Thermally active two dimensional artificial spin-ice systems: experiment and simulation

Peter M. Derlet
Condensed Matter Theory Group
Paul Scherrer Institute
Switzerland

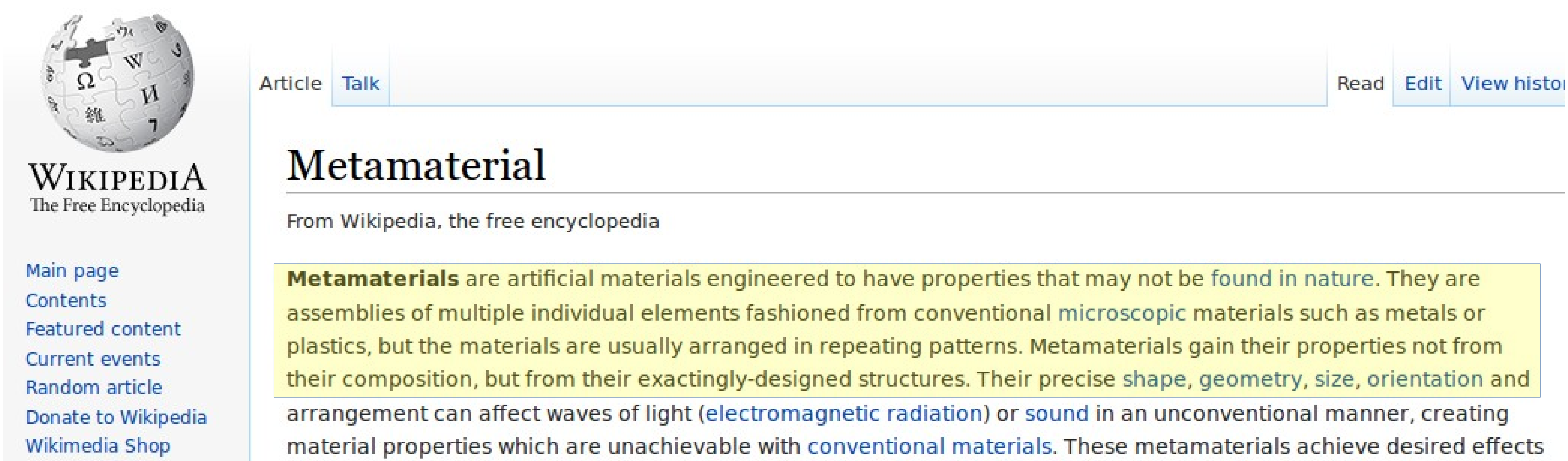
Collaborators

Collaborators:	Prof. Laura Heyderman Alan Farhan Luca Anghinolfi Valerio Scagnoli Oles Sendetskyi Sebastian Gliga	PSI-SYN-LMN/ETHZ → electron beam lithography & experiments
	Prof. Frithjof Nolting Armin Kleibert Ana Balan	PSI-SYN-LSC → PEEM/XMCD experiments
	Hubertus Luetkens	PSI-NUM-LMU → Muon spectroscopy experiments
	Tom Fennel	PSI-NUM-LNS → Discussions
	Steven Lee	Uni St. Andrews, UK → neutrons and SQUID

Talk overview

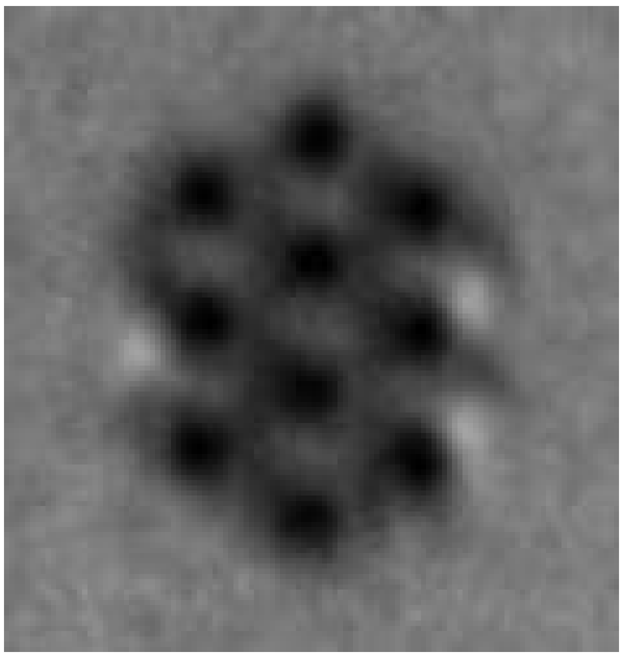
- Experiment & Simulation – our general approach
- Kagome building blocks
- Kagome lattice
- Square lattice
- Future directions & concluding remarks

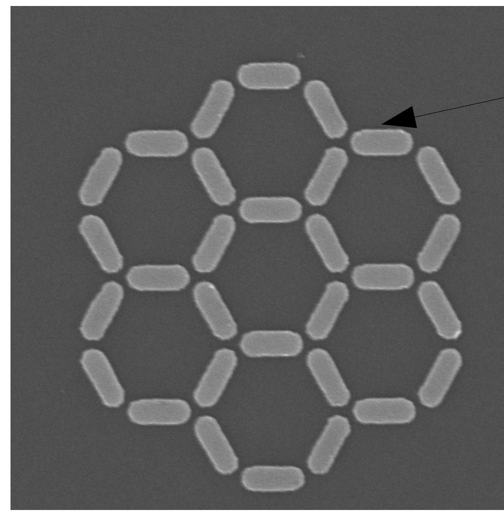
To demonstrate a meta-material approach to constructing, observing and understanding novel mesoscopic magnetic systems.

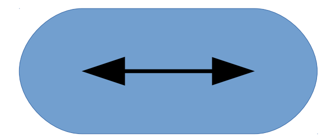


Experiment & Simulation

Experimental context: thermally active and dipolar interacting nano-magnets







Shape anisotropy leads to an in-plane magnetic moment whose direction is parallel/anti-parallel to the axial length

$$\text{island length} \times \text{width} \times \text{height} \simeq 470 \times 170 \times 3\text{nm}^3$$

XMCD/PEEM is used to spatially and temporally resolve magnetic degrees of freedom

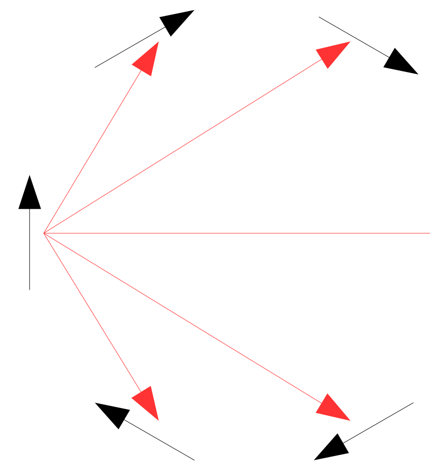
Experimental context: thermally active and dipolar interacting nano-magnets

$\text{island length} \times \text{width} \times \text{height} \simeq 470 \times 170 \times 3\text{nm}^3$?

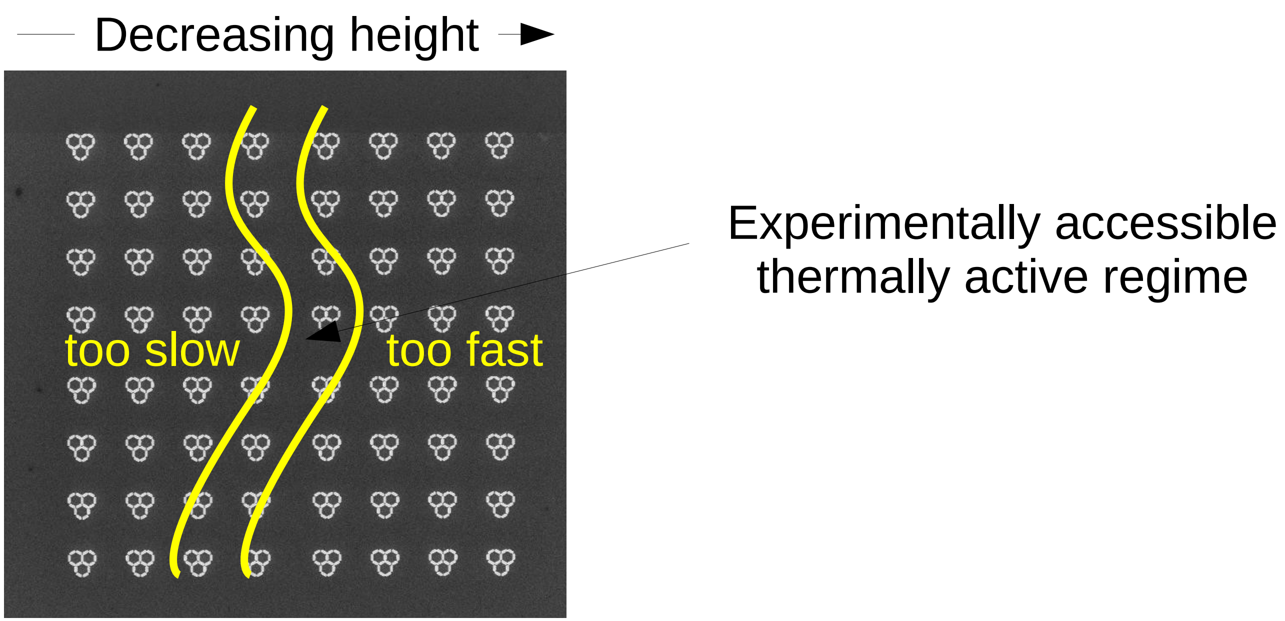
Islands feel each other via the dipolar interaction

$$V_{ij} = -\frac{\mu_0 (M_s \Delta V)^2}{4\pi} \frac{3(\hat{\mathbf{m}}_i \cdot \hat{\mathbf{e}}_{ij})(\hat{\mathbf{m}}_j \cdot \hat{\mathbf{e}}_{ij}) - \hat{\mathbf{m}}_i \cdot \hat{\mathbf{m}}_j}{r_{ij}^3}$$

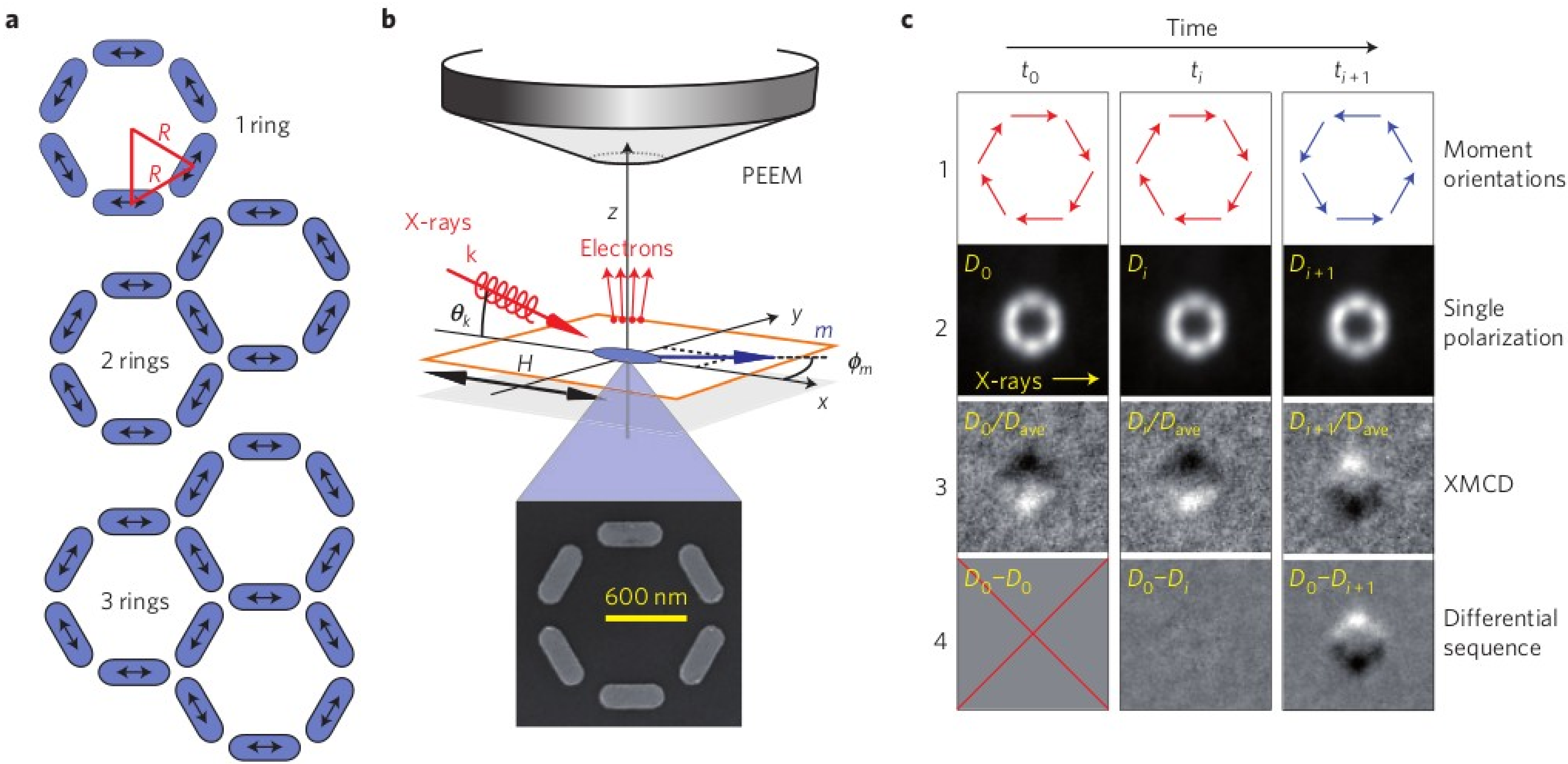
The island length, width and island-island separation were chosen to optimize the dipolar energy scale.



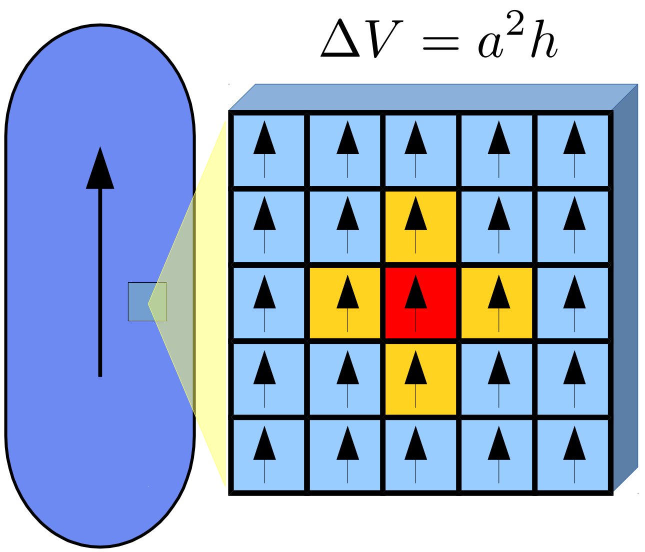
Produce a wedge of Permalloy and look at which thicknesses the systems are thermally active under ambient conditions



PEEM/XMCD experiments – real space resolution of magnetic DOF



Simulation strategy: magneto-statics



Magnetic energy is obtained numerically via 2D discretization of magnetization into microscopic interacting magnetic moments

$$E_{\text{ex}} = -\frac{2A\Delta V}{a^2}\sum_{i<j}\hat{\mathbf{m}}_i\cdot\hat{\mathbf{m}}_j$$

intra-island elements
→ internal relaxation

$$E_{\text{dip}} = -\frac{\mu_0(M_{\text{s}}\Delta V)^2}{4\pi}\sum_{i<j}\frac{3(\hat{\mathbf{m}}_i\cdot\hat{\mathbf{e}}_{ij})(\hat{\mathbf{m}}_j\cdot\hat{\mathbf{e}}_{ij})-\hat{\mathbf{m}}_i\cdot\hat{\mathbf{m}}_j}{r_{ij}^3}$$

intra- and inter-island elements
→ shape anisotropy and internal relaxation

$$E_{\text{ex}} \sim \frac{A\Delta V}{a^2} = Ah$$

$$E_{\text{dip}} \sim \mu_0\frac{(M_{\text{s}}\Delta V)^2}{a^3} = \mu_0 M_{\text{s}}^2 a h^2$$

$$\frac{E_{\text{ex}}}{E_{\text{dip}}} \sim \frac{1}{h}$$

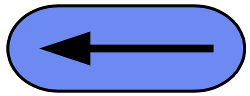
With decreasing height, exchange will dominate internal structure → the exchange energy is frozen out → the energy scale is controlled by the inter-island dipolar energy:

$$E_{\text{dip}} \sim (M_{\text{s}}\Delta V)^2 \sim M_{\text{s}}^2$$

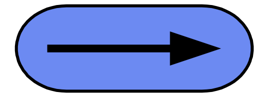
the important material parameter

Simulation strategy: nano-magnet moment reorientation

Over a restricted temperature range, assume reorientation rate is Arrhenius.

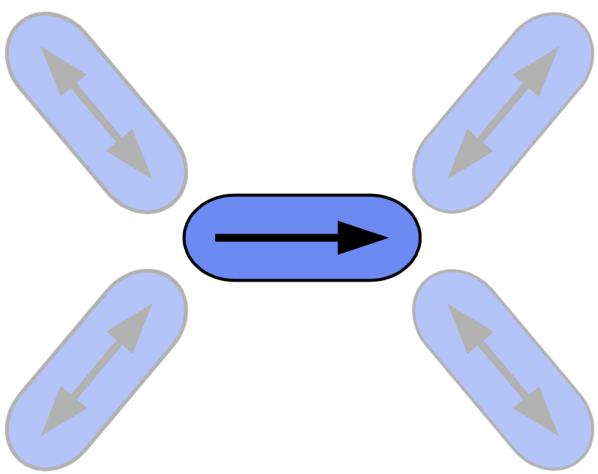


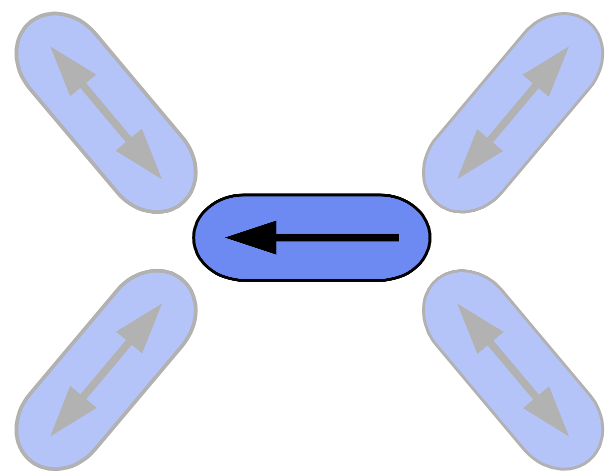
$$\Gamma = \nu_0 \exp\left(-\frac{E_0}{k_{\mathrm{b}T}}\right)$$



E_0, ν_0 : Isolated nano-magnet energy barrier and attempt rate

Due to the inter-island dipolar interaction, the barrier energy of each nano-magnet will also depend on the change in magnetic energy associated with the reorientation

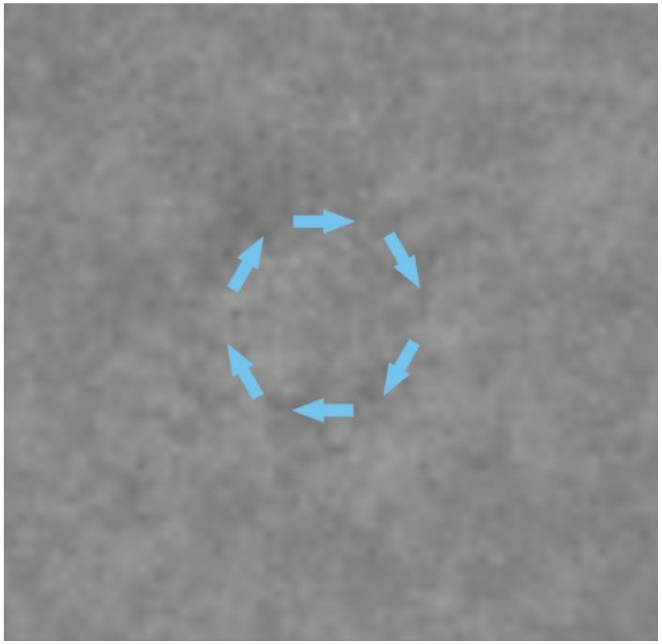




$$E_i = E_0 + \frac{E_{\mathrm{final}} - E_{\mathrm{initial}}}{2}$$

Kagome building blocks

Kagome building blocks: a single ring

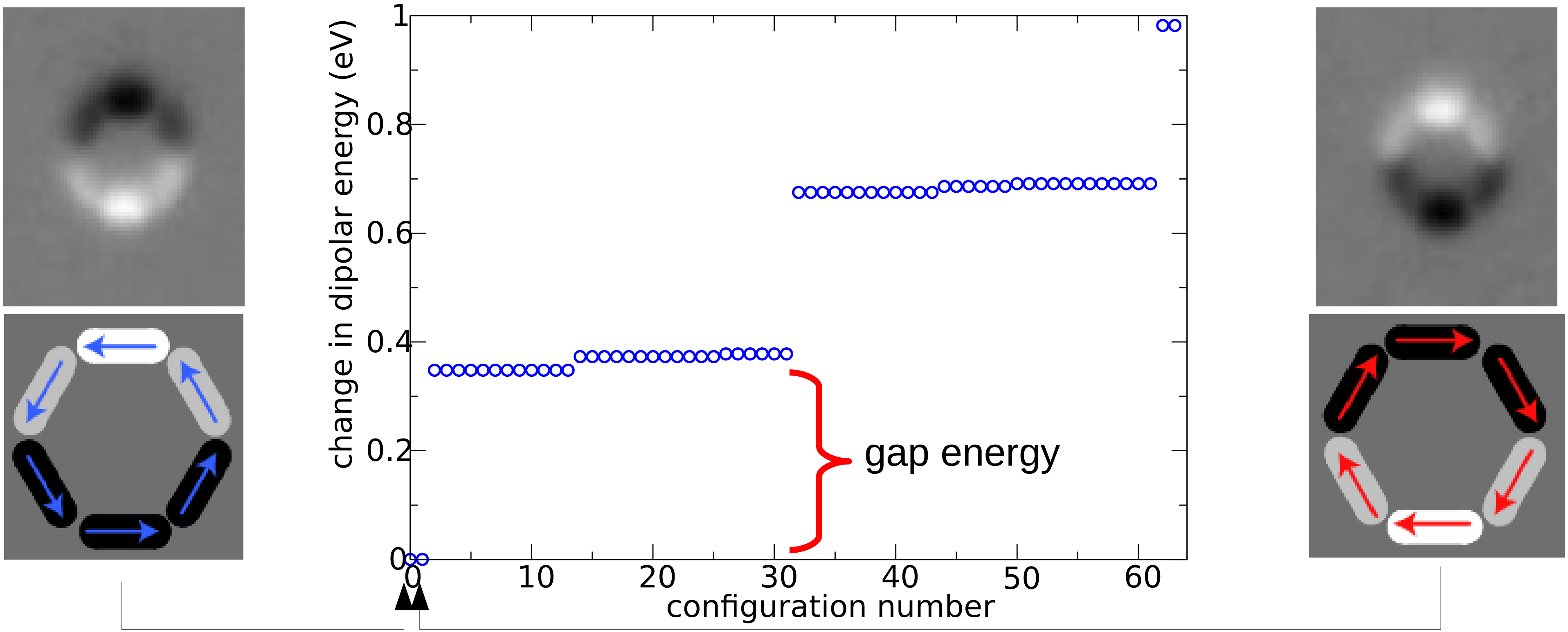


Difference image → relative to the initial clockwise ground state

Experimentally, the single ring is seen to collectively flip between its two lowest energy states.

Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Anghinolfi L, Nolting F, Heyderman LJ, Nature Physics 9, 375, 2013

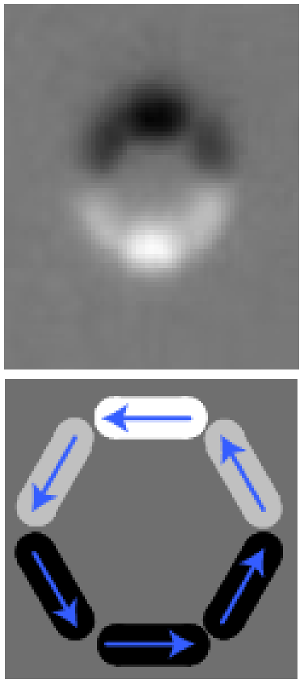
Kagome building blocks: a single ring

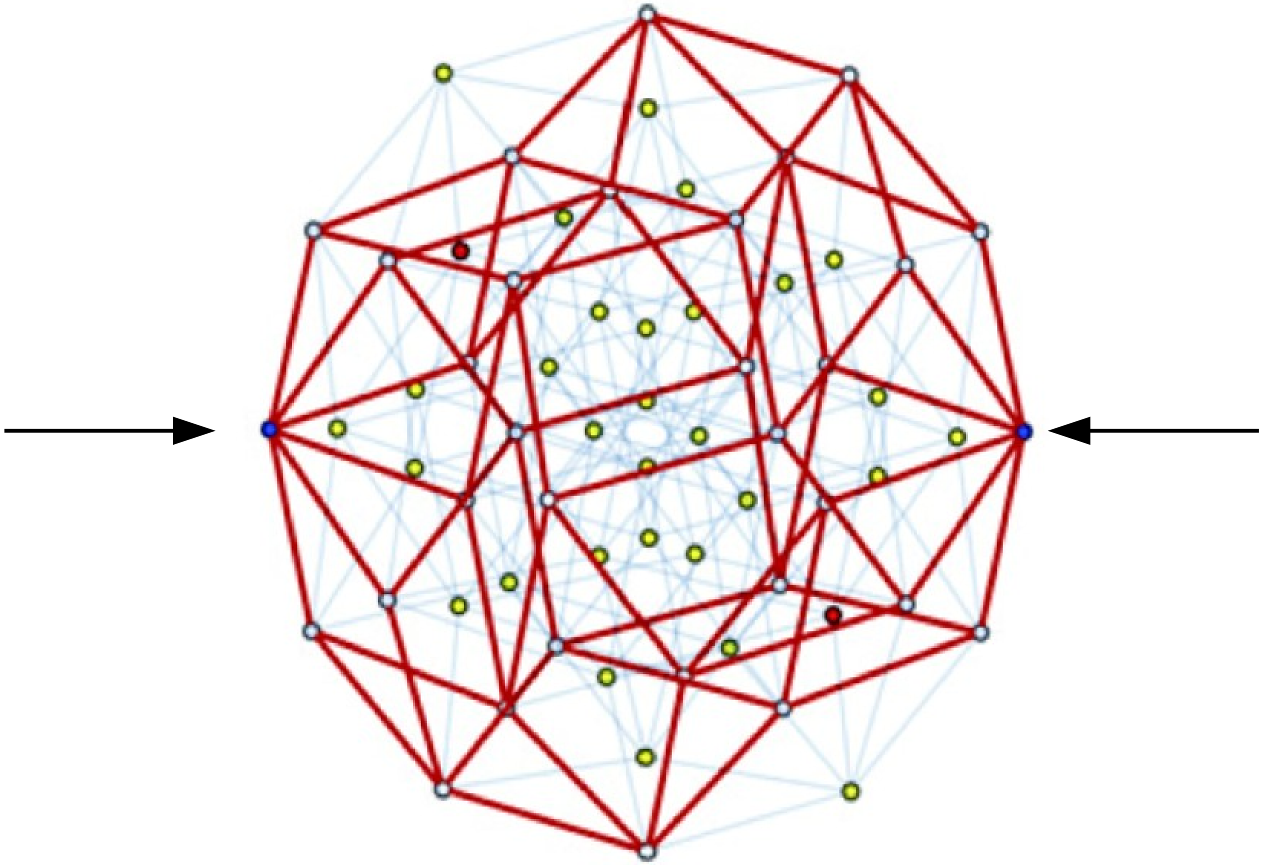


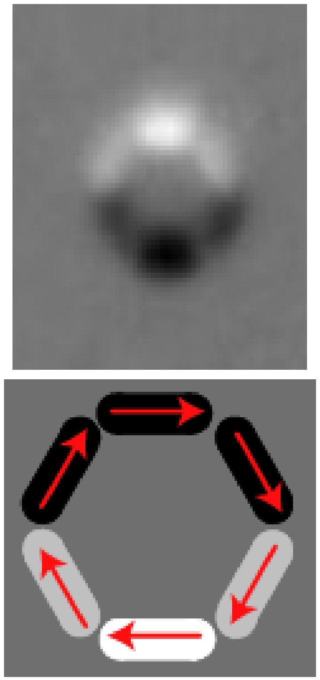
→ the collective reorientation is mediated by single nano-magnet reorientations

Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Anghinolfi L, Nolting F, Heyderman LJ, Nature Physics 9, 375, 2013

Kagome building blocks: a single ring



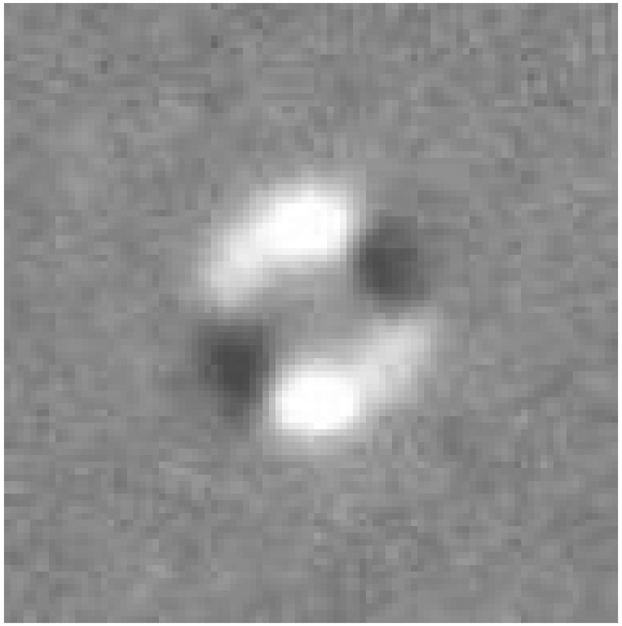


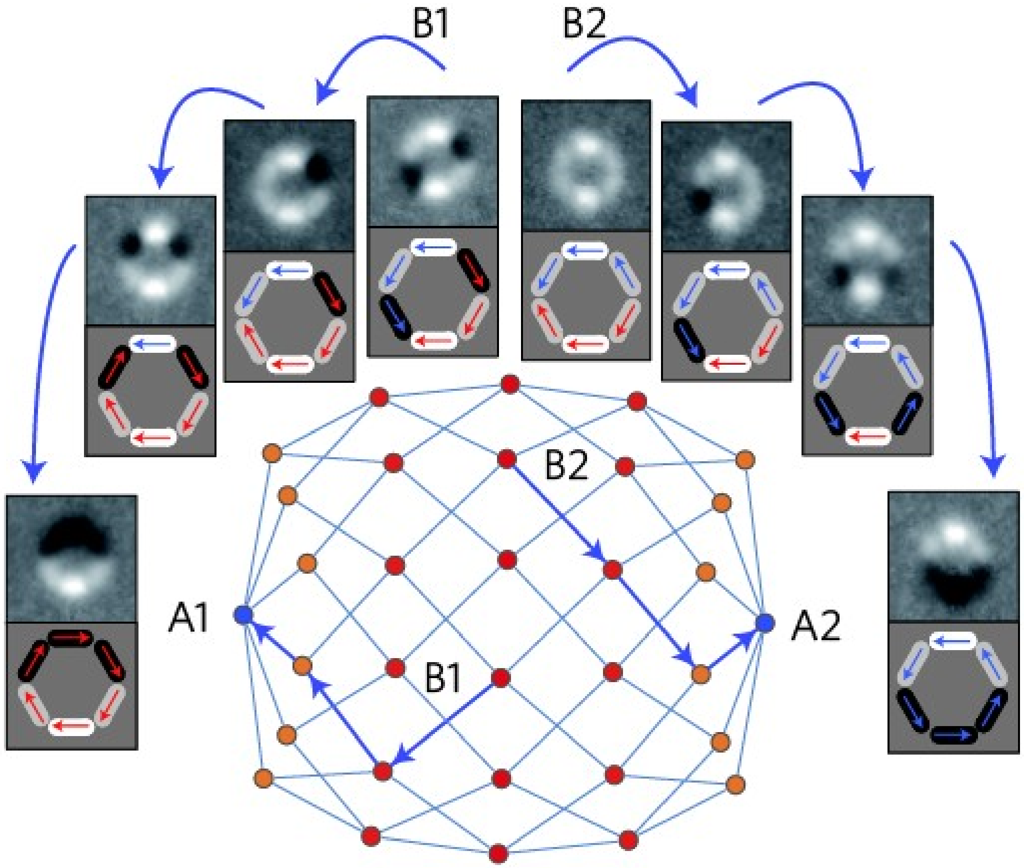


6-dimensional hyper-cube visualizes the potential energy landscape

Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Anghinolfi L, Nolting F, Heyderman LJ, Nature Physics 9, 375, 2013

Kagome building blocks: a single ring

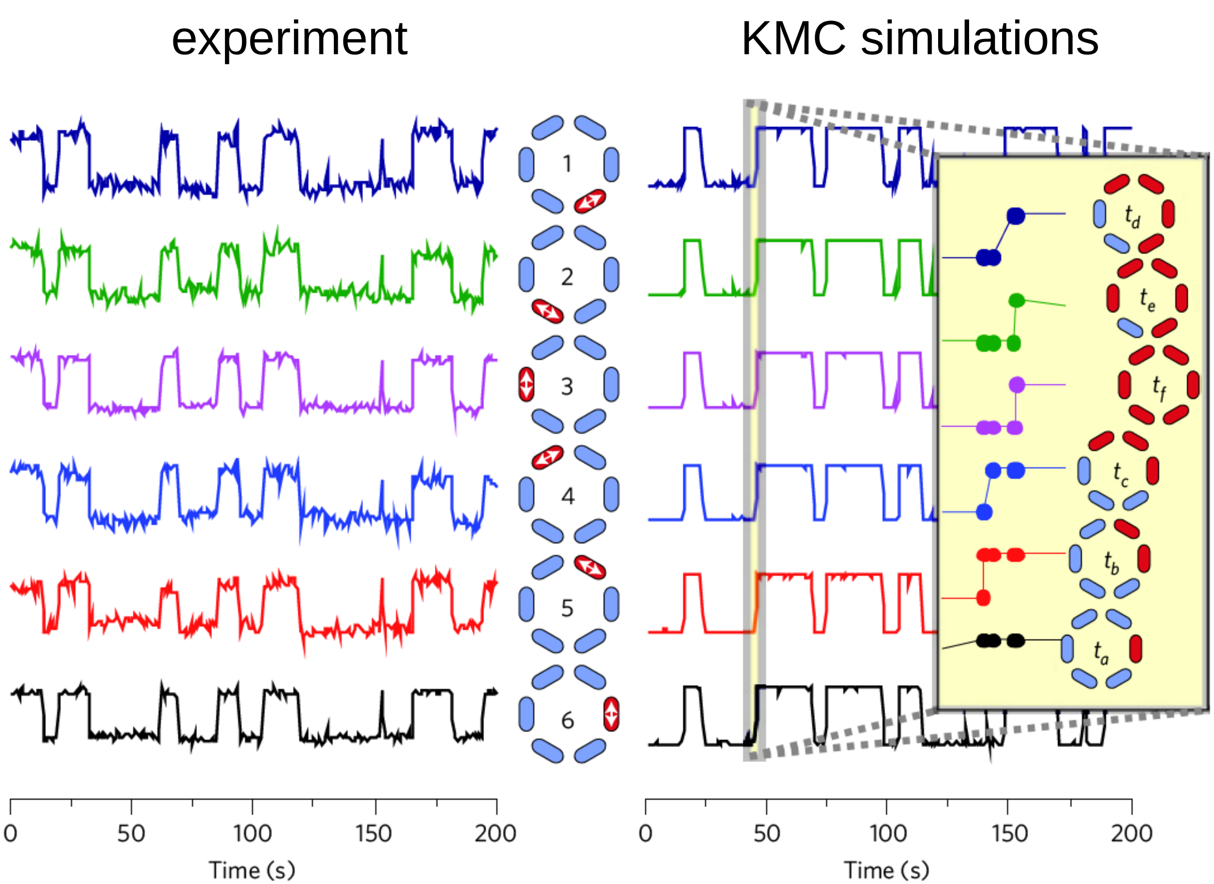




At lower temperature can observe how the system relaxes to one of the lowest energy configurations

Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Anghinolfi L, Nolting F, Heyderman LJ, Nature Physics 9, 375, 2013

Kagome building blocks: a single ring



$$\nu_0 = 1 \times 10^{12}\ \mathrm{s}^{-1}$$
$$E_0 = 0.952\ \mathrm{eV}$$
$$M_\mathrm{s} = 200\ \mathrm{kA/m}$$

At a higher temperature the system flips “collectively” between these two lowest energy configurations

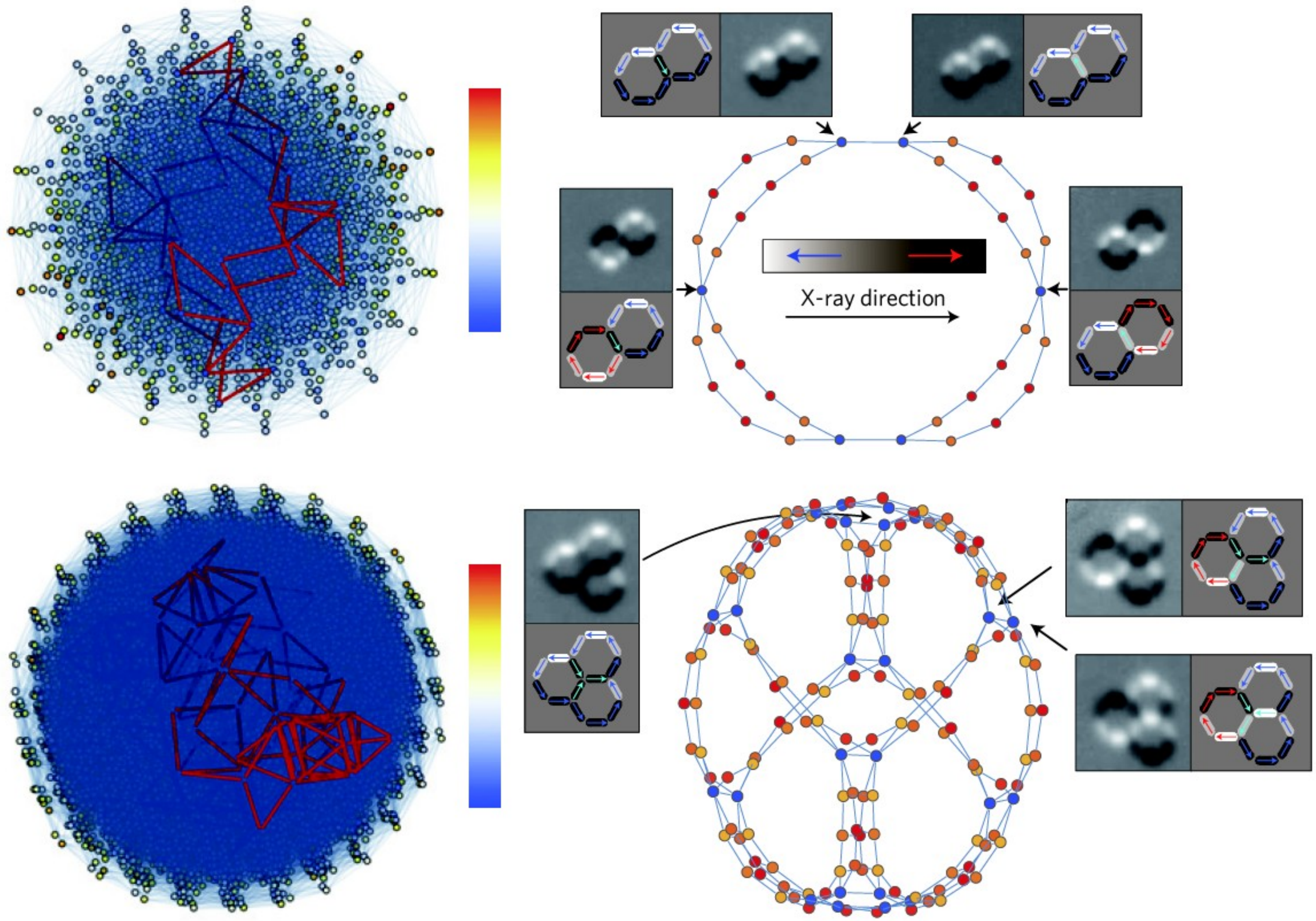
Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Anghinolfi L, Nolting F, Heyderman LJ, Nature Physics 9, 375, 2013

Kagome building blocks: two and three rings

Collective re-orientations are observed only at the edges, whilst the inner islands re-orient individually (and at a faster rate)

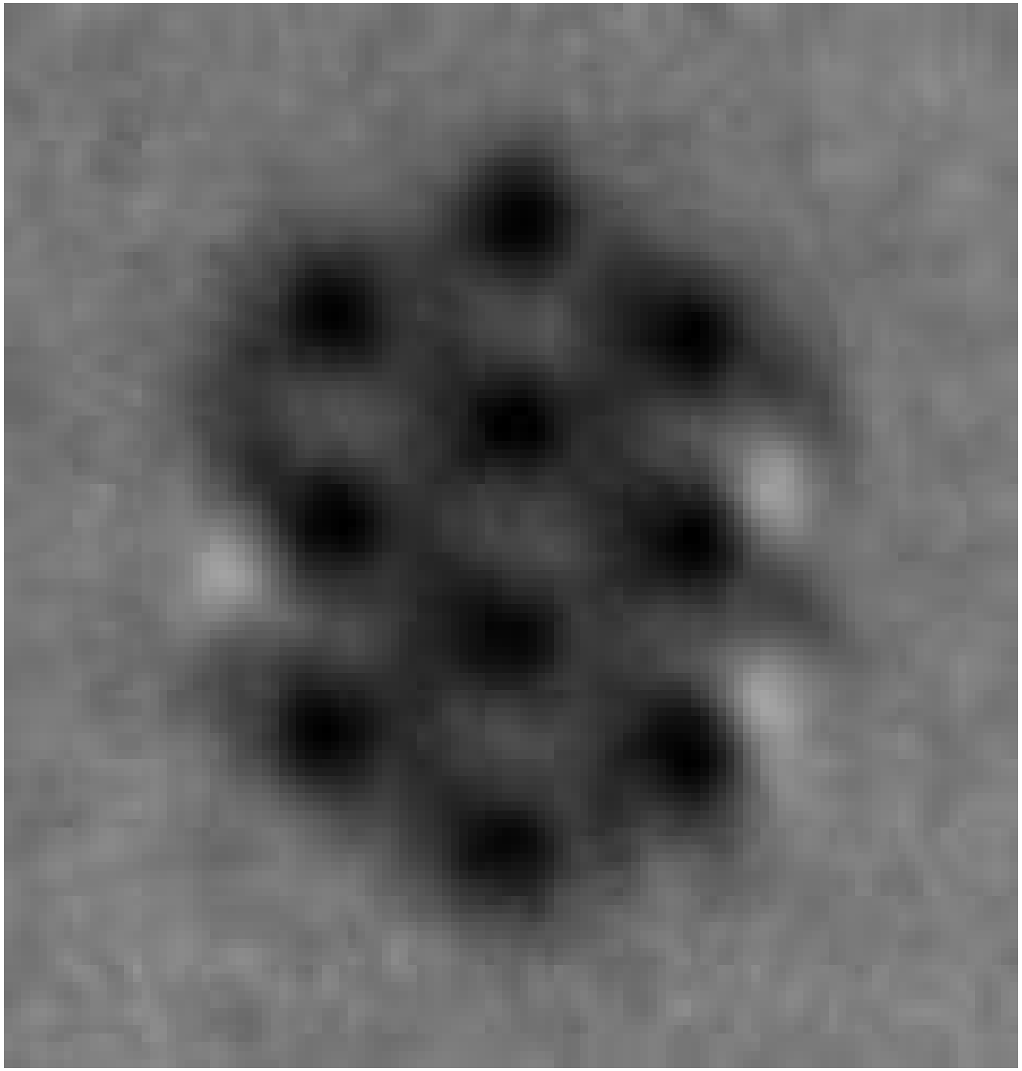
2^{11} states

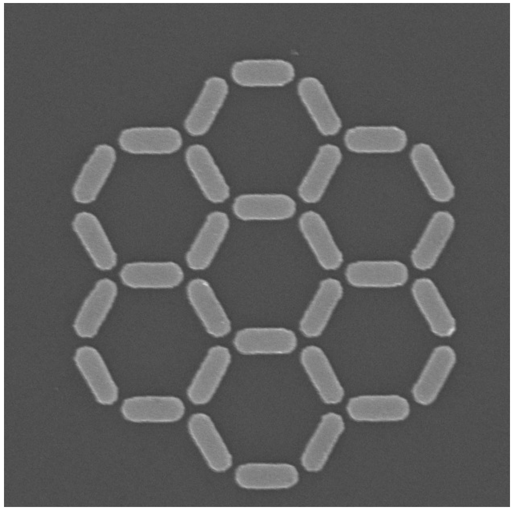
2^{15} states



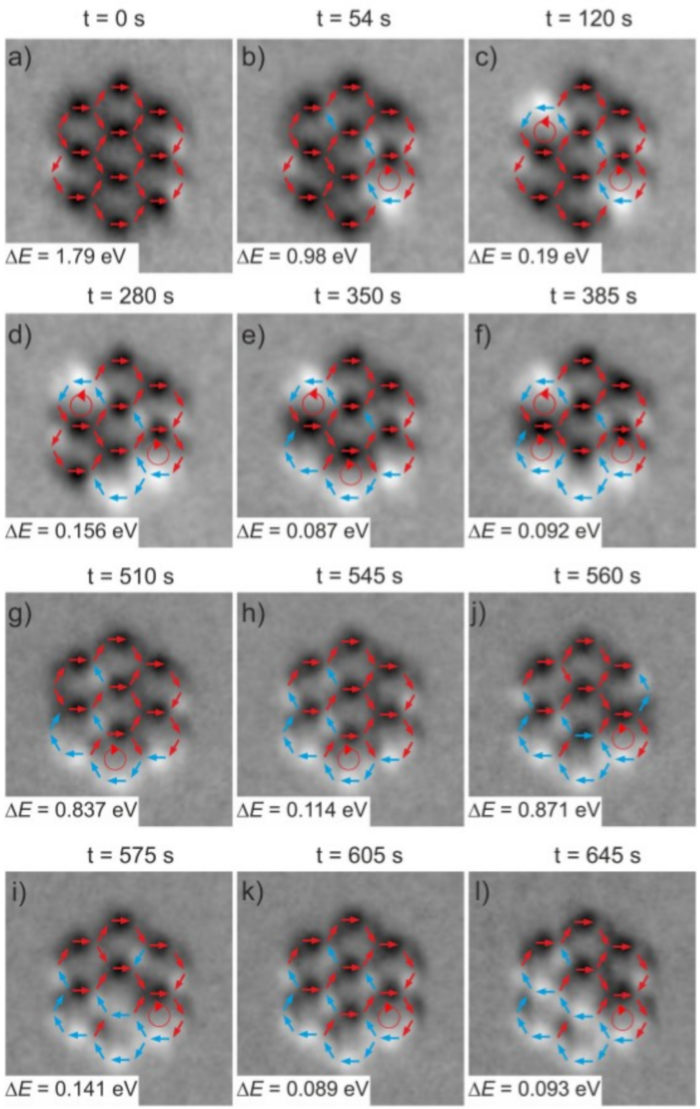
Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Anghinolfi L, Nolting F, Heyderman LJ, Nature Physics 9, 375, 2013

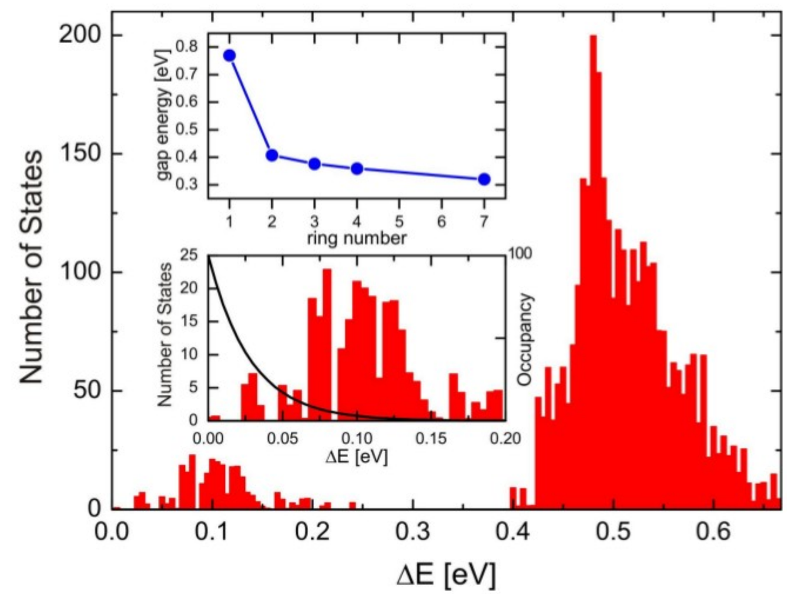
Kagome building blocks: seven rings

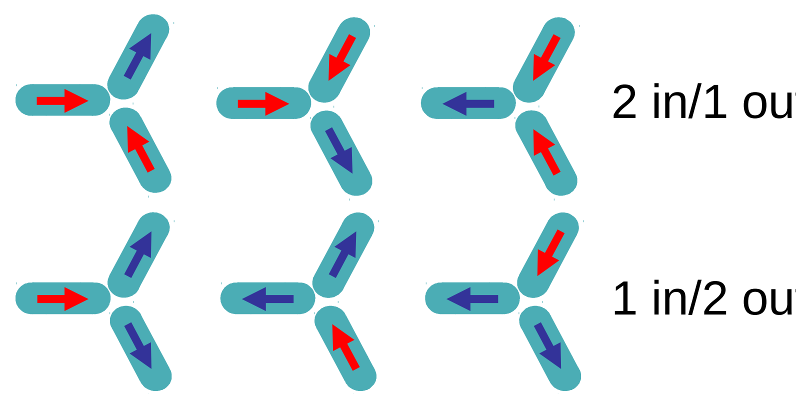




Kagome building blocks: seven rings



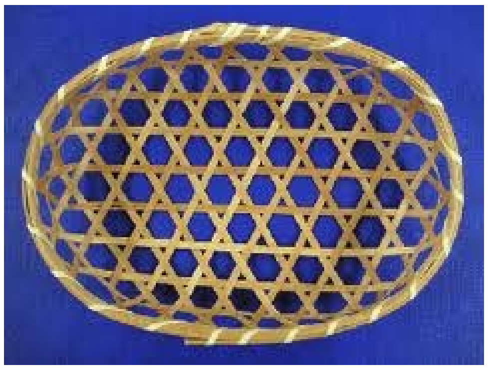


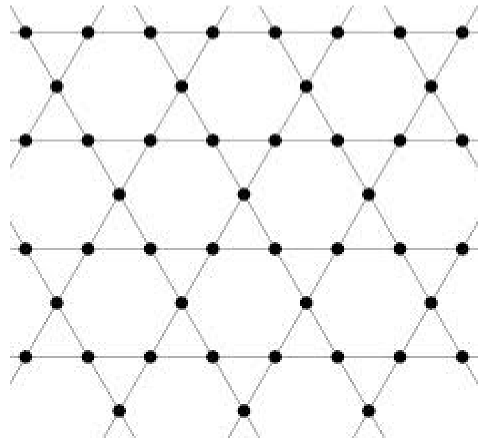


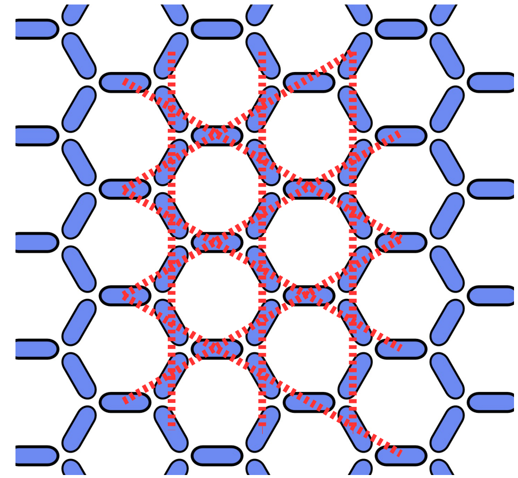
A Farhan, A Kleibert, PMD, L Anghinolfi, A Balan, R. V. Chopdekar, M. Wyss, S. Gliga, F Nolting, and L. J. Heyderman, Phys. Rev. B 89, 214405 (2014).

Kagome lattice

The kagome lattice

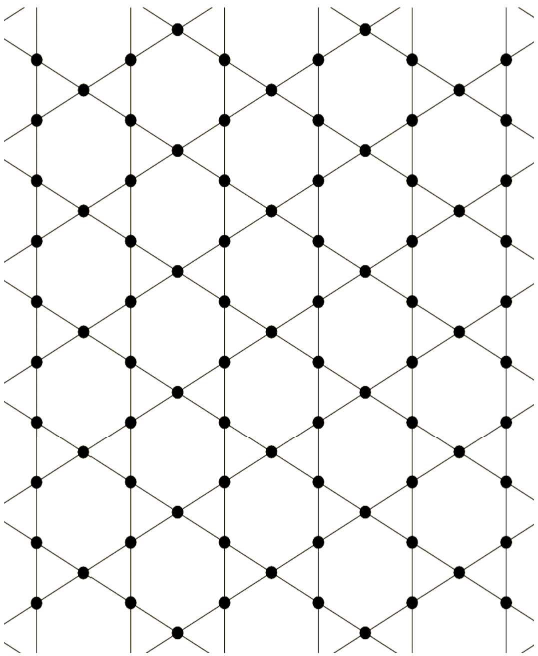


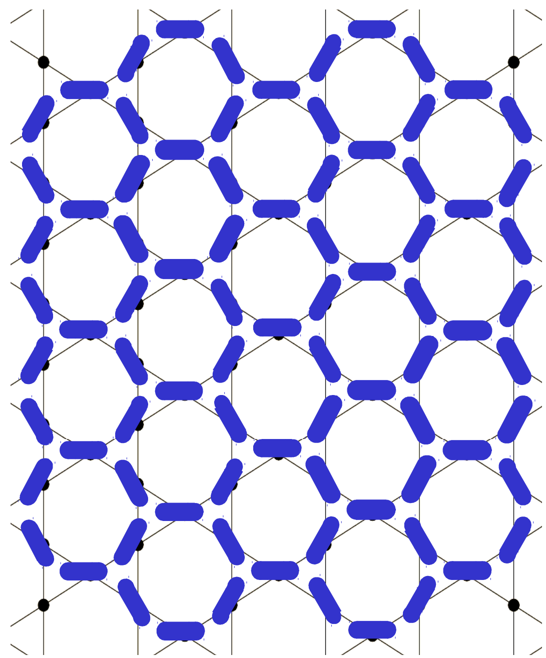




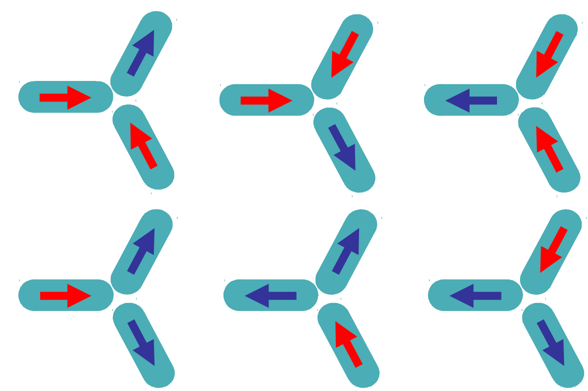
Kagome (籠目) is a traditional Japanese woven bamboo pattern; its name is composed from the words kago, meaning "basket", and me, meaning "eye(s)", referring to the pattern of holes in a woven basket.

The kagome lattice: geometry and exponential degeneracy





Spin-ice rule (minimizes nn dipolar energy)



2 in/1 out

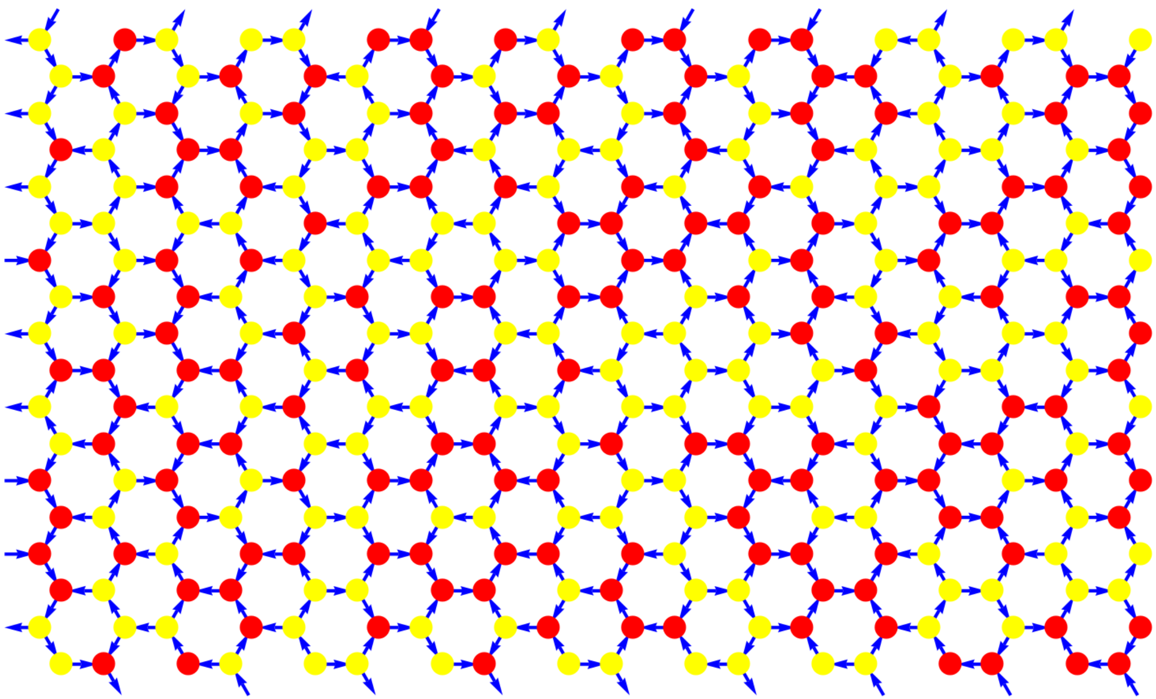
1 in/2 out

Within the lattice there will exist an exponential number of spin-ice configurations.

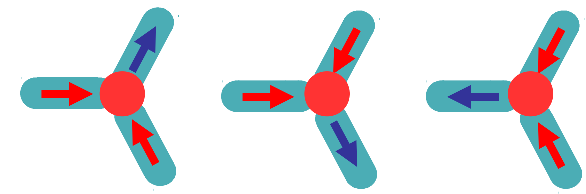
$$\exp(\alpha N) \quad \alpha = \frac{S_\mathrm{c}}{k_\mathrm{B}} \simeq \frac{2}{3} \ln \frac{3}{\sqrt{2}} \simeq 0.723 \ln 2$$

Perfect exponential degeneracy will occur if each island only interacts with its neighbours → “classical spin liquid” (cooperative paramagnet) down to zero temperature

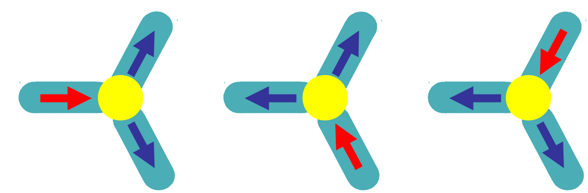
In 2D, magnetic charges everywhere



2 in/1 out → +1 magnetic charge

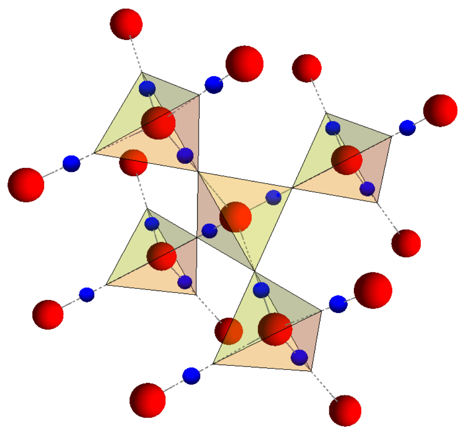


2 out/1 in → -1 magnetic charge

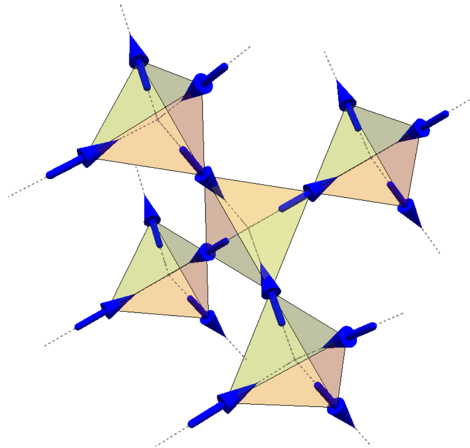


Kagome spin ice configuration → a (parent) honeycomb lattice of magnetic charges

A short aside: 3D spin-ice systems



Water ice



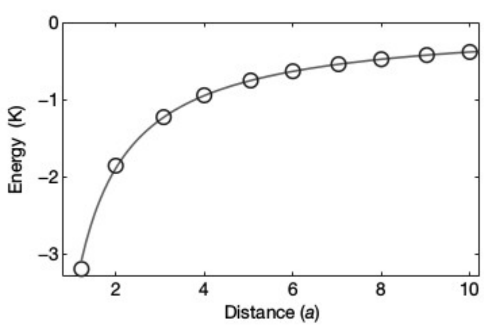
Spin ice

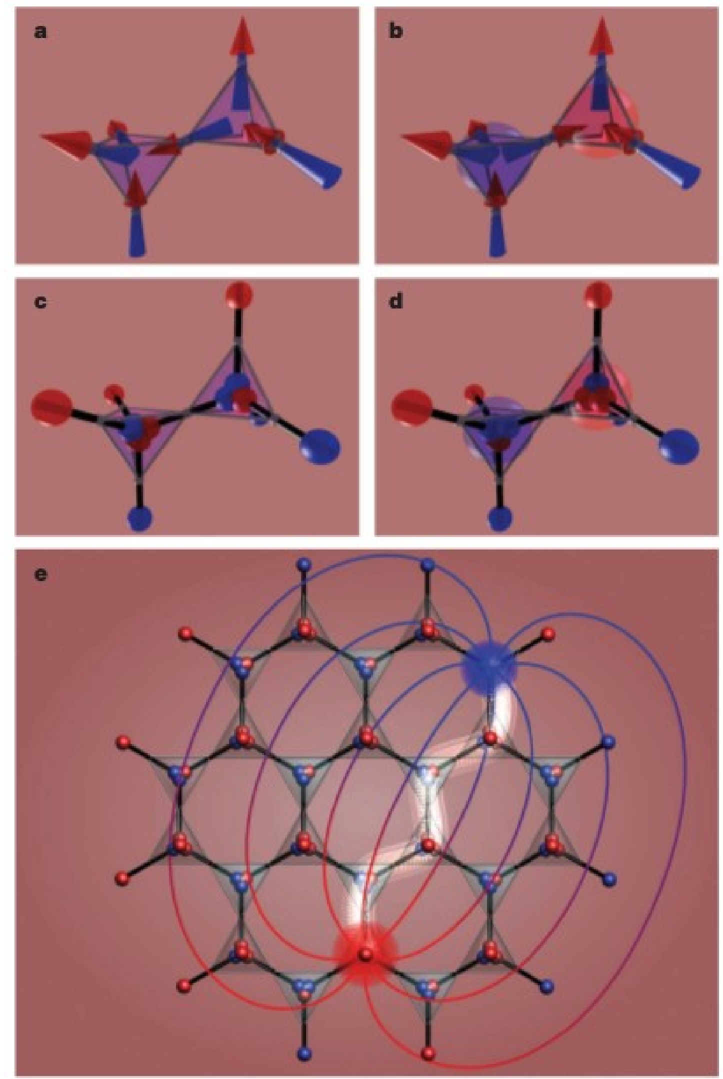
nature Vol 451 | 3 January 2008 | doi:10.1038/nature06433

LETTERS

Magnetic monopoles in spin ice

C. Castelnovo[1], R. Moessner[1,2] & S. L. Sondhi[3]

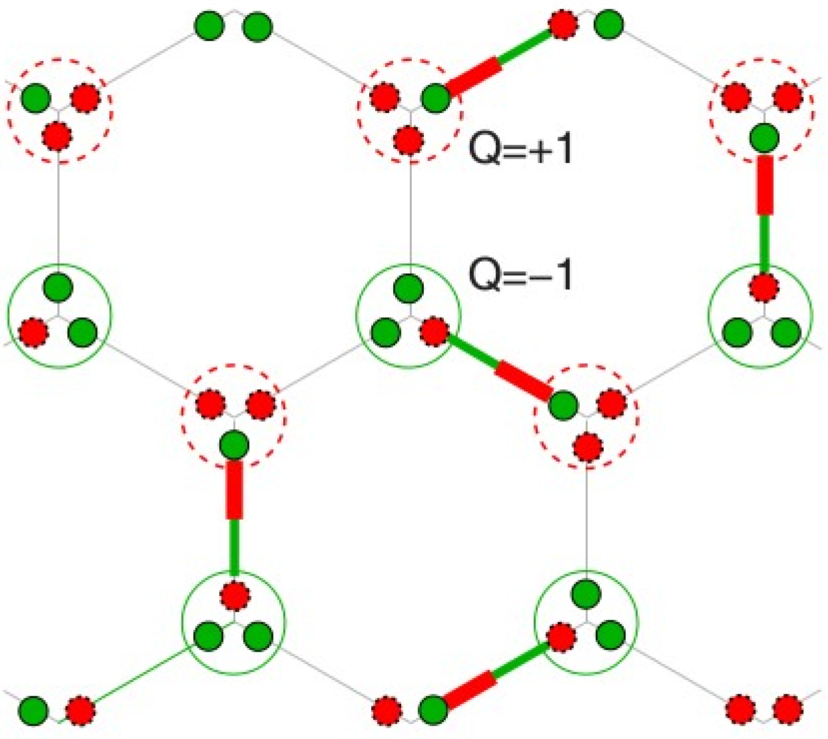




C. Castelnovo, R. Moessner & S. L. Sondhi, Nature 451, 42 (2008).

Kagome dipolar lattice & magnetic charges

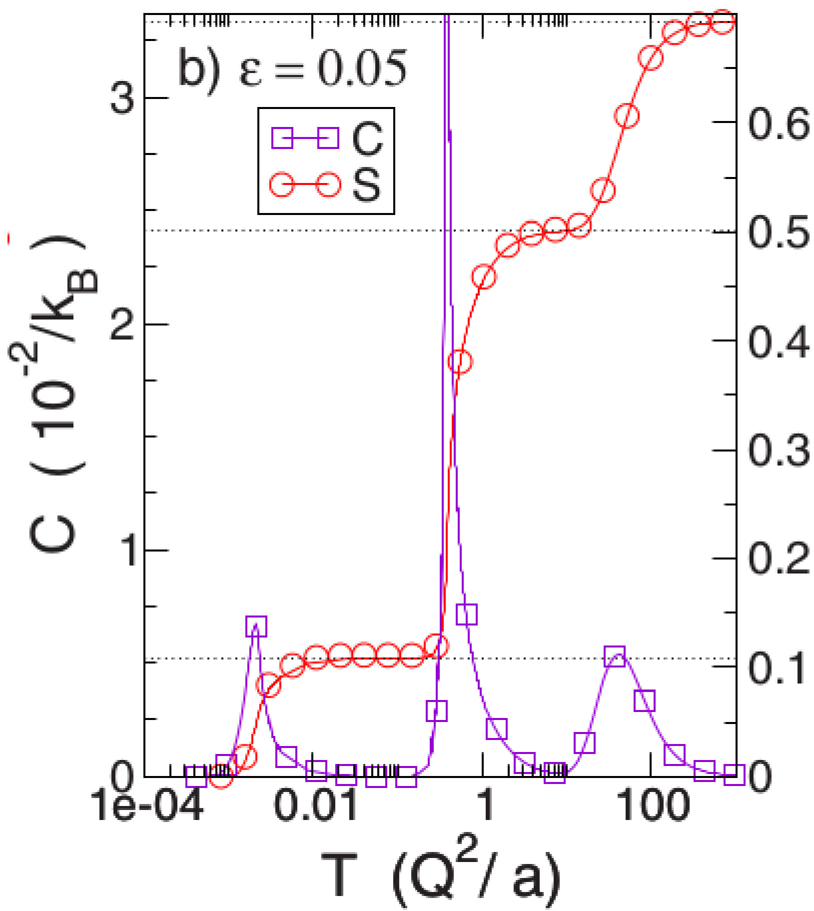
Each island is treated as an infinitesimally thin compass needle → a dipole of magnetic charge.

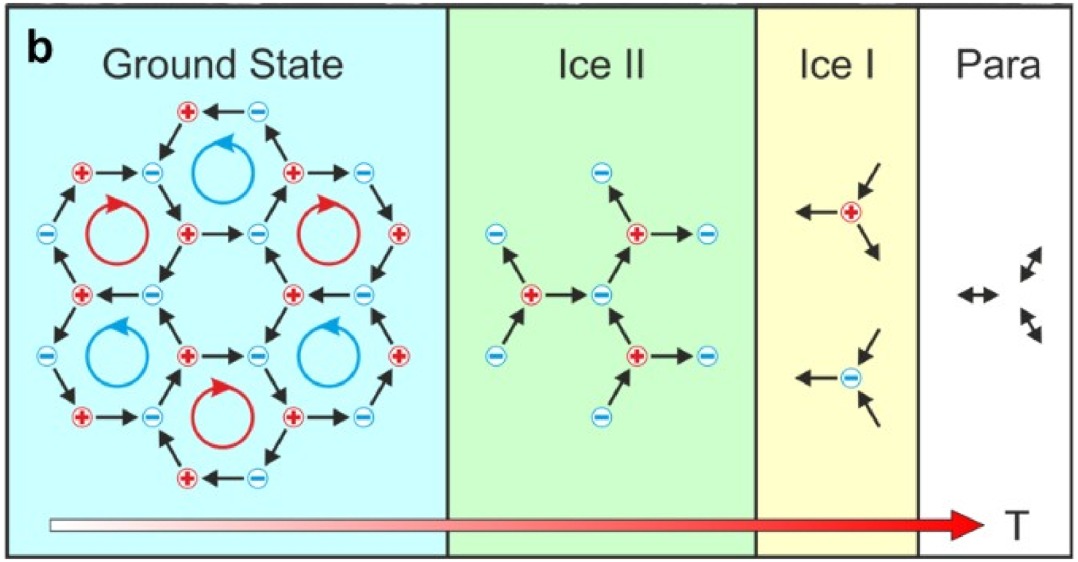


A parent honeycomb lattice of magnetic charge.

G. Möller & R. Moessner, PRB 80, 140409(R) (2009).

A hierarchy of interactions/phases



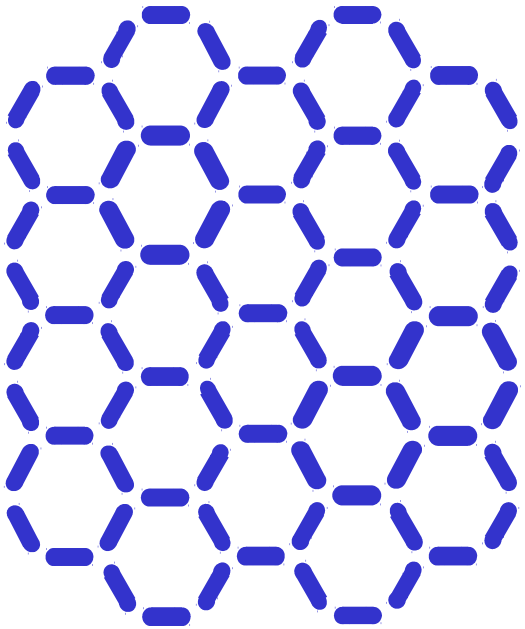


$$E = \frac{q^2}{a}\left\{ \frac{-2}{\sqrt{3}\epsilon} + \left(\frac{3}{2} - \frac{\alpha}{2}\right) + \frac{3}{2}\epsilon + \left(\gamma + \frac{\delta}{4} + \frac{3}{2}\right)\epsilon^2 \right\}$$

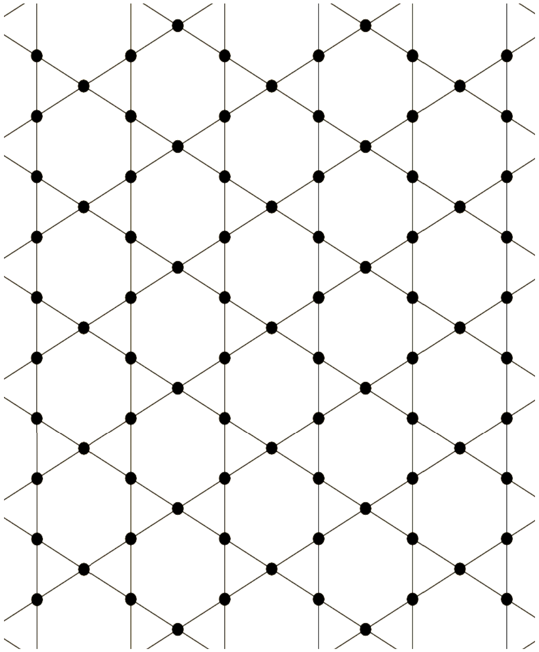
- Madelung term drives charge order (underlying spin disorder).
- Dipolar term drives spin order via flux closure of hexagons.

G. Möller & R. Moessner, PRB 80, 140409(R) (2009).

How we model the kagome system



Treat each nano-magnet as a point dipole



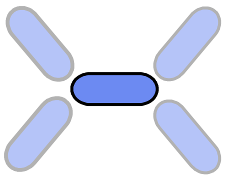
$$E_{\text{magnetic}} = -\frac{\mu_0 (M_{\text{s}} V_{\text{nanomagnet}})^2}{4\pi} \sum_{i<j} \frac{3(\hat{\mathbf{m}}_i \cdot \hat{\mathbf{e}}_{ij})(\hat{\mathbf{m}}_j \cdot \hat{\mathbf{e}}_{ij}) - \hat{\mathbf{m}}_i \cdot \hat{\mathbf{m}}_j}{r_{ij}^3}$$

$$E_{\text{magnetic}} = \sum_{i<j} J_{ij} \sigma_i \sigma_j$$

Ising-like Hamiltonian

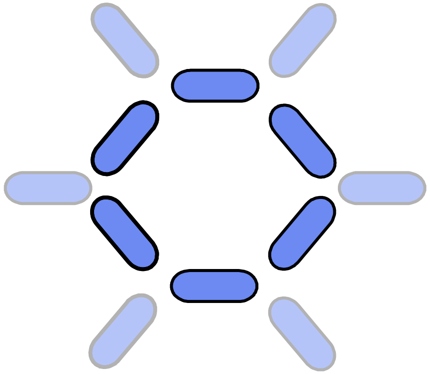
Modified MC to obtain the LRO phase

One site MC "sweep" involves N steps of:



1) Randomly choose a spin
2) Flip it and calculate the change in energy: ΔE
3) If energy decreases accept the flip, otherwise accept with probability:

$$\exp\left(\frac{-\Delta E}{k_b T}\right)$$

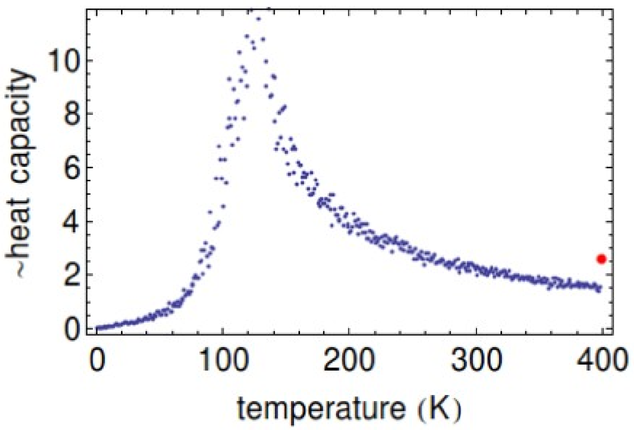


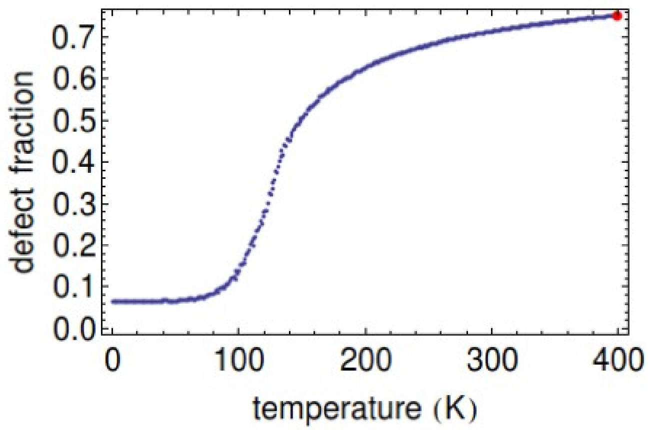
One cluster MC "sweep" involves N/3 steps of:

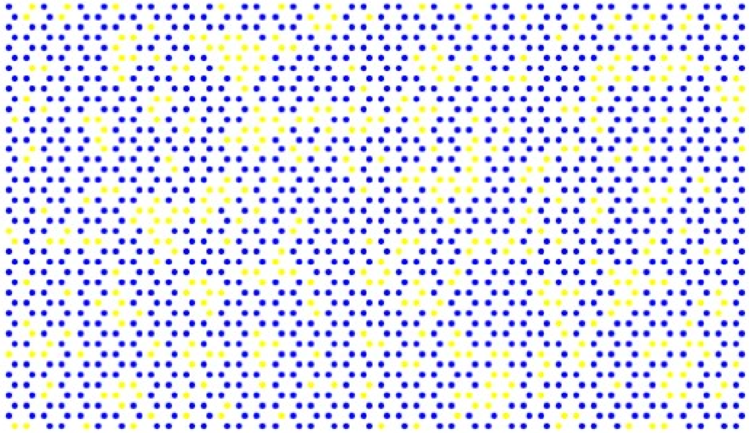
1) Randomly choose a hexagon
2) Flip all spins within the hexagon and calculate the change in energy: ΔE
3) If energy decreases accept the hexagon flips, otherwise accept with probability:

$$\exp\left(\frac{-\Delta E}{k_b T}\right)$$

(site) MC temperature quench

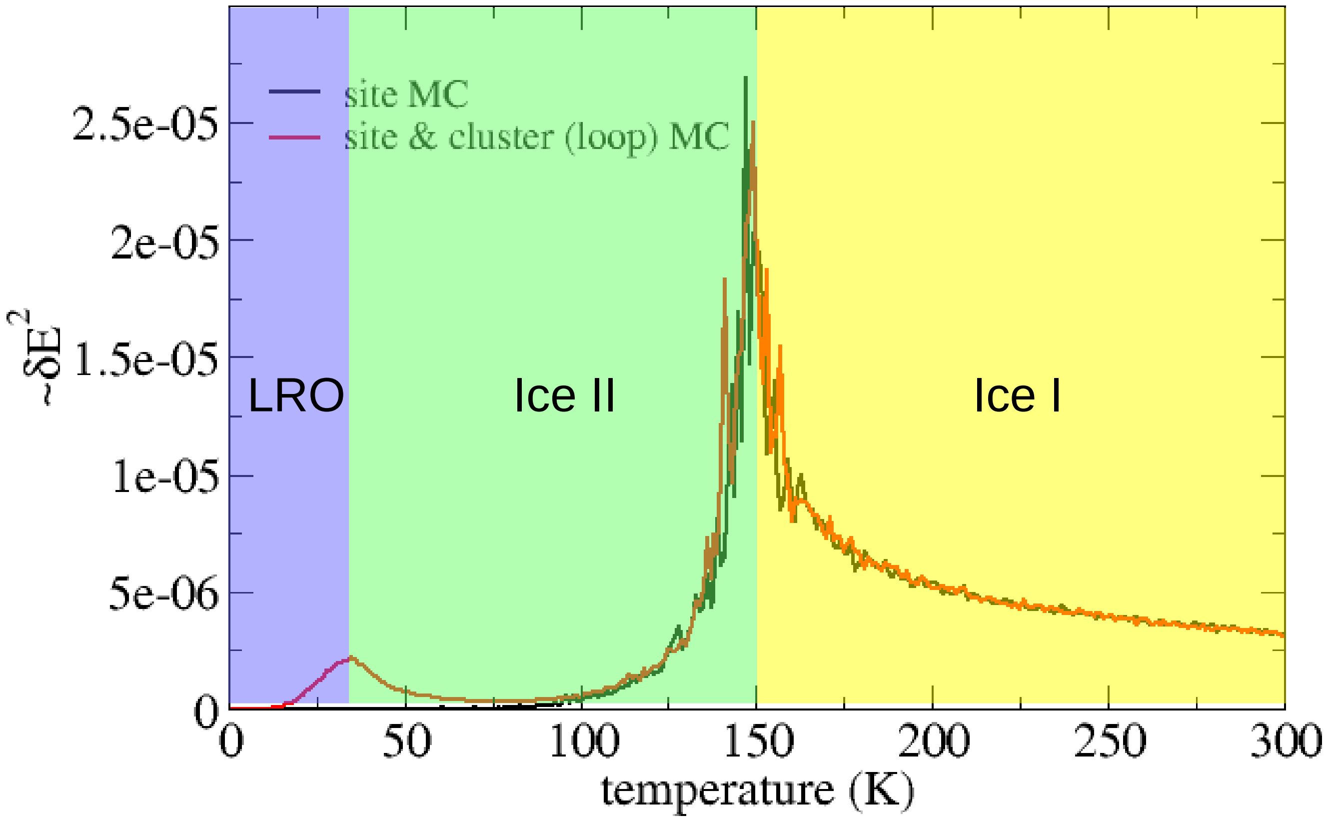






● → if a vertex is only surrounded by charges of opposite sign, otherwise ●

Site & cluster MC temperature quench



Cluster MC essential to obtain LRO phase

Can these phases be observed in extended artificial kagome systems?

LETTER

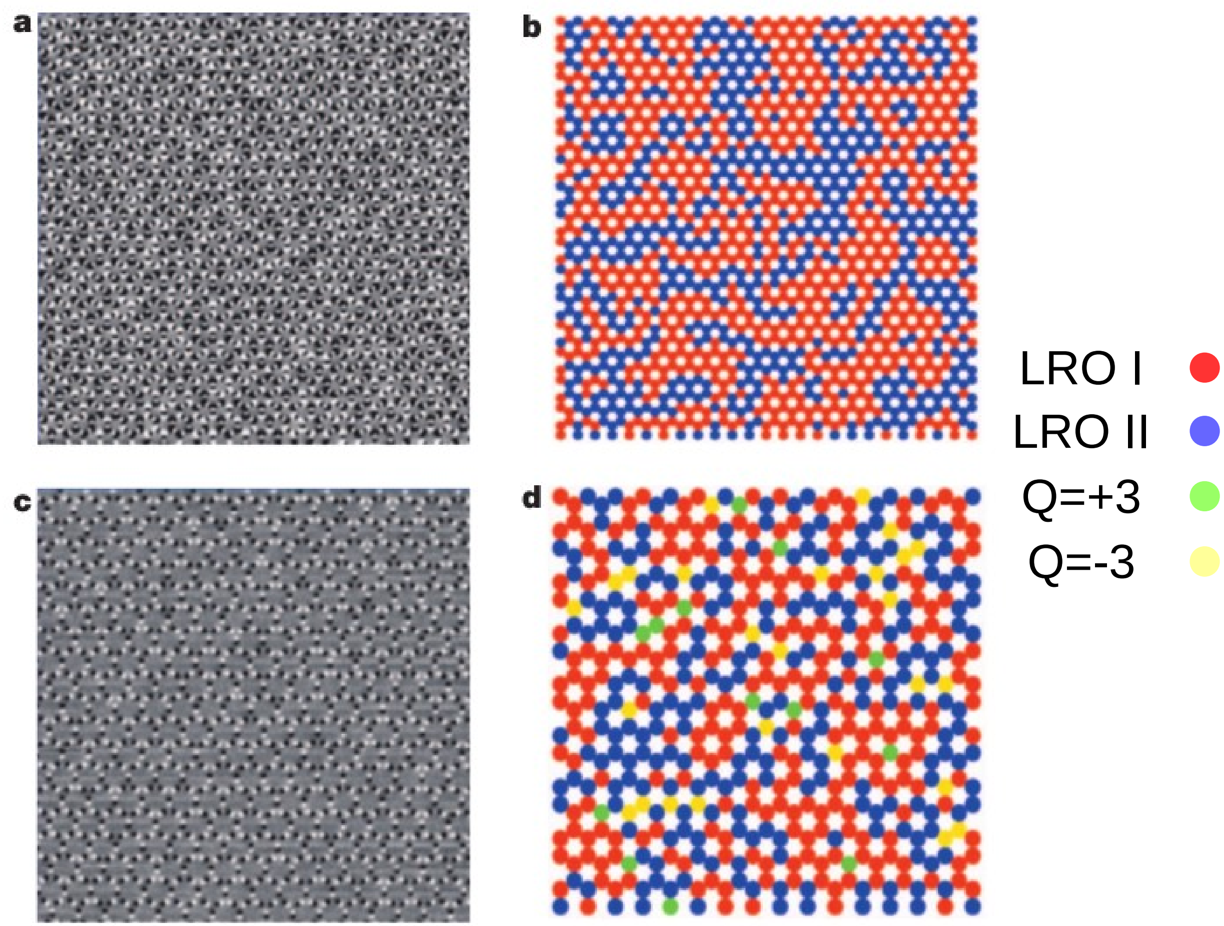
doi:10.1038/nature12399

Crystallites of magnetic charges in artificial spin ice

Sheng Zhang[1]*, Ian Gilbert[2]*, Cristiano Nisoli[3], Gia-Wei Chern[3], Michael J. Erickson[4], Liam O'Brien[4,5], Chris Leighton[4], Paul E. Lammert[1], Vincent H. Crespi[1] & Peter Schiffer[2]

The temperature is raised to the nanomagnets' Curie temperature, and then slowly quenched to ambient temperatures.

The resulting frozen configurations are representative of spin ice I



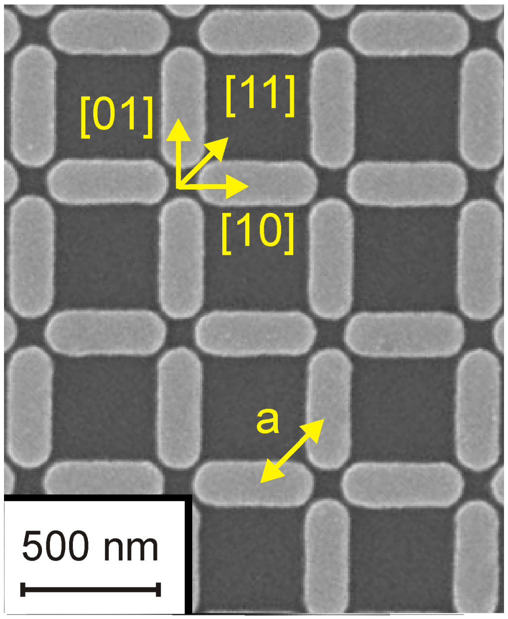
Magnetic force microscopy images

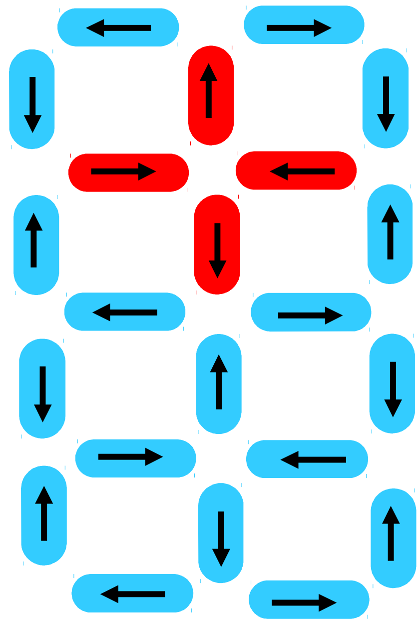
A thermally active Kagome lattice

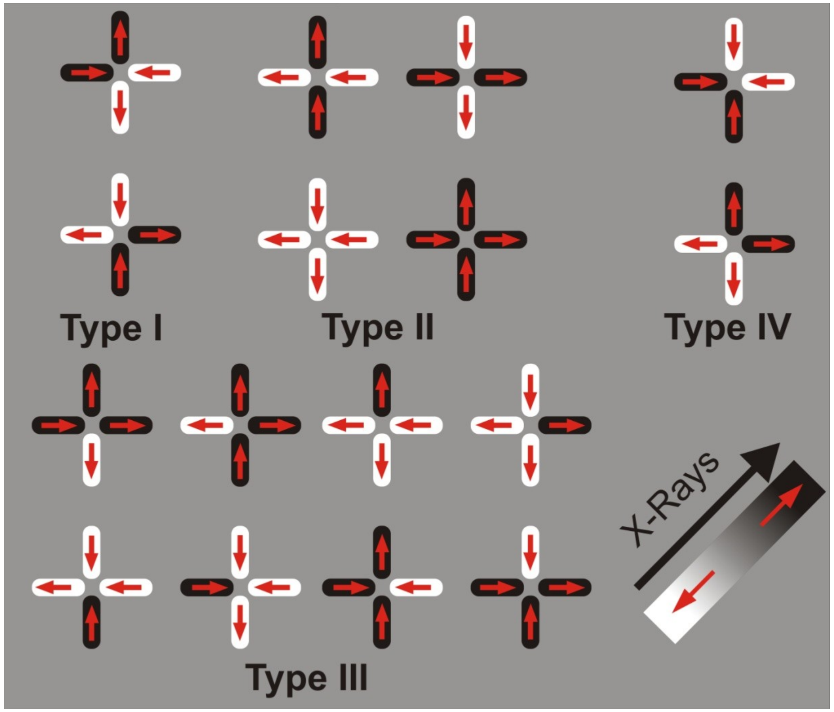
(To be shown at time of talk)

The square lattice

The extended square lattice







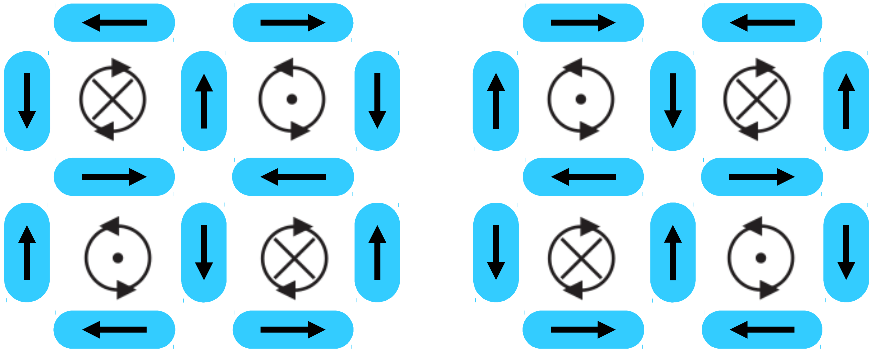
The ice rule is two in/two out, but now there exist two classes of ice-rule configurations

→ No low-energy exponential degeneracy

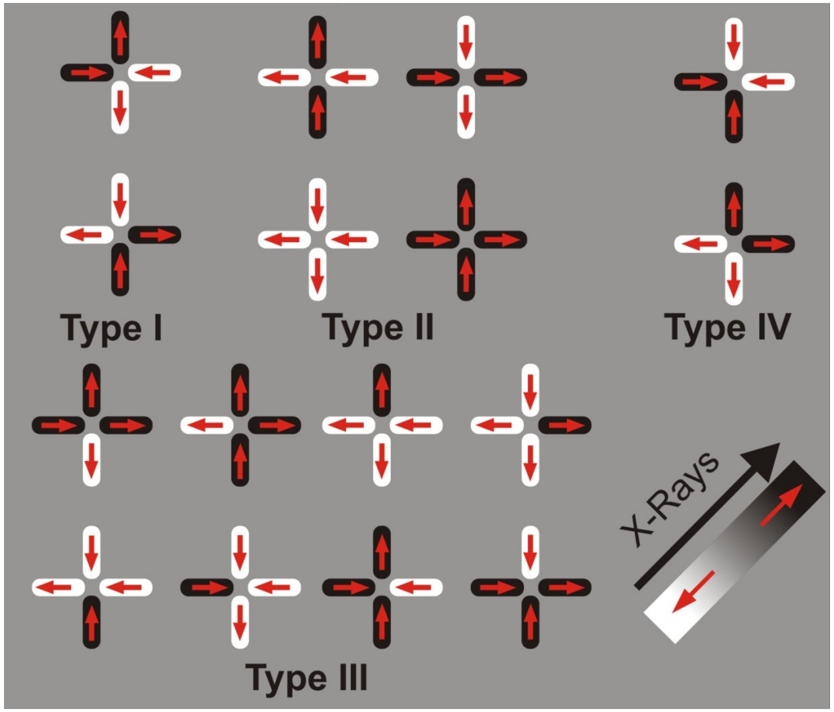
Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Perron J, Scholl A, Nolting F, Heyderman LJ, Phys. Rev. Lett. 111, 057204 (2013)

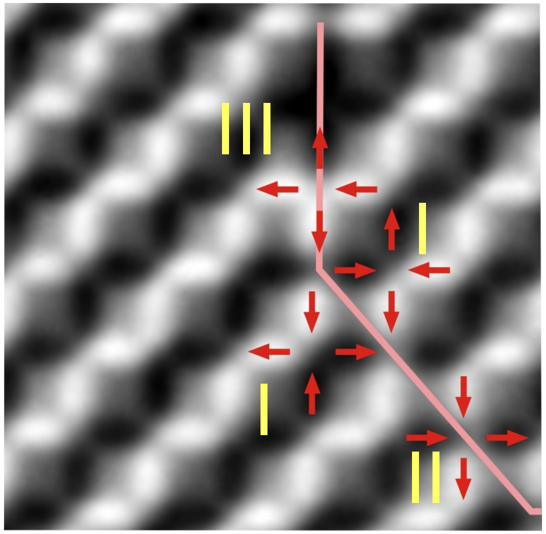
The square lattice: domain walls

The two lowest energy configurations are distinguished by their chirality



Morgan et al, Nat. Phys. 7, 75 (2011).





Leads to domains of different chiralities → domain wall dynamics mediated by type II and III vertices

Budrikis et al, New J. Phys. 14, 035014 (2012).

Direct Observation of Thermally Driven Ground State Ordering in Artificial Spin Ice

Under an external magnetic field
prepare a type II ordered state

↓

Turn off external field

↓

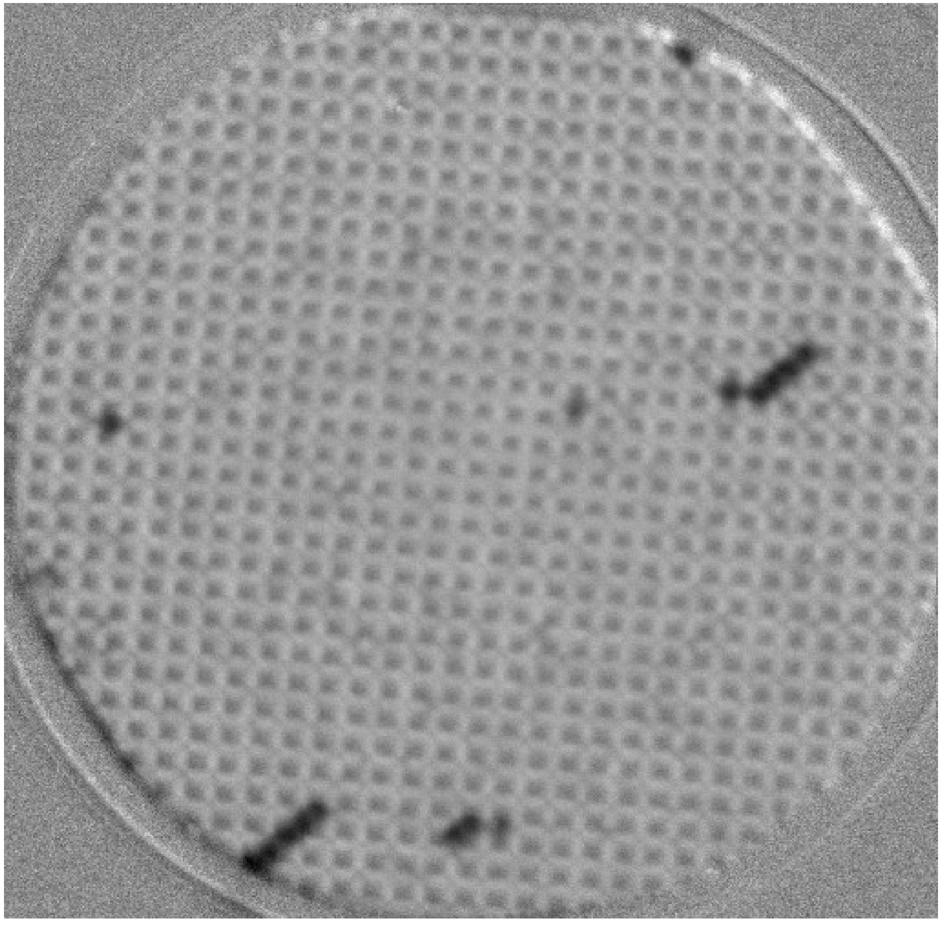
Homogeneous pair nucleation of
of type III vertices

↓

Repulsion of type III vertex pair
(connected via type I vertex chain)

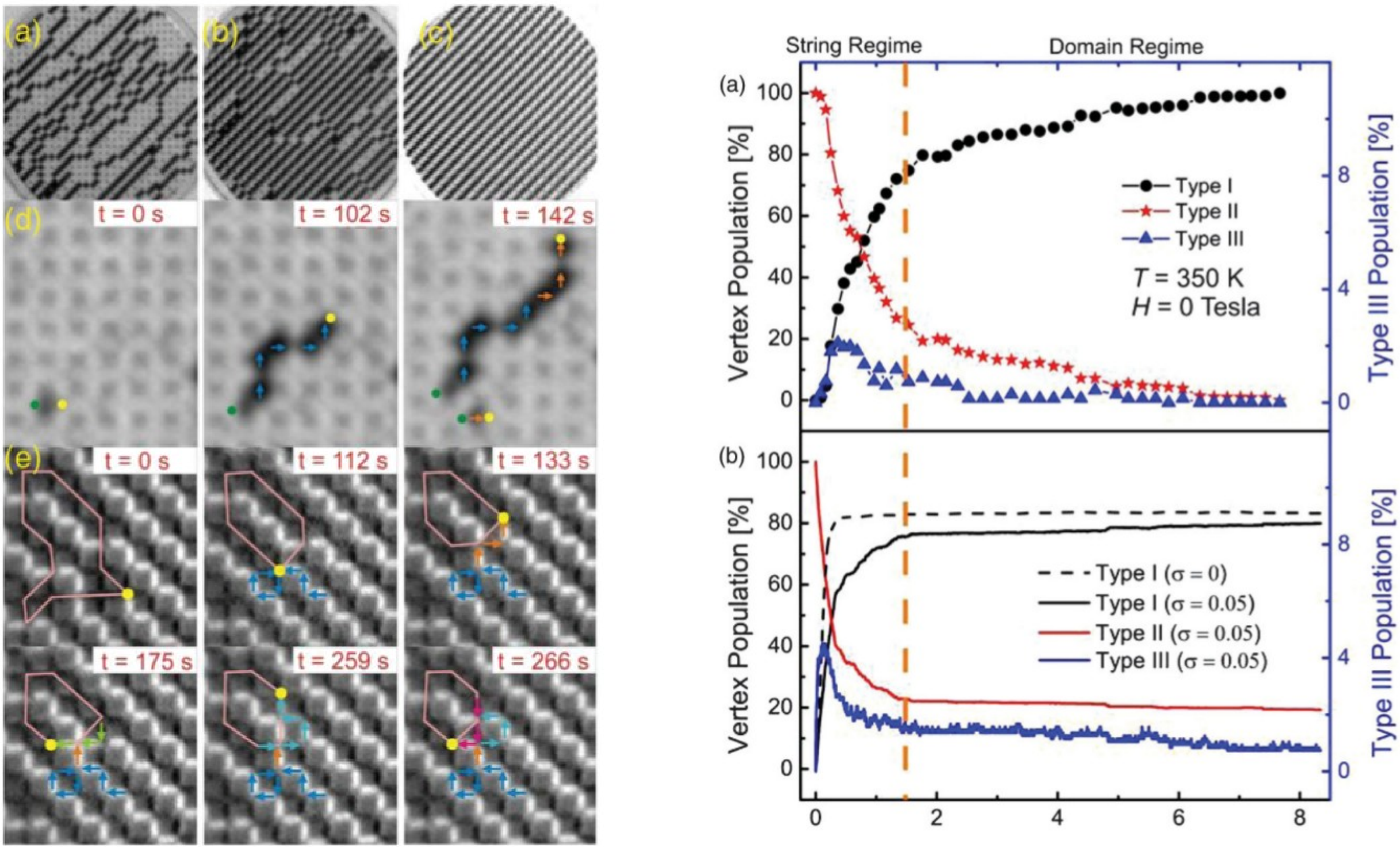
↓

Growth of type I vertex domains
→ domain wall dynamics



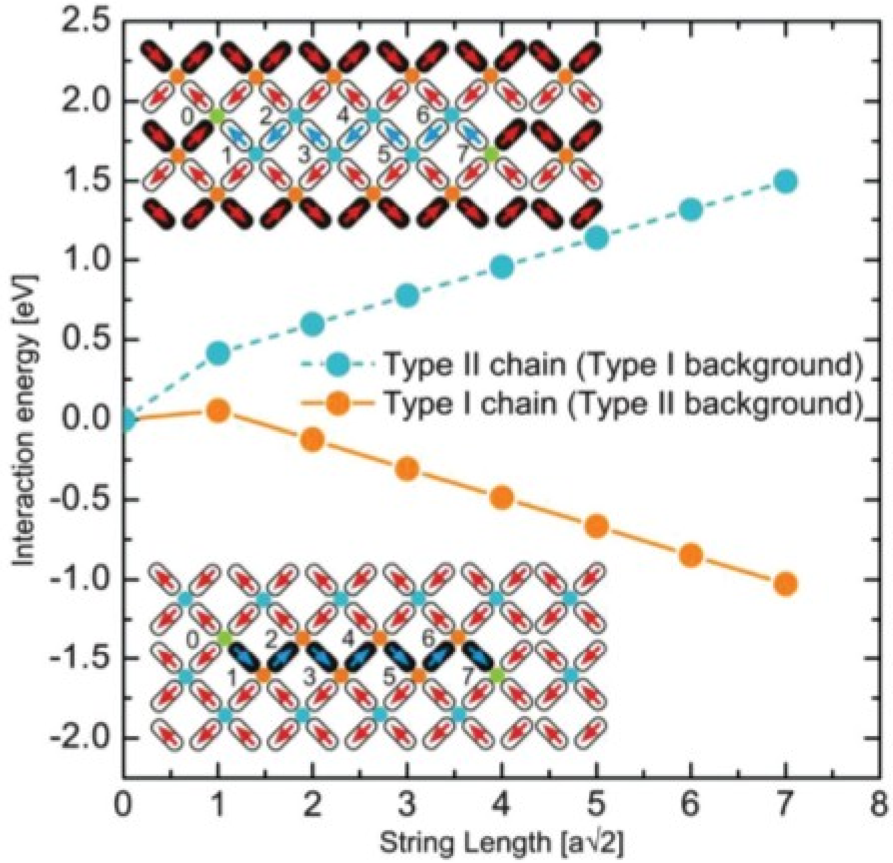
Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Perron J, Scholl A, Nolting F, Heyderman LJ, Phys. Rev. Lett. 111, 057204 (2013)

Direct Observation of Thermally Driven Ground State Ordering in Artificial Spin Ice



Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Perron J, Scholl A, Nolting F, Heyderman LJ, Phys. Rev. Lett. 111, 057204 (2013)

The square lattice and emergent magnetic monopoles



An almost linear interaction → strong confining potential → true monopoles?

Farhan A, PMD, Kleibert A, Balan A, Chopdekar RV, Wyss M, Perron J, Scholl A, Nolting F, Heyderman LJ, Phys. Rev. Lett. 111, 057204 (2013)

Future directions & concluding remarks

- The ability to pattern almost any shape allows control of shape anisotropy and therefore magnetic moment form and behaviour.
- Large extended arrays can be patterned allowing for the creation of 2D artificial bulk-like materials.
- To produce thermally active systems allows the study of both non-equilibrium and equilibrium dynamics with degree-of-freedom temporal and spatial resolution.
- Disorder appears to be minimal → it can be enhanced and controlled.