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ETH zürich

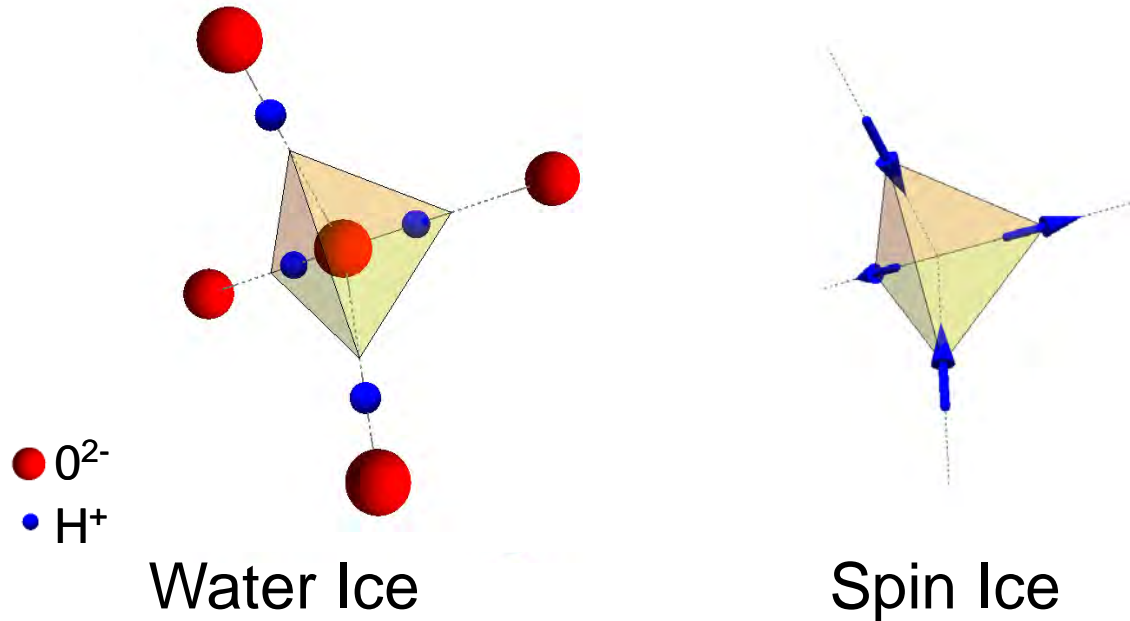


Prof. Laura Heyderman :: ETH Zurich - Paul Scherrer Institute

Artificial Spin Ice and Elements of Control for Computation

“Spintronics meets Neuromorphics” SPICE-Workshop , October 2018

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

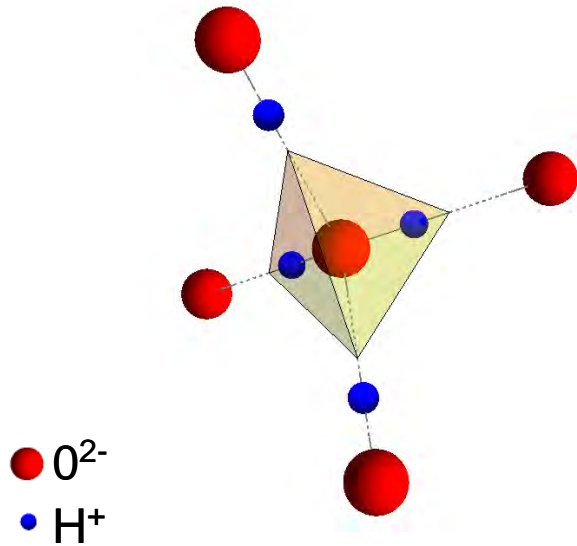


Spin ice model & Ferromagnetic Pyrochlore $Ho_2Ti_2O_7$

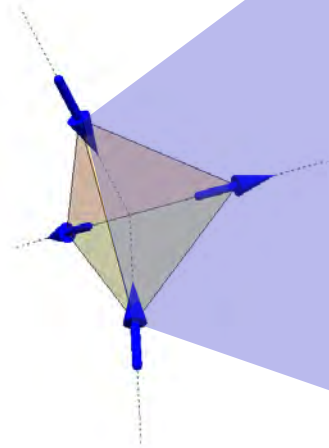
M. J. Harris, S. T. Bramwell, D. F. McMorrow, T. Zeiske, and K. W. Godfrey, PRL (1997)

$Dy_2Ti_2O_7$ - How 'spin ice' freezes

J. Snyder, J. S. Slusky, R. J. Cava, P. Schiffer, Nature (2001)



Water Ice



Spin Ice

FRUSTRATION:

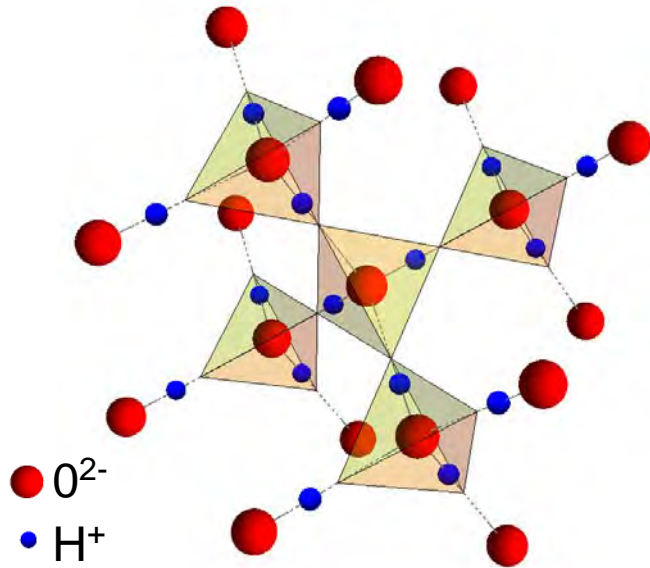
- *protein folding*
- *liquid crystals*
- *diblock copolymers*
- *ferrofluids*
- *neural networks*

Spin ice model & Ferromagnetic Pyrochlore $Ho_2Ti_2O_7$

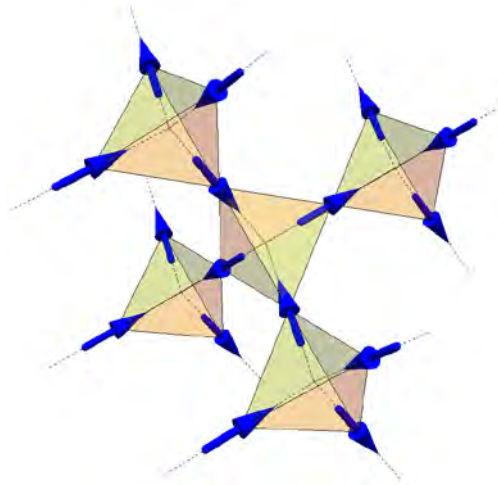
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Water Ice



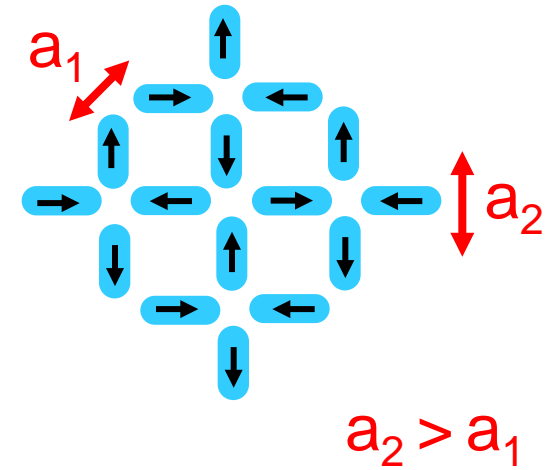
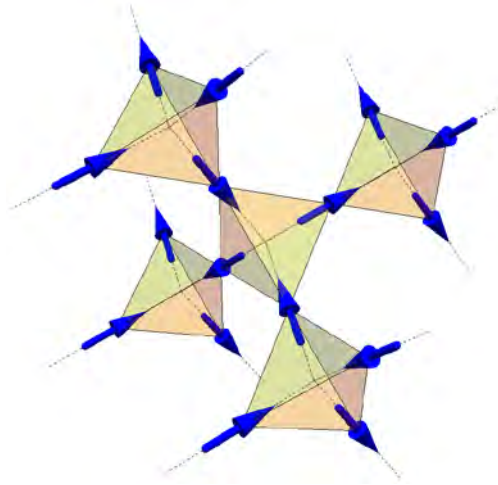
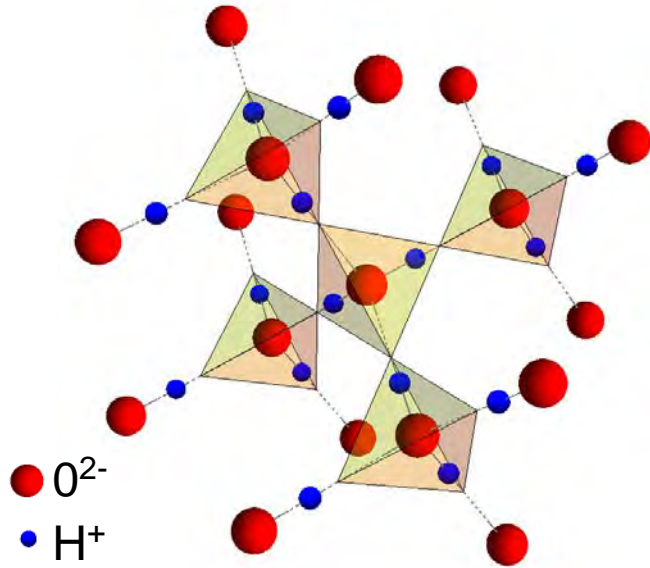
Spin Ice

Spin ice model & Ferromagnetic Pyrochlore $Ho_2Ti_2O_7$

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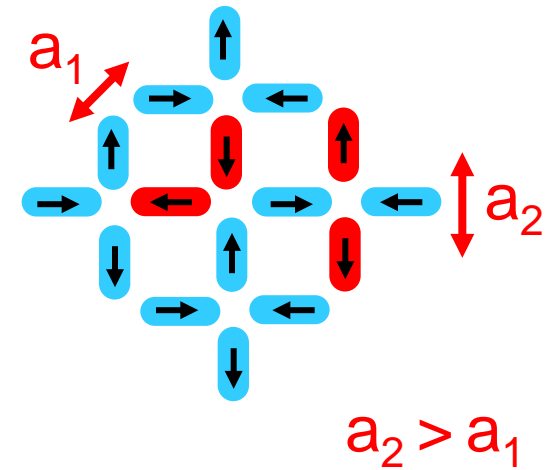
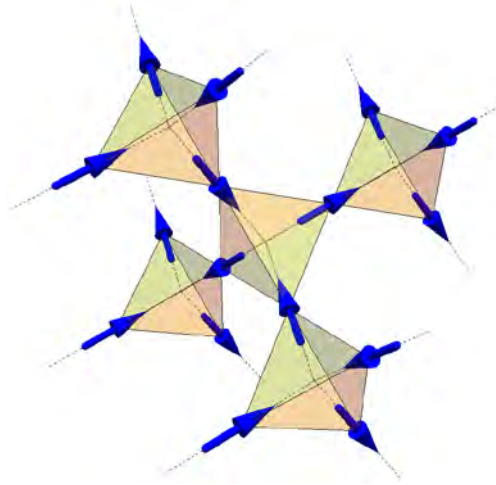
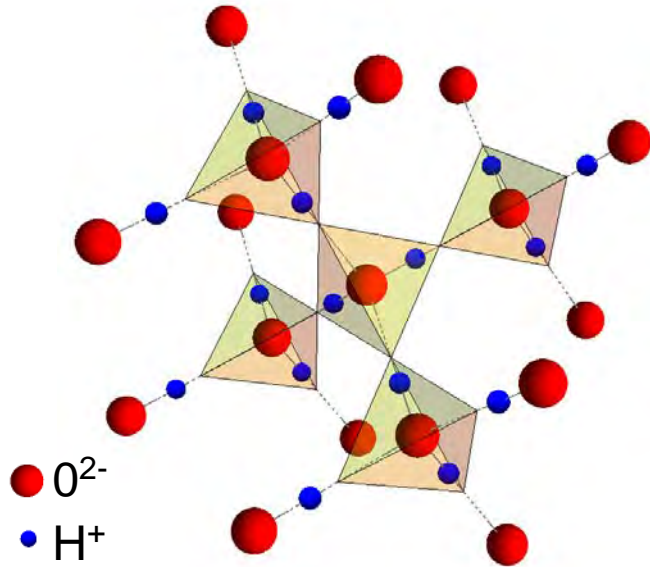
$Dy_2Ti_2O_7$ - How 'spin ice' freezes

J. Snyder, J. S. Slusky, R. J. Cava, P. Schiffer, Nature (2001)



Artificial 'spin ice'

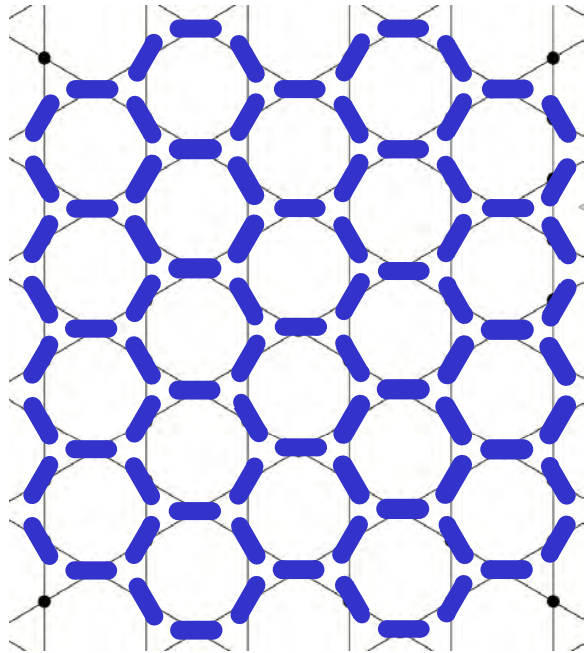
R. F. Wang, C. Nisoli, R. S. Freitas, J. Li, W. McConville, B. J. Cooley, M. S. Lund, N. Samarth, C. Leighton, V. H. Crespi, and P. Schiffer, Nature (2006)



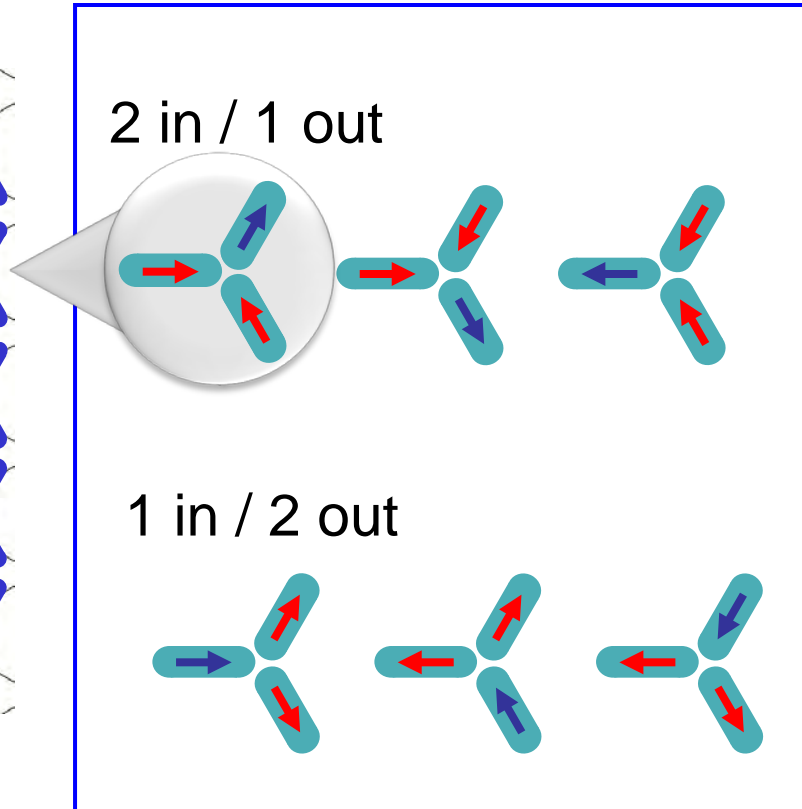
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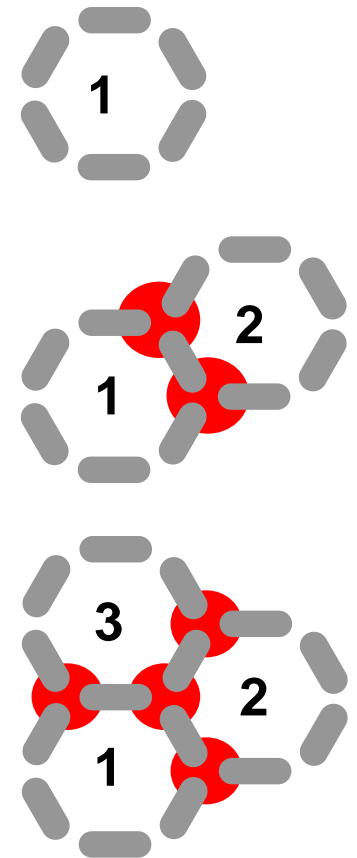
Artificial Kagome Spin Ice



Kagome lattice

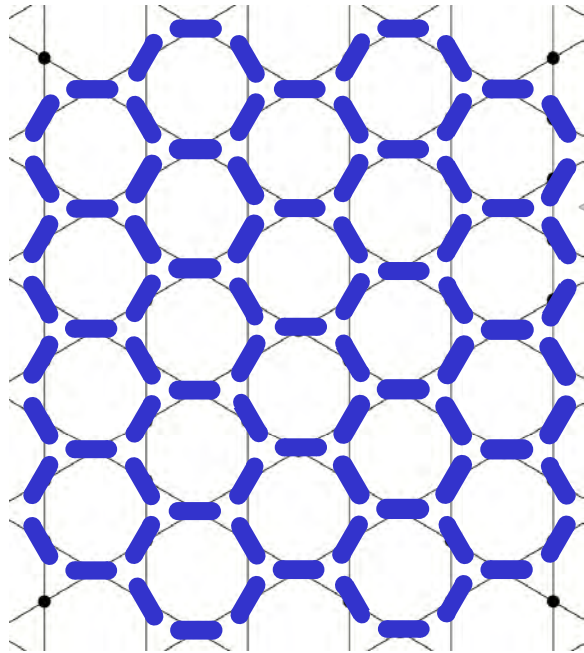


Spin ice rule

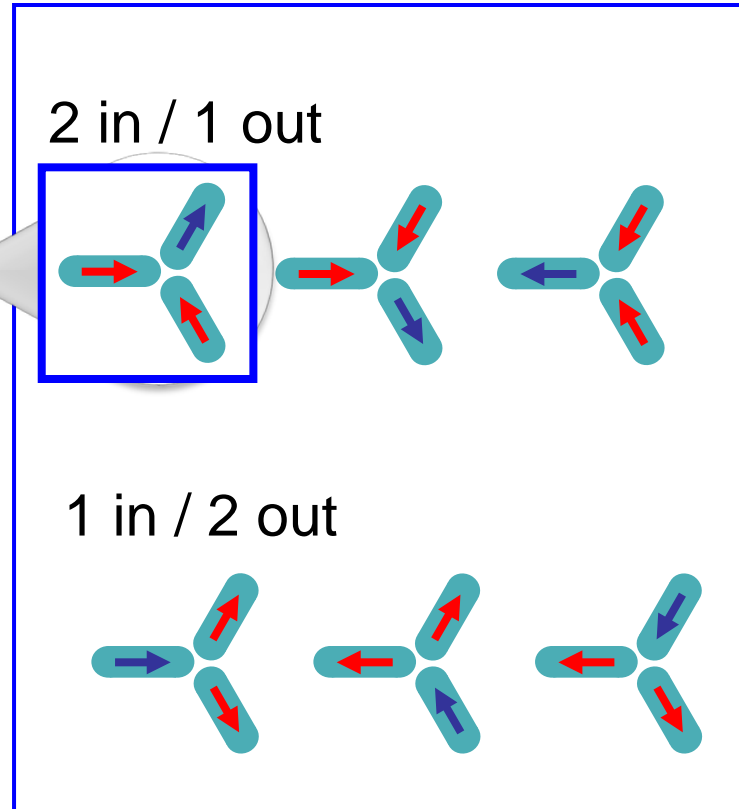


Building Blocks

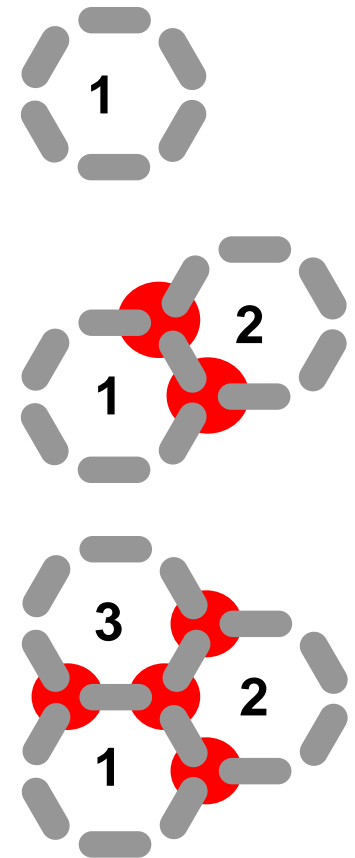
Artificial Kagome Spin Ice



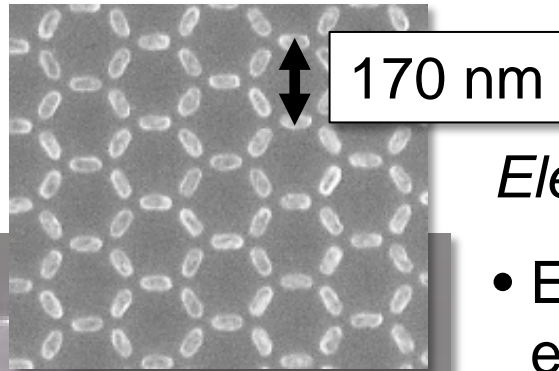
Kagome lattice



Spin ice rule

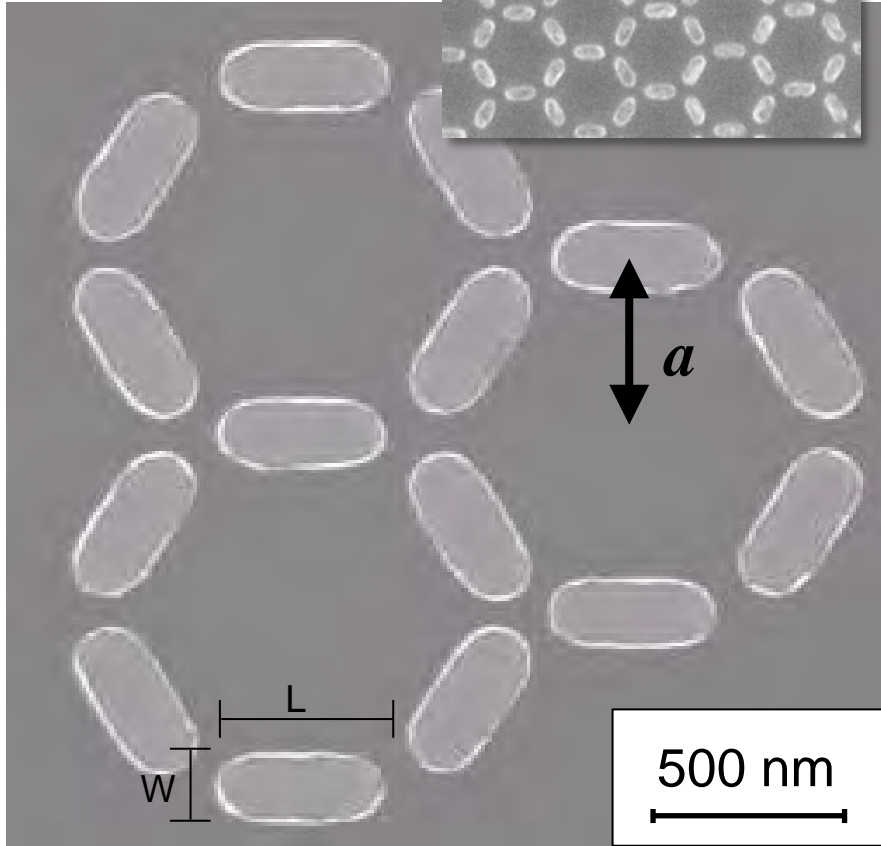


Building Blocks



Electron Beam Lithography

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

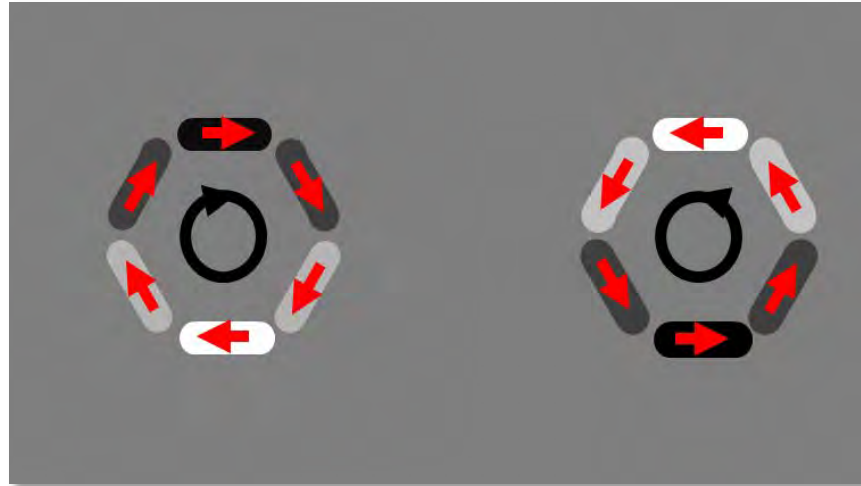
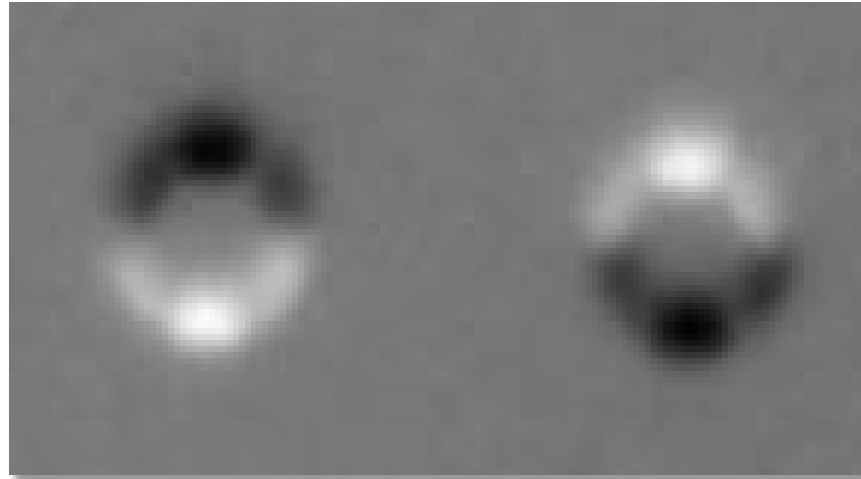


Width	=	170 nm	→	26 nm
Length	=	470 nm	→	63 nm
Smallest a	=	500 nm	→	85 nm
Thickness	=	3-40 nm		

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

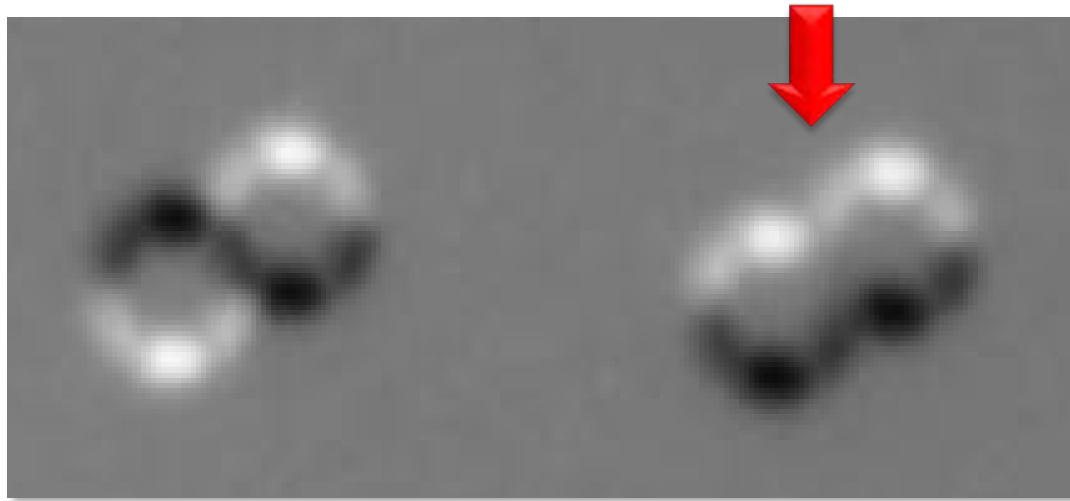
A. Trabesinger, News & Views, Nature Physics, 4, 832 (2008)

Ground States in PEEM

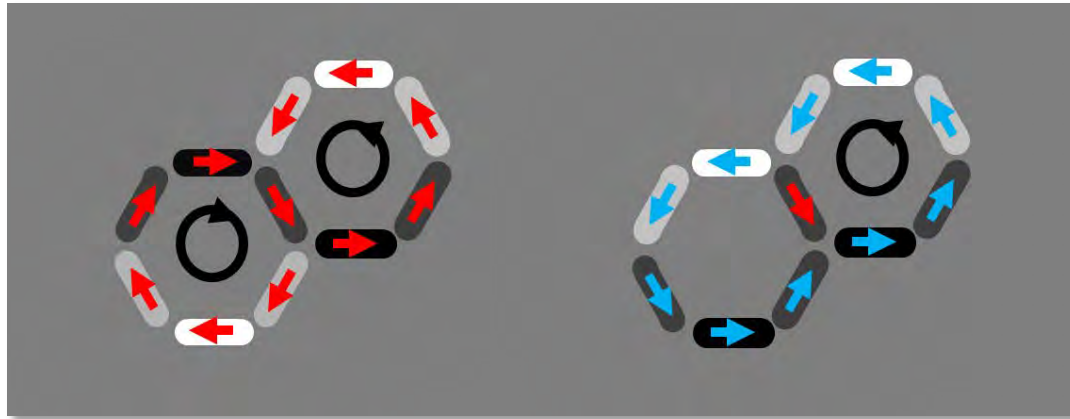
**Vortex****Degeneracy: 2**

X-ray direction





Double
Vortex



External
Flux
Closure

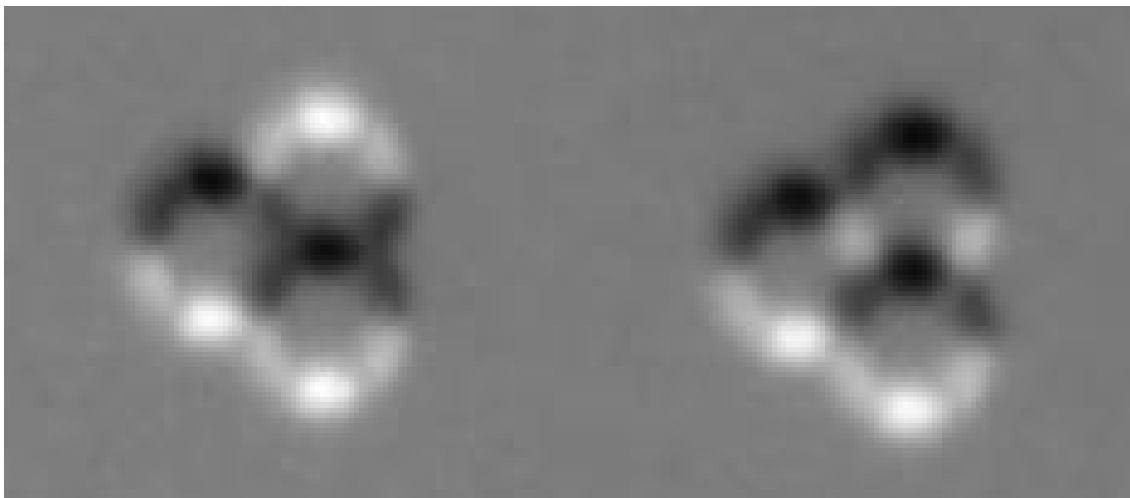
Degeneracy: 2

4

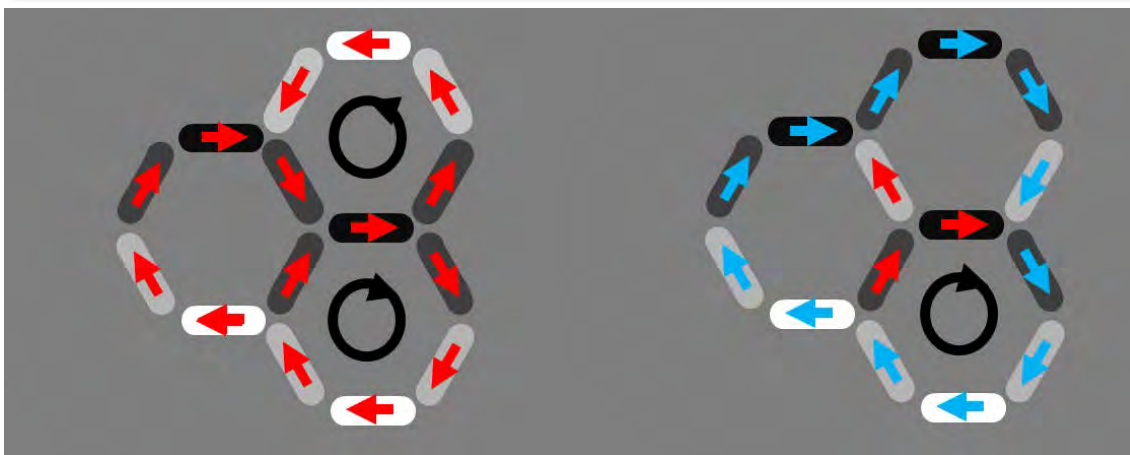


X-ray direction





Double
Vortex



External
Flux
Closure

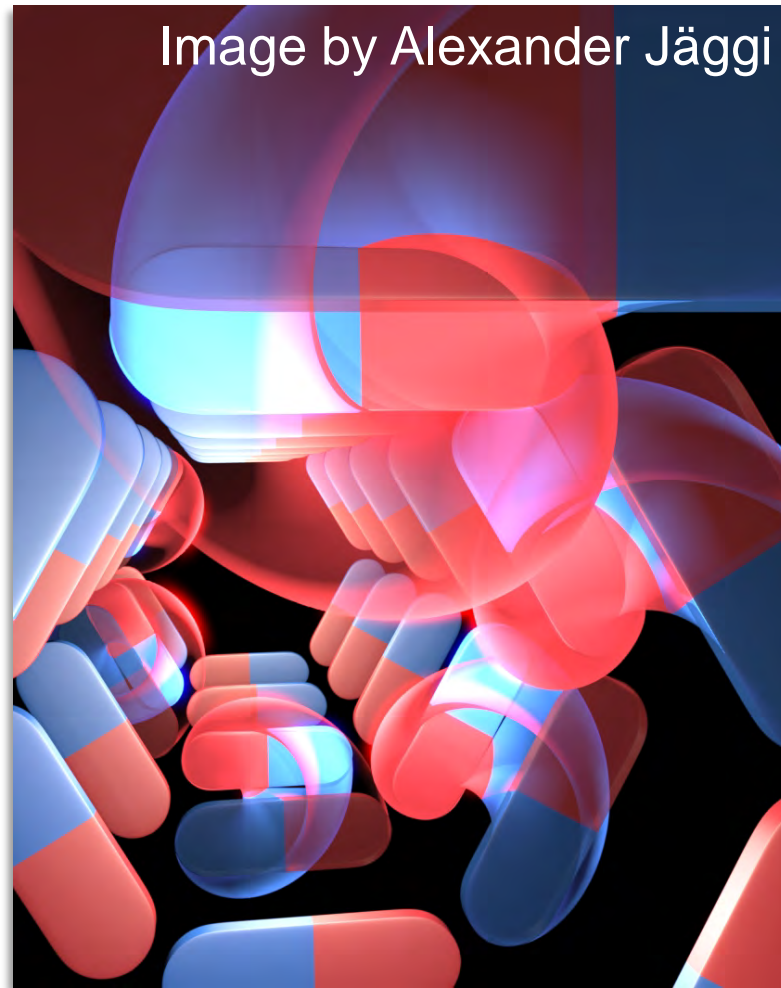
Degeneracy: 12

12

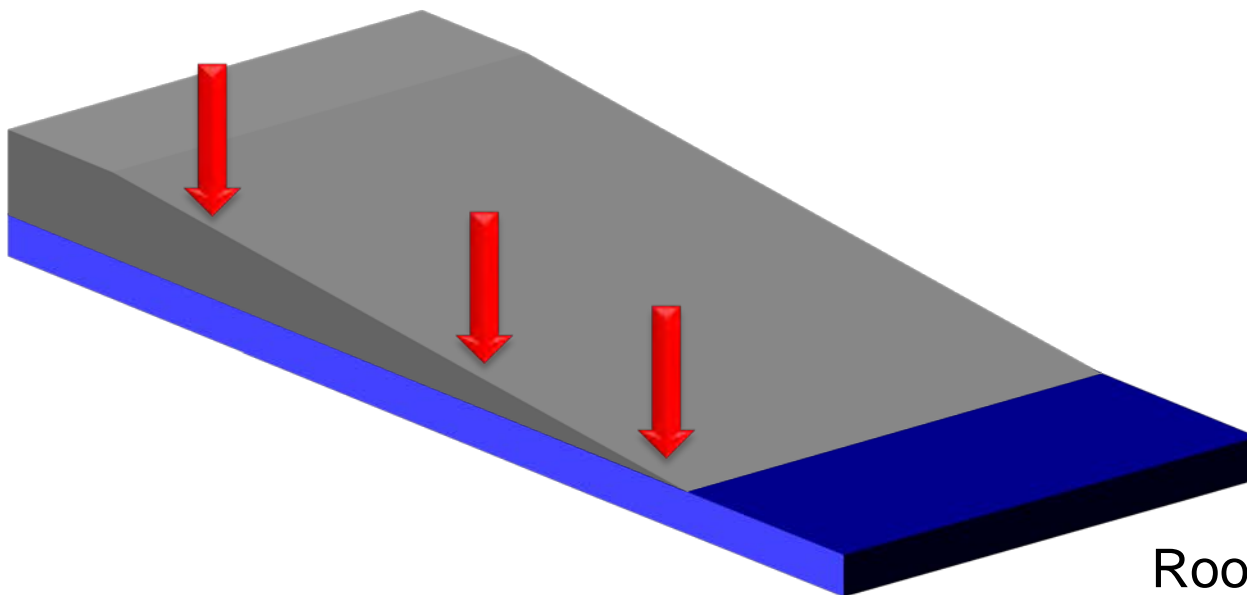


X-ray direction

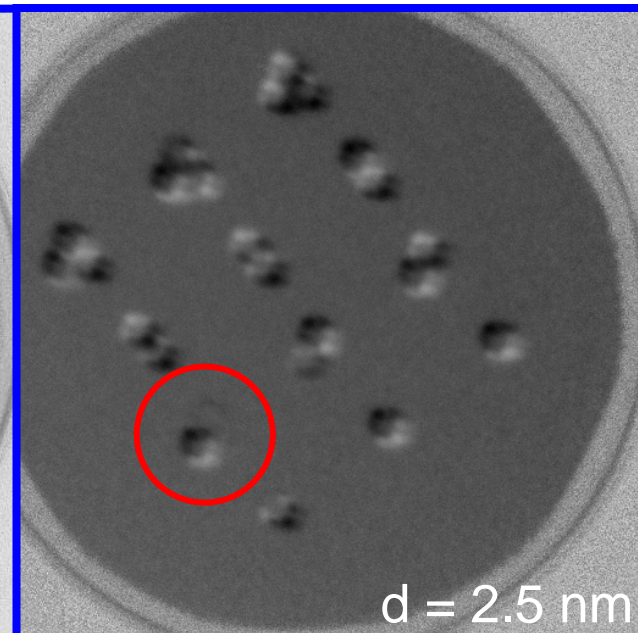
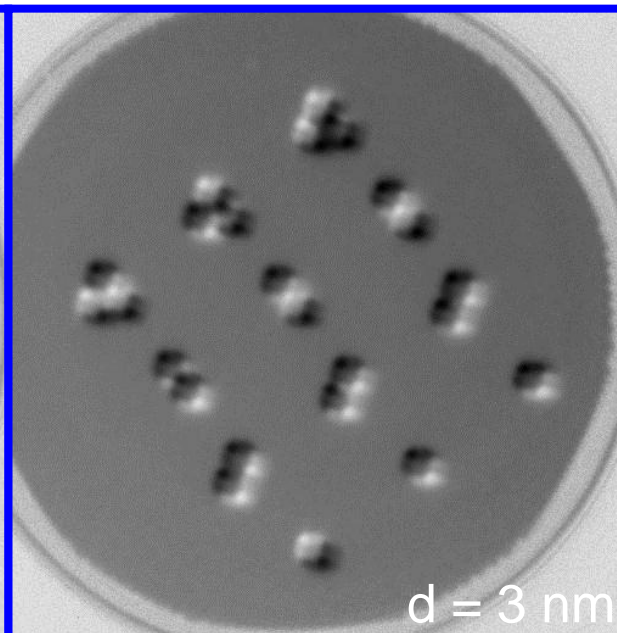
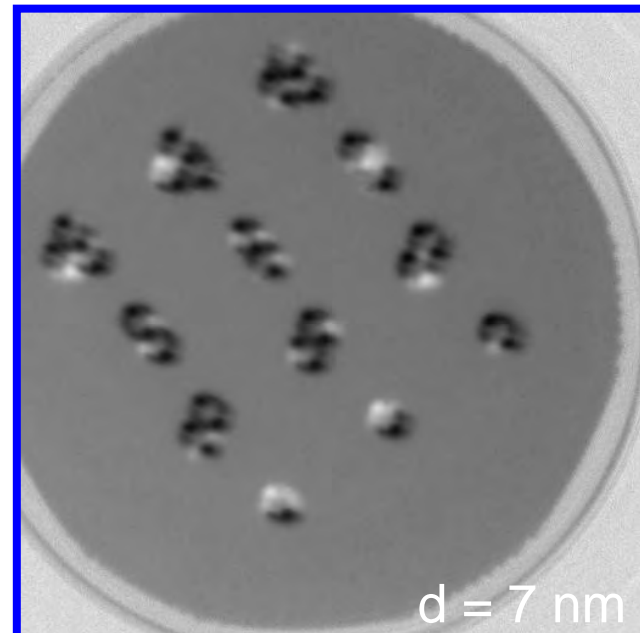




L. Heyderman, *News & Views*,
Nature Nanotechnology (2013)



Room Temperature

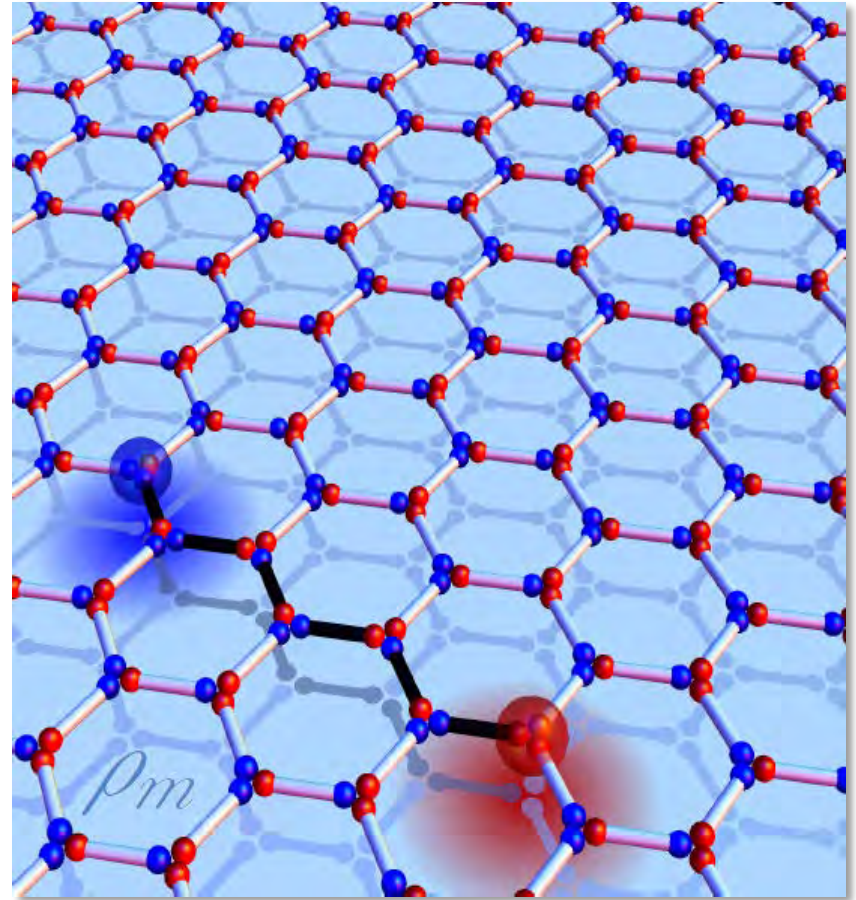
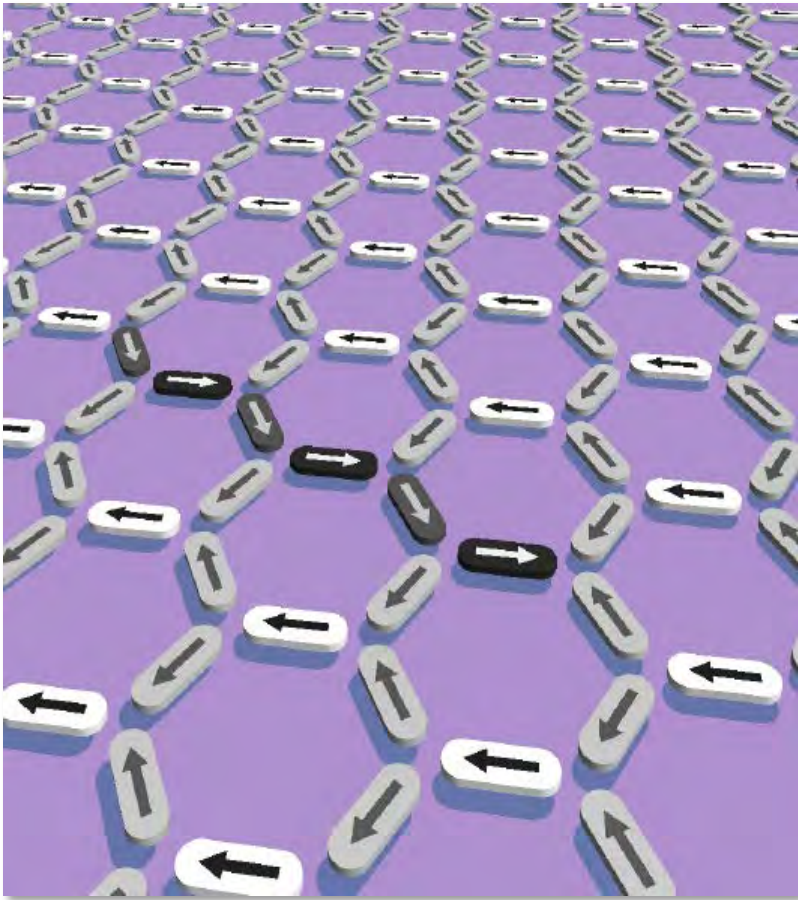


The background of the slide is a microscopic image of a spin ice lattice. It consists of a regular grid of bright yellow-orange spots, which represent the magnetic ions. Superimposed on this grid are several dark, irregular lines or paths, representing the emergent magnetic monopoles. These paths appear to be formed by the arrangement of the ions in a way that creates a net magnetic charge at certain points.

Topic 1

**Emergent Magnetic Monopoles
in Artificial Spin Ice**

Emergent Magnetic Monopoles & Dirac Strings

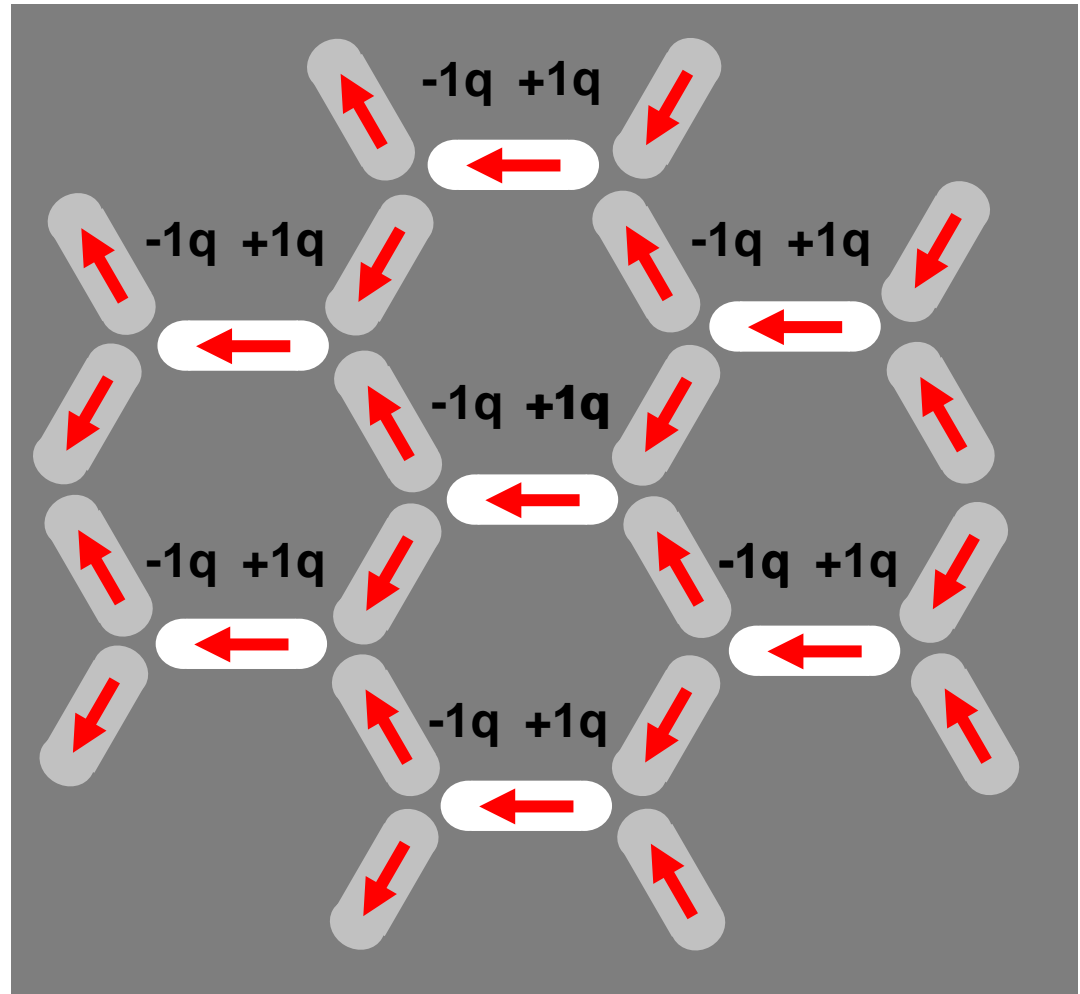


H. B. Braun

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

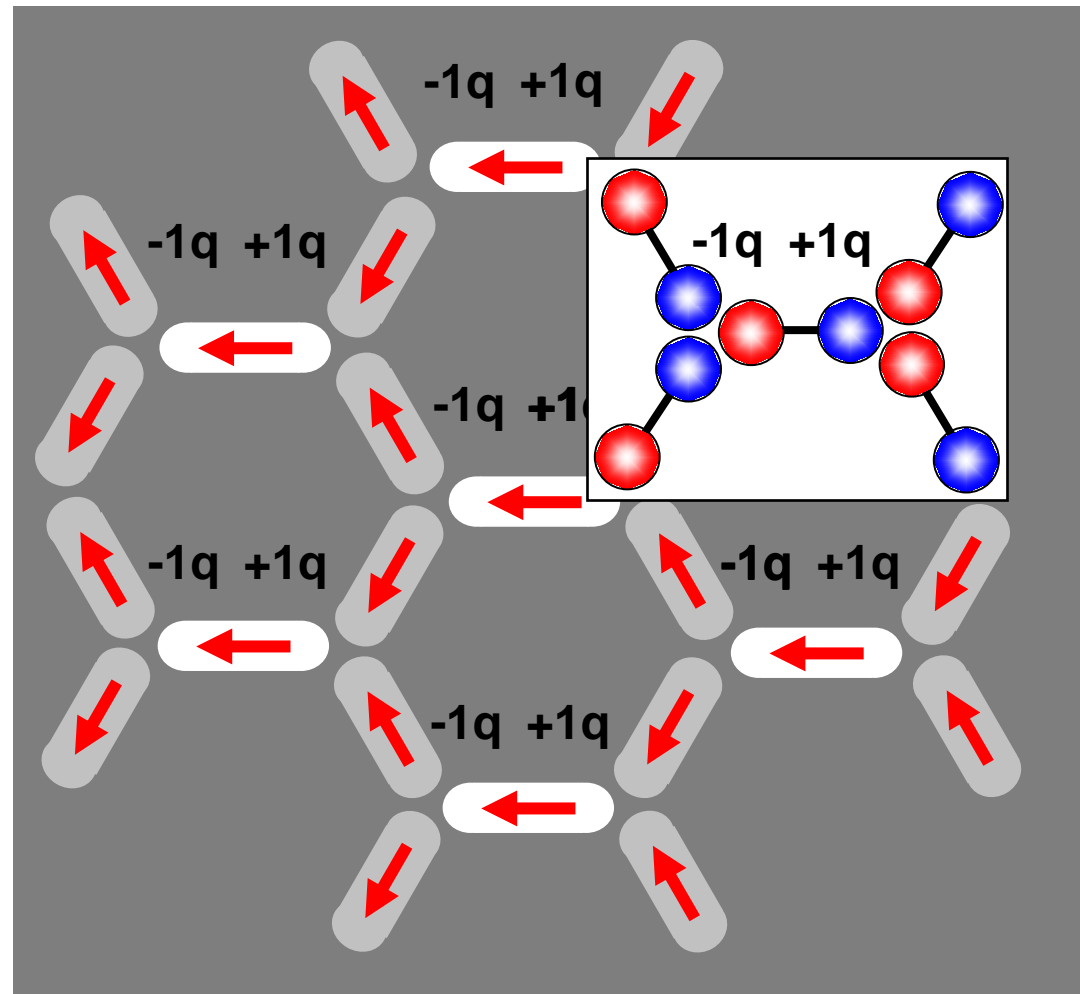
The Charge Model

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



The Charge Model

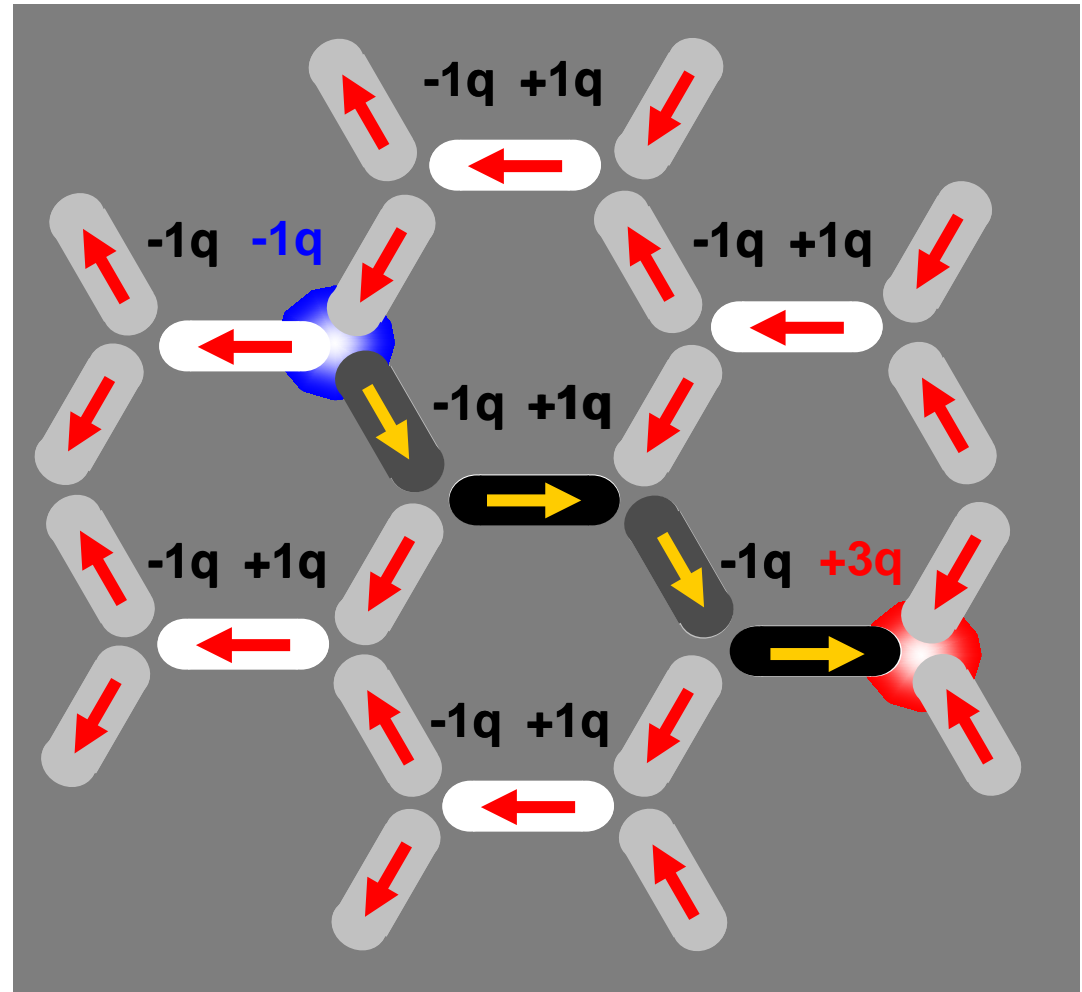
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➔ C Castelnovo, R Moessner & SL Sondhi Nature (2008)

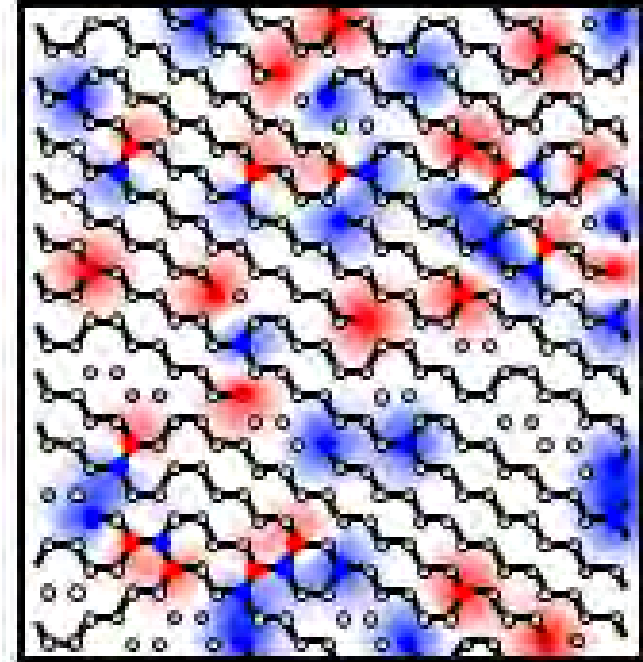
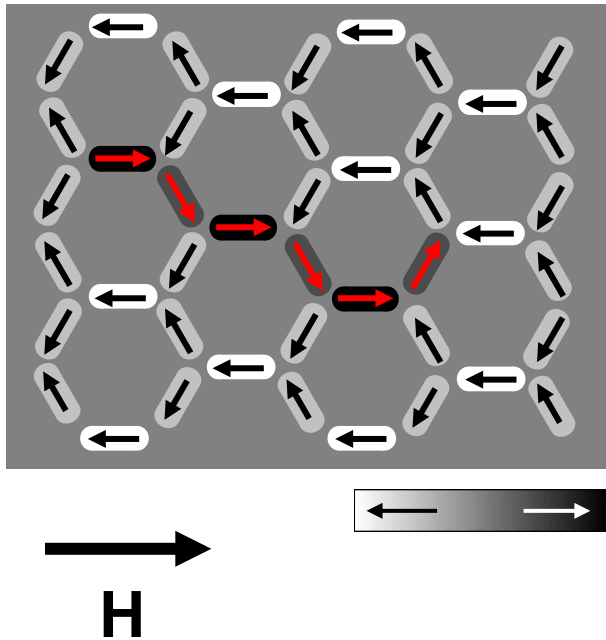
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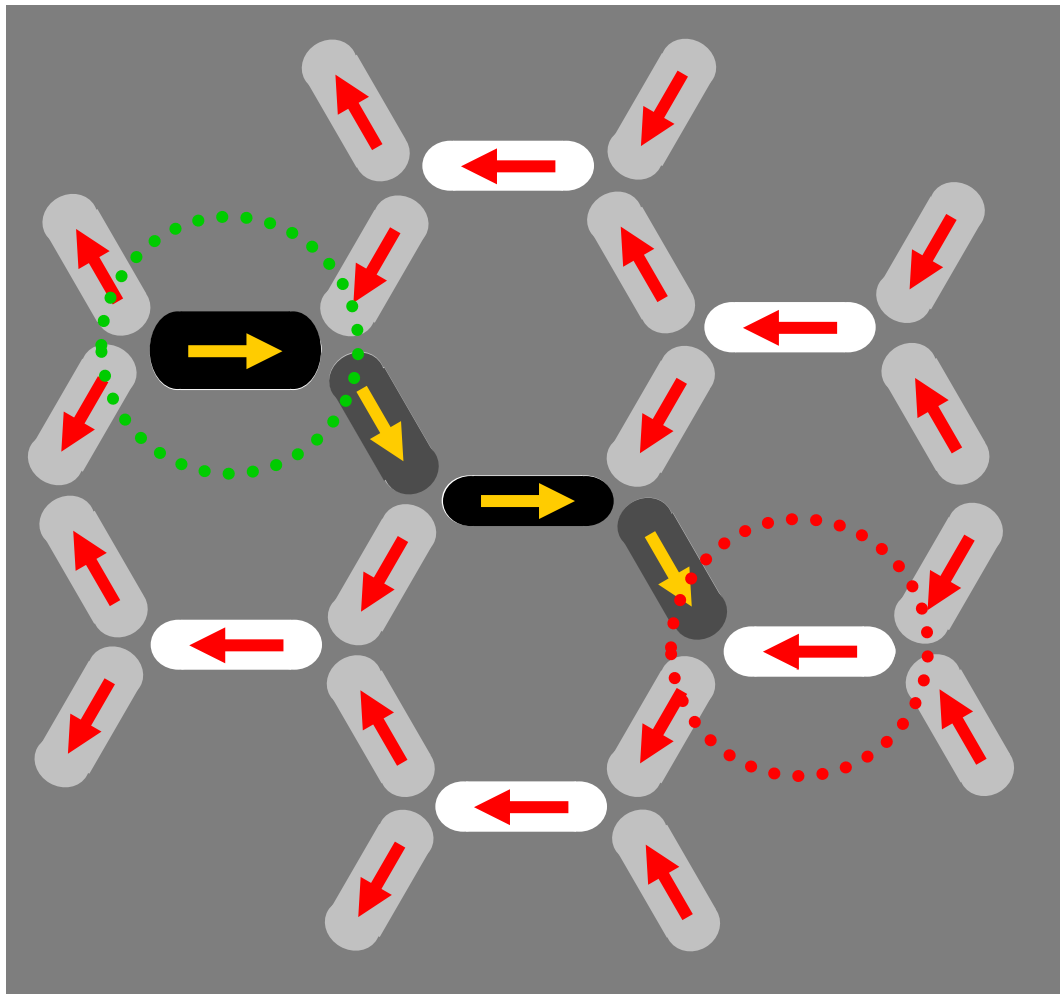


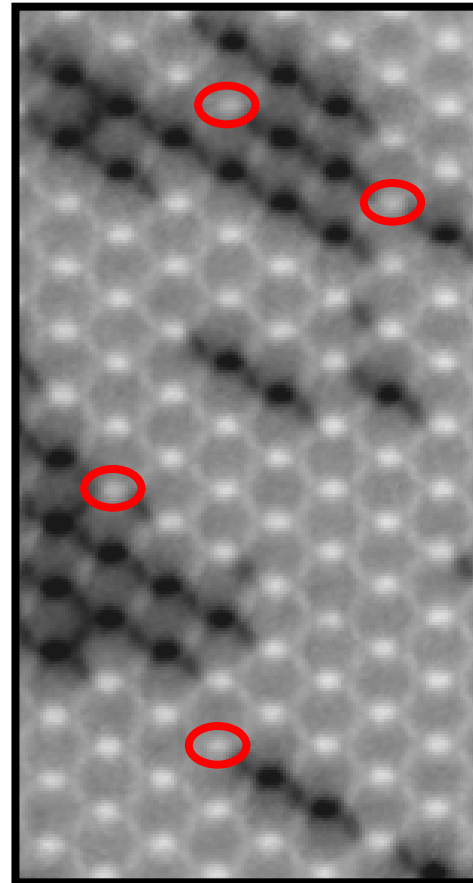
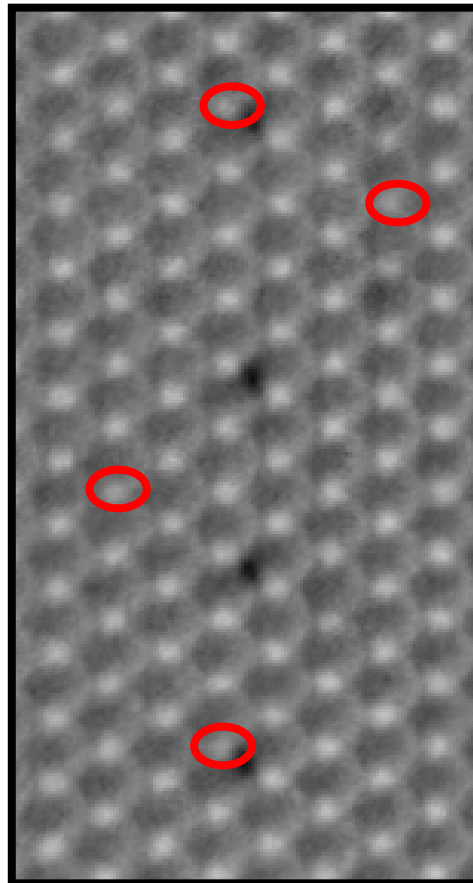
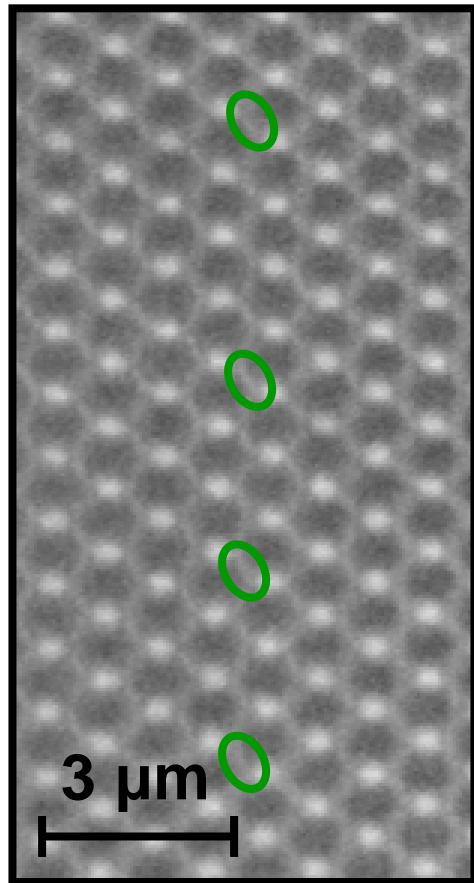
➔ C Castelnovo, R Moessner & SL Sondhi Nature (2008)

Emergent Magnetic Monopoles & Dirac Strings



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



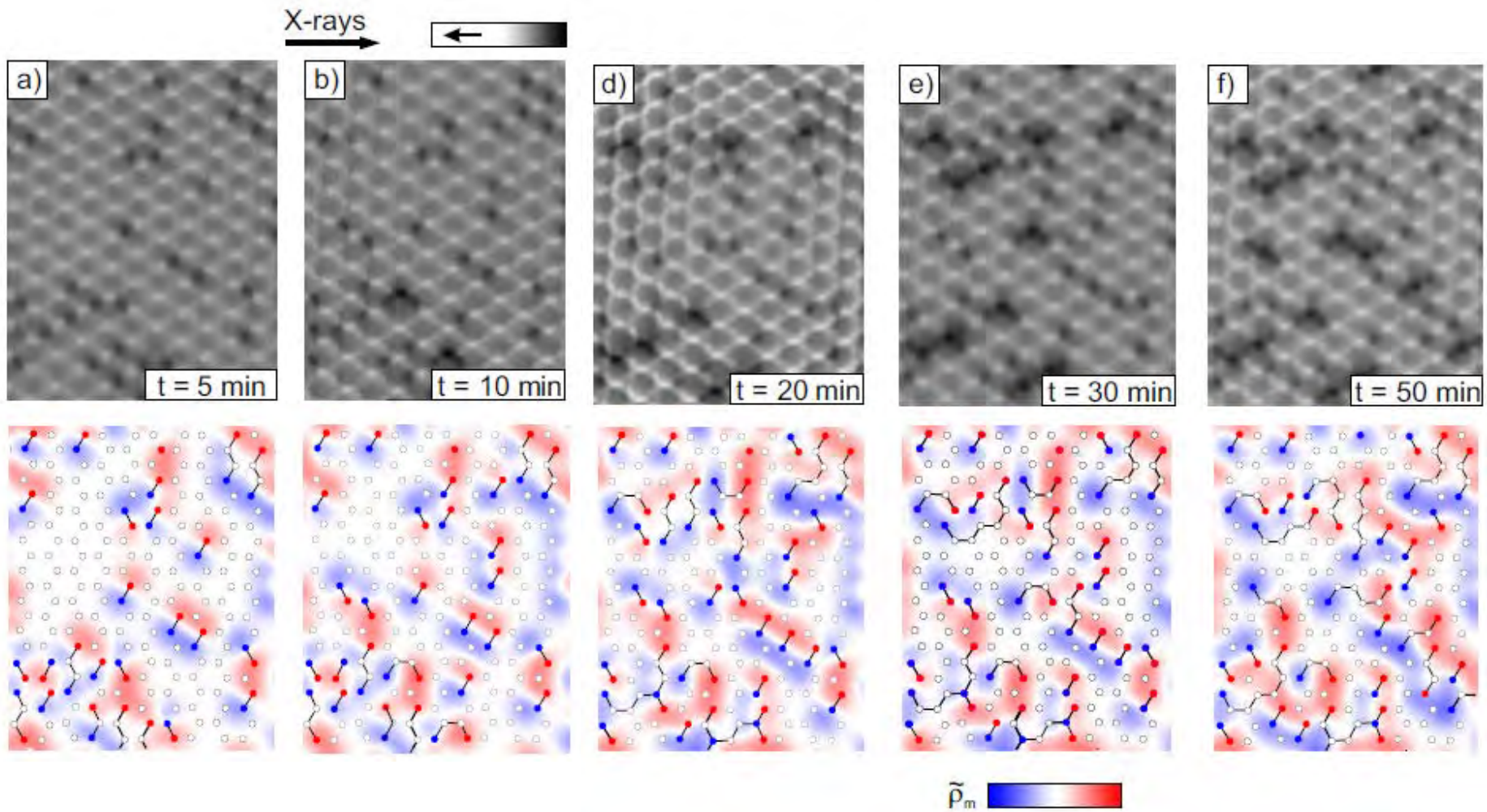


 **Start Islands**
Low shape anisotropy

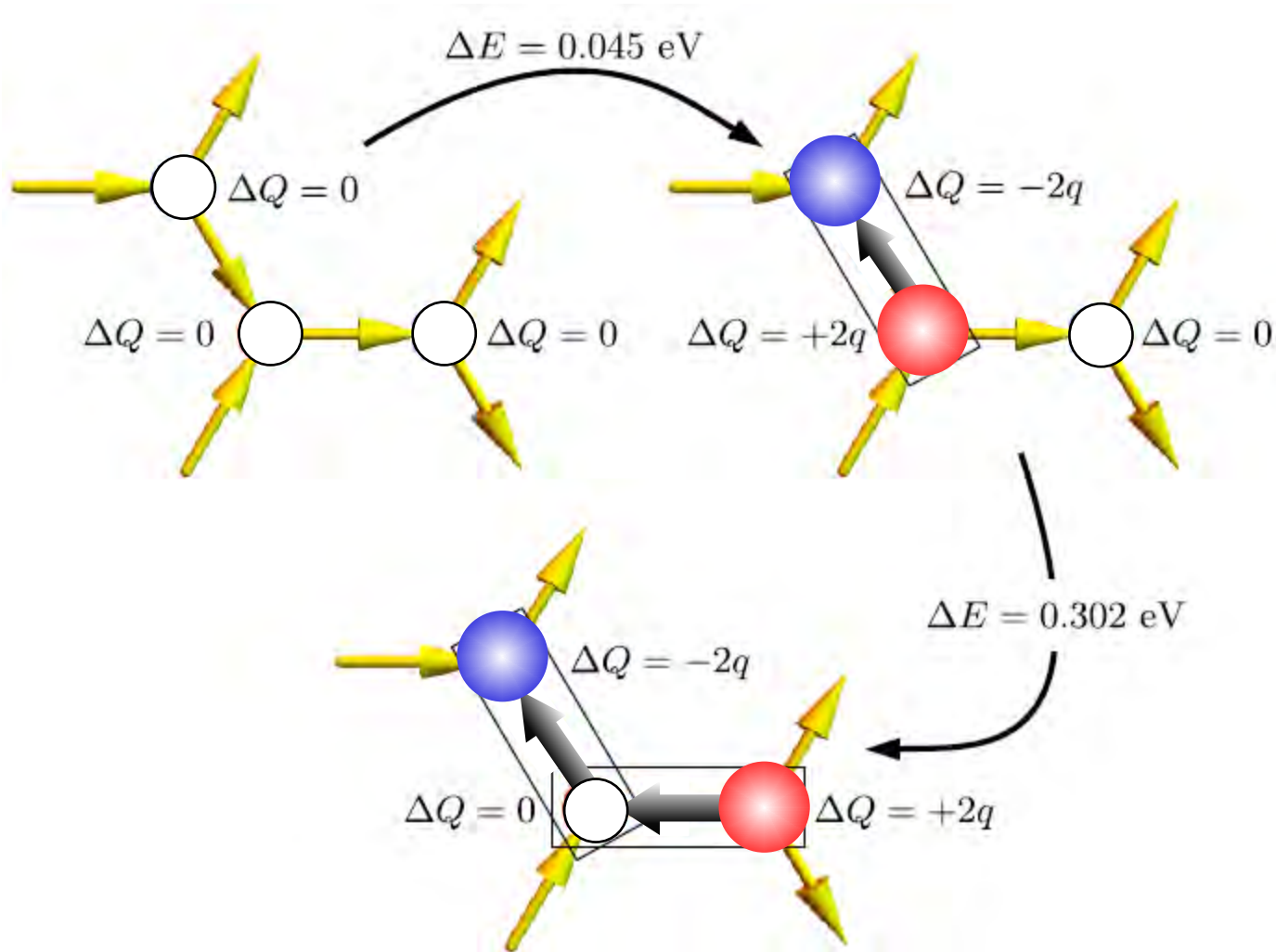
 **Stop Islands**
High shape anisotropy

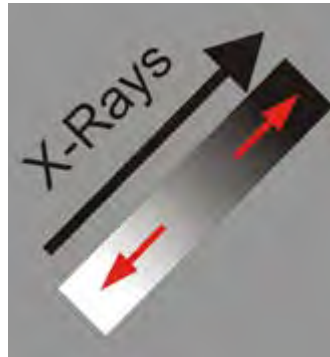
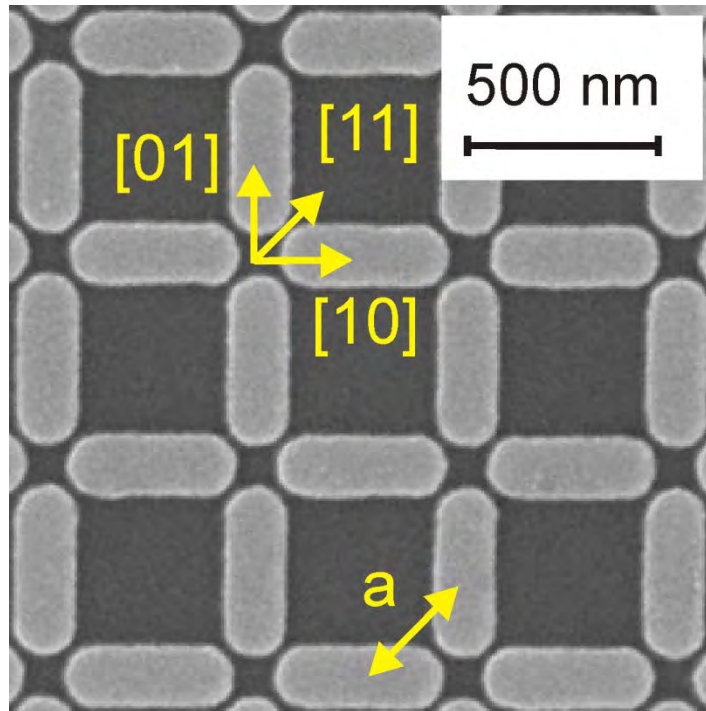
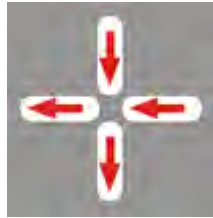
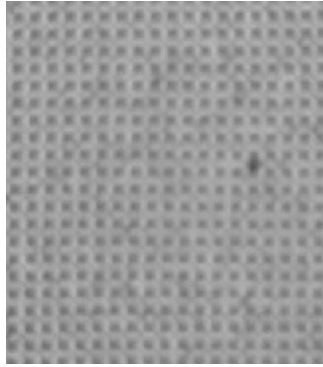
Regular islands:	470 x 160 x 30 nm ³
Wide islands:	400 x 180 x 30 nm ³
Narrow islands:	460 x 130 x 30 nm ³

Thermally Active Artificial Kagome Ice



Thermally Active Artificial Kagome Ice



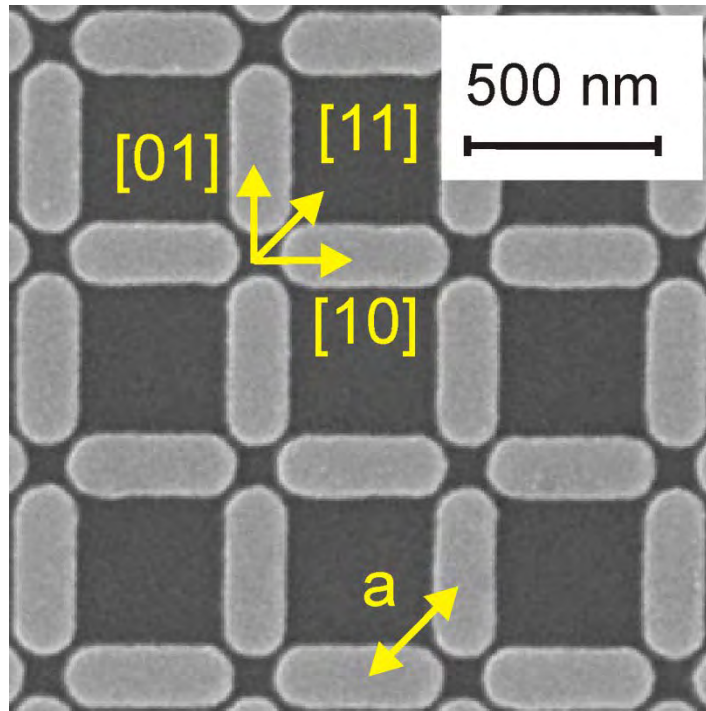
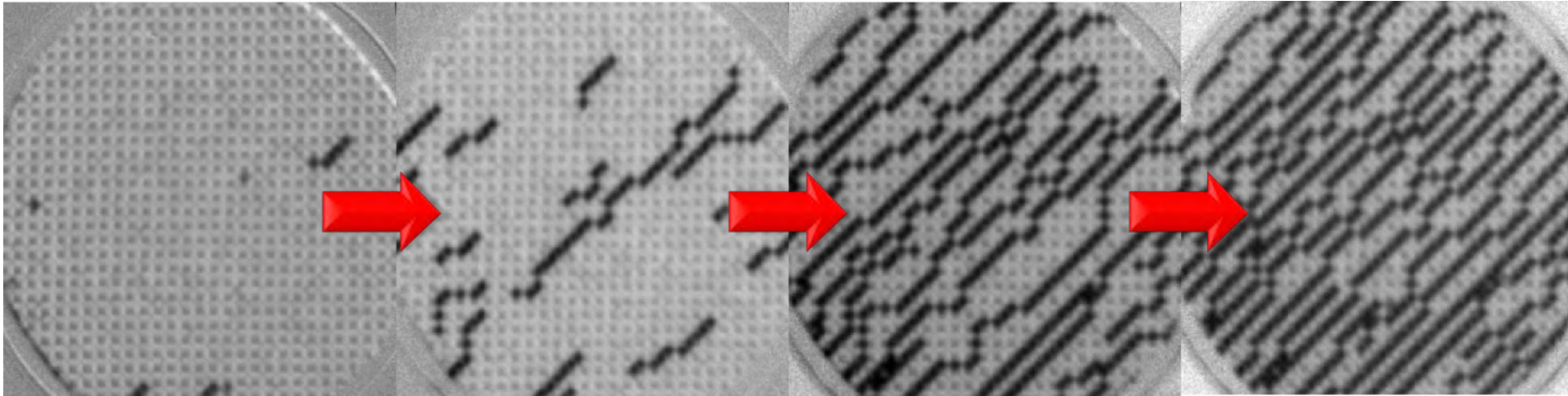


“String Regime”

A Farhan et al. PRL (2013)

V Kapaklis et al. Nature Nanotech. (2014)

Field of View 20 μm

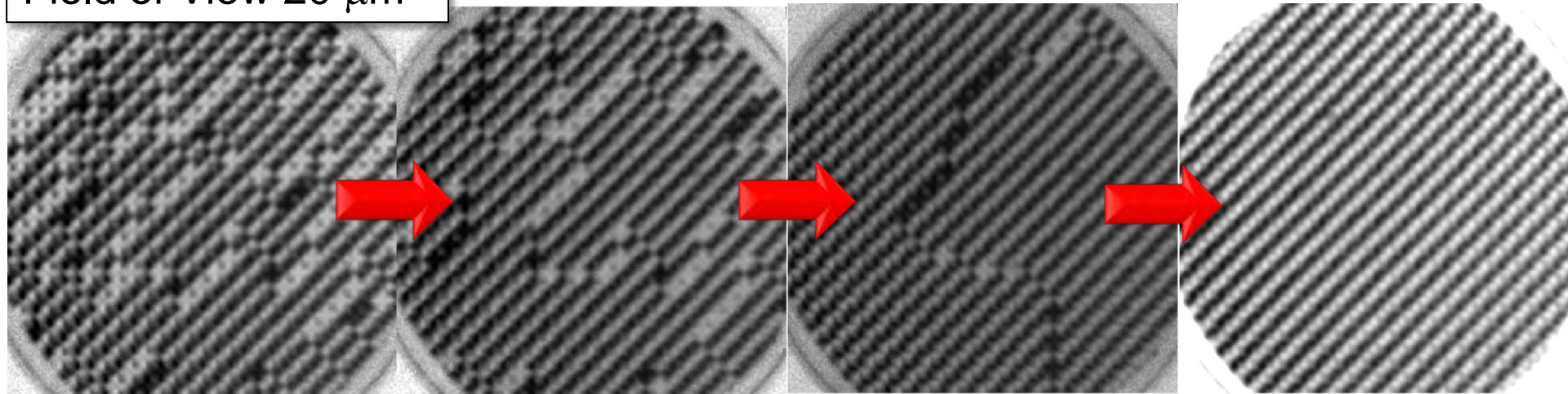


“String Regime”

A Farhan et al. PRL (2013)

V Kapaklis et al. Nature Nanotech. (2014)

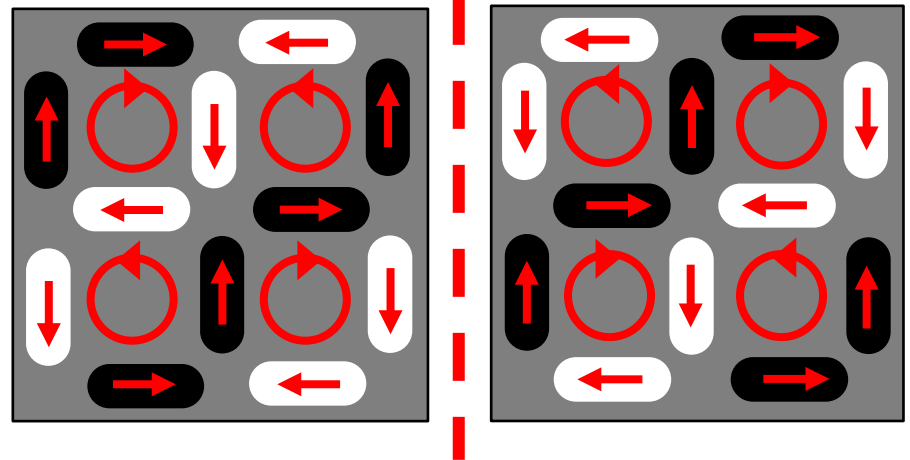
Field of View 20 μm



Field of View 50 μm



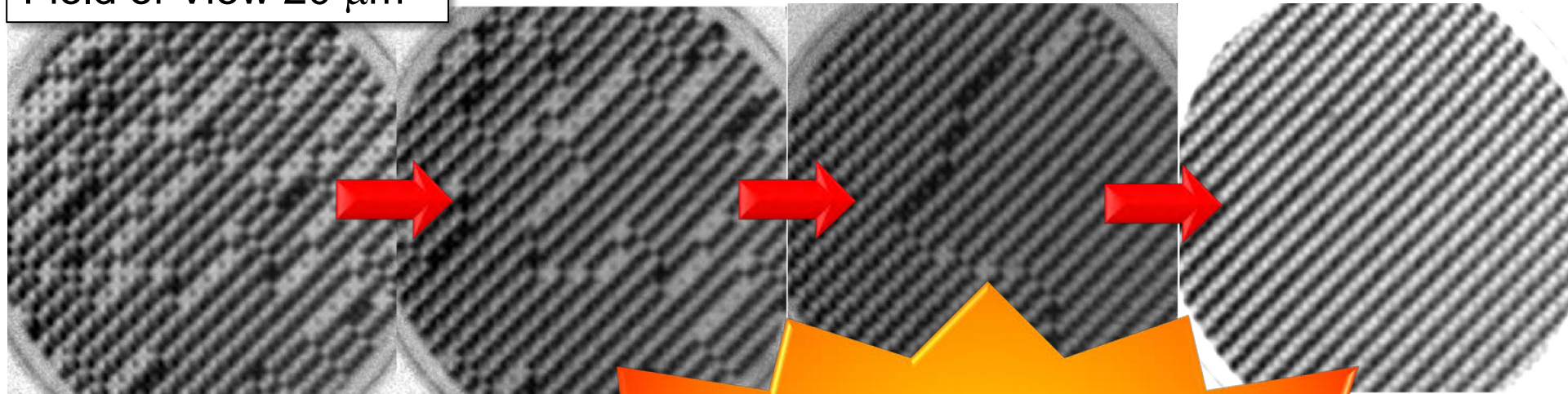
“Domain Regime”



A Farhan et al. PRL (2013)

V Kapaklis et al. Nature Nanotech. (2014)

Field of View 20 μm



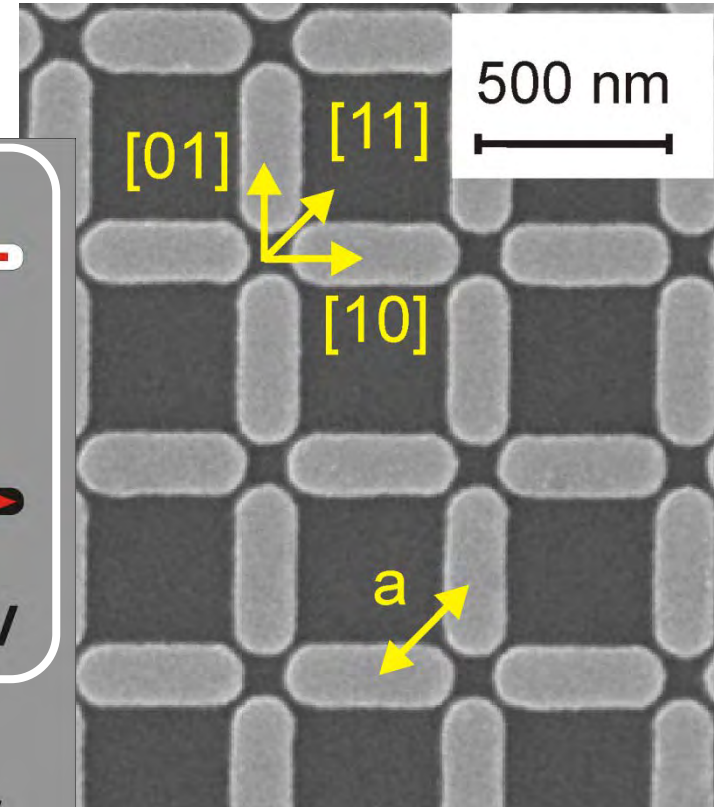
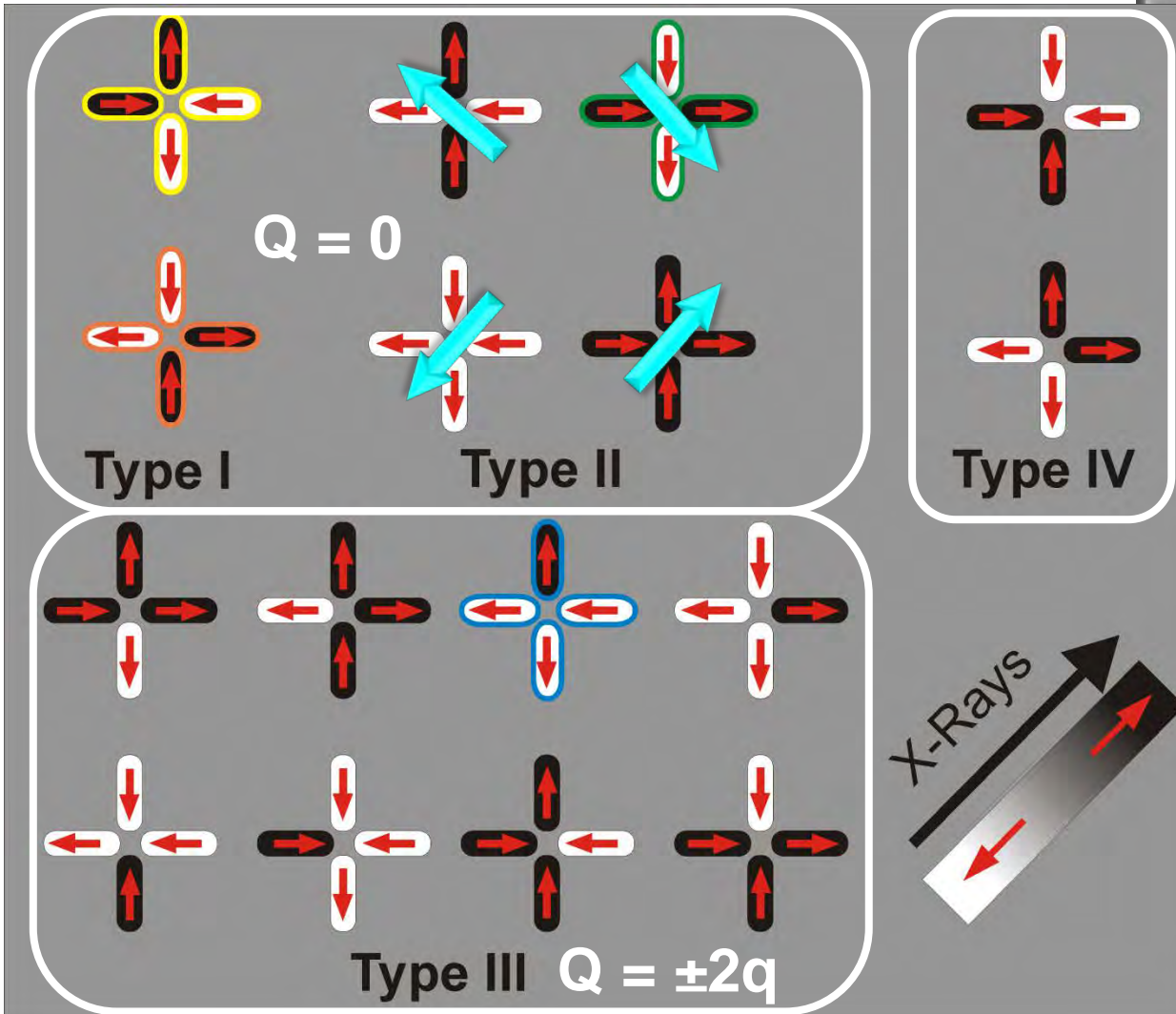
Field of View 50 μm



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

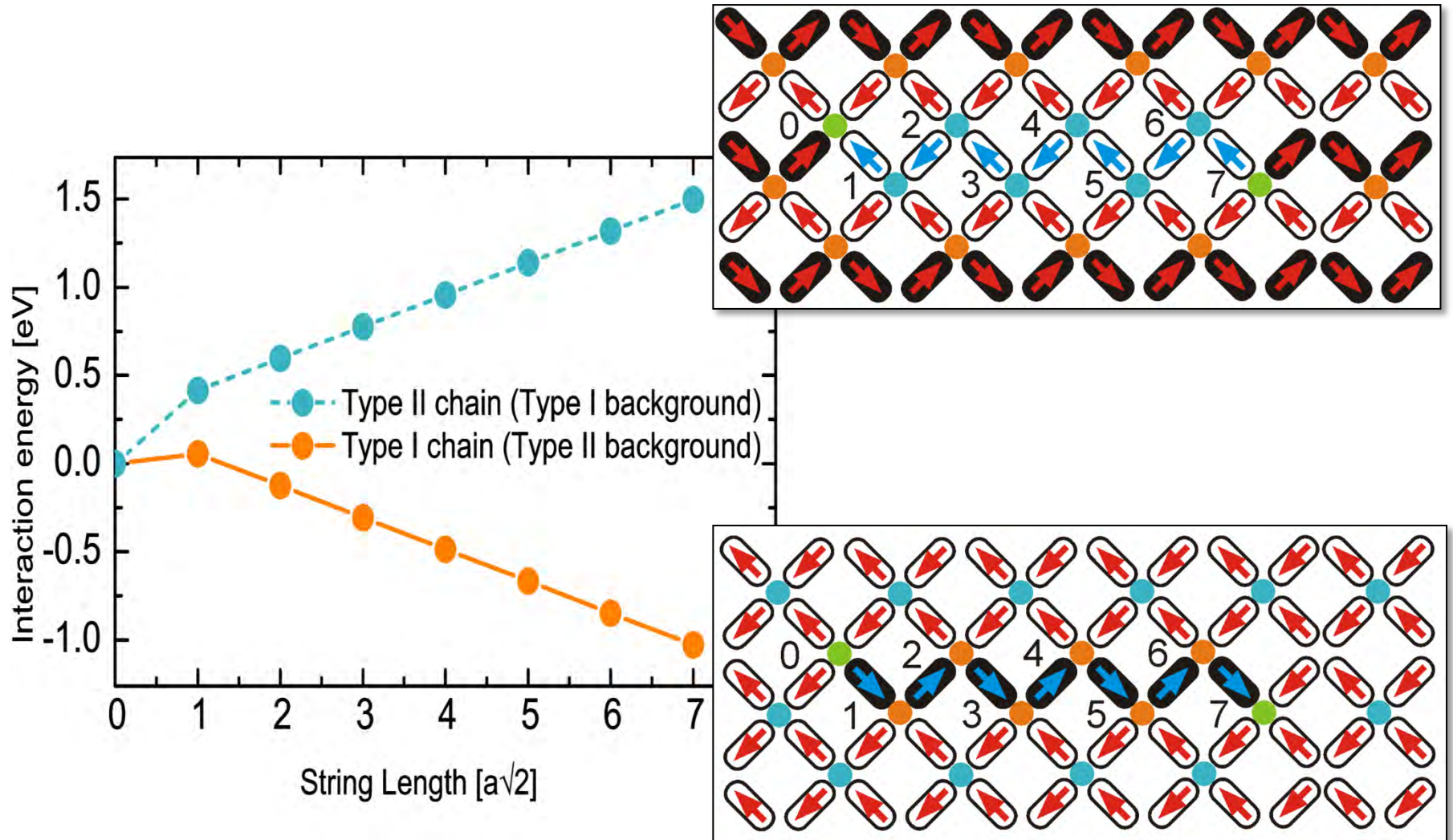
A Farhan et al. PRL (2013)

V Kapaklis et al. Nature Nanotech. (2014)



$$Q_0 = 0$$

$$\Delta Q \rightarrow Q !!!$$



A Farhan et al. PRL (2013)

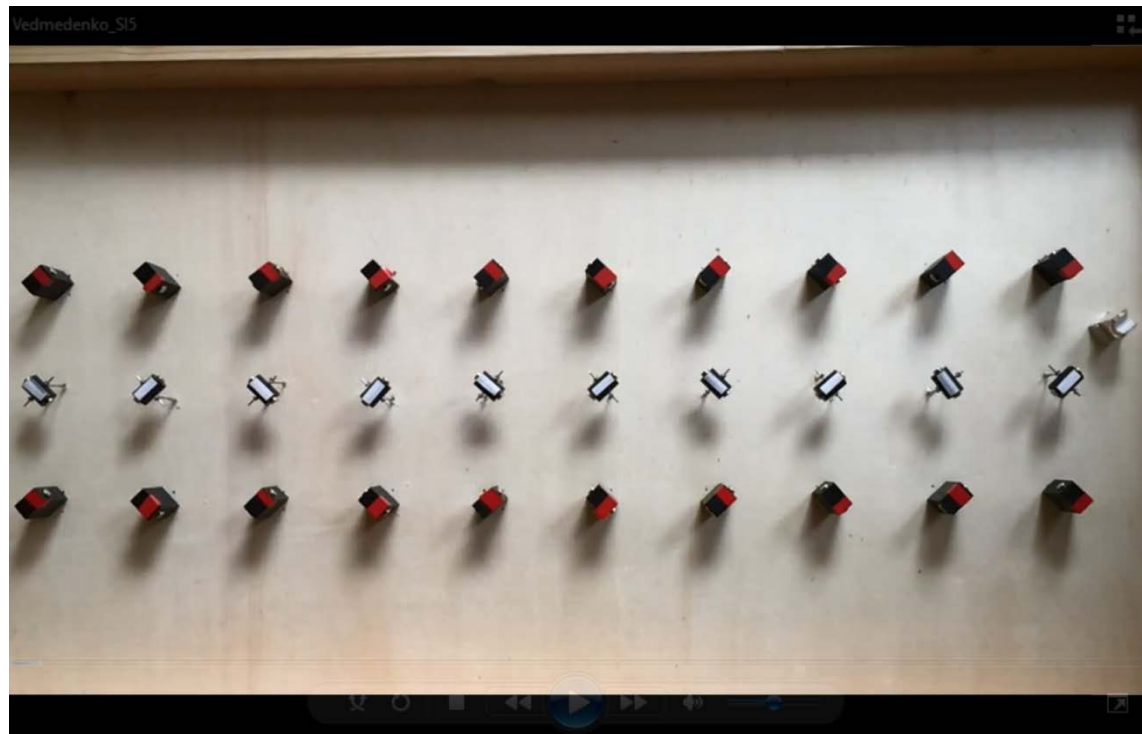
V Kapaklis et al. Nature Nanotech. (2014)

Dynamics of Bound Monopoles in Artificial Spin Ice: How to Store Energy in Dirac Strings

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University of Hamburg, Institute for Applied Physics, Jungiusstrasse 11a, 20355 Hamburg, Germany

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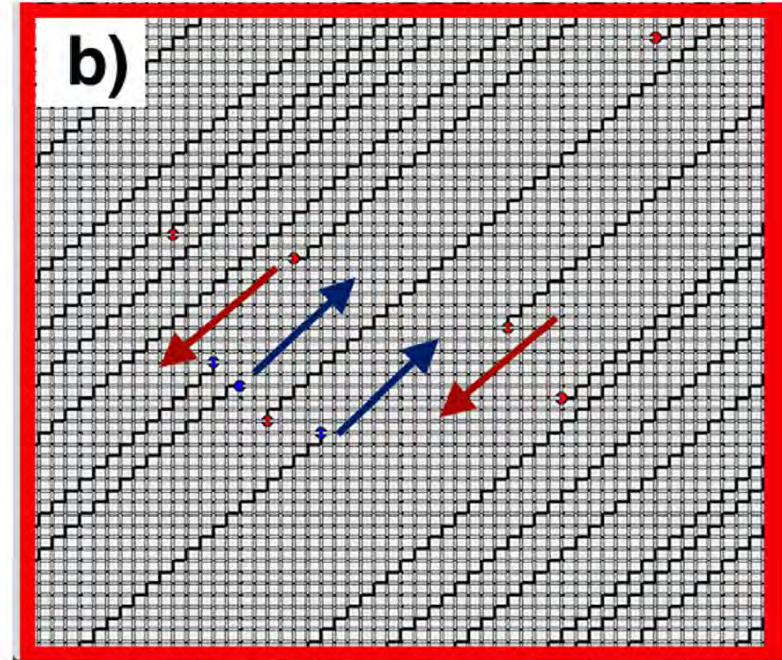
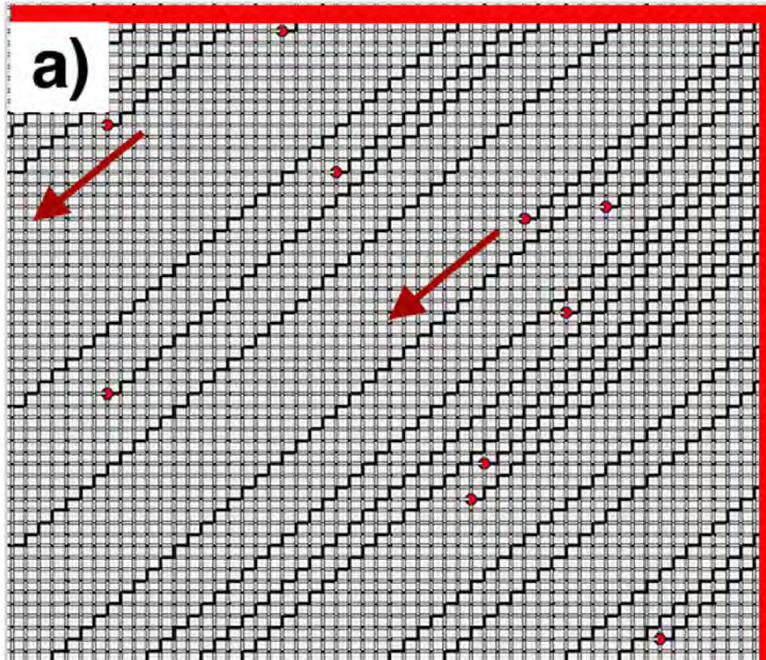
Physica B 500 (2016) 59–65

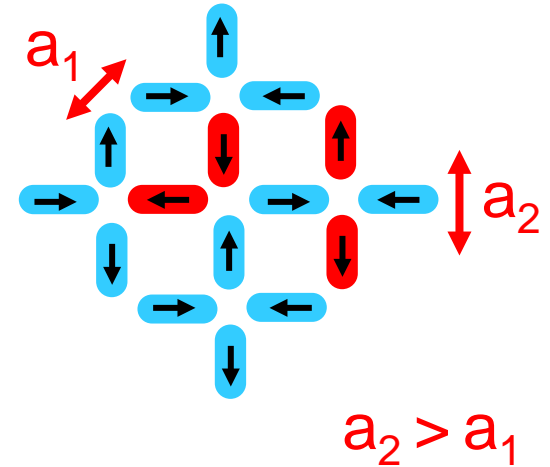
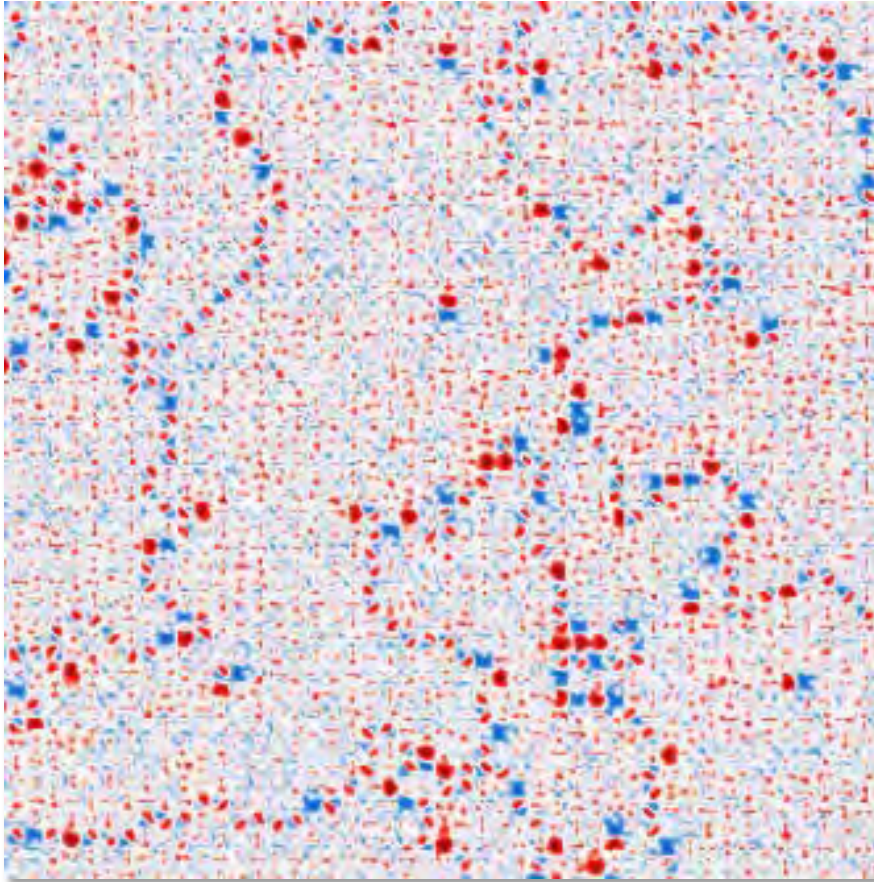
journal homepage: www.elsevier.com/locate/physb

Thermal phase transition in artificial spin ice systems induces the formation and migration of monopole-like magnetic excitations

Alejandro León

Facultad de Ingeniería, Universidad Diego Portales, Ejército 441, Santiago, Chile



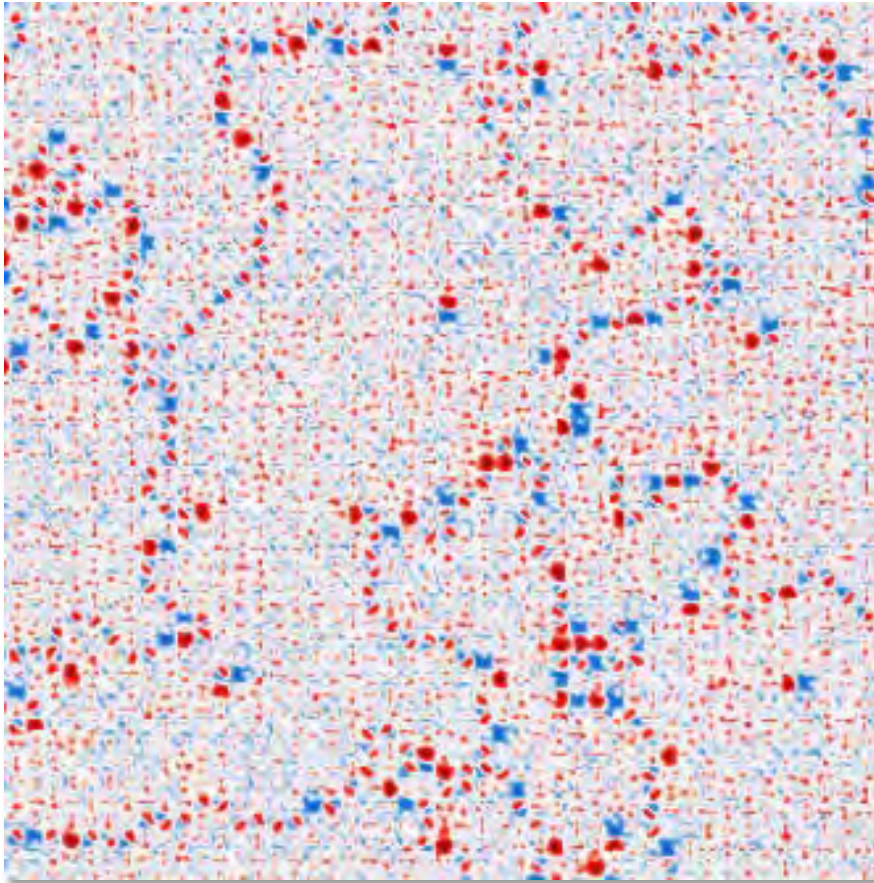


Artificial Square Ice

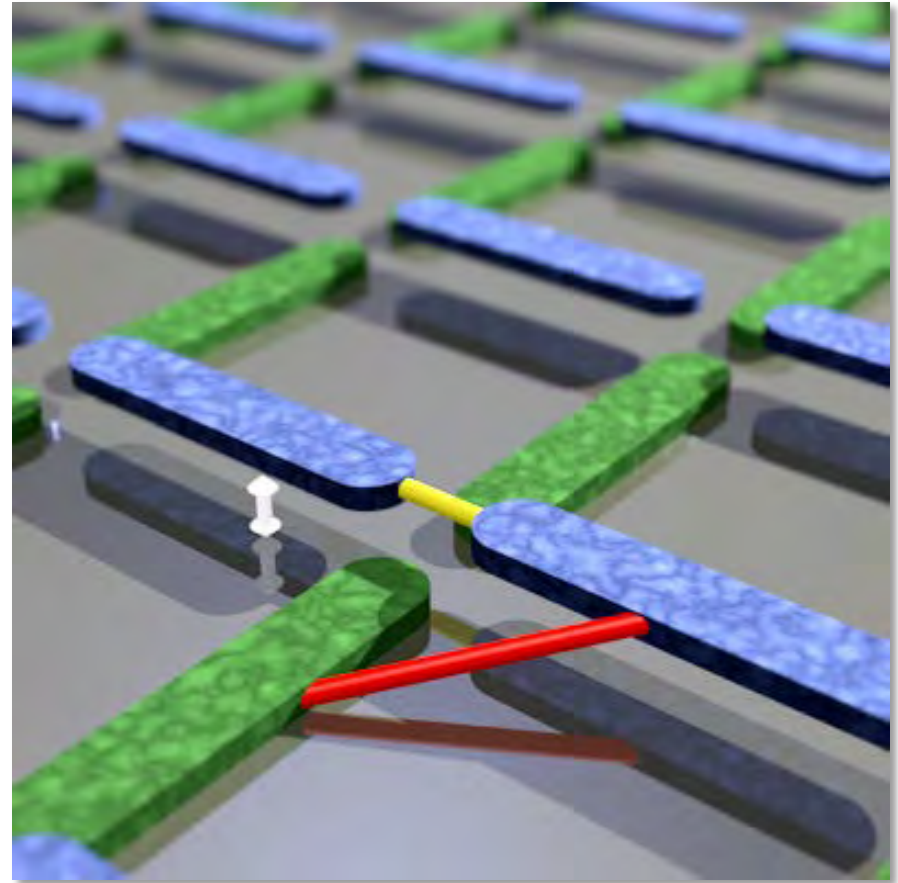
J Morgan et al. Nature Physics (2011)

JM Porro et al. NJP (2013)

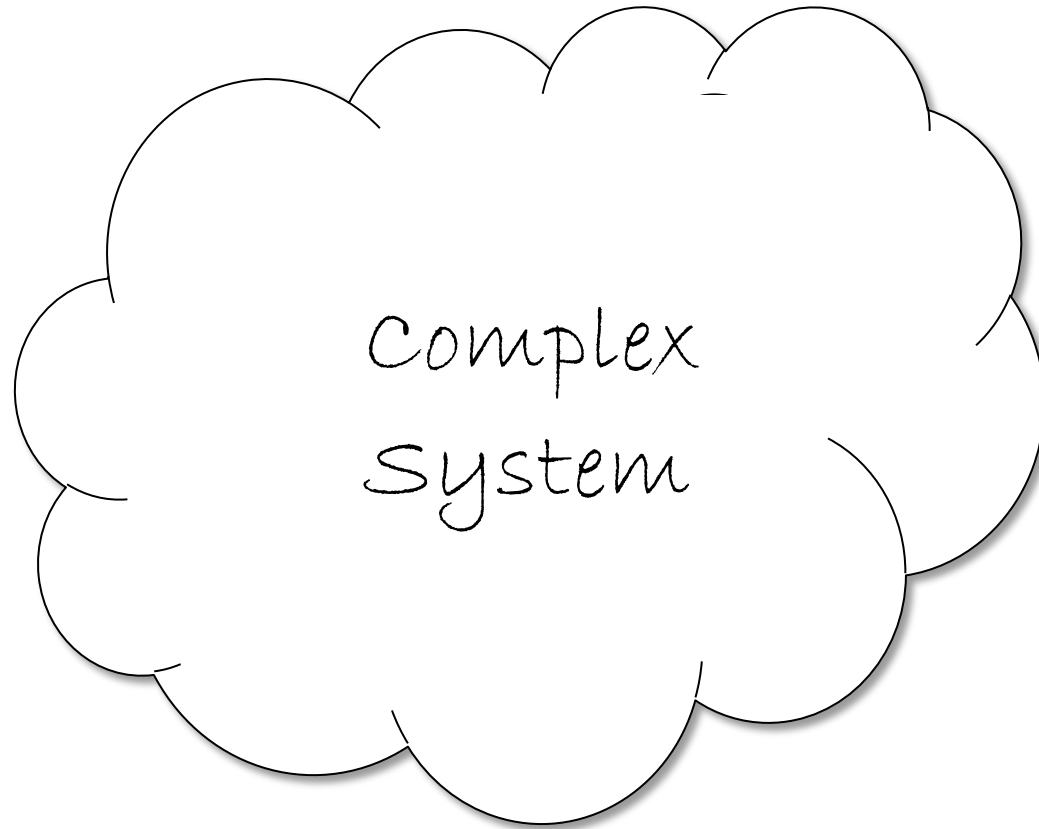
S Zhang et al. Nature (2013)



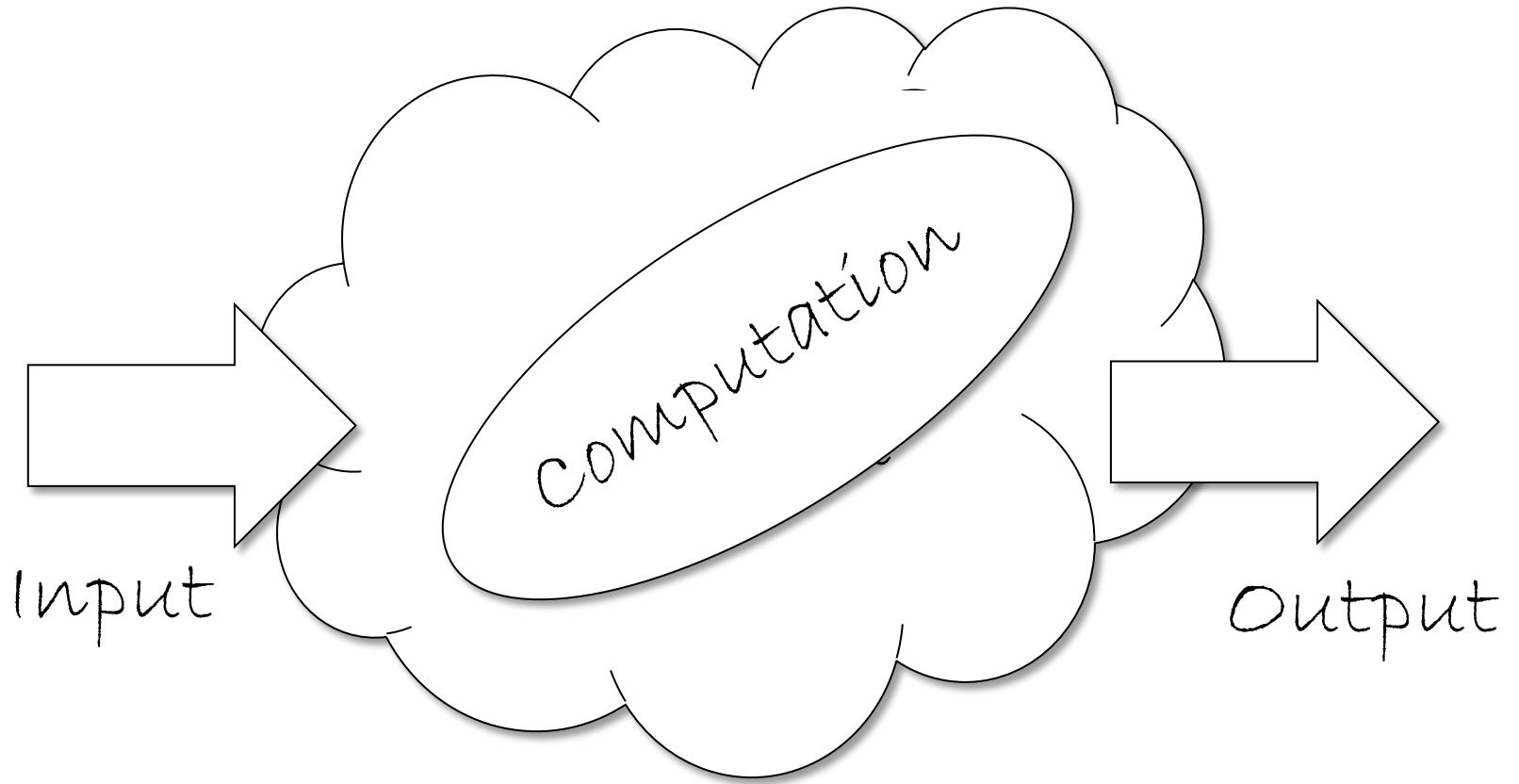
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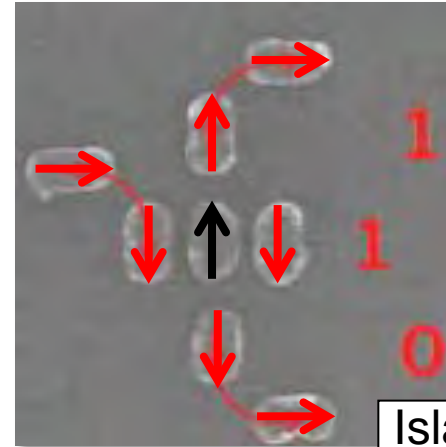
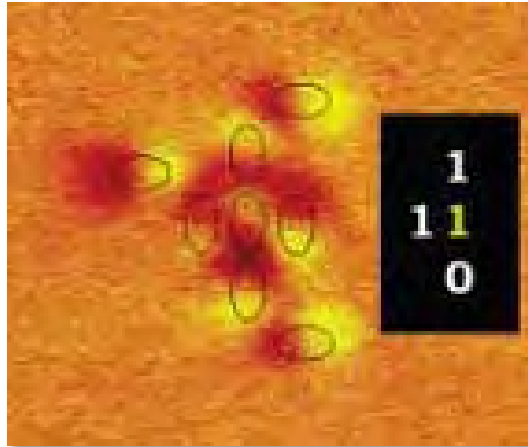
G Moller & R Moessner PRL (2006)
G-W Chern et al. APL (2014)
Y Perrin et al. Nature (2016)



Topic 2
Towards Bioinspired Computation

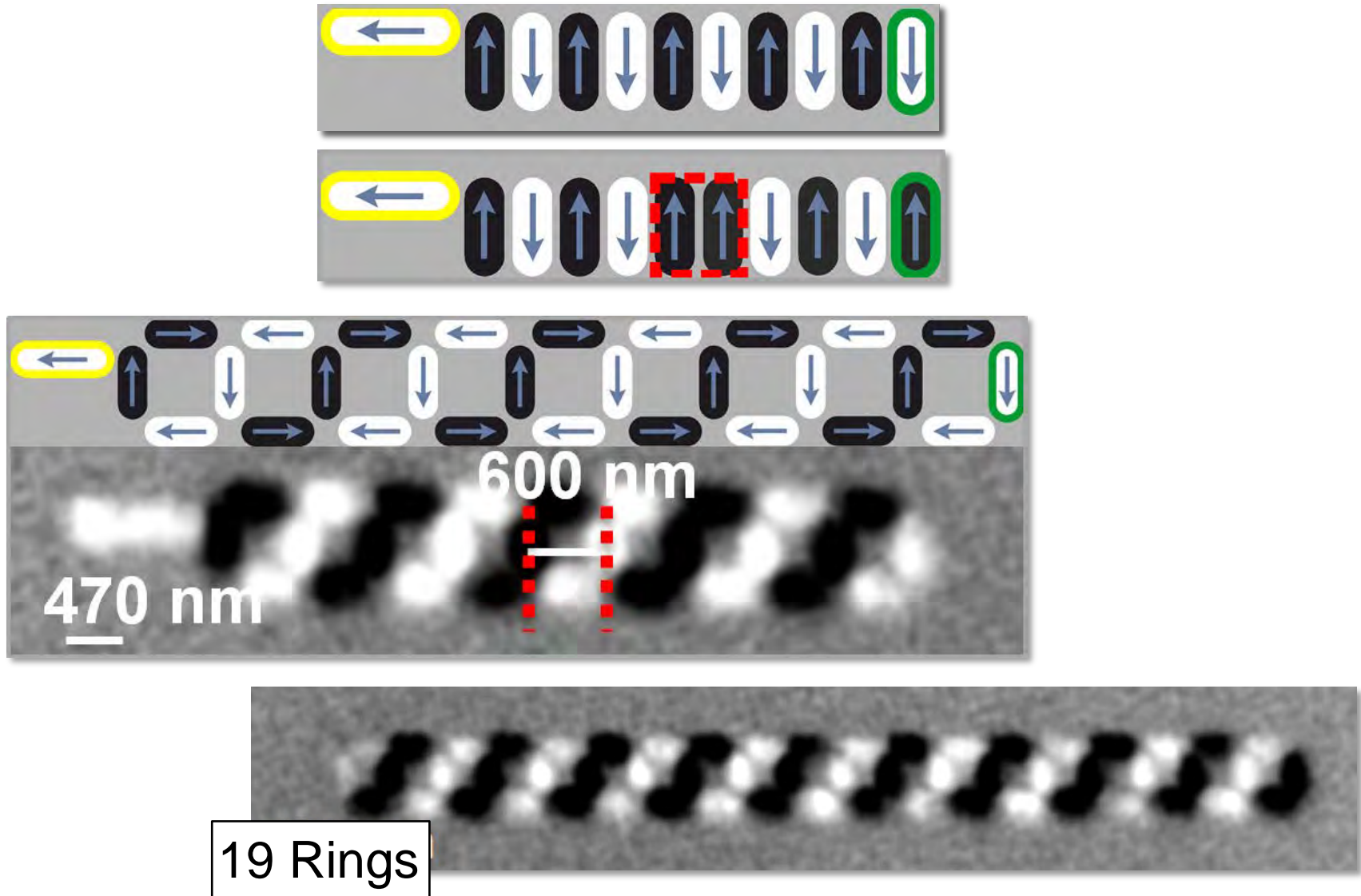


Topic 2
Towards Bioinspired Computation

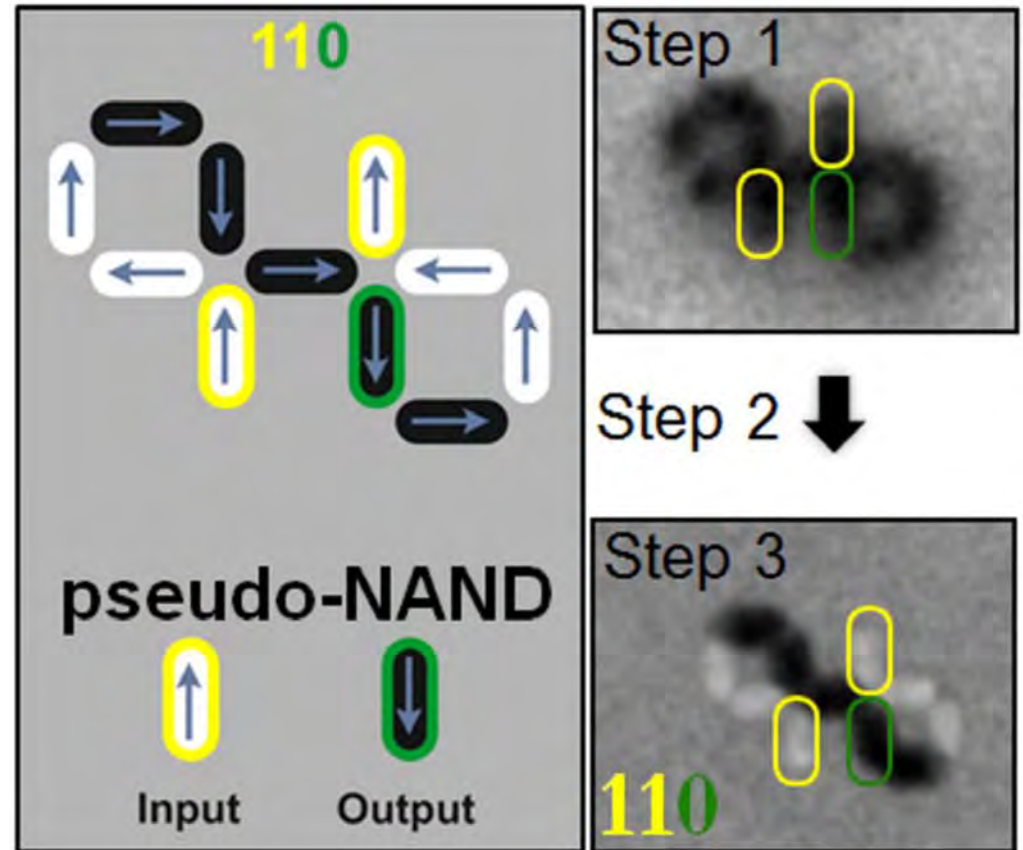
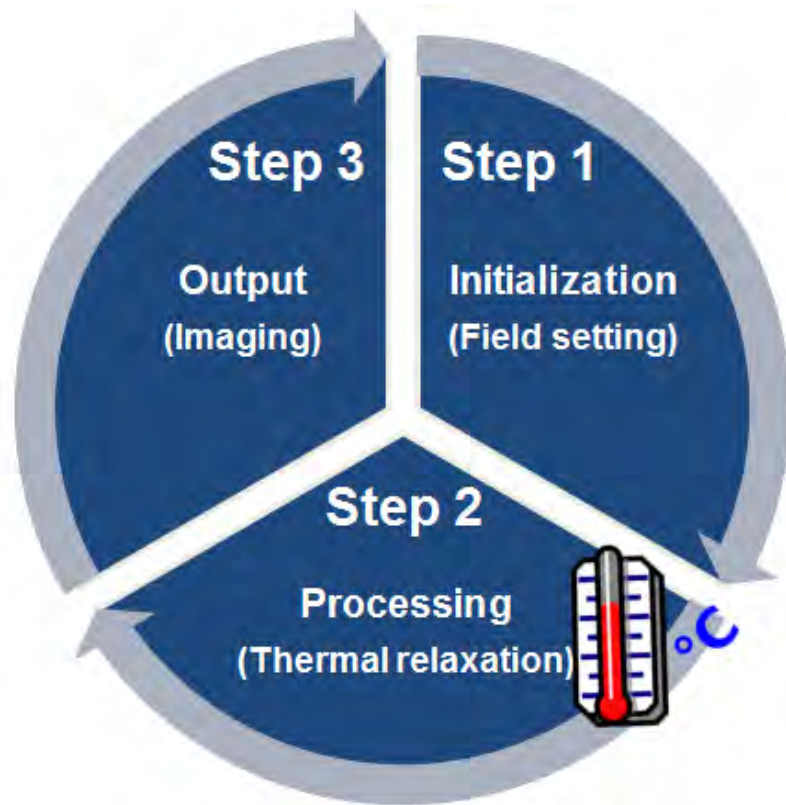


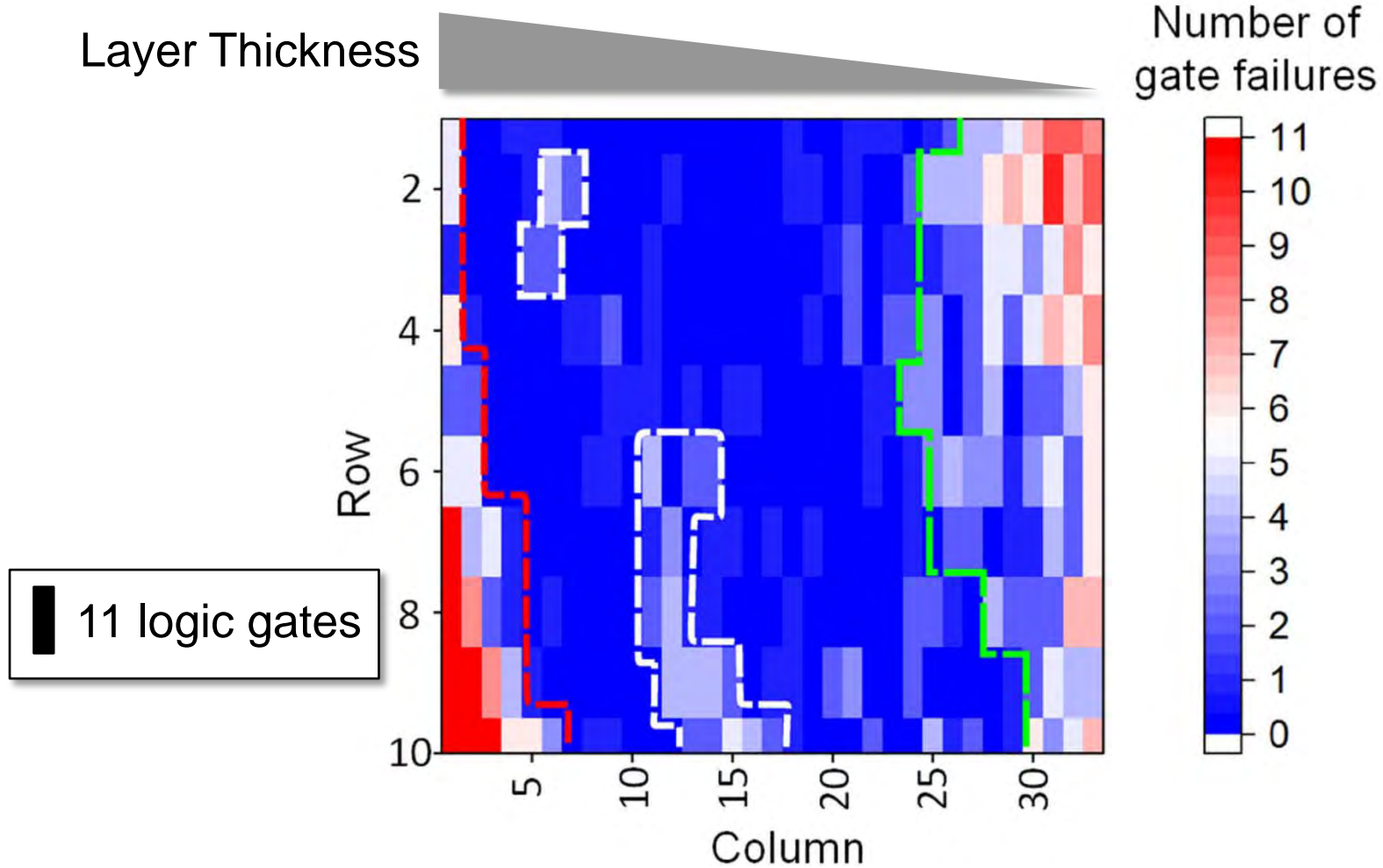
A Imre et al. Science (2006)

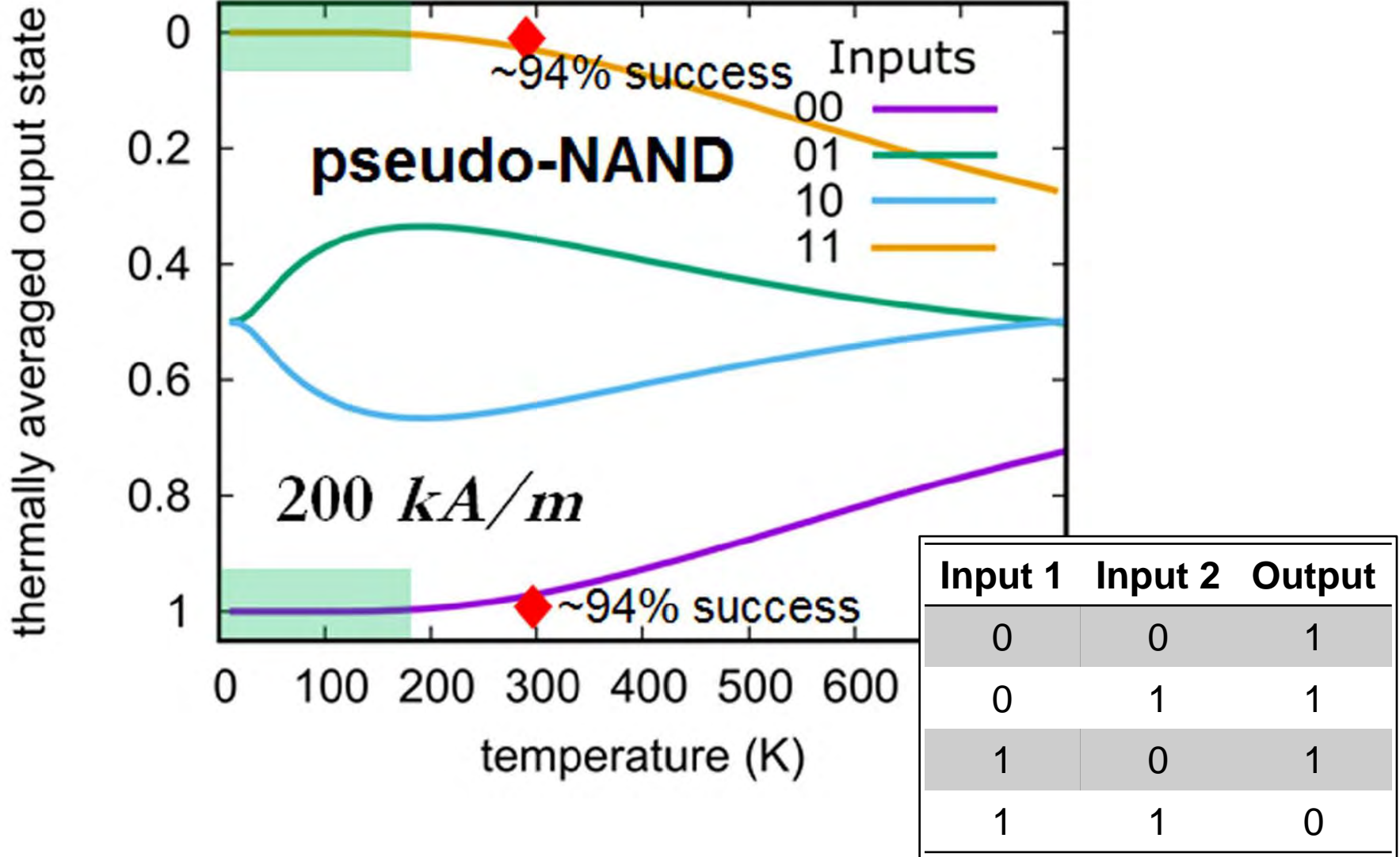
Island size:
120x70 nm

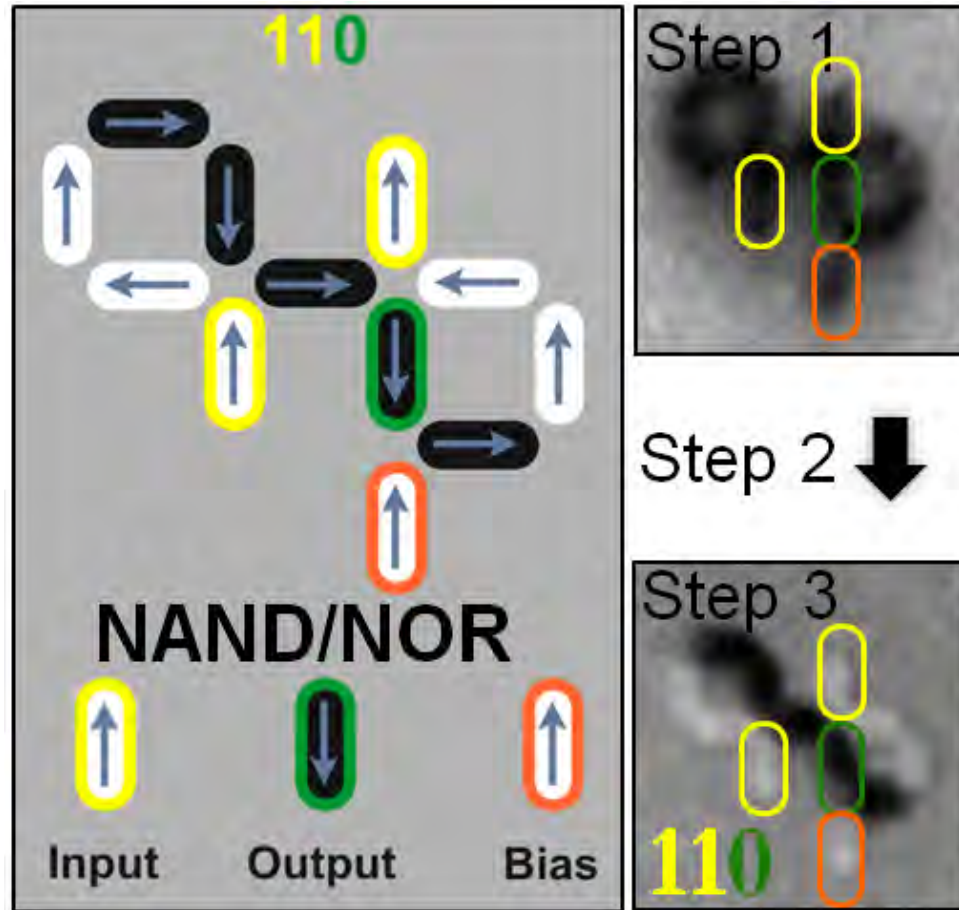


19 Rings





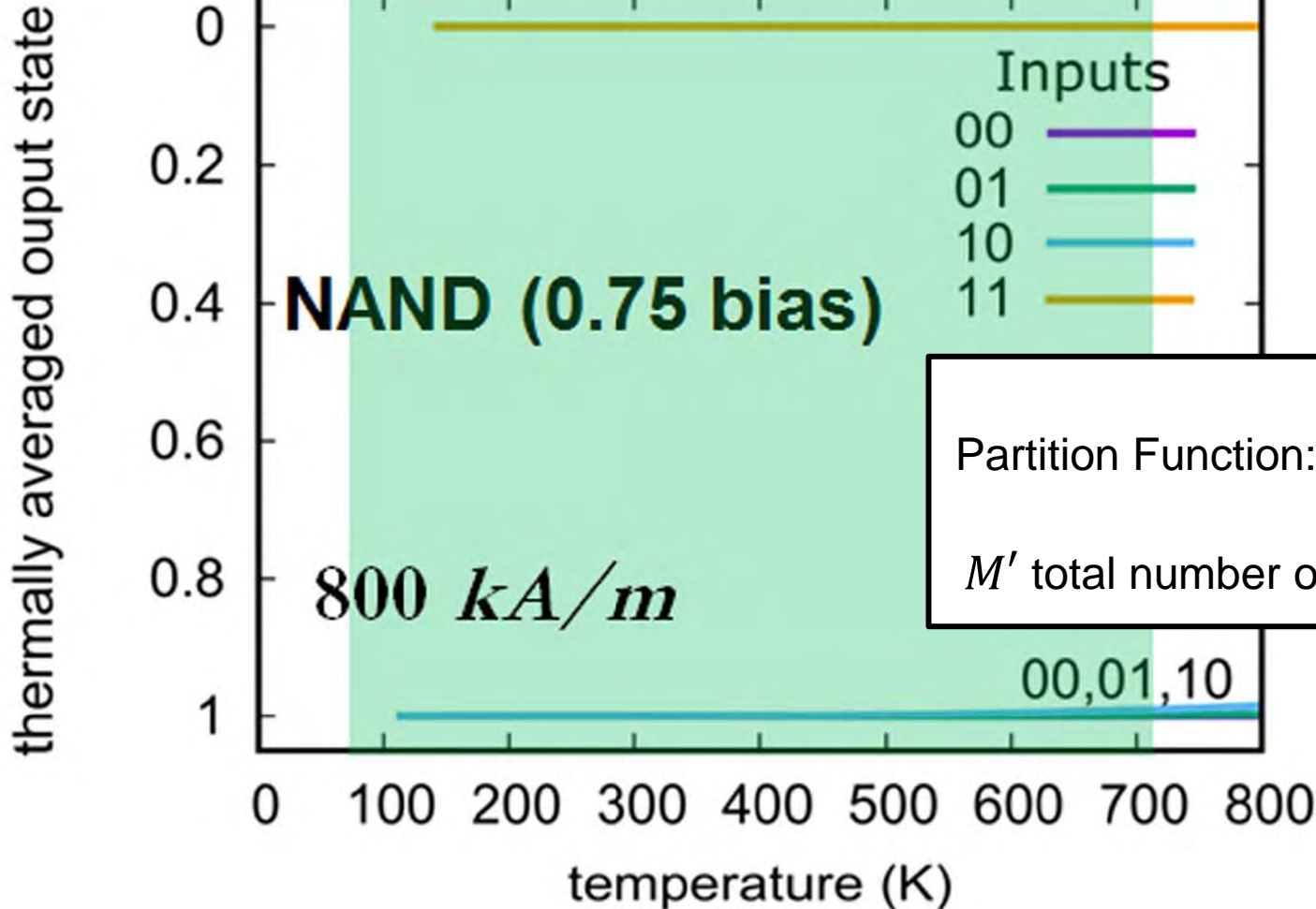




$$M_s \text{ (gate)} = 800 \text{ kA m}^{-1}$$

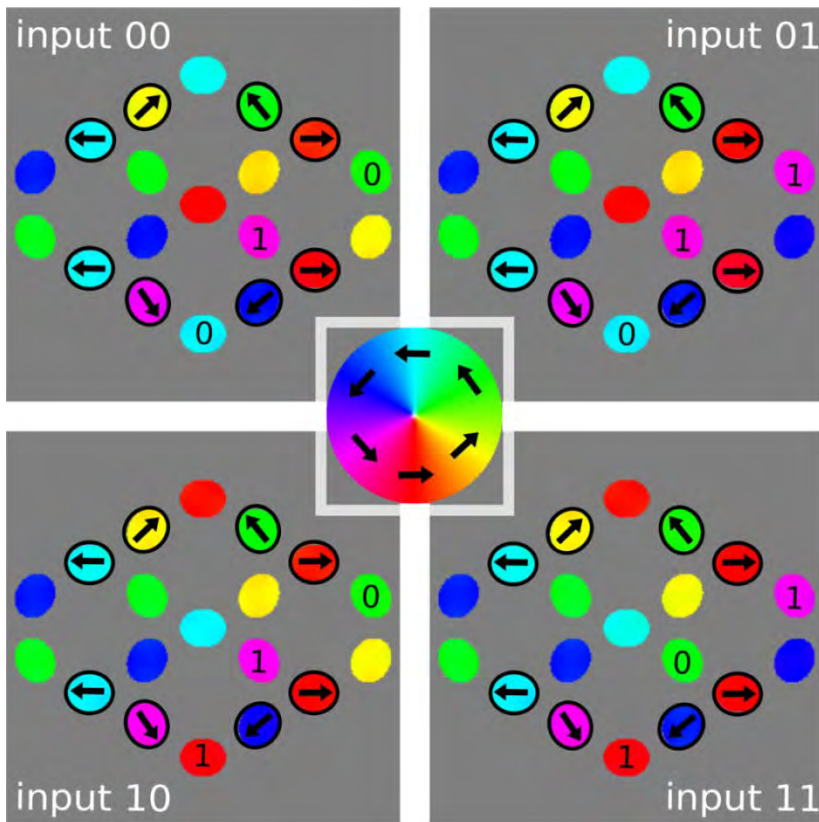
$$M_s \text{ (bias)} = 600 \text{ kA m}^{-1}$$

$$b = \frac{M_s \text{ (bias)}}{M_s \text{ (gate)}}$$



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

M' total number of gate operations



Balanced Magnetic Logic Gates in a Kagome Spin Ice

P Gypens, J Leliaert and B. Van Waeyenberge

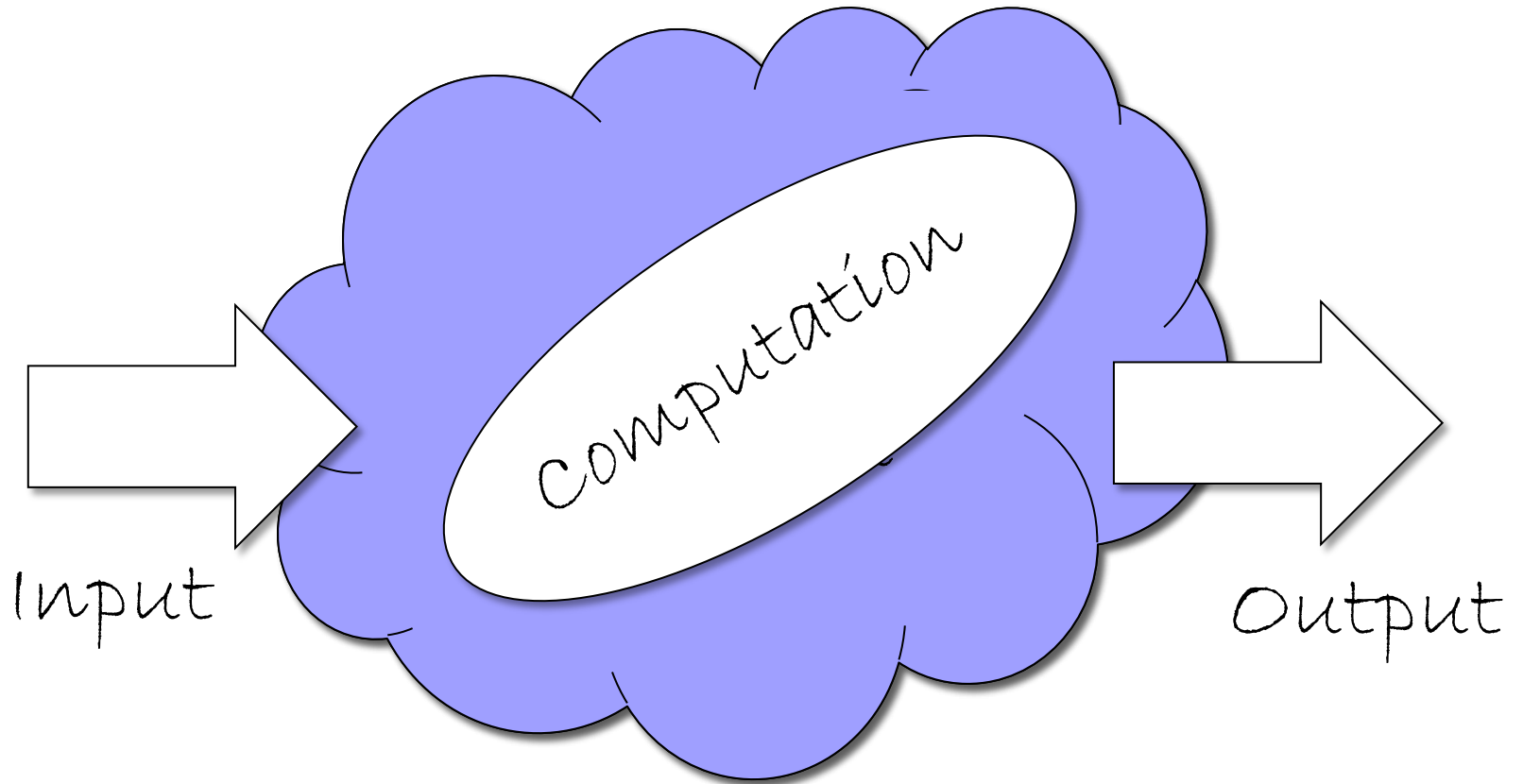
Phys Rev Applied (2018)

Computation in artificial spin ice

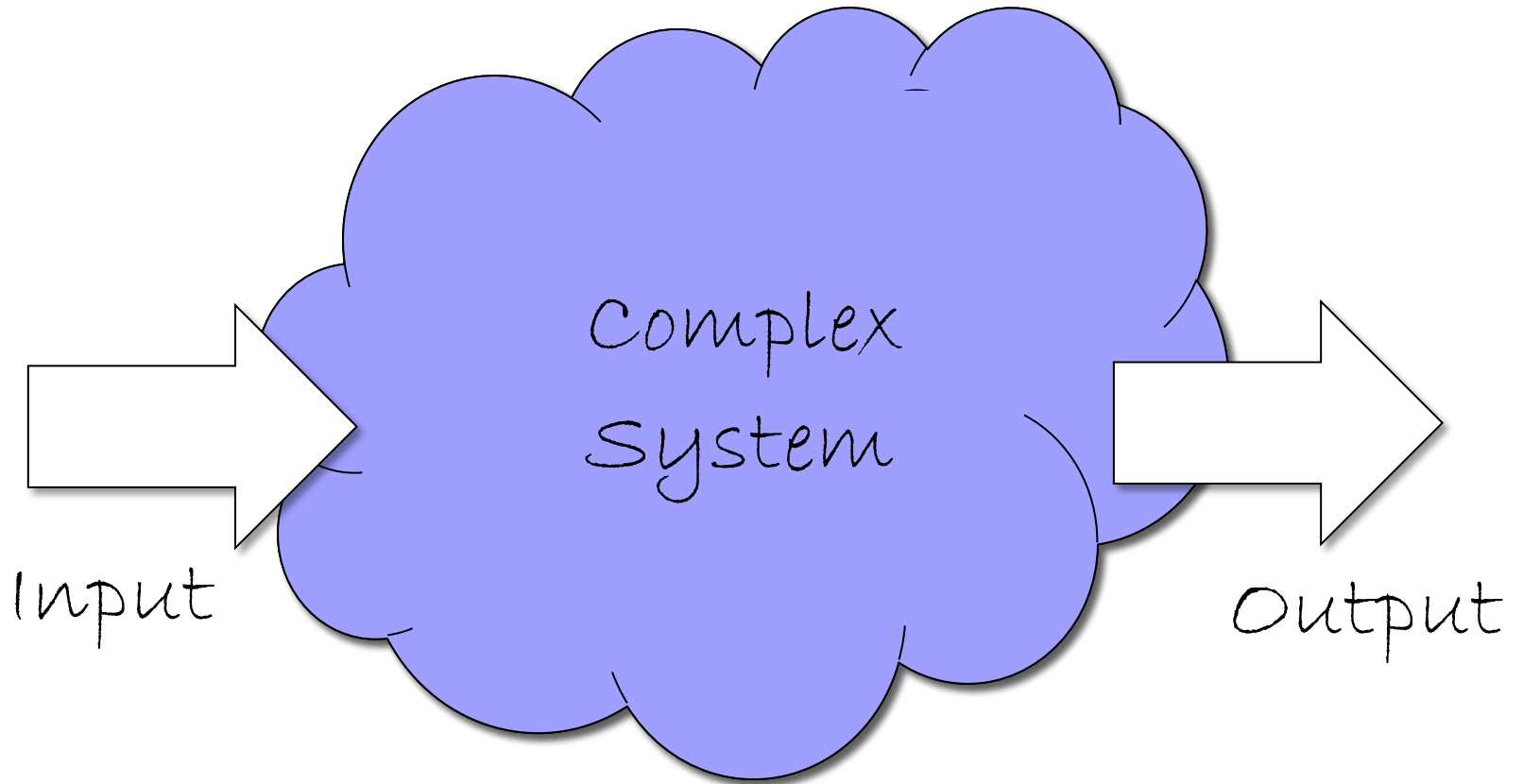
JH Jensen , E Folven & G Tufte

DOI: [10.1162/isal_a_00011](https://doi.org/10.1162/isal_a_00011)

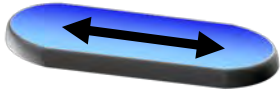
Ground states corresponding to all possible input states have the same energy



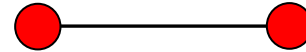
Topic 2
Towards Bioinspired Computation



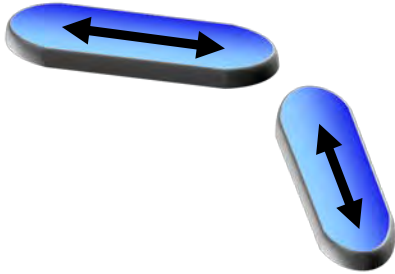
Topic 2
Towards Bioinspired Computation



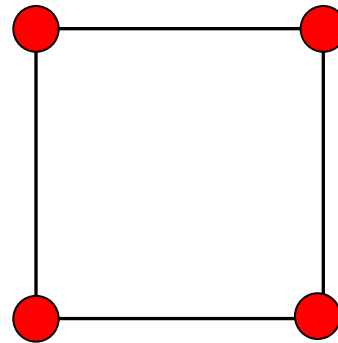
$2^1 = 2$ possible states



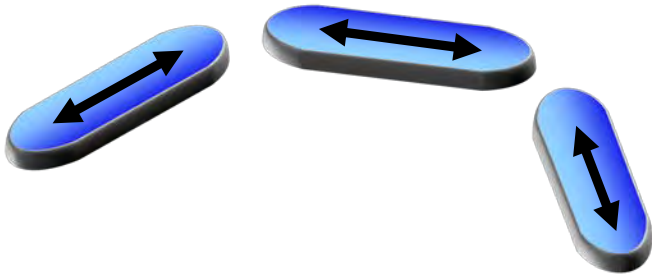
Network Graph



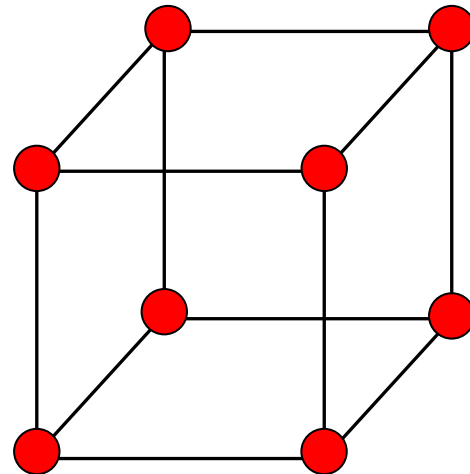
$2^2 = 4$ possible states

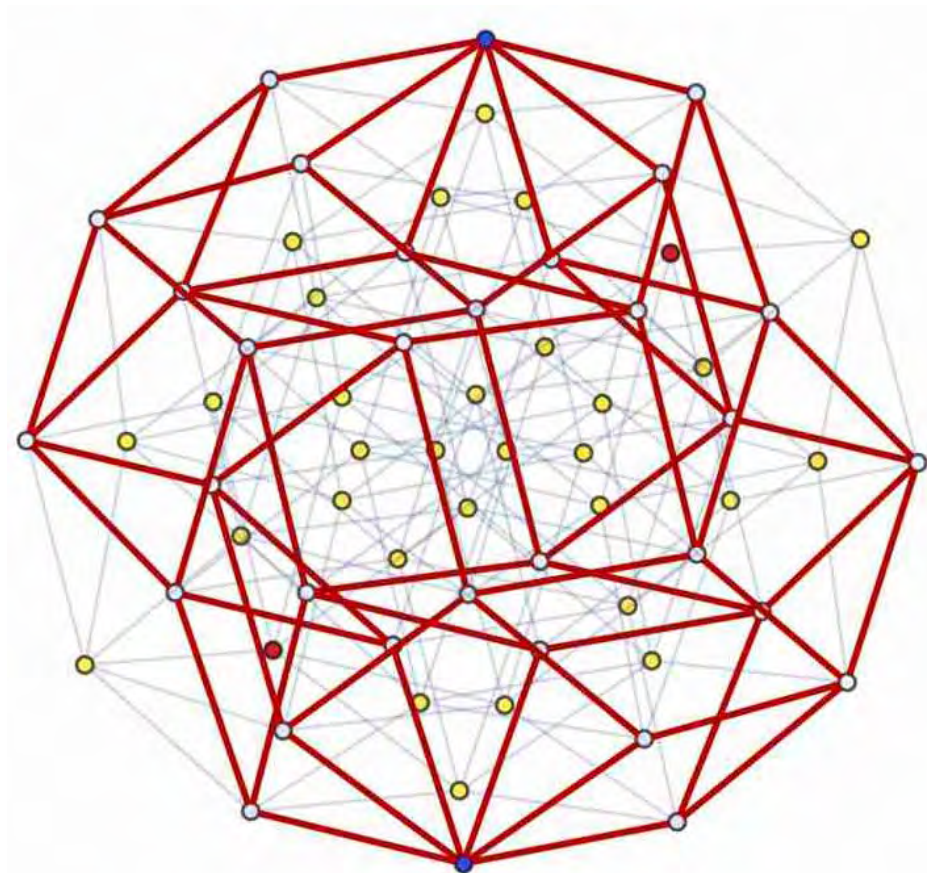
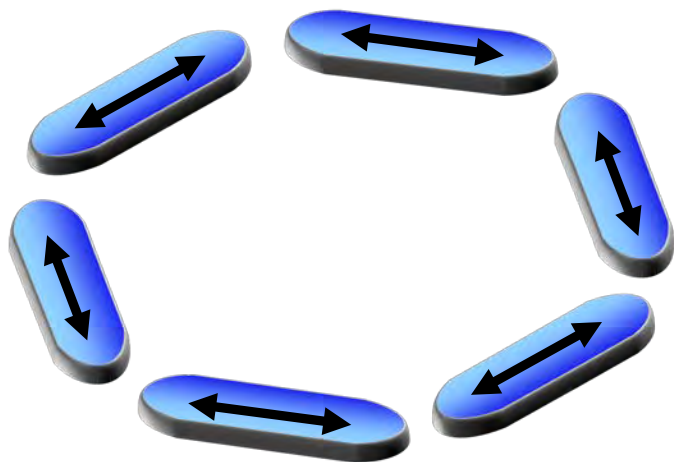


Network Graph

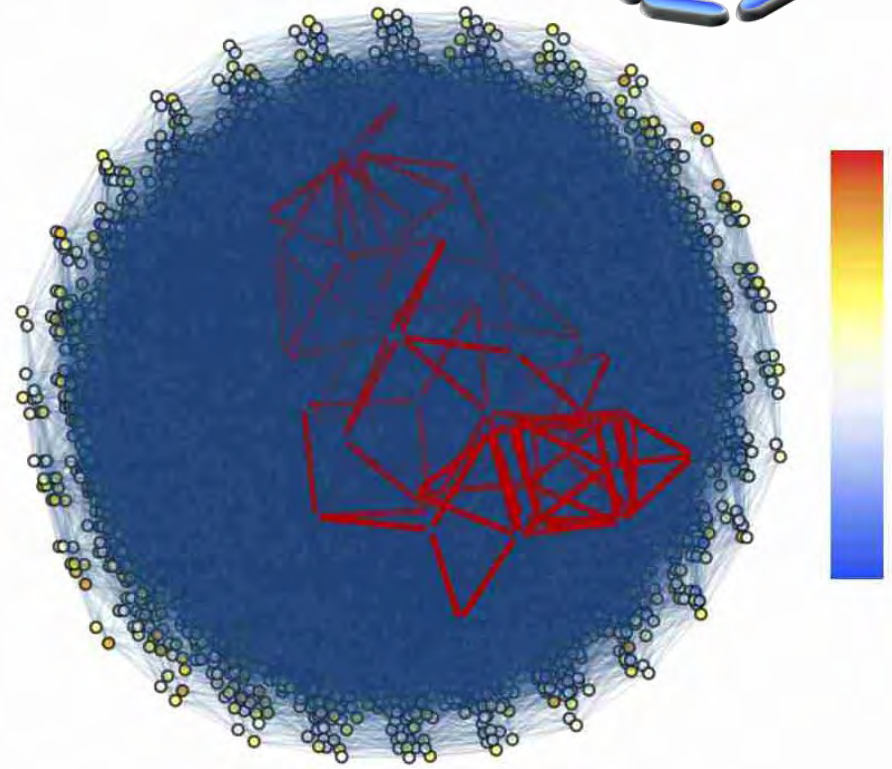
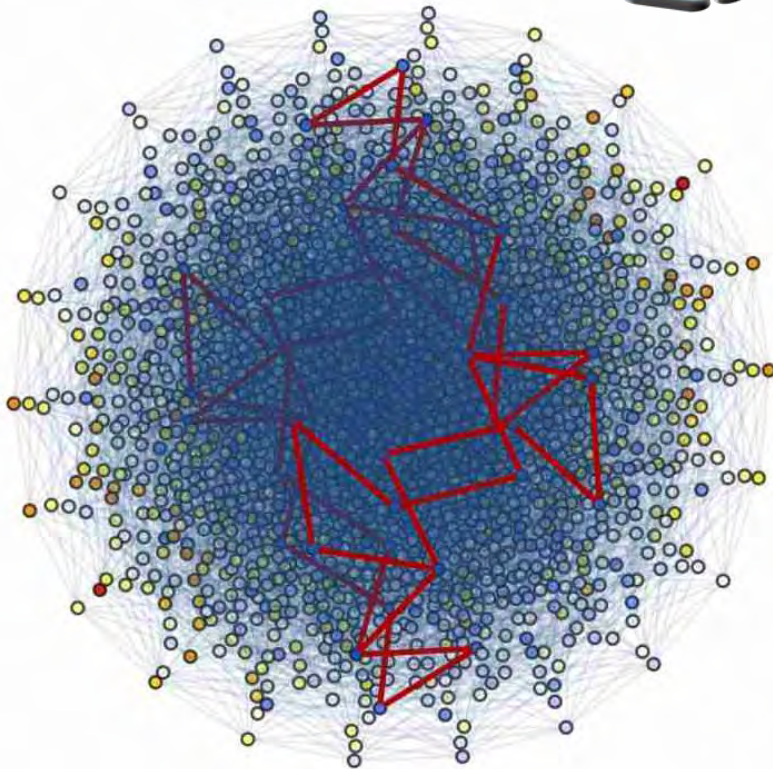
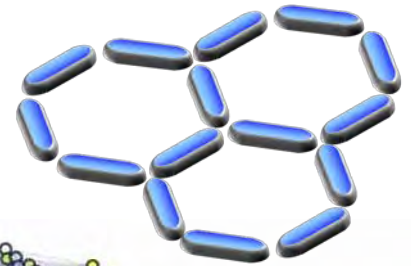


$2^3 = 8$ possible states



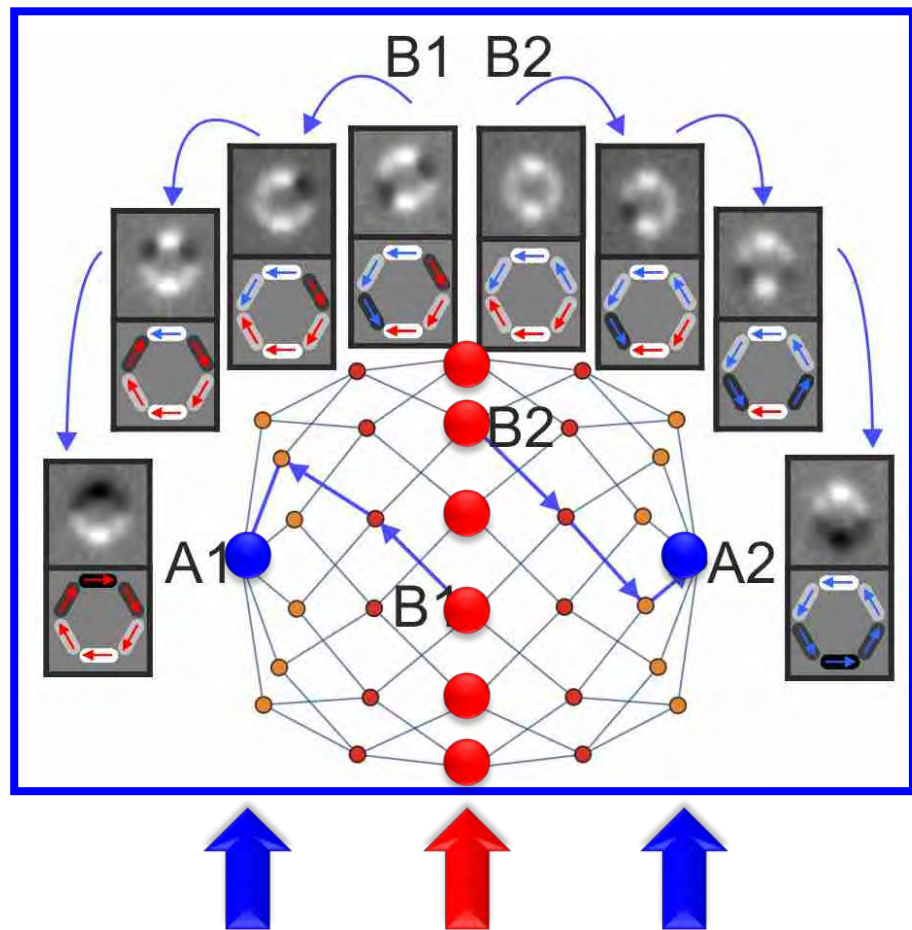


$2^6 = 64$ possible states \rightarrow 6D hyper-cube

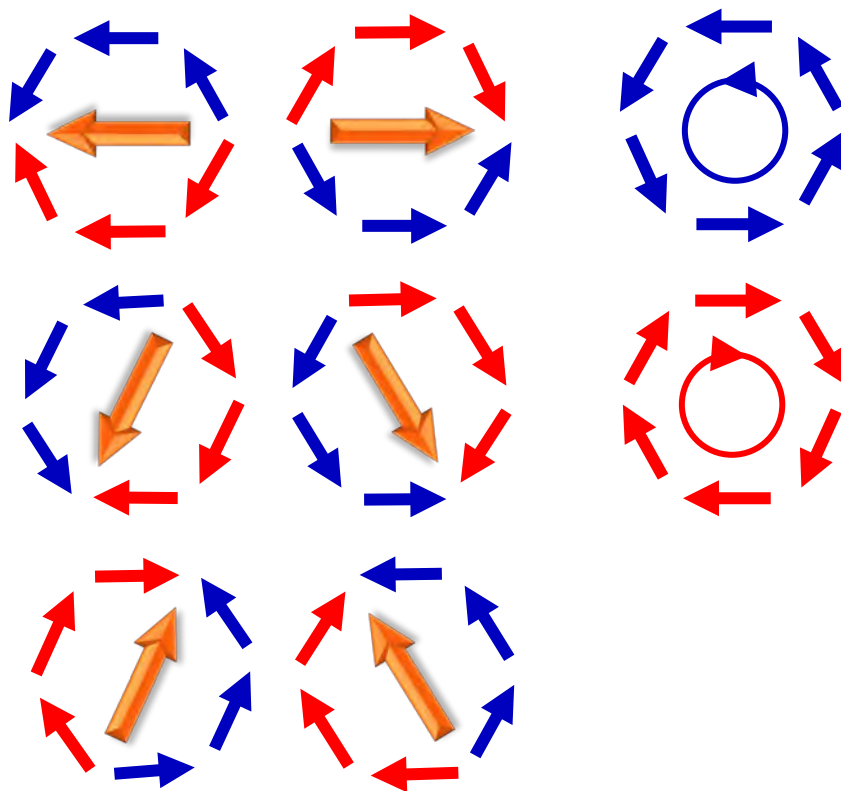


$2^{11} = 2048$ possible states

$2^{15} = 32\,768$ possible states



Single Ring

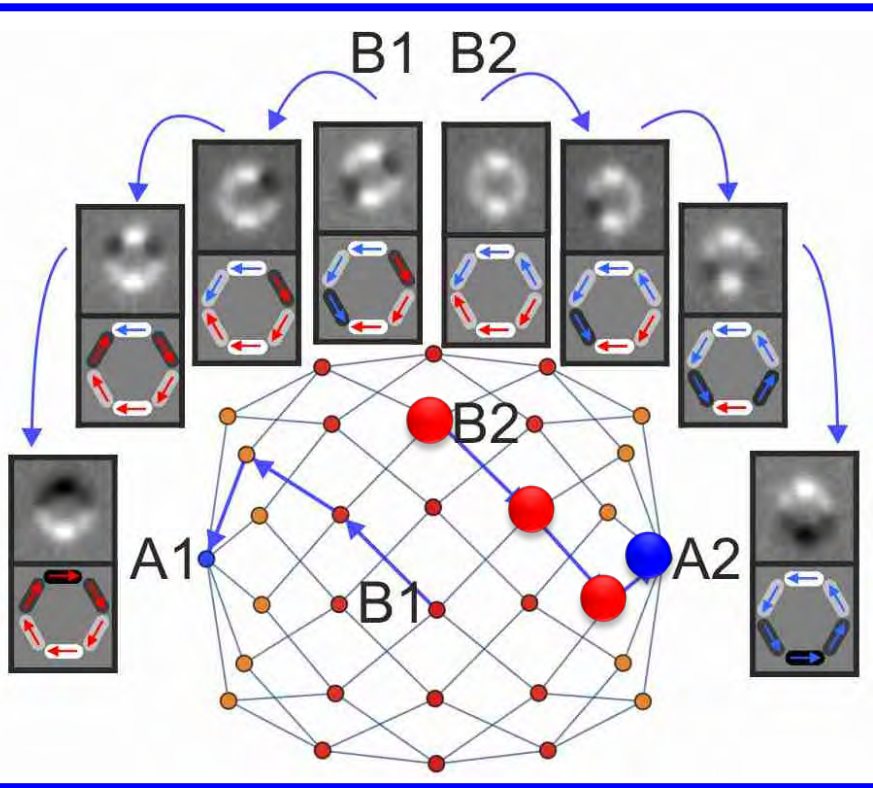
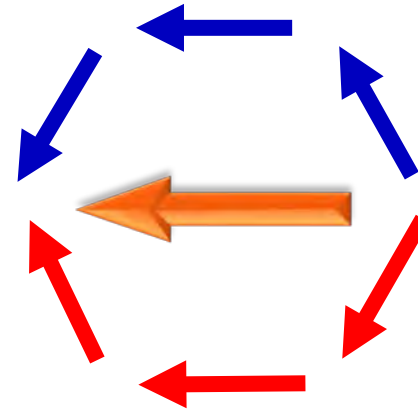


Low-dipolar-energy sub-network → spring electrical embedding

❖ *strong coupling*

❖ *emergence of frustration with system size*

Single Ring

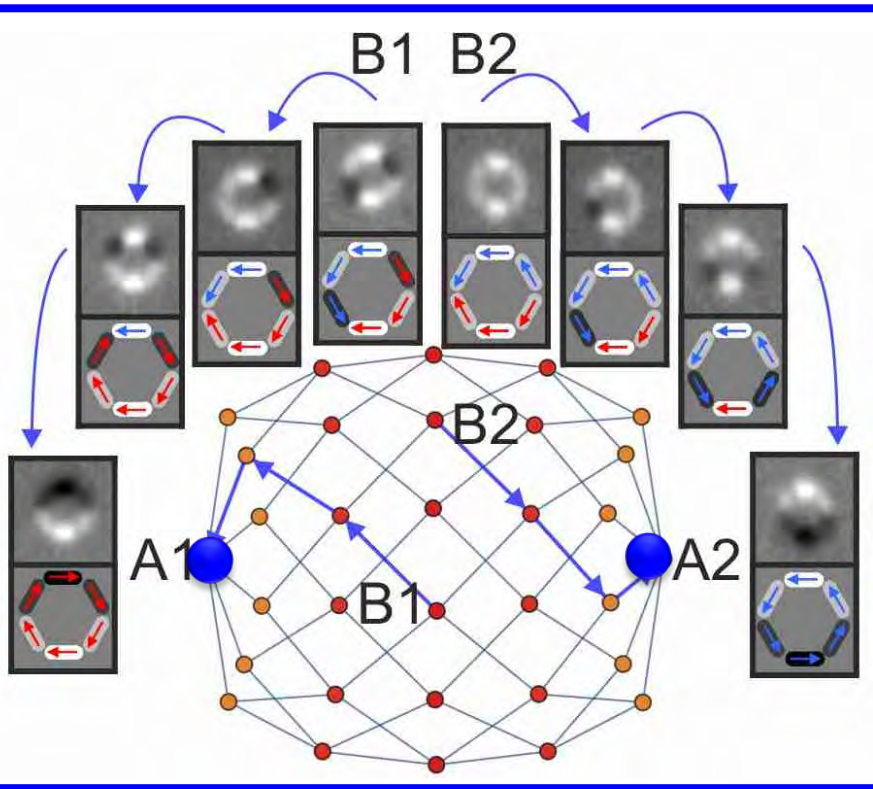
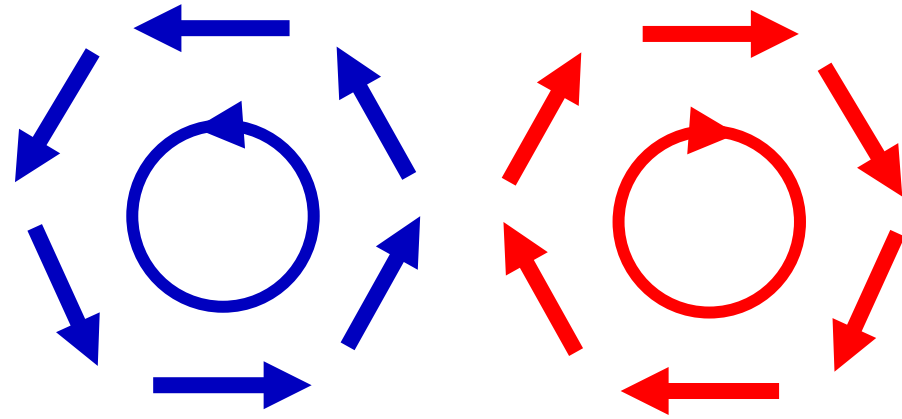


Low-dipolar-energy sub-network → spring electrical embedding

❖ *strong coupling*

❖ *emergence of frustration with system size*

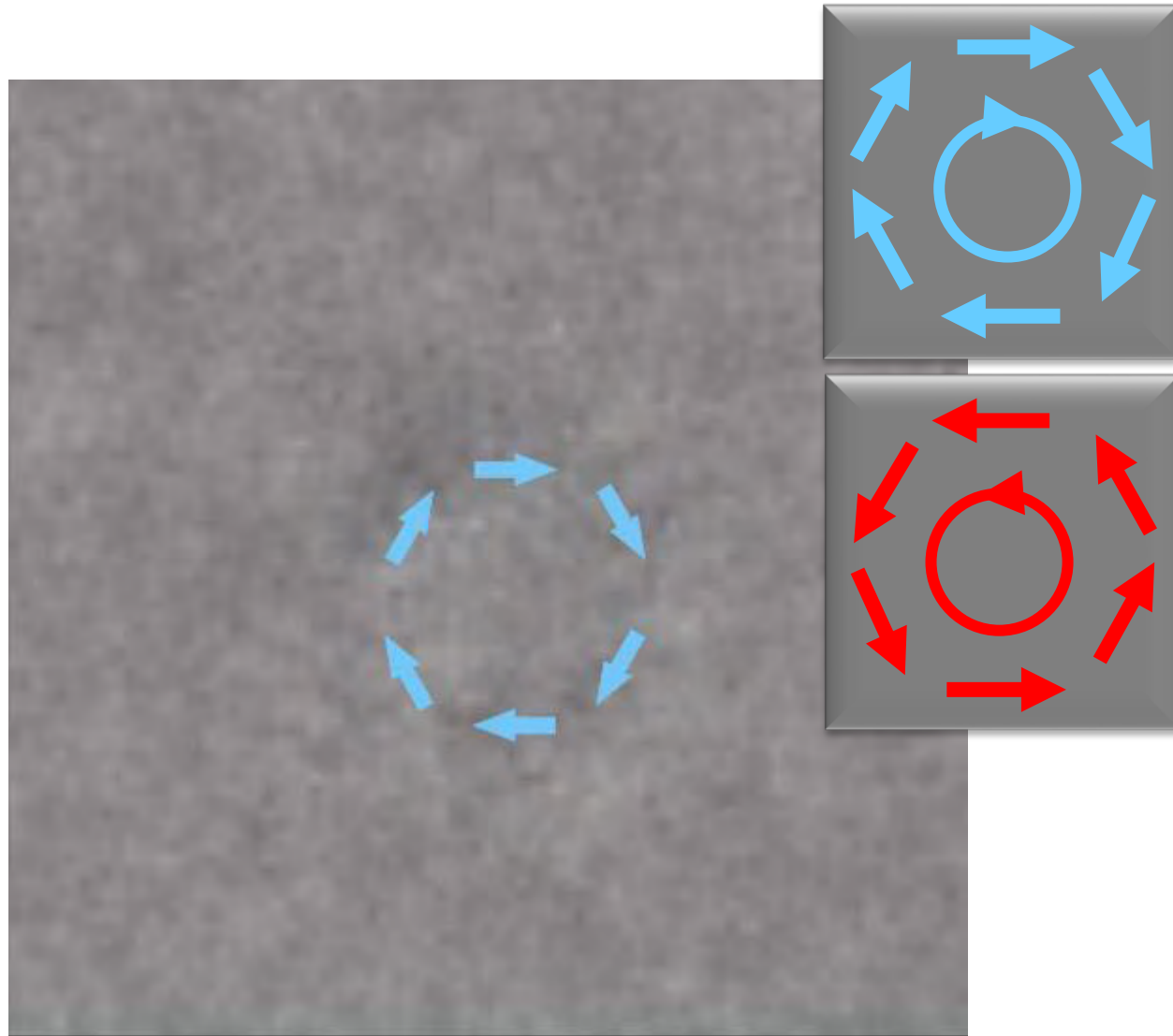
Single Ring



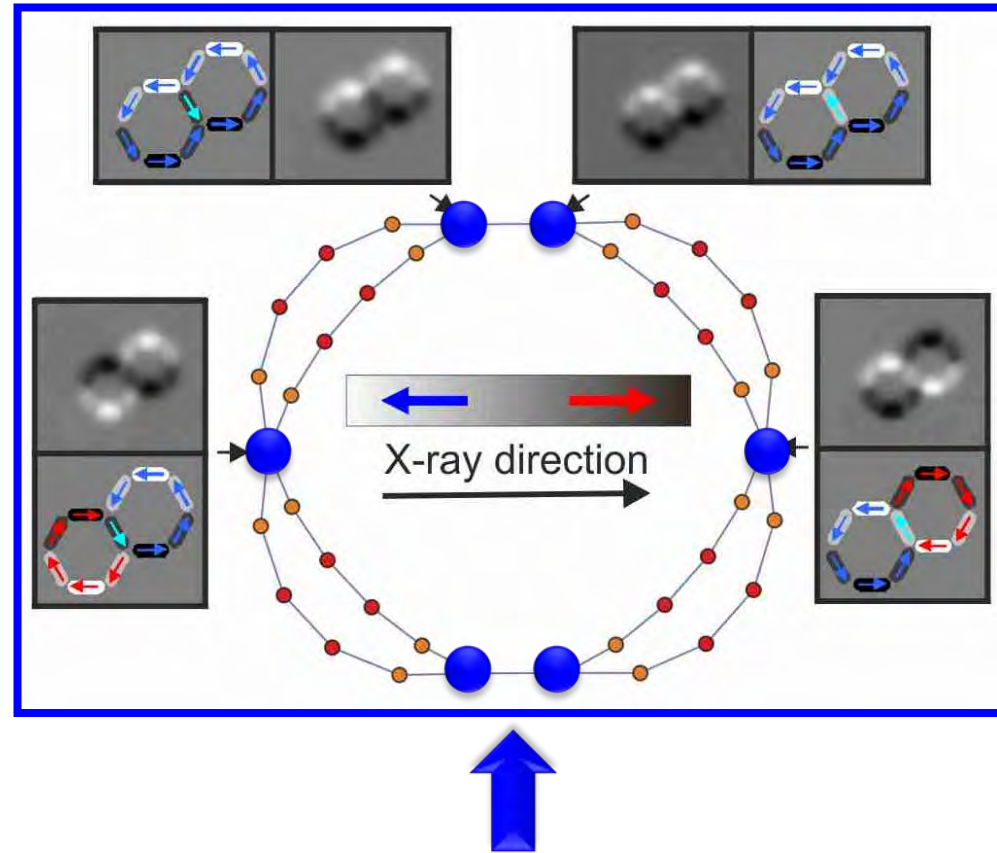
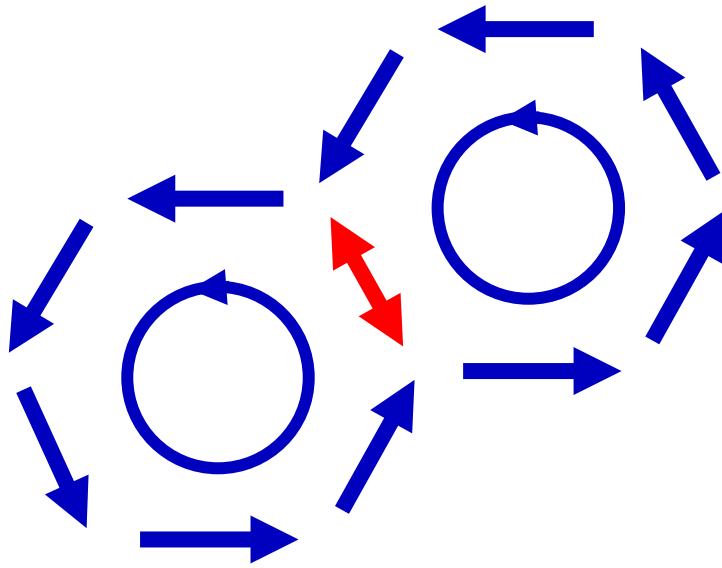
Low-dipolar-energy sub-network → spring electrical embedding

❖ *strong coupling*

❖ *emergence of frustration with system size*



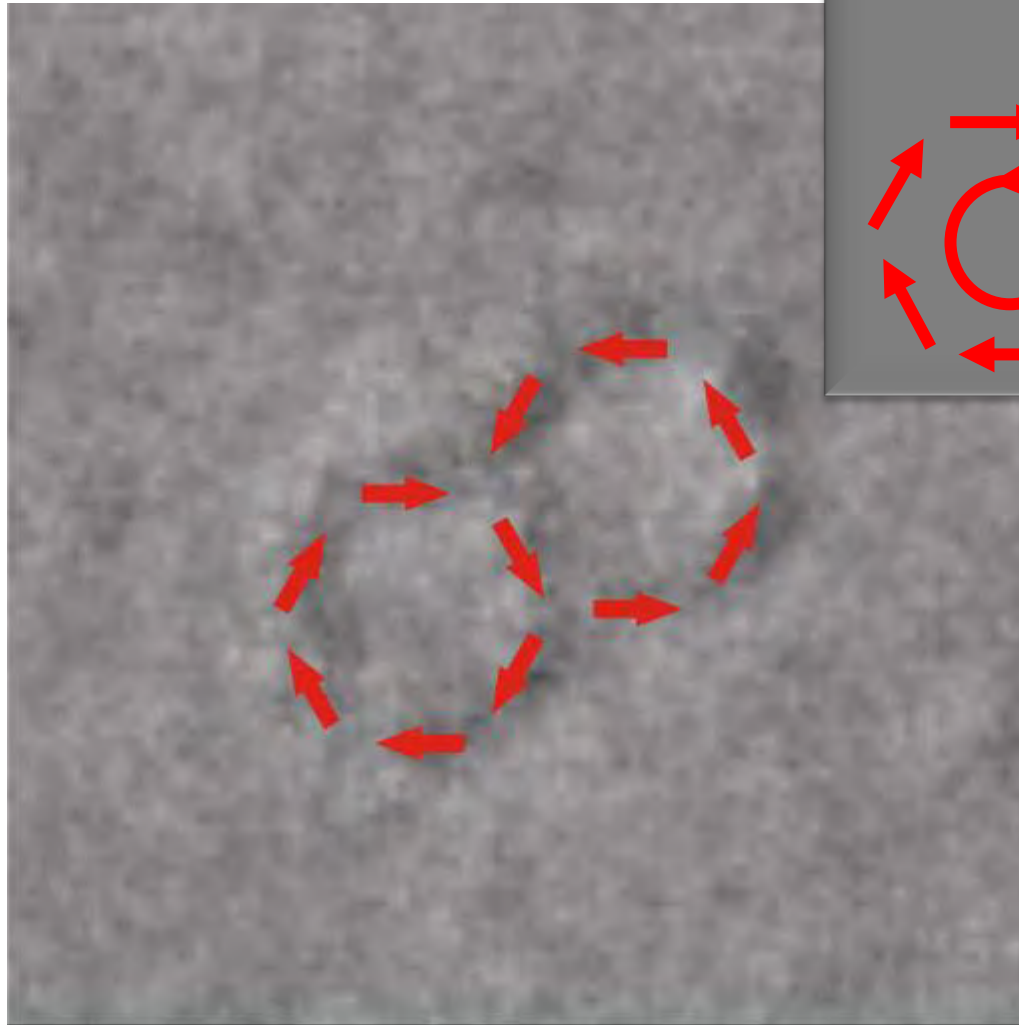
Double Ring

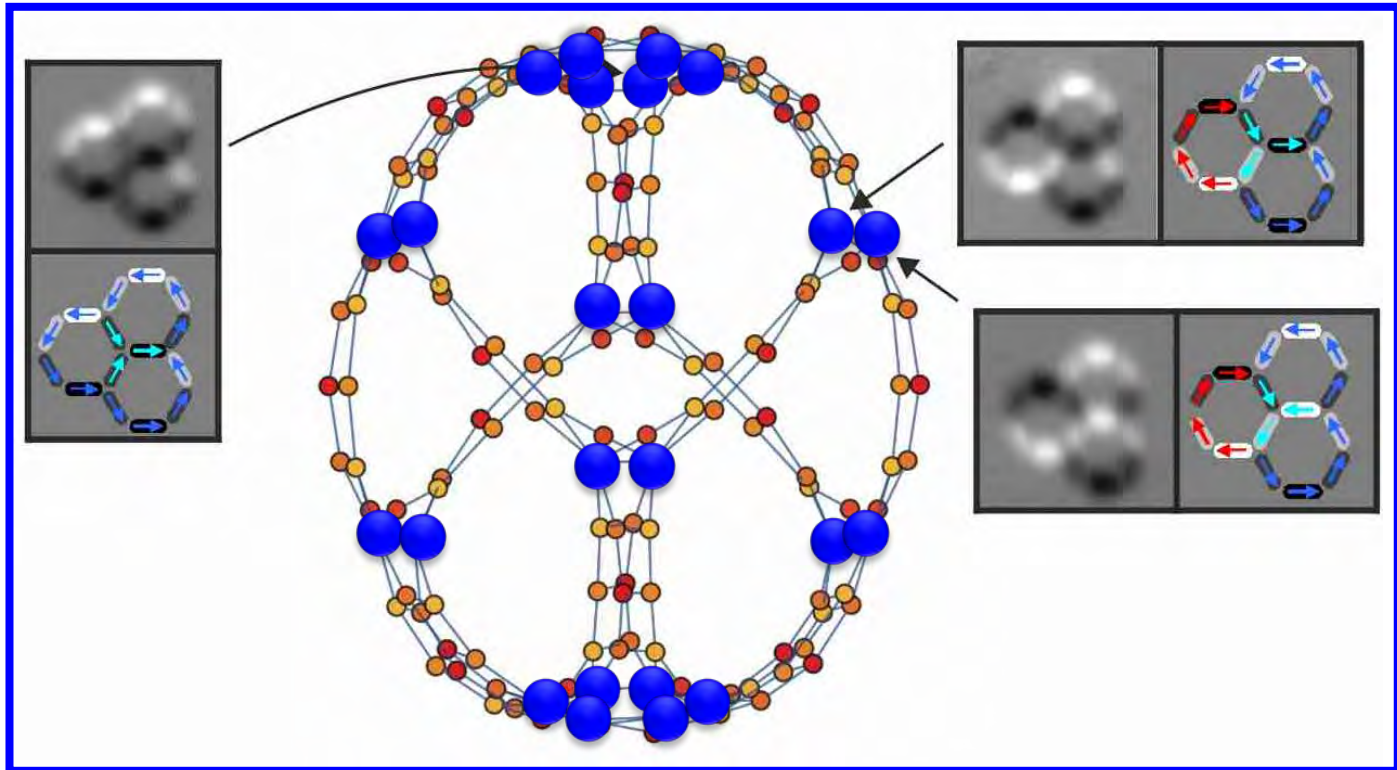


Low-dipolar-energy sub-network → spring electrical embedding

❖ *strong coupling*

❖ *emergence of frustration with system size*

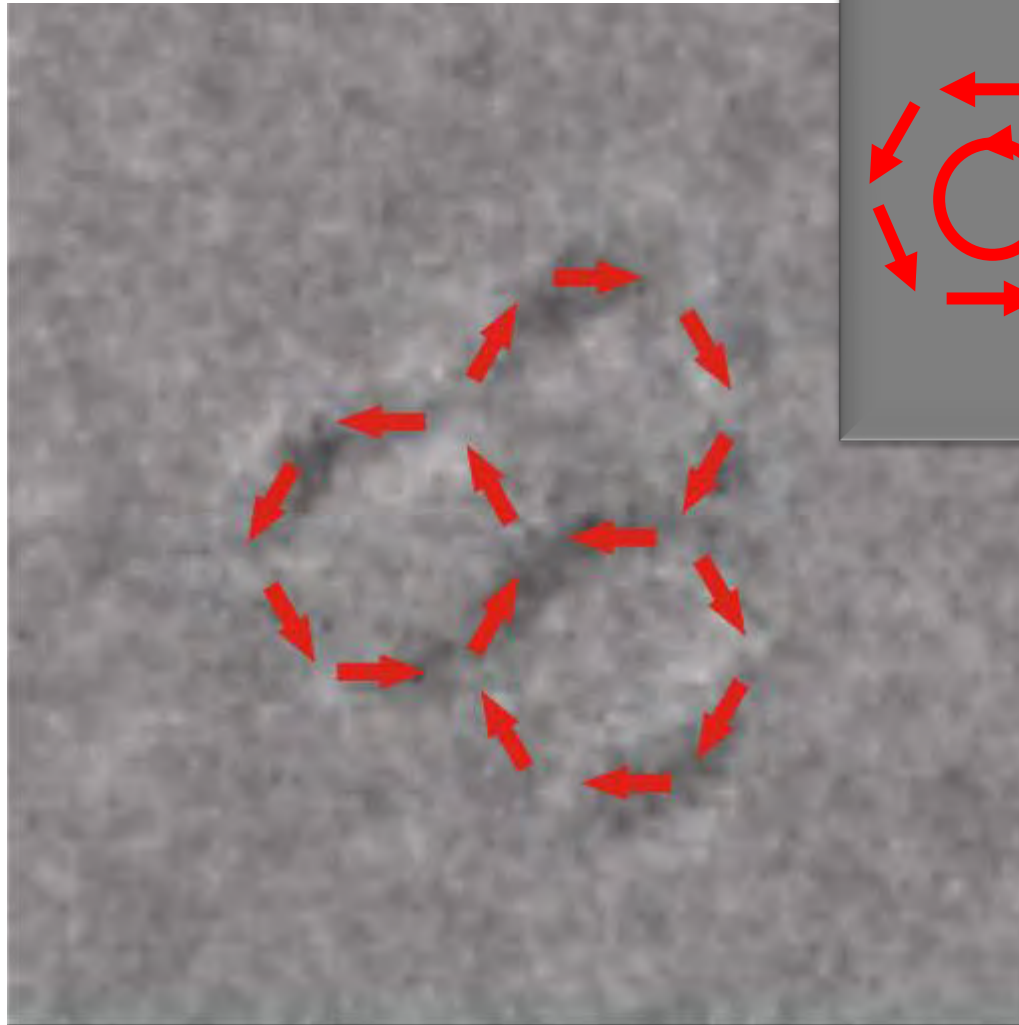




Low-dipolar-energy sub-network → spring electrical embedding

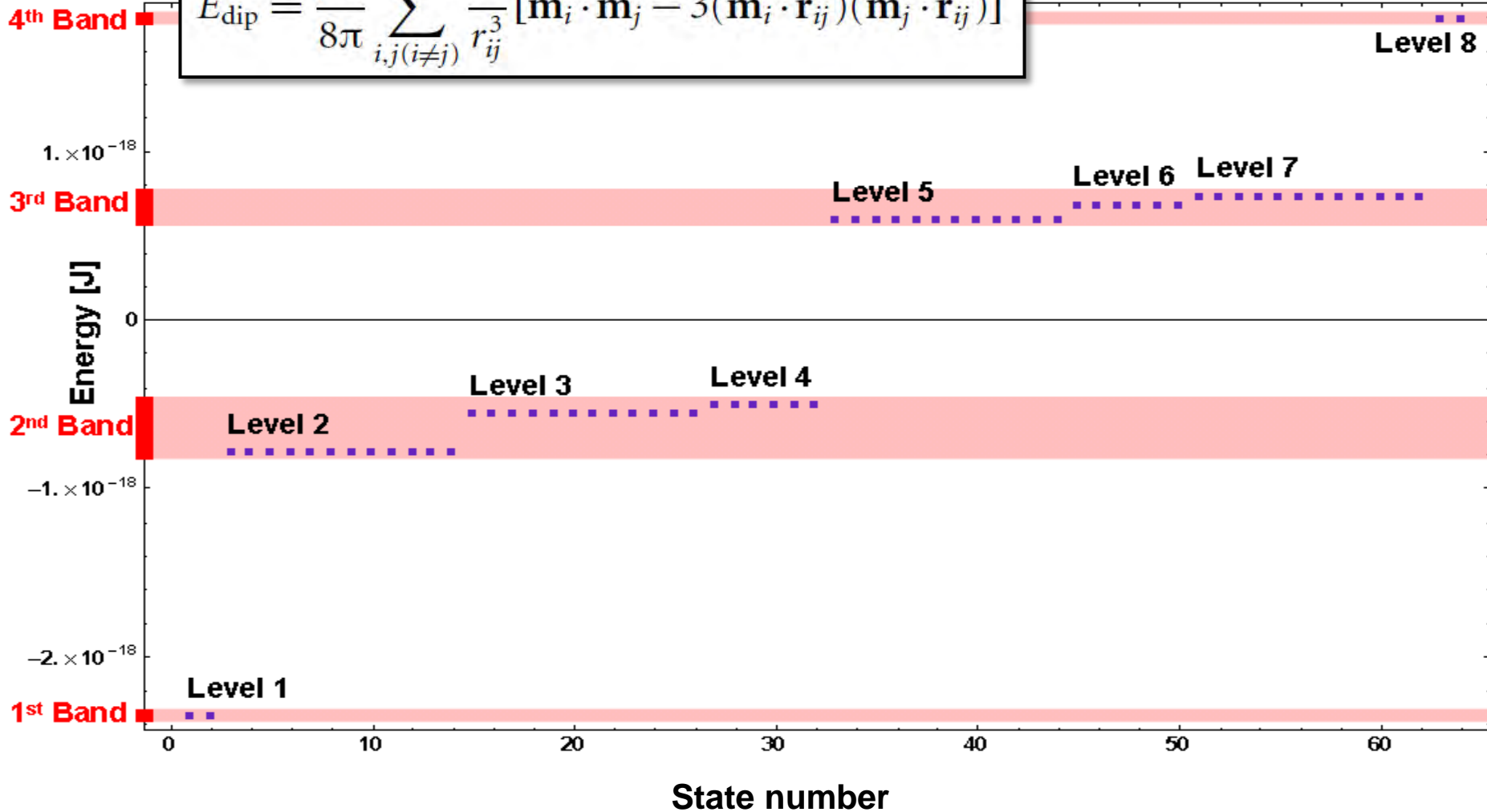
❖ *strong coupling*

❖ *emergence of frustration with system size*



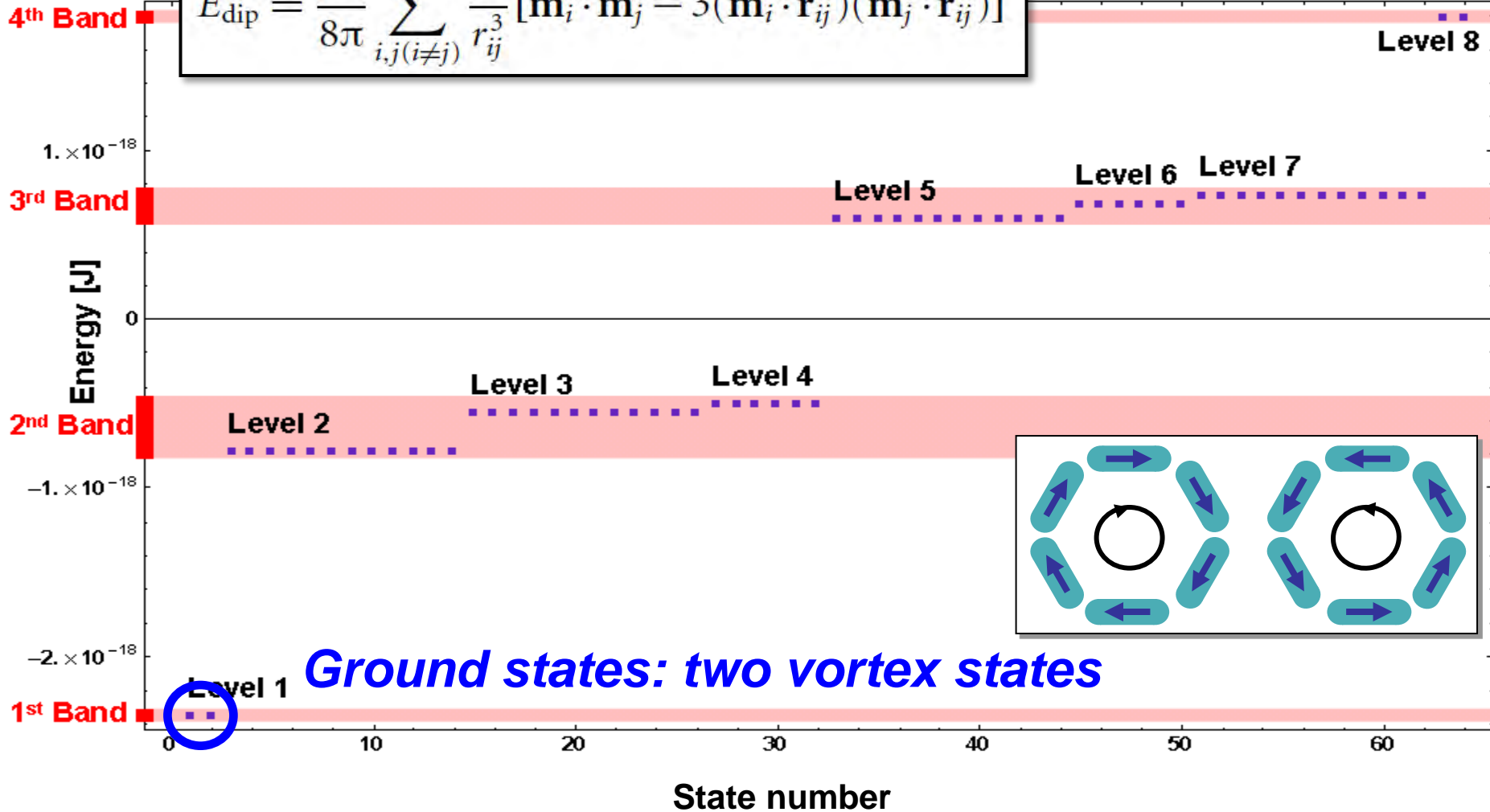
$2^6 = 64$ possible configurations

$$E_{\text{dip}} = \frac{\mu_0}{8\pi} \sum_{i,j(i \neq j)} \frac{1}{r_{ij}^3} [\mathbf{m}_i \cdot \mathbf{m}_j - 3(\mathbf{m}_i \cdot \hat{\mathbf{r}}_{ij})(\mathbf{m}_j \cdot \hat{\mathbf{r}}_{ij})]$$

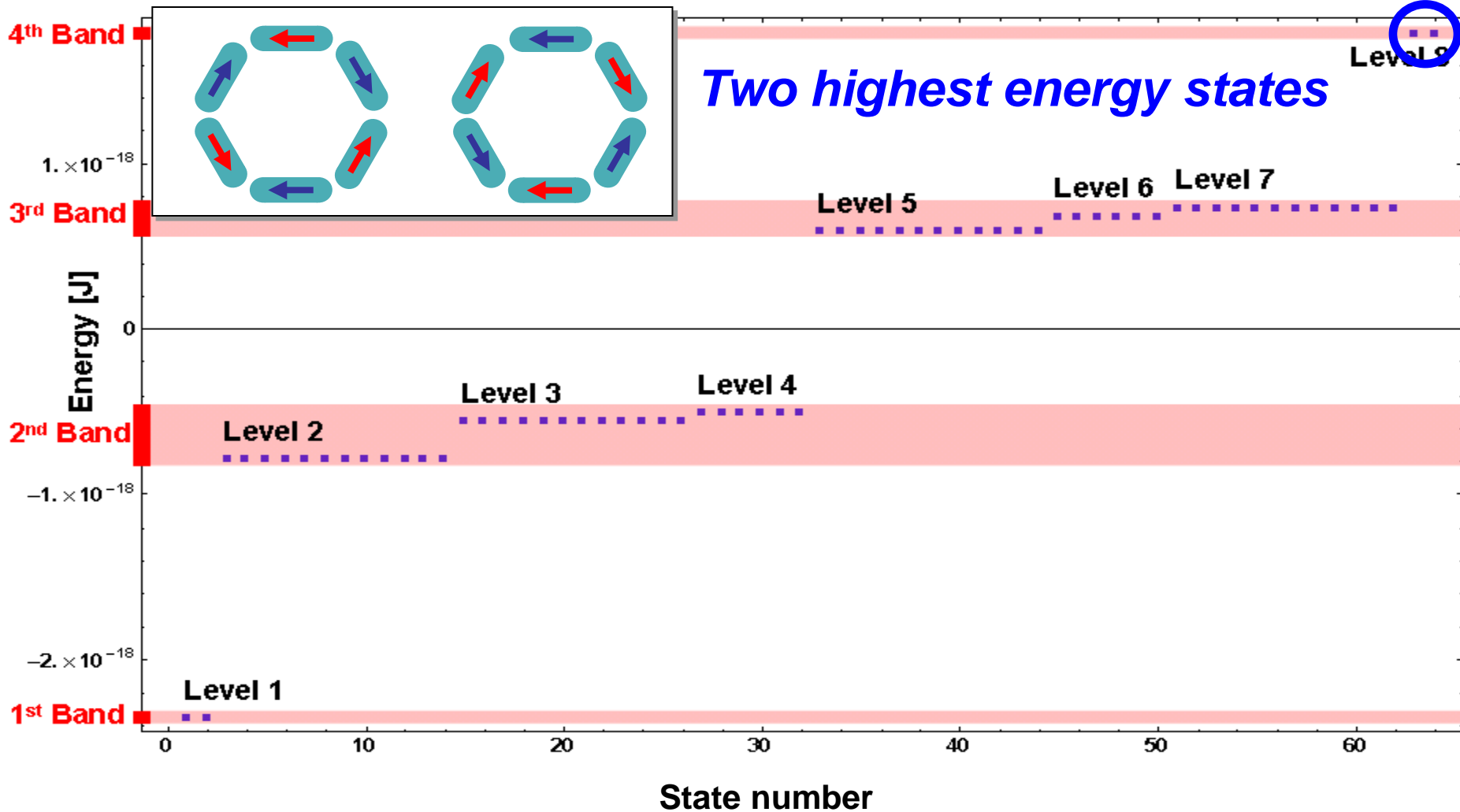


$2^6 = 64$ possible configurations

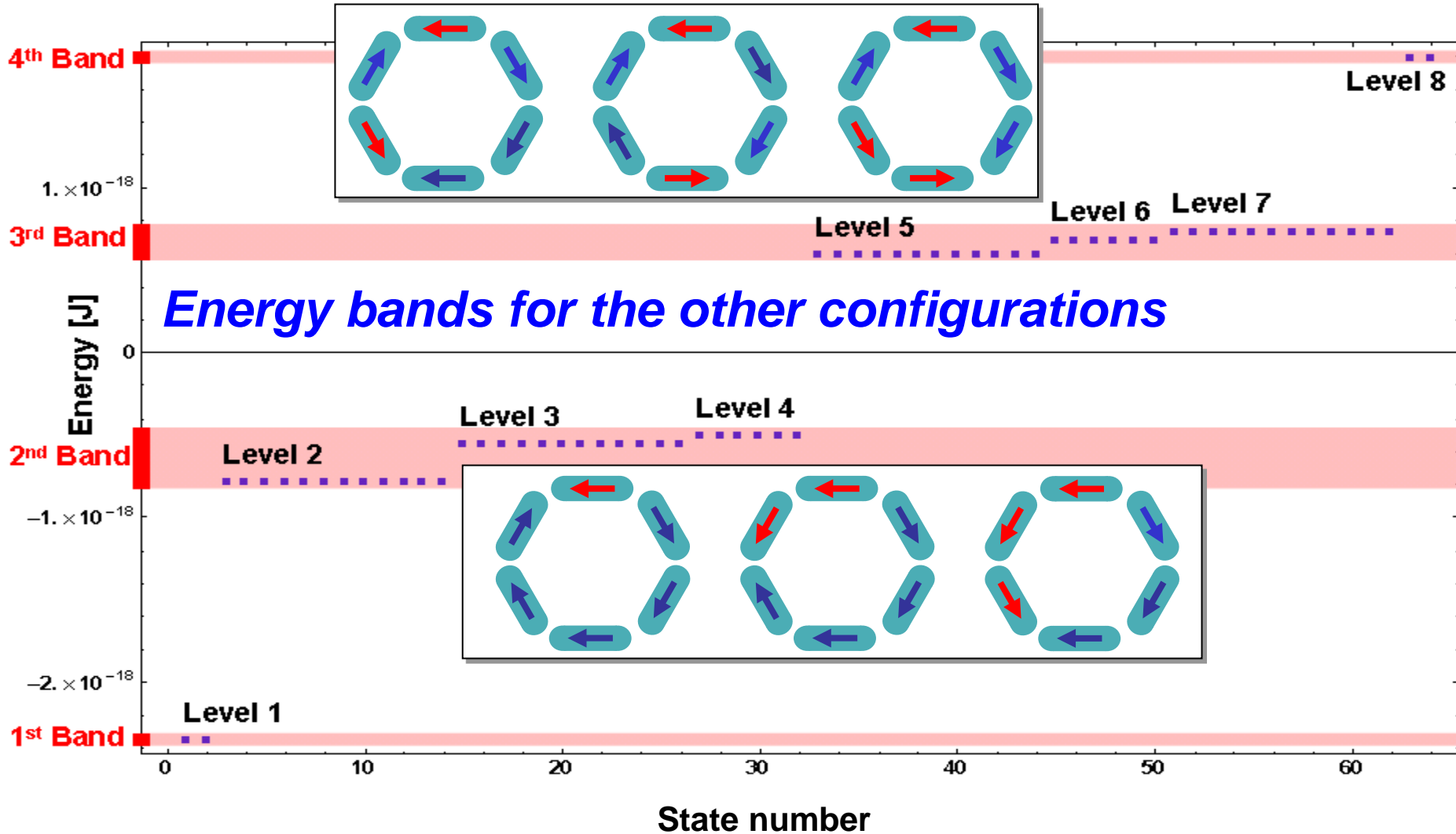
$$E_{\text{dip}} = \frac{\mu_0}{8\pi} \sum_{i,j(i \neq j)} \frac{1}{r_{ij}^3} [\mathbf{m}_i \cdot \mathbf{m}_j - 3(\mathbf{m}_i \cdot \hat{\mathbf{r}}_{ij})(\mathbf{m}_j \cdot \hat{\mathbf{r}}_{ij})]$$



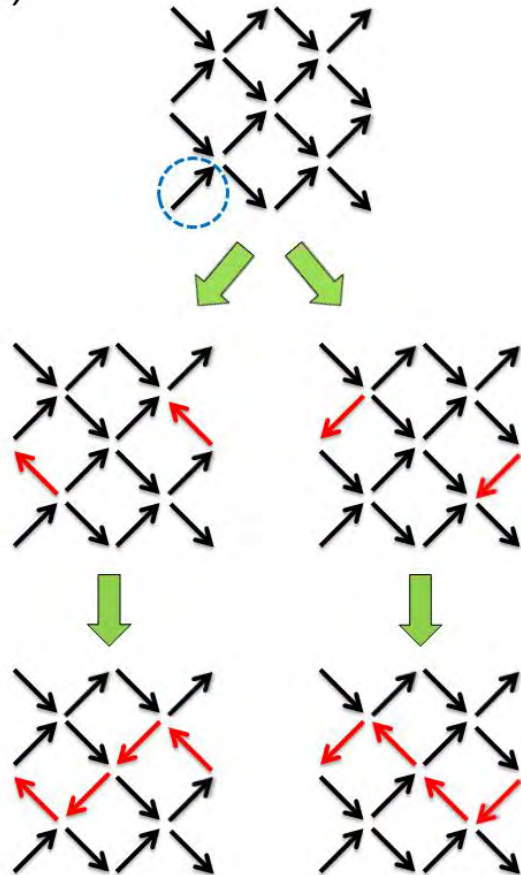
$2^6 = 64$ possible configurations



$2^6 = 64$ possible configurations



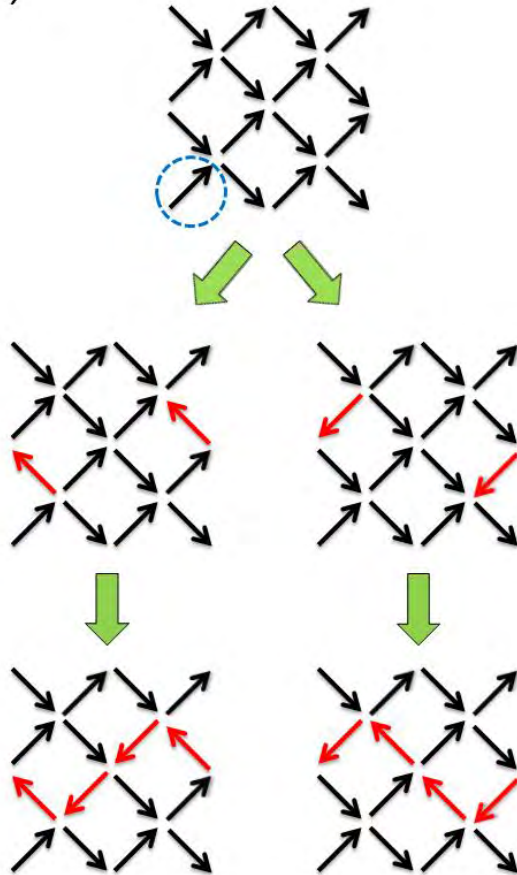
(a)



Field strength ~ Switching Field
→ Large enough to access only the four configurations

Complexity & Control

(a)



(b)

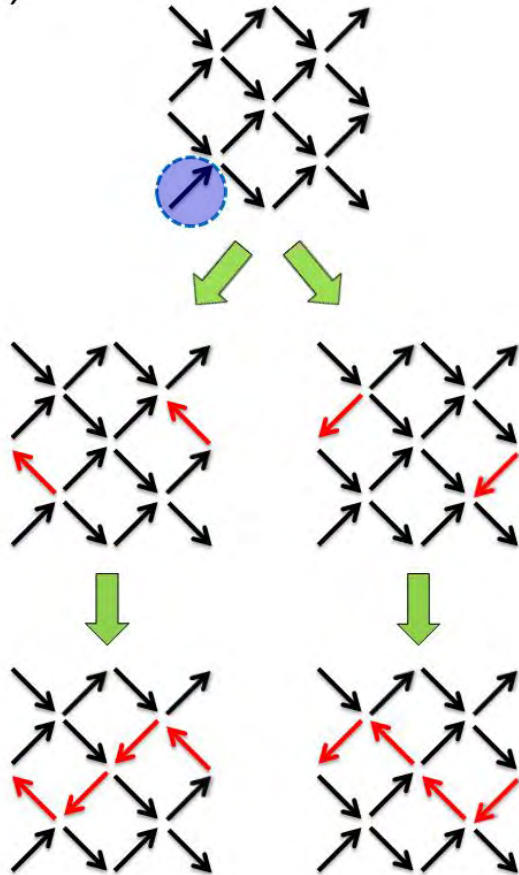


Dot: a configuration of element spins

Line: an orientation of the field with fixed magnitude

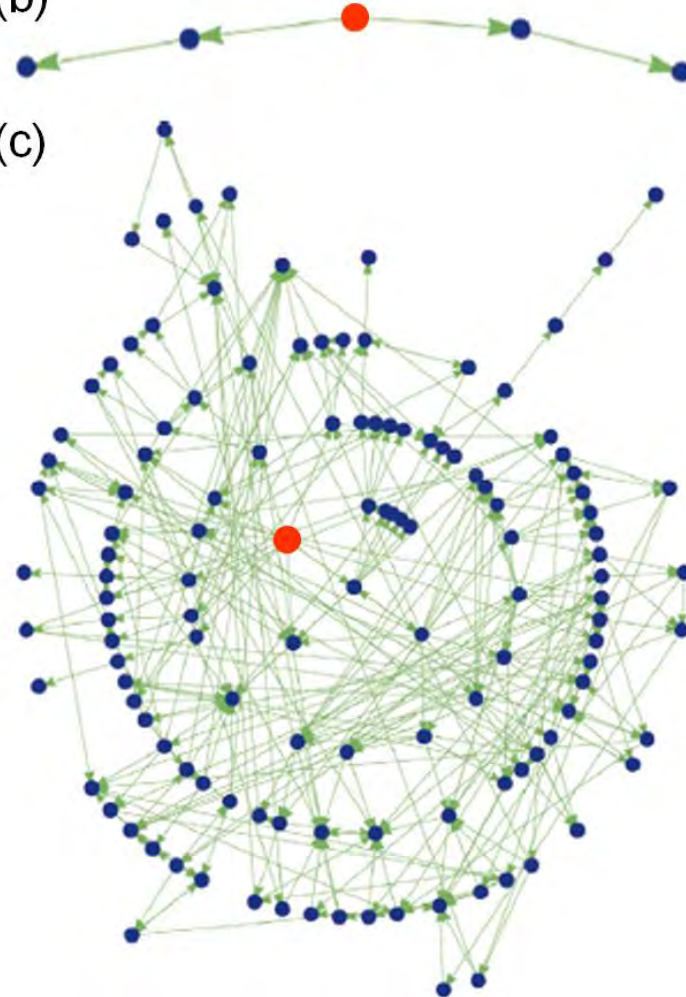
Field strength ~ Switching Field
 → Large enough to access only the four configurations

(a)



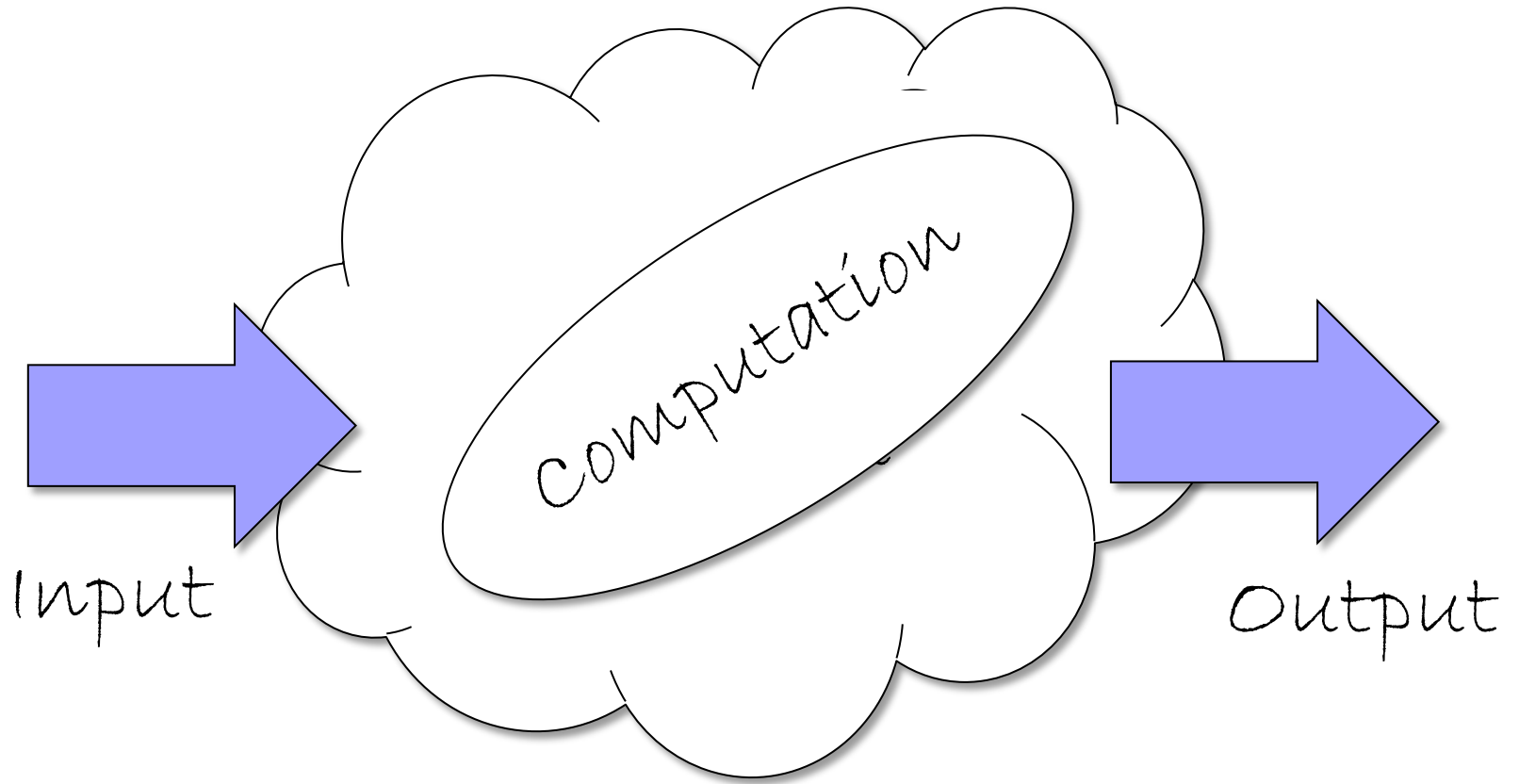
(b)

(c)



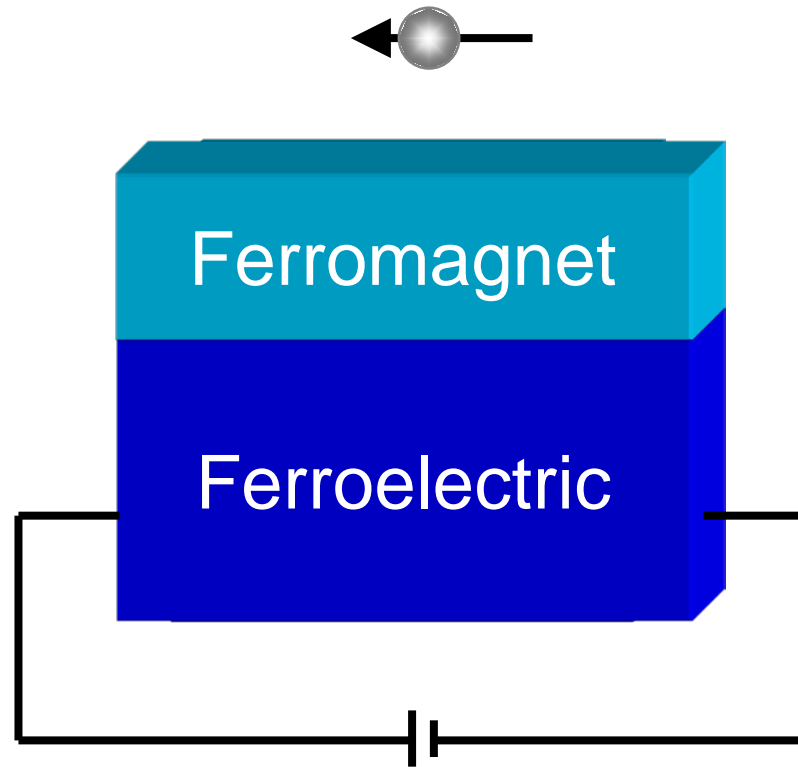
Control Spin

128 configurations can be accessed, depending on the orientation of the control spin and the applied field direction



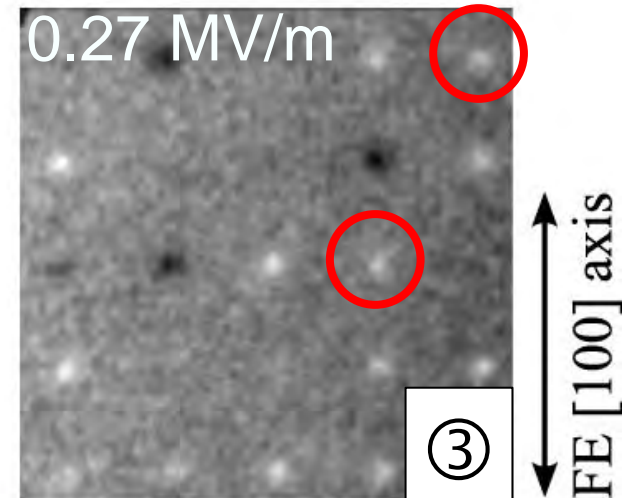
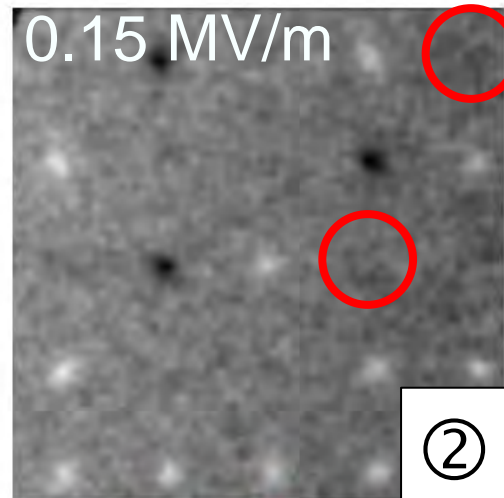
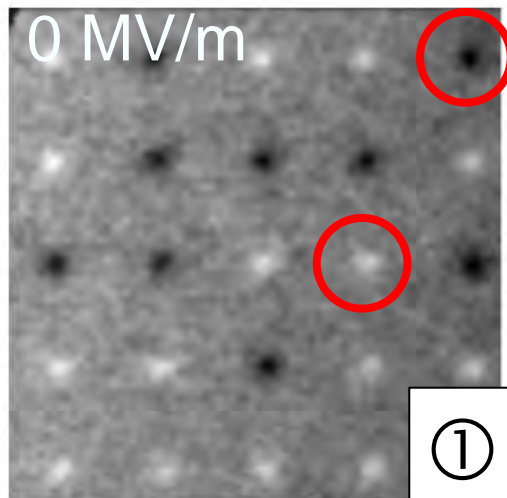
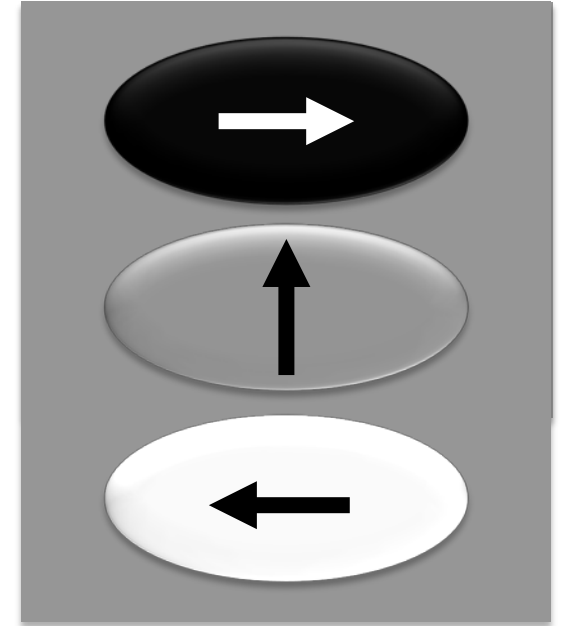
Topic 2
Towards Bioinspired Computation

Multiferroic Composite/Artificial Multiferroic



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

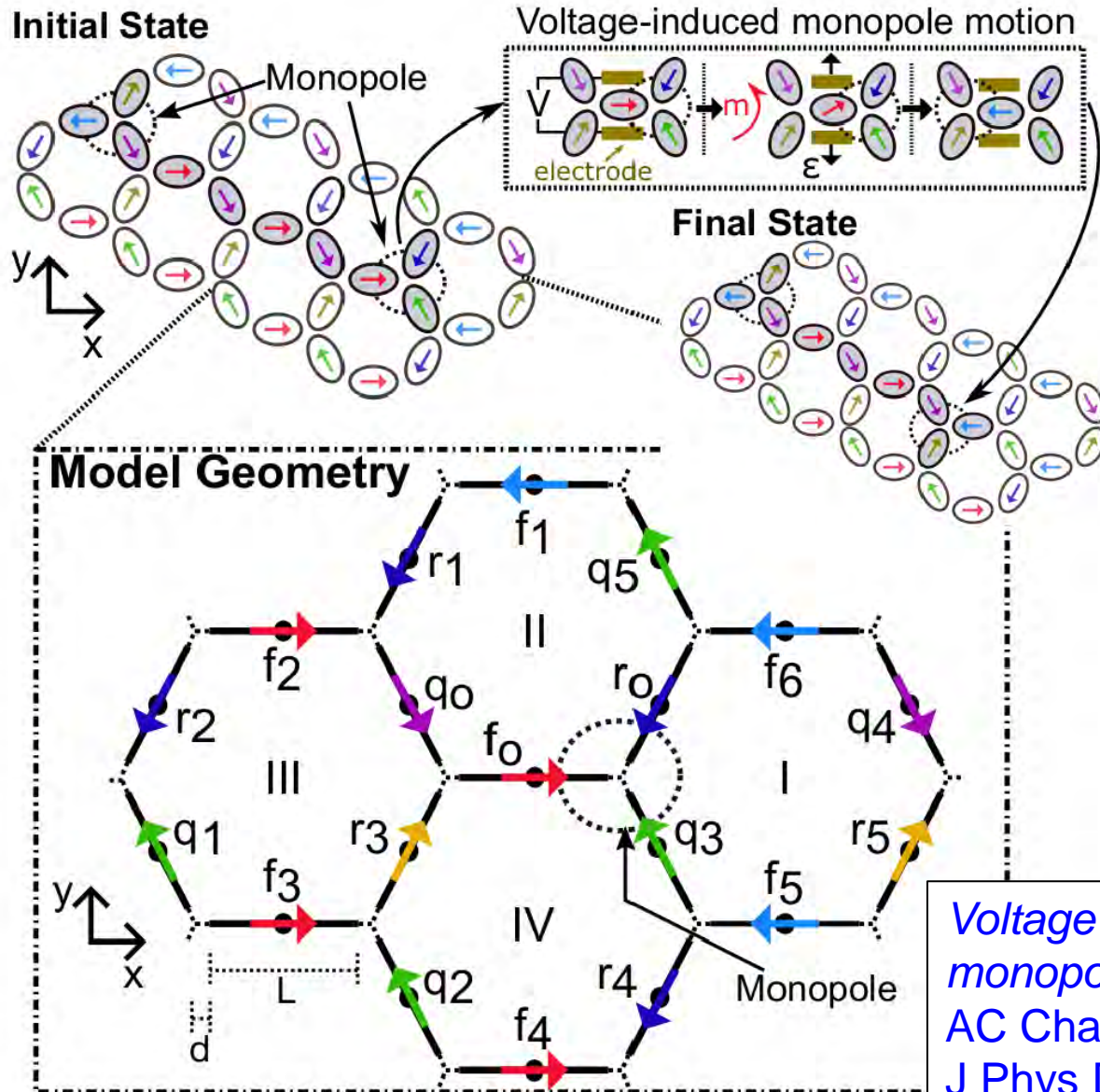
Nickel Nanoislands



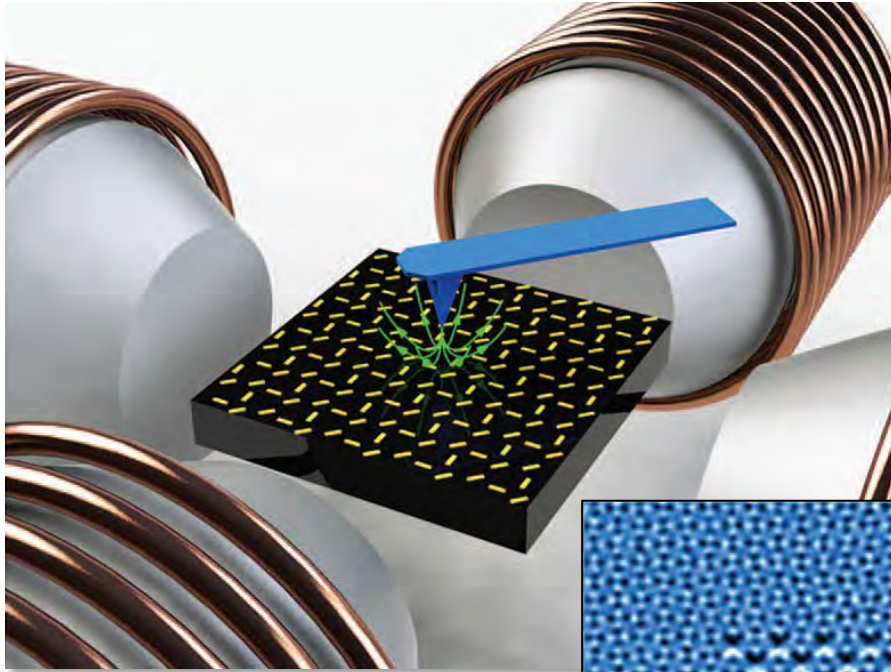
● Ellipse
 Orientation 1 μm



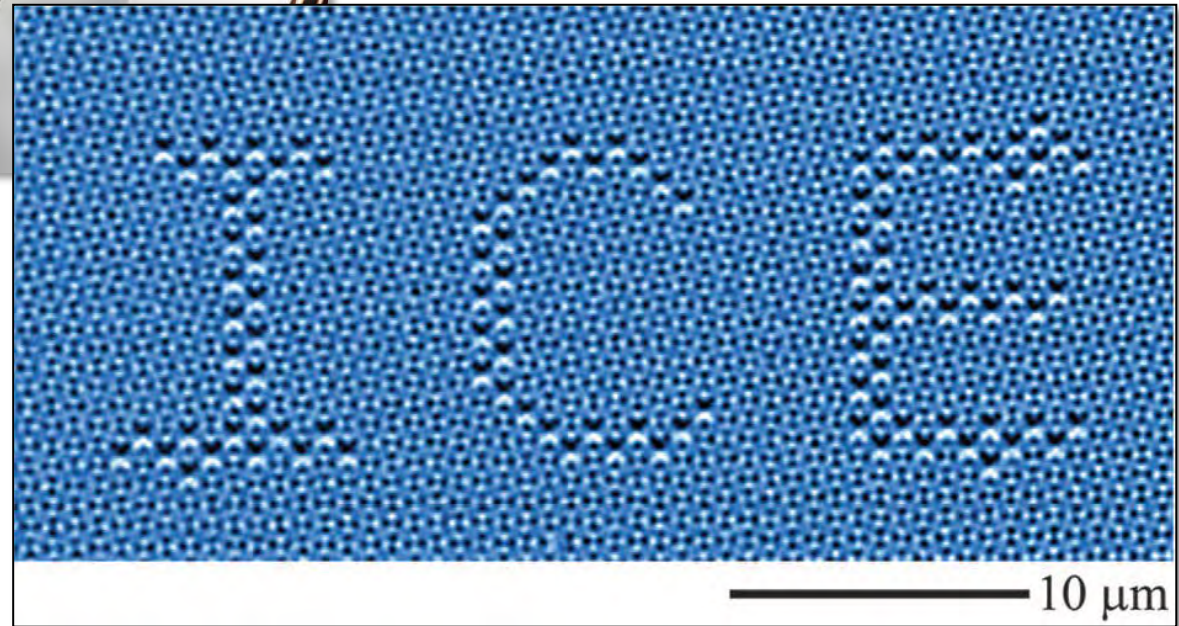
FE [100] axis
 FE [011̄] axis



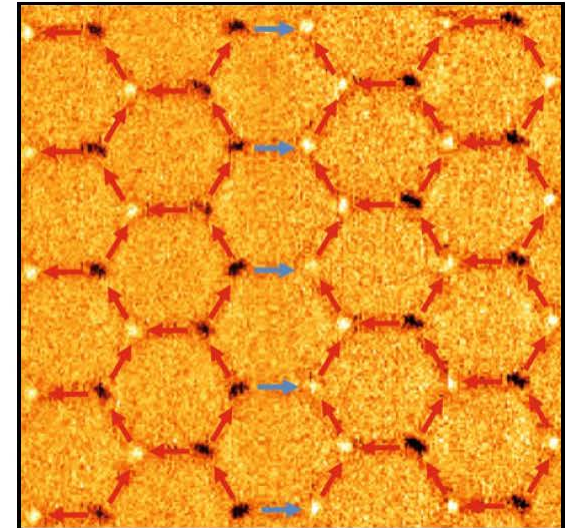
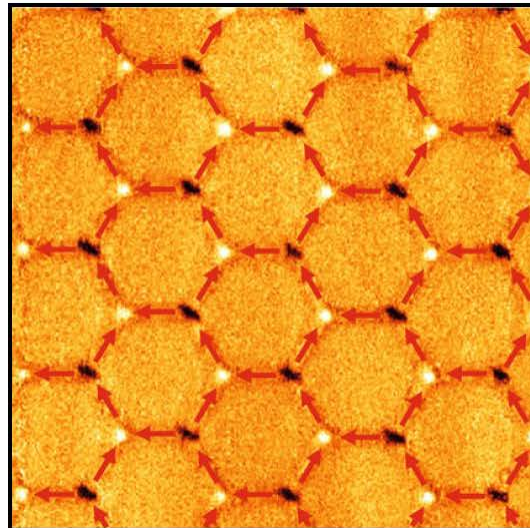
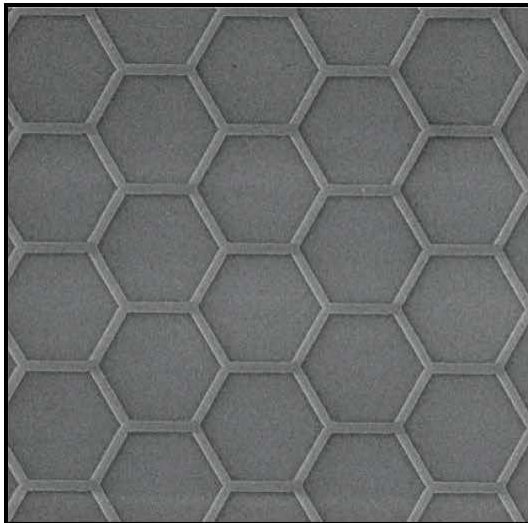
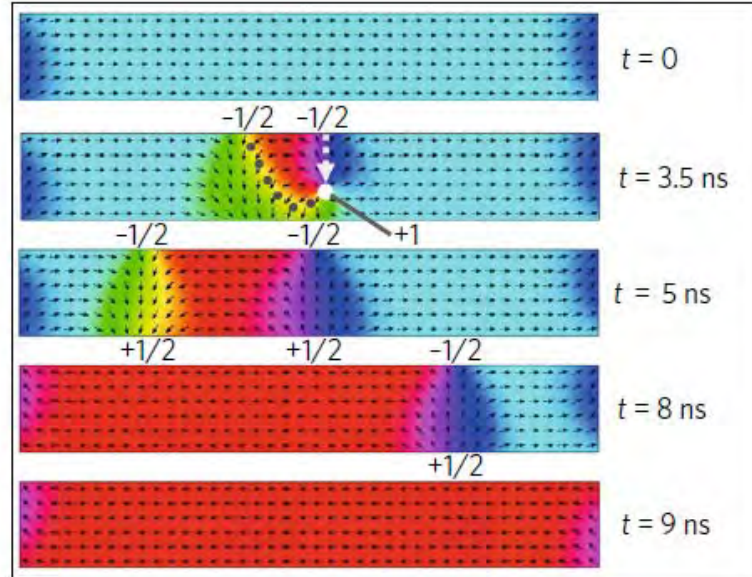
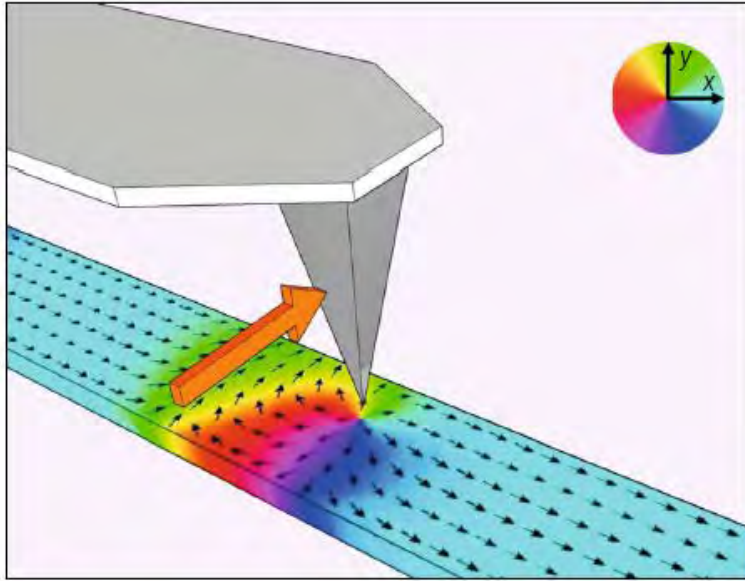
Voltage control of magnetic monopoles in artificial spin ice
 AC Chavez, A Barra & GP Carman
 J Phys D 2018



Wang et al. Science 2016



Read-Write with MFM Tip



1 μm

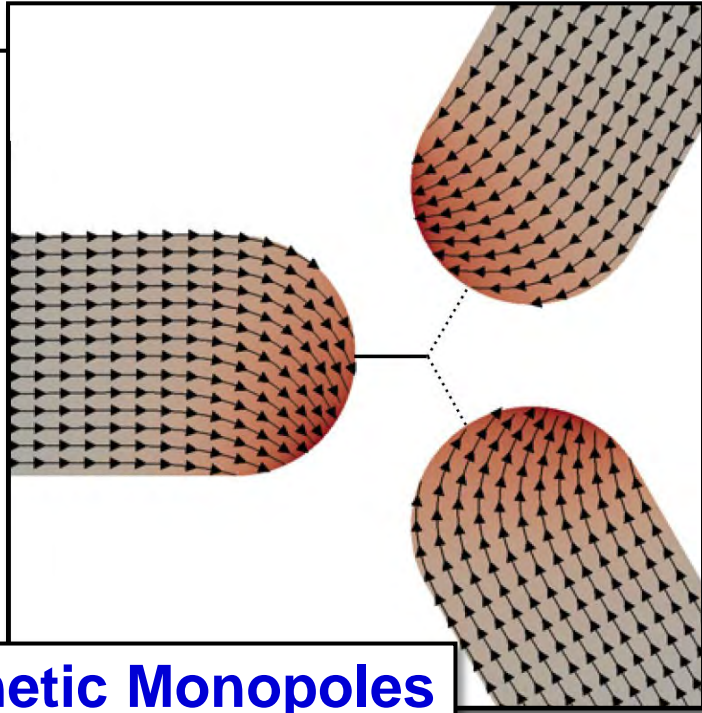


H_{sat}



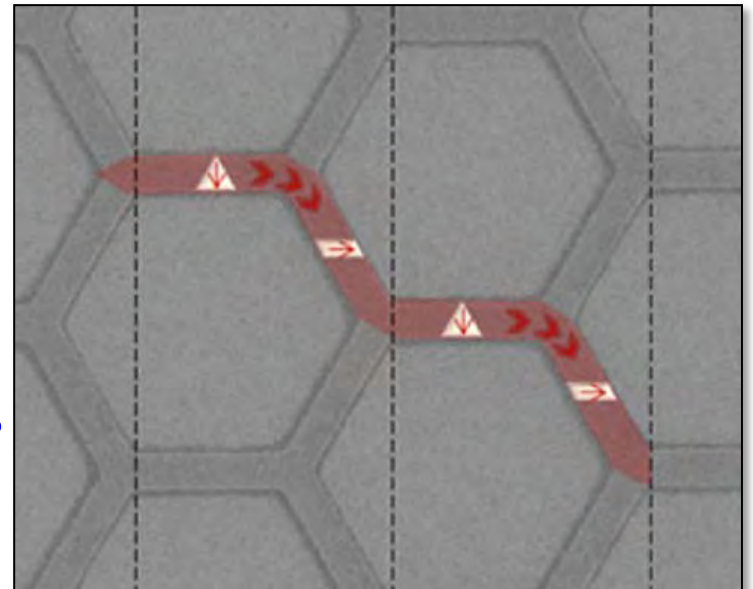
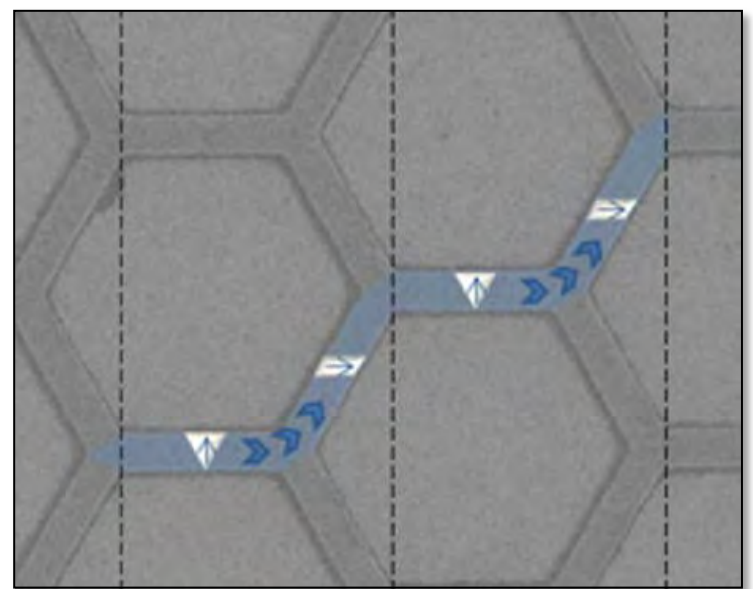


Topic 3 - Chirality Control



Chiral Magnetic Monopoles

N Rougemaille et al. NJP 2013

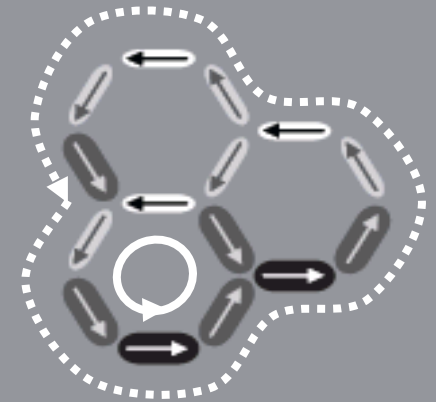
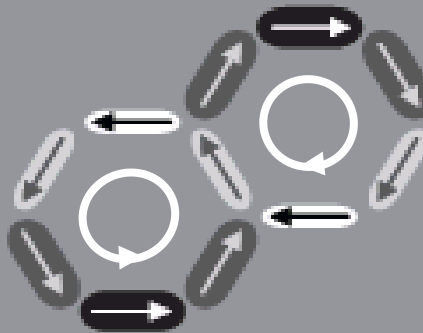
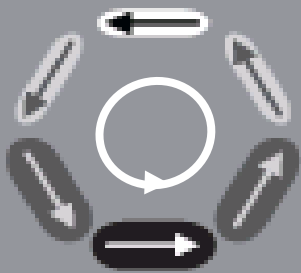
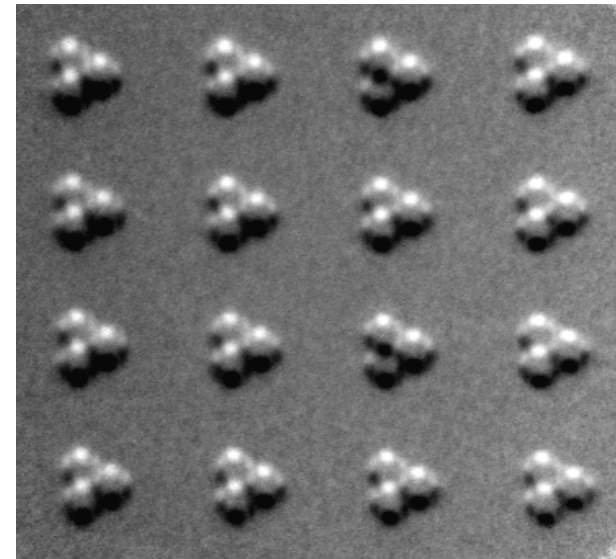
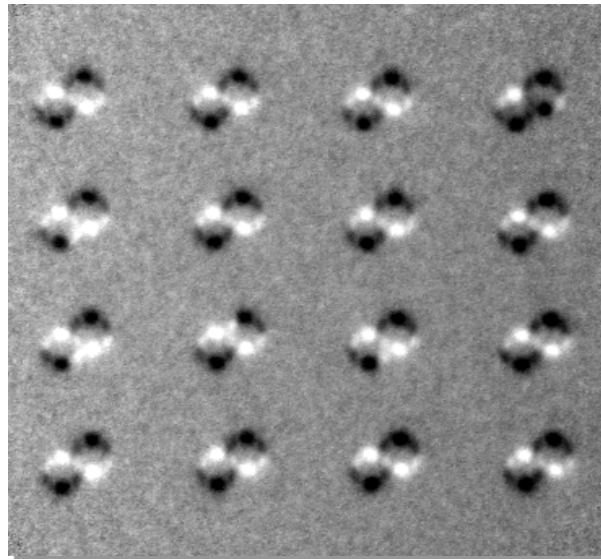
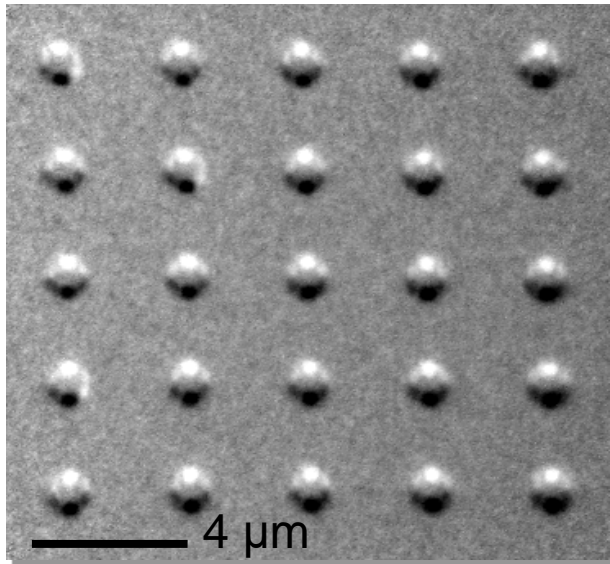


Domain Walls & Connected Networks

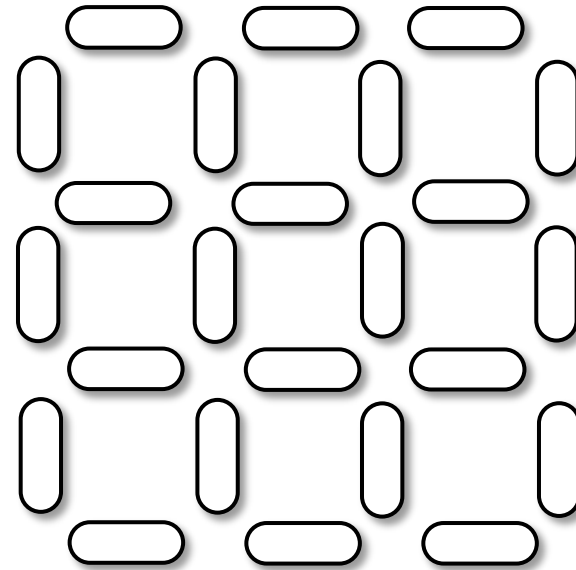
A Pushp et al. Nature Phys 2013

K Zeissler et al. Sci. Rep. 2013

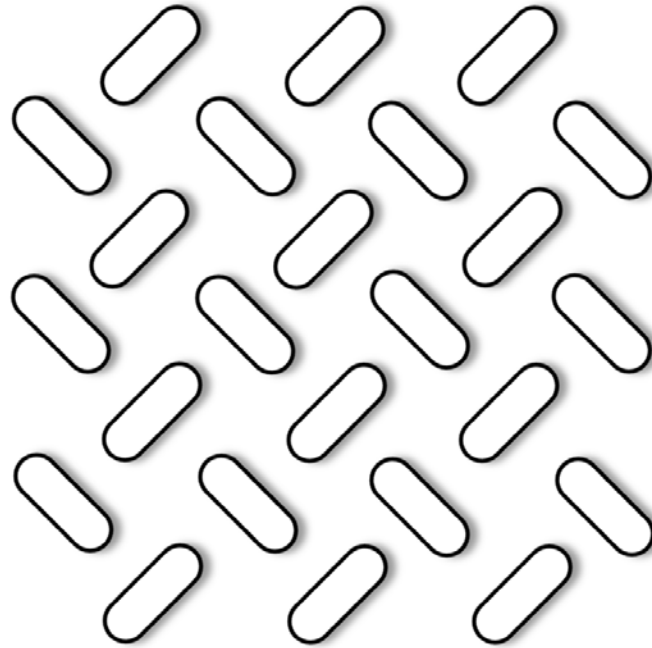
Chirality Control



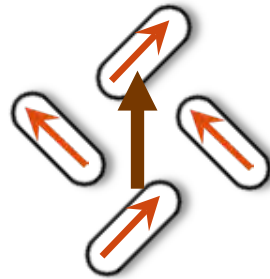
X-ray direction 



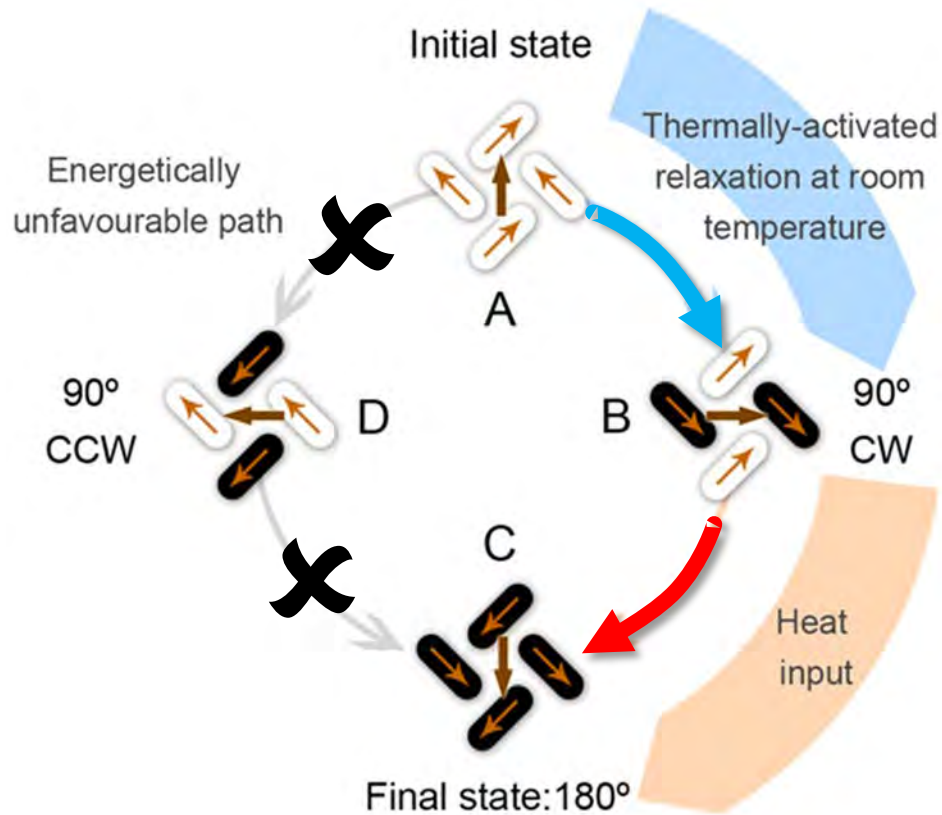
Square Ice → Chiral Ice



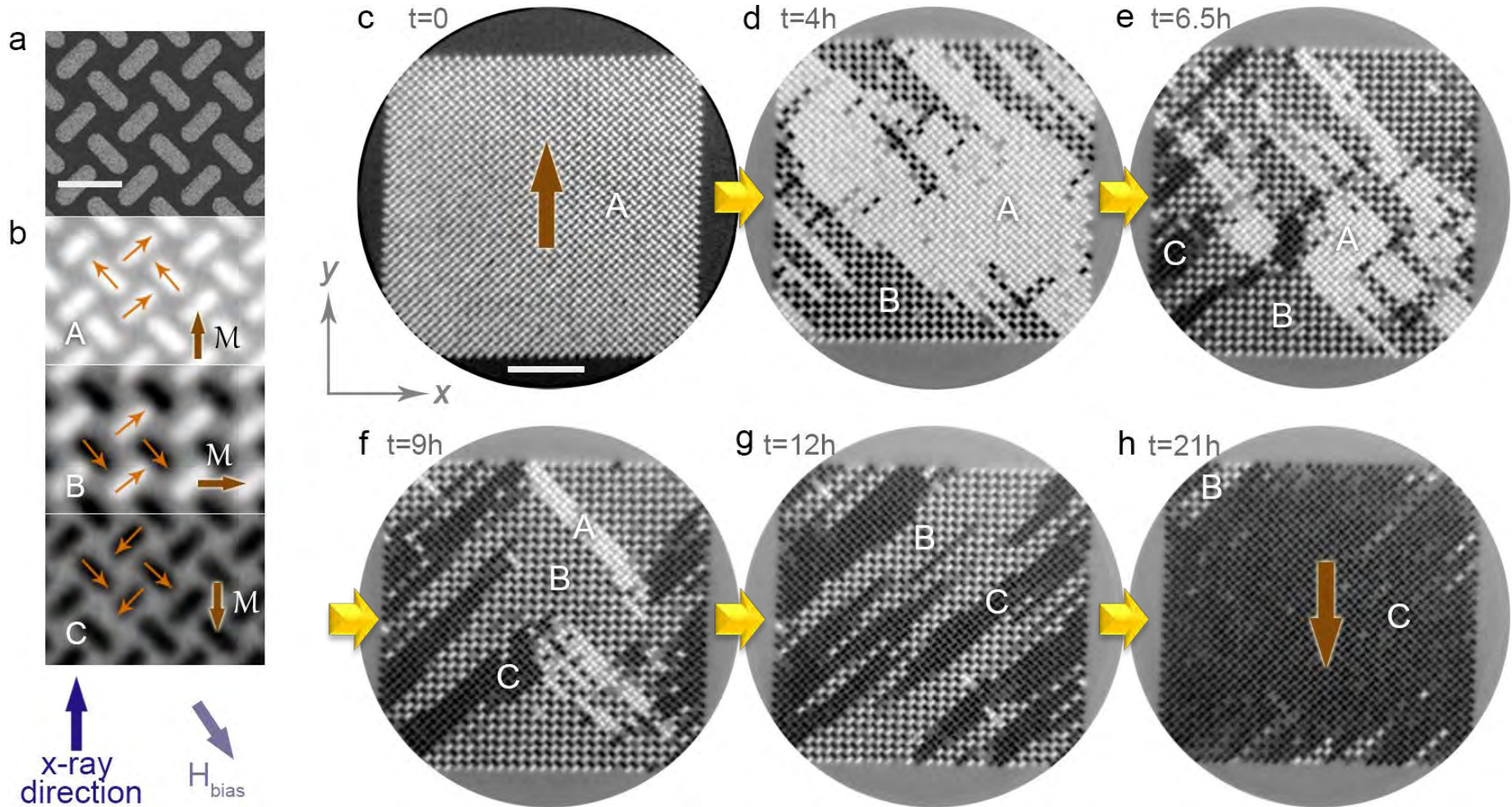
Square Ice → Chiral Ice

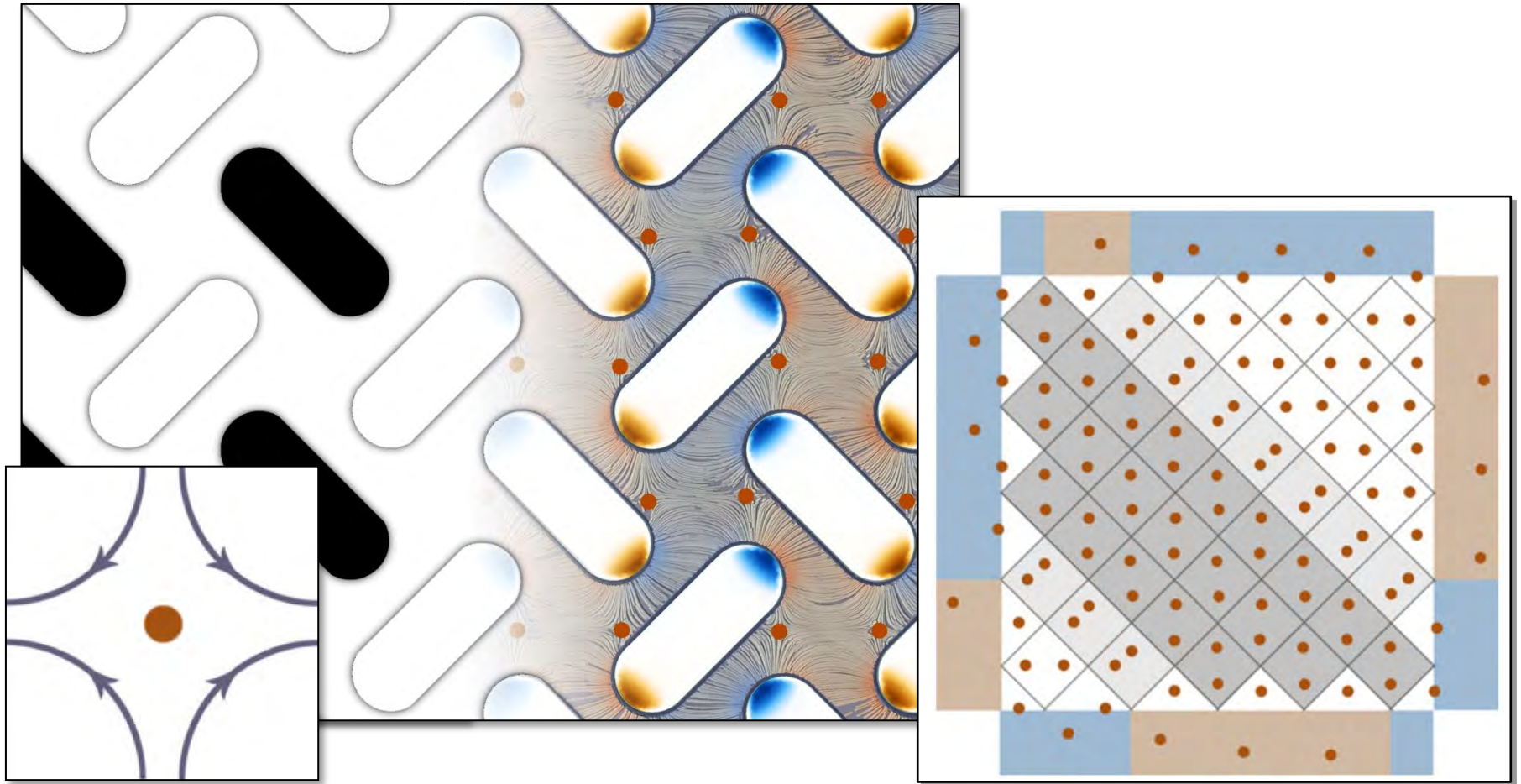


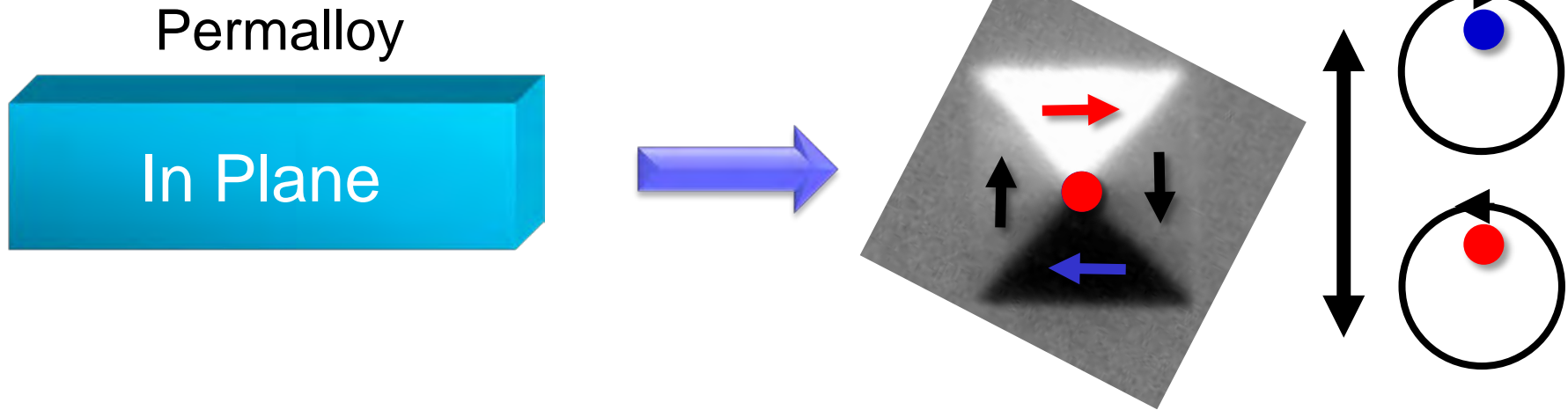
Square Ice → Chiral Ice



Chiral Dynamics !

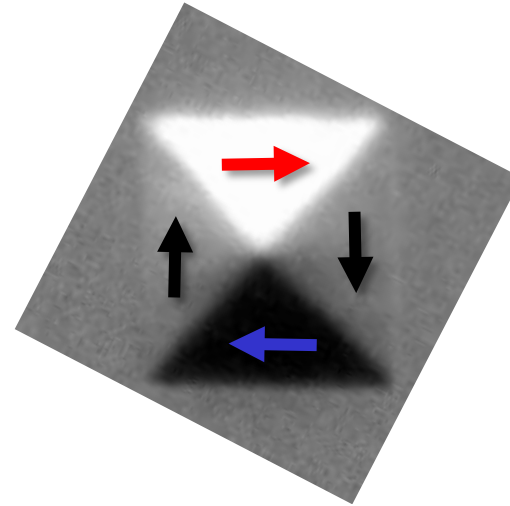
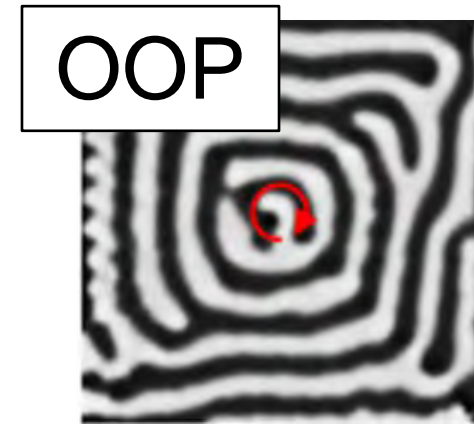
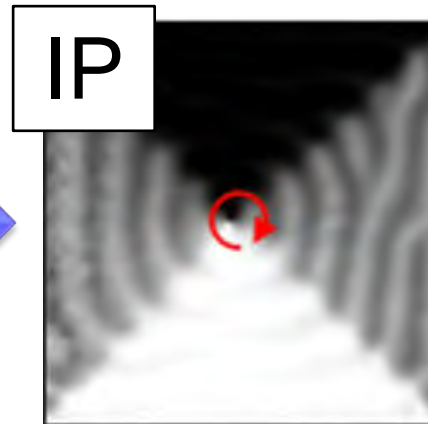
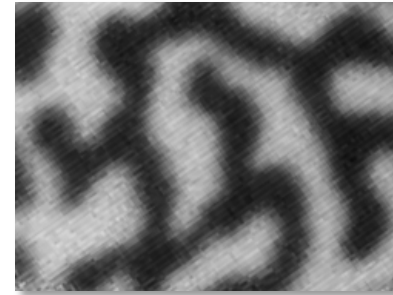


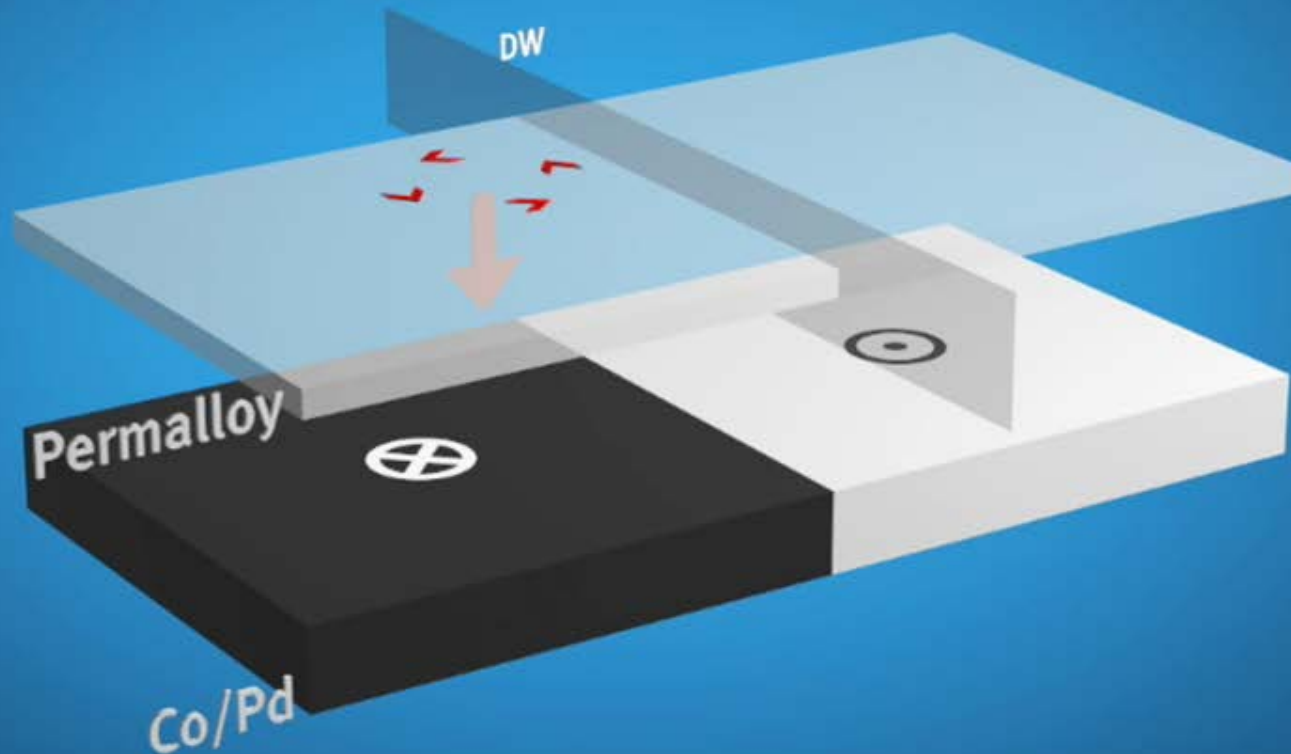




From chiral dynamics to dynamic chirality....

Permalloy

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

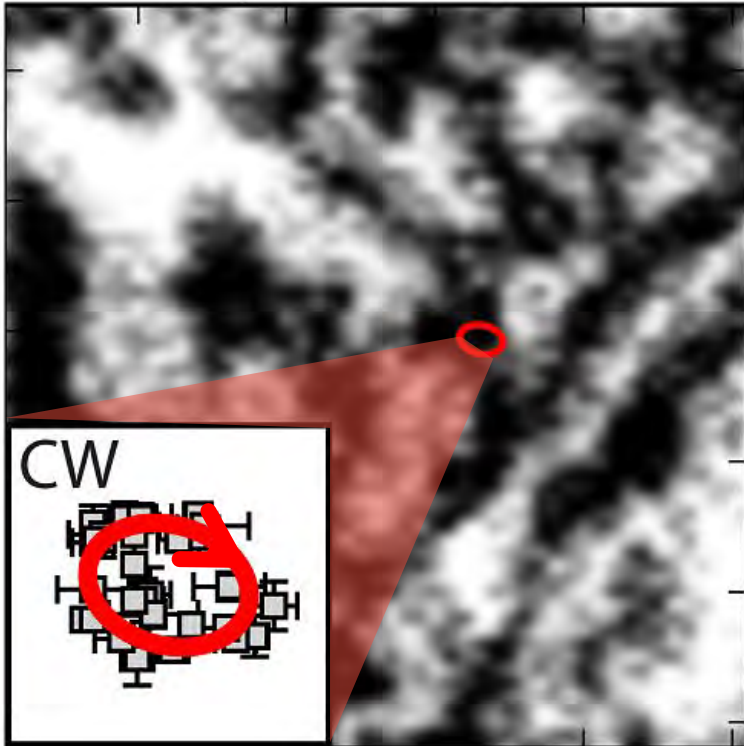


Animation: Mahir Dzambegovic/Paul Scherrer Institute

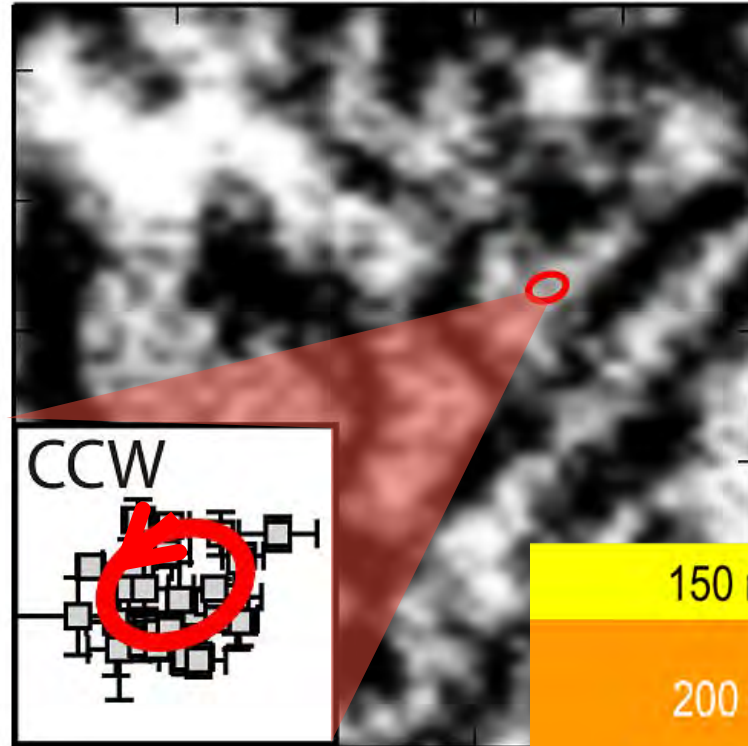
P Wohlhüter et al. Nature Communications (2015)

G. Heldt et al. Appl Phys Letts (2014)

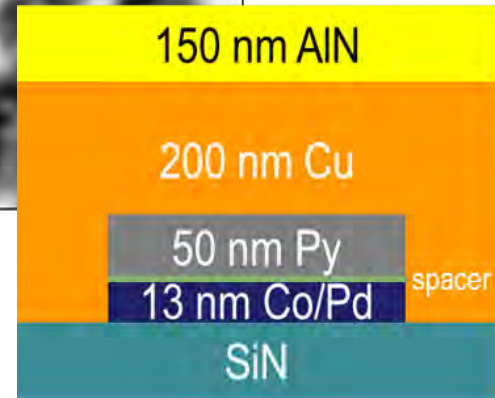
← 1.5 mT



← 2.2 mT

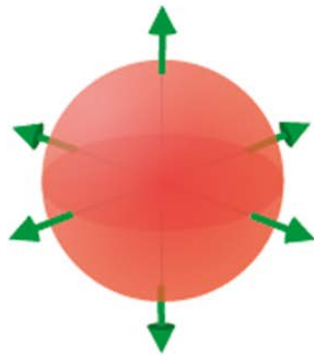
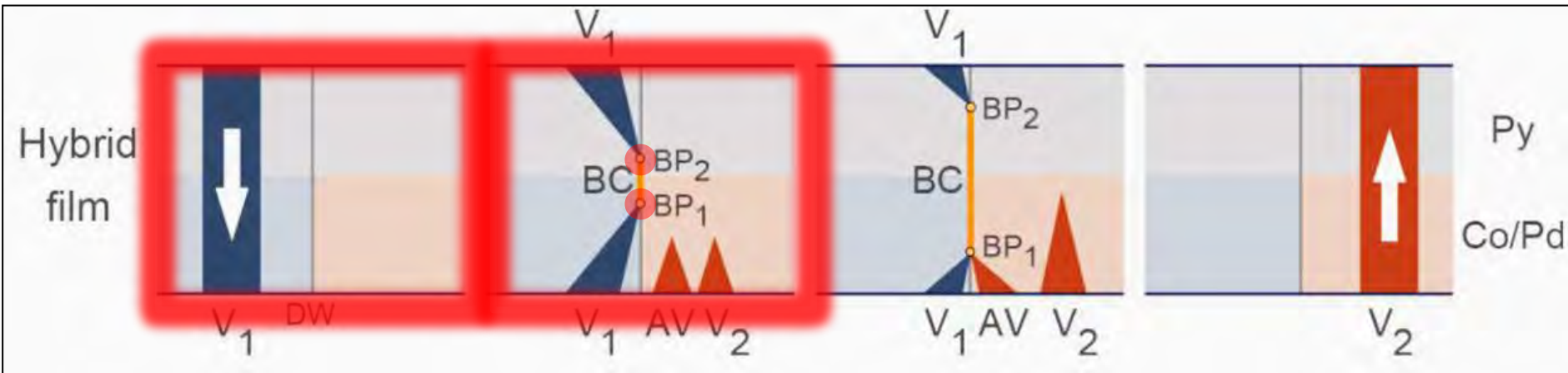


Scanning Transmission X-ray Microscope Images

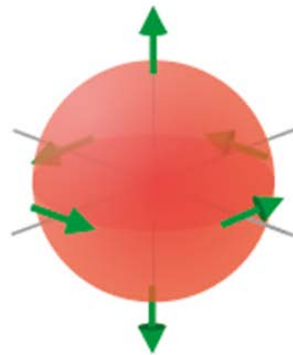


P Wohlhüter, MT Bryan, P Warnicke, S Gliga, SE Stevenson, G Heldt, L Saharan, AK Suszka, C Moutafis, RV Chopdekar, J Raabe, T Thomson, G Hrkac, LJ Heyderman
 Nature Communications (2015)

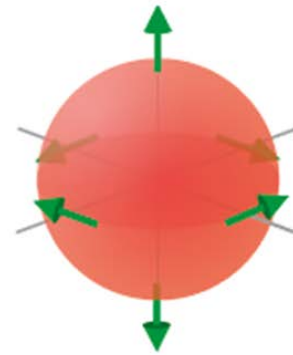
Nanoscale Vortex Core Switch



Hedgehog



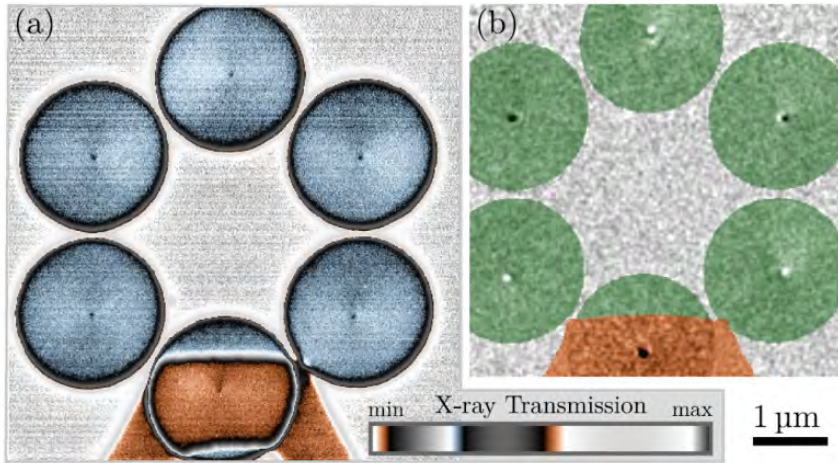
Circulating



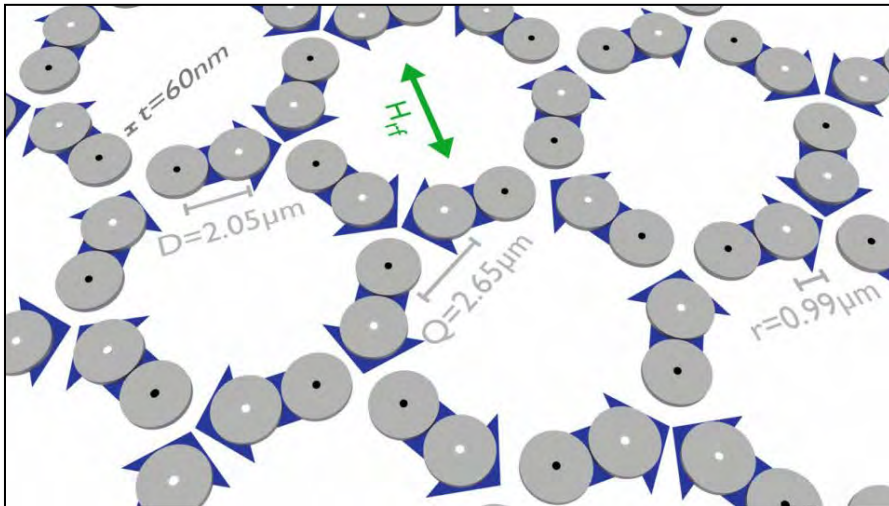
Contra-circulating

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)

Coupled Vortices

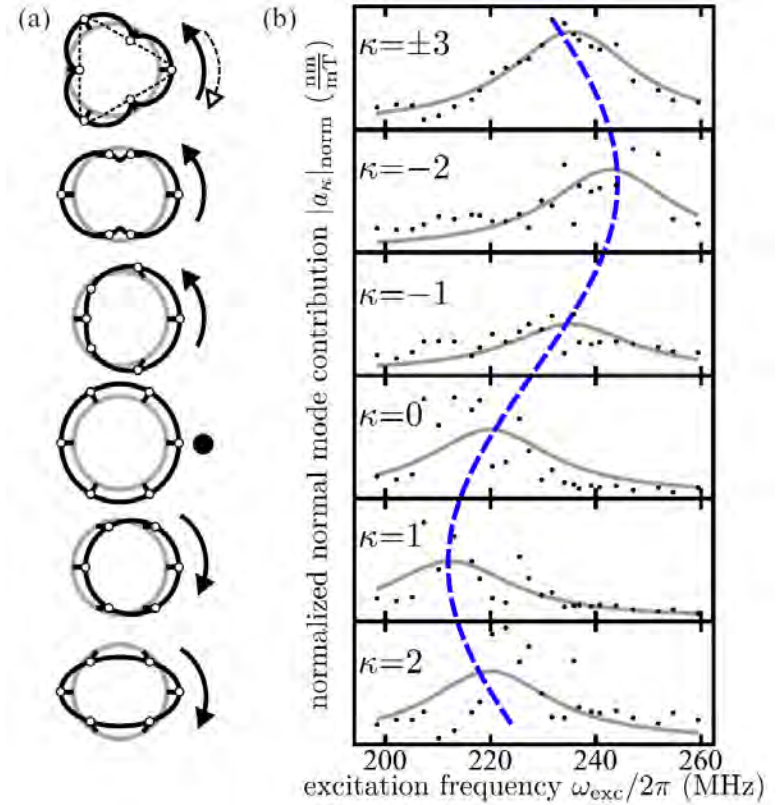


CF Adolff PRB 2015



Frequency dependent behaviour

→ tune frustration, and turn on & off at will

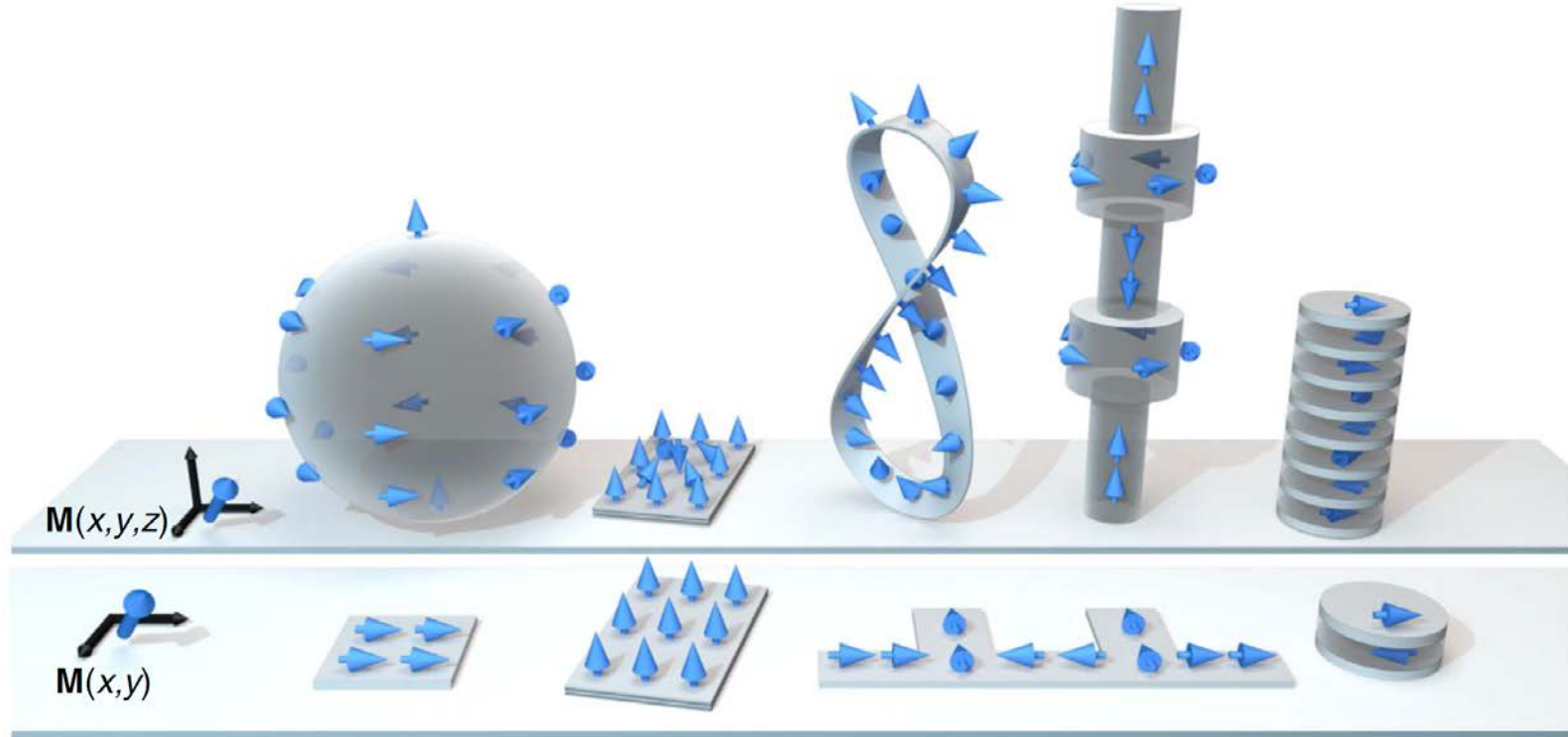


→ Time-dependent trajectories of the vortices for the six eigenmodes

C Behncke et al.
Scientific Reports 2018



Topic 4
Three dimensional magnetic systems



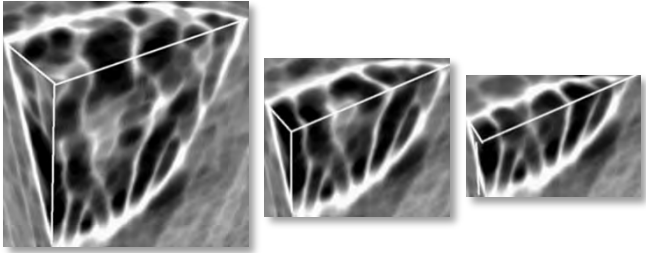
Three-dimensional nanomagnetism

A Fernández-Pacheco et al. Nature Communications (2017)

Magnetism in curved geometries

R Streubel et al. J Phys D (2016)

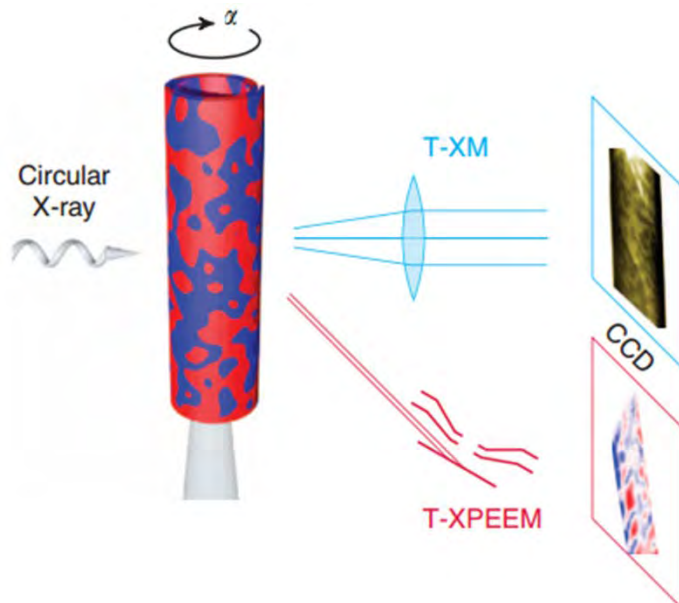
Neutron Tomography



Manke et al. Nat Comm 2010

Kardjilov et al. Nat Phys 2008

Soft X-ray tomography



Streubel et al. Nat Commun 2015

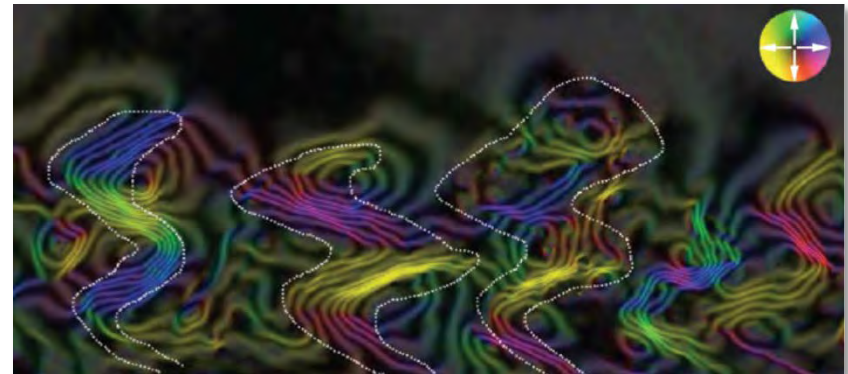
Blanco-Roldan et al. Nat Commun 2015

- Spatial Resolution: **10s - 100 μm**
- Sample thickness: **up to mm's**

Hard X-rays

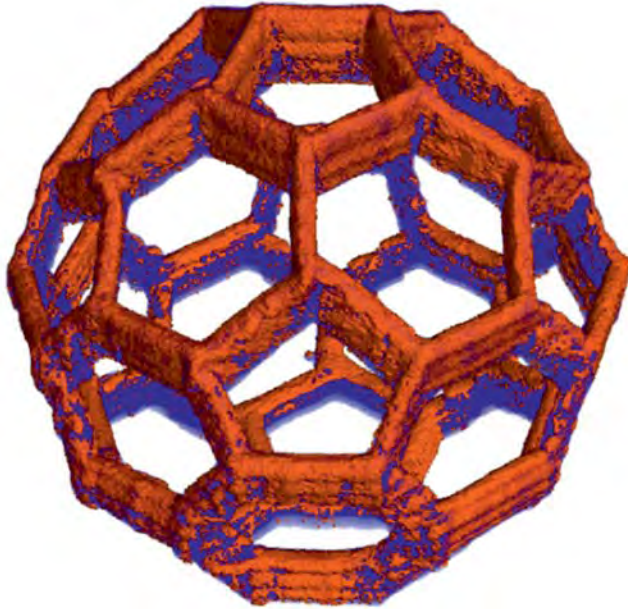
- Spatial Resolution: **< 10 nm**
- Sample thickness: **< 200 nm**

Electron tomography



Phatak et al. Nano Lett 2014

Tanigaki et al., Nano Lett 2015

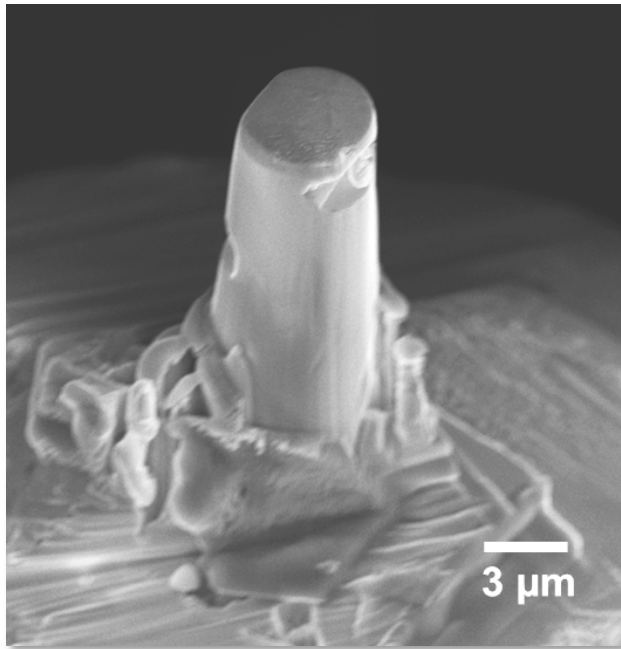


6 μm Buckyball



Resonant Ptychographic Tomography

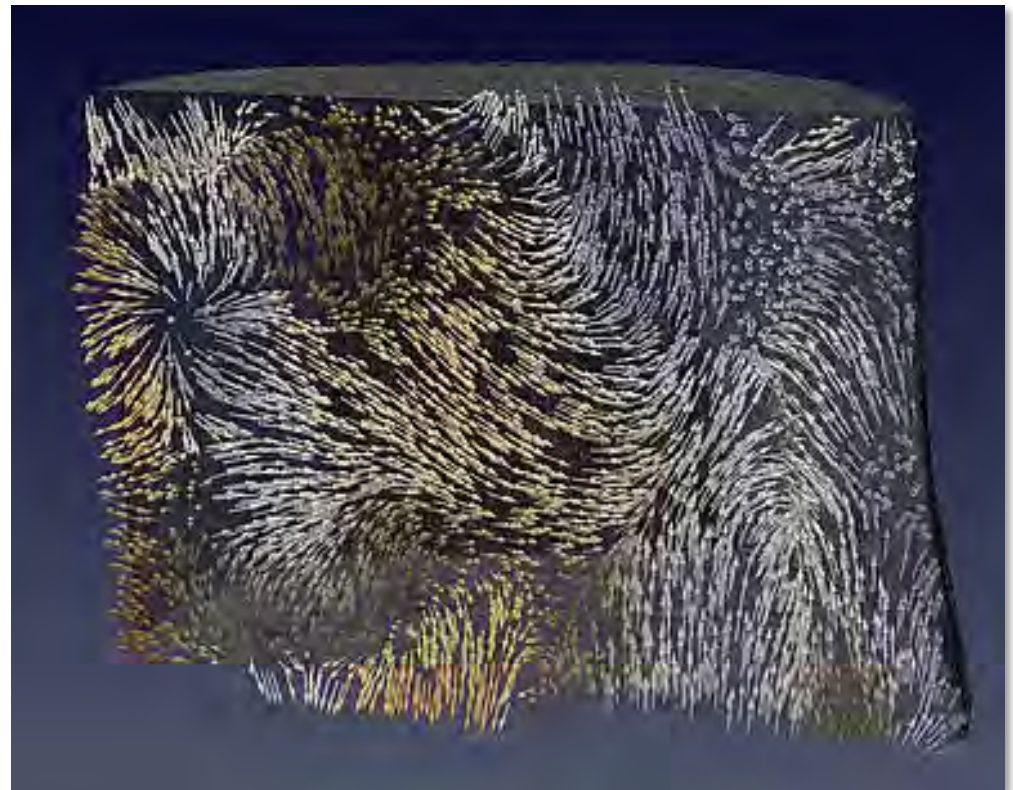
*Quantitative hard x-ray phase imaging & resonant elastic scattering
→ element-specific 3D characterization with 25 nm spatial resolution*



GdCo₂ Pillar

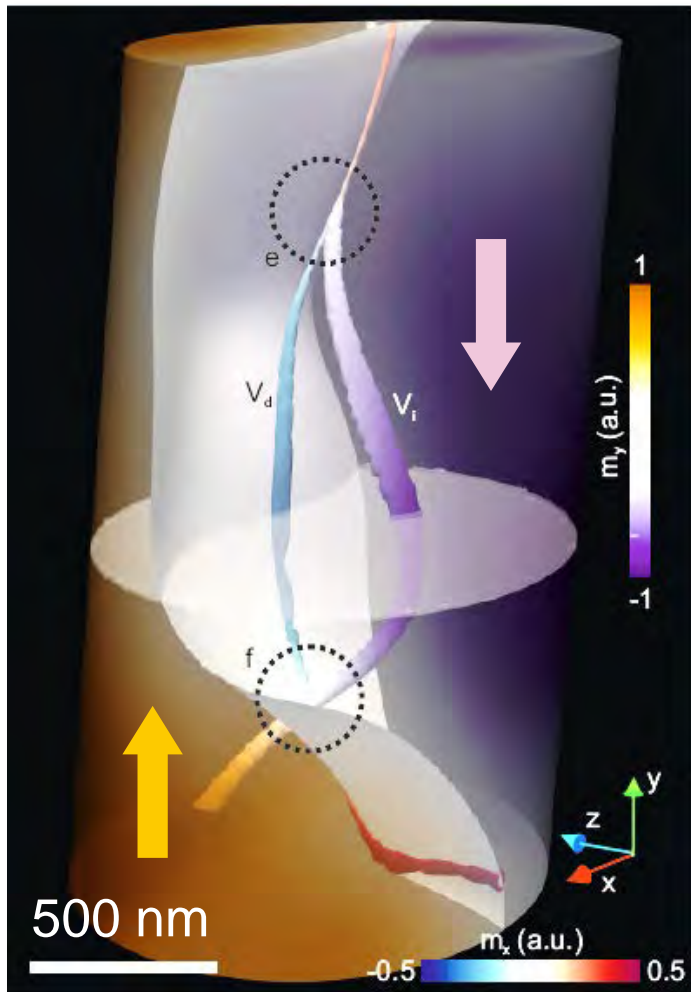
Cut from nugget with FIB

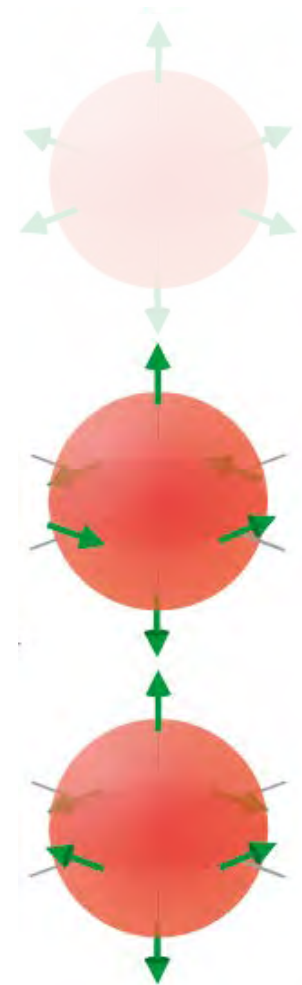
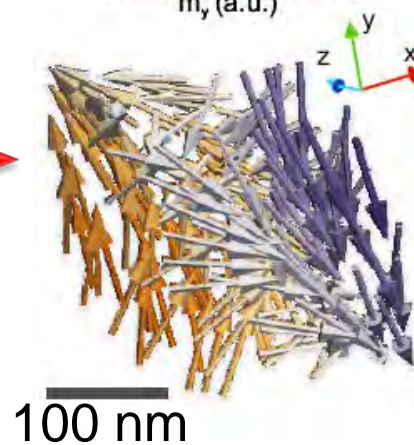
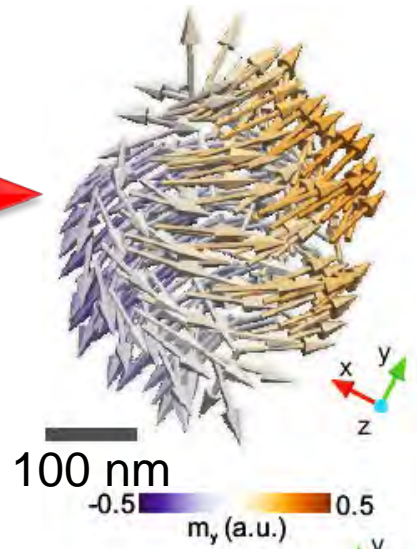
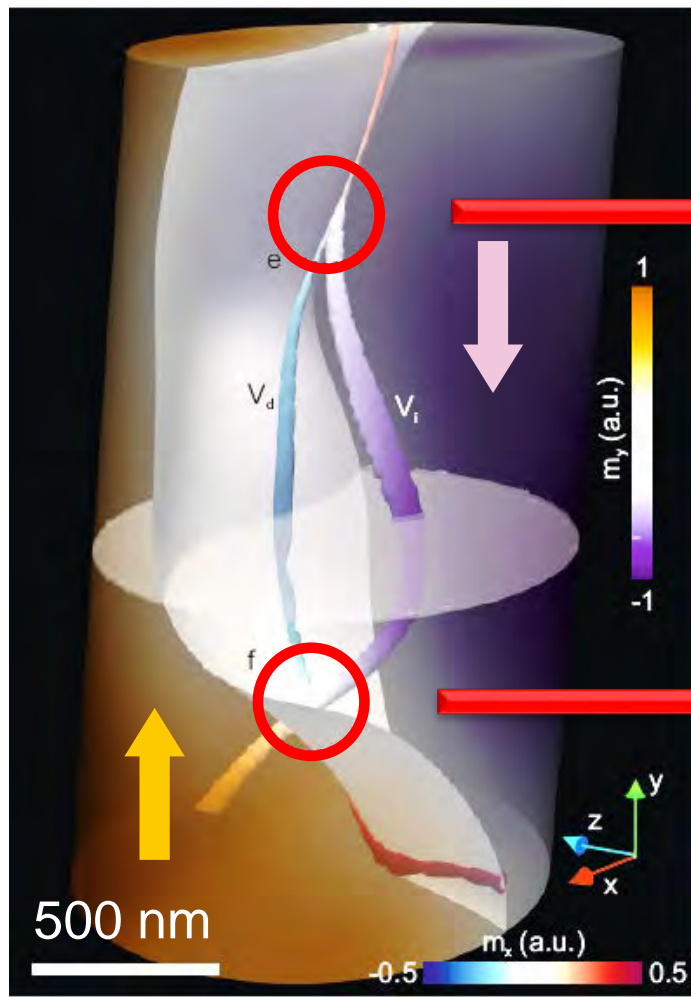
Sample from:
R. Galera, CNRS, Grenoble



1 μm

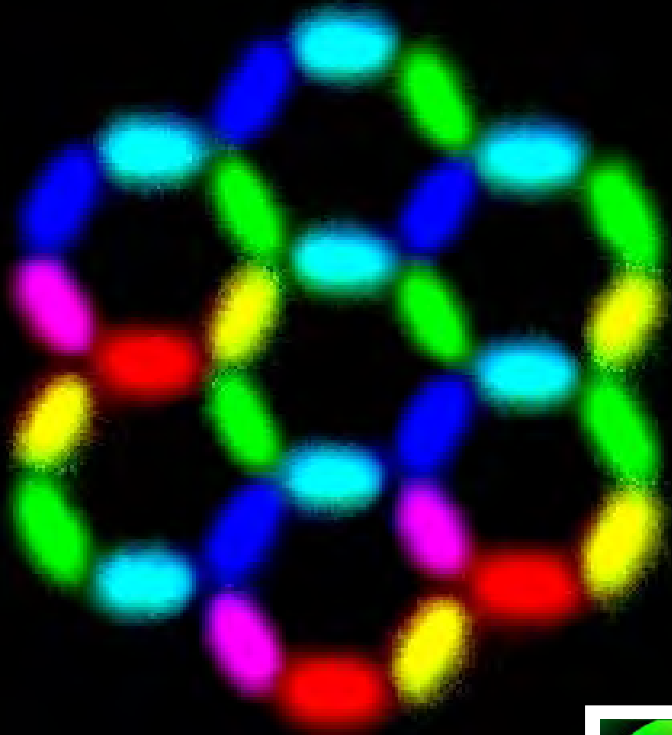




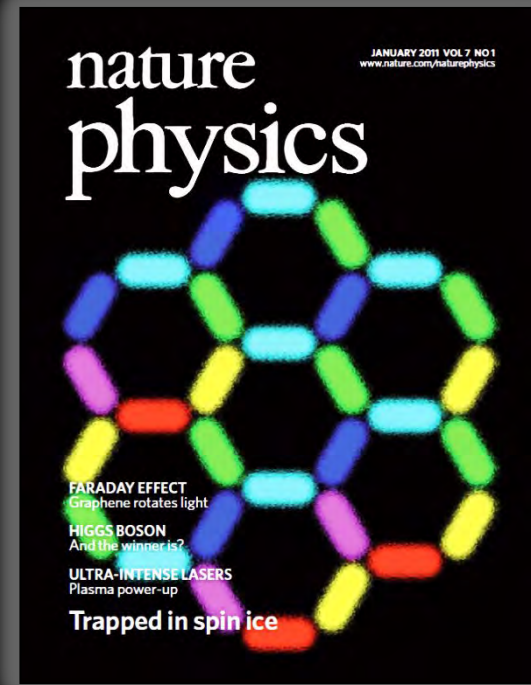
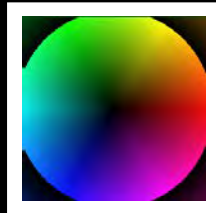


Artificial Spin Ice

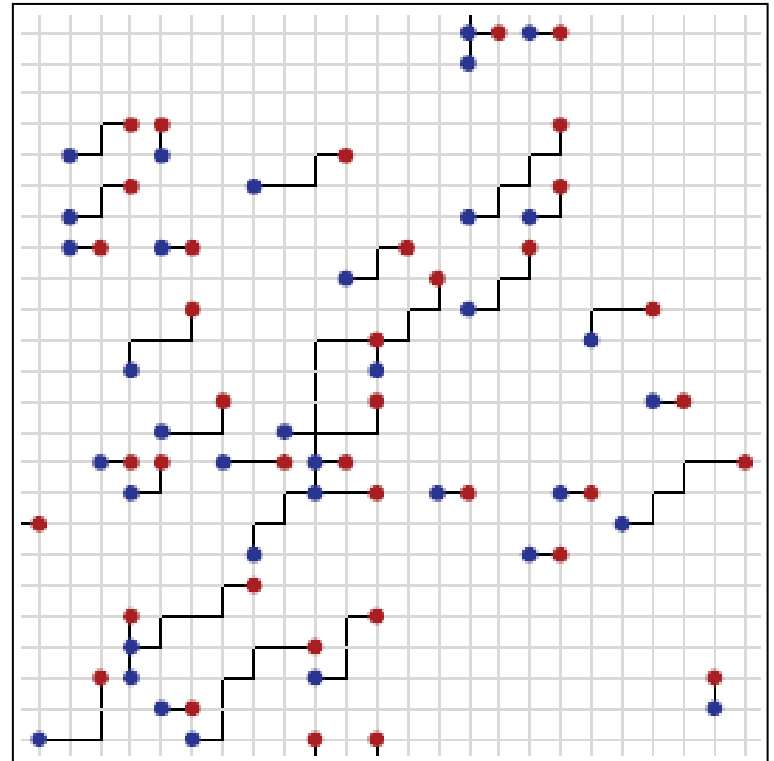
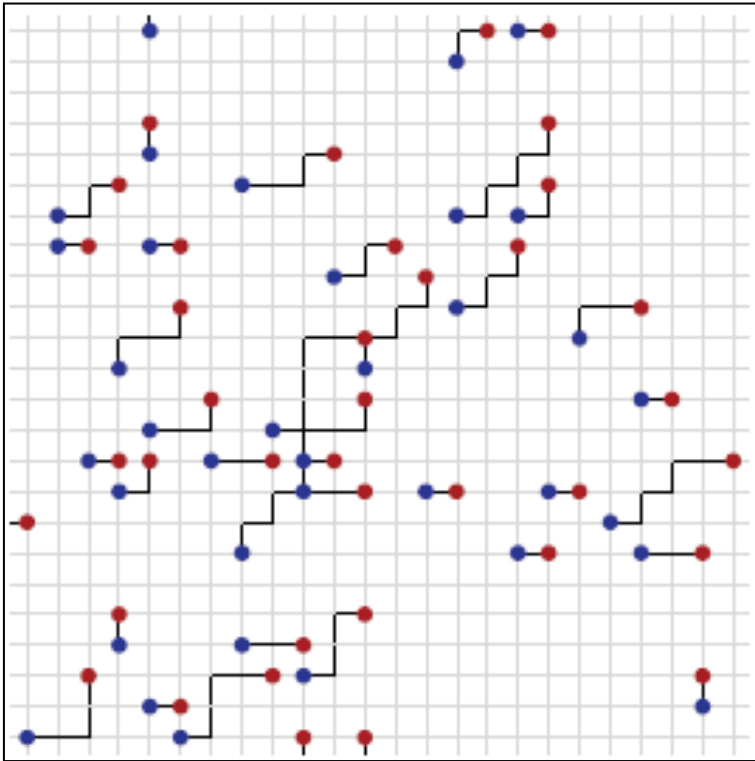
*A few more things
you should know....*



500 nm
—



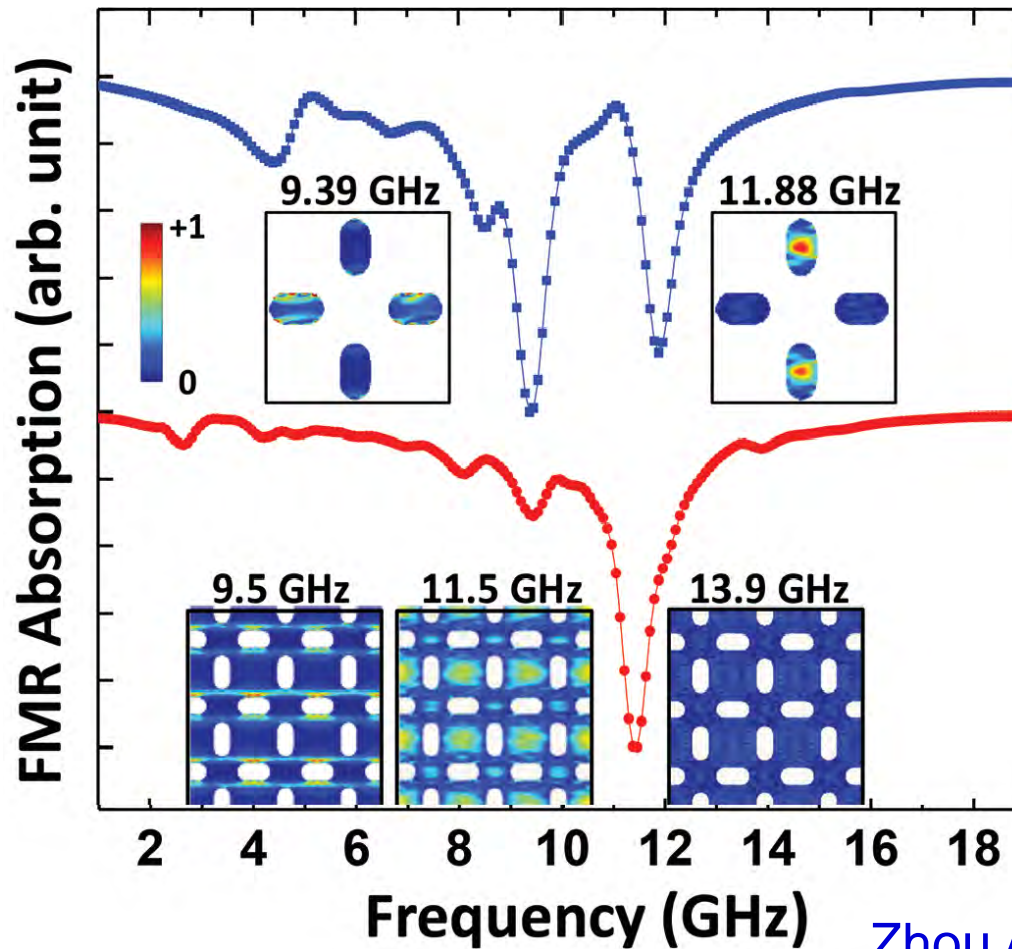
Memory Effects



Gilbert et al. PRB 2015

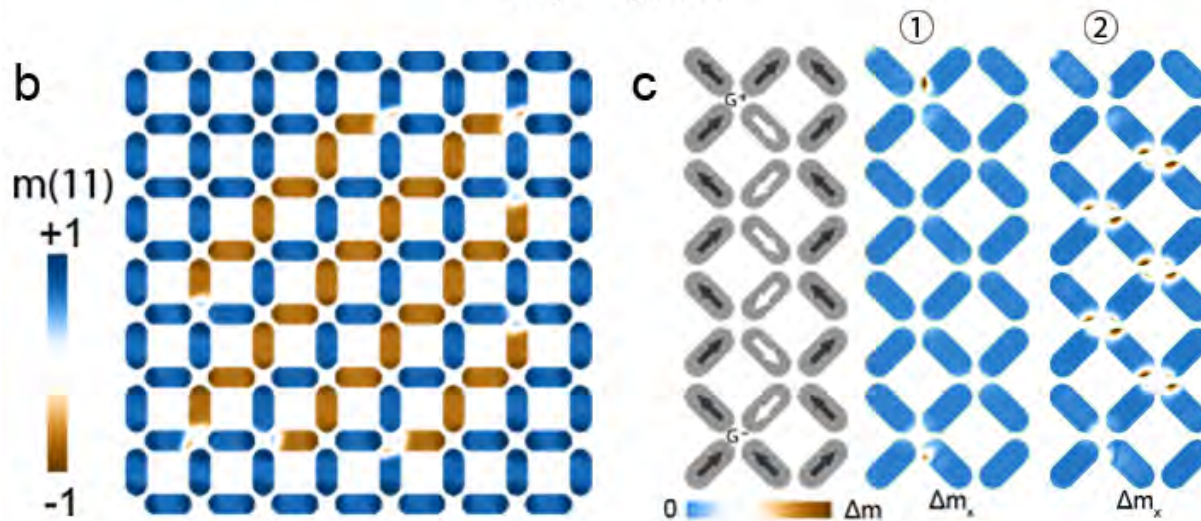
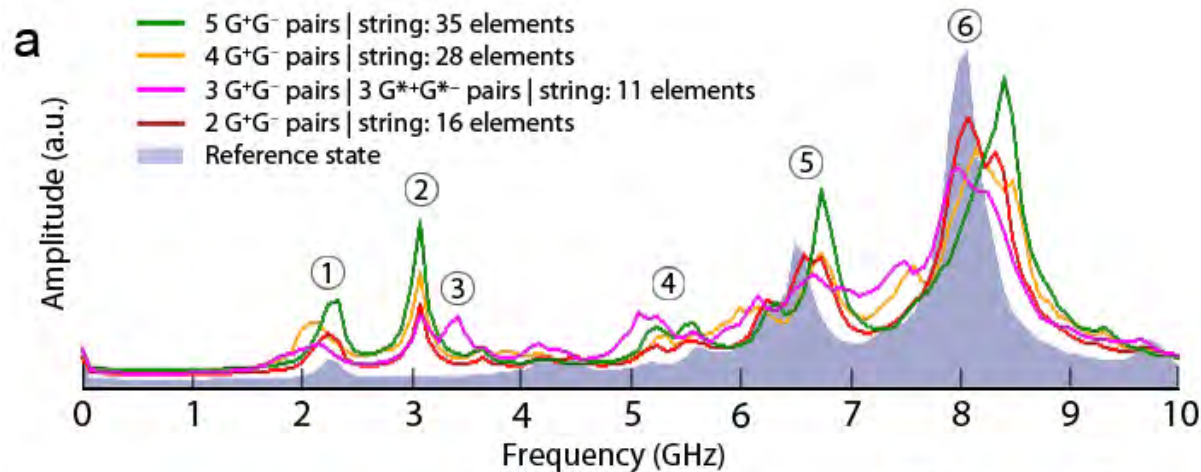
Fast Dynamics – Reconfigurable Magnonic Crystals

→ Transmit and process information as spin waves



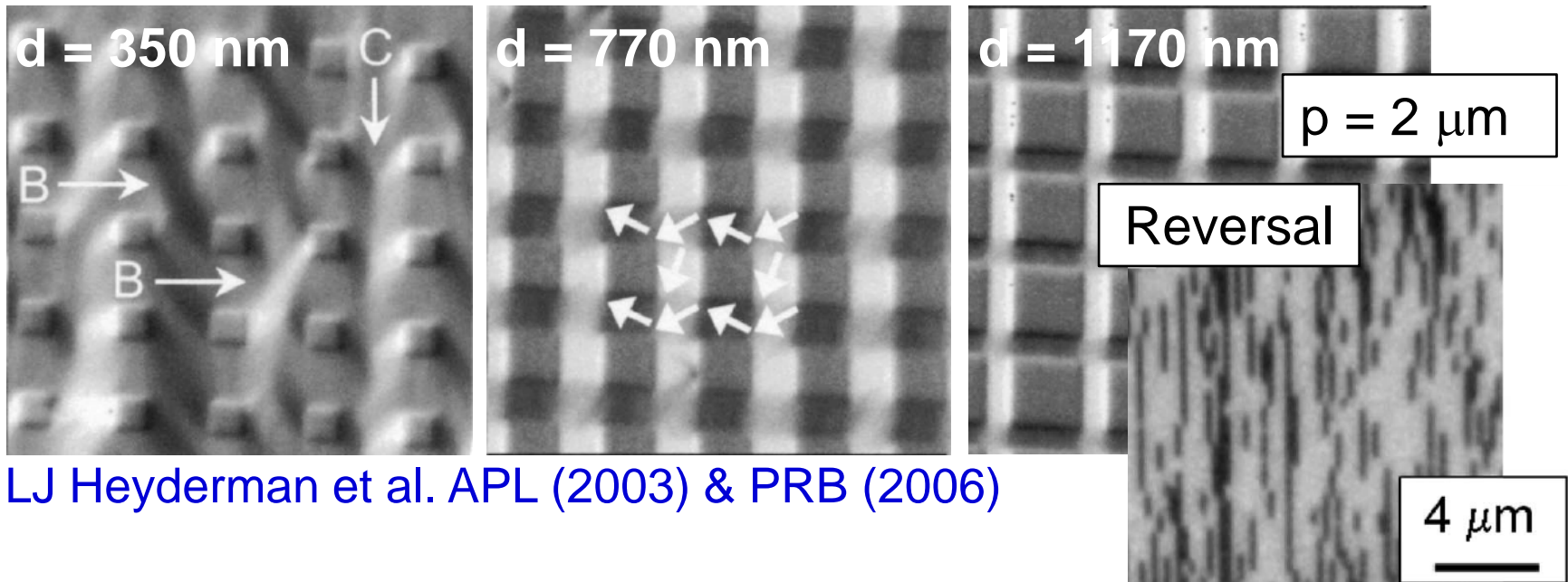
Zhou Adv. Funct. Mater. 2016

Fast Dynamics – Reconfigurable Magnonic Crystals

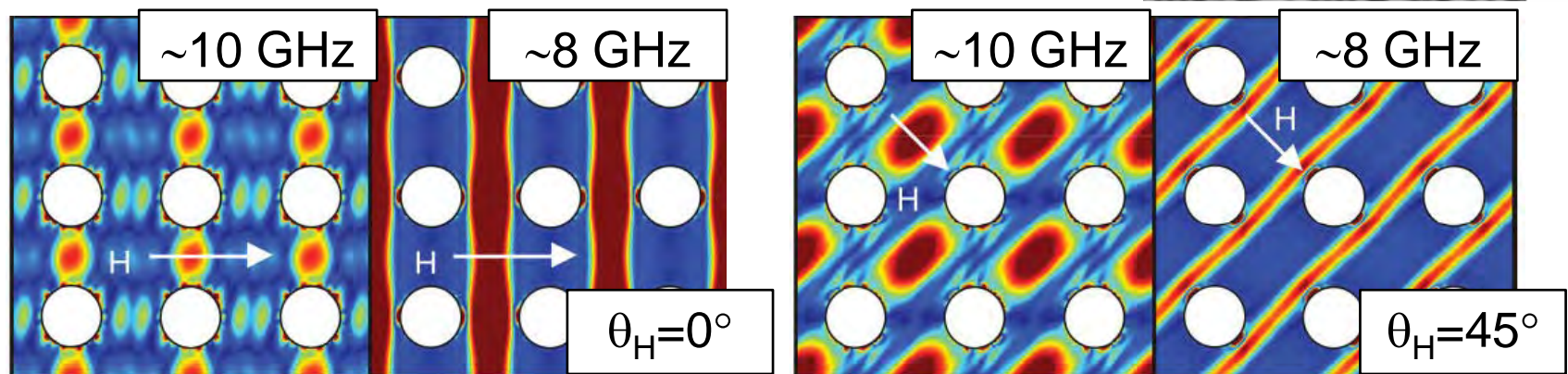


S Gliga et al. PRL (2013)

Fast Dynamics – Reconfigurable Magnonic Crystals & Antidot Arrays



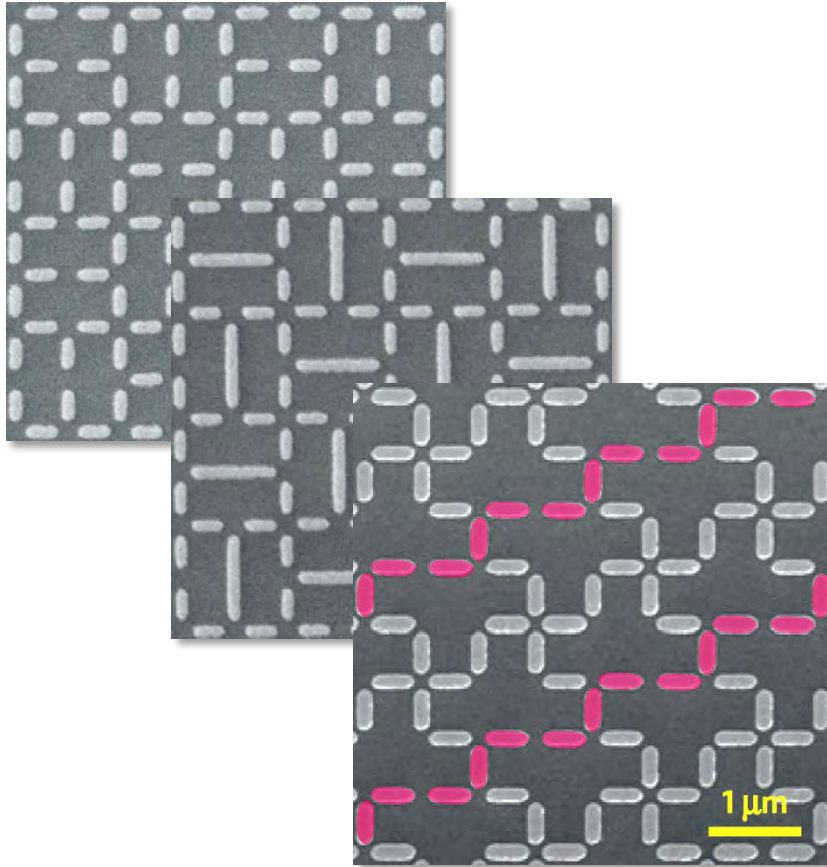
LJ Heyderman et al. APL (2003) & PRB (2006)



S Neusser and D Grundler Advanced Materials (2009)

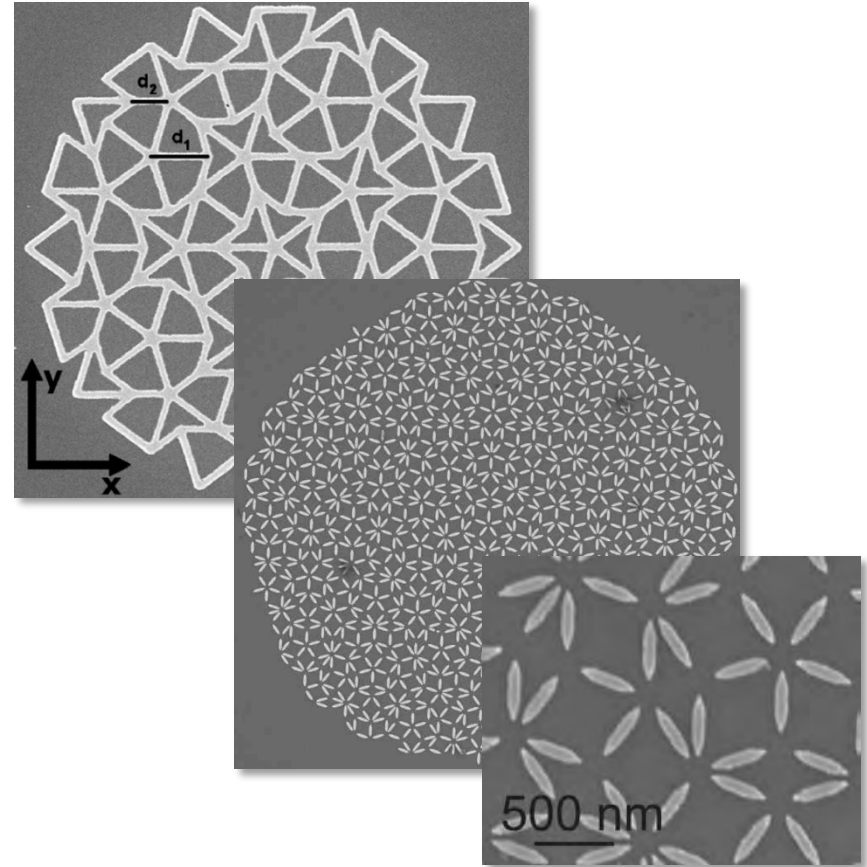
Geometries

Shakti & Tetris Lattices



Gilbert et al. Nature Phys 2014 & 2016

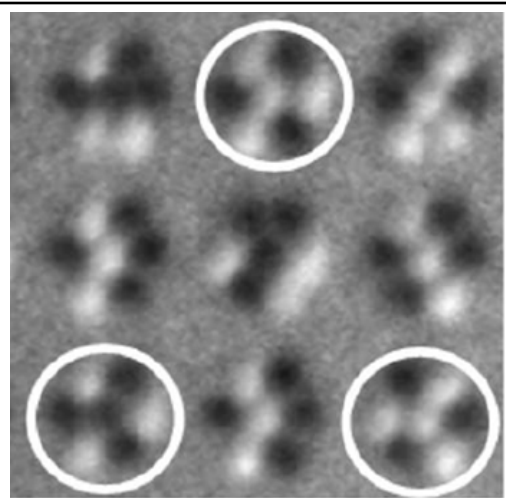
Artificial Quasicrystals



Bhat et al. PRB 2013

Shi et al. Nat Phys 2018

Perpendicular Dots & Scalability

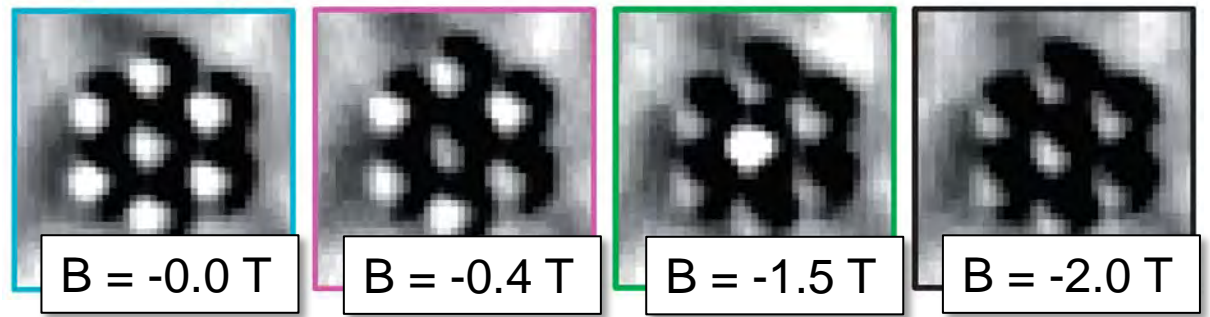
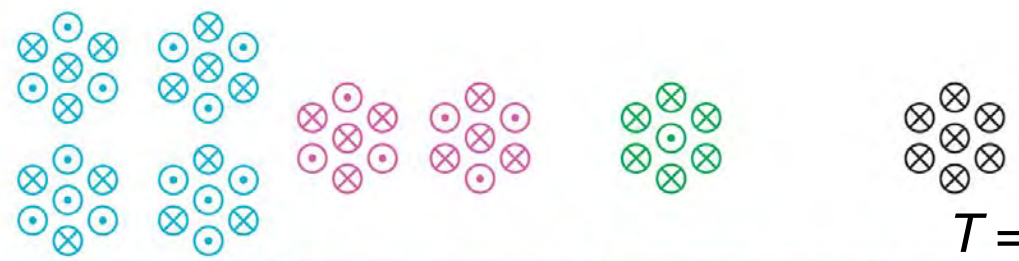


● up ● down

2 μm

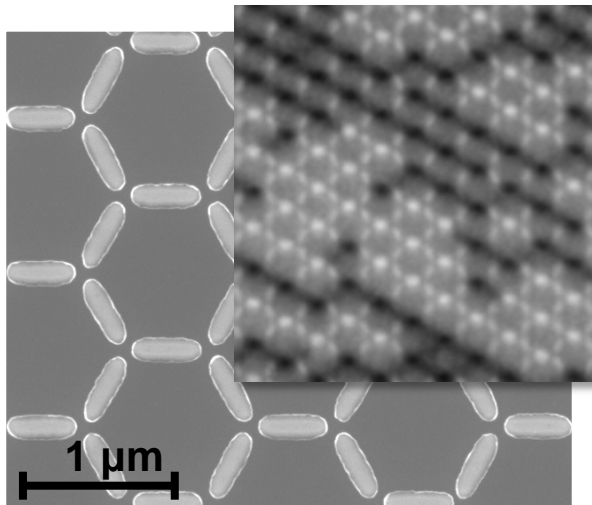
E Mengotti et al. JAP (2009)
S Zhang et al. (2012)

At the atomic scale.....

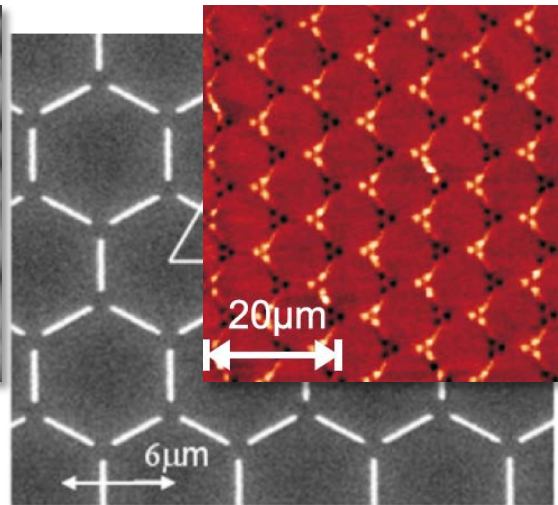


RKKY Coupled Fe Atoms on Cu(111) measured with spin-resolved scanning tunnelling spectroscopy
AA Khajetoorians et al. Nat. Phys. 2012

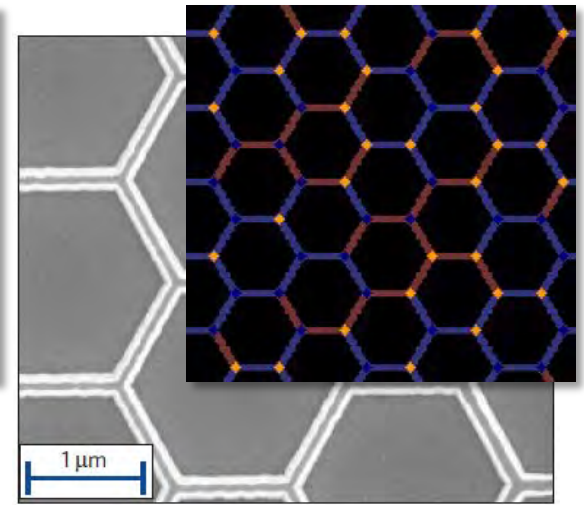
Sample Geometry



Mengotti et al.
Nat. Phys. (2011)



Schumann et al.
Appl. Phys. Letts. (2010)



S. Ladak et al.
Nature Physics (2010)

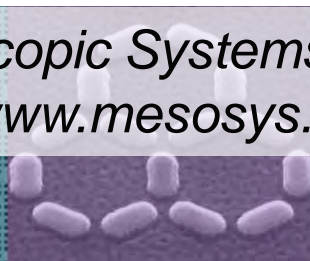
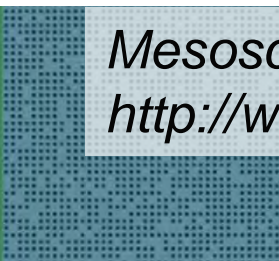
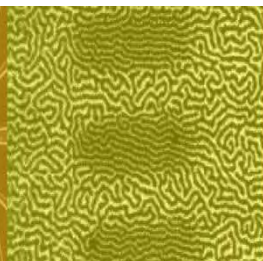
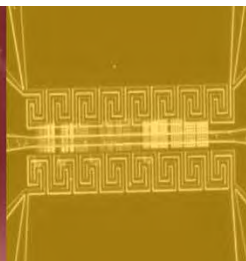
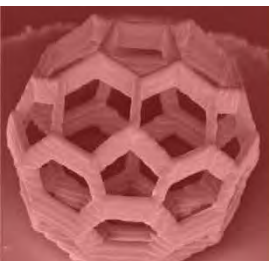
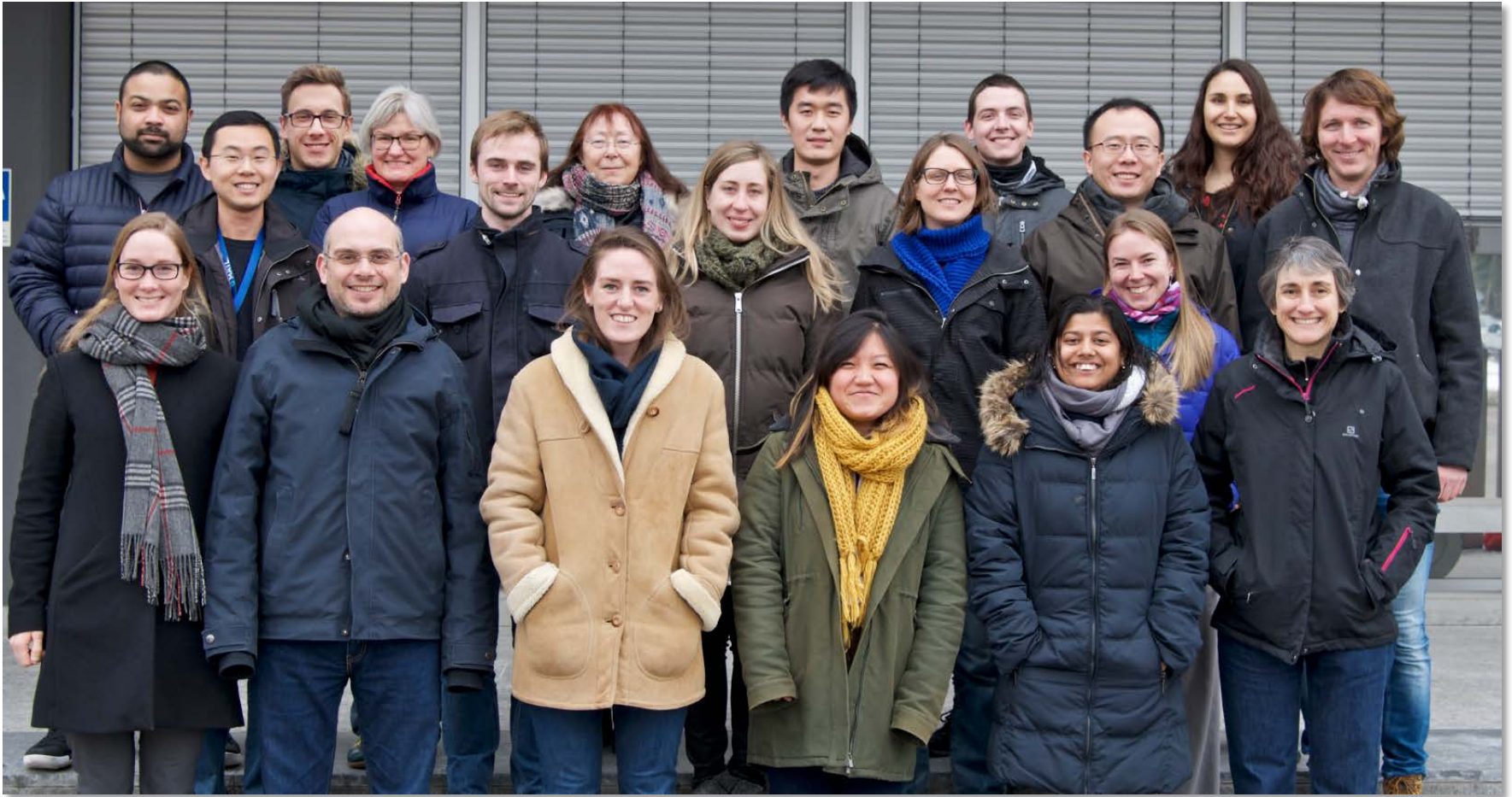
Magnetic behaviour influenced by:

- Magnet dimensions → single domain or multidomain
- Intermagnet distance → dipolar coupling ($\sim 1/r^3$)
- Material (M_s), dimensions & thickness → energy barrier & dipolar coupling
- Connected network → reversal by DW propagation

Acknowledgements



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



Mesoscopic Systems
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**Research & Technical Staff, Paul Scherrer Institute
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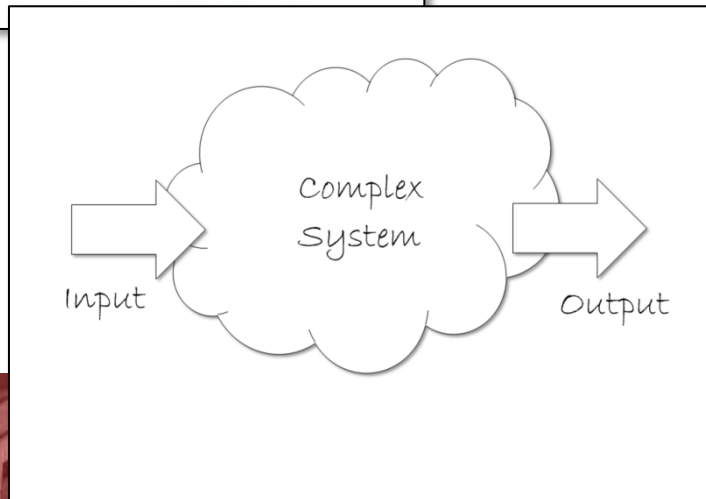
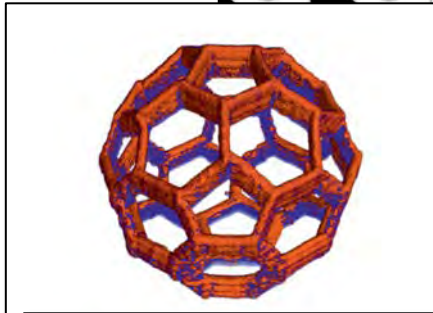
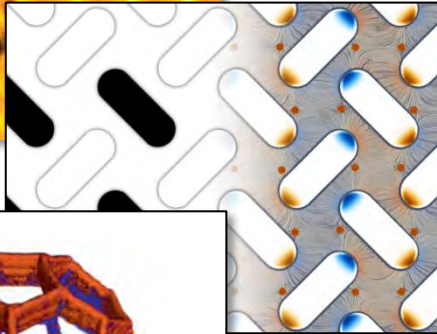
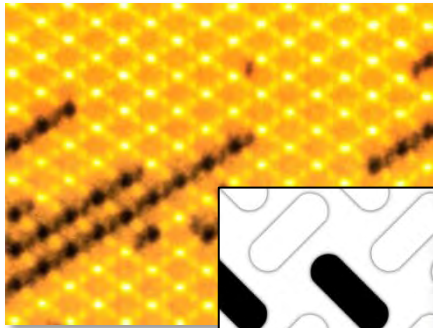
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1. Emergent magnetic monopoles in Artificial Spin Ice
2. Chirality Control
3. 3D magnetic systems
4. Towards Bioinspired Computation

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

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