Quantum spin ice

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SO-Tanaka, PRL **105**, 047201 (2010), PRB **83**, 094411 (2011).
SO, J. Phys.: Conf. Series **320**, 012065 (2011).
L.-J. Chang, SO, Y. Su et al. Nature Comm. 3:992 (2012).
S. Lee, SO, L. Balents, PRB, to be published (arXiv:1204.2262).
Some unpublished works.

Thanks to

Theory:

Y. Tanaka (RIKEN)	Superexchange int.
L. Balents, S. Lee (KITP, UCSB)	Gauge theory
Y.-J. Kao (Natl. Taiwan Univ.)	Fitting with neutron exp.

Experiments on Yb pyrochlore:

L.-J. Chang (Natl. Cheng Kung Univ.)	Neutron exp.
Y. Su (Julich Centre for Neutron Science)	Neutron exp.
Y. Yasui (Nagoya Univ),	Sample
K. Kakurai (JAEA)	Neutron exp.
M. R. Lees (Univ. of Warwick)	Specific heat
K.-D. Tsuei (NSSRC, Hsinchu)	EXAFS

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Outline

- Introduction

  Spin ice: emergent magnetic monopoles

  Simple quantum effects on monopoles: U(1) QSL

  Indication of quantum spin ice in materials

- Generic quantum spin ice model

  Nontrivial superexchange interaction between

  local doublets of f-electrons for Pr, Yb, (Nd, Er)

- Gauge theory

  Analogous QED with gapless “photon”

  A novel excitation

- Experiments on $Yb_2Ti_2O_7$

  A first-order phase transition via the Higgs mechanism

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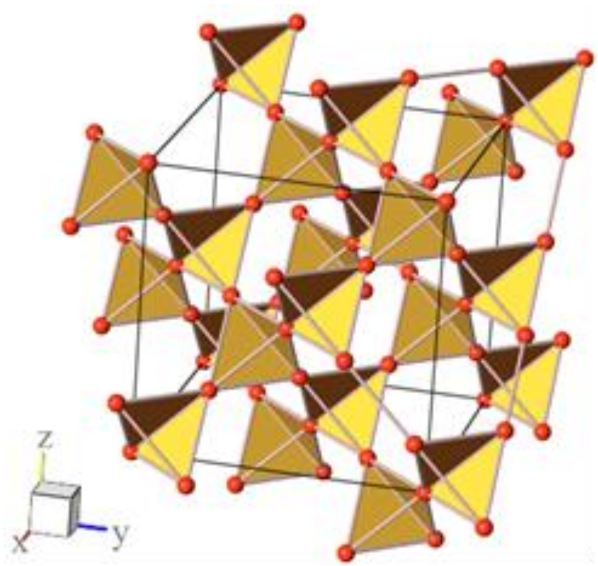
Spin ice & emergent monopoles

AF Ising model on a pyrochlore lattice

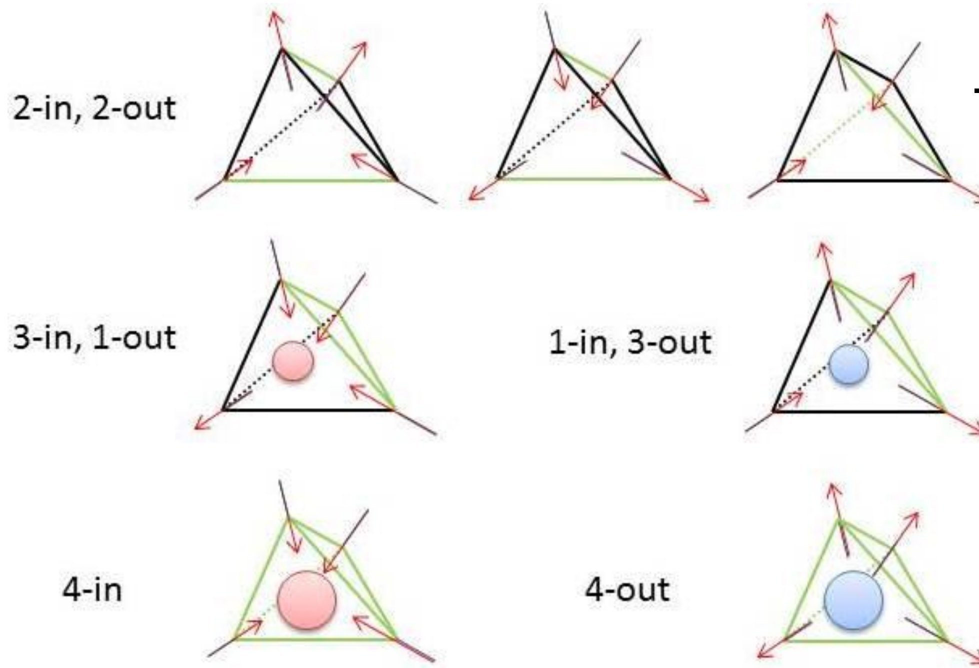
Moessner-Sondhi

$$H = 4J \sum_{<r,r'>}^{n.n.} S_r^z S_{r'}^z$$

S_r^z : Ising (S=1/2) spin



Energy/Monopole charge



$-2J / 0$

$0 / \pm 1$

$6J / \pm 2$

Classical Coulomb-phase physics: divergence-free $\nabla \cdot S^z = 0$

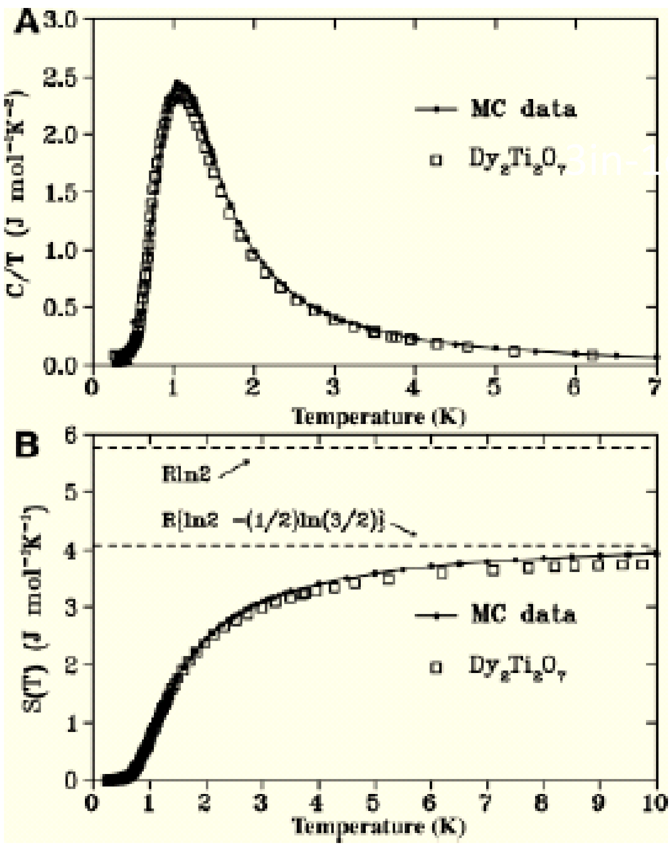
Experiments and numerics on dipolar spin ice

Harris, Ramirez, Bramwell, Sakakibara , Hiroi, Maeno, Gingras

$Dy_2Ti_2O_7$, $Ho_2Ti_2O_7$

N.N. Ising coupling J∼ 2.4 K

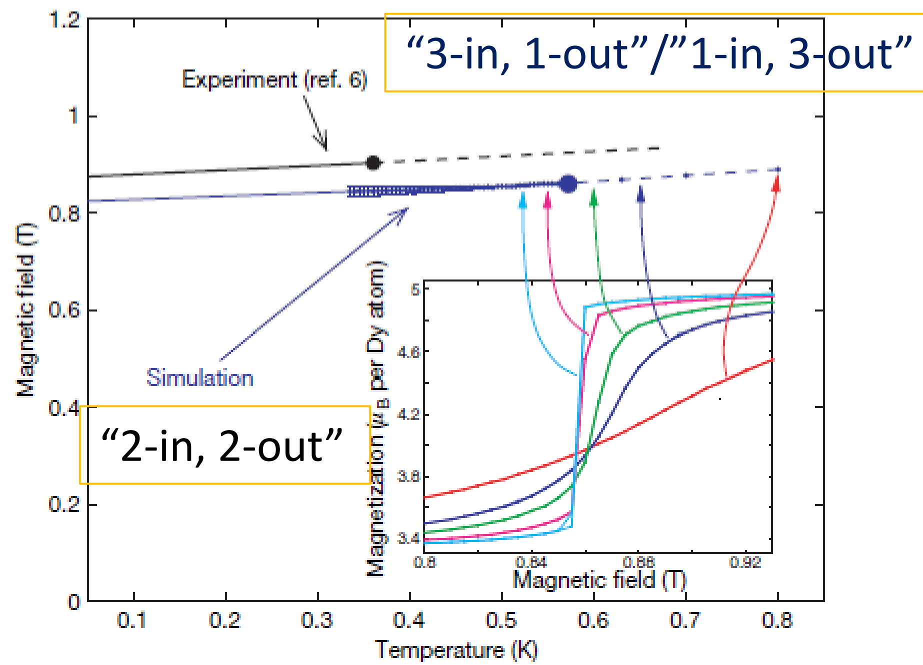
Castelnovo-Moessner-Songhi, Nature 451, 42-45 (2008)



Gingras

Metamagnetic transition under H // (111)

→ **liquid-gas phase transition of monopoles**



Exp., Sakakibara et al., *Phys. Rev. Lett.* 90, 207205 (2003).

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Dipolar spin correlations

- O(N) Heisenberg antiferromagnet

S.V. Isakov, K. Gregor, R. Moessner, S. L. Sondhi, *Phys. Rev. Lett.* 93, 167204 (2004).

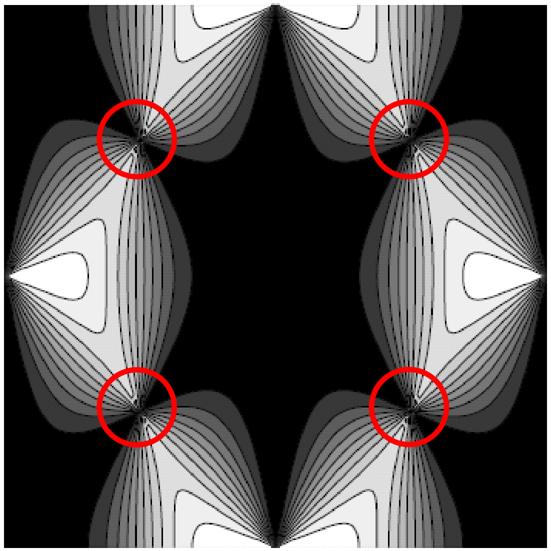
1/N expansion → dipolar spin correlations

$$\mathcal{L}(S,\lambda) = \sum_{i,j}\sum_{\alpha=1}^{N}\frac{1}{2}S_i^\alpha A_{ij} S_j^\alpha + i\frac{\lambda_i}{2}\delta_{i,j}(S_i^\alpha S_i^\alpha - N),$$

$$2\begin{pmatrix} 1 & c_{xz} & c_{xy} & c_{yz} \\ c_{xz} & 1 & c_{\overline{yz}} & c_{\overline{xy}} \\ c_{xy} & c_{\overline{yz}} & 1 & c_{\overline{xz}} \\ c_{yz} & c_{\overline{xy}} & c_{\overline{xz}} & 1 \end{pmatrix}$$

$$c_{ab} = \cos(\tfrac{q_a+q_b}{4}) \text{ and } c_{\overline{ab}} = \cos(\tfrac{q_a-q_b}{4})$$

Works well for N=1 (Ising) and infinity.



cf. pinch-point singularity

C. L. Henley, *Phys. Rev. B* 71 014424 (2005)

divergence-free condition of spin-ice rule

Experiments on dipolar spin ice: Morris et al., Fennell et al.

From classical to quantum spin ice

Assumptions:

(i) A large amplitude of magnetic moments.

$$\hat{H}_{\mathrm{D}} = \frac{\mu_0}{4\pi} \sum_{\langle \boldsymbol{r},\boldsymbol{r}' \rangle} \left[\frac{\hat{\boldsymbol{m}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{m}}_{\boldsymbol{r}'}}{(\Delta r)^3} - 3\frac{(\hat{\boldsymbol{m}}_{\boldsymbol{r}} \cdot \Delta \boldsymbol{r})(\Delta \boldsymbol{r} \cdot \hat{\boldsymbol{m}}_{\boldsymbol{r}'})}{(\Delta r)^5} \right]$$

(ii) Spins obey the classical statistics.

$$\hat{H}_{\mathrm{Ising}} = -D_{\mathrm{Ising}} \sum_{\boldsymbol{r}} (\boldsymbol{n}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{J}}_{\boldsymbol{r}}/J)^2,$$

→ This is taken to infinity!

(iii) Higher-order multipolar interactions are ignored.

$$\hat{H}_{\mathrm{H}} = -3J_{\mathrm{n.n.}} \sum_{\langle \boldsymbol{r},\boldsymbol{r}' \rangle}^{\mathrm{n.n.}} \hat{\boldsymbol{J}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{J}}_{\boldsymbol{r}'}/J^2.$$

← Ad-hoc Heisenberg exch. Int.
Not so simple

With a smaller moment amplitude and/or a larger D_{3d} crystal field, these assumptions do not hold in general.

Tb_2*TM_2*O_7, Pr_2*TM_2O_7, $Yb_2TM_2O_7$ (TM=Ti, Zr, Sn, Hf, Ir, …)*

Spin-flipping interactions: quantum mechanics!

Classical-to-quantum Coulomb-phase physics

- Classical case: particles obeying a Coulombic law

$$H_{cl} \approx \frac{1}{8\pi}\mathbf{E}^2 - \mu\psi^+\psi + u\psi^+\psi\psi^+\psi$$

→ Coulomb propagator

$$\nabla\cdot\mathbf{E} = g(\psi^+\psi) \leftarrow \hat{S}^z = \mathbf{E}\cdot\mathbf{z}$$

ψ^+, ψ : **Spinon** operators creating and annihilating the gauge charge

- Quantum case: kinetic energy with gauge field

$$H_{qm} \approx \frac{1}{8\pi}(\mathbf{E}^2 + \mathbf{B}^2) + \frac{1}{2m}\psi^+(-i\hbar\nabla + g\mathrm{A})^2\psi - \mu\psi^+\psi + u\psi^+\psi\psi^+\psi$$

$$\nabla\cdot\mathbf{E} = g(\psi^+\psi) \leftarrow \hat{S}^z = \mathbf{E}\cdot\mathbf{z}$$

$$\mathbf{B} = \nabla\times\mathbf{A} \leftarrow \hat{S}_r^{\pm} = \psi^+_{r\pm d}e^{\pm iA_{r+d,r-d}}\psi_{r\mp d}$$

$$[A_{r+d,r-d}, E_{r+d,r-d}] = i$$

Abelian Higgs models:
Savary-Balents
(non-interacting spinons)
S.Lee-S.O.-Balents
(interacting spinons)

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Weak quantum effects on spin-ice manifold

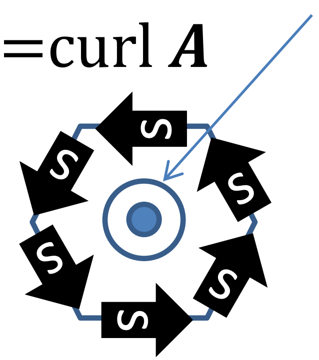
A simple quantum pseudospin-1/2 Hamiltonian

Hermele-Fisher-Balents, PRB 69, 64404

$$\hat{H} = J_{n.n.} \sum_{\langle r,r' \rangle}^{n.n.} \left[\underbrace{g^{\parallel}}_{J_{zz}} \hat{\sigma}_r^z \hat{\sigma}_{r'}^z + \underbrace{g^{\perp}}_{J_{+-}/2} \left(\hat{\sigma}_r^x \hat{\sigma}_{r'}^x + \hat{\sigma}_r^y \hat{\sigma}_{r'}^y \right) \right]$$

Fictitious "magnetic" field

$\boldsymbol{B}$=curl $\boldsymbol{A}$



1. Assume $J_{n.n.} > 0$, $g^{\parallel} > 0$.
2. Start from degenerate spin-ice ground states
3. 3rd-order perturbation in $g^{\perp}$

→π-flux ($g^{\perp} > 0$) or 0-flux ($g^{\perp} < 0$)

→ emergent gauge fields!

→ deconfined bosonic spinons

The model is oversimplified for real materials, though...

Fictitious QED

Ignore gapped spinon excitations first!

curl

$$\mathcal{H}_p = \frac{U}{2} \sum_{\langle \mathbf{r}\mathbf{r}' \rangle} e_{\mathbf{r}\mathbf{r}'}^2 - K \sum_{\bigcirc} \cos\left(\sum_{\mathbf{r}\mathbf{r}' \in \bigcirc} a_{\mathbf{r}\mathbf{r}'} \right)$$

→Hamiltonian for electric field

Constraints for pseudospin-1/2 ($U \to \infty$)

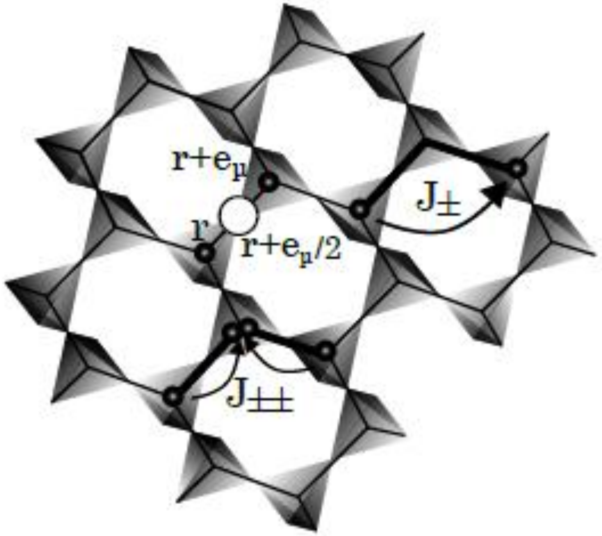
→ Hamiltonian for magnetic field penetrating hexagons

→ Deconfined Coulomb phase of 3+1D QED

Linearly dispersive gapless “photons” excitations

What is “quantum spin ice”?

- **Deconfined spinons carrying monopole chagre**
  - hosted by a frustrated N.N. Ising interaction as in classical spin ice
  - “Gapped” dressed quasiparticles, but not exactly classical monopole defects in spin ice



- **Perturbed by weak quantum-mechanical spin-flip interactions**
  - spinon hopping, spinon-spinon interaction
  - **Yb2Ti2O7** → Higgs transition from a Coulomb liquid to a ferromagnet
    Chang, SO et al., Nature Comm. 3:992 (2012)
  - **Pr2Zr2O7** → U(1) spin liquid? [SO, unpublished]
- However, … spinons are confined by strong Q.M. interaction or unfrustrated Ising interation → not a QSI
  - Er2Ti2O7 (Ross et al), Nd2Zr2O7 (Aldus et al.)

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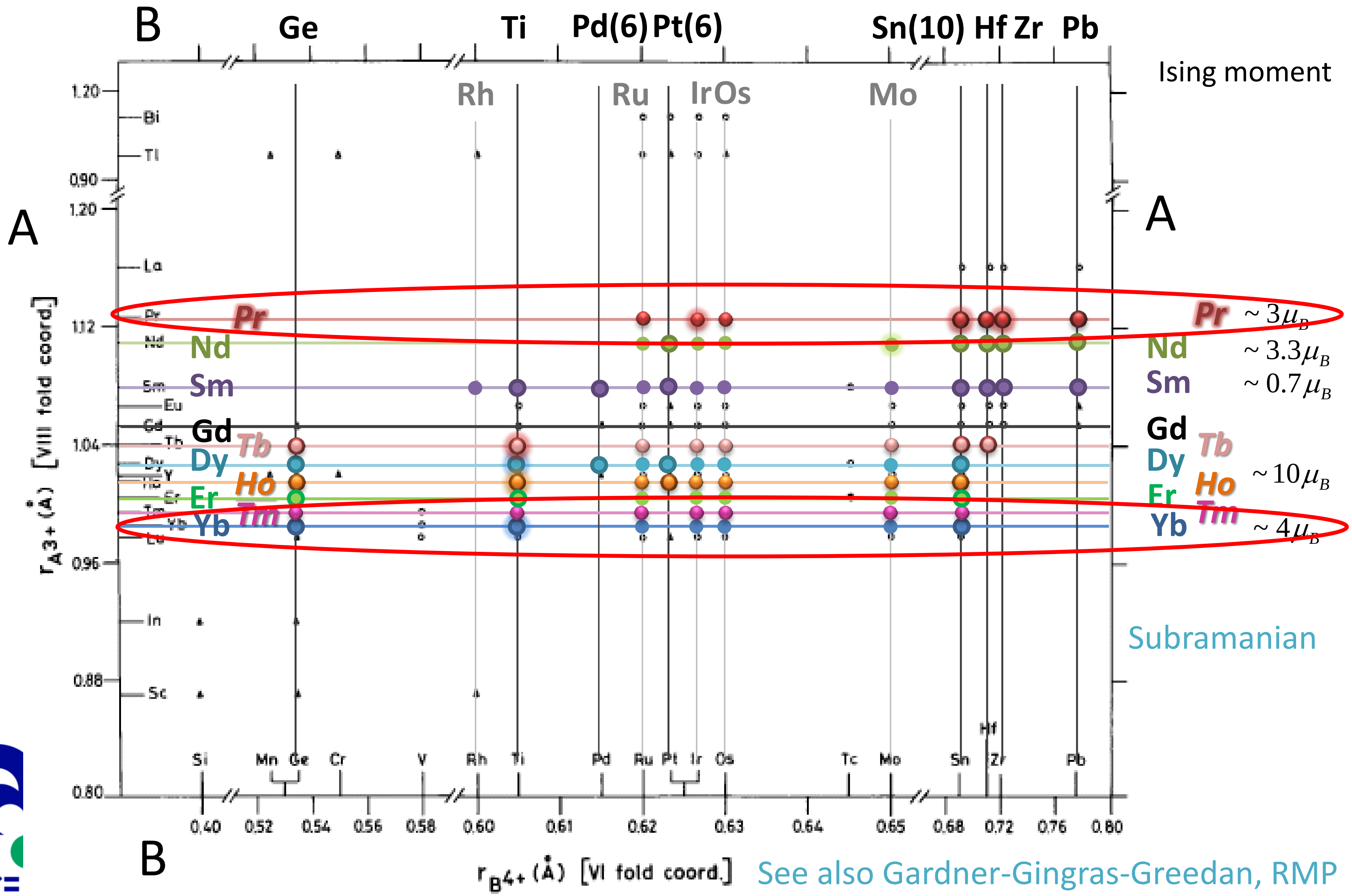
Candidate pyrochlore magnets $A_2B_2O_7$



Subramanian

See also Gardner-Gingras-Greedan, RMP

Pr2TM2O7

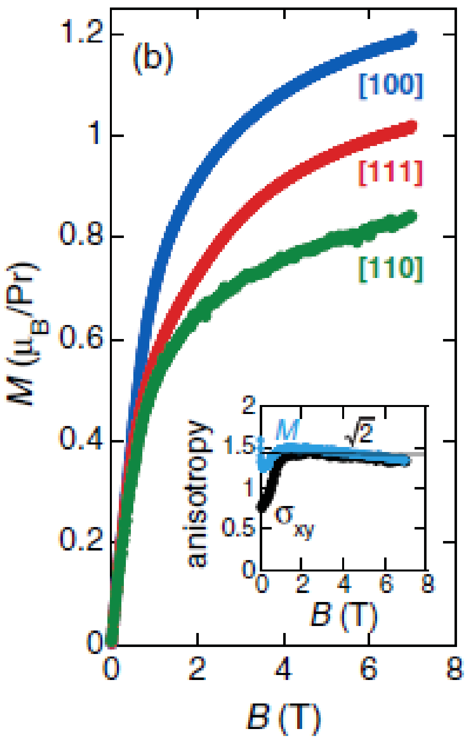
Chiral spin (Pr) state in $Pr_2Ir_2O_7$

doi:10.103

Machida, Nakatsuji, SO et al. Nature 463, 210 (2010)

Time-reversal symmetry breaking and spontaneous Hall effect without magnetic dipole order

Yo Machida[1]†, Satoru Nakatsuji[1], Shigeki Onoda[2], Takashi Tayama[1]† & Toshiro Sakakibara[1]



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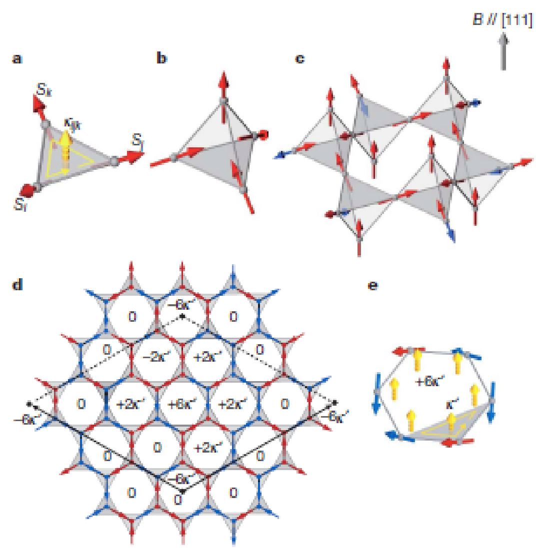
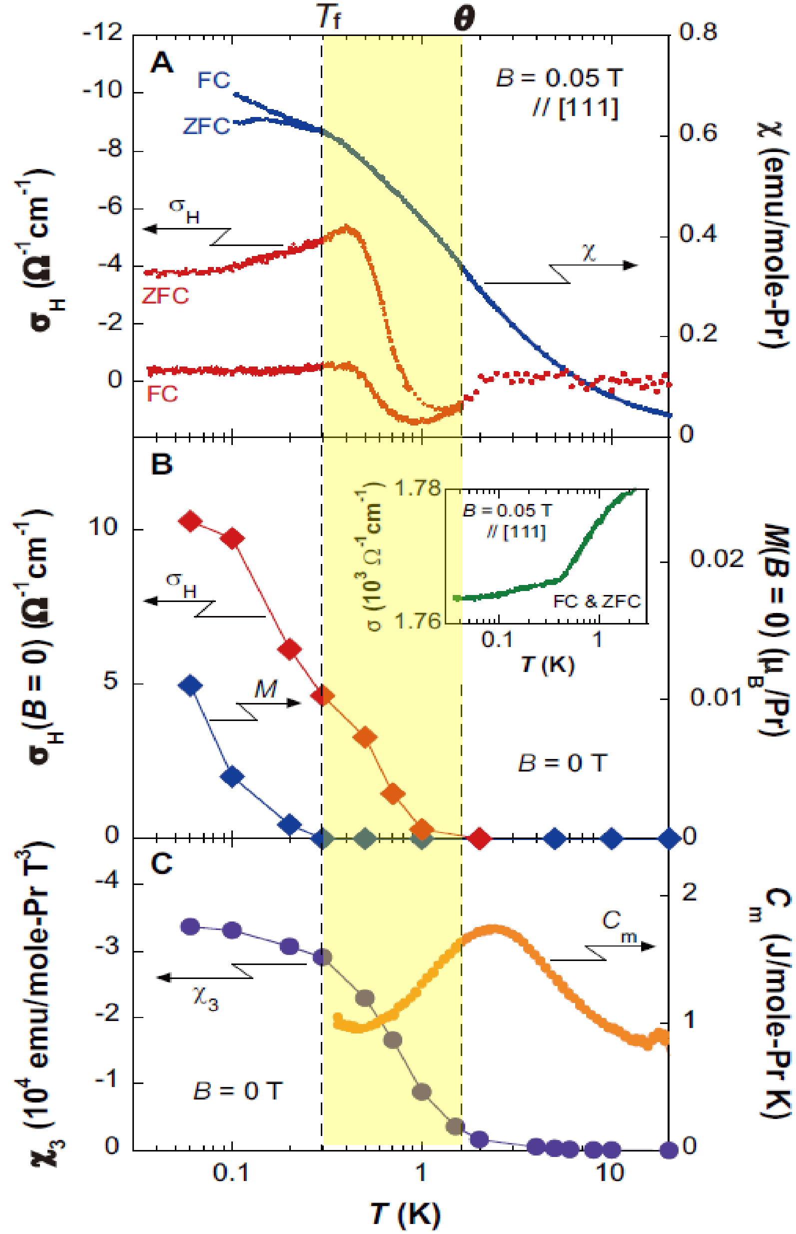
spins are essentially ordered. However, it is usually difficult to extract the scalar spin chirality κ_{ijk} reliably unless the spins are long-range-ordered[8]. In metallic magnets, on the other hand, a promising probe is available: the anomalous Hall effect (AHE)[4,11], which is the spontaneous Hall effect at zero applied magnetic field.





<111> Ising moments of Pr ions

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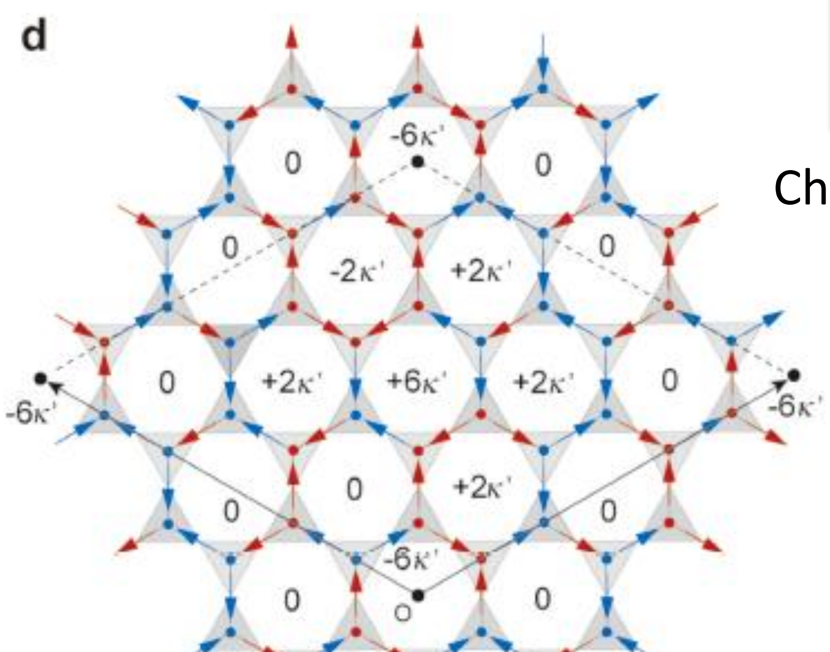
Nonzero uniform chirality with M～0 at H=0: *classical analysis* (Pr)

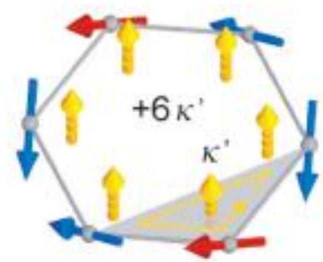
Machida, Nakatsuji, SO et al. Nature 463, 210 (2010)

T-broken spin liquid at $T_f < T < \theta$ ($T_f \sim 0.3$ K, $\theta \sim 1.5$ K)



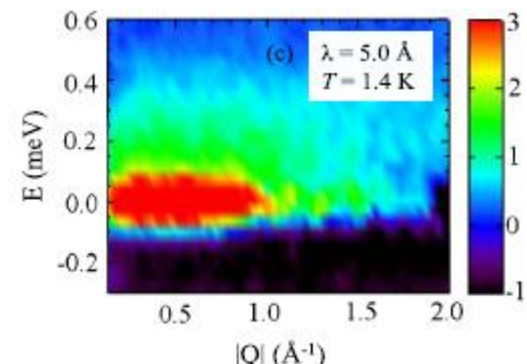
2I2O state having M～0 but nonzero chirality and thus nonzero AHE

Chiral submanifold of the spin ice manifold



Nonvanishing uniform chirality summed over the hexagon

Pr2Sn2O7 Zhou et al.



Quantum spin fluctuations

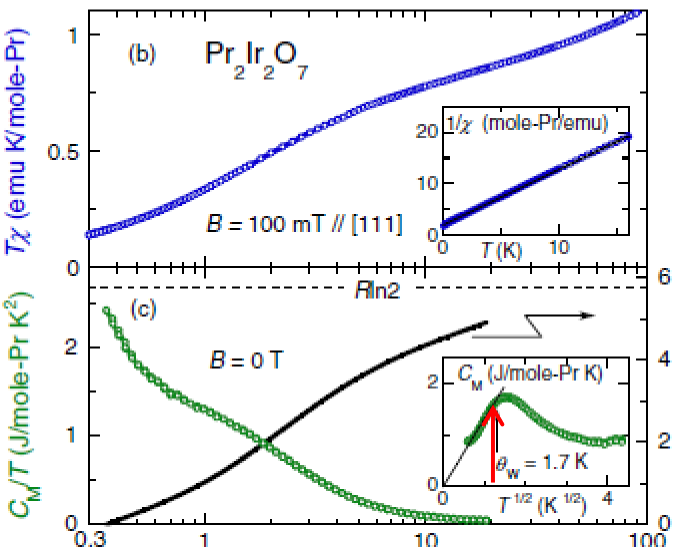
Quantum-mechanical superposition of such classical chiral states, produced by dynamical generation of monopoles?

However, classical spins are long-range ordered or frozen, destabilizing a chiral spin-liquid state.

Similar low-T magnetism in $Pr_2B_2O_7$

B=Ir | **B=Sn** (powder) | *Insulating* **B=Zr**

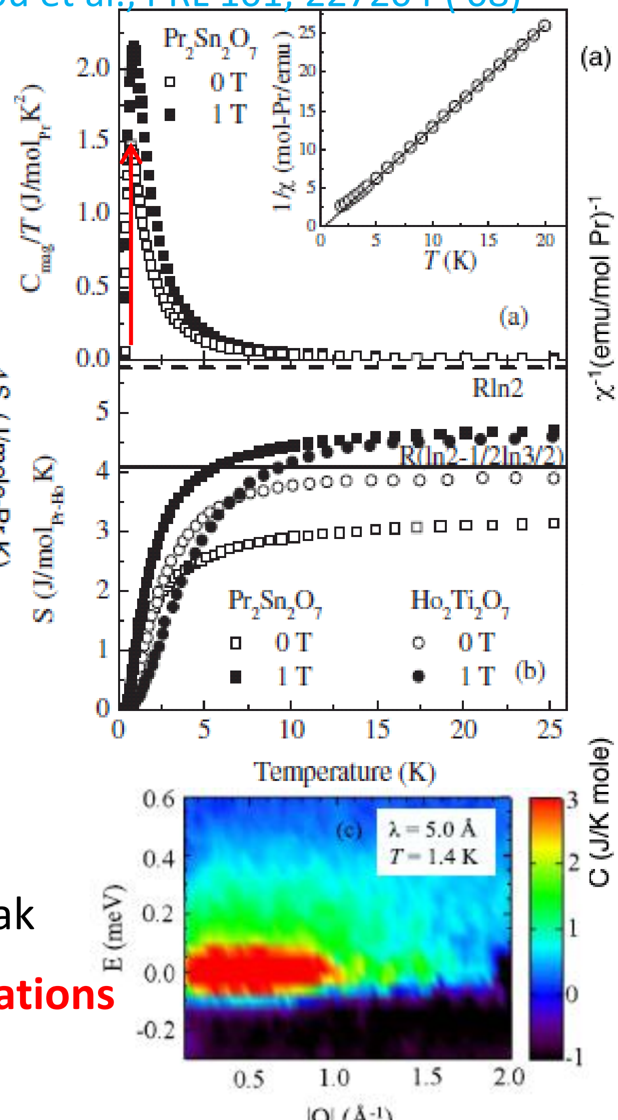
Metallic



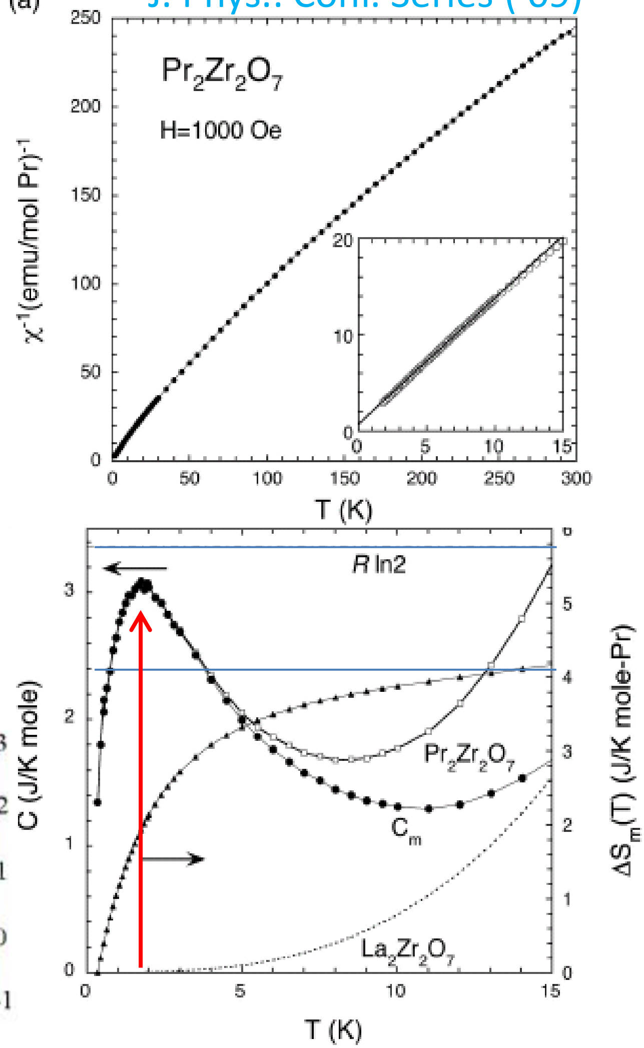
Nakatsuji et al. PRL 96, 087204 ('06)

c.f. Kondo effect at ~20-40 K

Zhou et al., PRL 101, 227204 ('08)



Matsuhira et al.,
J. Phys.: Conf. Series ('09)



No magnetic Bragg peak

Quantum spin fluctuations
～0.4 meV

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$Yb_2Ti_2O_7$

First-order phase transition in Yb2Ti2O7

Hodges et al. 2002

Mossbauer and muon spin relaxation spectroscopies:

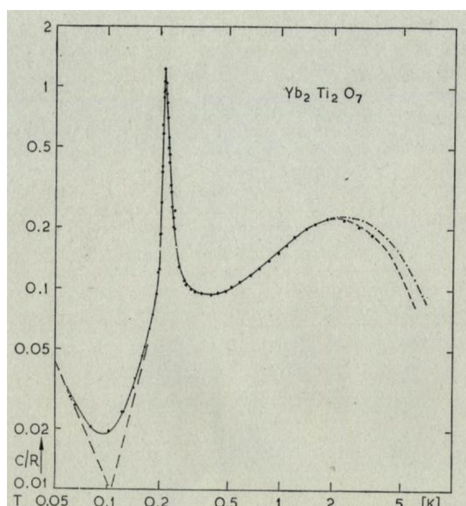
Local Yb ions → Jz=1/2 doublet

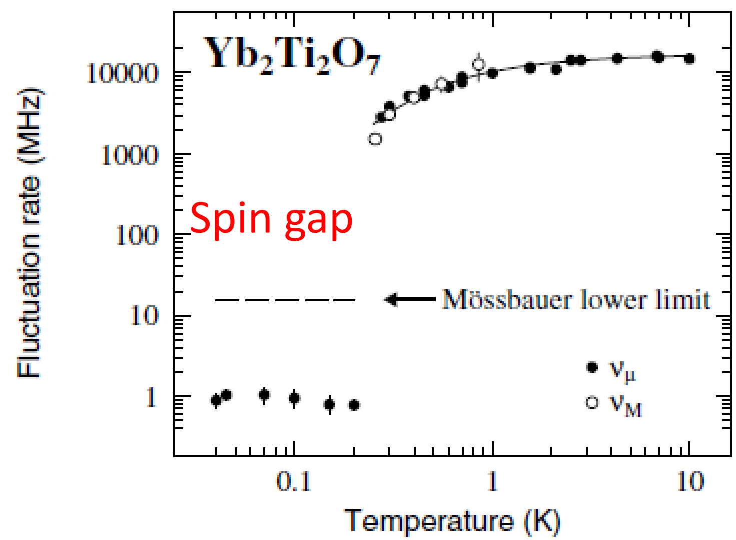
$$|\sigma\rangle_D = -\alpha\sigma|J_z = \frac{7}{2}\sigma\rangle + \beta|J_z = \frac{1}{2}\sigma\rangle + \gamma\sigma|J_z = -\frac{5}{2}\sigma\rangle$$

$$\alpha \approx 0.388, \; \beta \approx 0.889, \; \text{and} \; \gamma \approx 0.242$$

1st-order phase transition @ T ~ 0.21 K

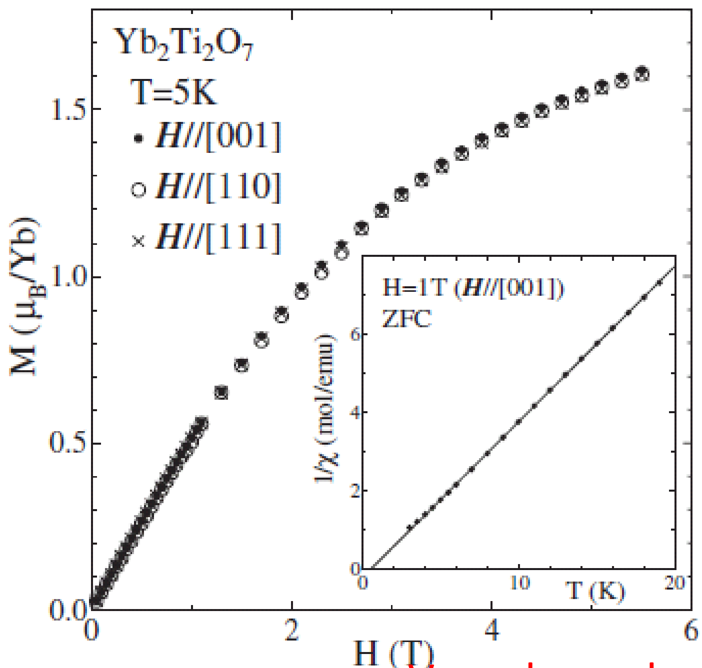
Blotte et al. 1969

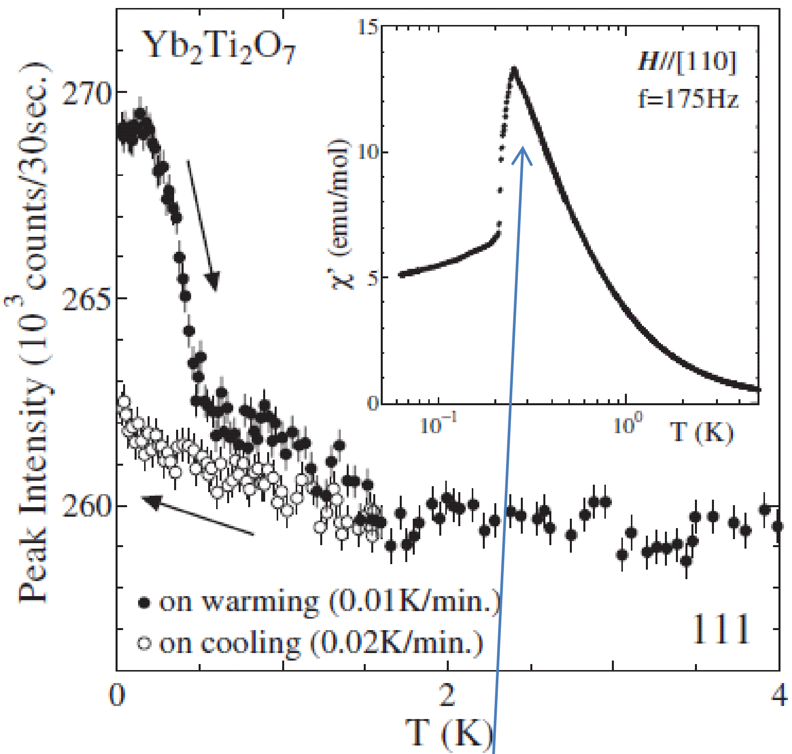




Evidence of the 1st–order phase ferromagnetic transition at ~0.21 K

Yasui et al. JPSJ (2003)





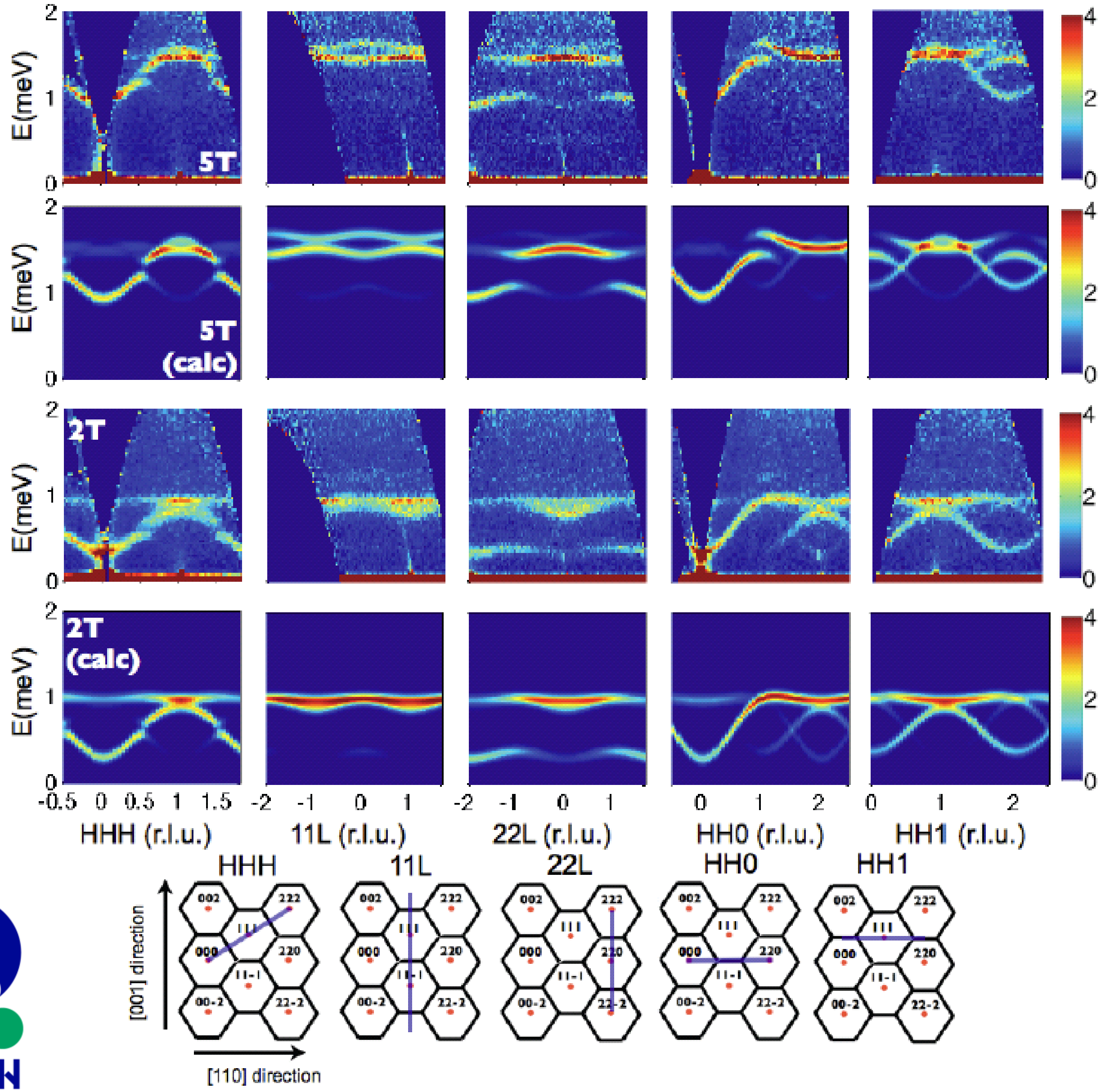
Very slow relaxation of magnetization
Magnetic Bragg peak evolves in 2 hours!

Spin excitations are gapped.

Related anomaly in the specific heat [Blote et al. 1969]

c.f. Sample dependence: the best available sample shows FM, while others does not.
Hodges et al, Thompson et al, Gardner et al, Ross et al

Spin-wave analysis of the high-field state



Ross et al.

$g^{\perp} \sim -0.6$

$g^{q} \sim -0.6$

$g^{K} \sim -1.6$

c.f.
Thompson-…-Gingras
Applegate-…-Gingras

Specific examples:
Derivation of realistic superexchange int.

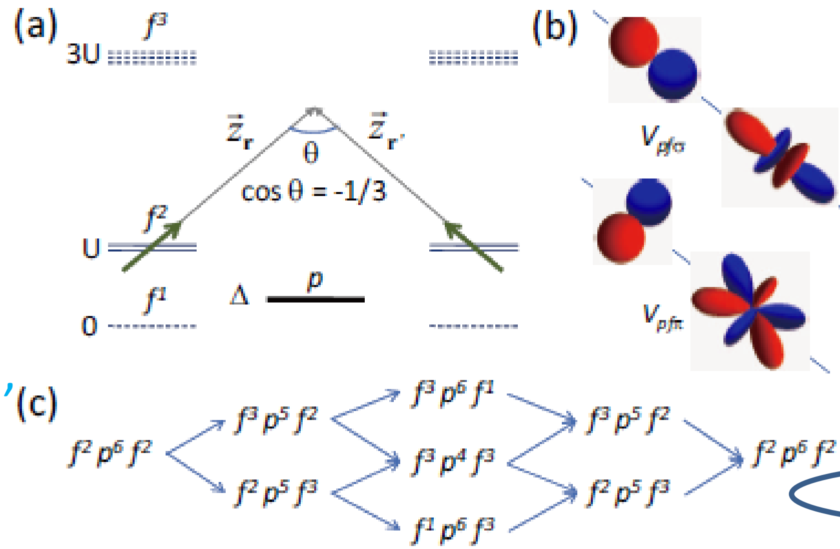
Anderson's superexchange int. →Project onto the gr. doublets

- $Pr_2TM_2O_7$

non-Kramers doublet

(integer-spins)

SO-Tanaka,
PRL **105**, 047201 (2010),
PRB **83**, 094411 (2011).



5th 1392 K Γ_1
4th 1218 K Γ_2
3rd 1044 K Γ_3
2nd 580 K Γ_3
1st 162 K Γ_1
Gr. state 0 K Γ_3

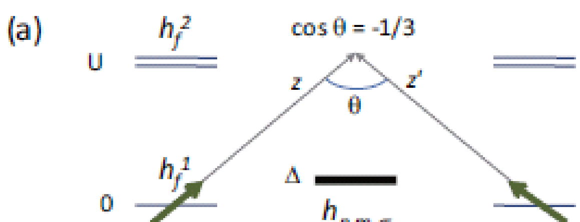
$$|\sigma\rangle = \alpha|M=4\sigma\rangle + \sigma\beta|M=\sigma\rangle - \gamma|M=-2\sigma\rangle$$

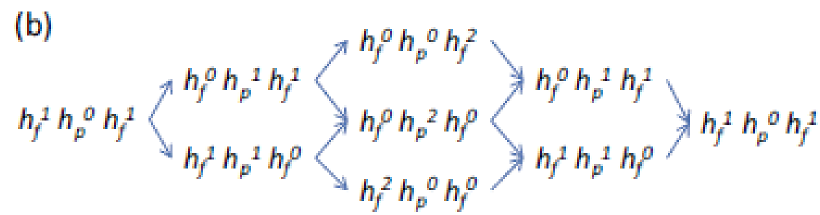
- $Yb_2TM_2O_7$

Kramers doublet (half-integer spins)

SO, J. Phys.: Conf. Series 320, 012065 (2011)

$$|\sigma\rangle_D = -\alpha\sigma|J_z = \frac{7}{2}\sigma\rangle + \beta|J_z = \frac{1}{2}\sigma\rangle + \gamma\sigma|J_z = -\frac{5}{2}\sigma\rangle$$





Effective pseudospin-1/2 model

Anisotropic superexchange interaction
[SO-Tanaka (2009, 2010), SO (2011)]

$$\hat{H}^R_{\mathrm{SE}} = \frac{|J^R_{n.n.}|}{2}\sum_{\langle \boldsymbol{r},\boldsymbol{r}'\rangle}^{n.n.}\Big[sgn(J^R_{n.n.})\hat{S}^z_{\boldsymbol{r}}\hat{S}^z_{\boldsymbol{r}'} + \lambda^R_\perp \hat{S}^+_{\boldsymbol{r}}\hat{S}^-_{\boldsymbol{r}'}$$
$$+\lambda^R_q e^{2i\phi_{\boldsymbol{r},\boldsymbol{r}'}}\hat{S}^+_{\boldsymbol{r}}\hat{S}^+_{\boldsymbol{r}'} + \lambda^R_K e^{i\phi_{\boldsymbol{r},\boldsymbol{r}'}}\left(\hat{S}^z_{\boldsymbol{r}}\hat{S}^+_{\boldsymbol{r}'} + \hat{S}^+_{\boldsymbol{r}}\hat{S}^z_{\boldsymbol{r}'}\right)\Big] + h.c.$$

Magnetic moment

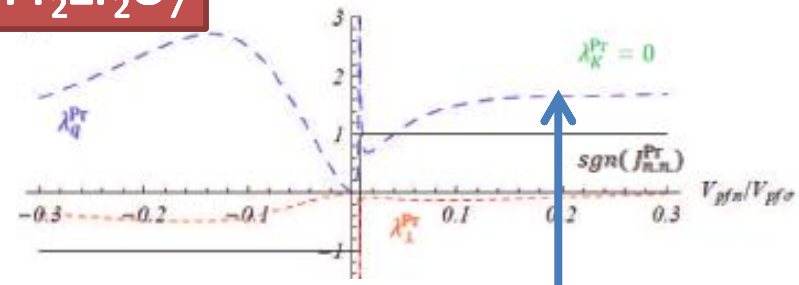
$$\hat{\boldsymbol{m}}^R_{\boldsymbol{r}} = g_J\mu_B\hat{\boldsymbol{J}}^R_{\boldsymbol{r}} = \mu_B\left[g^R_\perp\left(\hat{S}^x_{\boldsymbol{r}}\boldsymbol{x}_i + \hat{S}^y_{\boldsymbol{r}}\boldsymbol{y}_i\right) + g^R_\parallel\hat{S}^z_{\boldsymbol{r}}\boldsymbol{z}_i\right]$$

Magnetic dipole interaction

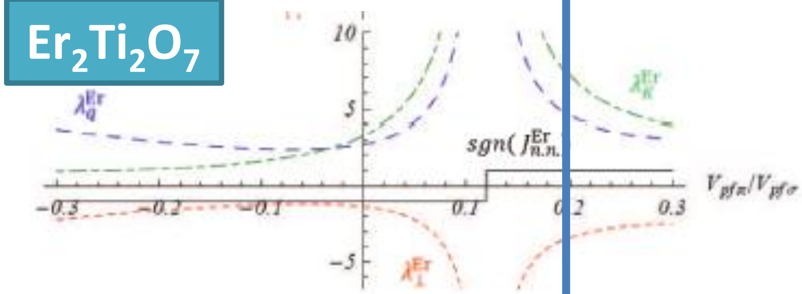
$$\hat{H}^R_{\mathrm{D}} = \frac{\mu_0}{4\pi}\sum_{\langle \boldsymbol{r},\boldsymbol{r}'\rangle}\left[\frac{\hat{\boldsymbol{m}}^R_{\boldsymbol{r}}\cdot\hat{\boldsymbol{m}}^R_{\boldsymbol{r}'}}{(\Delta r)^3} - 3\frac{(\hat{\boldsymbol{m}}^R_{\boldsymbol{r}}\cdot\Delta\boldsymbol{r})(\Delta\boldsymbol{r}\cdot\hat{\boldsymbol{m}}^R_{\boldsymbol{r}'})}{(\Delta r)^5}\right]$$

$Pr_2Zr_2O_7$

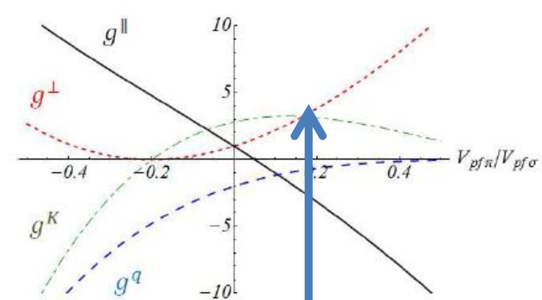
Vpfπ / Vpfσ



$Er_2Ti_2O_7$



Yb2Ti2O7

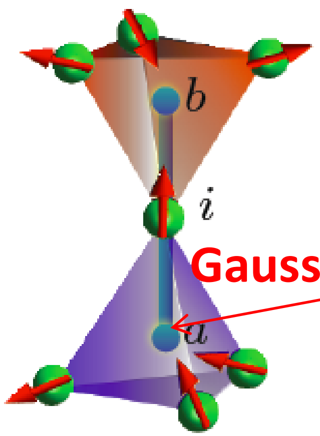


Best fit to
neutron-scattering exp.

RIKEN

Interacting U(1) Higgs model: QED with charged bosonic spinons

S. Lee, S.O., L. Balents
PRB, in press



Gauss' law

$$S_i^z = \eta_a E_{ab} \qquad \eta_a = \pm 1 [a \in A(B)]$$

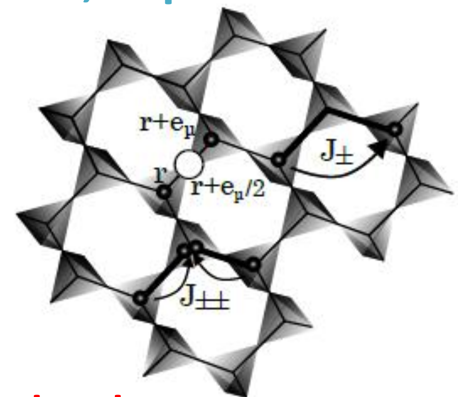
$$S_i^+ = \Phi_a^\dagger e^{iA_{ab}} \Phi_b \qquad \Phi_a = e^{-i\varphi_a}$$

$$Q_a = (divE)_a \qquad \Phi_a^\dagger \Phi_a = 1$$

$$[A_{ab}, E_{ab}] = i$$

$$[\Phi_a, Q_a] = \Phi_a$$

Monopolar spinons
(Higgs bosons)
Increasing/decreasing the charge



c.f. Savary-Balents

$$H_{QED} = \frac{J_{zz}}{2} \sum_{\mathbf{r}} Q_{\mathbf{r}}^2 - J_{\pm} \sum_{\mathbf{r}} \sum_{\mu \neq \nu} \Phi^\dagger_{\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\mu} \Phi_{\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\nu} \mathrm{s}^{-\eta_{\mathbf{r}}}_{\mathbf{r},\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\mu} \mathrm{s}^{+\eta_{\mathbf{r}}}_{\mathbf{r},\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\nu}$$

+δ

$$\cancel{+ \frac{J_{\pm\pm}}{2} \sum_{\mathbf{r}} \sum_{\mu \neq \nu} (\gamma_{\mu\nu}^{-2\eta_{\mathbf{r}}} \Phi^\dagger_{\mathbf{r}} \Phi^\dagger_{\mathbf{r}} \Phi_{\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\mu} \Phi_{\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\nu} \mathrm{s}^{\eta_{\mathbf{r}}}_{\mathbf{r},\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\mu} \mathrm{s}^{\eta_{\mathbf{r}}}_{\mathbf{r},\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\nu} + h.c)}$$

+q

$$\cancel{+ J_{z\pm} \sum_{\mathbf{r}} \sum_{\mu \neq \nu} \mathrm{s}^z_{\mathbf{r},\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\mu} (\gamma_{\mu\nu}^{-\eta_{\mathbf{r}}} \Phi^\dagger_{\mathbf{r}} \Phi_{\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\nu} \mathrm{s}^{\eta_{\mathbf{r}}}_{\mathbf{r},\mathbf{r}+\eta_{\mathbf{r}}\mathbf{e}_\nu} + h.c.) + \mathrm{const.}.}$$

+K

Starting from U(1) spin liquid
with deconfined spinons

Non-Kramers doublets (integer spins) (Pr)

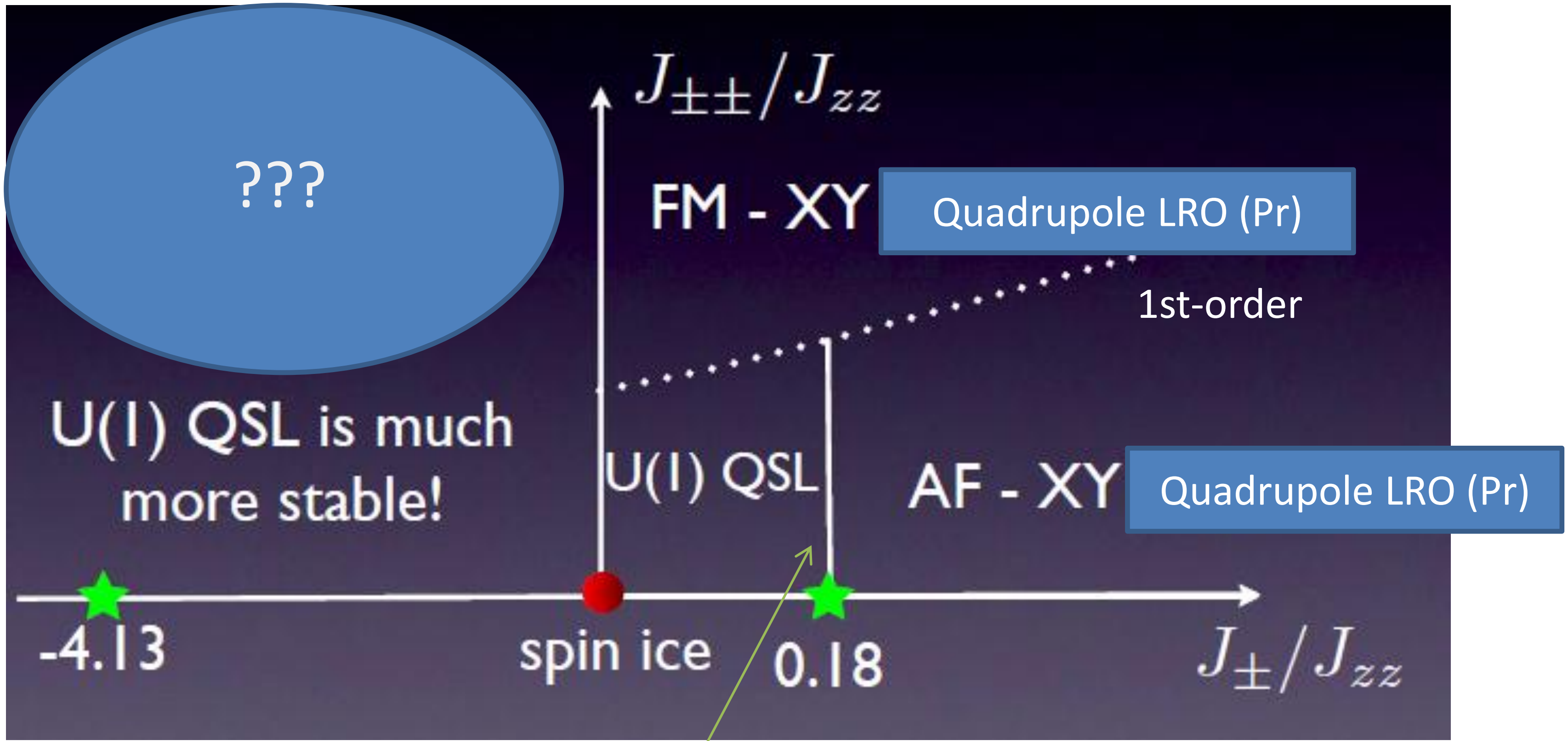
Classification of mean-field phases

Let’s study the case of integer spins: non-Kramers doublets (Pr)

	$\langle \mathrm{s}^z_{\mathbf{r},\mathbf{r}\pm\mathbf{e}_\mu} \rangle$	$\langle \mathrm{s}^\pm_{\mathbf{r},\mathbf{r}\pm\mathbf{e}_\mu} \rangle$	$\langle \Phi_\mathbf{r} \rangle$	$\langle \Phi_\mathbf{r} \Phi_\mathbf{r} \rangle$	$\langle \Phi^\dagger_\mathbf{r} \Phi_{\mathbf{r}\pm\mathbf{e}_\mu} \rangle$
Ising order (confined)	$\neq 0$	0	0	0	0
QSL					
U(1)	0	$\neq 0$	0	0	0
Z_2	0	$\neq 0$	0	$\neq 0$	0
(charge-2 Higgs)					
XY order					
U(1)	0	$\neq 0$	0	0	$\neq 0$
Classical	0	$\neq 0$	$\neq 0$	$\neq 0$	$\neq 0$
(confined Higgs)					

S. Lee, SO, L. Balents, arXiv:1204.2262

Mean-field phase diagram in the case of non-Kramers doublets (Pr)



S. Lee, SO, L. Balents

Weakly first-order Higgs transition

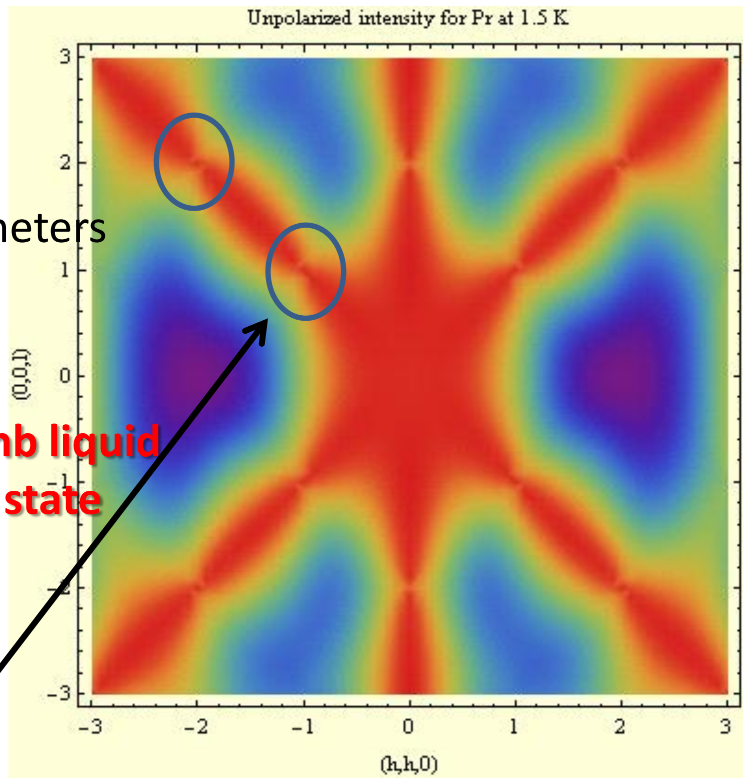
Is $Pr_2Zr_2O_7$ a U(1) QSL?

$$\frac{S(\vec{q})}{M_0^2} = \frac{1}{N}\sum_{r,r'}\sum_{i,j}\left(\delta_{i,j} - \frac{q_i q_j}{|\vec{q}|^2}\right) n_r^i \, n_{r'}^j \left\langle \sigma_r^z \sigma_{r'}^z \right\rangle_{\text{ave}} e^{i\vec{q}\cdot(r-r')}$$

$$\vec{q} = \frac{2\pi}{a}(hhl), \quad M_0 = g_J \mu_B \left(4\alpha^2 + \beta^2 - 2\gamma^2\right)$$

(1/N) expansion

For exchange parameters for $Pr_2Zr_2O_7$



Indication of Coulomb liquid down to the ground state

SO, unpublished

Pinch point singularity is broadened by a dynamical violation of the ice rule

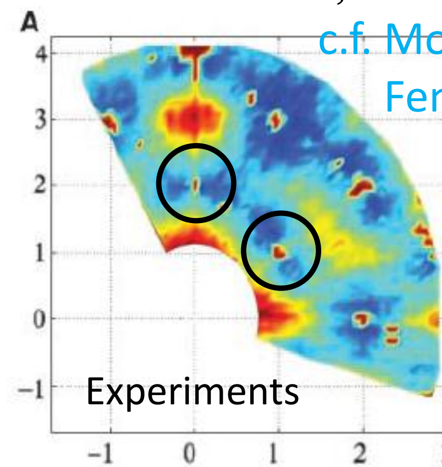
SB theory: no phase transition down to T=0, in the absence of H_D

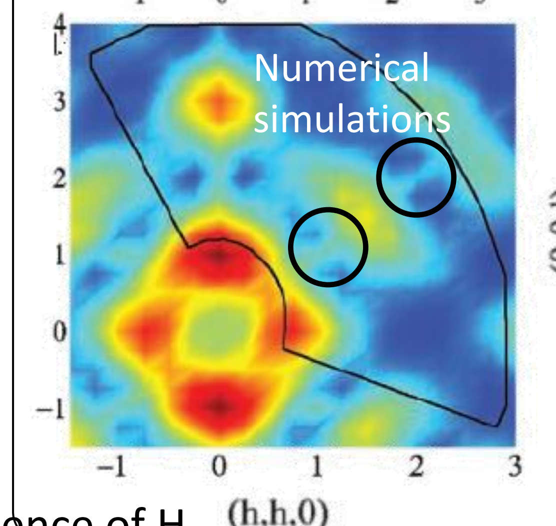
Dipolar spin ice

S.T. Bramwell and M.J.P. Gingras

Science **294**, 1495 (2001)

c.f. Morris et al.
Fennell et al.





Higgs transition

- Superconductivity:
  - Bose condensation of electrically charged particles
  - Described as a Higgs transition

    Higgs mechanism:

    fixing a U(1) phase → broken U(1) gauge structure

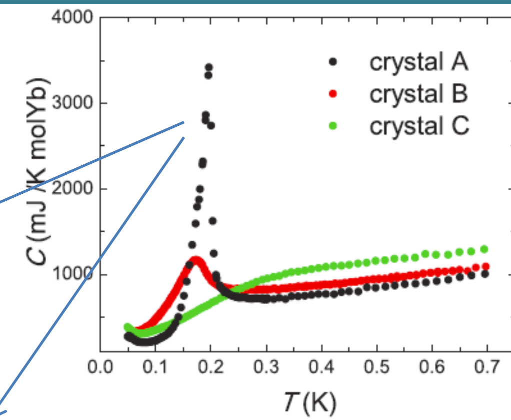
    → Nambu-Goldstone mode is absorbed into plasmons
- Bose condensation of magnetically charged particles
  - Possible in quantum spin ice!
  - Analogous superconducting transition in magnetic monopoles
  - Higgs mechanism: gapped spin excitations!
- T>0 case: Low Tc → could be described with a Higgs tansition!
- Smoothly connected to conventional transitions with increasing Tc.

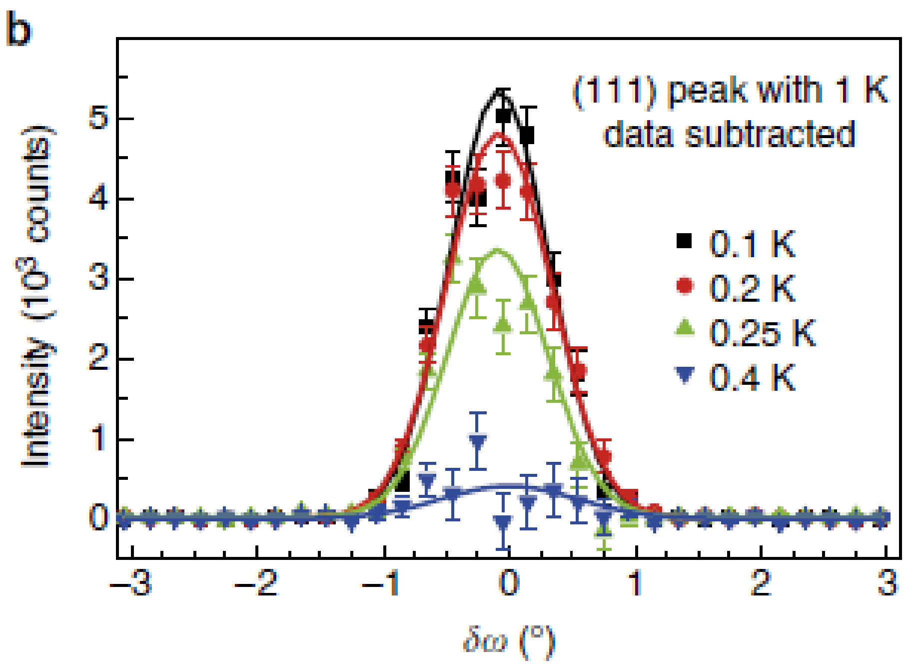
Evidence of first-order ferromagnetic transition

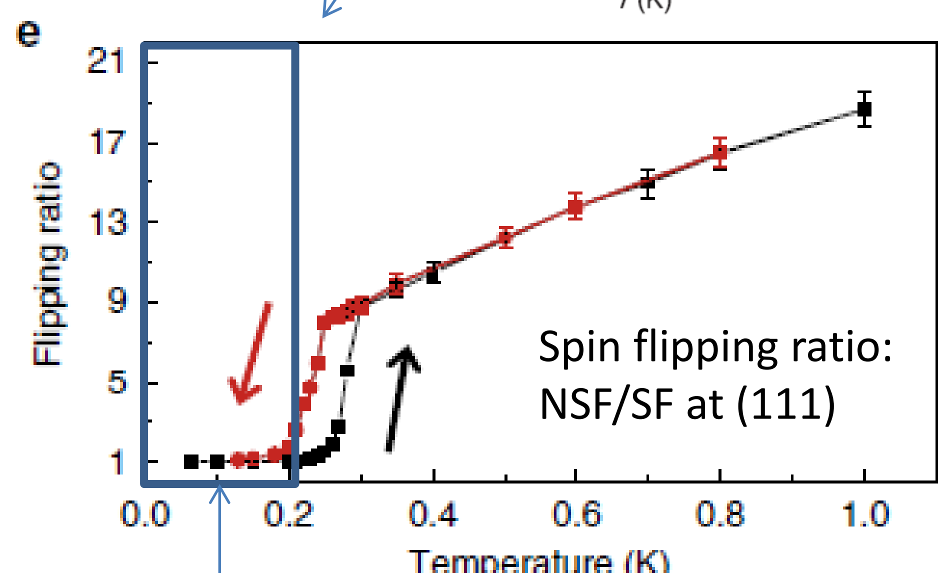
Polarized neutron-scattering intensity

Neutron-spin flipping ratio

showing thermal hysteresis







Full depolarization of neutron spins below 0.21 K

→ Macroscopic ferromagnetic domain

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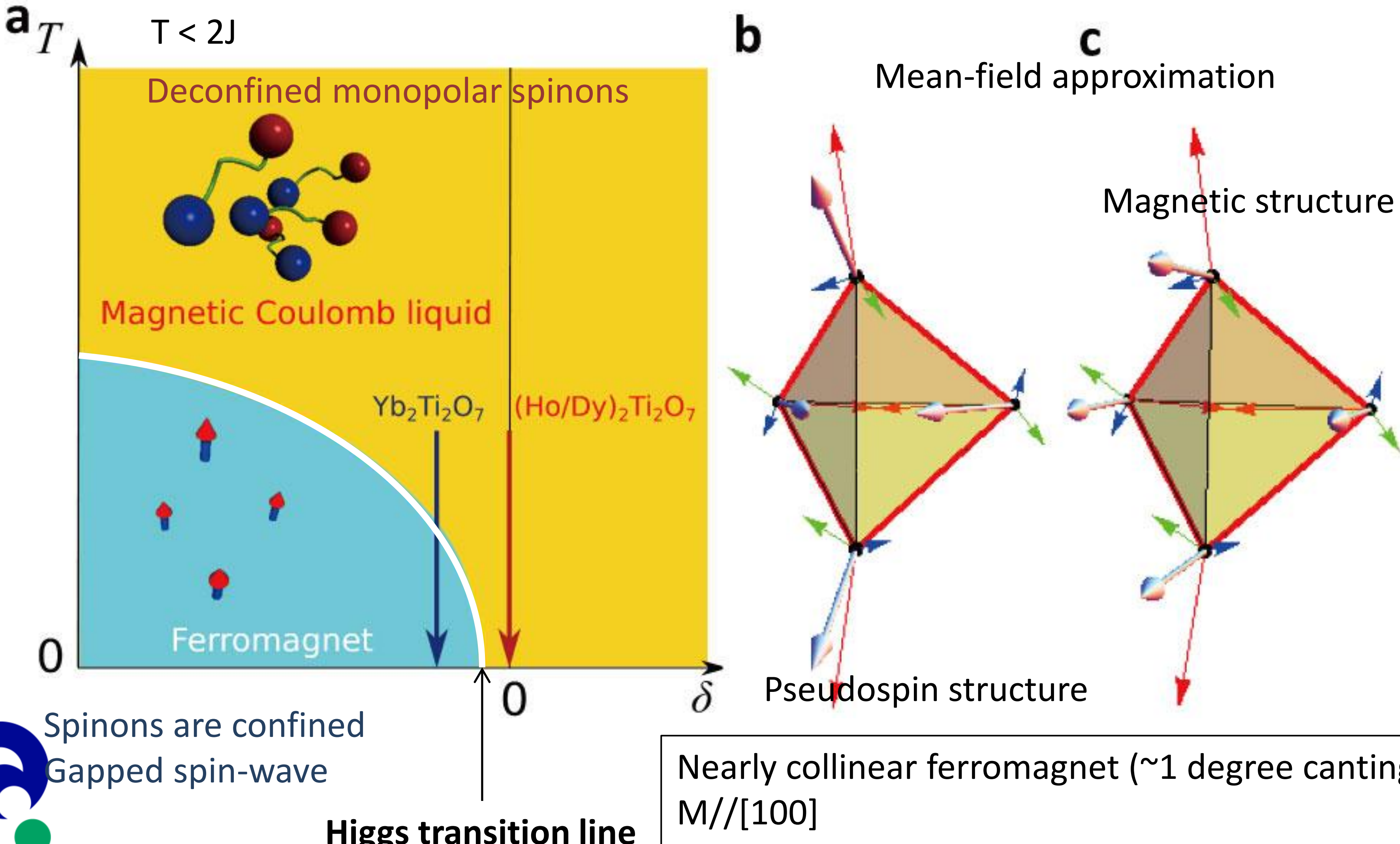
Phase diagram and the hypothetical magnetic structure



Nearly collinear ferromagnet (~1 degree canting)
M//[100]
Consistent with the magnetic structure analysis

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Summary

- Effective quantum pseudospin-1/2 models for $(Pr,Yb)_2 TM_2 O_7$
  - Anisotropic superexchange interaction
    ferromagnetic Ising coupling → start from spin ice
  - Magnetic monopole charges ($\nabla \cdot M \neq 0$) carried by spinons!

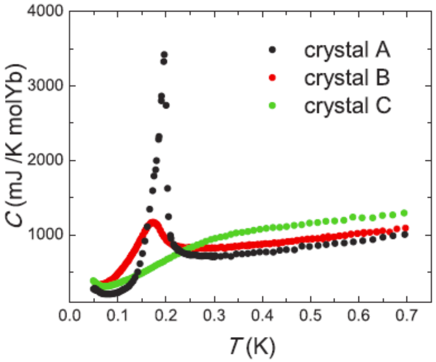
  → Emergent gapless U(1) spin liquid (Fictitous QED)

  → Higgs transitions to classical gapped ferromagnets
  superconductivity of magnetic monopoles

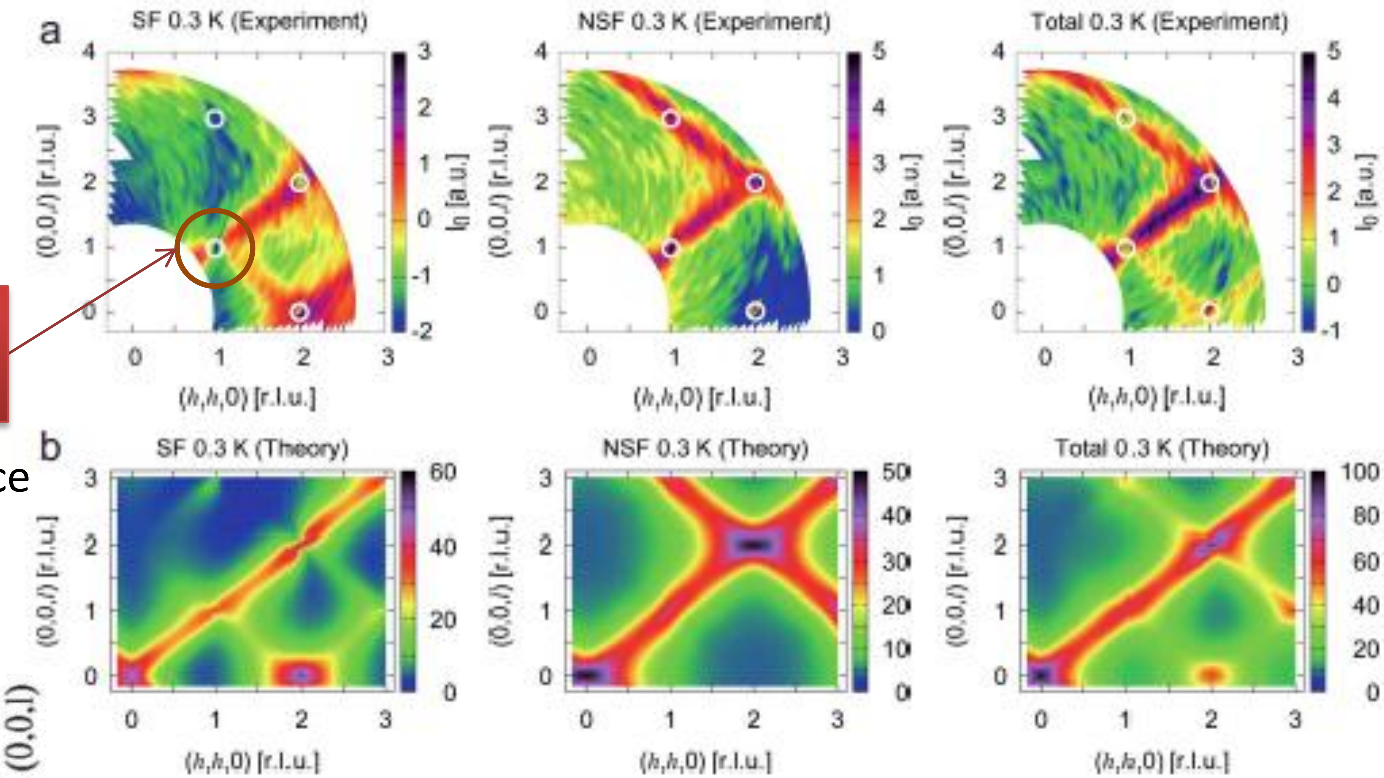
  → Neutron-scattering experiments on high-quality single crystal $Yb_2Ti_2O_7$
  1. deconfined bosonic spinons carrying monopole charge in the high-temperature phase
  2. Confined spinons to form classical ferromagnetism in the low-temperature phase

  → $Pr_2Zr_2O_7$:
  U(1) quatum spin ?
  Remnants of pinch-point singularity

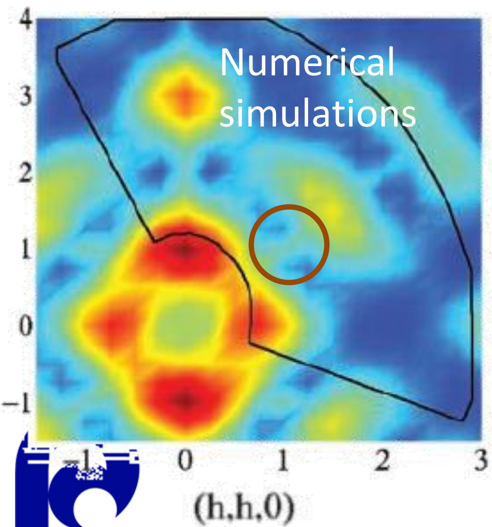
Fitting polarized neutron scattering results within the RPA

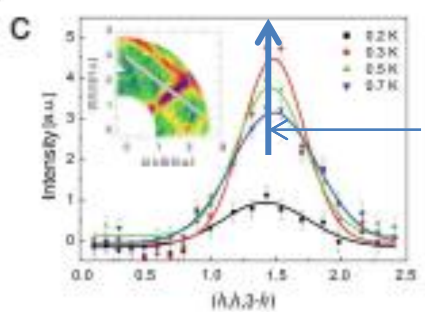


a remnant of pinch-point singularity



c.f. classical dipolar spin ice





Anisotropic nature around (111) grows with decreasing T!

Indication of Coulomb phase

$g^{\perp} \sim -0.8$

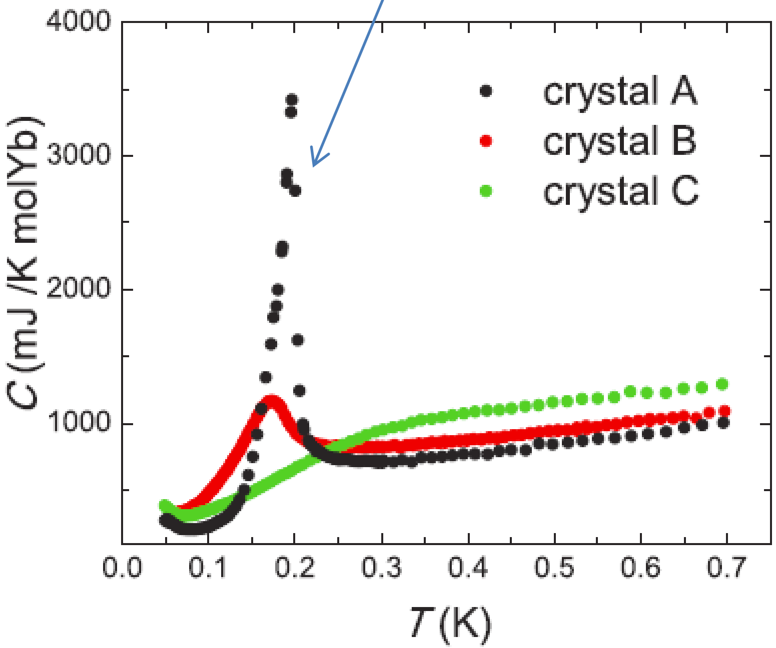
$g^{q} \sim -0.6$

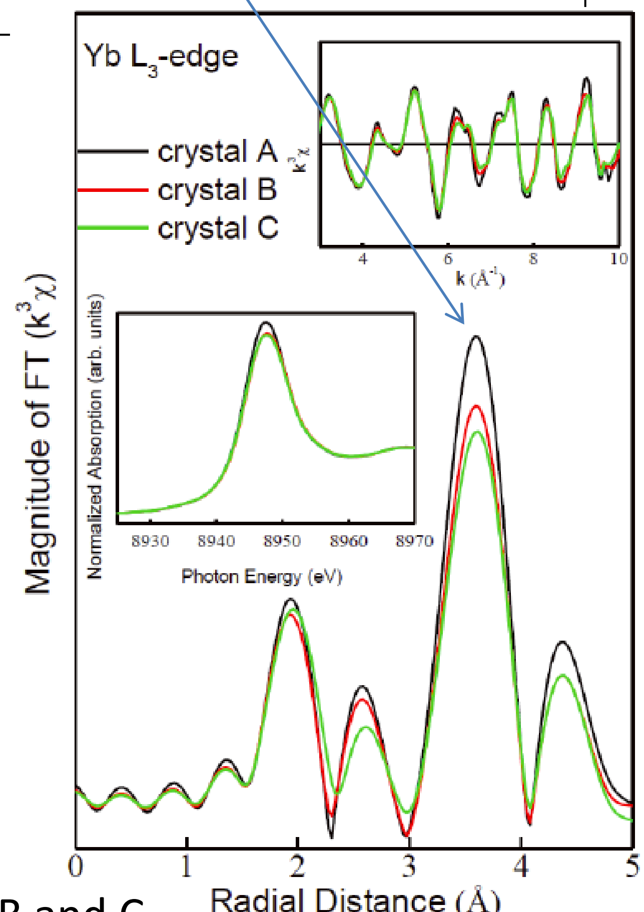
$g^{K} \sim -1.2$

Close to results by Ross et al.

Ferromagnetic ground state is intrinsic!
Dependence on different single crystals

The sample studied for unpolarized (2003) and polarized (2011) neutron scattering
Ferromagnet
Comparable to the result on powder samples by Blote





A bit sharper distribution of bond length
for single crystals showing sharper anomaly
in the specific heat
It turned out that Yb ions are more deficient in B and C.

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