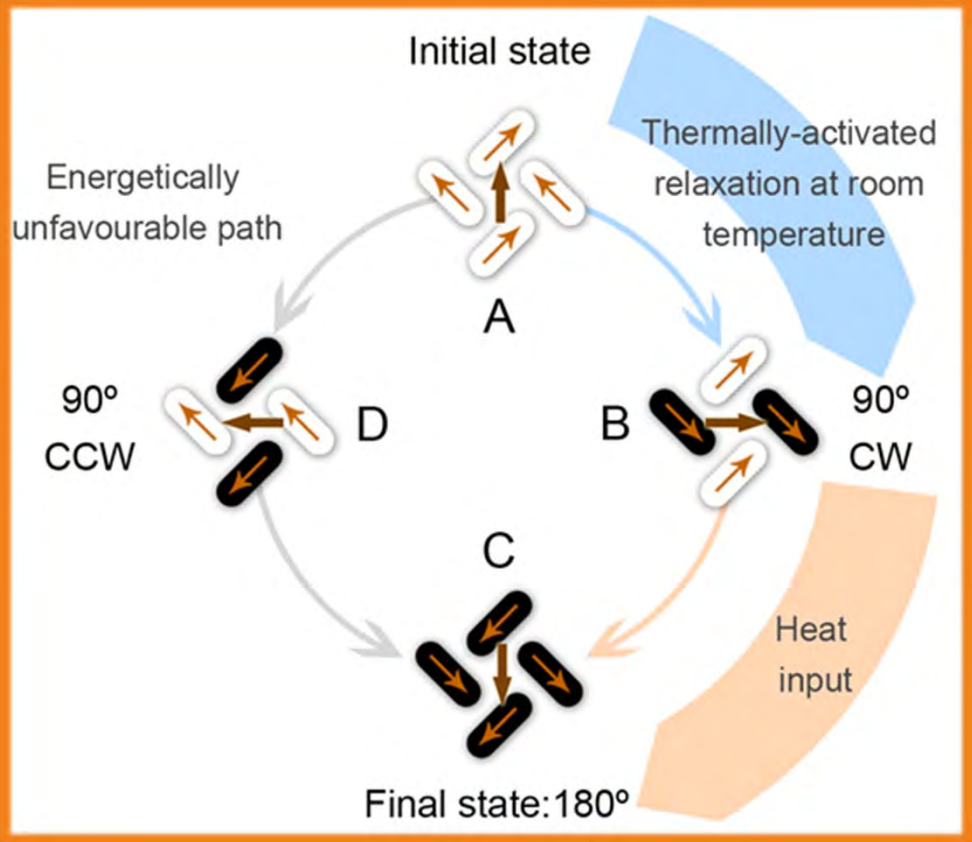

Devices

Materials

Geometries

Timescales

Techniques

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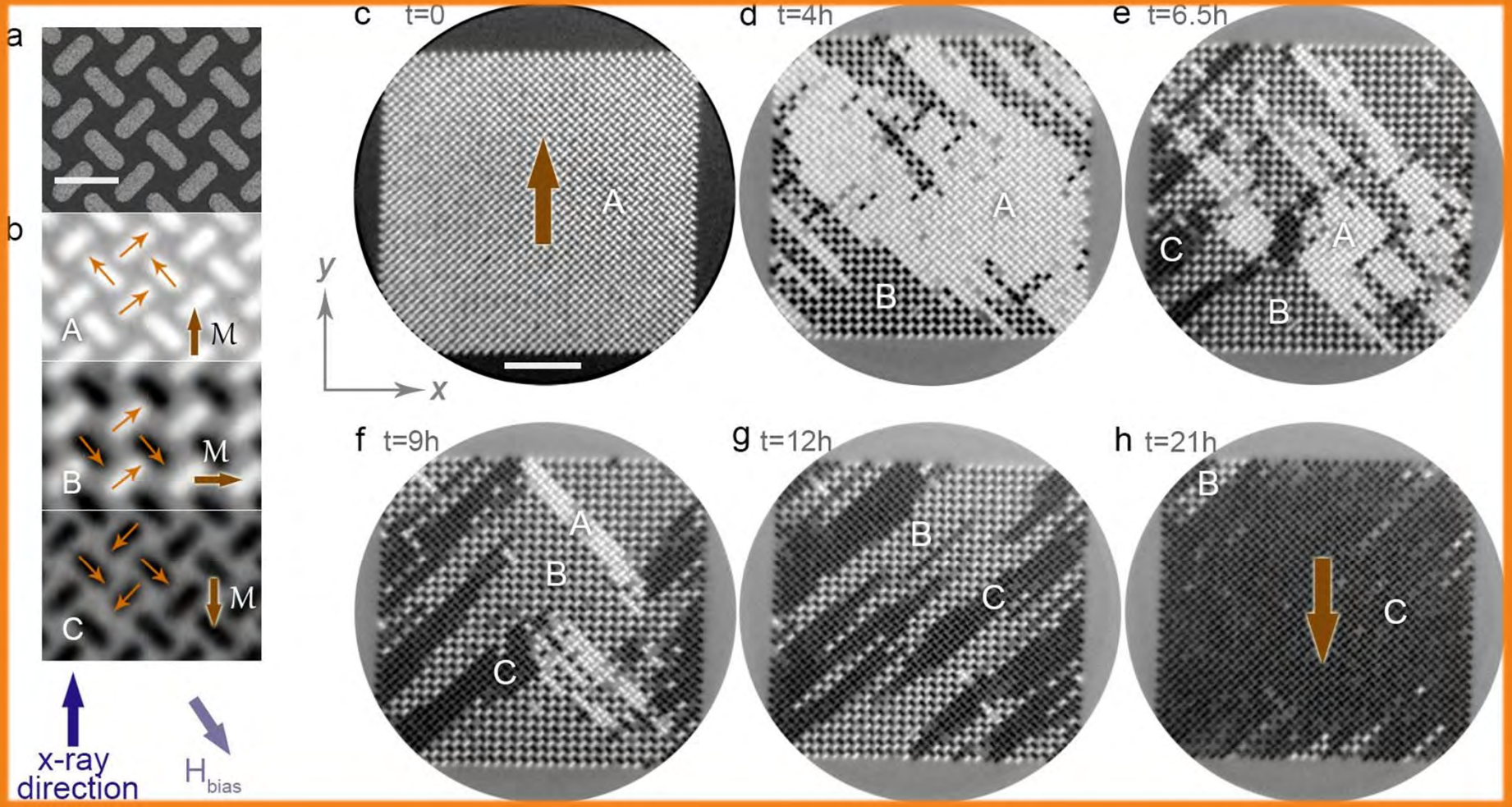
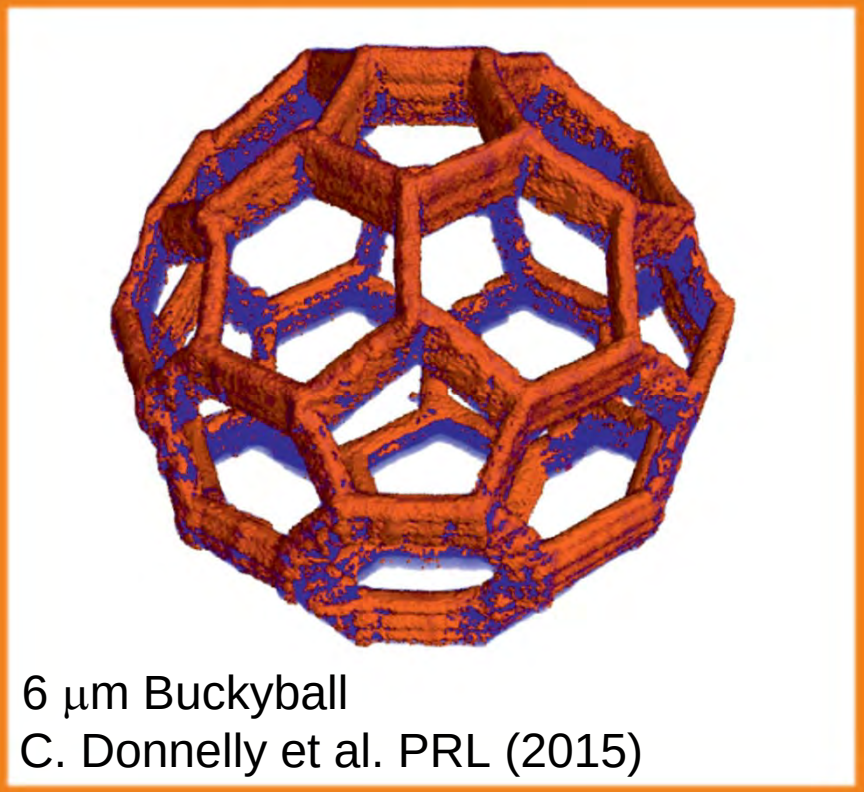
Chiral Ice



S Gliga, G Hrkac, C Donnelly, J Büchi, A Kleibert, J Cui, A Farhan, E Kirk, R Chopdekar, Y Masaki, NS Bingham, A Scholl, RL Stamps, LJ Heyderman In Review (2017)

Artificial Spin Ice – Three Dimensions



6 μm Buckyball
C. Donnelly et al. PRL (2015)

Devices

Materials

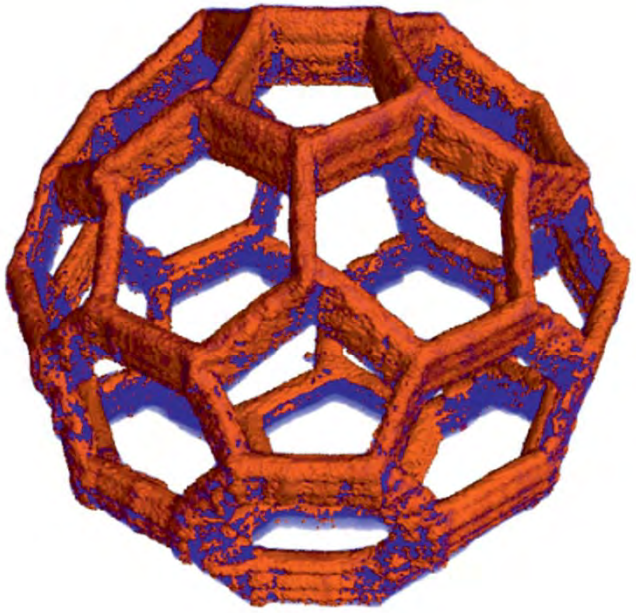
Geometries

Timescales

Techniques

L J Heyderman & R L Stamps, **Artificial Ferroic Systems**, J. Phys. Cond. Mat. (2013)

Resonant Ptychographic Tomography

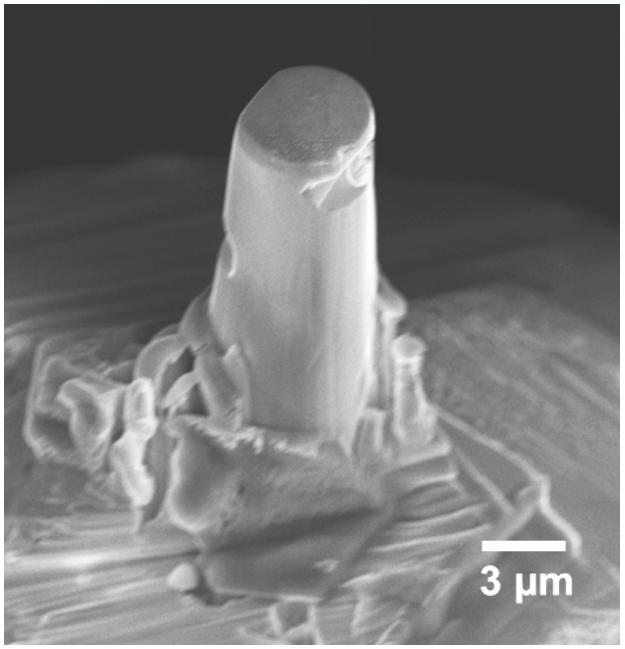


6 μm Buckyball
C. Donnelly et al. PRL (2015)

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

L J Heyderman & R L Stamps, **Artificial Ferroic Systems**, J. Phys. Cond. Mat. (2013)

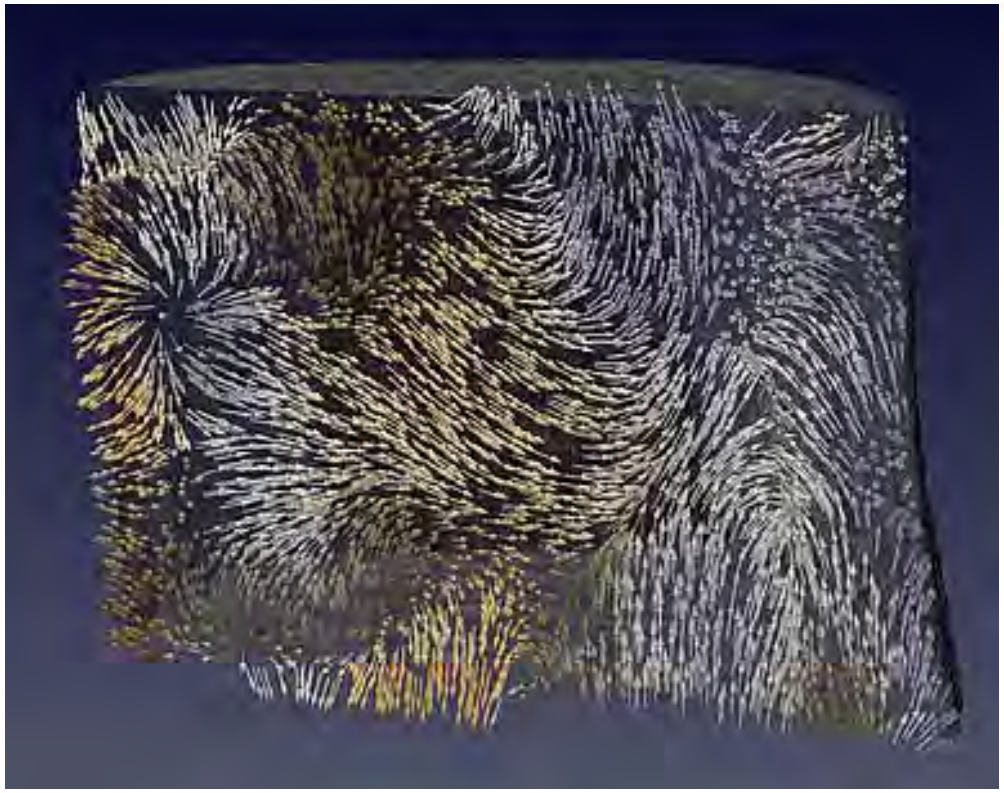
Hard X-ray Magnetic Tomography



$GdCo_2$ Pillar

Cut from nugget with FIB

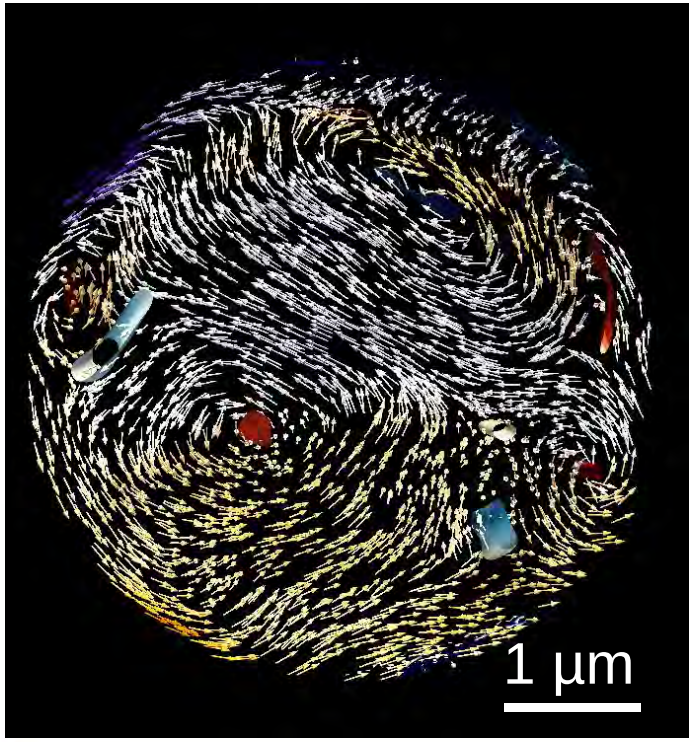
Sample from:
R. Galera, CNRS, Grenoble

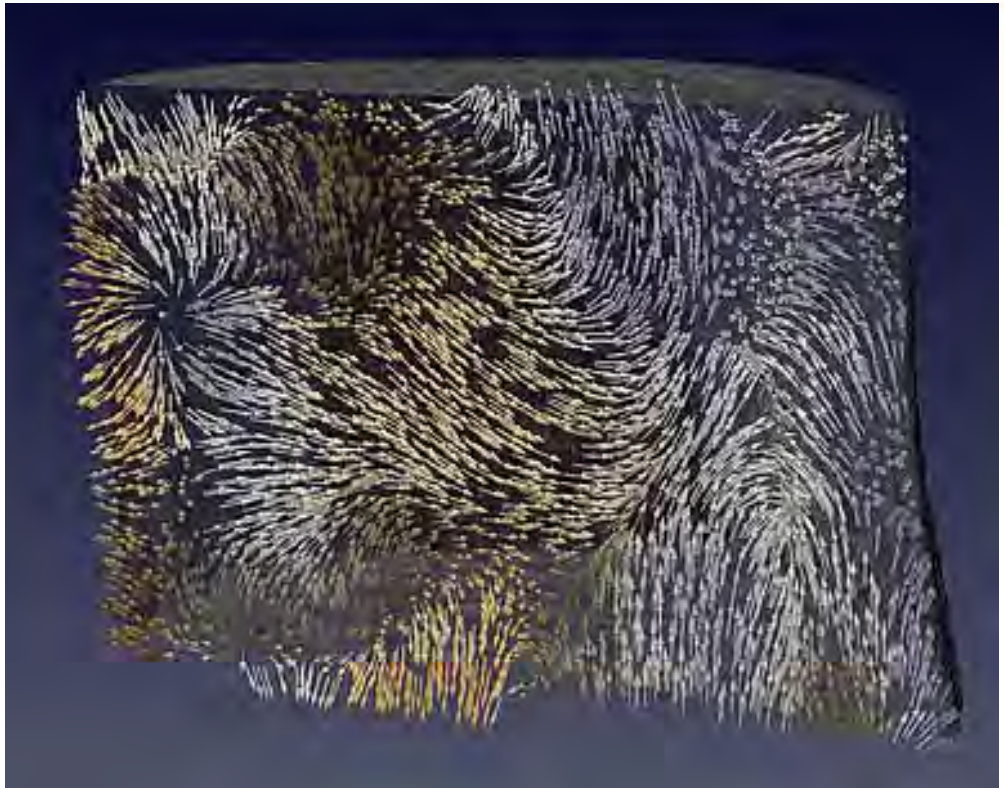


C. Donnelly et al. Nature (2017)
P. Fischer, *News & Views*, Nature (2017)
C. Donnelly et al. PRB (2016)

Hard X-ray Magnetic Tomography

One slice:

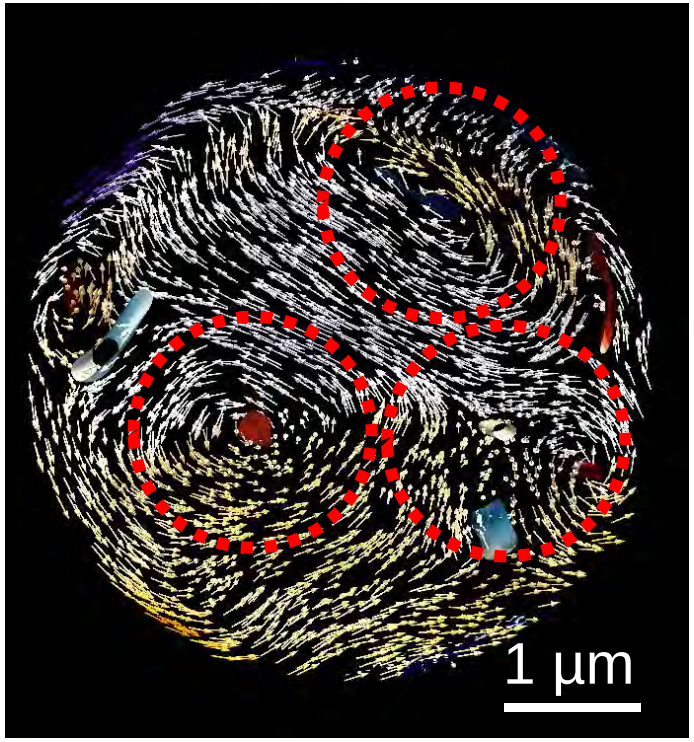




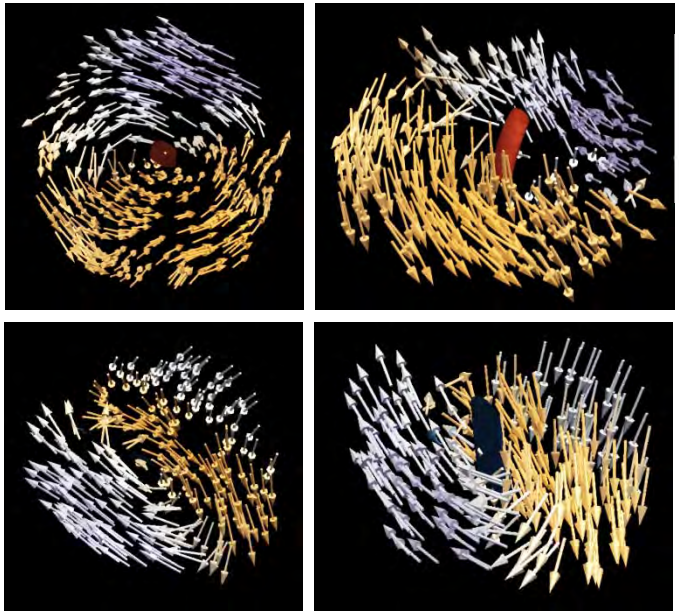
C. Donnelly et al. Nature (2017)
P. Fischer, *News & Views*, Nature (2017)
C. Donnelly et al. PRB (2016)

Hard X-ray Magnetic Tomography

C. Donnelly et al. Nature (2017)
P. Fischer, *News & Views*, Nature (2017)
C. Donnelly et al. PRB (2016)



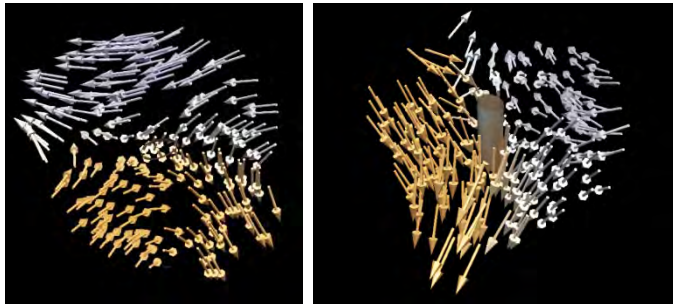
Vortex

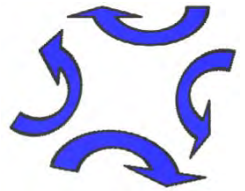


Clockwise

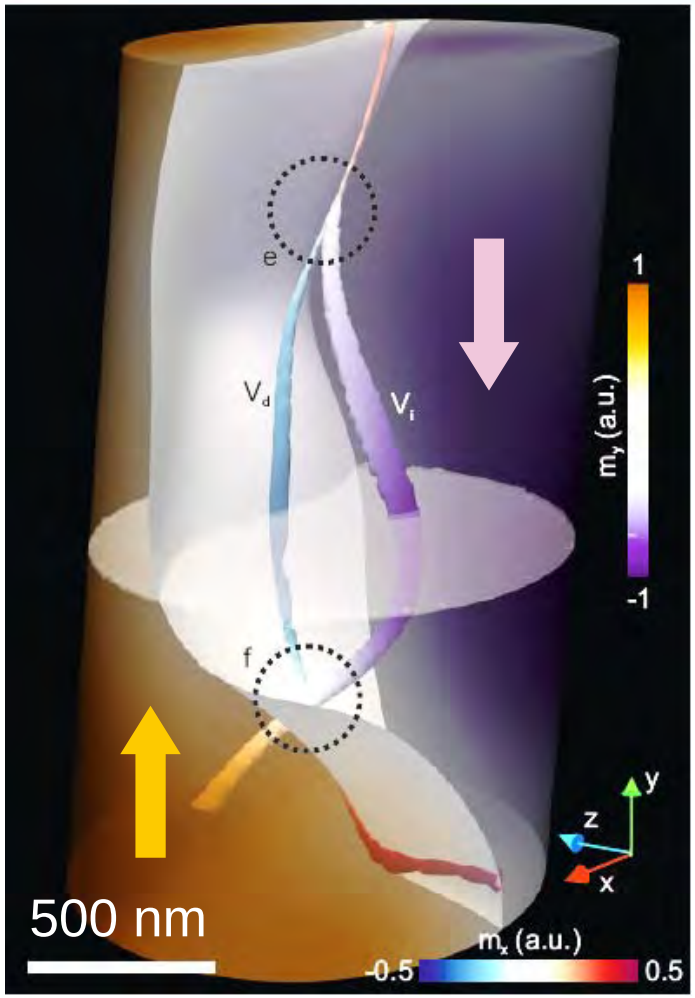
Anticlockwise

Antivortex



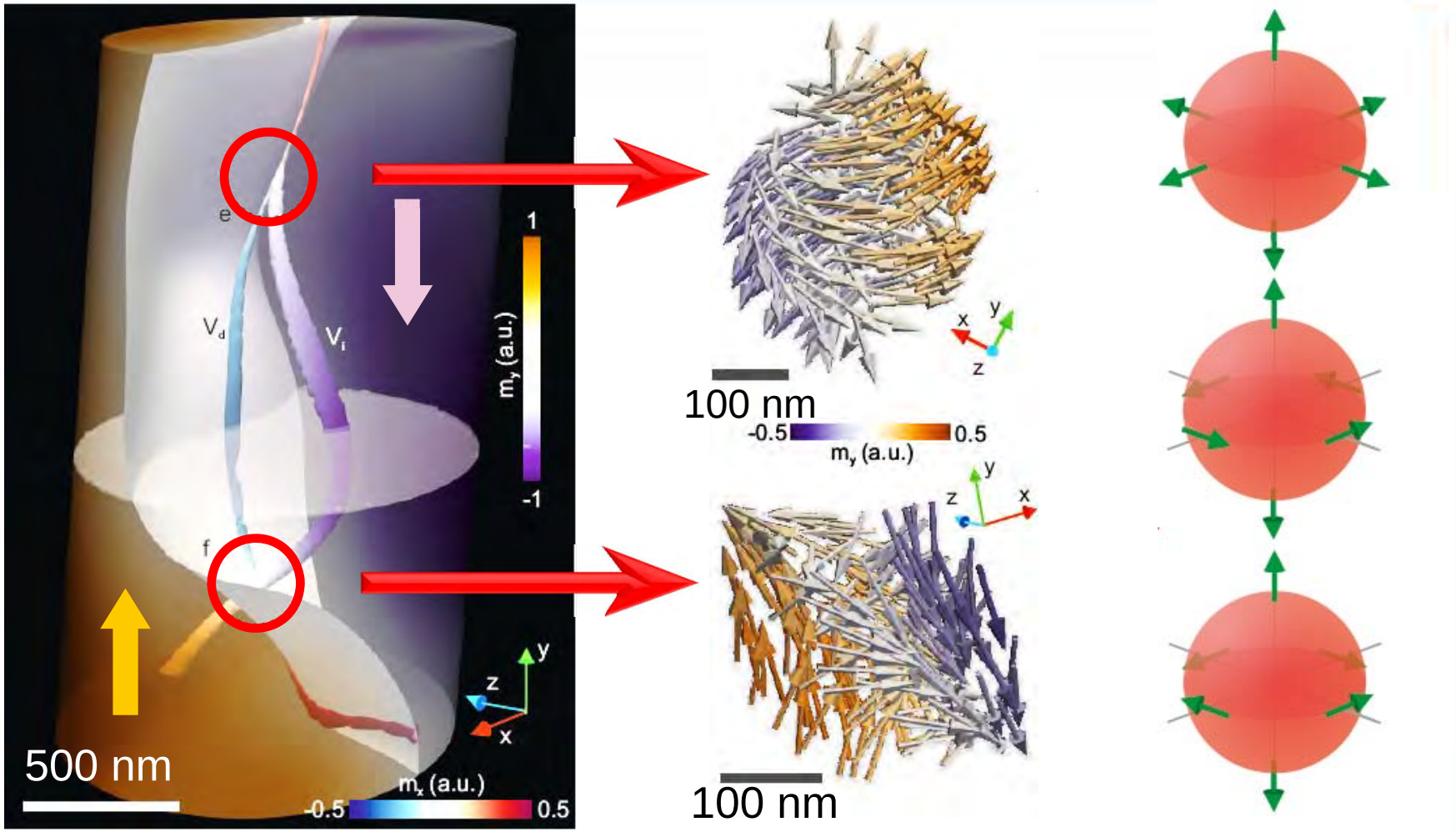


Hard X-ray Magnetic Tomography



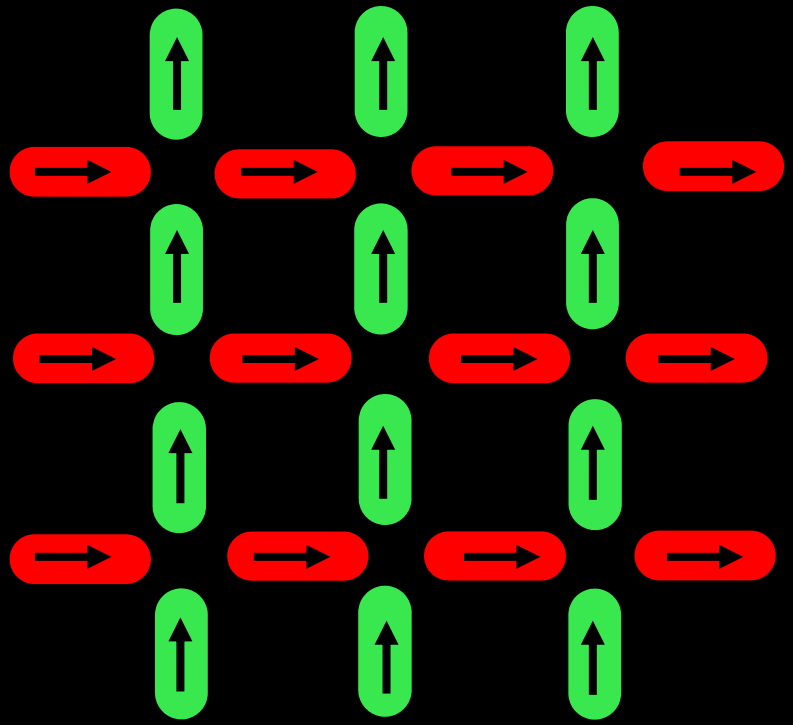
C. Donnelly et al. Nature (2017); P. Fischer, *News & Views*, Nature (2017)
C. Donnelly et al. PRB (2016)

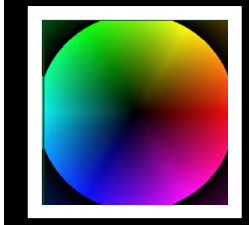
Hard X-ray Magnetic Tomography



C. Donnelly et al. Nature (2017); P. Fischer, *News & Views*, Nature (2017)
C. Donnelly et al. PRB (2016)

Artificial Spin Ice – Square Lattice





X-ray Magnetic Resonant Scattering
J. Perron et al. Phys. Rev. B (2013)

Devices

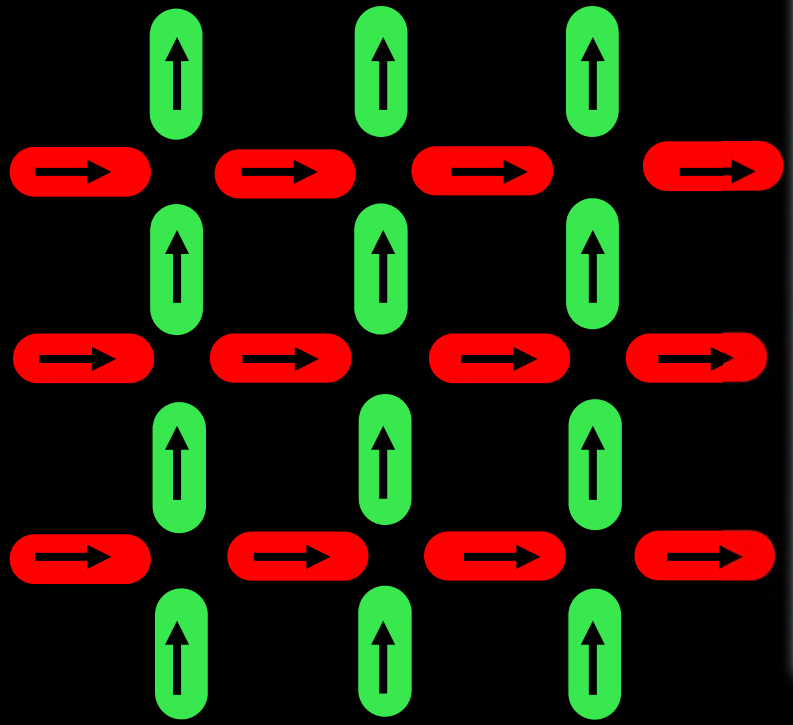
Materials

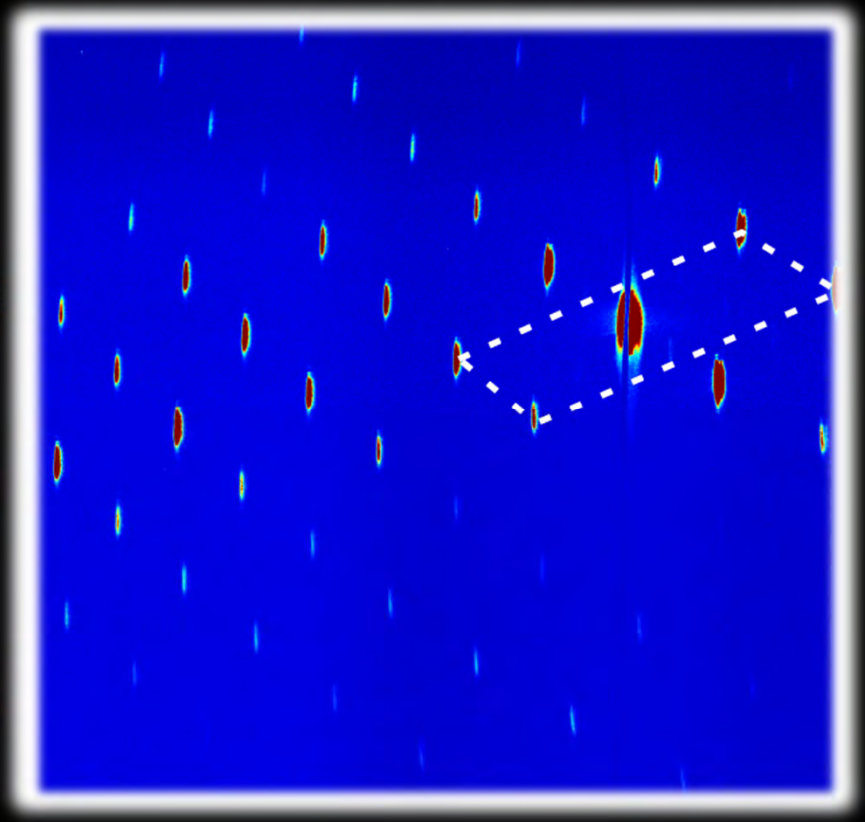
Geometries

Timescales

Techniques

Artificial Spin Ice – Square Lattice

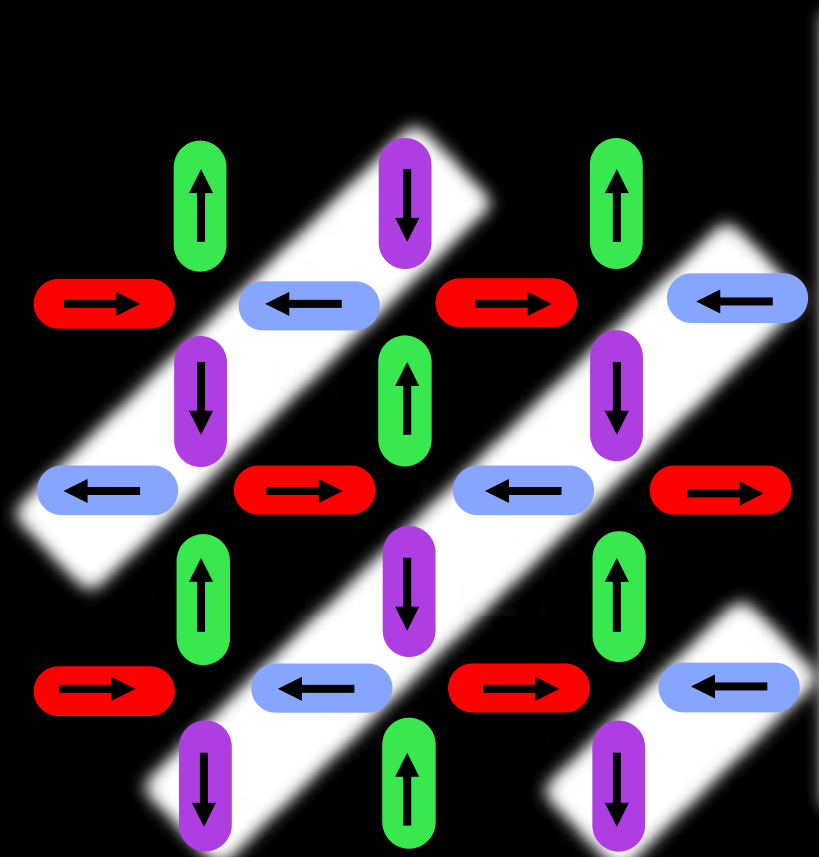


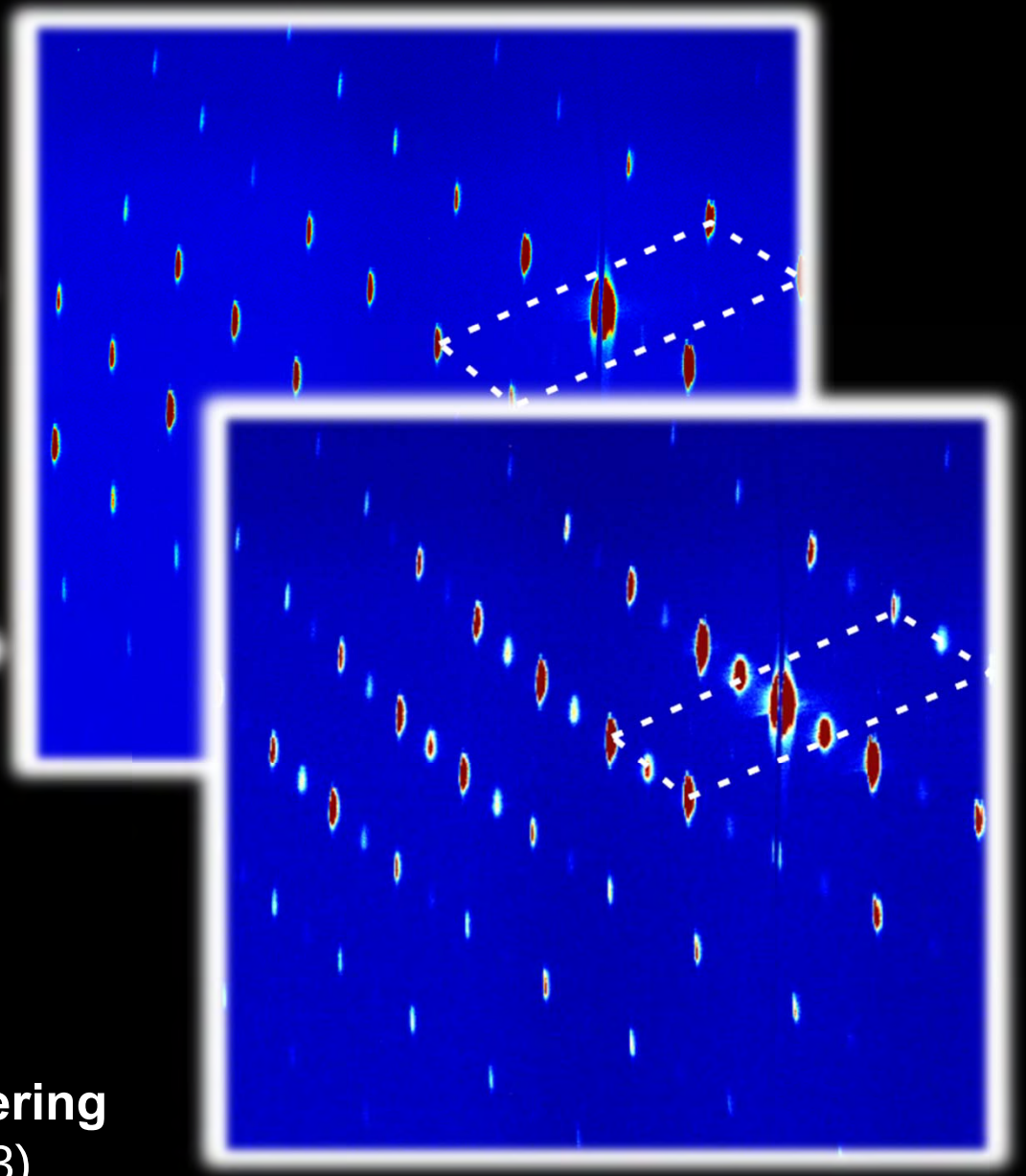


X-ray Magnetic Resonant Scattering

J. Perron et al. Phys. Rev. B (2013)

Artificial Spin Ice – Square Lattice

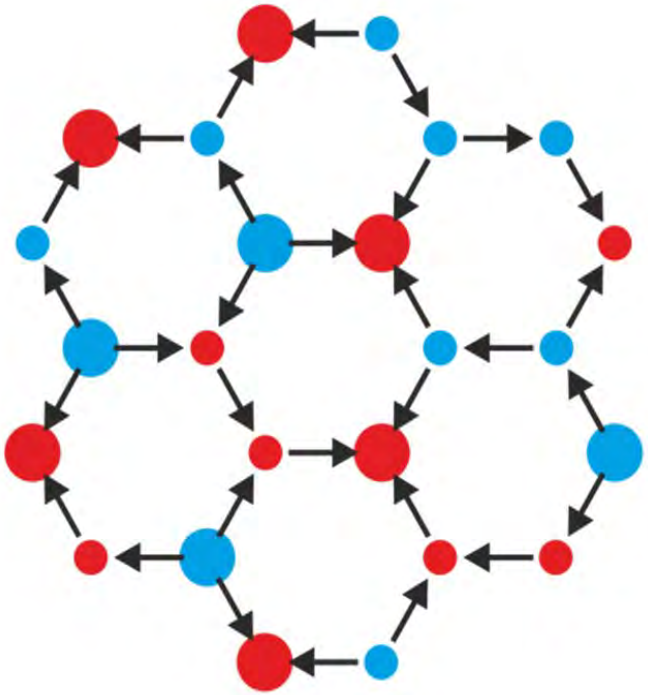




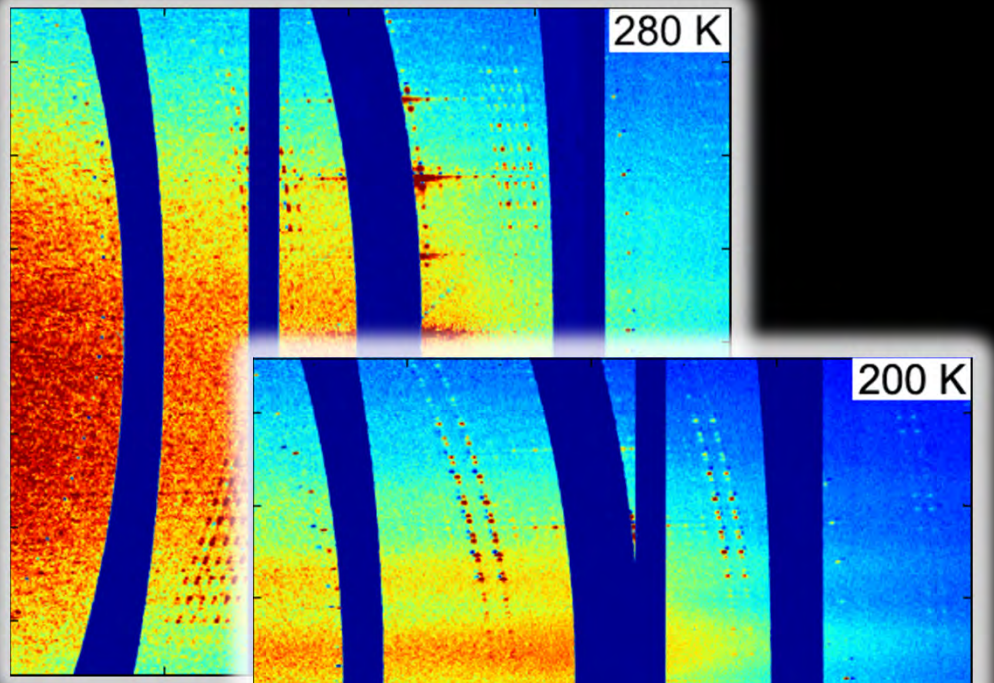
X-ray Magnetic Resonant Scattering

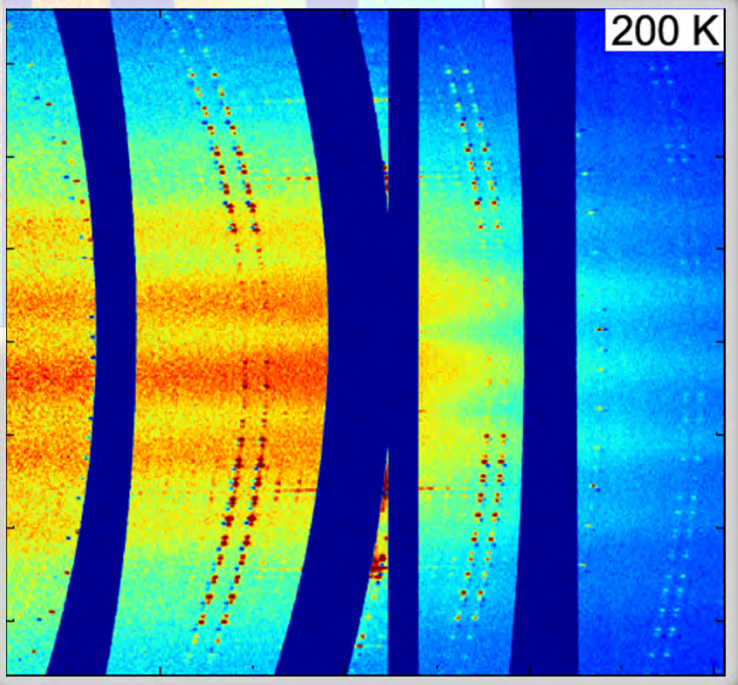
J. Perron et al. Phys. Rev. B (2013)

Artificial Spin Ice – Kagome Lattice



Paramagnetic

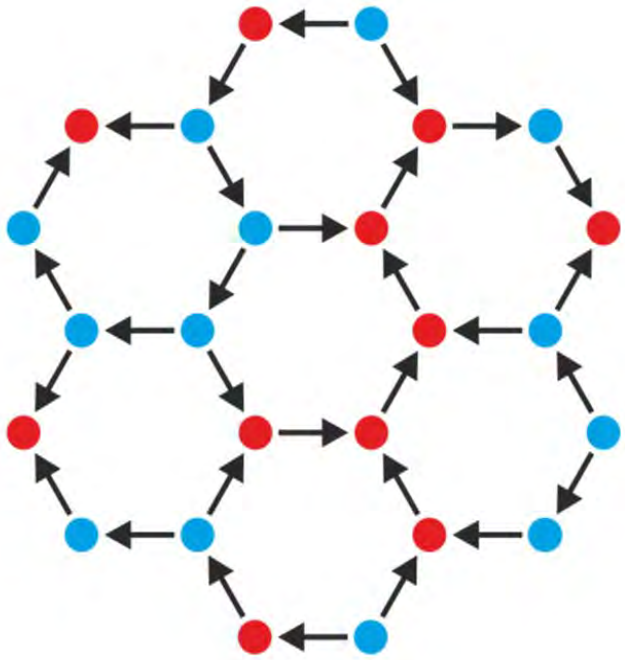




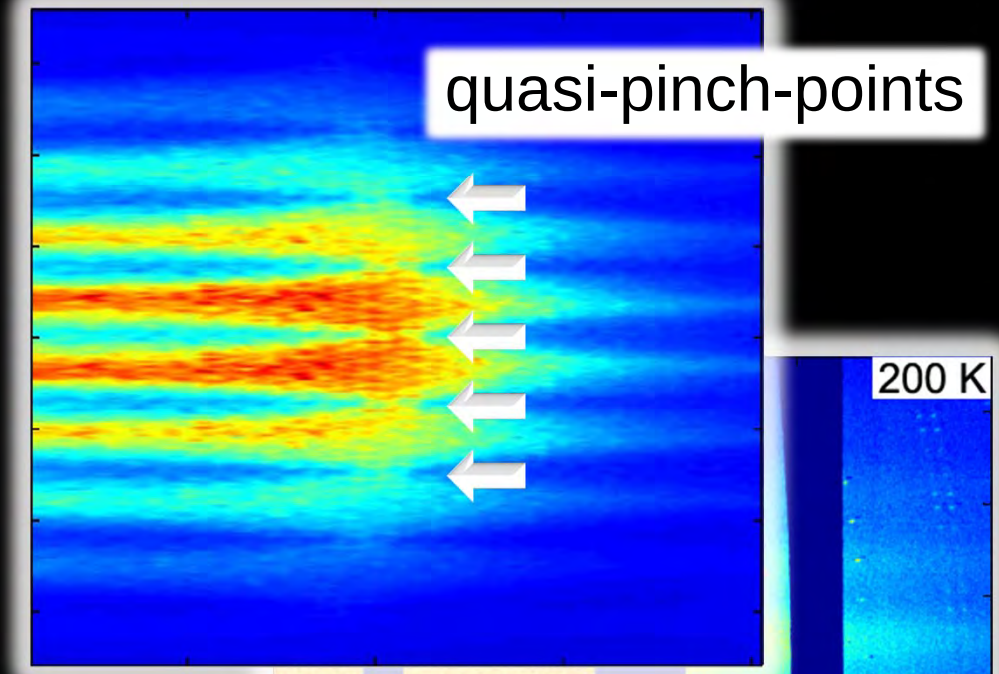
X-ray Magnetic Resonant Diffuse Scattering

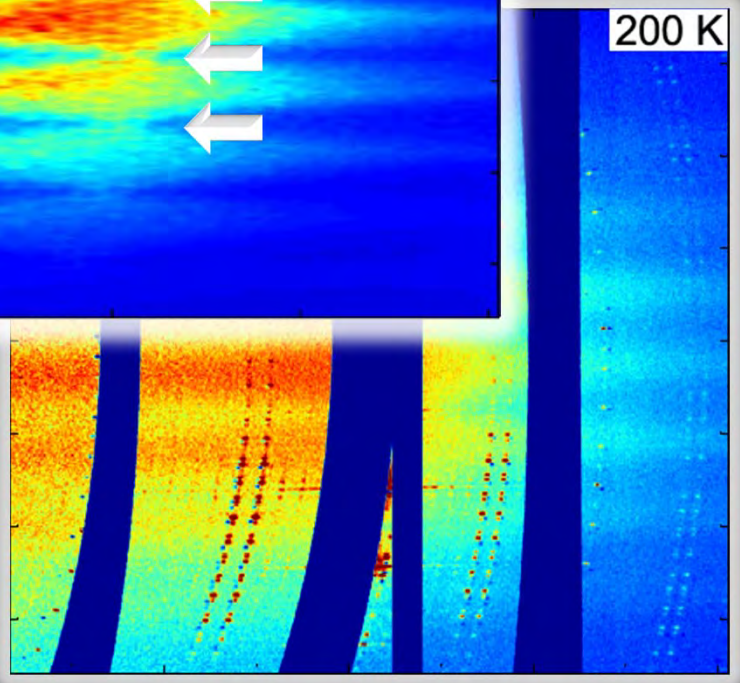
O Sendetskyi, L Anghinolfi, V Scagnoli, G Möller, N Leo, A Alberca, J Kohlbrecher, J Lüning, U Staub, LJ Heyderman Phys. Rev. B (2016)

Artificial Spin Ice – Kagome Lattice



Kagome Ice I





X-ray Magnetic Resonant Diffuse Scattering

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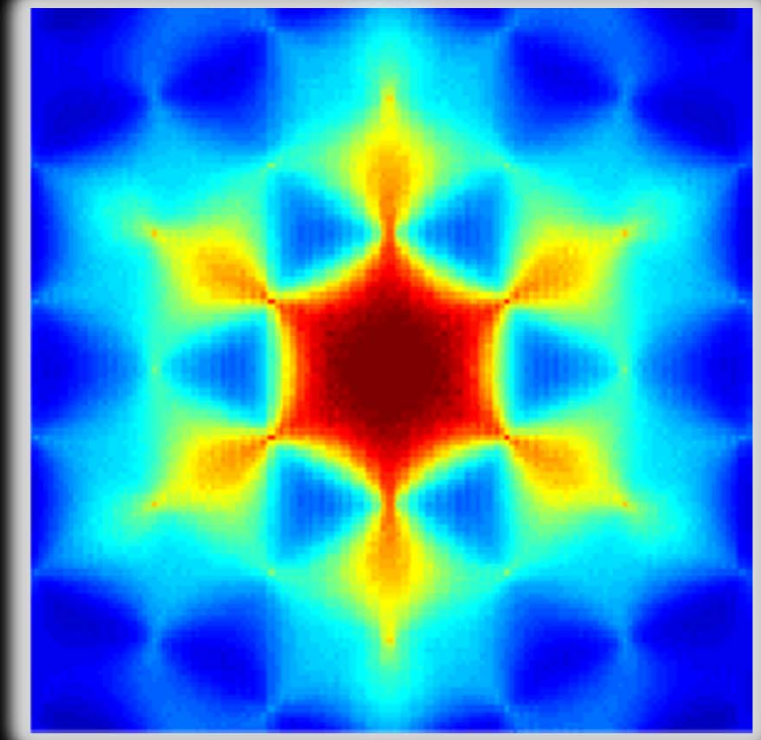
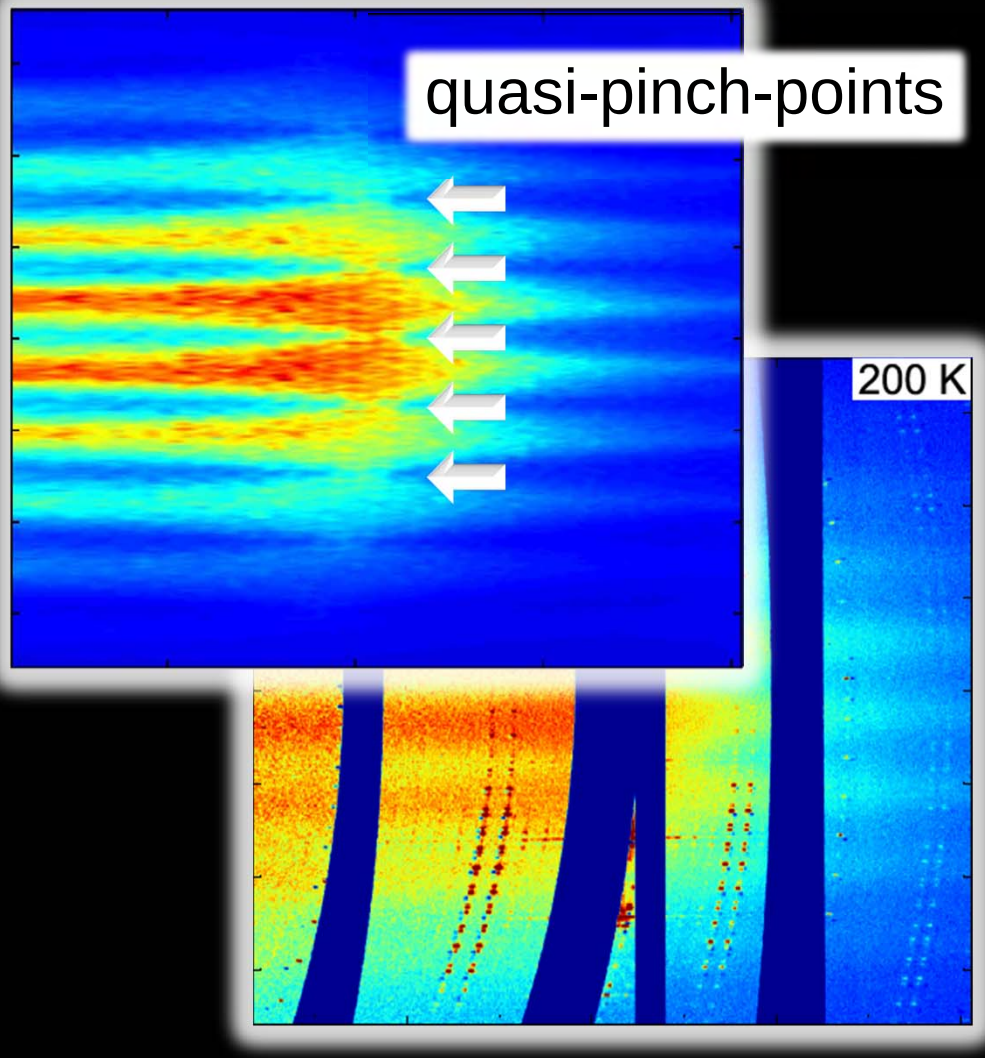
Artificial Spin Ice – Kagome Lattice





X-ray Magnetic Resonant Diffuse Scattering

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Artificial Spin Ice

Laura Heyderman

Research & Technical Staff, Paul Scherrer Institute

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Swiss Light Source

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Artificial Spin Ice

Laura Heyderman

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Adv. Light Source:	Andreas Scholl, Tony Young

Artificial Ferroic Systems

Laura Heyderman

HYBRID SYSTEMS

ARTIFICIAL SPIN SYSTEMS

3D

Hybrid Systems – Artificial Multiferroics

- Strain imprints magnetic states
- Cost effective nanoparticle dispersions
- Control:
  - with structural phase transitions of cap layer
  - magnetic state with electric field

Artificial Spin Ice

- Emergent magnetic monopoles & Dirac strings
- Thermally active artificial spin ice:
  - Switching in kagome spin ice structures
  - Thermal relaxation in square ice
  - Phase Transitions → Frustrated Magnetic Metamaterial

LJ Heyderman & RL Stamps, J. Phys. Cond. Mat. (2013)