Emergent monopoles and photons in rare earth pyrochlore magnets

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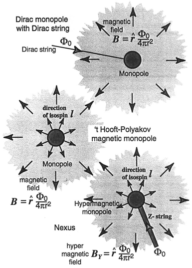
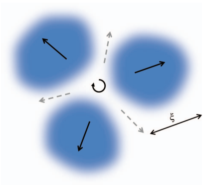
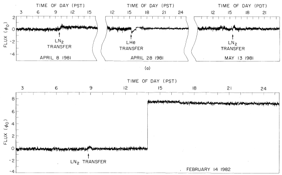






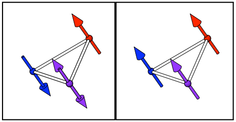
"... it is not certain that nobody has ever seen one. What seems certain is that nobody has ever seen two." Preskill, Ann. Rev. Nuc. Part. Sci. (1984); Cabrera, Phys. Rev. Lett. (1982); Rajantie, Cont. Phys. (2012);

"Their low-energy physics exhibits an emergent gauge field and their excitations are magnetic monopoles that arise from the fractionalization of the microscopic magnetic spin degrees of freedom." Castelnovo *et al.*, Ann. Rev. Cond. Matt. (2012)

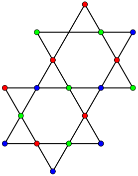
- Frustrated magnetism and rare earth pyrochlores
- Spin ice:
  - Coulomb phase
  - Monopoles
- Quantum spin ice:
  - “Maxwell phase”
  - Candidate materials
- $Tb_2Ti_2O_7$:
  - $Tb_2Ti_2O_7$ as a QSI
  - Power-law correlations
  - Magnetoelastic excitations

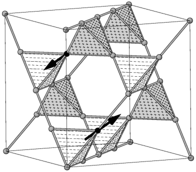
Spin liquids: frustration/competing interactions $\rightarrow$ degeneracy

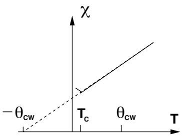
- Balents, Nature (2010)
- Normand, Contemporary Physics (2009)
- Gardner, Gingras, Greedan, Rev. Mod. Phys. (2010)
- Henley, Ann. Rev. Cond. Matt. (2009)
- Castelnovo, Moessner, Sondhi, Ann. Rev. Cond. Matt. (2012)

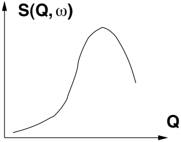


Wannier, Phys. Rev. 1950







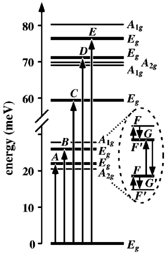


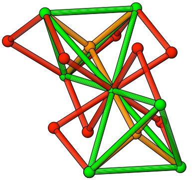
Frustration index: $\theta_{CW}/T_{\mathrm{N}}(>>1)$

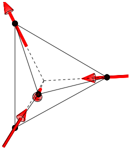
Chalker, arXiv.0901.3492

Rare earth pyrochlores: $Ho_2Ti_2O_7$ and $Dy_2Ti_2O_7$

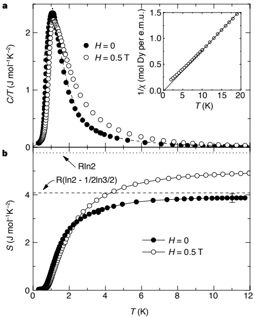
- $R_2Ti_2O_7$ series
- $Fd\bar{3}m$ (two pyrochlore lattices)
- R^{3+} magnetic, Ti^{4+} non-magnetic
- TbTiO - spin liquid
- ErTiO - O-by-D
- YbTiO - QSI







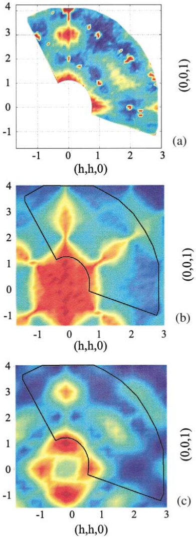
Rosenkranz, J. Appl. Phys., 2000



Ramirez, Nature, 1999

Subramanian *et al* Prog. Sol. St. Chem. **15**, 55 (1983); Gardner *et al.* Rev. Mod. Phys. **82**, 53 (2010)

Spin ice: Hamiltonians

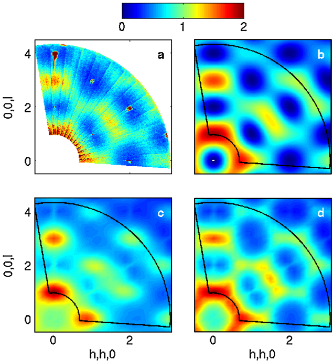


Bramwell, PRL, 2001

$$\boxed{\mathcal{H} = -J\sum_{\langle ij\rangle} S_i \cdot S_j}$$

$$\mathcal{H}_{DSM} = \sum_{n=1,3}(-J_n \sum_{\langle ij\rangle} \mathbf{S}_i^{z_i} \cdot \mathbf{S}_j^{z_j}) + Dr_{nn}^3 \sum_{j>i} \frac{\mathbf{S}_i^{z_i}\cdot\mathbf{S}_j^{z_j}}{|r_{ij}|^3} - \frac{3(\mathbf{S}_i^{z_i}\cdot\mathbf{r}_{ij})(\mathbf{S}_j^{z_j}\cdot\mathbf{r}_{ij})}{|r_{ij}|^5}$$

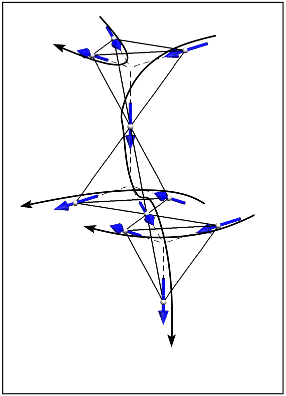
(den Hertog, PRL, 2000)

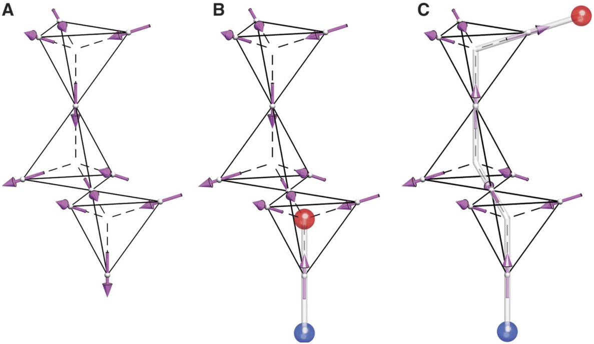


TF, PRB, 2004; Yavors'kii, PRL, 2008

Spin ice: "Classical spin liquid" → Coulomb phase/monopoles

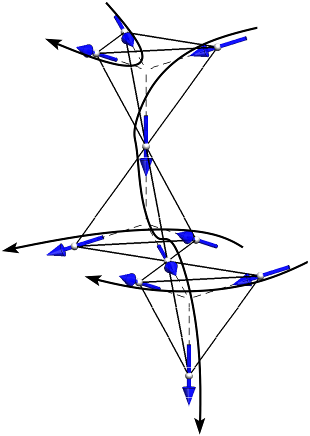
- Ice rule: 2-in-2-out
- Local degrees of freedom map to non-divergent field



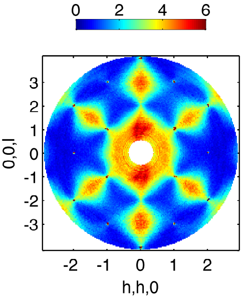


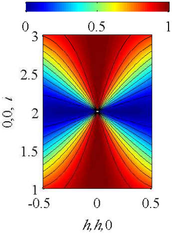
Isakov et al. PRL (2004, 2005); Henley, Ann. Rev. Cond. Matt. (2010); Castelnovo et al. Nature (2008); see also Rhyzkin JETP (2005)

Spin ice: Coulomb phase $\rightarrow$ pinch points



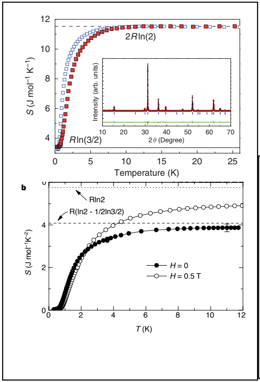
+ $\nabla \cdot M(\mathbf{r}) = 0 \Rightarrow \mathbf{k} \cdot M(\mathbf{k}) = 0$
+ Correlations have spatial dependence of dipolar interaction: *pinch points*

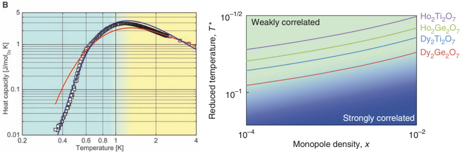


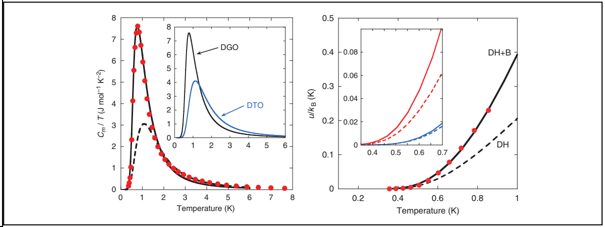


Isakov et al. PRL (2004, 2005); TF et al. Science (2009); Henley, Ann. Rev. Cond. Matt. (2010)

Spin ice: strongly correlated magnetic Coulomb liquid in $Dy_2Ge_2O_7$







Debye-Hückel theory for weak electrolyte, e.g.

$2H_2O = [H_3O^+OH^-] = H_3O^+ + OH^-$

monopole charge $= \pm\mu/(\sqrt{3/2}a)$, $a_{DTO} \sim 10.1$ Å, $a_{DGO} \sim 9.9$ Å

$J_{eff,DTO} = 1.1$ K, $\nu = 4.25$ K; $J_{eff,DGO} = 0.6$ K, $\nu = 3.35$ K

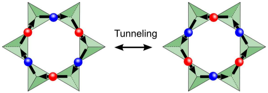
Bramwell *et. al.* Nature (2009); Onsager J. Chem. Phys. (1934); Zhou *et al.*, Nat. Comm. (2011); Morris *et al.*, Science (2009); Castelnovo *et al.* PRB (2011)

Spin ice: summary

+ Deconfined fractional quasiparticles (in 3d)
+ Emergent monopole character (and Coulomb phase)
+ "Magnetolyte"/electrolyte duality
+ Effective theory transforms questions $\rightarrow$ new ideas possible, care required in investigations

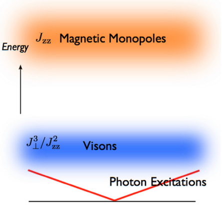
Quantum spin ice: "Maxwell phase" $\rightarrow$ magnetic photons

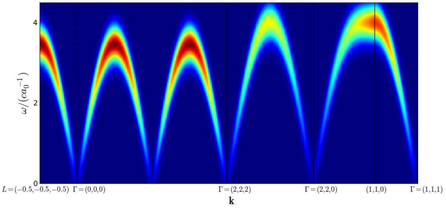
Quantum spin ice



$$\nabla \cdot \mathbf{B}(\mathbf{r}) = 0 \Rightarrow \nabla \times \mathbf{A}(\mathbf{r})$$
$$\Rightarrow \mathbf{E}(\mathbf{r}) = -\frac{\partial \mathbf{A}(\mathbf{r})}{\partial t}$$

Hermele et al., PRB (2004); Shannon et al., PRL (2012); Benton et al., PRB (2012)



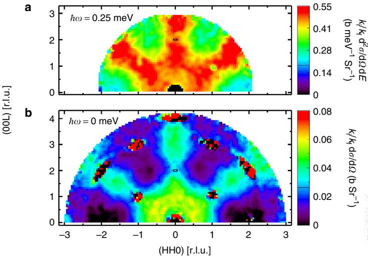


Benton et al., PRB (2012); Gingras & McClarty Rep. Prog. Phys. (2014)

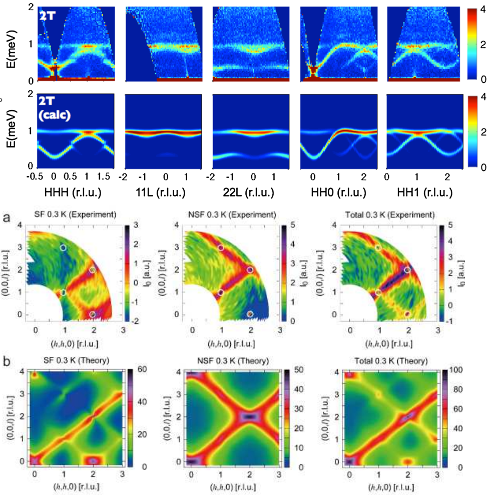
Quantum spin ice: candidate materials

$$\mathcal{H} = \sum_{\langle ij \rangle} \{ J_{zz} S_i^z S_j^z - J_{\pm}(S_i^+ S_j^- + S_i^+ S_j^-) +$$
$$J_{\pm\pm}[\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-] + J_{z\pm}[S_i^z(\zeta_{ij} S_j^+ + \zeta_{ij}^* S_j^-) + i \leftrightarrow j] \}$$

$Pr_2Zr_2O_7$



$Yb_2Ti_2O_7$

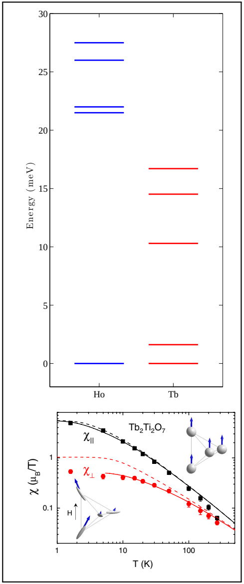


Kimura et al., Nat. Comm. (2013); Ross et al., PRX (2011); Chang et al., Nat. Comm. (2012)

Quantum spin ice: summary

- Quantum generalization of spin ice
- Spinons and photons - but no photons yet observed
- General purpose Hamiltonian for rare earth pyrochlores where dipolar interaction not too large

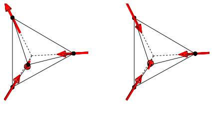
$Tb_2Ti_2O_7$: the original quantum spin ice

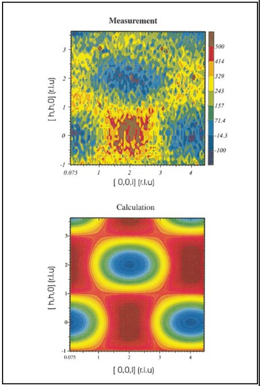


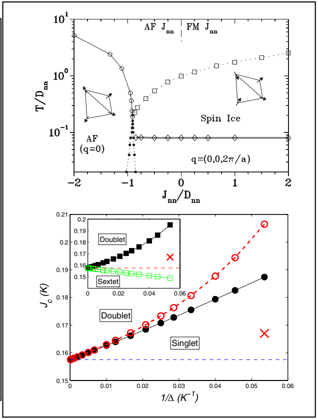
Tb^{3+}: $^7F_6$

$\theta_{CW} = -19$ K

$|\theta_{CW}/T_N| > 380$

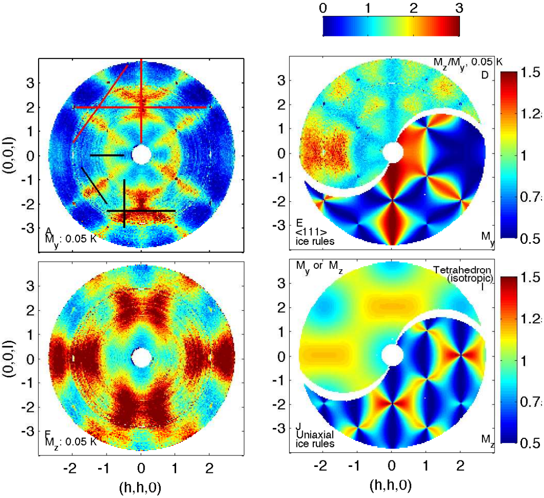


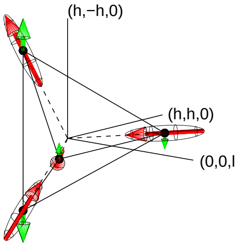




Gardner, RMP (2010); Cao, PRL (2009); Molavian et al., PRL (2007)

$Tb_2Ti_2O_7$: Coulomb phase correlations

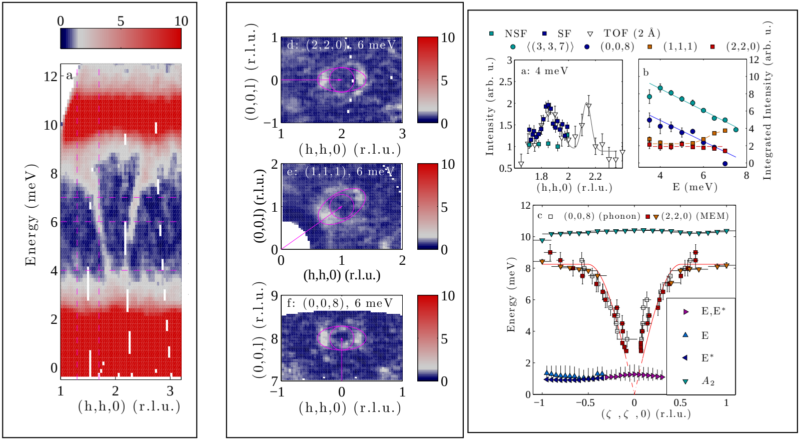




+ $h, \bar{h}, 0$ vertical
+ $I_{SF} \propto \mathbf{S}_{\perp \mathbf{Q}, \perp \mathbf{P}}$
+ $I_{NSF} \propto \mathbf{S}_{\perp \mathbf{Q}, \parallel \mathbf{P}}$

Henley, PRB (2005); TF, PRL (2012)

$Tb_2Ti_2O_7$: magnetoelastic excitations



IN5, TASP + MuPAD

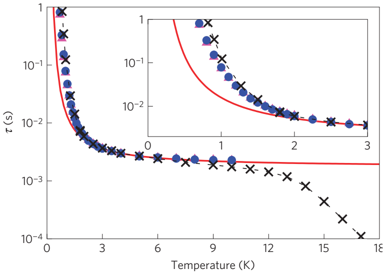
TF et al., PRL (2014)

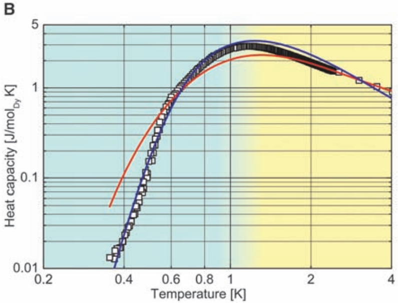
$Tb_2Ti_2O_7$: summary

- Power-law correlations - type of Coulomb phase
- Hybridization of spin and lattice excitations
- Source of fluctuations to melt expected order?

- Neutrons for the study of spin correlations and excitations on the meV energy scale and mK temperature scale

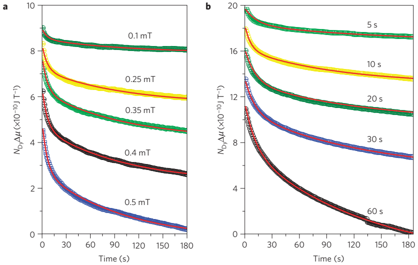
Spin ice: magnetic Coulomb liquid → susceptibility and relaxation at low temperature

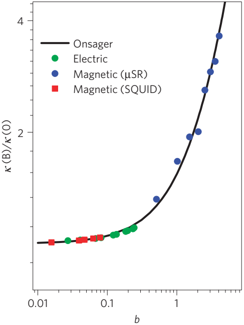




Jaubert, Nat. Phys. (2009); Morris, Tennant, Castelnovo, Moessner *et al.*, Science (2009); CMS, PRB (2011)

Spin ice: magnetic Coulomb liquid → electrolyte/magnetolyte duality





Giblin *et. al.* Nat. Phys. (2011)

Table 1 | Estimated parameters at $T = 0.36$ K.

Description	Symbol	Measured	Expected
Dissociation rate constant	k_D	$1.3(1)\times10^{-4}\ s^{-1}$	
Recombination rate constant	k_R	$1.04\times10^{3}\ s^{-1}$	
Pair-orientation rate constant	k_{Or}	$9.9(9)\times10^{-2}\ s^{-1}$	
Mean monopole hop rate	$\sim ck_R(a/l_T); c\approx7.7$	$1.8\times10^{3}\ s^{-1}$	$\sim10^{3}\ s^{-1}$ (refs 10,24)
Mean monopole lifetime	$\sim(2k_R n_f)^{-1}$	~150 s	
Dissociation equilibrium constant	$K = k_D/k_R = n_f^2/n_b$	1.25×10^{-7}	
Bound-pair density per Dy	$n_b = e^{-T_b/T}$	$1.0(1)\times10^{-4}$	$\sim10^{-6}$ (this work)
Free-charge density per Dy	$n_f = e^{-T_f/T}$	$4(1)\times10^{-6}$	2×10^{-6} (ref. 10)

Single standard-deviation errors on directly estimated quantities are given in brackets.