Manifestations of monopole physics in spin ice materials

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Engineering and Physical Sciences Research Council

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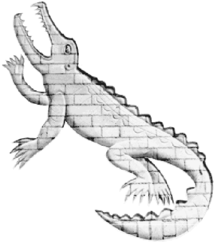

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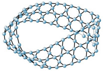
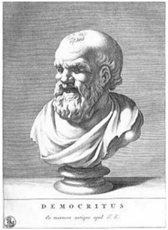
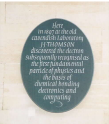


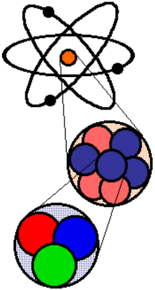
28-05-2014
New Frontiers of Theoretical Physics
Cortona

The atomistic route: elementary particles



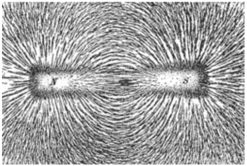
Leukippos, 5^{th} century B.C.
Demokritos, circa 460 - 370 B.C.

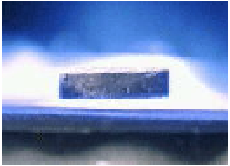




1896: J J Thomson $\rightarrow$ the electron
1917-19: E Rutherford $\rightarrow$ the proton
1932: J Chadwick $\rightarrow$ the neutron
...
modern particle physics: the Standard Model
(1950-2000) ... + *Higgs* (2012)

Different phases of matter and many body physics





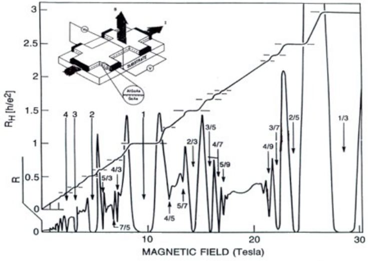
1937 L Landau, 1950 V L Ginzburg and L Landau:
classification of phases and phase transitions based on *local* order parameters and symmetries of the system

- solid-liquid phases
- ferro- and antiferro-magnetism
- superconductivity and superfluidity

New discoveries and a shift of paradigm

the fractional quantum Hall effect
(1982 D Tsui and H Störmer)

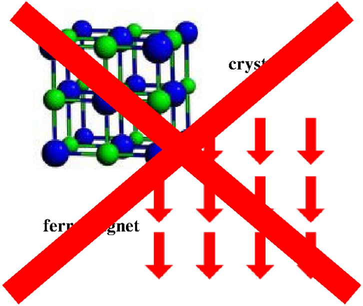
> a smorgasbord of new (gapped) phases but no symmetries to explain them!



New concepts had to be developed to understand the new phases:

- the order is *not* local! $\qquad m = \langle \sigma_i^z \rangle \to \Gamma = \langle \prod_{i\in\gamma} \sigma_i^z \rangle$
- no broken symmetry, yet there are (continuous) phase transition $\quad\longrightarrow$ new symmetries *emerge* in the new phases
- excitations in the new phases take on unprecedented properties: fractional charge and fractional statistics (anyons)

Frustrated magnetism: Gate to new exciting physics



$\Longrightarrow$

- emergent symmetries (e.g., Coulomb phases)
- new phases of matter (e.g., spin liquids and topological order)
- novel (effective) d.o.f. (e.g., anyons, monopoles)

A classic(al) example : emergent monopoles in spin ice

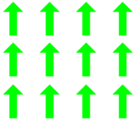
Outline

- brief introduction to frustrated magnetism
- spin ice:
  - emergent gauge symmetry in a short-ranged toy model
  - dipolar spin ice and magnetic monopole excitations
- effective Coulomb liquid description is key to understand both thermodynamic and dynamic properties
- conclusions and outlook

Conventional vs frustrated Ising models

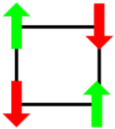
- Consider classical Ising spins, pointing either up or down: $\sigma_i = \pm 1$

- Uniform exchange interaction (strength J):

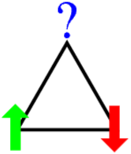


$$\mathcal{H} = J \sum_{\langle ij \rangle} \sigma_i \sigma_j$$

  - $J < 0$: ferromagnetic – spins align
  - $J > 0$: antiferromagnetic – spins antialign
  - ... but only where possible: ‘frustration’



$\Longrightarrow$ What happens instead?



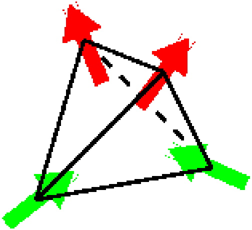
degeneracy: a large (oft-extensive) number of lowest energy states

Nearest-neighbour spin ice

Anderson 1956

a toy model: the classical nearest-neighbour Ising antiferromagnet on the pyrochlore lattice:

$$\mathcal{H} = J \sum_{\langle ij \rangle} \sigma_i \sigma_j \sim \frac{J}{2} \left(\sum_{i=1}^{4} \sigma_i \right)^2$$



- energy minimised when $\sum_i \sigma_i = 0 \Rightarrow$ 2in-2out ice rules
- degeneracy: for a single tetrahedron $\binom{4}{2} = 6$ ground states

Zero-point entropy on the pyrochlore lattice

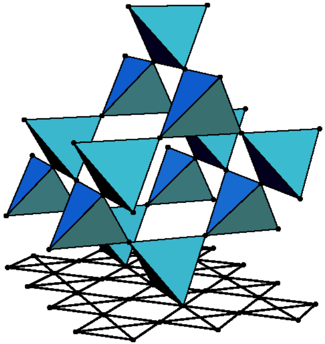
- Pyrochlore lattice = corner-sharing tetrahedra

$$\mathcal{H}_{\mathrm{pyro}} = \frac{J}{2}\sum_{\mathrm{tet}}\left(\sum_{i\in\mathrm{tet}}\sigma_i\right)^2$$

- Pauling estimate of ground state entropy $\mathcal{S}_0 = \ln N_{\mathrm{gs}}$:

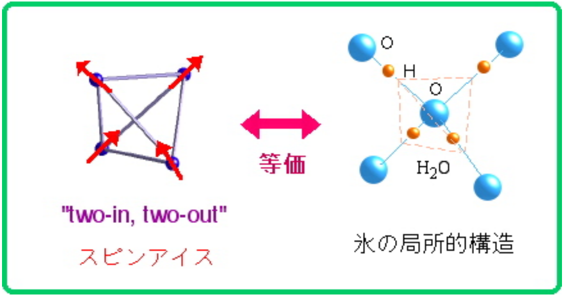
$$N_{\mathrm{gs}} = 2^N\left(\frac{6}{16}\right)^{N/2} \Rightarrow \mathcal{S}_0 = \frac{N}{2}\ln\frac{3}{2}$$

- microstates vs. constraints; N spins, $N/2$ tetrahedra



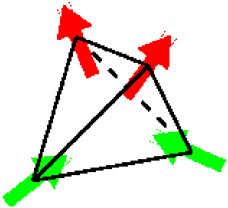
Mapping from ice to spin ice

- in ice, water molecules retain their identity
- hydrogen near oxygen $\leftrightarrow$ spin pointing in



150.69.54.33/takagi/matsuhirasan/SpinIce.jpg

Is spin ice ordered or not?



No order as in ferromagnet

- extensive degeneracy

Not disordered like a paramagnet

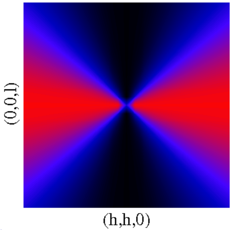
- ice rules ⇒ 'conservation law'

Consider magnetic moments $\vec{\mu}_i$ as a (lattice) 'flux' vector field

- Ice rules $\Leftrightarrow \nabla \cdot \vec{\mu} = 0 \;\Rightarrow\; \vec{\mu} = \nabla \times \vec{A}$
- Simplest assumption: free field
  $\mathcal{S} = (K/2) \int |\nabla \times A|^2 \, dr^3$
- Local constr. ⇒ emergent gauge struct.

  → algebraic spin corr. $\sim \frac{3\cos^2\theta - 1}{r^3}$

  → structure factor (saddle point)

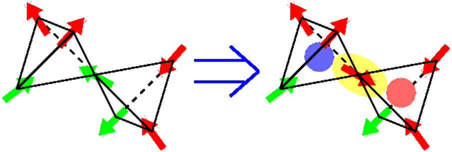


Elementary excitations I

Ising spins:

$\rightarrow$ excitation $=$ spin reversal

$\rightarrow$ two defective tetrahedra



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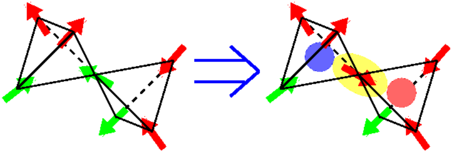

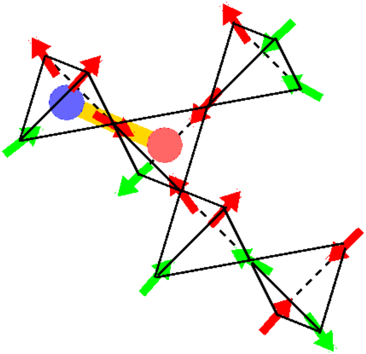

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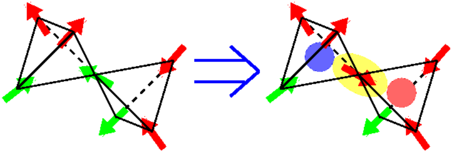
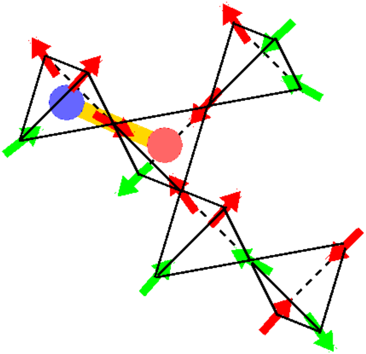
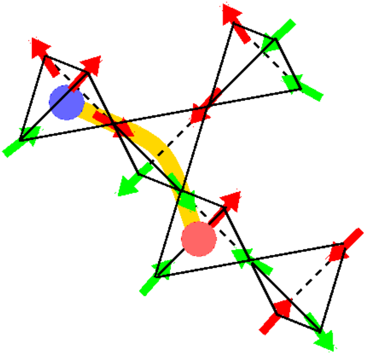


they can be separated at no energy cost!





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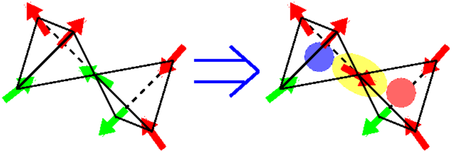

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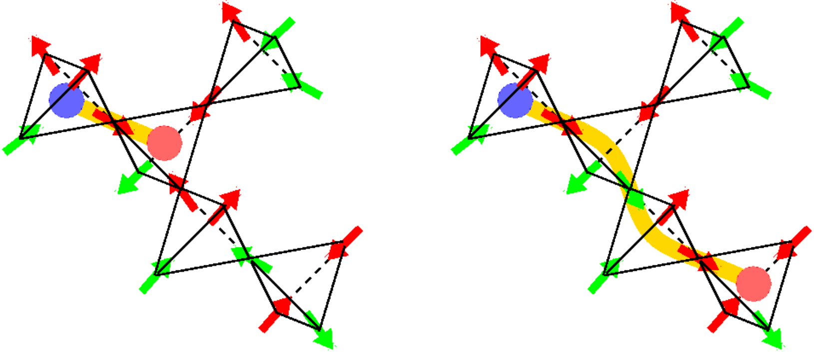
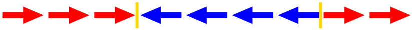


Spin ice vs. conventional ferromagnets

1D: domain walls are ‘point-like’ and deconfined



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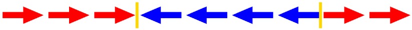
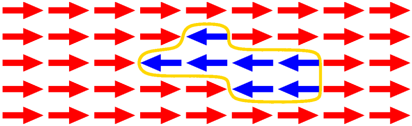


$\geq$ **2D**: defects are confined (extended domains with boundary energy cost)



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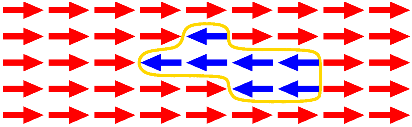


for instance, intrinsically different magnetisation processes (at low energies):

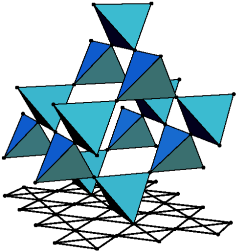
domain growth and coarsening $\leftrightarrow$ point-like defect motion

and similarly for specific heat, thermal transport, etc.

Spin Ice ($Dy_2Ti_2O_7$ and $Ho_2Ti_2O_7$)

Harris + Bramwell 1997

- local [111] crystal field $\sim$ 200 K
  $\Rightarrow$ Ising spins
- large spins (15/2 and 8)
  $\Rightarrow$ classical limit (small exchange $\sim$ 1 K)
- large magnetic moment $\sim 10\,\mu_B$
  $\Rightarrow$ long range dipolar interactions



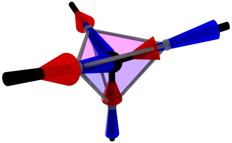
[credit: STFC]

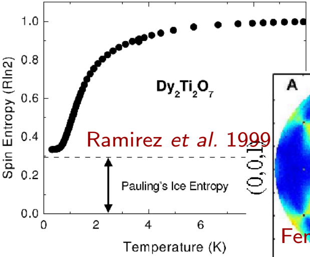
Single crystals

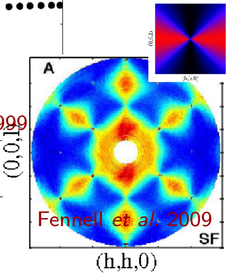
Frustration leads to (classical) degeneracy

dipolar interactions minimised by
2-in, 2-out ice rules $\Rightarrow$ local constraint

Gingras *et al.* , Shastry *et al.* 1999-2001







six ground states per tetrahedron:

$$N_{\rm gs} = 2^N \left(\frac{6}{16}\right)^{N/2}$$

$$\mathcal{S} = \frac{N}{2} \ln \frac{3}{2}$$

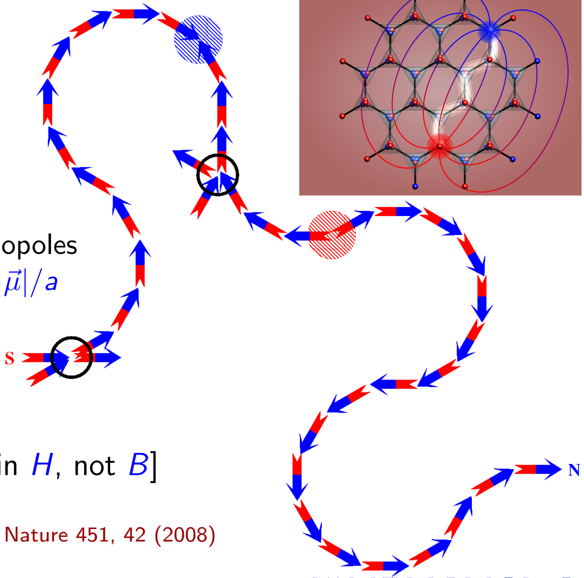
extensive degeneracy

Elementary excitations: *emergent* magnetic monopoles

magnetic Coulomb interaction

$$E(r) = -\frac{\mu_0}{4\pi}\frac{q_m^2}{r}$$

- **deconfined** monopoles
- charge $q_m = \pm 2|\vec{\mu}|/a$



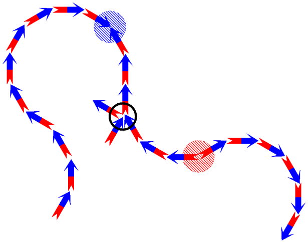
[monopoles in H, not B]

CC, Moessner, Sondhi, Nature 451, 42 (2008)

Magnetic monopoles? $\nabla \cdot \vec{M}$ vs. $\nabla \cdot \vec{H}$

no violation of $\nabla \cdot \vec{B} = 0$

- $\vec{B} = \vec{H} + \vec{M}$
- $\vec{M}$ is confined to the spins
- where a 'Dirac string' ends: $\nabla \cdot \vec{M} \neq 0$



$\Rightarrow$ defective tetrahedra ($\nabla \cdot \vec{M} \neq 0$) are sources and sinks of the magnetic field $\vec{H}$: $\nabla \cdot \vec{H} = -\nabla \cdot \vec{M}$

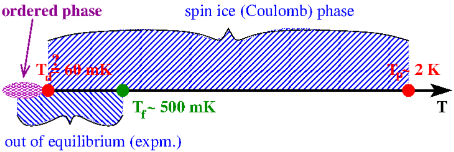
Unique setting!

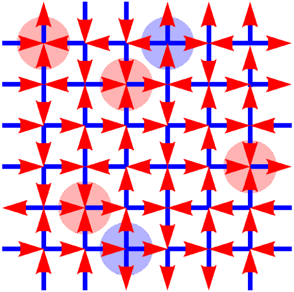
(i) rare instance of fractionalisation in 3D

(ii) magnetic charges and network of 'Dirac strings' in 3D!

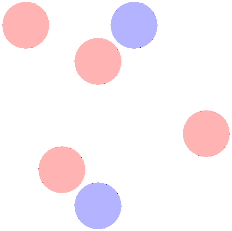
(iii) sources and sinks of magnetic field $\Rightarrow$ the monopoles couple to external probes (e.g., muons, SQUIDs, NMR-active nuclei)

Spin ice as a Coulomb liquid



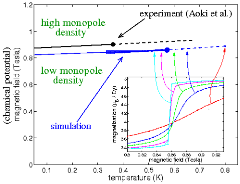


$\Longleftrightarrow$

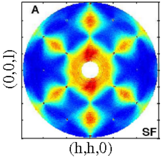


- $+$ Coulomb interactions
- $+$ entropic interactions
- $+$ kinematic constraints

Consistent (and key!) to understand thermodynamic properties



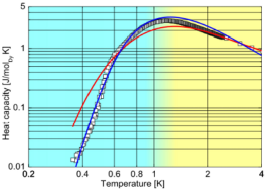
liquid-gas phase diagram CMS 2008



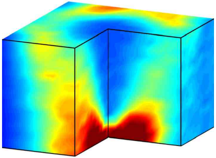
mag. corr.: pinch-points(*)

Fennel et al 2009, Kadowaki et al 2009

(*) **note**: both ice rules and long-range dipolar correlations contribute to pinch points! Sen, Moessner, Sondhi 2012



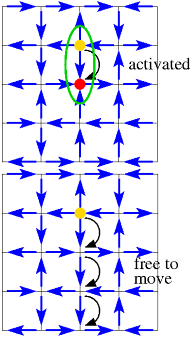
Debye-Hückel heat cap. Morris et al. '09



mag. corr.: "Dirac" strings

Morris et al. 2009

Monopoles act as facilitators of spin dynamics



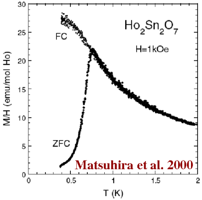
magnetic response ⇔ monopole motion

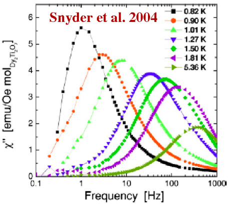
e.g., Ryzhkin 2005, Jaubert *et al.* 2009

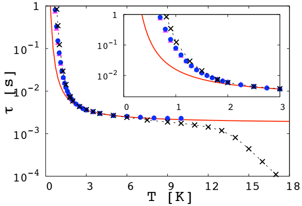
$$\Rightarrow \tau \sim \tau_0/\rho(T)$$

$T \lesssim 1$ K: paucity of monopoles

$(\rho \sim e^{-4.35/T})$ $\Rightarrow \tau \sim \tau_0\, e^{4.35/T}$



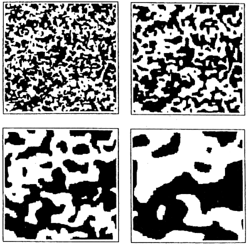


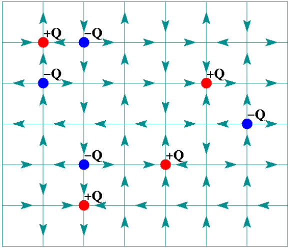


Thermal quenches

CC, Moessner, Sondhi 2010

sudden quench from a defect-rich phase $\rightarrow$ evolution reduces number of defects: reaction-annihilation system $A + B \rightarrow 0$





Ising model vs. spin ice

- defects are pointlike in $d = 3$; density vanishes only for $T \rightarrow 0$
- kinematic constraints due to the underlying spin configuration

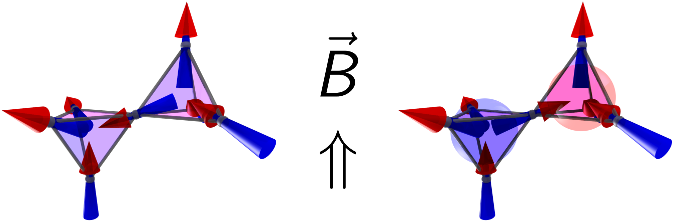
$\Leftrightarrow$ interplay of large- and lattice-scale physics

Field quenches

Mostame, CC, Moessner, Sondhi, PNAS 2014

novel setting: reaction diffusion processes of emergent topological defects + long Coulomb range interactions + kinematic constraints

- [111] saturated phase ⇔ fully packed monopoles *(ionic crystal)*
- field quench (⇔ *chem. pot.*): ρ_{eq} exponentially small at low T



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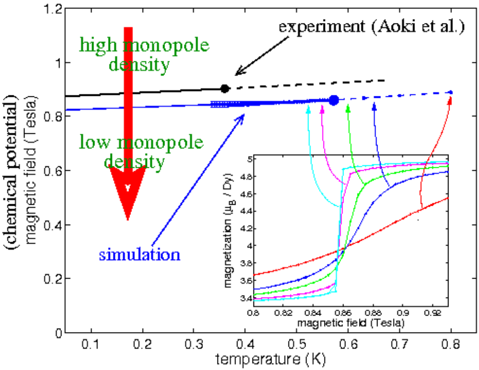
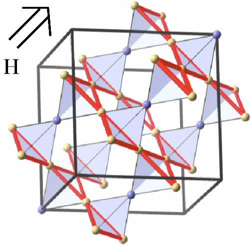


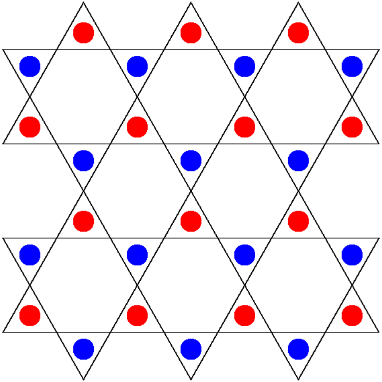


mag. $\propto$ monopole dens.

Field quenches

Mostame, CC, Moessner, Sondhi, PNAS 2014

triangular spins cannot flip in sat. phase!



- initial behaviour: direct annihilation of neighbouring pairs

Field quenches

Mostame, CC, Moessner, Sondhi, PNAS 2014

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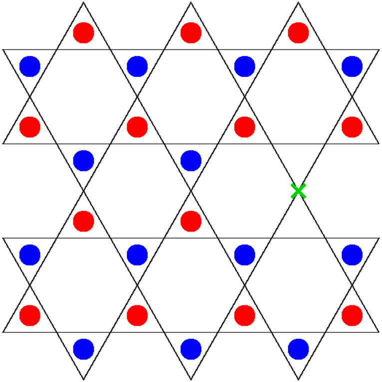

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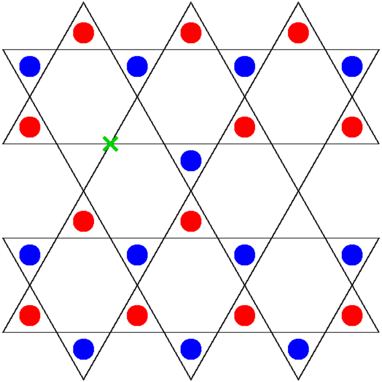

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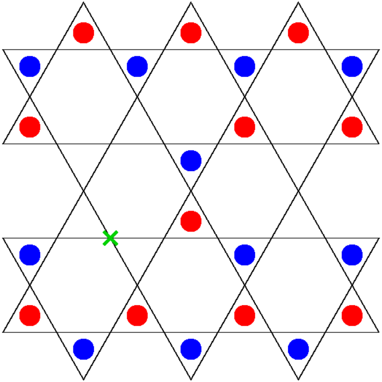
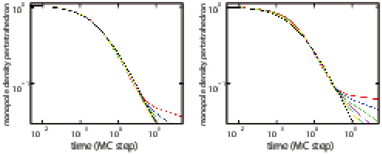


- initial behaviour: direct annihilation of neighbouring pairs

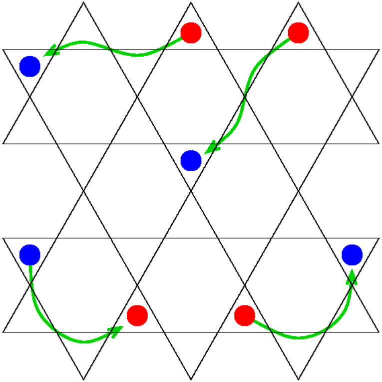
$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\frac{3}{\tau_0}\rho^2(t)$$

$$\rightarrow \quad \rho(t) = [1 + 3(t/\tau_0)]^{-1}$$

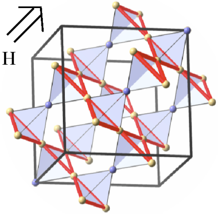


Field quenches

Mostame, CC, Moessner, Sondhi, PNAS 2014

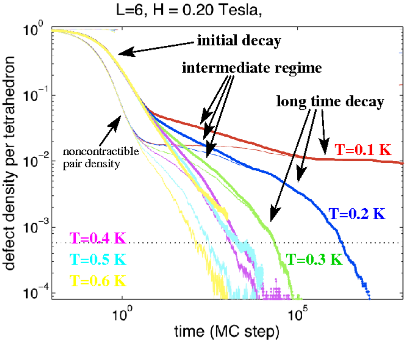


- intermediate behaviour: diffusion annihilation processes with long-range Coulomb interactions
- polarisation of triangular spins ⇔ dimensional reduction

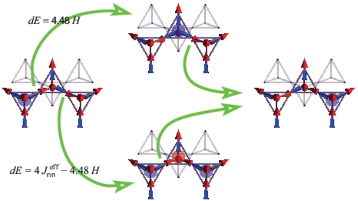


Field quenches

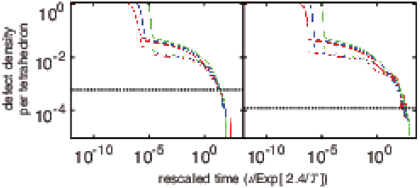
Mostame, CC, Moessner, Sondhi, PNAS 2014



- long time behaviour: activated dynamics



controlled by Zeeman and Coulomb barriers



Collaborators

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and several
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P. Holdsworth ENS Lyon
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HELMHOLTZ
ASSOCIATION
Virtual Institute: New States of Matter
and their Excitations

Conclusions

- frustration in spin ice leads to a degenerate ground state with emergent gauge symmetry and magnetic monopole excitations
- effective **Coulomb liquid description** is key to *understanding* the low-temperature properties of spin ice beyond Monte Carlo simulations (e.g., phase diagram, spec. heat, mag. suscept.)
- new exciting directions:
  - rich playground to study **out-of-equilibrium phenomena in Coulomb interacting systems**
  - '**electrolyte physics**' in regimes not accessible in conventional electrolytes (see Bramwell, Holdsworth, Moessner, et al.)
  - **tuneable magnetic disorder** through Oxygen stoichiometry (to appear in Nat. Mat.)
  - **quantum spin ice** and classical $\leftrightarrow$ quantum crossover: **microscopic modelling of spin dynamics** (collaboration with B.Tomasello and J.Quintanilla)

HFM2014, July 7-11, 2014, Cambridge, UK

UNIVERSITY OF CAMBRIDGE

International Conference on Highly Frustrated Magnetism 2014

Cavendish Laboratory

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Registration

Please follow the link below to register for the International Conference on Highly Frustrated Magnetism 2014 at Queens' College Cambridge, UK. The early-bird registration fee has been set to GBP 360 and applies until the 13th of April, 2014. The regular registration fee is GBP 420, and a late registration fee of GBP 490 applies to delegates who register after the 18th of May, 2014.

The registration fee includes the welcome dinner on Sunday evening, July 6th, as well as the conference dinner on Wednesday evening, July 9th.

We have reserved a block of rooms sufficient to accommodate approximately 180 delegates at Queens' College. Booking of the accommodation will open shortly on the conference website.

Click here to register for HFM2014.

Key Dates (tbc)

March 16, 2014
Contributed Abstract Deadline

April 7-8, 2014
Magnetism 2014 conference

April 13, 2014
End of early registration

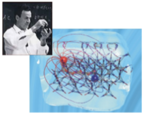
May 18, 2014
Late registration fee begins

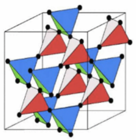
July 2-3, 2014
TEMM 2014 (Cosener's House)

July 6, 2014
Graduate focus workshop

July 7-11, 2014
Conference

July 14 - August 8, 2014
Nordita workshop on *Novel Directions in Frustrated and Critical Magnetism*





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