

Spin Liquids, Spin Glasses, and Quantum Protectorates

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Why study spin liquids?

- Interesting collective behavior: “quantum self-assembly”
- Competing ground states

Using non-linear dynamics...

- Encode Information
- Collective excitations with long coherence times (seconds)
- Extreme sensitivity to ground state

The Spin Liquid

- No long range order as $T \rightarrow 0$
- Not a **spin glass** – spins *not* frozen, fluctuations persist
- Not a **paramagnet** – develops short-range correlations

Collective behavior

What prevents freezing ?

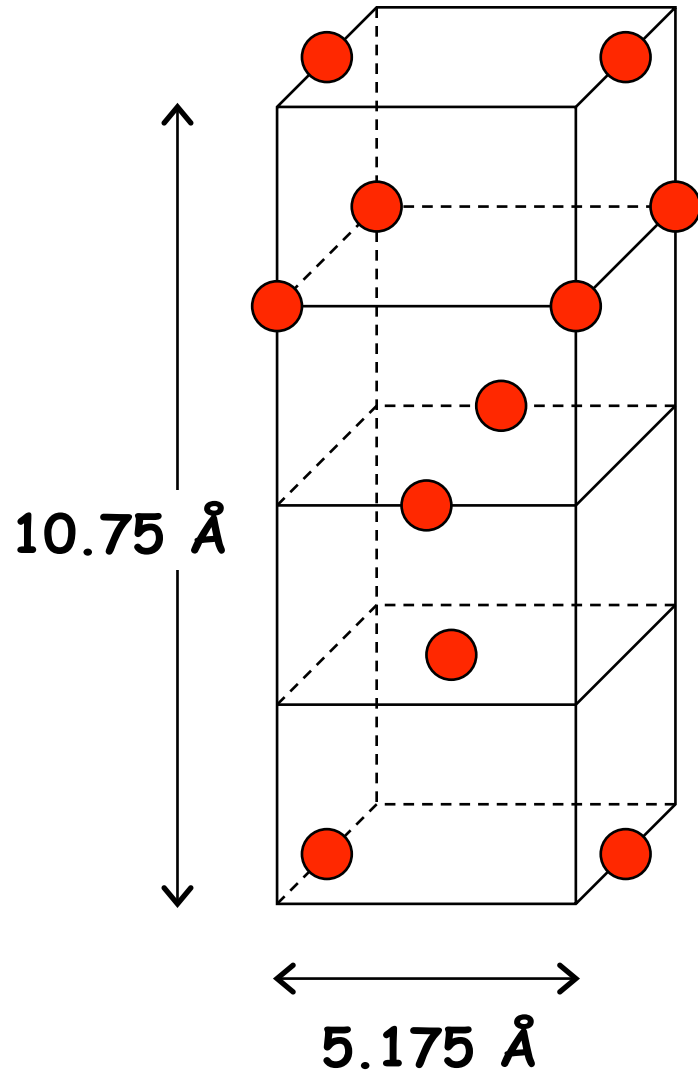
– Geometric frustration

– Quantum fluctuations

– Reduced dimensionality

Examples: CuHpCl, **Gd₃Ga₅O₁₂** (3D geometric frustration)
Tb₂Ti₂O₇, **LiHo_{0.045}Y_{0.955}F₄** (quantum fluctuations)
SrCu₂(BO₃)₂, Cs₂CuCl₄ (2D triangular lattice)

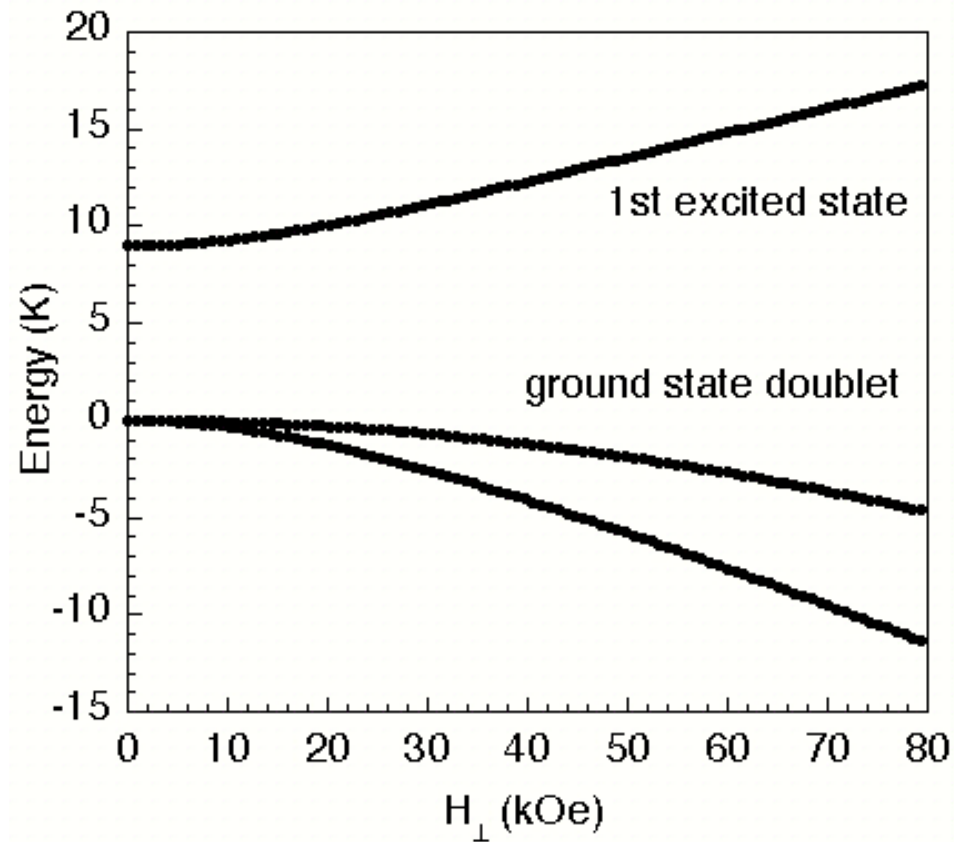
$\text{LiHo}_x\text{Y}_{1-x}\text{F}_4$



- Ho^{3+} magnetic, Y^{3+} inert
- Ising ($g_{\parallel} = 14$)
- Dipolar coupled (long ranged)

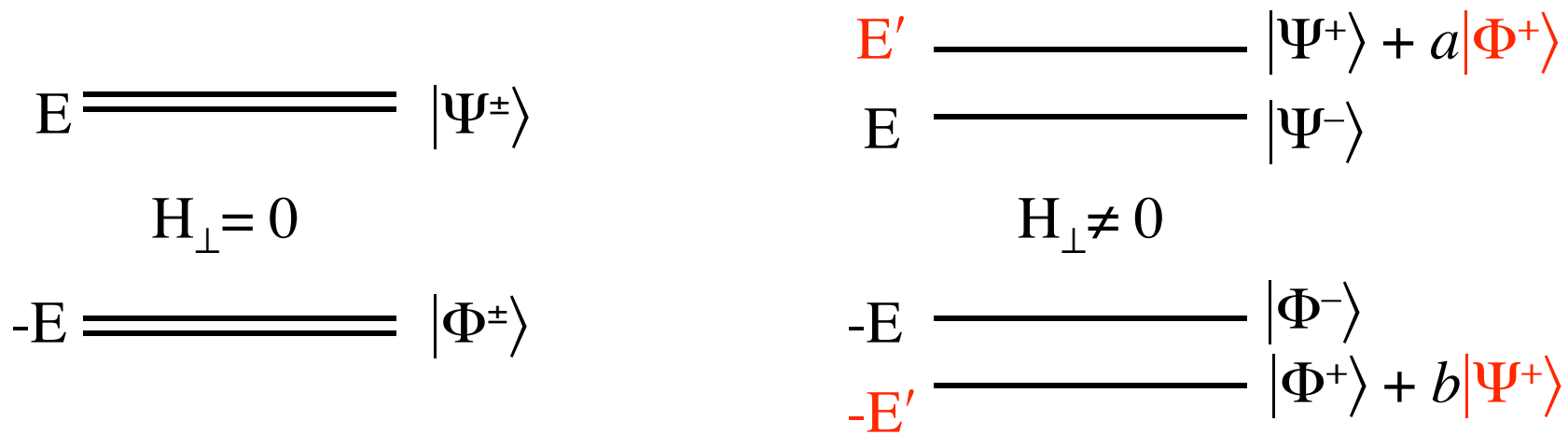
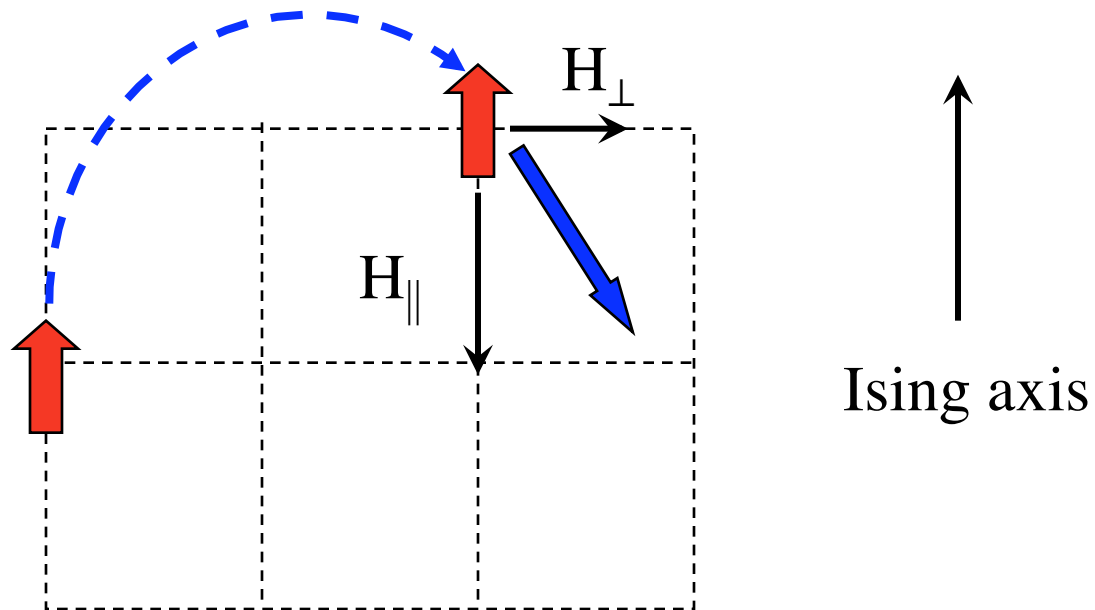
- $x = 1$ Ferromagnet
 $T_C = 1.53 \text{ K}$
- $x \sim 0.5$ Glassy FM
 $T_C = xT_C(x=1)$
- $x \sim 0.2$ Spin Glass
Frozen short-range order
- $x \sim 0.05$ Spin Liquid
Short-range correlations

Effect of a Transverse Field



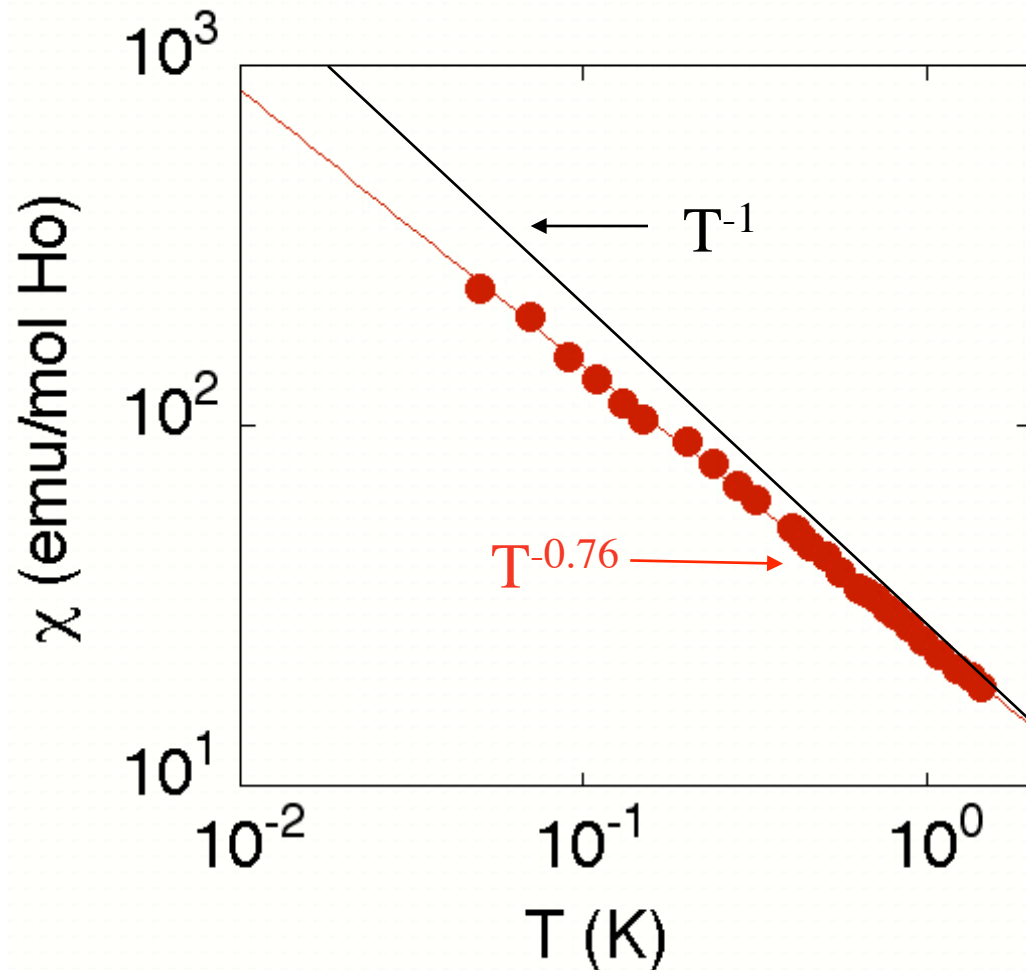
$$H = \sum_{i,j}^N J_{ij} \sigma_i^z \sigma_j^z - \Gamma \sum_i^N \sigma_i^x \quad \text{with } [H, \sigma^z] \neq 0$$

(Internal) Quantum Fluctuations



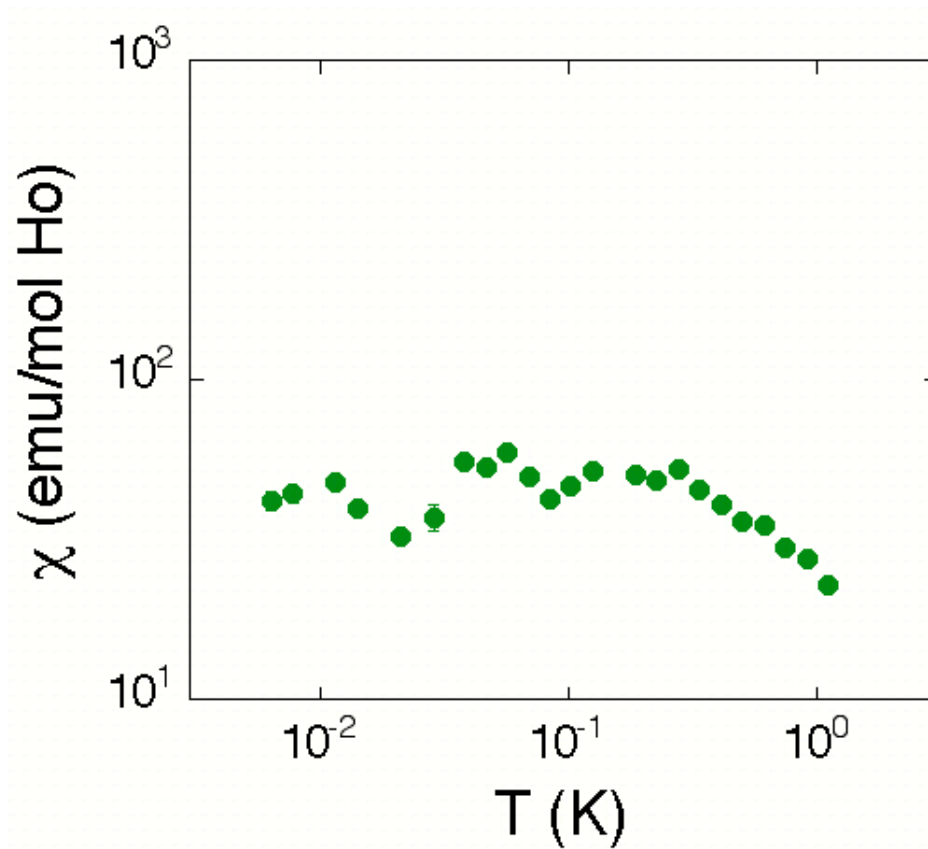
Signatures of spin liquid

dc susceptibility

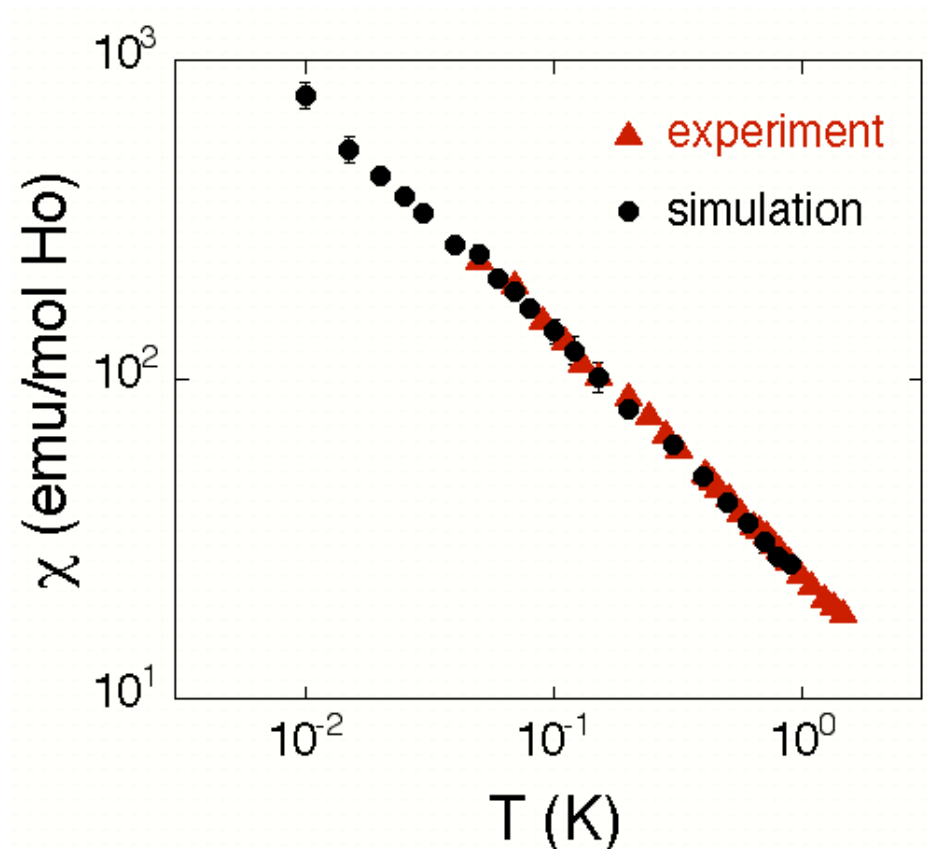


- no peak in χ
 \Rightarrow no LRO
- sub-Curie T dependence
 \Rightarrow correlations

Quantum spin liquid

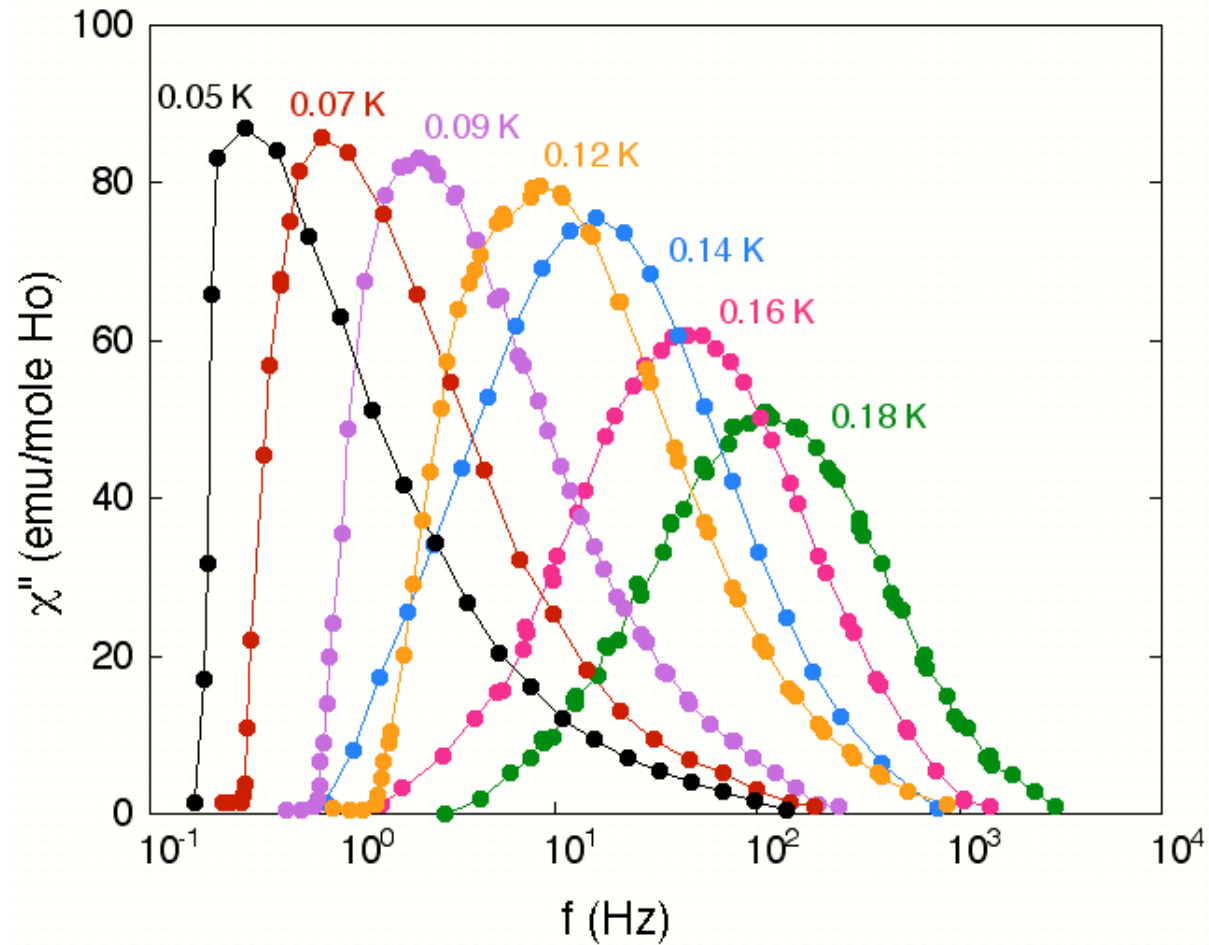


$H_{\perp} = 0$



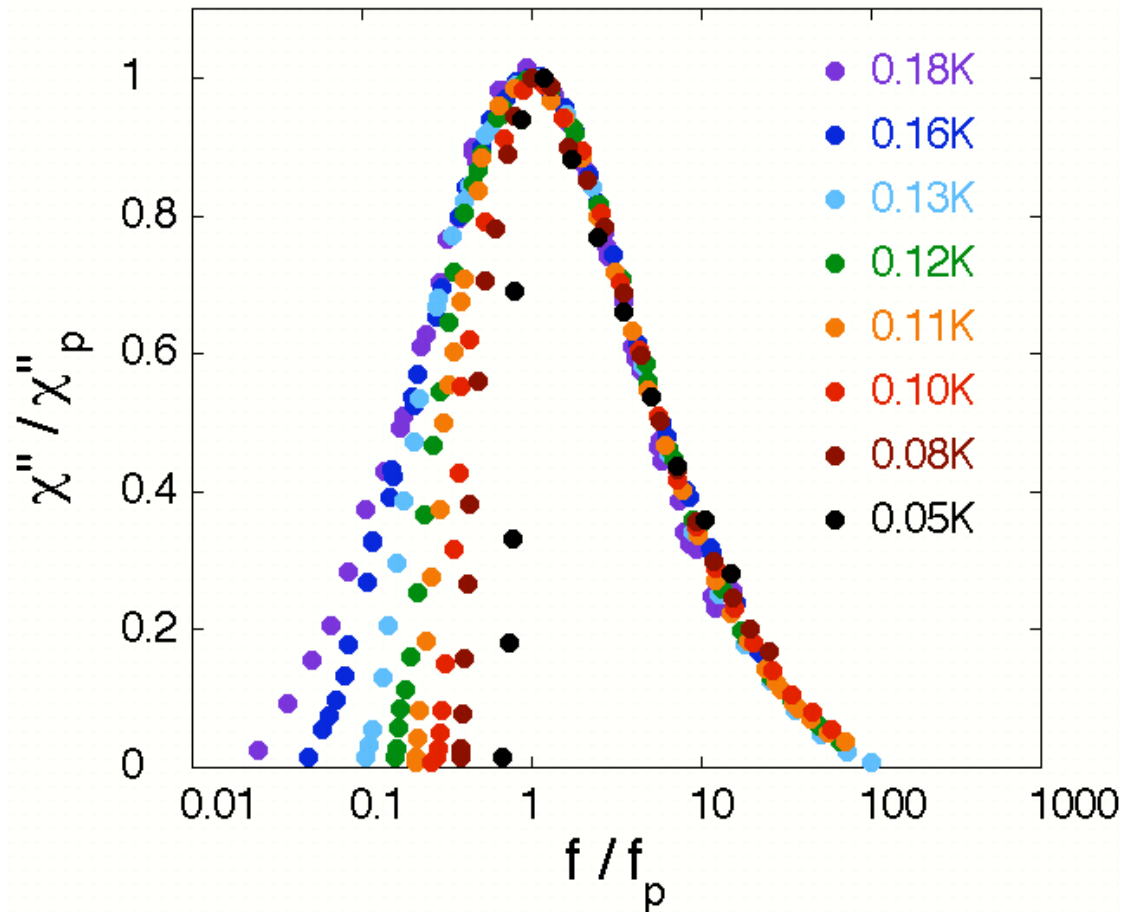
$H_{\perp} \neq 0$

Dynamic magnetic susceptibility



χ''_{ac} narrows with decreasing T
 \Rightarrow “Antiglass”

Scaled susceptibility

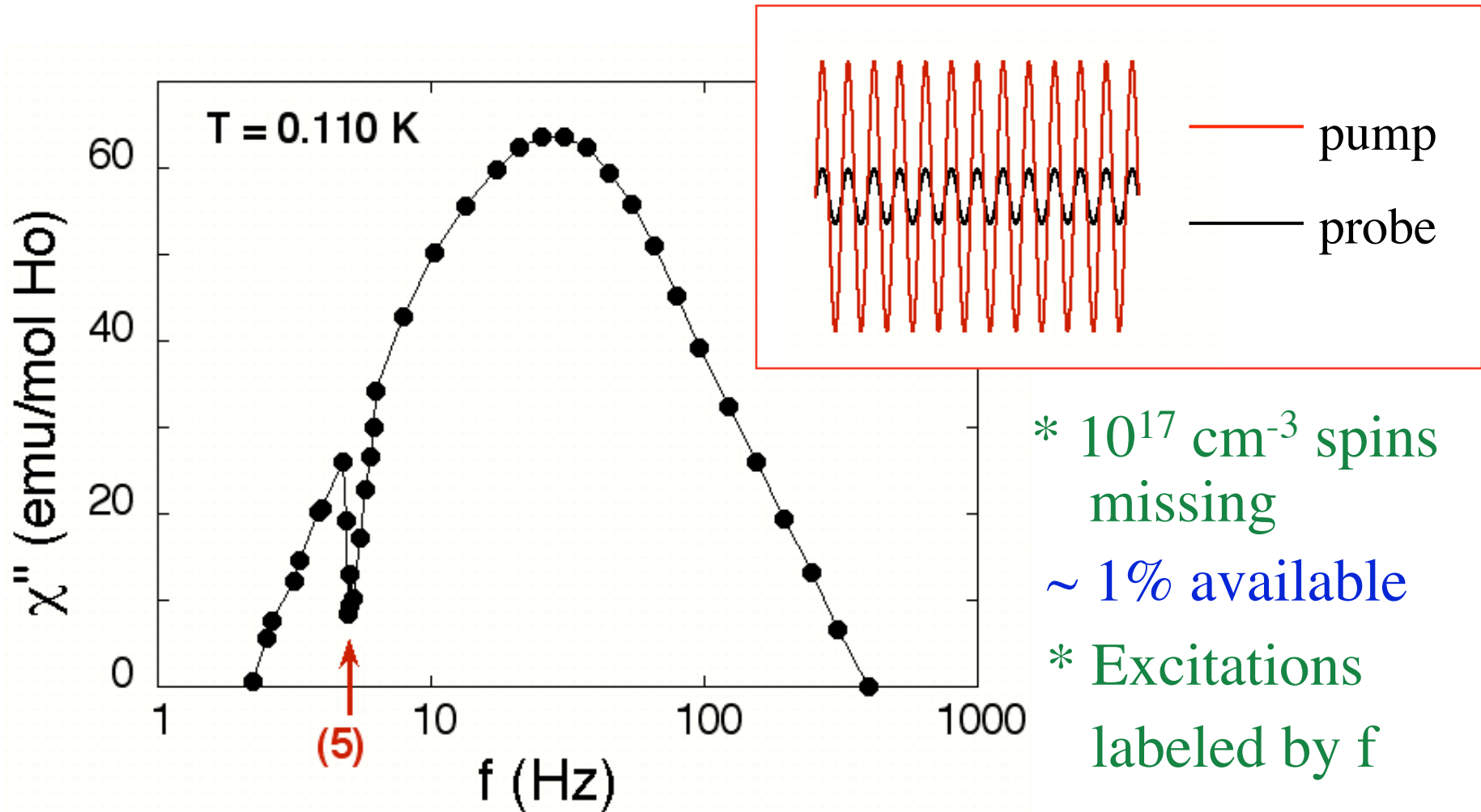


FWHM ≤ 0.8 decades in f

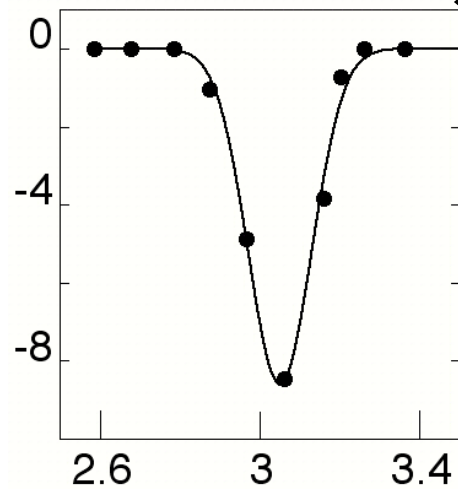
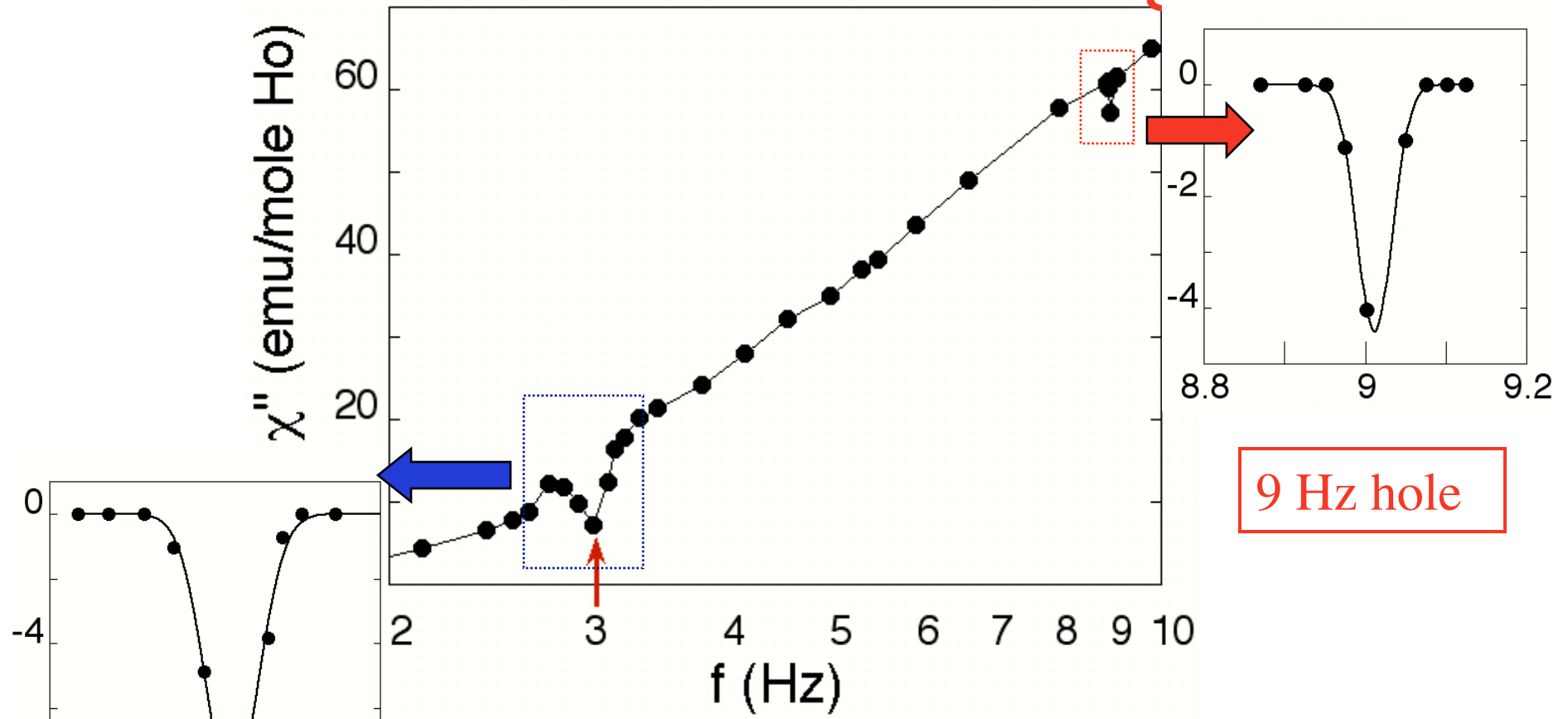
Relaxation spectral widths :

- *Debye width*
(1.14 decades in f)
single relaxation time
- *if broader...*
multiple relaxation times e.g. glasses
- *if narrower... not relaxation spectrum*

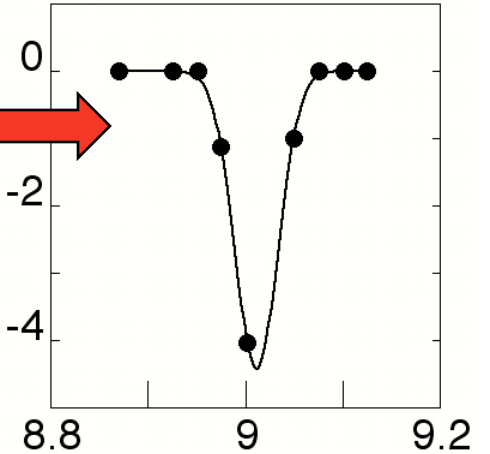
Hole Burning



Simultaneous Encoding



3 Hz hole

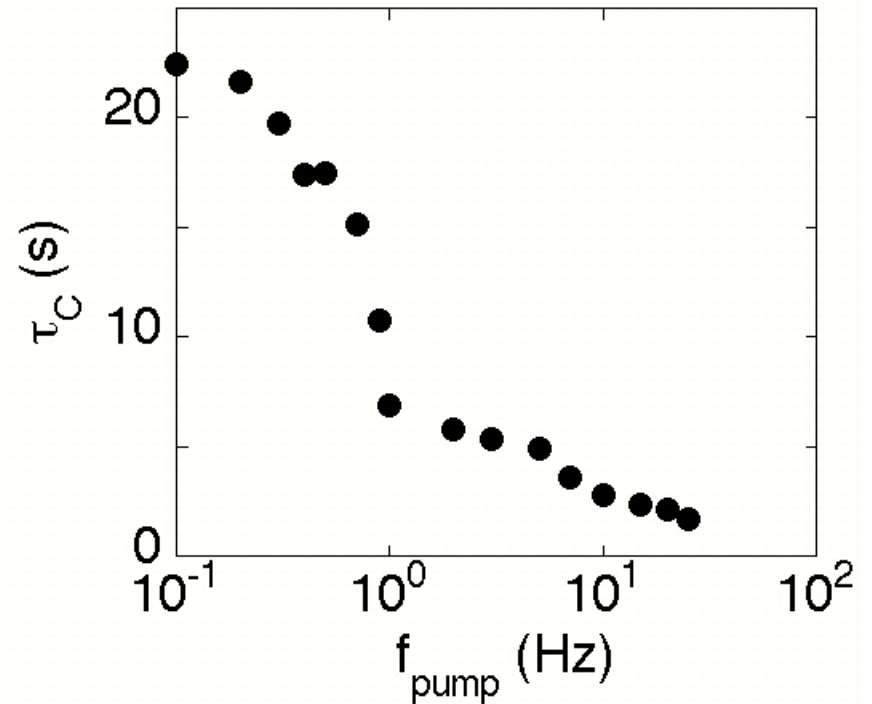
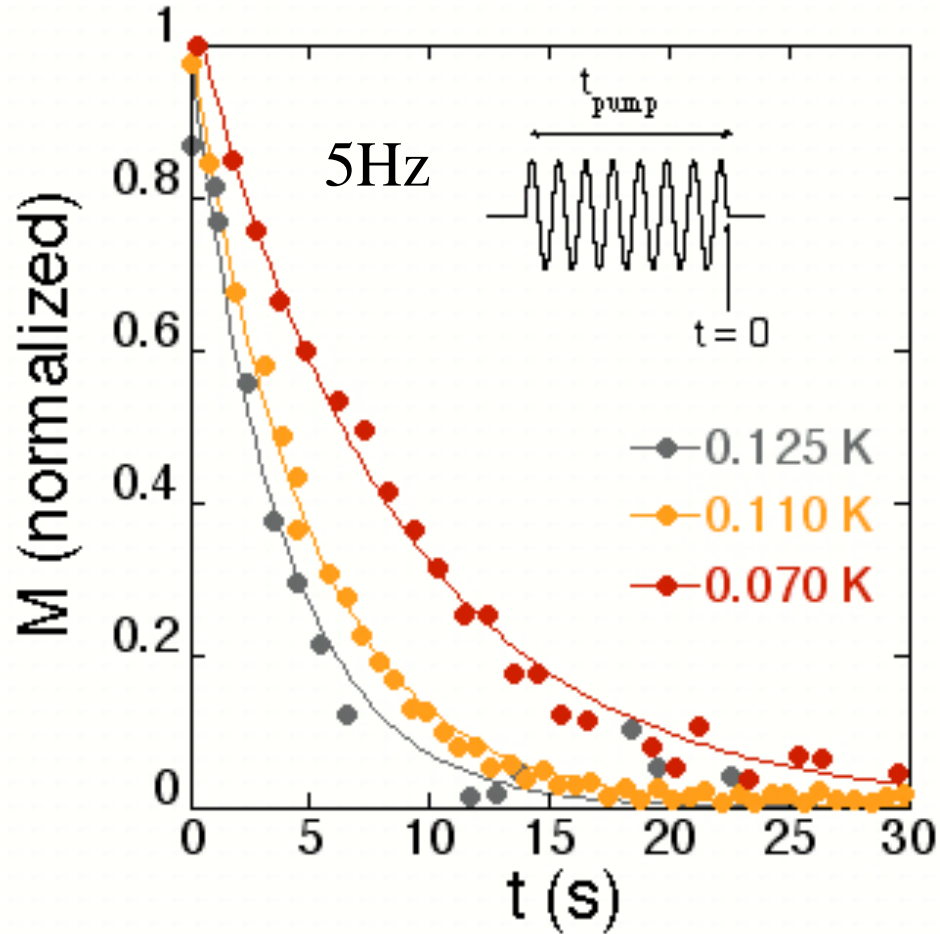


9 Hz hole



Square pump at 3 Hz

Coherent Oscillations

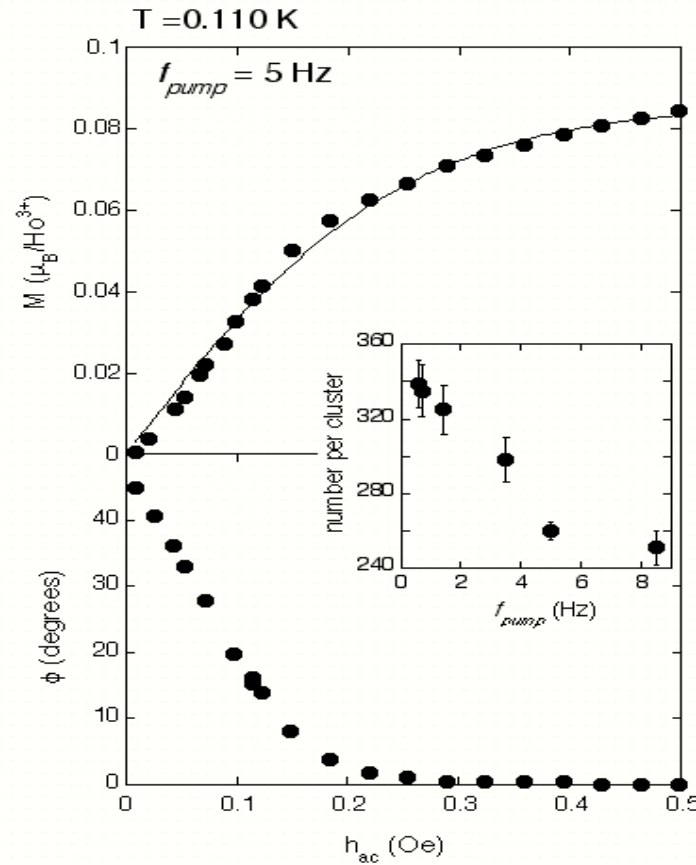


$Q \sim 50$

Brillouin Fit

Magnetization

Phase

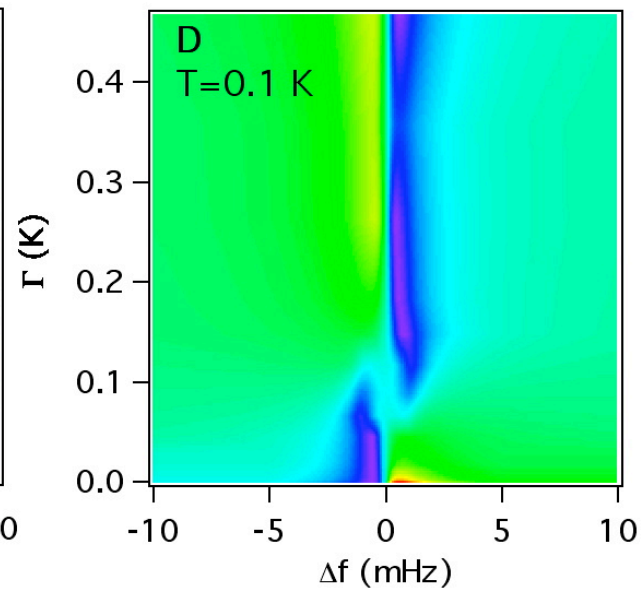
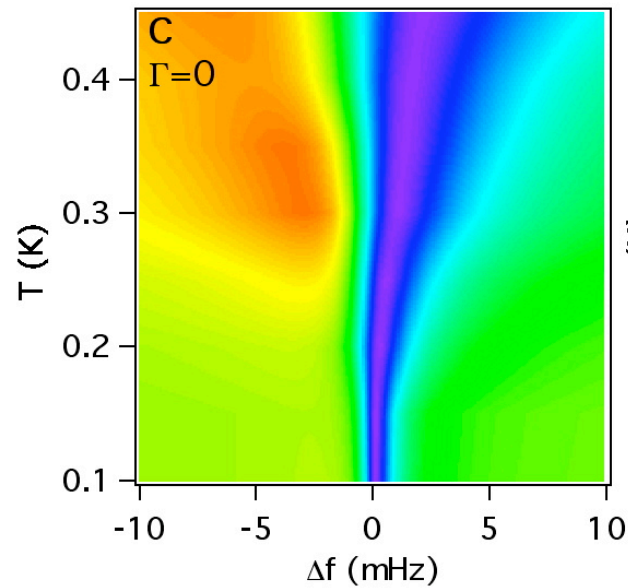
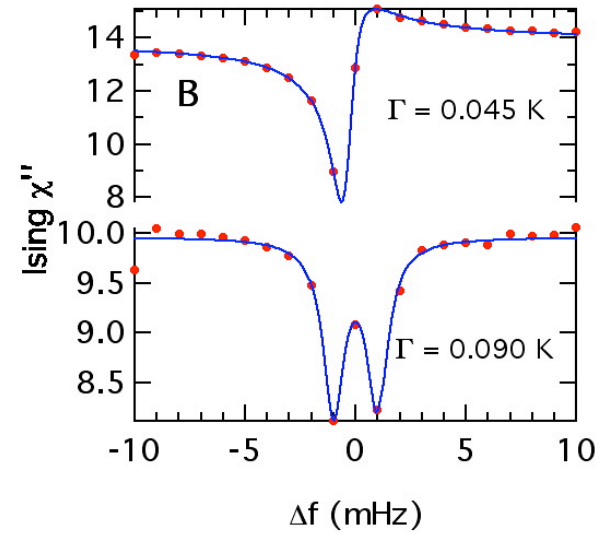
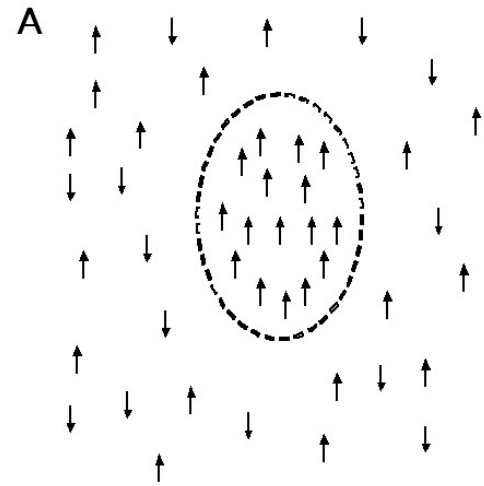


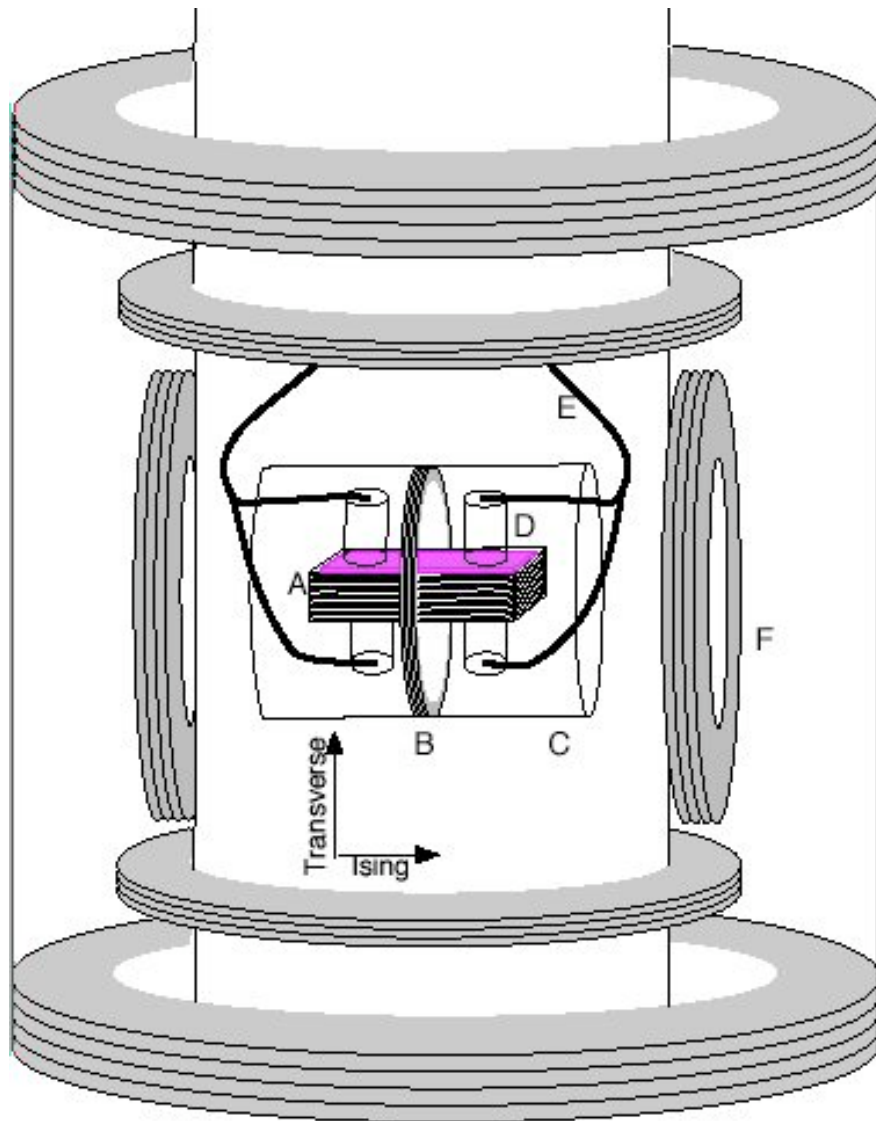
Spins per Cluster

$$M = Nsg\mu_B \tanh(ng\mu_B sh_{ac}/k_B T)$$

ac Excitation

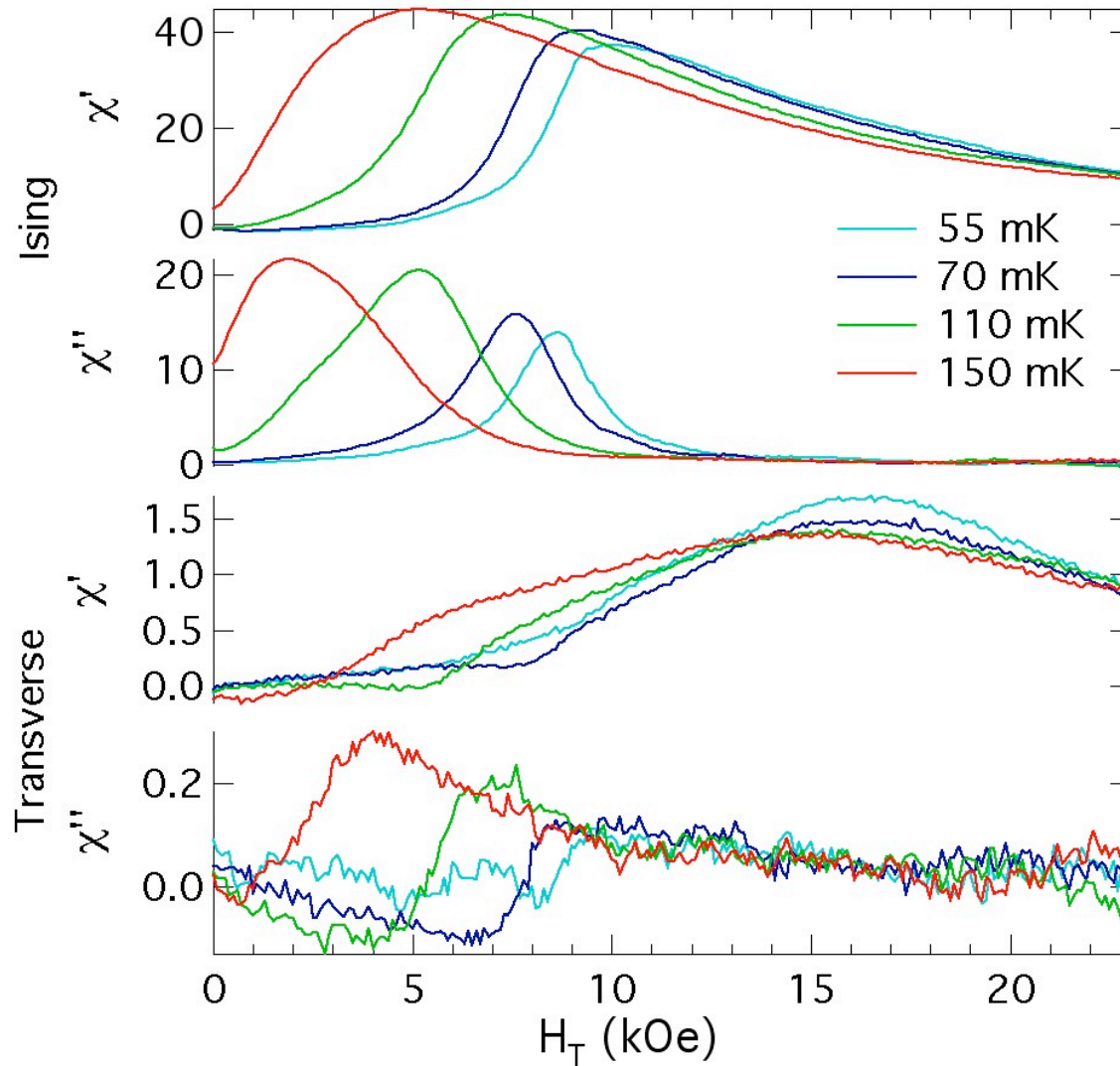
“Quantum Protectorate” in T and Γ





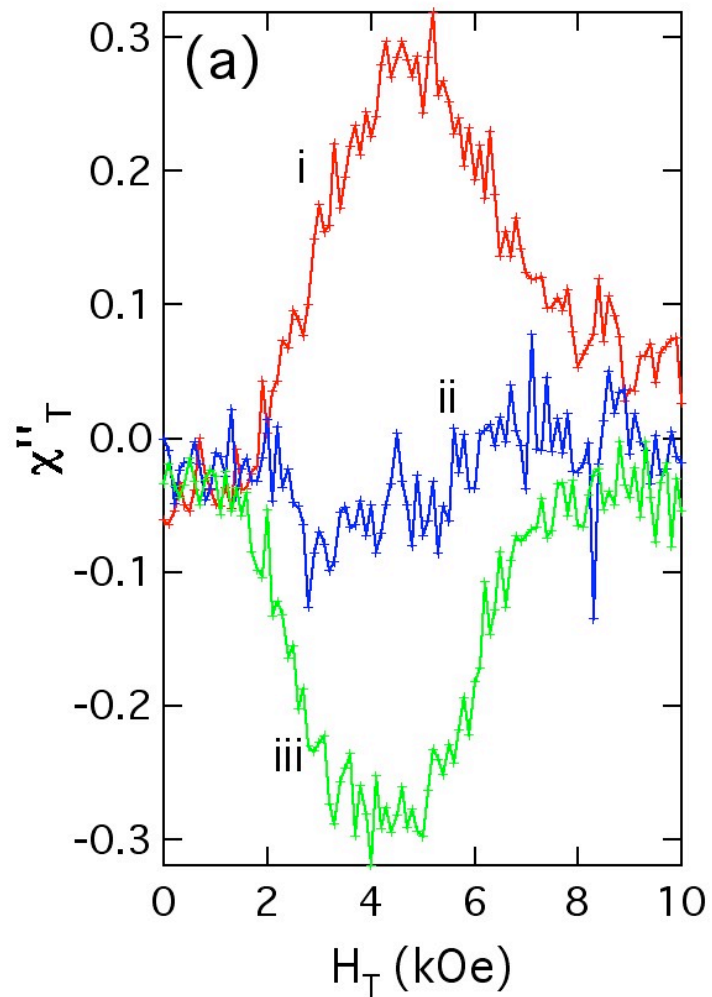
Quantum Projection
into the plane

Spins Rotating in Space and Phase

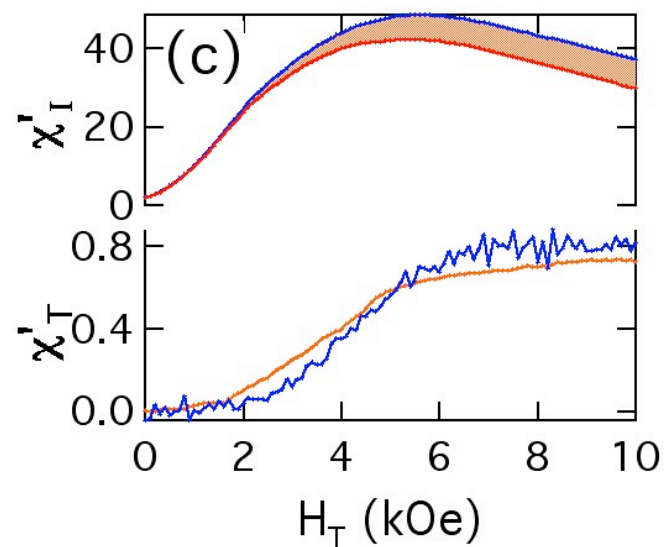
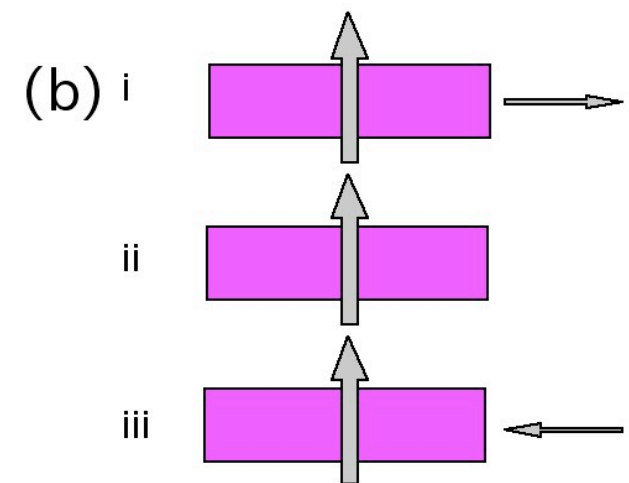


← 1% of Spins

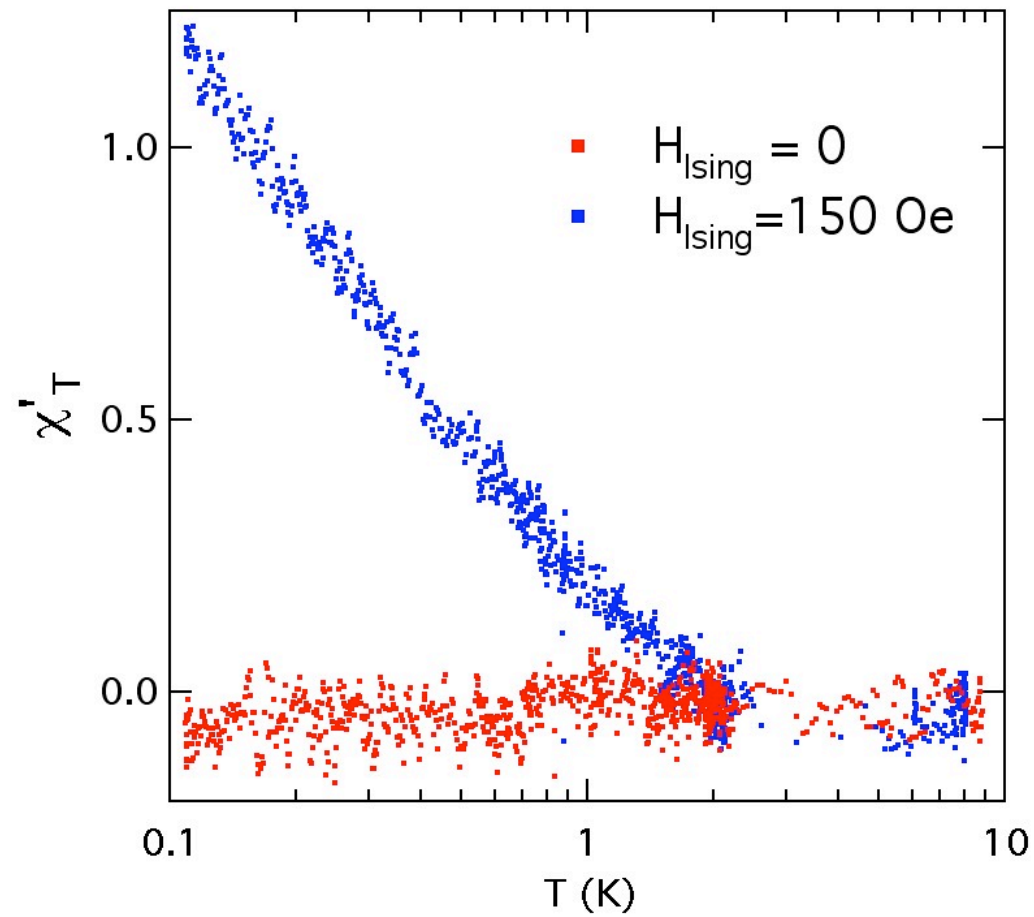
Phase Rotation



Spatial Rotation

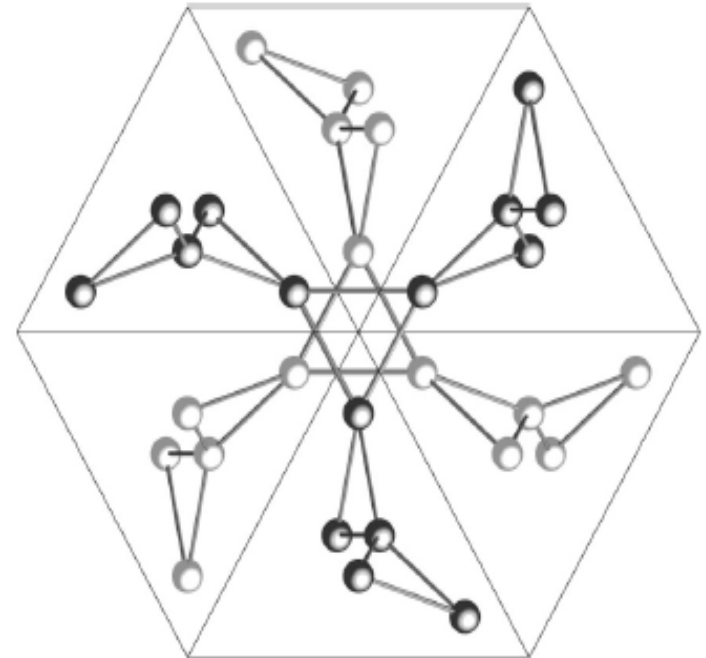
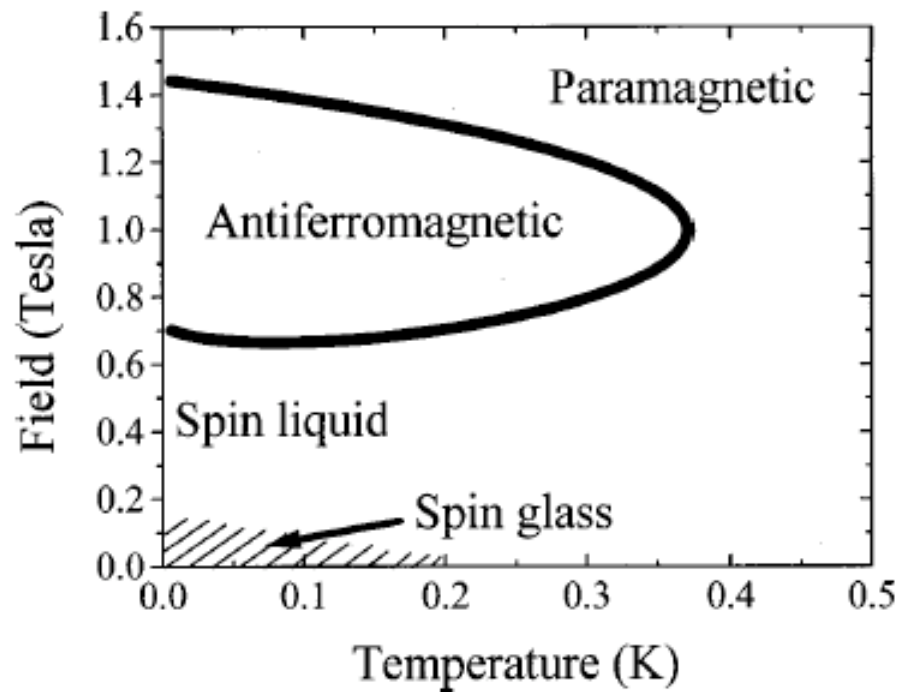


Griffiths Physics: *Spin Clusters*



$\text{Gd}_3\text{Ga}_5\text{O}_{12}$

Phase diagram

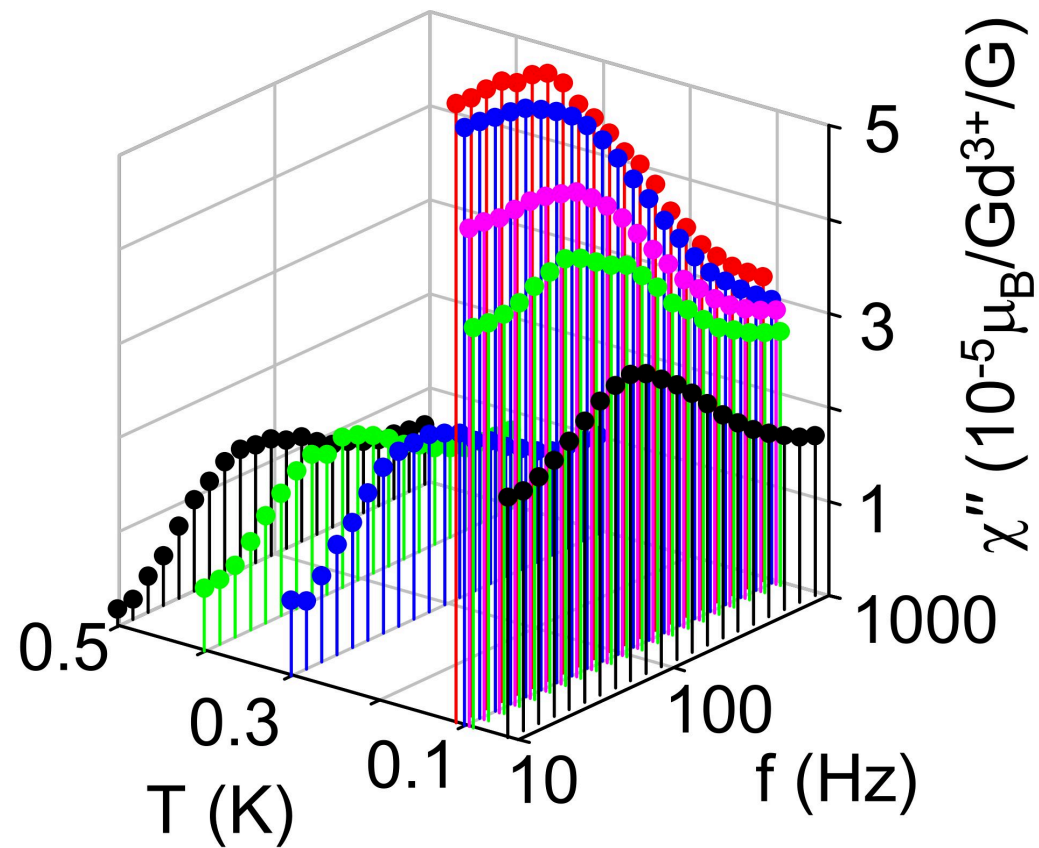


GGG : Geometrically frustrated, Heisenberg

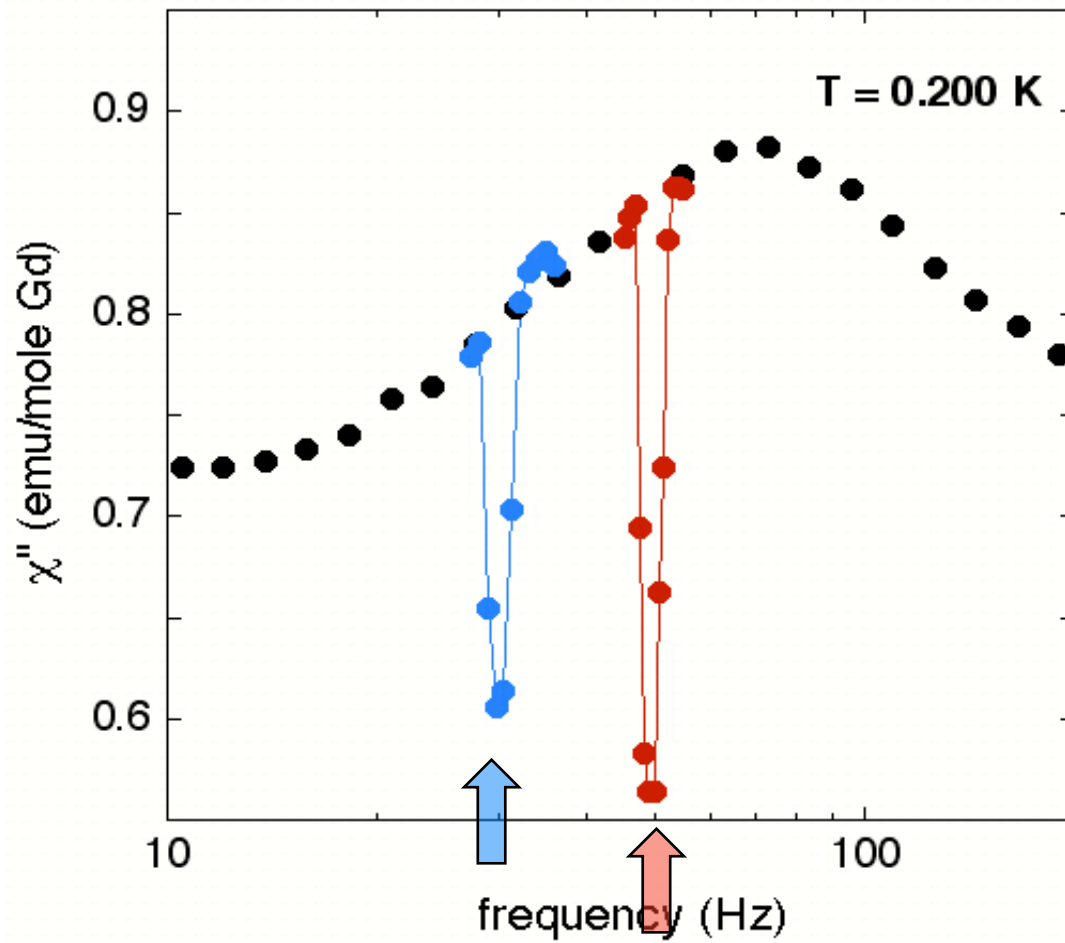
AFM exchange coupling

P.Schiffer, A. Ramirez, D. A. Huse and A. J. Valentin
PRL **73** 1994 2500-2503

Dynamic Susceptibility



Encryption in GGG Spin Liquid



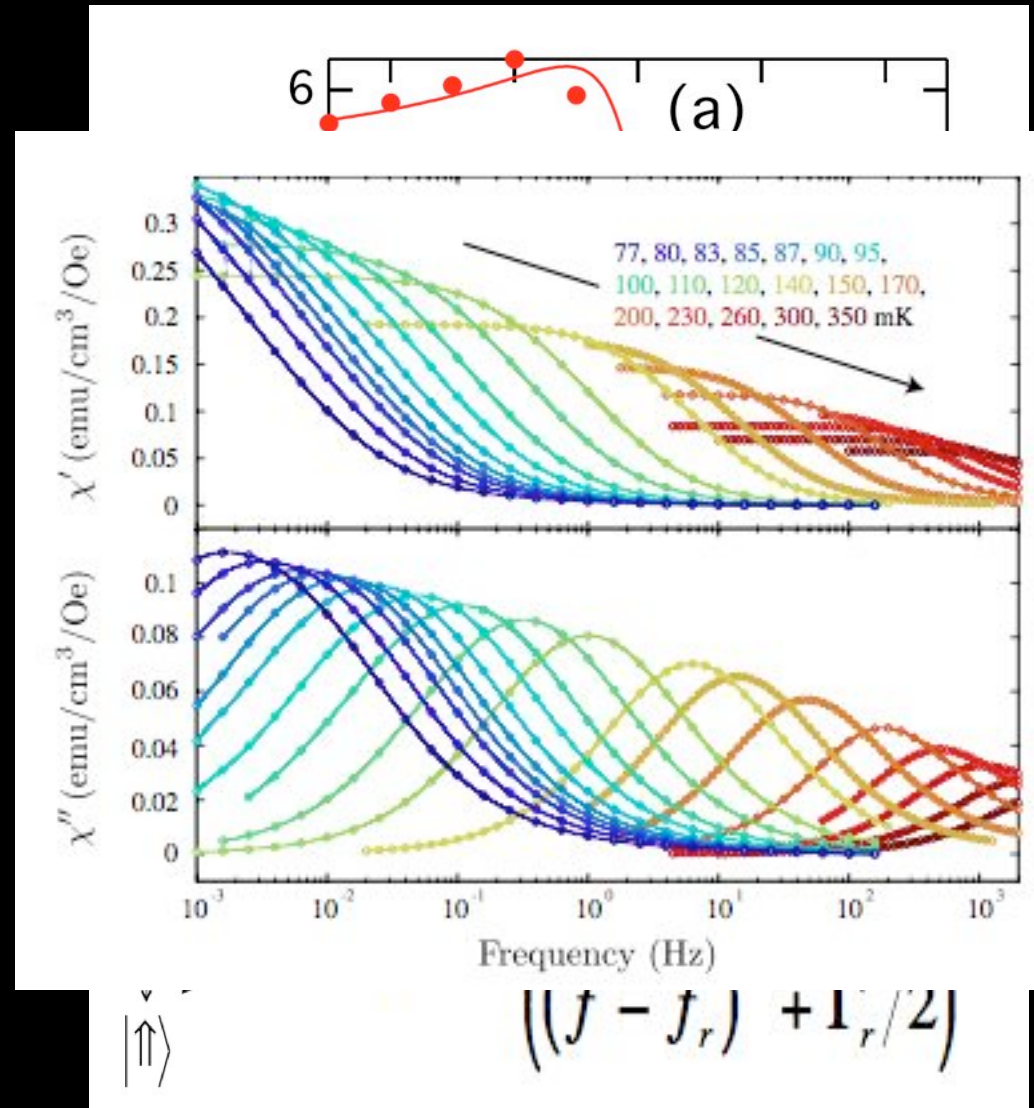
From Spin Liquid to Spin Glass in $\text{LiHo}_x\text{Y}_{1-x}\text{F}_4$

Coherent Spins versus Glassiness

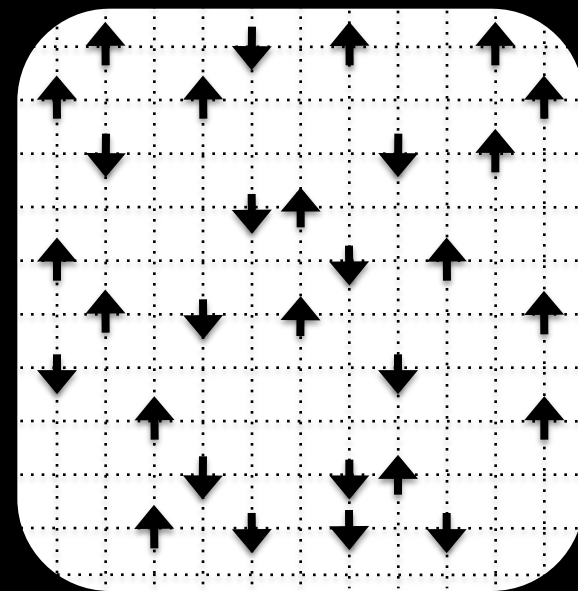
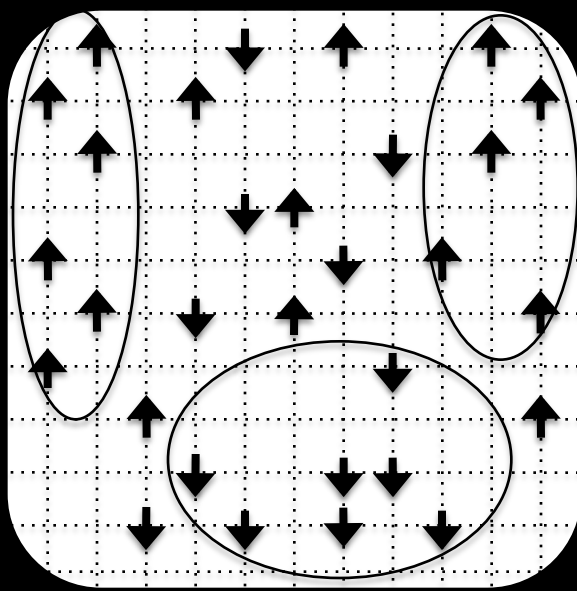
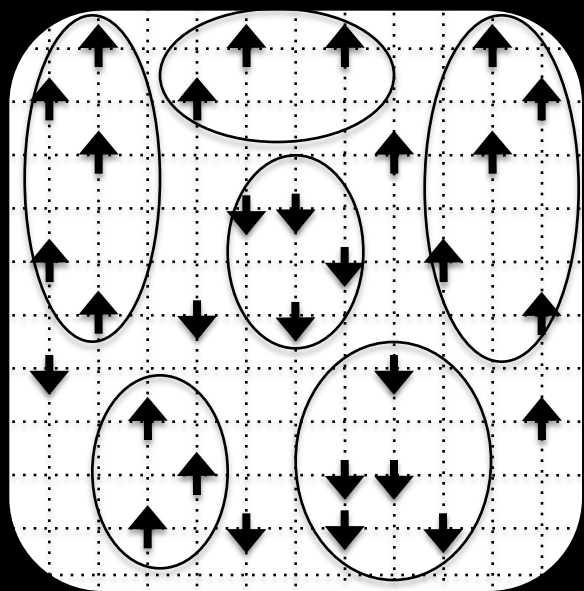
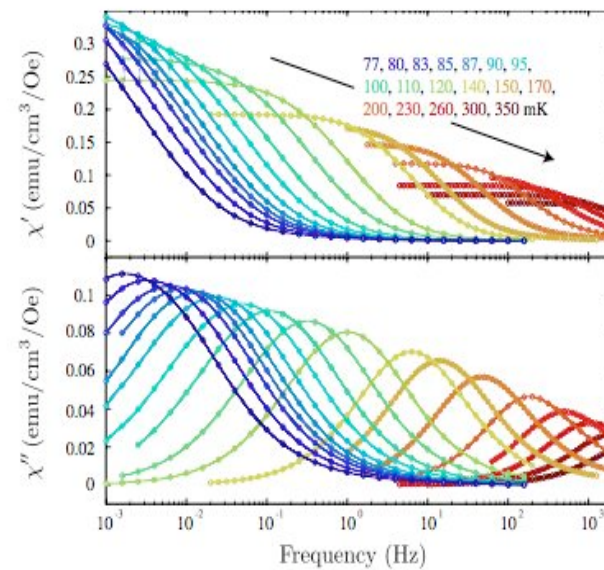
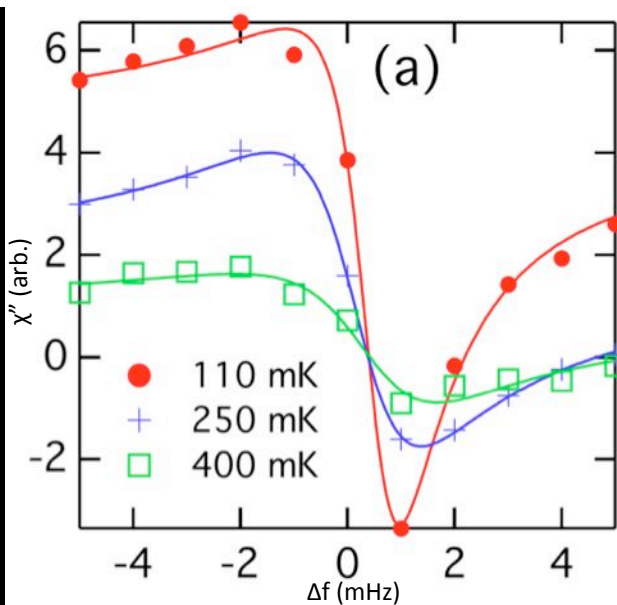
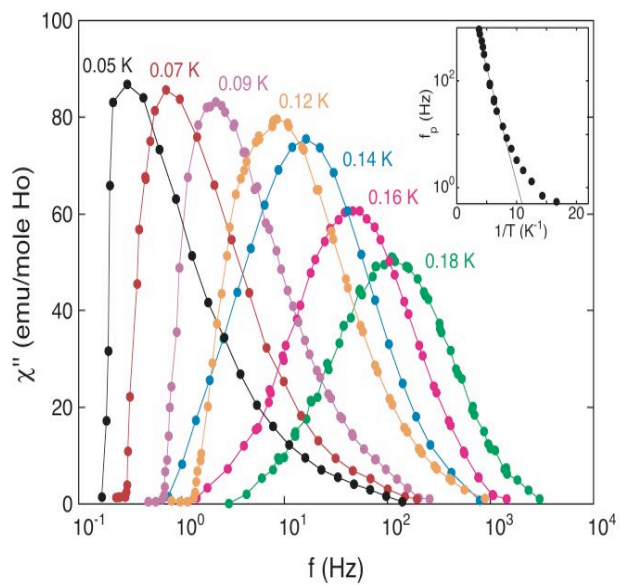
- S. Ghosh et al. (2002): gapped spin liquid, holes in non-linear response
- Silevitch et al. (2007): Fano resonance in non-linear susceptibility
- Quilliam et al. (2008): onset of glass state

Can we switch the system between states?

What variables are important: cooling rate, boundary conditions?



Source: Ghosh, S. et al., *Science*, 296 (2002)
 Source: Quilliam, S. et al., *Phys. Rev. Lett.* 101 (2008)



Weakly Coupled Clusters

No Clusters

Spin Liquid

Spin Glass

Conclusions

- Non-Linear Dynamics

Sensitive new avenue of study of spin liquids

- Coherent Collective Modes

Clusters of hundreds of spins labeled by frequency

- What is their Structure and Distribution?

Self-Organized: From Spin Liquids to Glasses (?)

- Possibility of manipulation and entanglement using a transverse field

cf. NMR Quantum computing

Further studies...starting point *(mixing with external H_t)*

