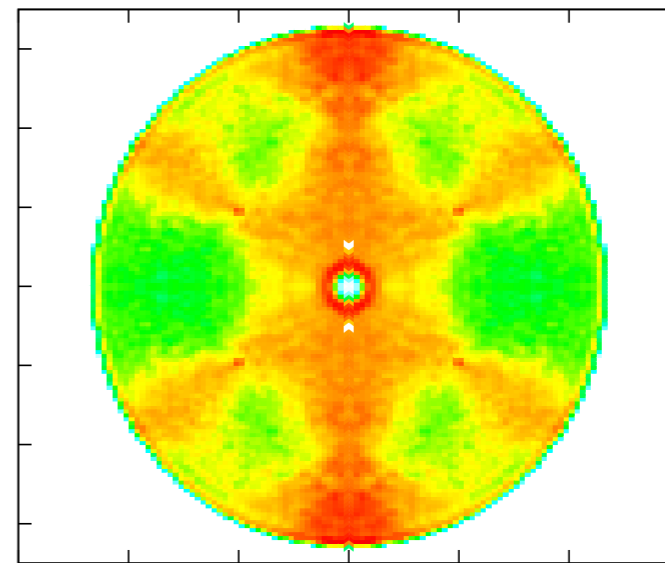
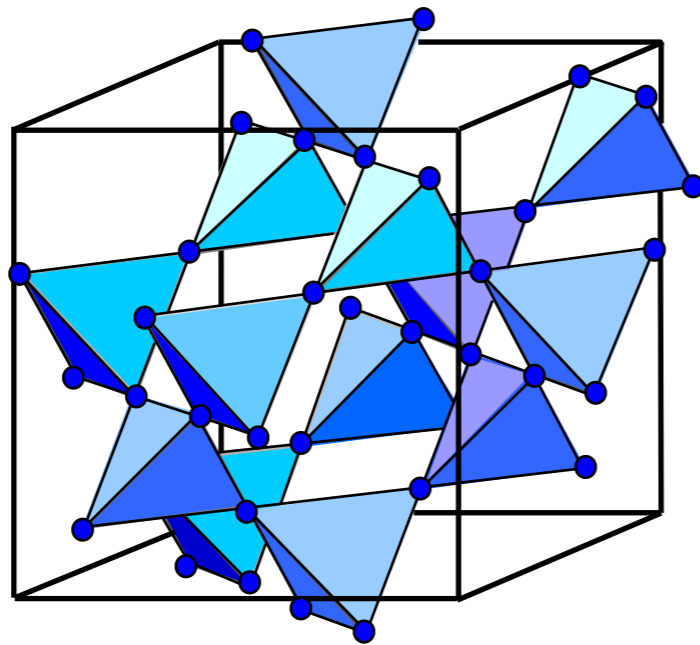


# Dynamic fragmentation in frustrated magnets

2FDN - UGA PhD thesis 2018-2021

PhD student: Mélanie Léger

Supervisors: Sylvain Petit - *LLB Saclay*  
Elsa Lhotel - *Institut Néel Grenoble*



# Context: Frustrated magnetism in pyrochlore oxides

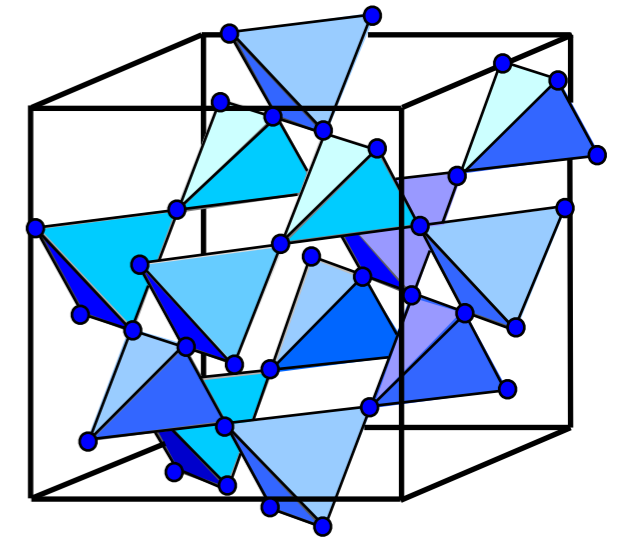
formula  $R_2M_2O_7$  (R = rare-earth, M = metal) - cubic lattice  $Fd\bar{3}m$

= two interpenetrated lattices of corner sharing tetrahedra

prone to frustration - rich playground to stabilize new magnetic phases

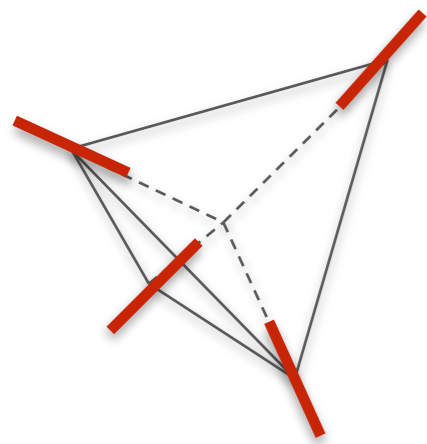
exchange interactions between R ions in the Kelvin range

=> need for very low temperature measurements

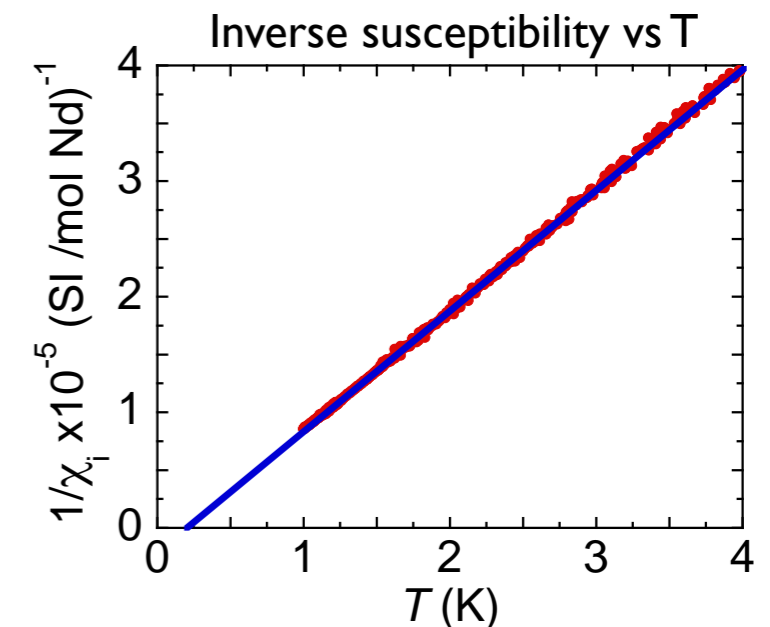


Gardner et al., Rev. Mod. Phys. 82 (2010)

$Nd_2Zr_2O_7$ :

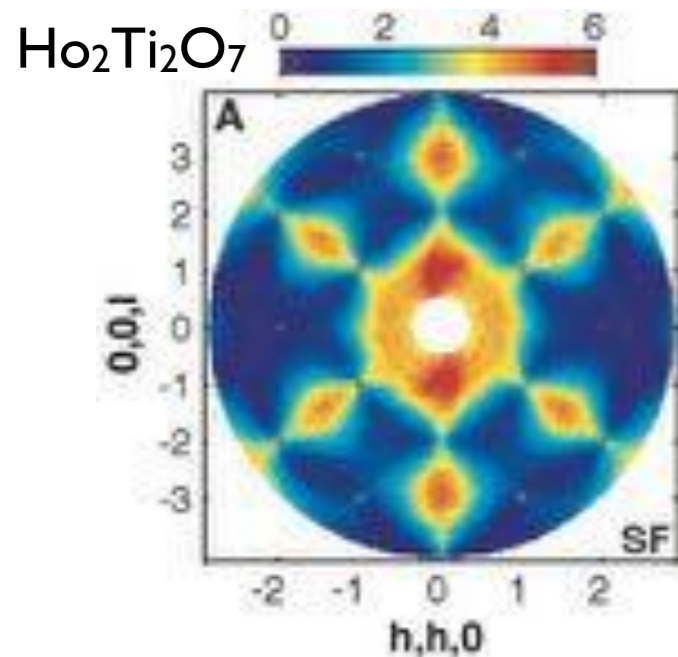
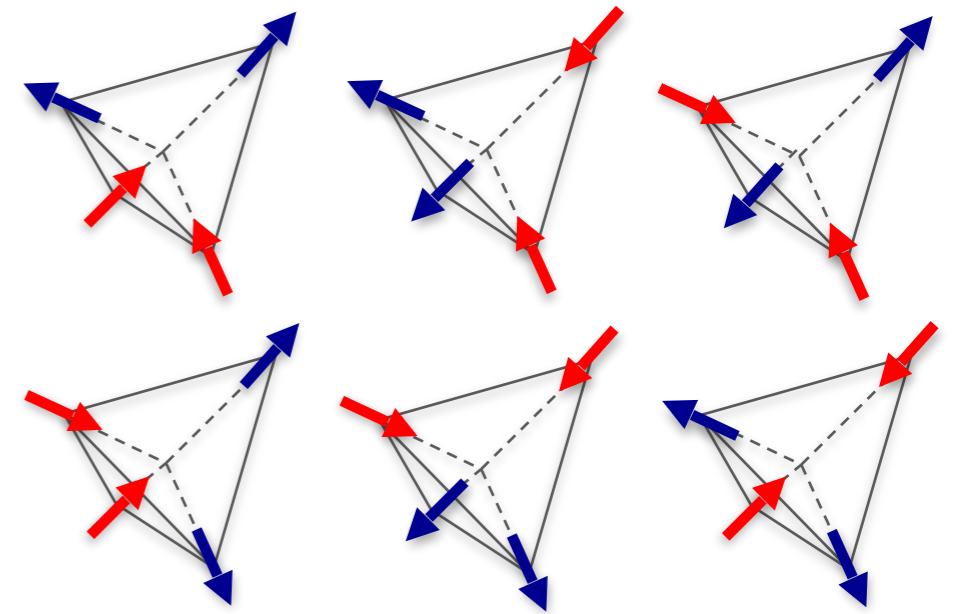


multi axis Ising spins + ferromagnetic interactions  
=> should stabilize the spin ice state



# Spin ice

= disordered degenerate ground state  
with a local constraint “2 spins in - 2 spins out”

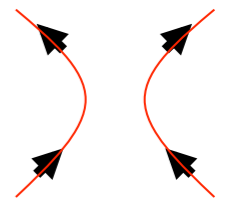


Fennell et al., Science 326 (2009)

Ice-rule can be mapped to a divergence-free field  
+ disordered ground state

=> **Coulomb phase**

Henley, Ann. Rev. Condens. Matter Phys. 1 (2010)

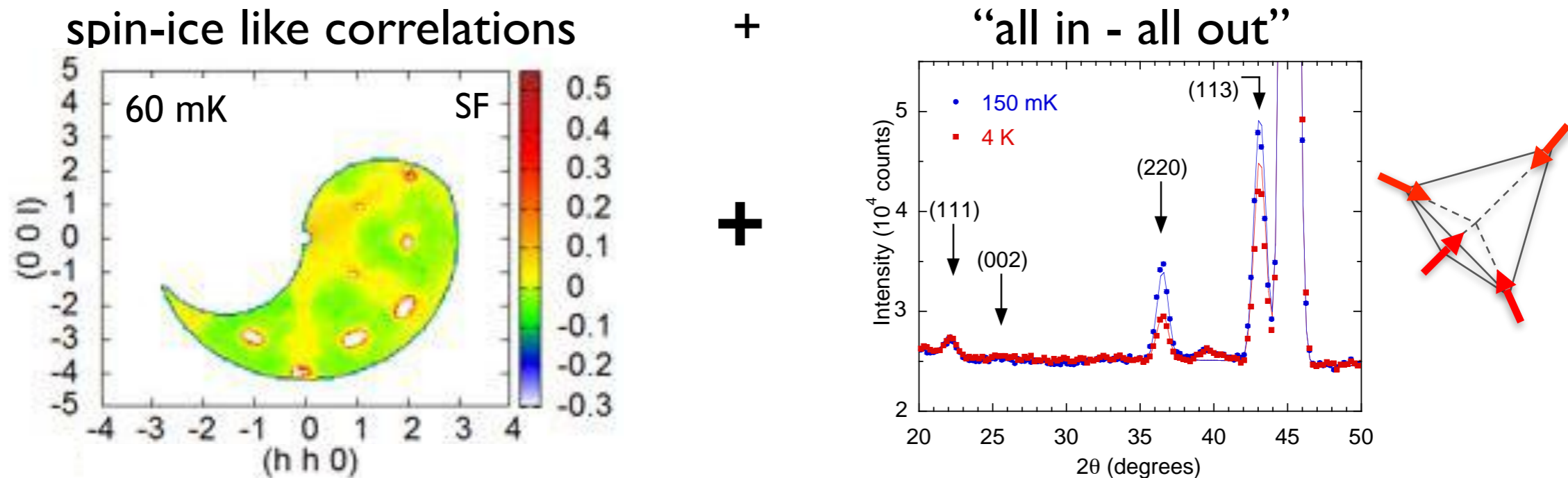


=> **power law correlations** in certain space directions:  
give rise to a specific pattern of the magnetic scattering function  
with **pinch points**

Isakov et al., Phys. Rev. Lett. 93 (2004)

Henley, Phys. Rev. B. 61 (2005)

# Magnetic fragmentation in $\text{Nd}_2\text{Zr}_2\text{O}_7$

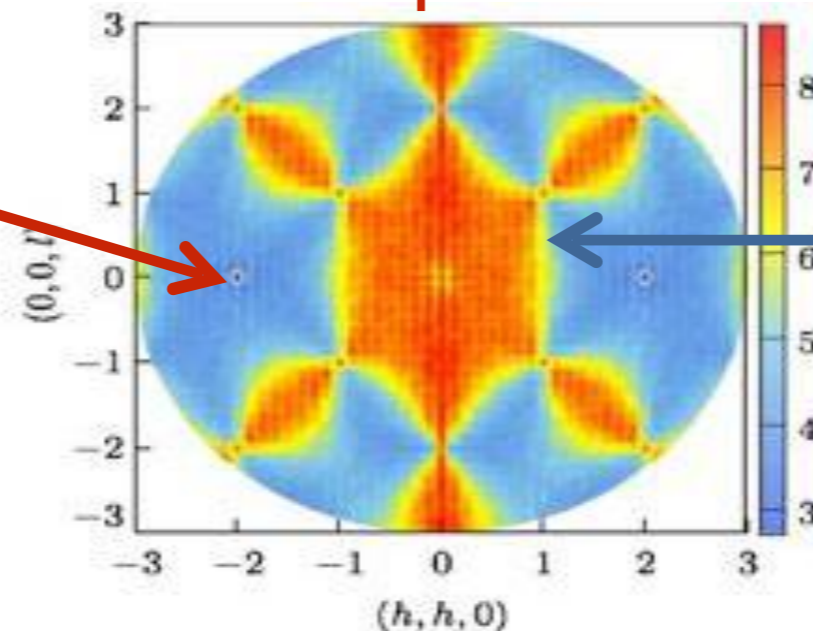


Theoretical proposition: **Magnetic moment fragmentation**

by Brooks-Bartlett et al., *Phys. Rev. X* 4 (2014)

Fragmentation = Coexistence of an **ordered phase** with a disordered **Coulomb phase**

**Bragg peaks**  
with reduced amplitude

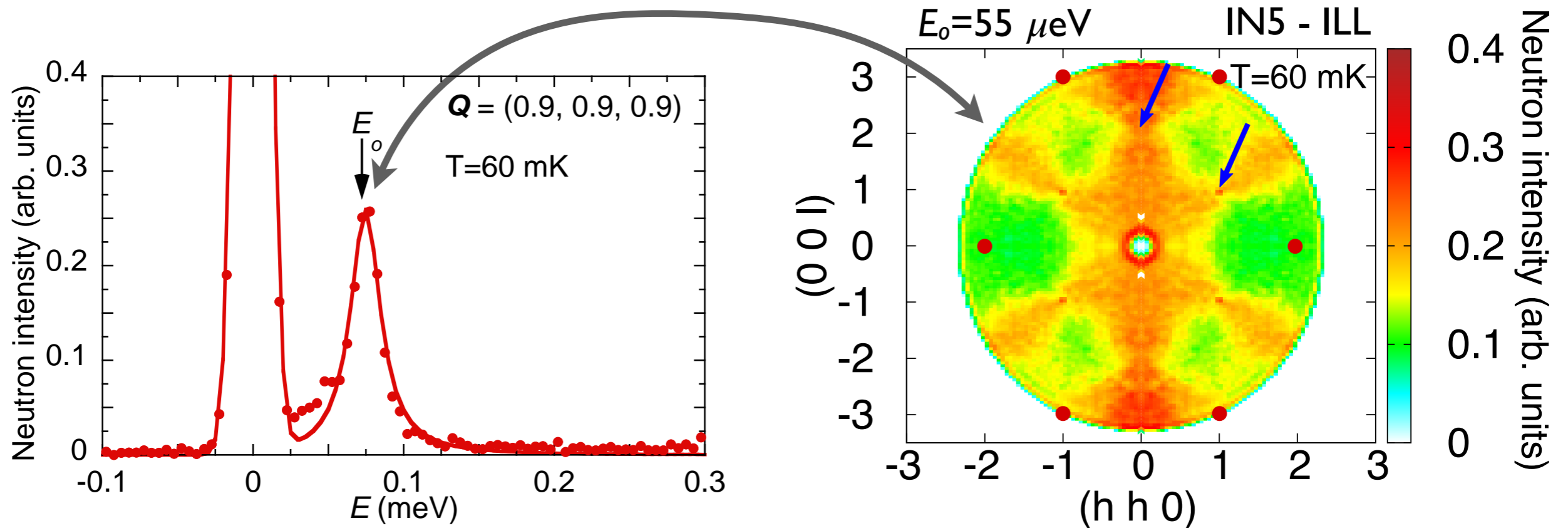


**Specific diffuse scattering**

# BUT... not a conventional fragmentation

Petit et al., Nature Phys. 12 (2016)

the spin ice pattern is shifted to finite energy



**=> spin ice correlations are dynamic**

**Mechanisms for this dynamic fragmentation not understood yet**

# PhD project

Probe the robustness of the fragmented state by doping the Nd and Zr sites:



synthesized in Warwick (UK) by M. Ciomaga-Hatnean

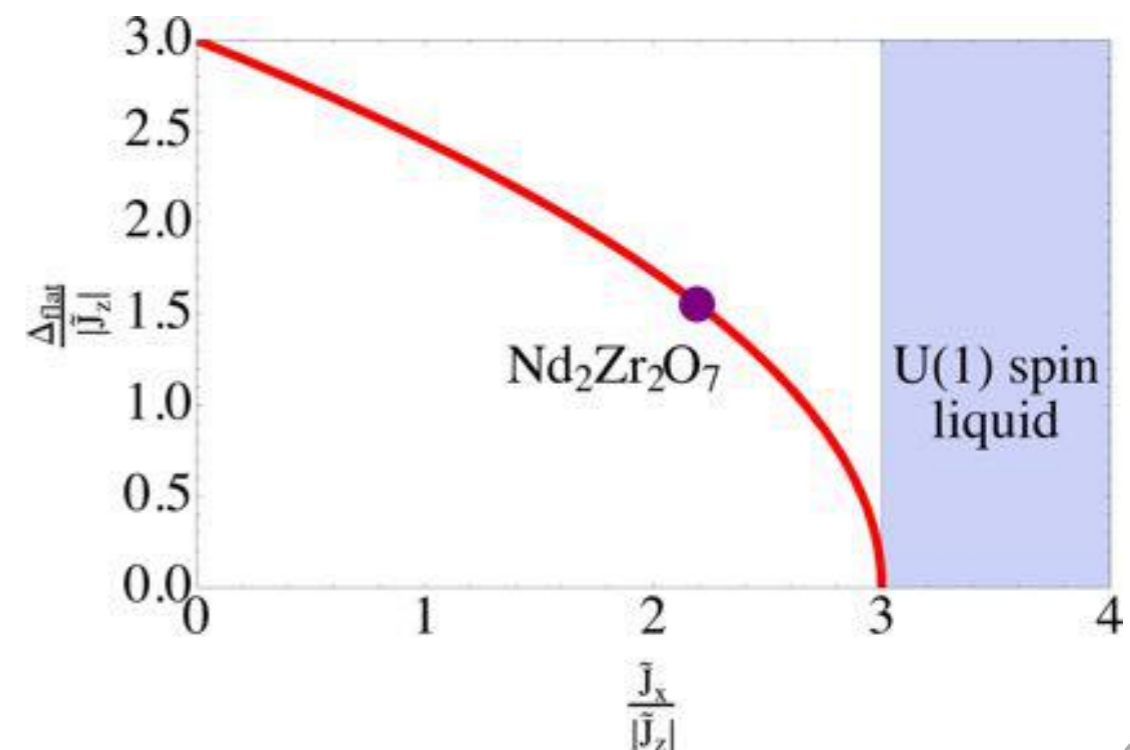
## Experimental tools:

- Magnetization and ac susceptibility at very low temperature  
=> determination of the transition temperature, field induced phase diagram
- Neutron diffraction (powder samples + single crystals) in zero and applied field  
=> magnetic structures
- Inelastic neutron scattering in zero and applied field  
=> CEF, magnetic excitations, robustness of the dynamic Coulomb phase

**Theoretical prediction:** *Benton, Phys. Rev. B 94 (2016)*

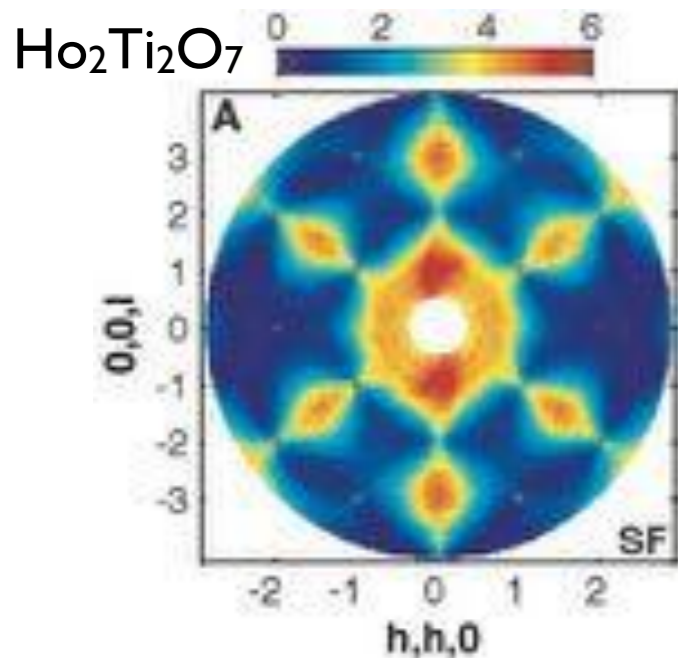
$\text{Nd}_2\text{Zr}_2\text{O}_7$  close to a quantum phase transition towards a U(1) spin liquid.

Could we reach this phase by doping ?





# Spin ice and magnetic monopoles

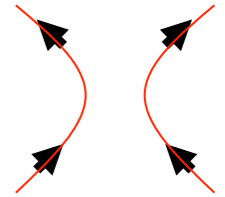


Fennell et al., Science 326 (2009)

Ice-rule can be mapped to a divergence-free field + disordered ground state

=> **Coulomb phase**

Henley, Ann. Rev. Condens. Matter Phys. 1 (2010)

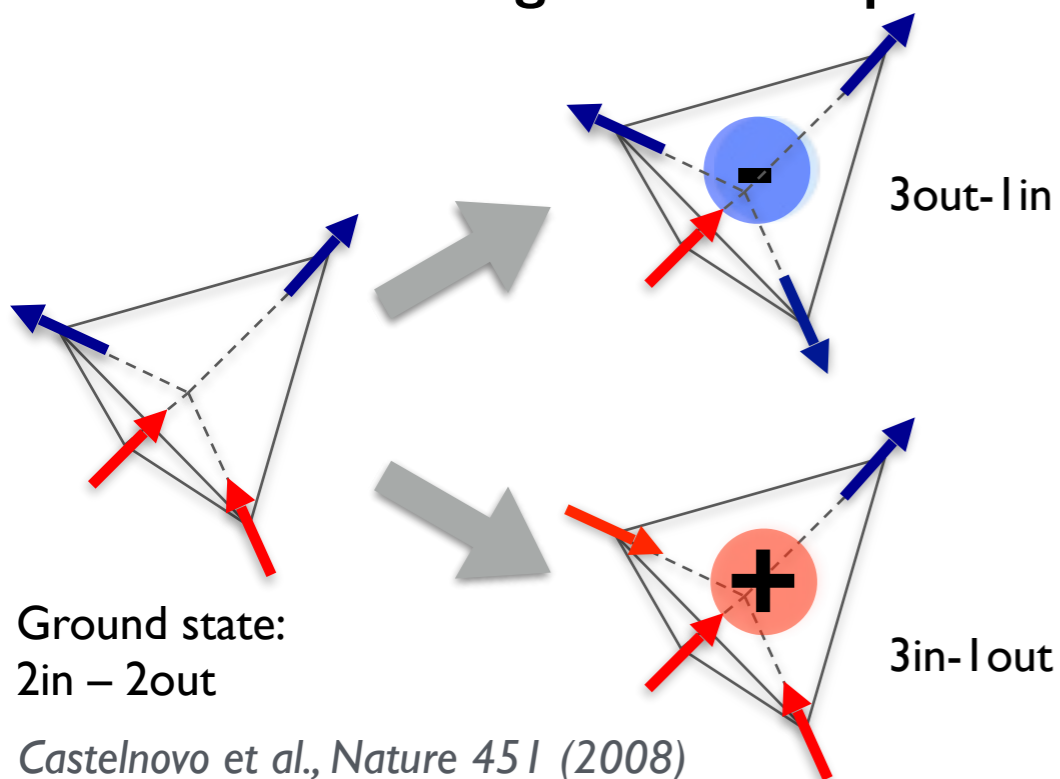


=> **power law correlations** in certain space directions: give rise to a specific pattern of the magnetic scattering function with **pinch points**

Isakov et al., Phys. Rev. Lett. 93 (2004)

Henley, Phys. Rev. B. 61 (2005)

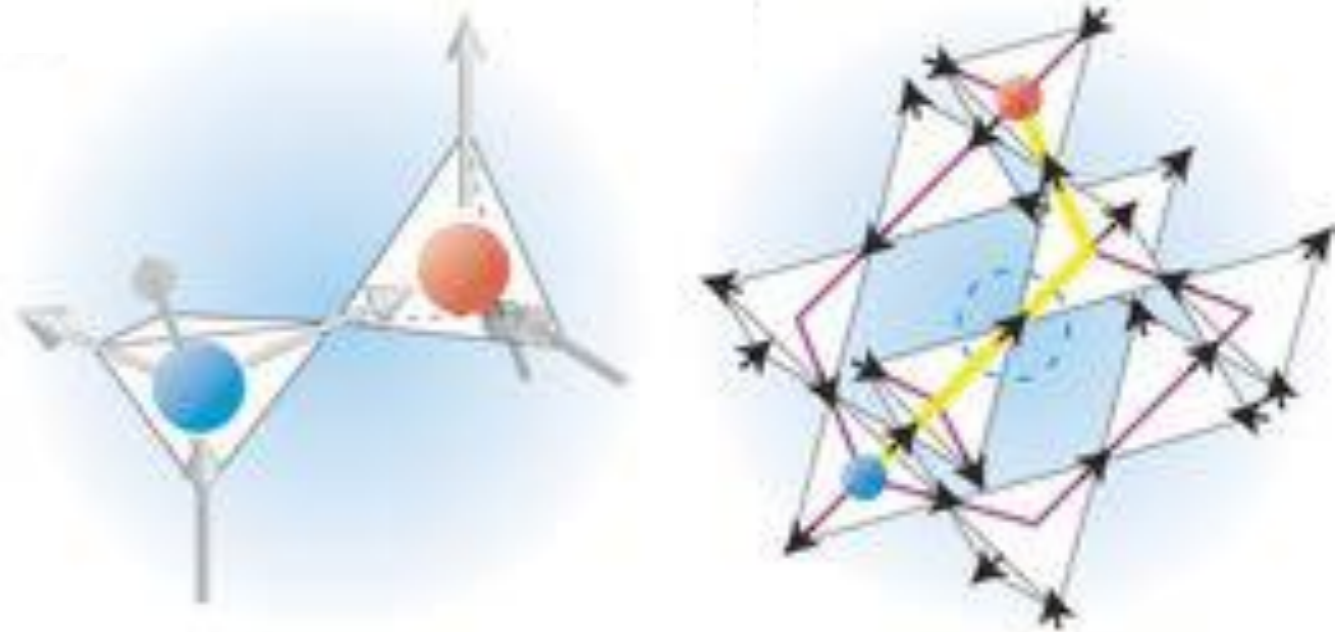
A spin flip costs energy  
=> excitation = magnetic monopole



Ground state:  
2in - 2out

Castelnovo et al., Nature 451 (2008)

in the crystal => creation of a monopole pair  
Once created, **monopoles can separate and move**



from Moessner et al., Nature Phys. 5 (2009)

# Magnetic fragmentation

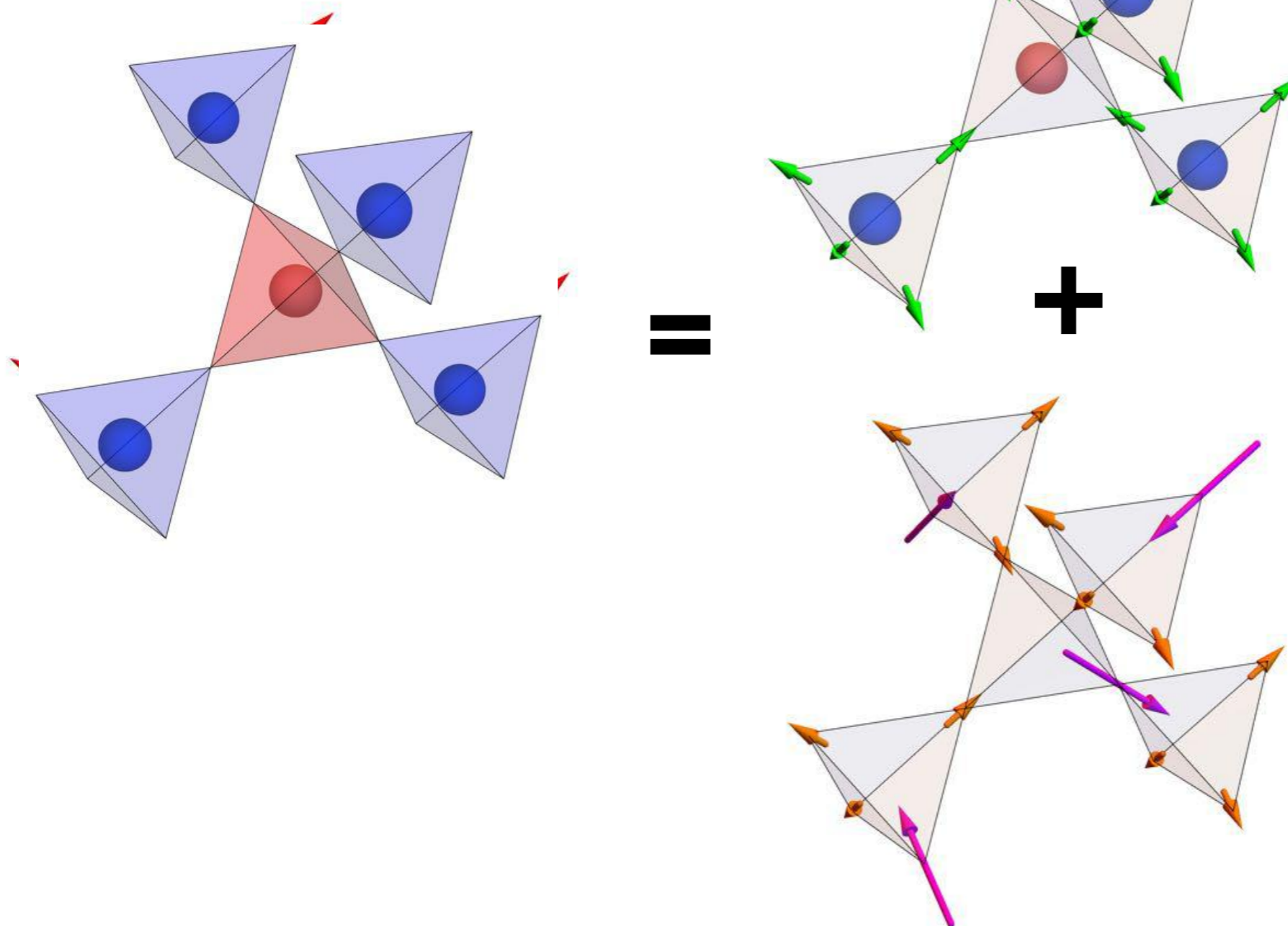
= Coexistence of a fluctuating and an ordered states

Brooks-Bartlett et al., *Phys. Rev. X* 4 (2014)

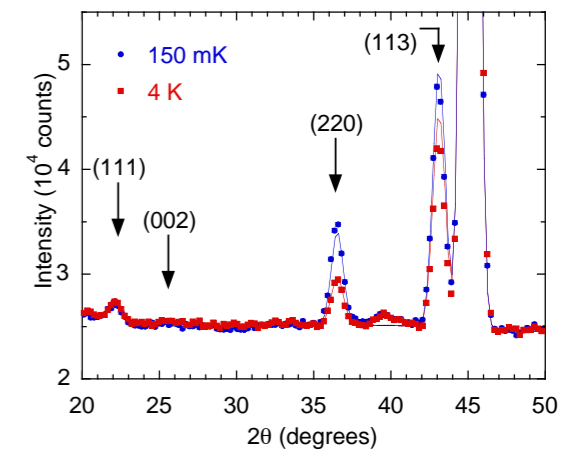
If a monopole crystal is stabilized:

Magnetic charge ordering but “3in-1out” / “1in-3out” disordered configurations

To minimize energy / maximize entropy:  
the magnetic moment fragments into 2 parts



an ordered component  
"all-in all-out"  
= carries the charge



$\text{Nd}_2\text{Zr}_2\text{O}_7$

Petit et al., *Nature Phys.* 12 (2016)

a fluctuating component  
= carries the degeneracy

