

Non-equilibrium Glassy Spin Ice



Ludovic Jaubert





Collaborators



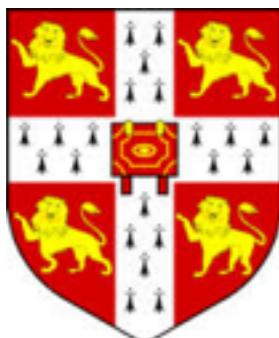
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Cambridge University, UK



Motivation

why non-equilibrium physics ?



Motivation

why non-equilibrium physics ?

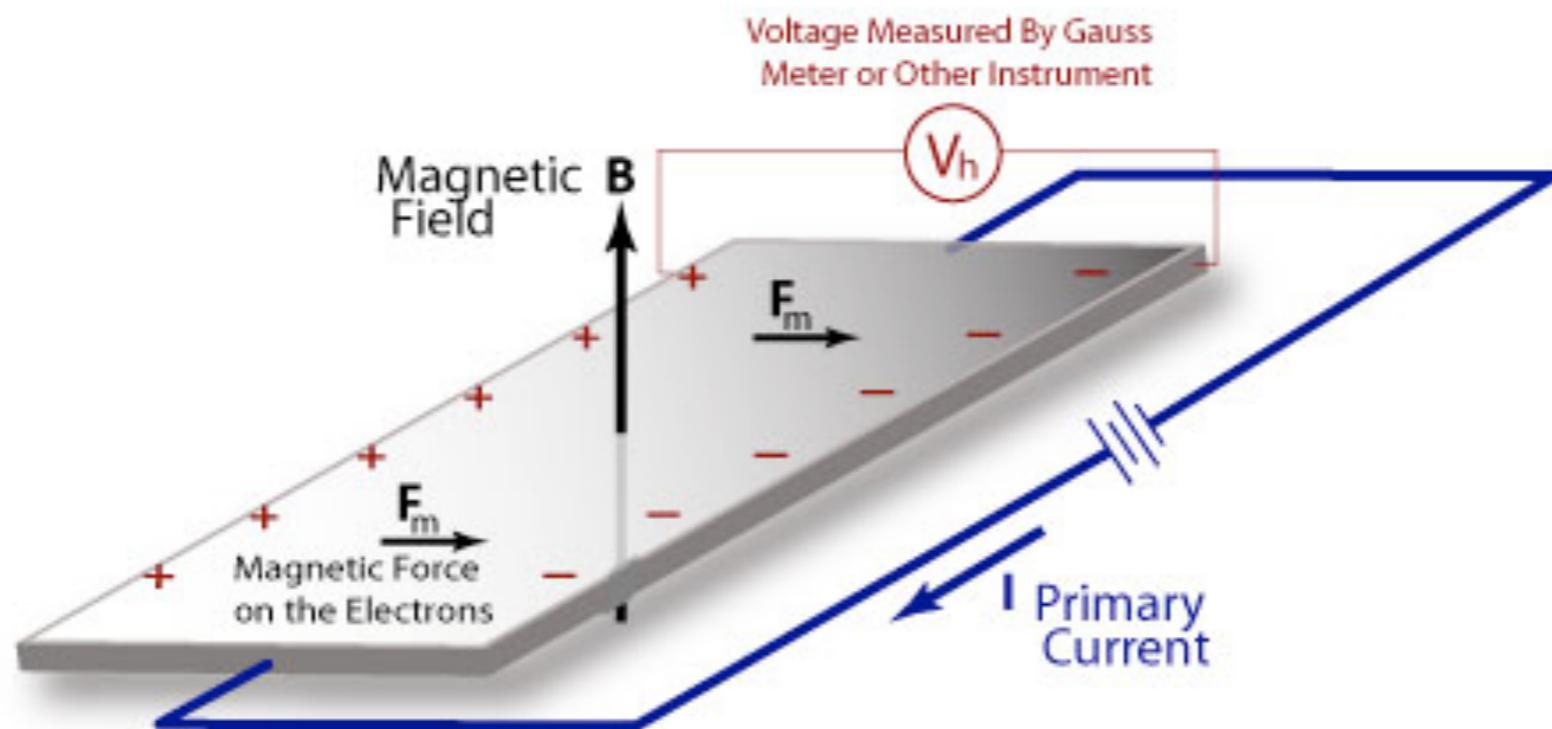
Model

why spin ice ?

Results

*why non-equilibrium
physics in spin ice ?*

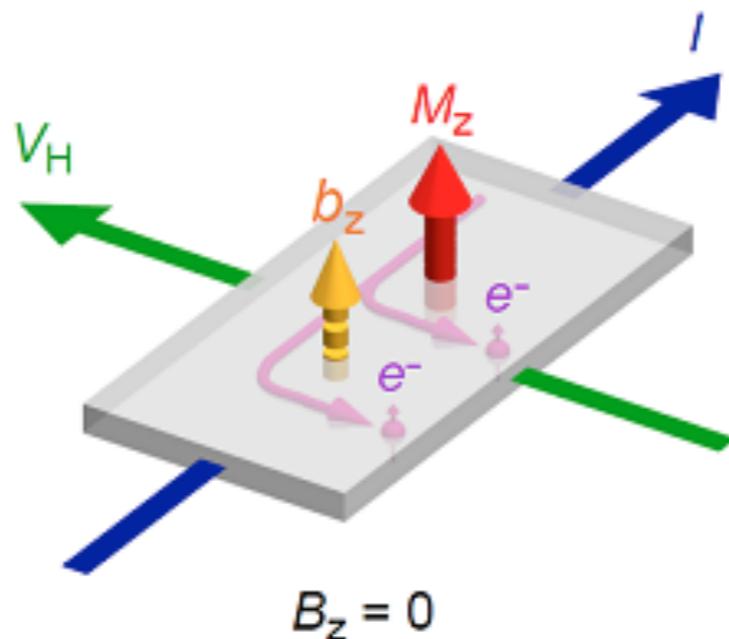
Hall Effect



Time-reversal symmetry breaking

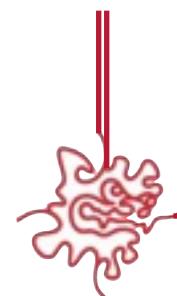


Anomalous Hall Effect

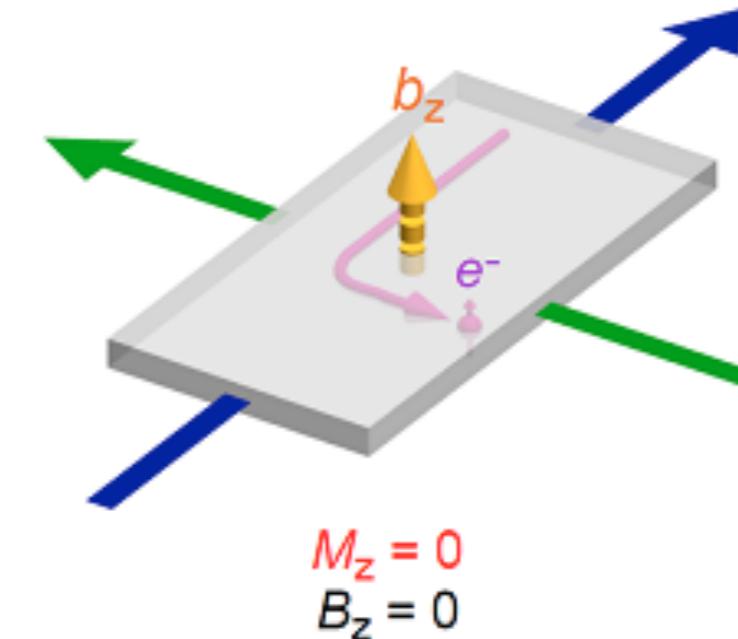
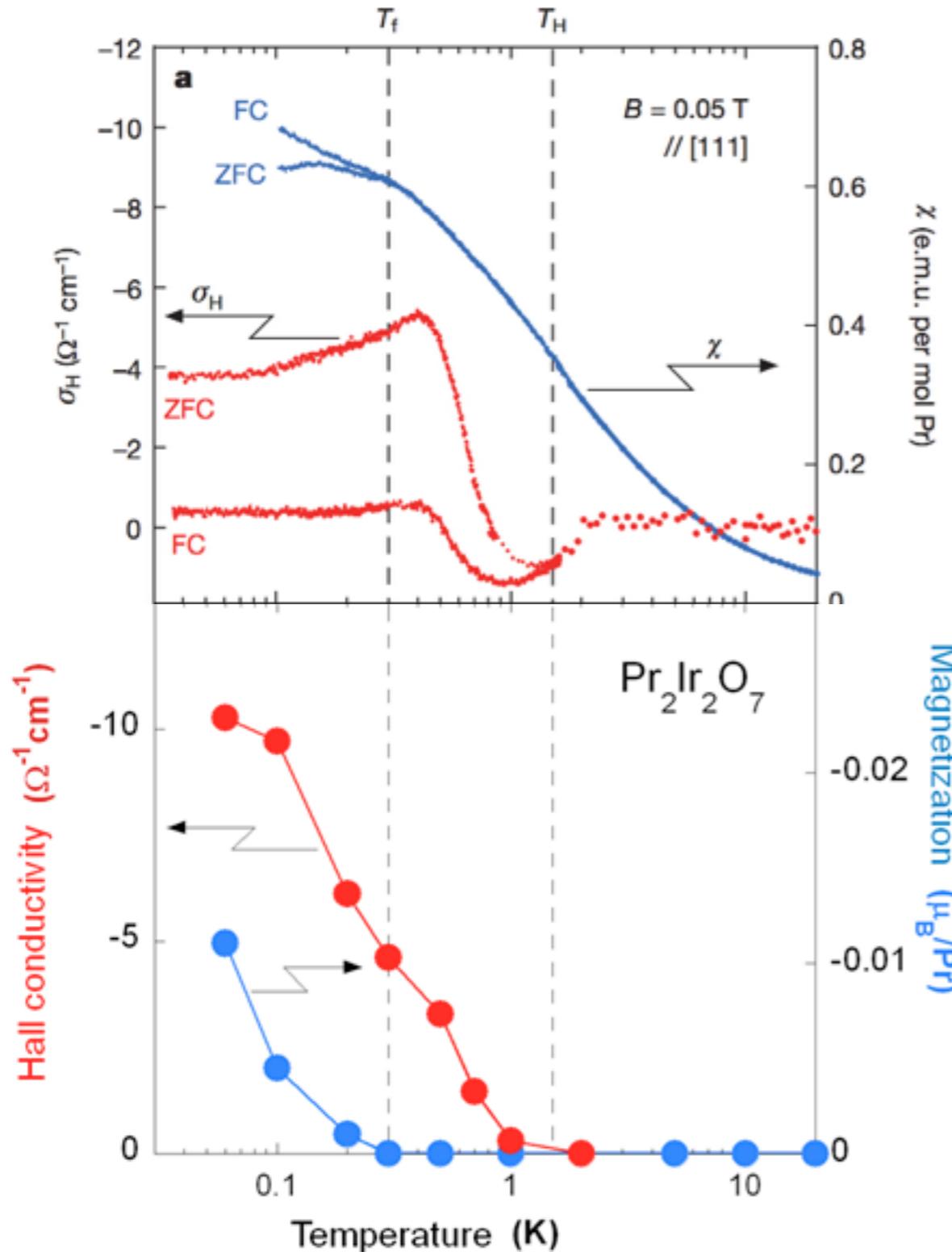


Time-reversal symmetry breaking
→ no magnetic field, but *usually* ferromagnetism

$\text{Pr}_2\text{Ir}_2\text{O}_7$: “*Spontaneous*” Hall Effect



freezing temperature



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

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What is spin ice ?

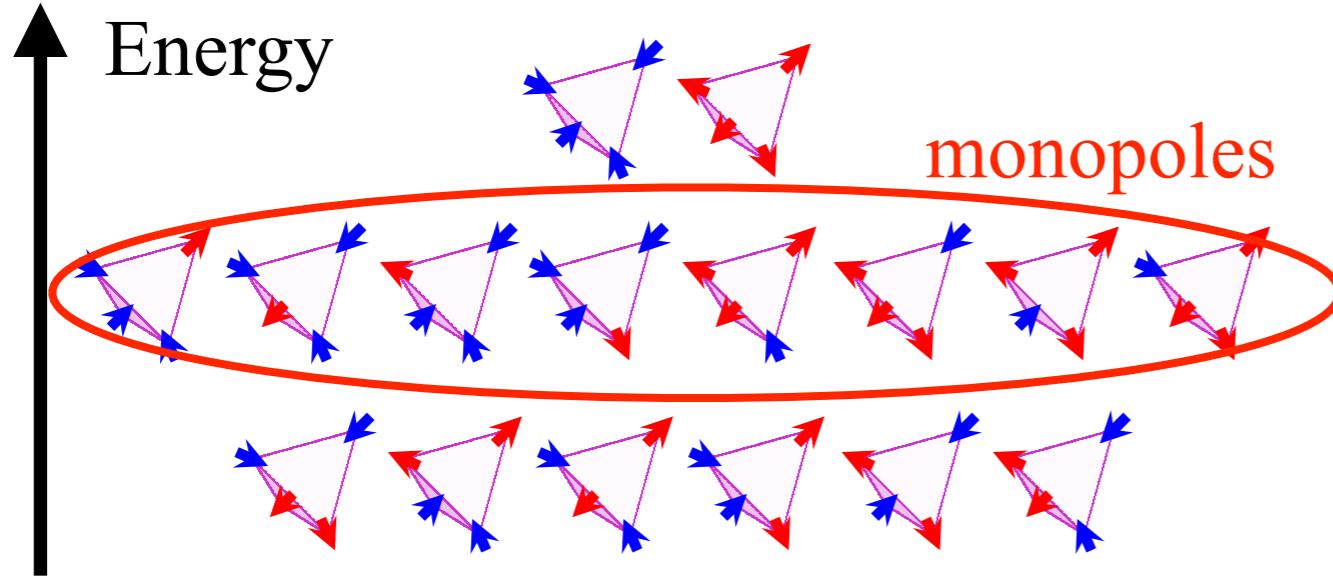


Periodic Table of Elements

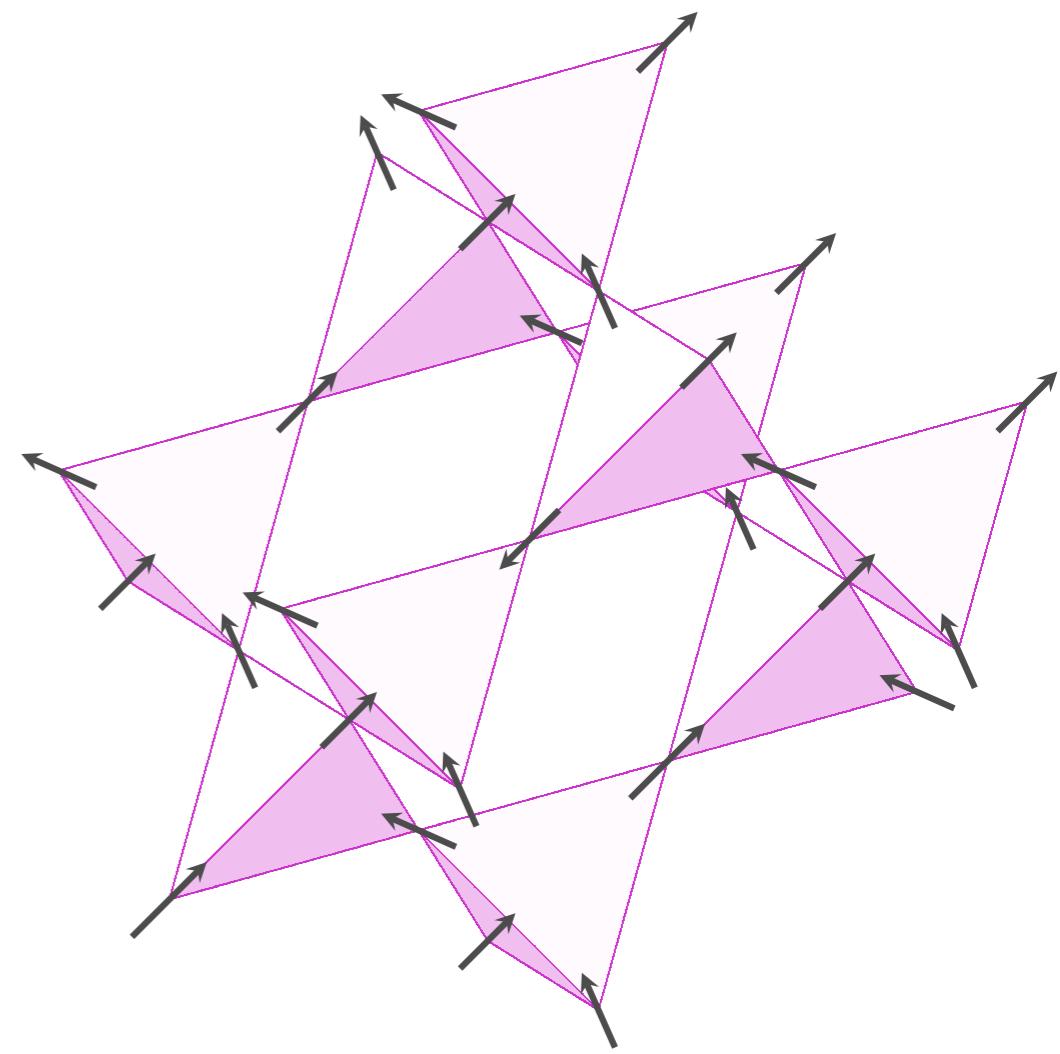
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
1 H	Atomic # Hydrogen 1.00794	Symbol H	Solid C	Liquid Hg	Gas H	Unknown Rf	Metals	Alkal metals	Alkaline earth metals	Lanthanoids	Transition metals	Poor metals	Nonmetals	Other	Nonmetals	Gaseous He			
2 Li	Li	1	4 Be	Be	90 Beryllium	8.974										10 Ne	Neon		
11 Na	Na	11	12 Mg	Mg	Magnesium	24.300										18 Ar	Argon		
19 K	K	19	20 Ca	Ca	Calcium	40.078	21 Sc	Sc	Titanium	47.867	22 V	Vanadium	50.941	24 Cr	Chromium	51.987	25 Mn	Manganese	54.938
37 Rb	Rb	37	38 Sr	Sr	Sodium	87.678	39 Y	Y	Zirconium	87.678	40 Zr	Zirconium	87.224	41 Nb	Niobium	91.961	42 Mo	Molybdenum	95.961
55 Cs	Cs	55	56 Ba	Ba	Boron	152.04498	57 Hf	Hf	Hafnium	178.49	72 Ta	Tantalum	180.9476	73 W	Wolfram	183.54	74 Re	Rhenium	190.21
87 Fr	Fr	87	88 Ra	Ra	Radium	226.03870	89 Rf	Rutherfordium	(261)	104 Db	Dubnium	(261)	105 Sg	Singeenium	(261)	106 Bh	Bh	Bhrium	(261)
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.																			

Ptable.com

57 La	La	138.90547	58 Ce	Ce	140.118	59 Pr	Praseodymium	141.924	60 Nd	Nd	140.90765	61 Pm	Promethium	(141)	62 Sm	Sm	150.938	63 Eu	Europium	151.941	64 Gd	Gadolinium	157.931	65 Tb	Terbium	158.933	66 Dy	Dysprosium	162.933	67 Ho	Holmium	164.933	68 Er	Erbium	167.939	69 Tm	Thulium	168.931	70 Yb	Ytterbium	173.939	71 Lu	Lu	174.939							
89 Ac	Ac	227	90 Th	Th	232.0368	91 Pa	Protactinium	231.0368	92 U	U	238.0368	93 Np	Neptunium	237	94 Pu	Pu	244	95 Am	Americium	243	96 Cm	Cm	247	97 Bk	Bk	Berkelium	247	98 Cf	Cf	Berkelium	251	99 Es	Es	Einsteinium	252	100 Fm	Fm	Fermium	257	101 Md	Md	Mendelevium	258	102 No	No	Nobelium	258	103 Lr	Lr	Livermorium	262

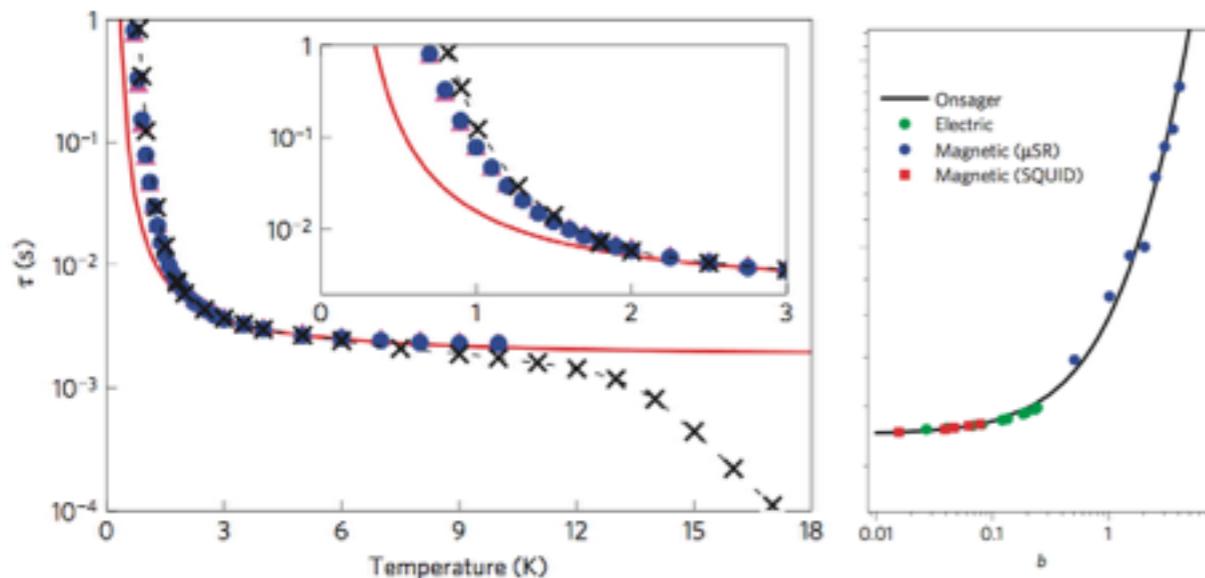


pyrochlore lattice
Ising spins
nearest neighbour



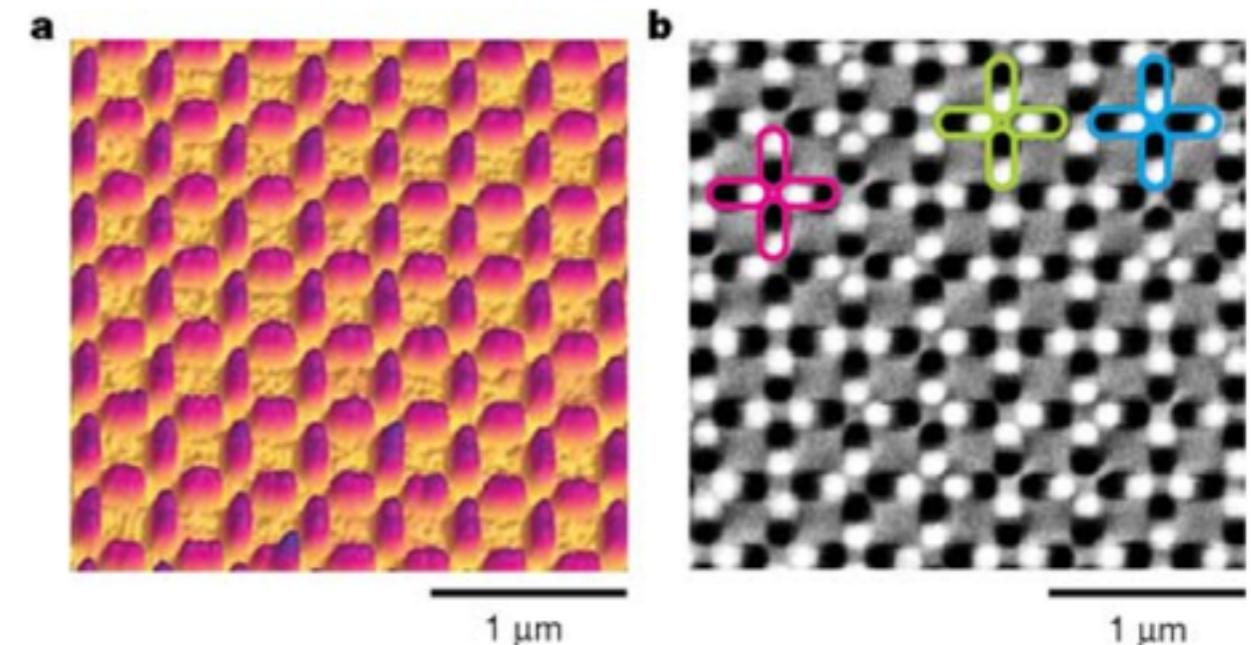
See also...

Monopole dynamics and Wien effect
in $\text{Dy}_2\text{Ti}_2\text{O}_7$, $\text{Ho}_2\text{Ti}_2\text{O}_7$...



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



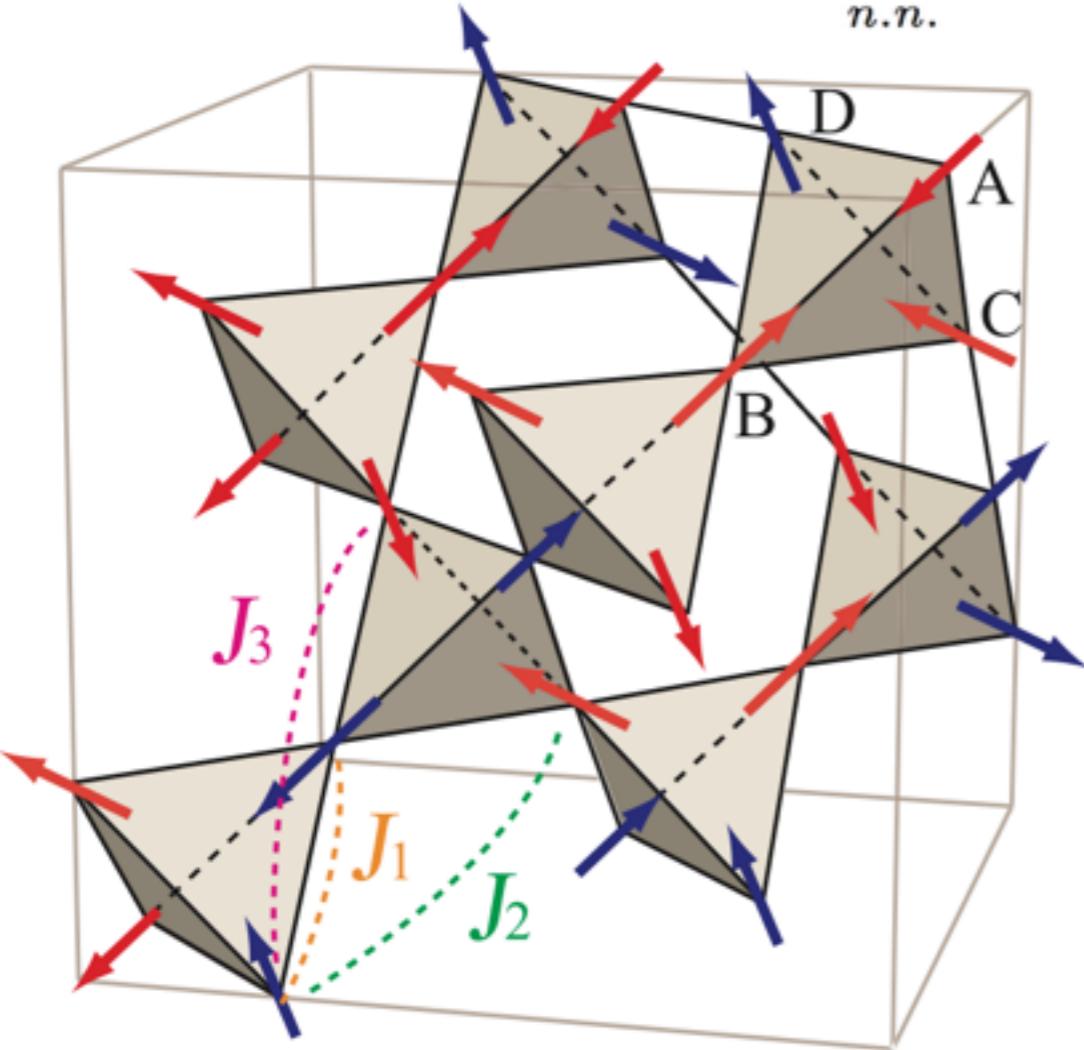
Wang *et al*. Nature 2006

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

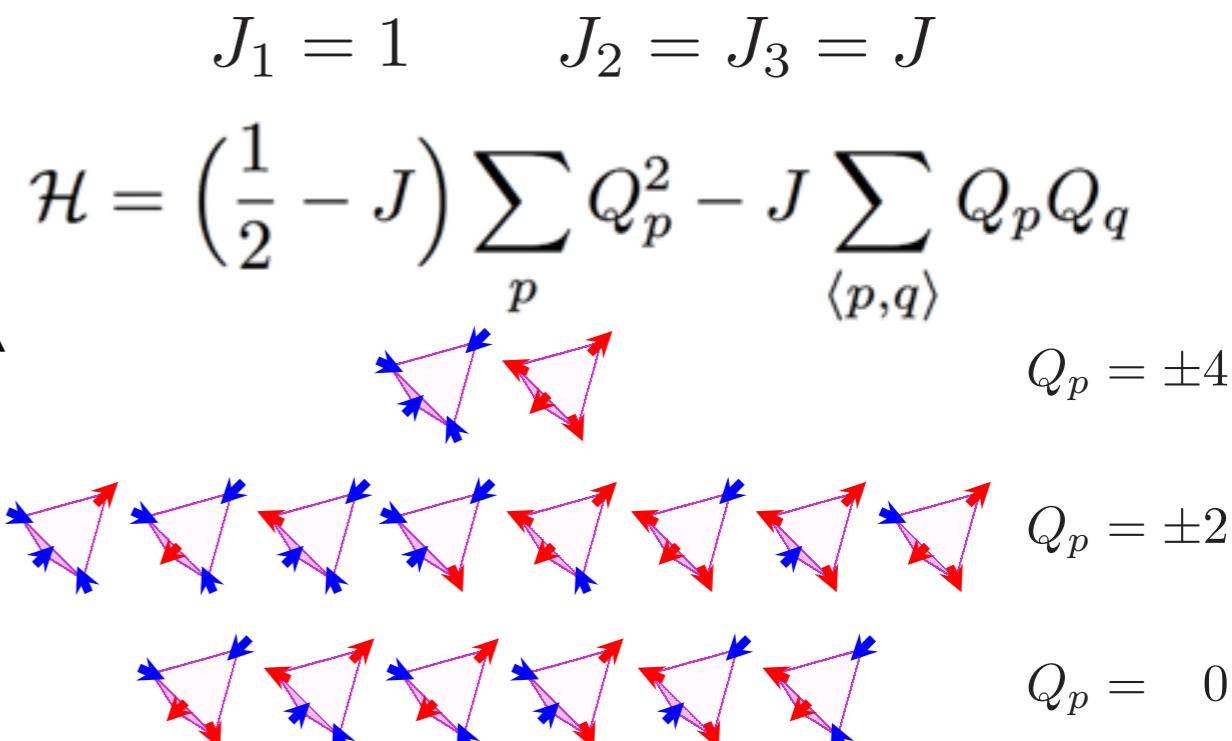
Coupling to itinerant electrons

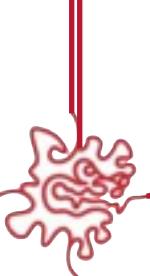
Truncated Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions
→ next-next-nearest neighbour interactions

$$\begin{aligned}\mathcal{H} &= \tilde{J}_1 \sum_{n.n.} \mathbf{S}_i \cdot \mathbf{S}_j + \tilde{J}_2 \sum_{2nd.} \mathbf{S}_i \cdot \mathbf{S}_j + \tilde{J}_3 \sum_{3rd.} \mathbf{S}_i \cdot \mathbf{S}_j \\ &= J_1 \sum_{n.n.} \eta_i \eta_j + J_2 \sum_{2nd.} \eta_i \eta_j + J_3 \sum_{3rd.} \eta_i \eta_j\end{aligned}$$



Can we make it simpler ?
Ishizuka & Motome PRB 2013



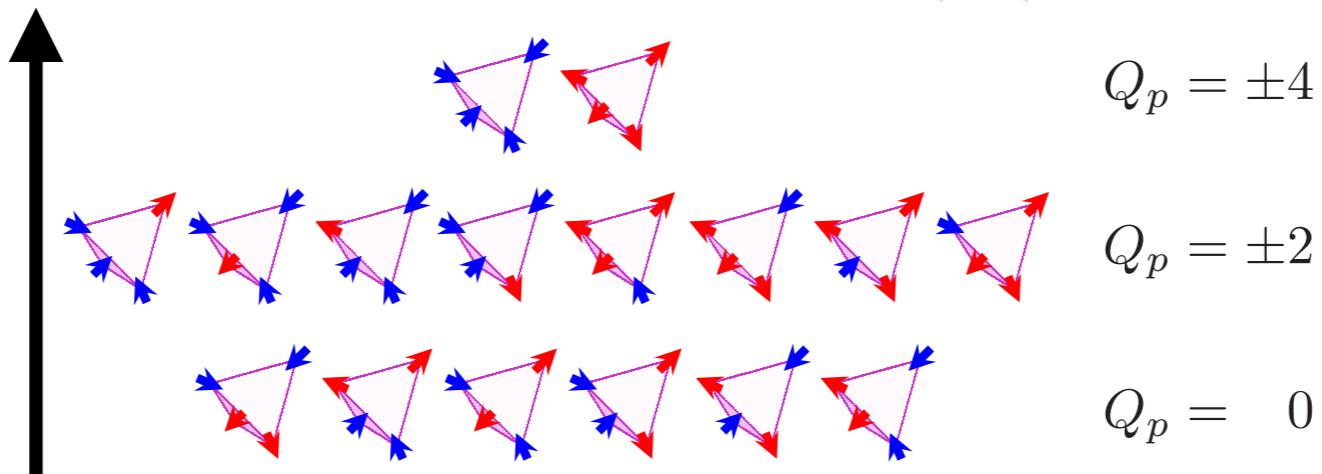


Summary of the model

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)

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

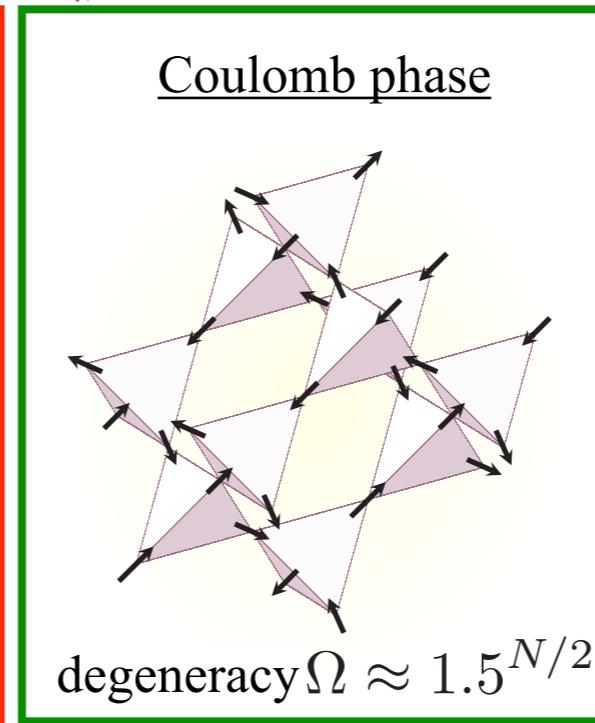
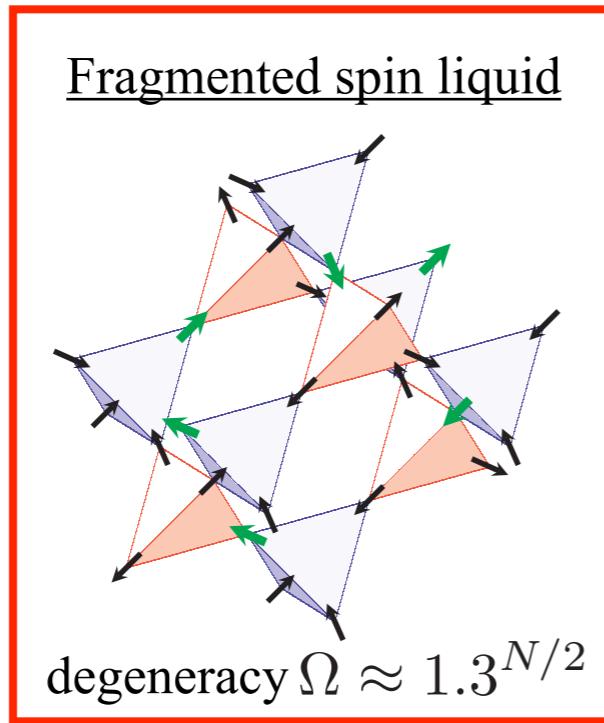
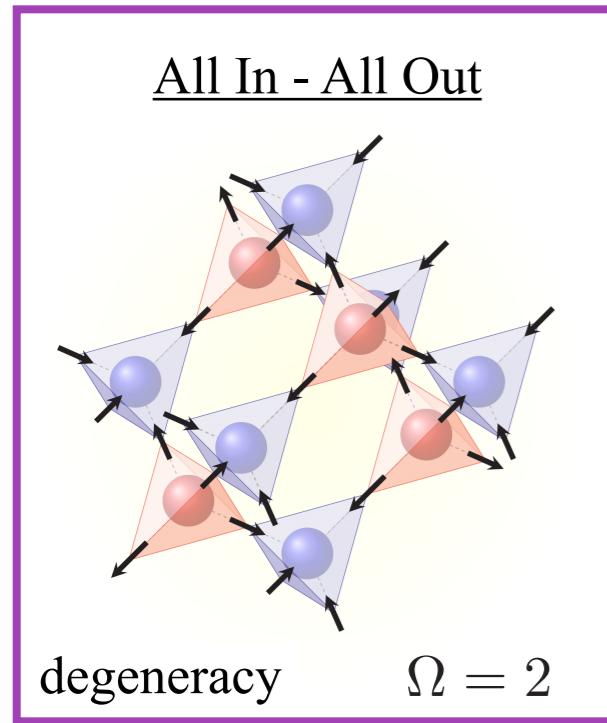
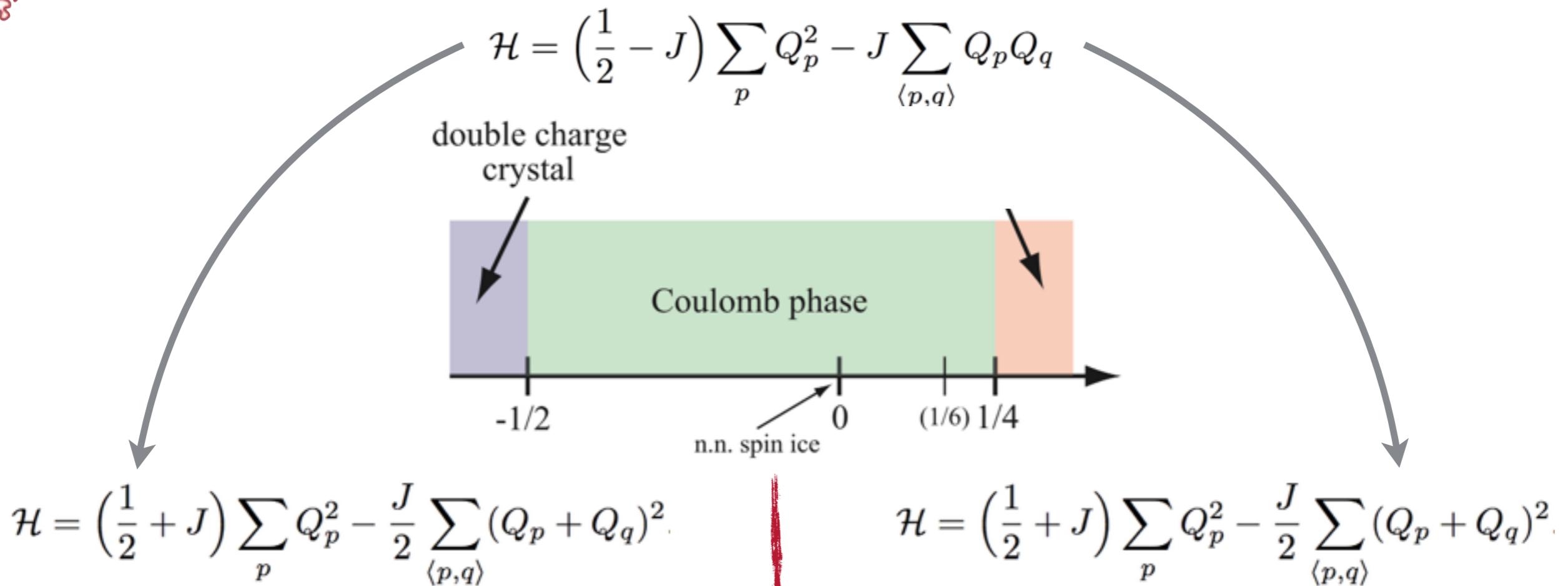


Motivation
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Model
why spin ice ?

👉 Results
*why non-equilibrium
physics in spin ice ?*

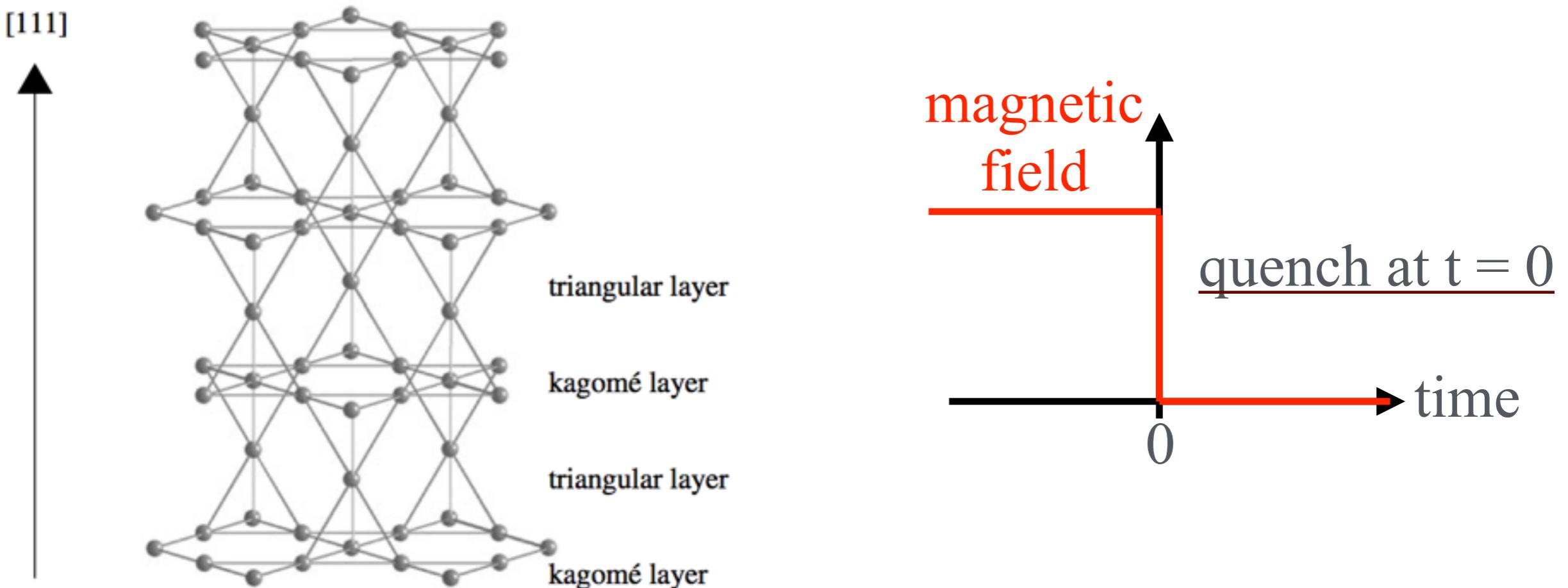
Phase diagram at equilibrium



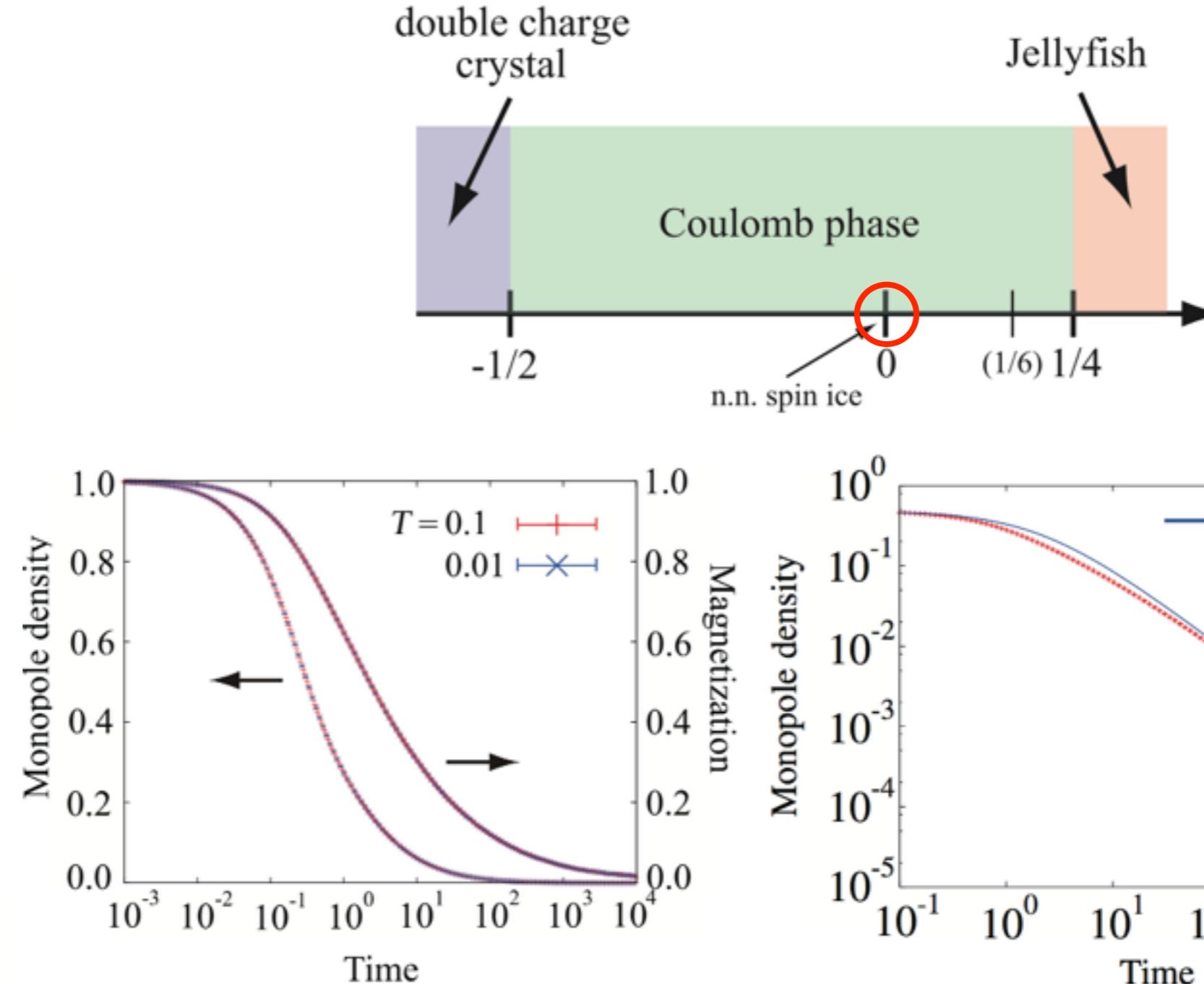
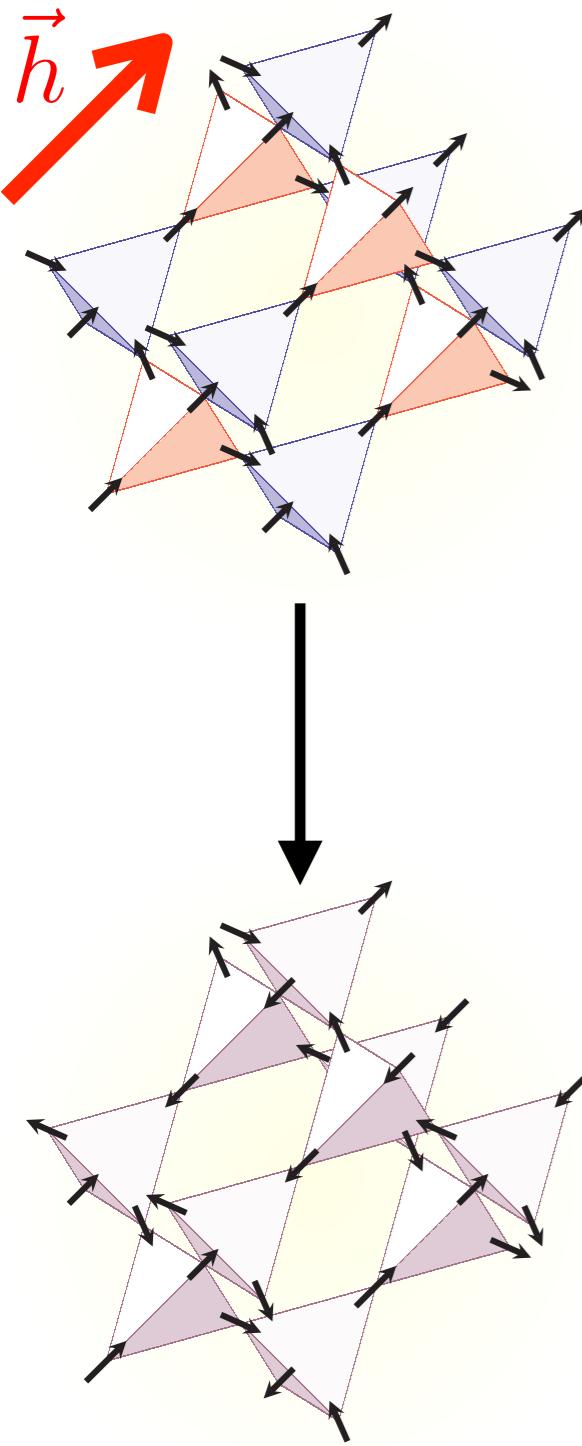


Field quench

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



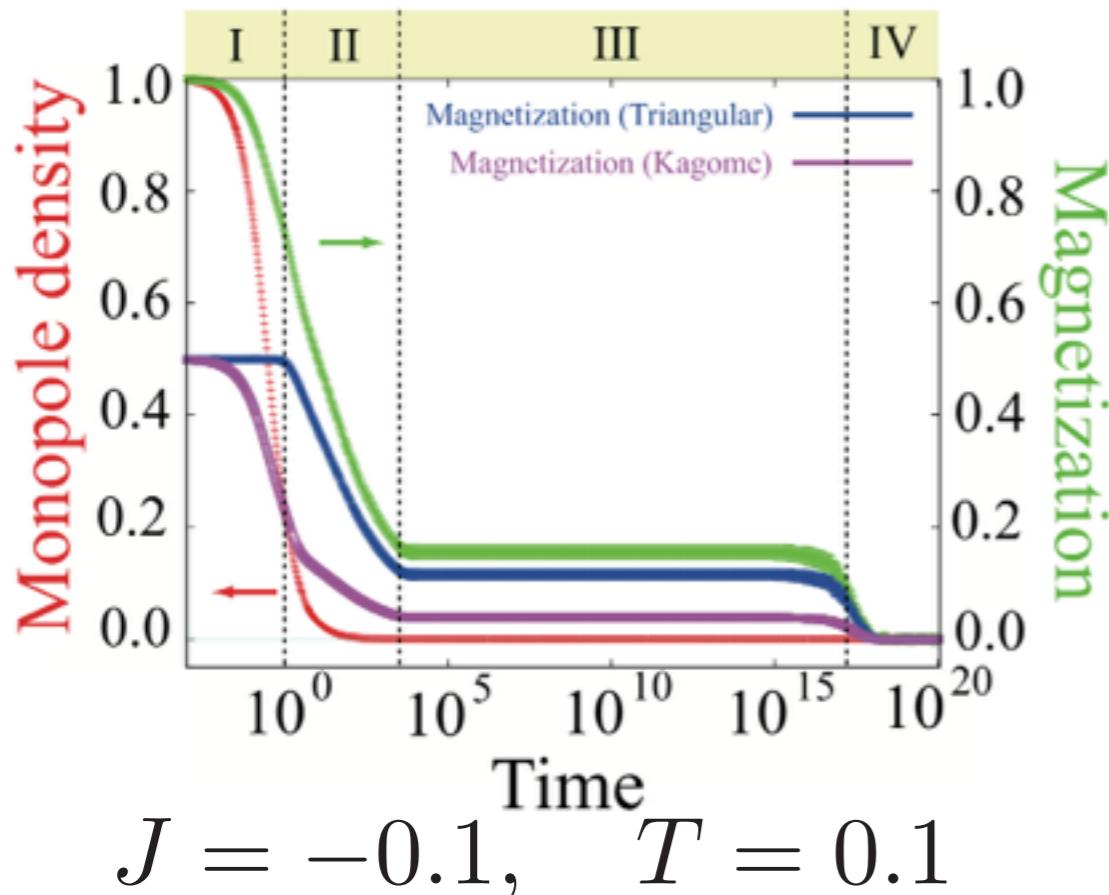
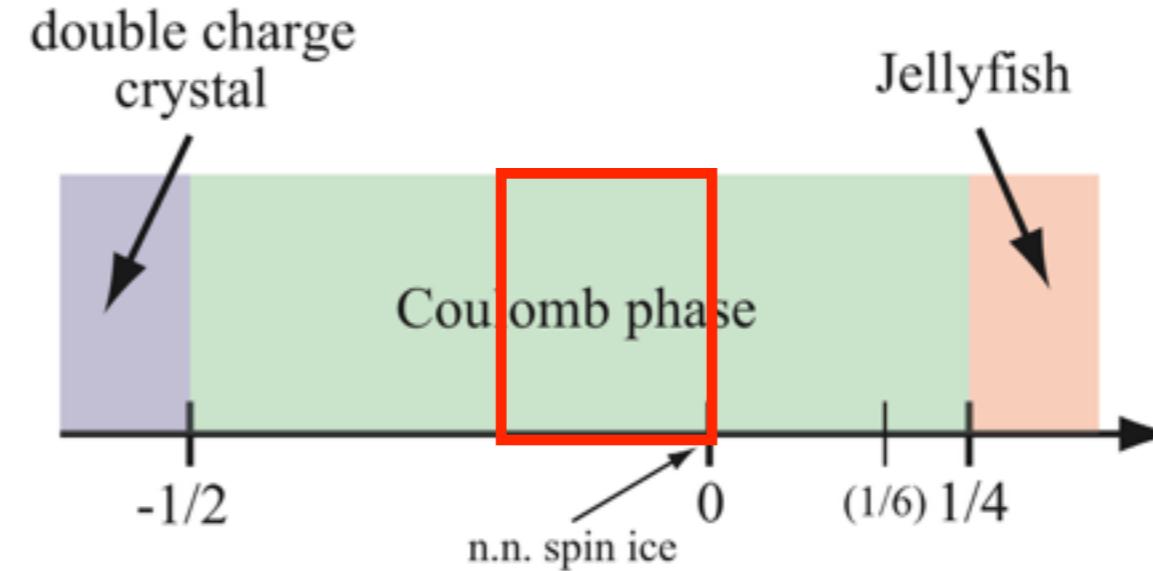
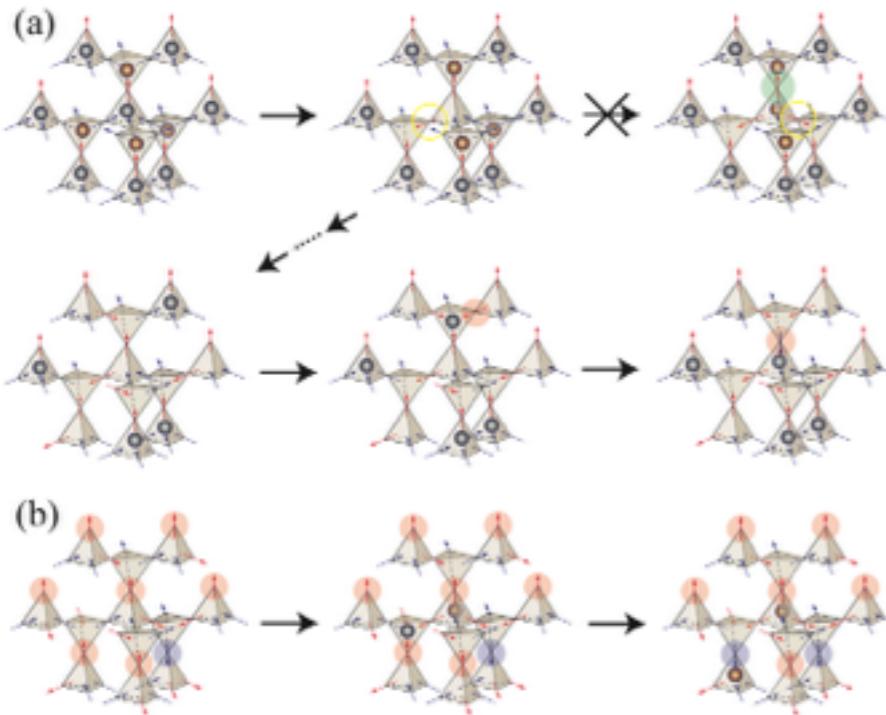
Field quench for spin ice ($J = 0$)



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

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

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



(I) kagome pair annihilation

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

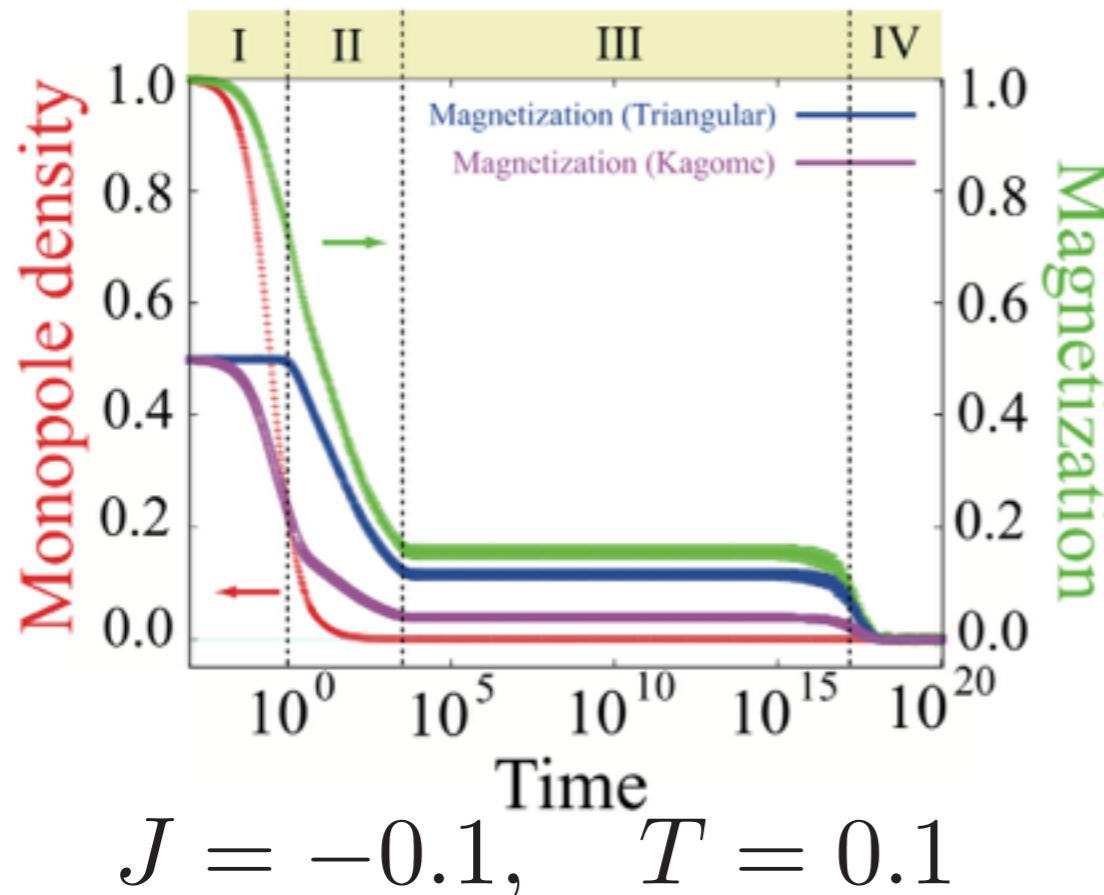
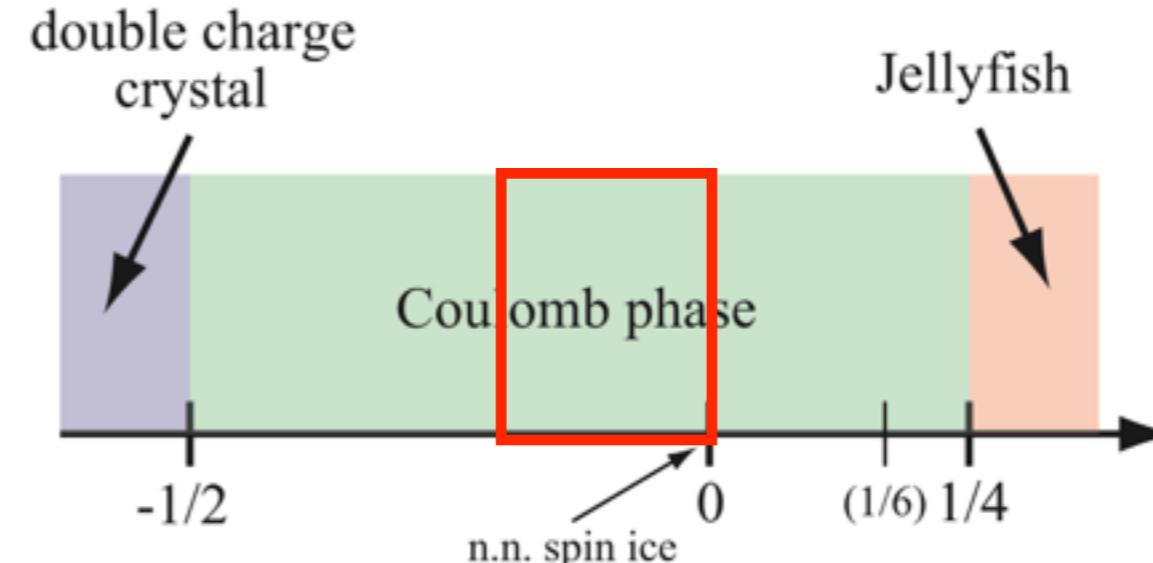
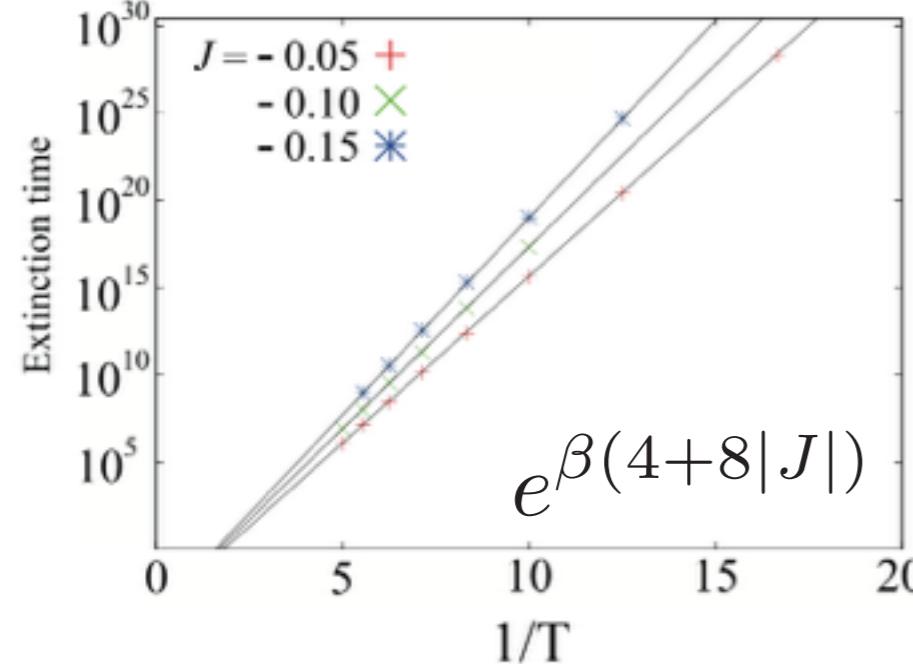
(II) diluted monopoles \Rightarrow free diffusion

(III) no monopoles left \Rightarrow spin freezing

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

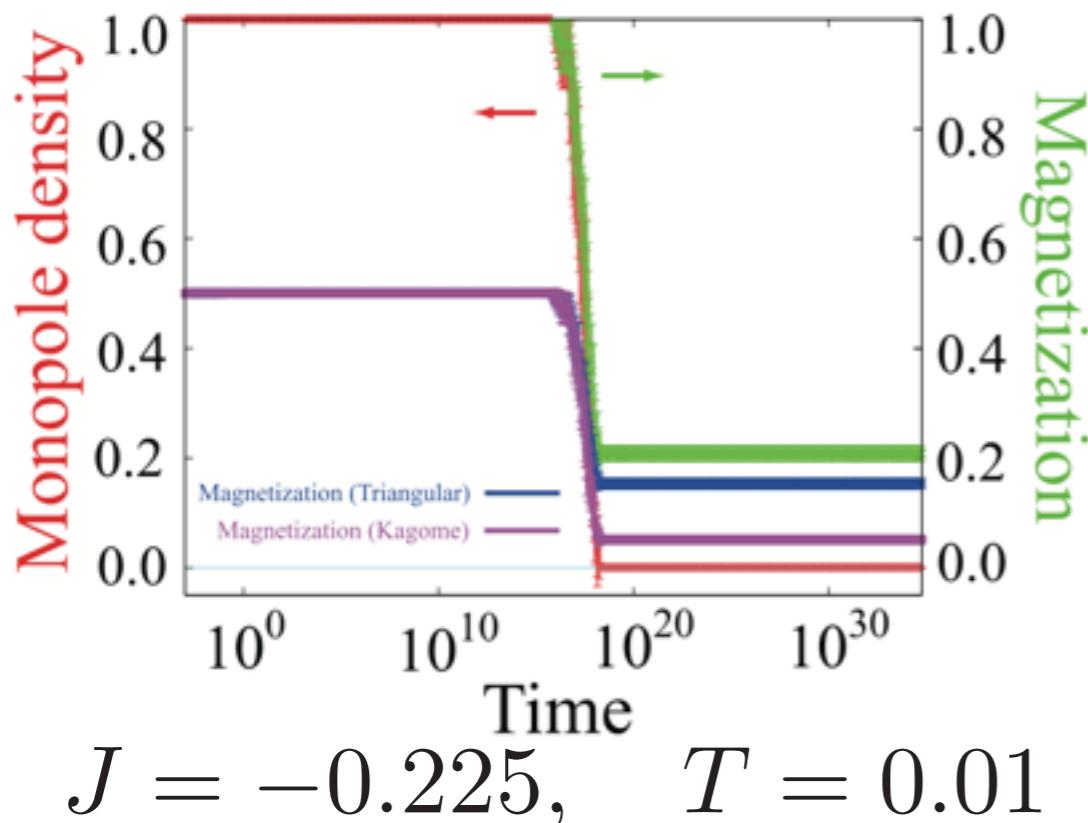
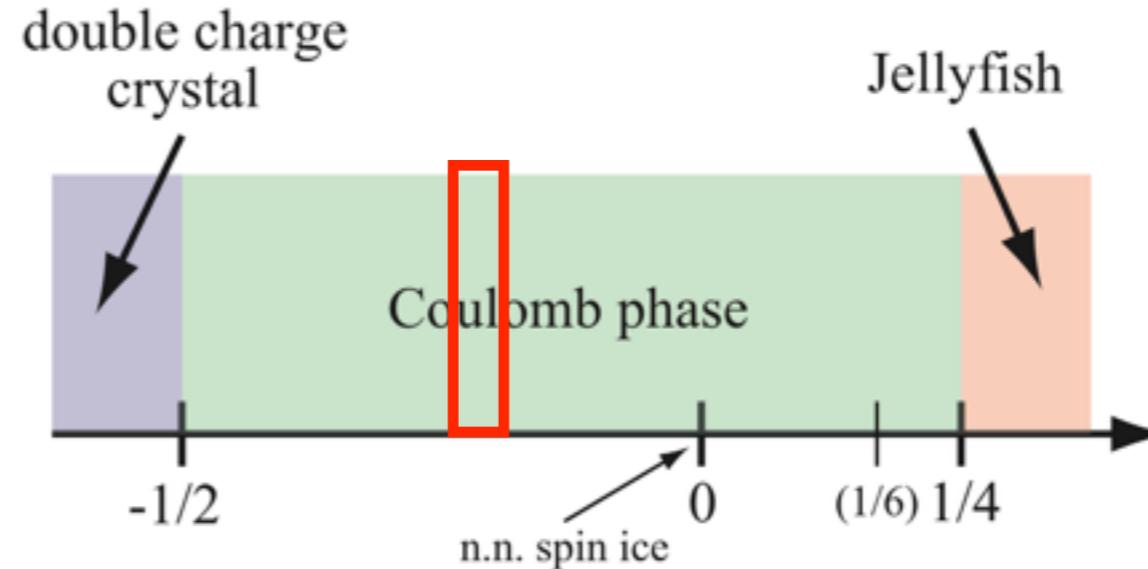
(IV) thermal creation of a pair of monopoles
 \Rightarrow end of decorrelation

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



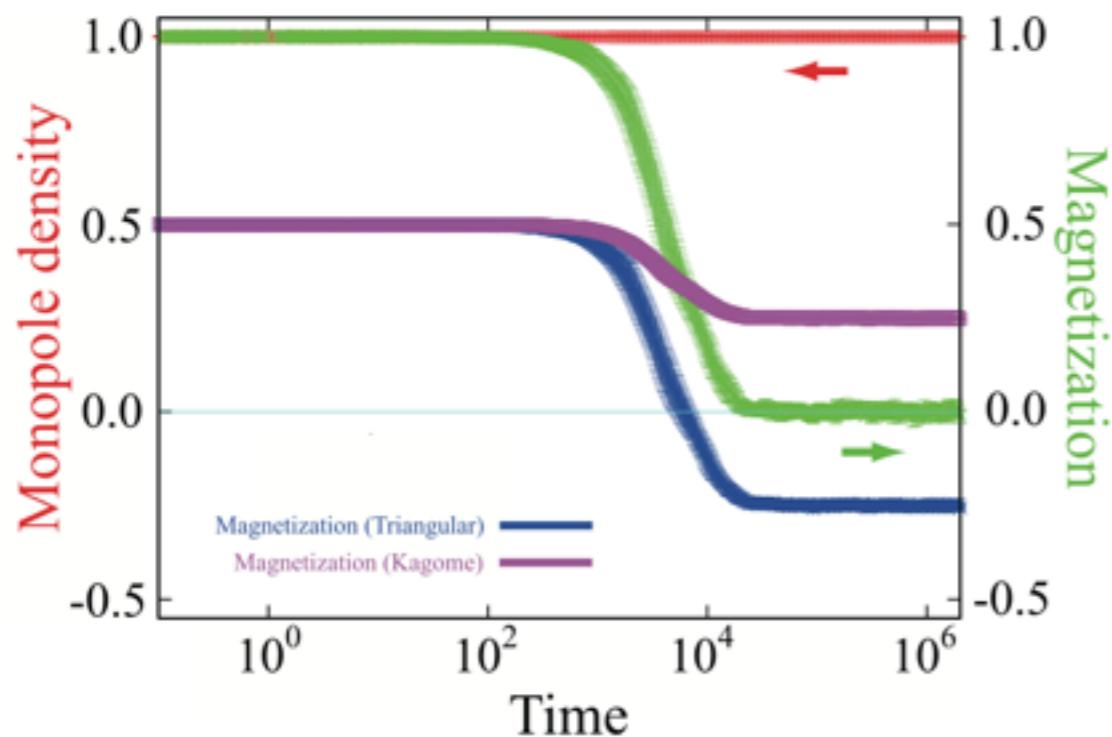
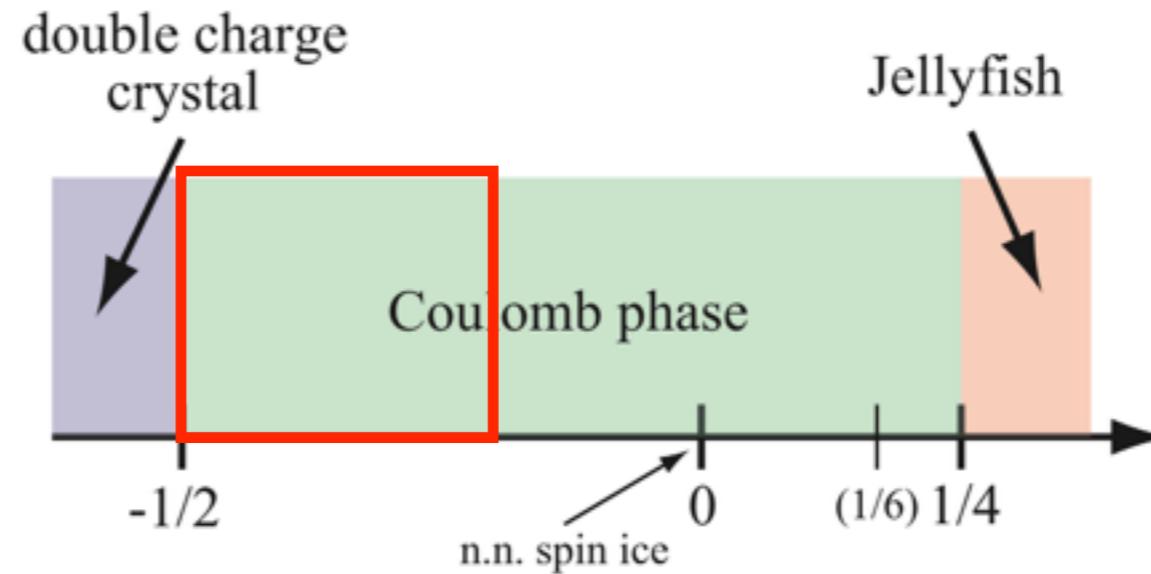
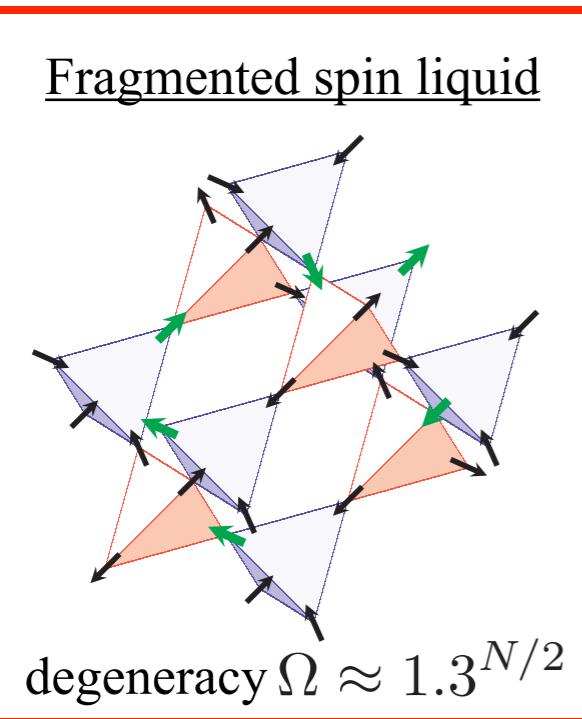
- (I) kagome pair annihilation
 $\Delta_1 = -4 + 20|J|$
- (II) diluted monopoles \Rightarrow free diffusion
- (III) no monopoles left \Rightarrow spin freezing
 $\Delta_3 = 4 + 4|J| \quad \Delta_4 = 4|J|$
- (IV) thermal creation of a pair of monopoles
 \Rightarrow end of decorrelation

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



- (I) kagome pair annihilation is now blocking
 $\Delta_1 = -4 + 20|J|$
- (II) but diffusion is still free \Rightarrow avalanche
 $\Delta_2 = -4 + 16|J|$
- (III) no monopoles left \Rightarrow spin freezing
- (IV) thermal creation of a pair of monopoles
 \Rightarrow end of decorrelation

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



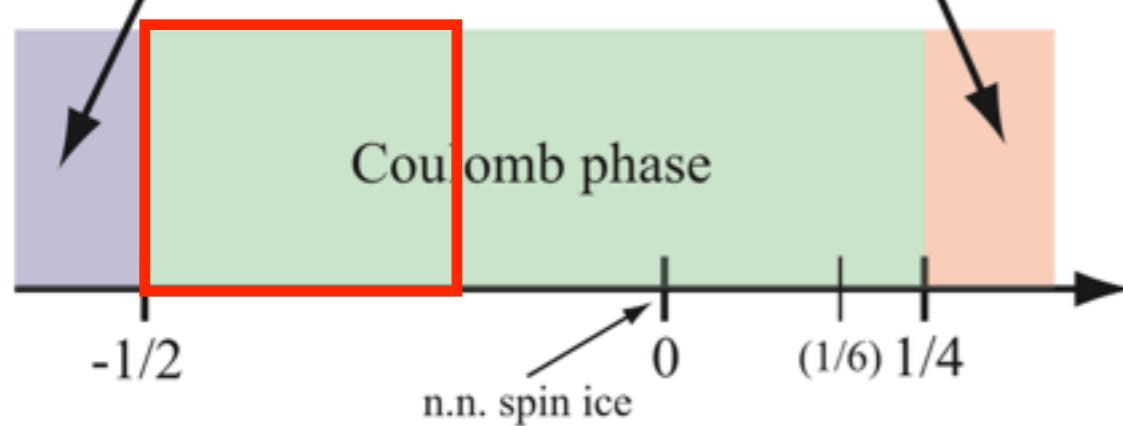
(I) kagome pair annihilation and diffusion
are now blocking

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

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

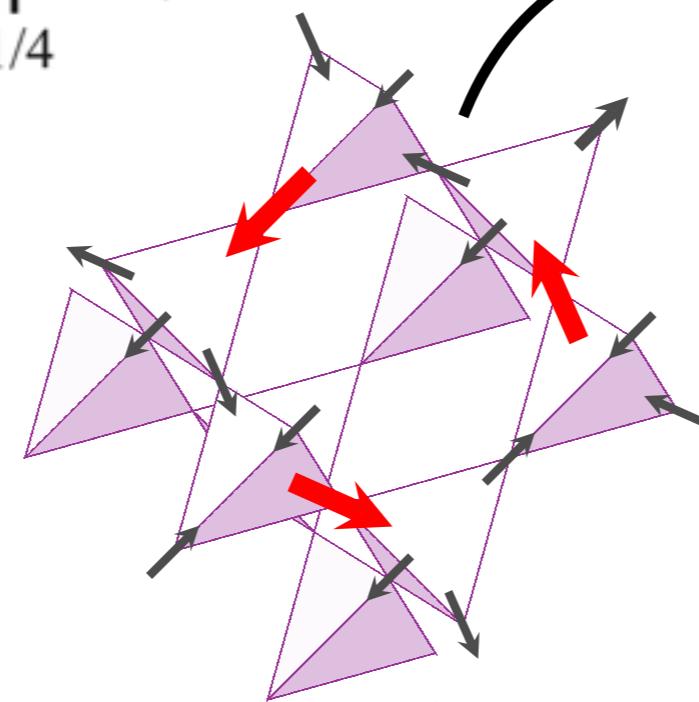
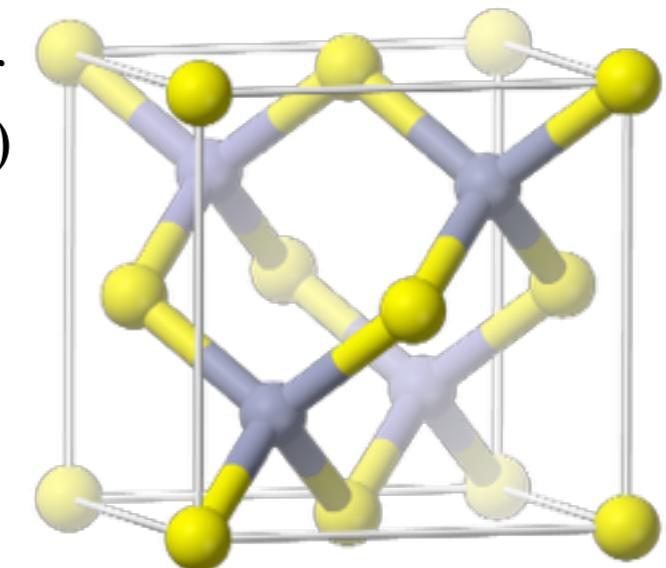
Fragmented Spin Liquid

double charge
crystal

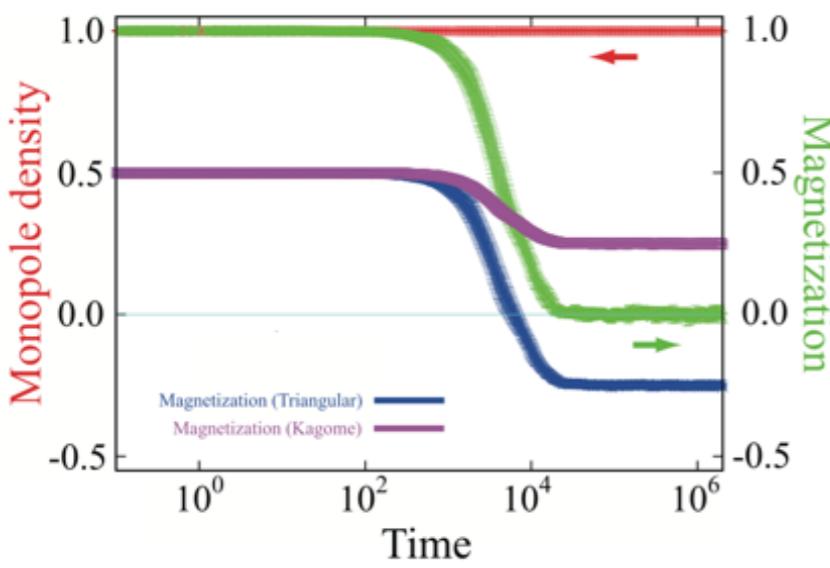


Jellyfish

charge order
(zinc blonde)



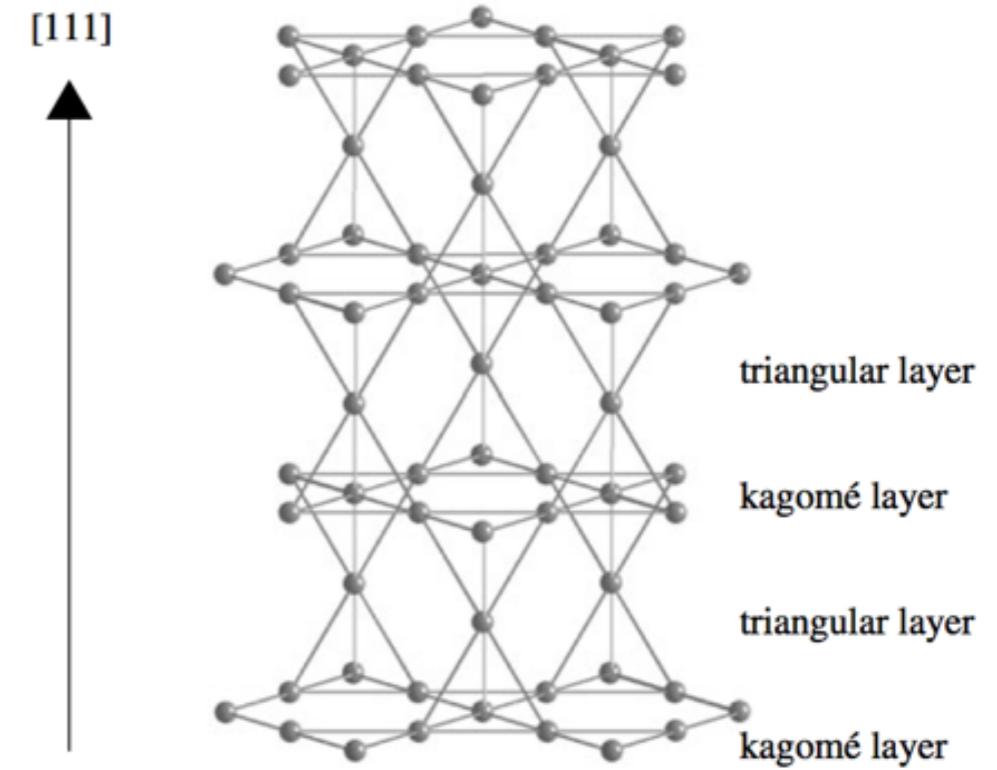
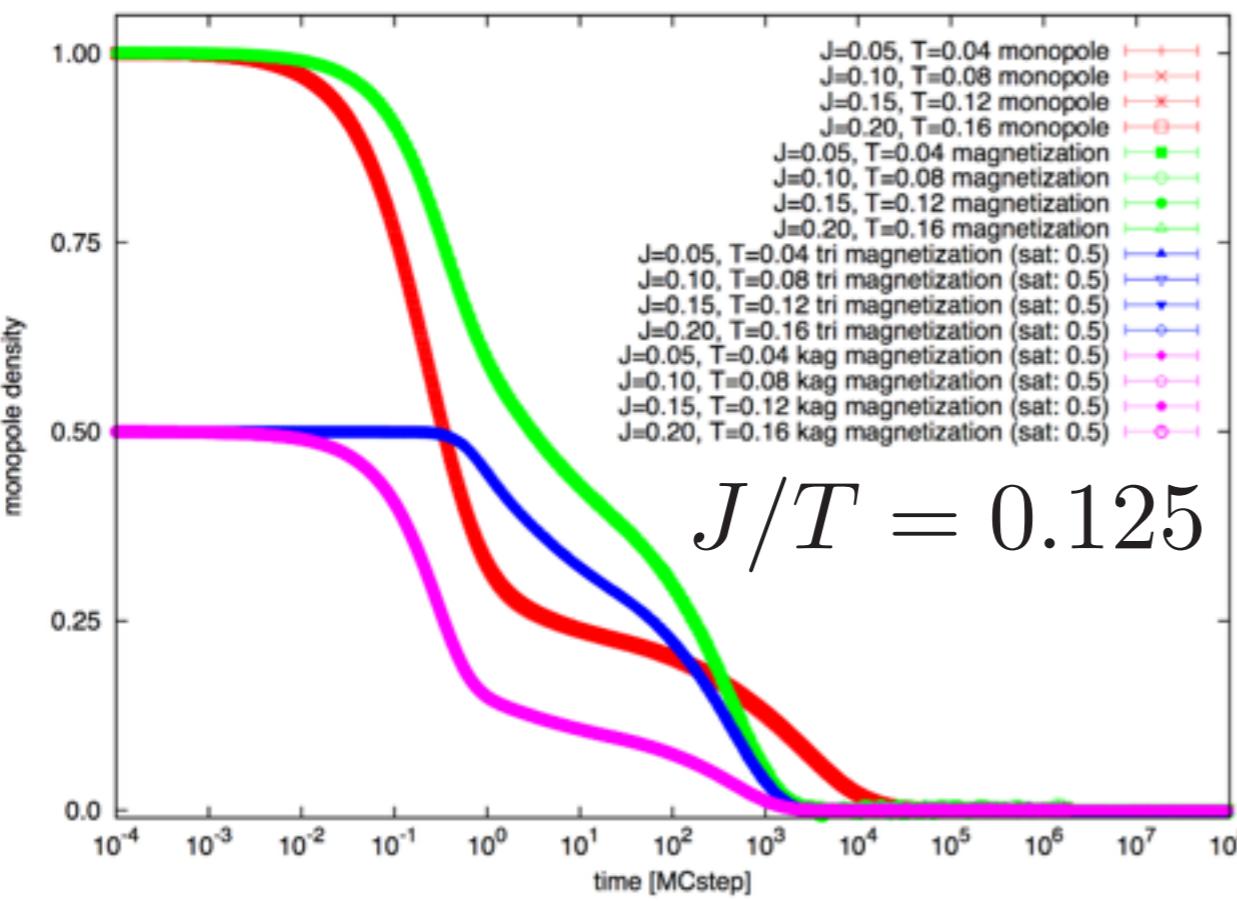
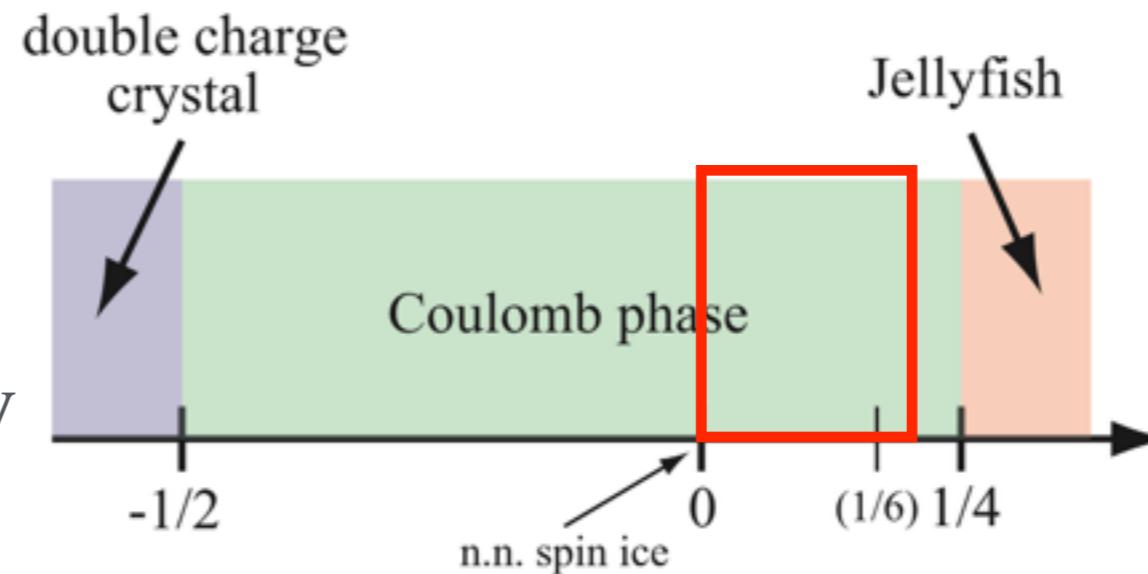
dimer model
diamond lattice



Field quench for $0 < J < 1/5$

Same charge monopoles
are repulsive

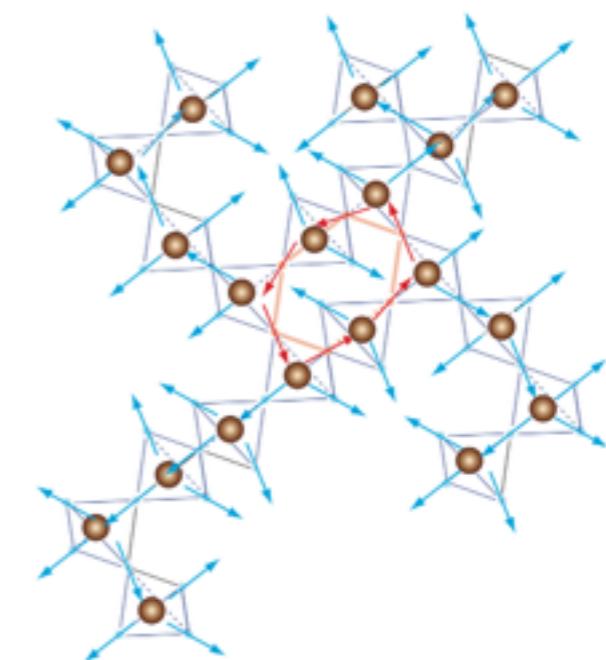
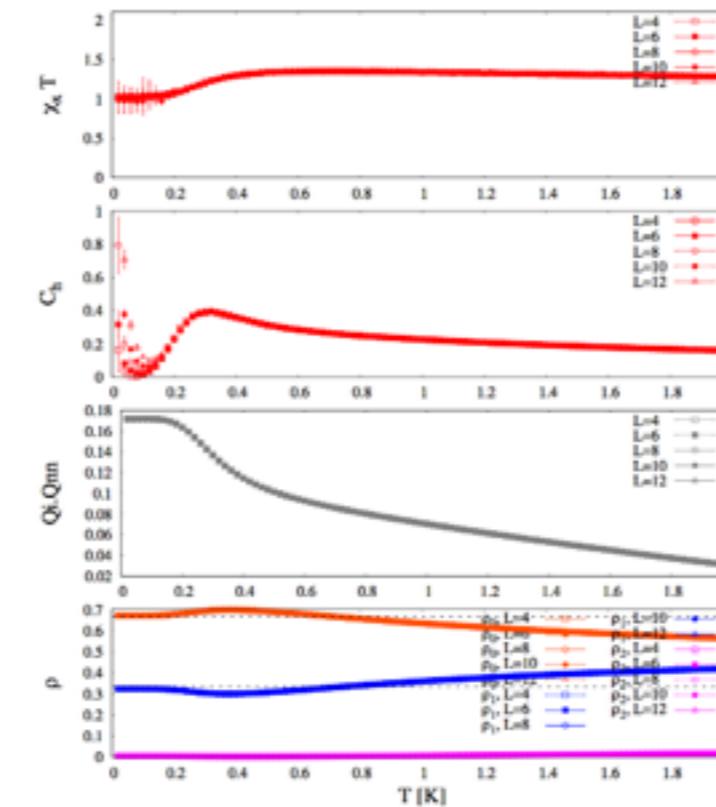
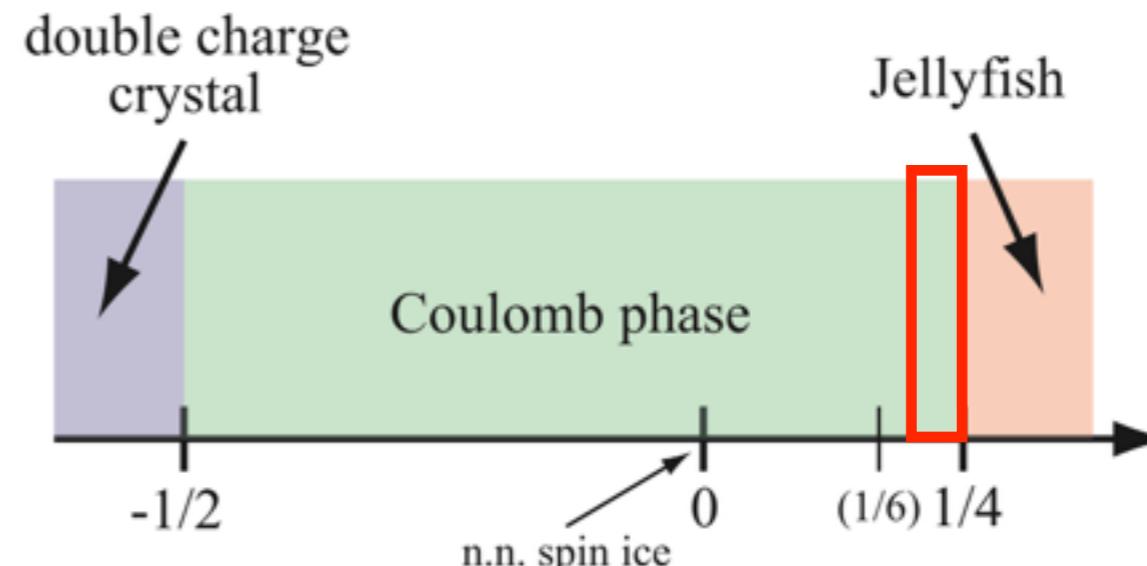
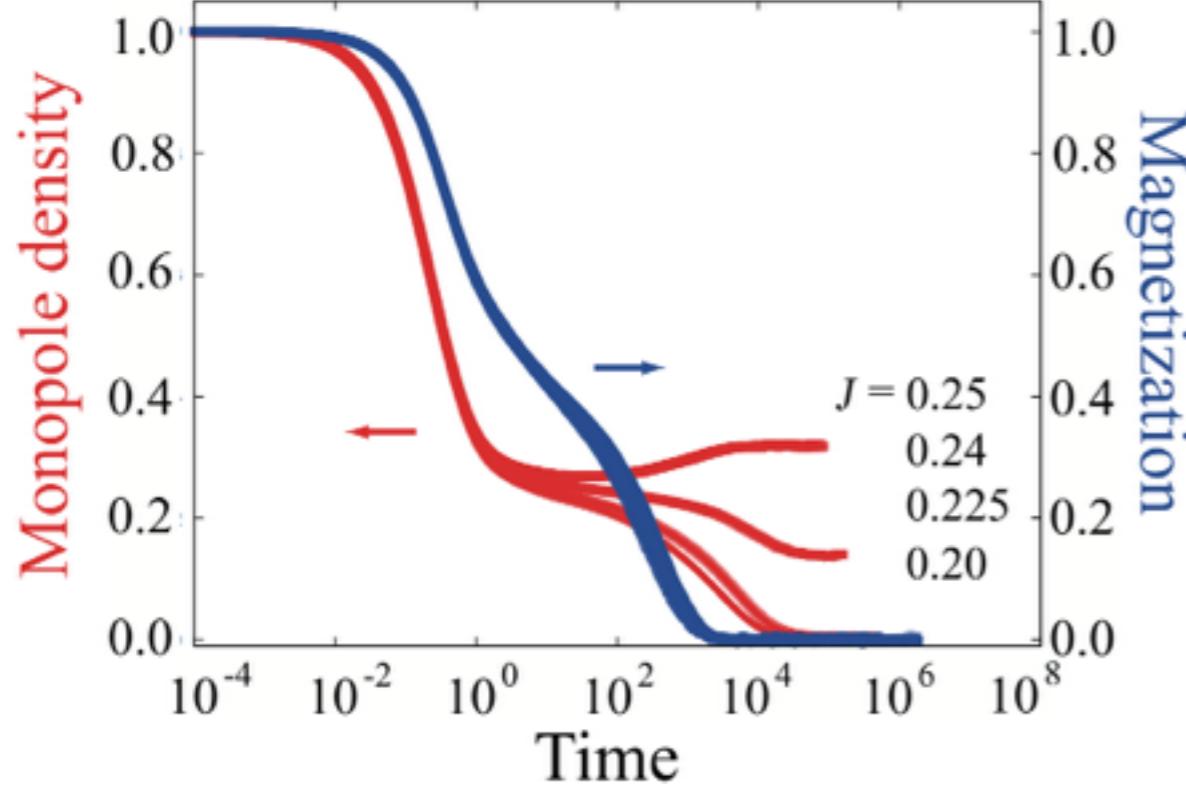
=> the initial state is strongly
out-of-equilibrium



Field quench for $J \leq 1/4$

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