Réseaux artificiels magnétiquement frustrés

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Spin models on a chip

Elaborate **artificial** arrays of magnetic nanostructures to study spin models through the **lab-on-a-chip** concept

Nanofabrication processes

-> design on demand the lattice geometry, the shape of the nanomagnets, the size of the array ...

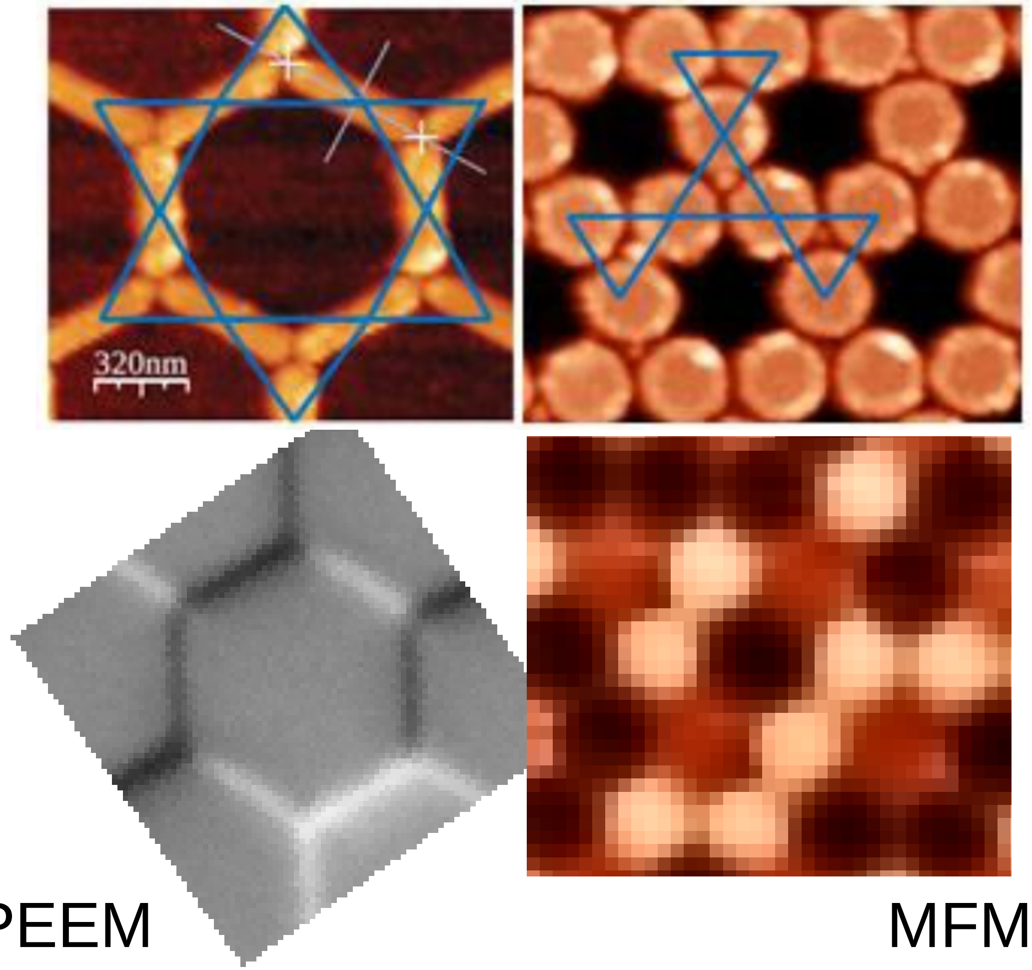
Material engineering:

-> choice of the magnetic anisotropy, but also Tc, Hc ...

Magnetic imaging

-> measure magnetization of each individual nanomagnet

AFM



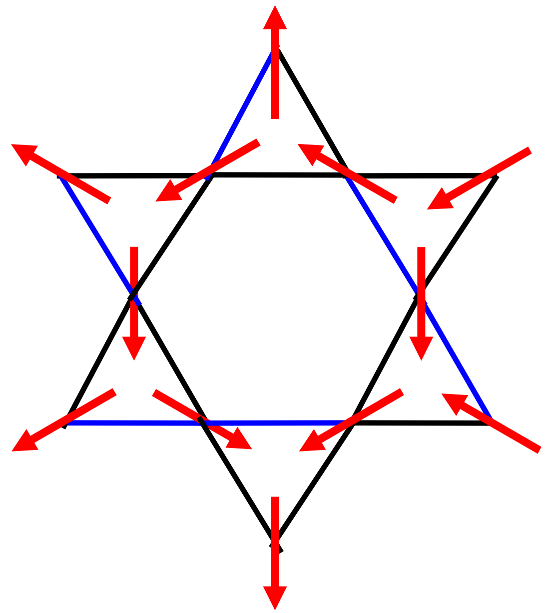
PEEM

MFM

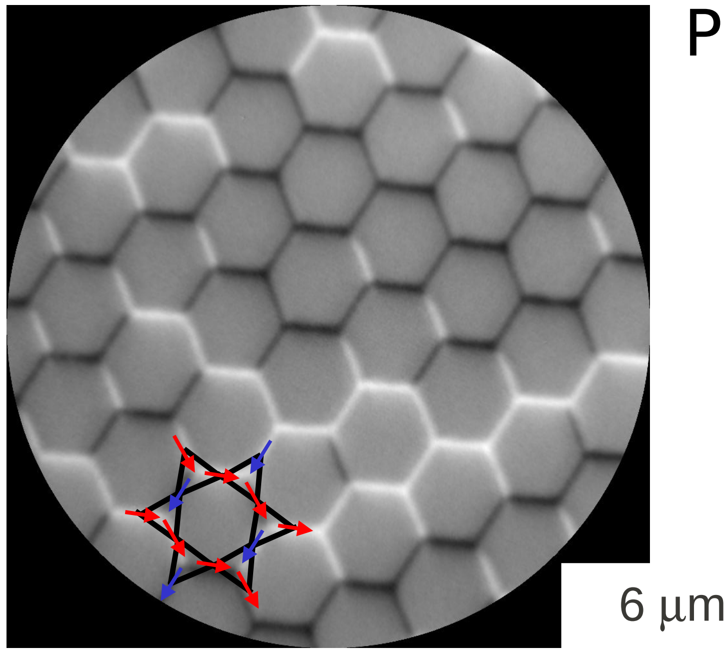
Exploring magnetic frustration effects

Frustrated (**classical**) spin models: directly observe how spins accomodate magnetic frustration (Wang et al., Nature 2006)

spin models
(monte carlo simulations)



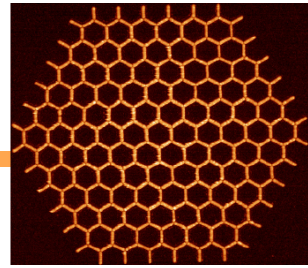
Nanomagnets
(magnetic imaging)



PEEM

Prediction and observation of exotic magnetic phases

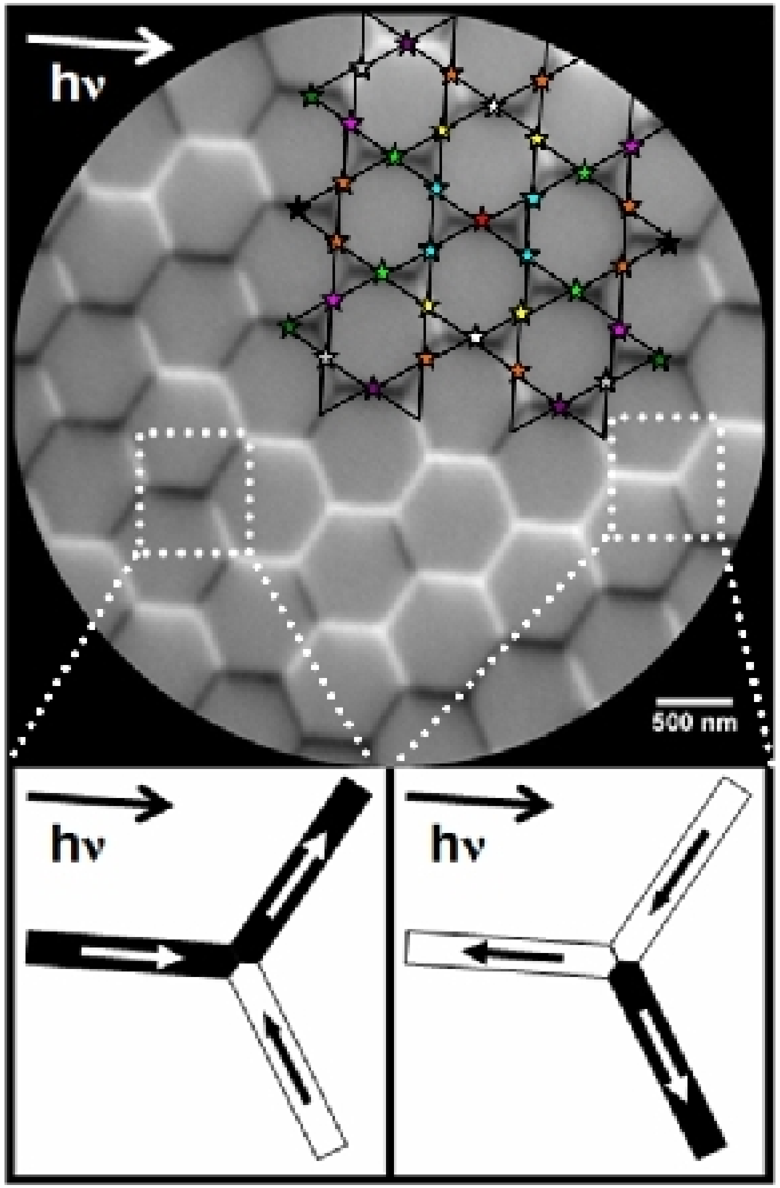
2 complementary approaches



	Condensed matter systems	Artificial arrays
fabrication	synthesis	lithography
dimensionality	1D - 2D - 3D	1D - 2D
# of spins	10^{23}	10^2 - 10^5
spin	"real"	macro / pseudo
type of spin	all	let's see...
energy barrier	"0"	10^4 - 10^5 K
local info	indirect	direct
reaching the GS	thermalization	demagnetization
probing	dynamics	static

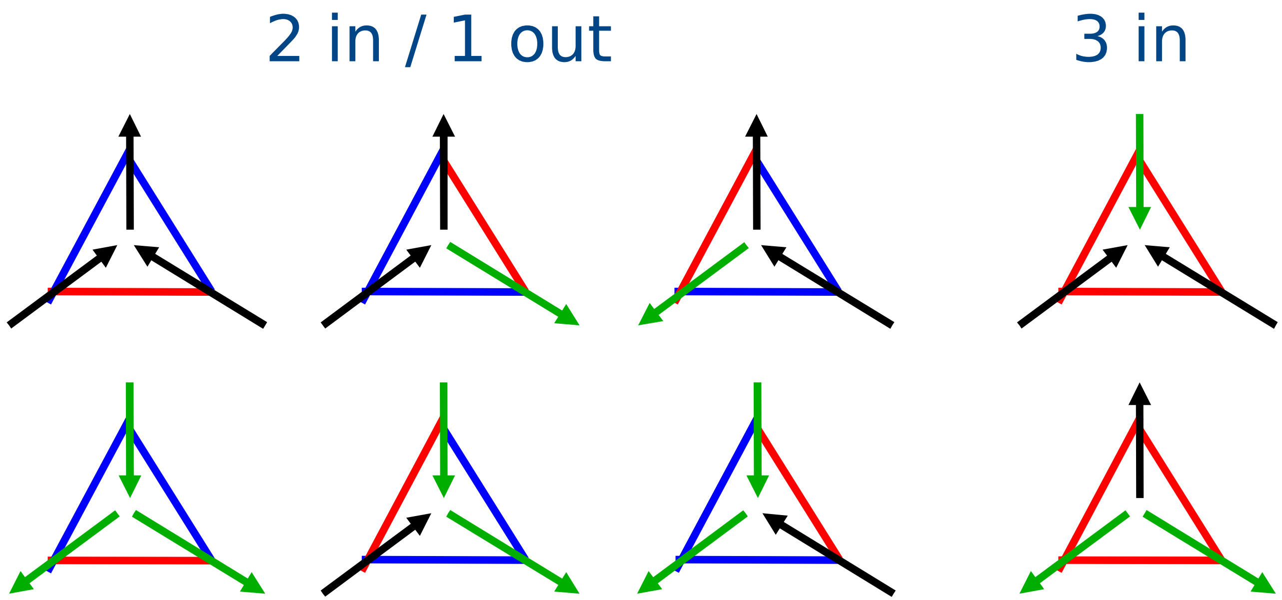
Other artificial arrays: Josephson junctions, superconducting wires, compass needles, colloids

Ground state manifold



PEEM

Demagnetization is efficient (M=0)

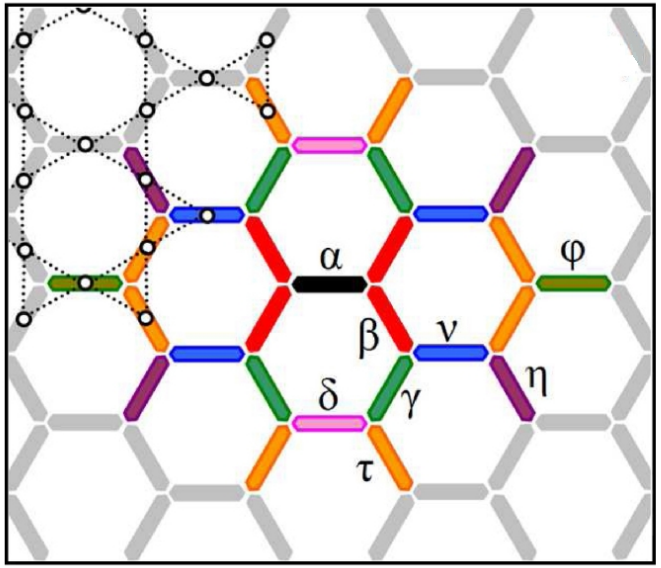


"2 in / 1 out"-like configuration everywhere

Different spin configurations after identical demagnetization procedures
(some stochasticity...)

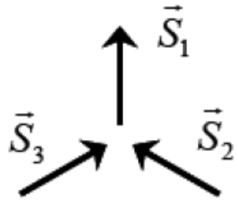
Characterizing magnetic disorder

$$C_{ij} = \langle \vec{S}_i . \vec{S}_j \rangle$$



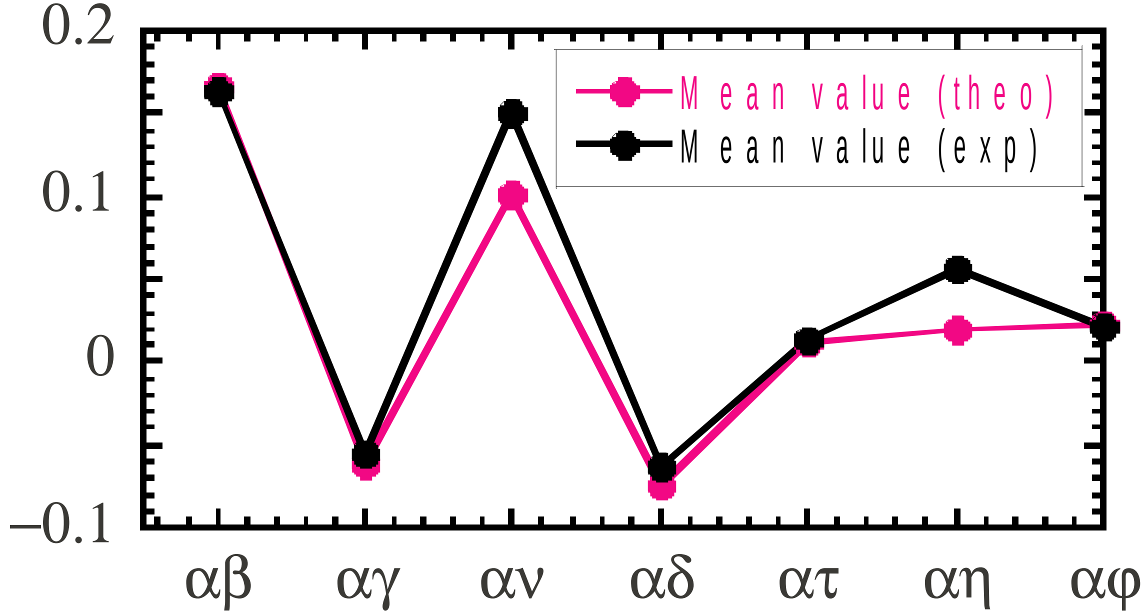
34 demagnetized networks

Ice rule :



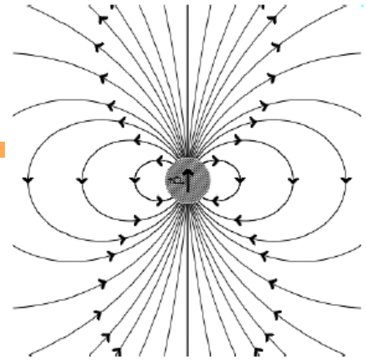
$$C'_{\alpha\beta} = \frac{1+1+(-1)}{3} = \frac{1}{3}$$

Wills et al., PRB 2002



At first sight, good agreement between experiments and the corresponding spin model with nearest neighbor interactions only

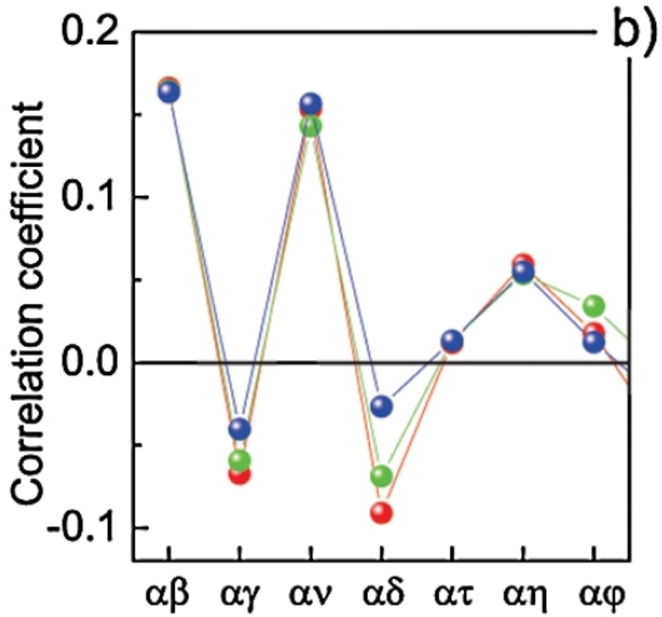
Artificial spin ice are dipolar

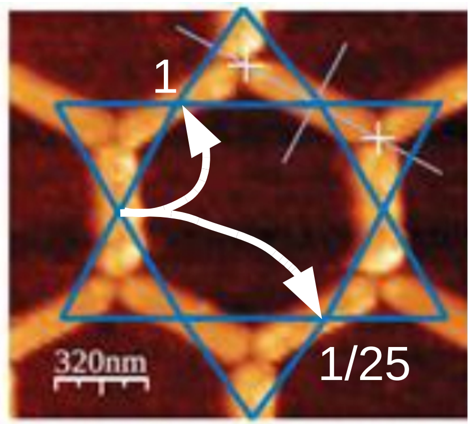


Interactions between nanomagnets are long range

We observe signatures of these interactions

34 demagnetized networks

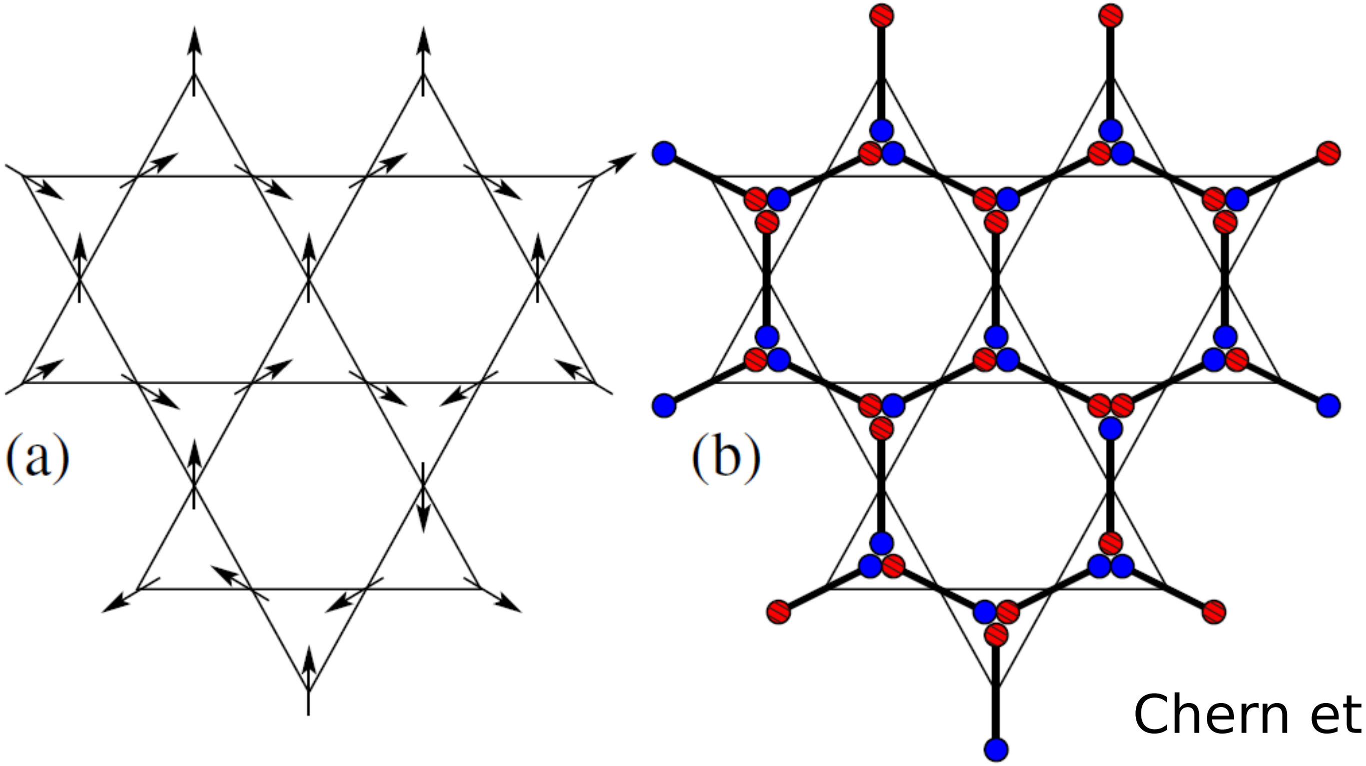




Physics is different

Qi et al., PRB 2008
Mengotti et al., PRB 2008
Moeller et al., PRB 2009
Chern et al., PRL 2011
Rougemaille et al., PRL 2011

New phase transitions predicted

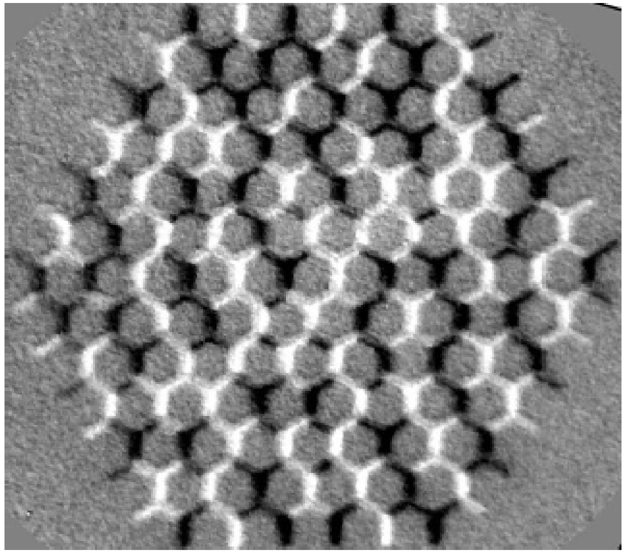


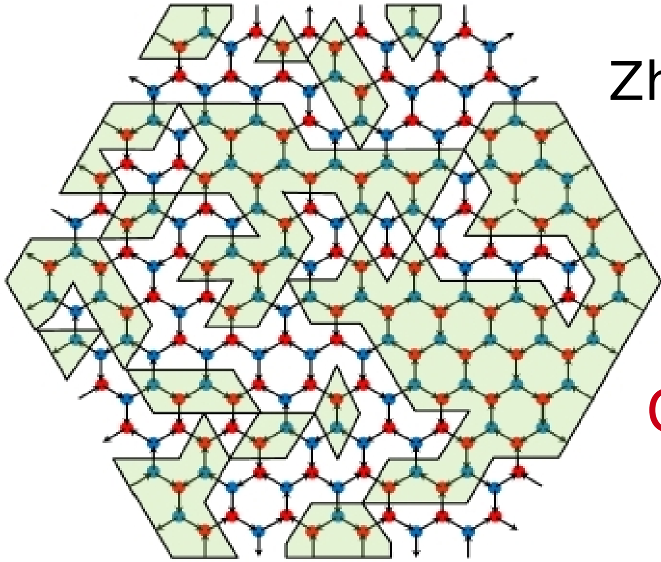
Chern et al., PRL 2011

Ground	Spin Ice II	Spin Ice	Paramagnetic
Ice rule obeyed Charge ordered Spin order	Ice rule obeyed Charge order	Ice rule obeyed Charges disordered	Ice rule disobeyed Charge disorder Spin disorder

$$E = -\sum J_{ij} S_i S_j$$

Emergence of a magnetic charge crystal





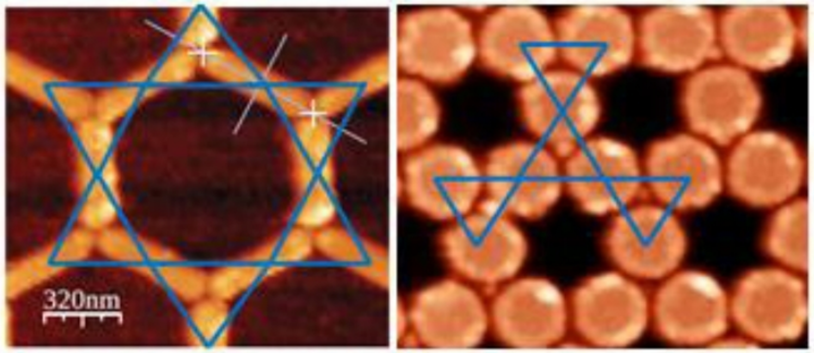
Our work, unpublished
Zhang et al. Nature 2013

Charge crystal

See poster entitled « new magnetic phase and charge crystals »

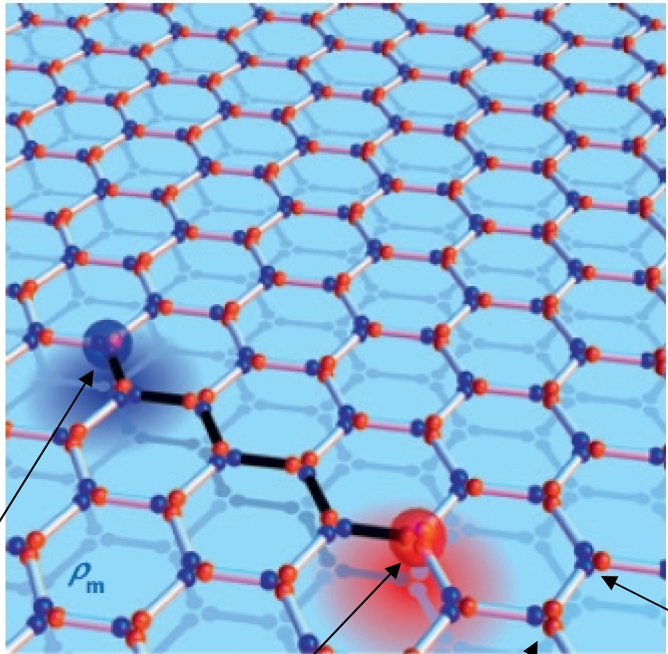
Next talk :
« non-universality of artificial frustrated spin systems »

Ioan Chioar



Magnetic monopoles in kagome lattices

The athermal nature of artificial spin ice systems allow the preparation, characterization and imaging of monopole defects.



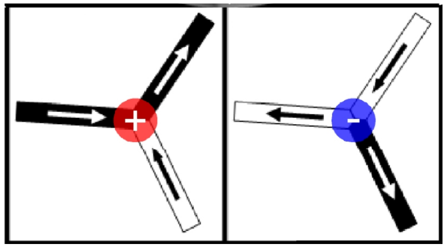
q=-3

q=+3

q=+1

q=-1

Ladak et al., Nat. Phys. 2010
Mengotti et al., Nat. Phys. 2011
Morgan et al., Nat. Phys. 2011
Phatak et al., PRB 2011
…
Zeissler et al., Sci. Rep. 2013
Pushp et al., Nat. Phys. 2013

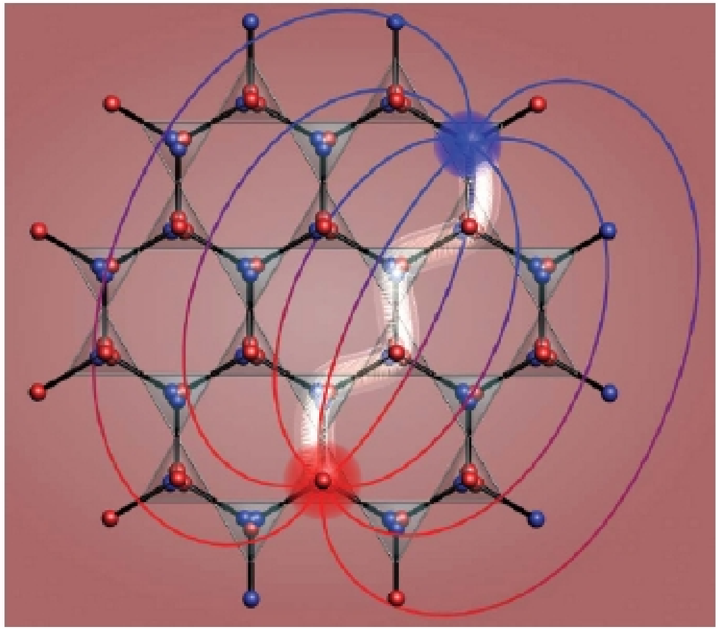


Yann Perrin

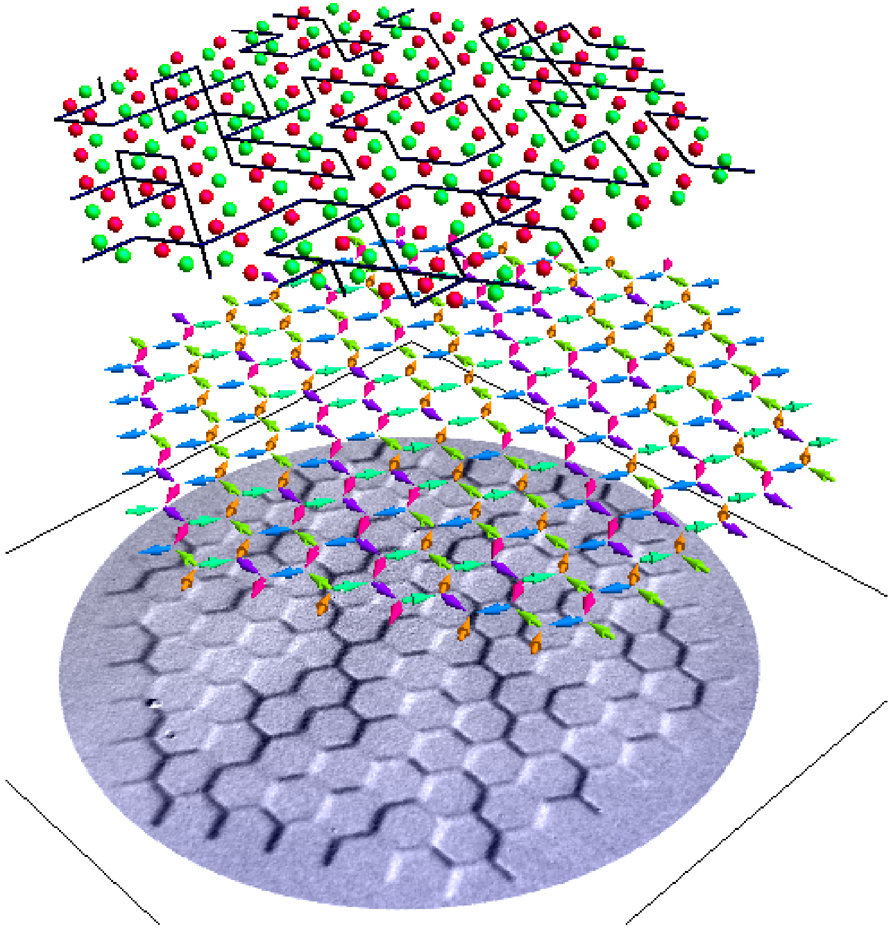
Monopole can even be chiral... see poster

Take home messages

We observe (exotic) magnetic phases and « magnetic excitations » in athermal systems !



Moessner et al., Nature 2008



Temperature enters the game...

Morgan et al., Nat. Phys. 2011, Farhan et al, Nat. Phys. 2013, PRL 2013, Zhang et al., Nature 2013

… and new geometries arrive on the market

Breaking the ice

List of all collaborators, students and hard workers

Les Fondus du synchrotron

Les Gelés du labo

Alphabetic order: R. Belkhou, A. Bendounan, B. Canals, I. Chioar, A. Duluard, S. El Moussaoui, O. Fruchart, A. Grimm, M. Hehn, D. Lacour, S. Le-Denmat, D. Louis, A. Locatelli, F. Maccherozzi, S. Mc Murtry, T. O. Mentes, F. Montaigne, Y. Perrin, H. Riahi, N. Rougemaille, A. Sala, B. Santos Burgos, J.-C. Toussaint, E. Wagner

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Acknowledgments

ANR12-BS04-009
FRUSTRATED