Non-equilibrium physics in Spin Ice / Spin Glass physics in Spin Ice

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paper in preparation

Motivation

why non-equilibrium physics ?

☞**<u>Motivation</u>**

why non-equilibrium physics ?

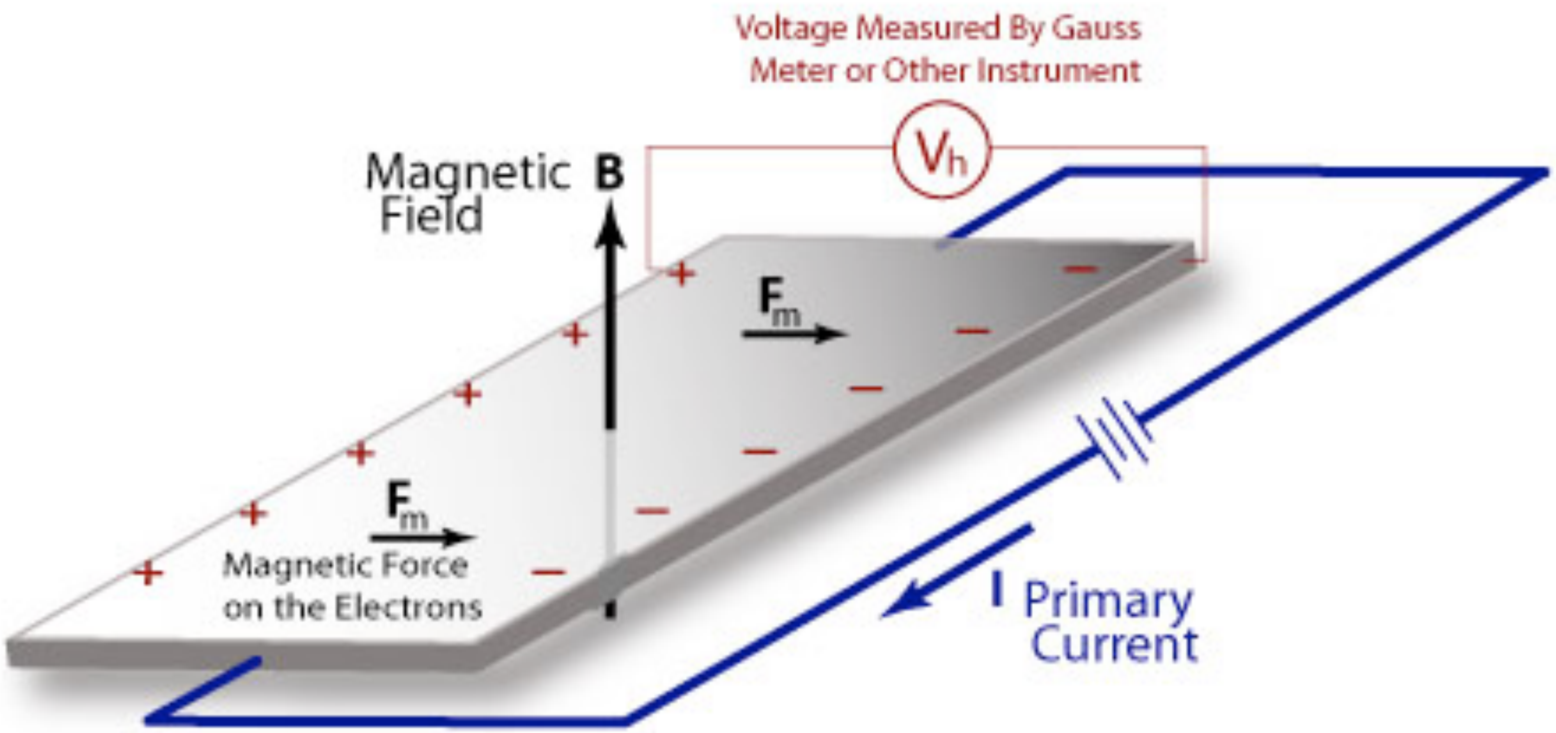
<u>Model</u>

why spin ice ?

<u>Results</u>

why non-equilibrium
physics in spin ice ?

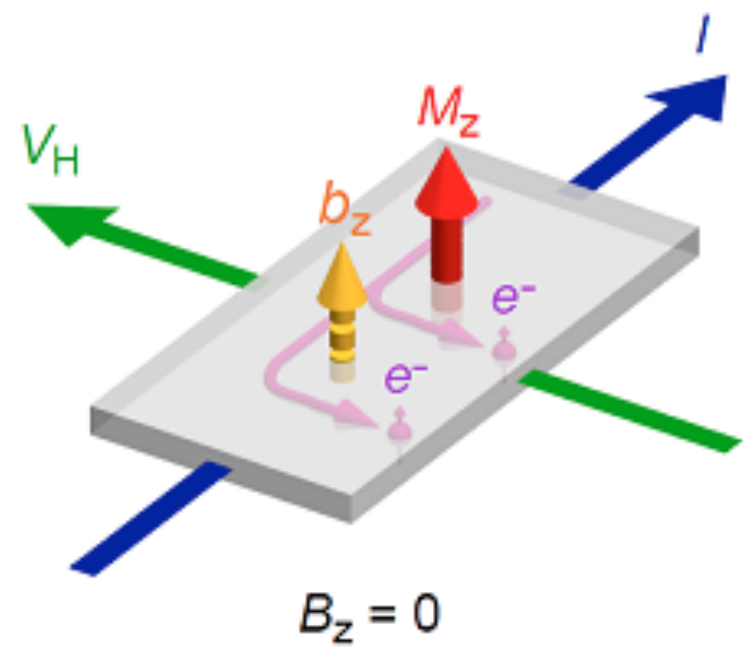
Hall Effect



Time-reversal symmetry breaking

image taken from https://www.nde-ed.org/

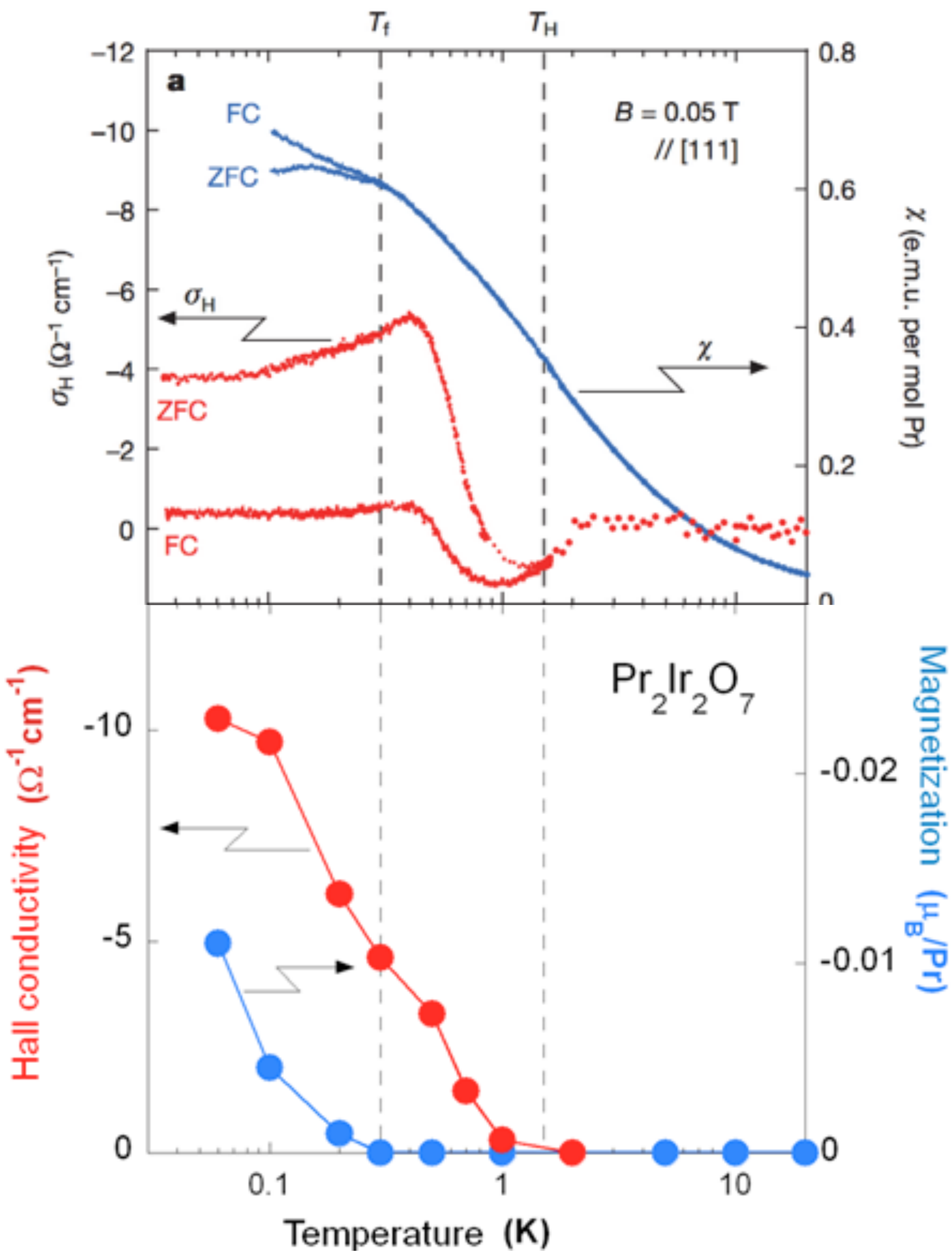
Anomalous Hall Effect

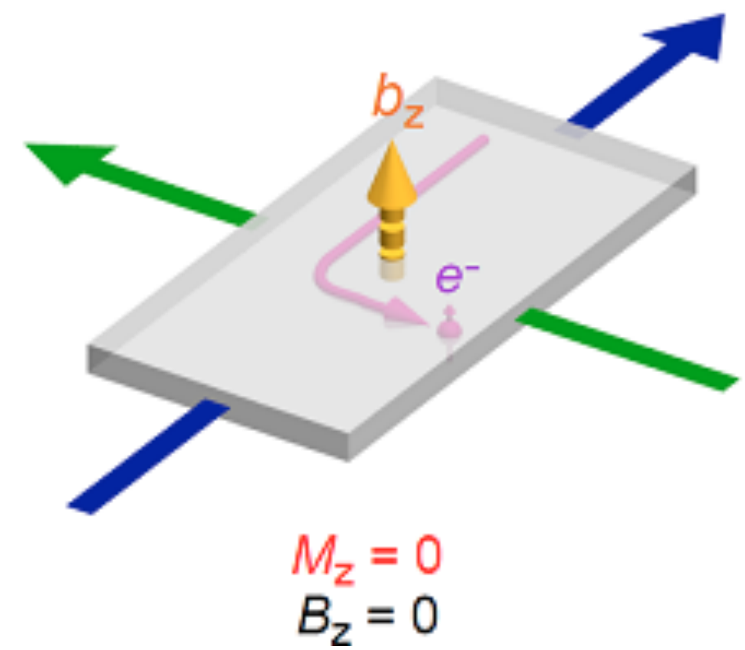


Time-reversal symmetry breaking
➥ no magnetic field, but *usually* ferromagnetism

$Pr_2Ir_2O_7$: "*Spontaneous*" Hall Effect

freezing temperature





Time-reversal symmetry breaking
but <u>no chemical disorder</u>,
<u>no long-range order</u>
and <u>no finite magnetization</u>

Machida et al. Nature 2010

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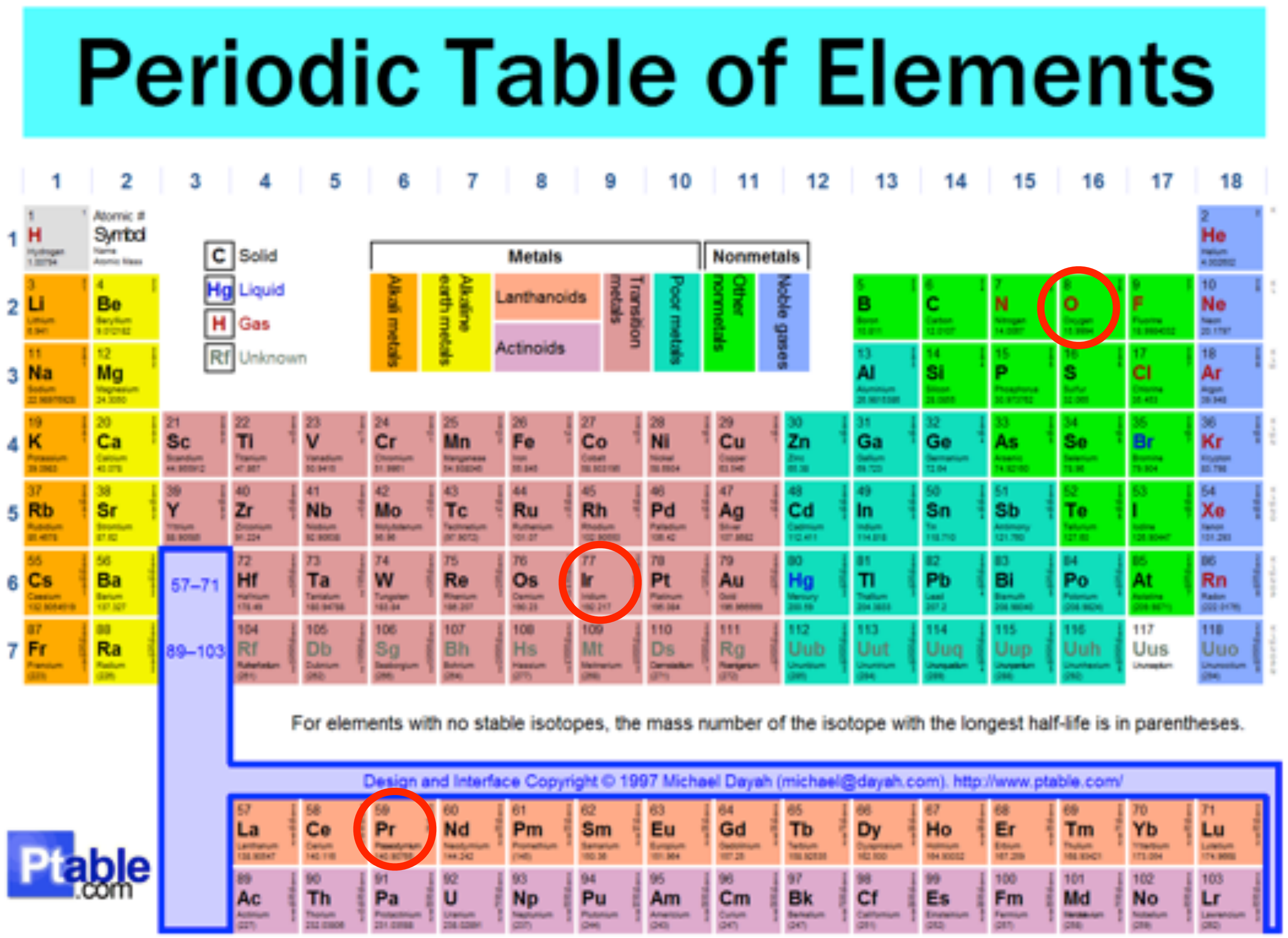
☞ **Model**

why spin ice ?

Results

why non-equilibrium
physics in spin ice ?

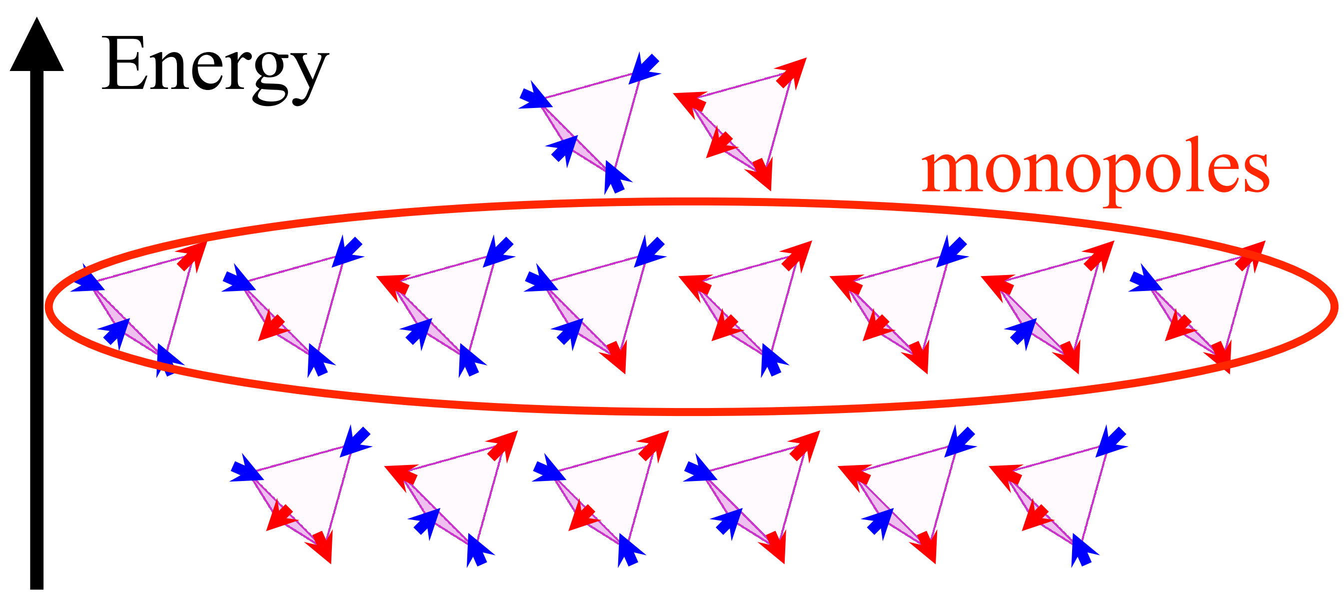
What is spin ice ?

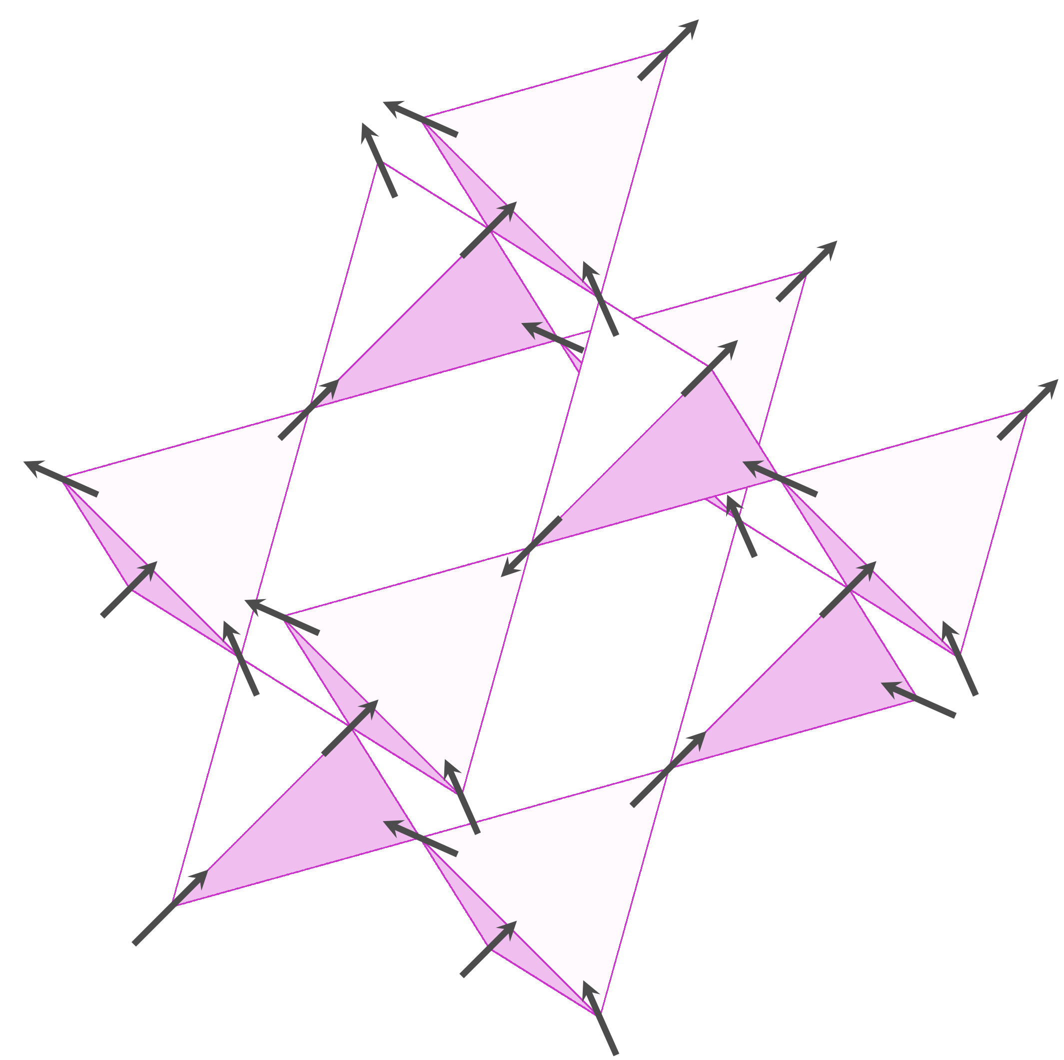


pyrochlore lattice

Ising spins

nearest neighbour

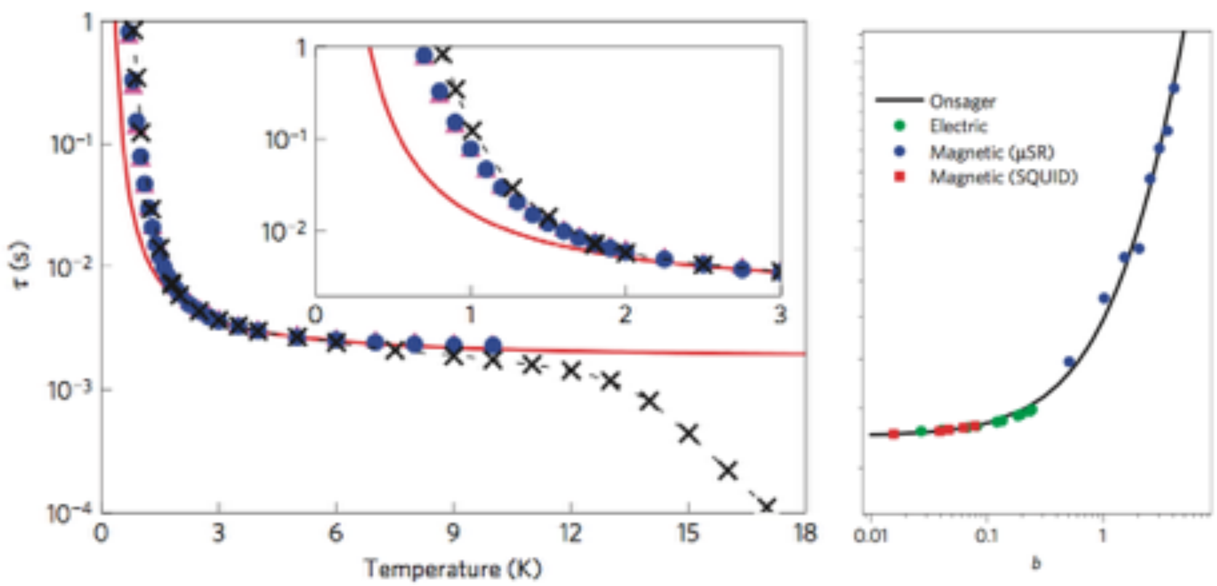




Harris *et al* PRL 1997 — Gardner *et al.* RMP 2010 — Rau & Gingras arXiv:1503.04808

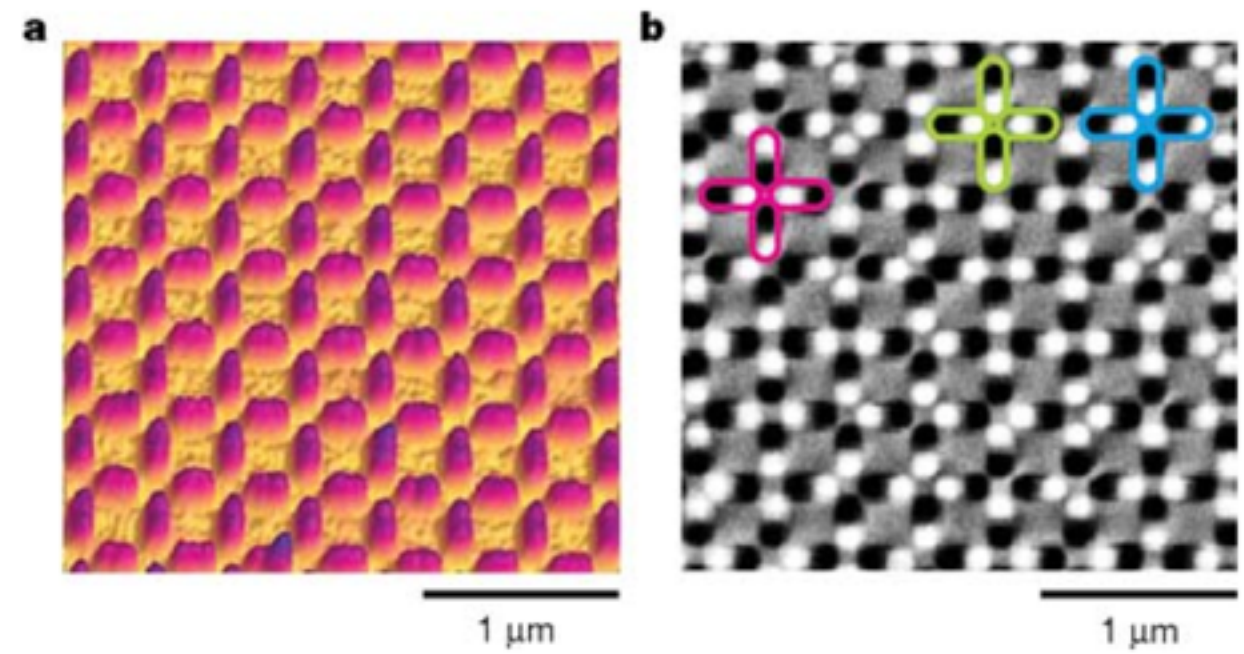
See also…

Monopole dynamics and Wien effect in $Dy_2Ti_2O_7$, $Ho_2Ti_2O_7$ …



Jaubert *et al* Nature Phys. 2009
Slobinsky *et al* PRL 2010
Giblin *et al* Nature Phys. 2011
Kaiser *et al* Nature Mater. 2013
Mostame *et al* PNAS 2014

Artificial Spin Ice in 2D nano-lithography



Wang *et al.* Nature 2006

Levis & Cugliandolo PRB 2013
Levis *et al.* PRL 2013
Foini *et al.* JSM 2013
Levis & Cugliandolo EPL 2012

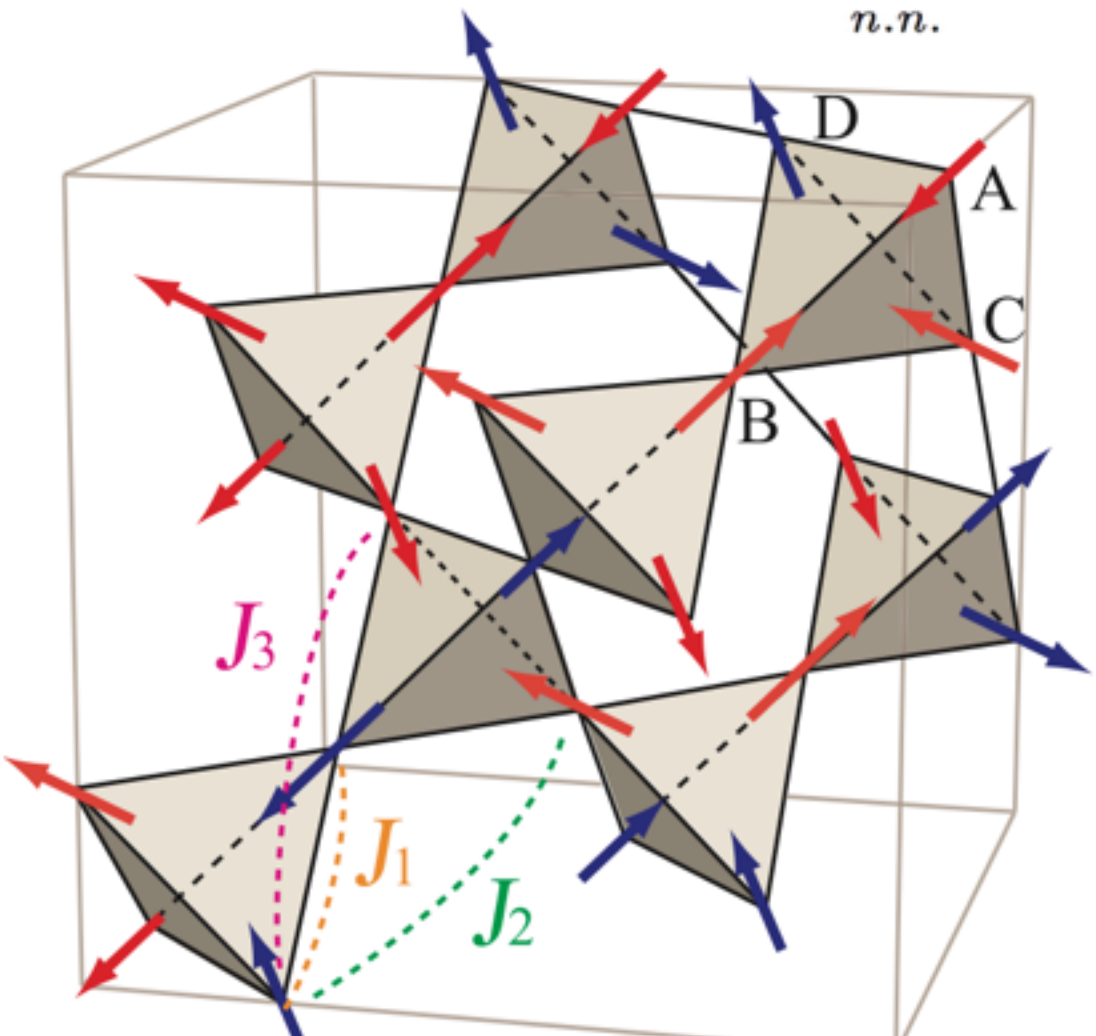
Coupling to itinerant electrons

Truncated Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions

➥ next-next-nearest neighbour interactions

$$\mathcal{H} = \tilde{J}_1 \sum_{n.n.} \mathbf{S}_i \cdot \mathbf{S}_j + \tilde{J}_2 \sum_{2nd.} \mathbf{S}_i \cdot \mathbf{S}_j + \tilde{J}_3 \sum_{3rd.} \mathbf{S}_i \cdot \mathbf{S}_j$$

$$= J_1 \sum_{n.n.} \eta_i \eta_j + J_2 \sum_{2nd.} \eta_i \eta_j + J_3 \sum_{3rd.} \eta_i \eta_j$$

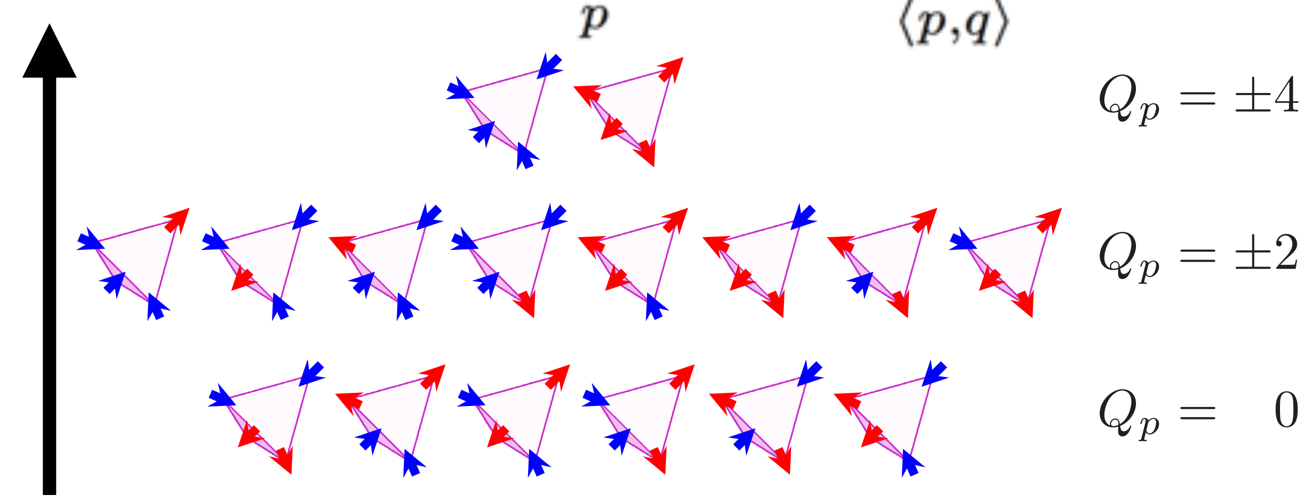


Can we make it simpler ?

Ishizuka & Motome PRB 2013

$J_1 = 1 \qquad J_2 = J_3 = J$

$$\mathcal{H} = \left(\frac{1}{2} - J\right) \sum_p Q_p^2 - J \sum_{\langle p,q \rangle} Q_p Q_q$$

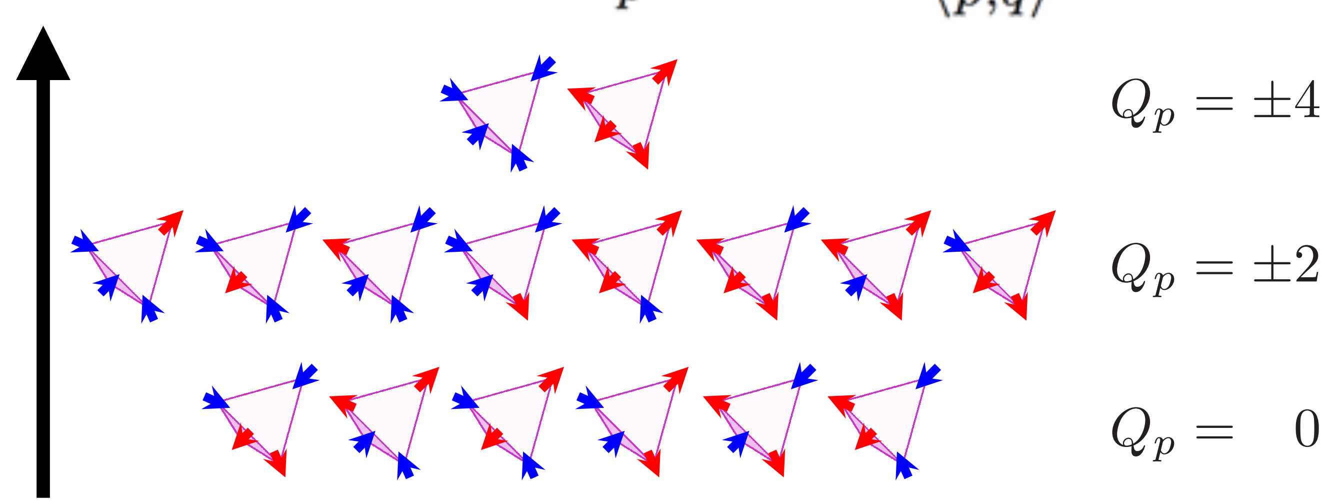


Summary of the model

Effective model of particles on a lattice constrained by the underlying spins, with chemical potential and contact repulsion/attraction.

Dynamics = single-spin flip = particle hopping (waiting-time Monte Carlo method)

$$\mathcal{H} = \left(\frac{1}{2} - J\right) \sum_{p} Q_p^2 - J \sum_{\langle p,q \rangle} Q_p Q_q$$



Motivation

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Model

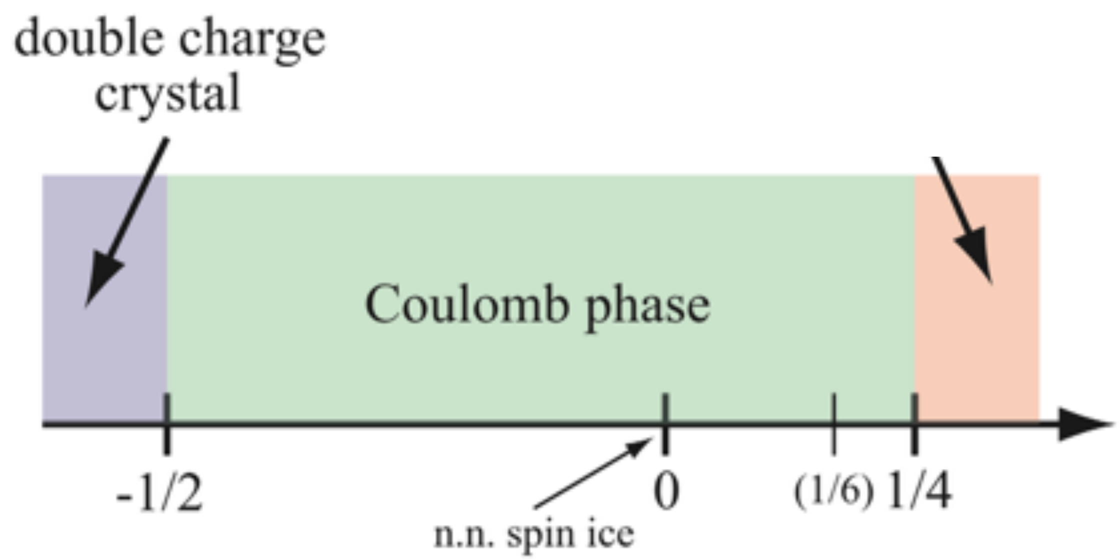
why spin ice ?

☞**Results**

why non-equilibrium physics in spin ice ?

Phase diagram at equilibrium

$$\mathcal{H} = \left(\frac{1}{2} - J\right)\sum_p Q_p^2 - J\sum_{\langle p,q\rangle} Q_p Q_q$$



$$\mathcal{H} = \left(\frac{1}{2} + J\right)\sum_p Q_p^2 - \frac{J}{2}\sum_{\langle p,q\rangle} (Q_p + Q_q)^2$$

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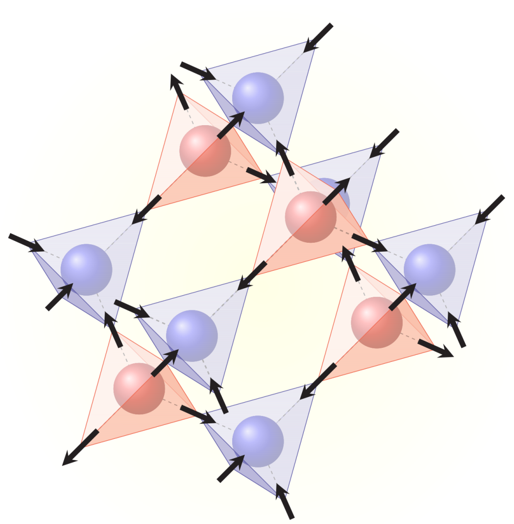
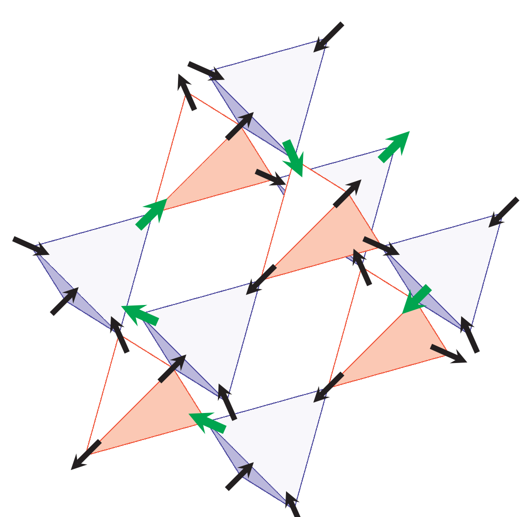
All In - All Out



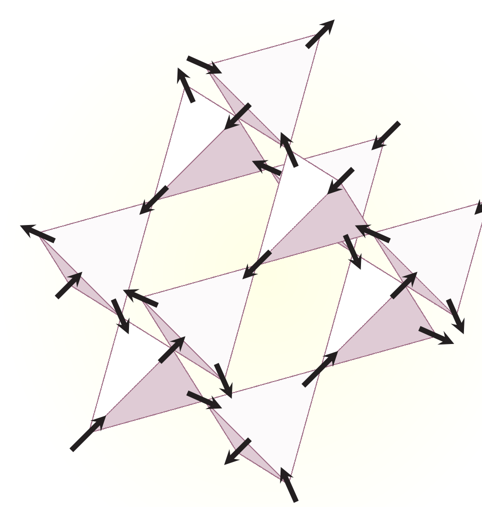
degeneracy $\Omega = 2$

Fragmented spin liquid



degeneracy $\Omega \approx 1.3^{N/2}$

Coulomb phase

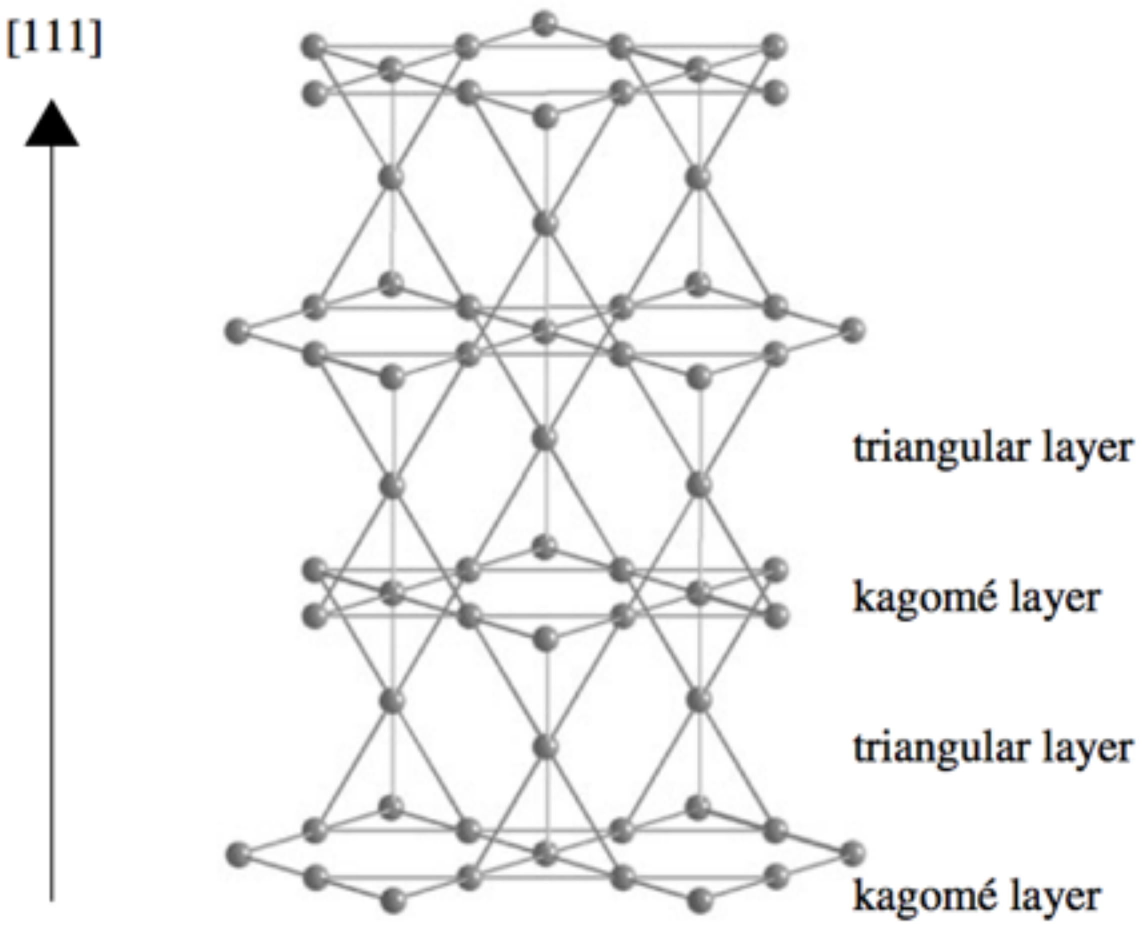


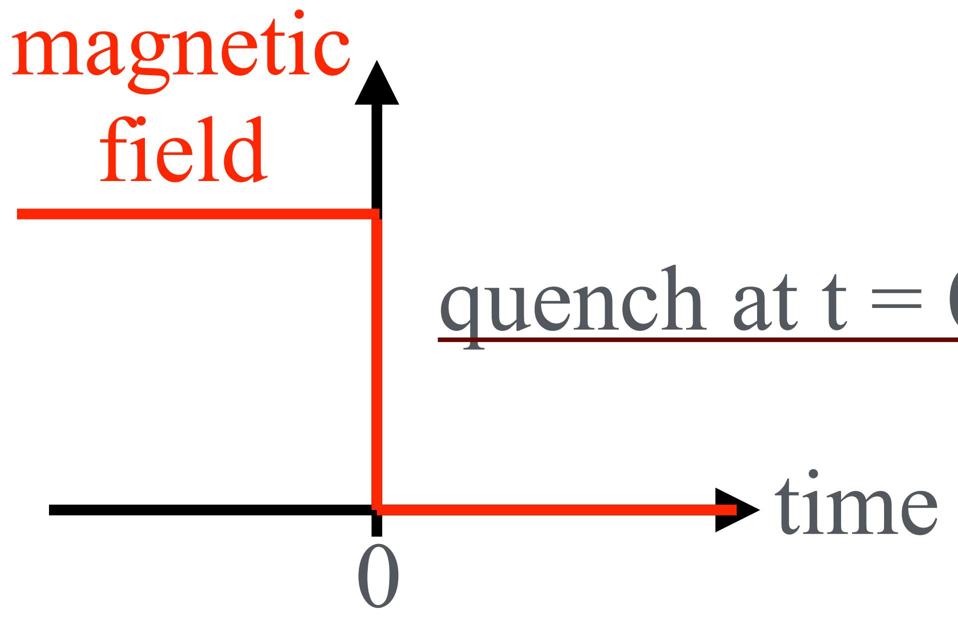
degeneracy $\Omega \approx 1.5^{N/2}$

Jellyfish

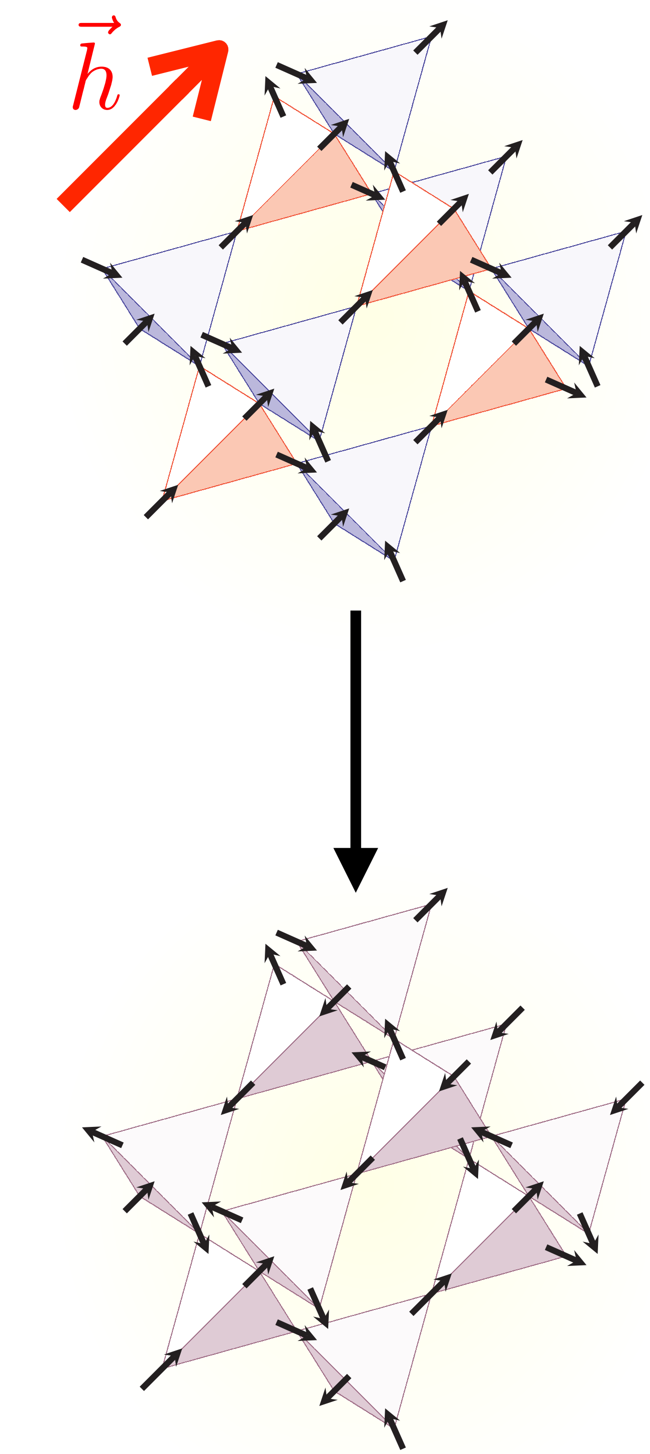
Field quench

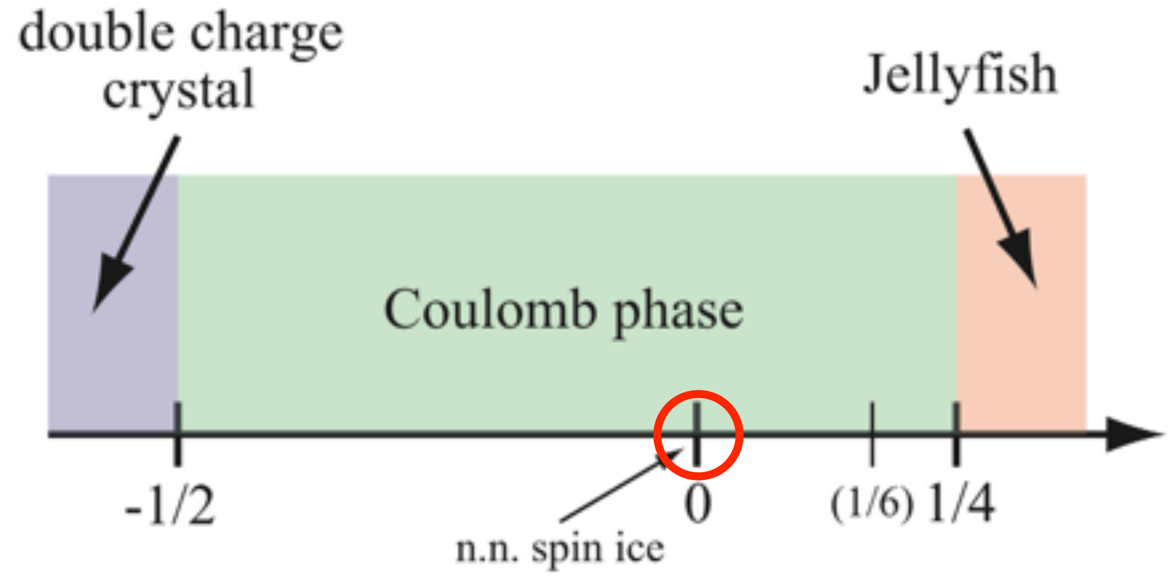
This is an anisotropic system, so the field direction is important.

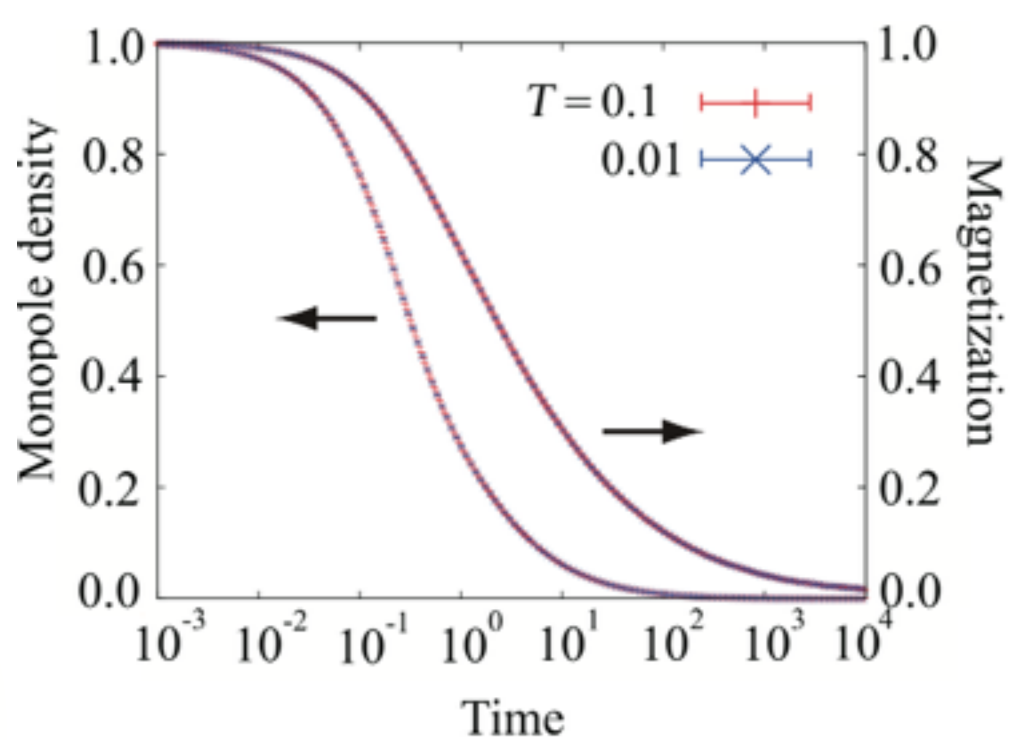


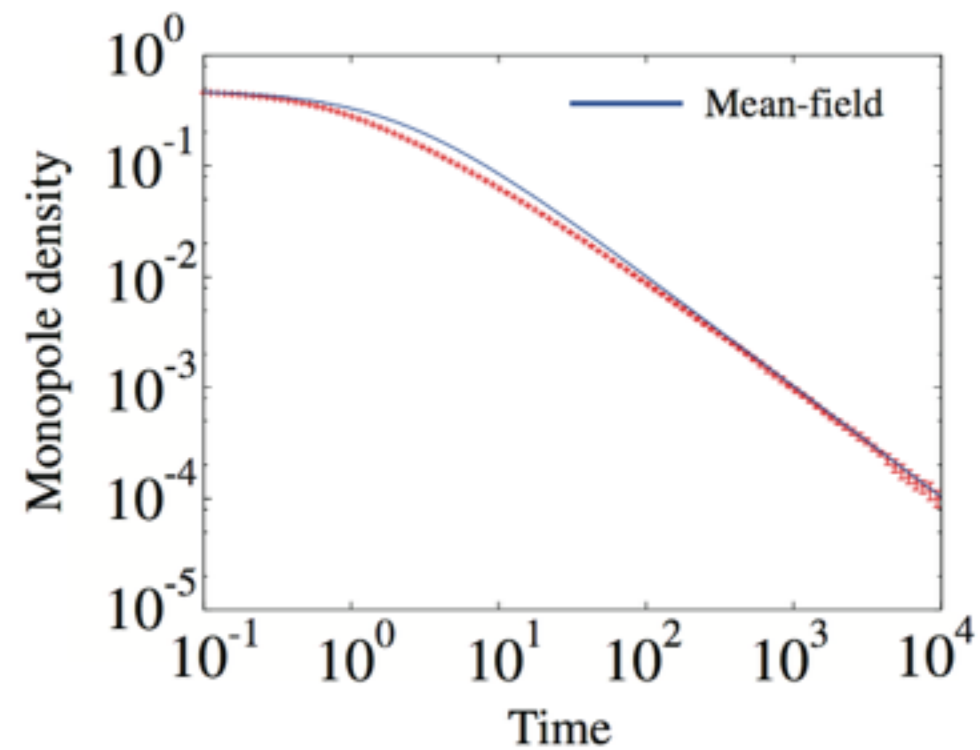


Field quench for spin ice (J = 0)







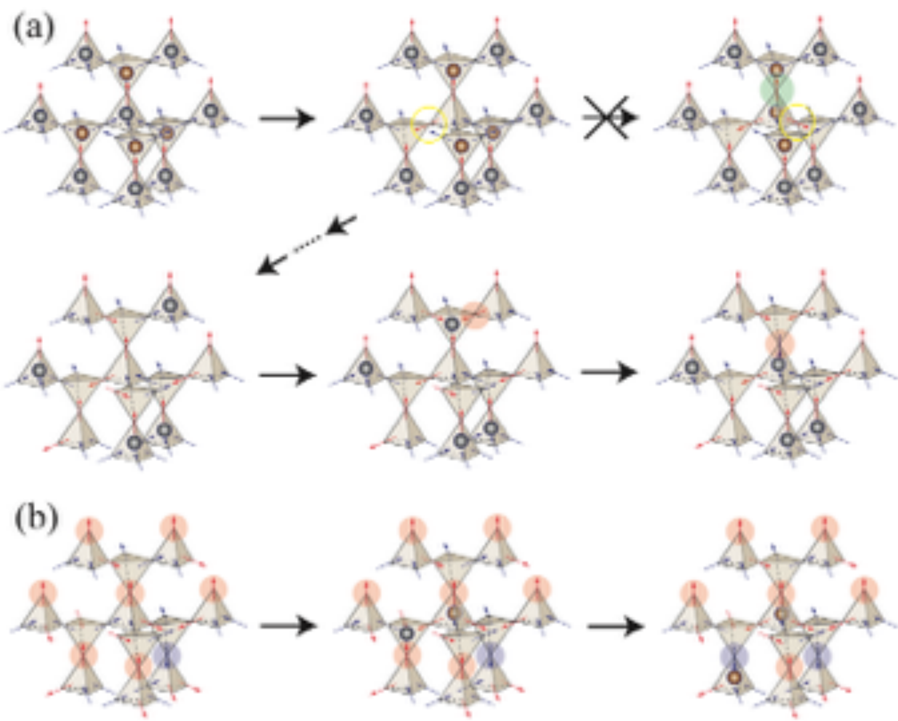


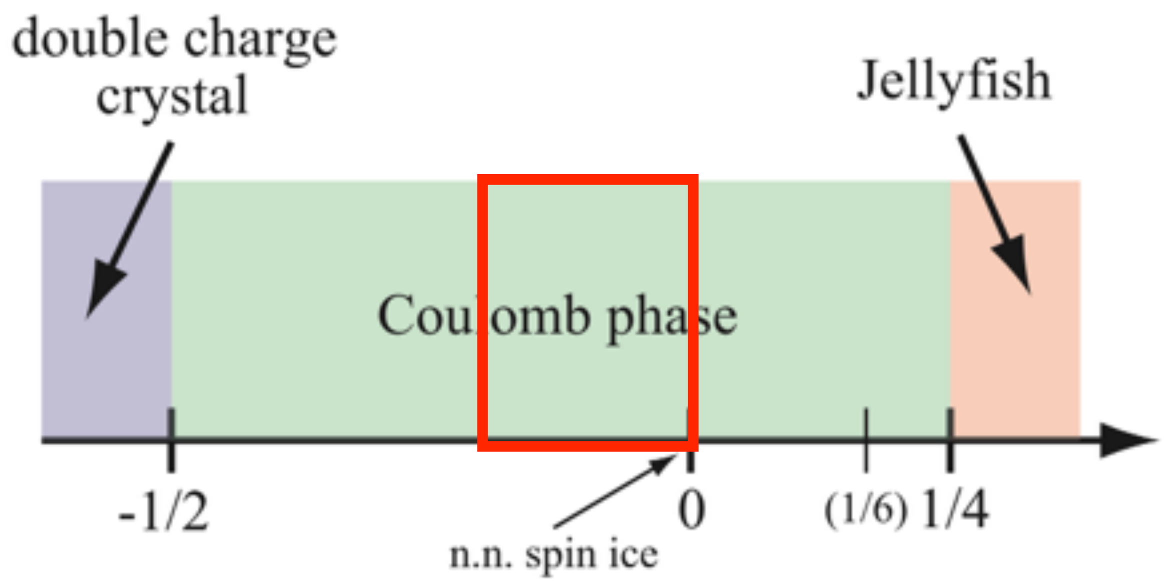
$$\frac{dn_+(r)}{dt} = \frac{dn_-(r)}{dt} = -\mathcal{K} n_+(r) n_-(r),$$

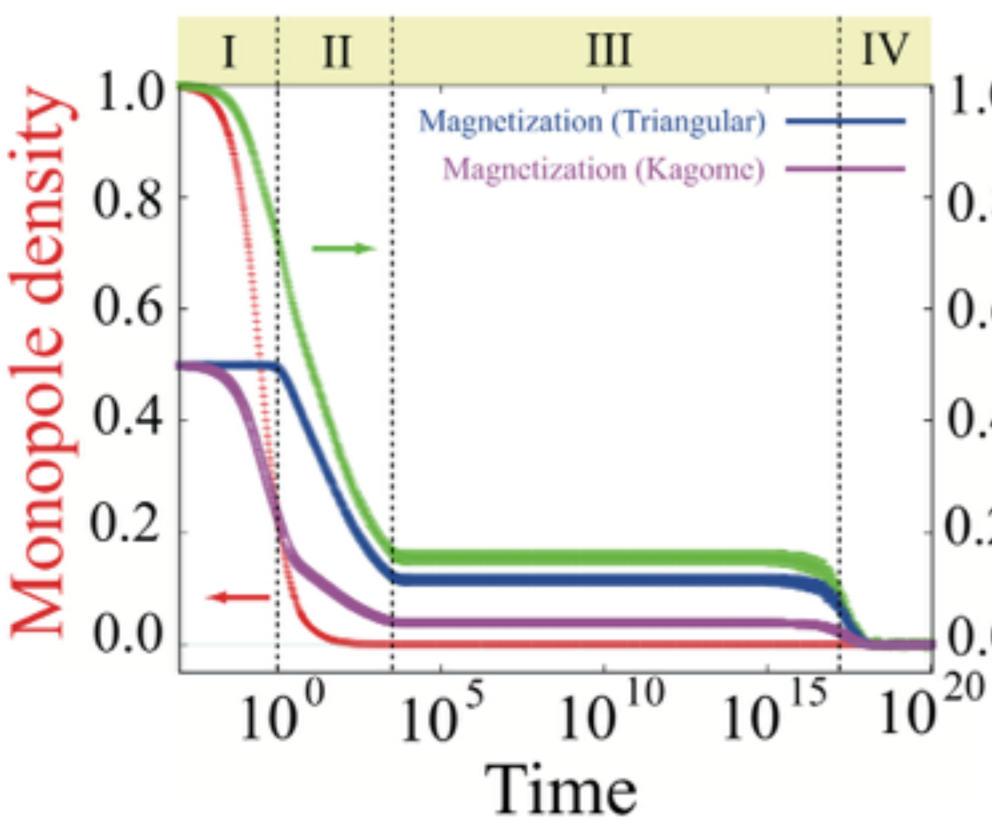
$$\rho(t) \equiv \frac{n_+ + n_-}{2} = \frac{\rho_0}{1 + \mathcal{K}\rho_0 t}$$

Castelnovo *et al.* PRL 2010 — Castelnovo *et al.* PRB 2011

Field quench for (-1/5 < J < 0)







$J = -0.1, \quad T = 0.1$

(I) kagome pair annihilation

$$\Delta_1 = -4 + 20|J|$$

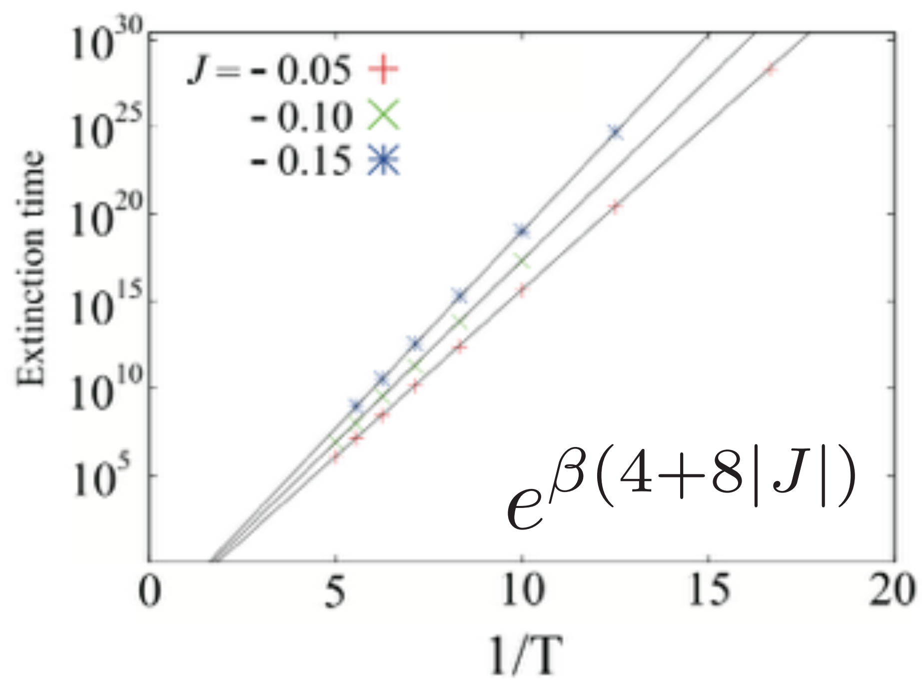
(II) diluted monopoles => free diffusion

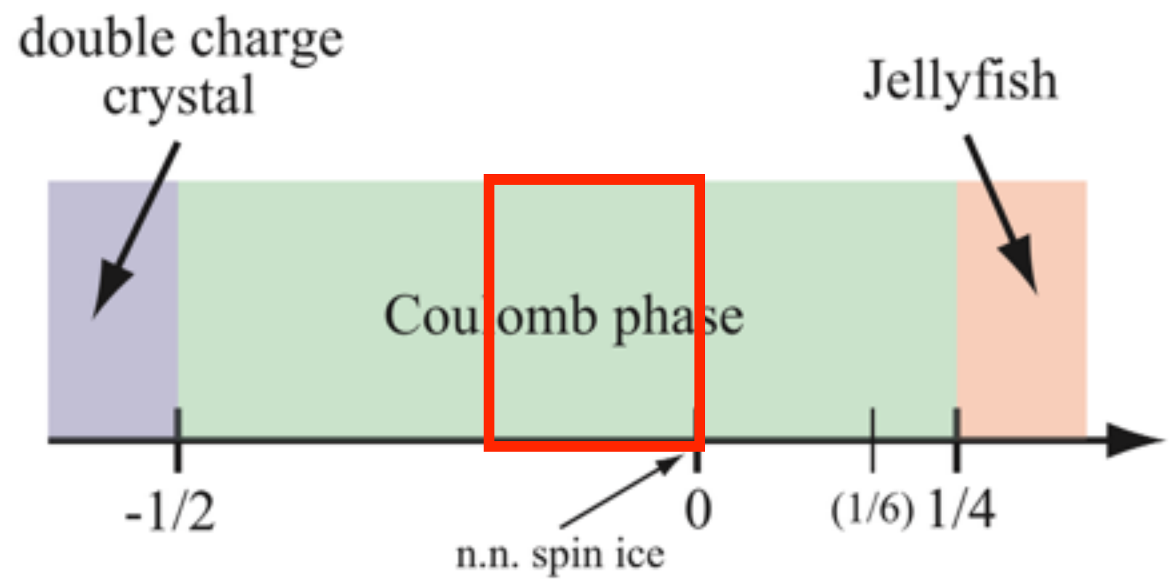
(III) no monopoles left => spin freezing

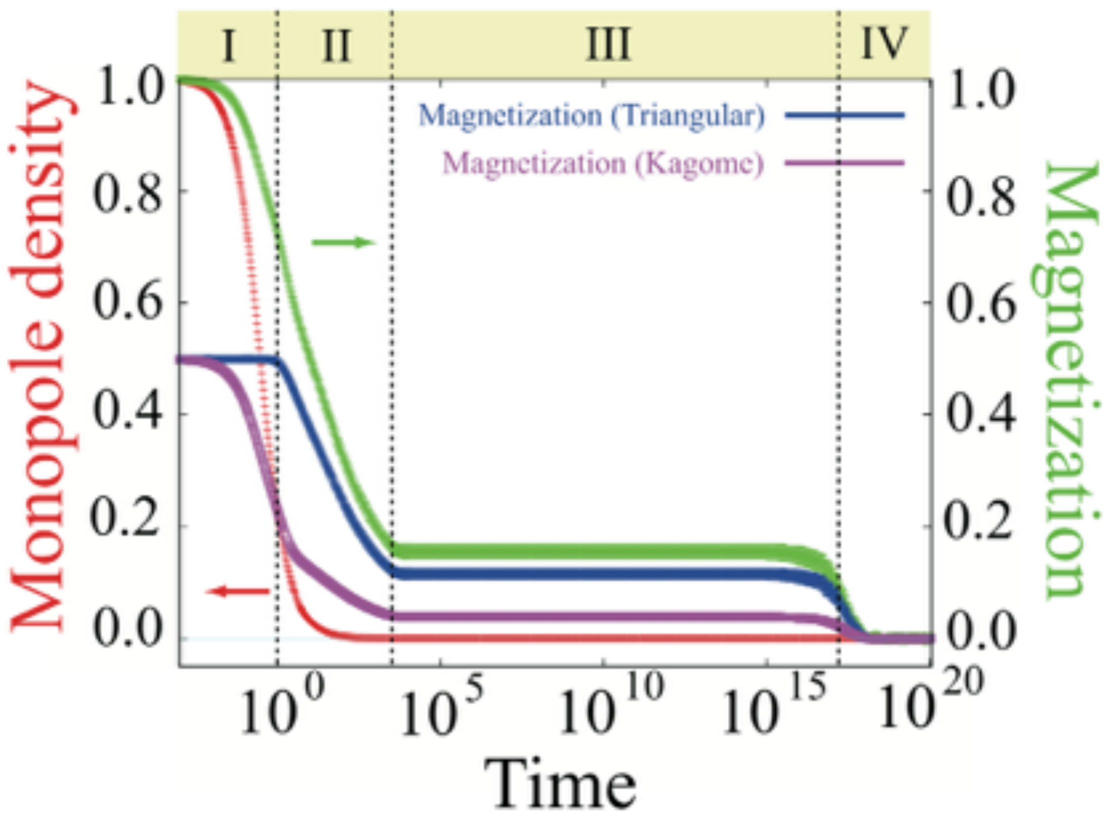
$$\Delta_3 = 4 + 4|J| \qquad \Delta_4 = 4|J|$$

(IV) thermal creation of a pair of monopoles
=> end of decorrelation

Field quench for (-1/5 < J < 0)







$J = -0.1, \quad T = 0.1$

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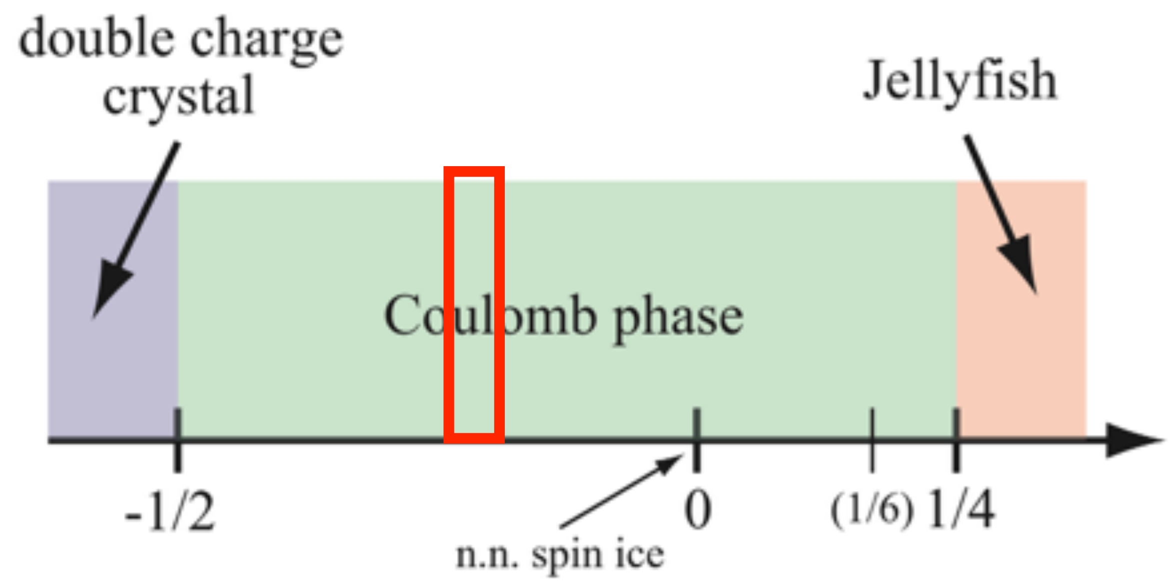
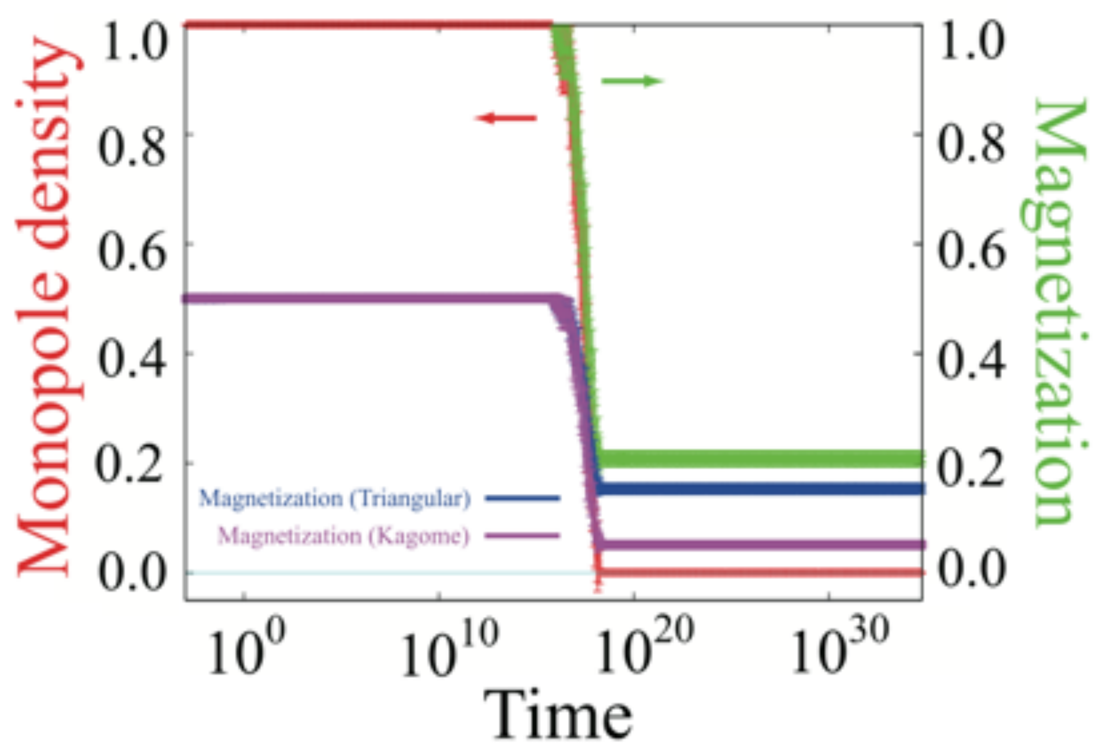
(IV) thermal creation of a pair of monopoles => end of decorrelation

Field quench for (-1/4 < J < -1/5)





$$J = -0.225, \quad T = 0.01$$

(I) kagome pair annihilation is now blocking

$$\Delta_1 = -4 + 20|J|$$

(II) but diffusion is still free => avalanche

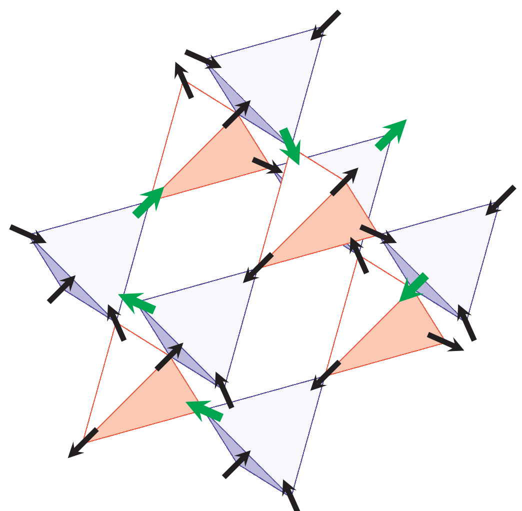
$$\Delta_2 = -4 + 16|J|$$

(III) no monopoles left => spin freezing

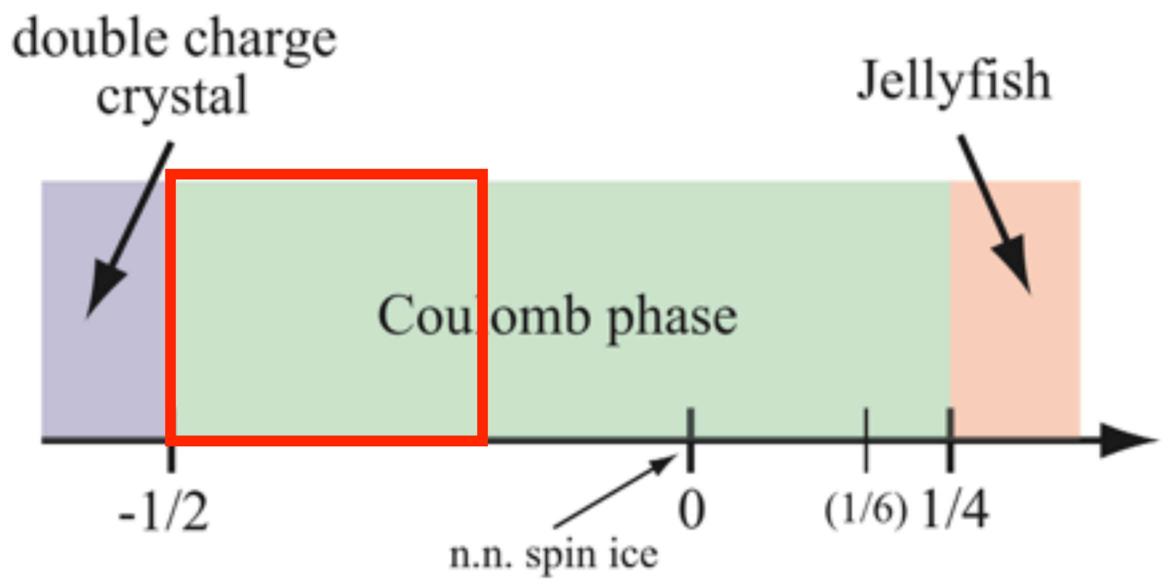
(IV) thermal creation of a pair of monopoles => end of decorrelation

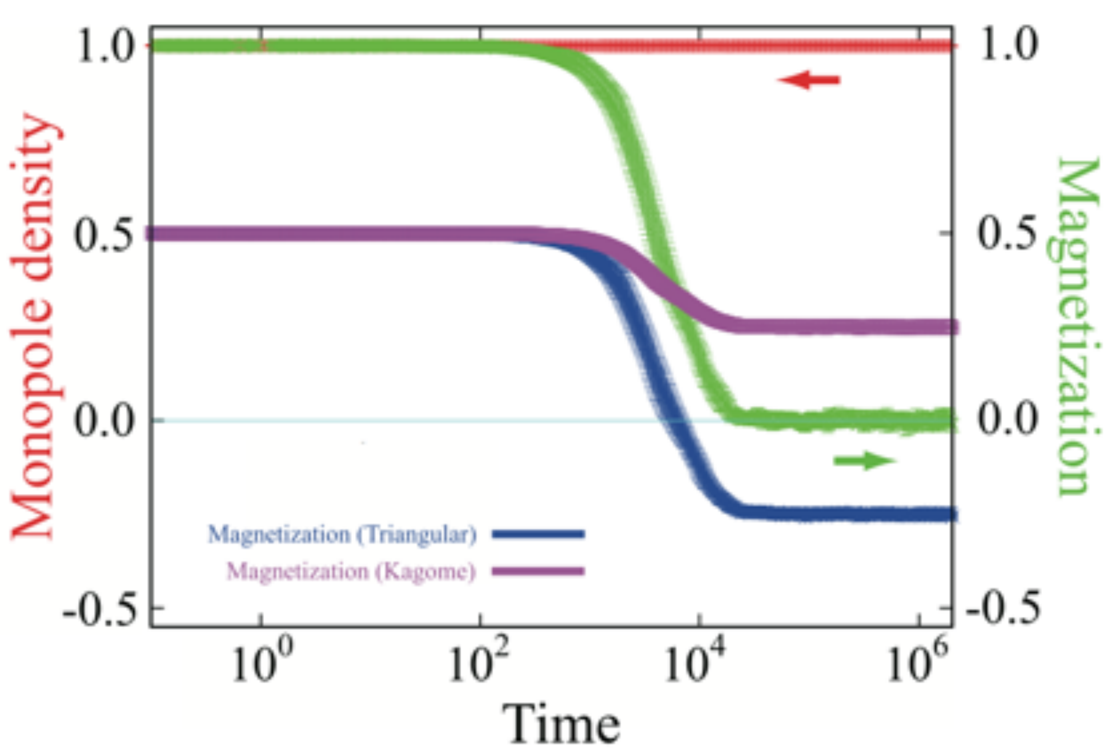
Field quench for (-1/2 < J < -1/4)

Fragmented spin liquid



degeneracy $\Omega \approx 1.3^{N/2}$



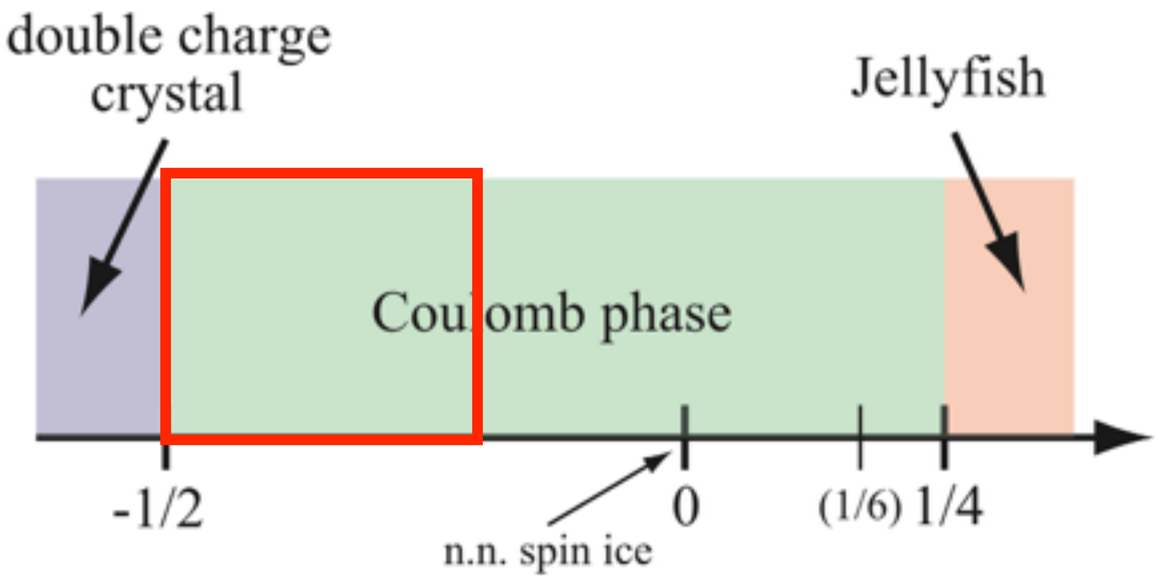


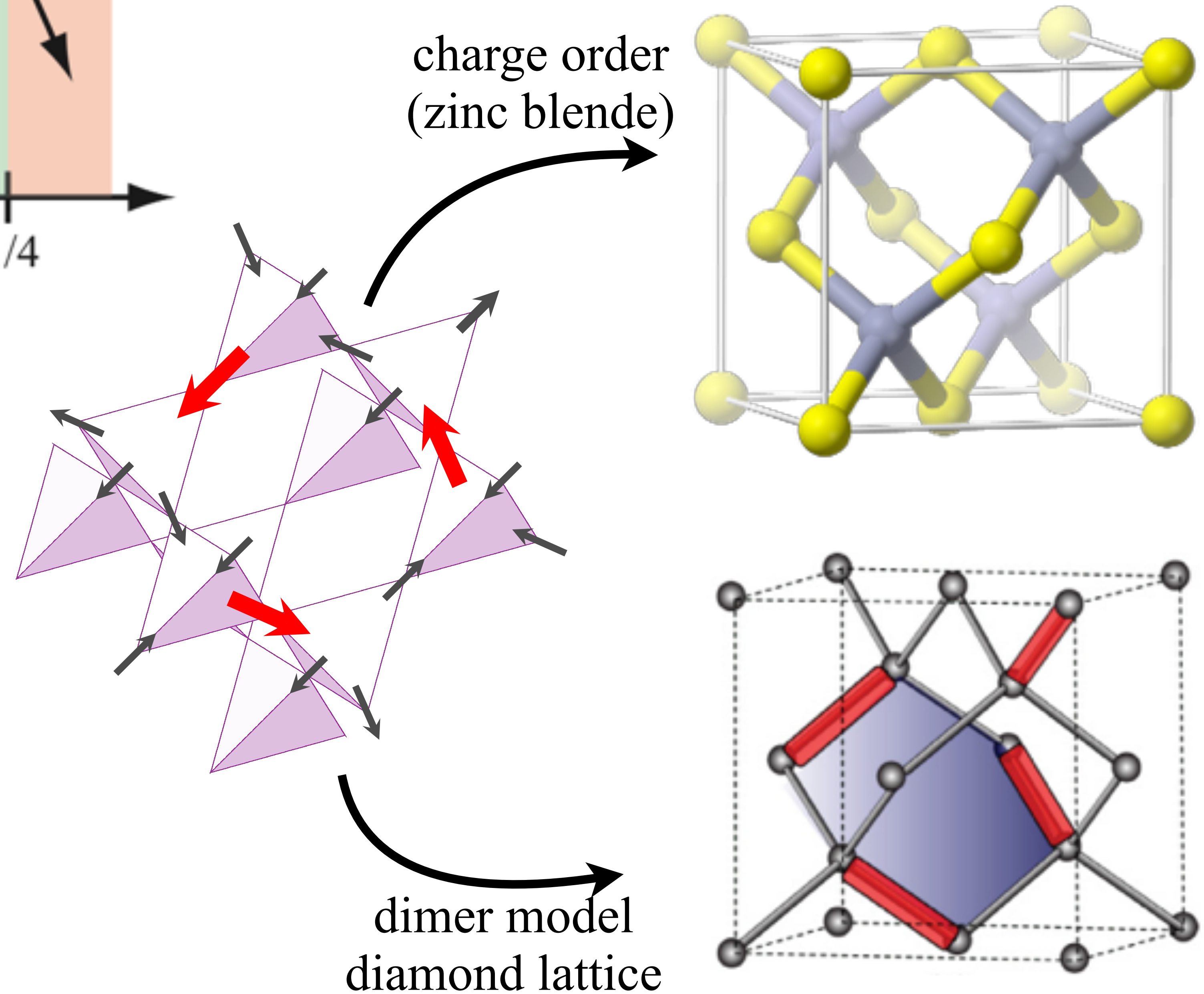
(I) kagome pair annihilation and diffusion are now blocking

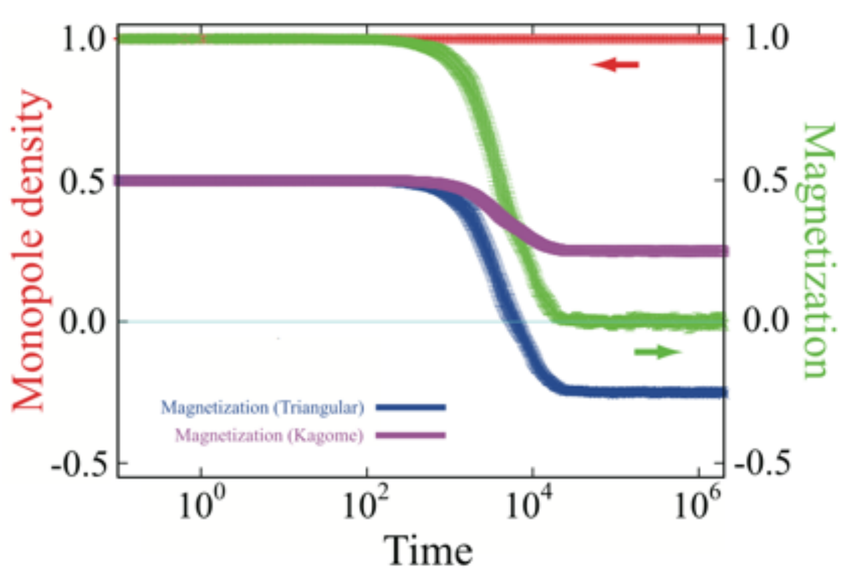
$$\Delta_1 = -4 + 20|J| \qquad \Delta_2 = -4 + 16|J|$$

(II) fragmented spin liquid is stabilized over a finite time.

Fragmented Spin Liquid



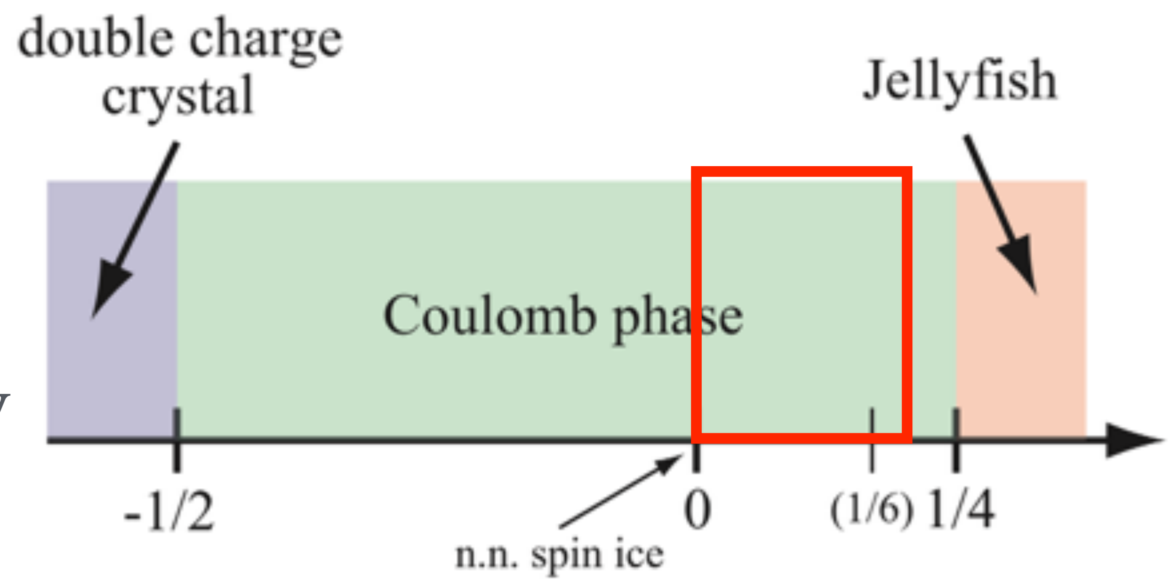


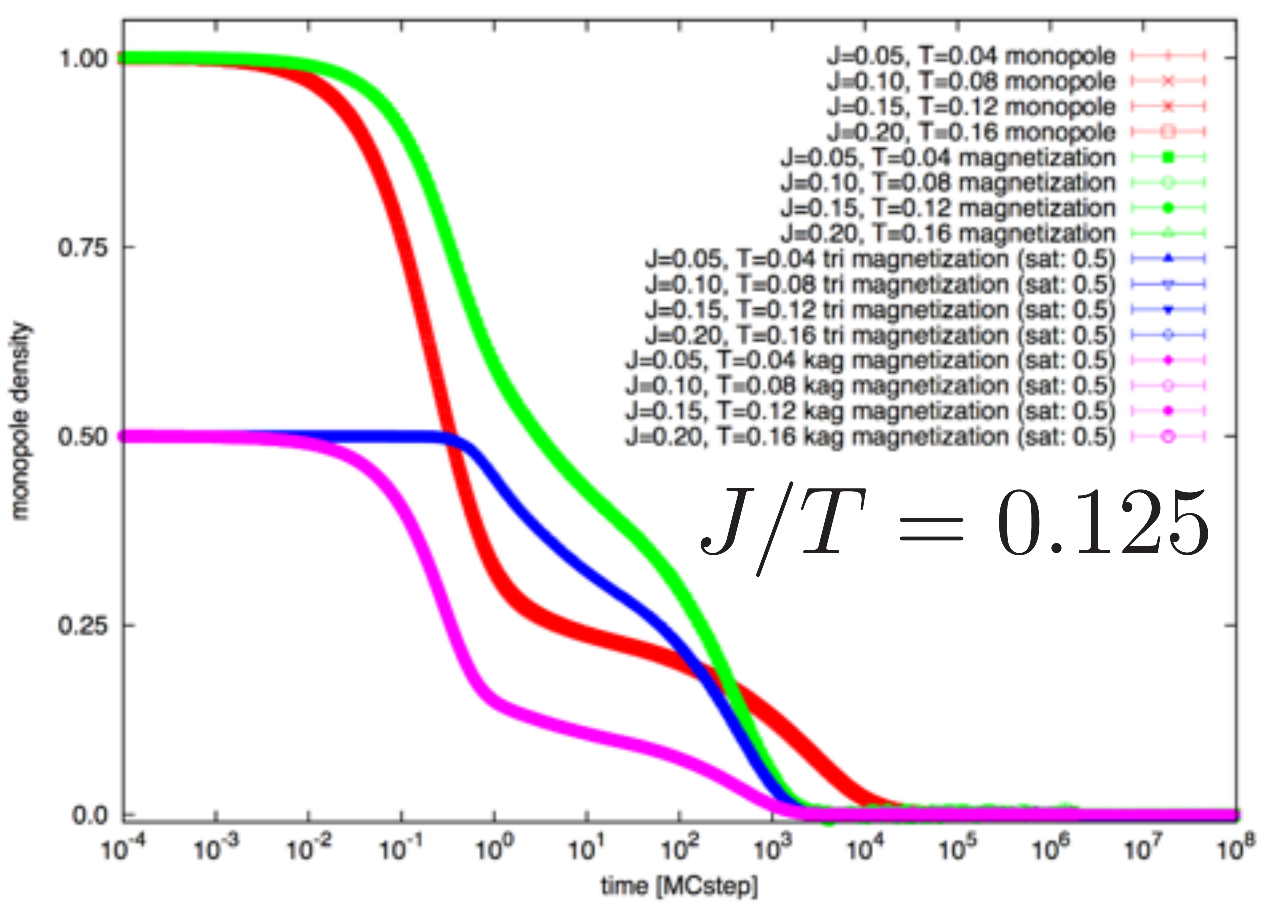


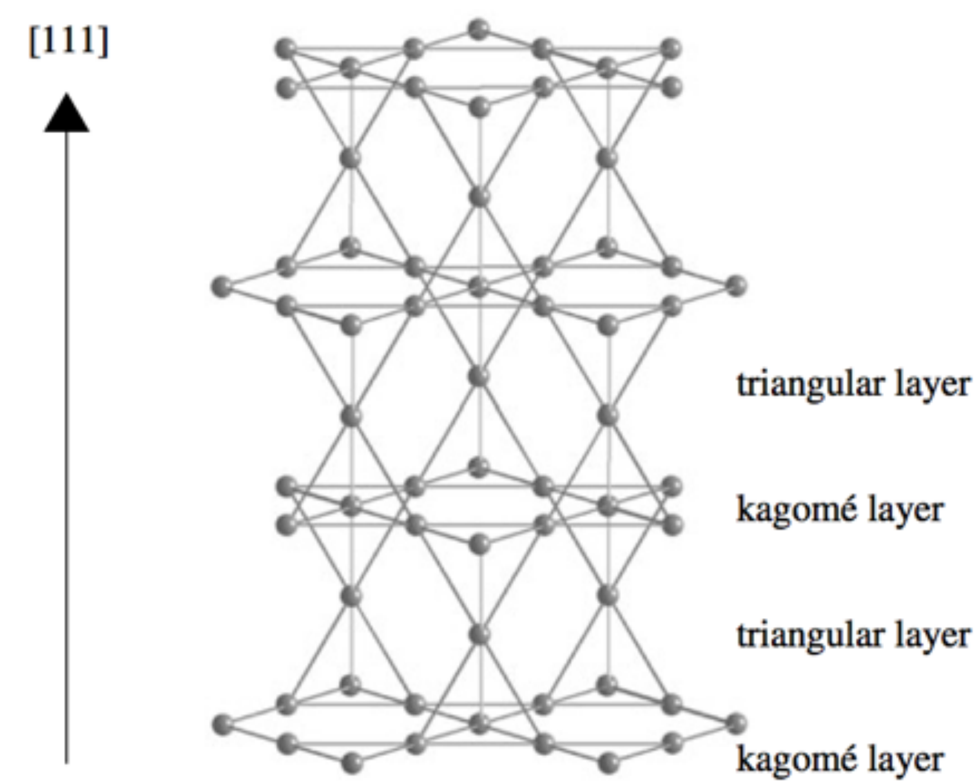
Borzi et al. PRL 2013, Brooks et al. PRX 2014, Jaubert Spin 2015

Field quench for 0 < J < 1/5

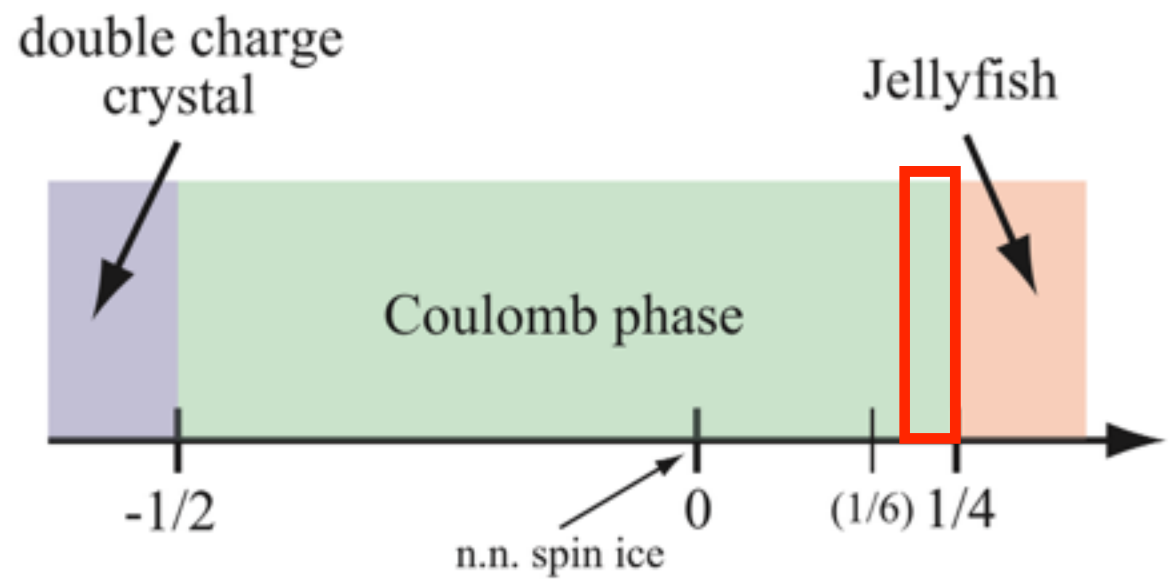
Same charge monopoles are repulsive
=> the initial state is strongly out-of-equilibrium





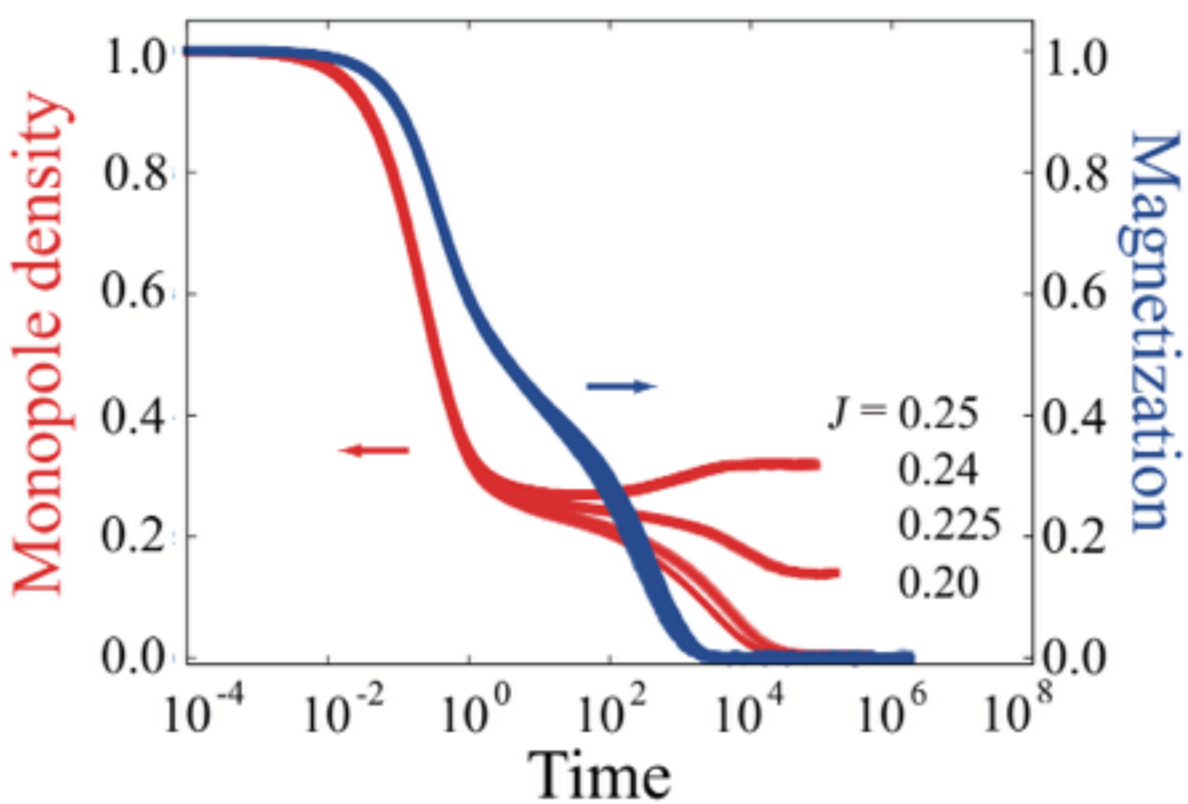


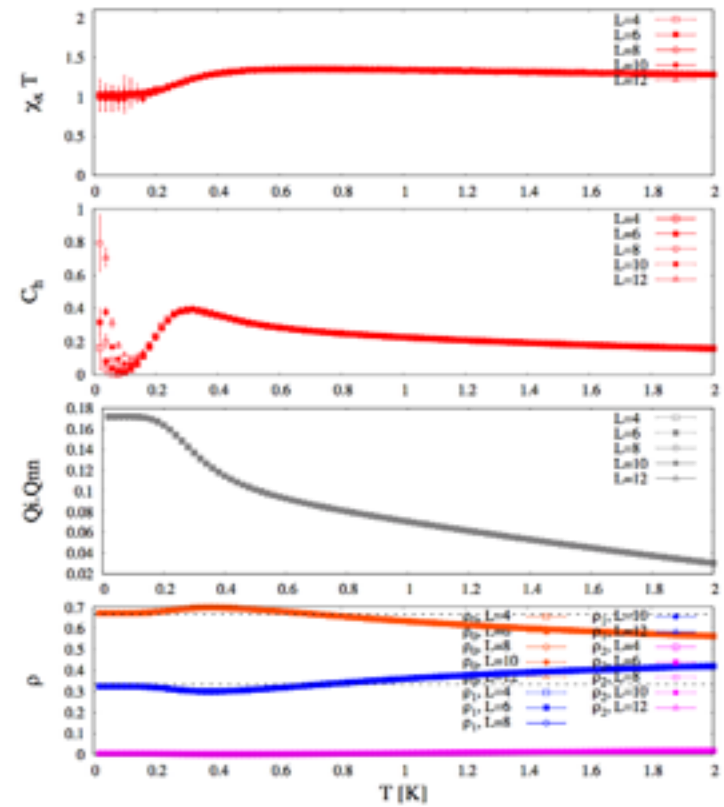
Field quench for J ≲ 1/4

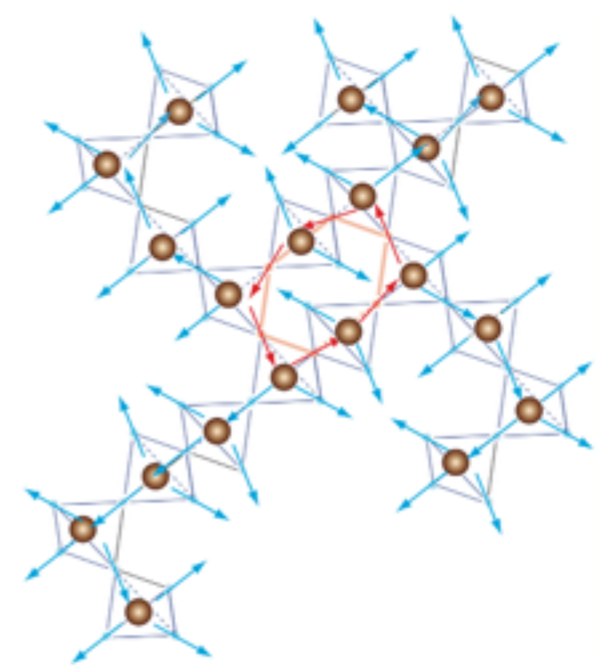


Qualitative change of behaviour as we approach J = 0.25

$$\mathcal{H} = \frac{1}{4}\sum_{p} Q_p^2 - \frac{1}{4}\sum_{\langle p,q\rangle} Q_p Q_q .$$







Conclusion

J1-J2-J3 model (truncated RKKY)

nearest-neighbour monopole coupling

- very diverse out-of-equilibrium dynamics
- AF Coulomb spin liquid stabilized by [111] magnetic field quench.
- attraction between magnetic charges of same sign => new kind of charge frustration
- chiral jellyfish structure