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Coherence in a Disordered Magnet

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D. Reich(Hopkins)

D. Belanger(Santa Cruz)

B. Ellman(Kent State)

H. Guggenheim(Bell)

J. Brooke (NEC/UChicago)

T. F. Rosenbaum (UChicago)

D. Bitko (UChicago)

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some references

- "Coherent Spin Oscillations in a Disordered Magnet", S. Ghosh, R. Parthasarathy, T.F. Rosenbaum, G. Aeppli, Science 296, pp. 2195-2198, (2002)
- "Quantum Critical Points – Experiments", G. Aeppli, T. F. Rosenbaum, *Dynamical Properties of Unconventional Magnetic Systems"*, A. T. Skjeltorp and D. Sherrington, (eds.), Kluwer Academic Publishers, pp. 107-122, (1998)
- "Quantum Critical Behavior for a Model Magnet", D. Bitko, T. F. Rosenbaum, G. Aeppli, *Phys. Rev. Lett.*77(5), pp. 940-943, (1996)
- "Dipolar Magnets and Glasses: Neutron Scattering, Dynamical, and Calorimetric Studies of Randomly Distributed Ising Spins", D. Reich, B. Ellman, J. Yang, T. Rosenbaum, G. Aeppli and D. P. Belanger, *Phys. Rev. B,* 42, p. 4631 (1990)

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The world's simplest disordered magnet – 10^{23} interacting Ising dipoles

Expected ground state – spin glass (Aharony/Stephens)

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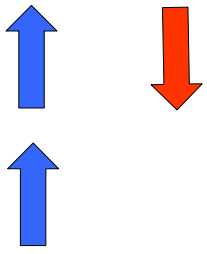
Why?

dipolar interaction between randomly placed spins leads to frustration

$$E=S_1S_2g^2M_B^2[1-3(r_z/r)^2]/r^3$$

ferro for $(r_z/r)^2 > 1/3$
antiferro for $(r_z/r)^2 < 1/3$



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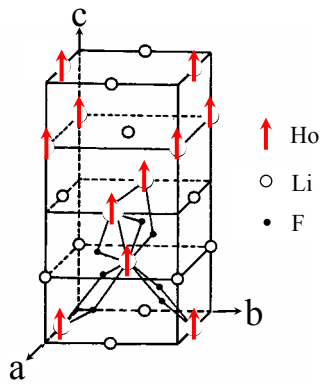
Experimental realization of Ising model with interacting dipoles $LiHoF_4$



- g=14 doublet
- 9K gap to next state
- dipolar coupled

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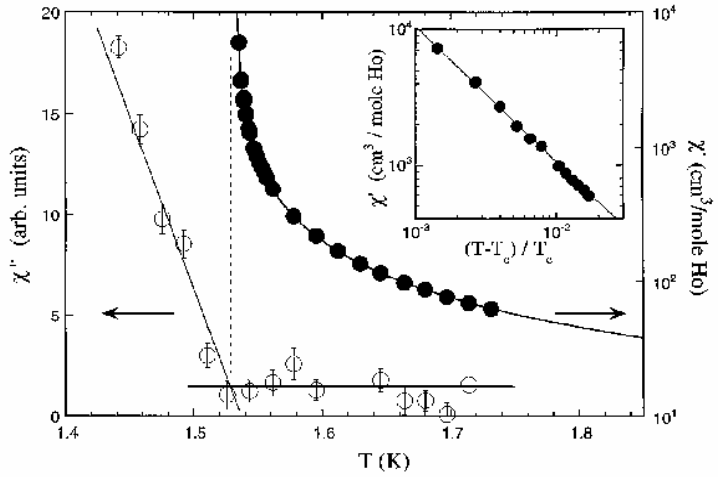
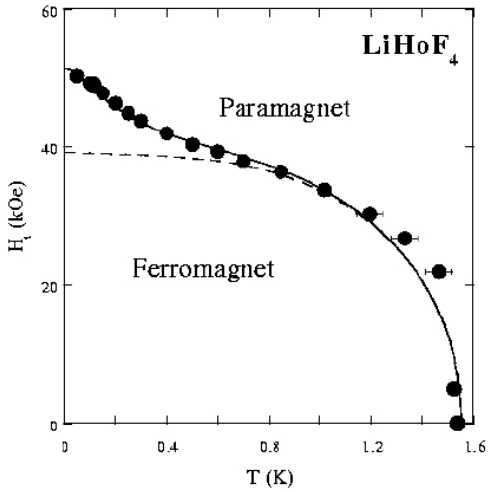
•D. Bitko, T. F. Rosenbaum, G. Aeppli, *Phys. Rev. Lett.*77(5), pp. 940-943, (1996)

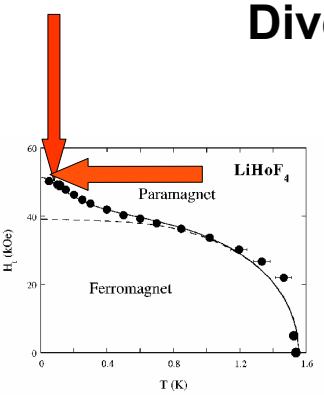
χ vs T for H_t=0



Mean-Field Ferromagnet



Diverging χ



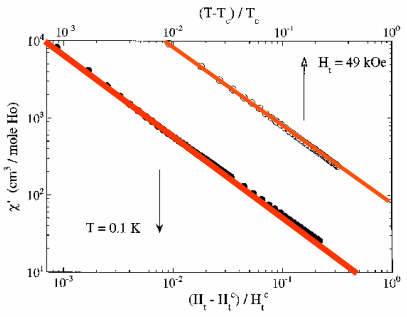


FIG. 2. Mean-field critical behavior of the magnetic susceptibility in the $T \to 0$ limit as functions of reduced temperature (open circles, $T_c = 0.114$ K, $H_t = 49.0$ kOe) and reduced transverse field (filled circles, $H_t^c = 49.3$ kOe, $T = 0.100$ K).

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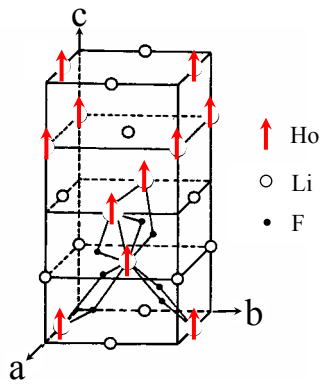

- g=14 doublet
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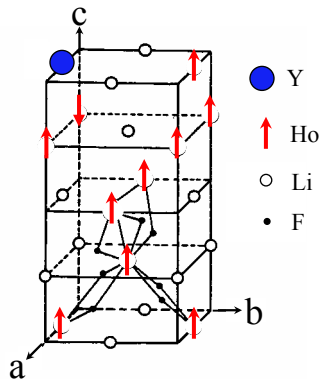

- g=14 doublet
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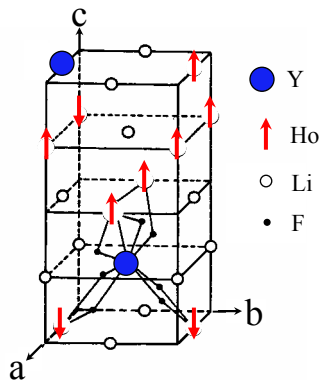
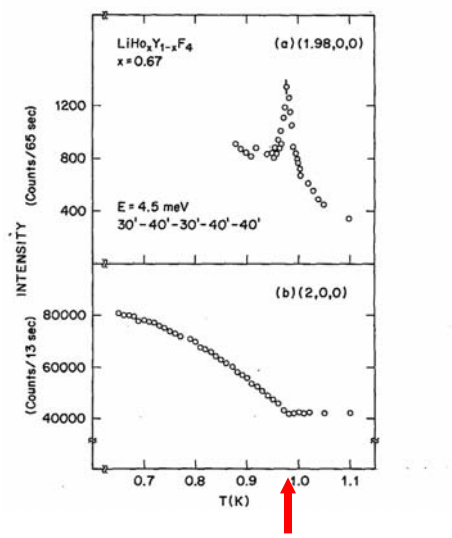
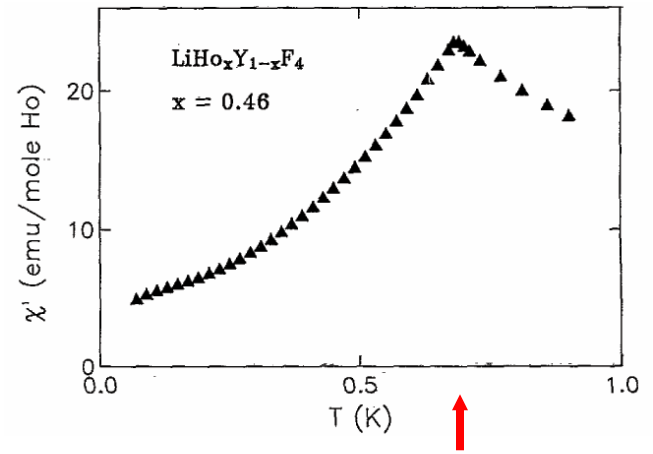


- g=14 doublet
- 9K gap to next state
- dipolar coupled

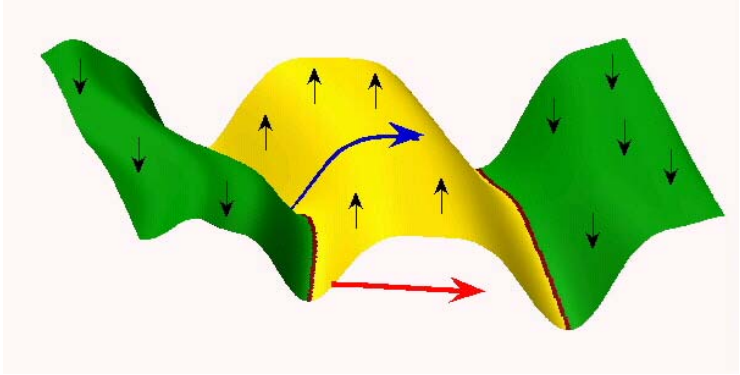


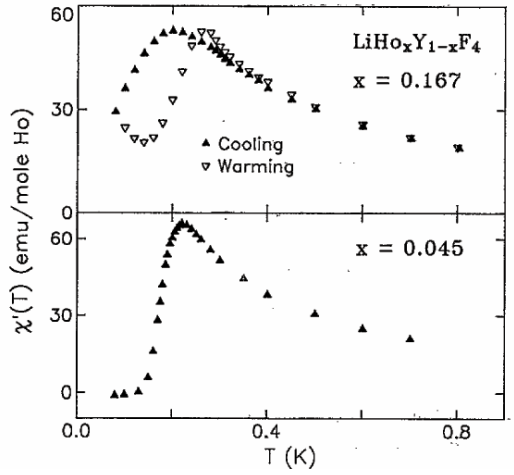
$T_c = xT_c(x=1)$

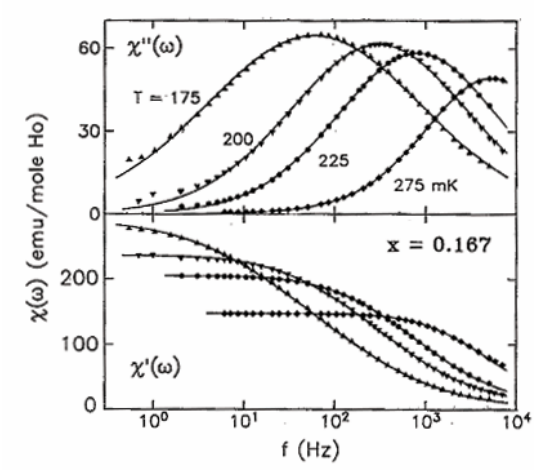


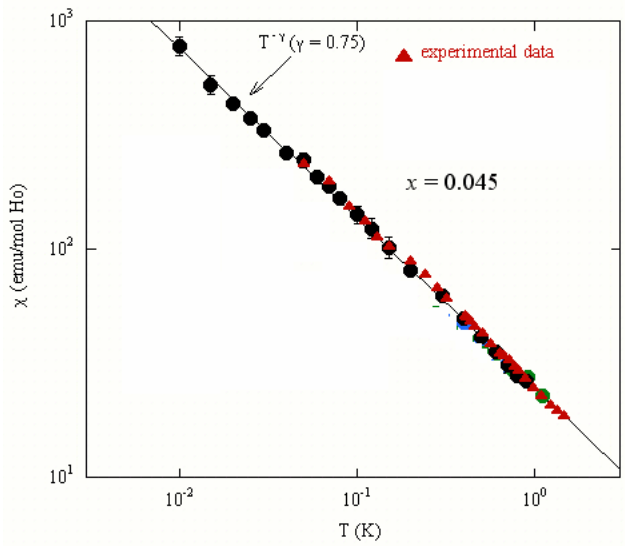
$T_c = xT_c(x=1)$

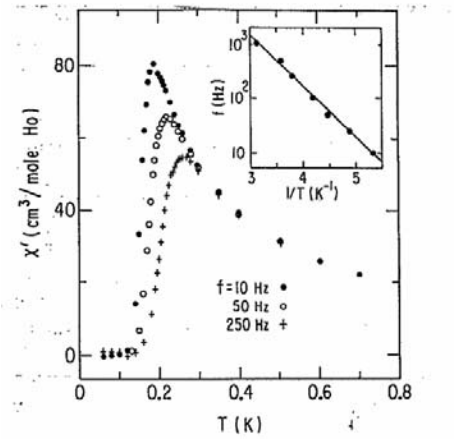
J.Brooke, T.F.Rosenbaum & G.A, *Nature* 413,610(2001)

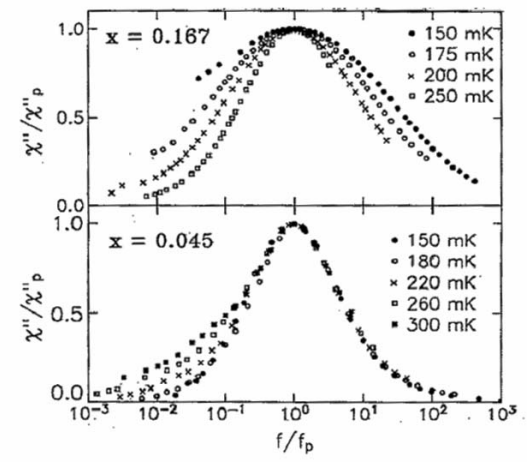


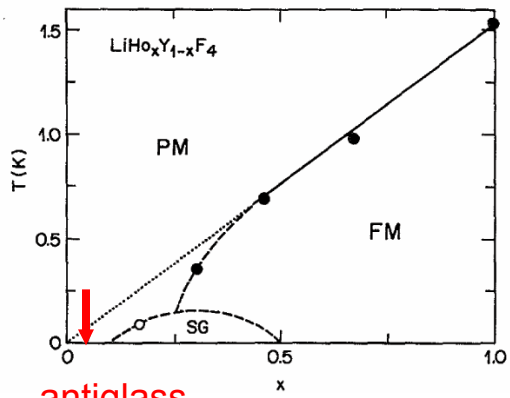

LiHoxY1-xF4
x = 0.167
Cooling
Warming
x = 0.045
χ'(T) (emu/mole Ho)
T (K)
60
30
0
0.0
0.4
0.8


χ''(ω)
T = 175
200
225
275 mK
x = 0.167
χ'(ω)
χ(ω) (emu/mole Ho)
f (Hz)
60
30
0
200
100
0
10^0
10^1
10^2
10^3
10^4


10^3
10^2
10^1
$T^{-\gamma}(\gamma = 0.75)$
experimental data
$x = 0.045$
χ (emu/mol Ho)
10^{-2}
10^{-1}
10^0
T (K)


80
40
0
χ' (cm³/mole Ho)
f (Hz)
10^3
10^2
10
3
4
5
1/T (K⁻¹)
f=10 Hz
50 Hz
250 Hz
0
0.2
0.4
0.6
0.8
T (K)


x = 0.167
150 mK
175 mK
200 mK
250 mK
x = 0.045
150 mK
180 mK
220 mK
260 mK
300 mK
χ''/χ''p
f/fp


LiHoxY1-xF4
PM
FM
SG
T(K)
x

antiglass

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What is the antiglass and why does it exist?

not expected for classical dipoles

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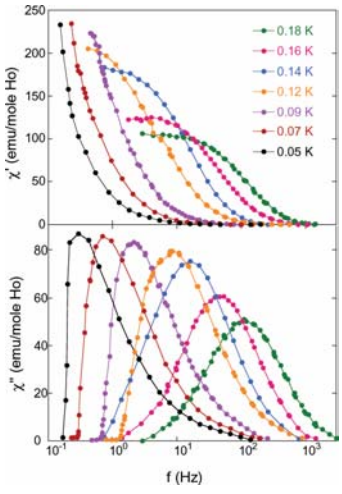

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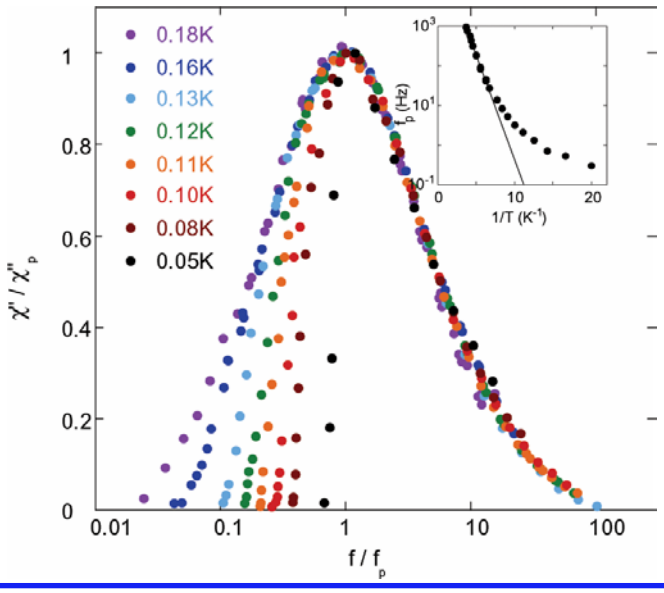
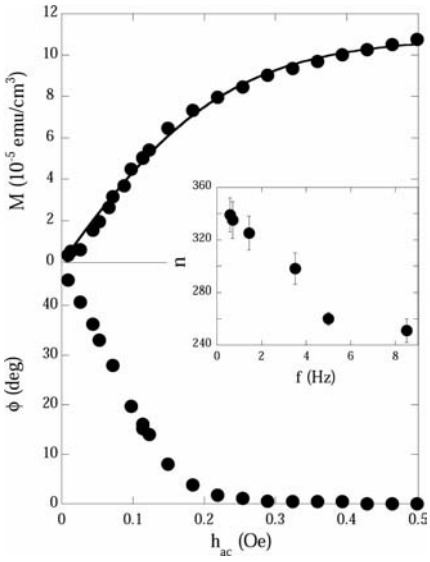
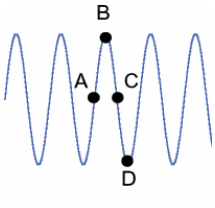
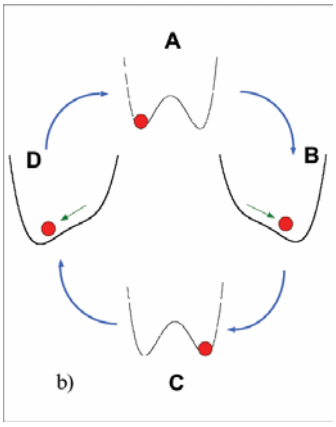


Emergence of a gap

- Not a simple relaxational form
- Scaling at high f but not low
- Are we dealing with a set of weakly coupled oscillators?


M (10^{-5} emu/cm^3)
ϕ (deg)
h$_{ac}$ (Oe)
n
f (Hz)


B
A
C
D


A
B
C
D
b)

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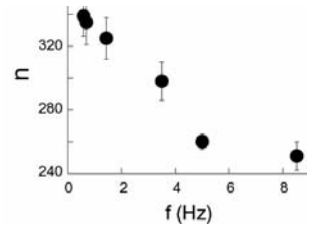
Phase locked spin clusters with n Ho moments, as determined from Brillouin function analysis $M(h) \sim h f_B(n m_{Ho}/kT)$



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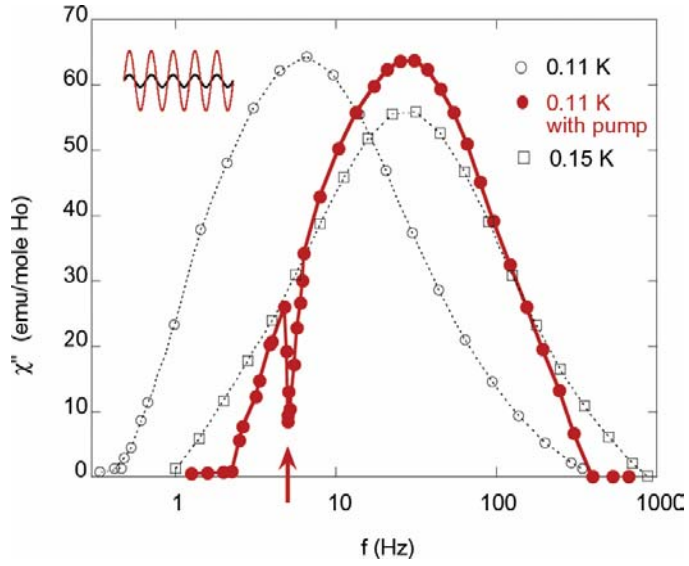
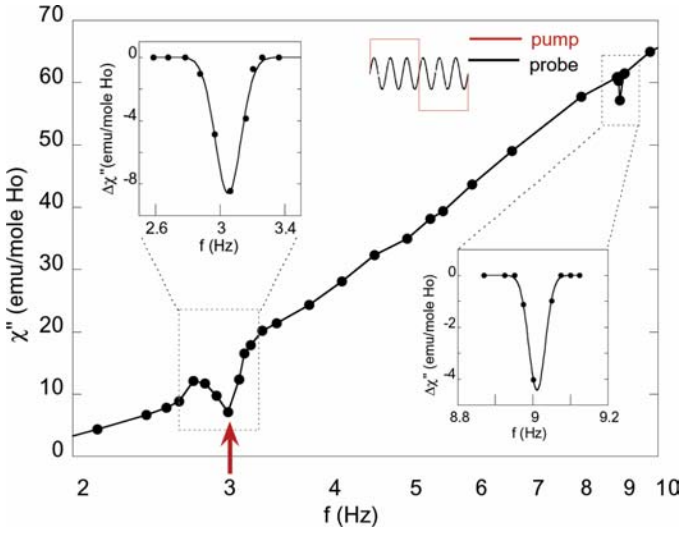
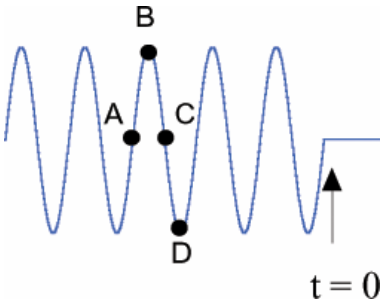
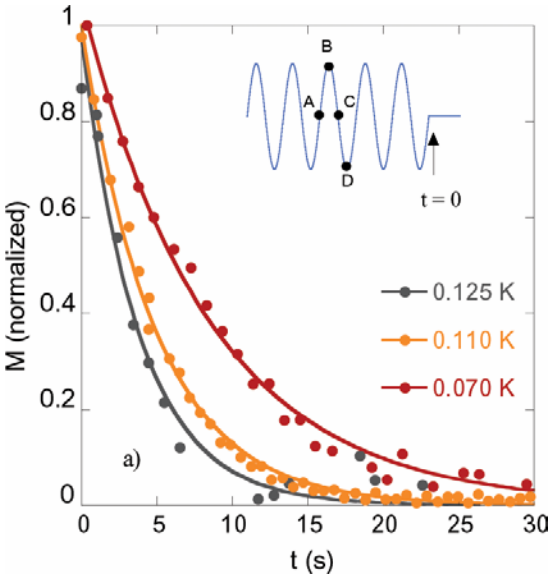




Persistence of oscillations- free induction decay aka coherence



5 Hz



Antiglass state

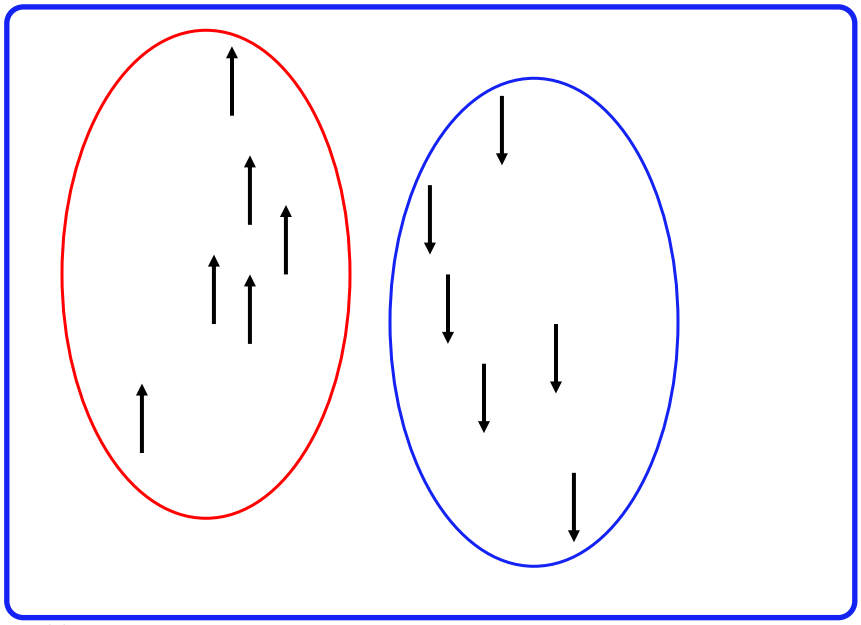
- Narrowing distribution of scaled relaxation times
- Appearance of gap structure at low T
- Hole burning
- Phase locking
- Persistent(coherent) spin oscillations
- No signature of phase(glass) transition in dc susceptibility
- Spectrum apparently due to clusters of ~200 spins undergoing coherent oscillations

Why?

- Crucial clue – all interesting effects seen at T where classical barrier hopping no longer dominates
- Quantum mechanics must play a role

Possible description of state

- Upon dilution, internal transverse fields due to off-diagonal terms in dipole intercation(terms vanish in pure limit)
- RVB state of nearly decoupled Ho clusters
- Ho clusters undergo Rabi oscillations in transverse fields generated by other clusters
- Spectrum is distribution of Rabi frequencies



conclusions

- Unexpected antiglass state in a disordered magnet
- Coherent oscillations (Q~50) in a disordered magnet
- Quantum mechanics implicated at intermediate dilution of a ‘model’ classical system
- Dense disordered solids are not hopeless for quantum oscillations

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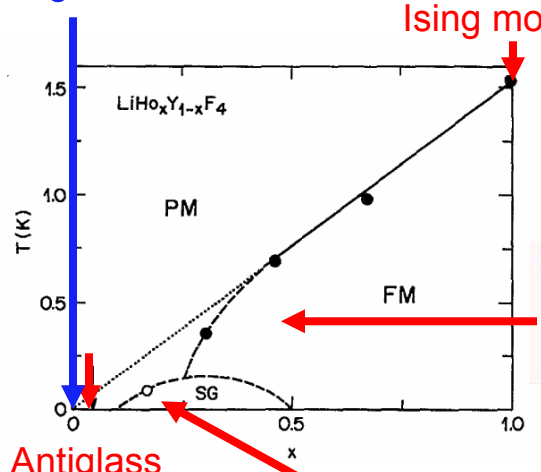
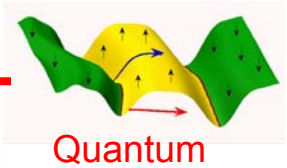
Single ion relaxation

Clean realization of TF Ising model





Quantum tunneling of domain walls

Antiglass

Quantum SG