General introduction to frustrated magnetism

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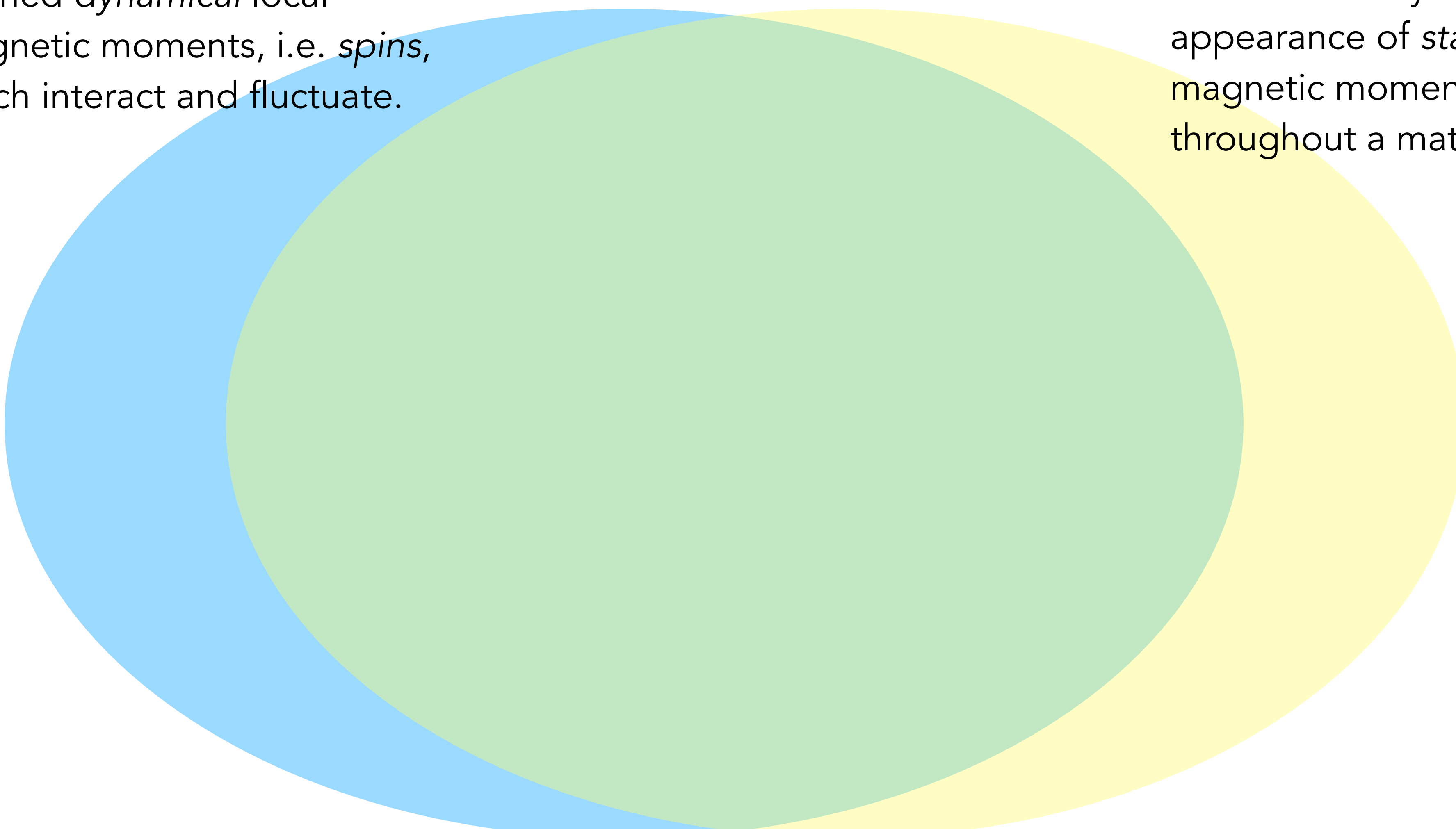
HFM Paris, June 2022

Magnetism

<u>Magnetic degrees of freedom</u>: existence of well-defined *dynamical* local magnetic moments, i.e. *spins*, which interact and fluctuate.

<u>Magnetic order:</u> spontaneous breaking of time-reversal symmetry, appearance of *static* magnetic moments throughout a material



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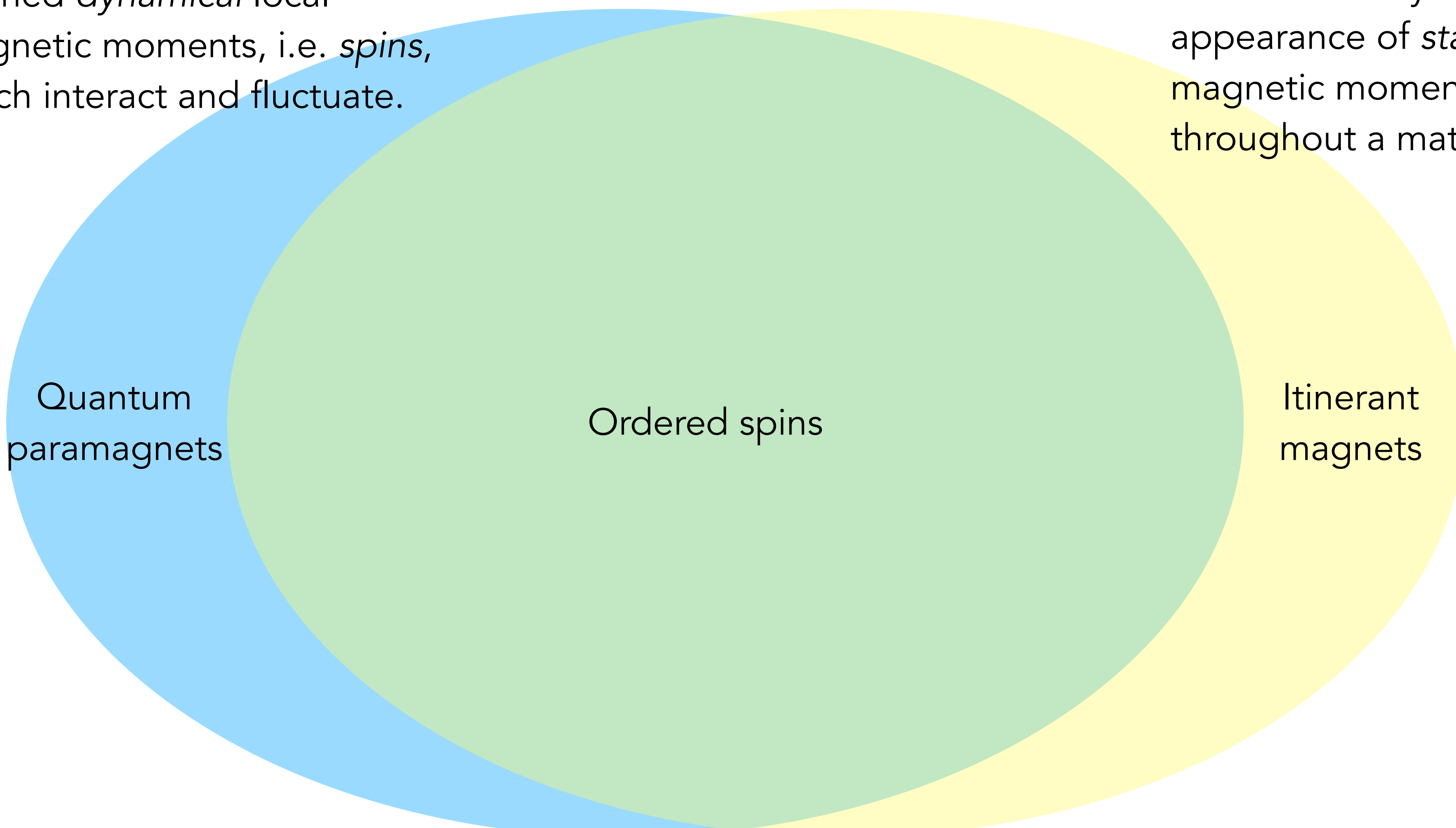

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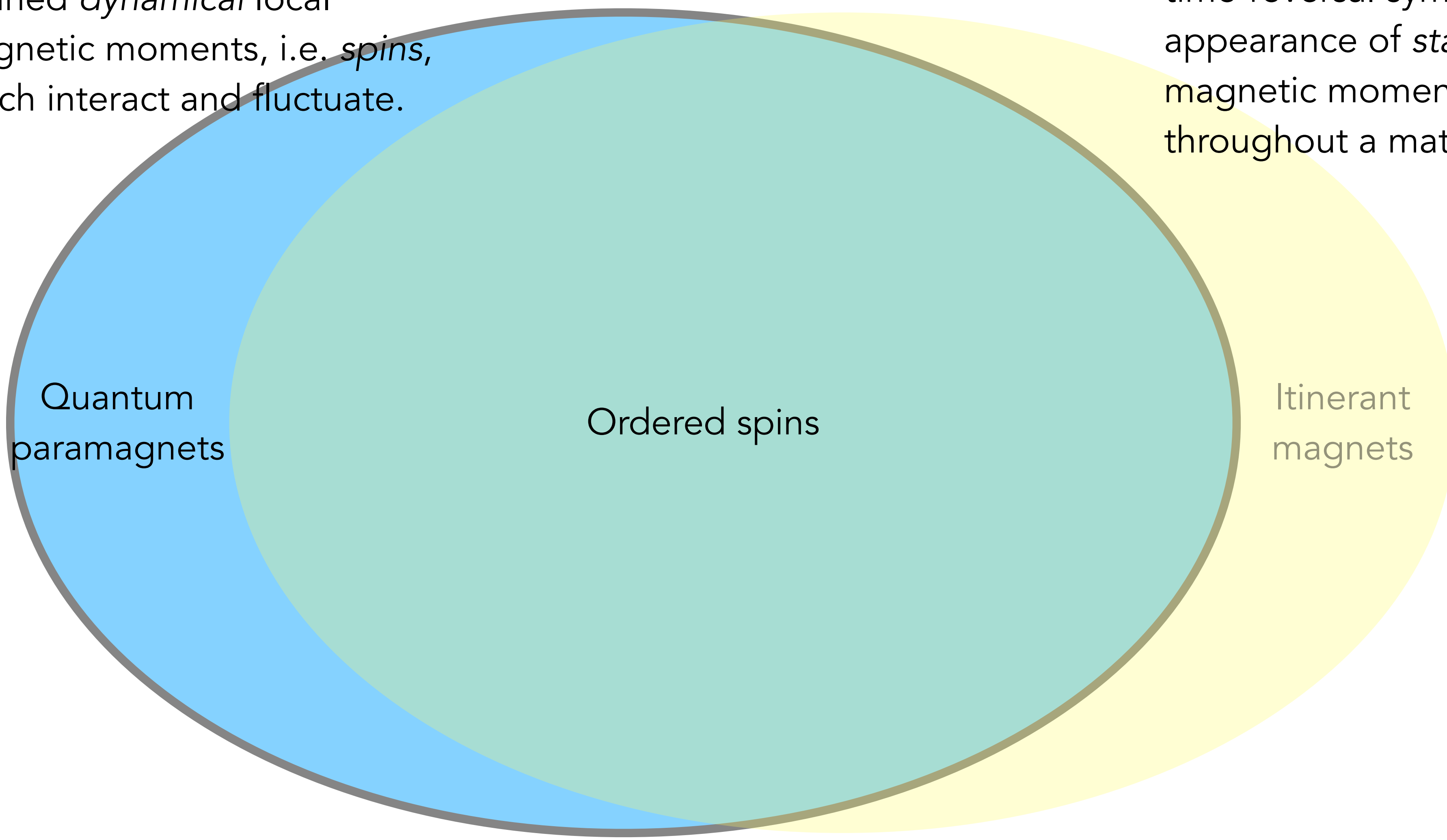


Theorist's view

$$H = \sum_{i<j} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j \quad (+ \ \ldots)$$

Ising = ±1

Vectors

Quantum operators

Coupling to the lattice

Coupling to itinerant electrons

Mulipolar, multi-spin interactions

Applied fields

…

Materials design: find good choices of J_{ij} , S_i (+…)

Design

Input

J_{ij} , S_i

(+…)

Physics →

Output

Emergent properties:

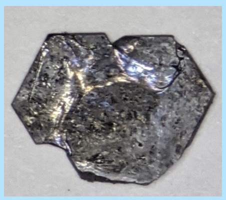
Ordering
- e.g. FM, AF, spiral, quadrupolar

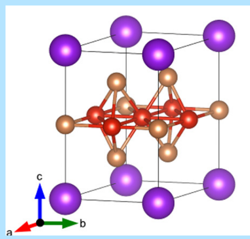
Collective excitations
- e.g. magnons, skyrmions, spinons

Response functions
- e.g. susceptibility, Hall effect

Design

Input





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J_{ij} , S_i

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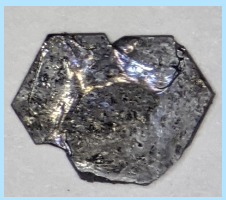


Output

nt properties:

l, AF, spiral,

polar

Collective excitations

e.g. magnons, skyrmions, spinons

Response functions

e.g. susceptibility, Hall effect

What do we really control?

- Atoms and environment
- Structure and symmetry

Physics

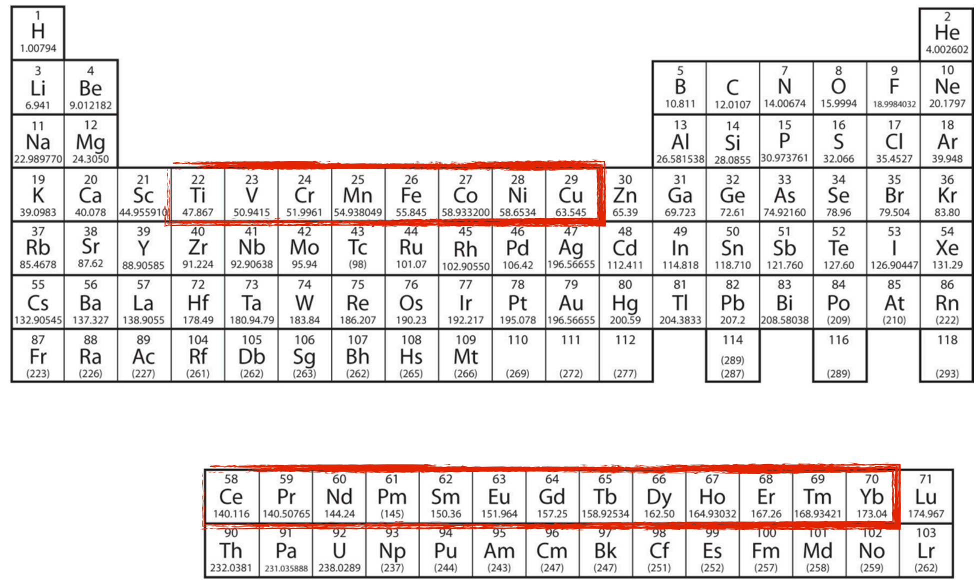
J_{ij} , S_i

(+…)

Physics

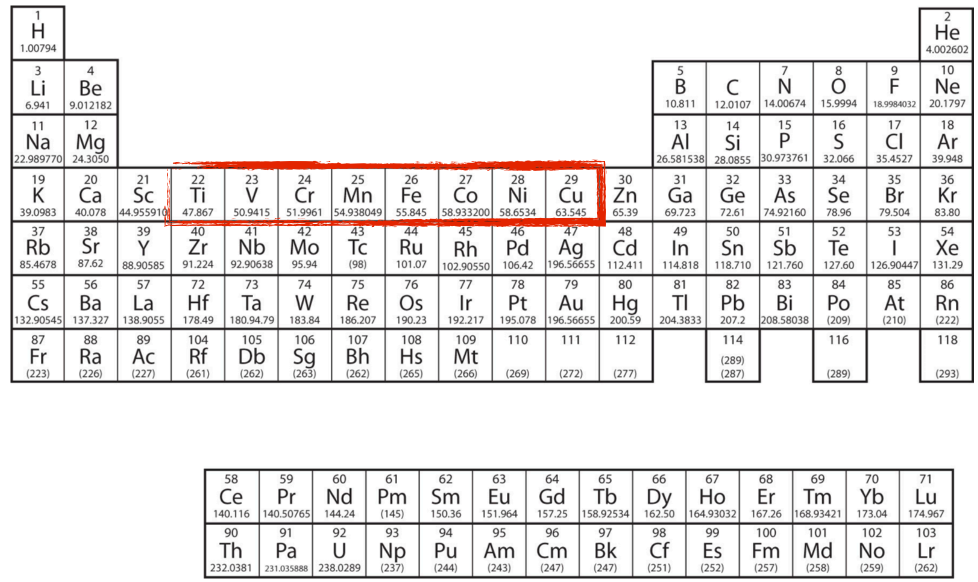
Design principle 1: get local moments

- Most magnetism in QMs comes from either 3d transition metal ions or 4f rare earths. These have relatively localized orbitals which don't overlap strongly with neighbors and have strong Coulomb repulsion, which localizes electrons best.



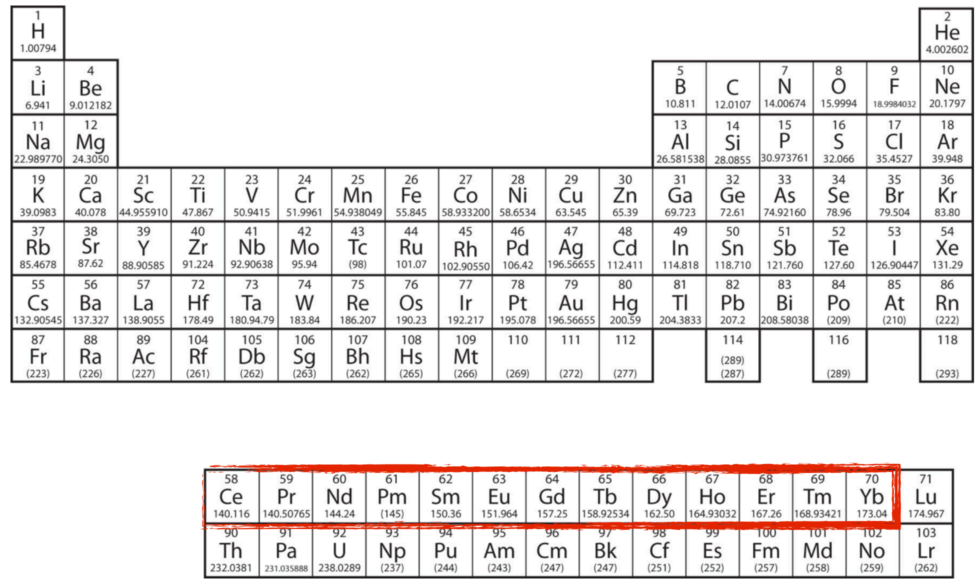
Local moments

- In 3d transition metals, *usually* magnetism is fairly isotropic, i.e. spins are "Heisenberg like", because crystal fields split the d orbitals and spin-orbit coupling is relatively weak (Co is most common exception, when very localized). Exchange interactions between spins vary from quite strong (1000K) to quite weak (1K).



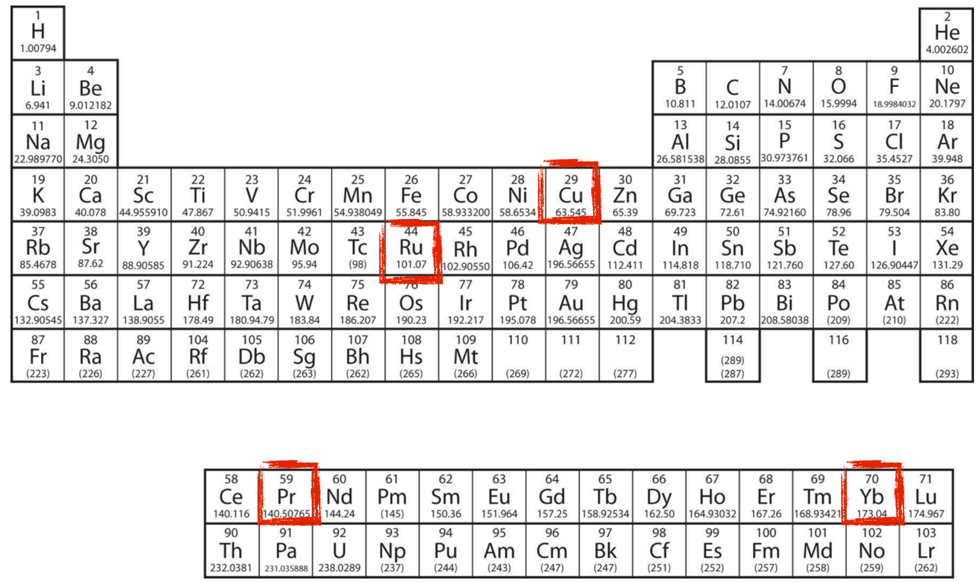
Local moments

- In 4f lanthanides, spin-orbit coupling is dominant over crystal fields and so magnetic moments become large (incorporating orbital moment) and often very anisotropic (due to large SOC). They have complex multiplet structures, and weak exchange interactions.



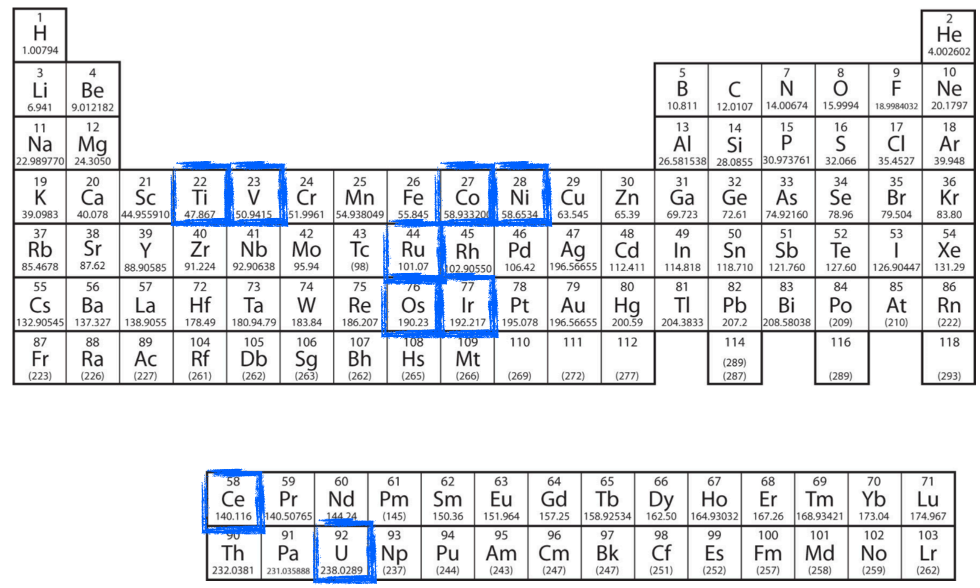
QM Materials

- Quantum spin liquids and interesting insulating antiferromagnets
  - $ZnCu_3(OH)_6Cl_2$, a-$RuCl_3$, $Pr_2Zr_2O_7$, Cs_2CuCl_4, $Yb_2Ti_2O_7$



QM Materials

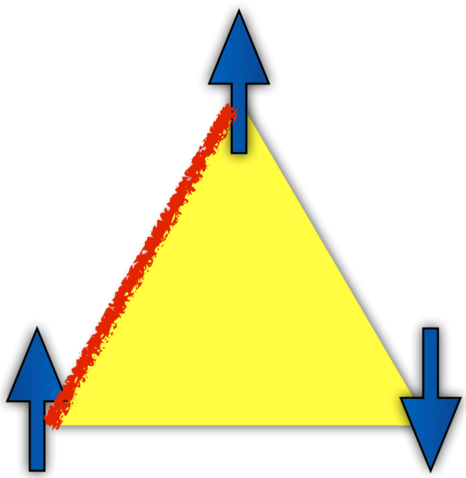
- Orbital degeneracy/spin-orbit interaction
  - RVO_3,$RCoO_3$,…
  - $Cd_2Os_2O_7$,Sr_2IrO_4, Na_2IrO_3, a-$RuCl_3$…
  - $NaYbO_2$,$TmMgGaO_4$,…



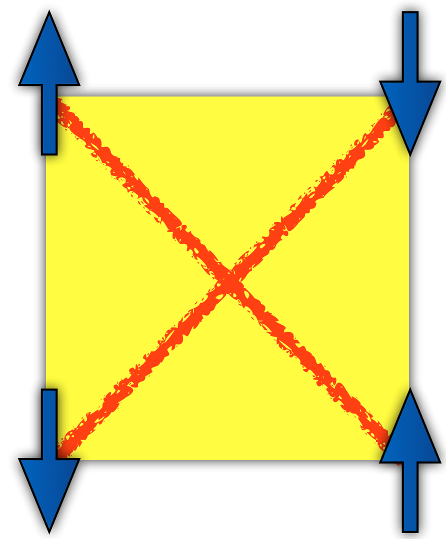
SOC increases with atomic number

Design principle 2: Frustration

- What is it? Competing multiple interactions that cannot be simultaneously satisfied



geometric frustration



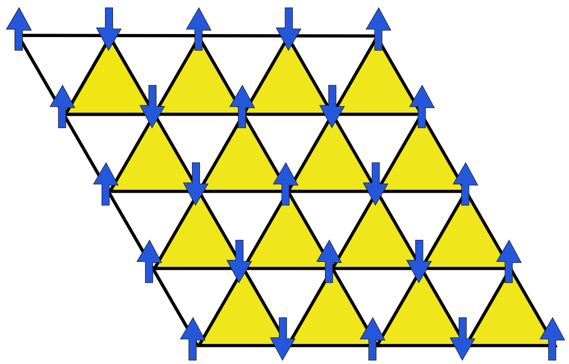
exchange frustration

Why frustration?

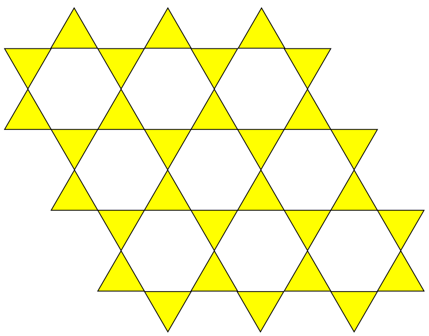
- Competition suppresses conventional ordered states: more exotic things are possible
- Fluctuating regimes
- Complex or quantum orders
- Spin liquids
- Unusual excitations

Examples

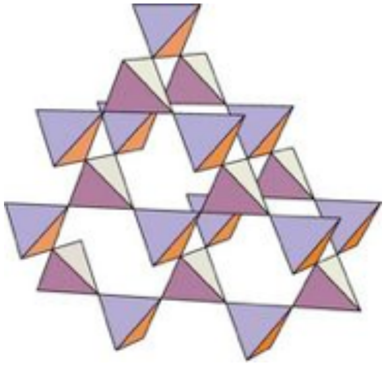
Triangle based lattices



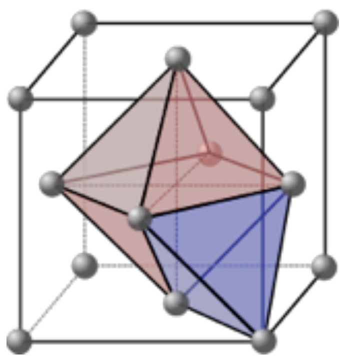
triangle



kagome



pyrochlore

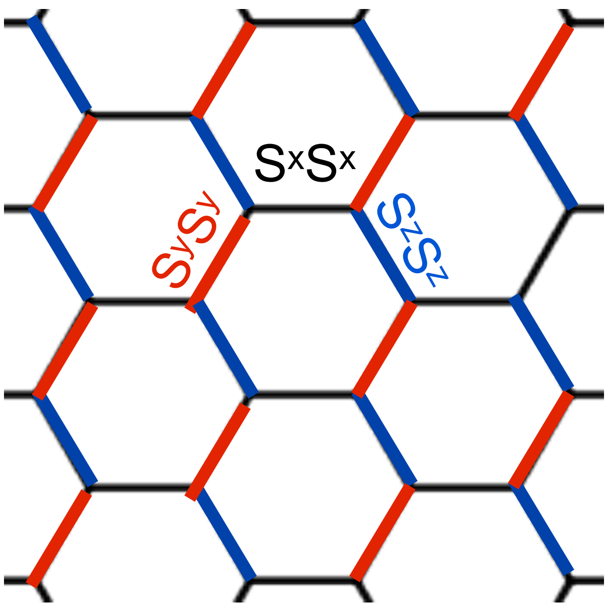


fcc

Other interactions

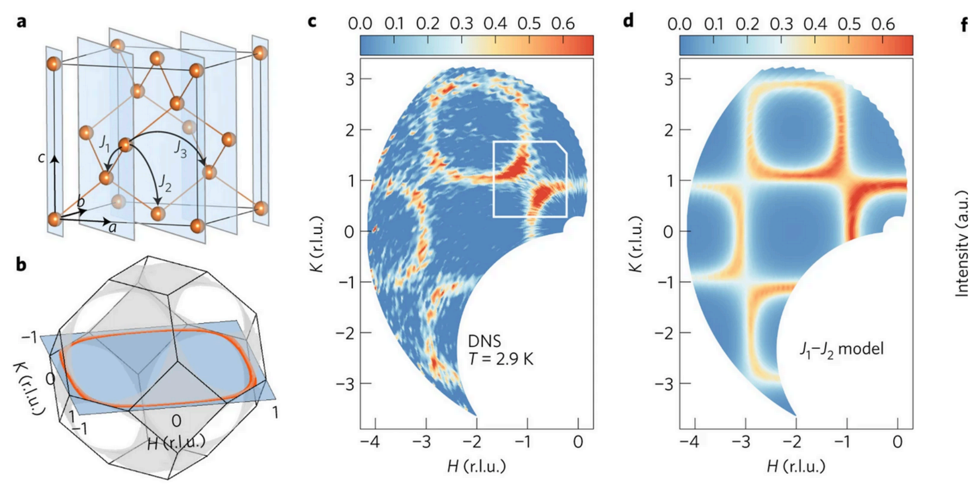
- With more structured interactions, even non-geometrically frustrated lattices can show frustration

"Kitaev" terms in Na_2IrO_3, $RuCl_3$…



Jackeli+Khalliulin, 2009

Spiral spin liquid in $MnSc_2S_4$



S. Gao *et al*, 2017

Ising systems

- Ising models $$H = \frac{1}{2}\sum_{ij} J_{ij}\sigma_i\sigma_j \qquad \sigma_i = \pm 1$$
- Physically occurs when single ion has a *doublet* ground state *and* only one component couples strongly

$$H_{\mathrm{real}} = \frac{1}{2}\sum_{ij} J_{ij} S_i^z S_j^z + H'[S_i^x, S_i^y]$$

- Requires significant spin-orbit coupling: some rare earths, Co, ...

Wannier

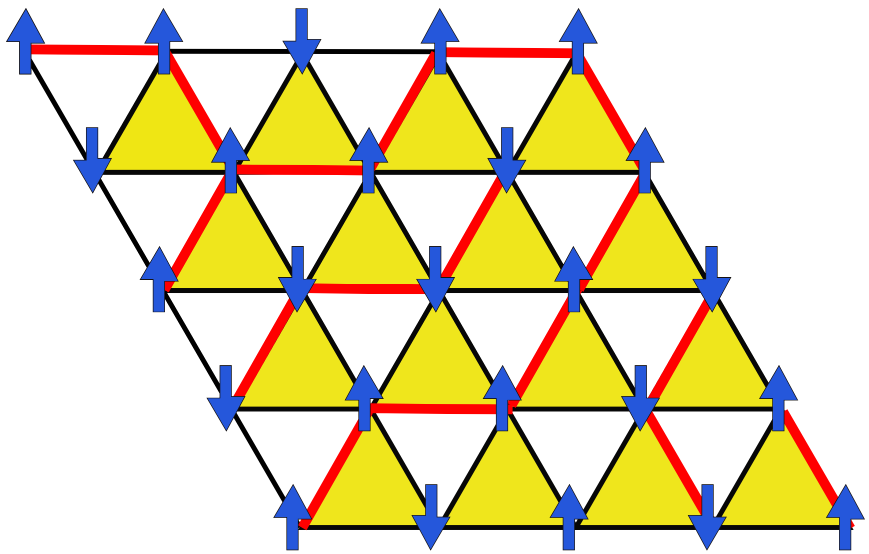
- Triangular lattice Ising AF: macroscopic degeneracy (Wannier, 1950)

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

$$\sigma_i = \pm 1$$

$$\Omega = e^{S/k_B}$$

$$S \approx 0.34 N k_B$$



1 frustrated bond per triangle

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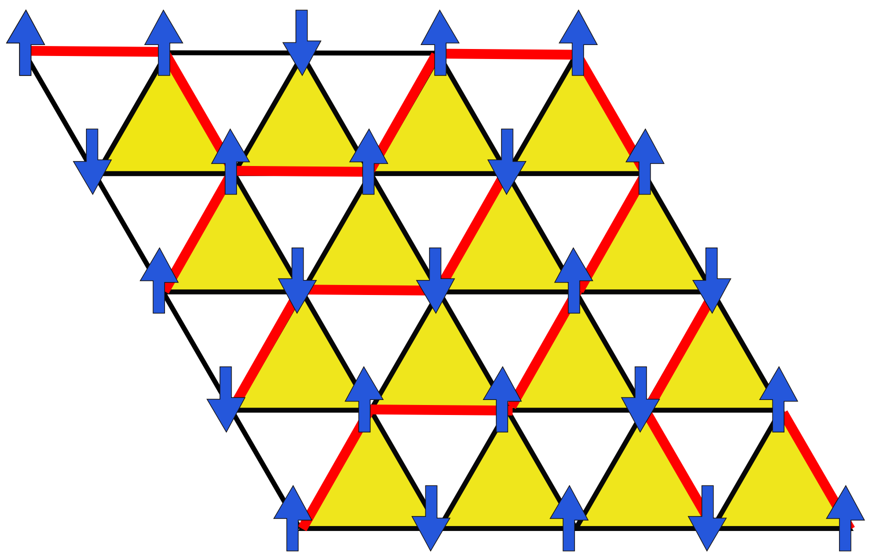
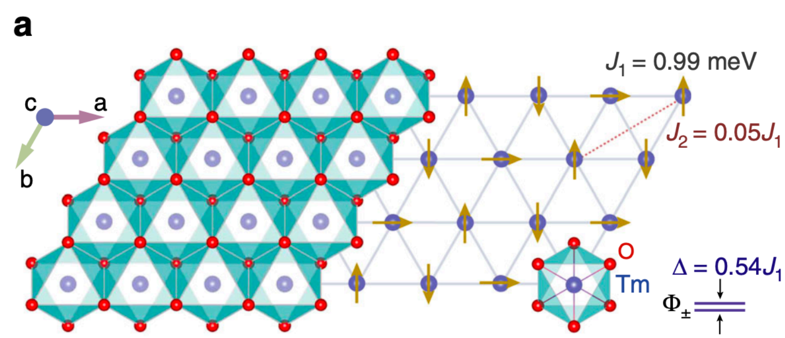


1 frustrated bond per triangle

Somewhat close realization?

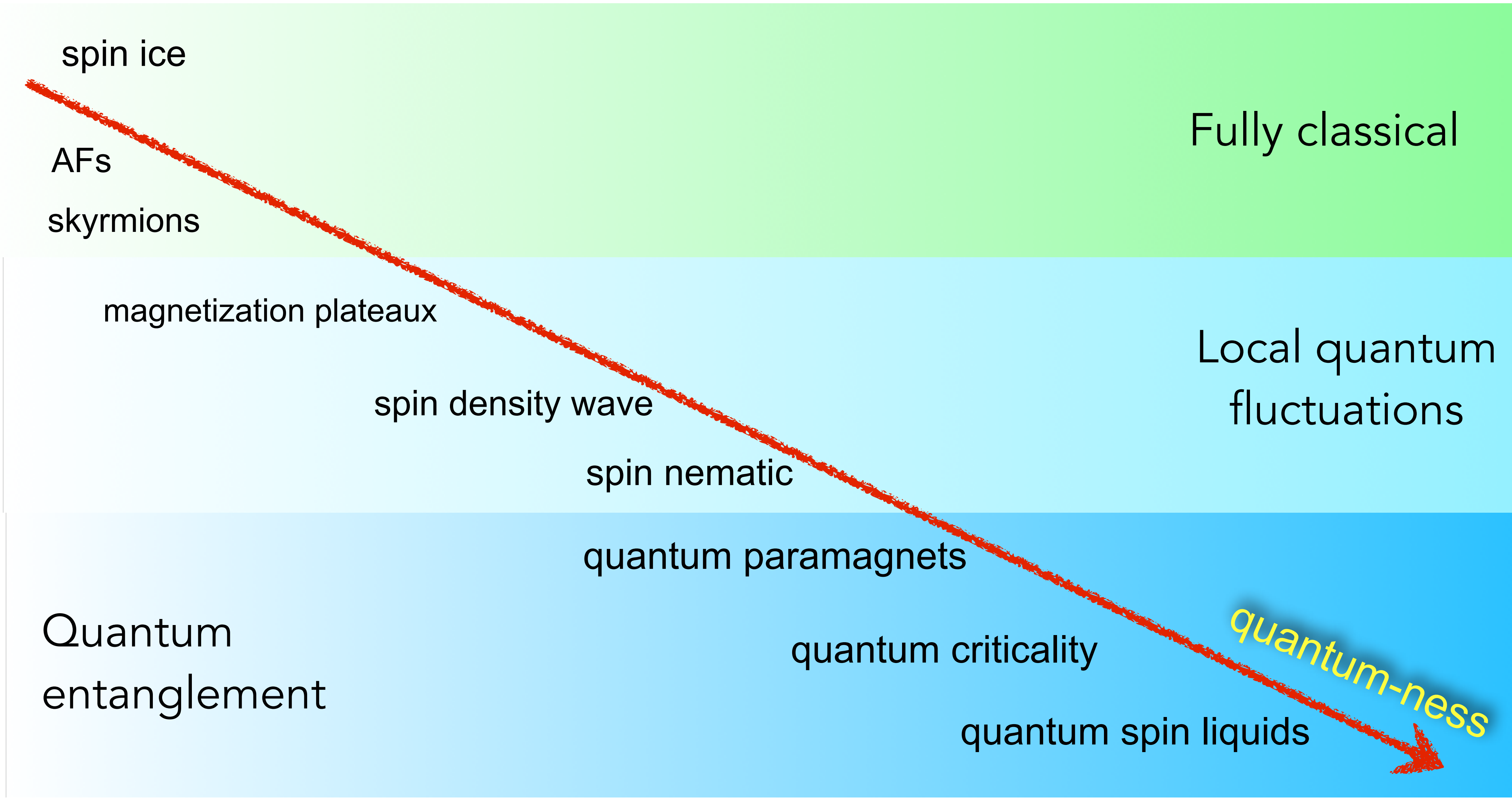
$TmMgGeO_4$

Degeneracy-breaking perturbations determine the low energy physics



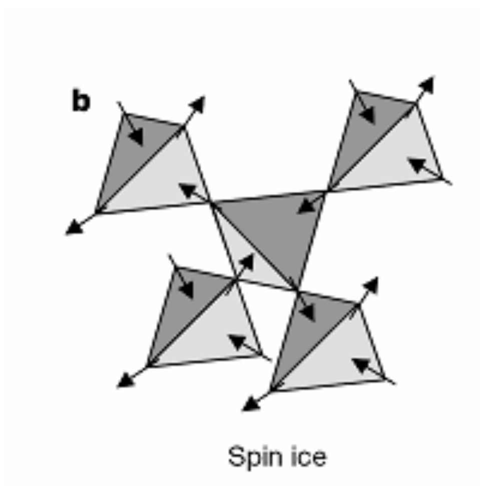
H. Li *et al*, 2020

Frustrated Magnetism



Spin ice

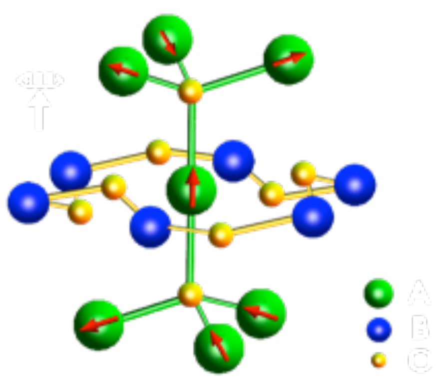
- Spins in $Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$ have Ising doublets with dominant NN coupling J_{zz} enforcing classical 2in-2out "ice rules" for T < 1K



$$H \approx J_{zz} \sum_{\langle ij \rangle} S_i^z S_j^z$$

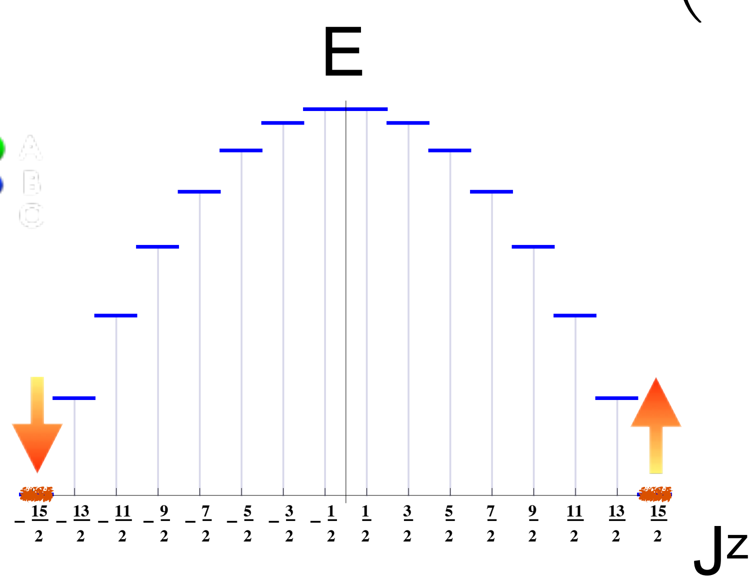
Spin ice

- rare earth pyrochlores $Dy_2Ti_2O_7$, $Ho_2Ti_2O_7$ with *Ising doublet* ground states



Local physics: L+S = J

$$H_{\text{ion}} = -D\left(\vec{J}_i \cdot \hat{n}_i\right)^2$$



flips between +-J states difficult

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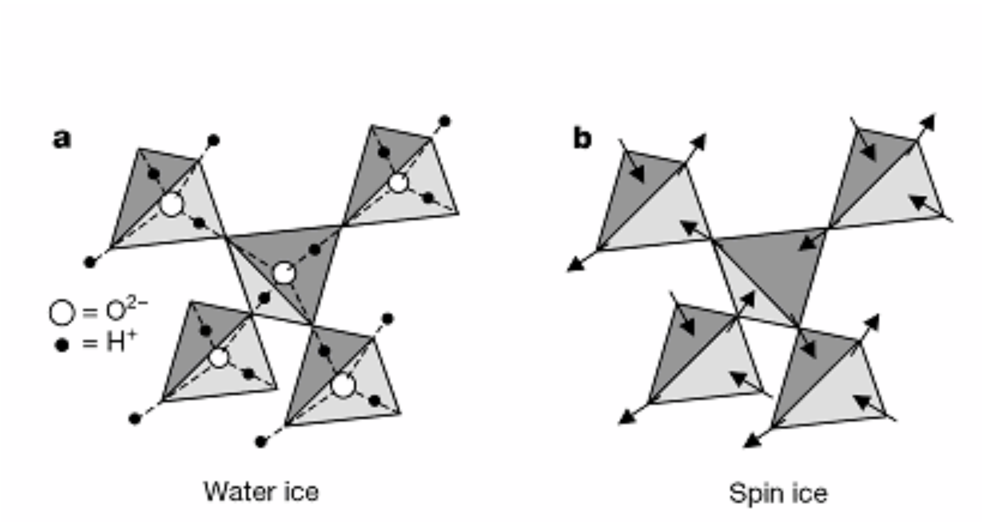

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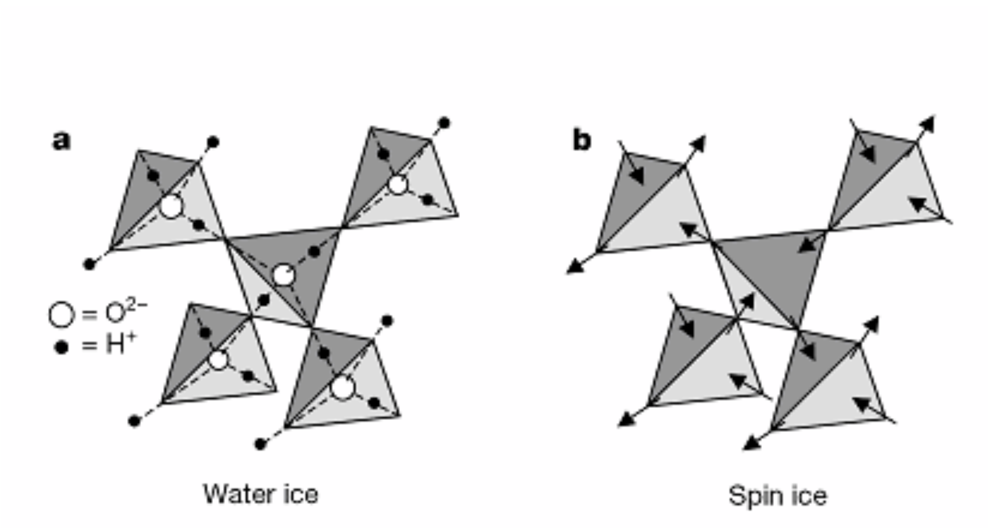
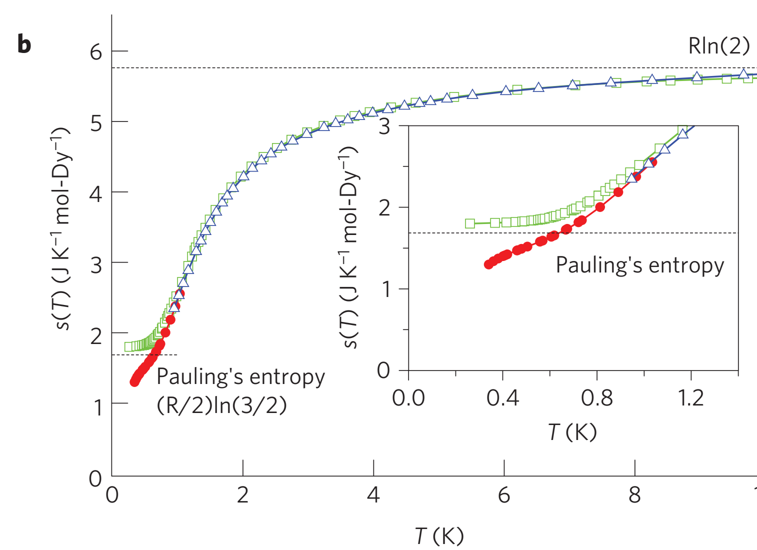
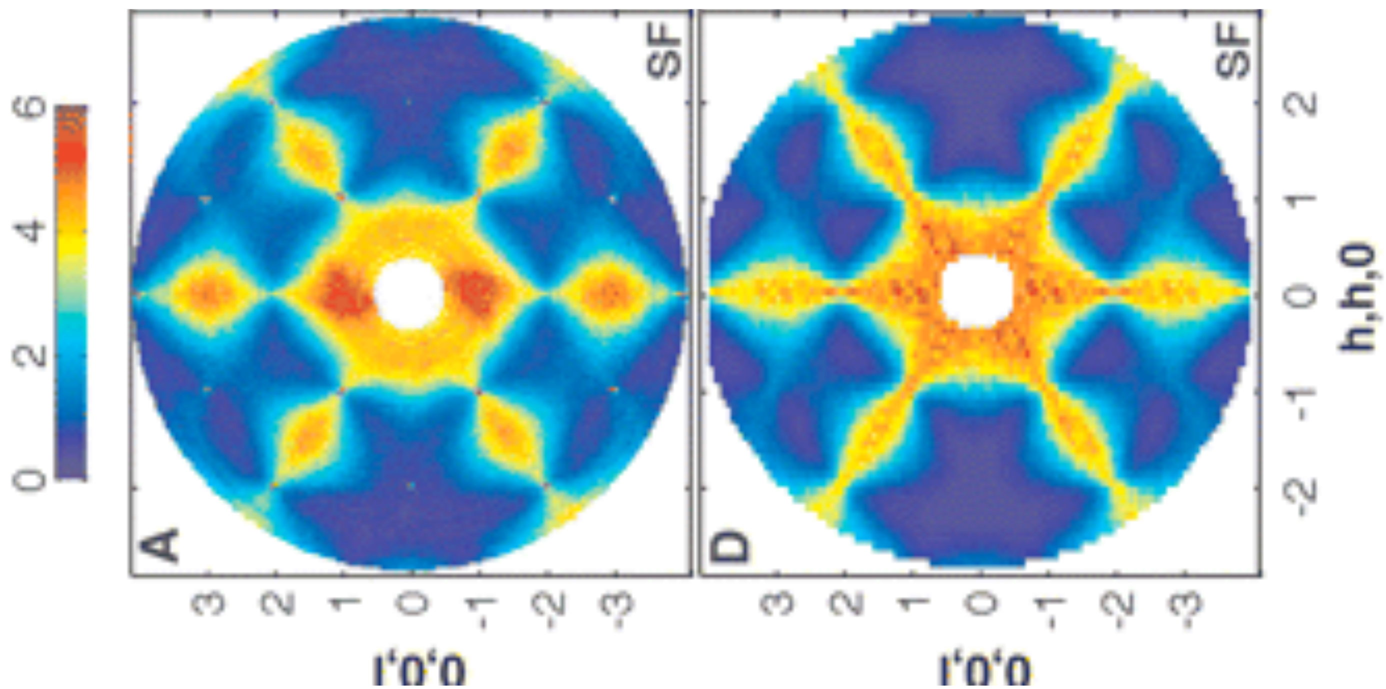




Pomaranski *et al*, $Dy_2Ti_2O_7$
(original expts. by Harris *et al*, 1999)

Ice correlations

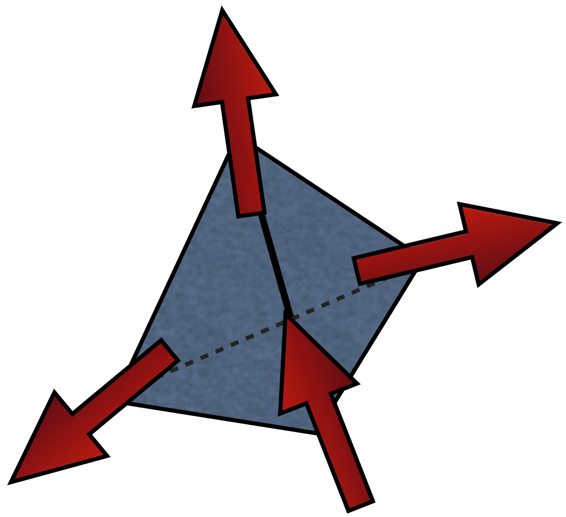
- "Pinch points" show that 2in-2out constraint holds



T. Fennell *et al*, 2009 experiment theory

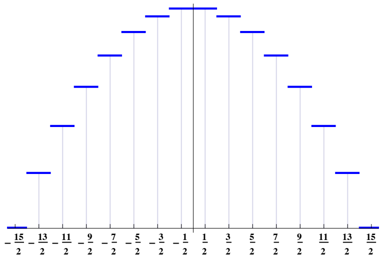
$Ho_2Ti_2O_7$

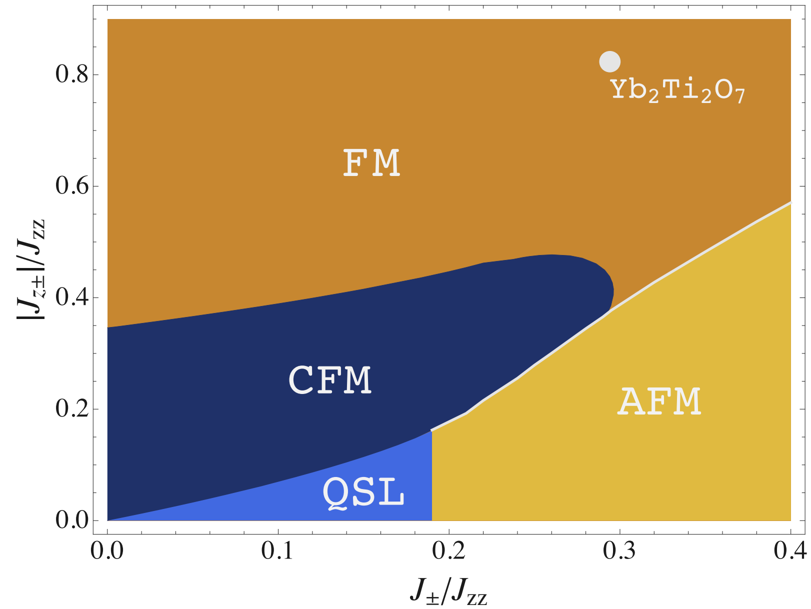
Monopoles



3in:1out defects act like monopoles,
and can move almost freely

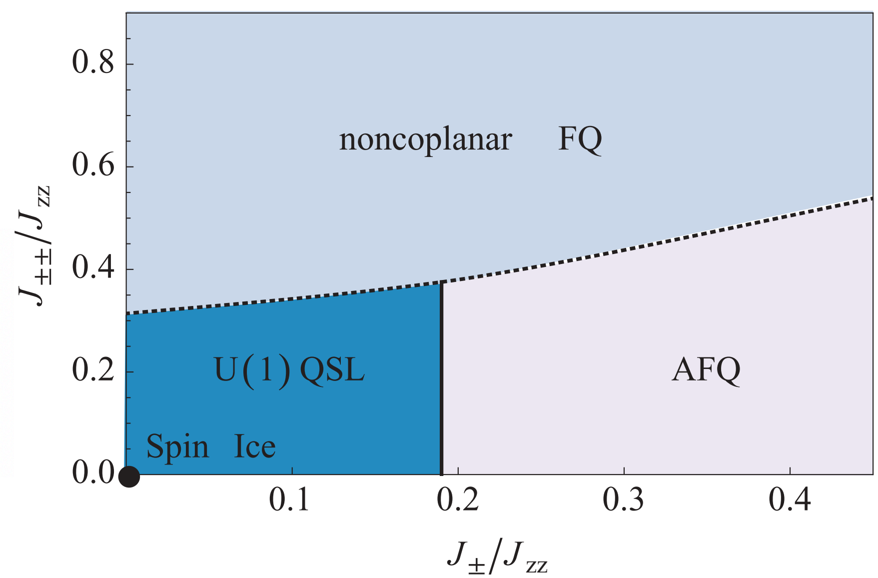
Quantum spin ice





M. Hermele, MPA Fisher, L.B., 2004;
A. Banerjee *et al*, 2008
L. Savary + LB, 2012
S.B. Lee, S. Onoda + LB, 2012
+ Many subsequent numerical and analytical works

Still looking…



- **Invited - E. Smith** (McMaster University, Canada)
"The case for a $U(1)_\pi$ Quantum Spin Liquid Ground State in the Dipole-Octupole Pyrochlore $Ce_2Zr_2O_7$"

- Y.B. Kim (University of Toronto, Canada)
"Competing dipolar-octupolar quantum spin liquids on the pyrochlore lattice"

- R. Sibille (Paul Sherrer Institut, Switzerland)
"Octupolar correlations and spinon spectrum in $Ce_2Sn_2O_7$ quantum spin ice"

- **Invited - R. Moessner** (Max Planck Institute for the Physics of Complex Systems, Germany)
"Emergent QED in the quantum spin ices"

Heisenberg systems

- Typically for *closed shells* - i.e. configurations w/o orbital degeneracy - of 3d transition metal ions, SOC effects are weak: good approximate spin-rotation symmetry

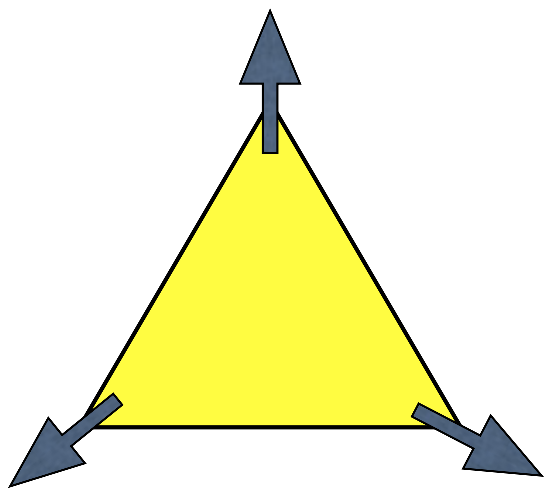
$$H = \frac{1}{2}\sum_{ij} J_{ij}\vec{S}_i \cdot \vec{S}_j + \cdots$$

single-ion and exchange anisotropy, $\lesssim$ 10% level

Spin “length” S =1/2 is most quantum, S>>1 is semiclassical

Triangle

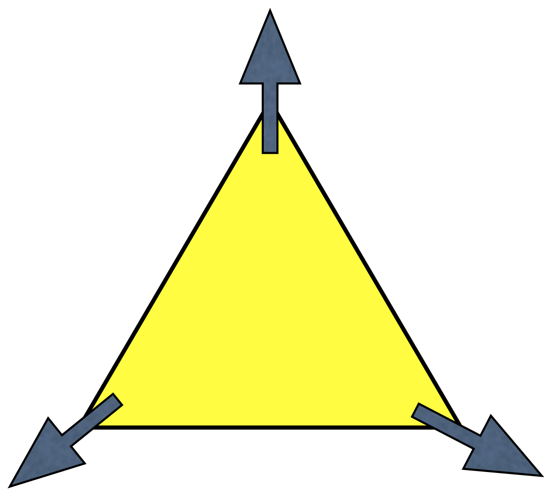
- Classically: spins must sum to zero



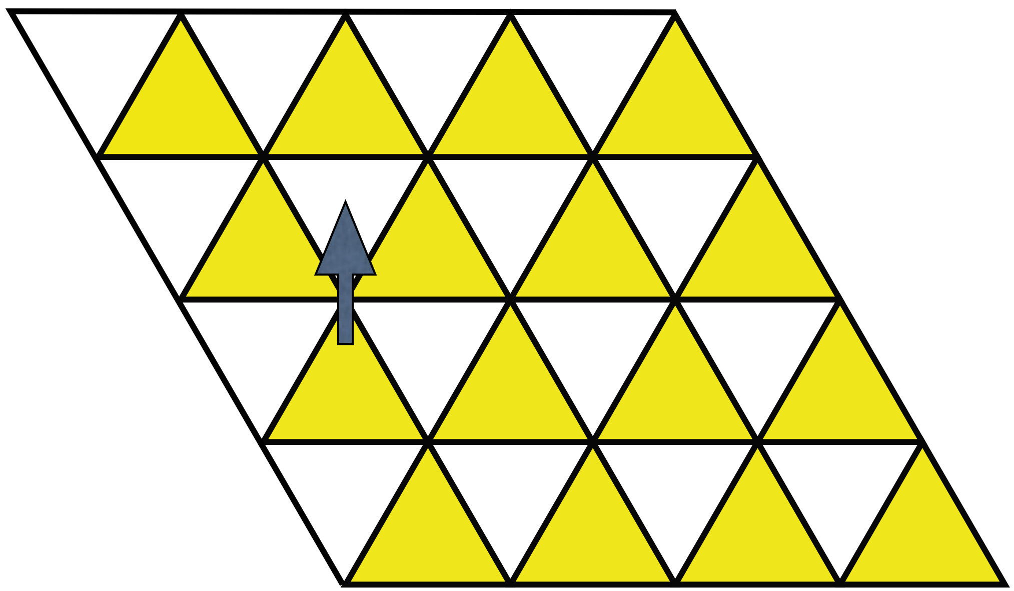
Tendency to non-collinear ordering

Triangular lattice

- Classically: spins must sum to zero

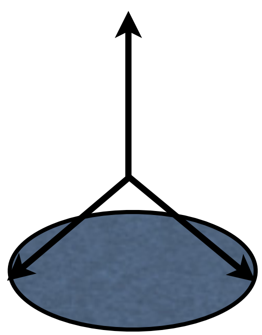


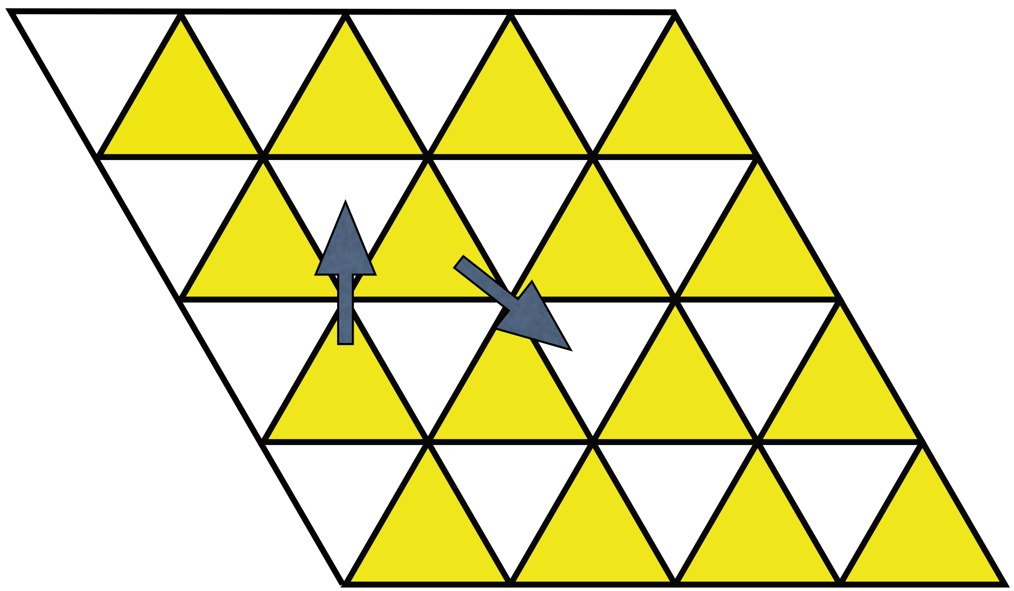
Triangular lattice



Degrees of freedom: 2

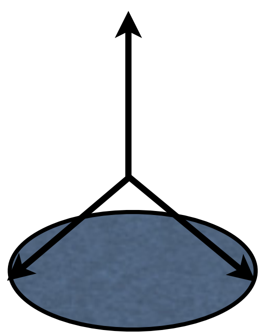
Triangular lattice

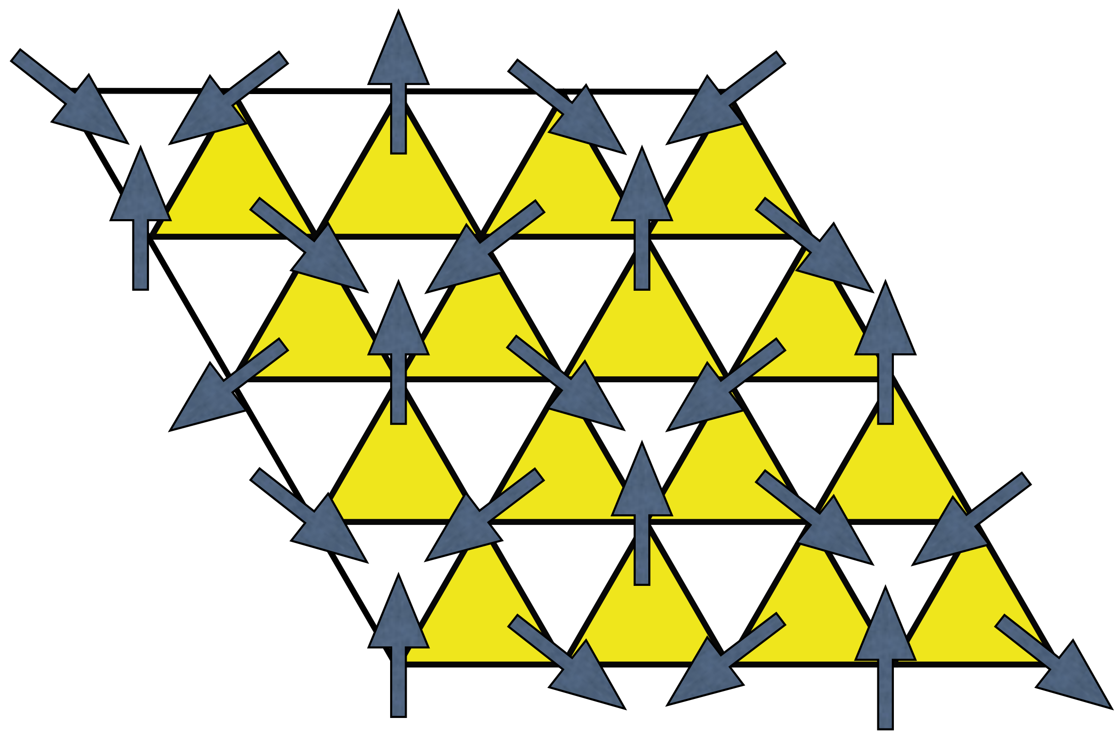




Degrees of freedom: 2+1

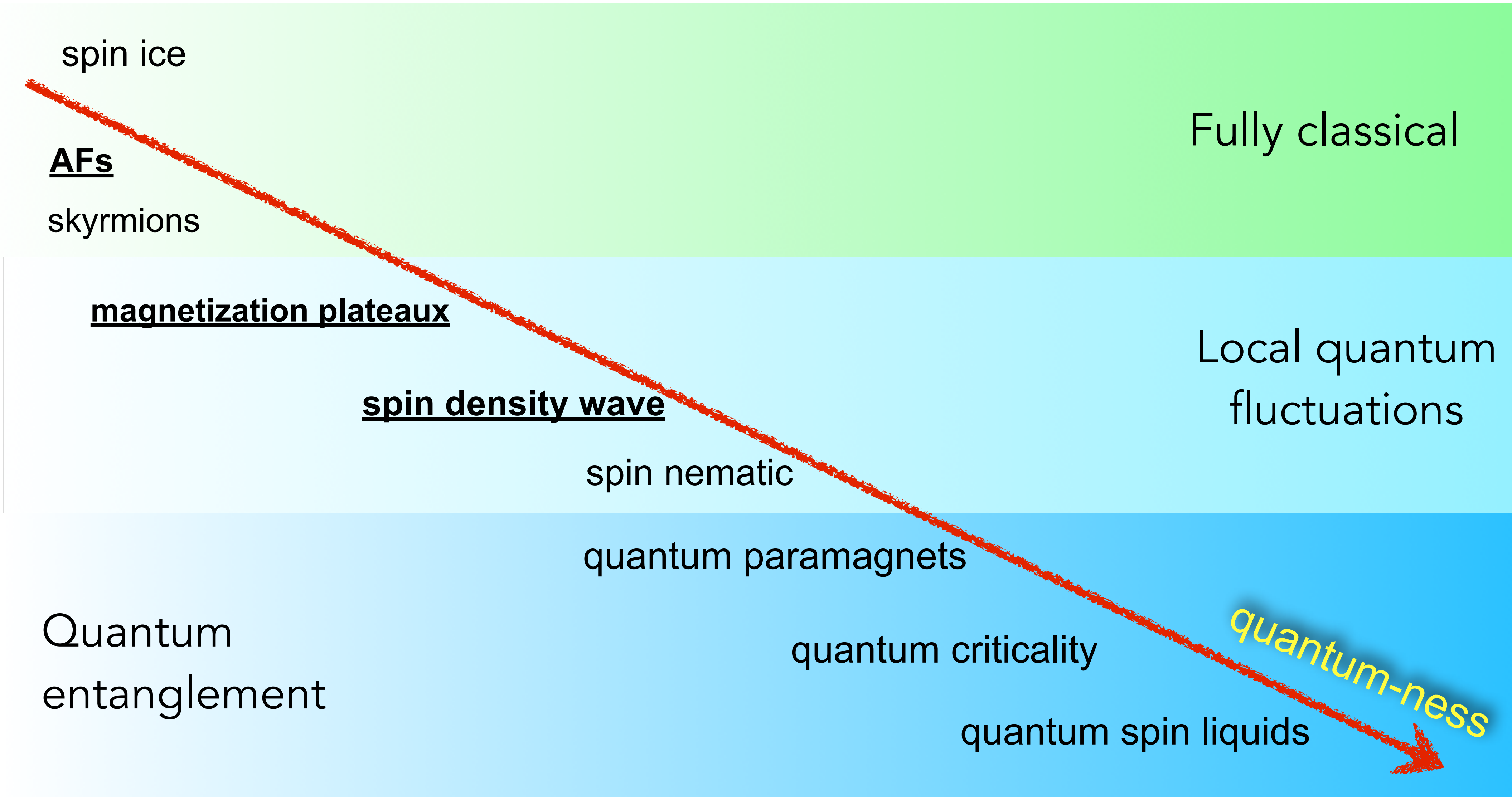
Triangular lattice



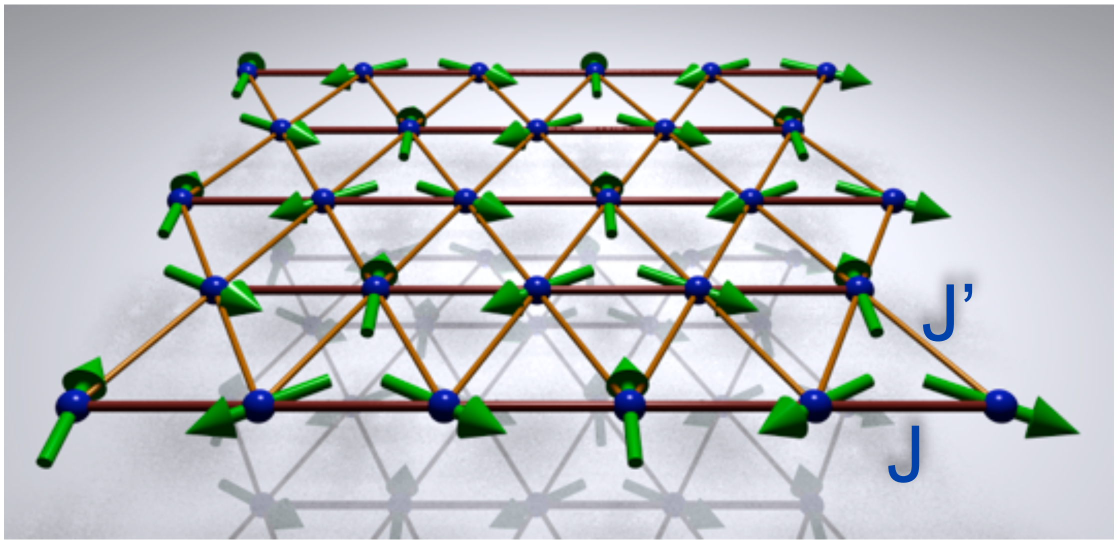


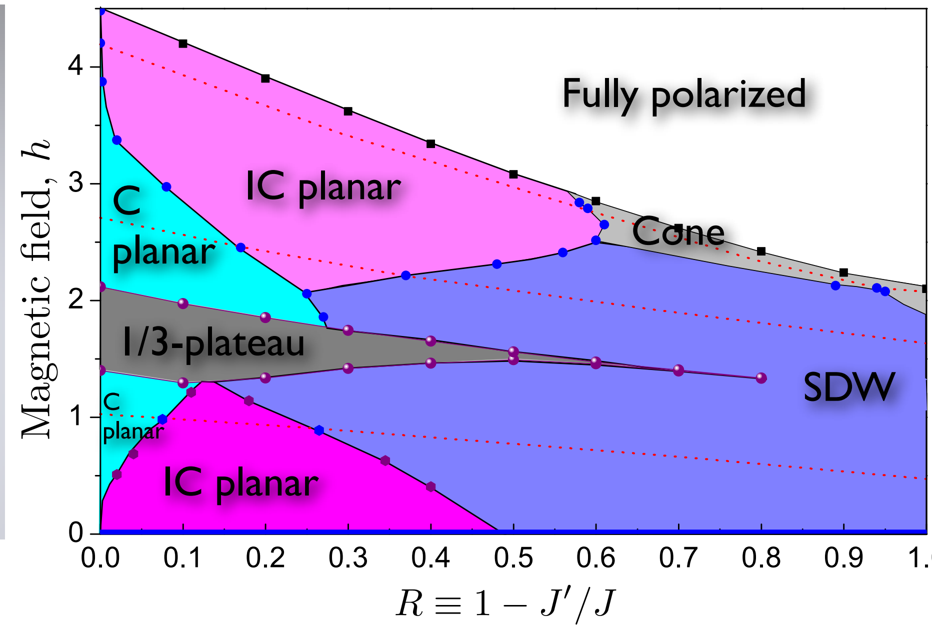
Degrees of freedom: 2+1

Frustrated Magnetism



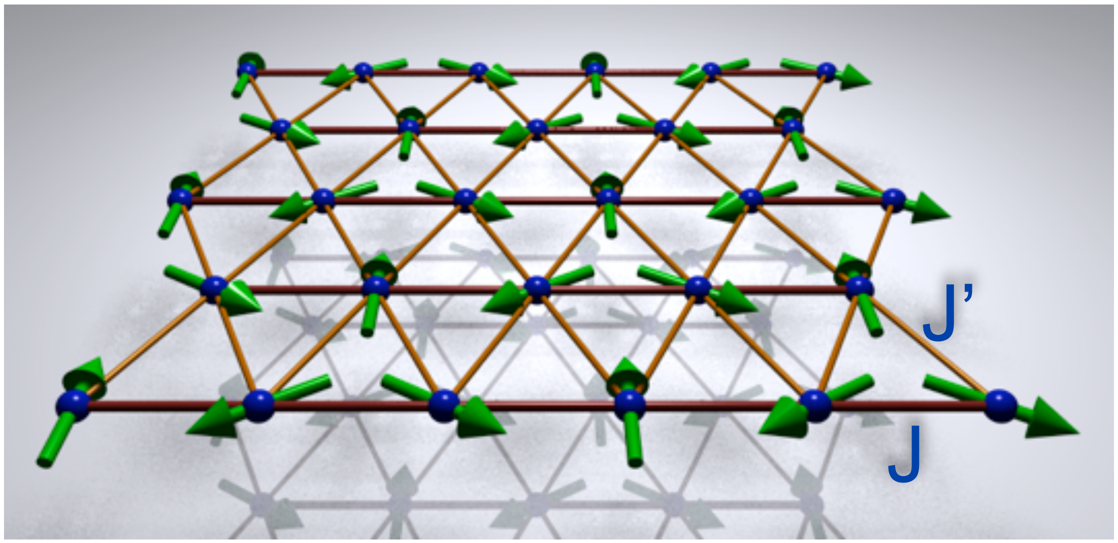
S=1/2 Triangular lattice

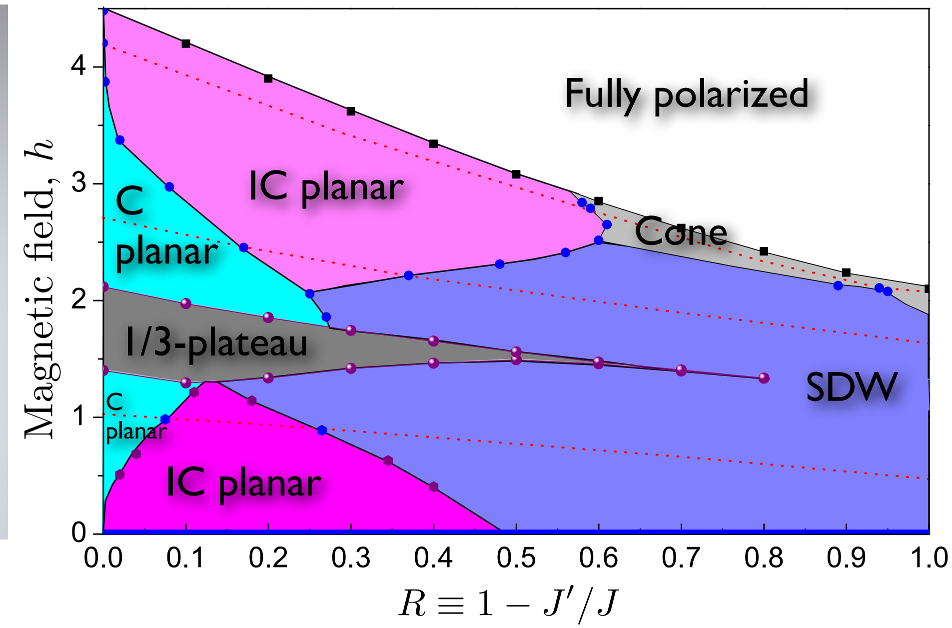




- Nice example with strong quantum renormalizations
  - All phases encountered are ordered, short-range entangled states
  - BUT most are different from those of the classical model
  - And excitations are highly renormalized from linear spin waves

S=1/2 Triangular lattice

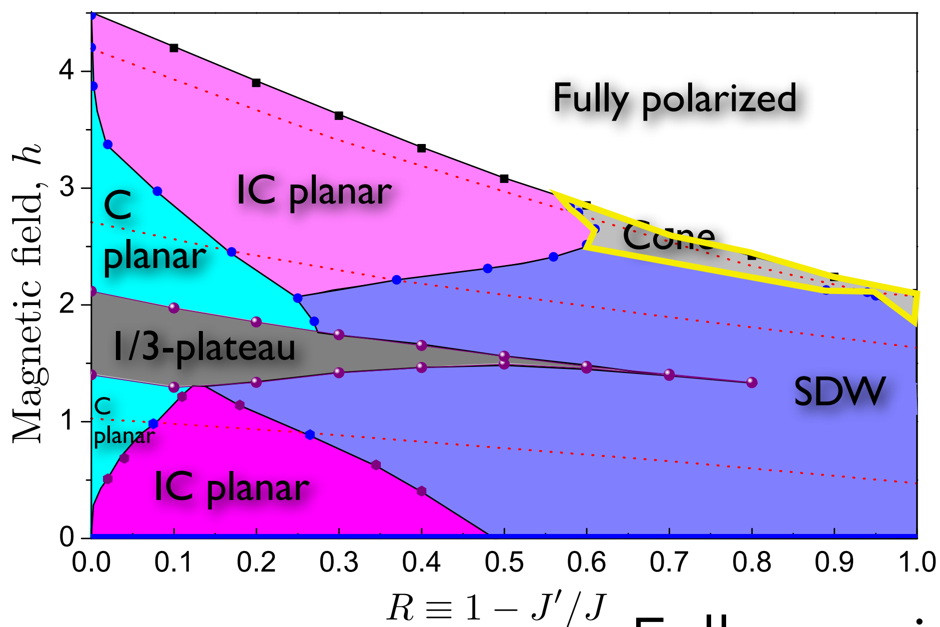


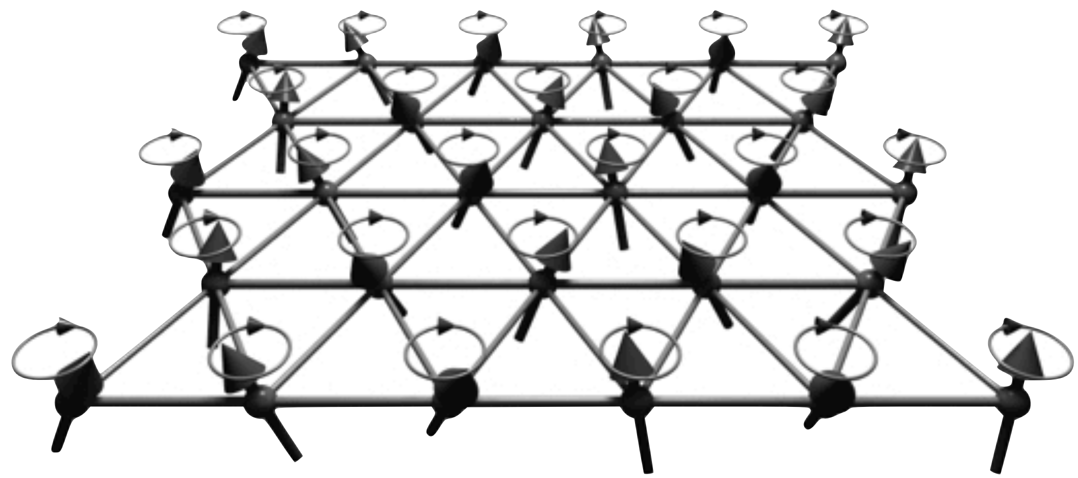


Ru Chen *et al* 2013

Review: O. Starykh, RPP, 2015

Cone state



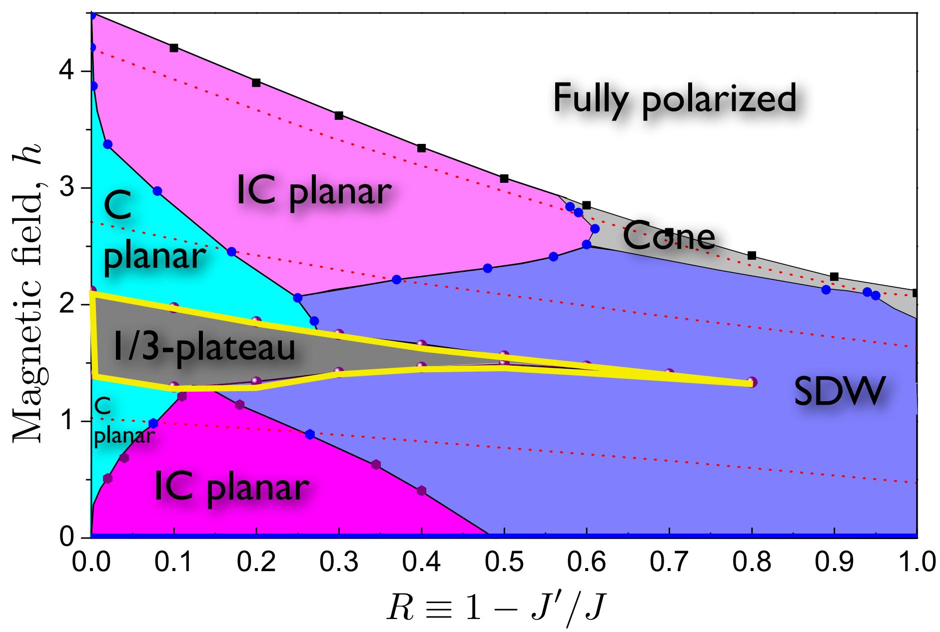


Fully consistent with rigid spins

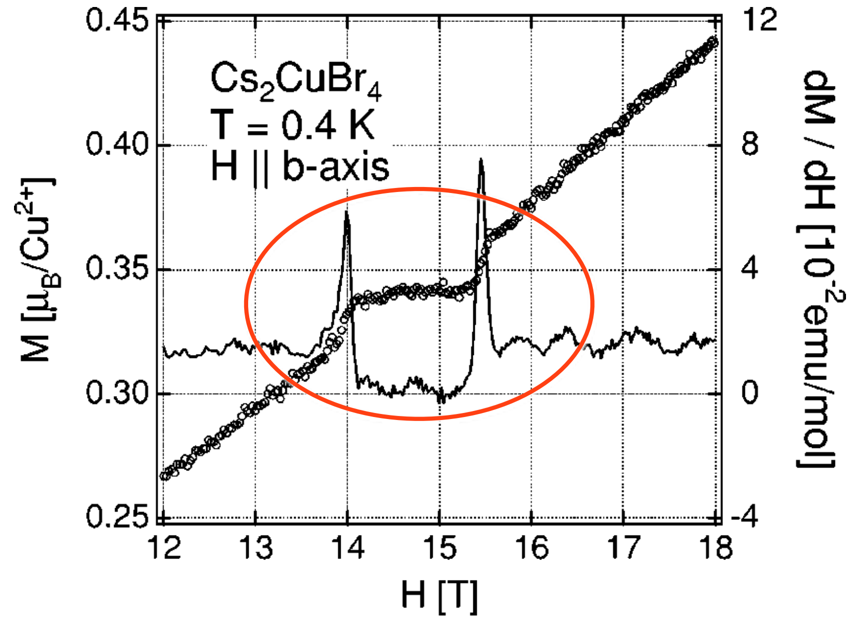
This is the classical ground state *throughout* the phase space

Excitations are gapless spin waves - semiclassical quantization of small oscillations of spins

Magnetization plateau



T. Ono *et al*, 2003

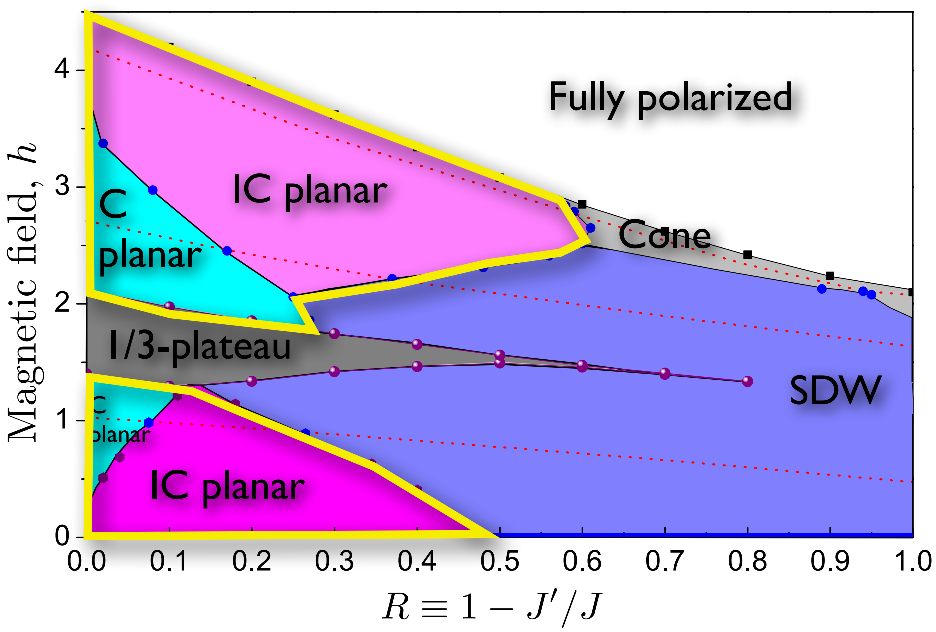


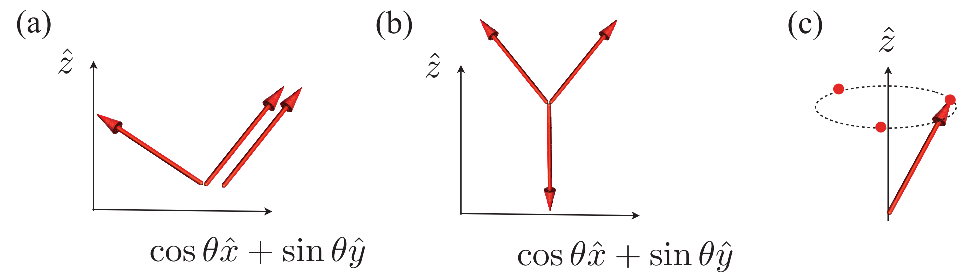
Spin gap stabilized by quantum zero point fluctuations

excitations are still spin waves but not Goldstone modes

c.f. Chubukov + Golosov, 91

Planar orders

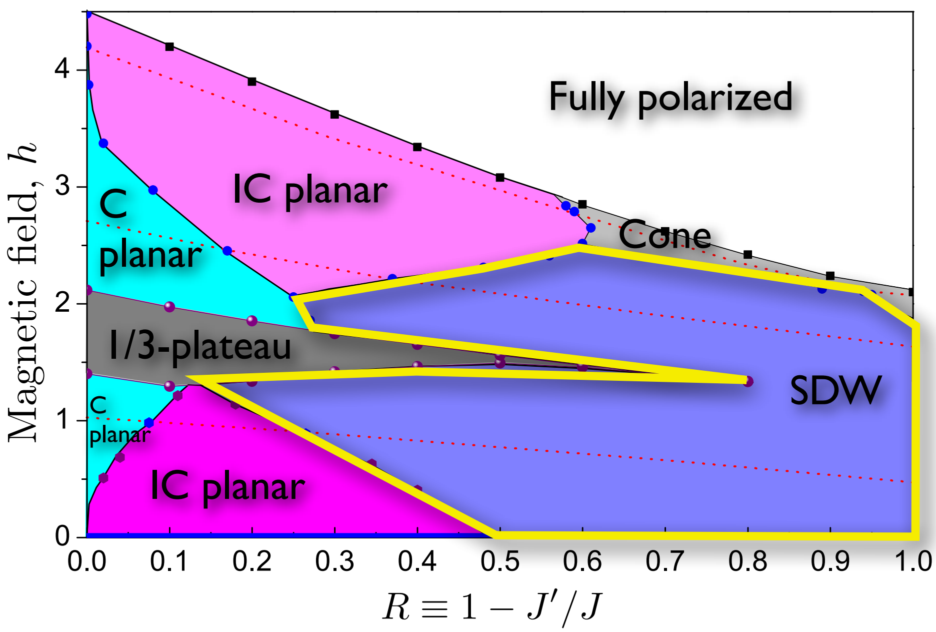


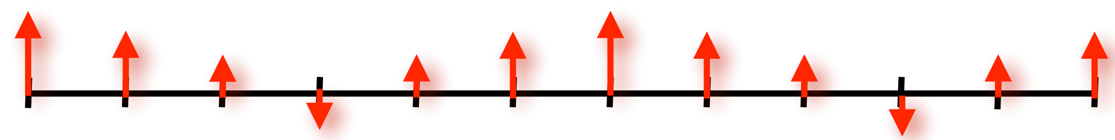


planar/fan cone/umbrella

Classical ground state is *always* umbrella-like, but quantum fluctuations almost completely remove this

SDW



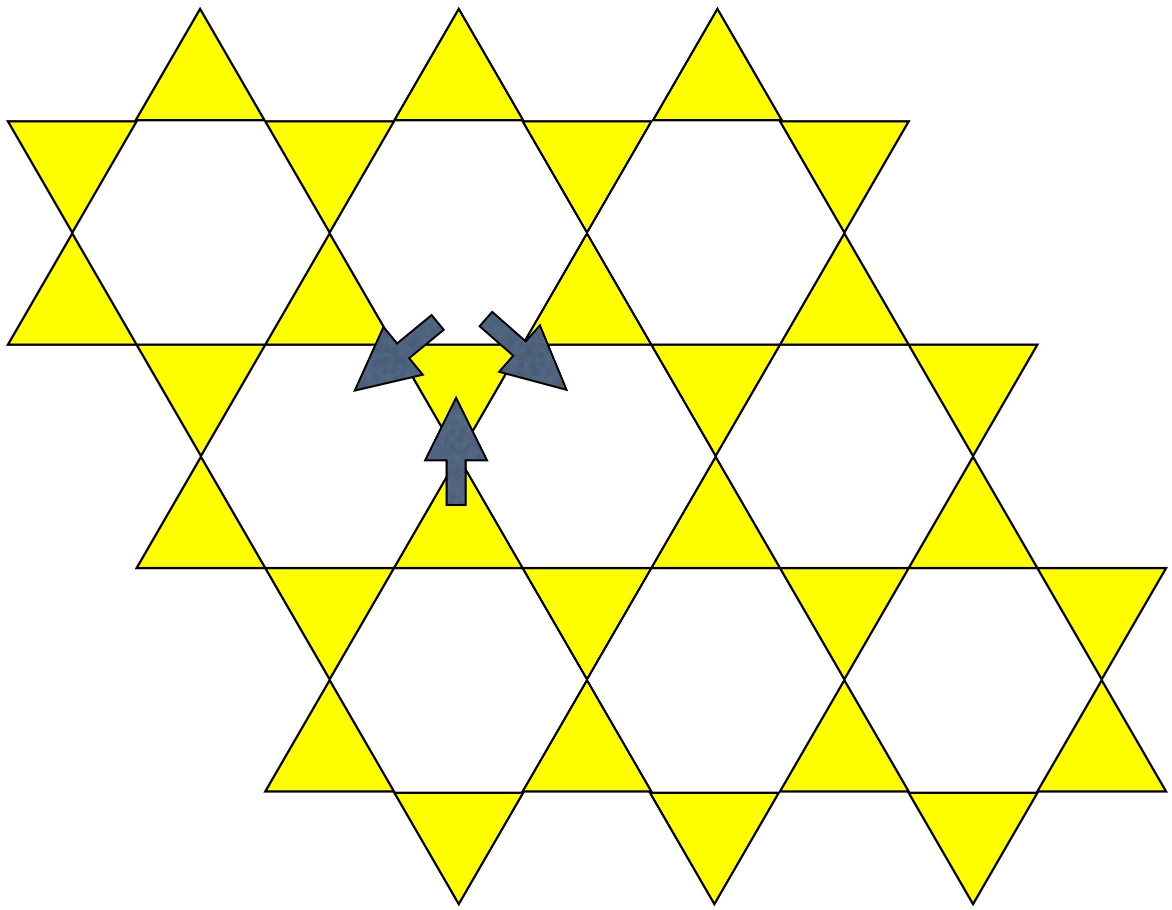


Non-uniform spin lengths
→ non-classical!

SDW states can be considered soliton lattices, and can be understood based on the behavior of spin chains

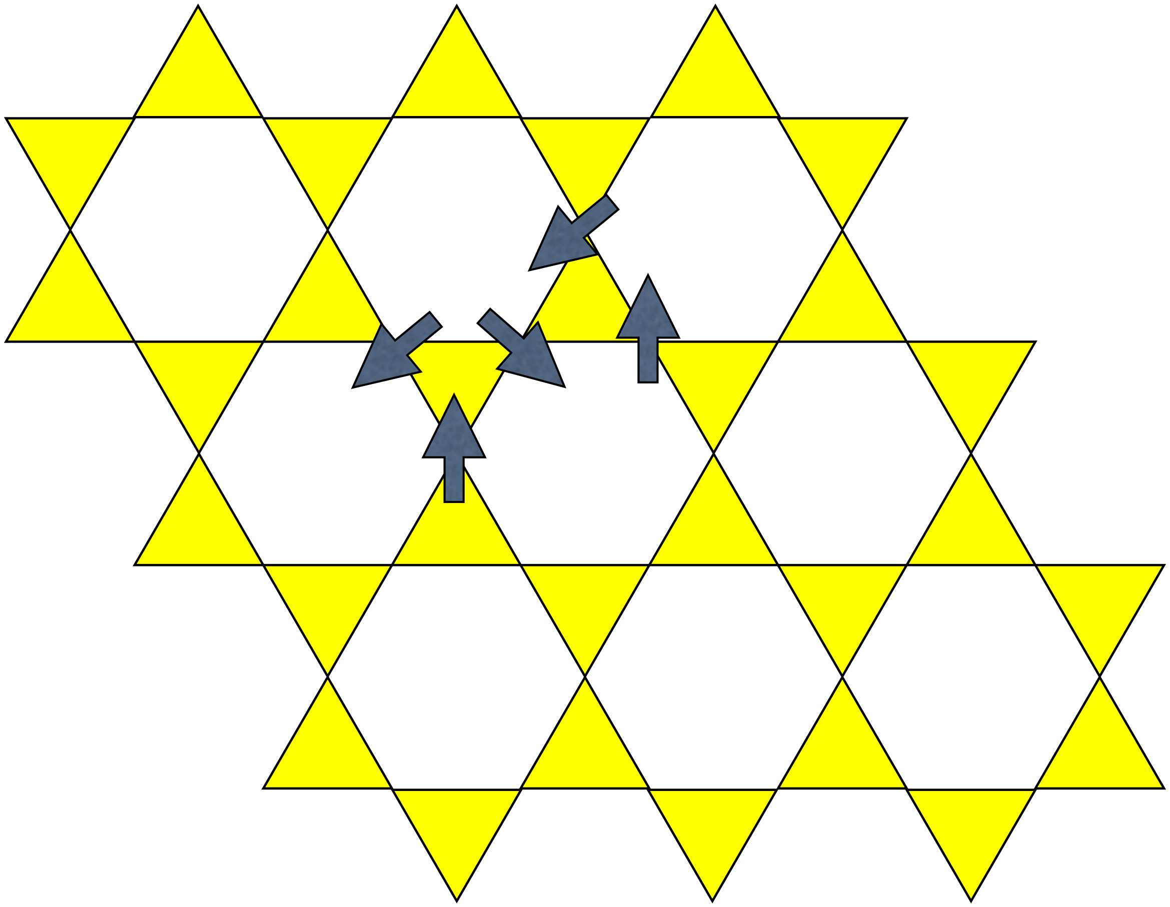
Large domain of SDW state means that quasi-1d nature is enhanced by quantum fluctuations

Kagome lattice



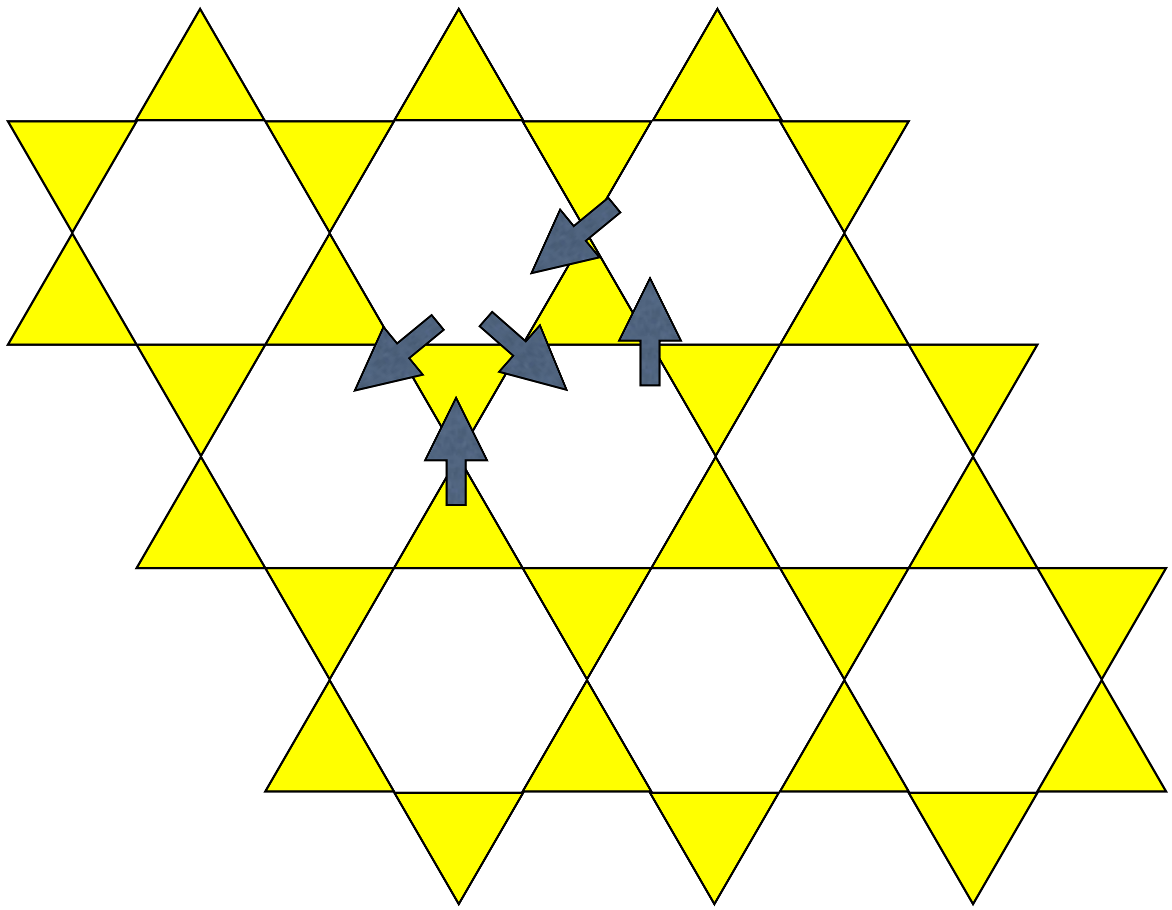
Degrees of freedom: 3

Kagome lattice



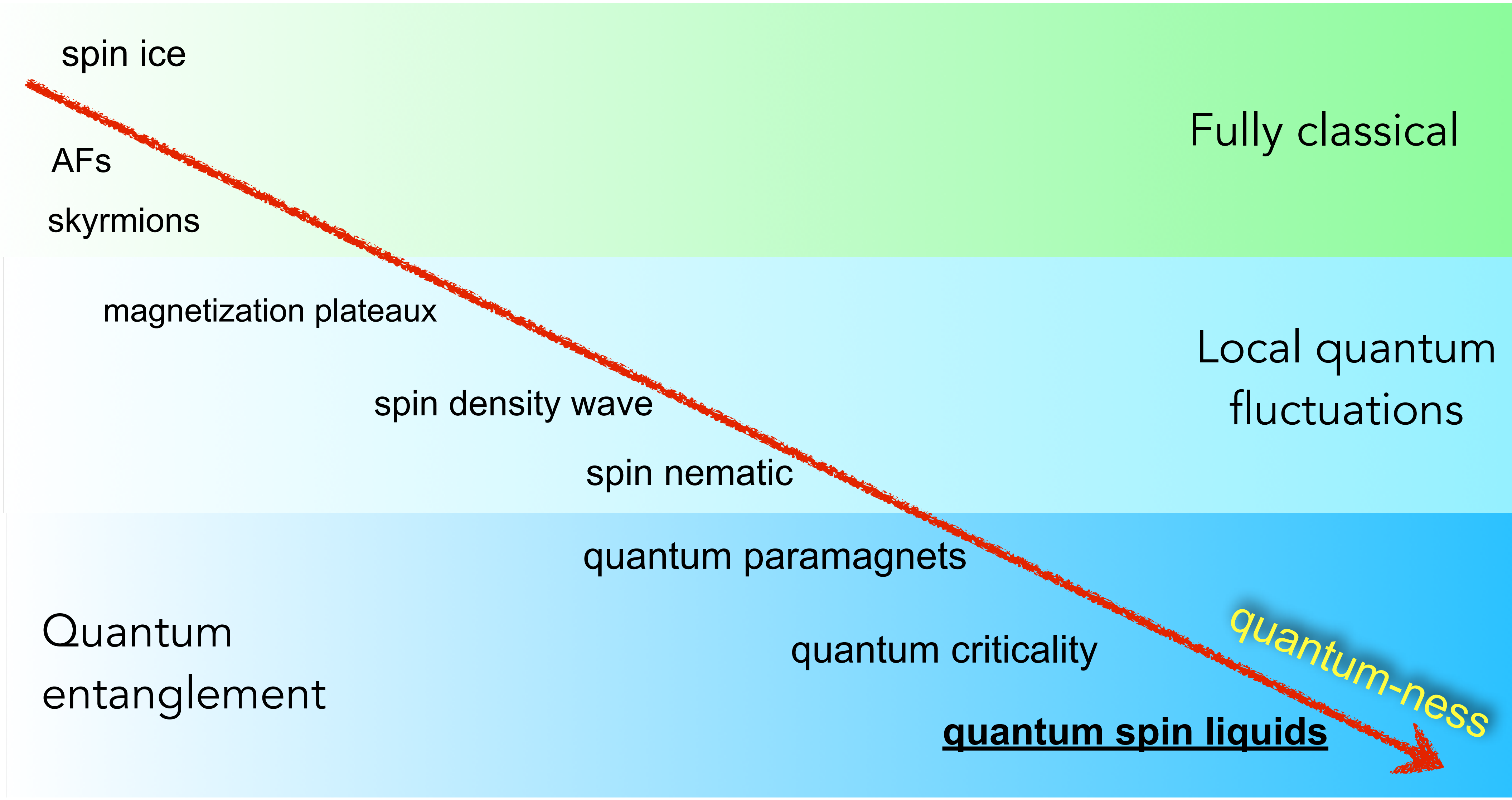
Degrees of freedom: 3+1+...

Kagome lattice



- Degrees of freedom: ~ N . Much less likely to order.

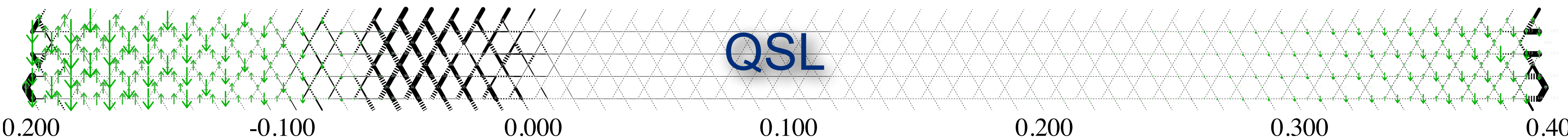
Frustrated Magnetism



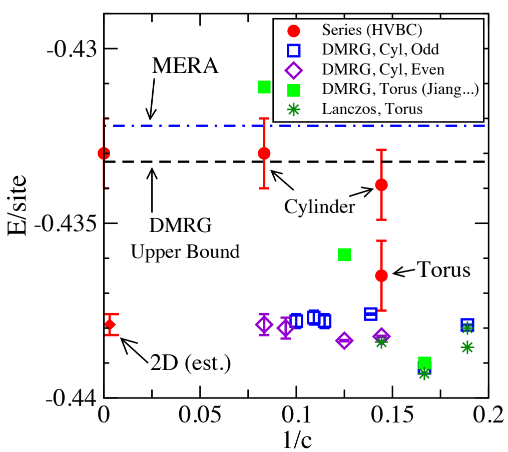
S=1/2 kagomé AF

- DMRG calculations give overwhelming evidence for QSL ground state

© Steve White

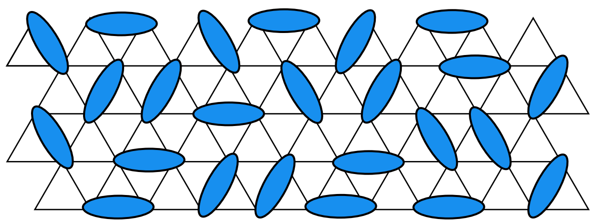
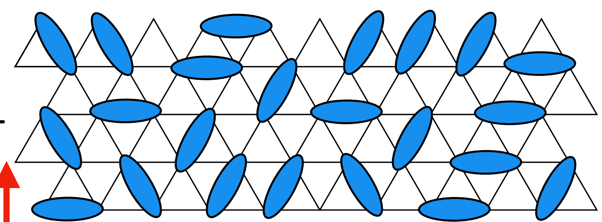


S. Yan *et al*, 2010



Theorists are still debating the nature of the QSL state. Experimentalists are also debating the meaning of their observations.

Many kinds of QSLs

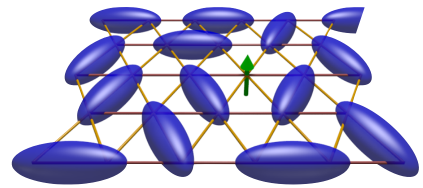
Ψ = #  + #′  + …

For ~500 spins, there are more amplitudes than there are atoms in the visible universe!

Different choices of amplitudes can realize different QSL phases of matter.

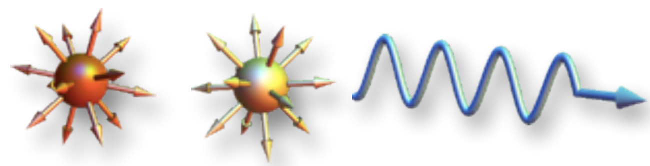
Classes of QSLs

- Topological QSLs



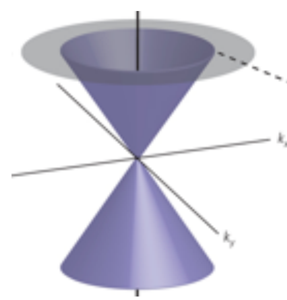
anyonic spinons

- U(1) QSL



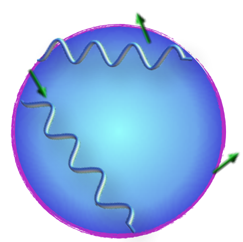
electric+magnetic monopoles, photon

- Dirac QSLs



strongly interacting Dirac fermions

- Spinon Fermi surface



non-Fermi liquid "spin metal"

QSLs @ HFM2022

- **Invited - L. Clark** (University of Birmingham, UK)
"Unravelling Complexity in the Barlowite Family of S=1/2 Kagome Antiferromagnets" ↓
- M. Georgopoulou (Institut Laue Langevin, France & University College London, UK)
"Zn-claringbullite, $ZnCu_3(OD)_6FCl$: a new quantum spin liquid candidate" ↓
- Q. Bartélemy (Université Paris-Saclay, France)
"Specific heat of the kagome antiferromagnet herbertsmithite in high magnetic fields" ↓
- G. Chen (University of Hong-Kong, China)
"Thermal Hall effects in spin liquids" ↓

- **Invited - P. Armitage** (John Hopkins University, USA)
"Recent results on Kitaev interactions in Co based magnets" ↓
- N.B. Perkins (University of Minnesota, USA)
"Footprints of the Kitaev spin liquid in the Fano lineshape of the Raman active optical phonons" ↓
- Y-J. Kao (National Taiwan University, Taiwan)
"Excitation spectrum of spin-1 Kitaev spin liquids" ↓
- M. Udagawa (Gakushuin University, Japan)
"Manipulation of non-Abelian anyons in Kitaev's magnet" ↓

- F. Grußler (University of Augsburg, Germany)
"Comparative study of the triangular spin-liquid candidates $NaYbO_2$, $KYbO_2$ and $KYbS_2$" ↓
- S.H.Y. Huang (McMaster University, Canada)
"Dynamic and frozen quantum magnetism in the ground states of triangular lattice magnets $ErMgGaO_4$ and $YbMgGaO_4$ from inelastic neutron scattering" ↓
- S. Niu (CNRS & Université de Toulouse, France)
"A variational tensor network study of magnetic properties of Heisenberg model with Dzyaloshinskii-Moriya interaction on kagome lattice" ↓

- **Invited - J. Nasu** (Tohoku University, Japan)
"Nonequilibrium dynamics and spin transport caused by fractional quasiparticles in Kitaev spin liquids" ↓
- S.C. Furuya (Ibaraki University, Japan & University of Tokyo, Japan)
"DC electric-field controls of Kitaev spin liquids and topological spin textures" ↓
- E. Lefrançois (Université de Sherbrooke, Canada)
"Evidence of a Phonon Hall Effect in the Kitaev Spin Liquid Candidate α-$RuCl_3$" ↓
- J. Bruin (Max Planck Institute for Solid State Research, Germany)
"Robustness of the thermal Hall effect close to half-quantization in α-$RuCl_3$

- R.P. Nutakki (University of Munich, Germany & University of Augsburg, Germany)
"Proximate Spin Liquids in Metal-Azolate Frameworks" ↓

- S. Zhang (Max Planck Institute for the Physics of Complex Systems, Germany)
"Modeling a three-dimensional S = 1 spin liquid $NaCaNi_2F_7$" ↓

- L. Vanderstraeten (University of Ghent, Belgium)
"Tensor networks and the spectral function of 2-D quantum spin liquids" ↓

4h-15h30 : Pyrochlore se

- **Invited - E. Smith** (McMaster University, Canada)
"The case for a $U(1)_\pi$ Quantum Spin Liquid Ground State in the Dipole-Octupole Pyrochlore $Ce_2Zr_2O_7$" ↓
- Y.B. Kim (University of Toronto, Canada)
"Competing dipolar-octupolar quantum spin liquids on the pyrochlore lattice" ↓
- R. Sibille (Paul Sherrer Institut, Switzerland)
"Octupolar correlations and spinon spectrum in $Ce_2Sn_2O_7$ quantum spin ice" ↓

- **Invited - F. Pratt** (ISISs Neutron and Muon Source, UK)
"Probing triangular-lattice quantum spin liquids with LF-μSR" ↓

Frustrated Magnetism

spin ice

This is all about the equilibrium phase/ground state.

We can also talk about excitations and response

spin density wave

spin nematic

fluctuations

quantum paramagnets

Quantum entanglement

quantum criticality

quantum spin liquids

quantum-ness

Excitations in the usual case

Hamiltonian

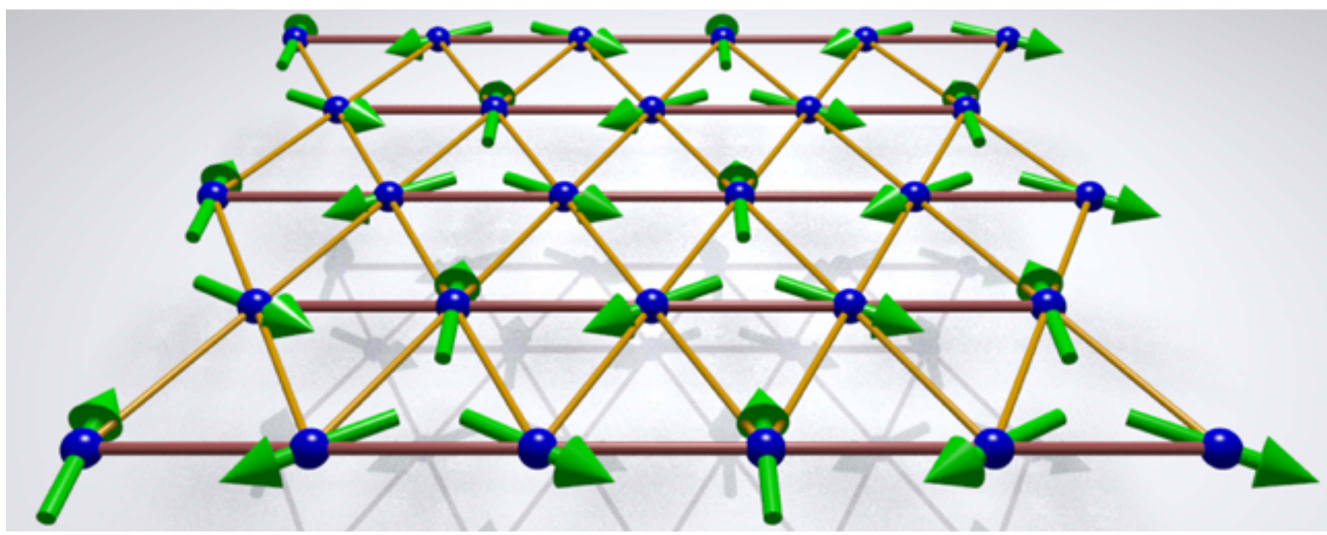
$$H = \sum_{(ij)} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

exchange is short-range: local

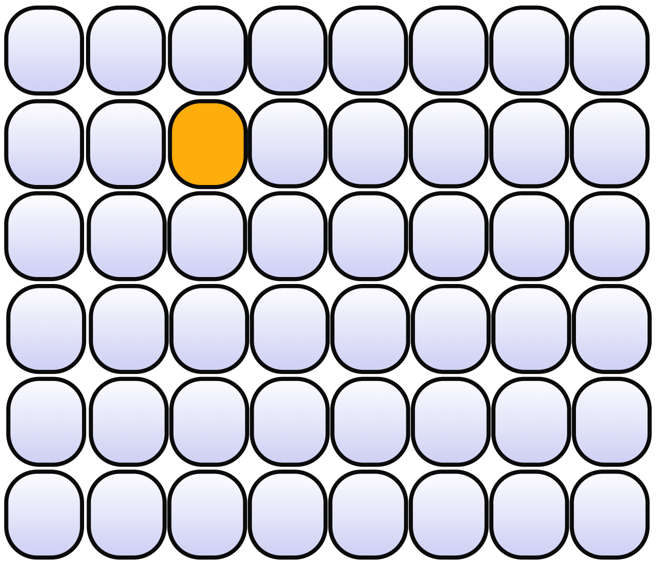
Wave function

$$|\Psi\rangle \approx \bigotimes_i |\boldsymbol{S}_i \cdot \hat{n}_i = +S\rangle$$

Product state



Quasiparticles

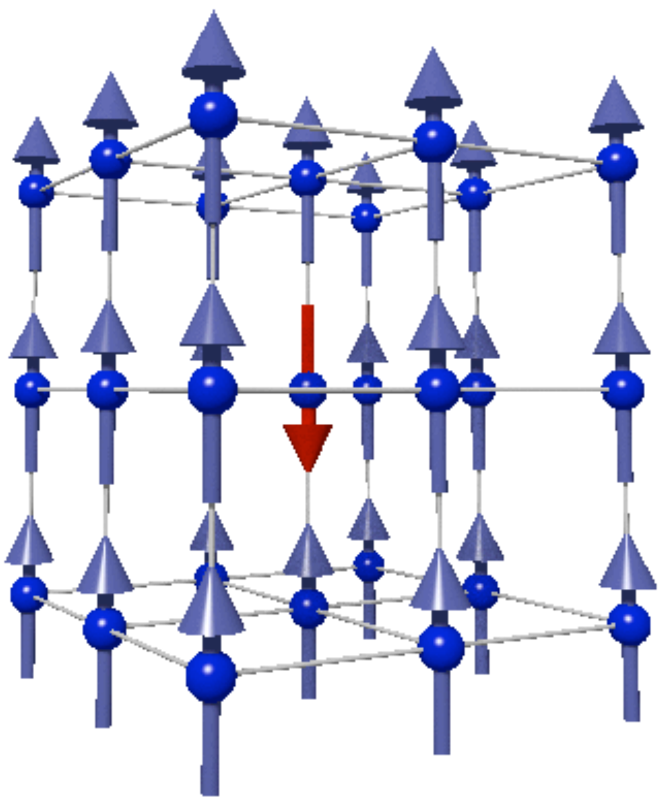


excited states ~ excited levels of one block

- local excitation can be created with operators in one block
- localized excitation has discrete spectrum with non-zero gap, and plane wave forms sharp band

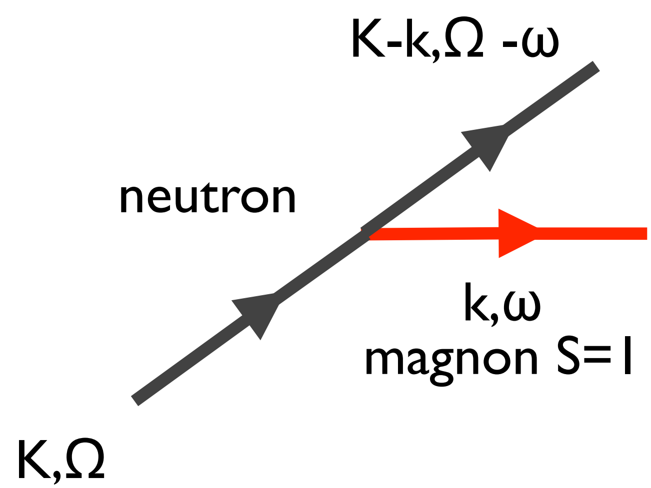
- quantum numbers consistent with finite system: no emergent or fractional quantum numbers

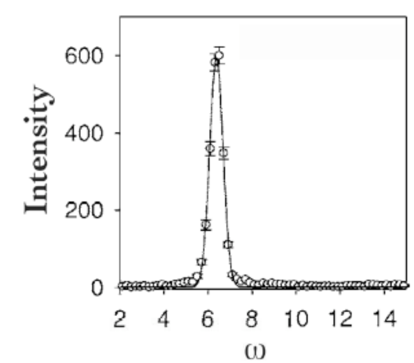
Spin wave



$$\omega(k) \approx \Delta - 2t\cos k_x a - \cdots$$

$$|f\rangle = S_k^+|i\rangle$$

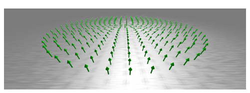




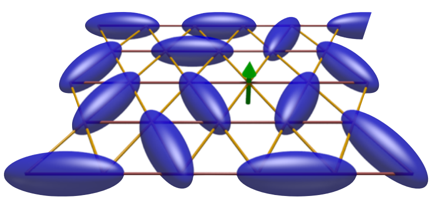
Line shape in Rb_2MnF_4

Emergent excitations

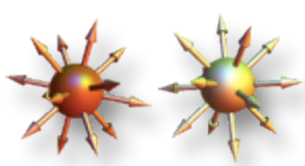
- Emergent excitations may be very different from spin flips
  - May be created in multiples, or very hard to create at all with a neutron, or just have different properties



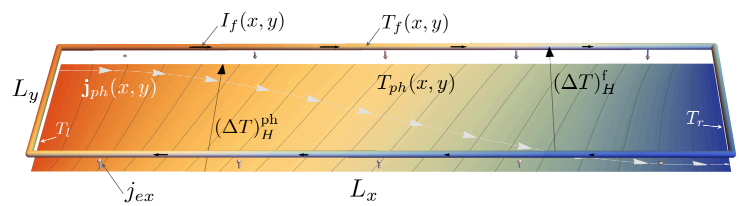
Skyrmion



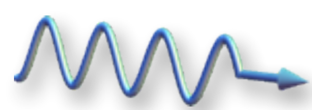
Spinon



Monopoles



Majorana

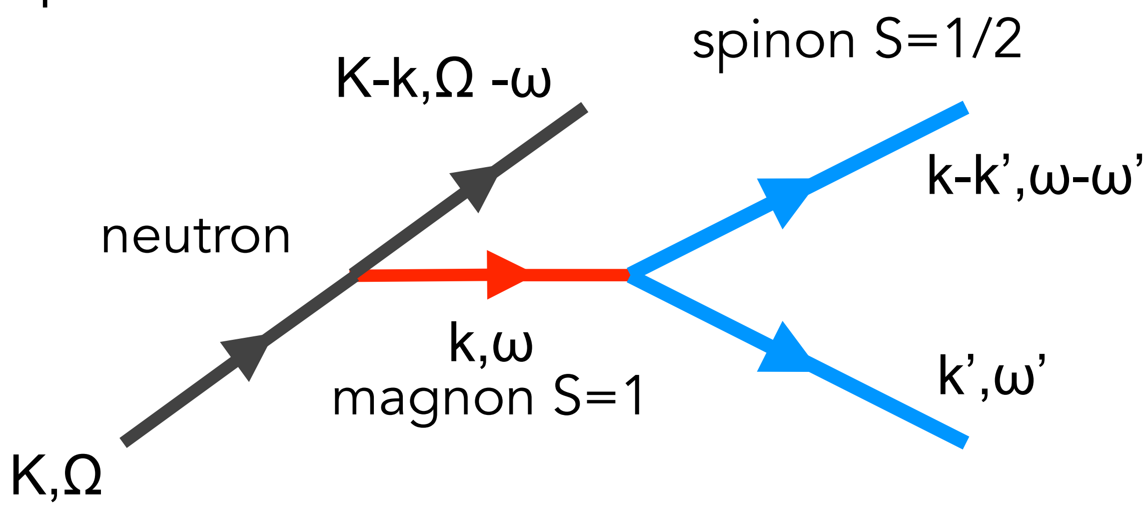


Emergent photon

Emergent excitations

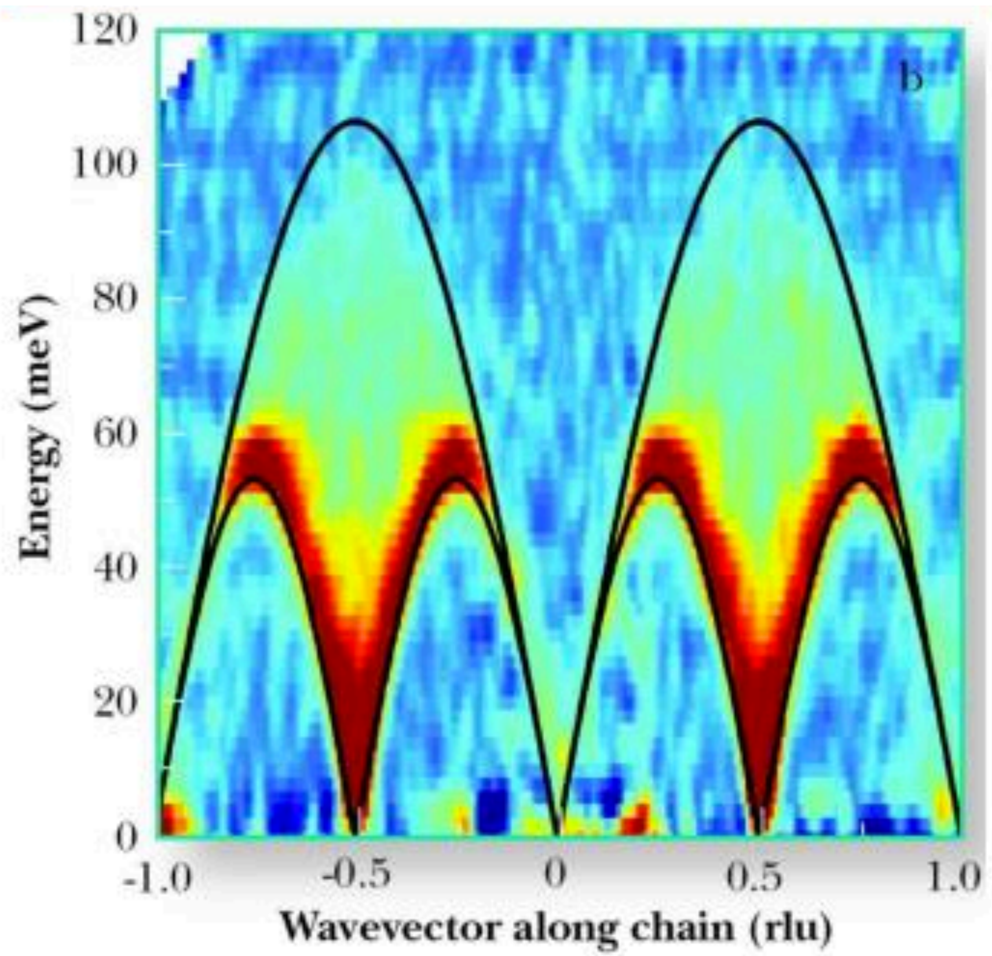
- Emergent excitations may be very different from spin flips
  - May be created in multiples, or very hard to create at all with a neutron, or just have different properties

e.g. spinons



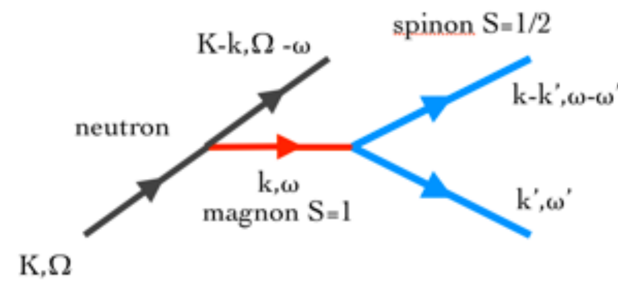
broad peak with
$\omega=\varepsilon(k')+\varepsilon(k-k')$

c.f. One dimension



A. Tennant *et al*, 2001

$KCuF_3$



Understanding in d>1 is much more limited

A rough guide to experiments on HFMs

Does it order?

- NMR line splitting
- muSR oscillation
- thermodynamic transition via specific heat, susceptibility
- Bragg peak in neutron/ x-ray

Is there a gap?

- Specific heat
- NMR $1/T_1$
- Dynamic susceptibility
- T-dependence of χ

Exotica

- Local measurements
- thermal Hall
- ARPES (on insulator!)
- Proximity effects

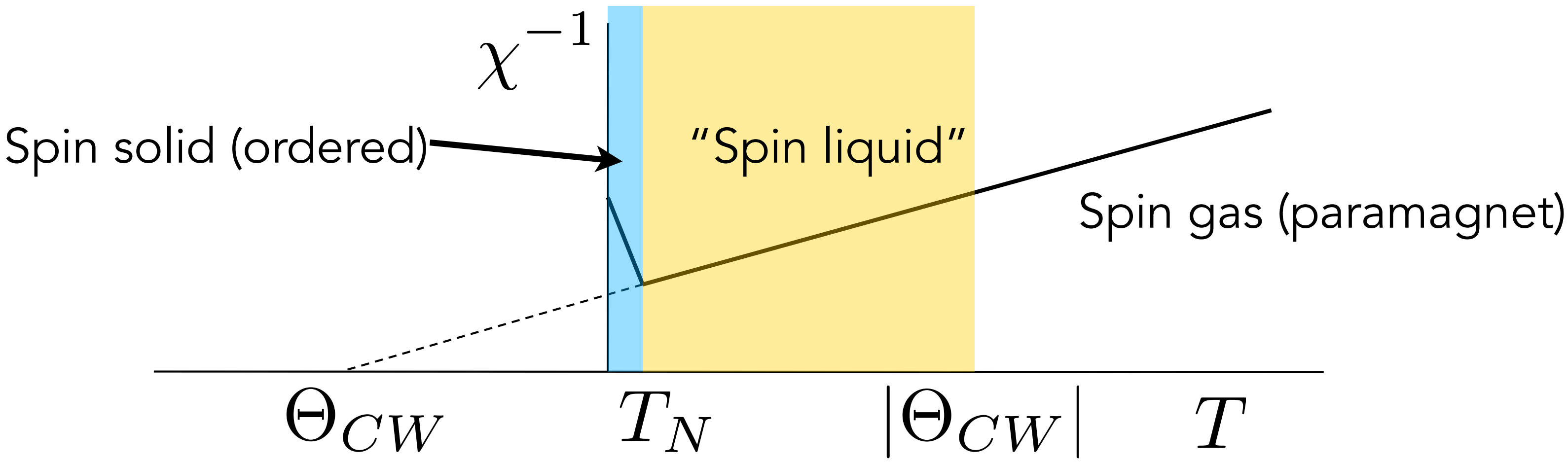
Delocalized excitations?

- thermal conductivity
- INS

Structure of excitations?

- E(k) from INS,RIXS
- optics, Raman

Ramirez Plot



- Local moments: Curie-Weiss law at high T

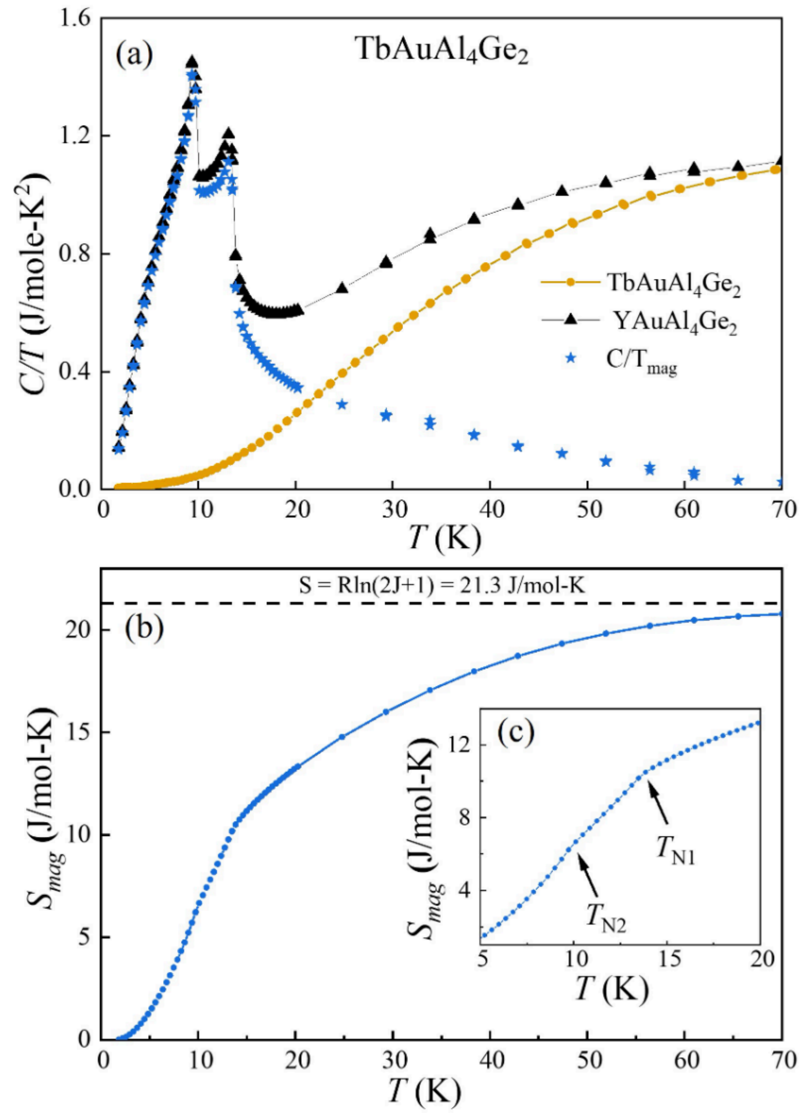
$$\chi \sim \frac{A}{T - \Theta_{CW}}$$

- Frustration parameter: $f = |\Theta_{CW}|/T_N$
- Larger f >> 1 is more frustrated (or fluctuating)

Heat capacity

- Sensitive indicator of phase transitions
- Useful to assess entropy, e.g. confirm effective spin

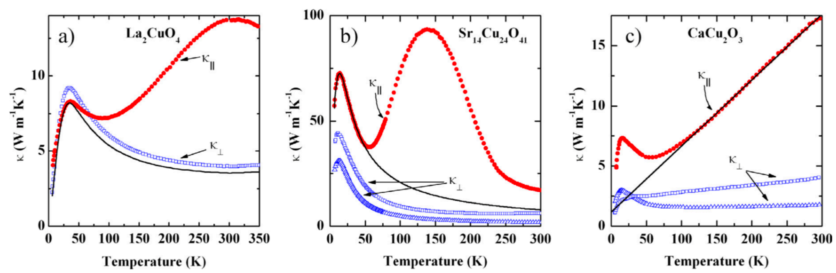
$$S(T) = \int_0^T dT' \, \frac{C(T')}{T'}$$



K. Feng *et al*, arXiv:2205.14063

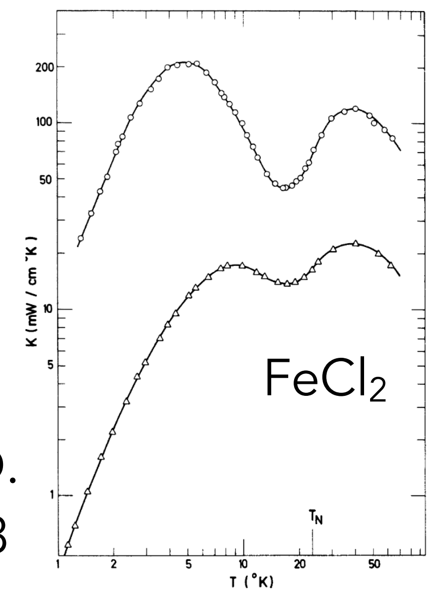
Thermal conductivity

Spins carry heat

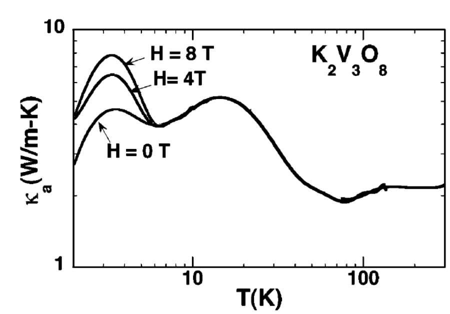


Review: C. Hess, 2019

Phonons carry heat but interact with spins



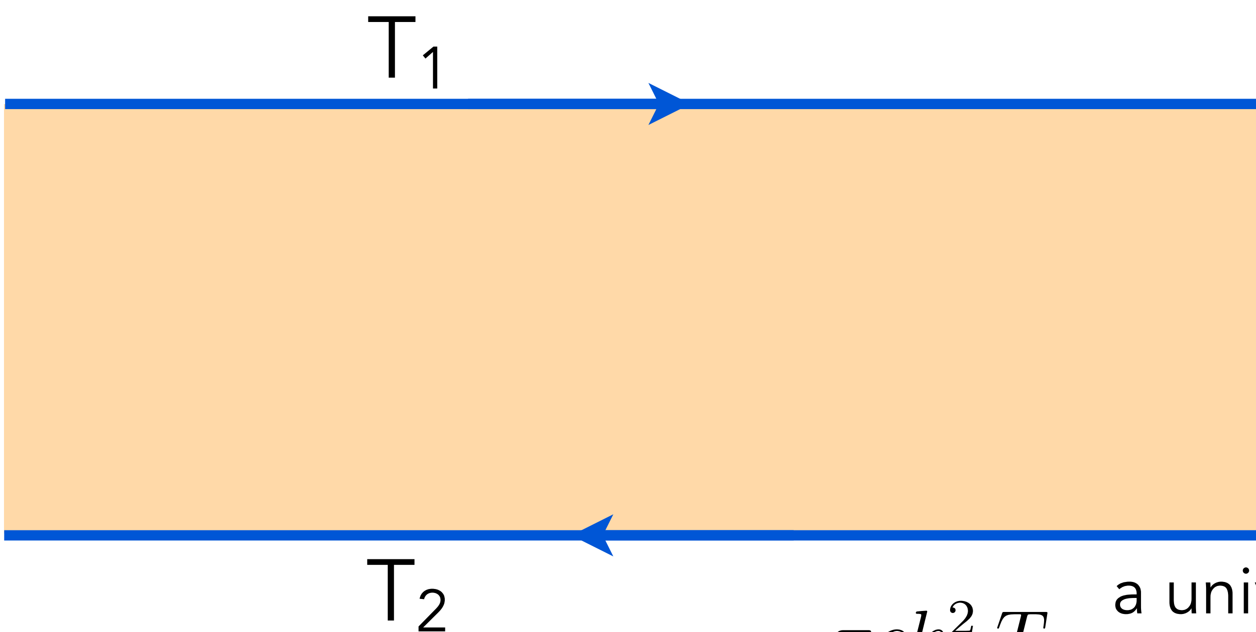
G. Laurence et D. Petitgrand, 1973



B.C. Sales *et al*, 2002

Thermal Hall effect

- Motivation: electronic/spin contribution theoretically closed tied to topology



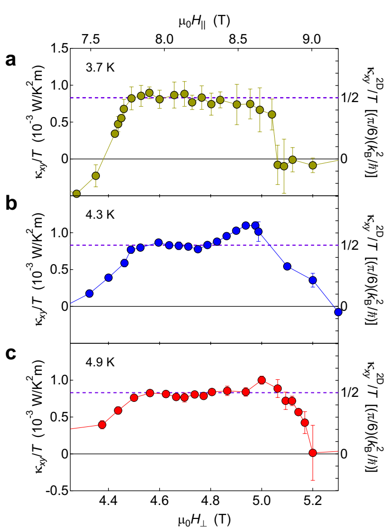
$$I_x = \kappa_H \Delta T_y$$

$$\kappa_H = \frac{\pi c k_B^2 T}{6\hbar}$$

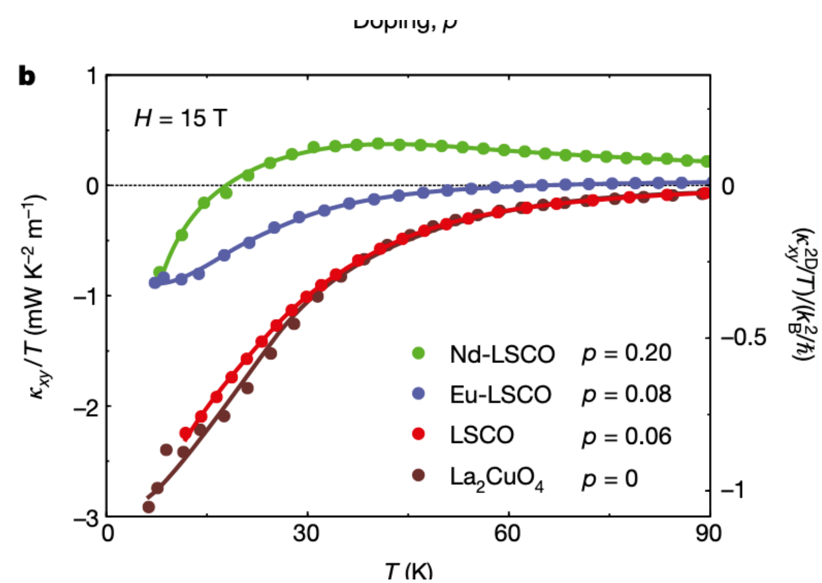
a universal prediction for chiral "Ising anyon" phase: *agnostic to microscopic spin interactions*

Thermal *Hall* conductivity

- Experimental situation very much under debate - electronic versus lattice transport, impurity versus intrinsic, Berry curvature versus scattering,…



Y. Kasahara *et al*, 2018



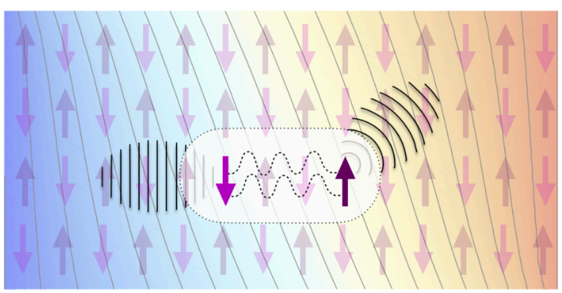
G. Grissonanche *et al*, 2019

Thermal *Hall* conductivity

- Advertisement for some theory work

	zero field	$\boldsymbol{h} = h\hat{\boldsymbol{z}}$	
		lattice and spin	lattice effective
paramagnet	$\mathsf{G} = P4/mmm1'$	$\mathsf{G}(\mathbf{0}, h\hat{\boldsymbol{z}}) = P4/mm'm'$	$\mathsf{G}^{\text{eff}}(\mathbf{0}, h\hat{\boldsymbol{z}}) = 4/mm'm'$
high sym. AFM	$\mathsf{G}(\hat{\boldsymbol{x}}, \mathbf{0}) = \langle i, \mathcal{T}X, \mathcal{T}Y, C_{2x}, \mathcal{T}C_{2z}\rangle$	$\mathsf{G}(\hat{\boldsymbol{x}}, h\hat{\boldsymbol{z}}) = \langle i, XY, \mathcal{T}C_{2y}, XC_{2z}\rangle$	$\mathsf{G}^{\text{eff}}(\hat{\boldsymbol{x}}, h\hat{\boldsymbol{z}}) = \langle i, \mathcal{T}C_{2y}, C_{2z}\rangle$
low sym. AFM	$\mathsf{G}(\hat{\boldsymbol{e}}, \mathbf{0}) = \langle i, \mathcal{T}X, \mathcal{T}Y, \mathcal{T}C_{2z}\rangle$	$\mathsf{G}(\hat{\boldsymbol{e}}, h\hat{\boldsymbol{z}}) = \langle i, XY, XC_{2z}\rangle$	$\mathsf{G}^{\text{eff}}(\hat{\boldsymbol{e}}, h\hat{\boldsymbol{z}}) = \langle i, C_{2z}\rangle$

arXiv:2103.04223
w/ Mengxing Ye+Lucile Savary



$$\kappa_H^{\mu\nu} = \frac{\hbar^2}{k_B T^2}\frac{1}{V}\sum_{n\mathbf{k}n'\mathbf{k}'} J^\mu_{n\mathbf{k}} \frac{e^{\beta\hbar\omega_{n\mathbf{k}}/2}}{2D_{n\mathbf{k}}}\left(\frac{1}{N_{\text{uc}}}\sum_{q=\pm}\frac{\left(e^{\beta\hbar\omega_{n\mathbf{k}}} - e^{q\beta\hbar\omega_{n'\mathbf{k}'}}\right)\mathfrak{W}^{\ominus,+,q}_{n\mathbf{k},n'\mathbf{k}'}}{\sinh(\beta\hbar\omega_{n\mathbf{k}}/2)\sinh(\beta\hbar\omega_{n'\mathbf{k}'}/2)}\right)\frac{e^{\beta\hbar\omega_{n'\mathbf{k}'}/2}}{2D_{n'\mathbf{k}'}} J^\nu_{n'\mathbf{k}'}, \tag{9}$$

where

$$\mathfrak{W}^{\ominus,qq'}_{n\mathbf{k}n'\mathbf{k}'} = \frac{2N_{\text{uc}}}{\hbar^4}\mathfrak{Re}\int_{t,t_1,t_2} e^{i[\Sigma^{q,q'}_{n\mathbf{k}n'\mathbf{k}'}t + \Delta^{q,q'}_{n\mathbf{k}n'\mathbf{k}'}(t_1+t_2)]}\text{sign}(t_2)\left\langle\left[Q^{-q}_{n\mathbf{k}}(-t-t_2), Q^{-q'}_{n'\mathbf{k}'}(-t+t_2)\right]\left\{Q^{q'}_{n'\mathbf{k}'}(-t_1), Q^q_{n\mathbf{k}}(t_1)\right\}\right\rangle, \tag{10}$$

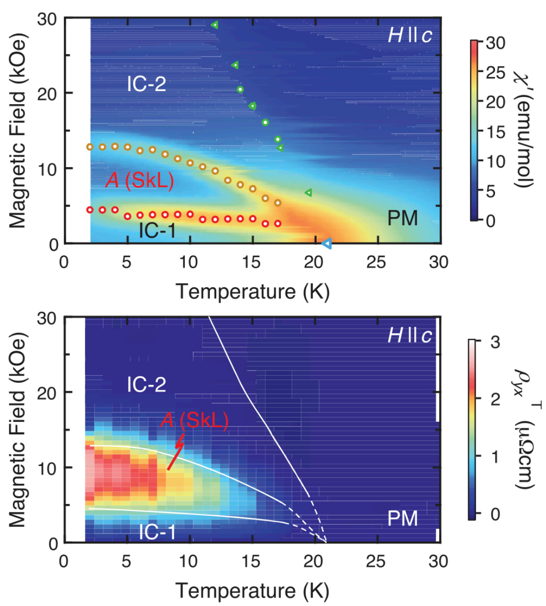
arXiv:2206.06183
arXiv:2202.10366
Poster W2 (Wed afternoon)
w/ **<u>Léo Mangeolle</u>**+Lucile Savary

Electrical conductivity

- Electron dynamics modified by magnet order

e.g. Hall conductivity due to skyrmions

e.g. Gd_2PdSi_3



T. Kuramaji *et al*, 2019

Friday, June 24th

9h-10h30 : Skyrmions & multi-Q phases session

- **Invited - O. Zaharko** (Paul Scherrer Institut, Switzerland)
"Spin textures in frustrated magnetic materials"

- K. Shimizu (University of Tokyo, Japan)
"Spin moiré engineering of topology and emergent electromagnetic fields in multiple-Q spin textures"

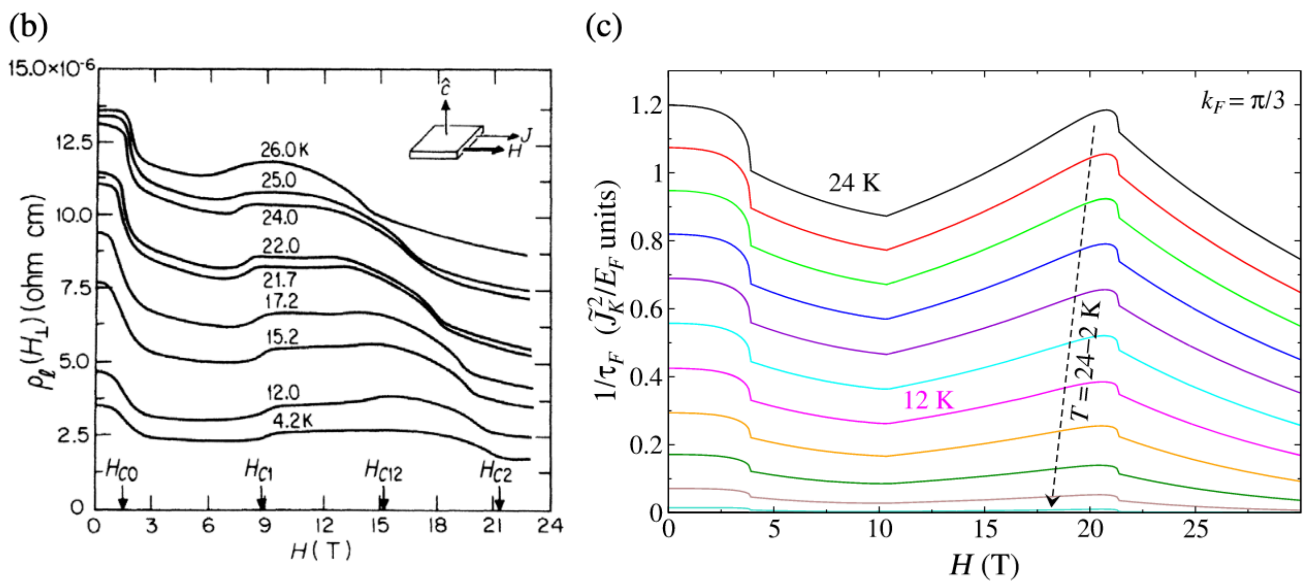
- P. Pujol (CNRS & University of Toulouse, France)
"A skyrmion fluid and bimeron glass emerging from a chiral spin liquid"

- K. Penc (Wigner Research Centre for Physics, Hungary)
"Unified theory of the spiral spin-liquids on layered honeycomb, diamond, and fcc lattices"

Electrical conductivity

- Electrons scattered by magnetic excitations

e.g. “Roller coaster”



- A.L. Chernyshev (Univeristy of California, USA)
“Roller-Coaster in a Flatland: Magnetism of Eu-intercalated Graphite”

More responses

- Diverse behaviors of HFMs demand a diverse set of probes:
  - NMR/muSR/ESR - **A. Zorko**
  - Scattering - neutron - **P. Deen** - Raman, X-ray
  - Optics, Kerr, Faraday, non-linear/ultrafast
  - Magnetostriction, ultrasound, …

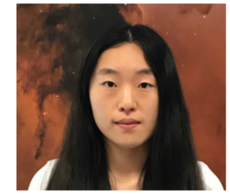
Moiré

mohair

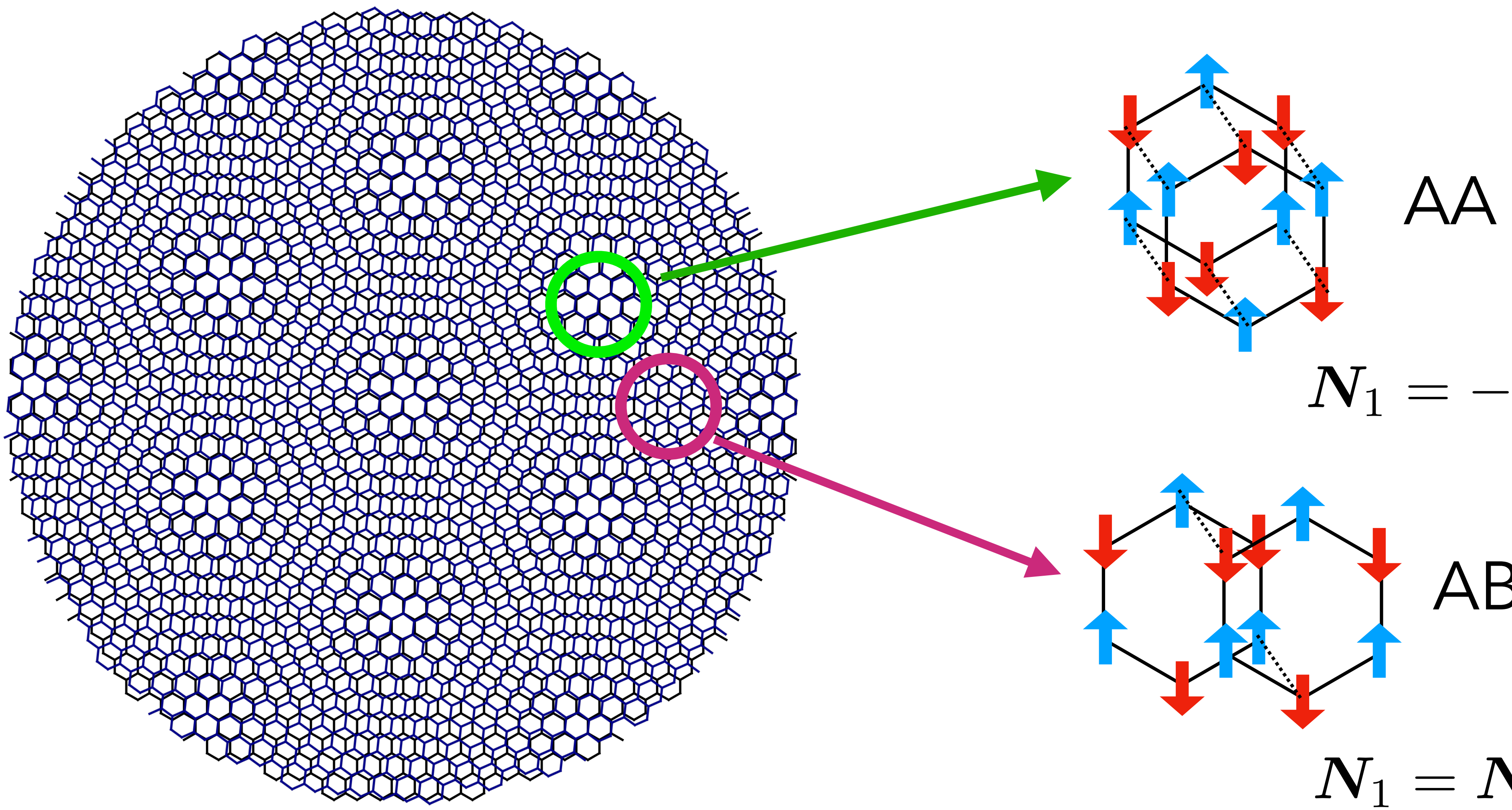
6°

Twisted AF

Kasra Hejazi



Zhu-Xi Luo



$N_1 = -N_2$

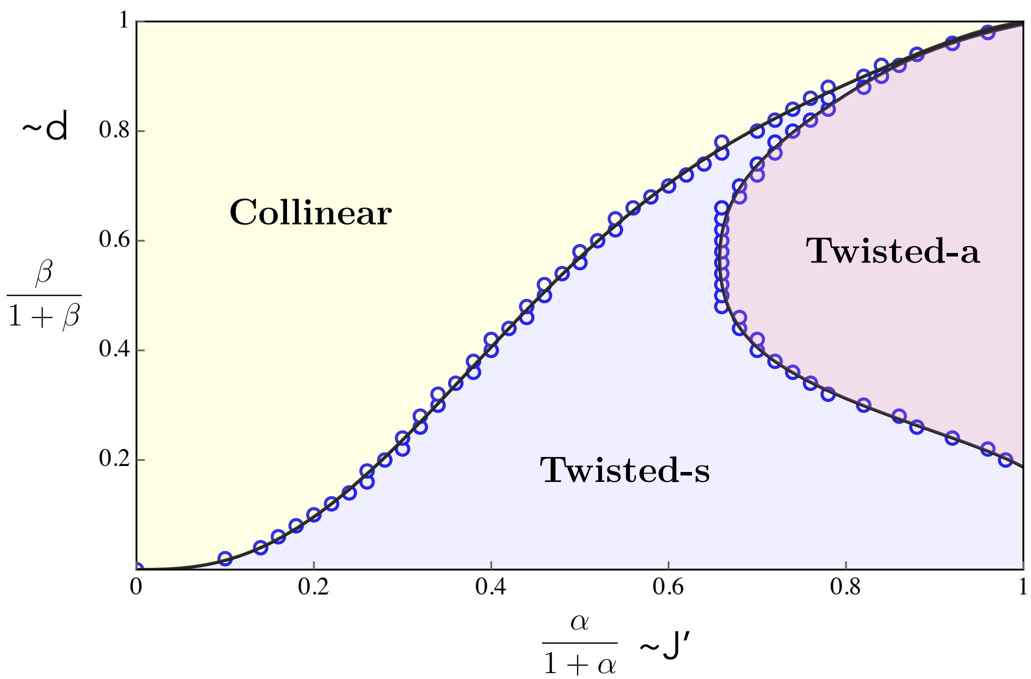
$N_1 = N_2$

Frustration: Neél vectors must rotate

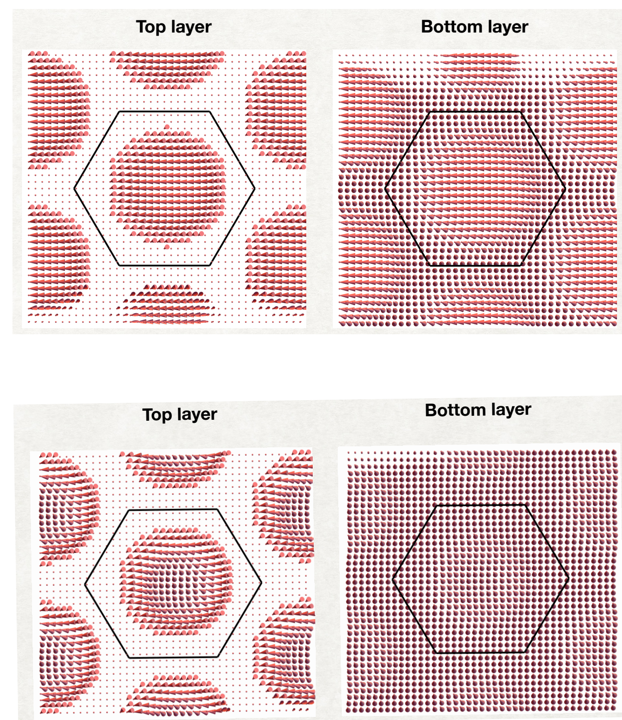
Twisted AF

$$\mathcal{H}_{\rm cl} = \sum_l \left[\frac{\rho}{2}\left(\nabla \boldsymbol{N}_l\right)^2 - d\left(N_l^z\right)^2\right] - J'\Phi(\boldsymbol{x})\boldsymbol{N}_1 \cdot \boldsymbol{N}_2$$

Dimensionless parameter $\alpha = \frac{2J'}{\rho q_m^2} \sim \frac{J'}{J\theta^2}$



Coplanar spin textures



Transitions should be tunable by applied field

CrI_3

(A twisted *ferro*magnet)

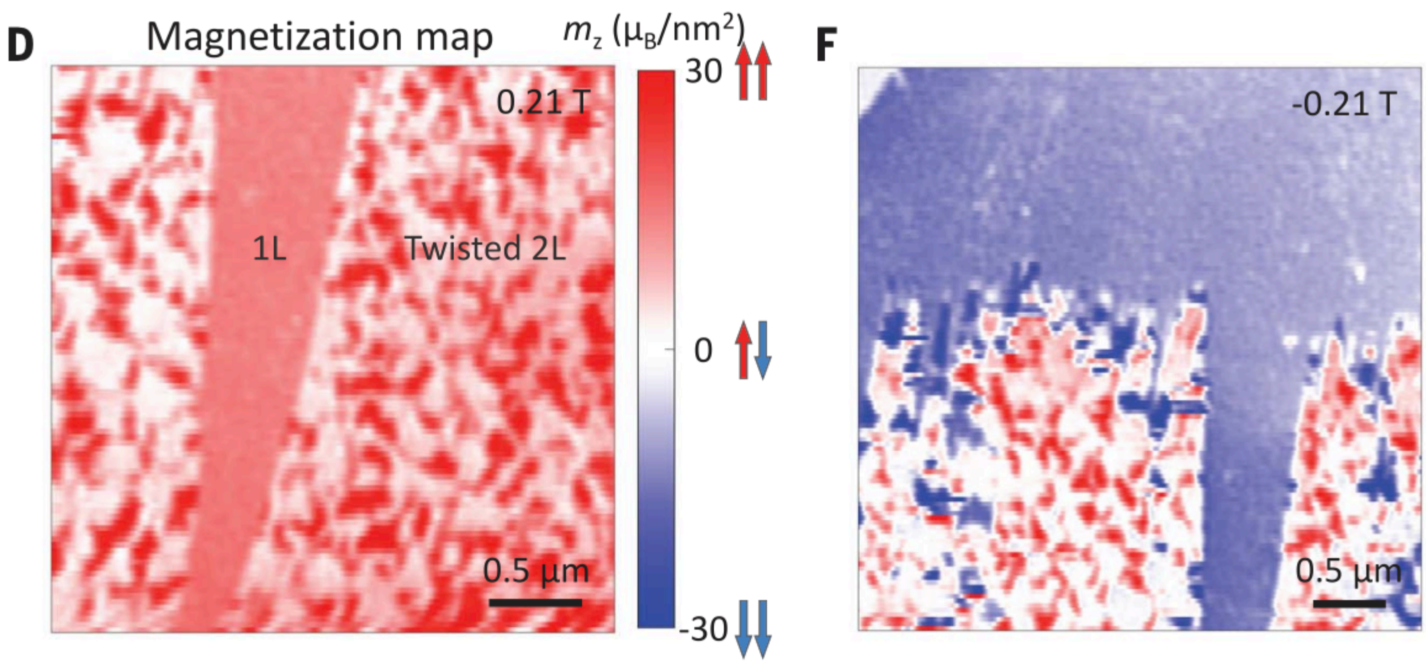
REPORT

MAGNETISM

Direct visualization of magnetic domains and moiré magnetism in twisted 2D magnets

Tiancheng Song[1]†, Qi-Chao Sun[2]†, Eric Anderson[1]†, Chong Wang[3], Jimin Qian[4], Takashi Taniguchi[5], Kenji Watanabe[6], Michael A. McGuire[7], Rainer Stöhr[2,8], Di Xiao[3], Ting Cao[4], Jörg Wrachtrup[2,9]*, Xiaodong Xu[1,4]*

Scanning NV magnetometry



(twist disorder is evident)

Thank you

- Frustrated and quantum magnetism is an exciting place for theory and experiment to meet
  - The basic point is frustration allows more unusual structures to emerge, be they atypical orders, unusual excitations, or unconventional responses
- We surely missed many things. That's why you need to go to the meeting!

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