PAUL SCHERRER INSTITUT

PSI

ETH zürich

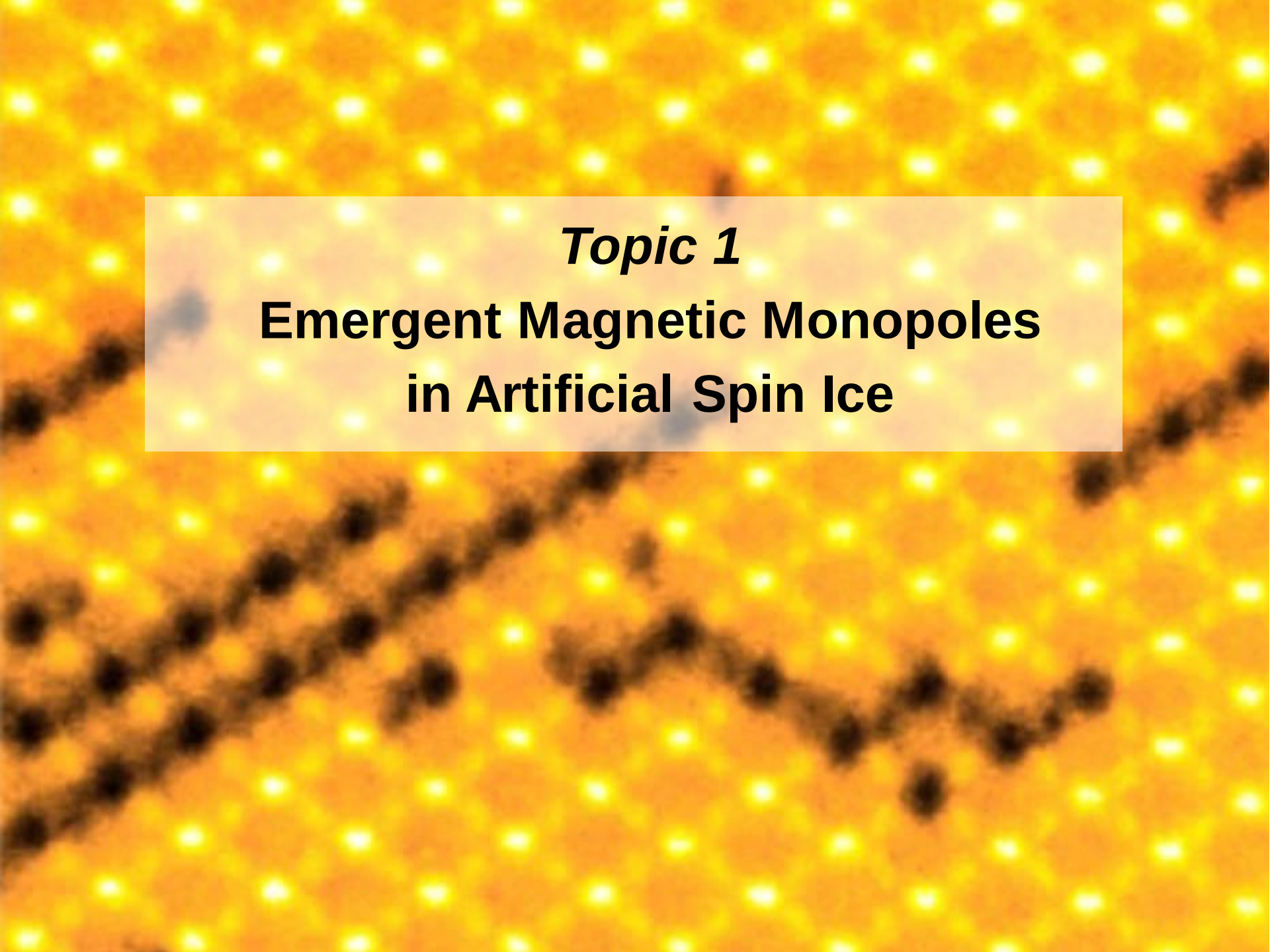
Prof. Laura Heyderman :: ETH Zurich - Paul Scherrer Institute

Artificial Ferroic Systems: Magnetic Monopoles, Chirality and Bloch Point Singularities

Session on Topology Matters: Structure-Property Relationships On Different Length Scales

APS March Meeting, Boston 2019

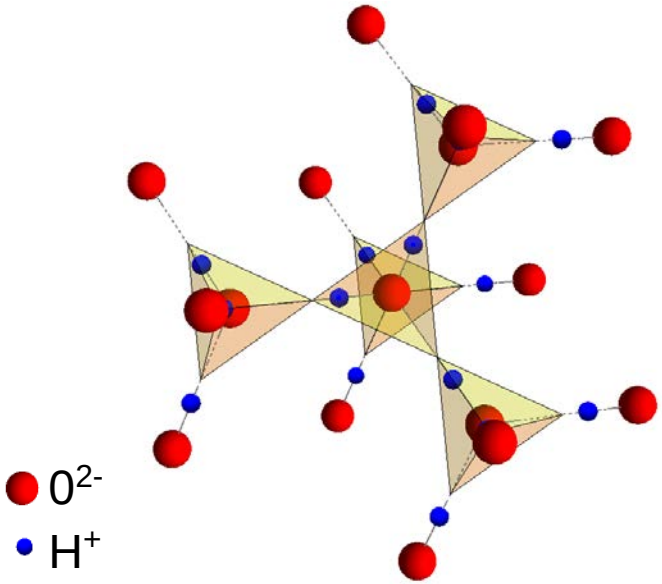
Mesoscopic Systems
http://www.mesosys.mat.ethz.ch



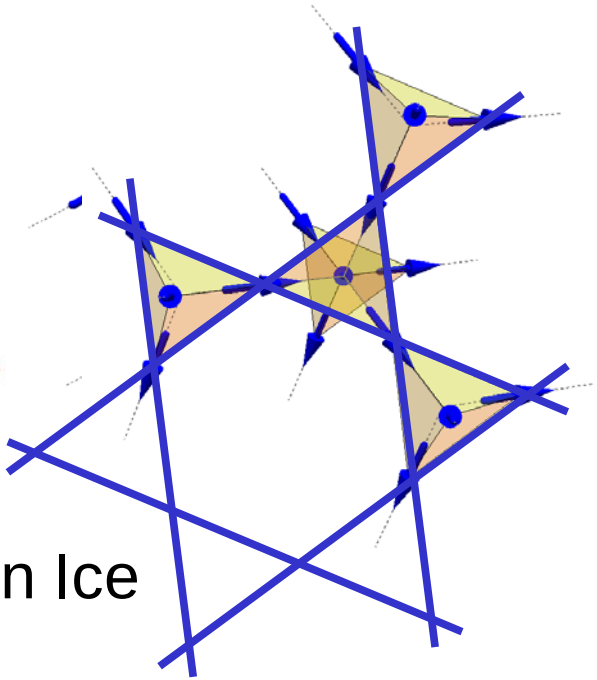
Topic 1

Emergent Magnetic Monopoles in Artificial Spin Ice

From Water Ice to Artificial Spin Ice



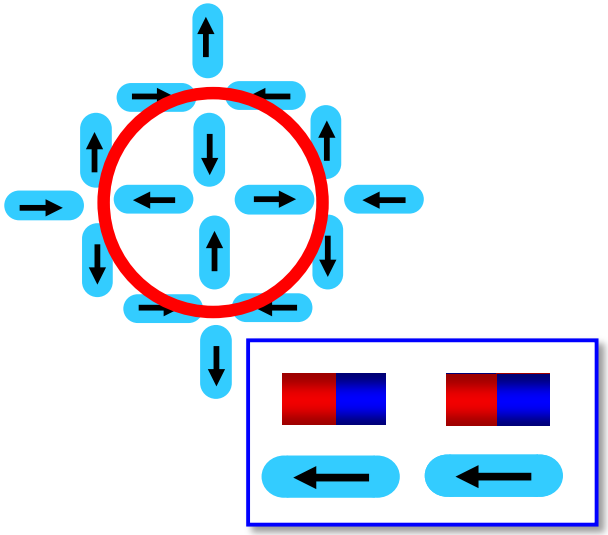
Water Ice



Spin Ice

MJ Harris *et al.*
PRL (1997)

Ice Rule

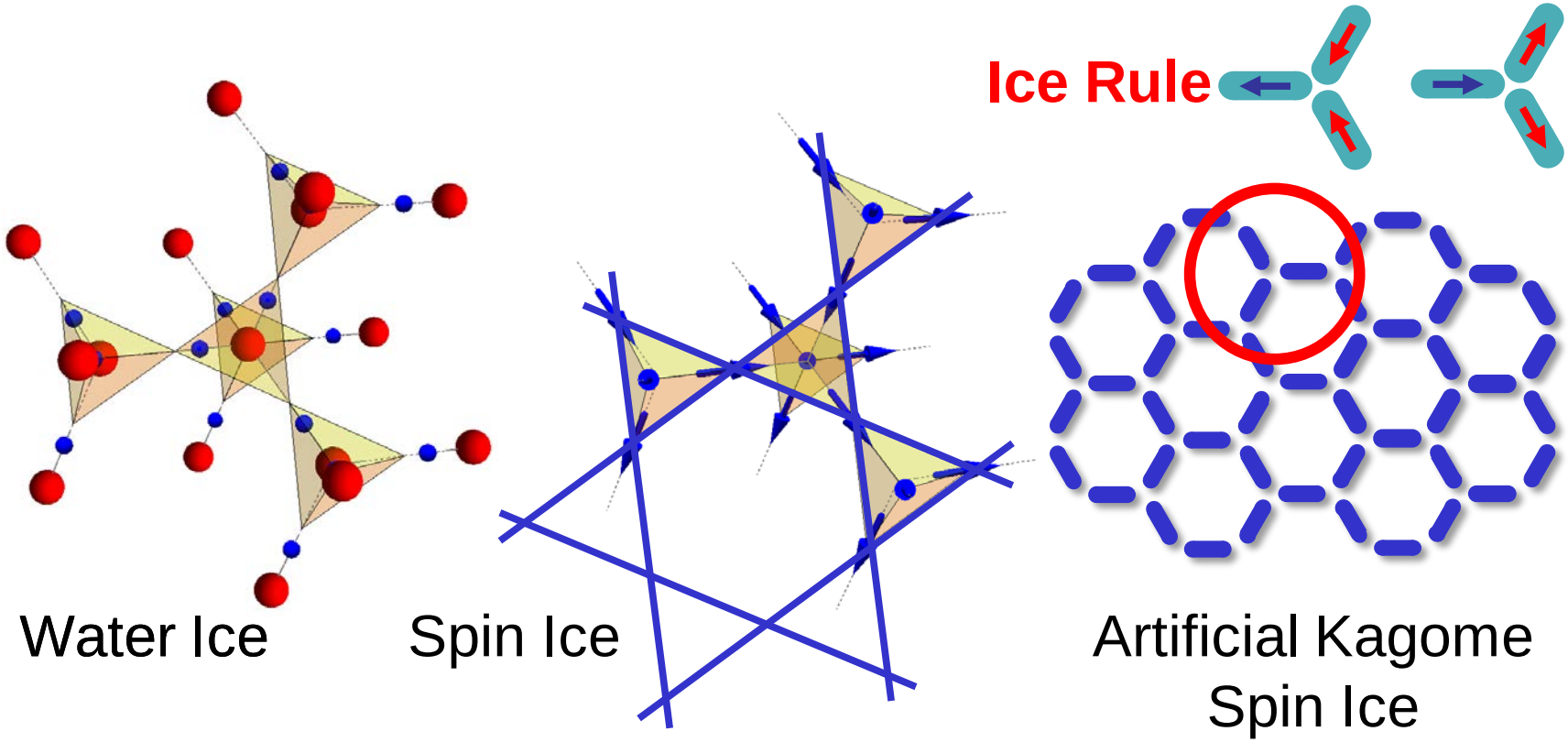


Artificial Spin Ice

RF Wang *et al.*
Nature (2006)

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

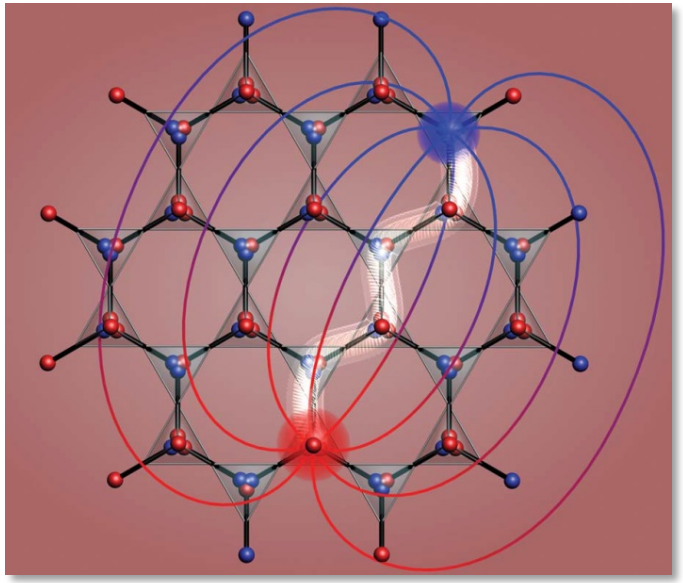
From Water Ice to Artificial Spin Ice



MJ Harris *et al.*
PRL (1997)

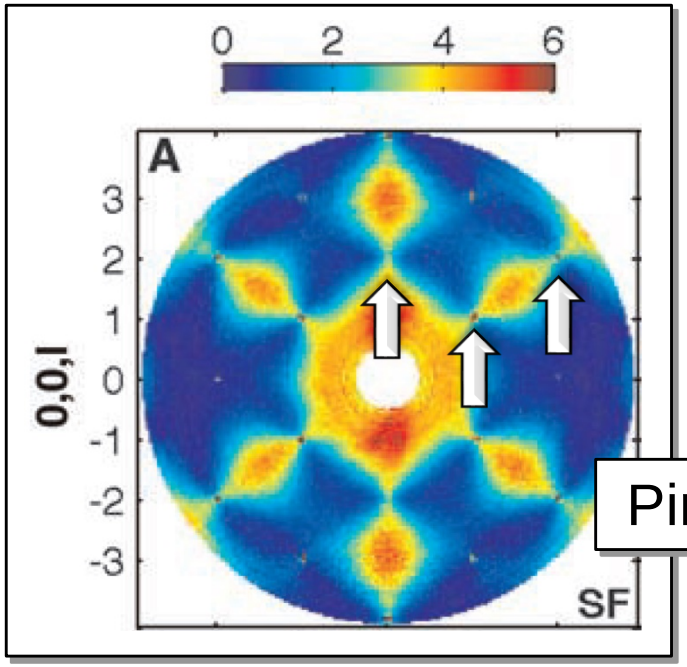
LJ Heyderman & RL Stamps
J Phys: Condens Matter (2013)

Emergent Magnetic Monopoles & Dirac Strings



Magnetic monopoles in spin ice
C Castelnovo, R Moessner & SL Sondhi
Nature (2008)

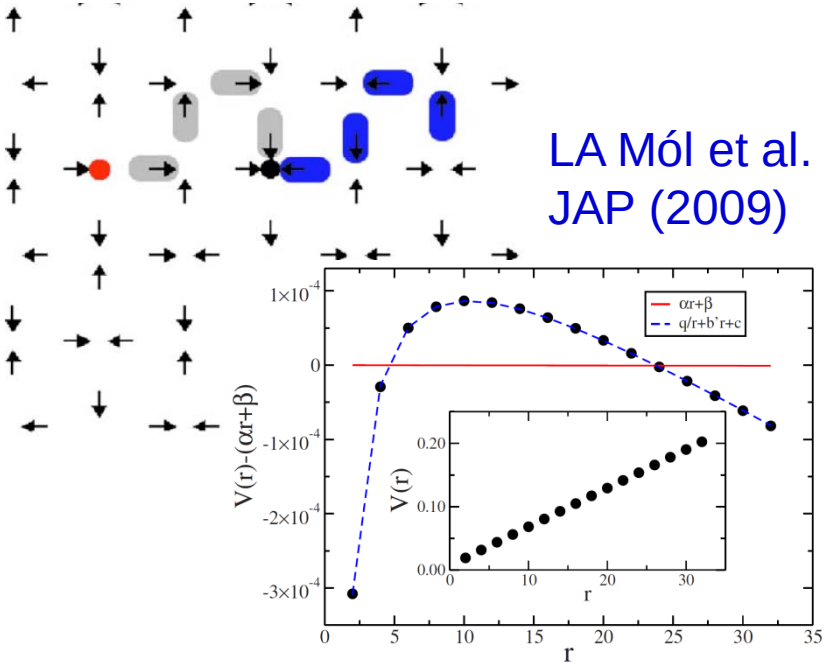
See also:
IA Ryzhkin J. Exp. Theor. Phys (2005)



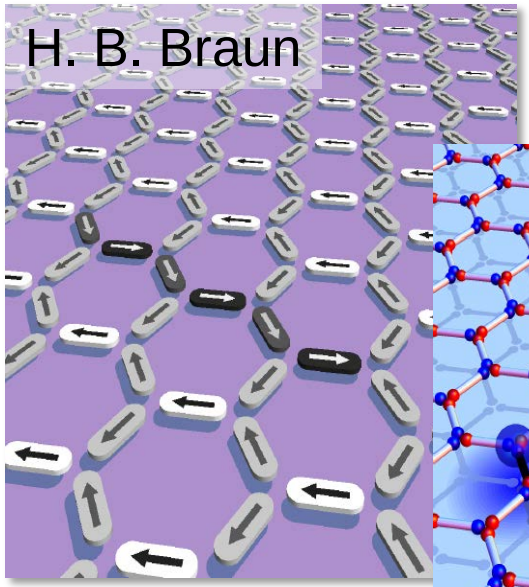
Spin Ice and Neutron Scattering
DJP Morris et al. Science (2009)
T Fennell et al. Science (2009)
H Kadowaki et al. J Phys Soc Jpn (2009)

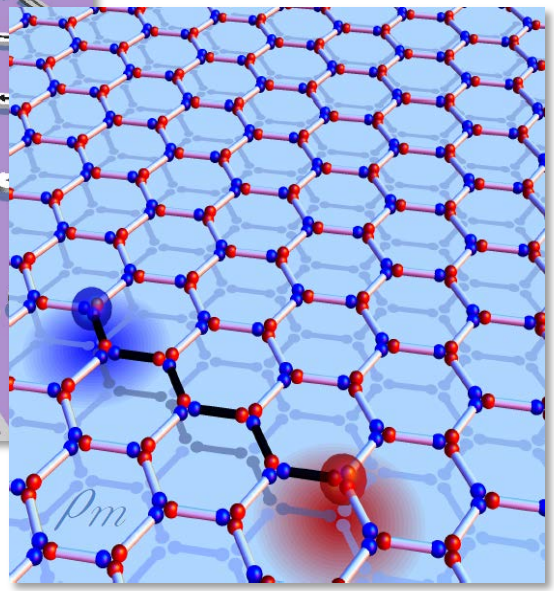
Pinch point singularities

Emergent Magnetic Monopoles & Dirac Strings

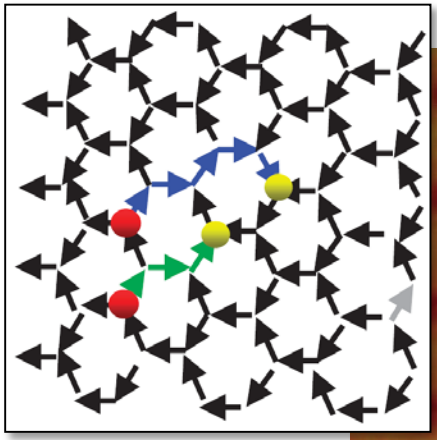


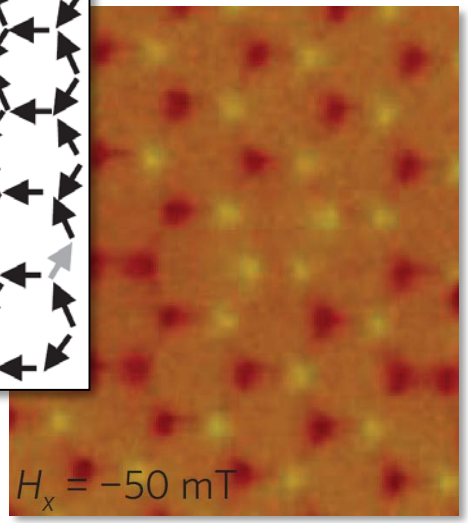
LA Mól et al.
JAP (2009)





E Mengotti et al.
Nature Physics (2011)



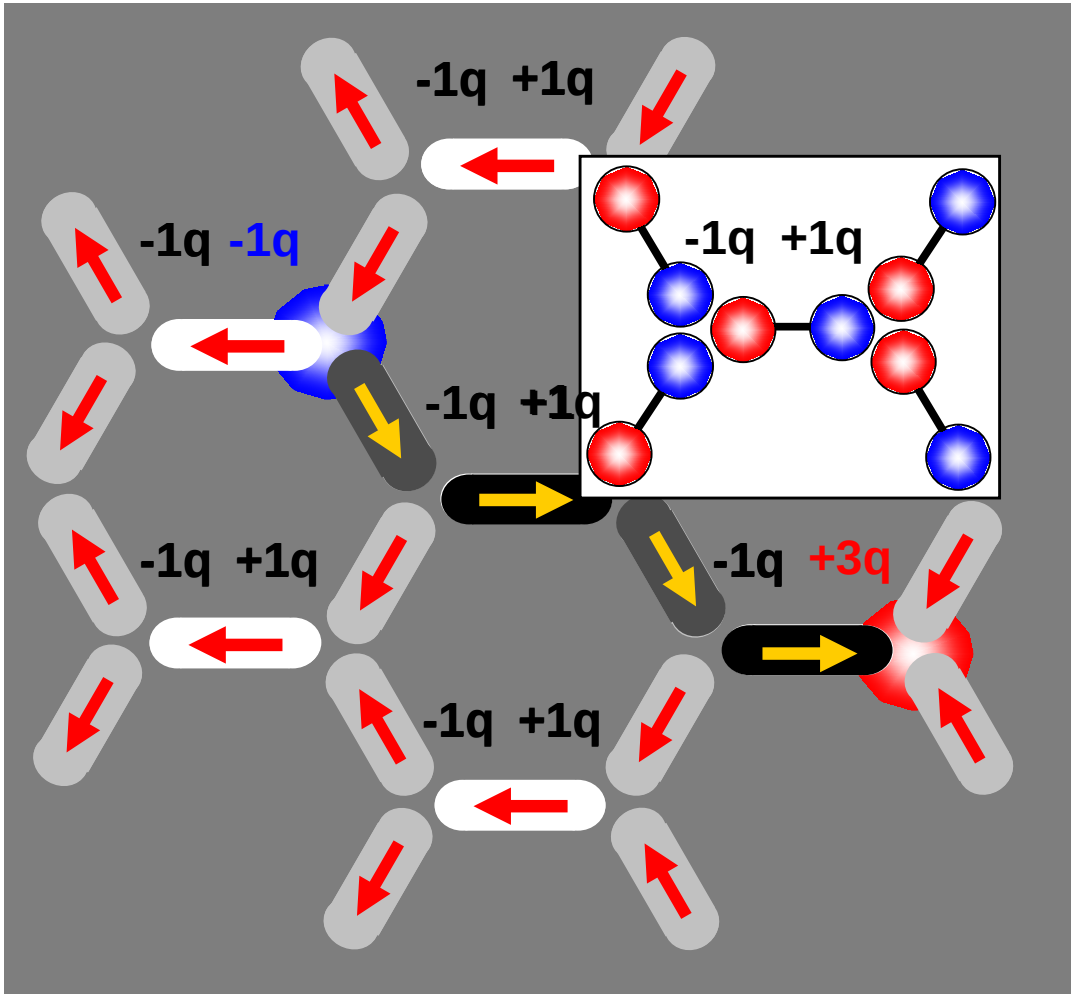


S Ladak et al.
Nature Physics (2010)

Monopoles and Dirac Strings

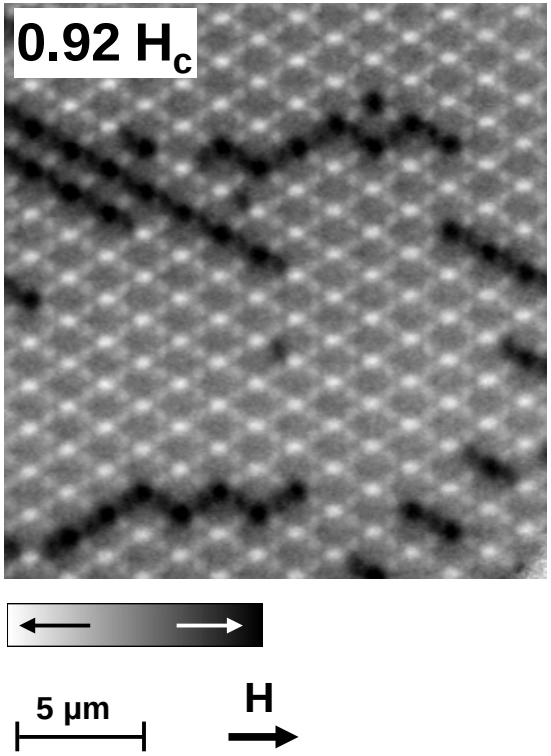
The Charge Model

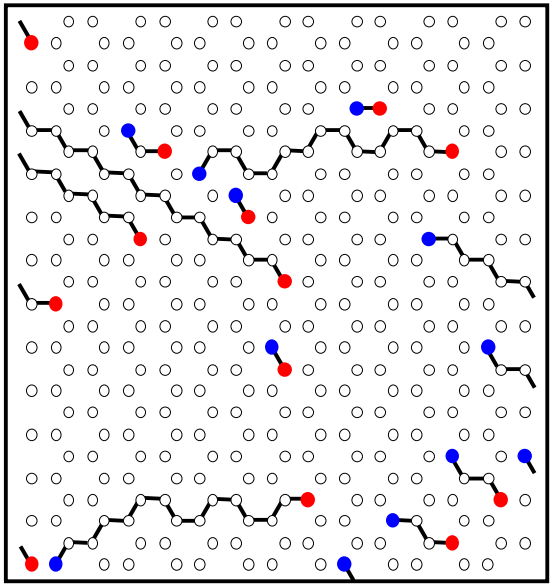
- predicts an NaCl-type charge-ordered ground state
- minimizes both the intrasite and intersite Coulomb interaction

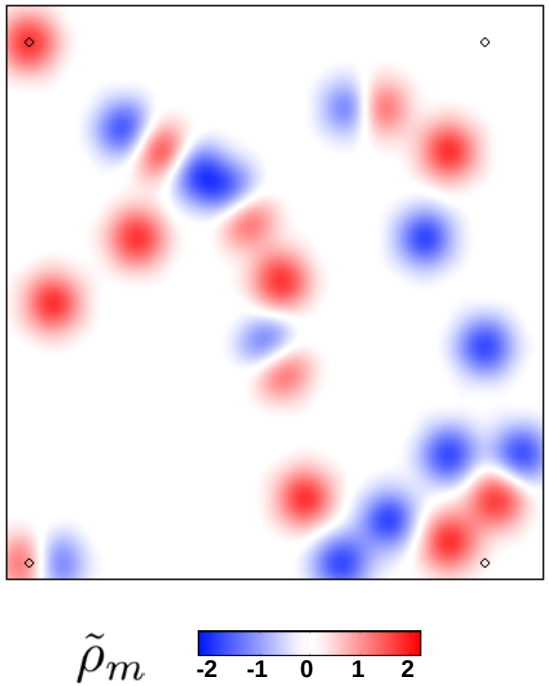


C Castelnovo, R Moessner & SL Sondhi Nature (2008)

Emergent Magnetic Monopoles & Dirac Strings



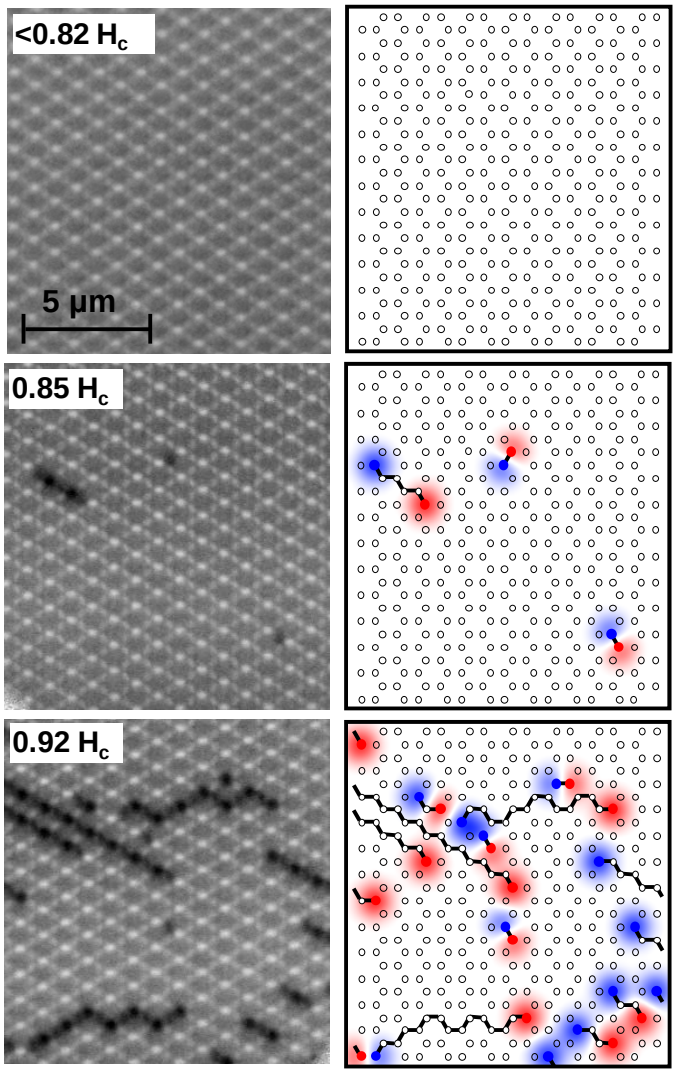


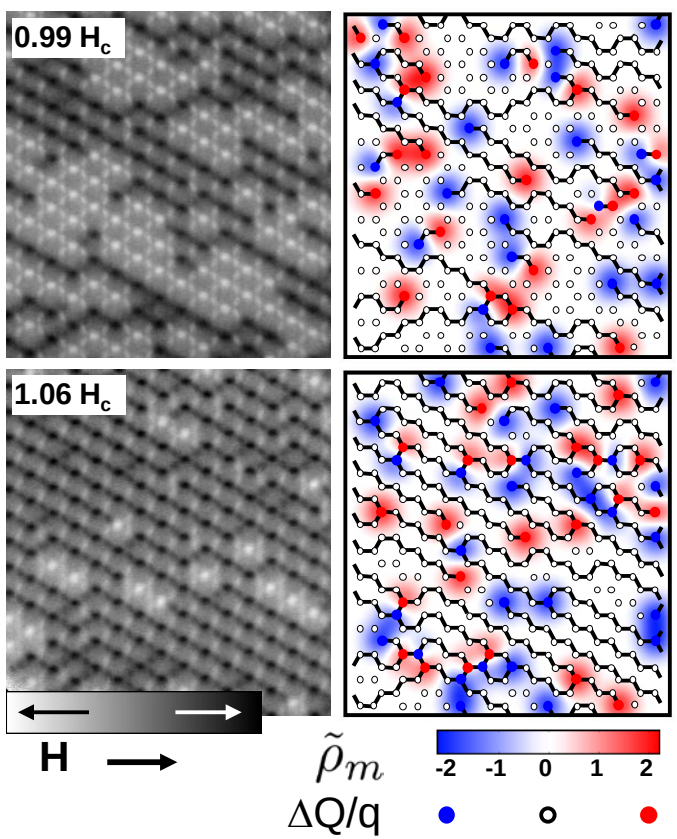


Smeared magnetic charge: $\rho_m(r)=\int d^3r' \exp(-|r'-r|^2/\xi^2)\,\mathrm{div}H$
Castelnovo et al. Nature (2008)

E Mengotti, LJ Heyderman, A Fraile Rodríguez, F Nolting, RV Hügli, HB Braun
Nature Physics (2011)

Emergent Magnetic Monopoles & Dirac Strings

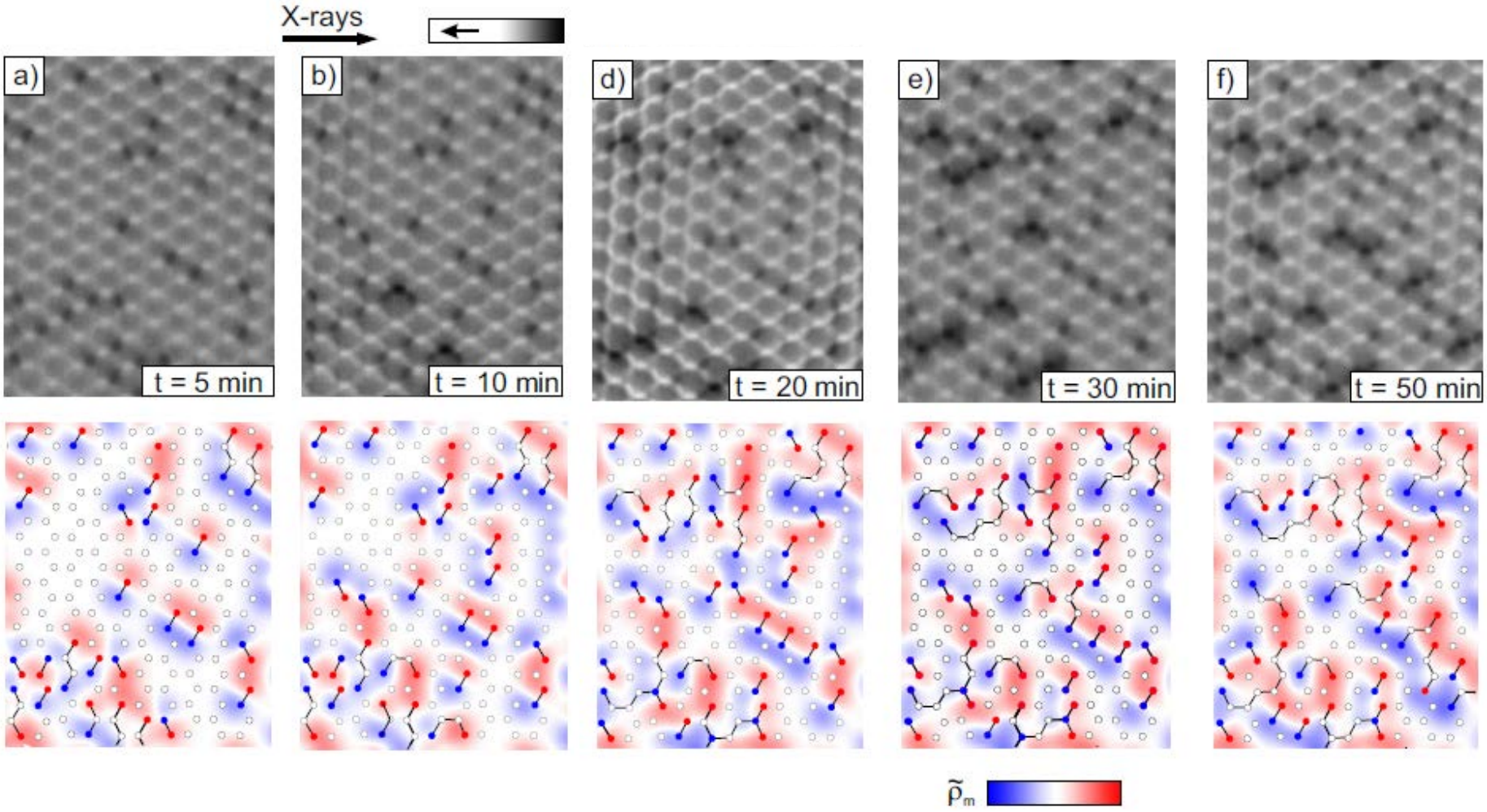




- 1D Avalanches: no branching or u-turns
- Importance of Disorder
- Control of Avalanches

E Mengotti, LJ Heyderman, A Fraile Rodríguez, F Nolting, RV Hügli, HB Braun
Nature Phys (2011); RV Hügli et al. JAP & Phil Trans Roy Soc A (2012)

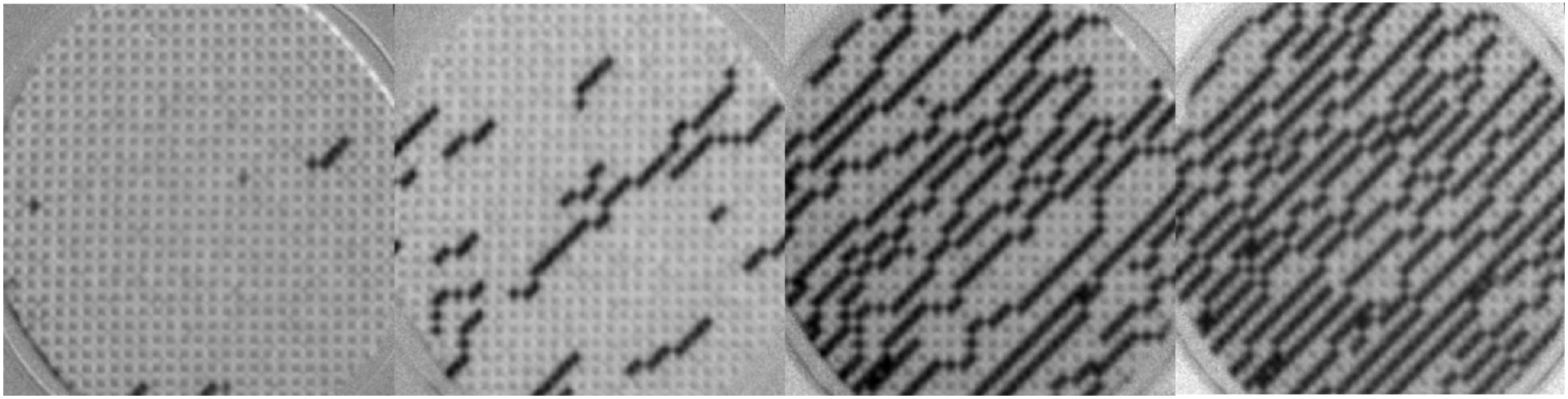
Thermally Active Artificial Kagome Ice

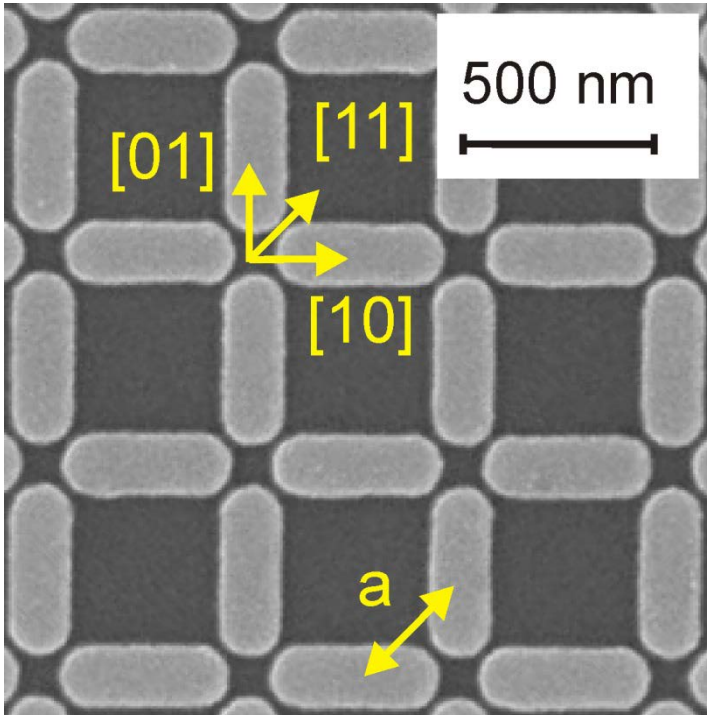


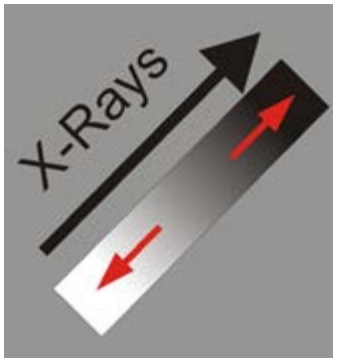
A Farhan, PM Derlet, L Anghinolfi, A Kleibert and LJ Heyderman PRB (2017)

Thermal Artificial Square Ice

Field of View 20 μm





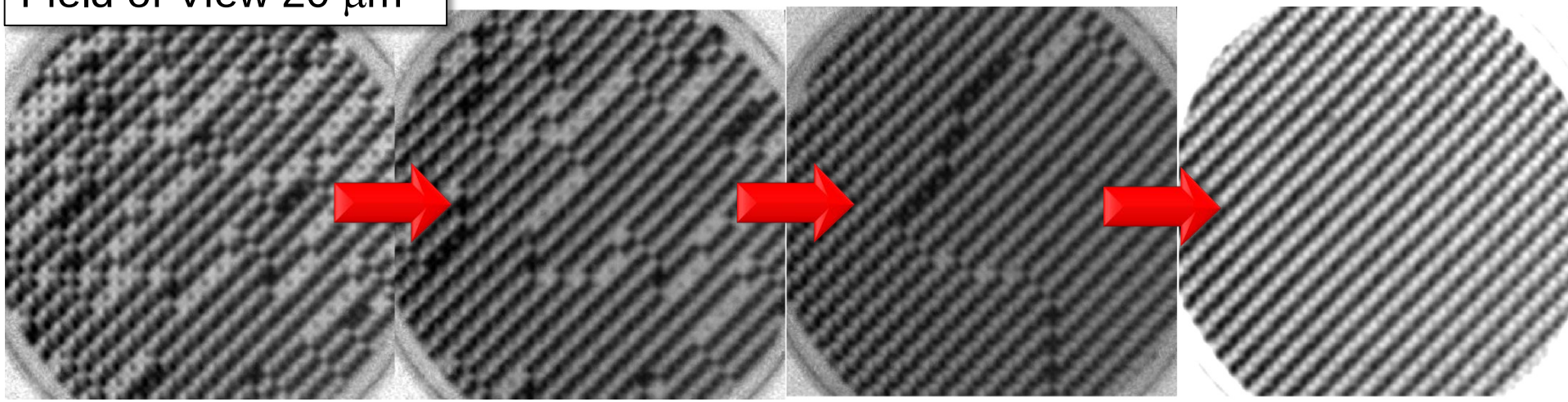


"String Regime"

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

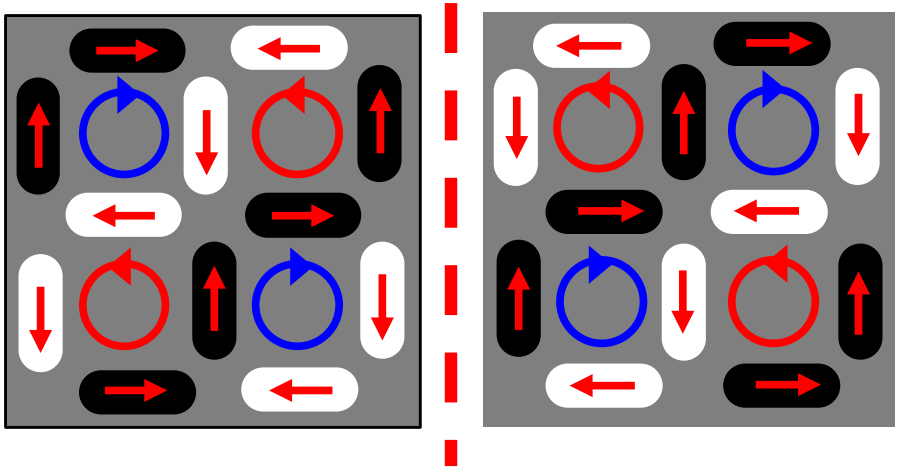
Thermal Artificial Square Ice

Field of View 20 μm



Field of View 50 μm

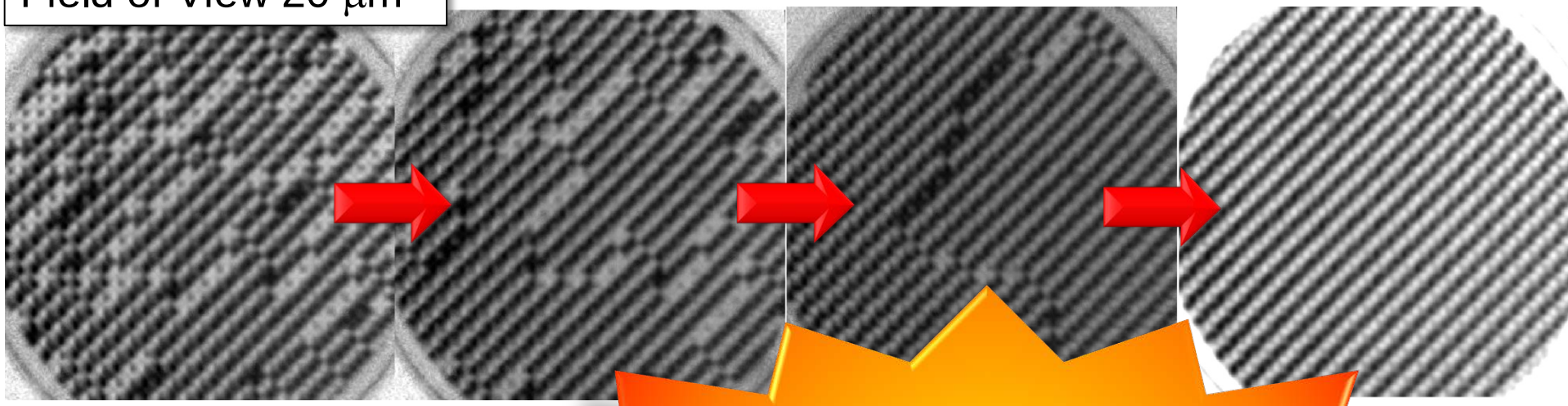
“Domain Regime”



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

Thermal Artificial Square Ice

Field of View 20 μm

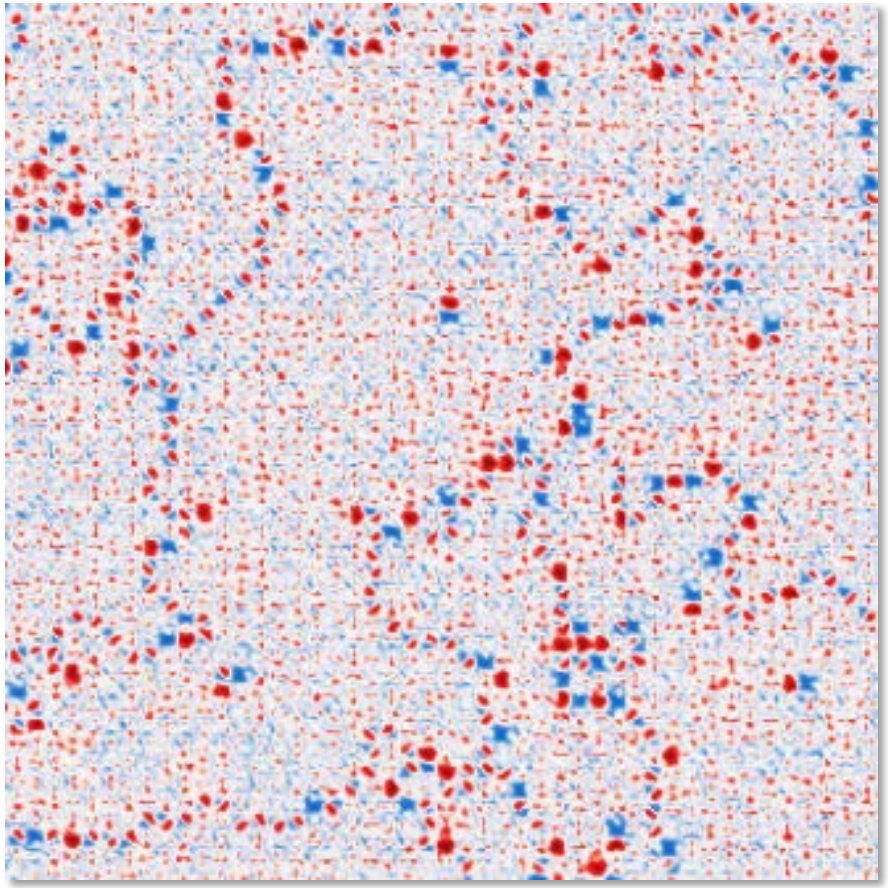


Field of View 50 μm

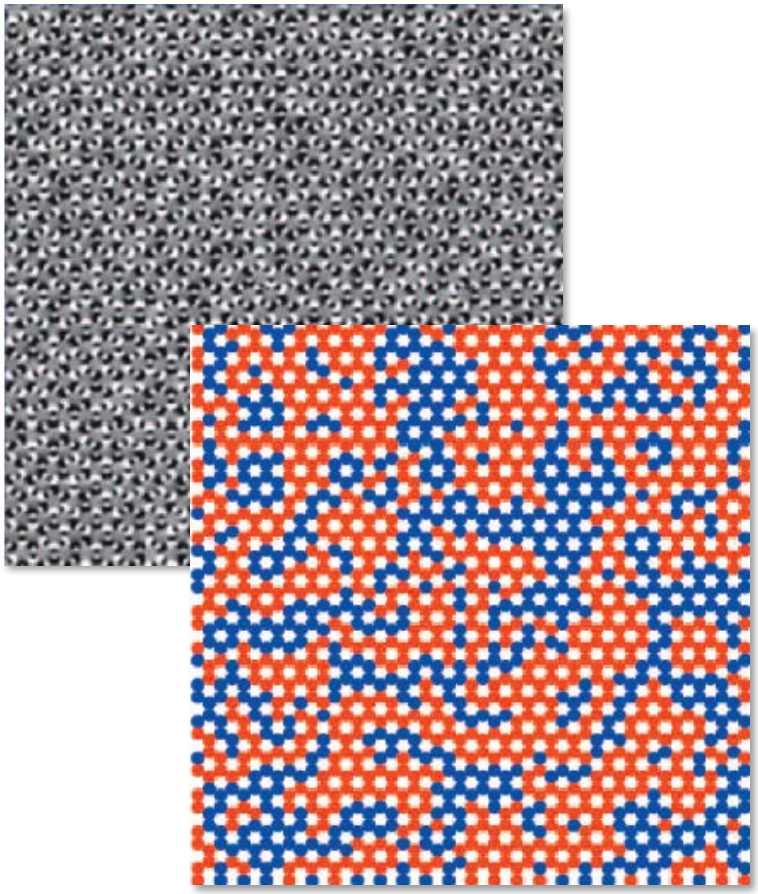
Thermally active systems provide a route to the ground state…..

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

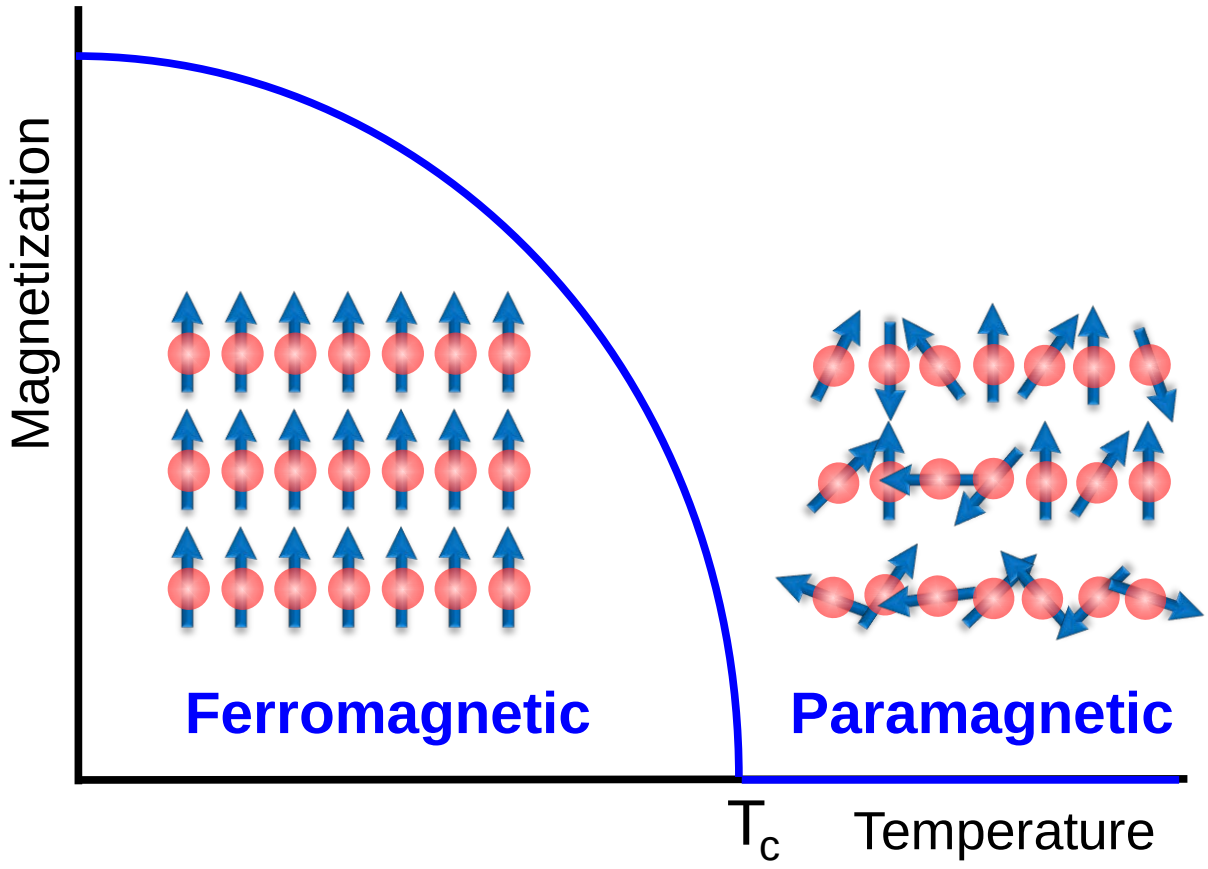
Thermal Behaviour



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



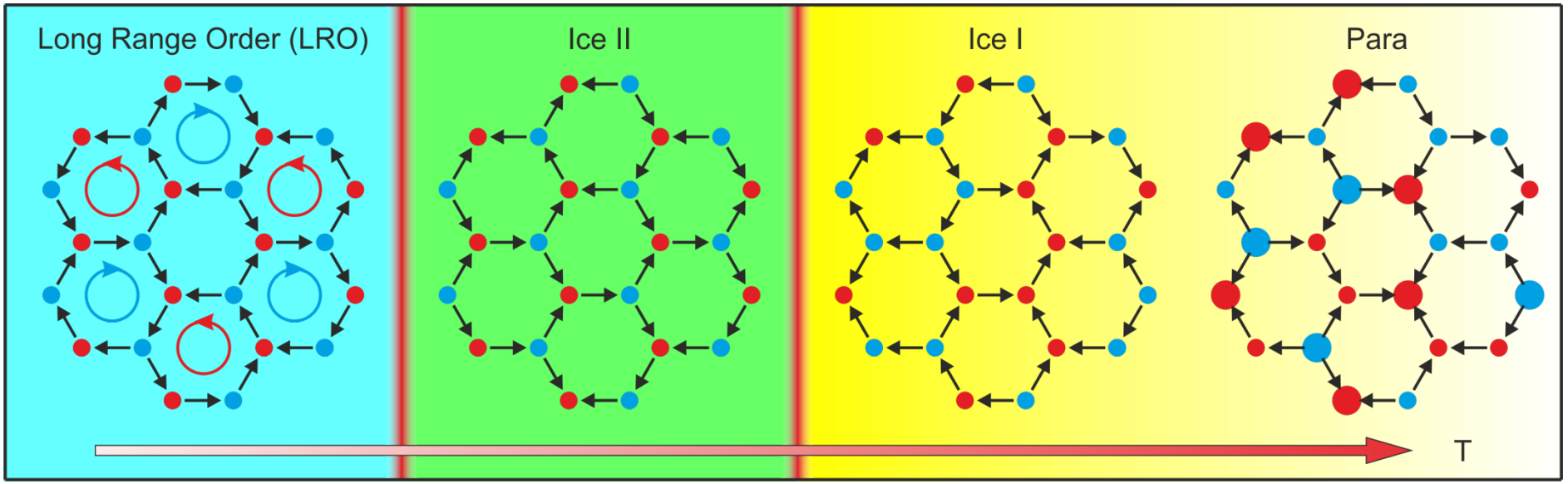
S Zhang et al. Nature (2013)



Topic 2

Phase transitions in a magnetic metamaterial

Kagome Spin Ice Phases

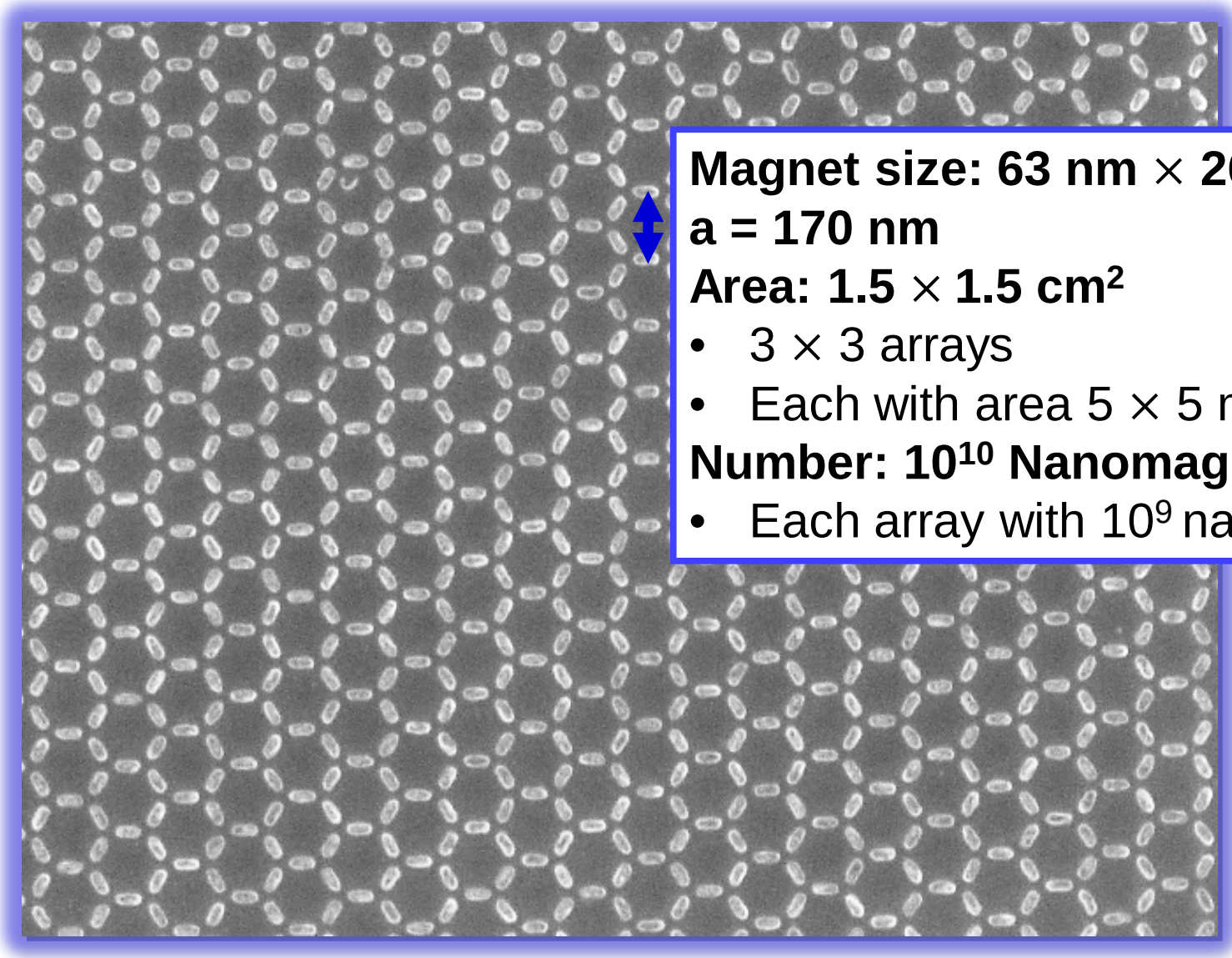


G Moller, R Moessner
Magnetic multipole analysis of kagome and artificial spin-ice dipolar arrays
Phys Rev B (2009)

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 cm^2

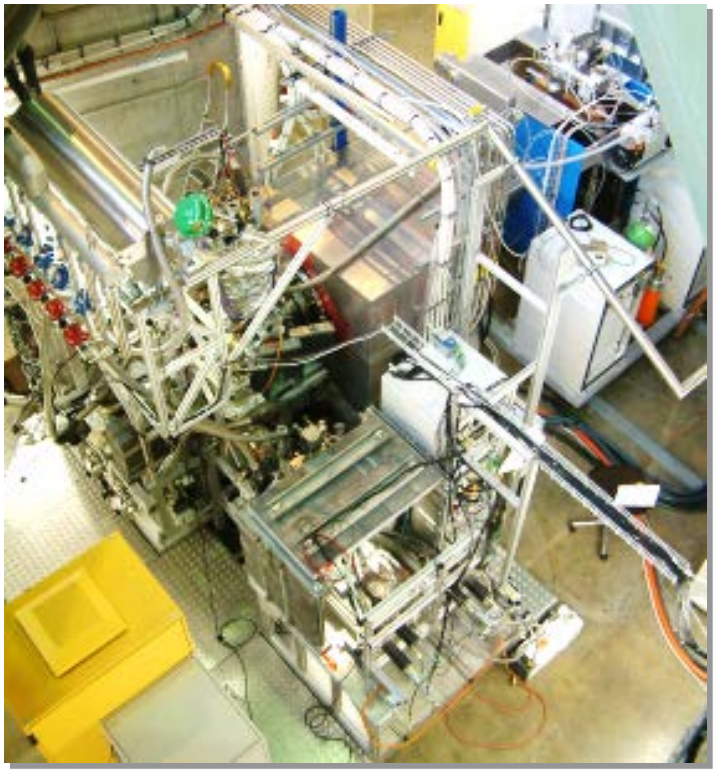
- 3 × 3 arrays
- Each with area 5 × 5 mm^2

Number: 10^{10} Nanomagnets

- Each array with 10^9 nanomagnets

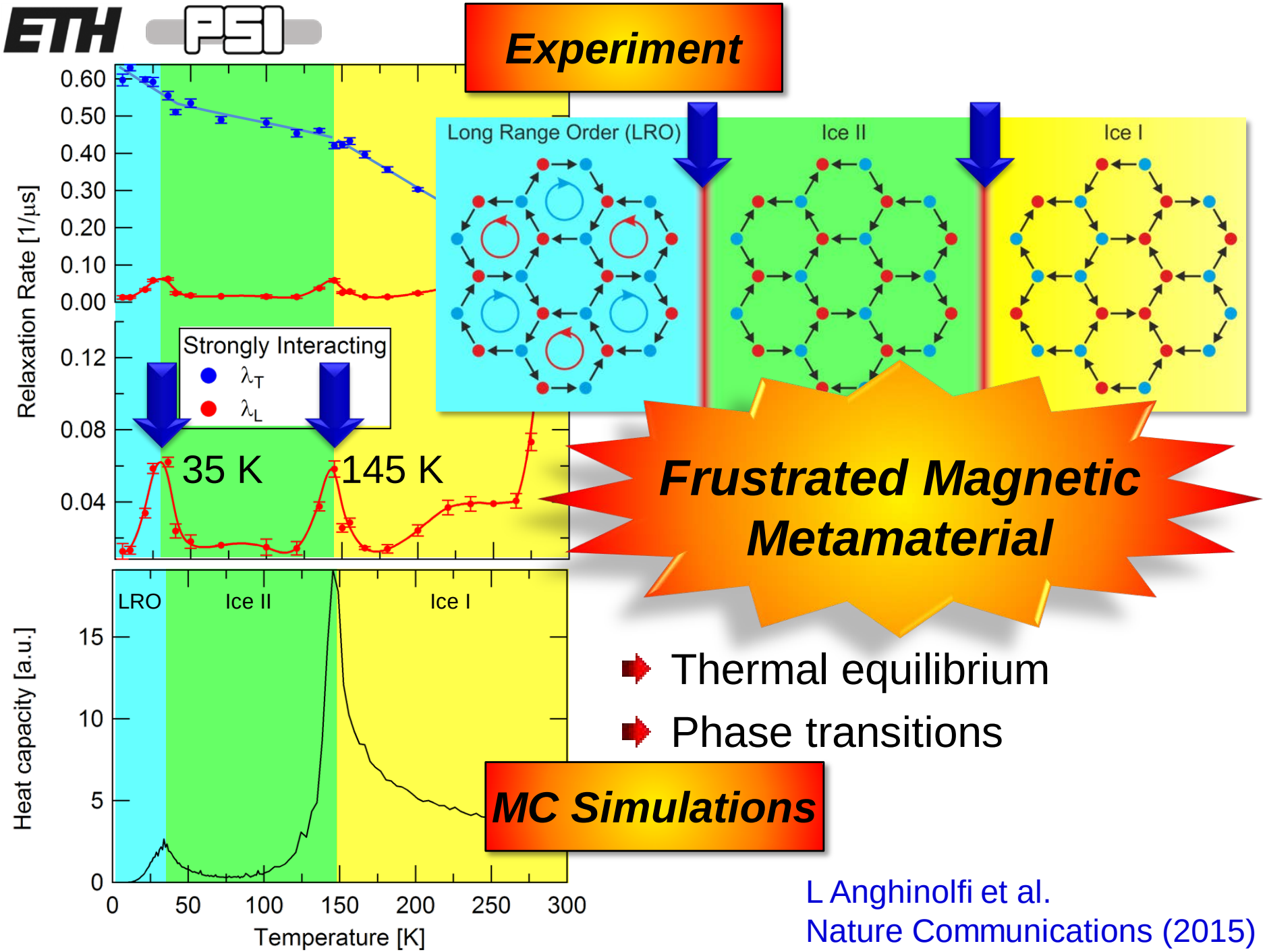
L Anghinolfi et al. Nature Communications (2015)

Low Energy Muons (LEM, PSI)

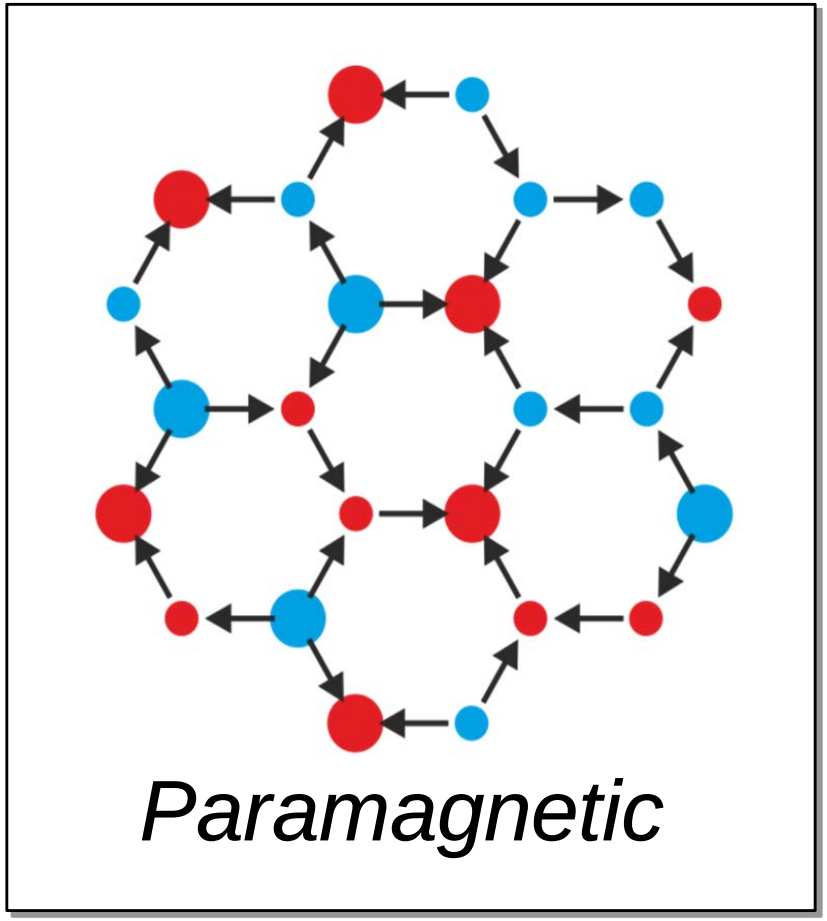


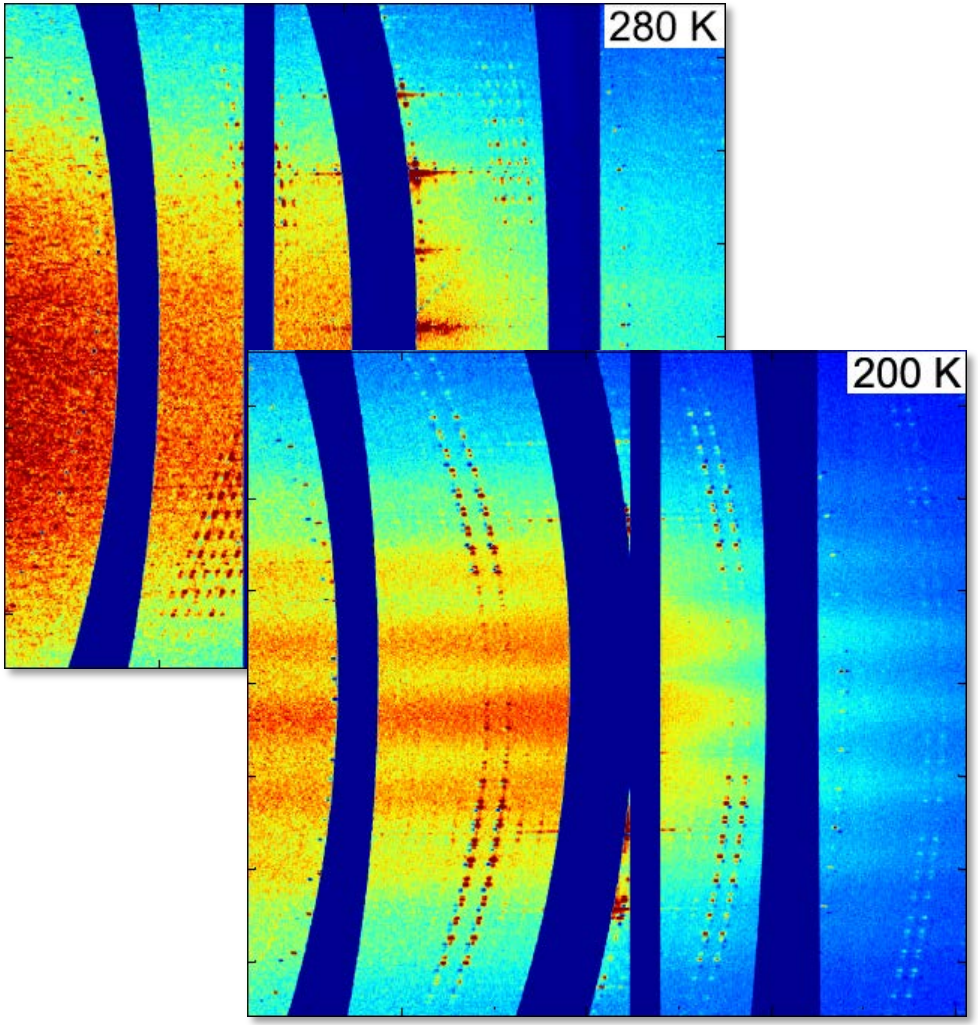
- Zero applied field
- Temperature control
- Local probe
- Magnetic phase transitions
- Tunable implantation depths: 1-100 nm
- Ideal for thin films and nanostructures

L Anghinolfi et al. Nature Communications (2015)


Experiment
Relaxation Rate [1/μs]
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.12
0.08
0.04
Strongly Interacting
λT
λL
35 K
145 K
Long Range Order (LRO)
Ice II
Ice I
Frustrated Magnetic Metamaterial
Thermal equilibrium
Phase transitions
Heat capacity [a.u.]
LRO
Ice II
Ice I
15
10
5
0
0
50
100
150
200
250
300
Temperature [K]
MC Simulations
L Anghinolfi et al.
Nature Communications (2015)

Artificial Kagome Spin Ice



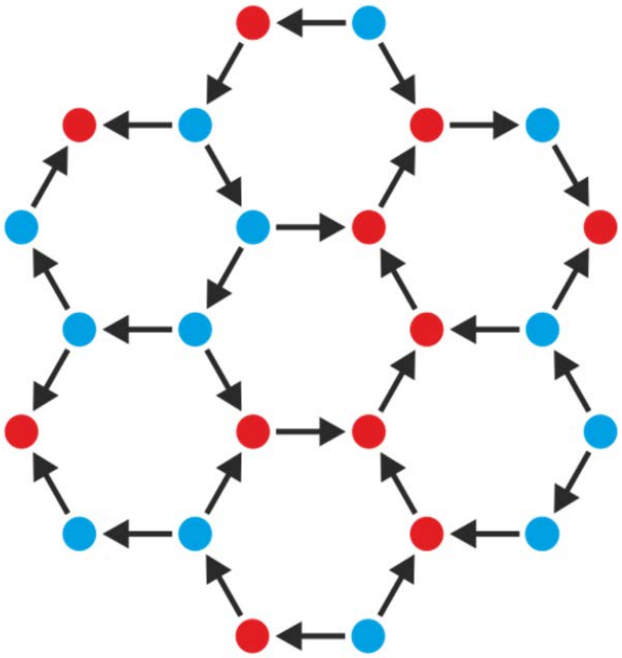


Soft X-ray Resonant Magnetic Scattering

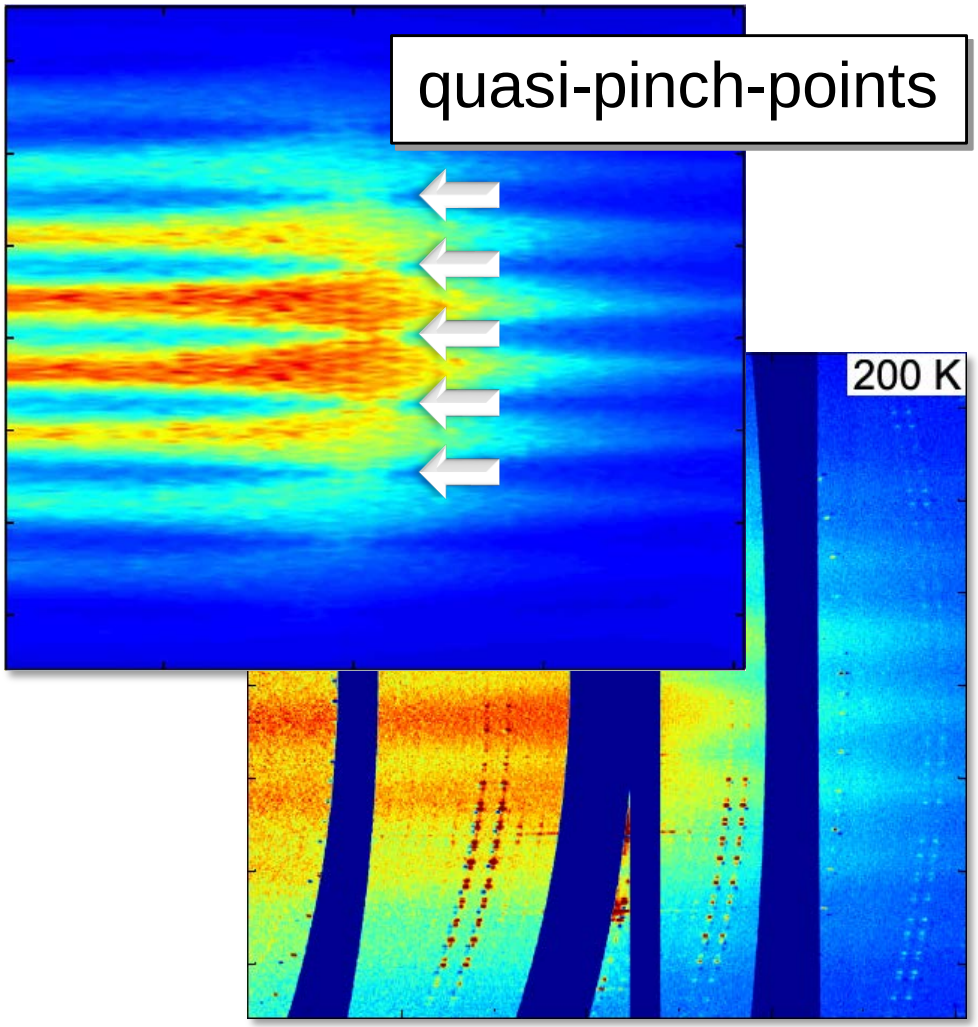
J Perron et al. Phys Rev B (2013)

O Sendetskyi et al. Phys Rev B (2016)

Artificial Kagome Spin Ice



Kagome Ice I



Soft X-ray Resonant Magnetic Scattering

J Perron et al. Phys Rev B (2013)

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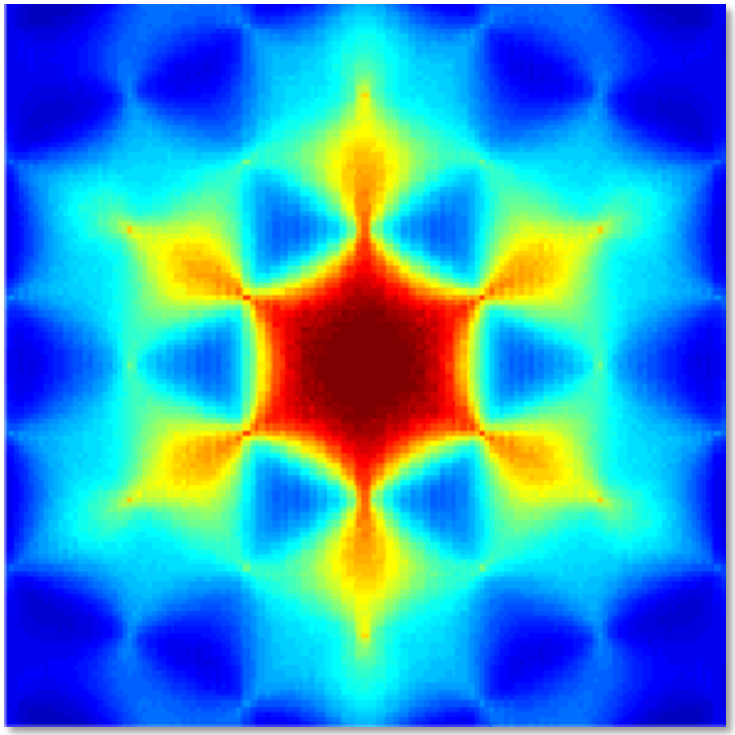
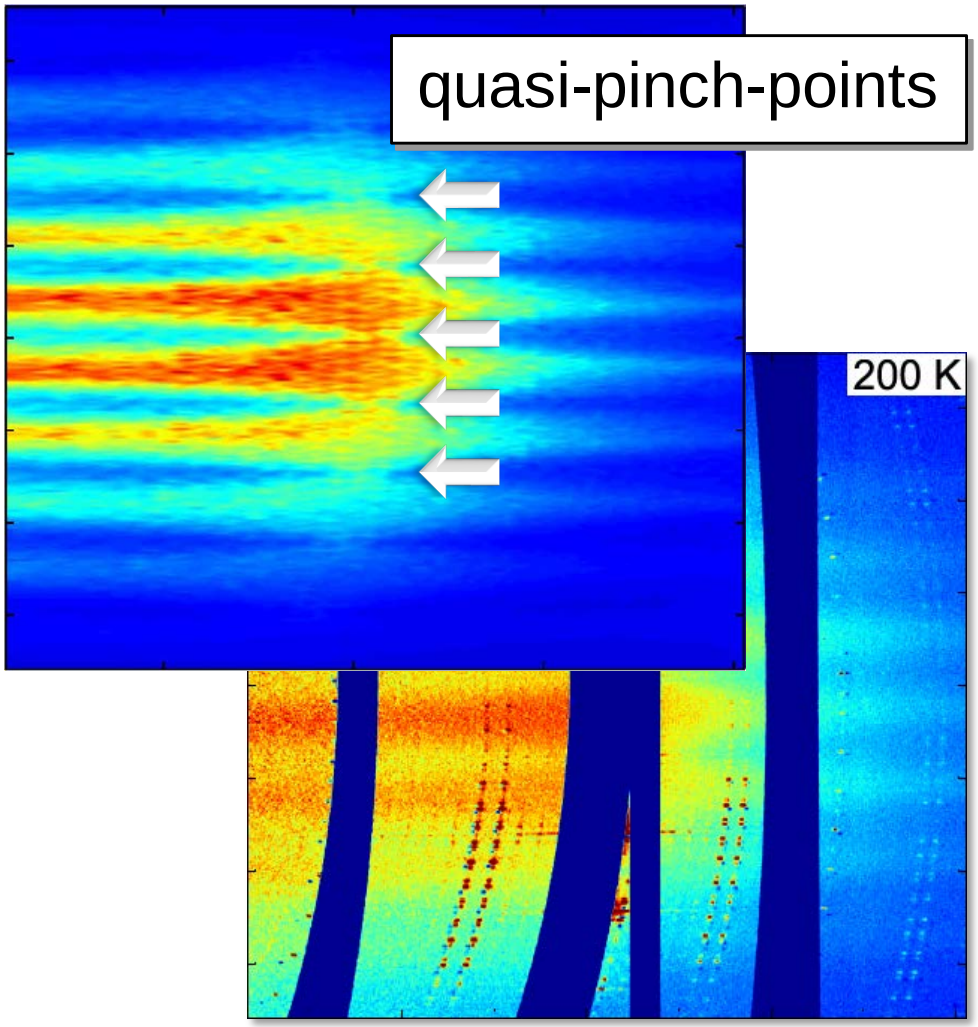
Artificial Kagome Spin Ice



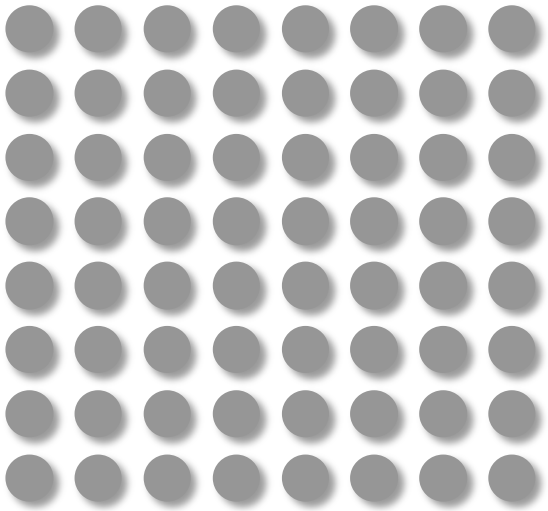


Soft X-ray Resonant Magnetic Scattering

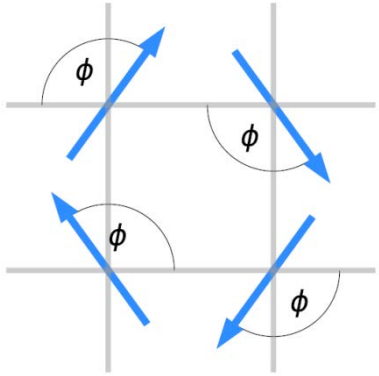
J Perron et al. Phys Rev B (2013)

O Sendetskyi et al. Phys Rev B (2016)

dXY System - Theory



Stripe Phas

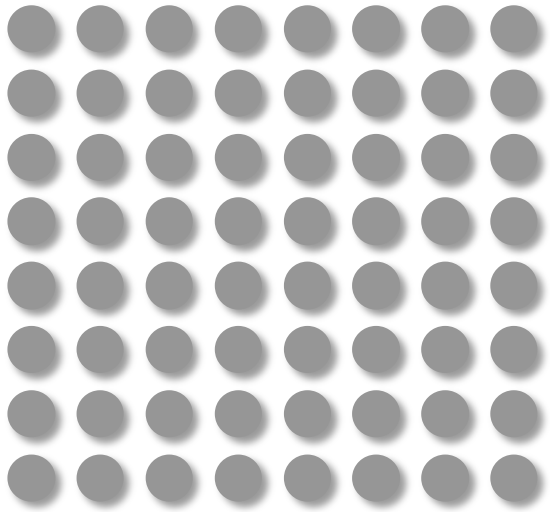


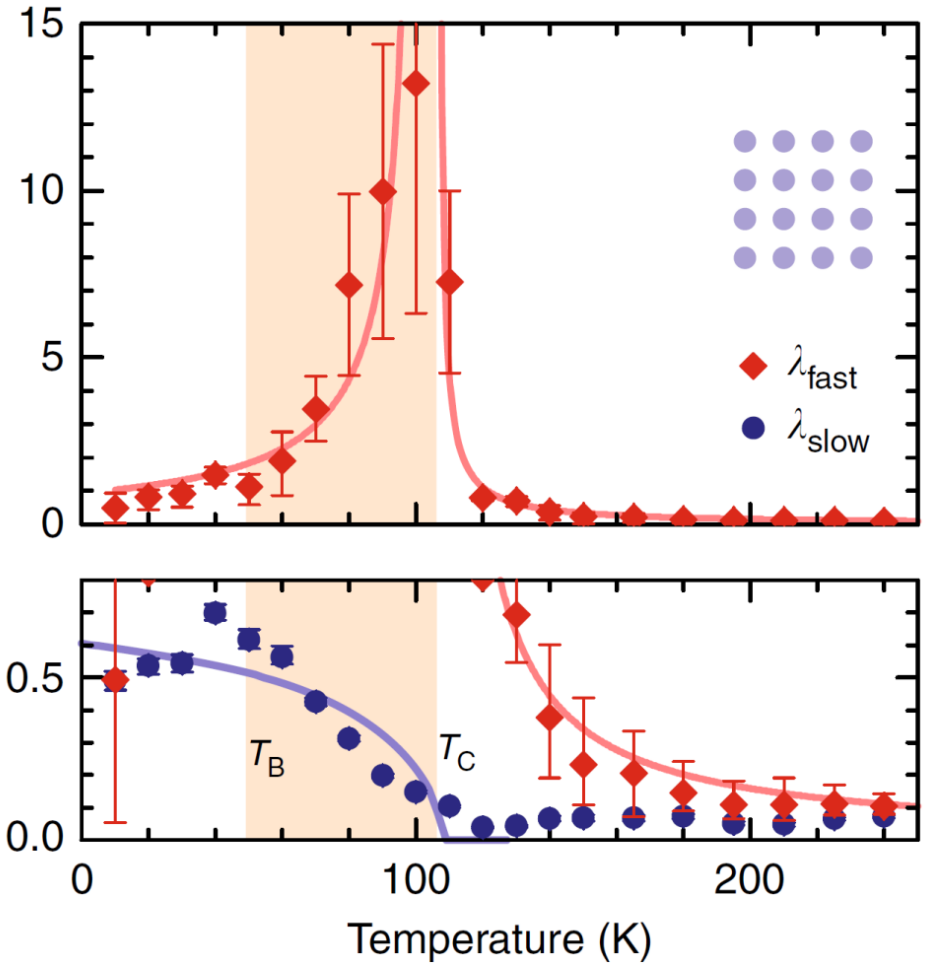
- Continuous ground-state degeneracy
- Order-by-disorder transition: thermal fluctuations → long-range ordered phase
- Theory predicts a continuous transition to AFM stripe order

N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

D Schildknecht, L Heyderman & P Derlet Phys Rev B (2018)

dXY System

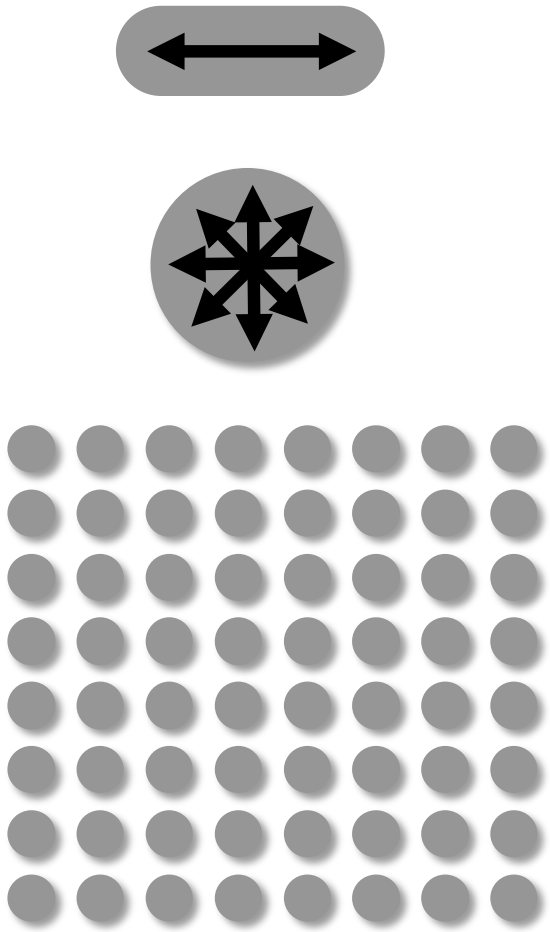


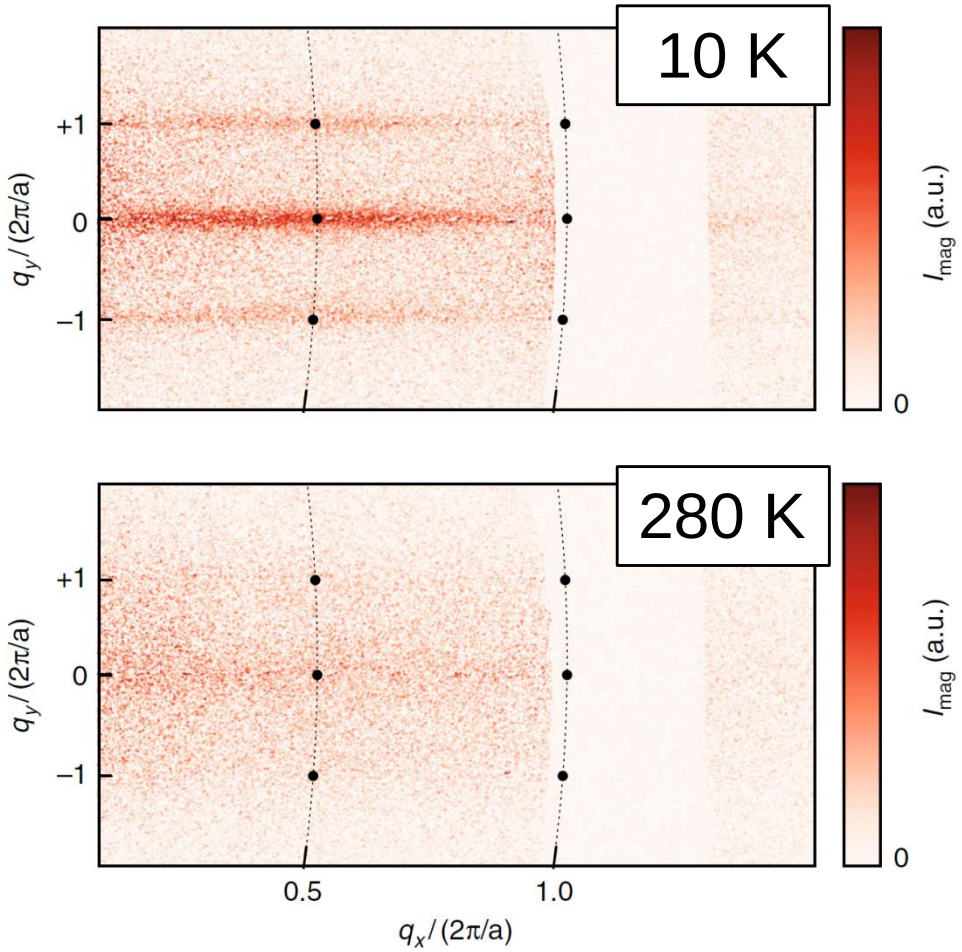


N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

D Schildknecht, L Heyderman & P Derlet Phys Rev B (2018)

dXY System

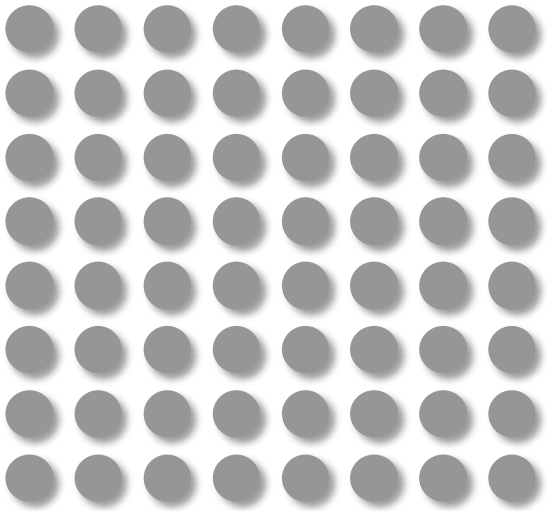




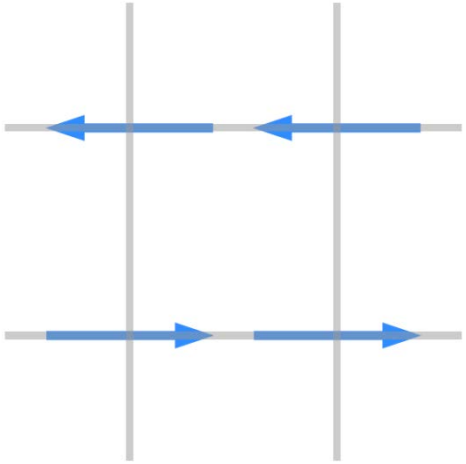
N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

D Schildknecht, L Heyderman & P Derlet Phys Rev B (2018)

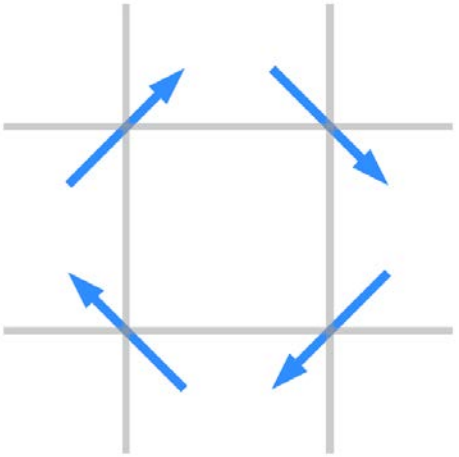
dXY System & Disorder



Stripe Phase



Microvortex Phase

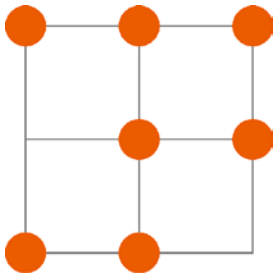


N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

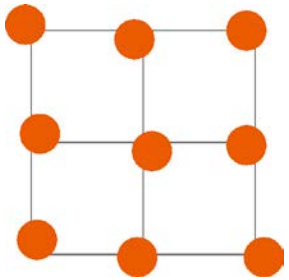
D Schildknecht, L Heyderman & P Derlet Phys Rev B (2018)

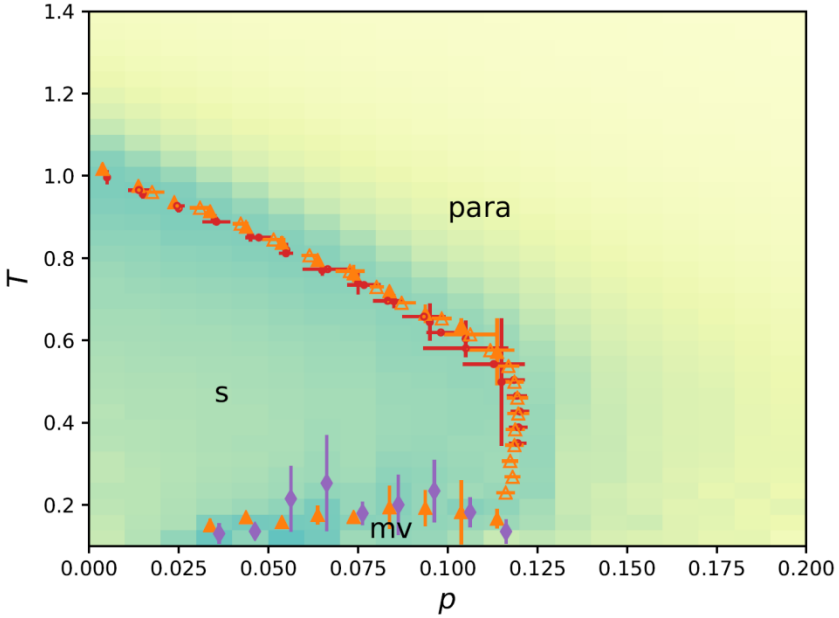
dXY System & Disorder

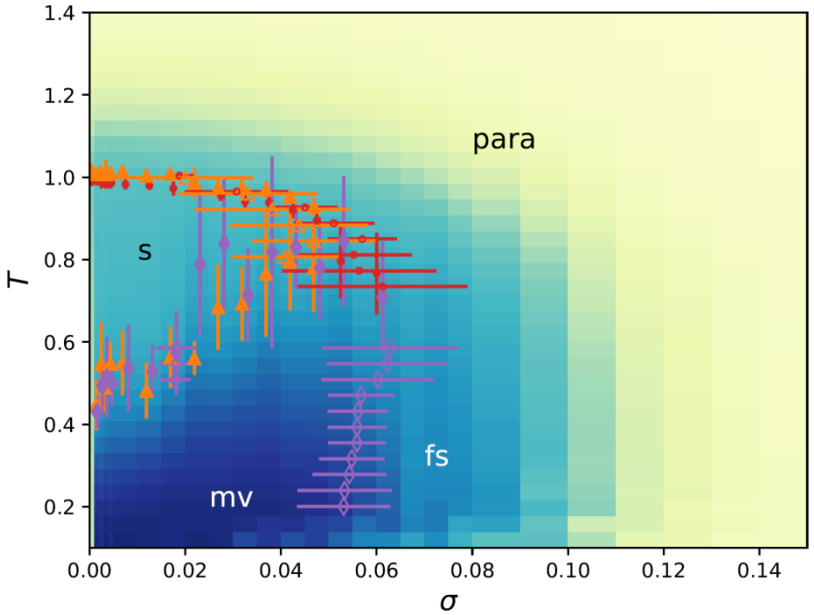
Diluted



Random Displacement

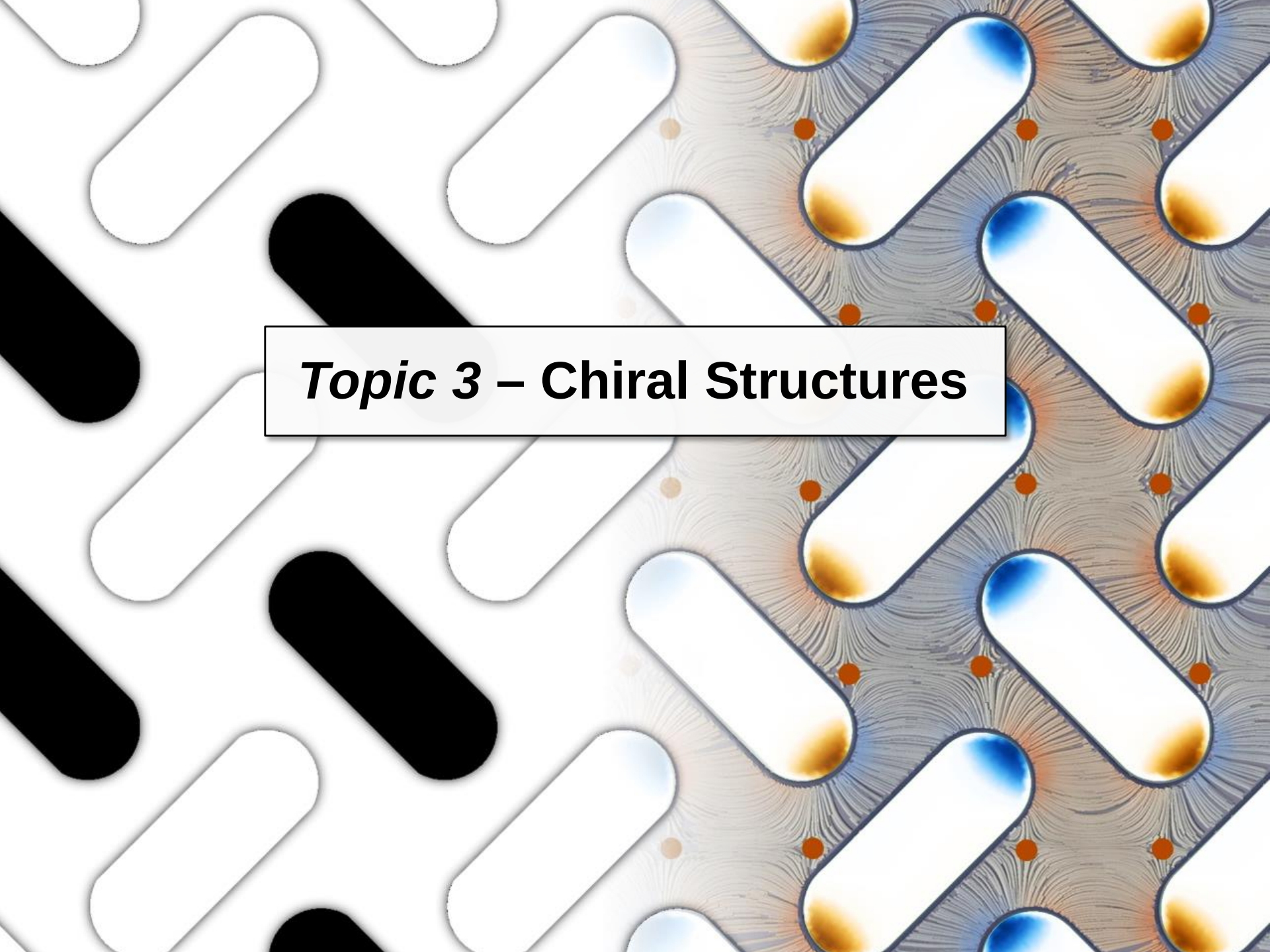






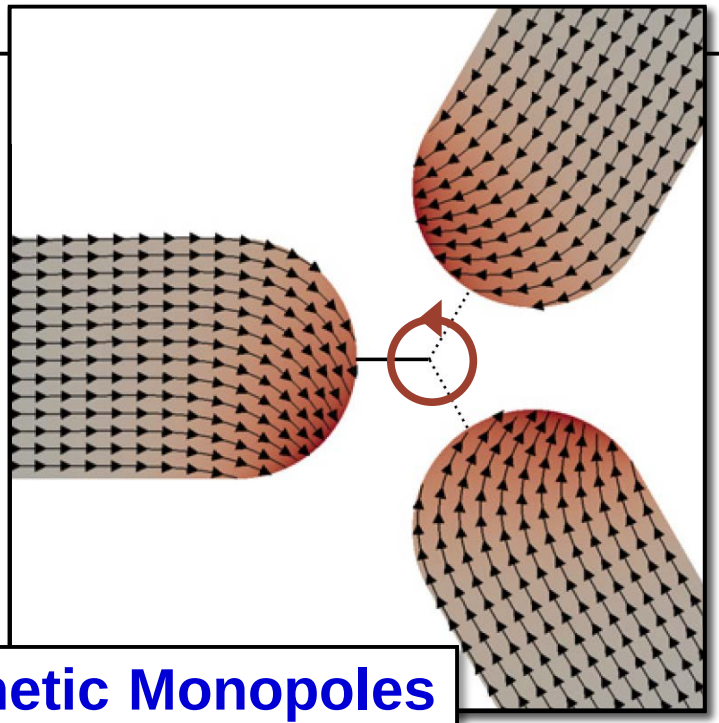
N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

D Schildknecht, L Heyderman & P Derlet Phys Rev B (2018)



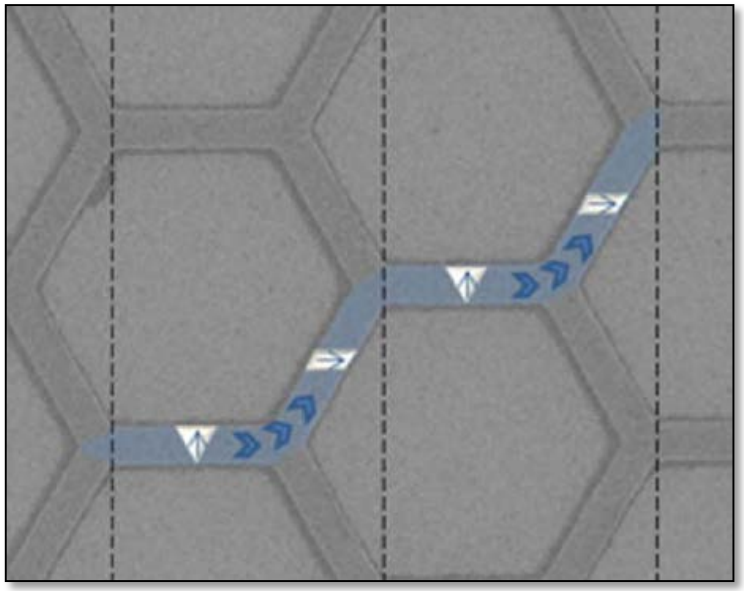
Topic 3 – Chiral Structures

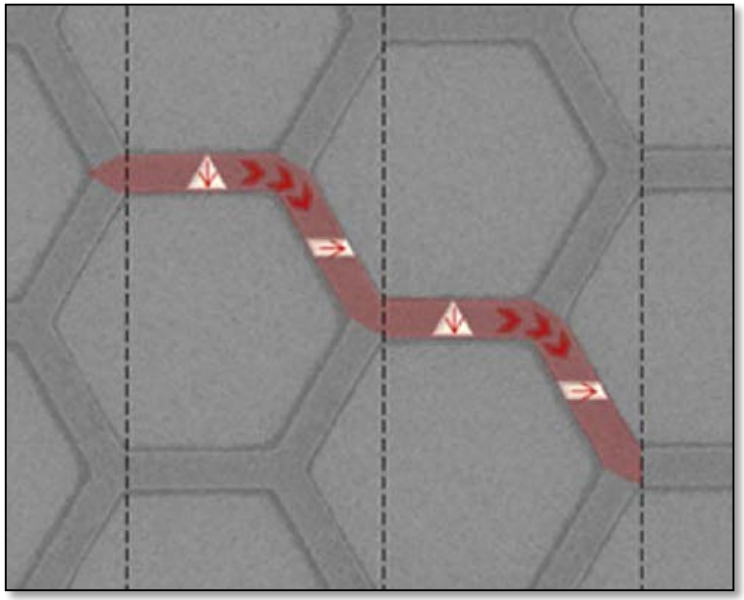
Chirality in Artificial Spin Ice



Chiral Magnetic Monopoles

N Rougemaille et al. NJP 2013

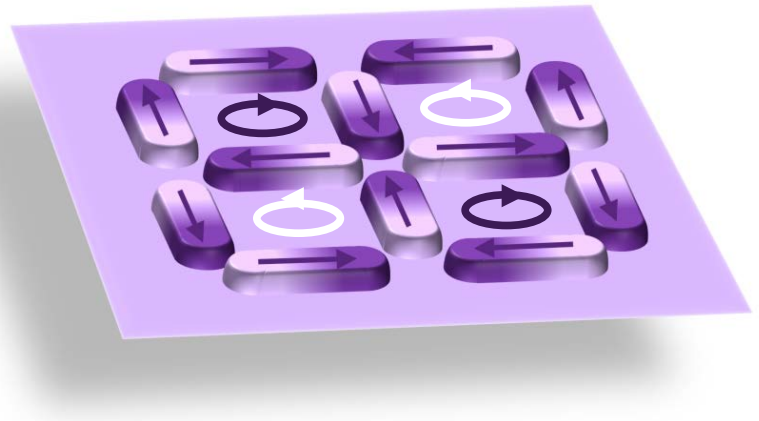




Domain Walls & Connected Networks

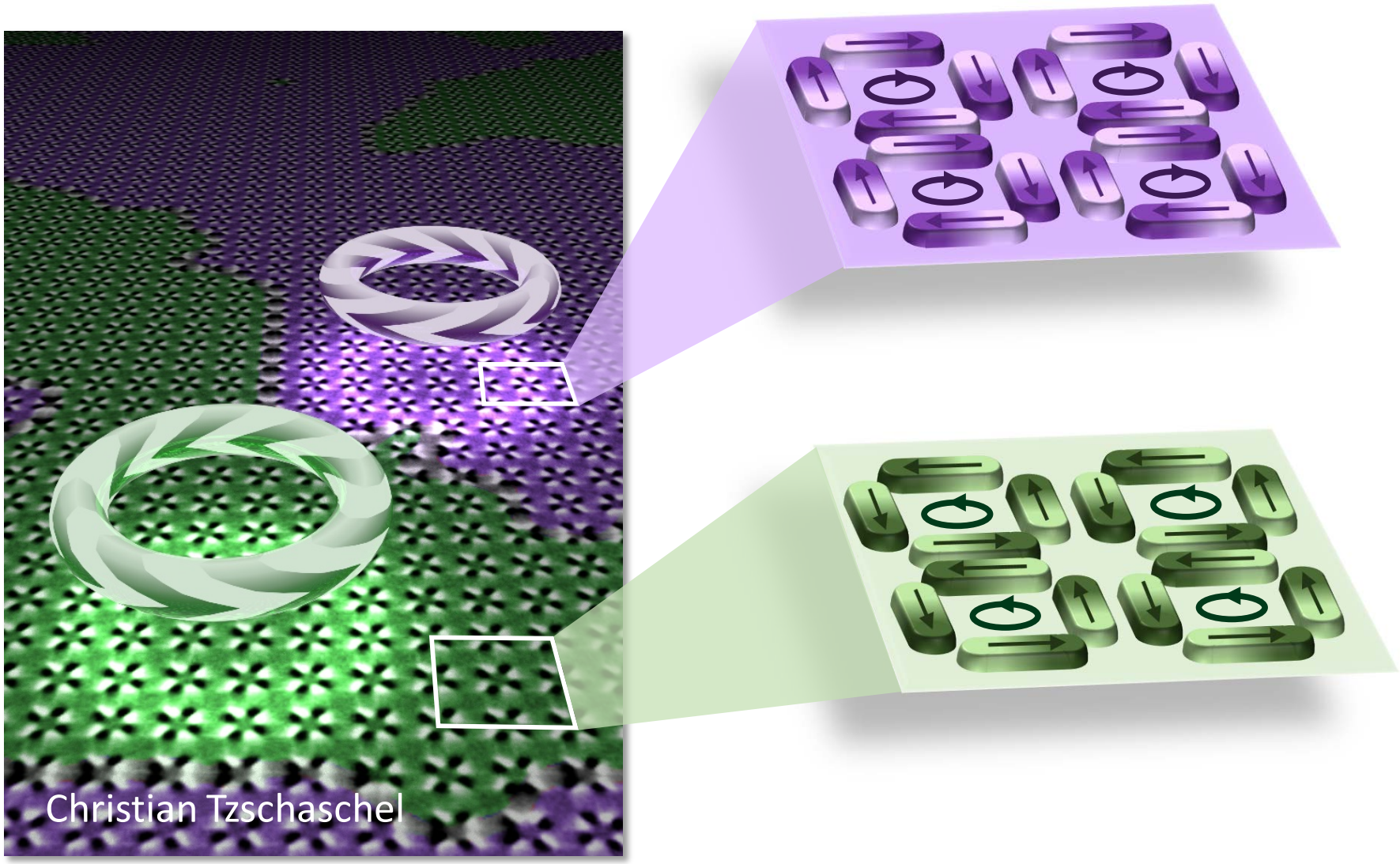
A Pushp et al. Nature Phys 2013
K Zeissler et al. Sci. Rep. 2013

Artificial Magneto-Toroidal Crystal



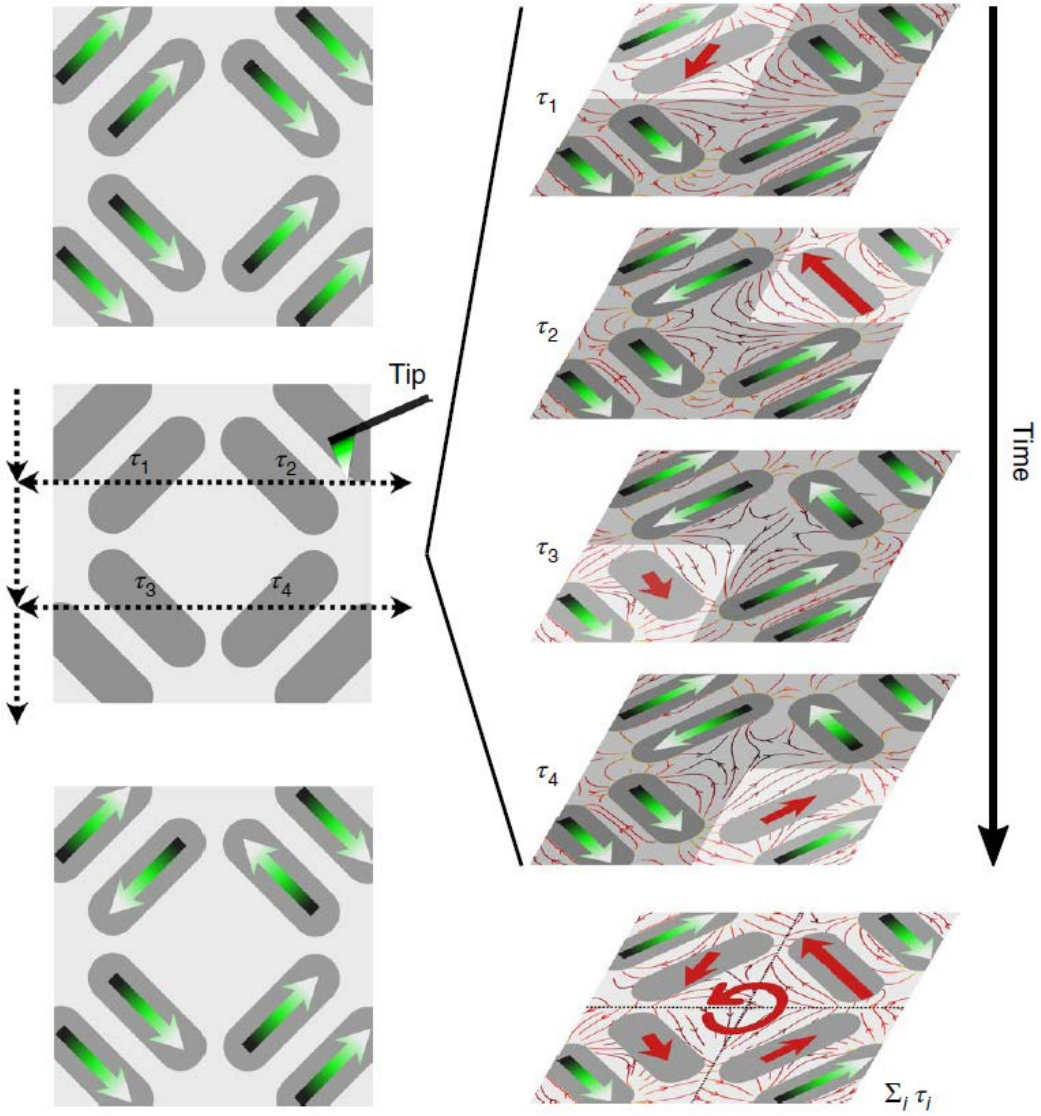
J Lehmann, C Donnelly, PM Derlet, LJ Heyderman and M Fiebig
Nature Nanotechnology (2018)

Artificial Magneto-Toroidal Crystal



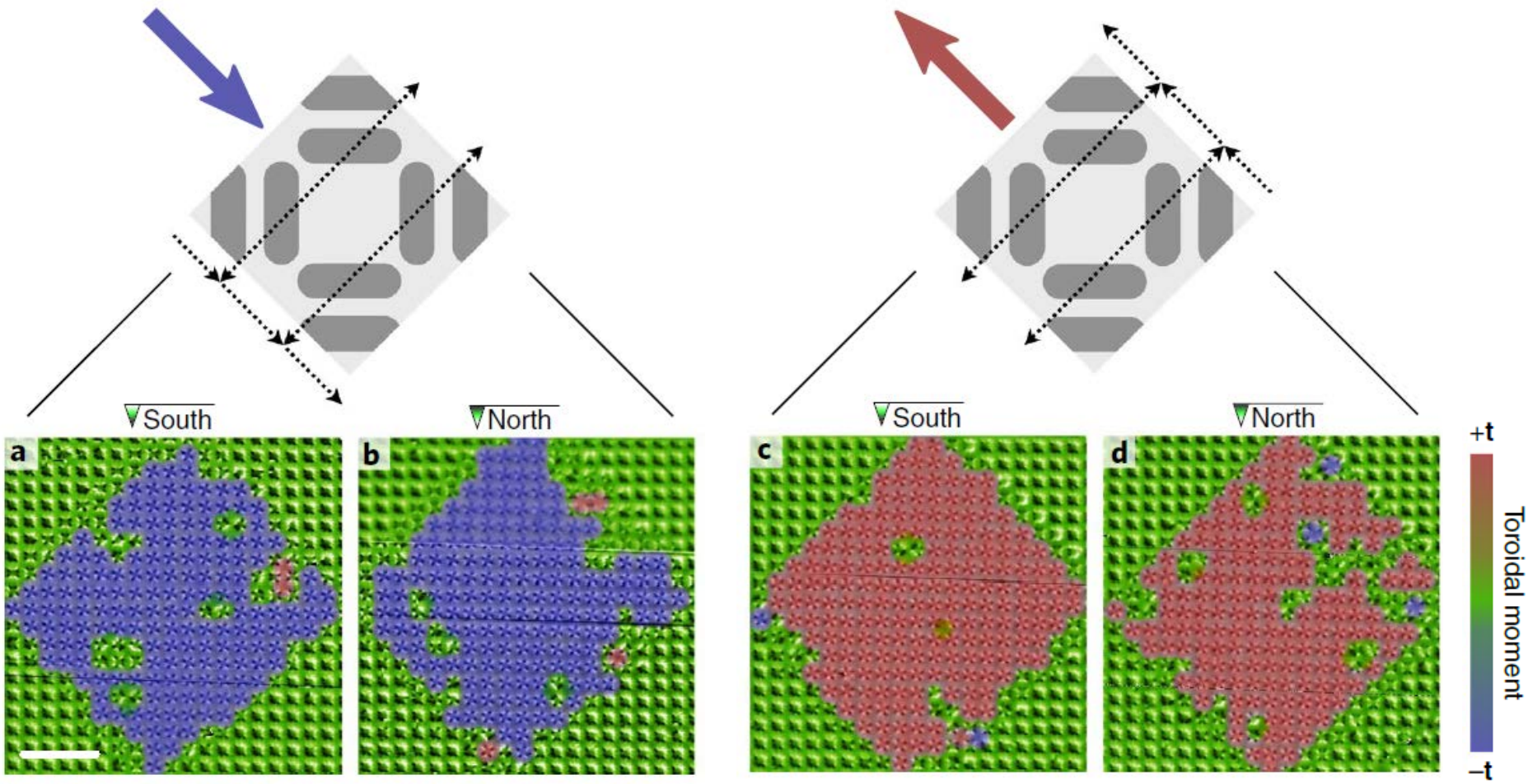
J Lehmann, C Donnelly, PM Derlet, LJ Heyderman and M Fiebig
Nature Nanotechnology (2018)

Artificial Magneto-Toroidal Crystal



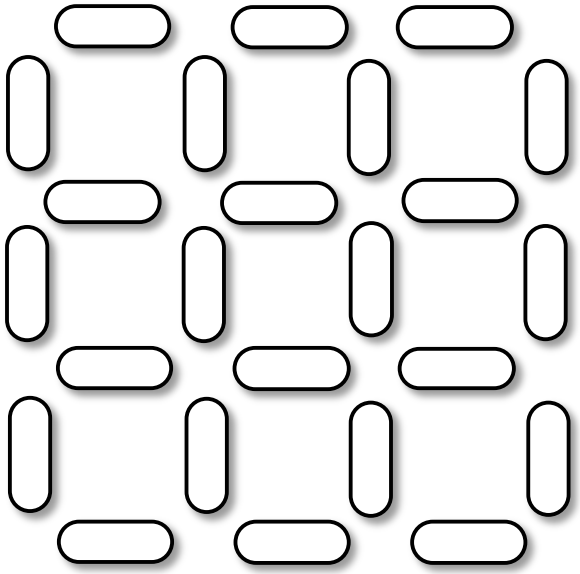
J Lehmann, C Donnelly, PM Derlet, LJ Heyderman and M Fiebig
Nature Nanotechnology (2018)

Artificial Magneto-Toroidal Crystal



J Lehmann, C Donnelly, PM Derlet, LJ Heyderman and M Fiebig
Nature Nanotechnology (2018)

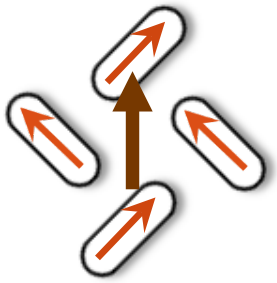
Chiral Ice



Square Ice → 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, Nature Materials (2017)

Chiral Ice



Square Ice → Chiral Ice

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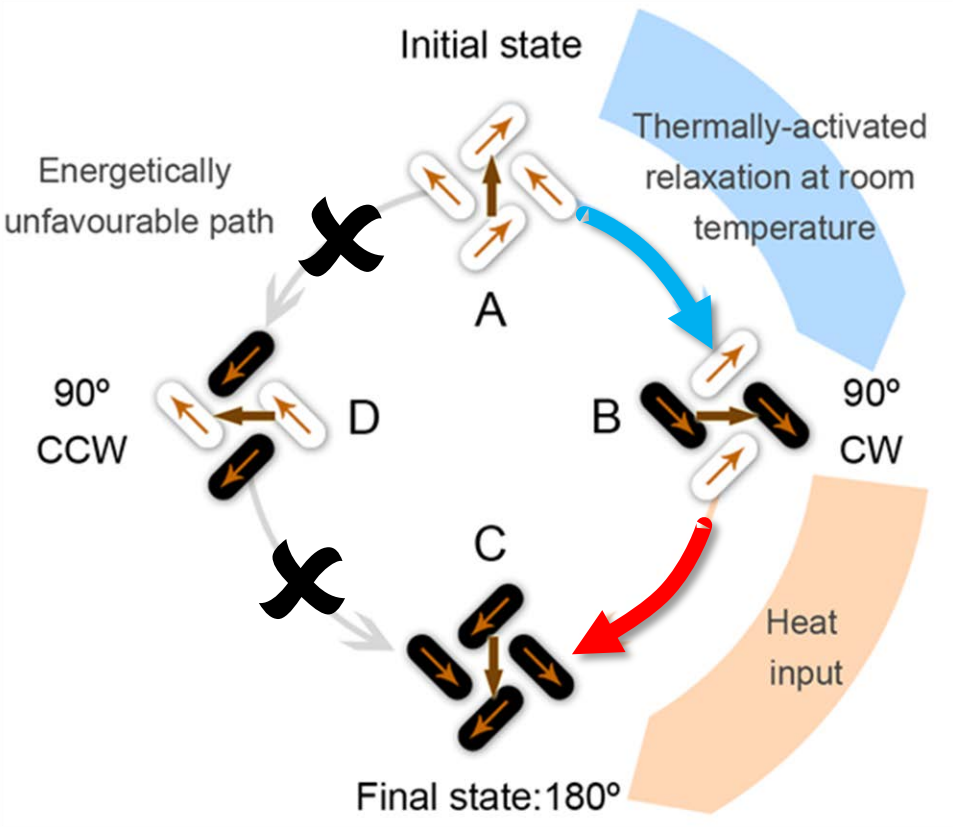
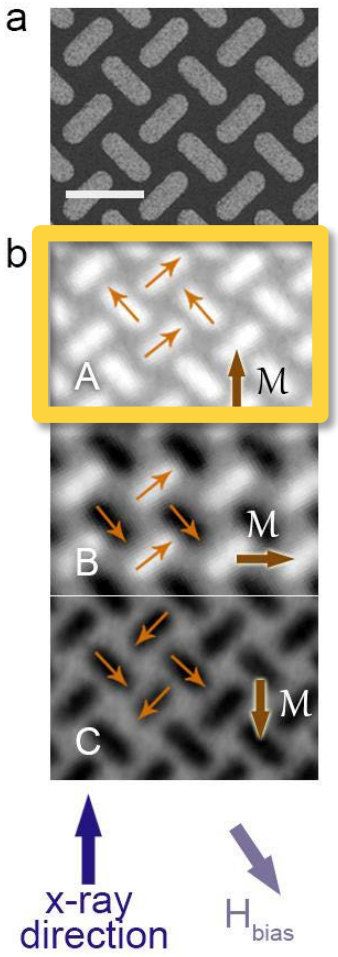
Chiral Ice – Thermal Relaxation



Chiral Dynamics !

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, Nature Materials (2017)

Chiral Ice – Thermal Relaxation



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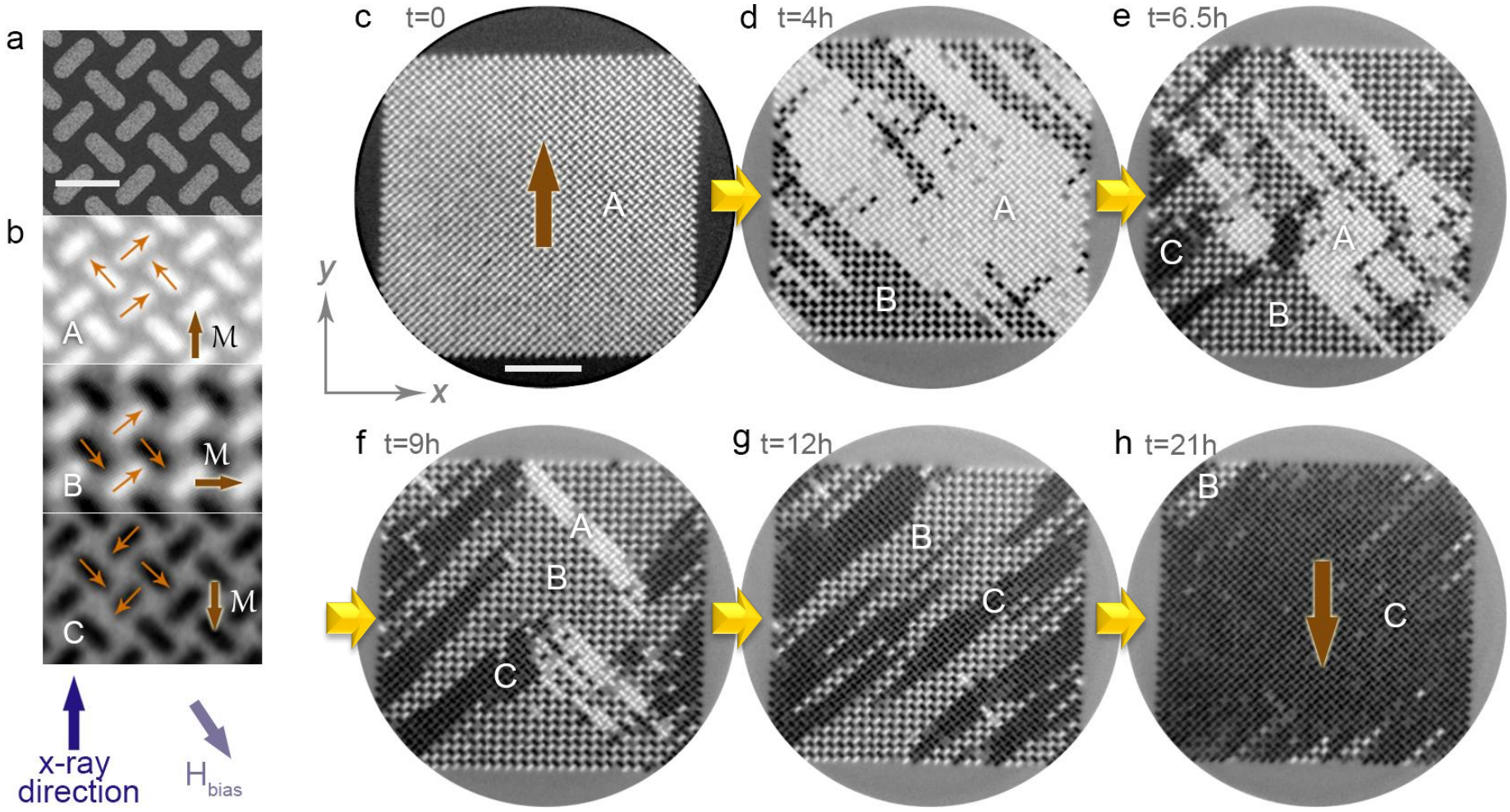
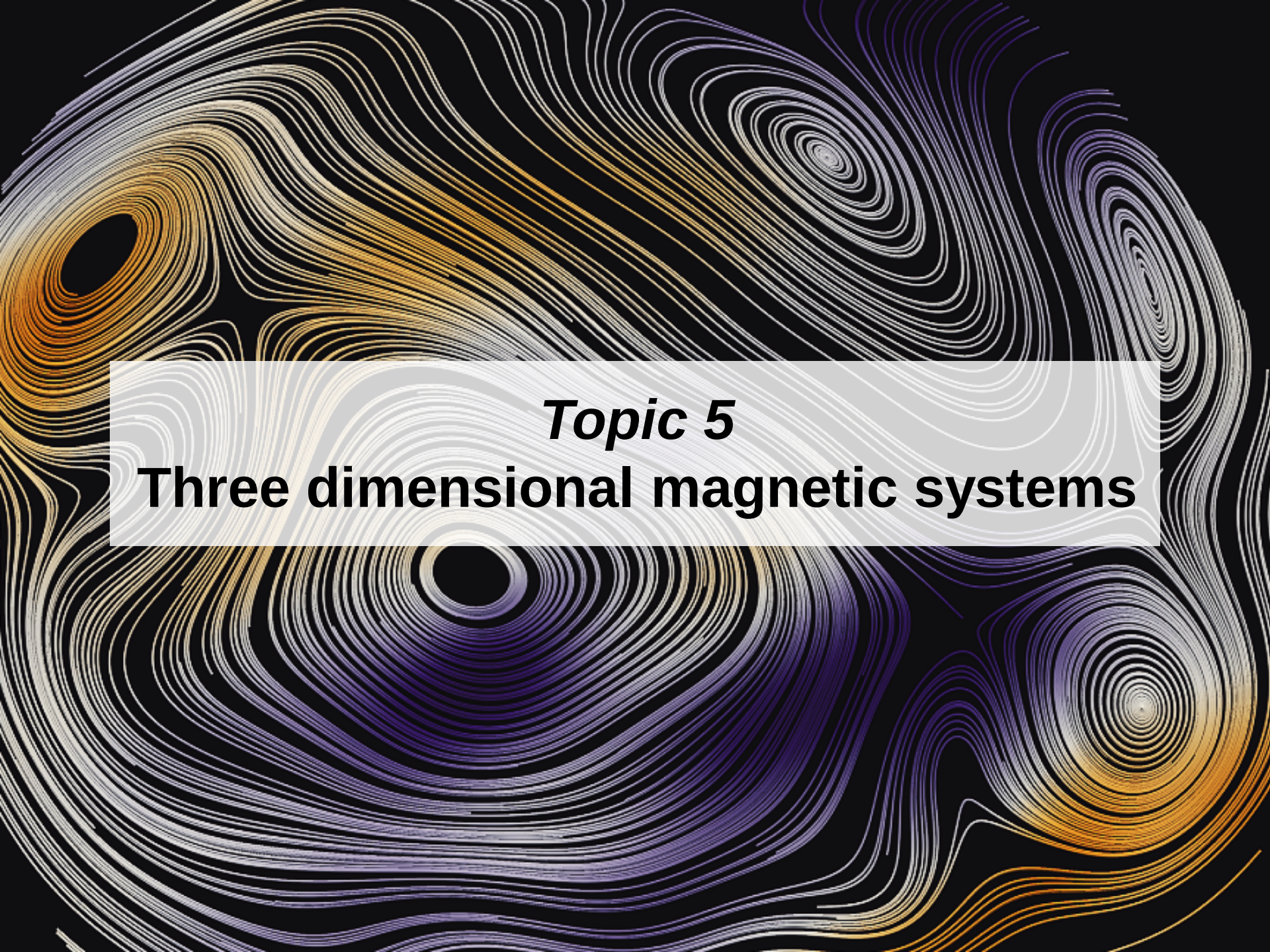
Chiral Ice – Thermal Relaxation



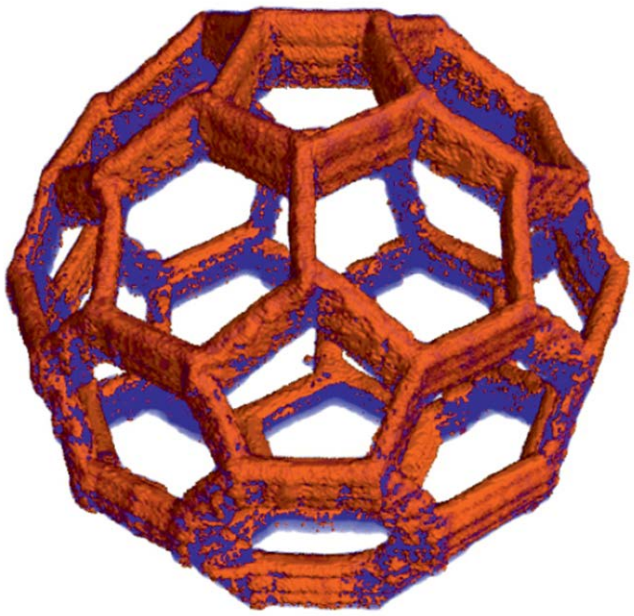
S Gliga, G Hrkac, C Donnelly, J Büchi, A Kleibert, J Cui, A Farhan, E Kirk, R Chopdekar, Y Masaki, NS Bingham, A Scholl, RL Stamps, LJ Heyderman, Nature Materials (2017)



Topic 5

Three dimensional magnetic systems

Three Dimensional Structures



6 μm Buckyball

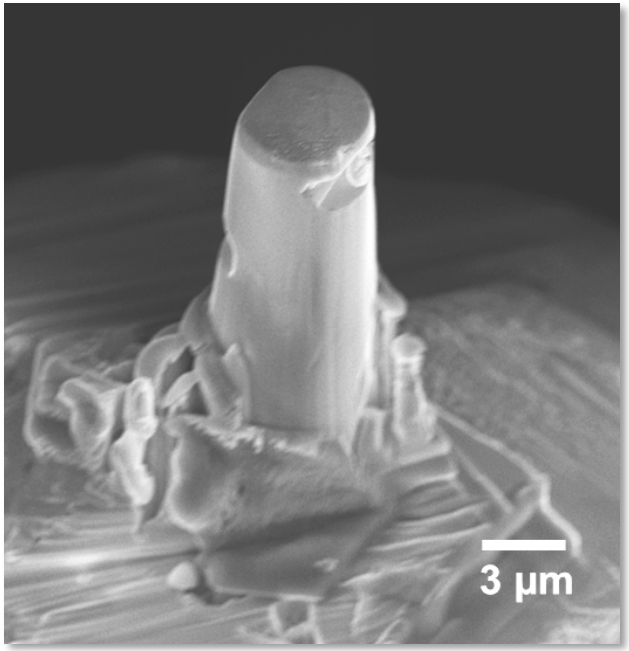
Resonant Ptychographic Tomography

Quantitative hard x-ray phase imaging & resonant elastic scattering

→ element-specific 3D characterization with 25 nm spatial resolution

C. Donnelly et al. PRL (2015)

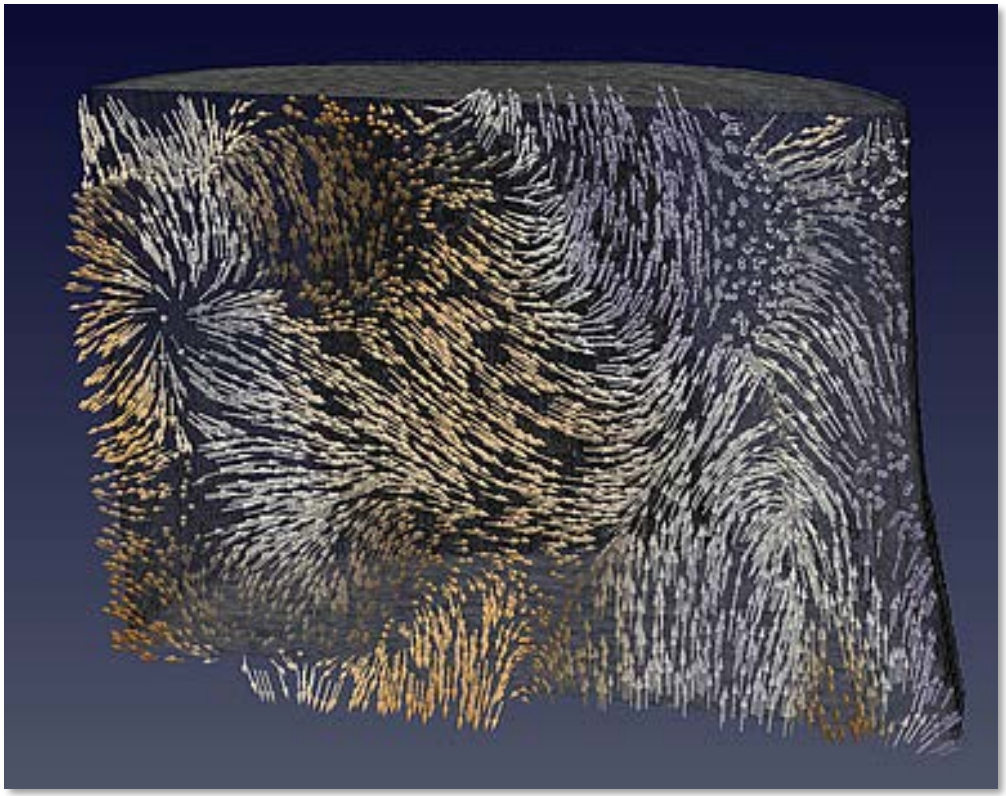
Hard X-ray Magnetic Tomography



$GdCo_2$ Pillar

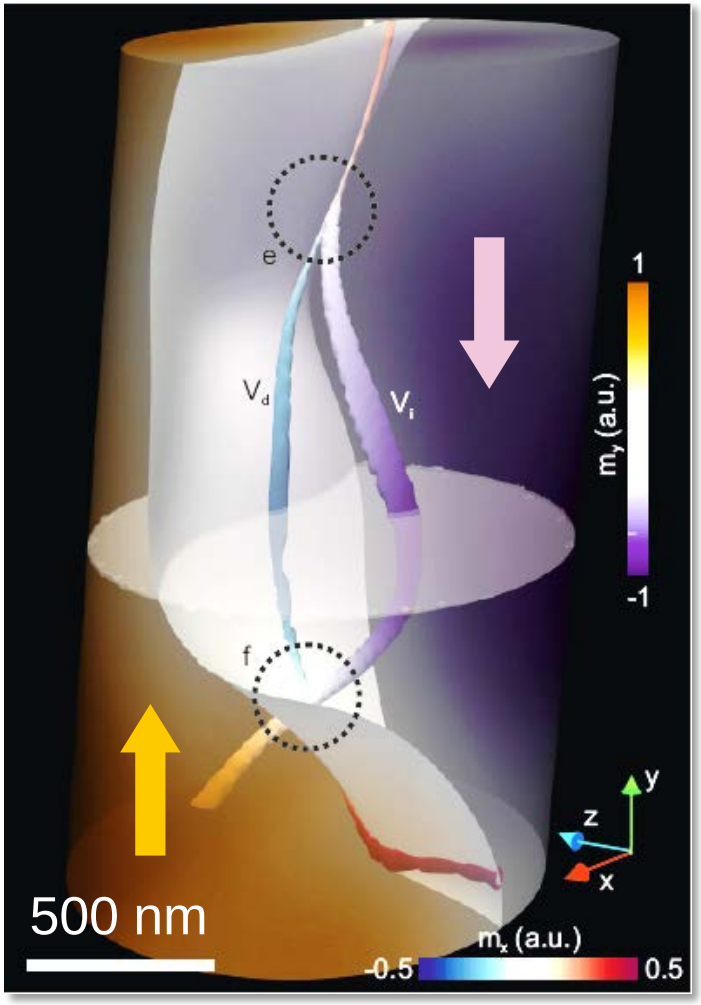
Cut from nugget with FIB

Sample from:
R. Galera, CNRS, Grenoble



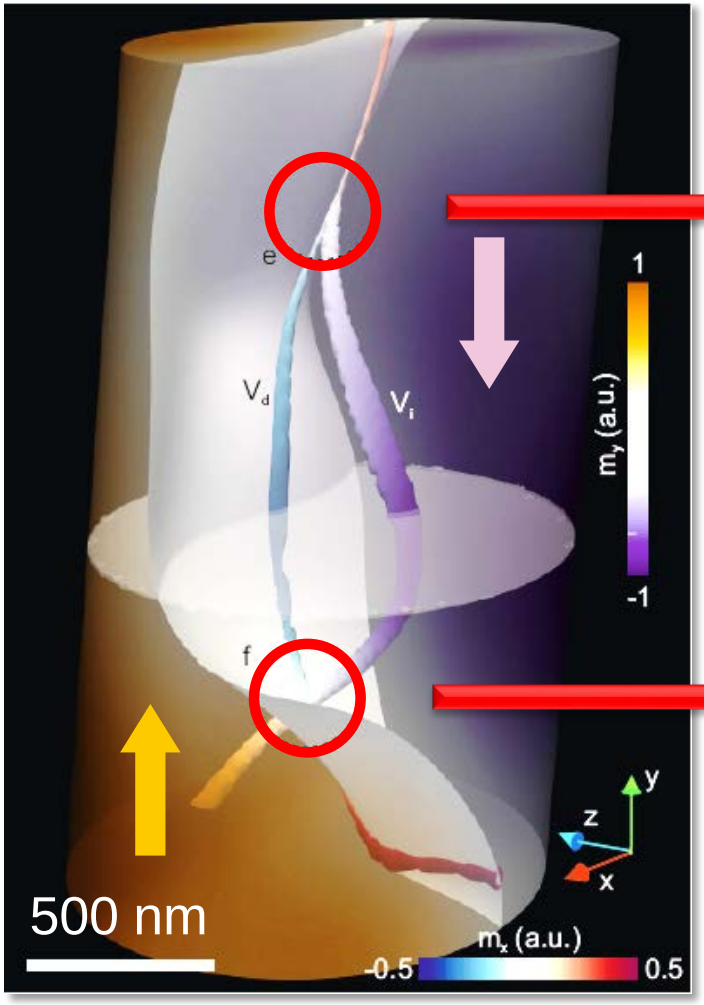
C Donnelly et al. PRB (2016), Nature (2017) and NJP (2018)

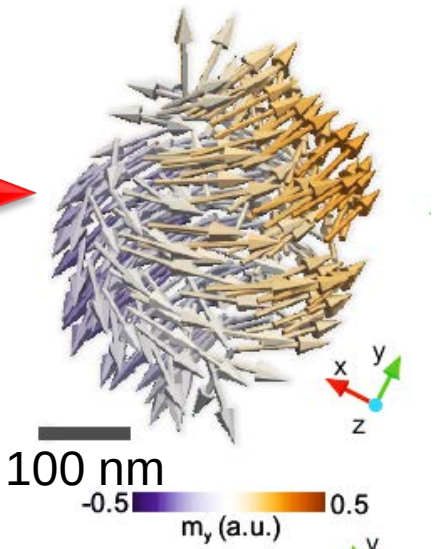
Hard X-ray Magnetic Tomography

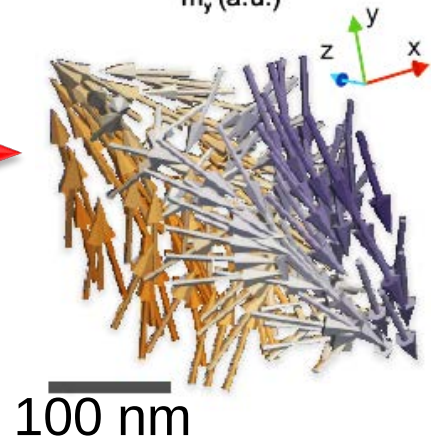


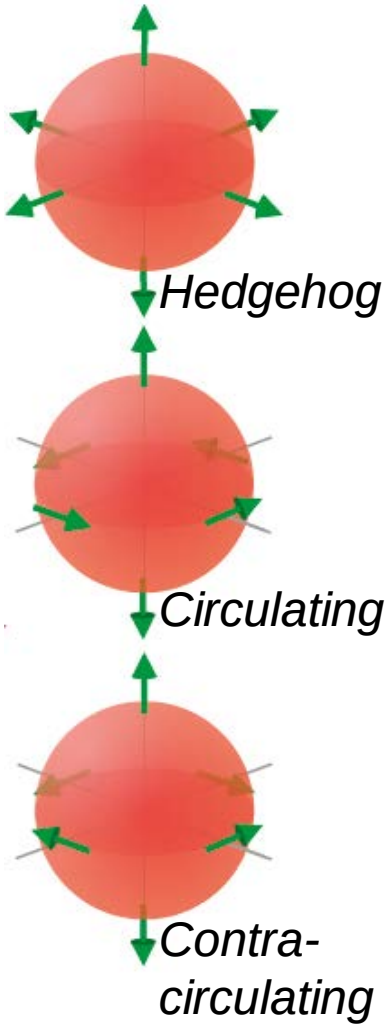
C Donnelly et al. PRB (2016), Nature (2017) and NJP (2018)

Hard X-ray Magnetic Tomography





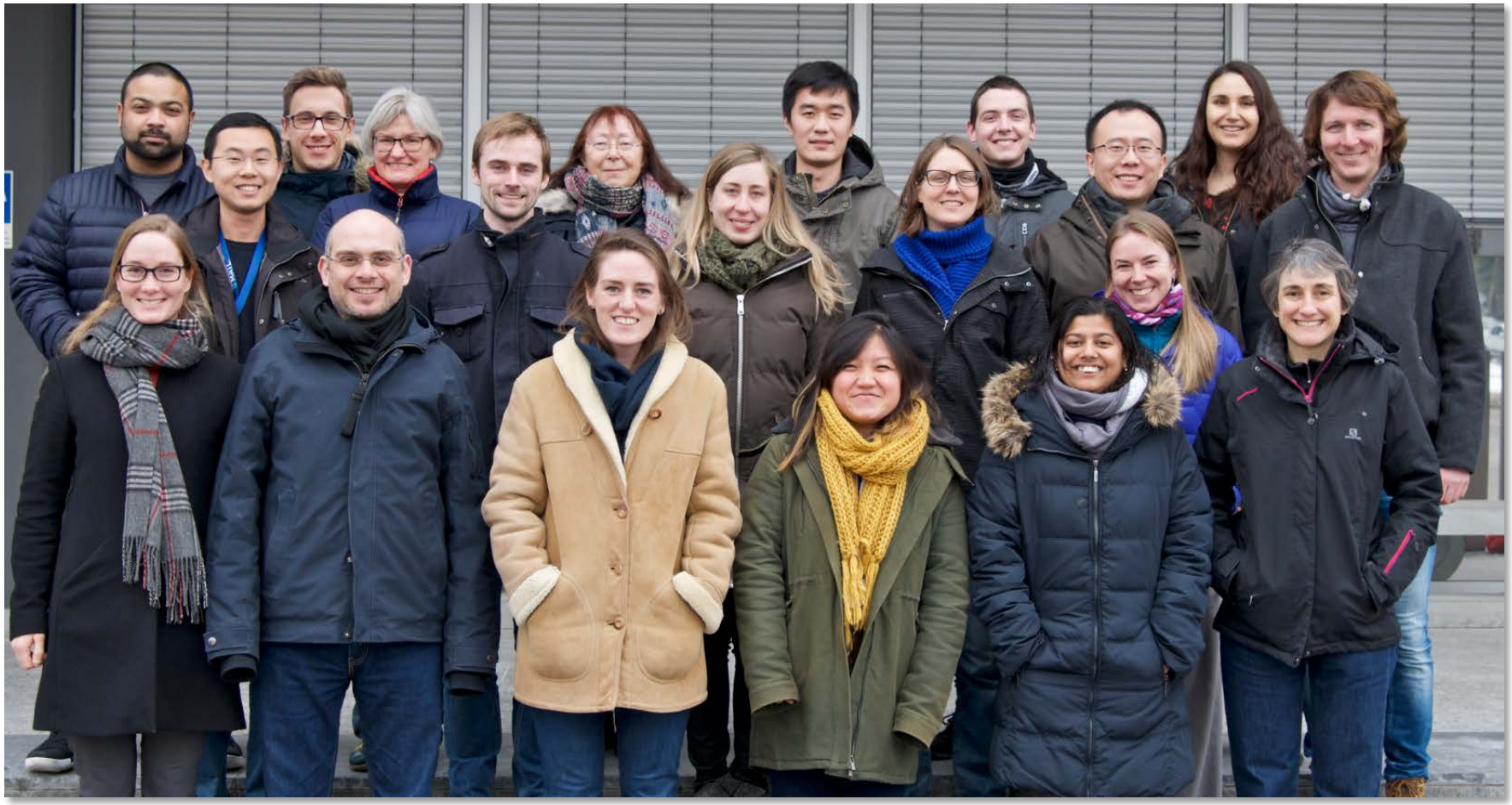




C Donnelly et al. PRB (2016), Nature (2017) and NJP (2018)

Acknowledgements

Thanks to Mesoscopic Systems



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

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Swiss Light Source

- *Photoemission Electron Microscopy:* Armin Kleibert, Carlos Vaz, Ana Balan, Jaianth Vijayakumar, Tatiana Savchenko, Arantxa Fraile Rodriguez, Loic Le Guyader, Frithjof Nolting
- *Scanning Transmission X-ray Microscopy:* Joerg Raabe, *Peter Warnicke,* Stephanie Stevenson, Christoforos Moutafis
- *X-ray Scattering:* Urs Staub, Aurora Alberca, Joachim Kohlbrecher, José Mardegan
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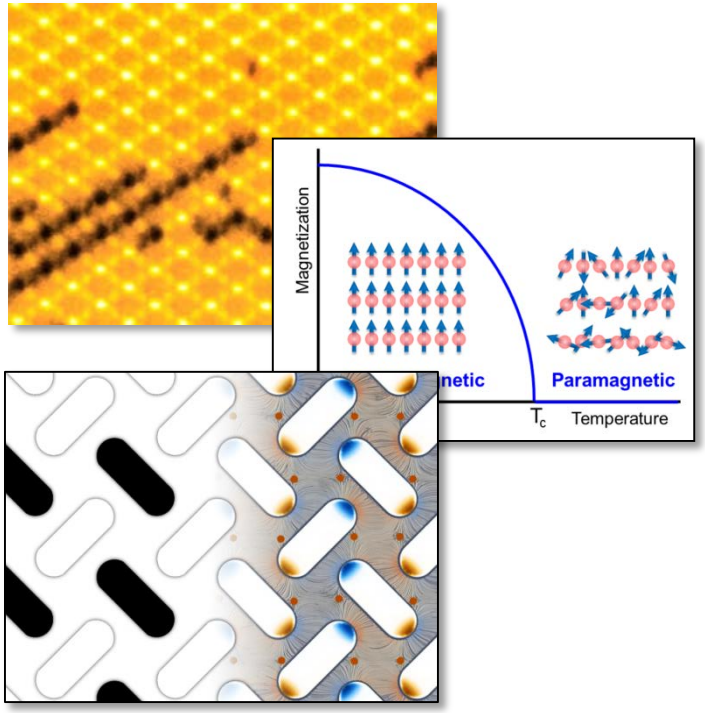
Andrei Rogalev, Carsten Detlefs

Adv. Light Source: Andreas Scholl, Tony Young

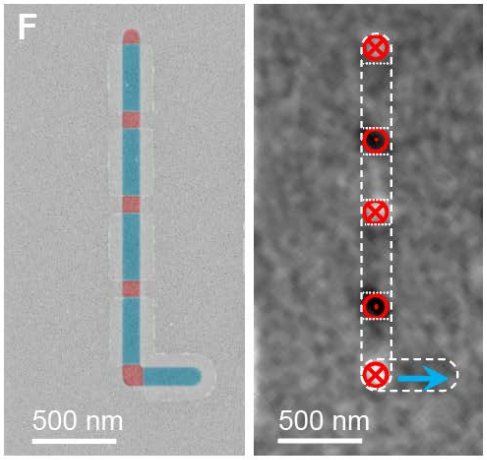
Artificial Ferroic Systems

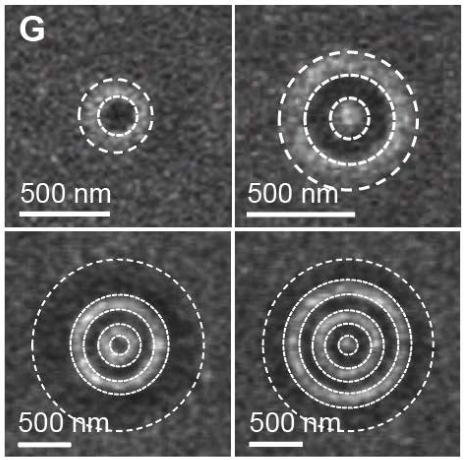


1. Emergent magnetic monopoles in Artificial Spin Ice
2. Phase transitions in a magnetic metamaterial
3. Chiral Structures

Artificial Spin Ice – Chirally Coupled Nanomagnets

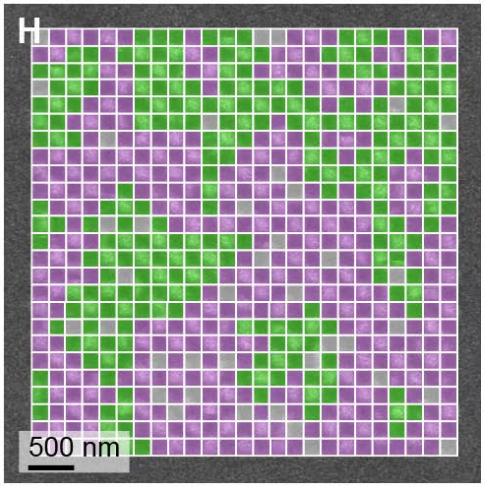
Chain of chirally coupled nanomagnets

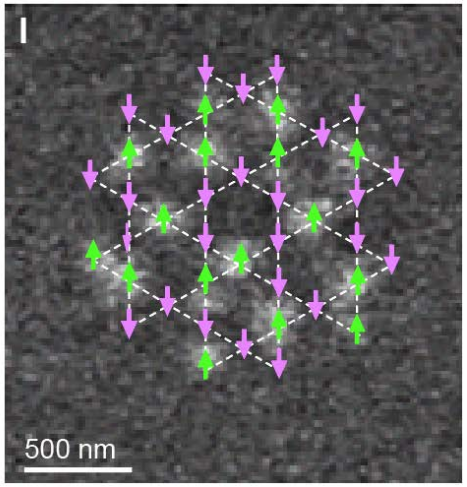




Artificial Skyrmions

Ising moments on a square lattice

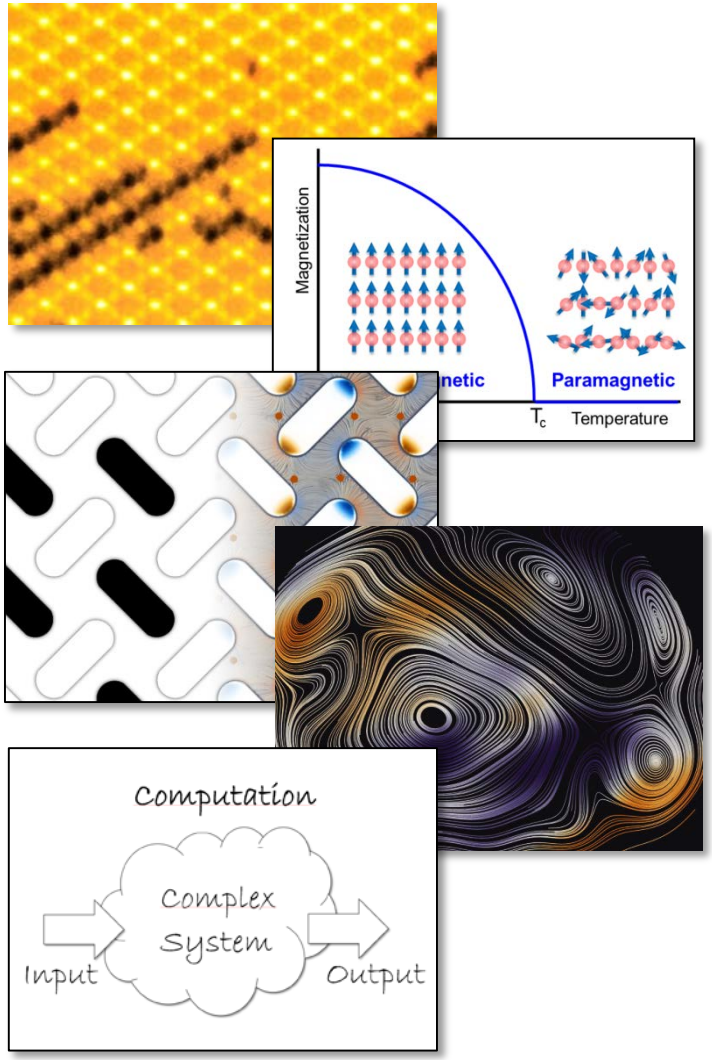




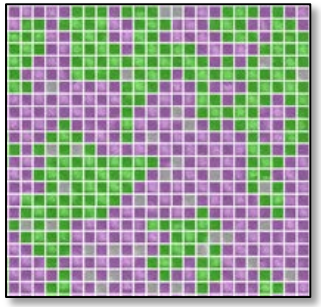
Ising moments on a kagome lattice

Z Luo, TP Dao, A Hrabec, J Vijayakumar, A Kleibert, M Baumgartner, E Kirk, J Cui, G Krishnaswamy, T Savchenko, LJ Heyderman, P Gambardella Science (Accepted 2019)

Artificial Ferroic Systems



1. Emergent magnetic monopoles in Artificial Spin Ice
2. Phase transitions in a magnetic metamaterial
3. Chiral Structures
4. Three-dimensional magnetic systems
5. Towards Bioinspired Computation



- H Arava, PM Derlet, J Vijayakumar, J Cui, NS Bingham, A Kleibert & LJ Heyderman, Nanotechnology (2018)
- P Gypens et al. Phys Rev Applied (2018)
- JH Jensen et al. DOI: 10.1162/isal_a_00011
- F Caravelli & C Nisoli ArXiv 2019

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