PAUL SCHERRER INSTITUT

PSI

ETH zürich

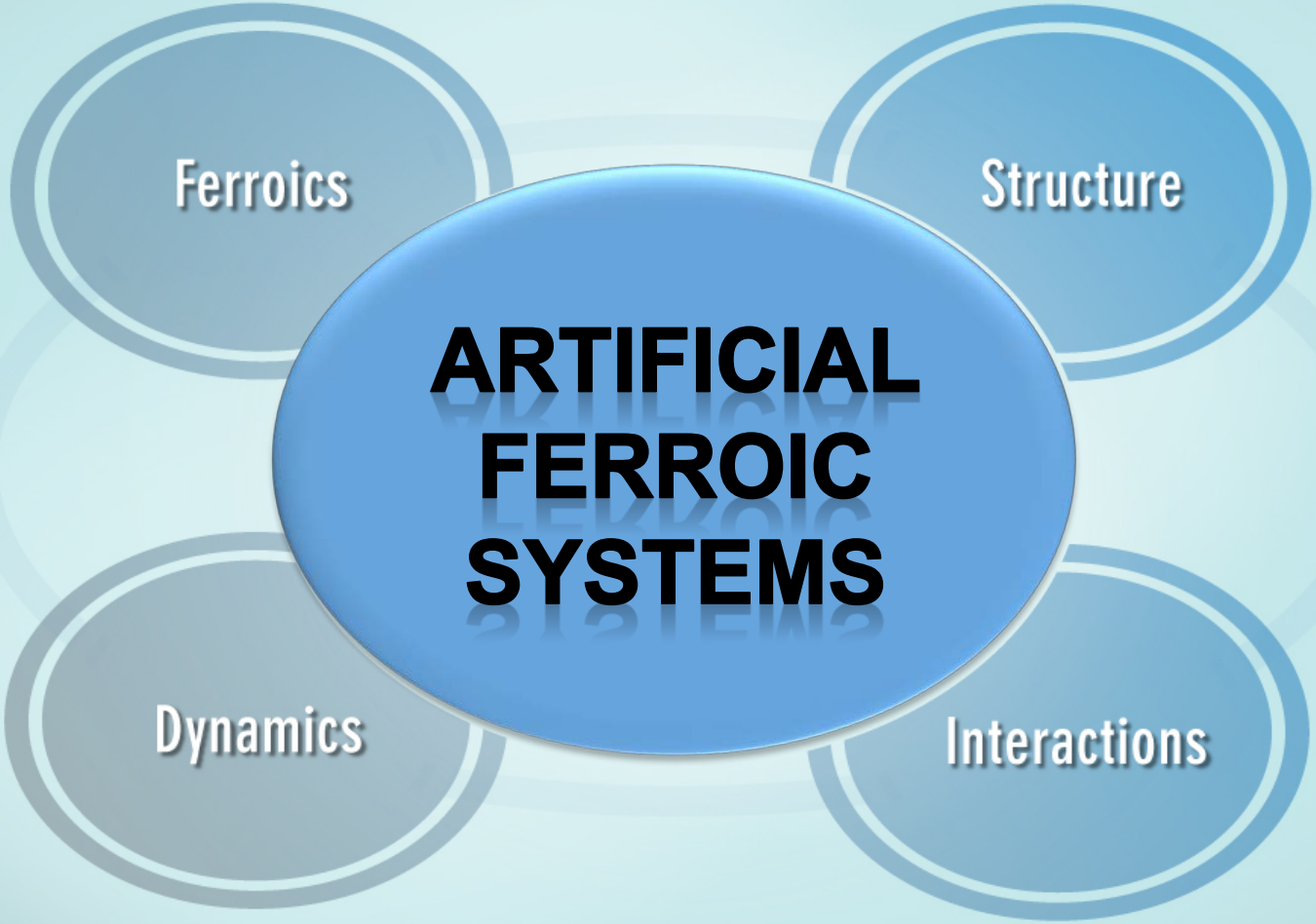
Prof. Laura Heyderman :: ETH Zurich - Paul Scherrer Institute

Artificial Ferroic Systems: From hybrid systems to magnetic metamaterials

JEMS 2018

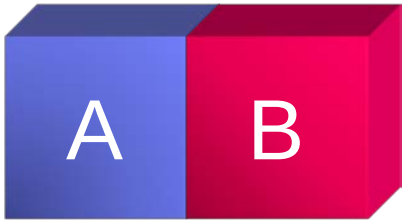
Mesoscopic Systems
http://www.mesosys.mat.ethz.ch

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



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

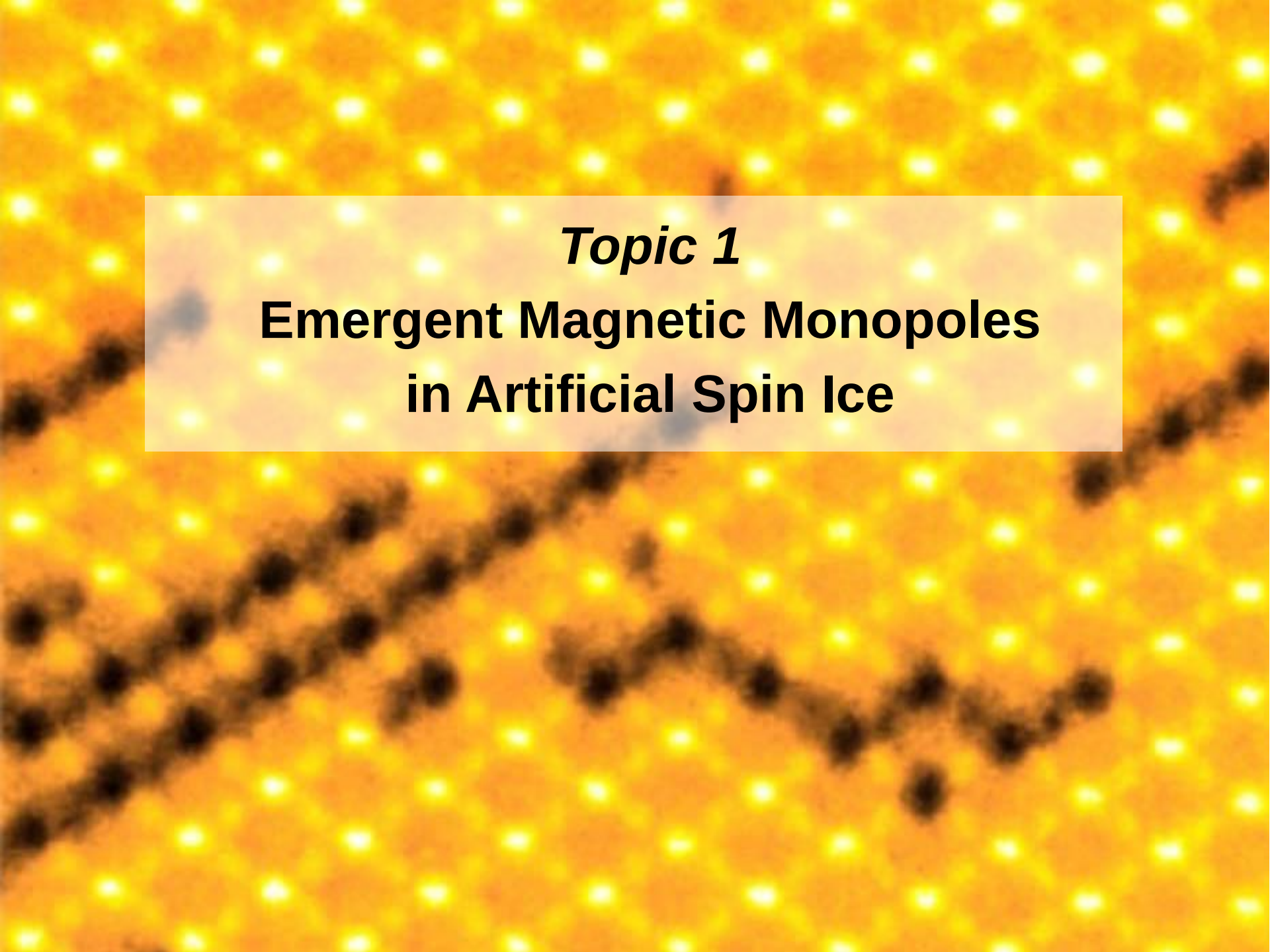
Artificial Ferroic Systems



Hybrid/Composite Systems

Artificial Spin Systems

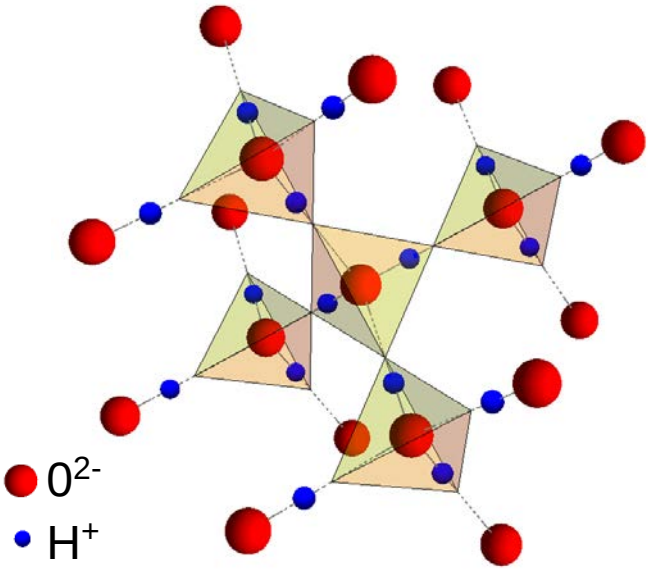
LJ Heyderman & RL Stamps
J Phys: Condens Matter (2013)



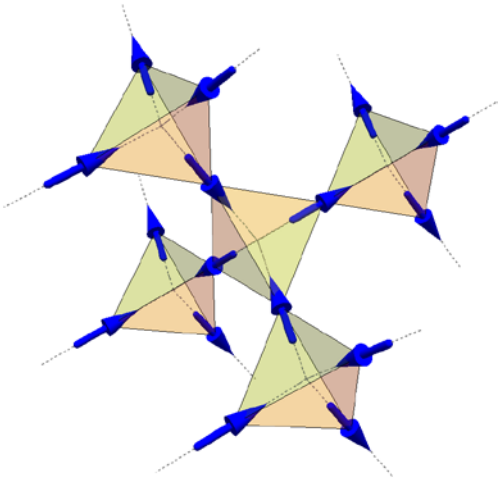
Topic 1

Emergent Magnetic Monopoles in Artificial Spin Ice

From Water Ice to Artificial Spin Ice



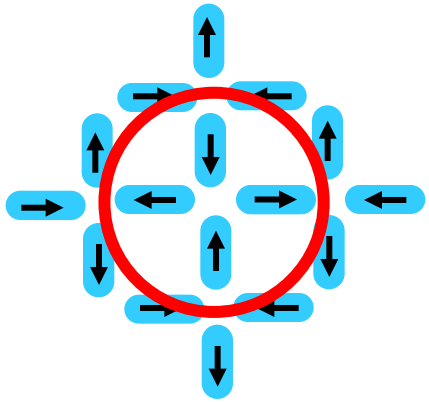
Water Ice



Spin Ice

MJ Harris *et al.*
PRL (1997)

Ice Rule

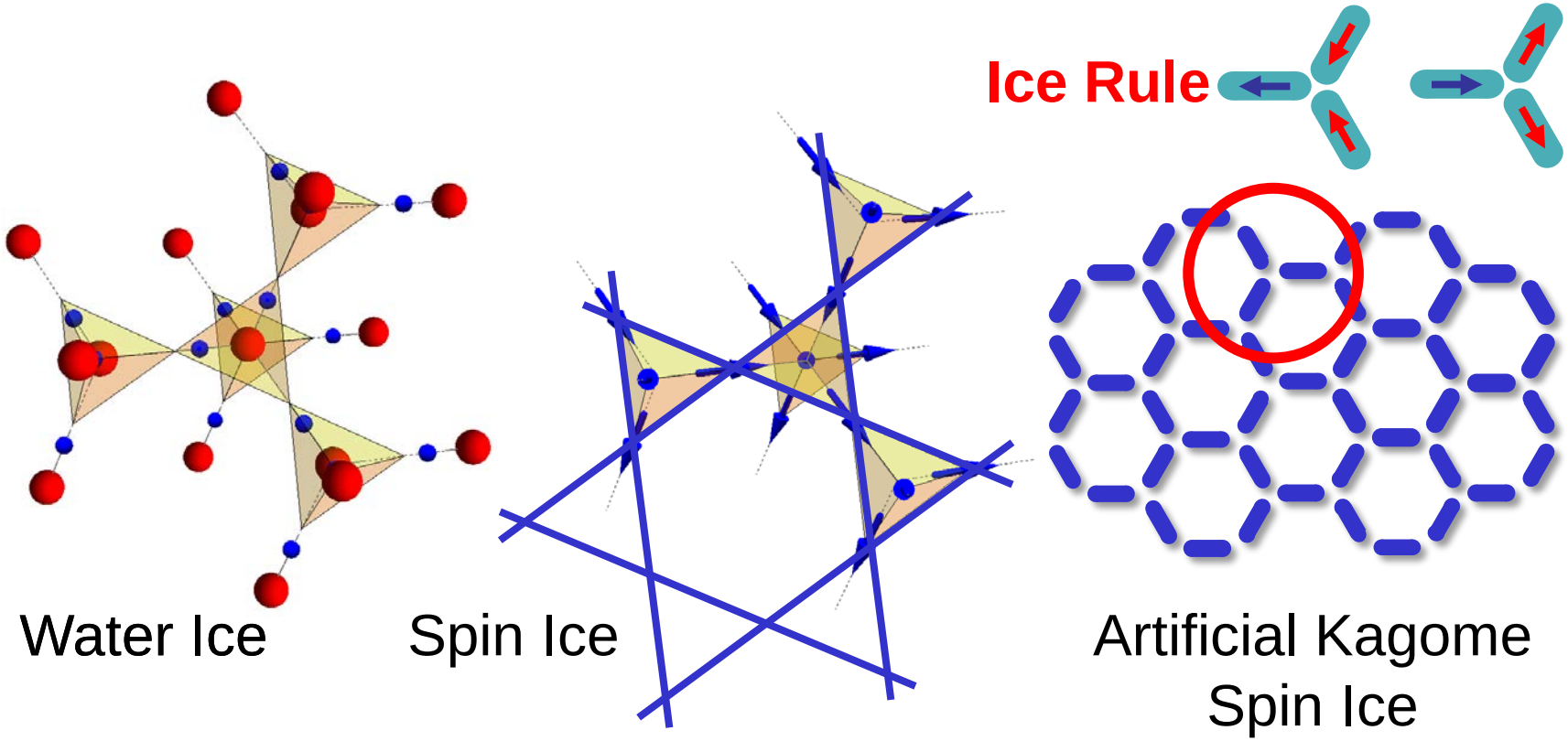


Artificial Spin Ice

RF Wang *et al.*
Nature (2006)

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

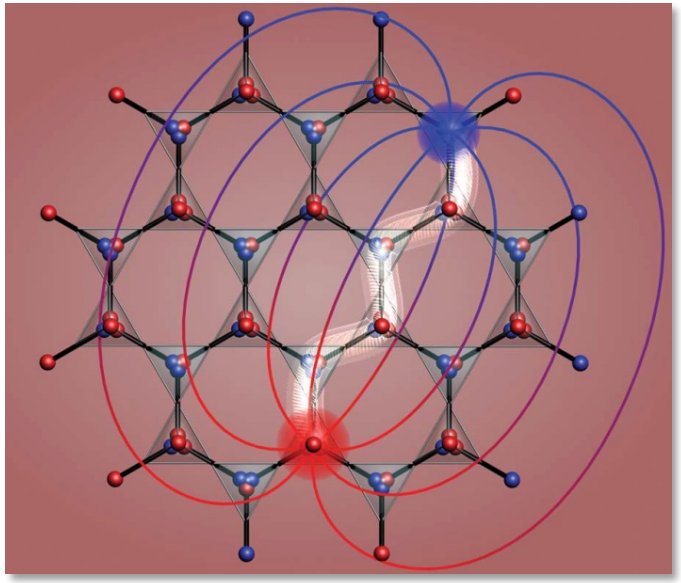
From Water Ice to Artificial Spin Ice



MJ Harris *et al.*
PRL (1997)

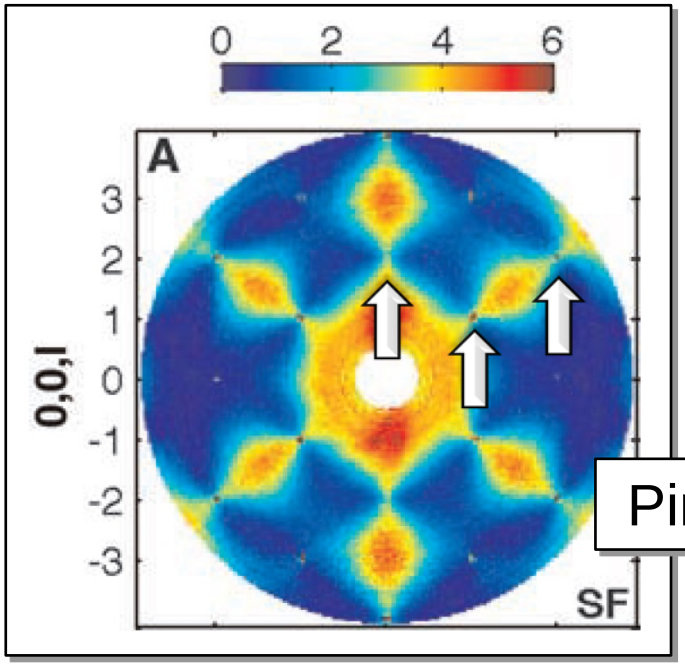
LJ Heyderman & RL Stamps
J Phys: Condens Matter (2013)

Emergent Magnetic Monopoles & Dirac Strings



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

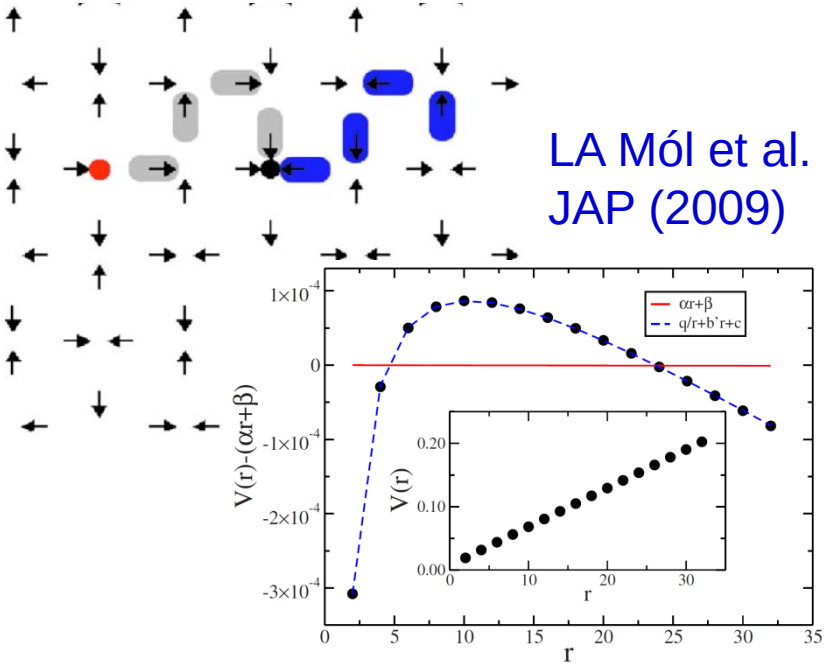
See also:
IA Ryzhkin J. Exp. Theor. Phys (2005)



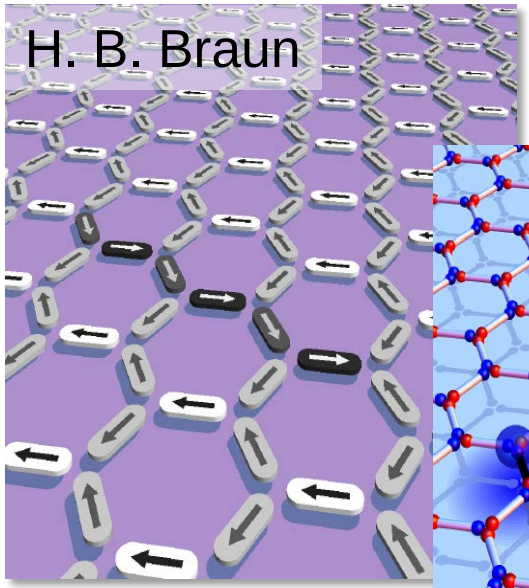
Spin Ice and Neutron Scattering
DJP Morris et al. Science (2009)
T Fennell et al. Science (2009)
H Kadowaki et al. J Phys Soc Jpn (2009)

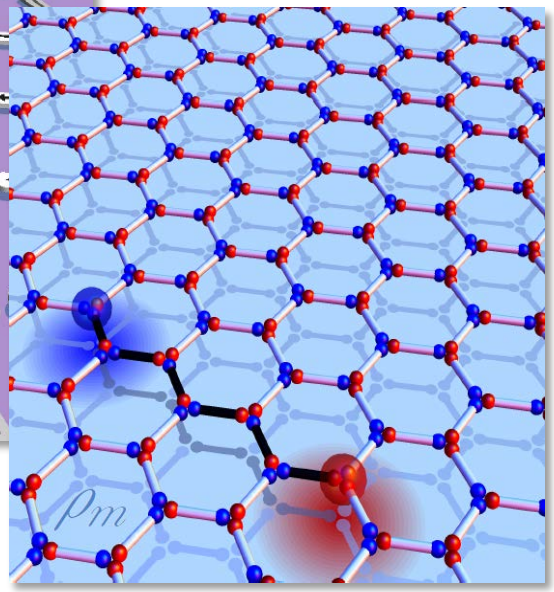
Pinch point singularities

Emergent Magnetic Monopoles & Dirac Strings

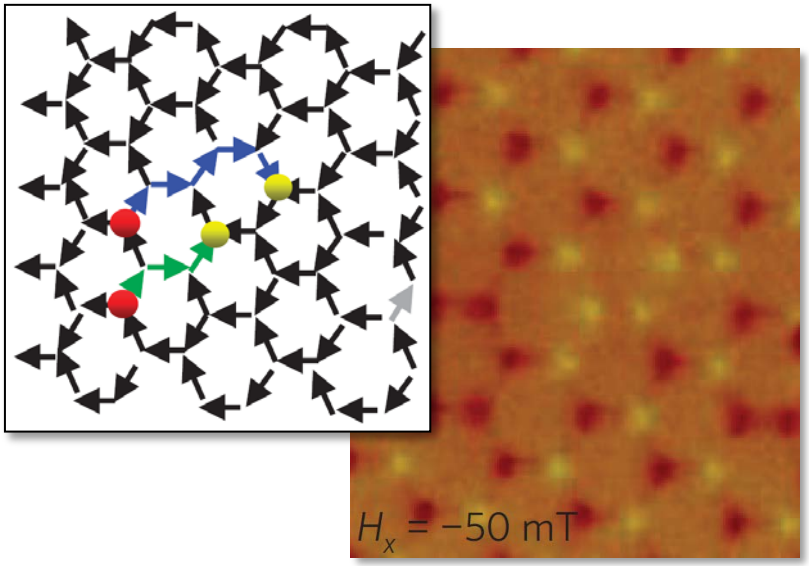


LA Mól et al.
JAP (2009)





E Mengotti et al.
Nature Physics (2011)

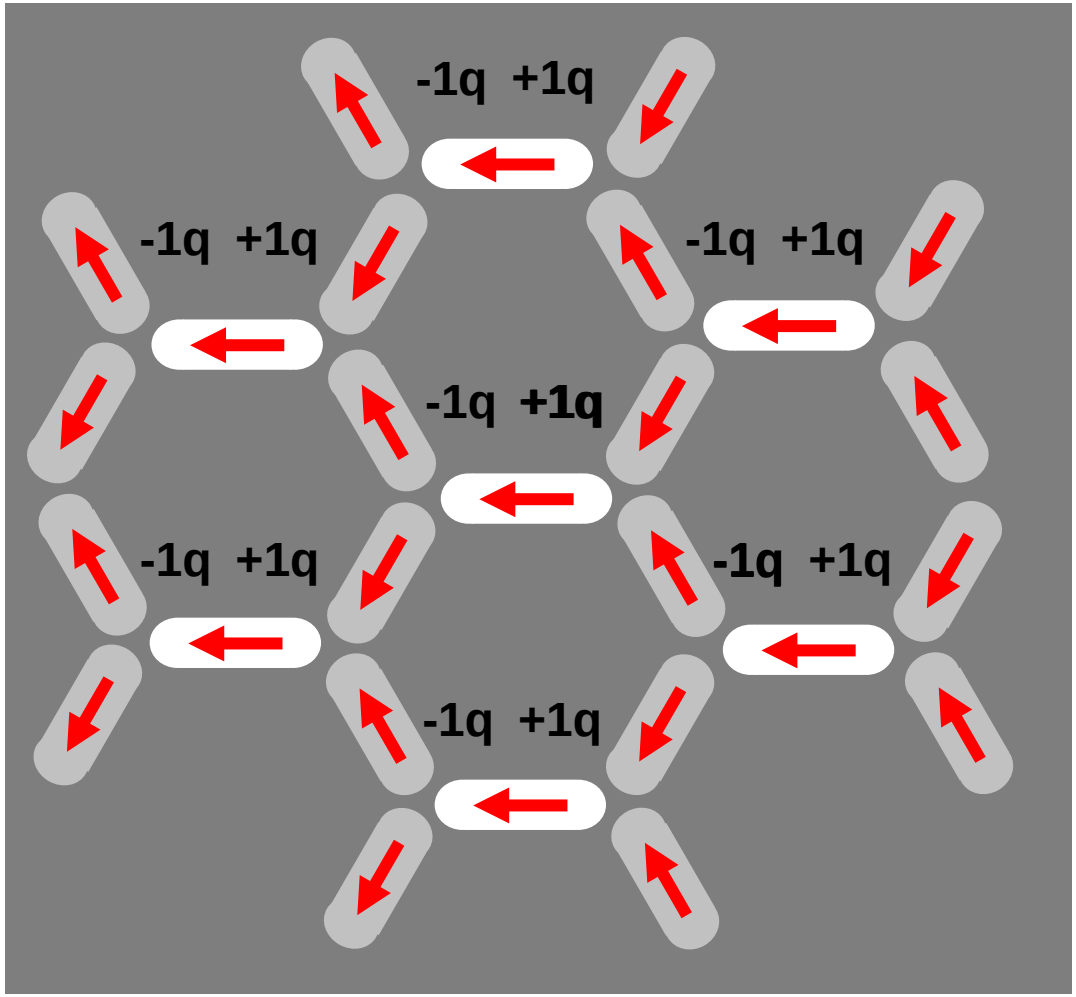


S Ladak et al.
Nature Physics (2010)

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)

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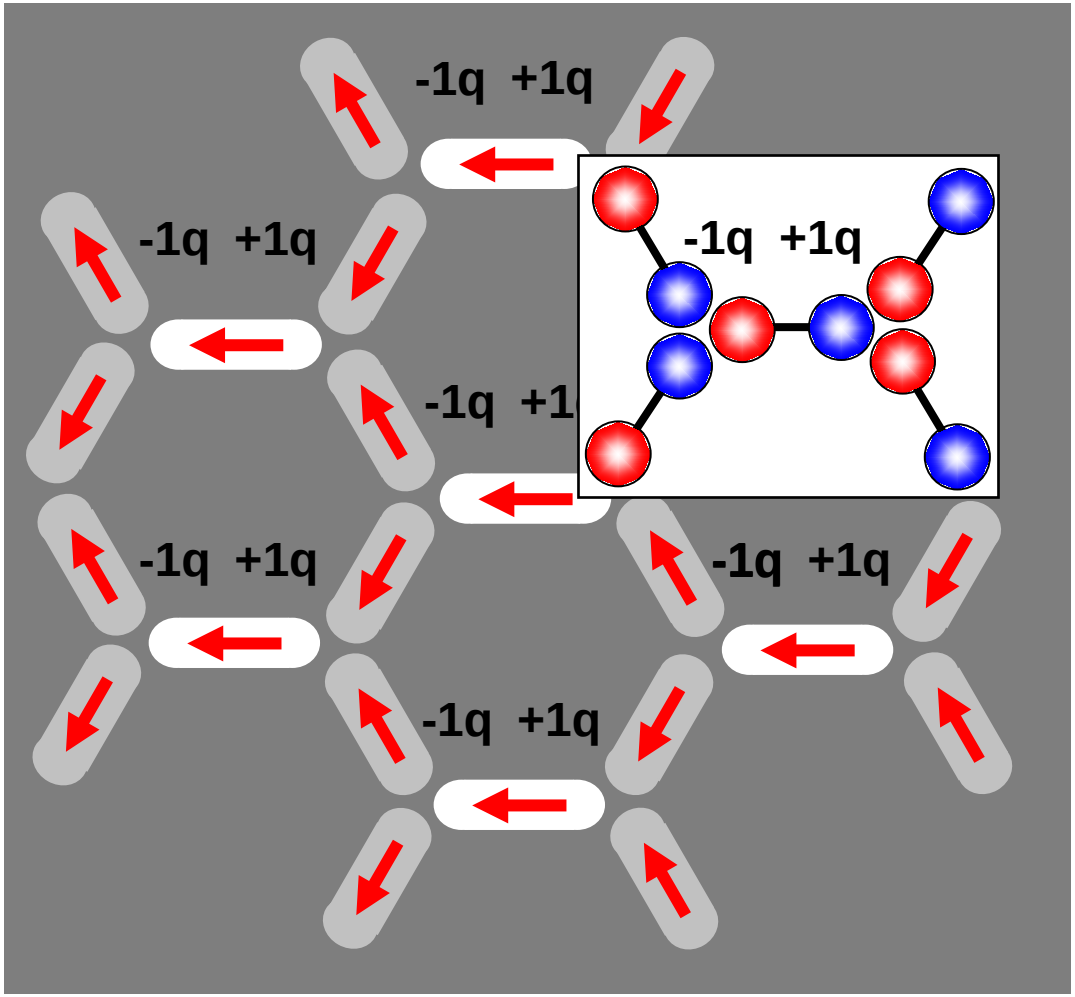

C Castelnovo, R Moessner & SL Sondhi Nature (2008)

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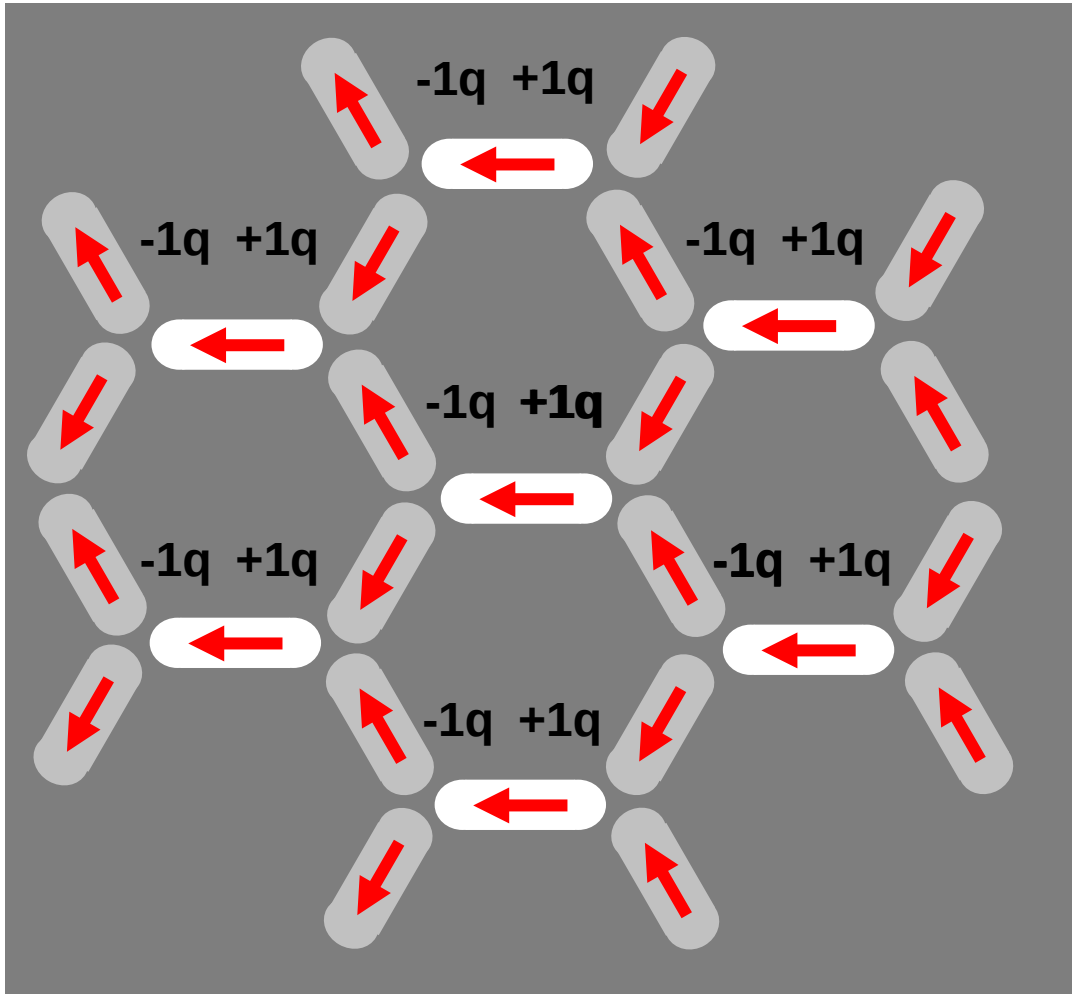

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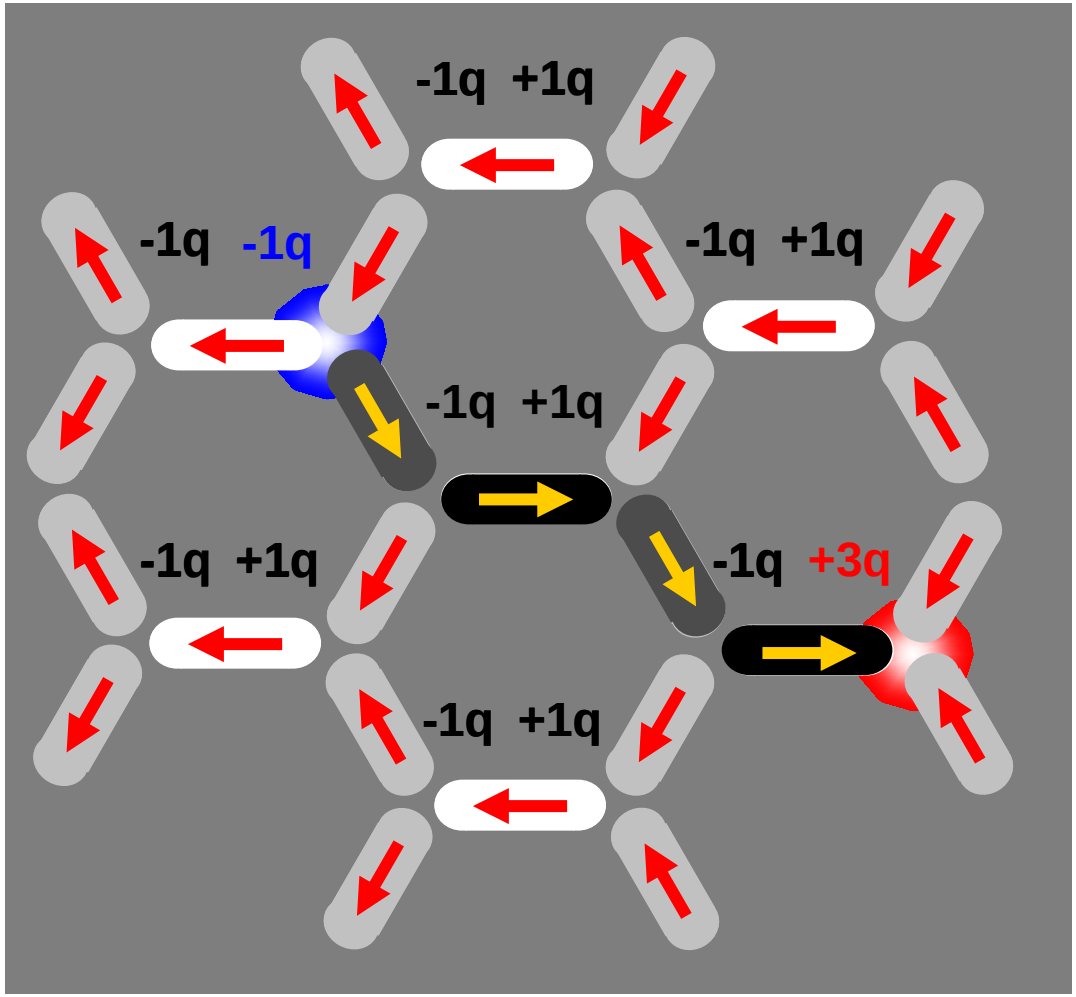
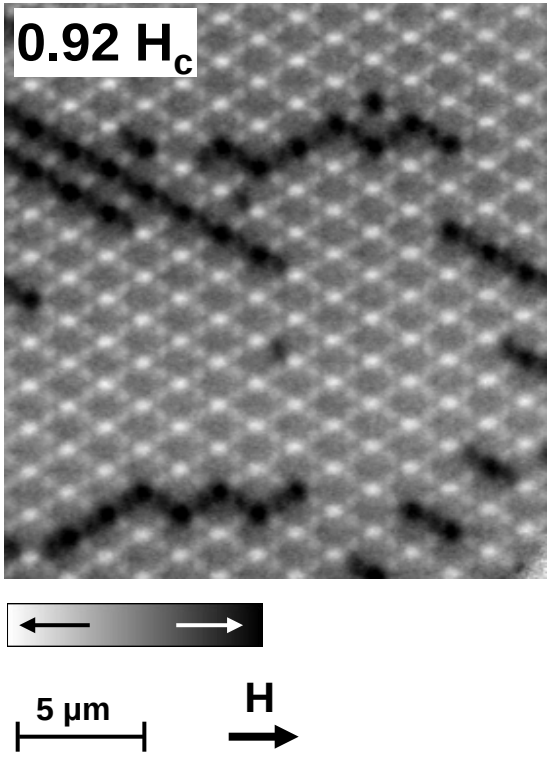
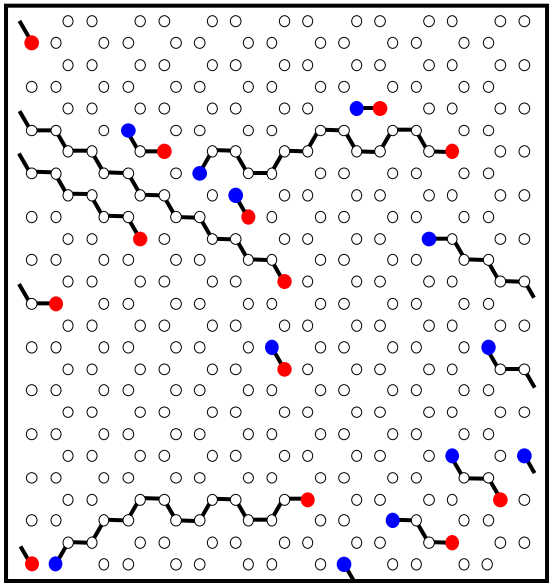
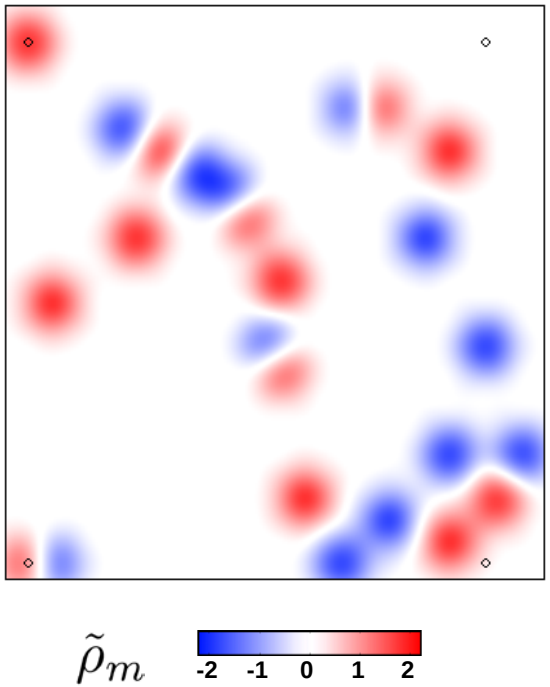


C Castelnovo, R Moessner & SL Sondhi Nature (2008)

Emergent Magnetic Monopoles & Dirac Strings



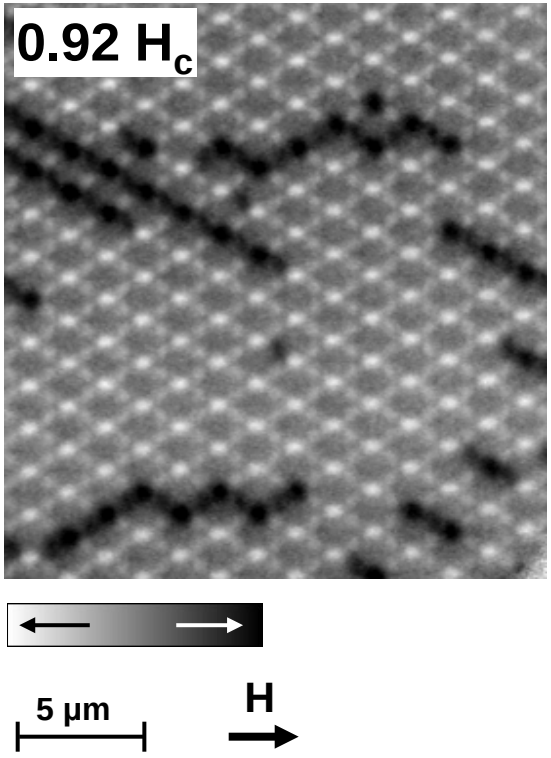


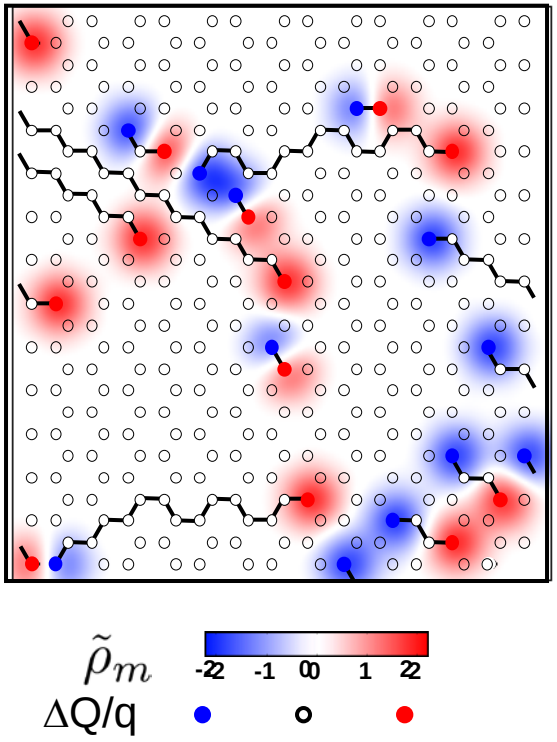


Smeared magnetic charge: $\rho_m(r)=\int d^3r' \exp(-|r'-r|^2/\xi^2)\,\mathrm{div}H$
Castelnovo et al. Nature (2008)

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

Emergent Magnetic Monopoles & Dirac Strings





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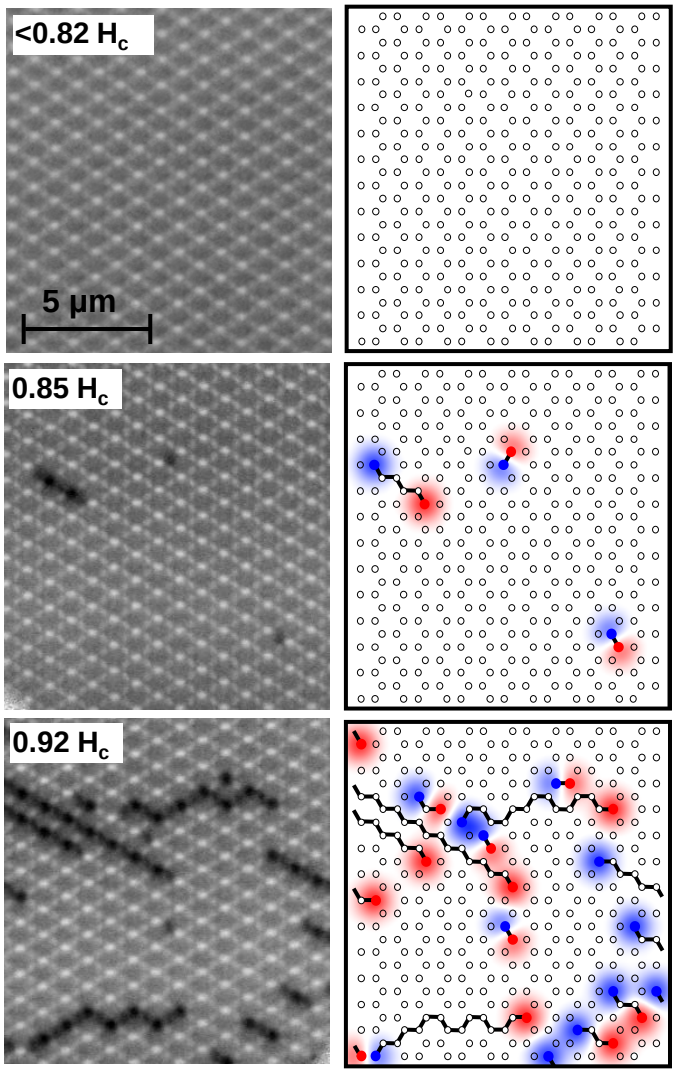
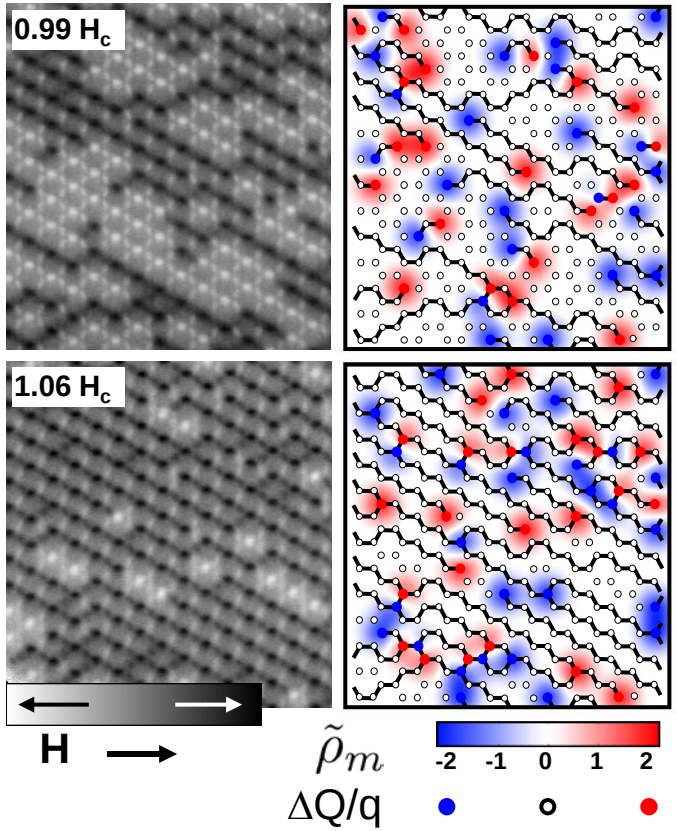
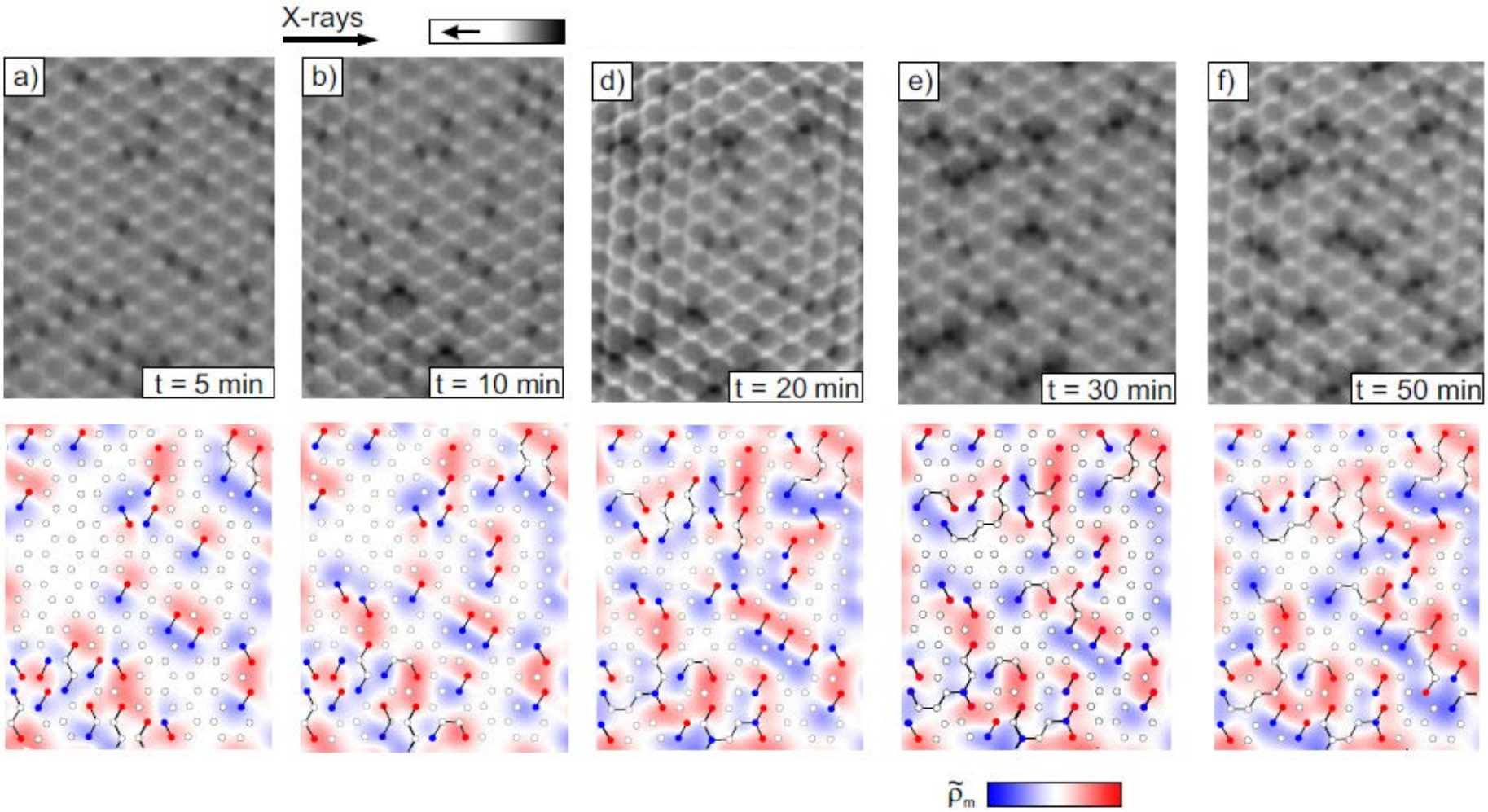




- 1D Avalanches: no branching or u-turns
- Importance of Disorder
- Control of Avalanches

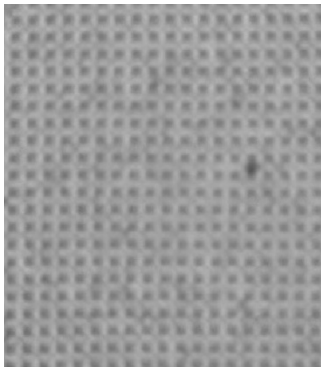
E Mengotti, LJ Heyderman, A Fraile Rodríguez, F Nolting, RV Hügli, HB Braun
Nature Phys (2011); RV Hügli et al. JAP & Phil Trans Roy Soc A (2012)

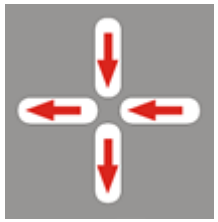
Thermally Active Artificial Kagome Ice



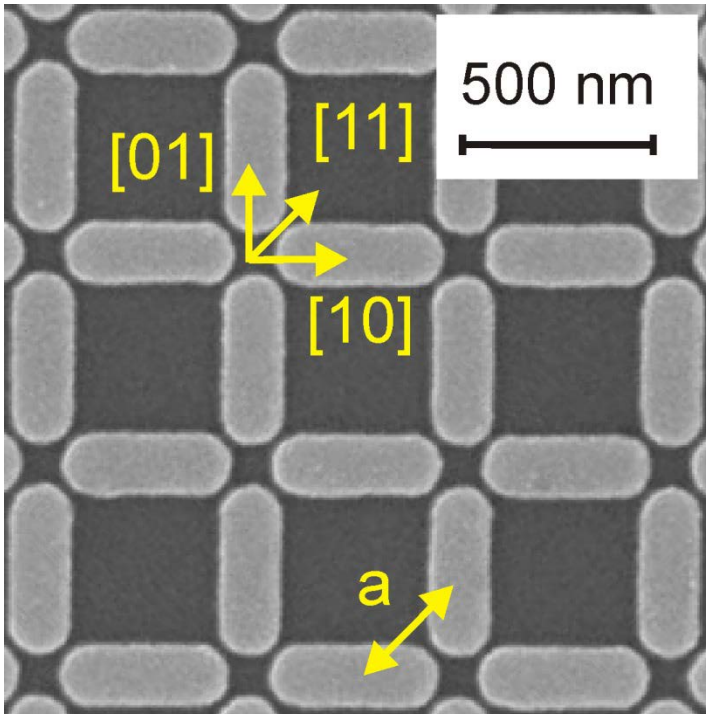
A Farhan, PM Derlet, L Anghinolfi, A Kleibert and LJ Heyderman PRB (2017)

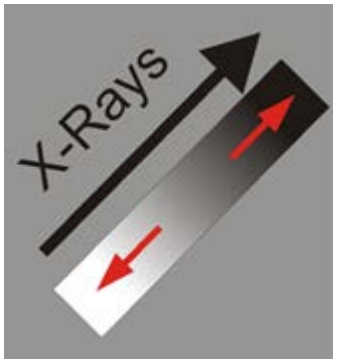
Thermal Artificial Square Ice





H_A



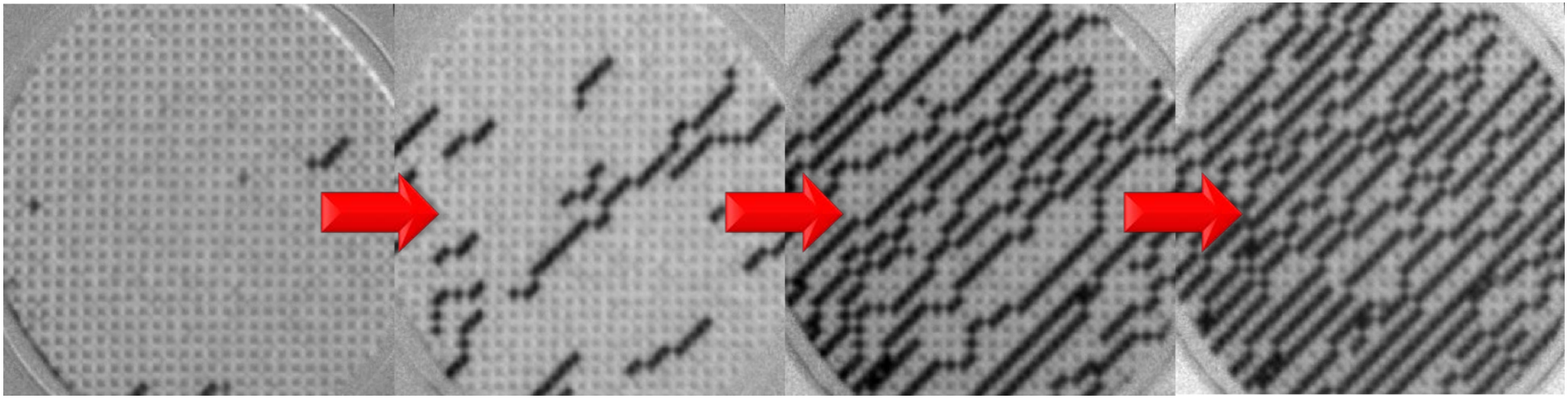


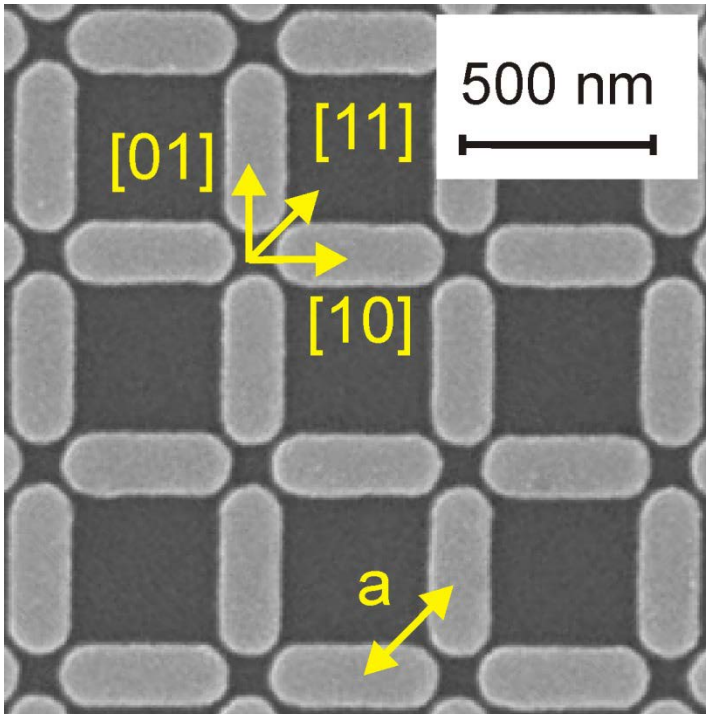
"String Regime"

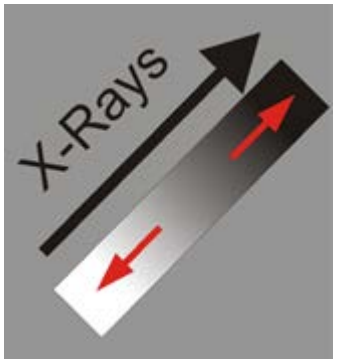
A Farhan et al. PRL (2013)
V Kapaklis et al. Nature Nanotech. (2014)

Thermal Artificial Square Ice

Field of View 20 μm





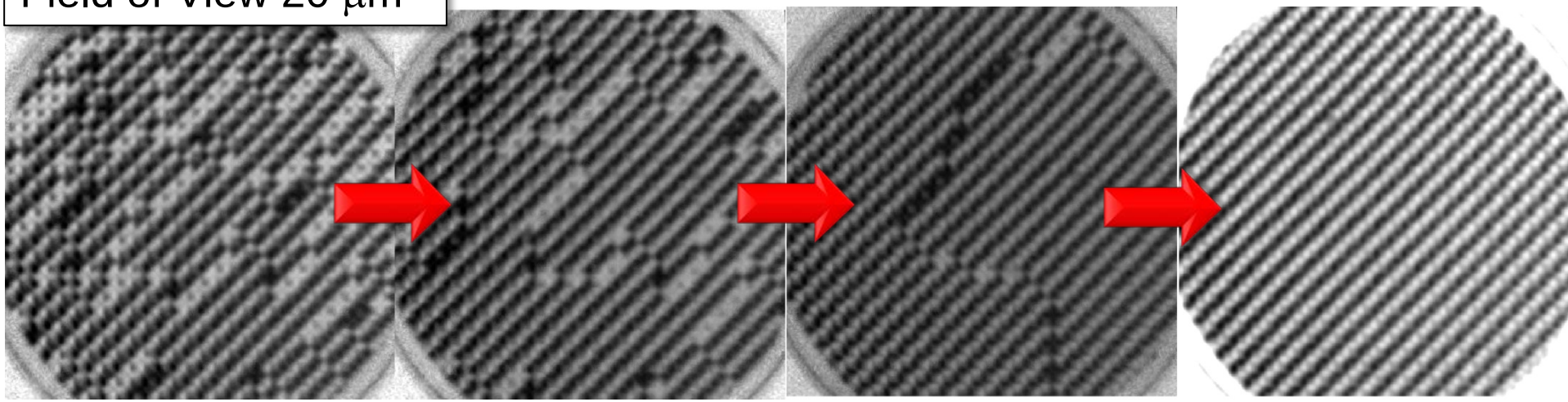


"String Regime"

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

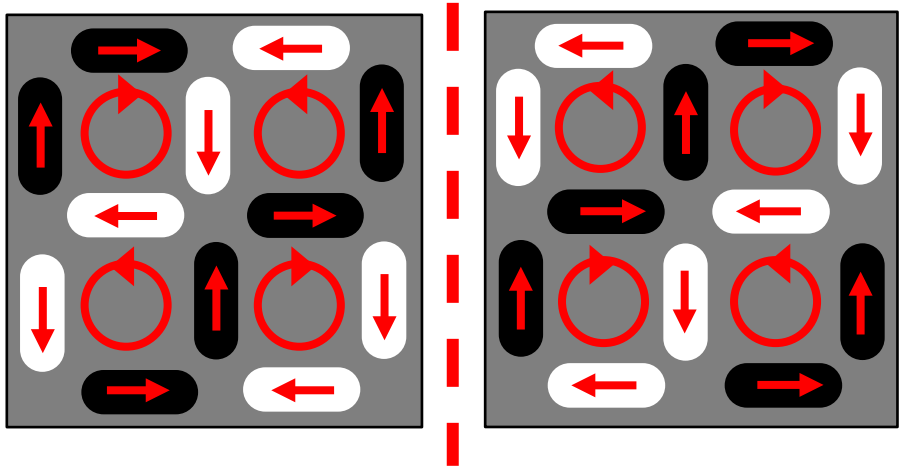
Thermal Artificial Square Ice

Field of View 20 μm



Field of View 50 μm

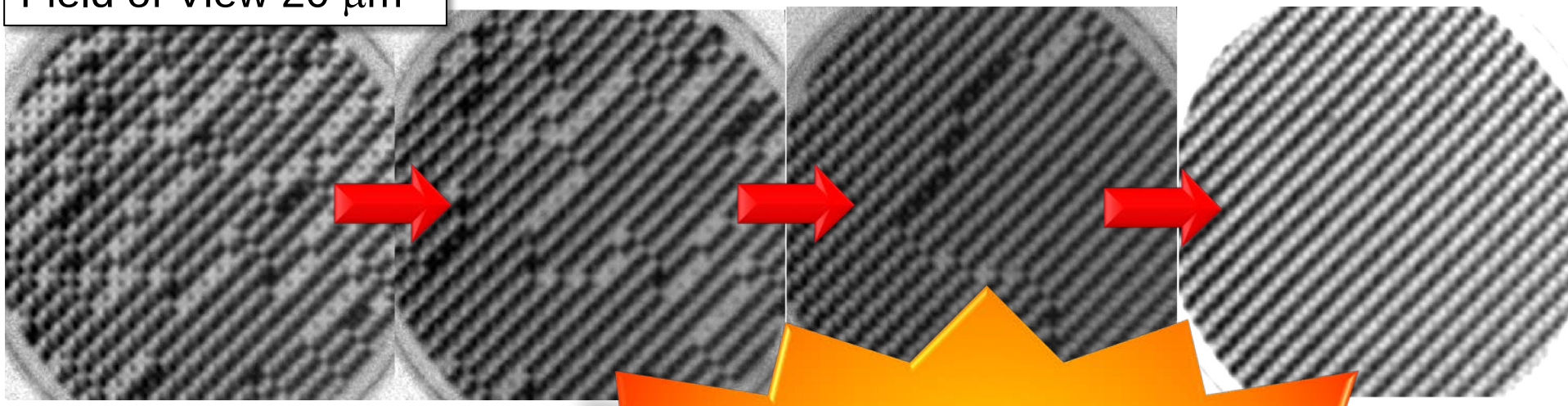
“Domain Regime”



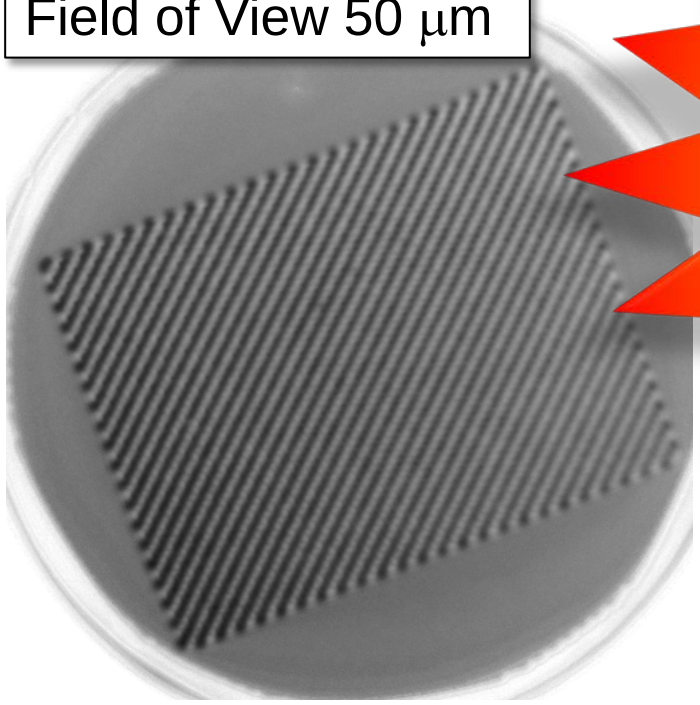
A Farhan et al. PRL (2013)
V Kapaklis et al. Nature Nanotech. (2014)

Thermal Artificial Square Ice

Field of View 20 μm



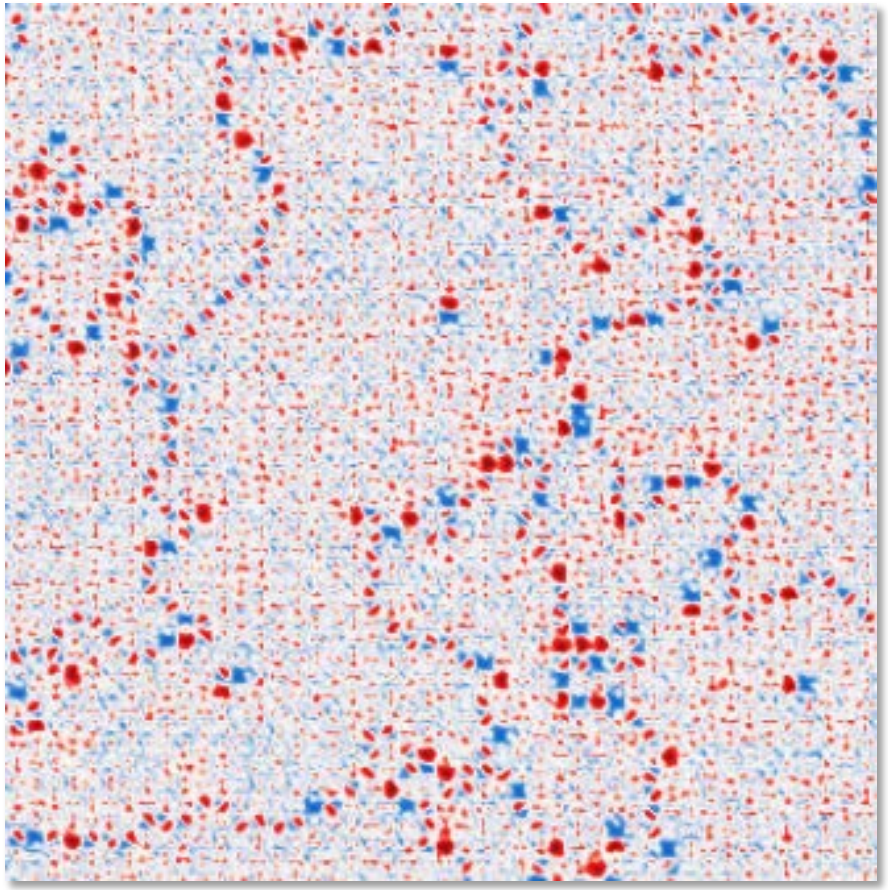
Field of View 50 μm



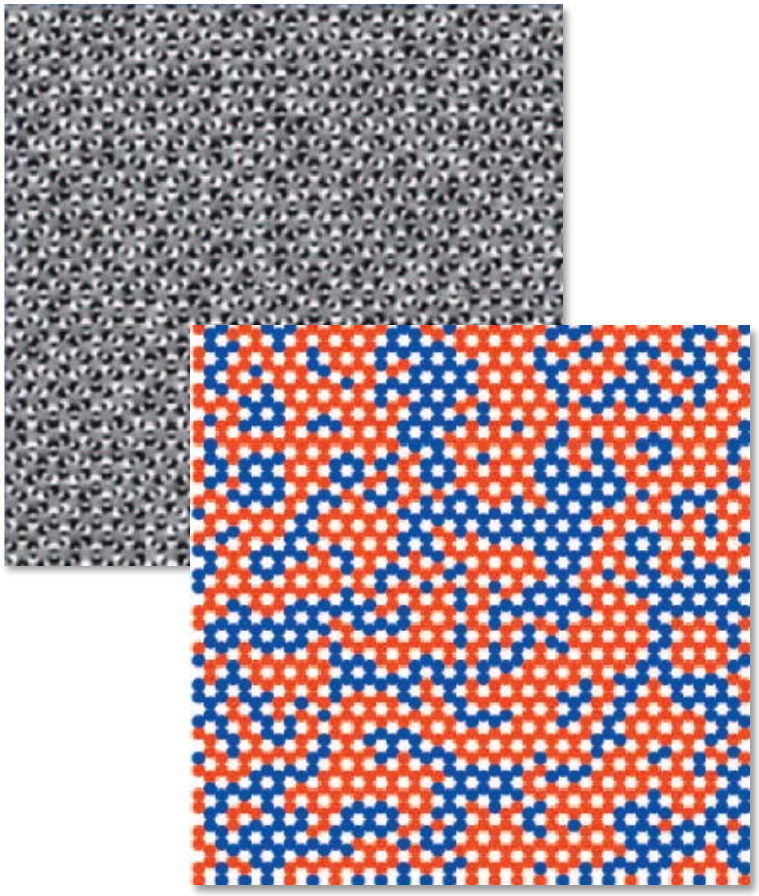
Thermally active systems provide a route to the ground state…..

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

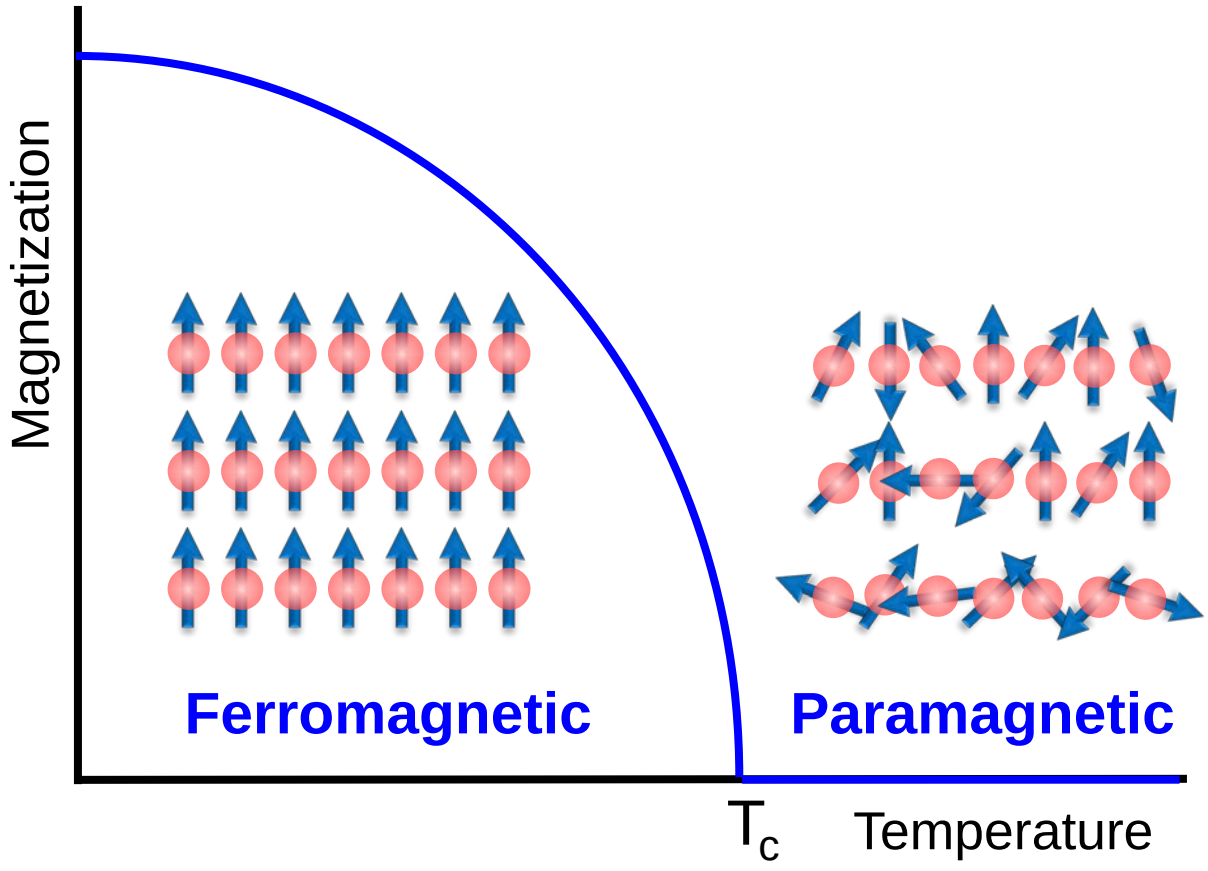
Thermal Behaviour



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



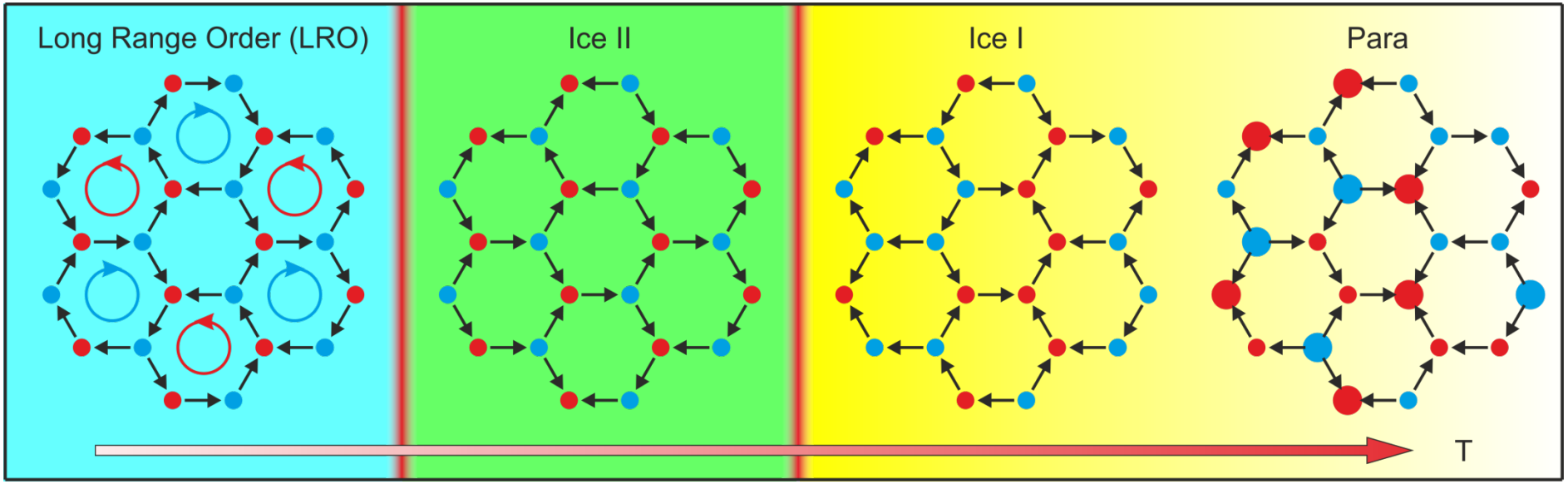
S Zhang et al. Nature (2013)



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

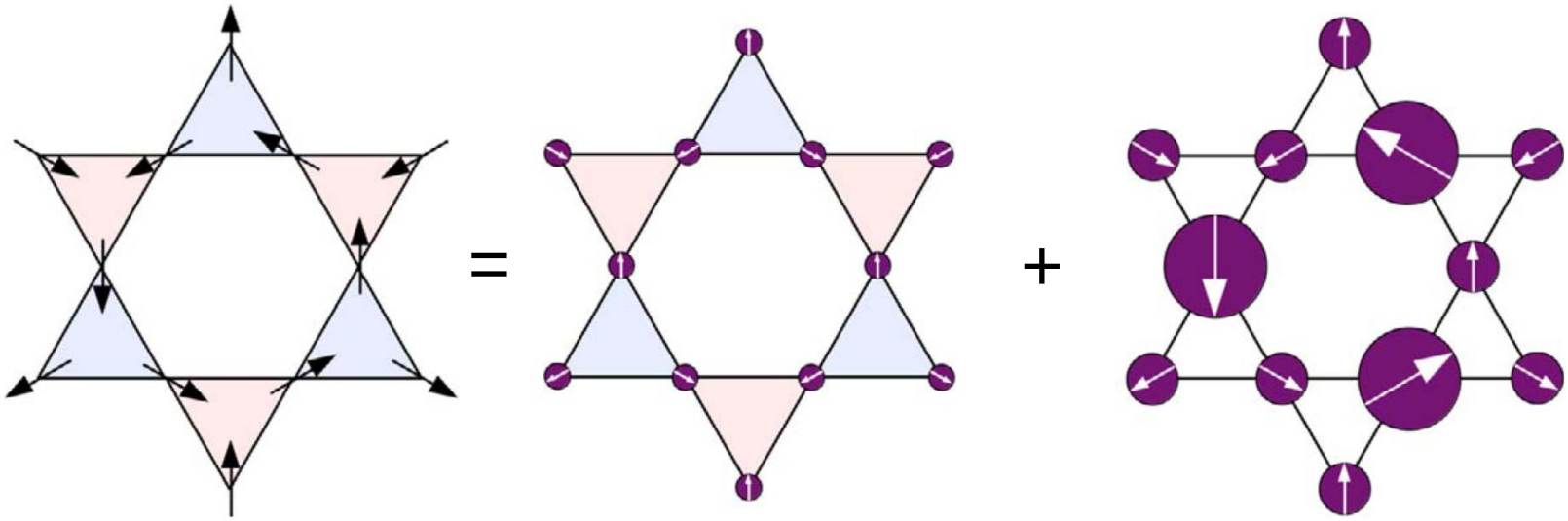
Phys Rev Lett (2011)

L Anghinolfi et al. Nature Communications (2015)

Spin Fragmentation

Curl Free/Divergence Full
→ Info on magnetic charge
→ Bragg Peaks

Divergence Free
→ Fluctuating/Coulomb Phase
→ Structured diffuse signal

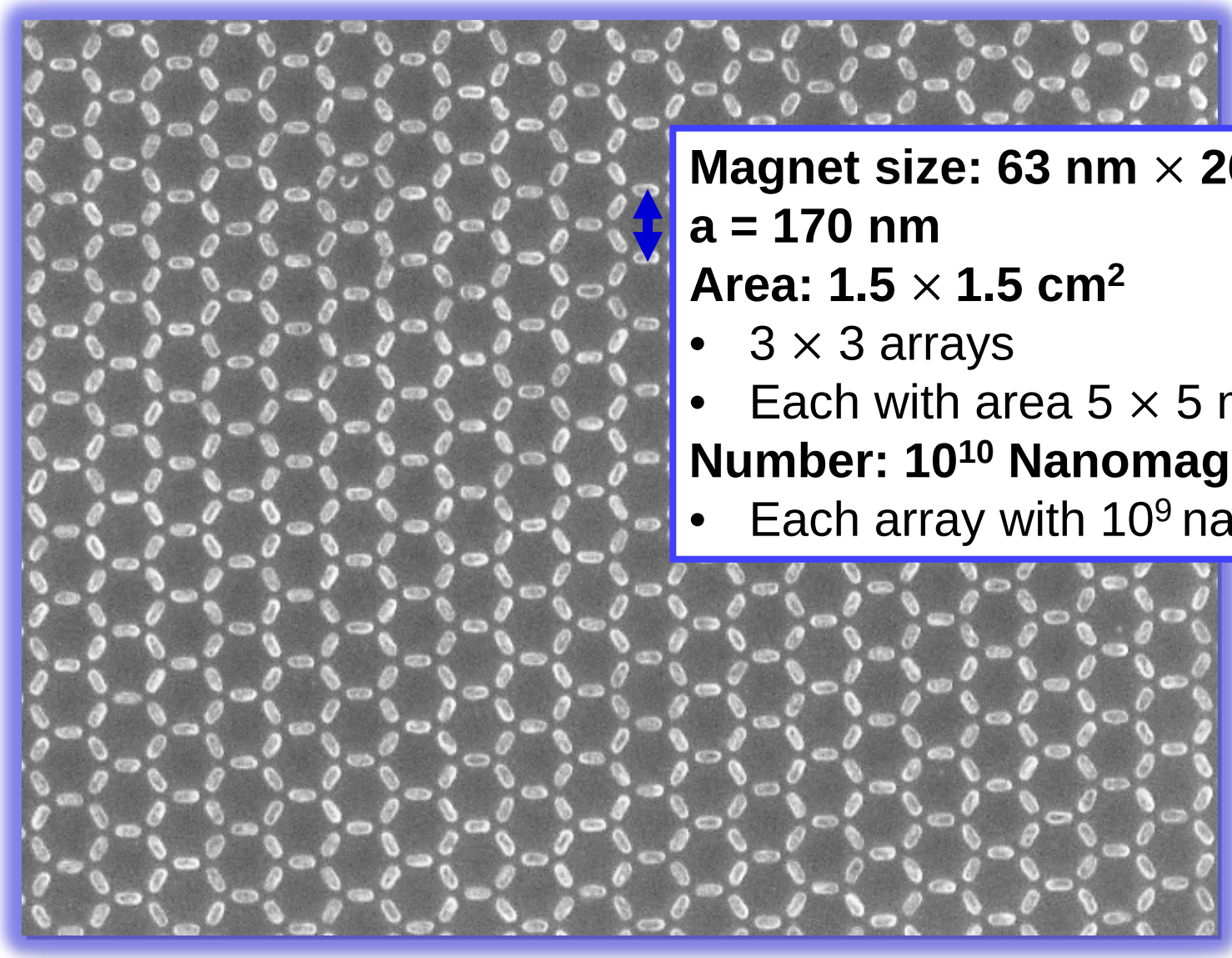


Fragmentation of magnetism in artificial kagome dipolar spin ice
B Canals et al. Nature Communications (2016)

Magnetic-Moment Fragmentation and Monopole Crystallization
ME Brooks-Bartlett et al. Phys Rev X (2014)

Extensive degeneracy, Coulomb phase & magnetic monopoles in artificial square ice
Y Perrin et al. Nature (2016)

Artificial Kagome Spin Ice



Magnet size: 63 nm × 26 nm × 6 nm

a = 170 nm

Area: 1.5 × 1.5 cm^2

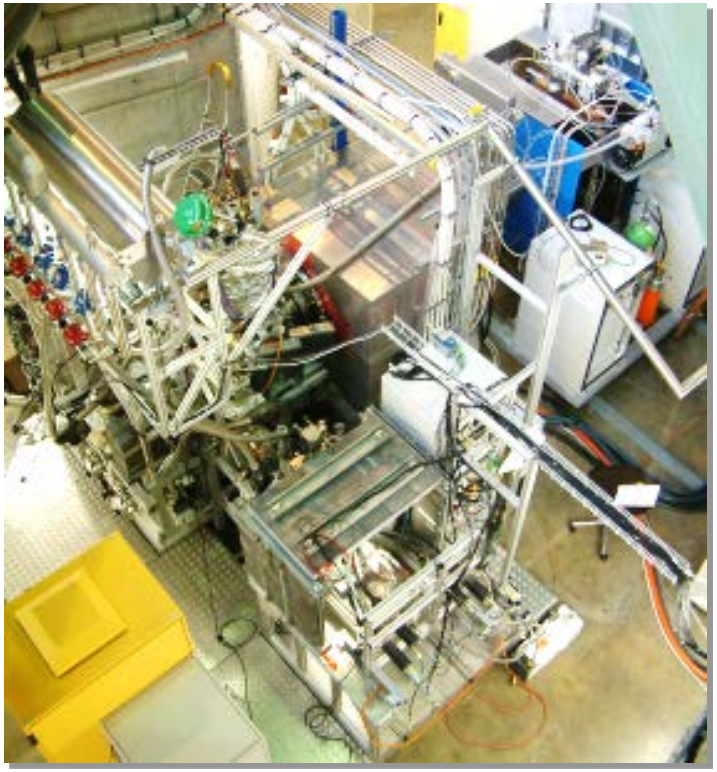
- 3 × 3 arrays
- Each with area 5 × 5 mm^2

Number: 10^{10} Nanomagnets

- Each array with 10^9 nanomagnets

L Anghinolfi et al. Nature Communications (2015)

Low Energy Muons (LEM, PSI)

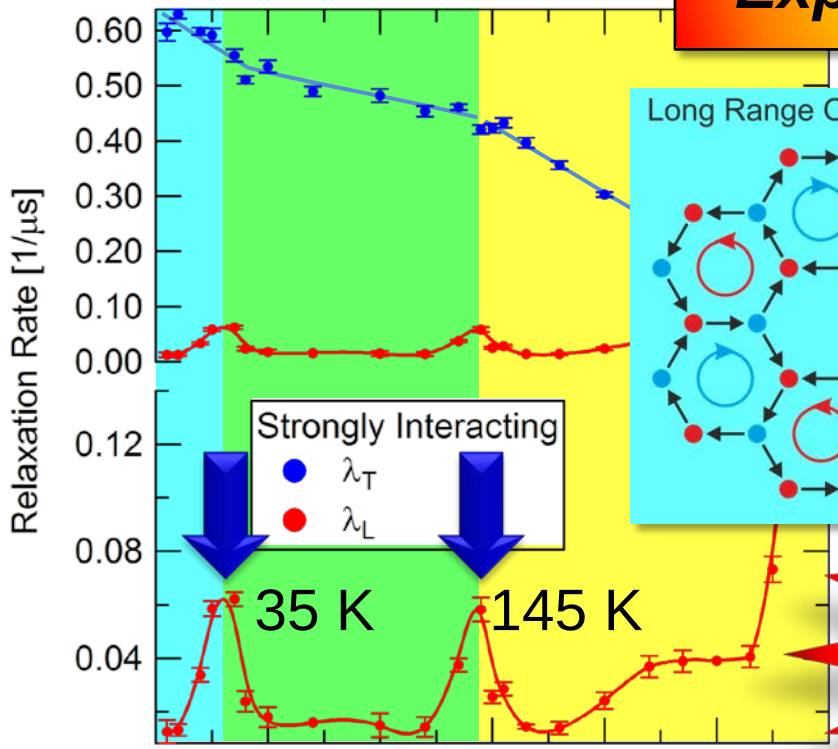


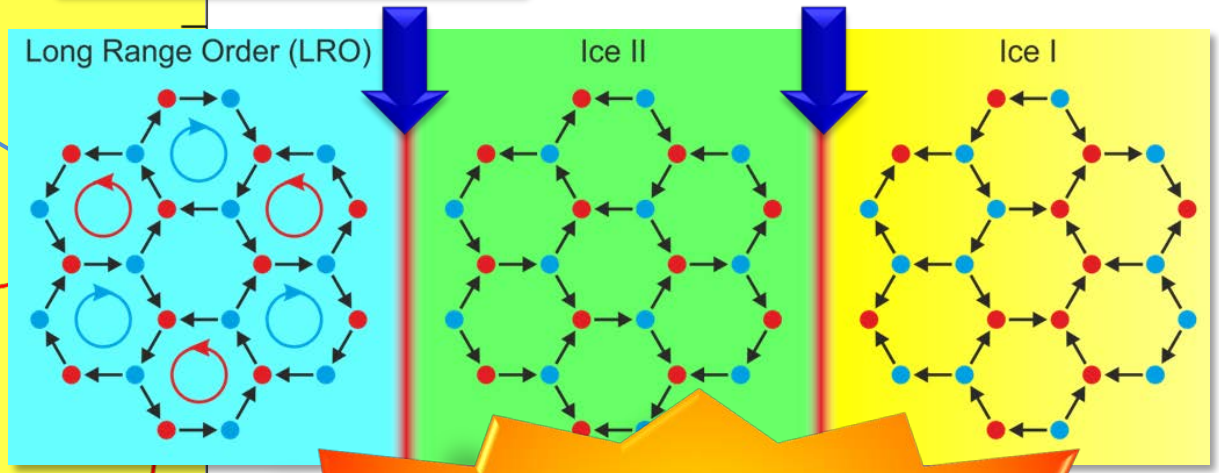
- Zero applied field
- Temperature control
- Local probe
- Magnetic phase transitions
- Tunable implantation depths: 1-100 nm
- Ideal for thin films and nanostructures

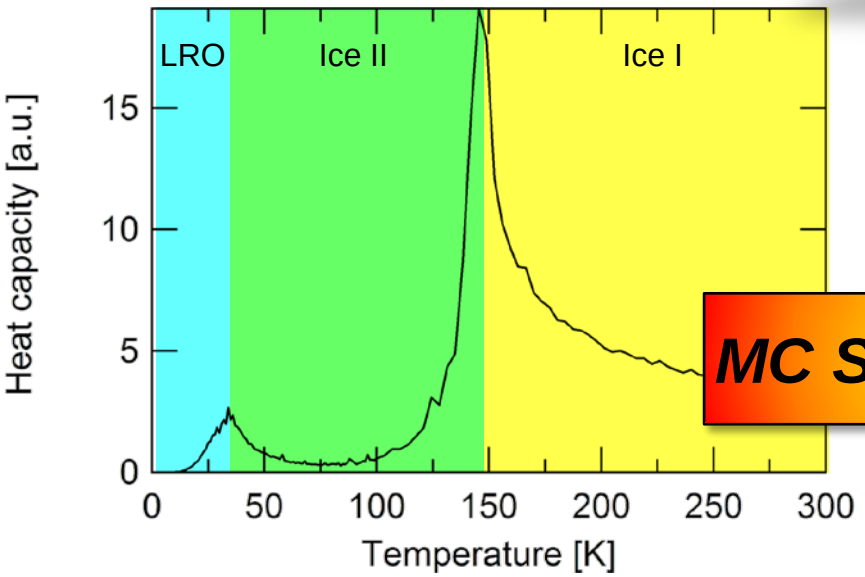
L Anghinolfi et al. Nature Communications (2015)

ETH PSI

Experiment







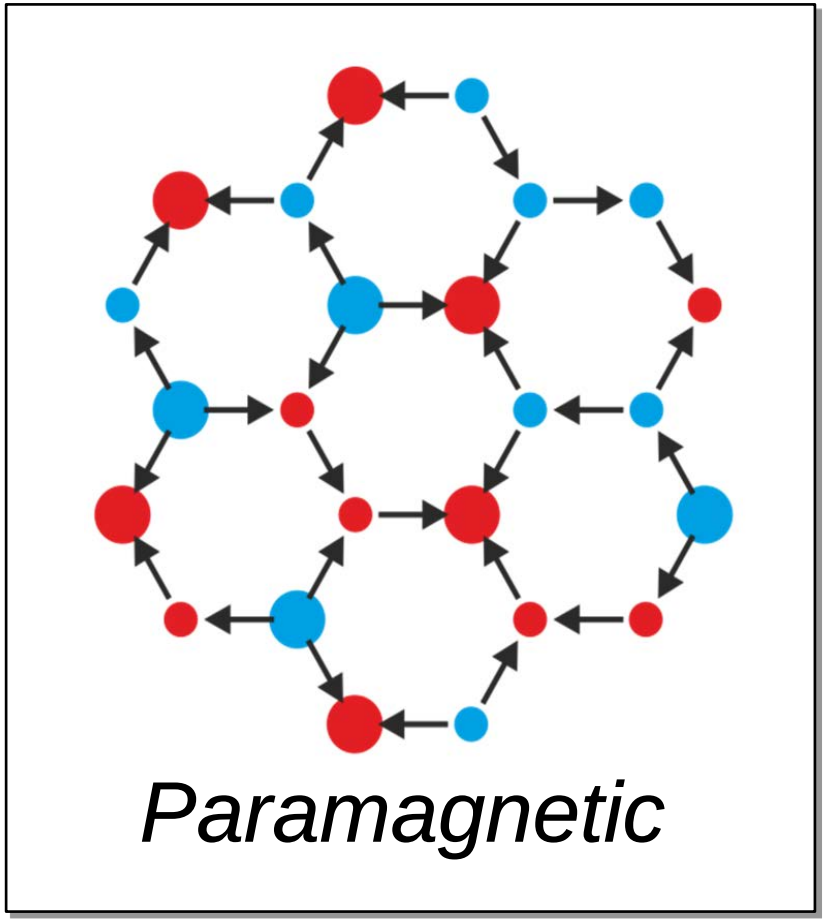
Frustrated Magnetic Metamaterial

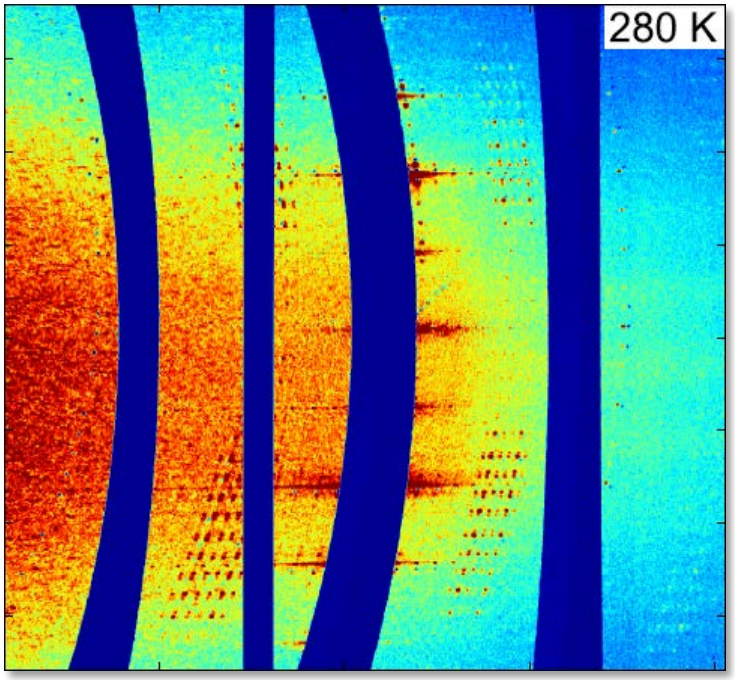
- Thermal equilibrium
- Phase transitions

MC Simulations

L Anghinolfi et al.
Nature Communications (2015)

Artificial Kagome Spin Ice



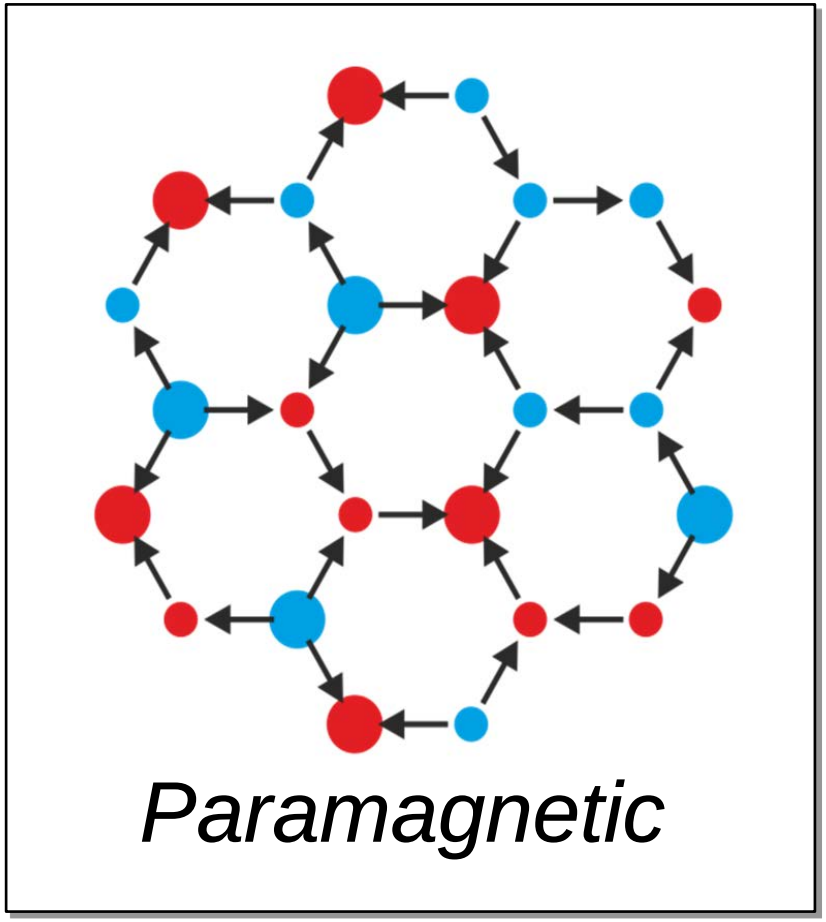


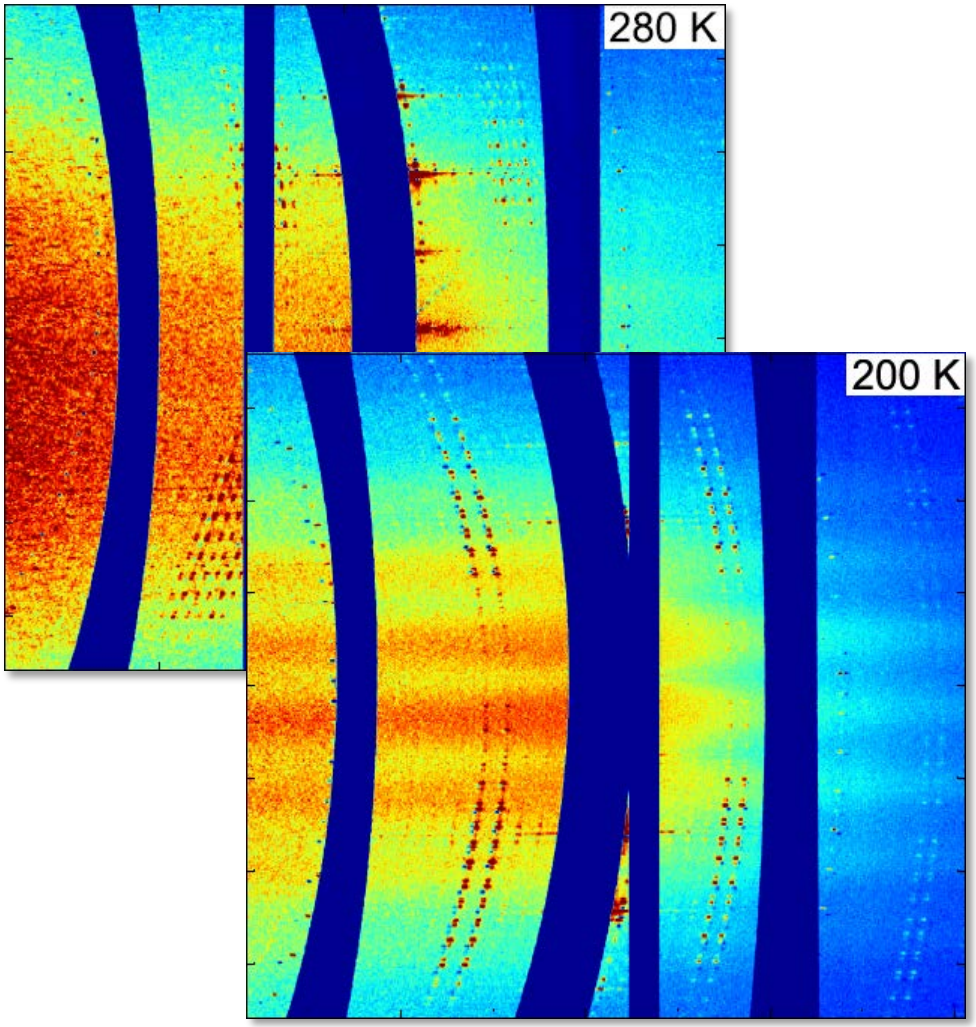
Soft X-ray Resonant Magnetic Scattering

J Perron et al. Phys Rev B (2013)

O Sendetskyi et al. Phys Rev B (2016)

Artificial Kagome Spin Ice



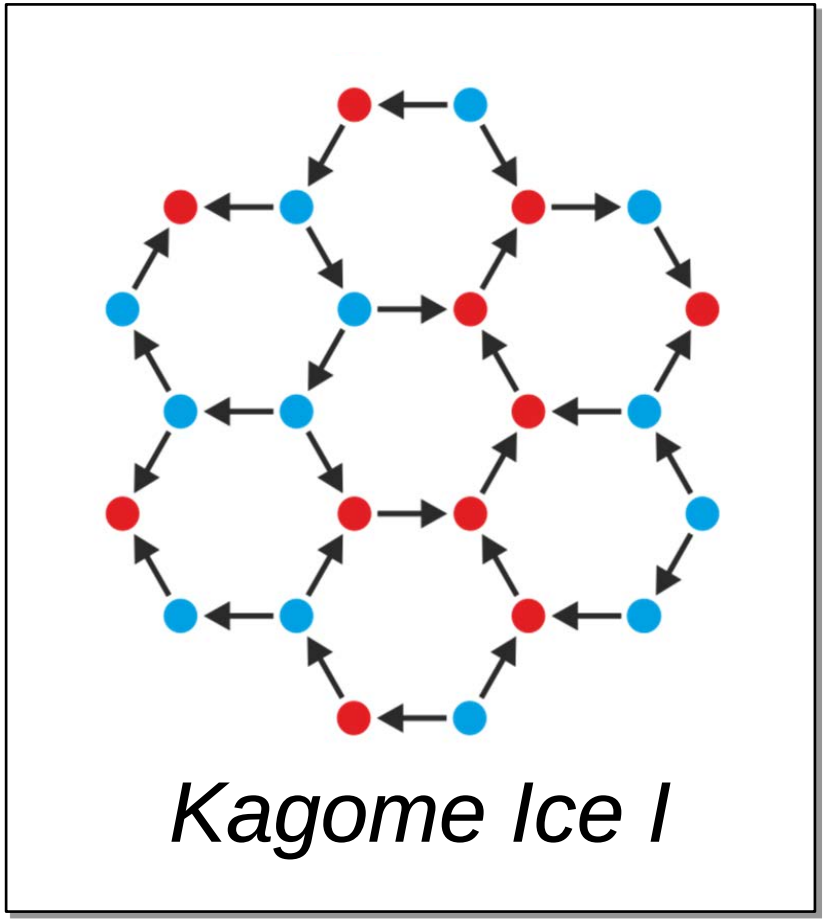


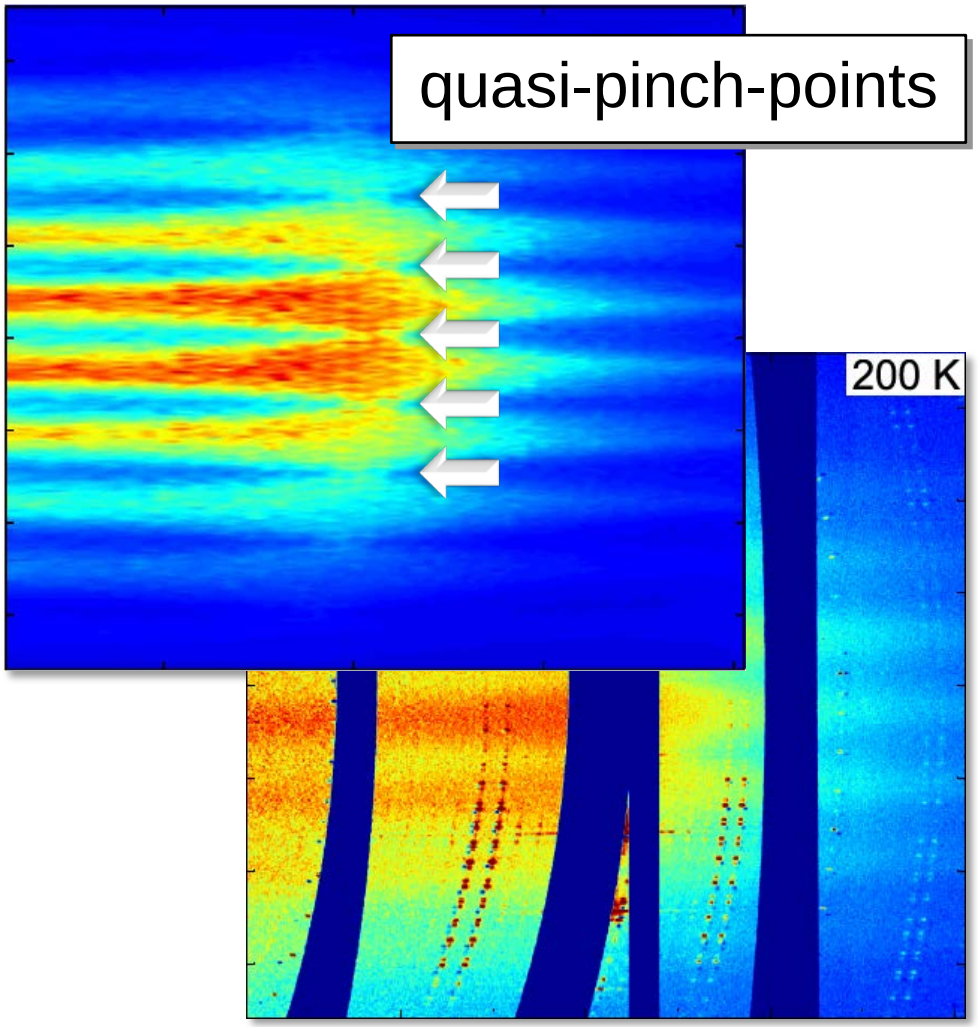
Soft X-ray Resonant Magnetic Scattering

J Perron et al. Phys Rev B (2013)

O Sendetskyi et al. Phys Rev B (2016)

Artificial Kagome Spin Ice



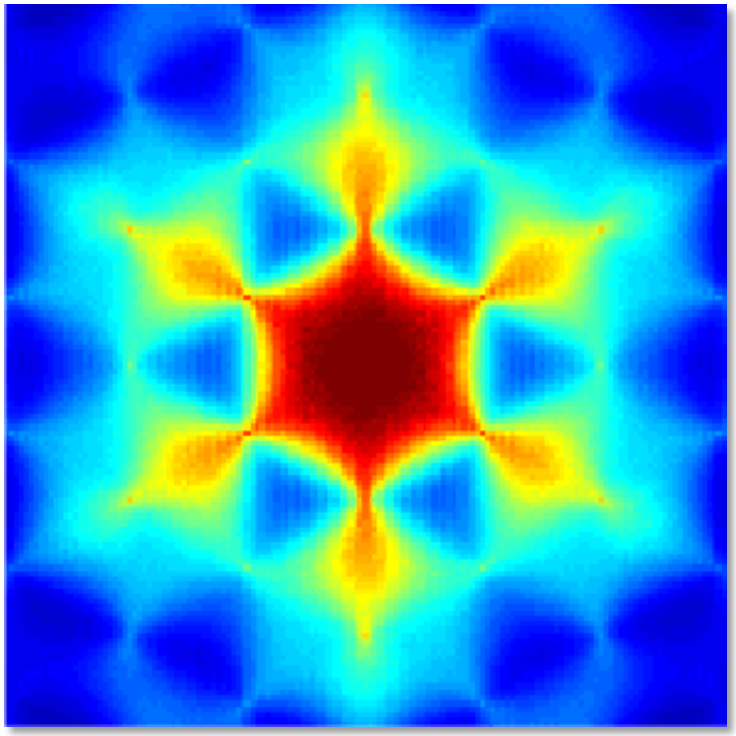


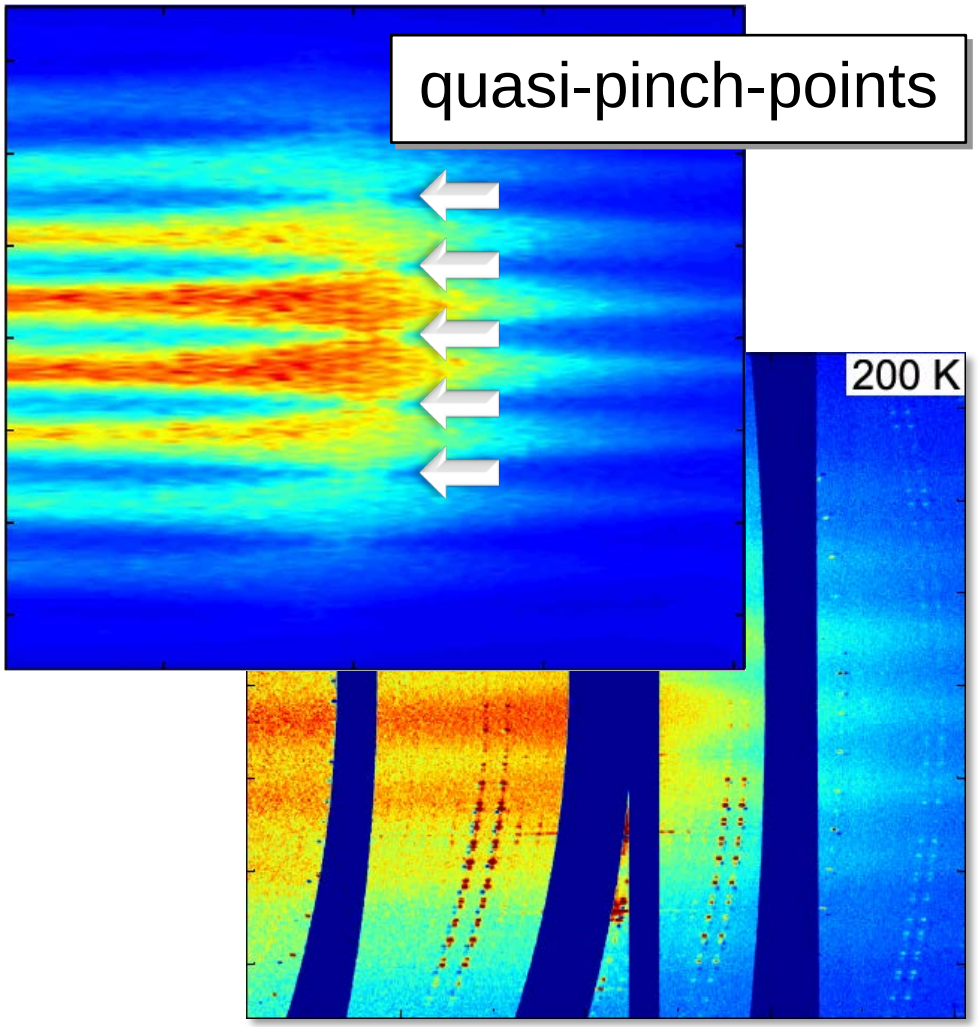
Soft X-ray Resonant Magnetic Scattering

J Perron et al. Phys Rev B (2013)

O Sendetskyi et al. Phys Rev B (2016)

Artificial Kagome Spin Ice



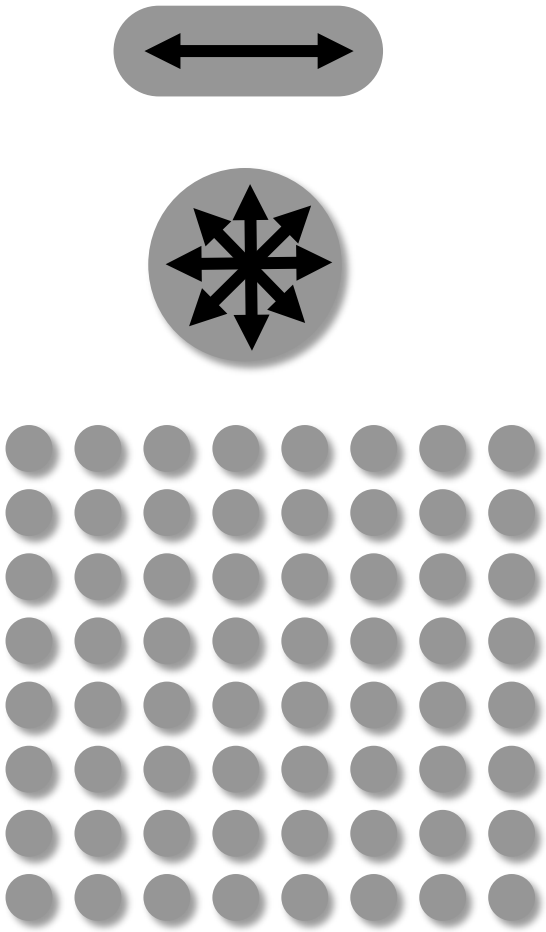


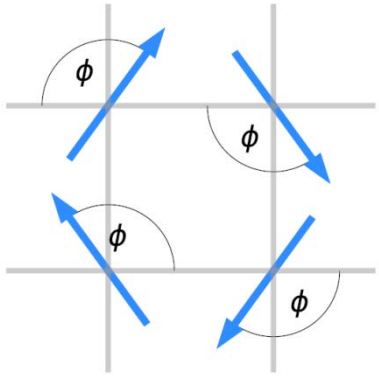
Soft X-ray Resonant Magnetic Scattering

J Perron et al. Phys Rev B (2013)

O Sendetskyi et al. Phys Rev B (2016)

dXY System - Theory



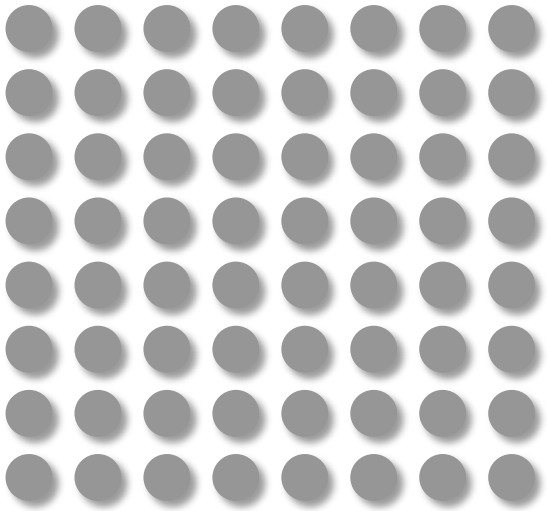


- Continuous ground-state degeneracy
- Order-by-disorder transition: thermal fluctuations → long-range ordered phase
- Theory predicts a continuous transition to AFM stripe order

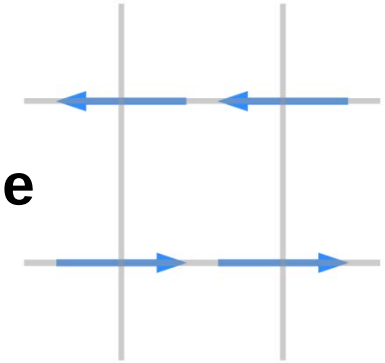
N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

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

dXY System - Theory



Stripe Phase



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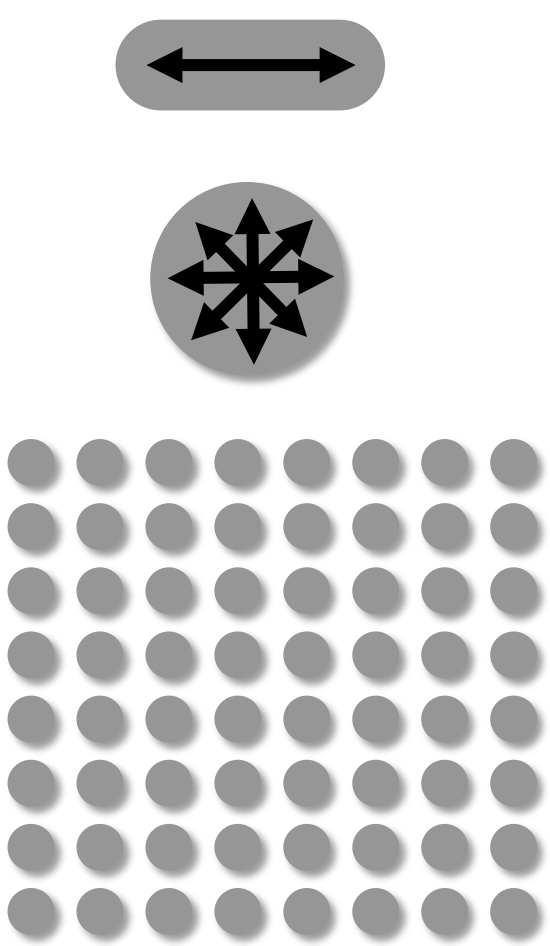
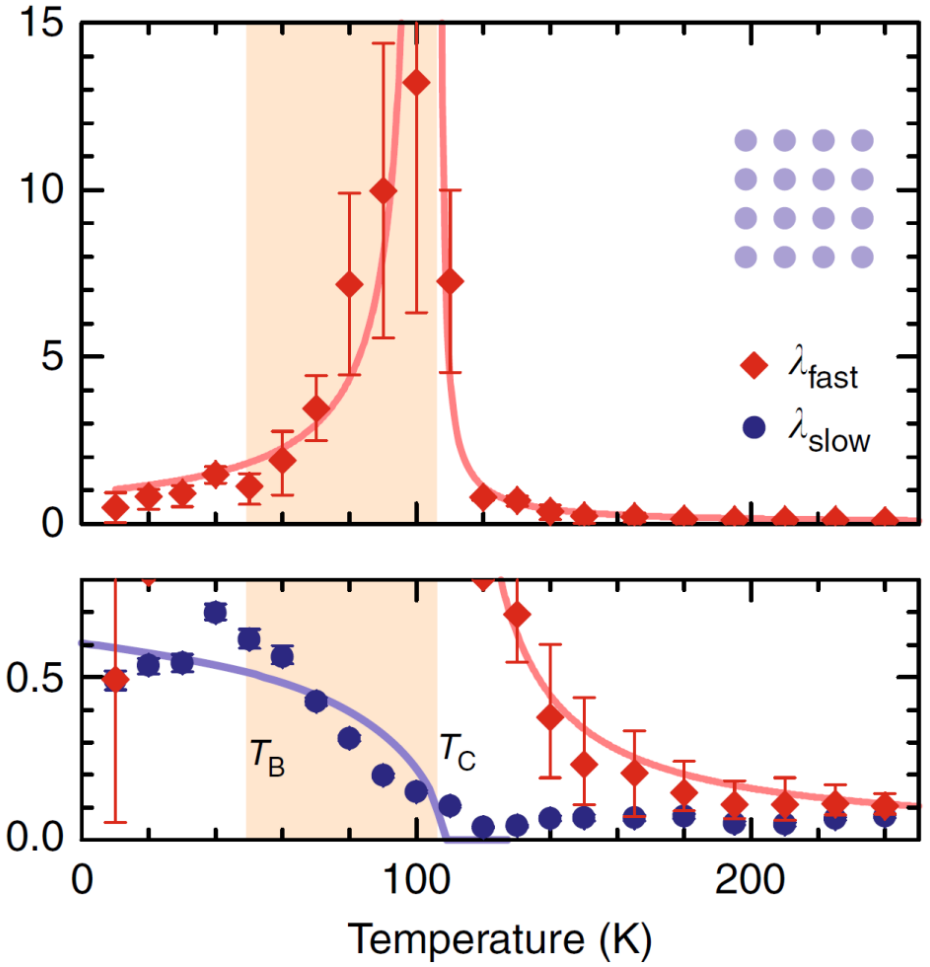
N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

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

dXY System

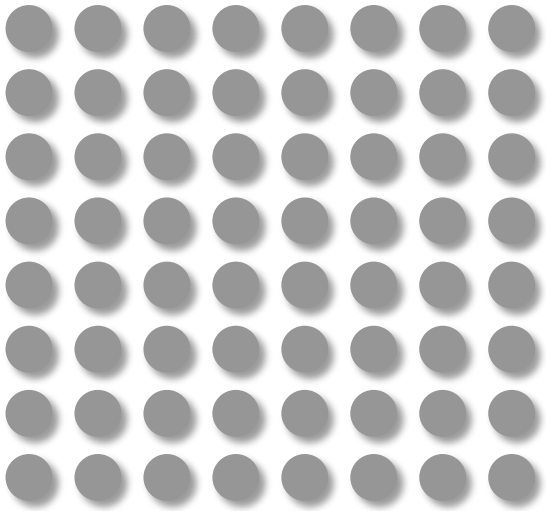


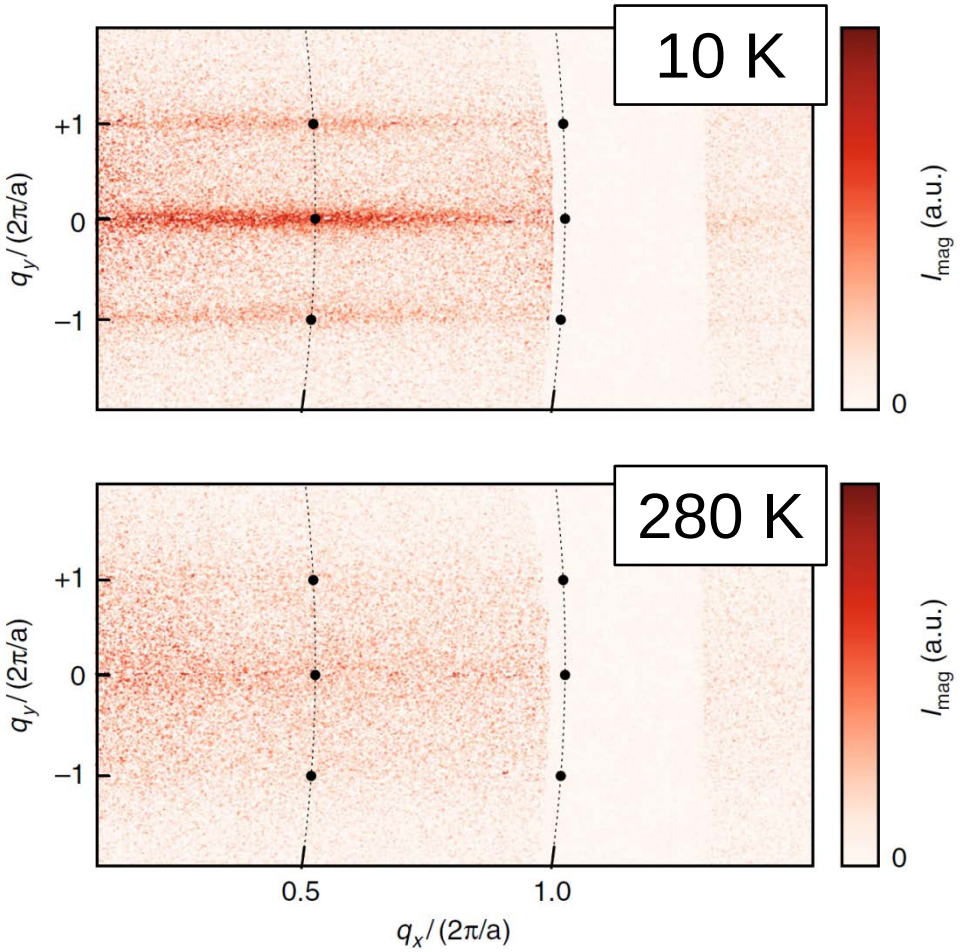


N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

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

dXY System

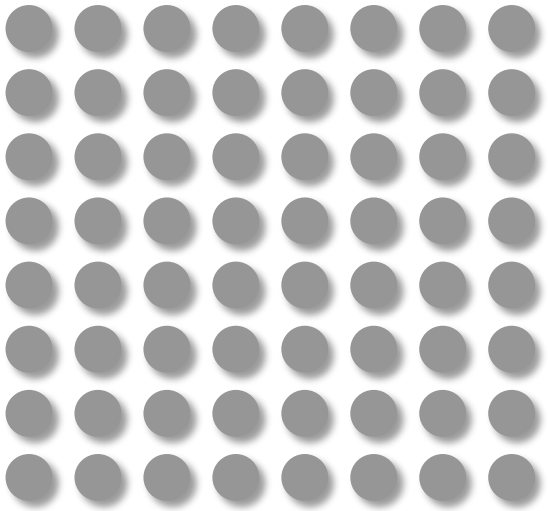




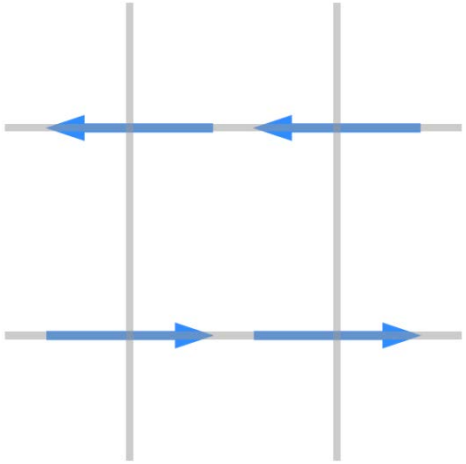
N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

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

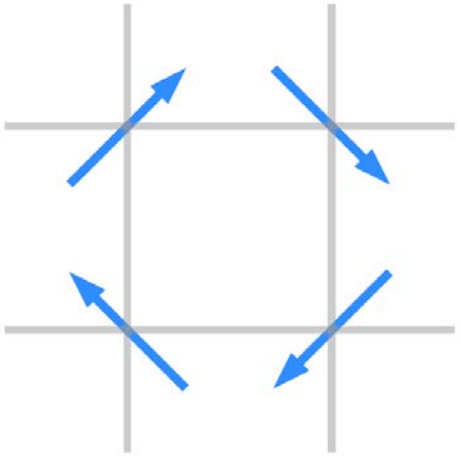
dXY System & Disorder



Stripe Phase



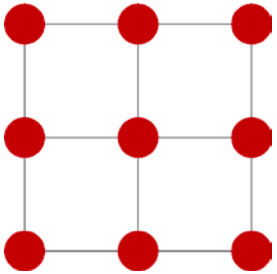
Microvortex Phase

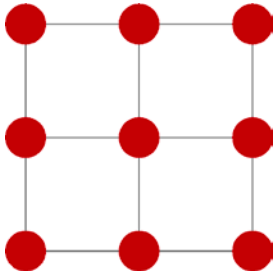


N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

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

dXY System & Disorder



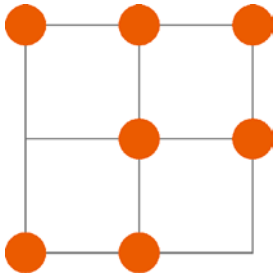


N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

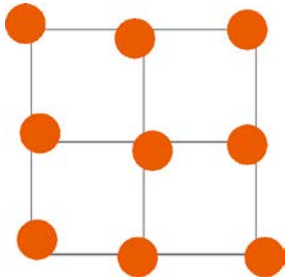
D Schildknecht, L Heyderman & P Derlet Phys Rev B (2018)

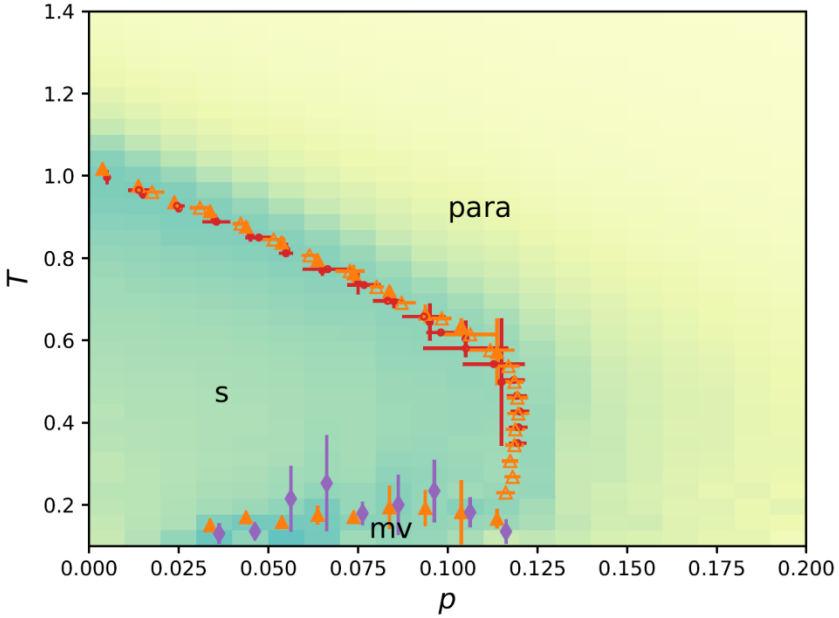
dXY System & Disorder

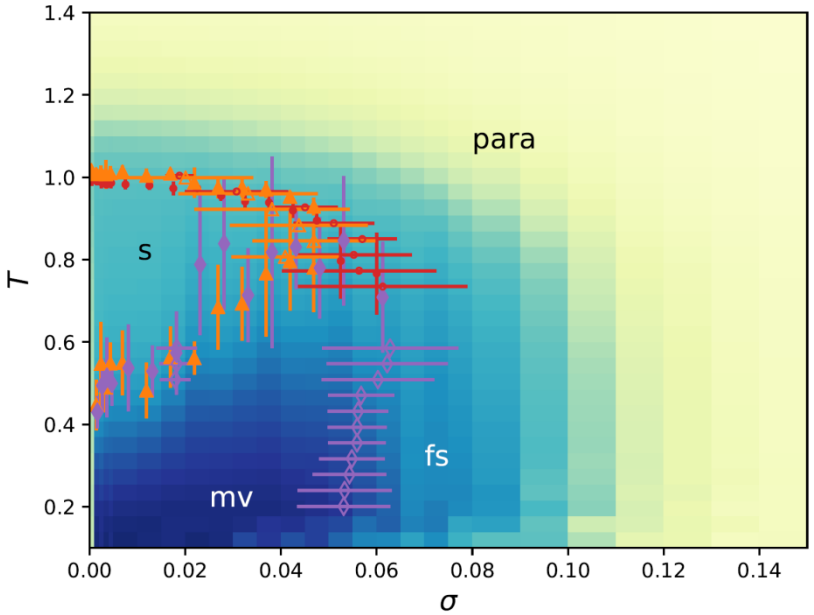
Diluted



Random Displacement

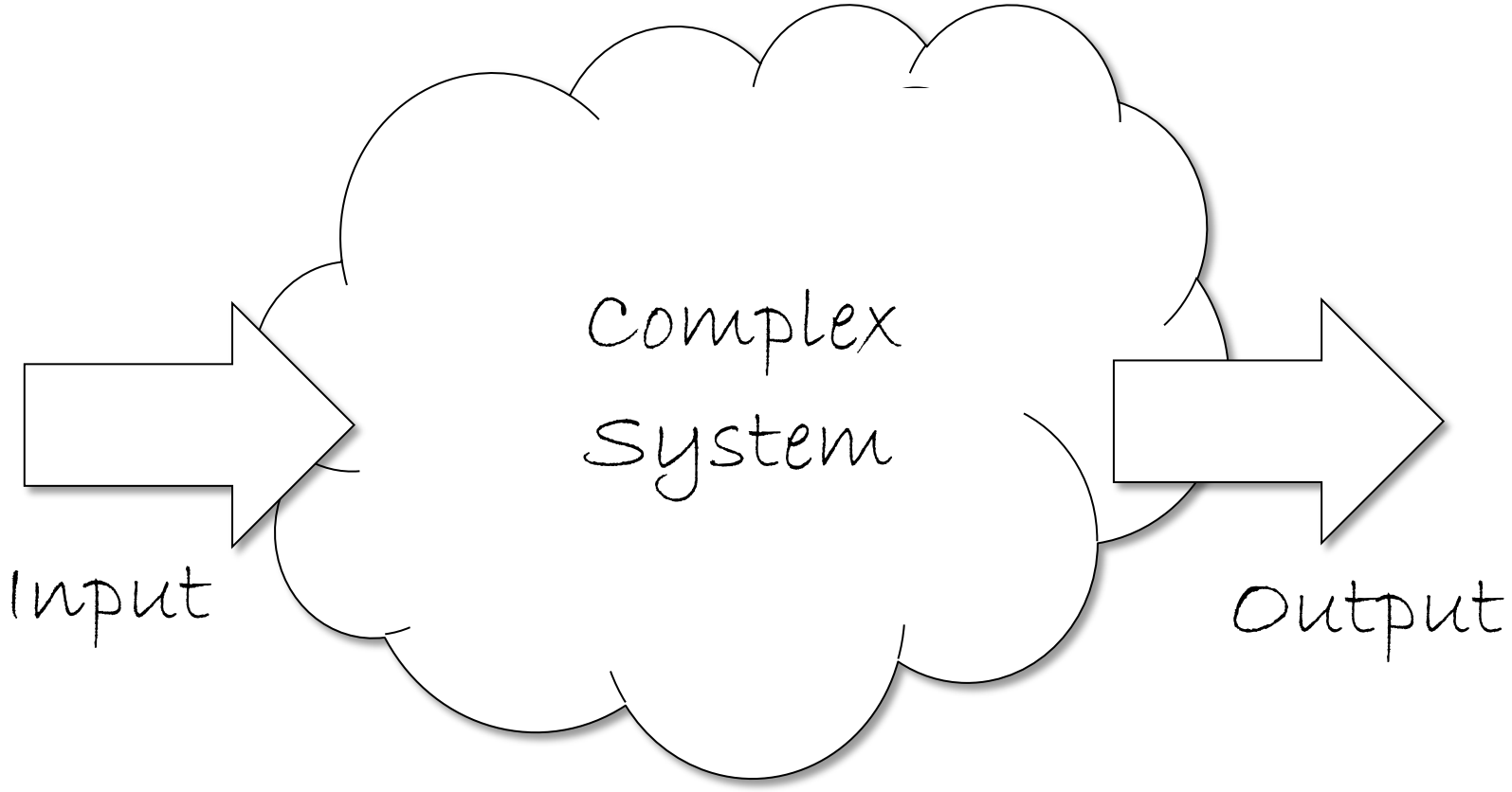






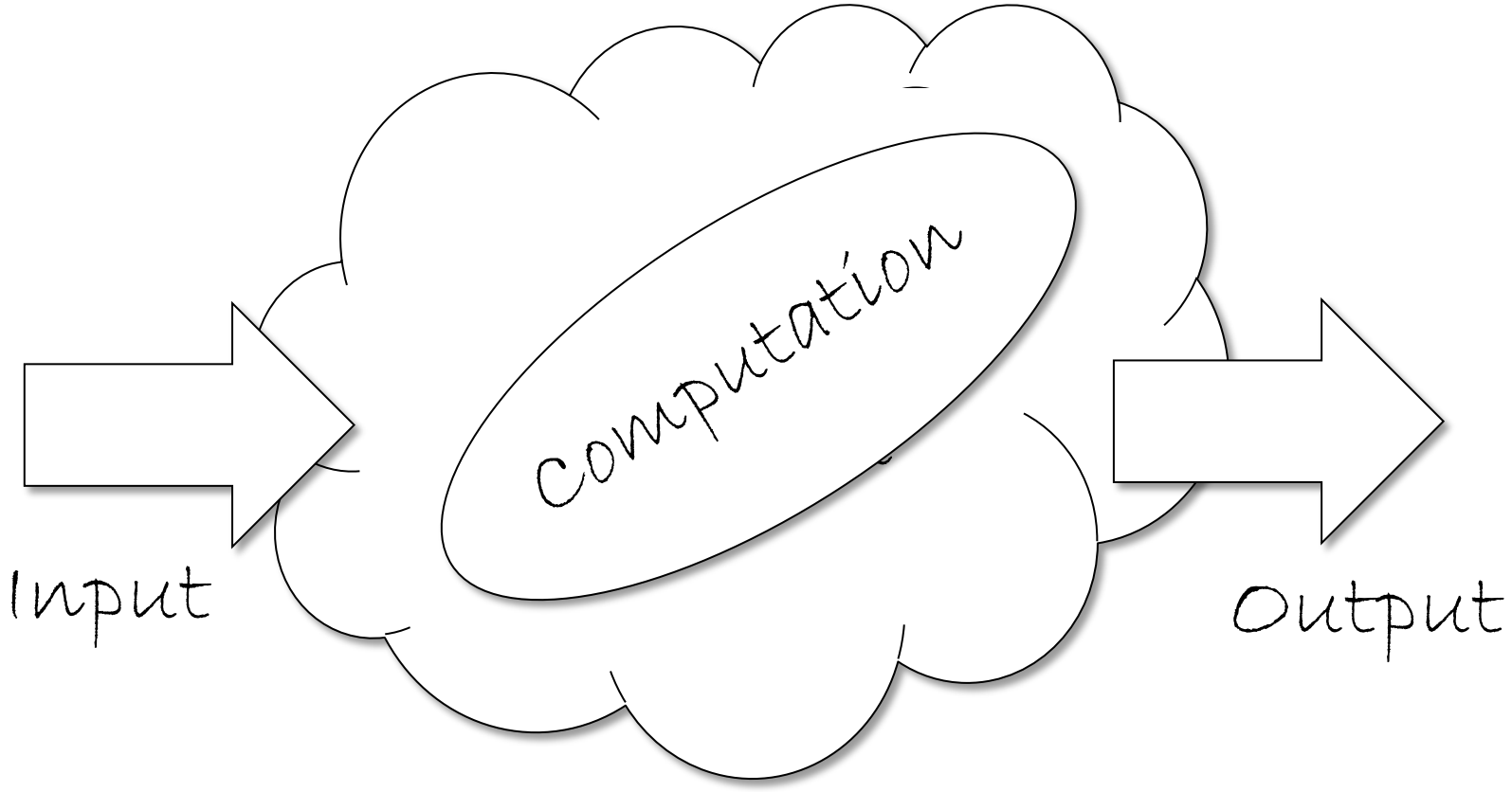
N Leo, S Holenstein, D Schildknecht, O Sendetskyi, H Luetkens, PM Derlet, V Scagnoli, D Lançon, JRL. Mardegan, T Prokscha, A Suter, Z Salman, S Lee & LJ Heyderman Nature Communications (2018)

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



Topic 3

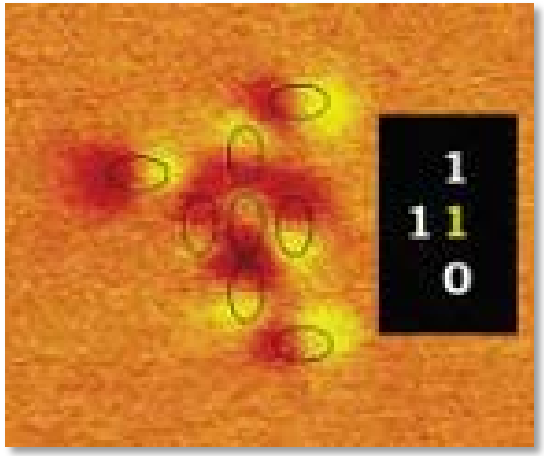
Towards Bioinspired Computation

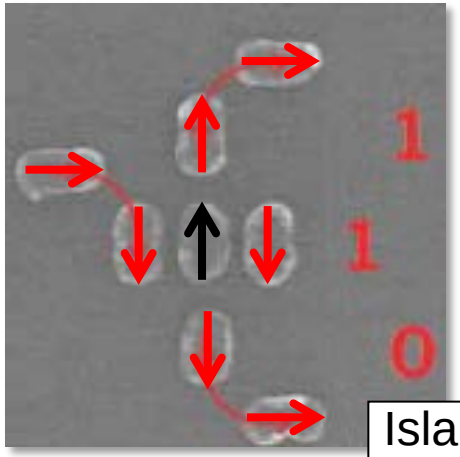


Topic 3

Towards Bioinspired Computation

Nanomagnetic Logic

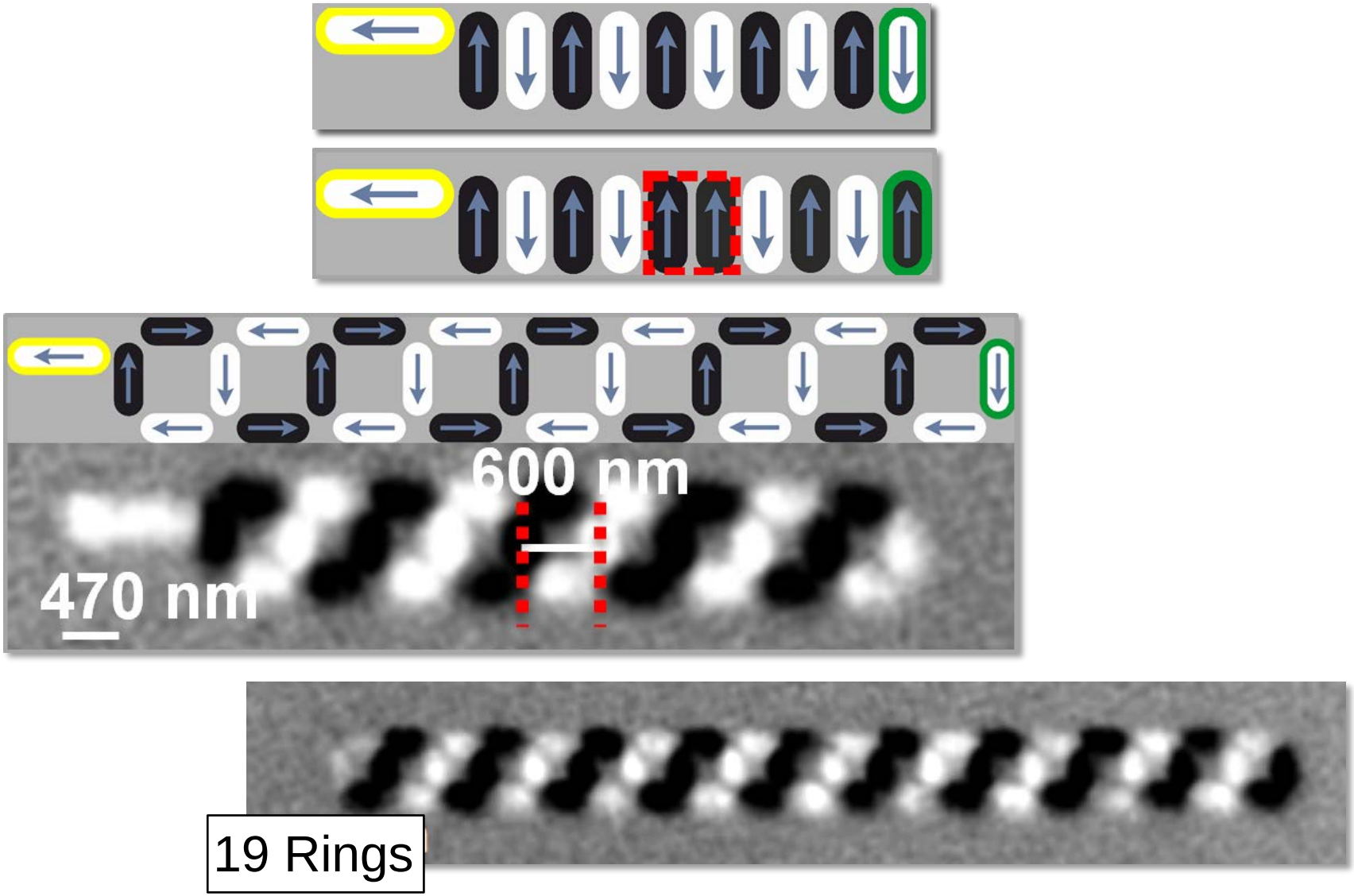




Island size:
120×70 nm

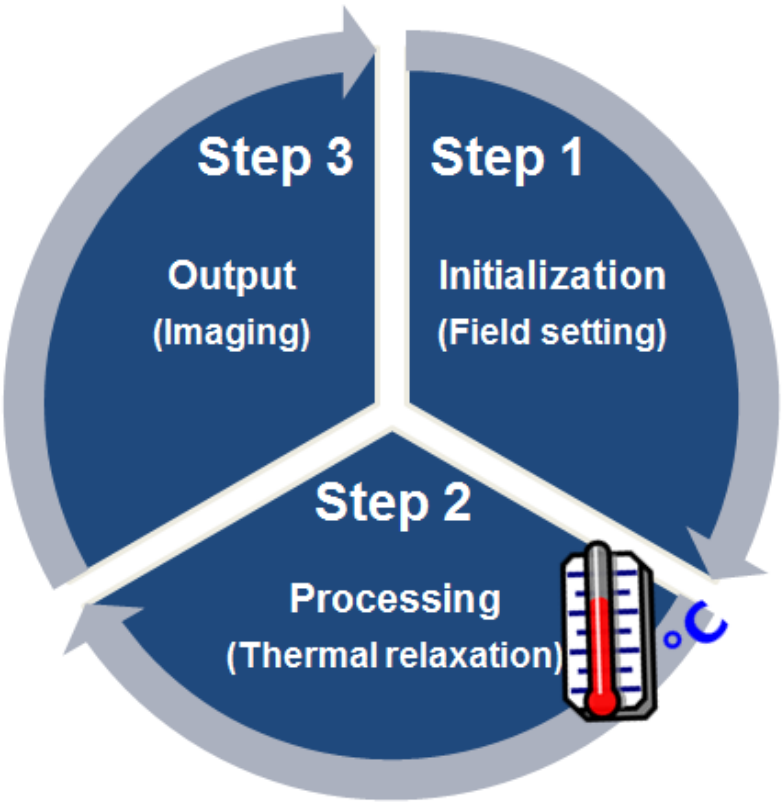
A Imre et al. Science (2006)

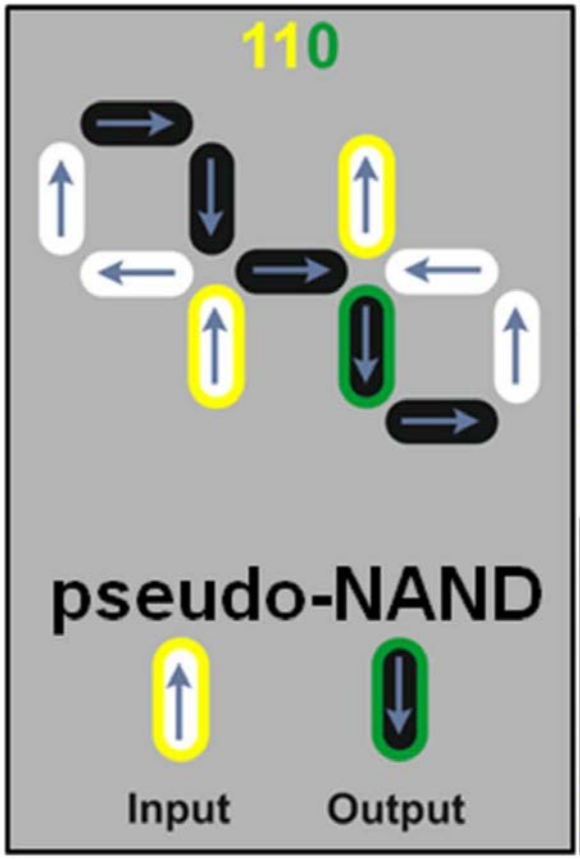
Nanomagnetic Logic

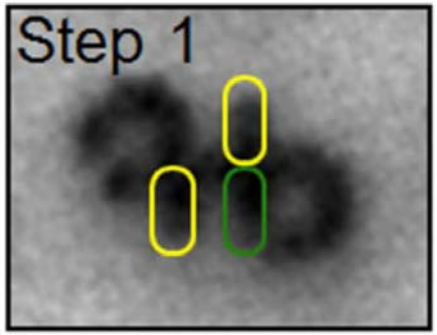


H Arava, PM Derlet, J Vijayakumar, J Cui, NS Bingham, A Kleibert and LJ Heyderman
Nanotechnology (2018)

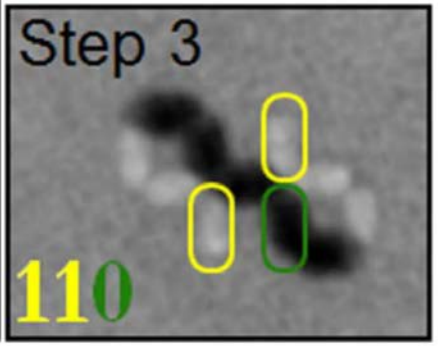
Nanomagnetic Logic





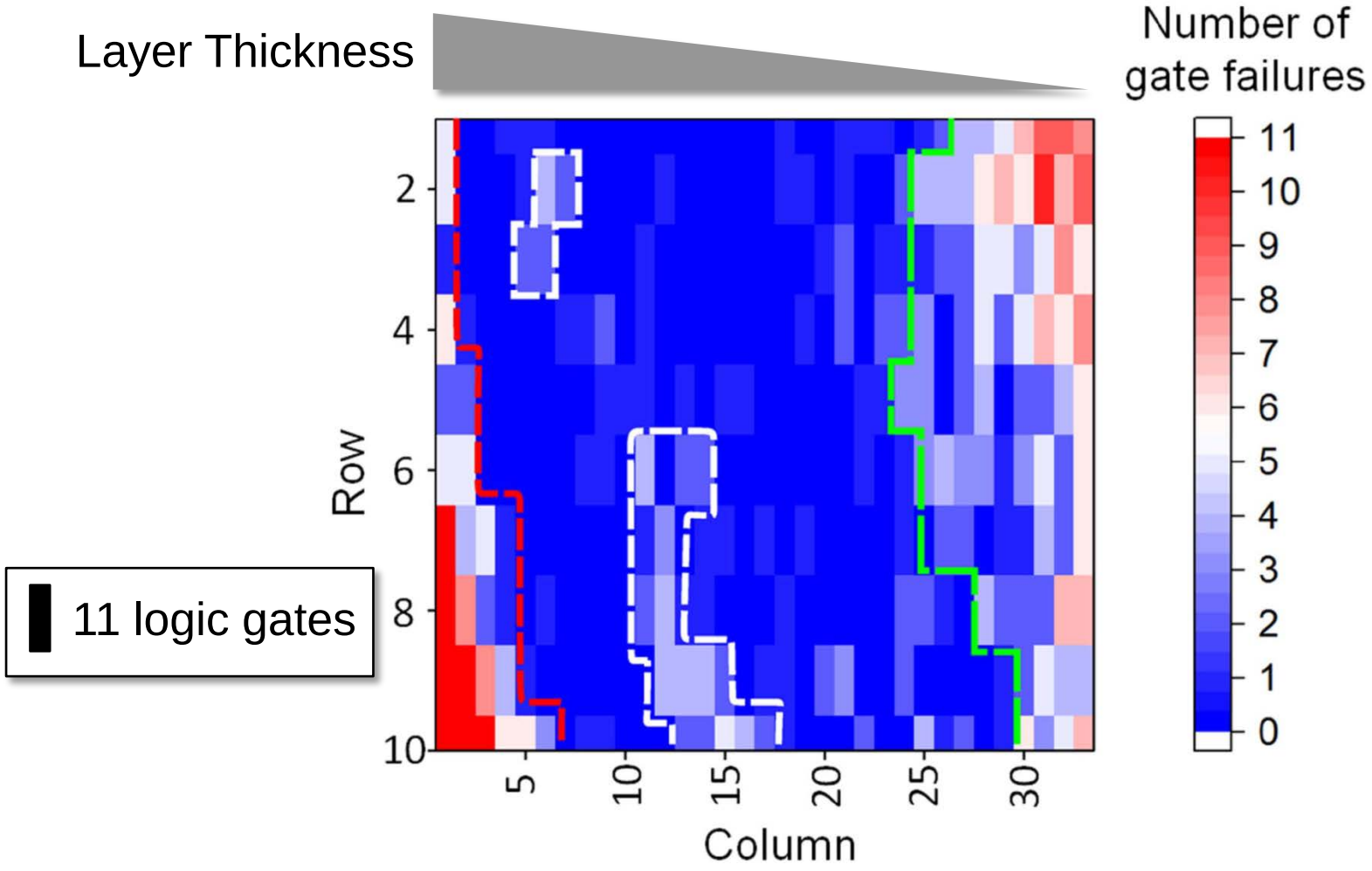


Step 2 ⬇



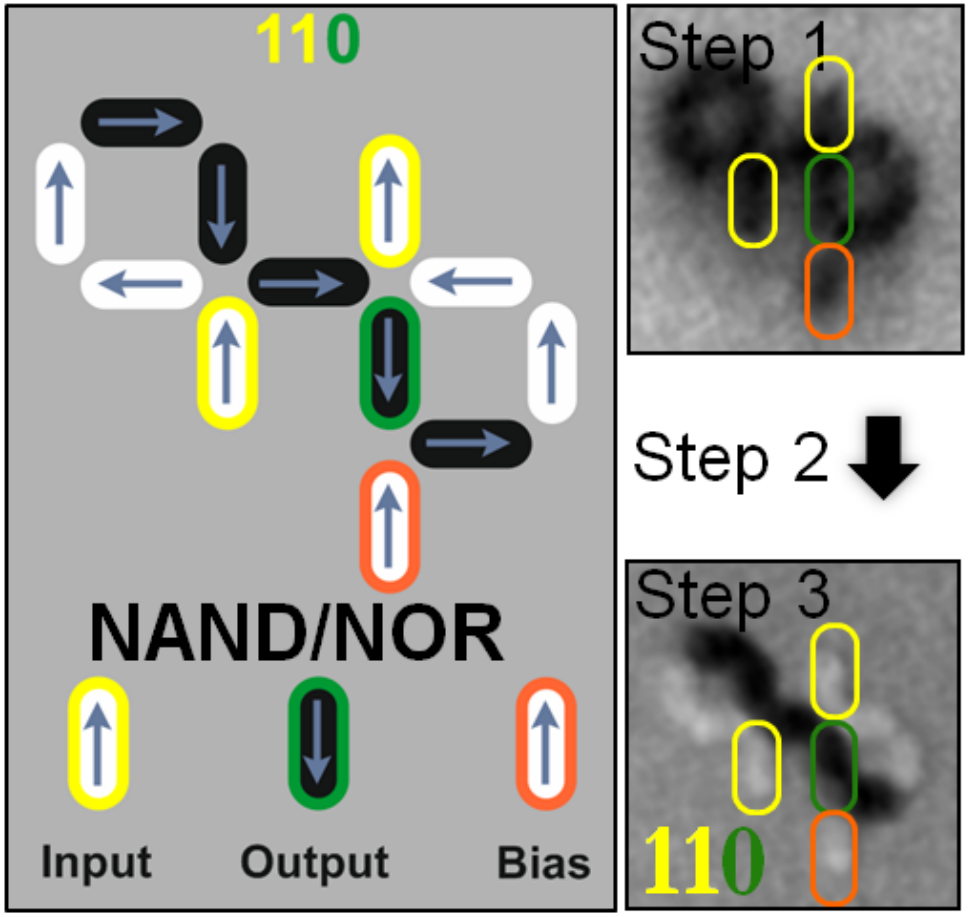
H Arava, PM Derlet, J Vijayakumar, J Cui, NS Bingham, A Kleibert and LJ Heyderman
Nanotechnology (2018)

Nanomagnetic Logic



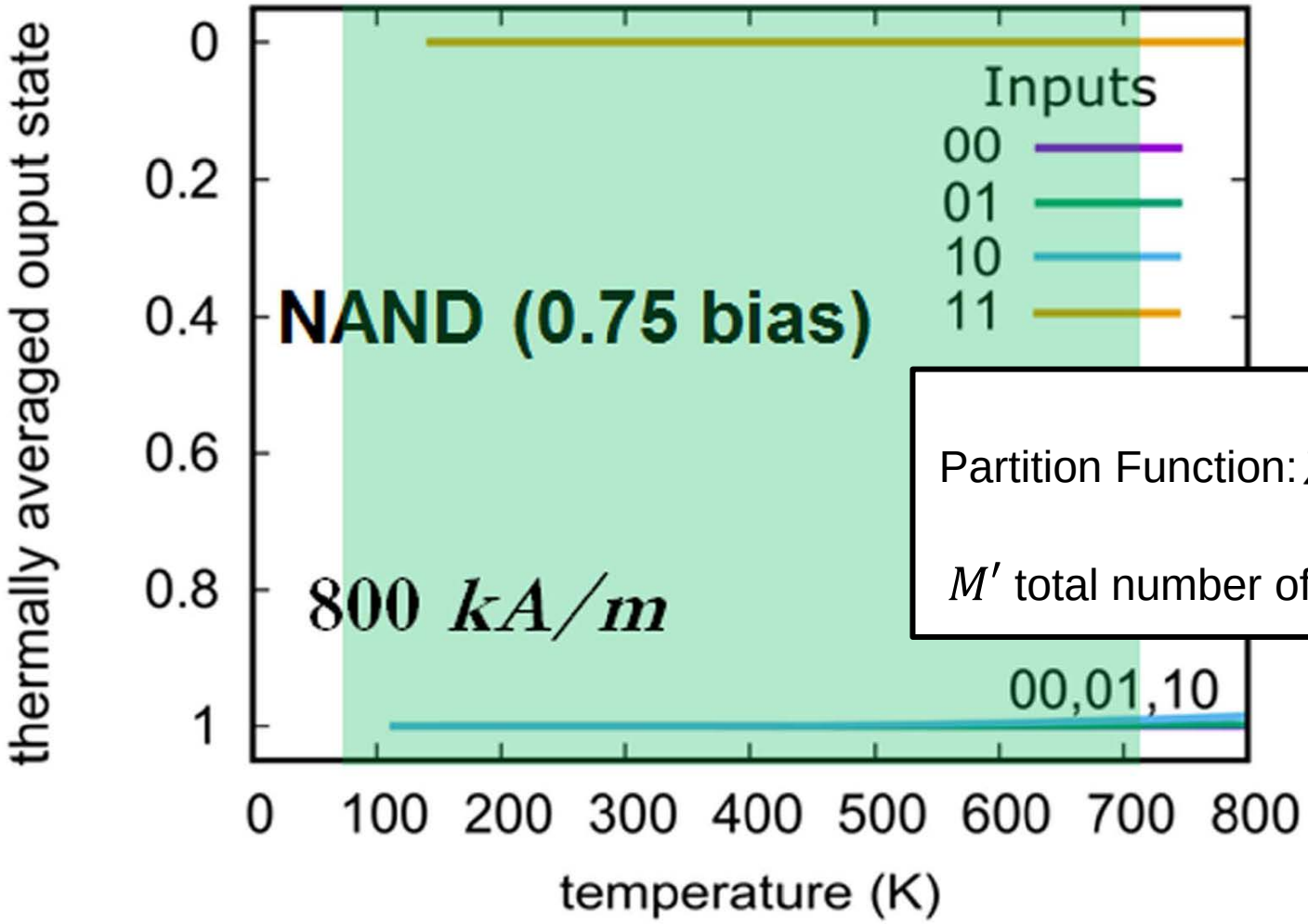
H Arava, PM Derlet, J Vijayakumar, J Cui, NS Bingham, A Kleibert and LJ Heyderman
Nanotechnology (2018)

Nanomagnetic Logic



H Arava, PM Derlet, J Vijayakumar, J Cui, NS Bingham, A Kleibert and LJ Heyderman
Nanotechnology (2018)

Nanomagnetic Logic

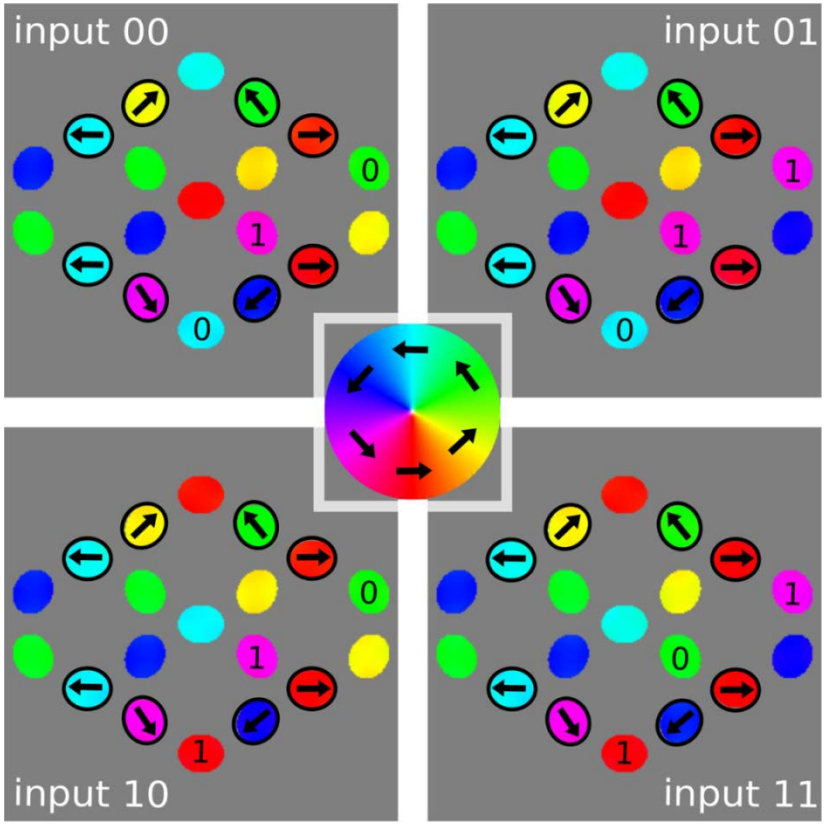


Partition Function: $Z = \prod_i^{M'} e_i^{-E_i/k_B T}$

M' total number of gate operations

H Arava, PM Derlet, J Vijayakumar, J Cui, NS Bingham, A Kleibert and LJ Heyderman Nanotechnology (2018)

Nanomagnetic Logic



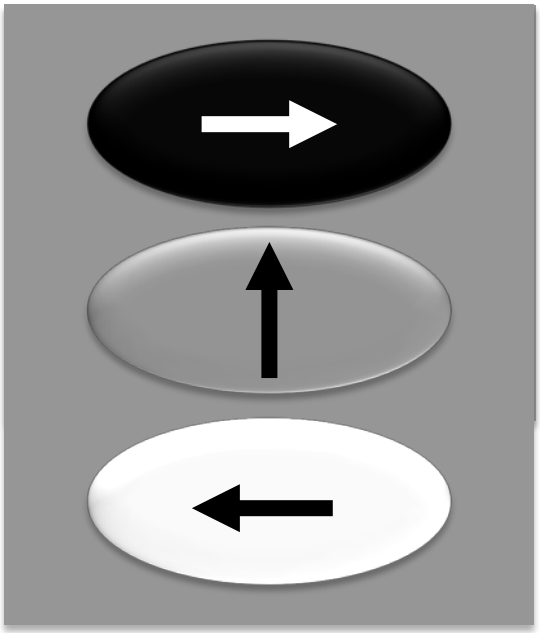
Ground states corresponding to all possible input states have the same energy

Balanced Magnetic Logic Gates in a Kagome Spin Ice
P Gypens, J Leliaert and B. Van Waeyenberge
Phys Rev Applied (2018)

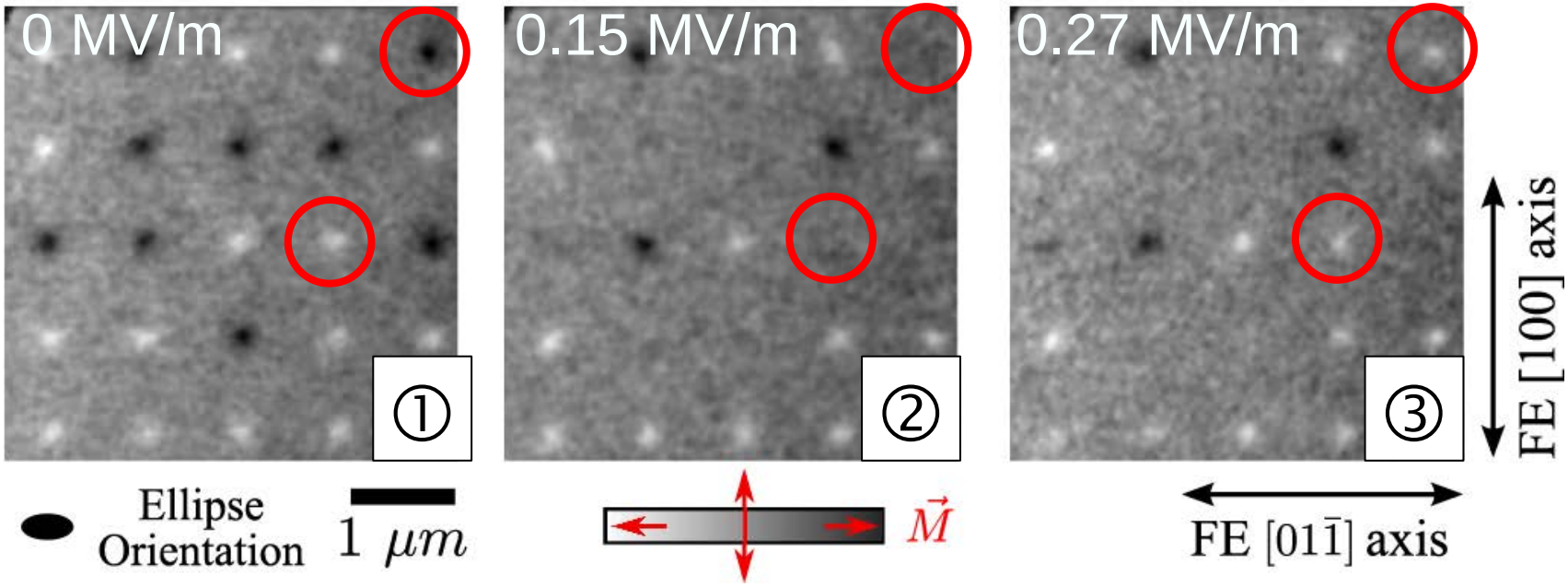
Computation in artificial spin ice
JH Jensen , E Folven & G Tufte
DOI: 10.1162/isal_a_00011

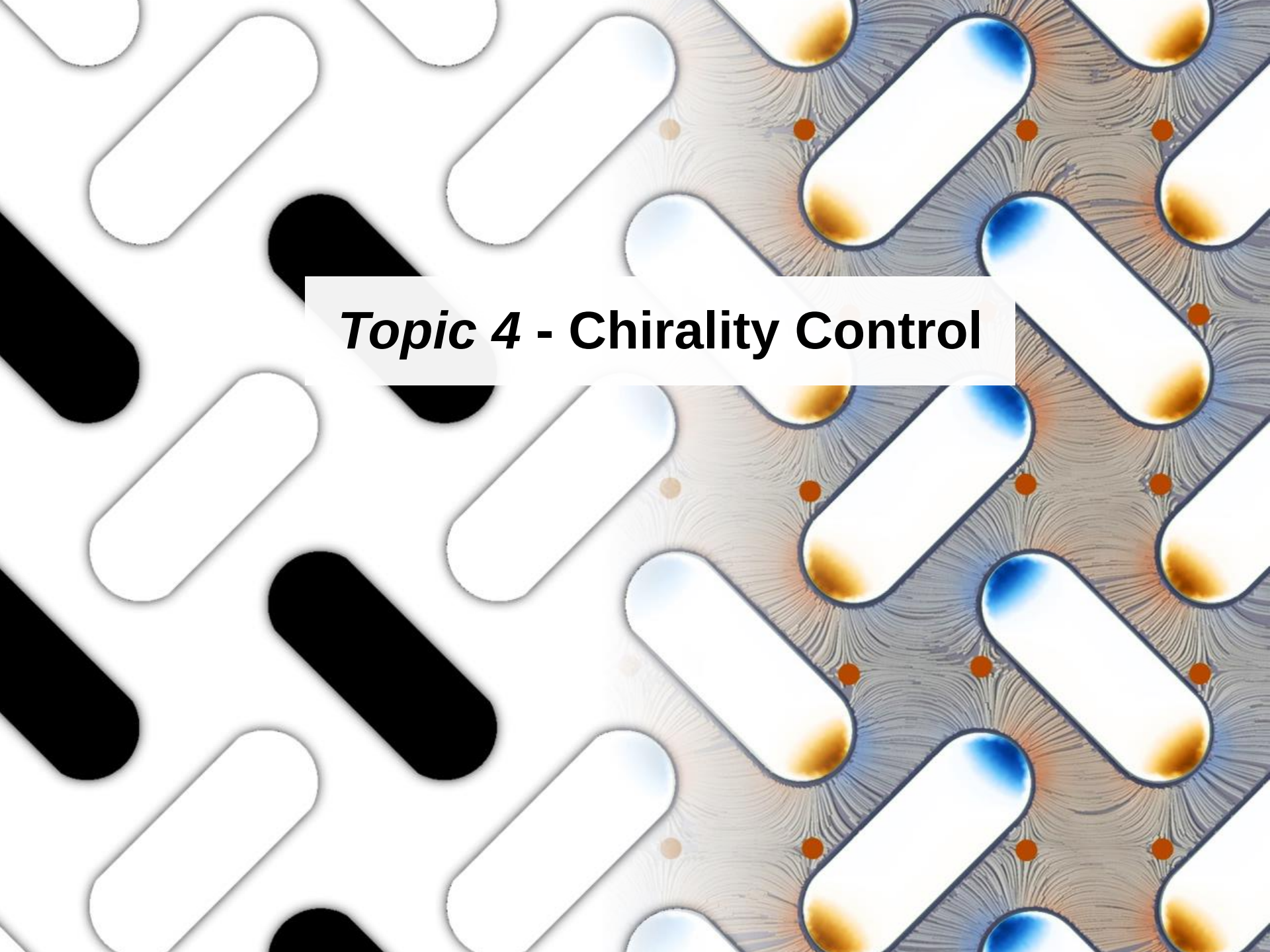
Manipulation via Electric Fields

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



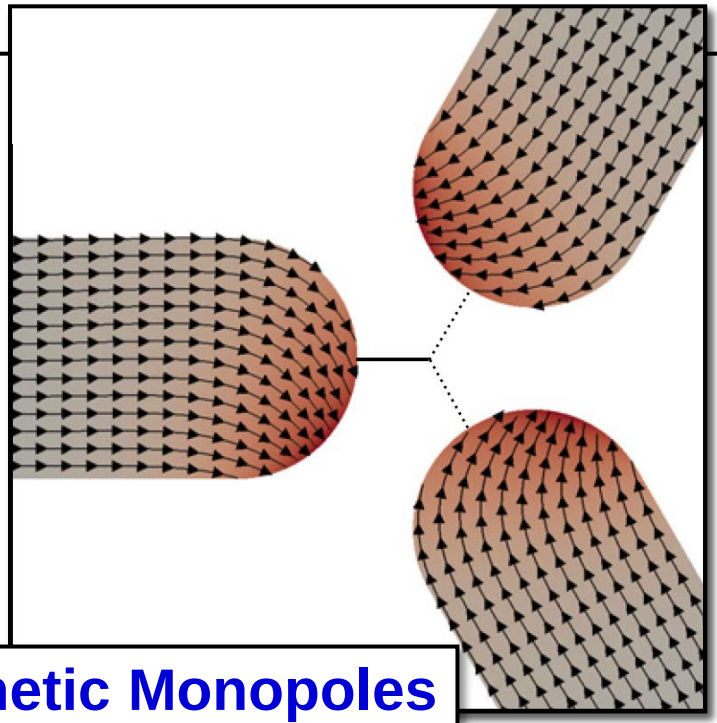
Nickel Nanoislands





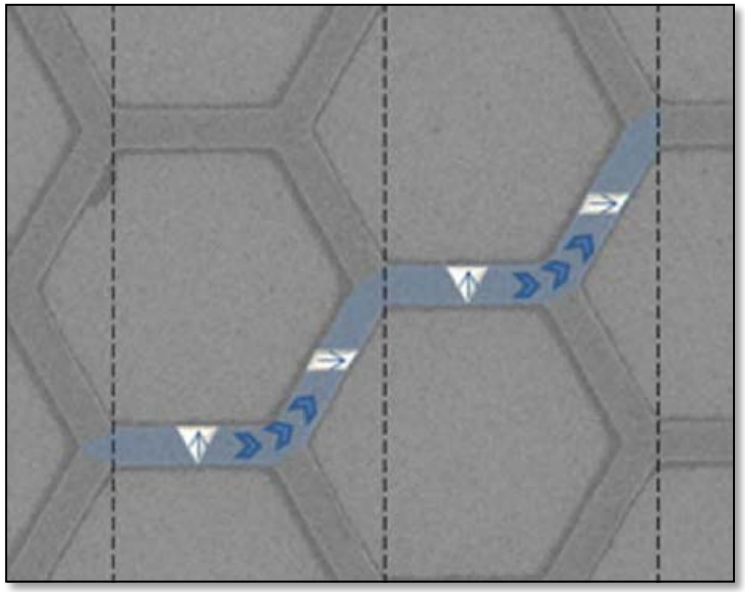
Topic 4 - Chirality Control

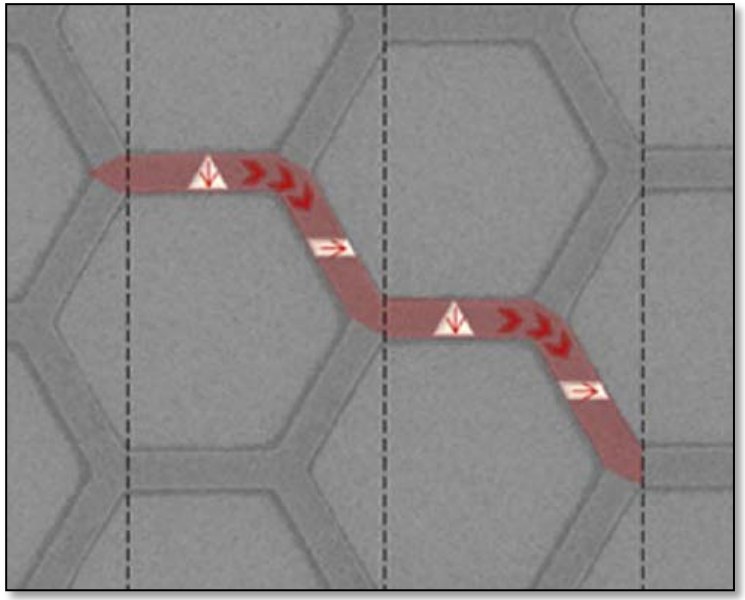
Chirality in Artificial Spin Ice



Chiral Magnetic Monopoles

N Rougemaille et al. NJP 2013



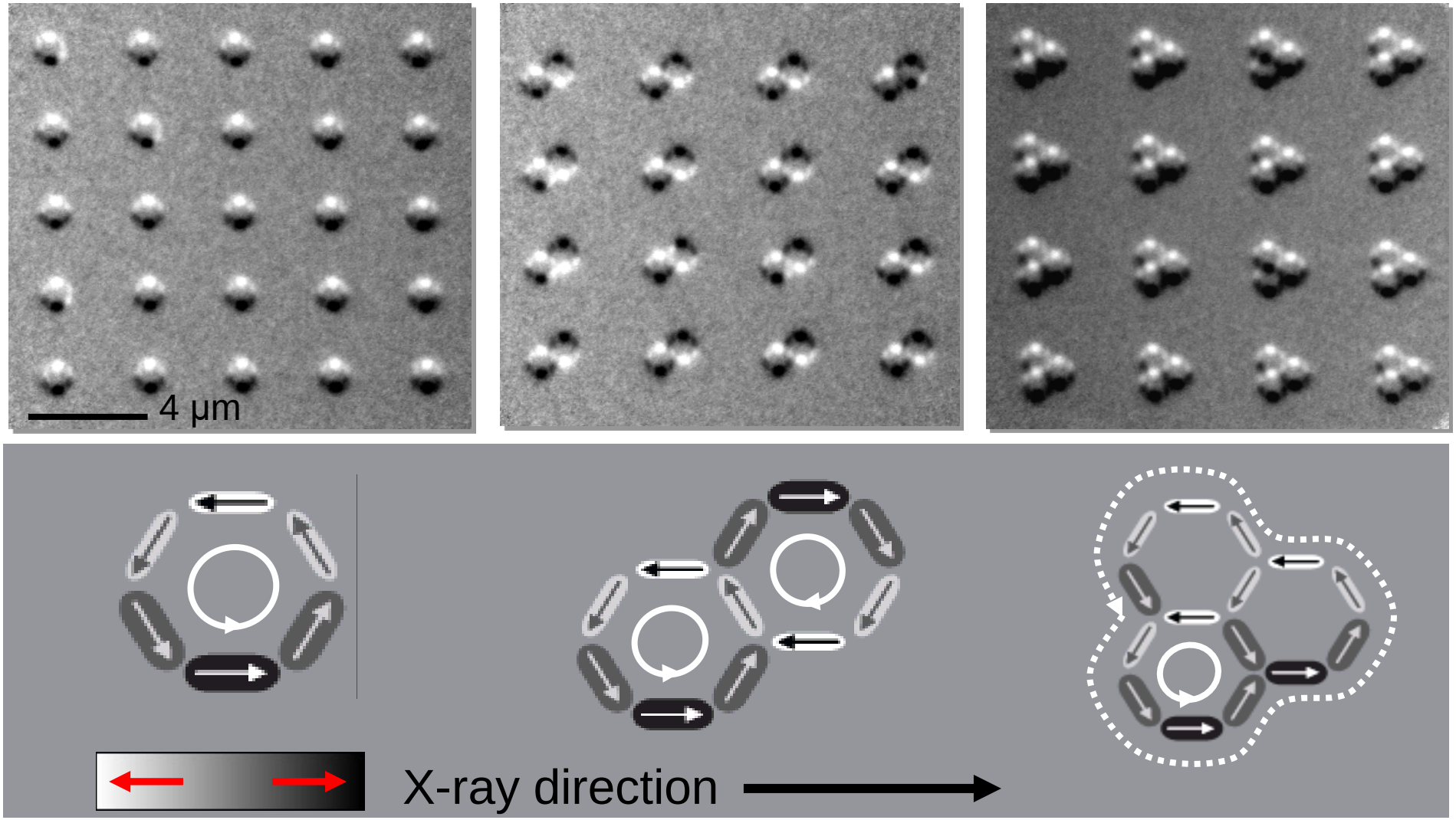


Domain Walls & Connected Networks

A Pushp et al. Nature Phys 2013

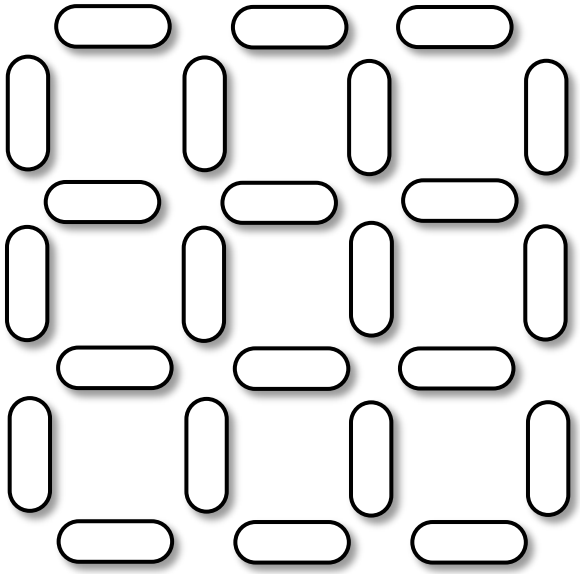
K Zeissler et al. Sci. Rep. 2013

Chirality Control



RV Chopdekar et al. NJP (2013)

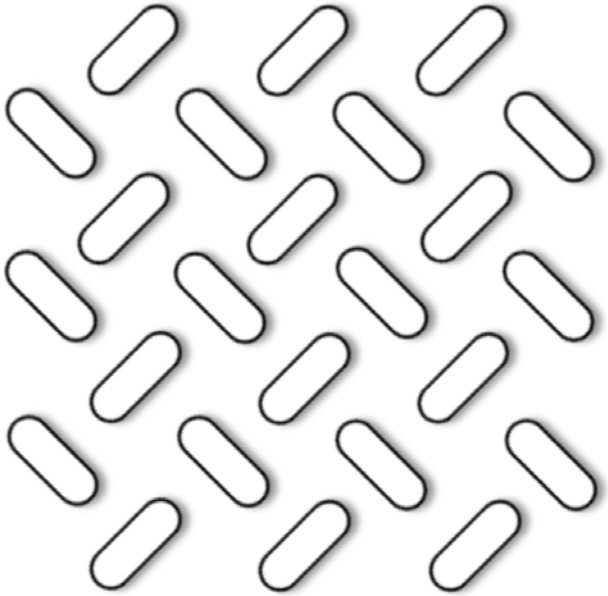
Chiral Ice



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



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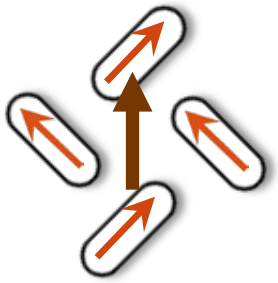
S Gliga, G Hrkac, C Donnelly, J Büchi, A Kleibert, J Cui, A Farhan, E Kirk, R Chopdekar, Y Masaki, NS Bingham, A Scholl, RL Stamps, LJ Heyderman, Nature Materials (2017)

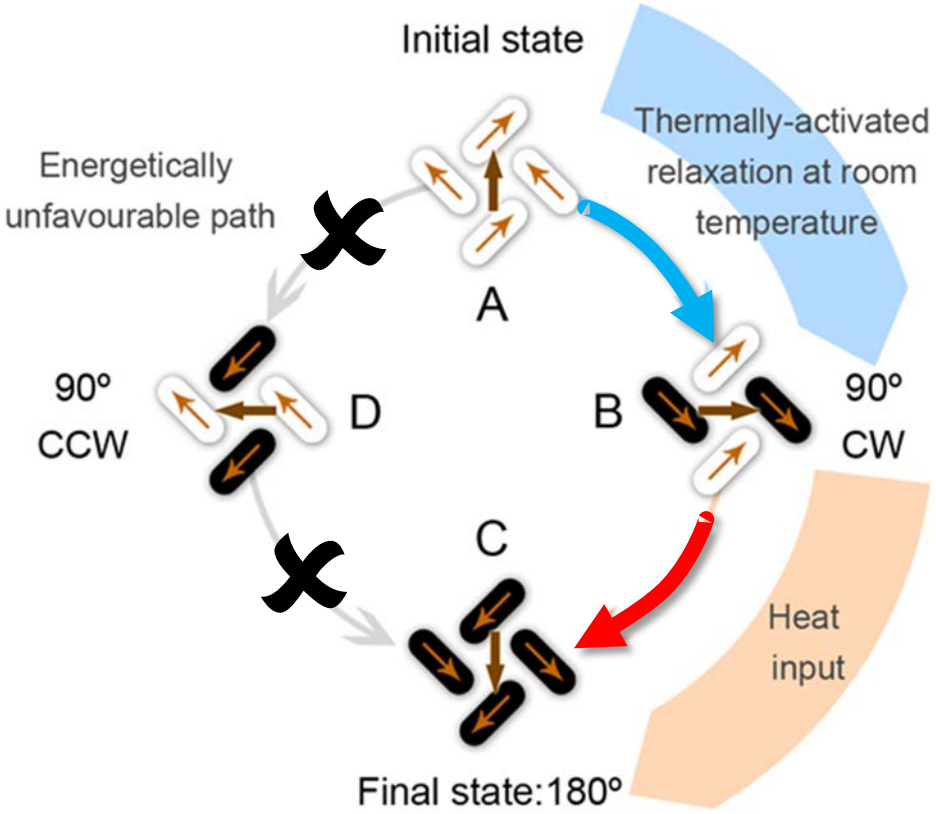
Chiral Ice



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)

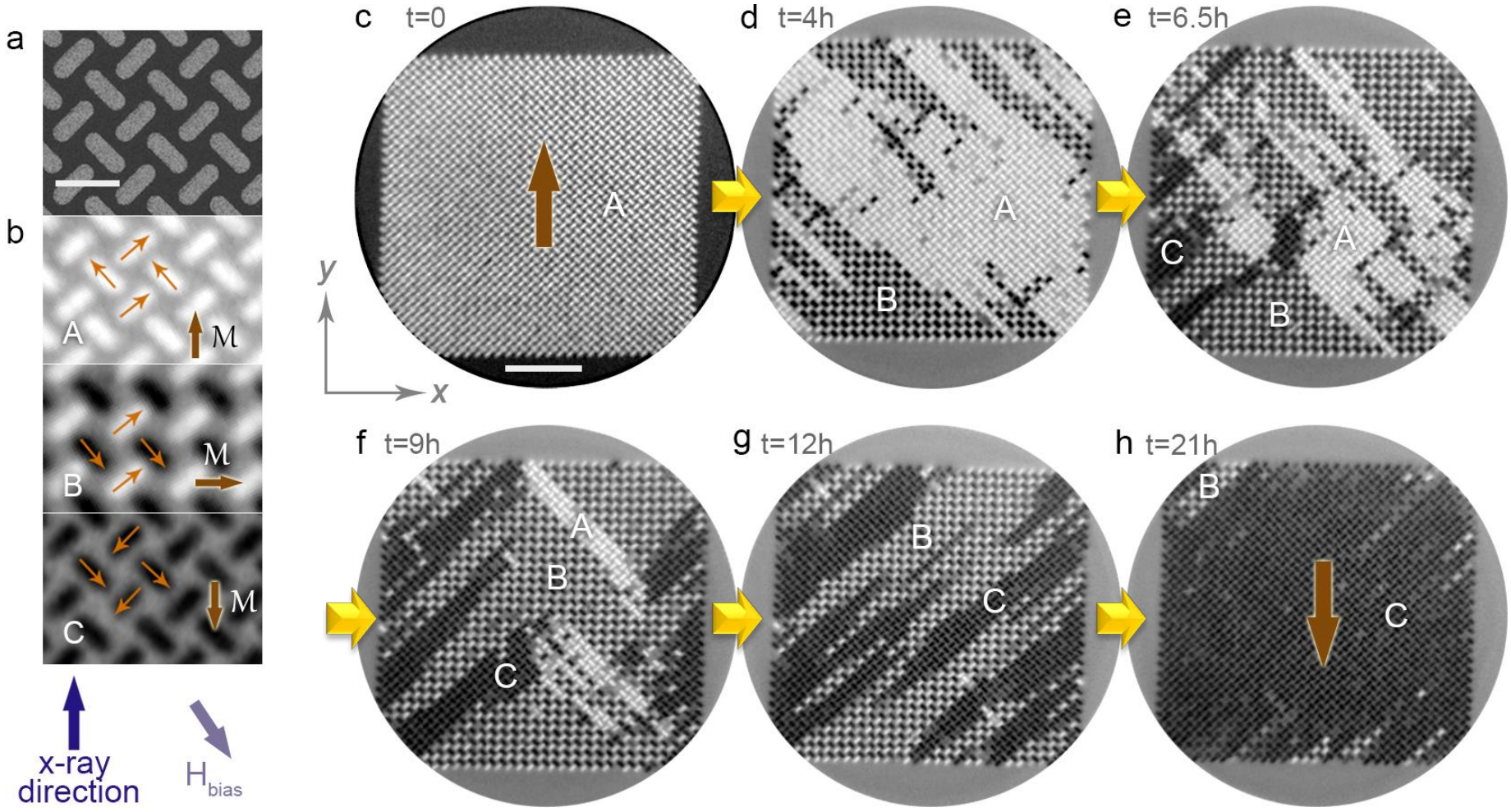
Chiral Ice – Thermal Relaxation



Chiral Dynamics !

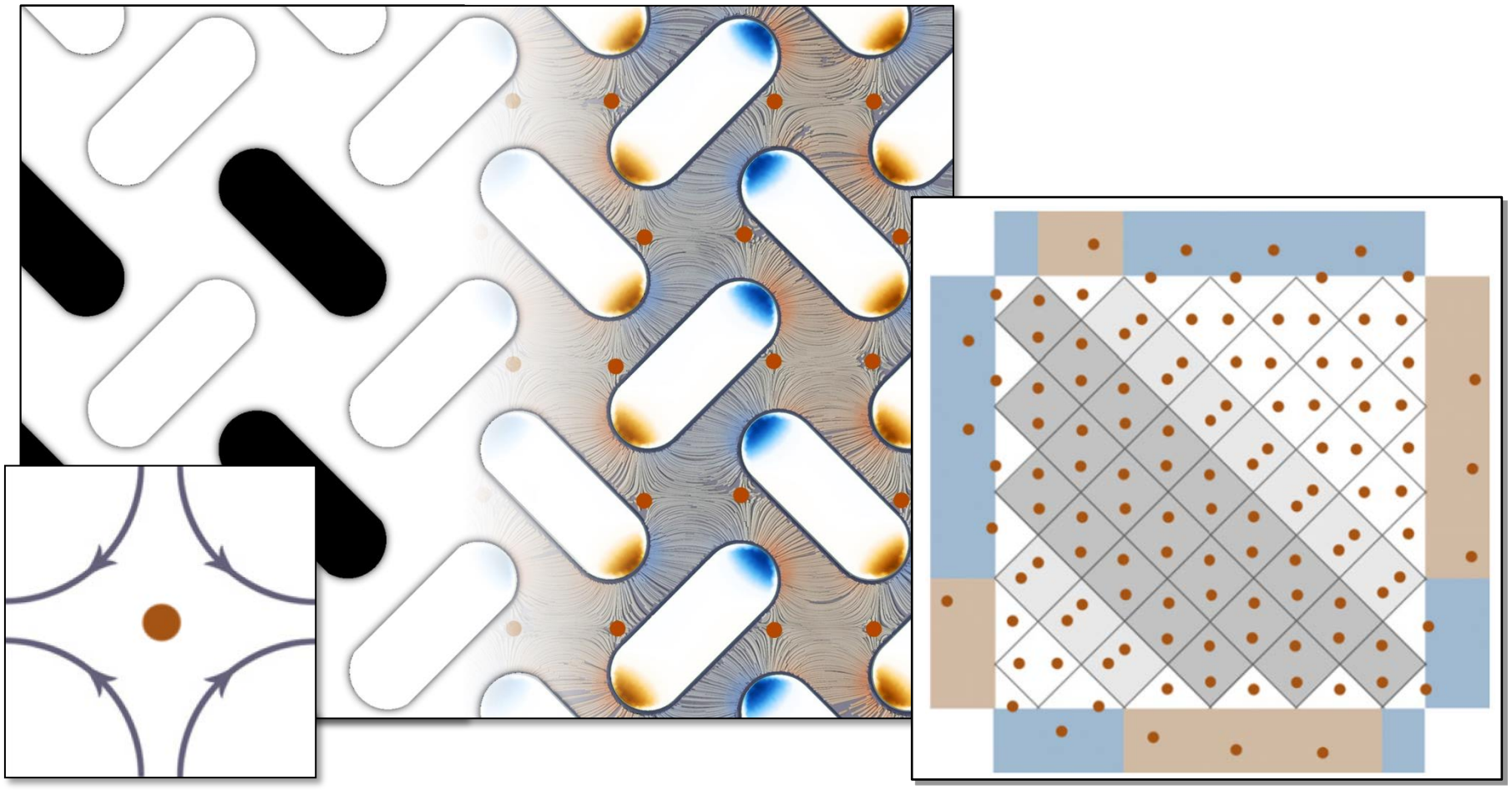
S Gliga, G Hrkac, C Donnelly, J Büchi, A Kleibert, J Cui, A Farhan, E Kirk, R Chopdekar, Y Masaki, NS Bingham, A Scholl, RL Stamps, LJ Heyderman, Nature Materials (2017)

Chiral Ice – Thermal Relaxation



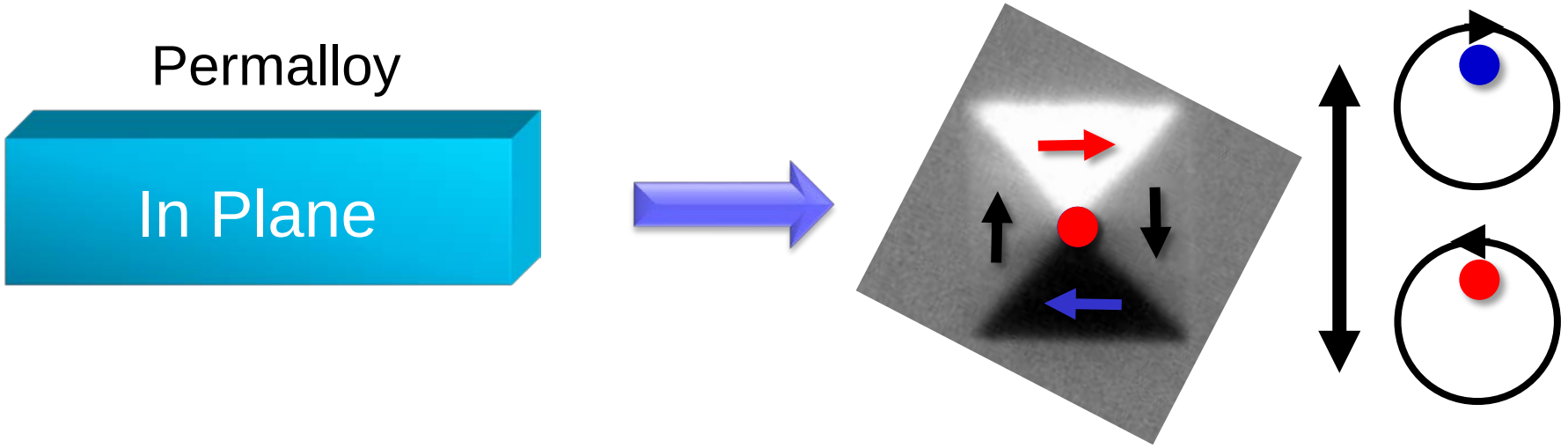
S Gliga, G Hrkac, C Donnelly, J Büchi, A Kleibert, J Cui, A Farhan, E Kirk, R Chopdekar, Y Masaki, NS Bingham, A Scholl, RL Stamps, LJ Heyderman, Nature Materials (2017)

Chiral Ice – Antivortex



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)

Ferromagnetic Hybrid Structures

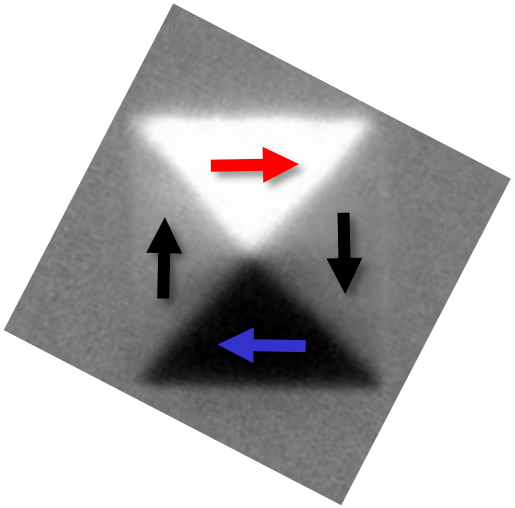


From chiral dynamics to dynamic chirality….

Ferromagnetic Hybrid Structures

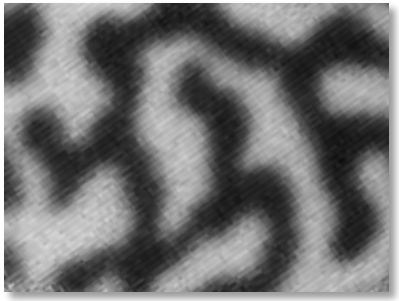
Permalloy

In Plane



$[Co(0.3\ nm)/Pd(0.9\ nm)]_8$

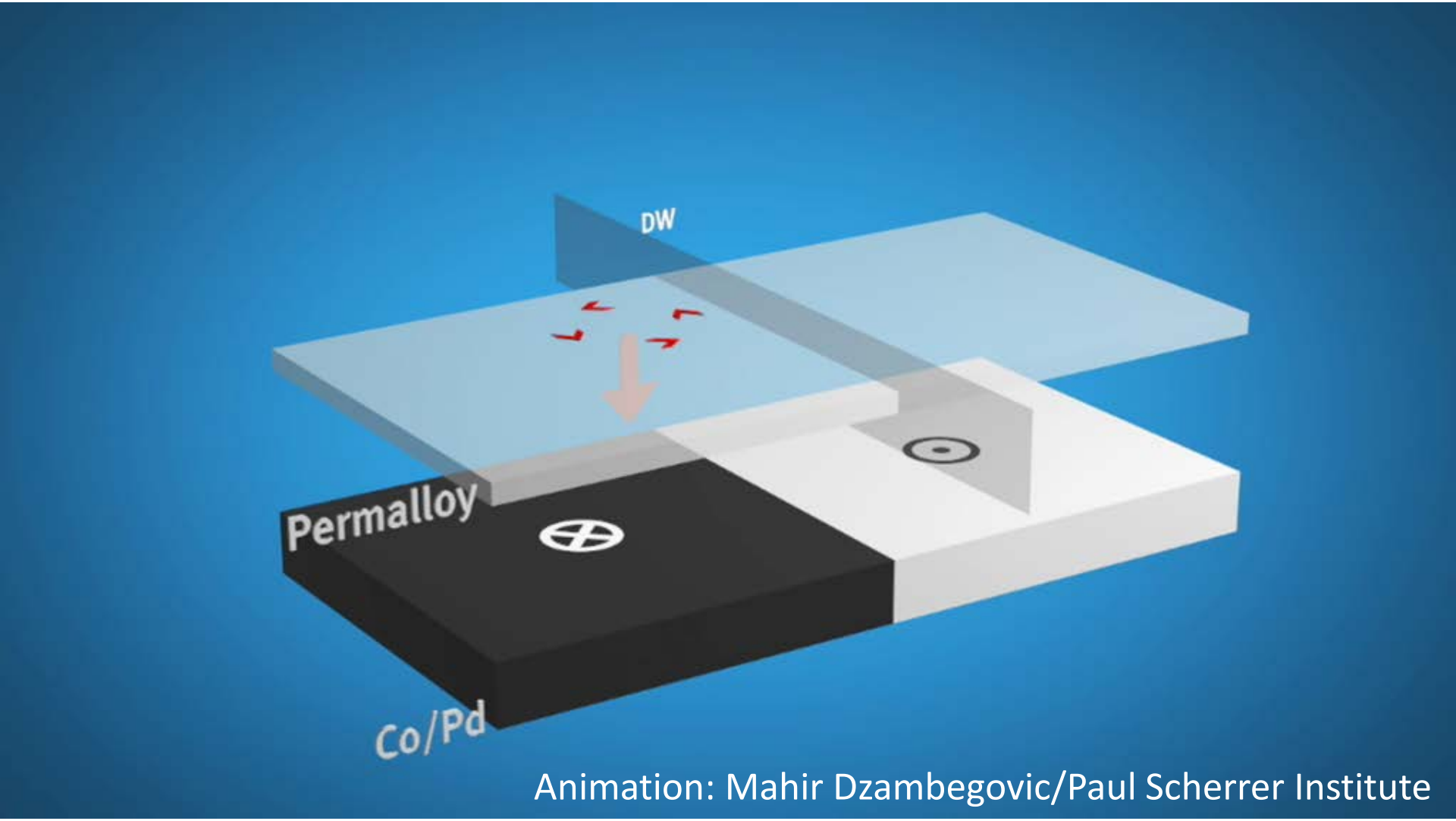
Out of Plane



In Plane

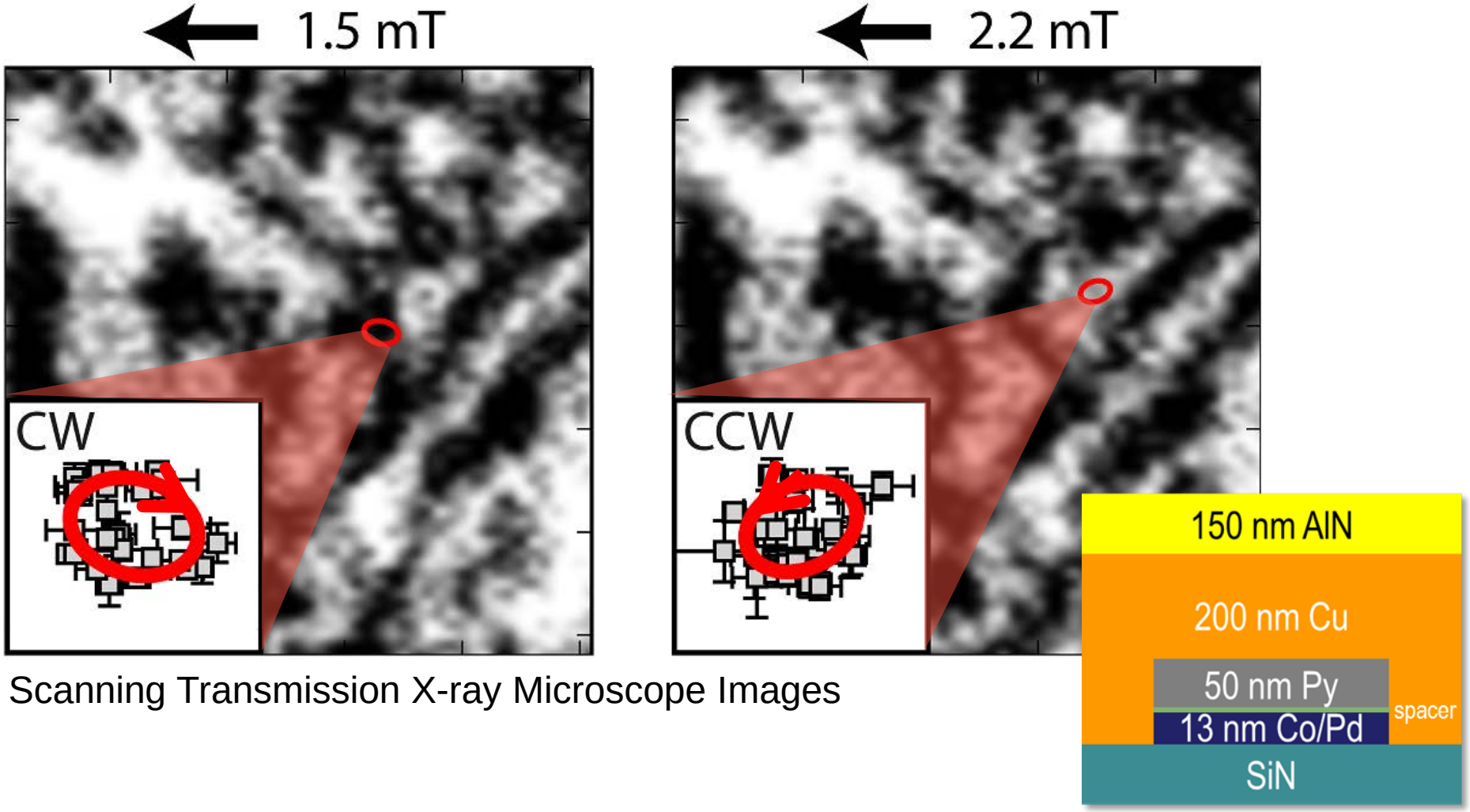
Out of Plane

Nanoscale Vortex Core Switch



P Wohlhüter et al. Nature Communications (2015)
G. Heldt et al. Appl Phys Letts (2014)

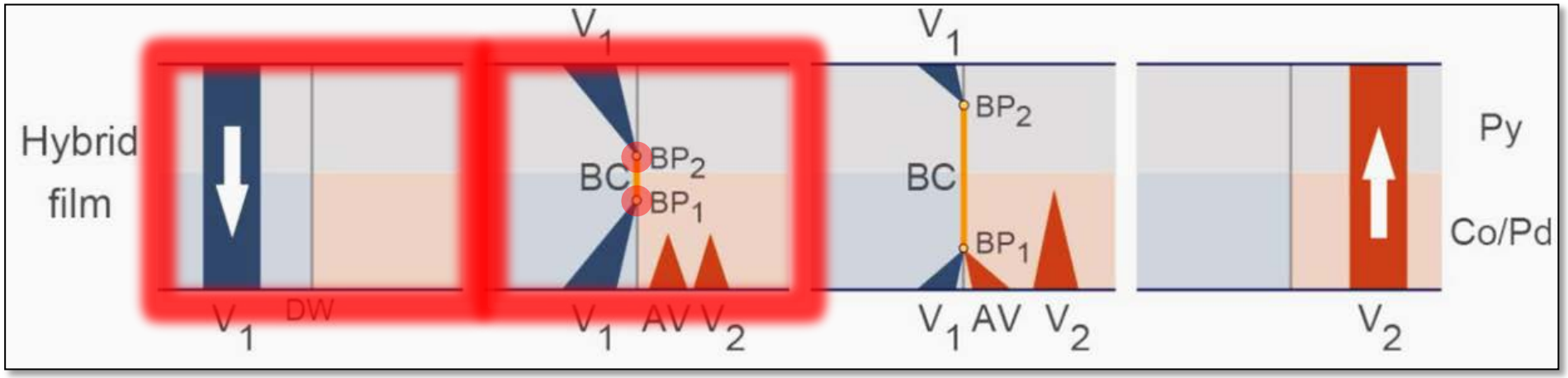
Nanoscale Vortex Core Switch

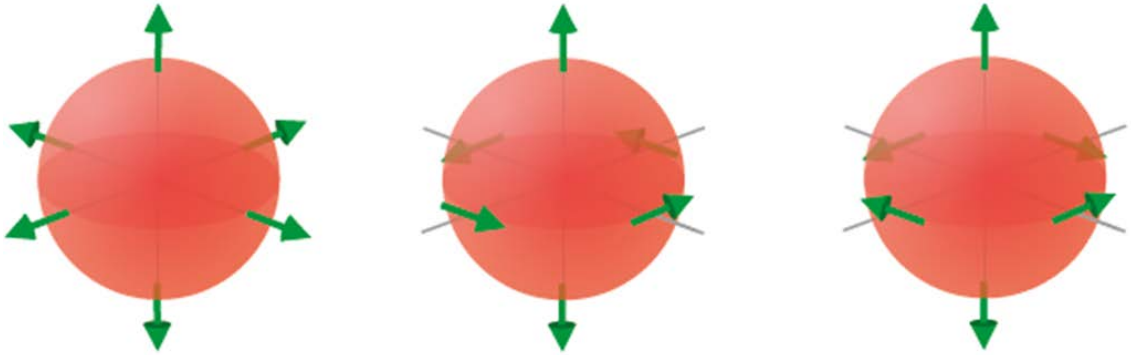


Scanning Transmission X-ray Microscope Images

P Wohlhüter, MT Bryan, P Warnicke, S Gliga, SE Stevenson, G Heldt, L Saharan, AK Suszka, C Moutafis, RV Chopdekar, J Raabe, T Thomson, G Hrkac, LJ Heyderman
Nature Communications (2015)

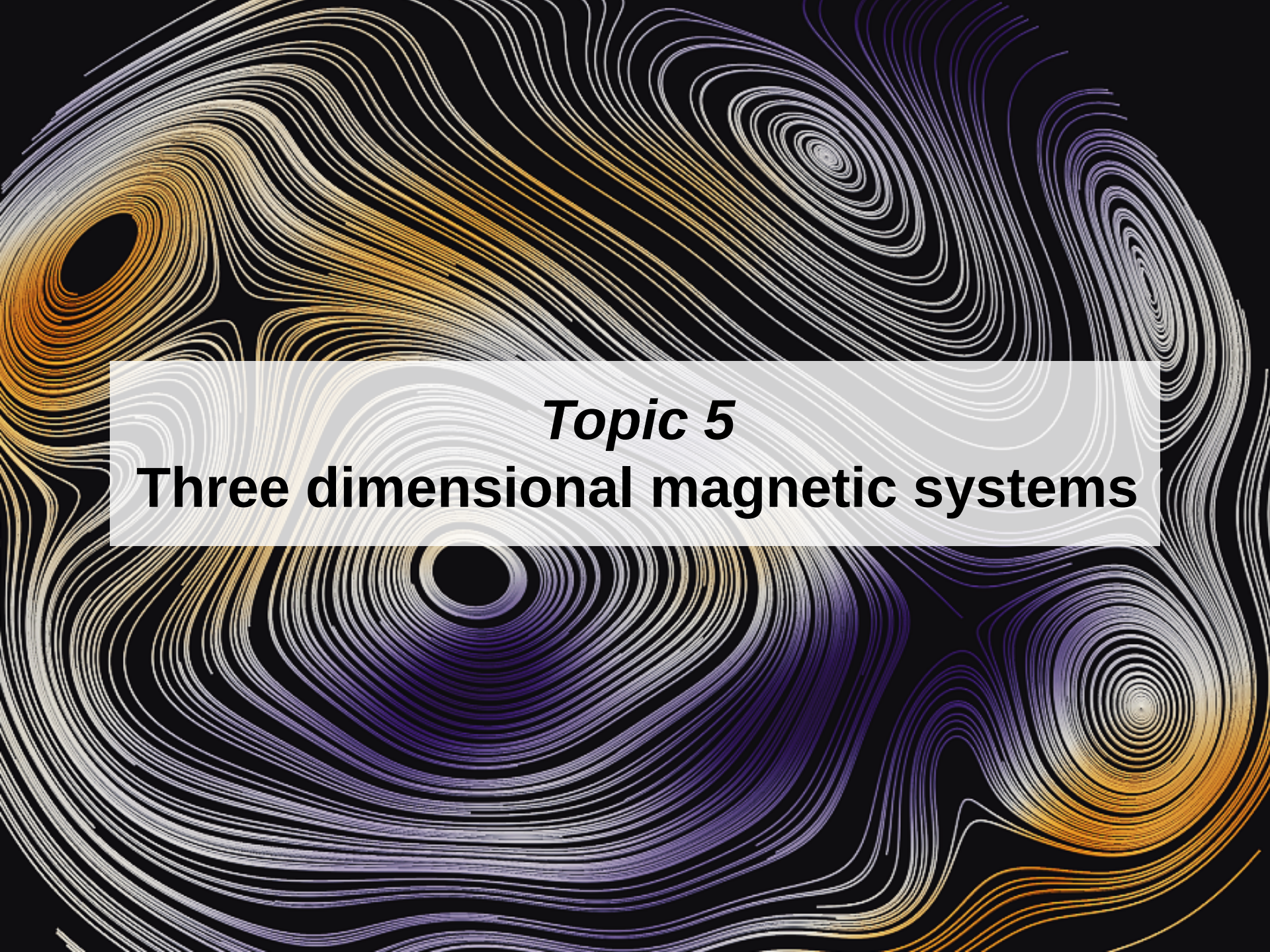
Nanoscale Vortex Core Switch





Hedgehog *Circulating* *Contra-circulating*

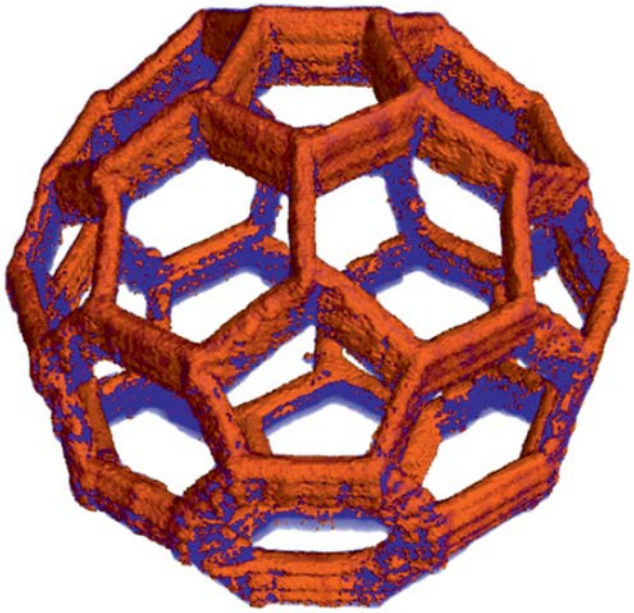
P Wohlhüter, MT Bryan, P Warnicke, S Gliga, SE Stevenson, G Heldt, L Saharan, AK Suszka, C Moutafis, RV Chopdekar, J Raabe, T Thomson, G Hrkac, LJ Heyderman Nature Communications (2015)



Topic 5

Three dimensional magnetic systems

Three Dimensional Structures



6 μm Buckyball

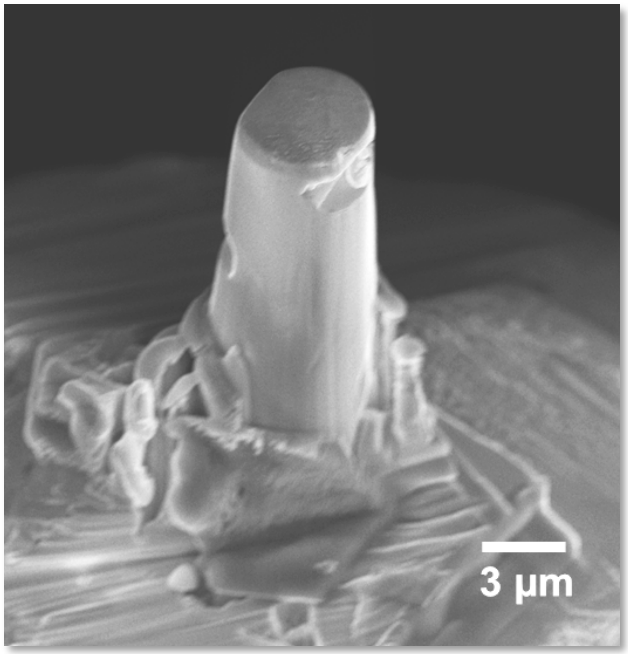
Resonant Ptychographic Tomography

Quantitative hard x-ray phase imaging & resonant elastic scattering

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

C. Donnelly et al. PRL (2015)

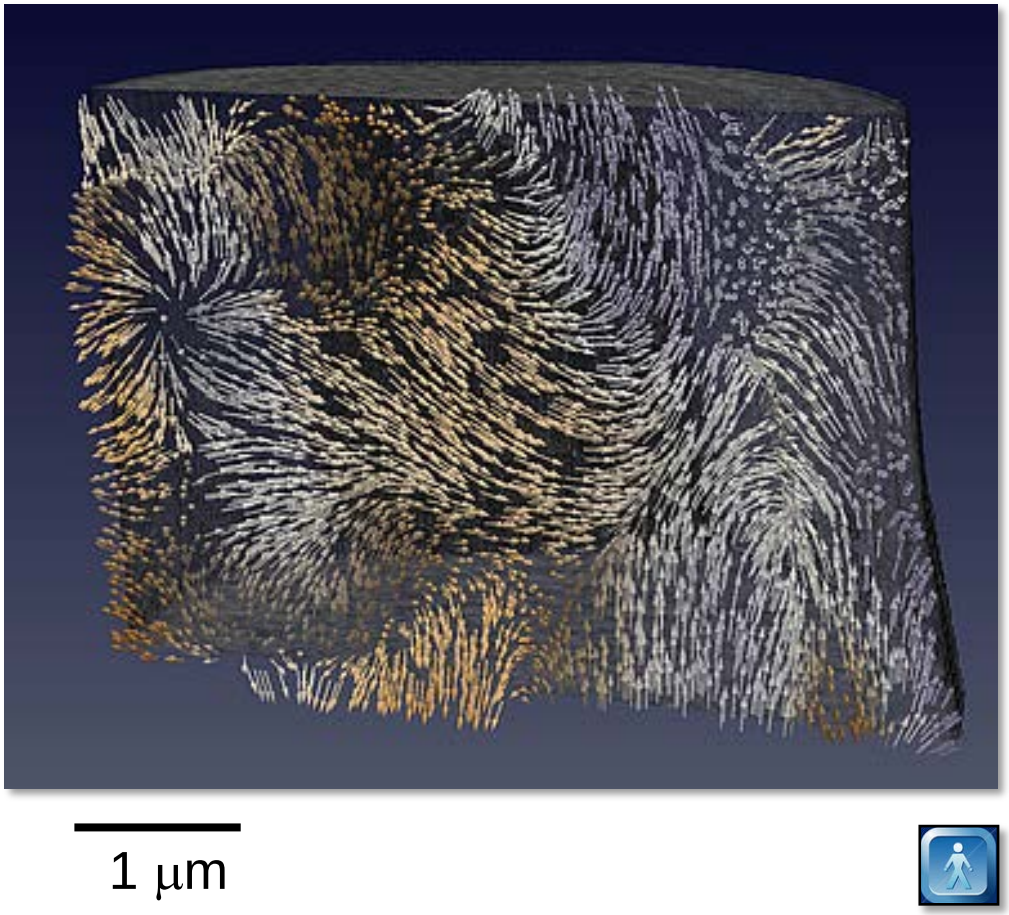
Hard X-ray Magnetic Tomography



$GdCo_2$ Pillar

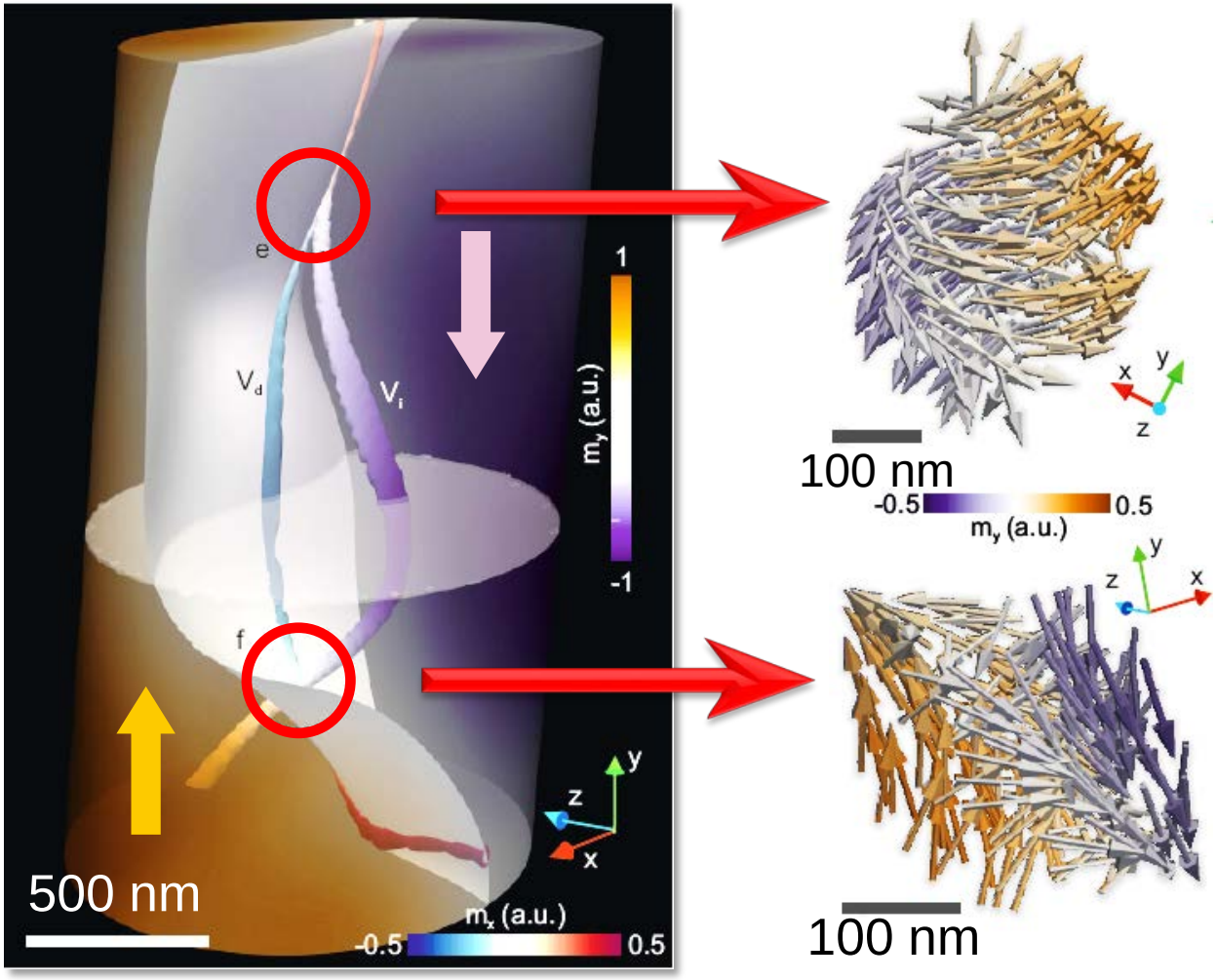
Cut from nugget with FIB

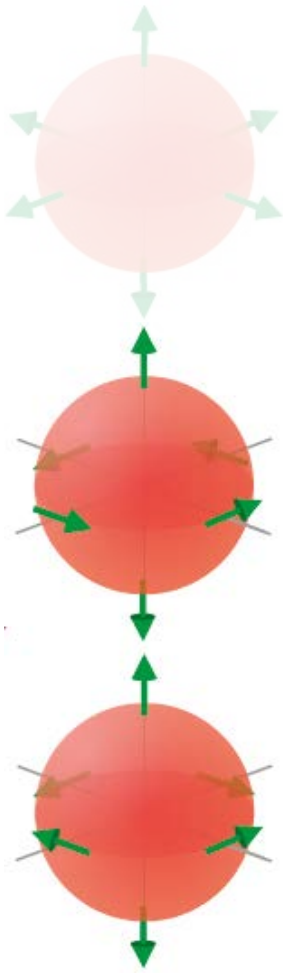
Sample from:
R. Galera, CNRS, Grenoble



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

Hard X-ray Magnetic Tomography

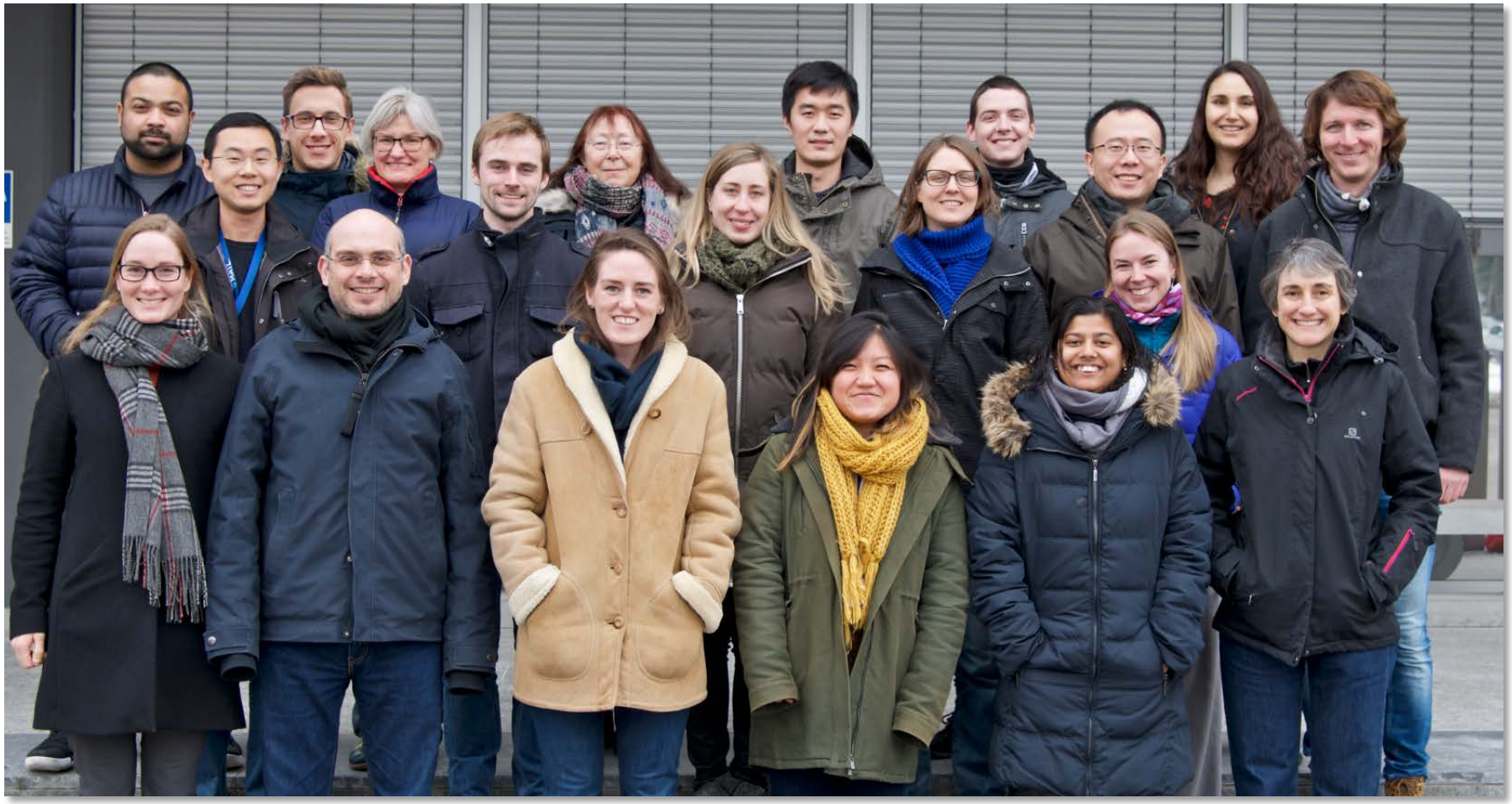




C Donnelly et al. PRB (2016), Nature (2017) and NJP (2018)

Acknowledgements

Thanks to Mesoscopic Systems



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

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- *X-ray Scattering:* Urs Staub, Aurora Alberca, Joachim Kohlbrecher, José Mardegan
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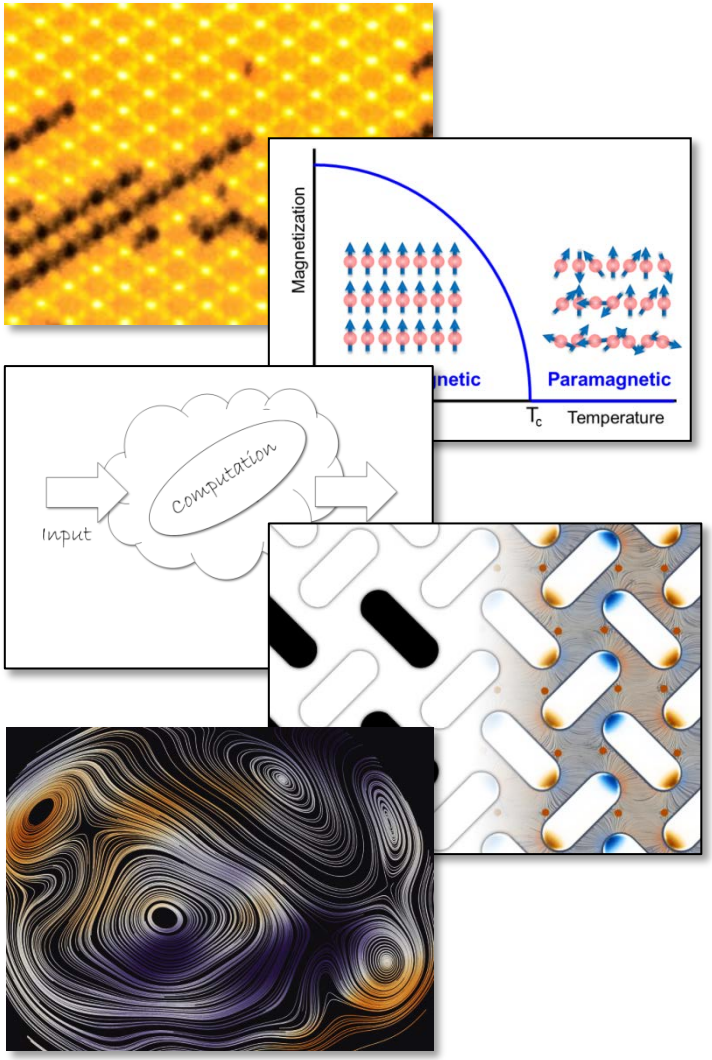
Andrei Rogalev, Carsten Detlefs

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. Towards Bioinspired Computation
4. Chirality Control
5. Three-dimensional magnetic systems