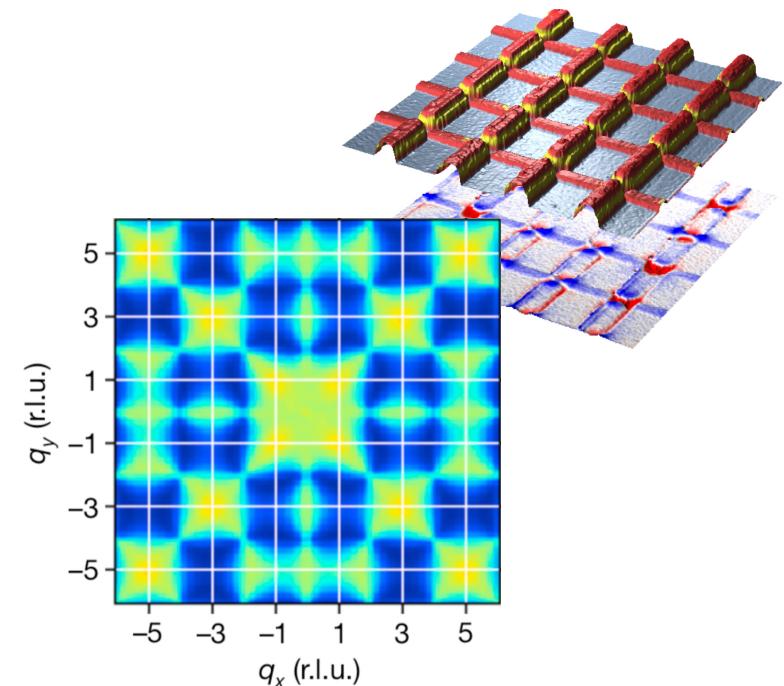
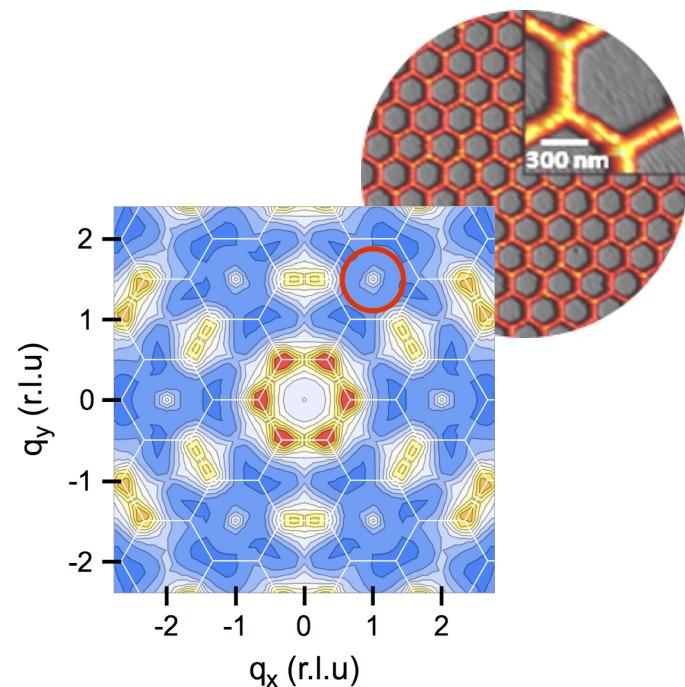


Artificial spin systems as experimental simulators of frustrated magnets: from the fragmentation of magnetization to the six vertex model



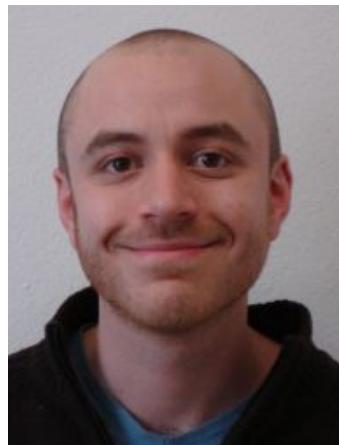
Most important first: Acknowledgments

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

Néel Institute - Jean Lamour Institute - ELETTRA / SOLEIL synchrotrons

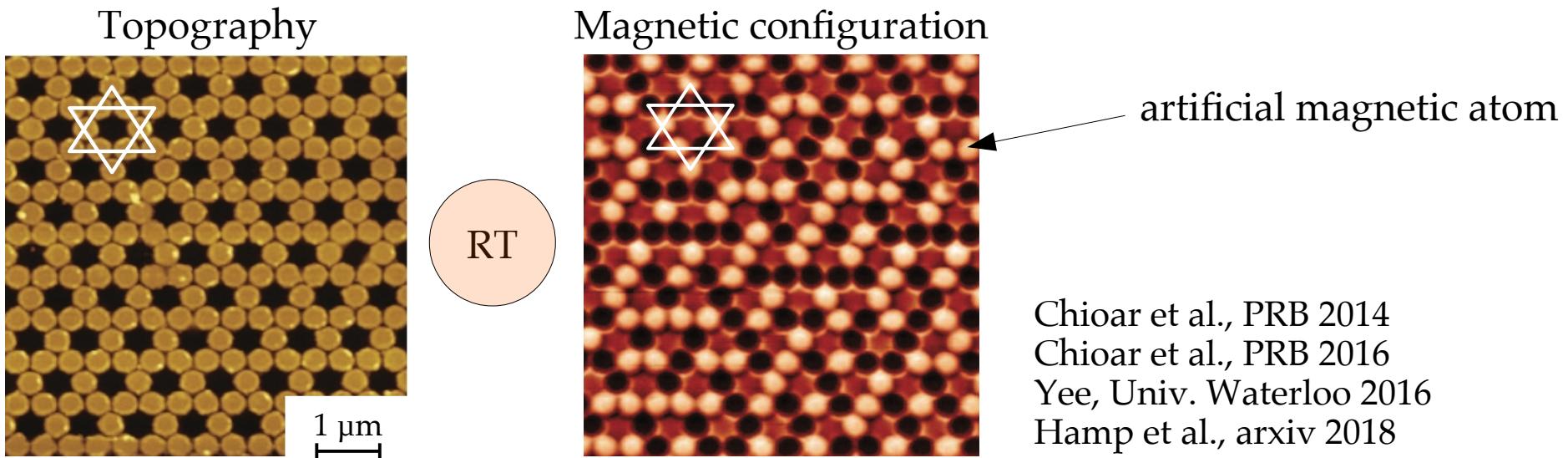
Nanofab: T. Fournier, T. Crozes, S. Dufresnes, G. Julie

PTA: T. Chevolleau



Artificial 2D materials

Dipolar kagome Ising antiferromagnet



$$H = \sum_{(i,j)} J_{ij} \sigma_i \sigma_j \quad - \text{magnetostatic framework}$$

- real space imaging at (or near) RT

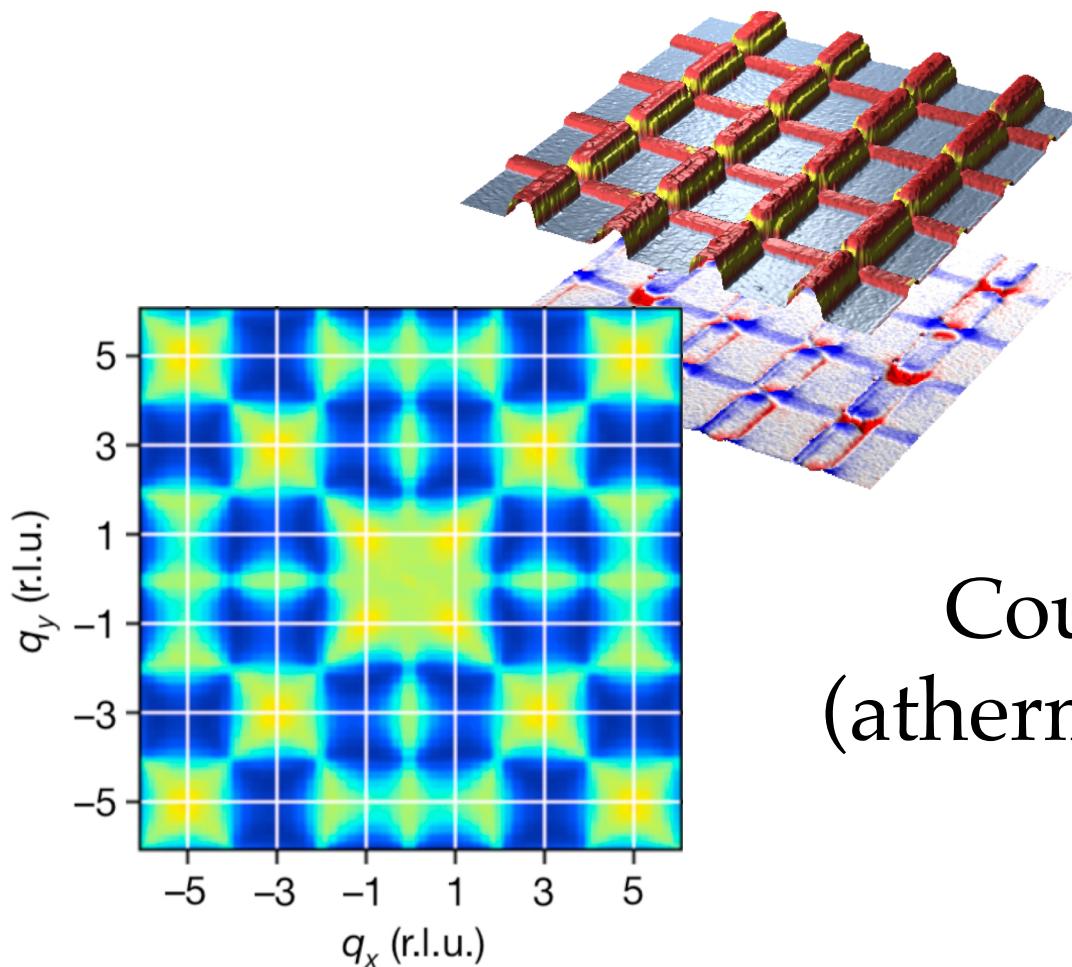
- tunability (geometry, spin degree of freedom, defects ...)

- adjustable dynamics

Tanaka et al., JAP 2005 ; PRB 2006
Wang et al., Nature 2006
Gilbert et al., Nat. Phys. 2014
Ewerlin et al., PRL 2013
Drisko et al., Nat. Comm. 2017
Farhan et al., PRL 2013 ; PRB 2017
Kapaklis et al., Nat. Nano. 2014

Lab-on-chip approach to access the many body physics of classical spin systems in real space

Cooperative magnetic phenomena. Part 1



Coulomb spin liquid in
(athermal) artificial square ice

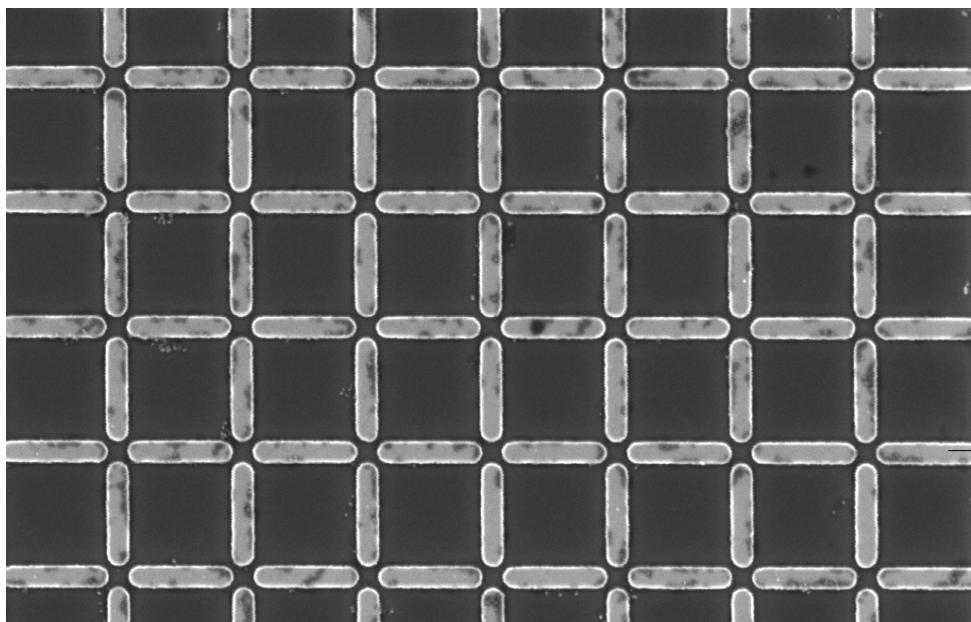
Magnetic nanostructures on a square lattice

Wang et al., Nature 2006

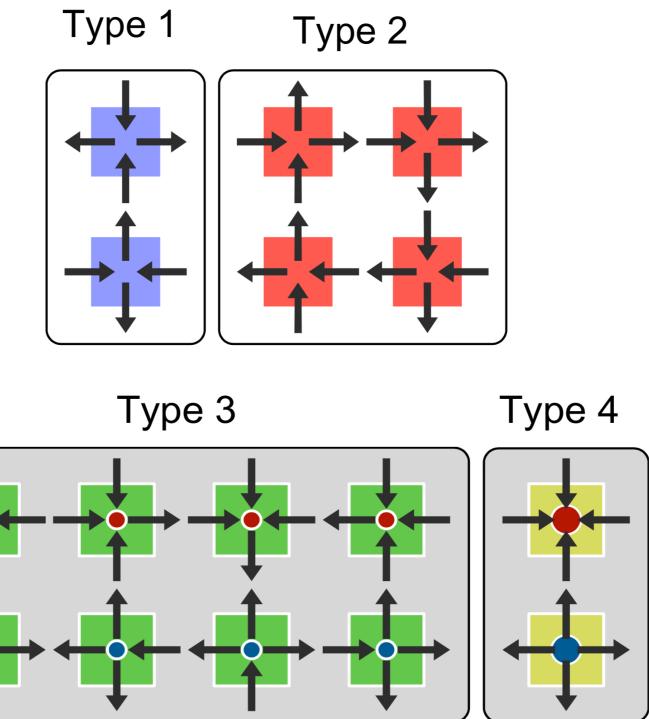
Nisoli, Moessner & Schiffer, Rev. Mod. Phys. 2013

Initially introduced to mimic the physics of spin ice materials and to reproduce celebrated two-dimensional models of statistical mechanics

- extensive degeneracy of the low-energy manifold ?
- capture the physics of the 6 vertex model ?

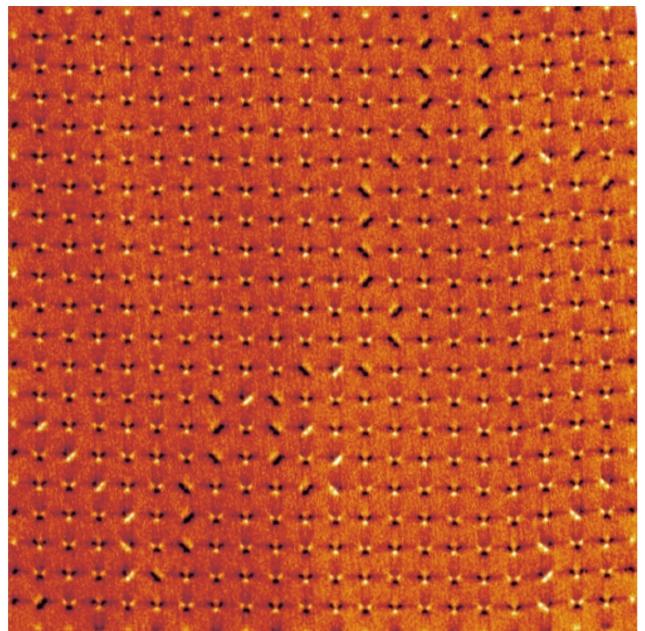


w = 150 nm
L = 750 nm
t = 30 nm



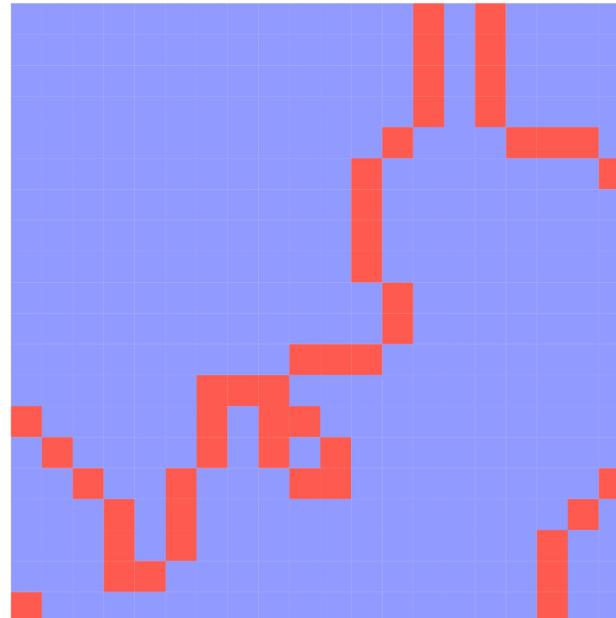
Antiferromagnetic ordering in the square lattice

Magnetic force microscopy image

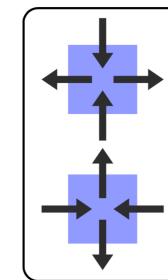


Field of view = $15 \times 15 \mu\text{m}$

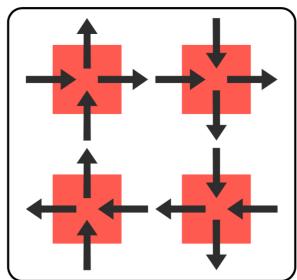
Image analysis



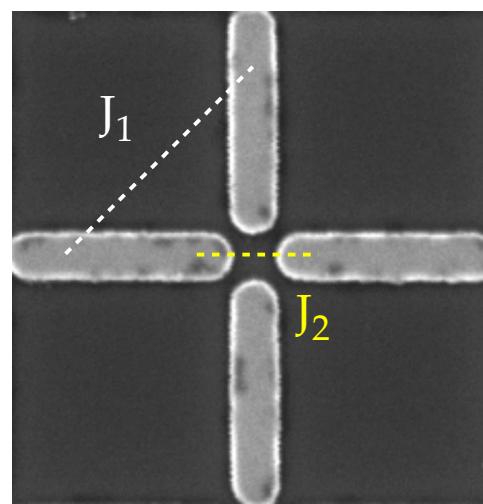
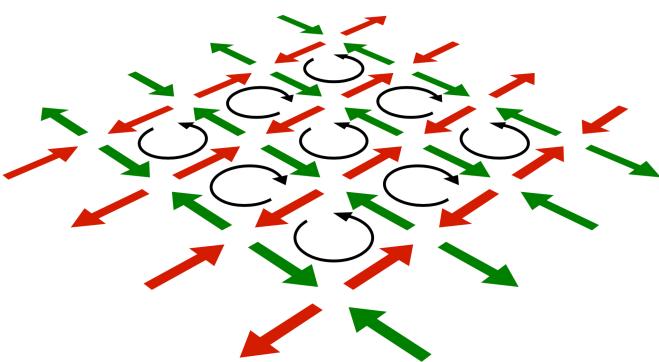
Type 1



Type 2



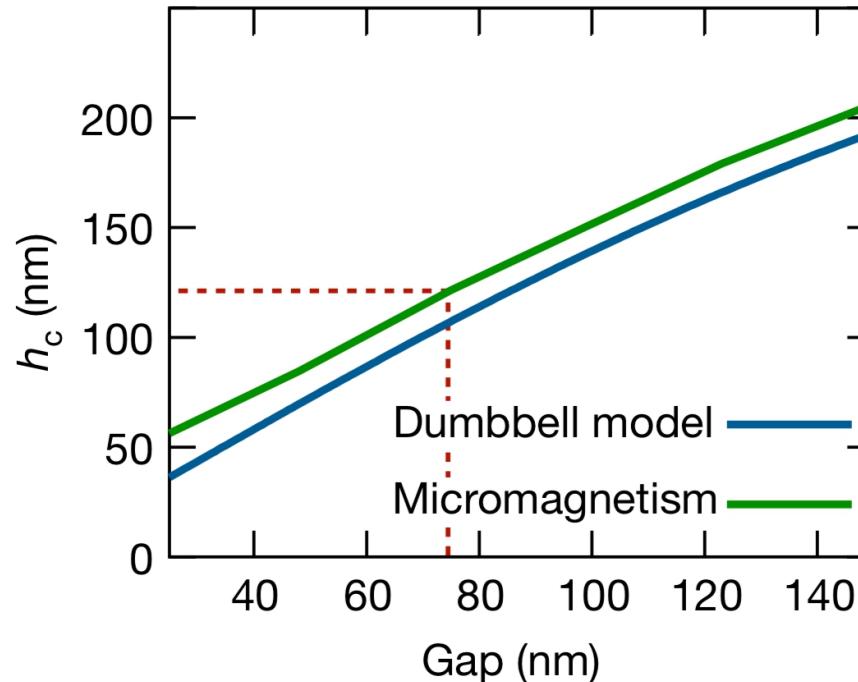
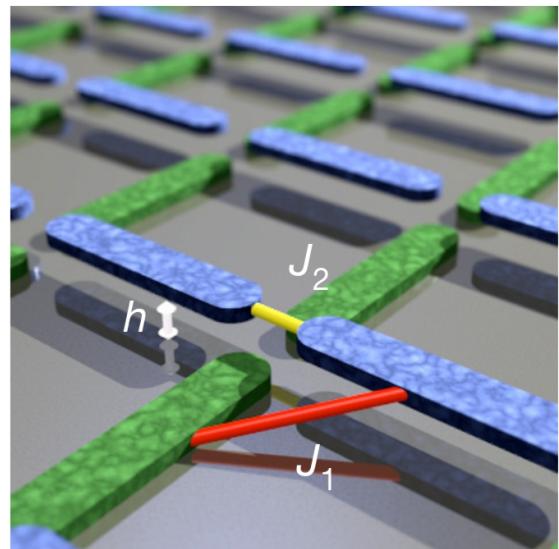
Why degeneracy is lost ?



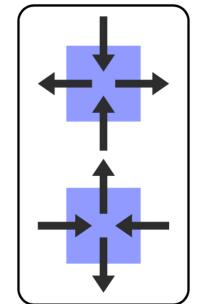
Artificial square ice: design

Proposal to recover degeneracy: shift vertically one sublattice - Möller & Moessner, PRL 2006

Experimental realization - Perrin et al., Nature 2016

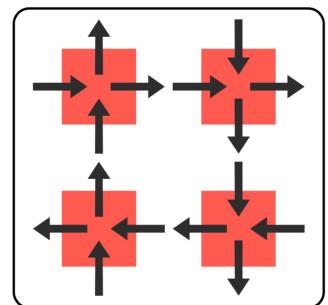


Type 1

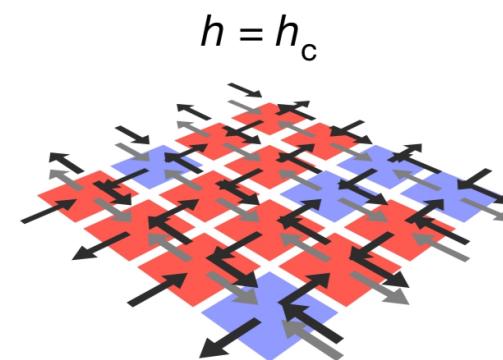
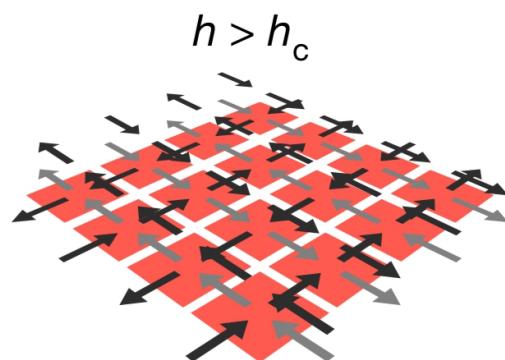
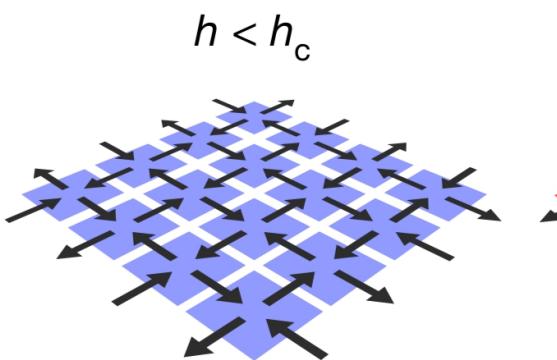


$$E_1 = -4J_1 + 2J_2$$

Type 2

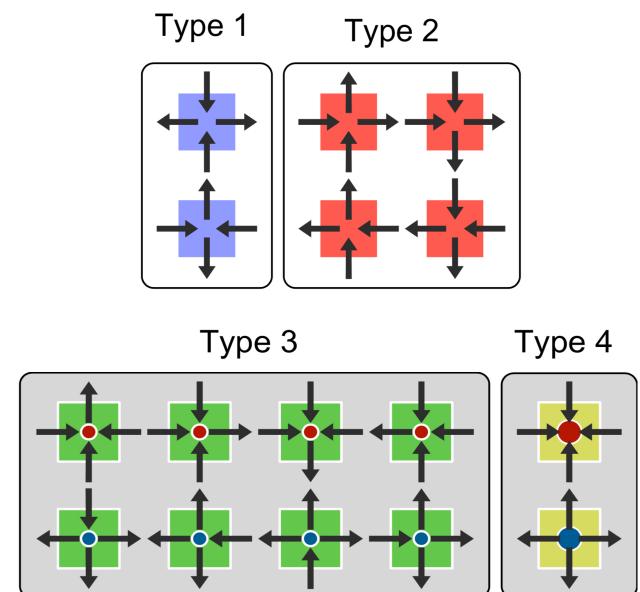
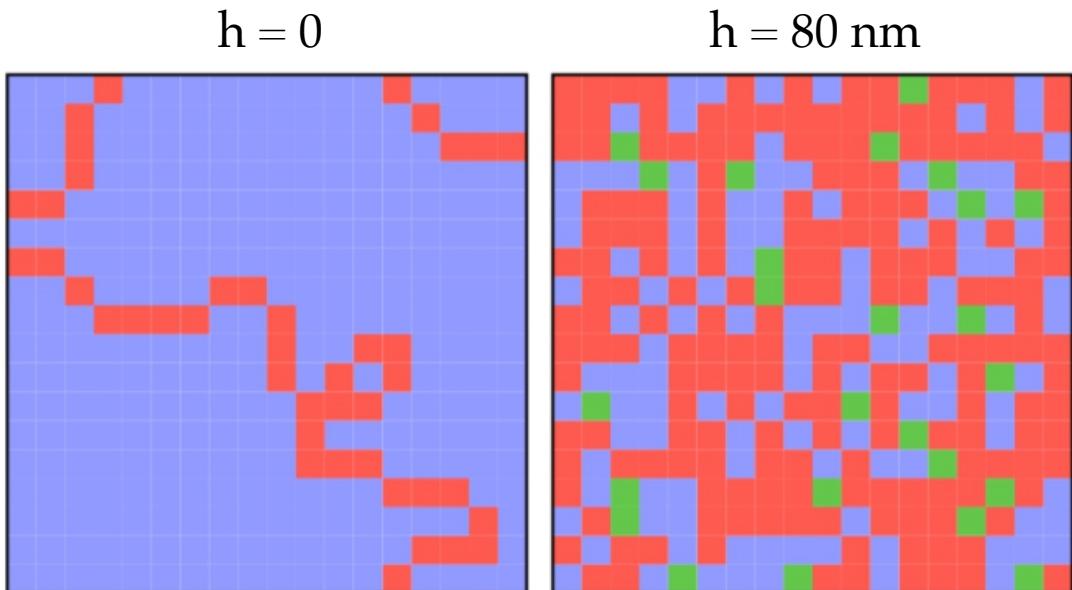
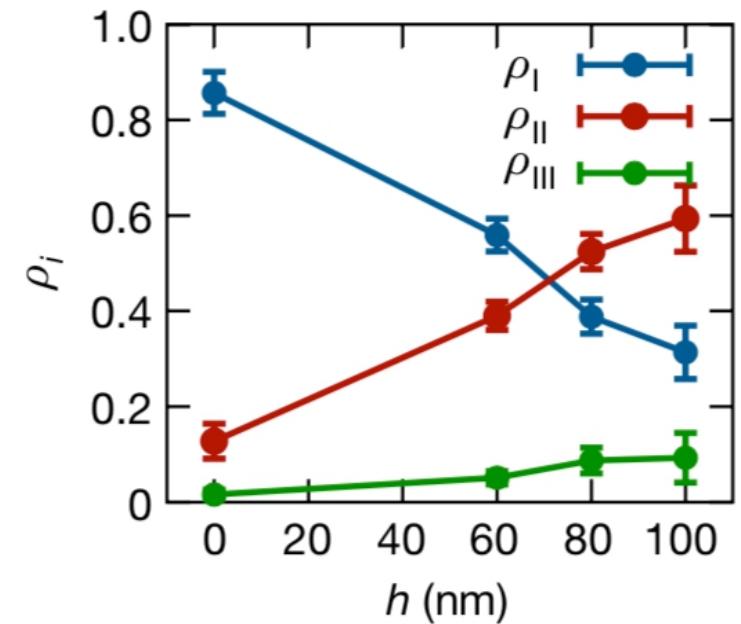
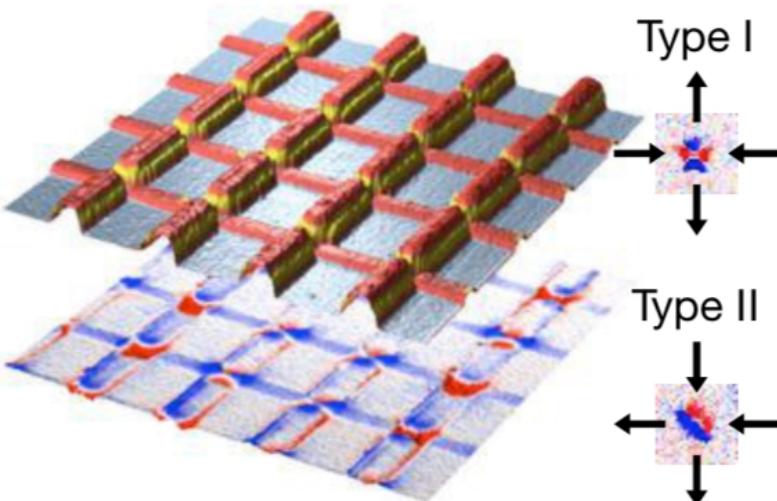


$$E_2 = -2J_2$$

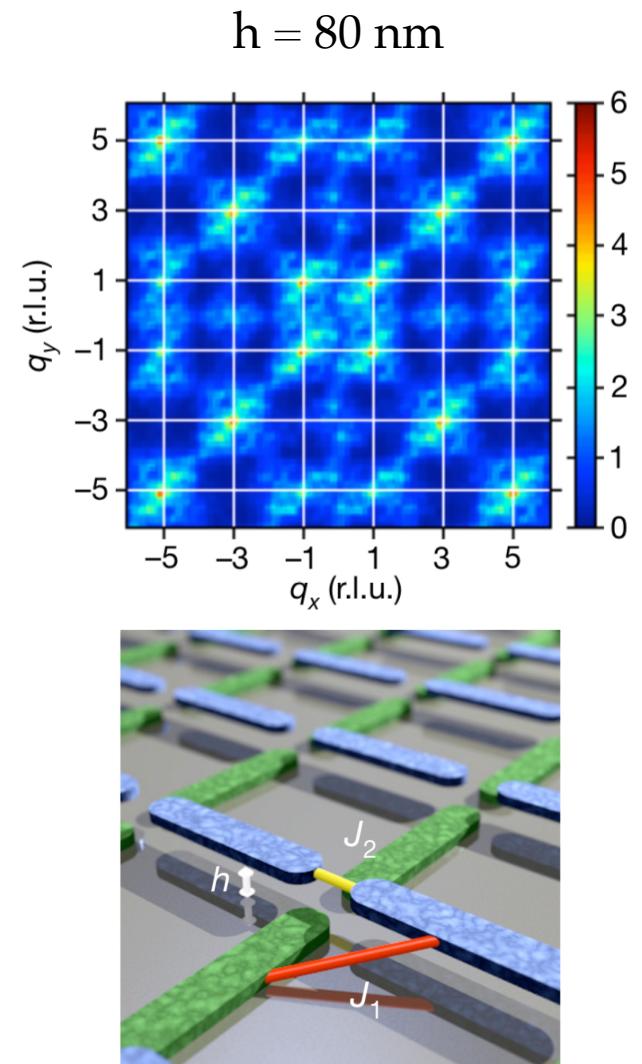
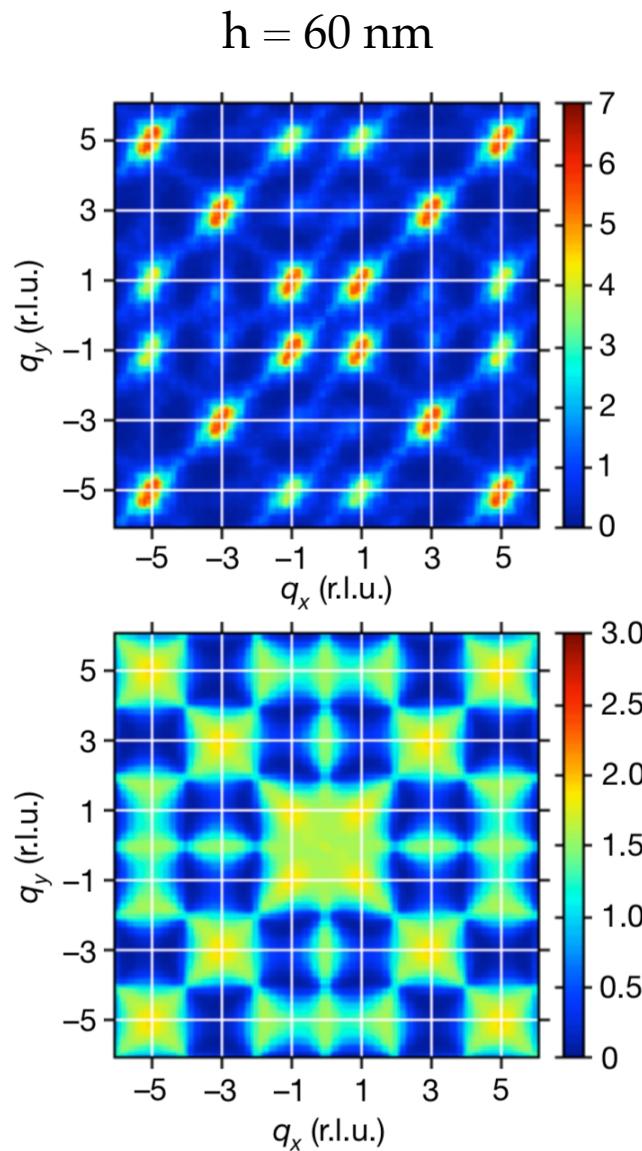
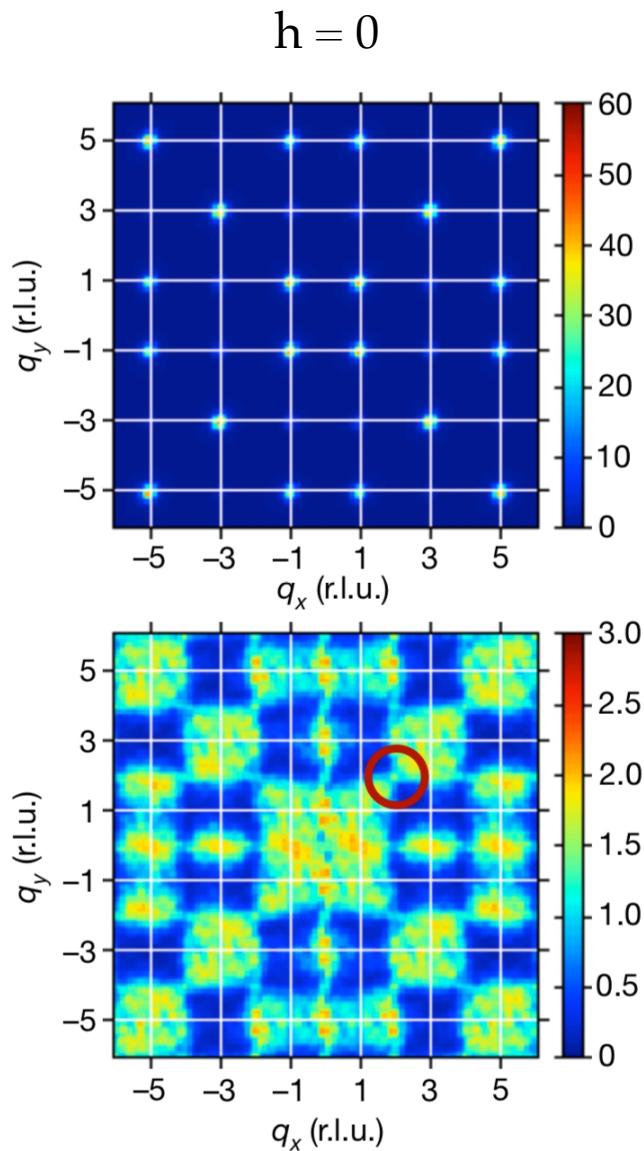


Artificial square ice: magnetic properties

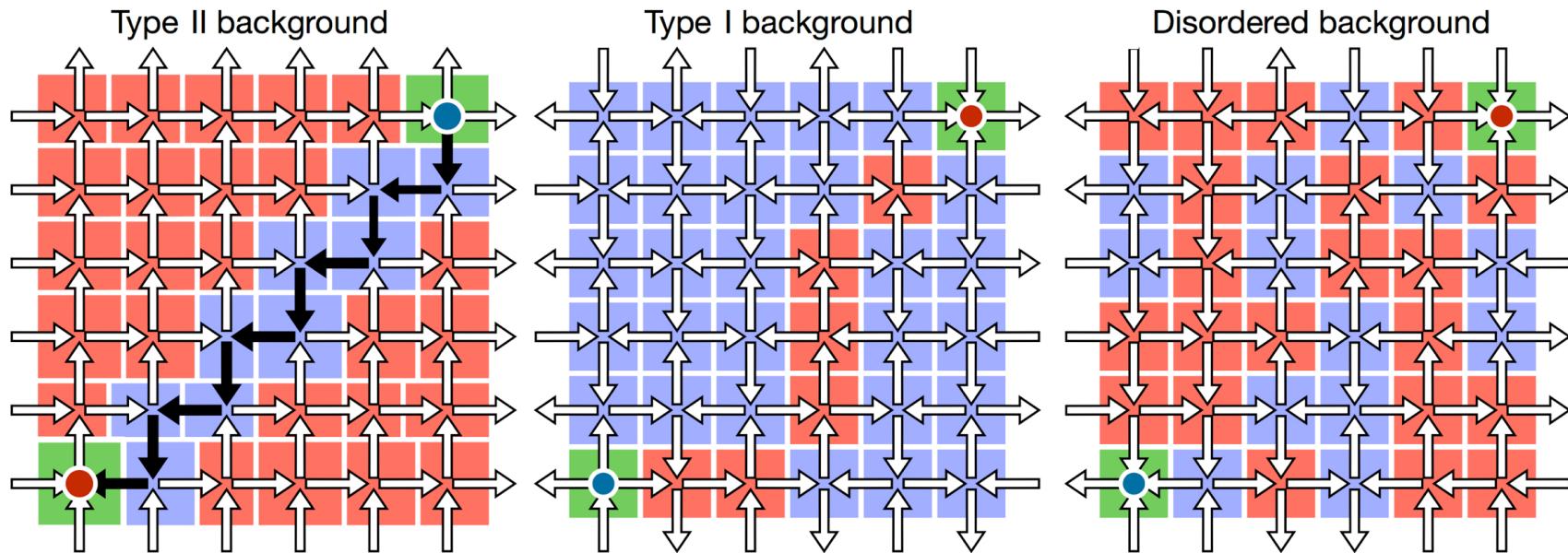
Athermal system
↓
Field protocol



Coulomb spin liquid



Charge defects and magnetic monopoles



Morgan et al., NJP 2011

Phatak et al., PRB 2011

Pollard et al., PRB 2012

Morgan et al., Nat. Phys. 2011

Farhan et al., PRL 2013

Porro et al., NJP 2013

kagome Ladak et al., Nat. Phys. 2010
 Mengotti et al., Nat. Phys. 2011

- Real space dynamics of contractible and non contractible monopole pairs

- Tuning the monopole density

- Phase diagram

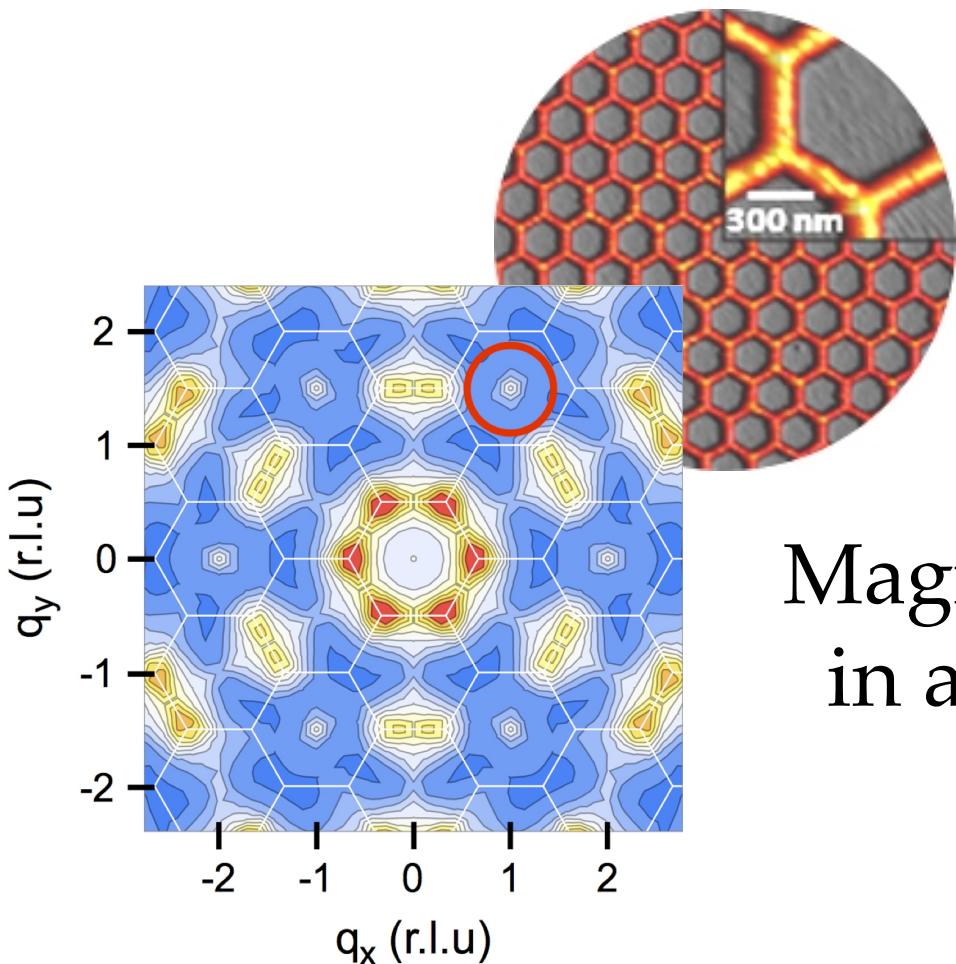
- Magnetic moment fragmentation

Castelnovo et al., PRL 2010

Borzi et al., PRL 2013

Brooks-Bartlett et al., PRX 2014

Cooperative magnetic phenomena. Part 2



Magnetic moment fragmentation
in a (thermally active) artificial
kagome Ising system

Magnetic moment fragmentation

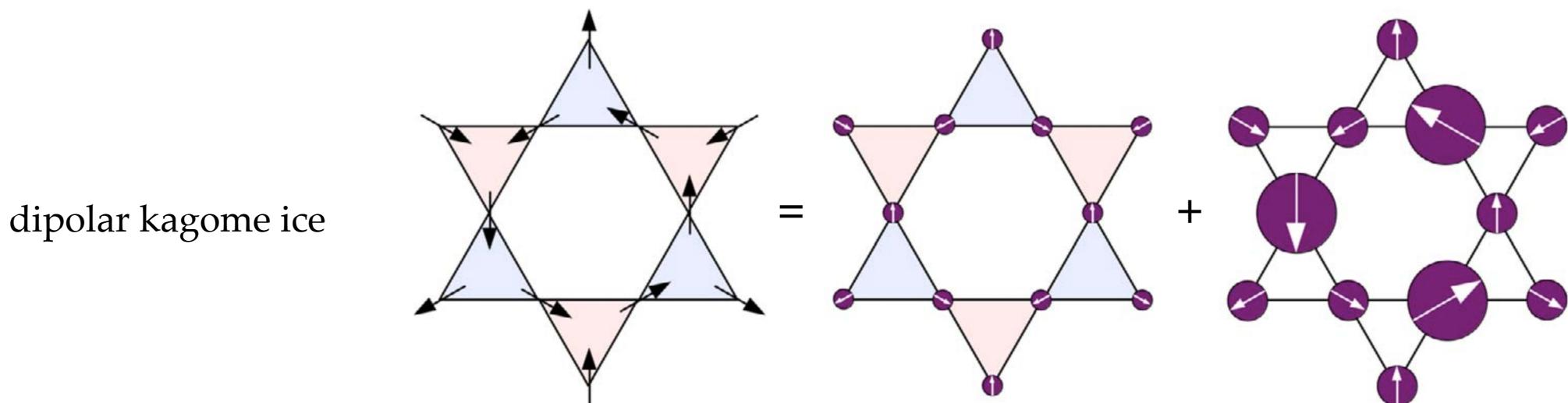
Brooks-Bartlett et al., PRX 2014

Petit et al., Nat. Phys. 2016 ; Benton, PRB 2016 ; Jaubert, SPIN 2016 ; Paddison et al., Nat. Commun. 2016 ; Lefrançois et al., Nat. Commun. 2017 ; Dun et al., arxiv 2018 ; ...

Fragmentation happens when the same degree of freedom (the magnetic moment) contributes, **everywhere** and **at any time**, to two **distinct** behaviors

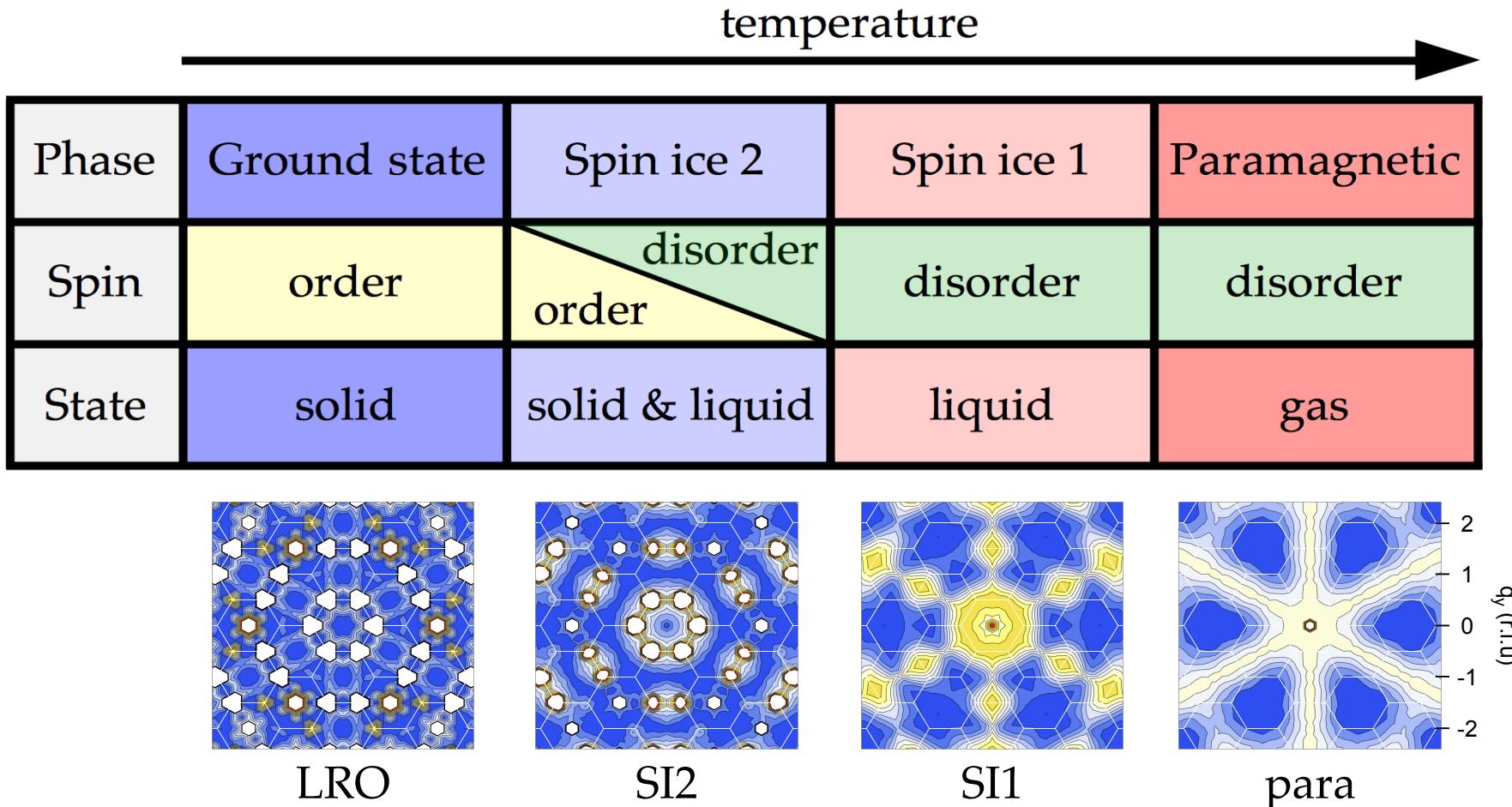
Collective & dynamical phenomenon

One magnet - Two separate entities (even for an Ising variable)



Phase transitions in the dipolar kagome spin ice

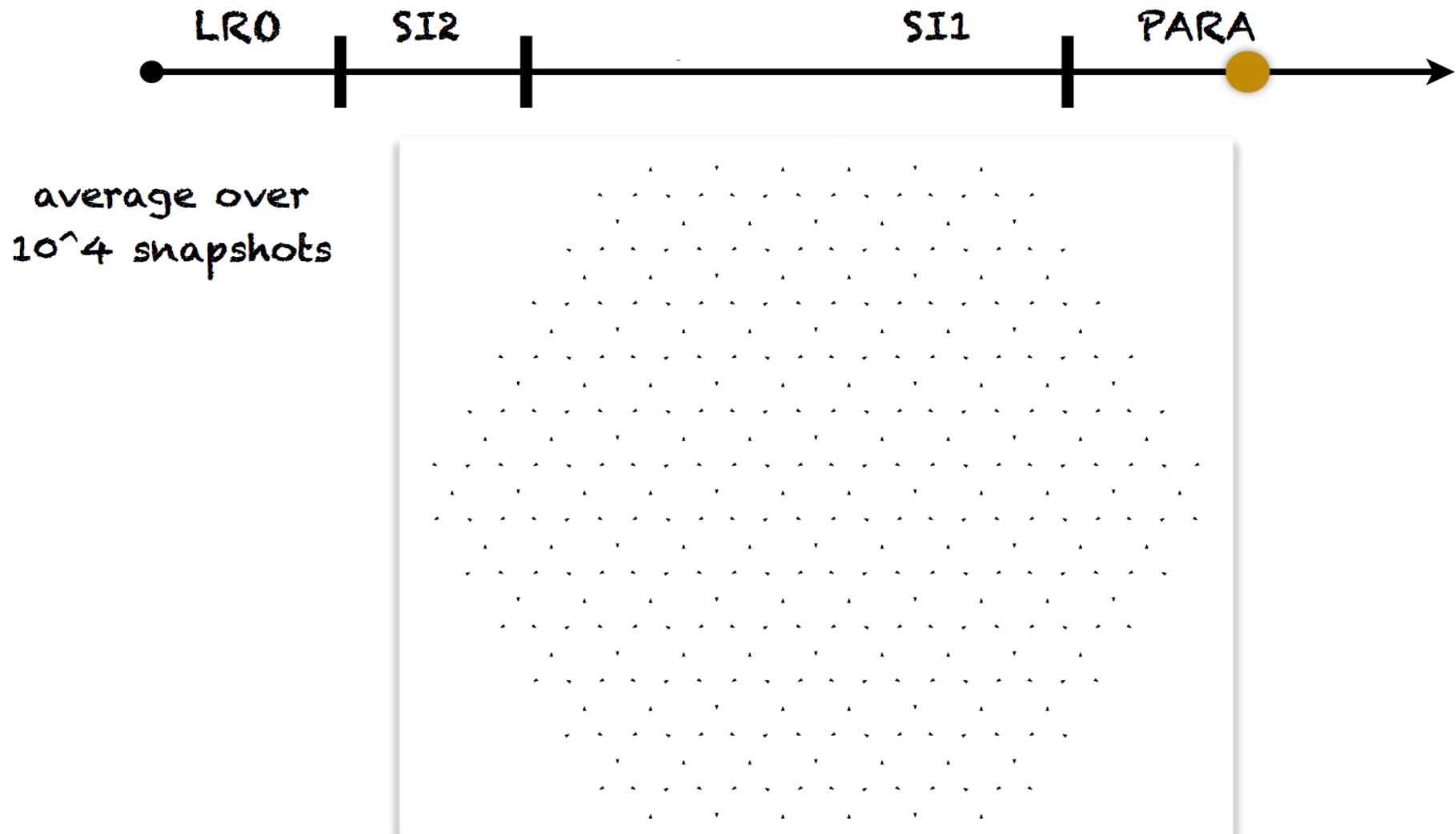
Spin Hamiltonian: $H_{DSI} = -J_1 \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j + D \cdot \sum_{(i,j)} \frac{\vec{S}_i \cdot \vec{S}_j}{|\vec{r}_{ij}|^3} - \frac{3(\vec{S}_i \vec{r}_{ij})(\vec{S}_j \vec{r}_{ij})}{|\vec{r}_{ij}|^5}$



Phase transitions in the dipolar kagome ice

Monte carlo simulations

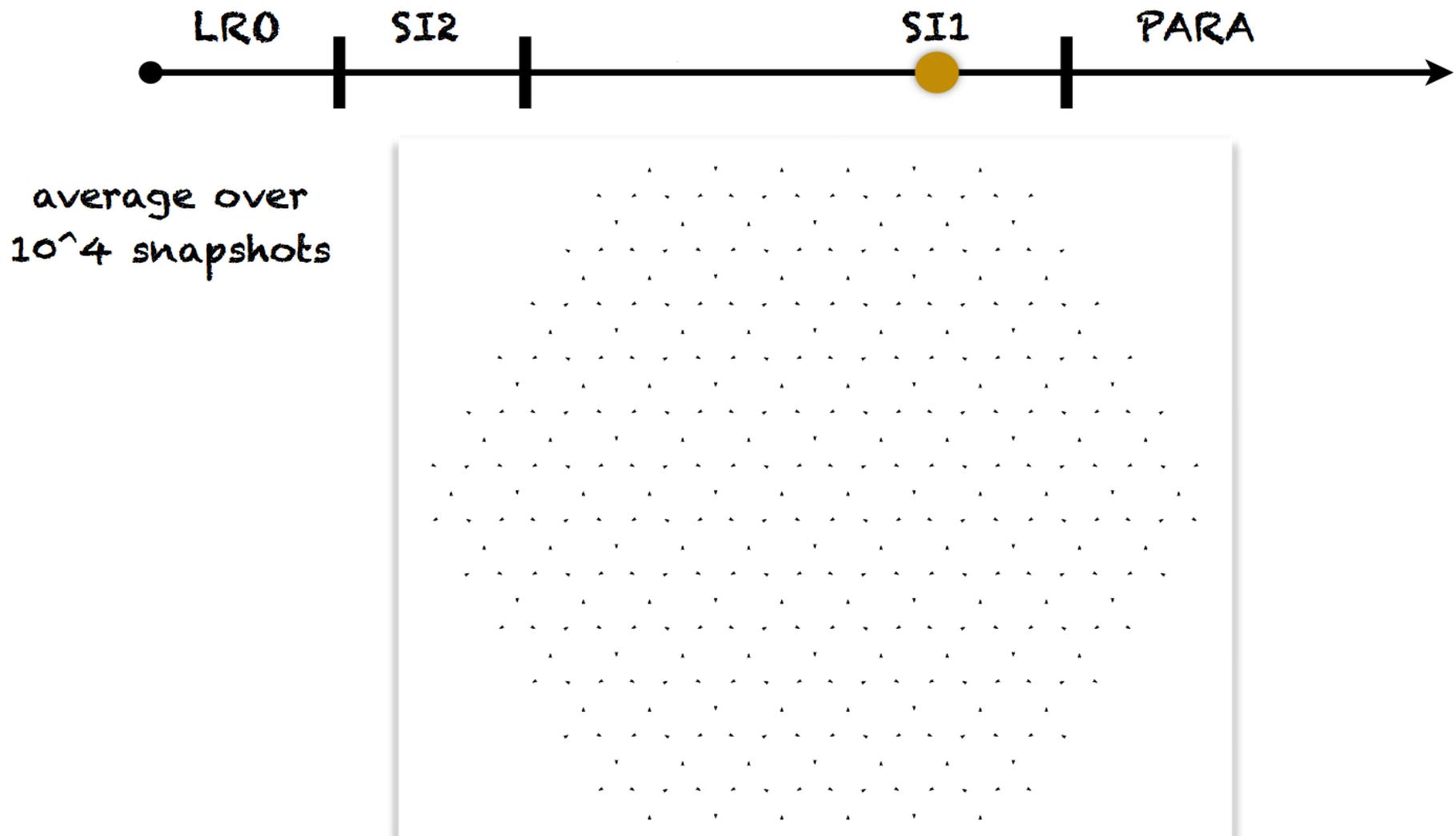
Real space – representation of the $\langle S \rangle$ value at each site



Phase transitions in the dipolar kagome ice

Monte carlo simulations

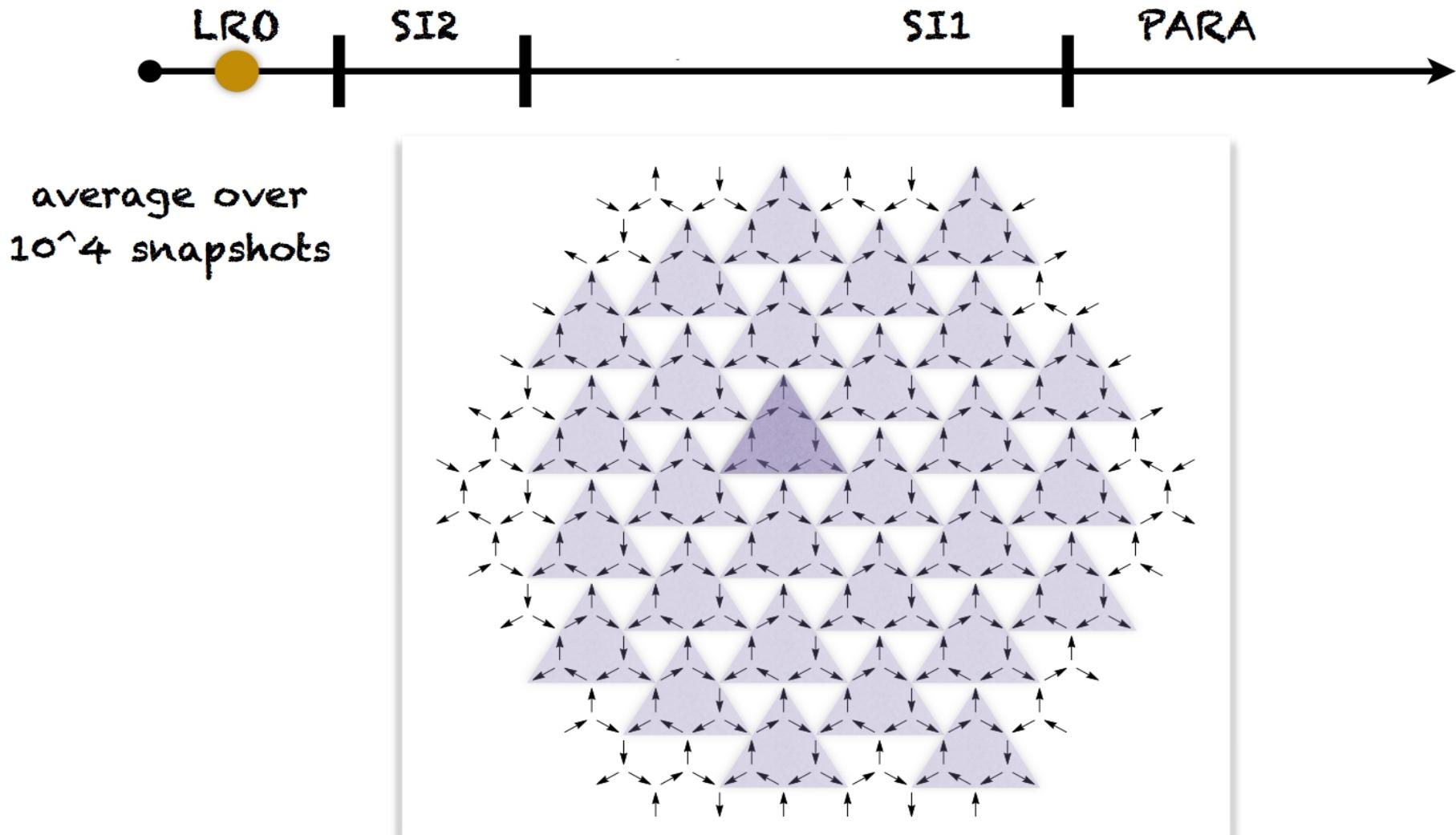
Real space – representation of the $\langle S \rangle$ value at each site



Phase transitions in the dipolar kagome ice

Monte carlo simulations

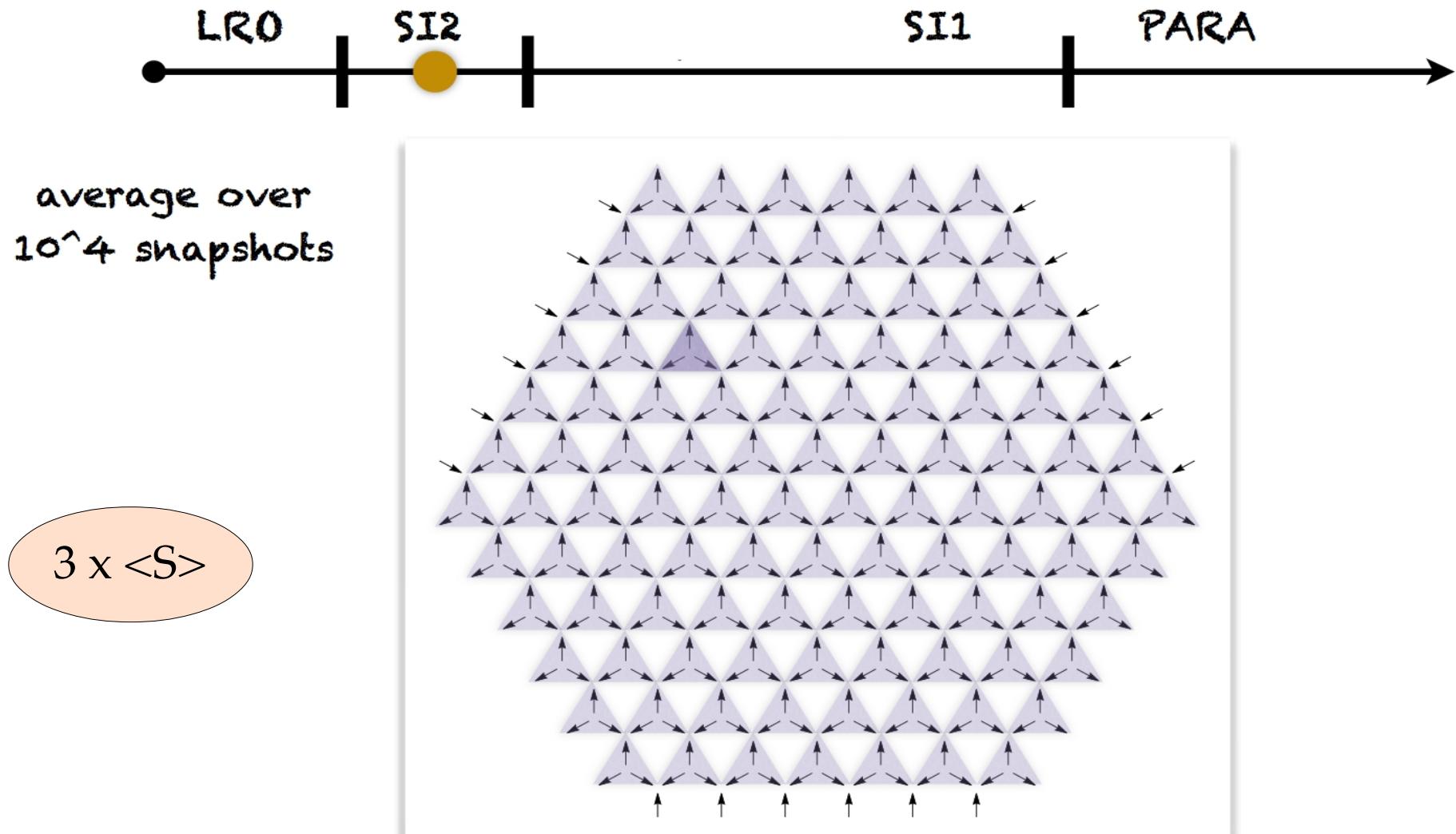
Real space – representation of the $\langle S \rangle$ value at each site



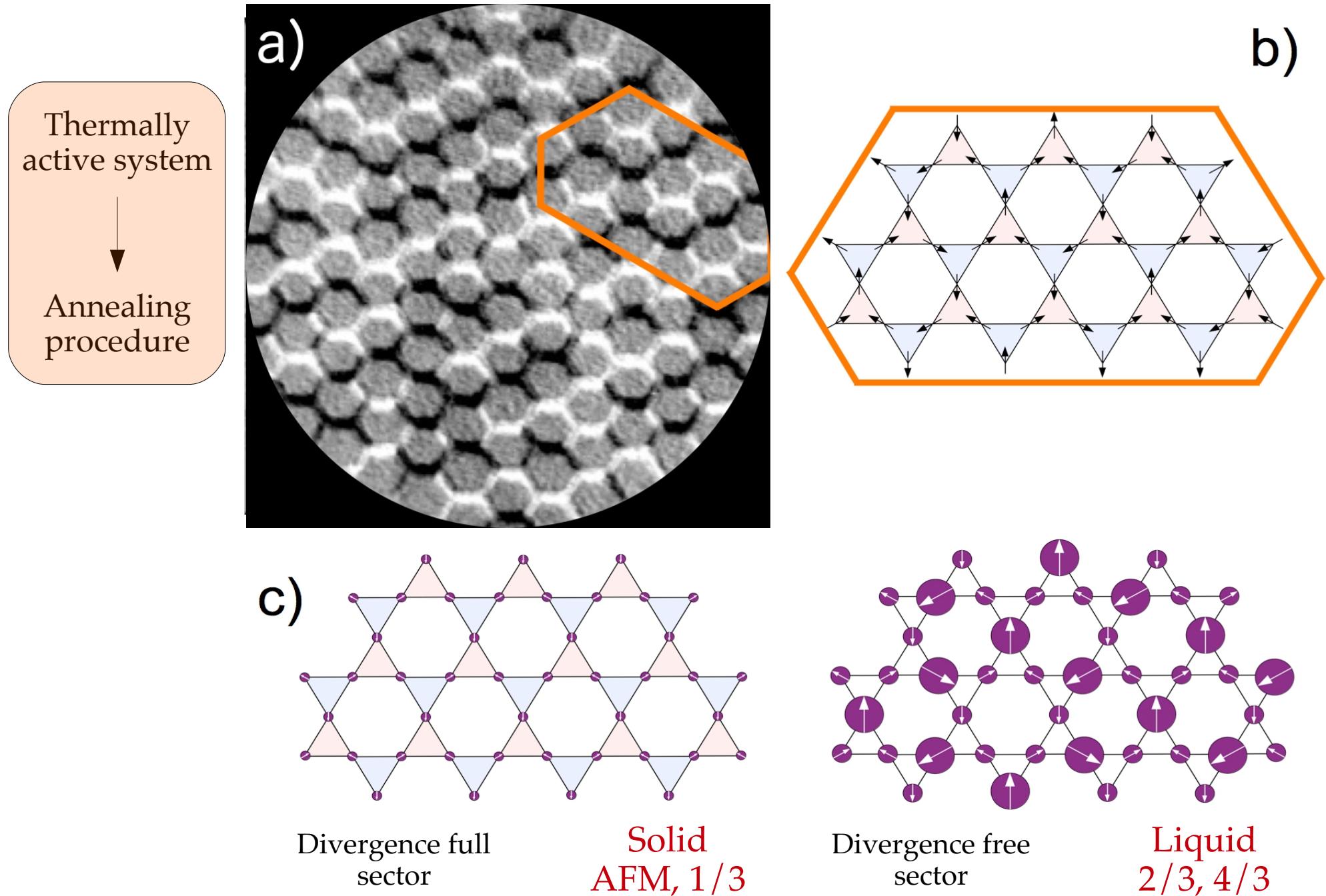
Phase transitions in the dipolar kagome ice

Monte carlo simulations

Real space – representation of the $\langle S \rangle$ value at each site

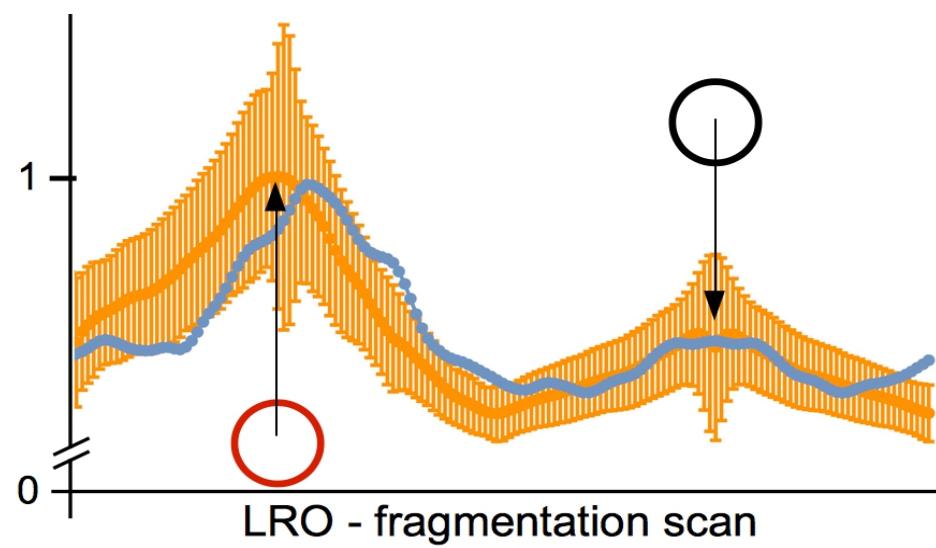
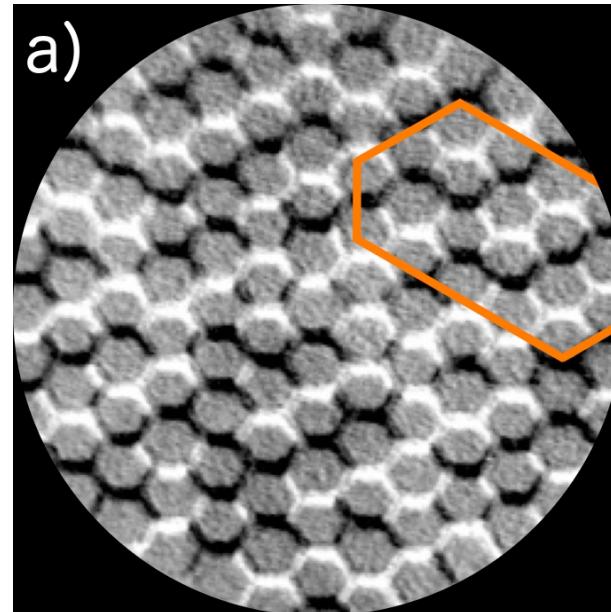
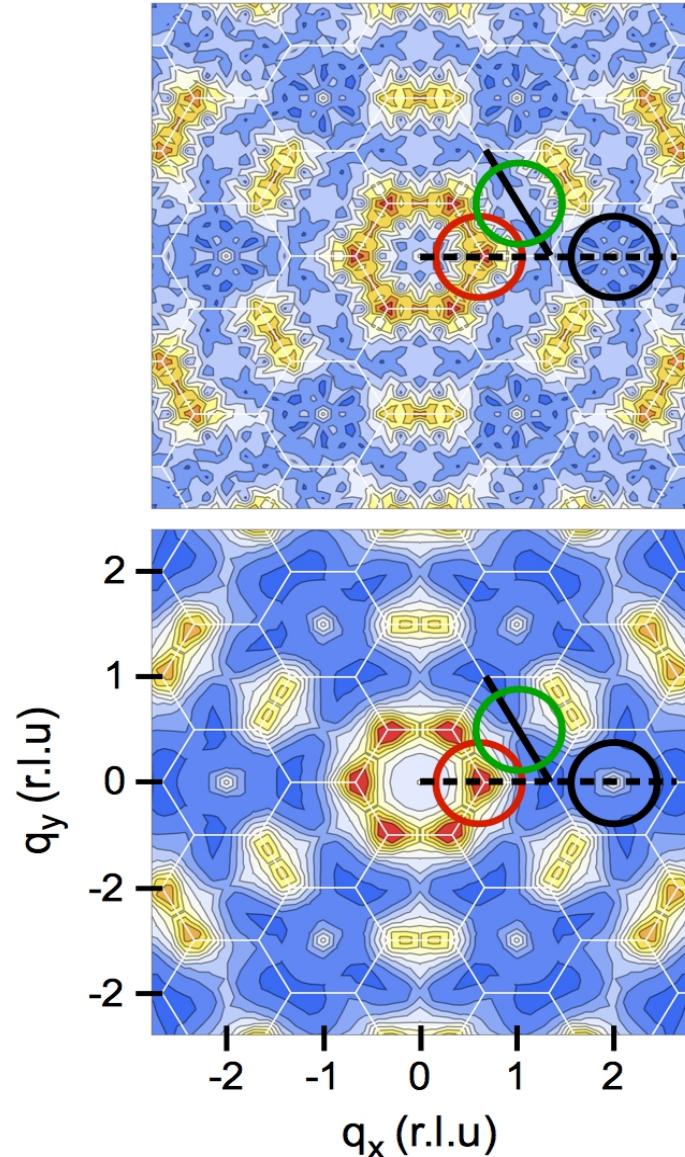


Real space imaging of magnetic fragmentation

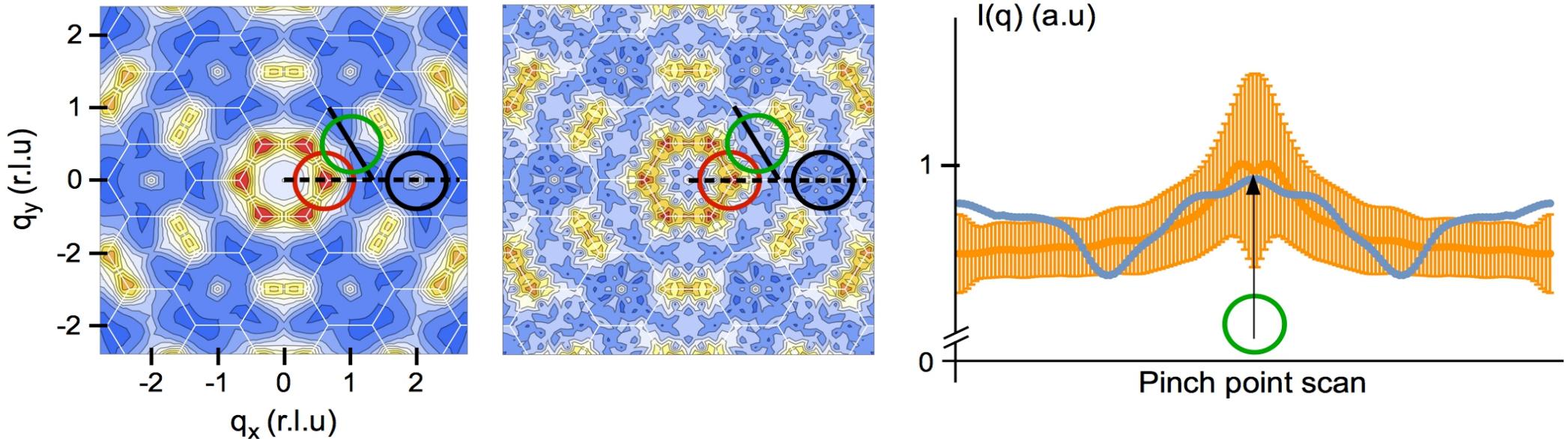


Reciprocal space imaging of magnetic fragmentation

Signature of magnetic moment fragmentation



A fragmented spin liquid



- Strategy to reach and explore lower energy configurations without loop moves ?
- Real space dynamics in the two sectors (div free / div full) when approaching the SI2 phase

Take home message

Lab-on-chip approach to investigate cooperative magnetic phenomena in artificial frustrated magnets

- spin liquids, Coulomb phase & magnetic monopoles, fragmentation of magnetism, ...

