CERN School of Computing 2019

The problems of modeling frustrating systems

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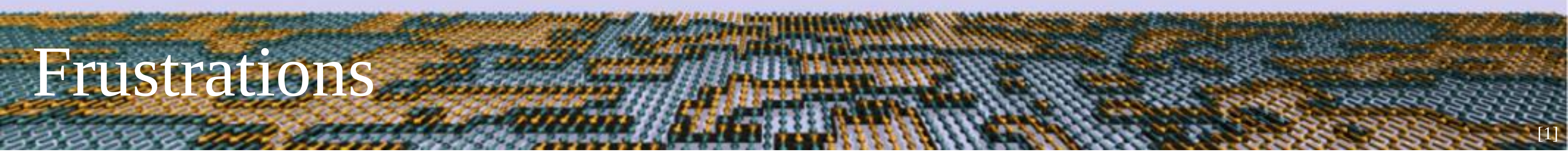
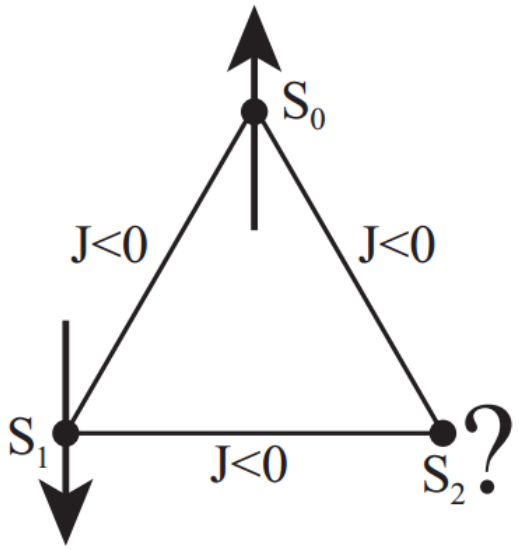
Frustrations





$$S_i = \pm 1$$

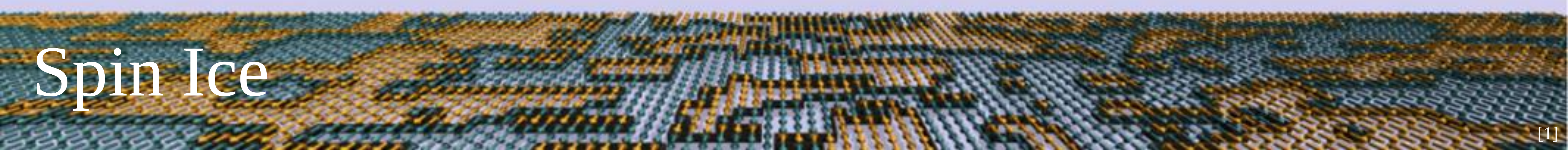
$$J_{ij} = \pm 1$$

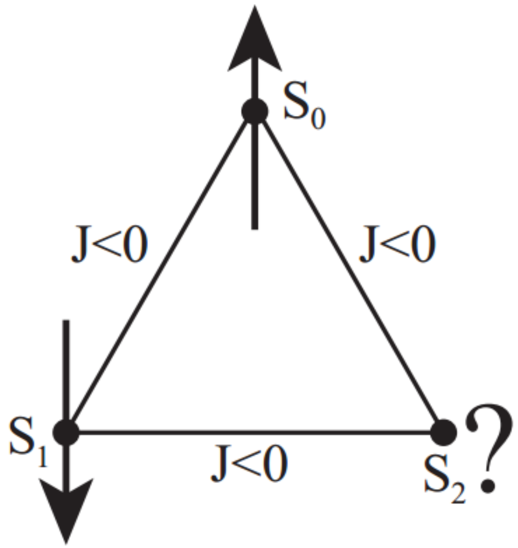
$$E = -(J_{01}S_0S_1 + J_{02}S_0S_2 + J_{12}S_1S_2)$$

Geometrical frustration

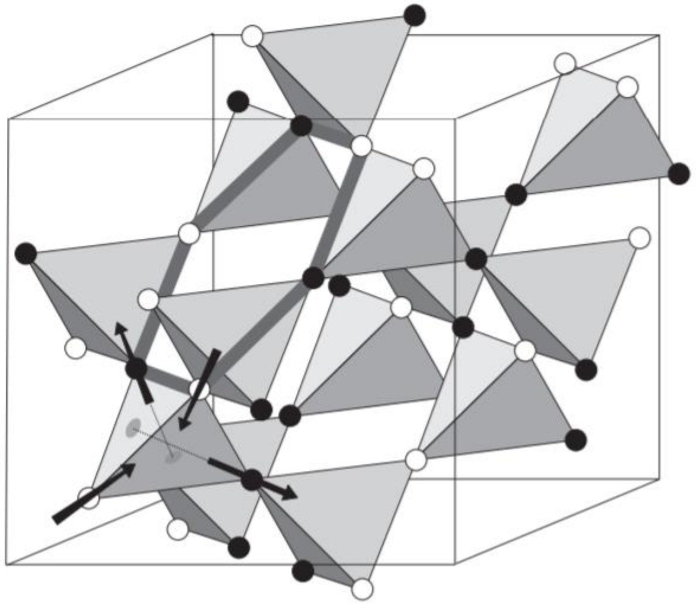
[1] Arnalds, Unnar B., et al. "A new look on the two-dimensional Ising model: thermal artificial spins." New Journal of Physics 18.2 (2016): 023008.

Spin Ice





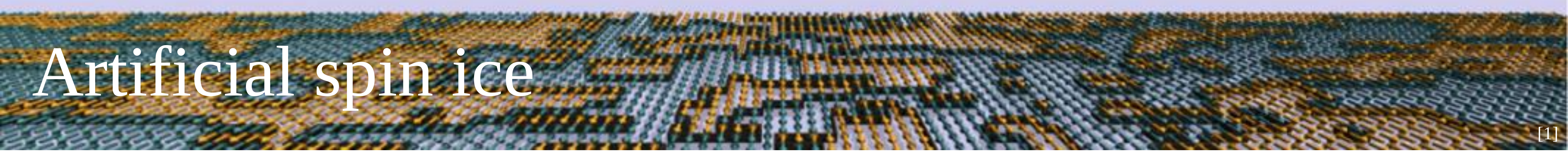
Geometrical frustration

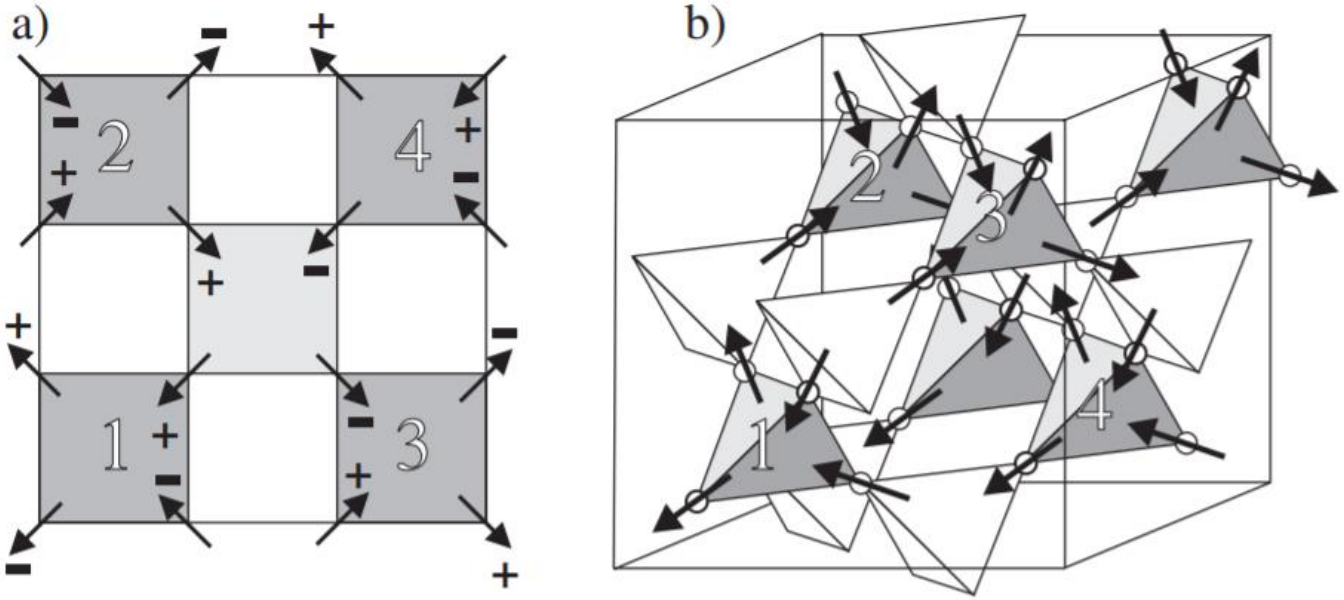


The Ising pyrochlore lattice [2]

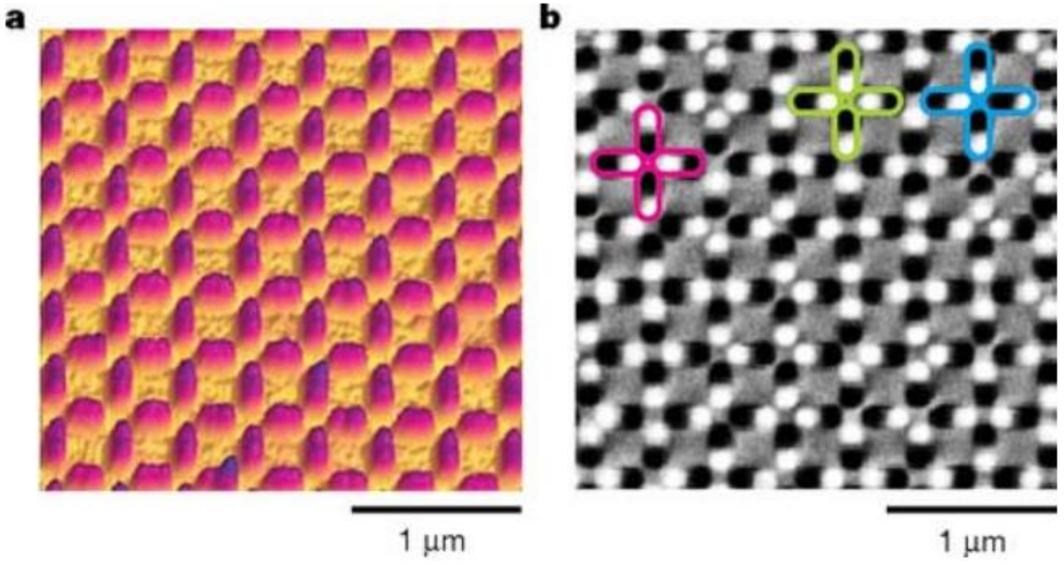
[1] Arnalds, Unnar B., et al. "A new look on the two-dimensional Ising model: thermal artificial spins." New Journal of Physics 18.2 (2016): 023008.
[2] Melko, Roger G., and Michel JP Gingras. "Monte Carlo studies of the dipolar spin ice model." Journal of Physics: Condensed Matter 16.43 (2004): R1277.

Artificial spin ice





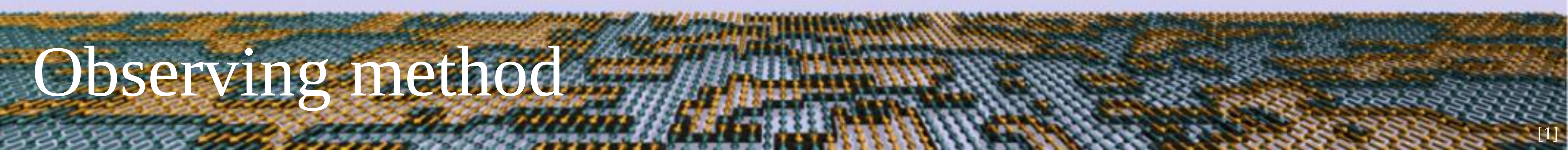
Z-axis projecting (a) of the four tetrahedra in (b) [2]



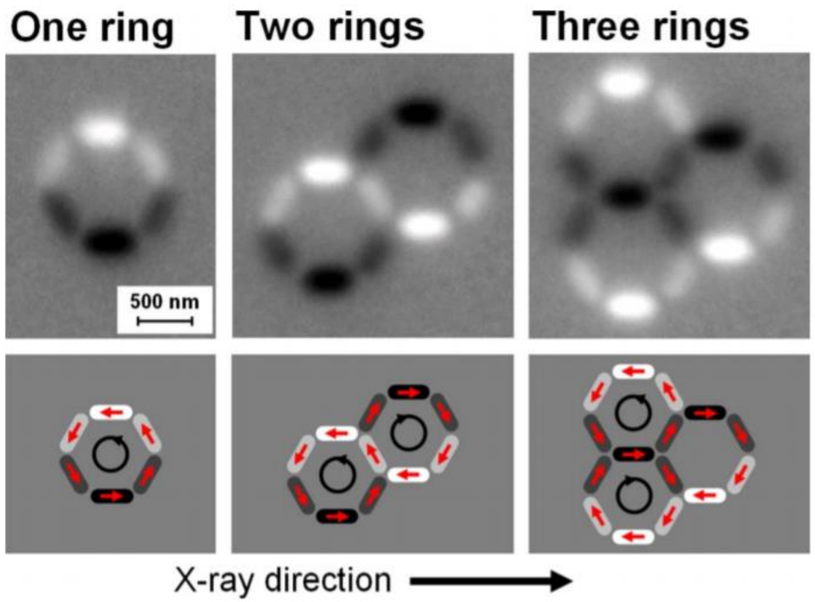
The first artificial spin ice [3]

[1] Arnalds, Unnar B., et al. "A new look on the two-dimensional Ising model: thermal artificial spins." New Journal of Physics 18.2 (2016): 023008.
[2] Melko, Roger G., and Michel JP Gingras. "Monte Carlo studies of the dipolar spin ice model." Journal of Physics: Condensed Matter 16.43 (2004): R1277.
[3] Wang, RF, et al. "Artificial 'spin ice' in a geometrically frustrated lattice of nanoscale ferromagnetic islands." Nature 439.7074 (2006): 303.

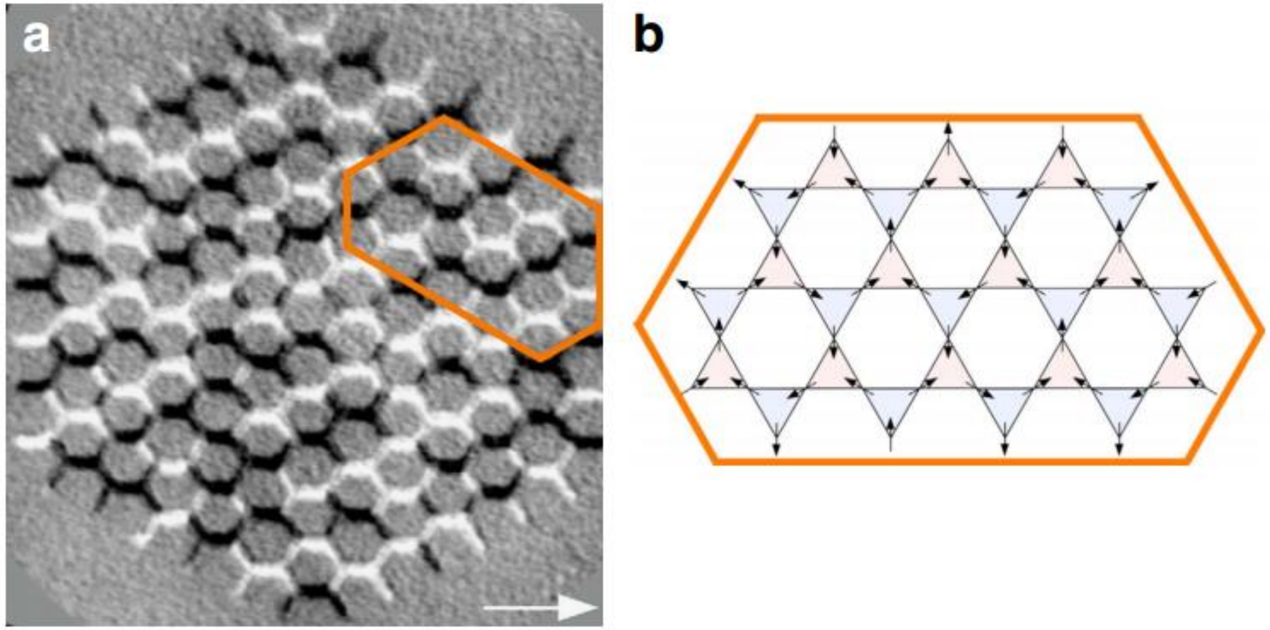
Observing method



[1]

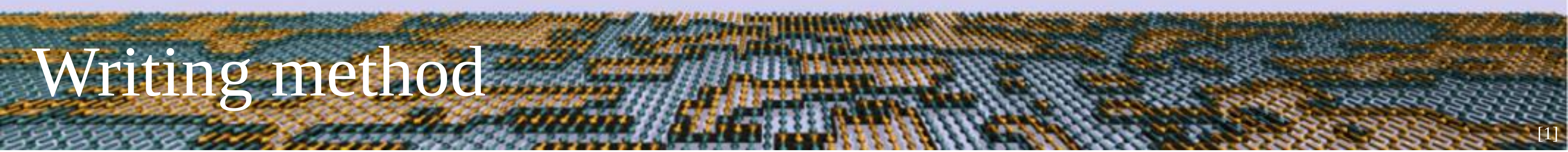


XMCD images of the ground states of the artificial kagome spin ice building blocks [4].

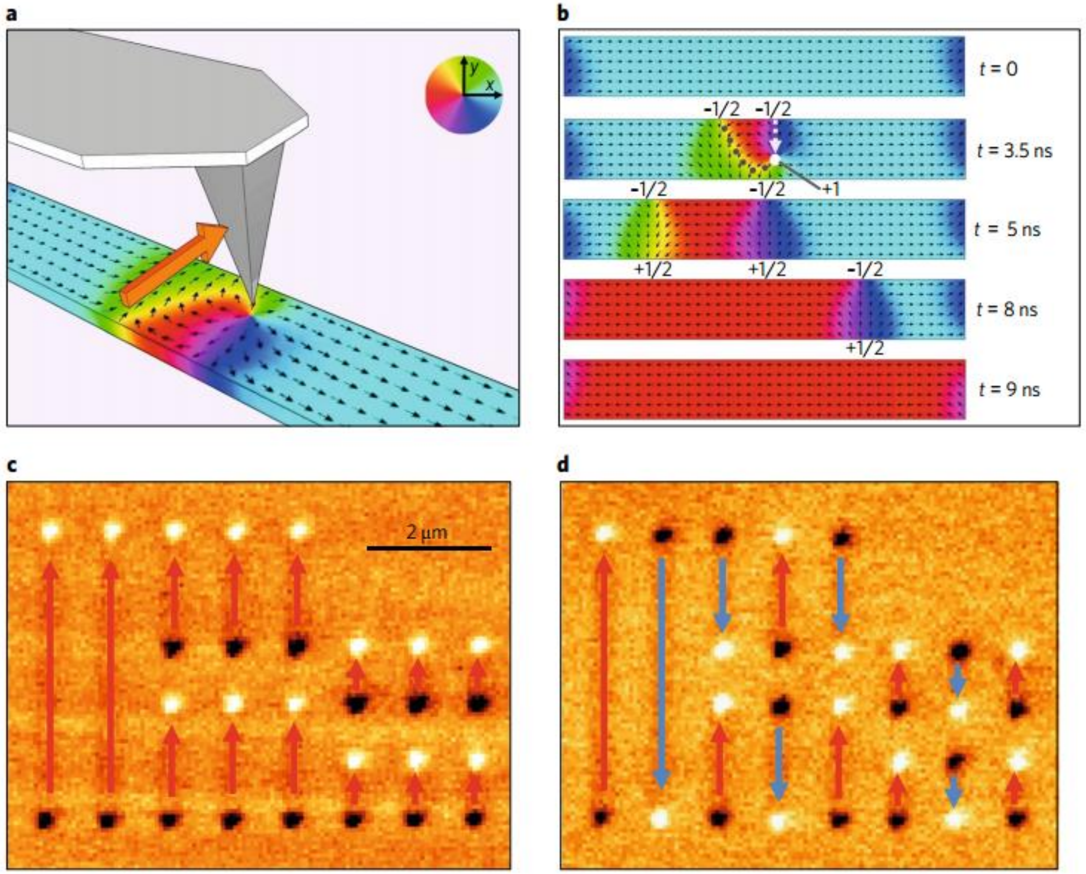


XMCD-PEEM mage of an artificial kagome array. The black and white contrasts give the local direction of the magnetization within each individual nanomagnet. The white arrow indicates the direction of the incident X-ray beam [5].

[1] Arnalds, Unnar B., et al. "A new look on the two-dimensional Ising model: thermal artificial spins." New Journal of Physics 18.2 (2016): 023008.
[4] Mengotti, E., et al. "Building blocks of an artificial kagome spin ice: Photoemission electron microscopy of arrays of ferromagnetic islands." Physical Review B 78.14 (2008): 144402.
[5] Canals, Benjamin, et al. "Fragmentation of magnetism in artificial kagome dipolar spin ice." Nature communications 7 (2016): 11446.



Writing method

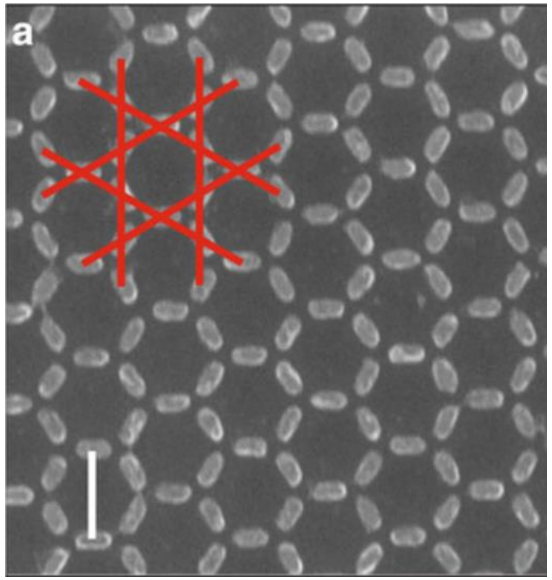


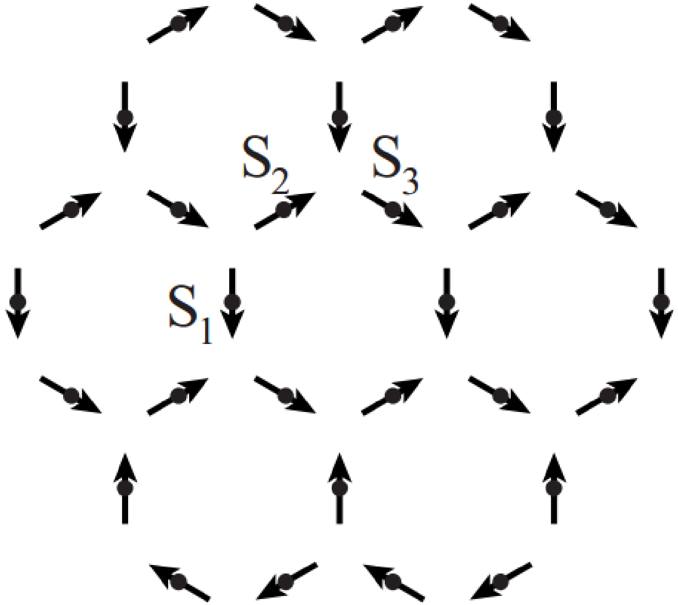
Topological defect-driven magnetic writing

a) Schematic of TMW operation. An MFM tip-induced vortex is moved through a nanostructure spin texture by the motion of the tip. The colour wheel represents the directions of magnetization direction in a and b, whereas the orange arrow indicates the direction of the tip velocity. **b)** Micromagnetic simulation of the time evolution of the TMW write-function used to reverse the magnetization of a 500 nm × 75 nm × 10 nm nanowire. The MFM tip and its direction of motion are represented by the white circle and dashed arrow, respectively. Topological defects are labelled with their winding numbers [6].

[1] Arnalds, Unnar B., et al. "A new look on the two-dimensional Ising model: thermal artificial spins." New Journal of Physics 18.2 (2016): 023008.
[6] Gartside, Jack C., et al. "Realization of ground state in artificial kagome spin ice via topological defect-driven magnetic writing." Nature nanotechnology 13.1 (2018): 53.

Kagome artificial spin ice model





STM image of a part of an array of artificial spin ice where macrospins located on the kagome lattice. The scale length is 170 nm [7].

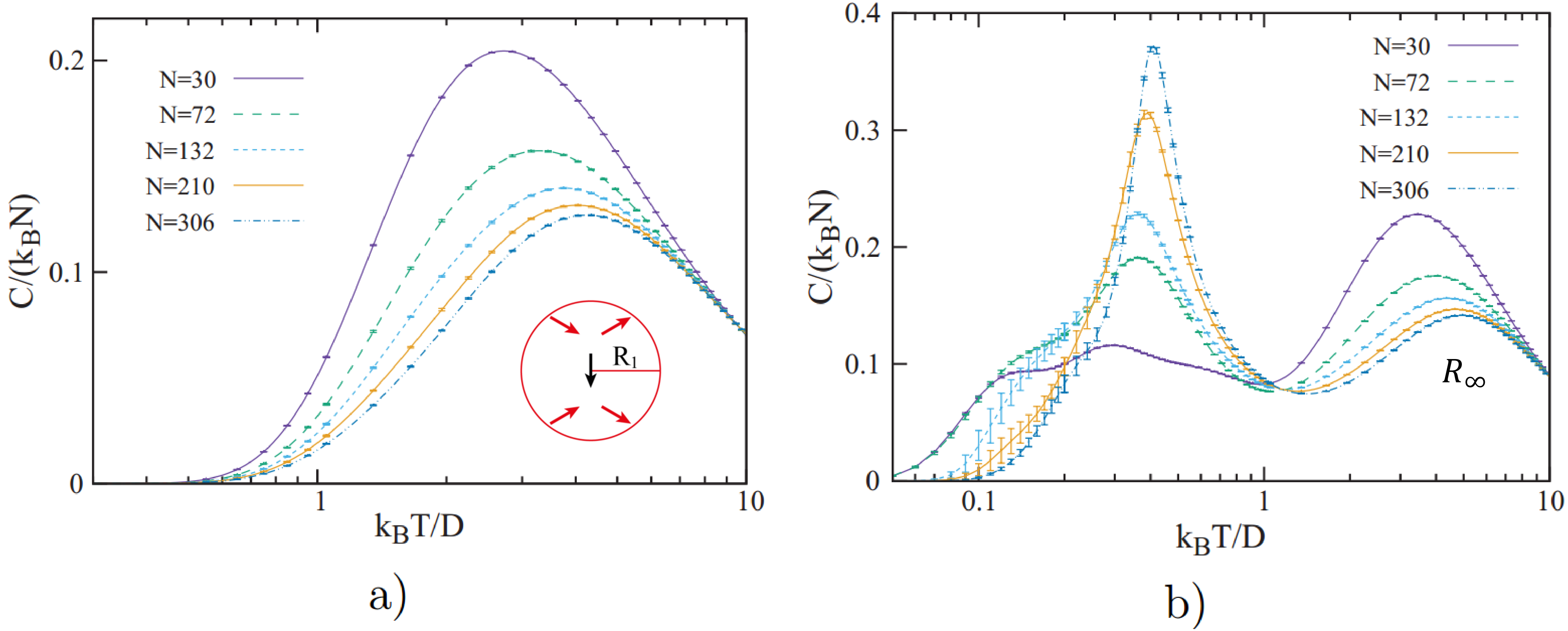
$$E_{dip}^{ij} = D\left(\frac{(\vec{m}_i\vec{m}_j)}{|\vec{r}_{ij}|^3} - 3\frac{(\vec{m}_i\vec{r}_{ij})(\vec{m}_j\vec{r}_{ij})}{|\vec{r}_{ij}|^5}\right) \quad (1)$$

$D = \mu^2/a^3$ - is a dimensional coefficient
μ - the total magnetic moment of the island
a - the lattice parameter

[1] Arnalds, Unnar B., et al. "A new look on the two-dimensional Ising model: thermal artificial spins." New Journal of Physics 18.2 (2016): 023008.
[7] Anghinolfi, Luca, et al. "Thermodynamic phase transitions in a frustrated magnetic metamaterial." Nature communications 6 (2015): 8278

Specific heat of kagome ASI

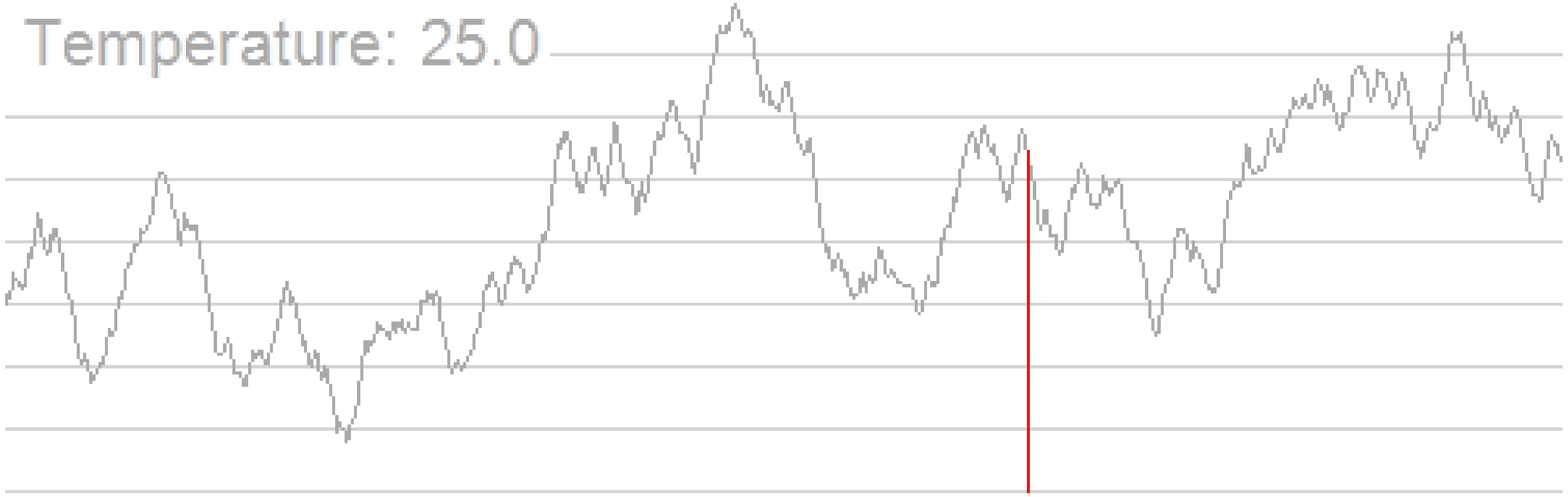
[1]



Specific heat as a function of temperature for kagome artificial spin ice (hexagonal sample with *N* macrospins) with cutoff interaction radius till nearest neighbors R1 (a) and without cutoff interaction radius (b) [8].

[8] Shevchenko, Yu A., et al. "Multicanonical sampling of the space of states of $\mathscr{H}$(2, n)-vector models." Journal of Experimental and Theoretical Physics 124.6 (2017): 982-993.

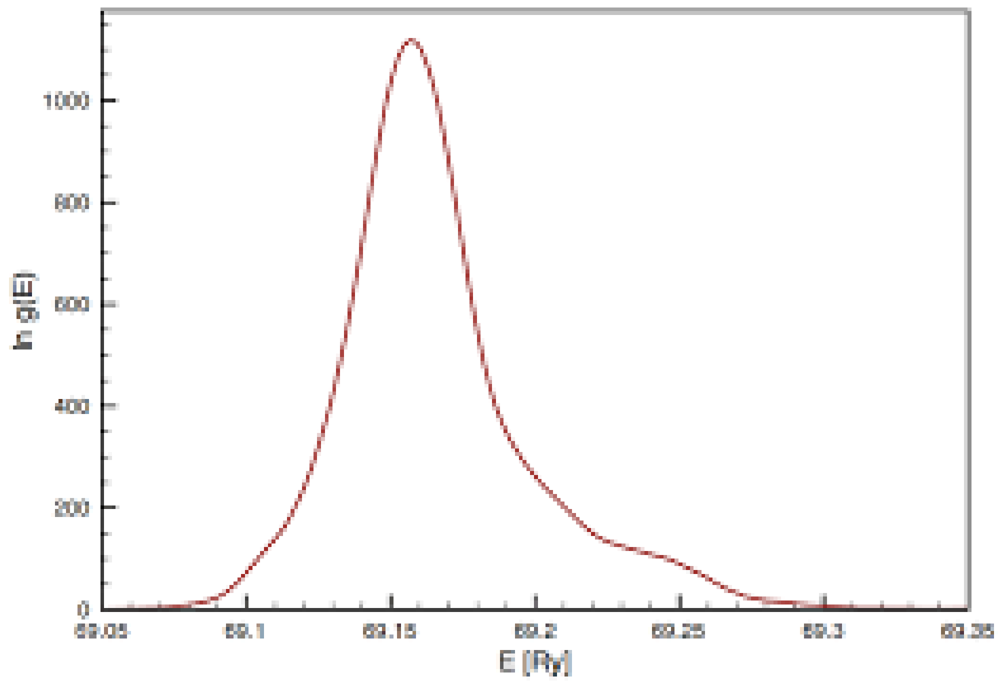
Rough energy landscape



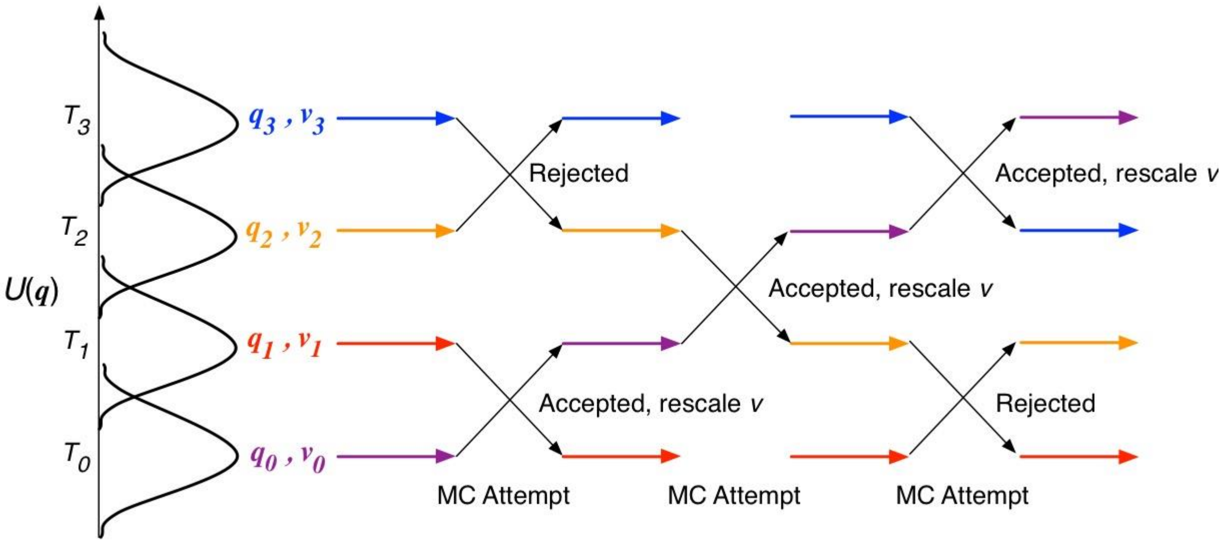
Rough energy landscape

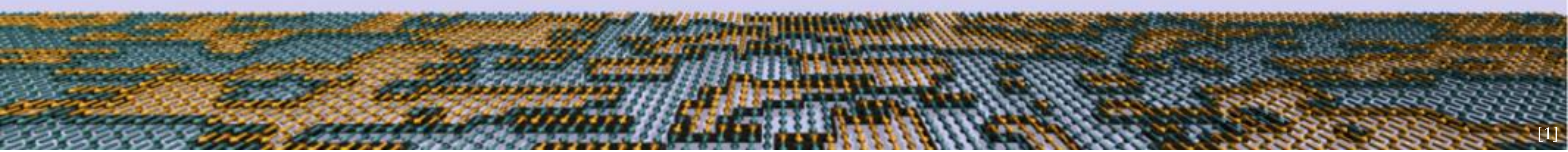
[1]

Wang-Landau MC method



Parallel tempering MC method





Thank you for attention

Ground state in kagome artificial spin ice model

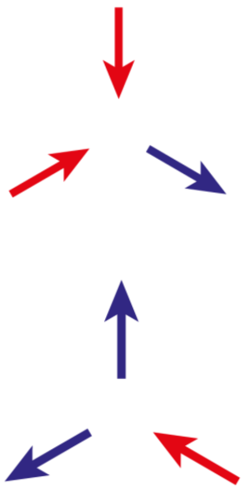
[1]

Short-order

Pseudo ice-rule:

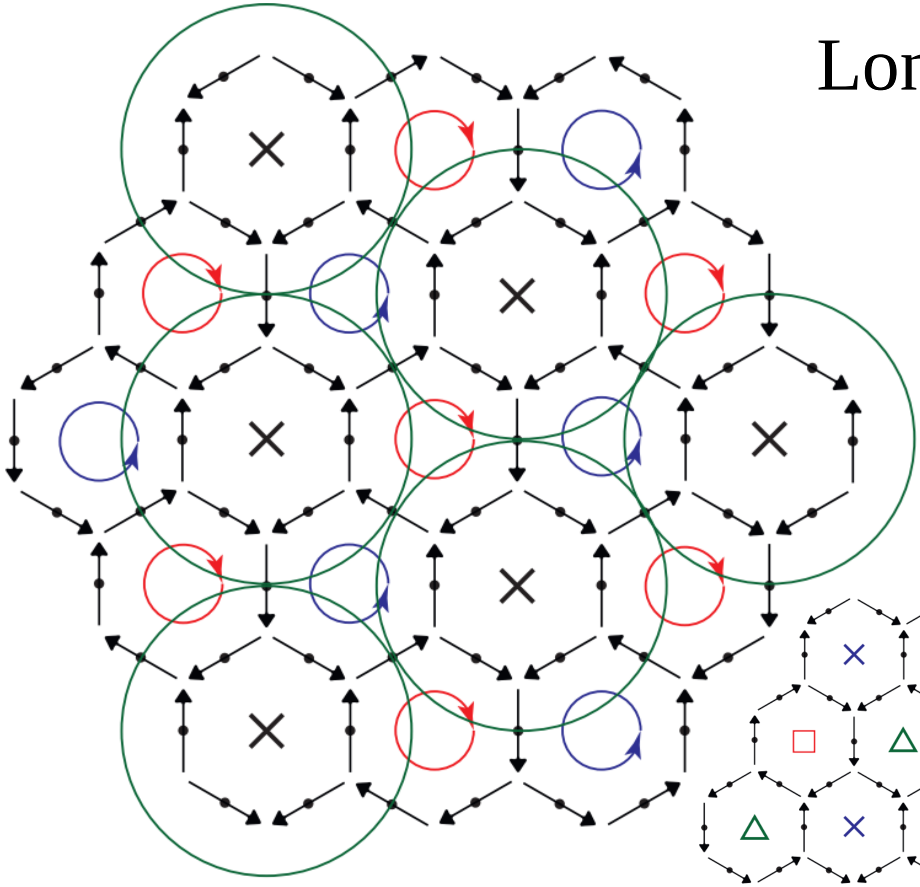
“2 in 1 out”

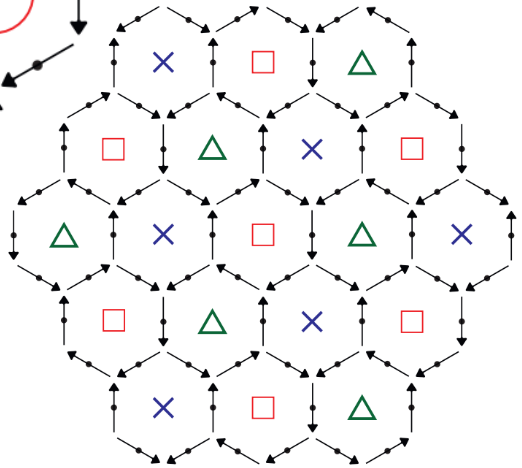
“1 in 2 out”



Huge degeneration

Long-order



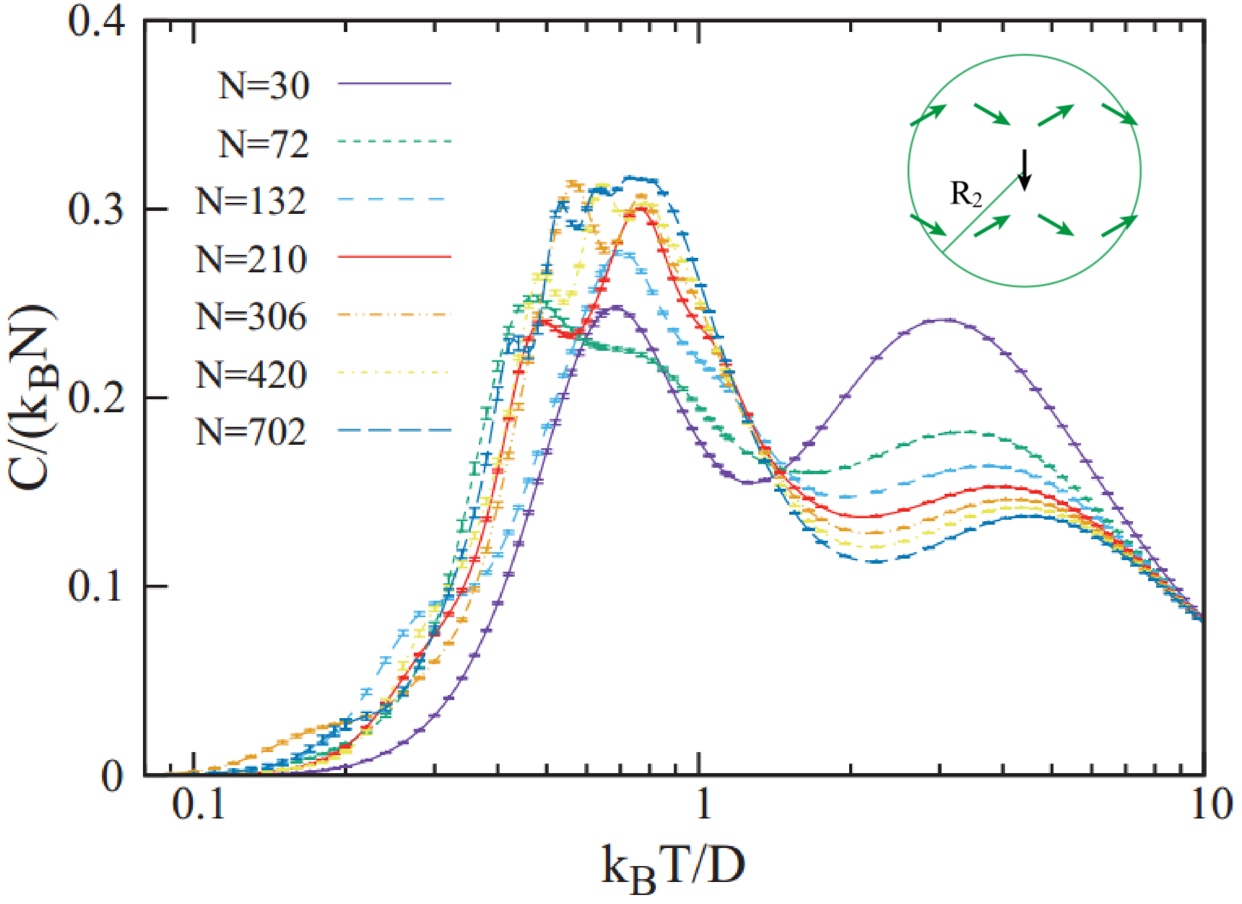


6 configuration

[1] Arnalds, Unnar B., et al. "A new look on the two-dimensional Ising model: thermal artificial spins." New Journal of Physics 18.2 (2016): 023008.

Specific heat of kagome ASI

[1]

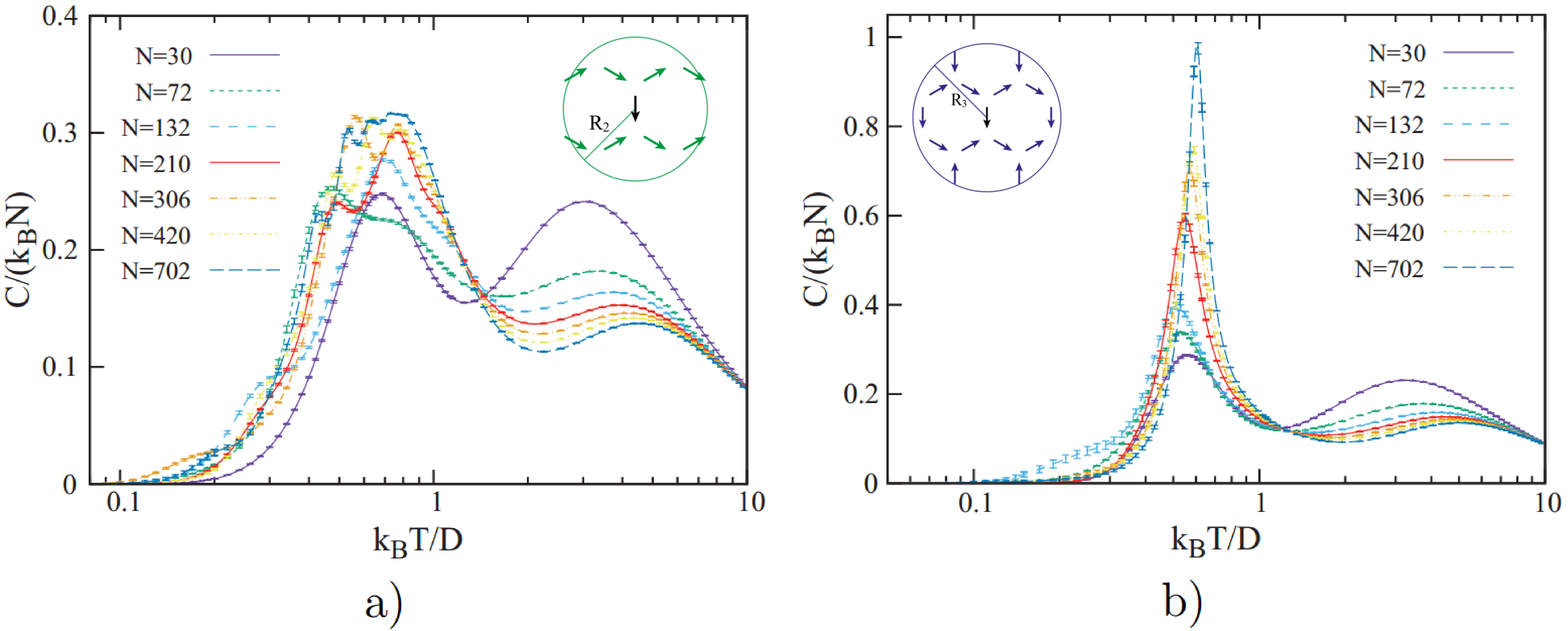


a)

Specific heat as a function of temperature for kagome artificial spin ice (hexagonal sample with *N* macrospins) with R2 cutoff interaction radius (8 nearest neighbors) (a).

Specific heat of kagome ASI

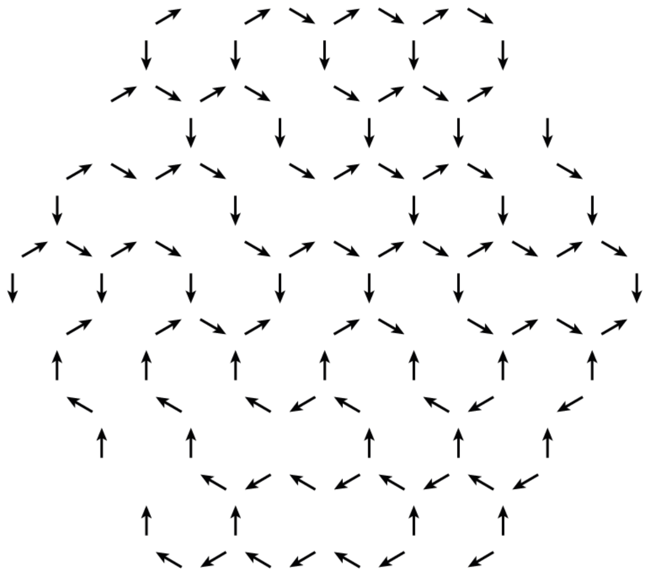
[1]



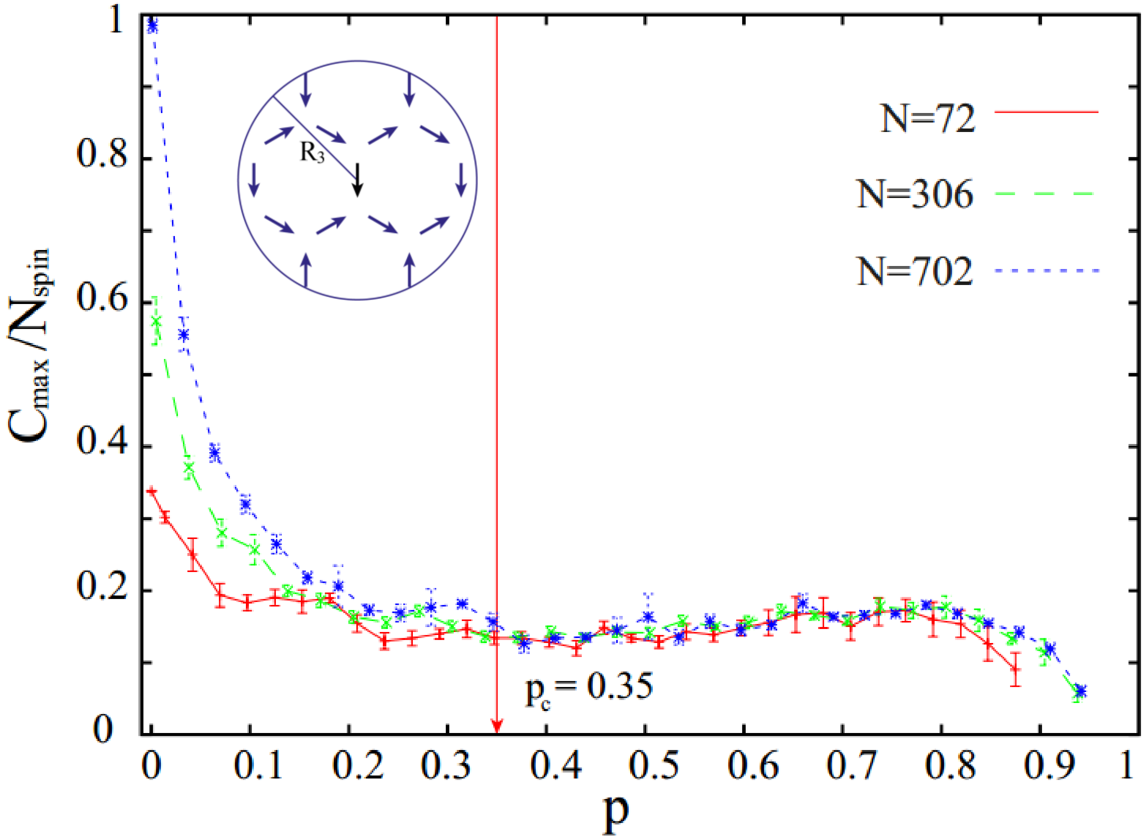
Specific heat as a function of temperature for kagome artificial spin ice (hexagonal sample with *N* macrospins) with R2 cutoff interaction radius (8 nearest neighbors) (a) and with R3 cutoff interaction radius (14 nearest neighbors) (b).

Percolation threshold

[1]



The sample of diluted kagome artificial spin ice with $p = 23/132 = 0.17$

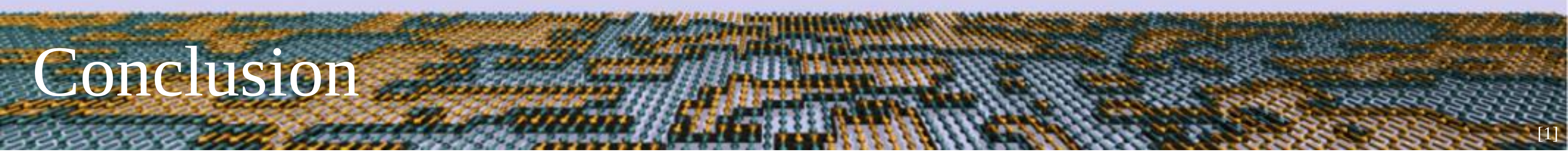


The dependence of the low-temperature peak value of the specific heat of the kagome artificial spin ice model with R3 cutoff dipole interaction radius (which includes 14 nearest neighbors) on the dilution concentration p. The vertical red line denotes the theoretical value of the percolation threshold [9].

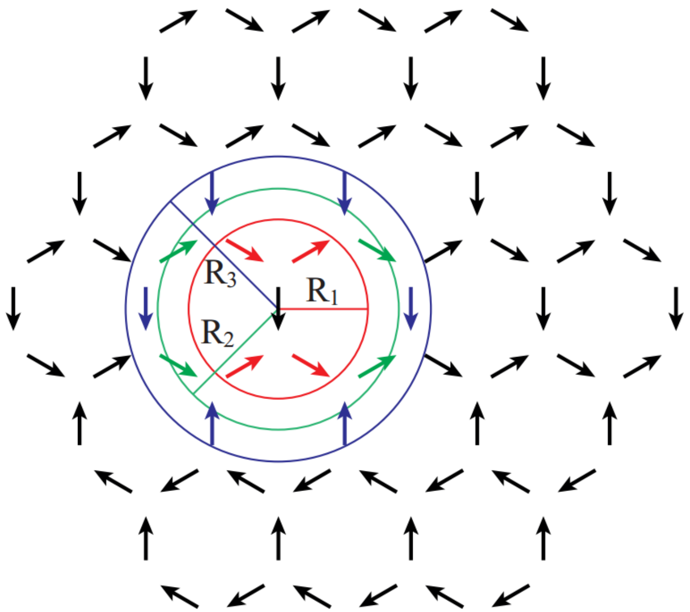
$$p_c = 1 - 2sin(\pi/18) \approx 0.35$$

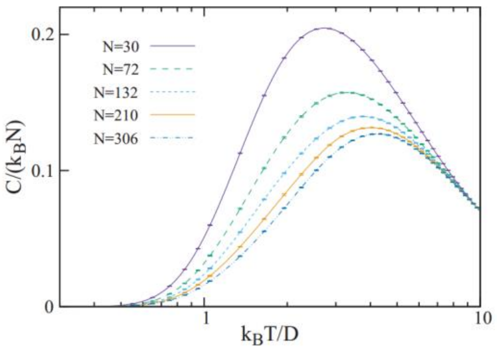
[9] M. F. Sykes, J. W. Essam, Exact critical percolation probabilities for site and bond problems in two dimensions, Journal of Mathematical Physics 5 (8) (1964) 1117–1127.

Conclusion

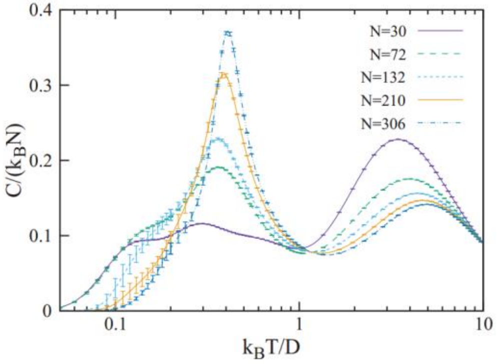


[1]

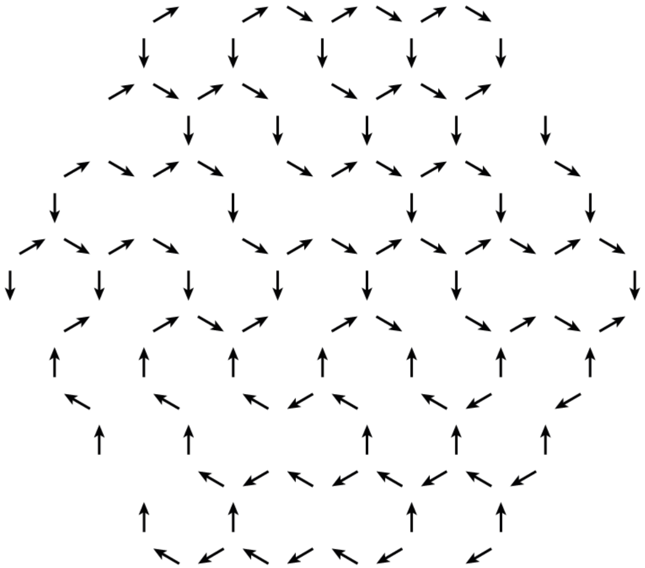


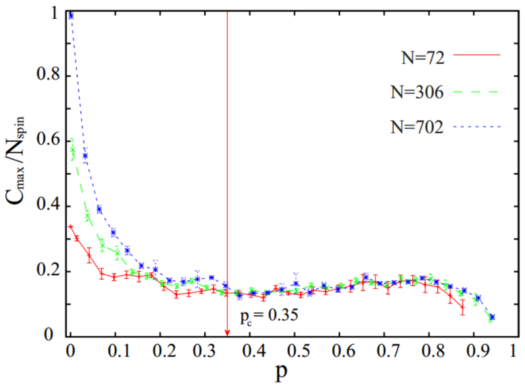


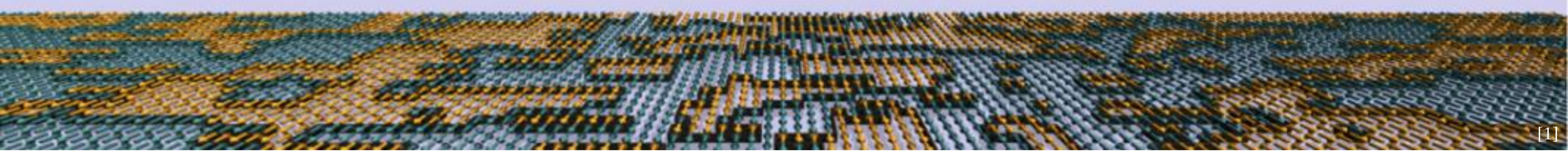
a)

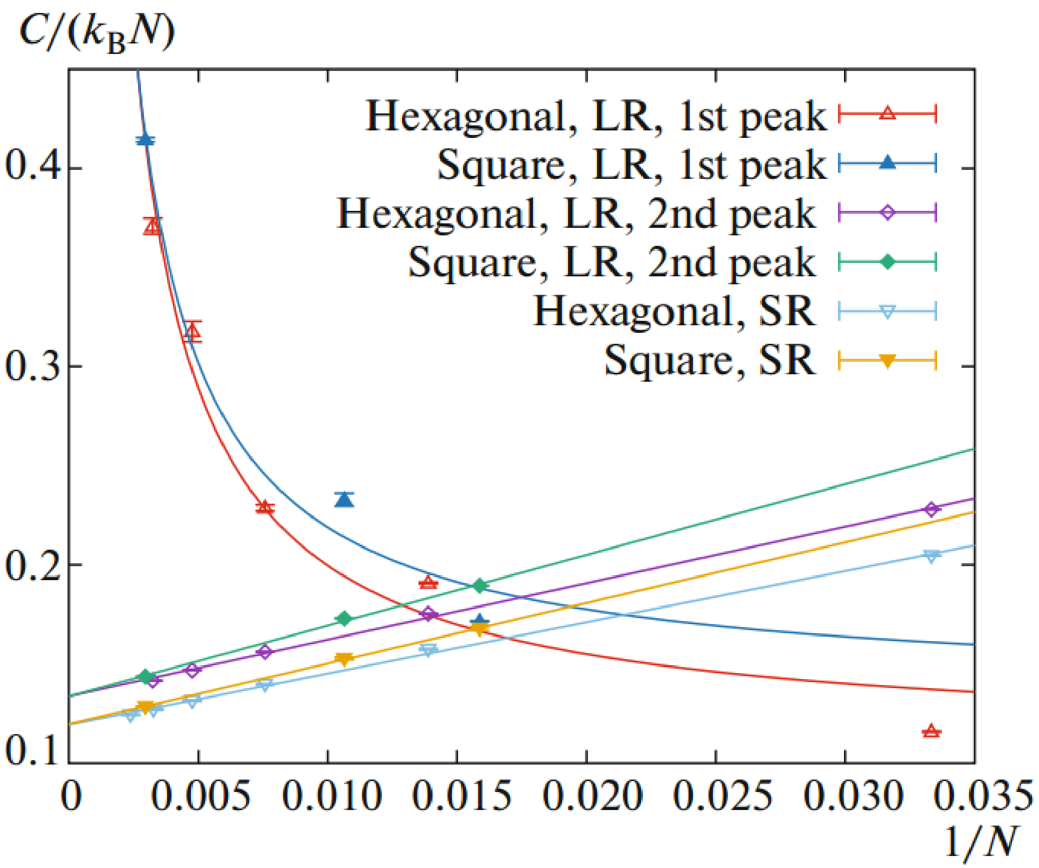


b)









Comparison of the growth of specific heat peaks depending on the number of particles in the system for hexagonal lattice models of square and hexagonal samples. As $N \to \infty$, for LR interaction, the temperature behavior of specific heat has a singularity, and the second peak tends to 0.133D/kB, while, for SR interaction, the specific heat peak tends to 0.119D/kB.