LiHo(Y)F4 and the quantum dipolar Ising spin glass

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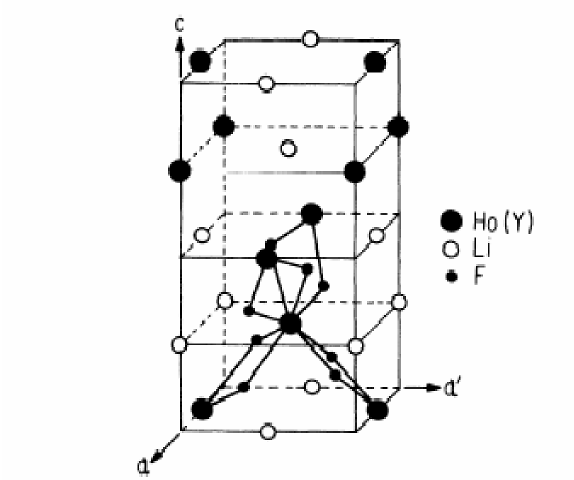


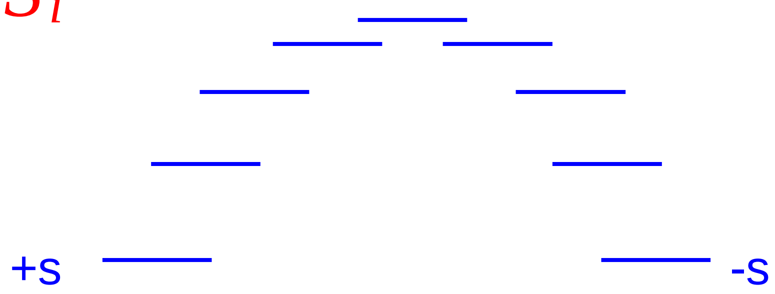
- Dipolar Ising, $LiHo_xY_{1-x}F_4$
- Q SG exp. puzzles
- Solutions
- Conclusions

- M.S. and P. Stamp, PRL 95, 267208 (2005)
- M.S. and N. Laflorencie, Cond-mat/0511304
- M.S. and P. Stamp, in preparation

Ising model in anisotropic dipolar systems

Large spin, strong lattice anisotropy

$$\mathrm{H}_{\mathrm{cf}} = -D\sum_{i} S_i^{z\,2}$$



$$\mathrm{H}_{\mathrm{D}} = \mathrm{H}_{\mathrm{cf}} - \sum_{ij} V_{ij}^{\alpha\beta} S_i^{\alpha} S_j^{\beta}$$

$$\mathrm{H}_{\mathrm{Is}} = -\sum_{ij} J_{ij}\, \tau_i^z \tau_j^z$$

Ising model in anisotropic dipolar systems

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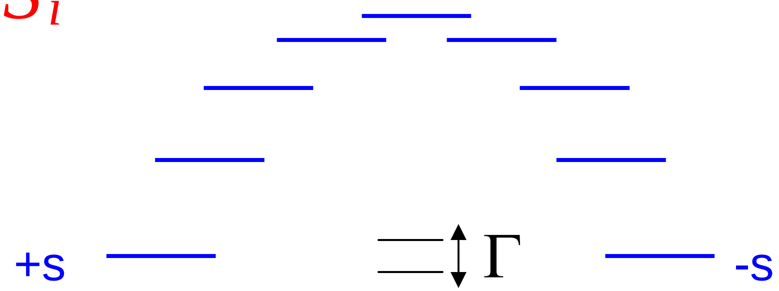
$$H_{cf} = -D\sum_i {S_i^z}^2$$



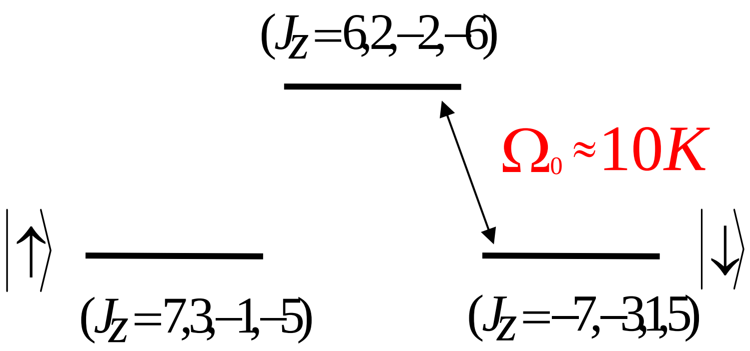
$$H_D = H_{cf} - \sum_{ij} V_{ij}^{\alpha\beta} S_i^{\alpha} S_j^{\beta} - \Delta \sum_i S_i^x$$

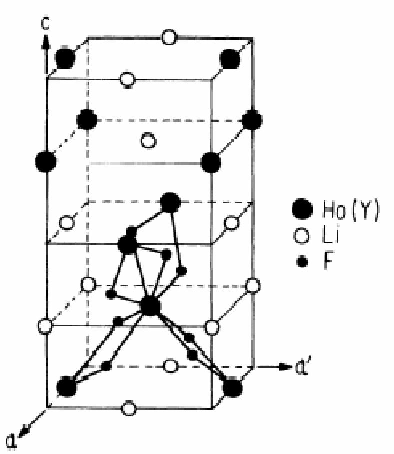
$$H_{Is} = -\sum_{ij} J_{ij}\tau_i^z \tau_j^z - \Gamma \sum_i \tau_i^x$$

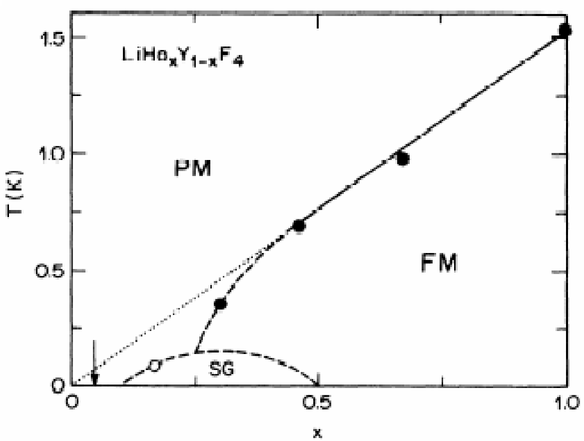
$LiHoF_4$

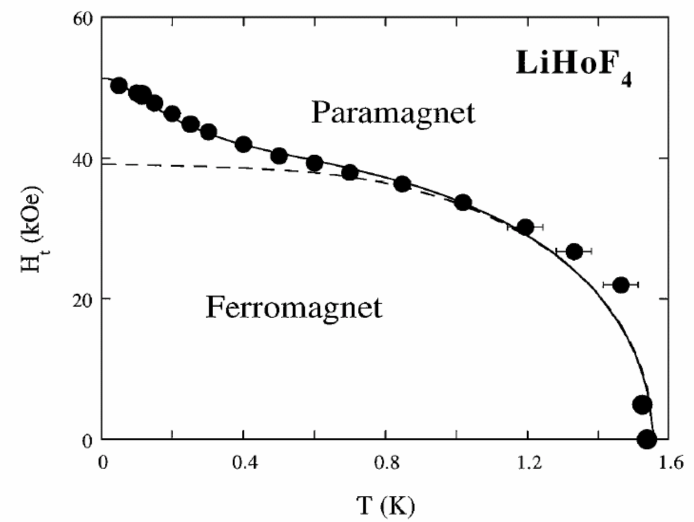
$$H_{Is} = -\sum_{ij} J_{ij}\tau_i^z\tau_j^z - \Gamma\sum_i \tau_i^x$$

$$\Gamma \propto \frac{\Delta^2}{\Omega_0}$$



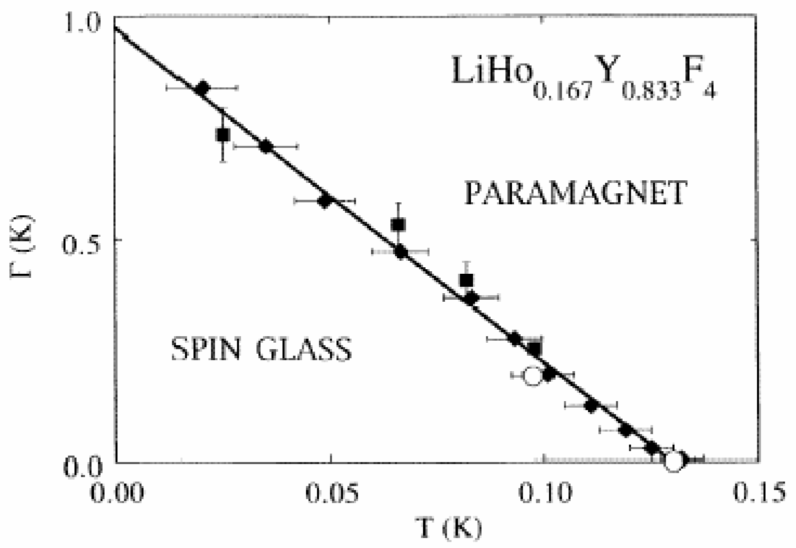


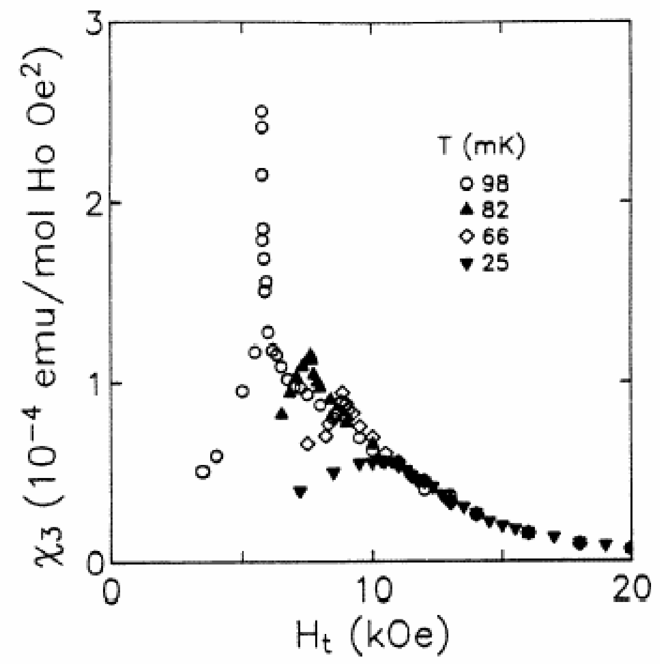


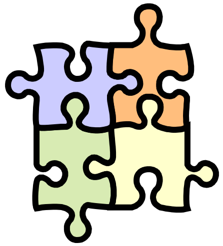


Bitko, Rosenbaum, Aeppli
PRL 77, 940 (1996)

Dilution: quantum spin-glass







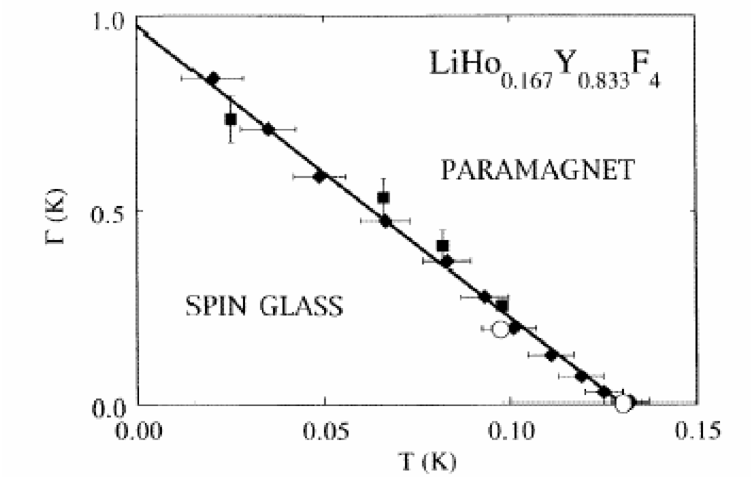
-Thermal vs. Quantum disorder
-Cusp diminishes as T lowered

Wu, Bitko, Rosenbaum, Aeppli, PRL 71, 1919 (1993)

Hyperfine interaction: electro-nuclear Ising states

$$H_{LH} = H_{cf} - \sum_{ij} V_{ij}^{\alpha\beta} S_i^{\alpha} S_j^{\beta} - \Delta \sum_i S_i^x$$

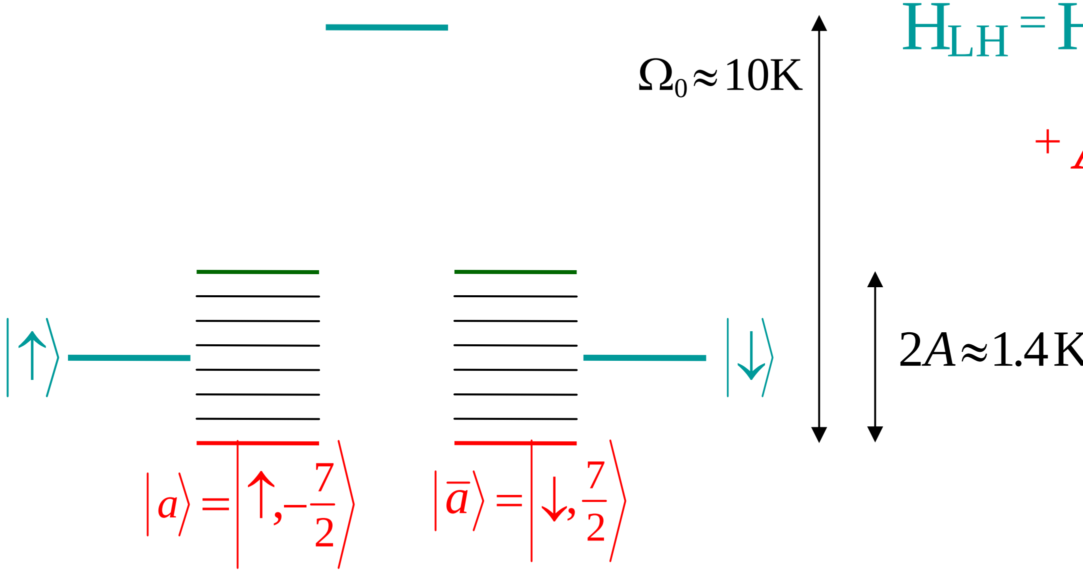
$|\uparrow\rangle$ $|\downarrow\rangle$



- M.S. and P. Stamp, PRL 95, 267208 (2005)

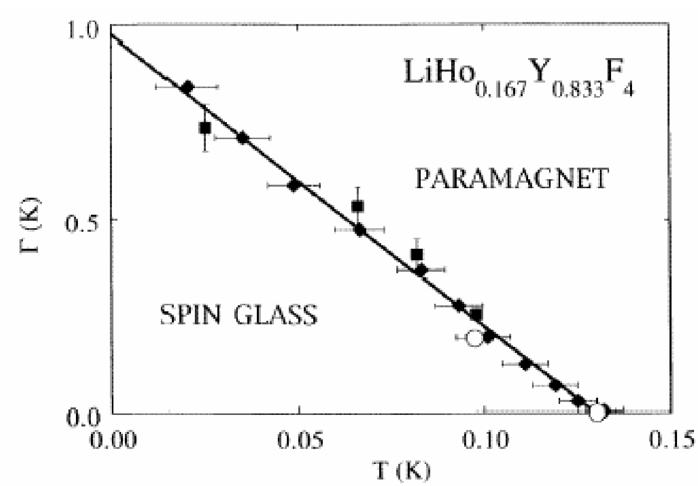
Hyperfine interaction: electro-nuclear Ising states

$$H_{LH} = H_{cf} - \sum_{ij} V_{ij}^{\alpha\beta} S_i^\alpha S_j^\beta - \Delta \sum_i S_i^x + A_J \sum_i I_i^z S_i^z + A_J \sum_i (I_i^+ S_i^- + I_i^- S_i^+)$$



Hyperfine spacing: 200 mK

$$I = 7/2$$



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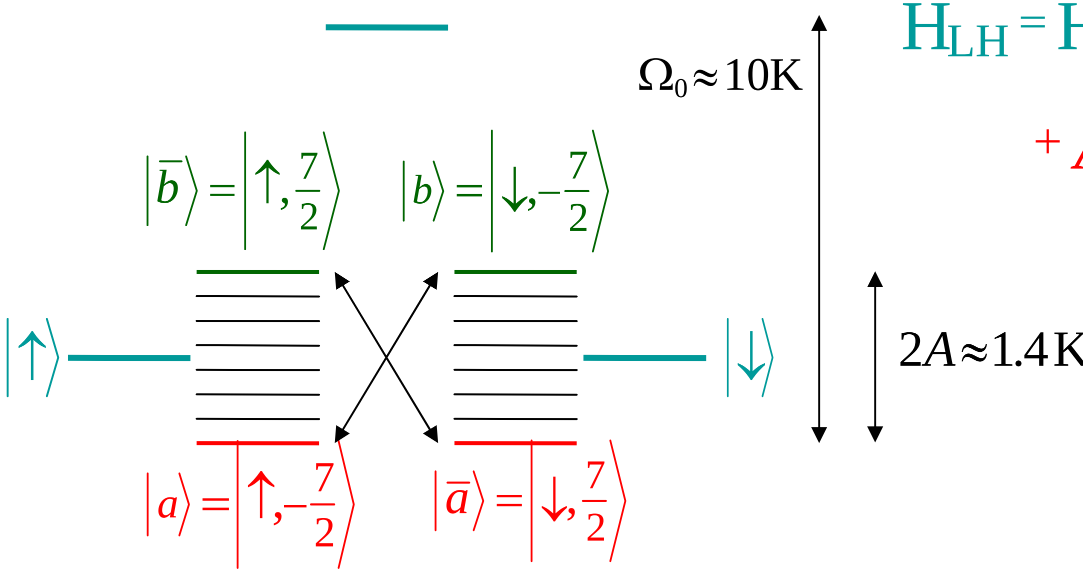
Hyperfine interaction: electro-nuclear Ising states

$$H_{LH} = H_{cf} - \sum_{ij} V_{ij}^{\alpha\beta} S_i^{\alpha} S_j^{\beta} - \Delta \sum_i S_i^x$$
$$+ A_J \sum_i I_i^z S_i^z + A_J \sum_i (I_i^+ S_i^- + I_i^- S_i^+)$$

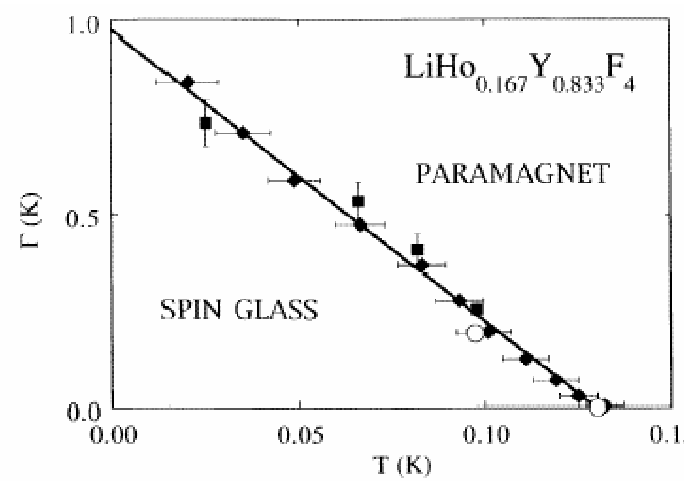


$$I = 7/2$$

Hyperfine spacing: 200 mK

$$|+\rangle = c_1|a\rangle + c_2|b\rangle$$
$$|-\rangle = c_1|\bar{a}\rangle + c_2|\bar{b}\rangle$$

$$\tilde{S}_z = c_1^2 - c_2^2$$
$$J_{eff} = J \cdot \tilde{S}_z^2$$



- M.S. and P. Stamp, PRL 95, 267208 (2005)

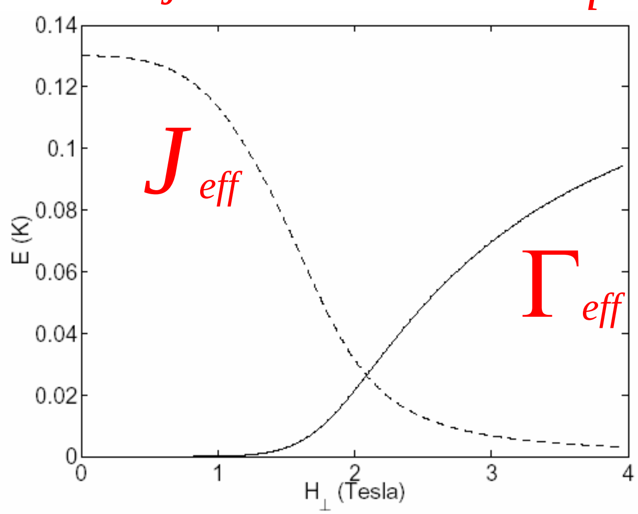
Phase diagram – transverse hyperfine and dipolar interactions

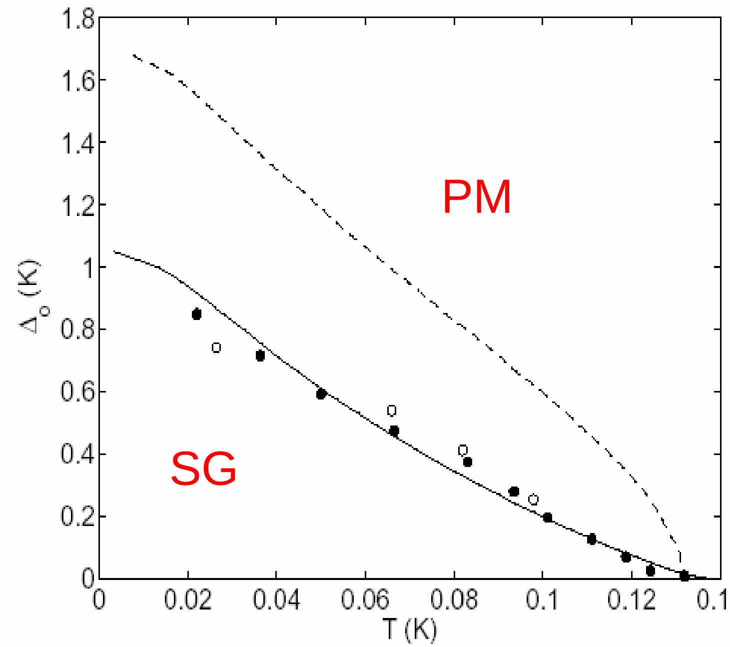
$$T_c \approx V$$

$$J_{eff} \sim A$$

$$H_c \approx \Omega_0$$

$$\mathrm{H}_{\mathrm{Is}} = -\sum_{ij} J_{eff}\,\tau_i^z \tau_j^z - \Gamma_{eff} \sum_i \tau_i^x$$



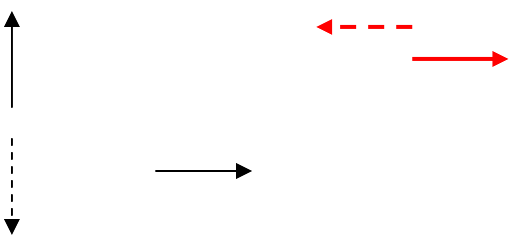


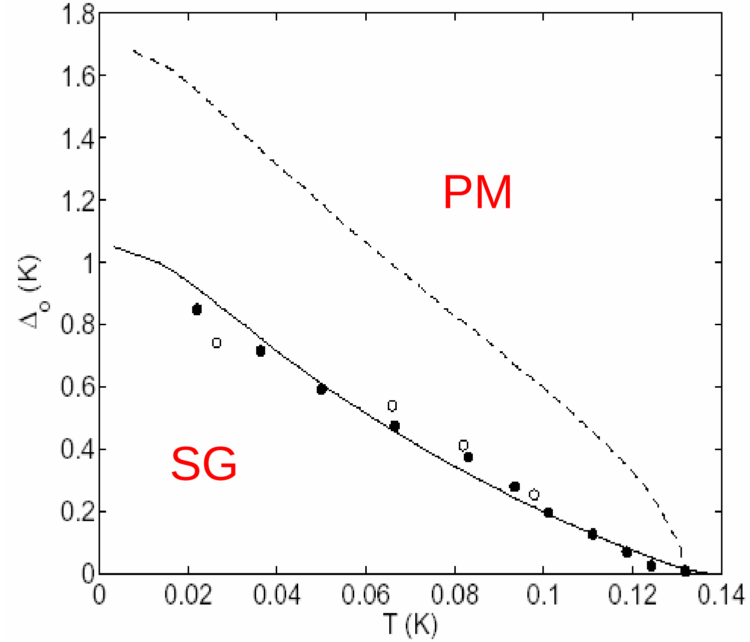
	● ○	Experiment
Eff. Dipolar int.	- - - - - - - -	No off. dip.
Splitting	———	With off. dip.

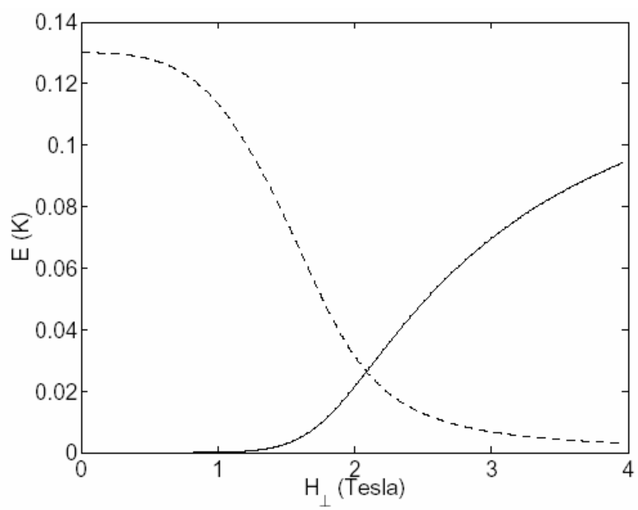
- M.S. and P. Stamp, PRL 95, 267208 (2005)

Phase diagram – significance of offdiagonal dipolar interactions

$$\sum_{ij} V_{ij}^{zx} S_i^z S_j^x - \Delta \sum_i S_i^x$$







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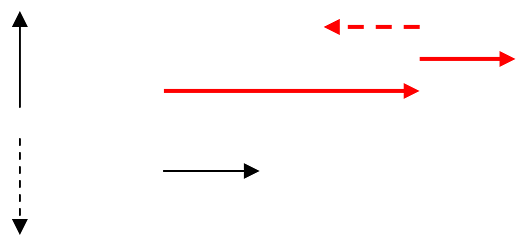
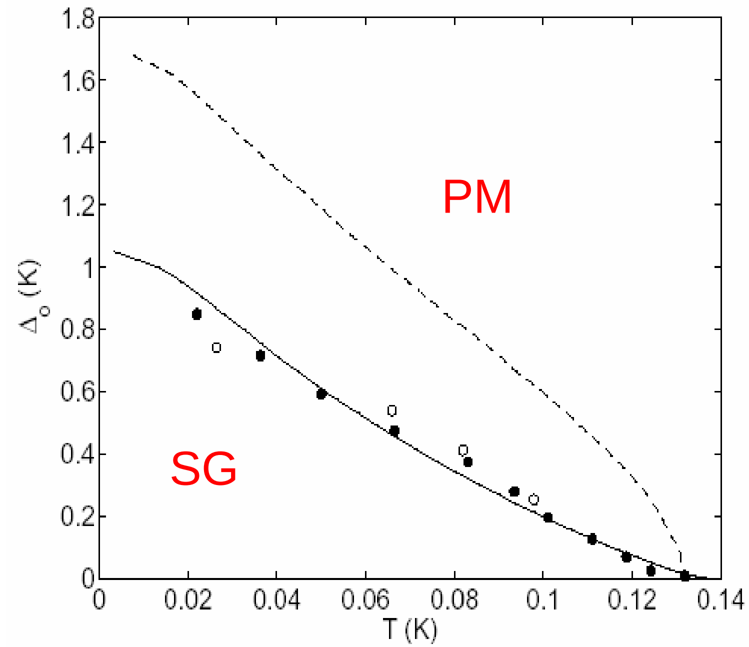
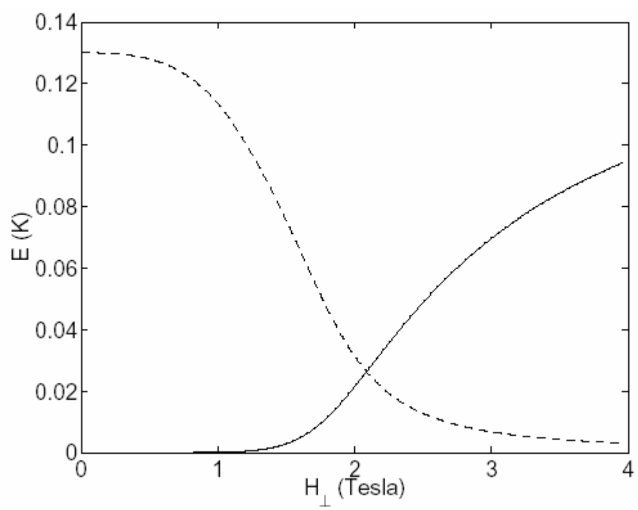






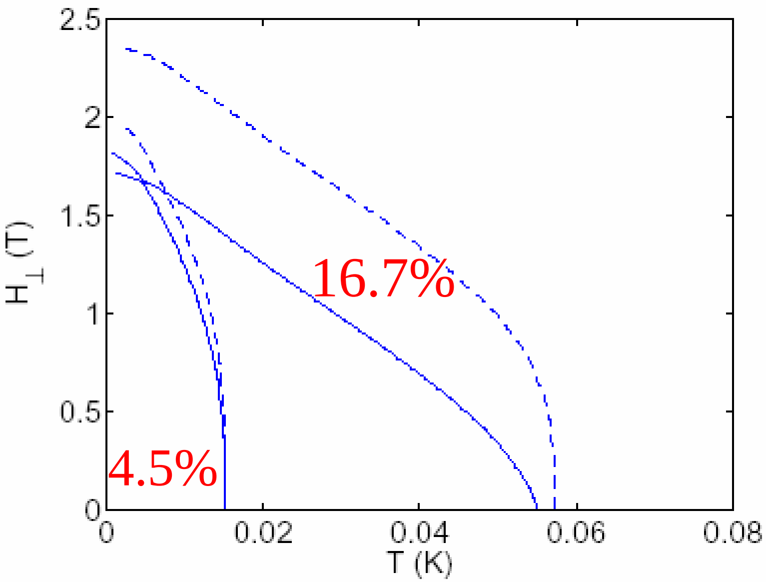
● ○ Experiment

Eff. Dipolar int. - - - - - - - No off. dip.

Splitting ——— With off. dip.

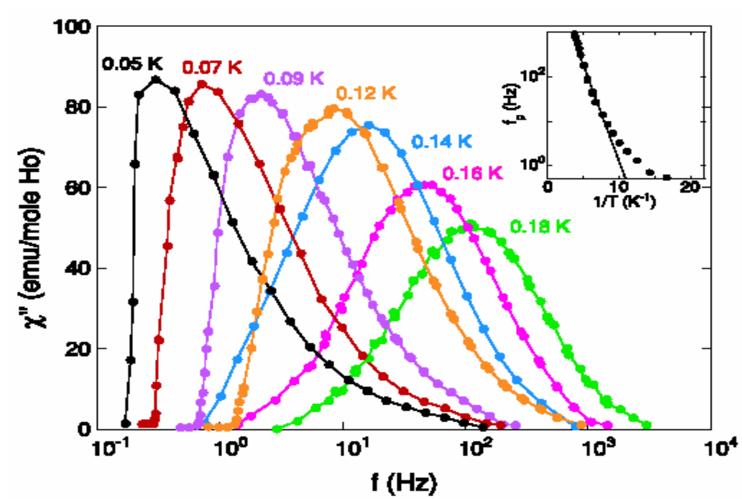
- M.S. and P. Stamp, PRL 95, 267208 (2005)

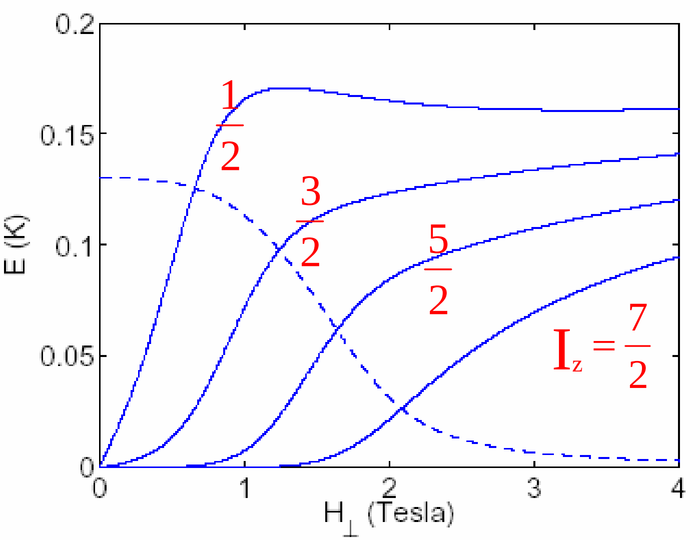
Other dilutions



$T_c \approx V \approx x \qquad H_c \approx \Omega_0$

Including off-diagonal dipolar:
Re-entrant H_c as function of x



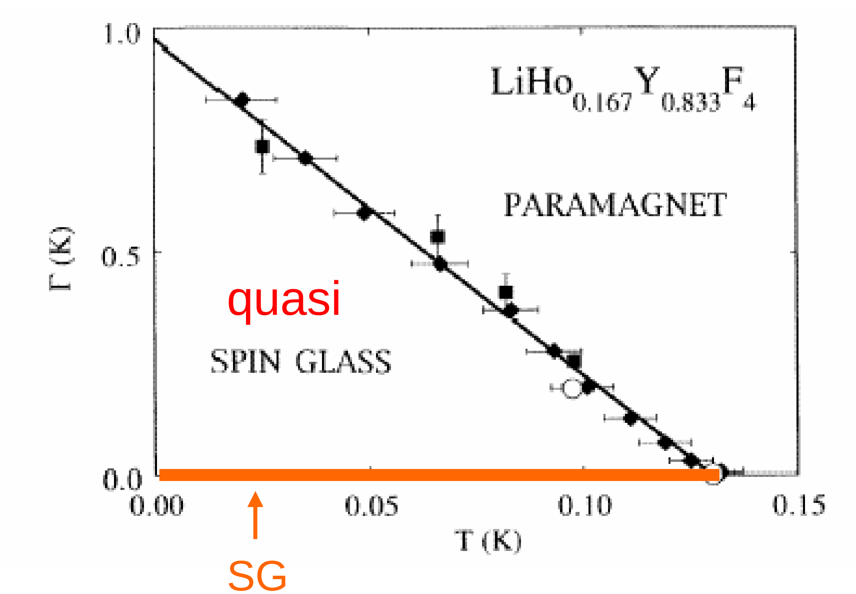


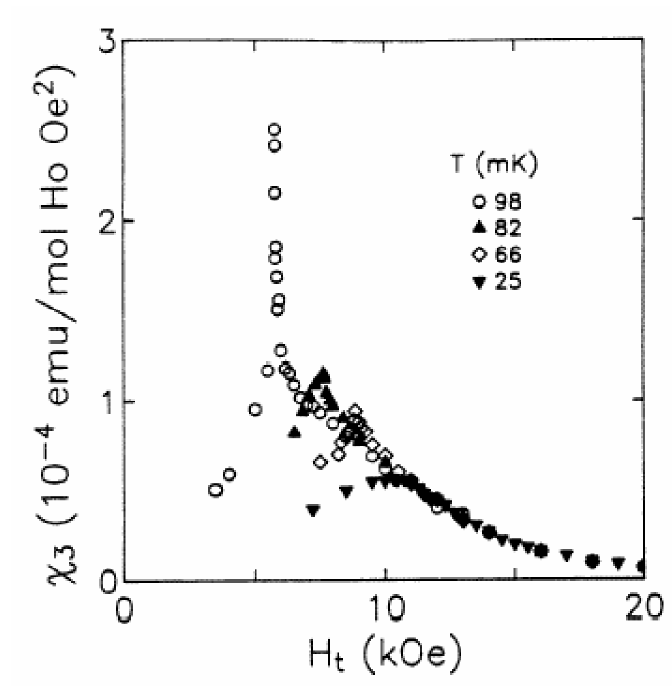
- Anti spin-glass: PM regime
- Narrowing at hf temperatures

- M.S. and P. Stamp, in preparation

Offdiagonal dipolar interactions

$$H_{LH} = H_{cf} - \sum_{ij} V_{ij}^{\alpha\beta} S_i^{\alpha} S_j^{\beta} - \Delta \sum_i S_i^x$$





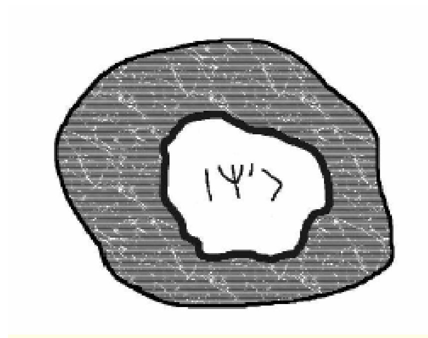
- M.S. and N. Laflorencie, Cond-mat/0511304

Spin glass, droplet model, Imry-Ma

BMY: Dipolar Ising glass equiv. to short range model

FH: Droplet model

Ground state: $|\psi\rangle$



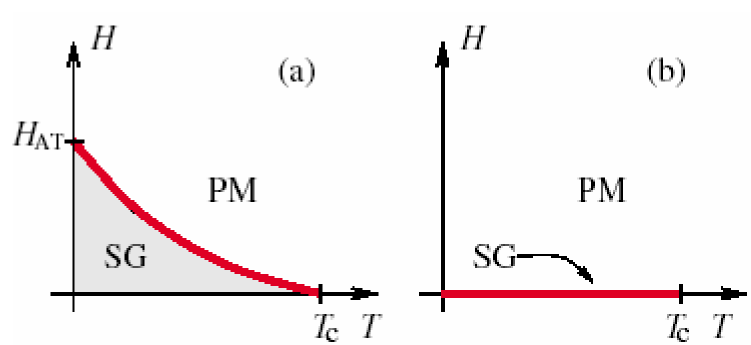
Imry-Ma

$$JL^{d-1} = hL^{d/2}$$

Energy to form a droplet: $\propto J L^{\theta}$

Longitudinal field – energy gain to flip a droplet: $\propto h L^{d/2}$

$$\xi \propto (J/h)^{1/(3/2-\theta)}$$



Bray, Moore, Young PRL 56, 2641 (86)
Fisher, Huse PRL 56, 1601 (86); PRB 38, 386 (88)
Imry, Ma PRL 35 1399 (75)

Dipolar Ising glass – significance of the offdiagonal terms

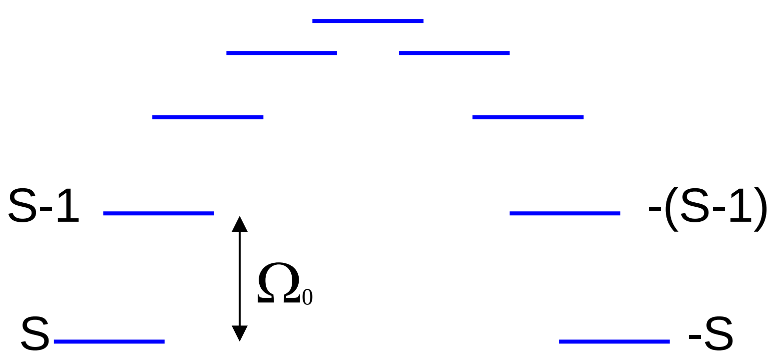
$$H_D = -D\sum_i {S_i^z}^2 - \sum_{ij} V_{ij}^{zz} S_i^z S_j^z - \Delta\sum_i S_i^x - \sum_{ij} V_{ij}^{zx} S_j^z S_i^x$$

Consider finite size droplet, N spins

$$\Delta \,;\, V_{ij}^{zx}$$

Each change GS energy.
Together split degeneracy

$$\delta E_\psi = \sum_i \frac{\Delta^2}{\Omega_0}$$



- M.S. and N. Laflorencie, Cond-mat/0511304

Dipolar Ising glass – significance of the offdiagonal terms

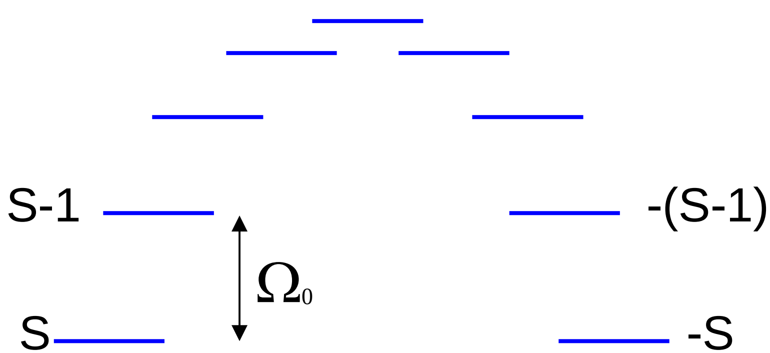
$$H_D = -D\sum_i {S_i^z}^2 - \sum_{ij} V_{ij}^{zz} S_i^z S_j^z - \Delta \sum_i S_i^x - \sum_{ij} V_{ij}^{zx} S_j^z S_i^x$$

Consider finite size droplet, N spins

$$\Delta ; V_{ij}^{zx}$$

Each change GS energy.
Together split degeneracy

$$\delta E_\psi = \sum_i \frac{(\Delta + \sum_j V_{ij}^{zx} S_j^z)^2}{\Omega_0}$$



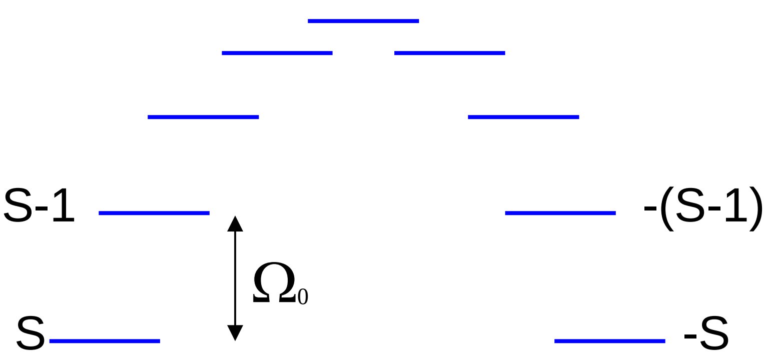
- M.S. and N. Laflorencie, Cond-mat/0511304

Dipolar Ising glass – significance of the offdiagonal terms

$$H_D = -D\sum_i {S_i^z}^2 - \sum_{ij} V_{ij}^{zz} S_i^z S_j^z - \Delta \sum_i S_i^x - \sum_{ij} V_{ij}^{zx} S_j^z S_i^x$$

Consider finite size droplet, N spins $\Delta\,;\,V_{ij}^{zx}$ Each change GS energy. Together split degeneracy

$$\delta E_\psi = \sum_i \frac{(\Delta + \sum_j V_{ij}^{zx} S_j^z)^2}{\Omega_0}$$



$$\delta E_\psi = \sum_i \frac{(\Delta + V_i)^2}{\Omega_0}$$

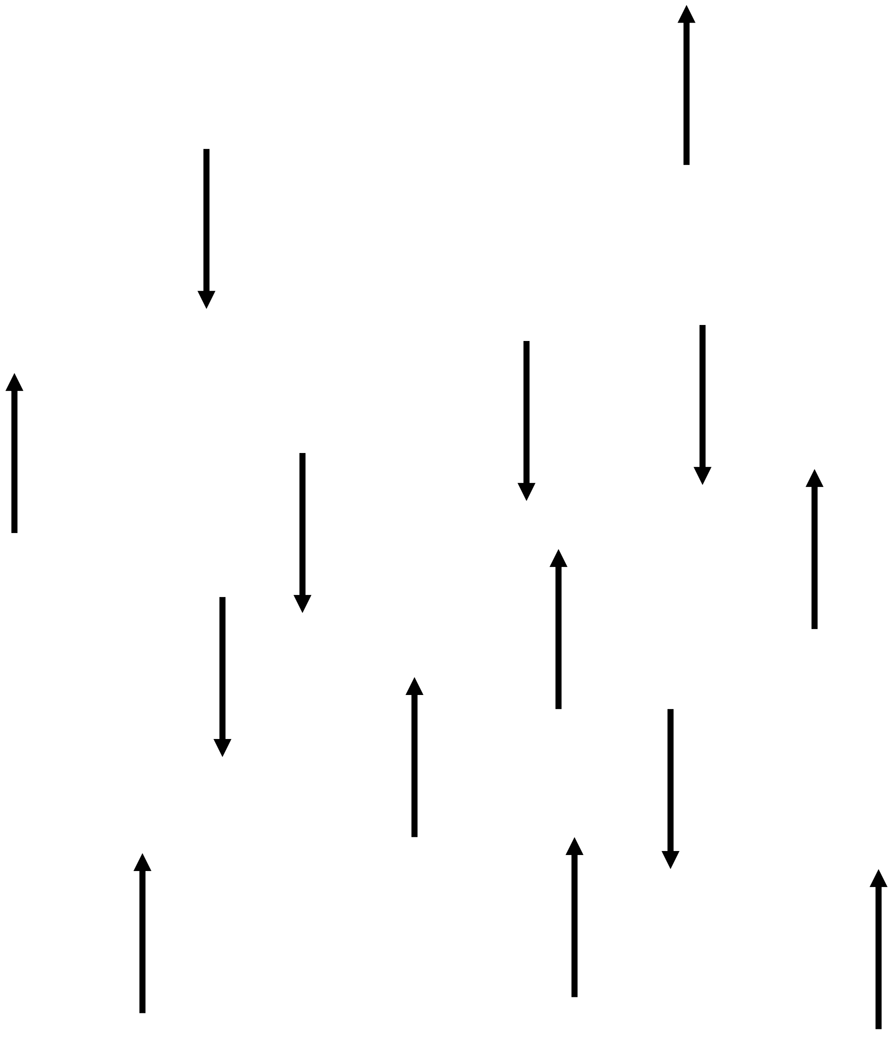
$$\delta E_{\psi'} = \sum_i \frac{(\Delta - V_i)^2}{\Omega_0}$$

$$E_\psi - E_{\psi'} \propto \sum_i \frac{\Delta V_i}{\Omega_0} \propto \frac{\Delta V}{\Omega_0}\sqrt{N}$$

- M.S. and N. Laflorencie, Cond-mat/0511304

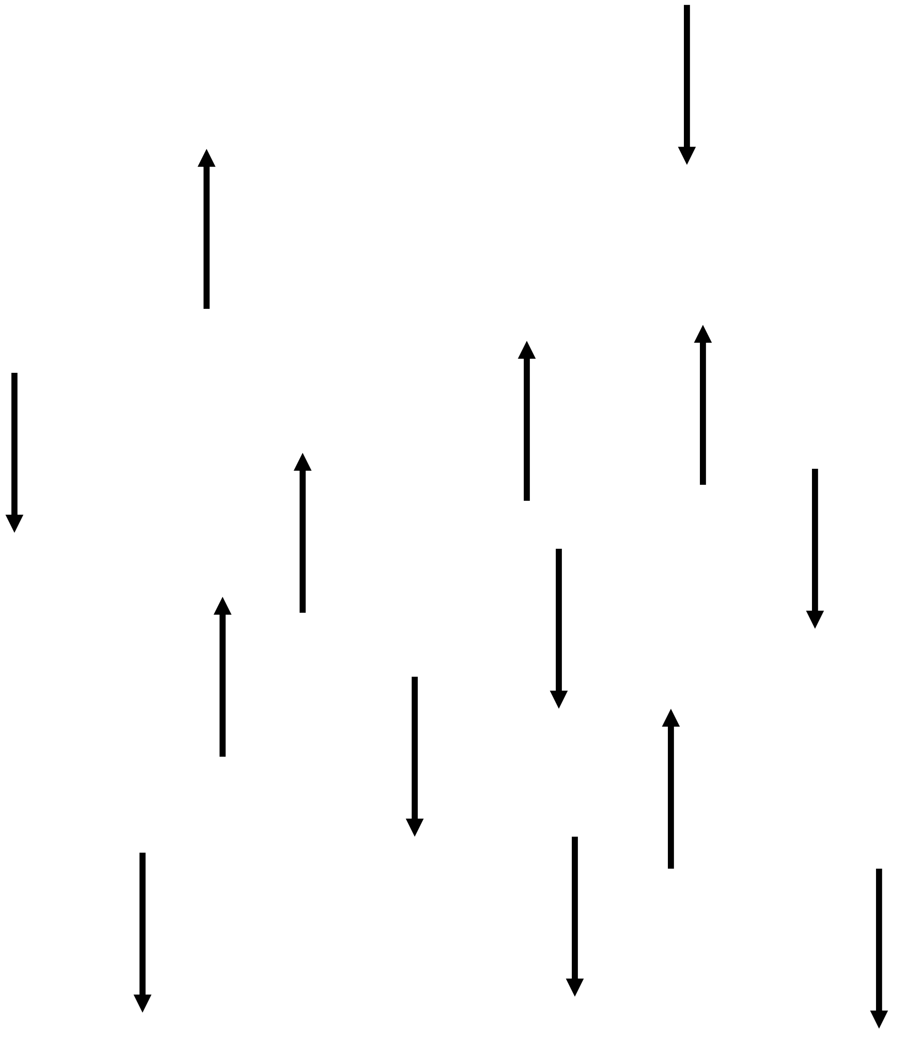
Ising ground states

$$|\psi_0\rangle$$



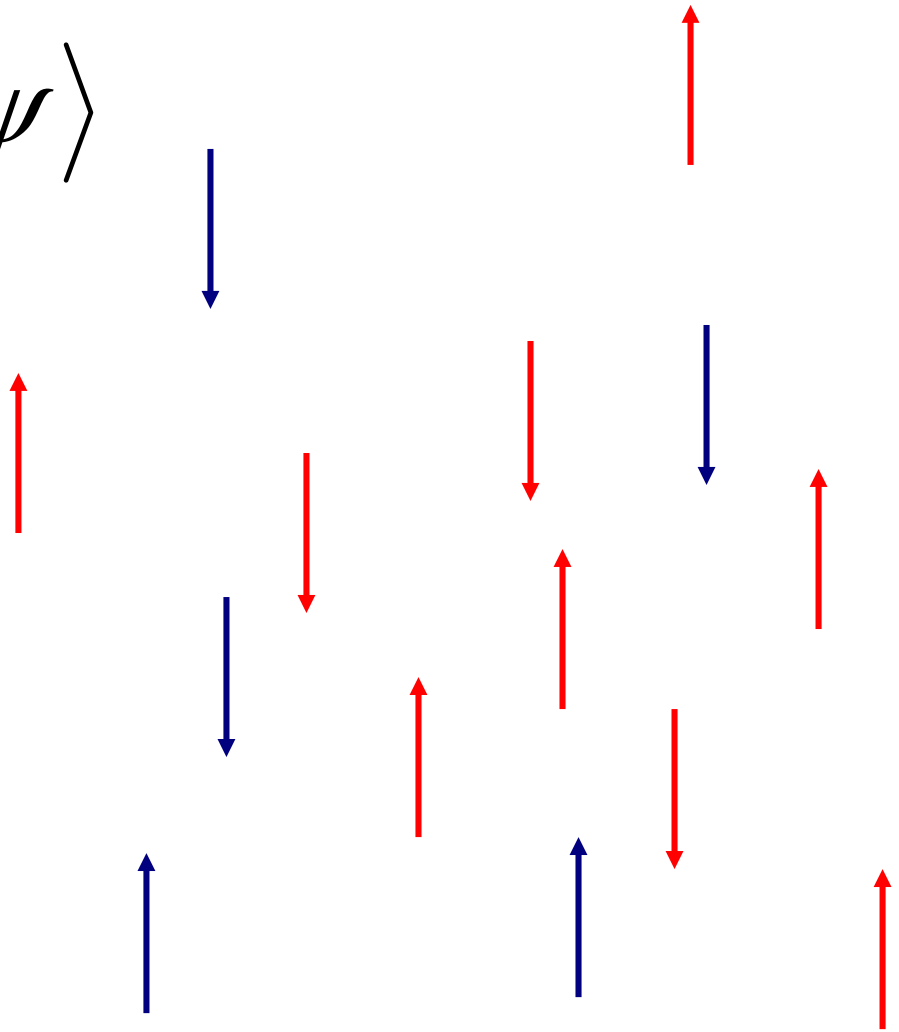
Ising ground states

$$\left|\overline{\psi}_0\right\rangle$$



Transverse field, offdiagonal dipolar

$$|\psi_0\rangle \rightarrow |\psi\rangle$$

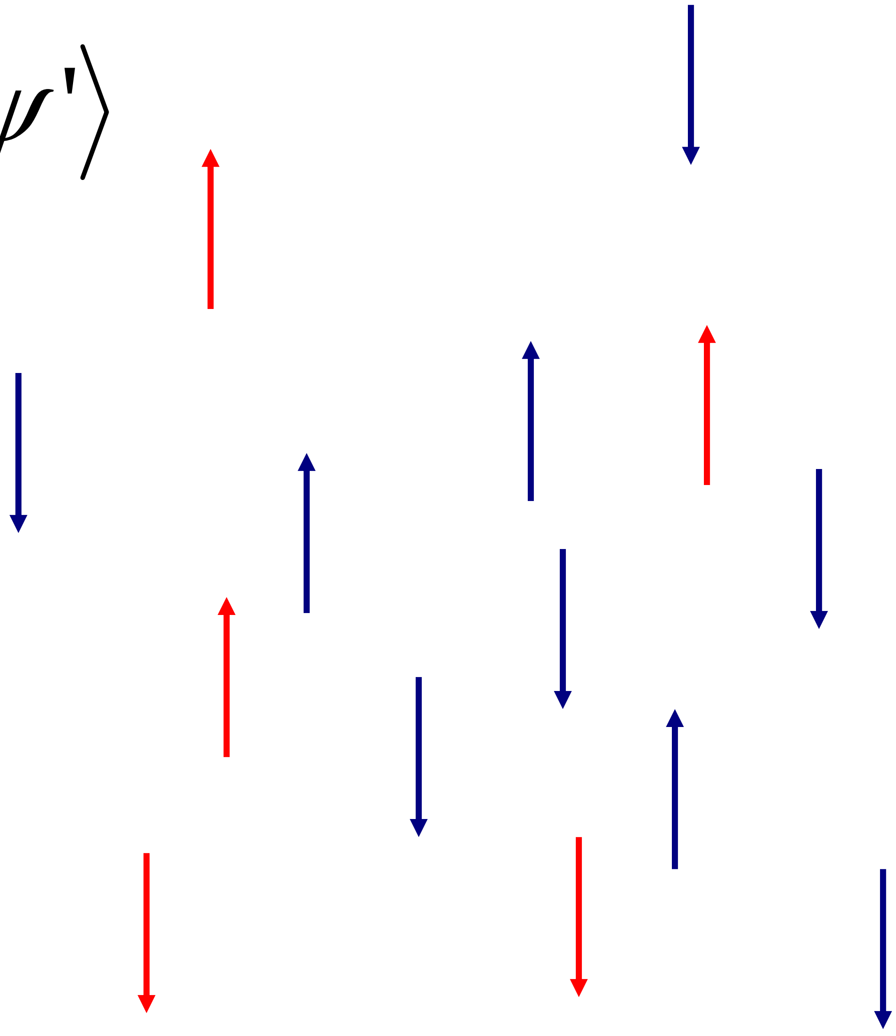


$$\Delta \parallel V$$

$$\Delta \parallel -V$$

Transverse field, offdiagonal dipolar

$$|\psi_0\rangle \rightarrow |\psi'\rangle$$



$\Delta \parallel V$

$\Delta \parallel -V$

Droplet size – coherence length

$$\mathrm{H_D} = -D\sum_i S_i^{z\,2} - \sum_{ij} V_{ij}^{zz} S_i^z S_j^z \; -\Delta \sum_i S_i^x - \sum_{ij} V_{ij}^{zx} S_j^z S_i^x$$

Flip a droplet - energy gain $\quad E_{\psi} - E_{\psi'} \propto \sum_i \frac{\Delta V_i}{\Omega_0} \propto \frac{\Delta V}{\Omega_0}\sqrt{N}$

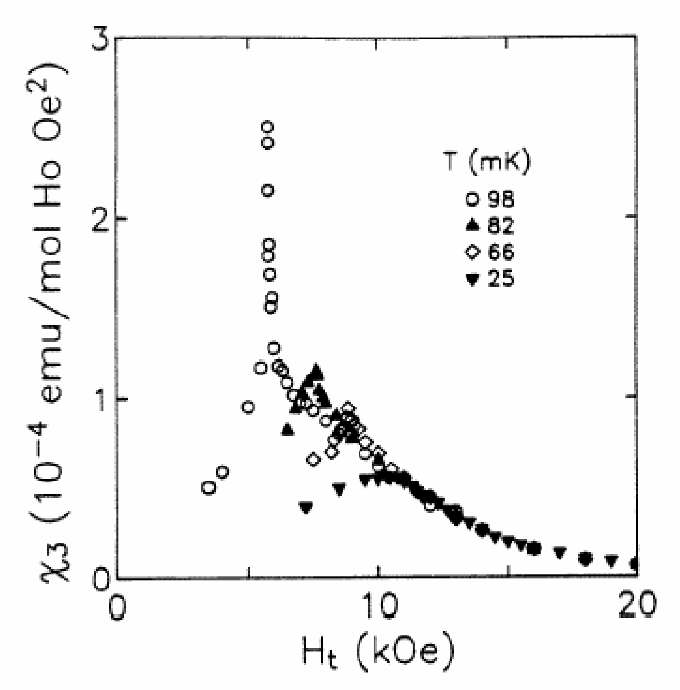
Equate to domain wall energy $\quad \frac{\Delta V S^2 L^{3/2}}{\Omega_0} = V S^2 L^{\theta}$

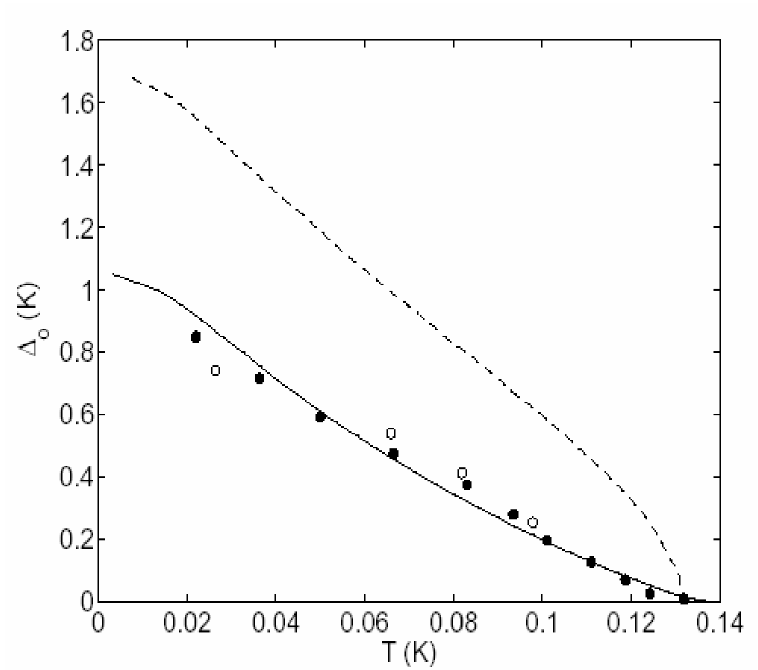
Droplet size - Coherence length $\quad \xi \propto (\Omega_0 / \Delta)^{1/(3/2-\theta)}$

$$\xi \propto (J/h)^{1/(3/2-\theta)}$$

- M.S. and N. Laflorencie, Cond-mat/0511304

Diminishing cusp in nonlinear susceptibility





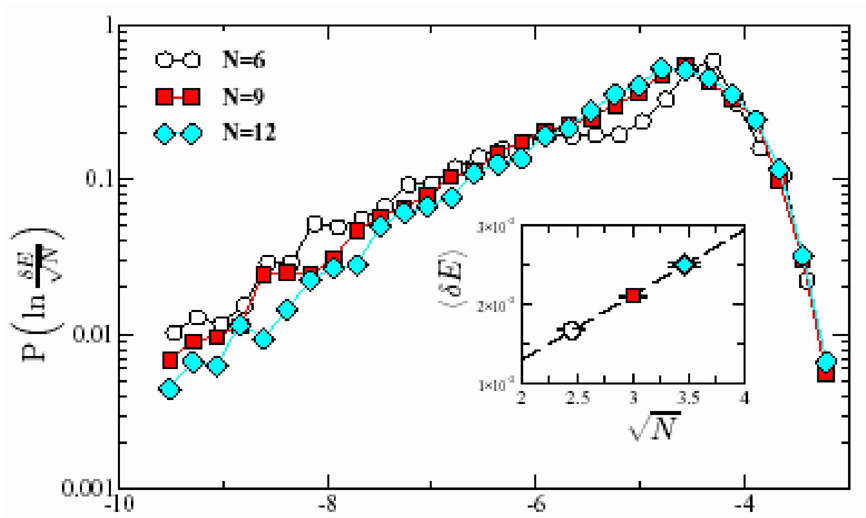
$$\xi \propto (\Omega_0 / \Delta)^{1/(3/2-\theta)}$$

Wu, Bitko, Rosenbaum, Aeppli, PRL 71, 1919 (1993)

$\sqrt{N}$ scaling

$$x = 1/12 = 8.33\%$$

$$3 \times 3 \times N/3$$

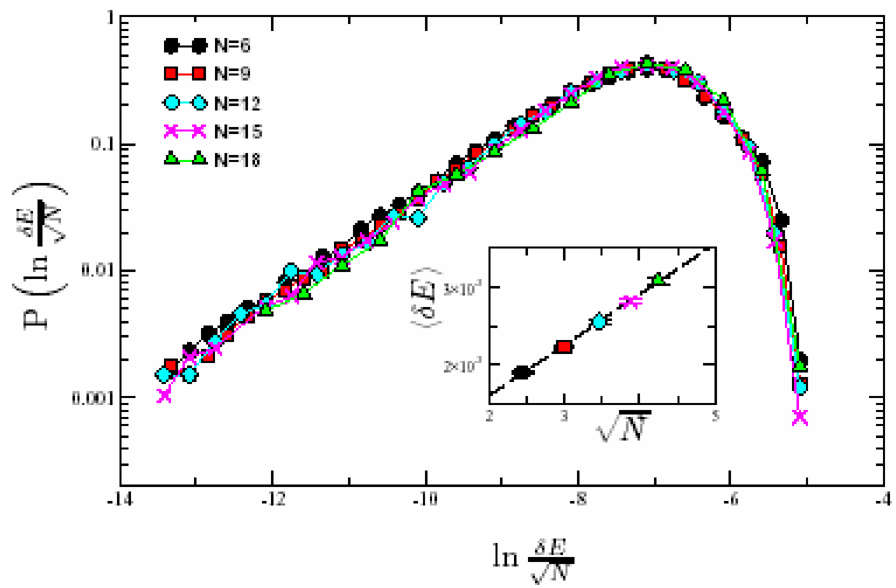


S=1

$$x = 3/16 = 18.75\%$$

$$2 \times 2 \times N/3$$

S=1/2



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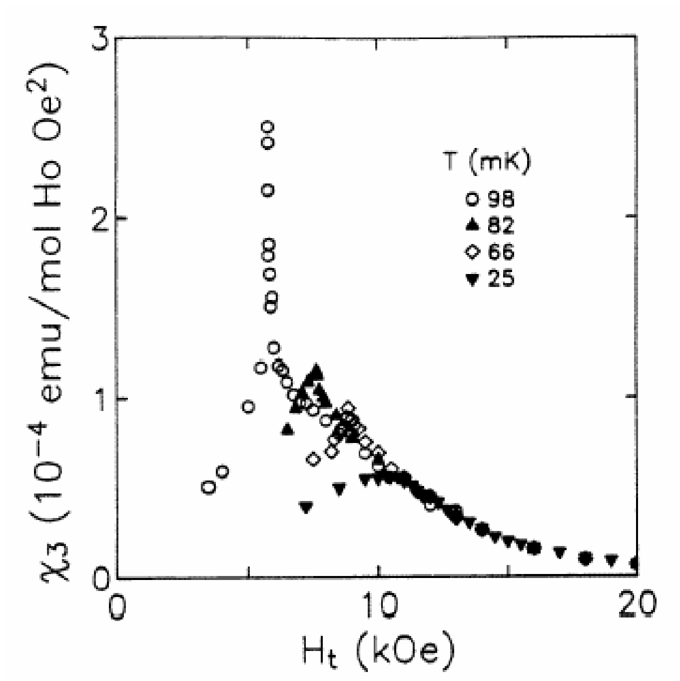
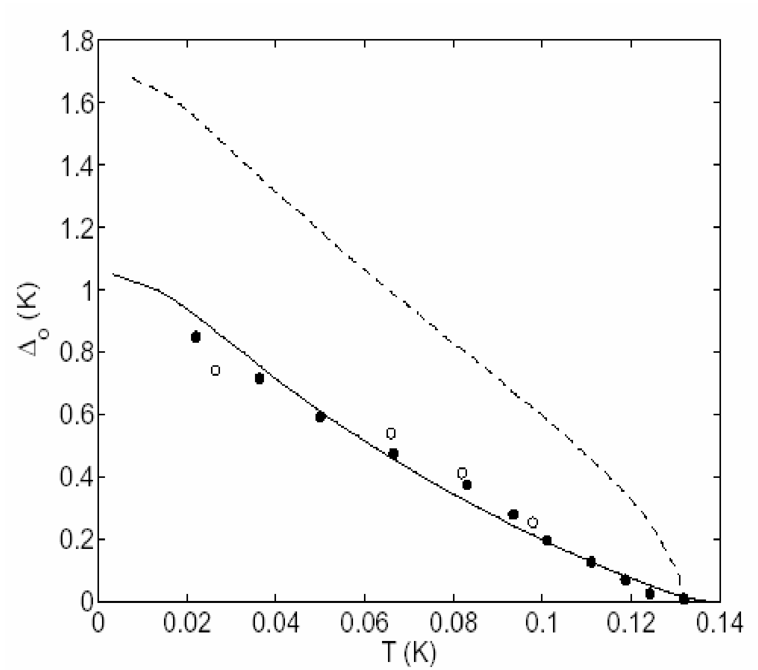




$$\xi \propto (\Omega_0 / \Delta)^{1/(3/2-\theta)}$$

Wu, Bitko, Rosenbaum, Aeppli, PRL 71, 1919 (1993)

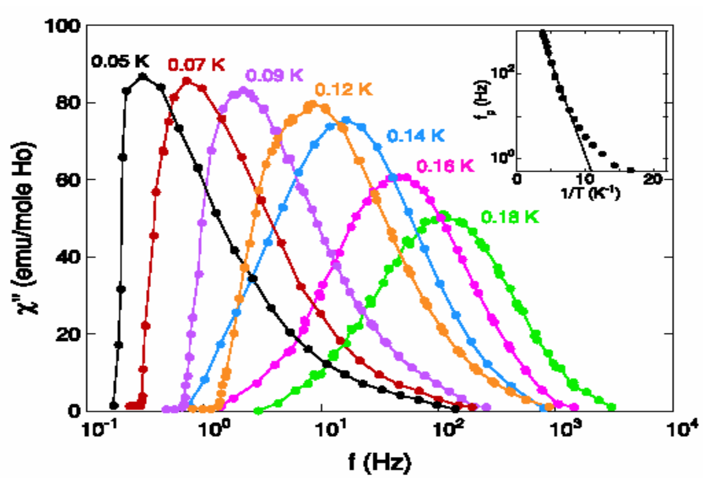
Remarks

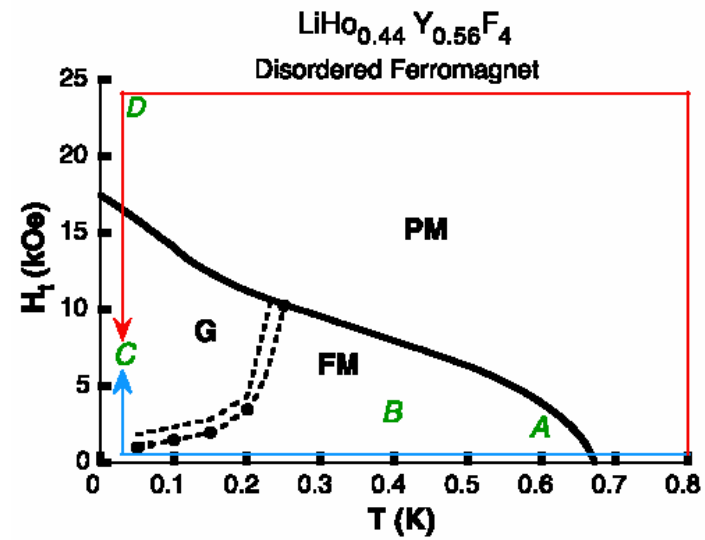
- Nuclear spins – part of the system
- Off-diagonal terms can not be neglected because change symmetry of the system!
- Effective spin half – not always sufficient

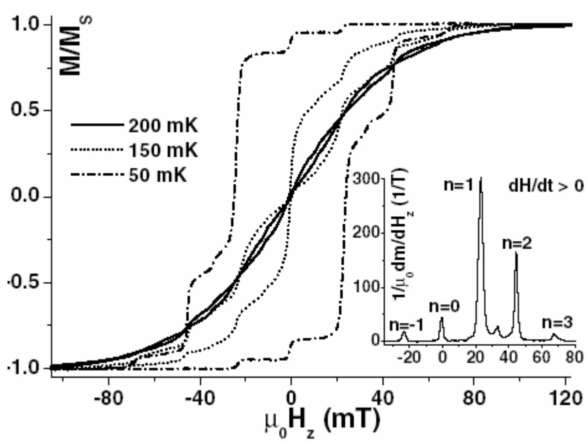
Conclusions and Implications

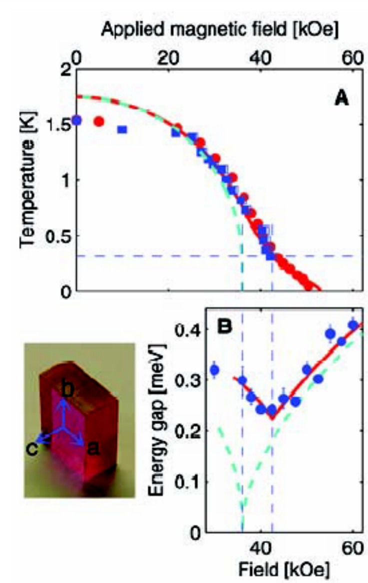
- Experiment: Crossover field, n.l. susc.
- $LiHo_xY_{1-x}F_4$: Significance of hf and offdiag. dipolar interactions. Full model.
- Dipolar Ising SG – finite ξ at any Δ, nature of crossover.
- $LiHo_xY_{1-x}F_4$: Framework for other dilutions
- Ising spin glasses – How can observe QPT? Other systems with dipolar interactions and randomness

More $LiHoF_4$









Ghosh, Parthasarathy, Rosenbaum, Aeppli Science 296, 2195 (2002)

Brooke, Bitko, Rosenbaum, Aeppli Science 284, 779 (1999)

Ronnow et. Al. Science 308, 389 (2005)

Giraud et. Al. PRL 87, 057203 (2001)