Magnetic Spin Echo Experiments

Jason S Gardner

NIST Center for Neutron Research

&

Indiana University

Collaboration

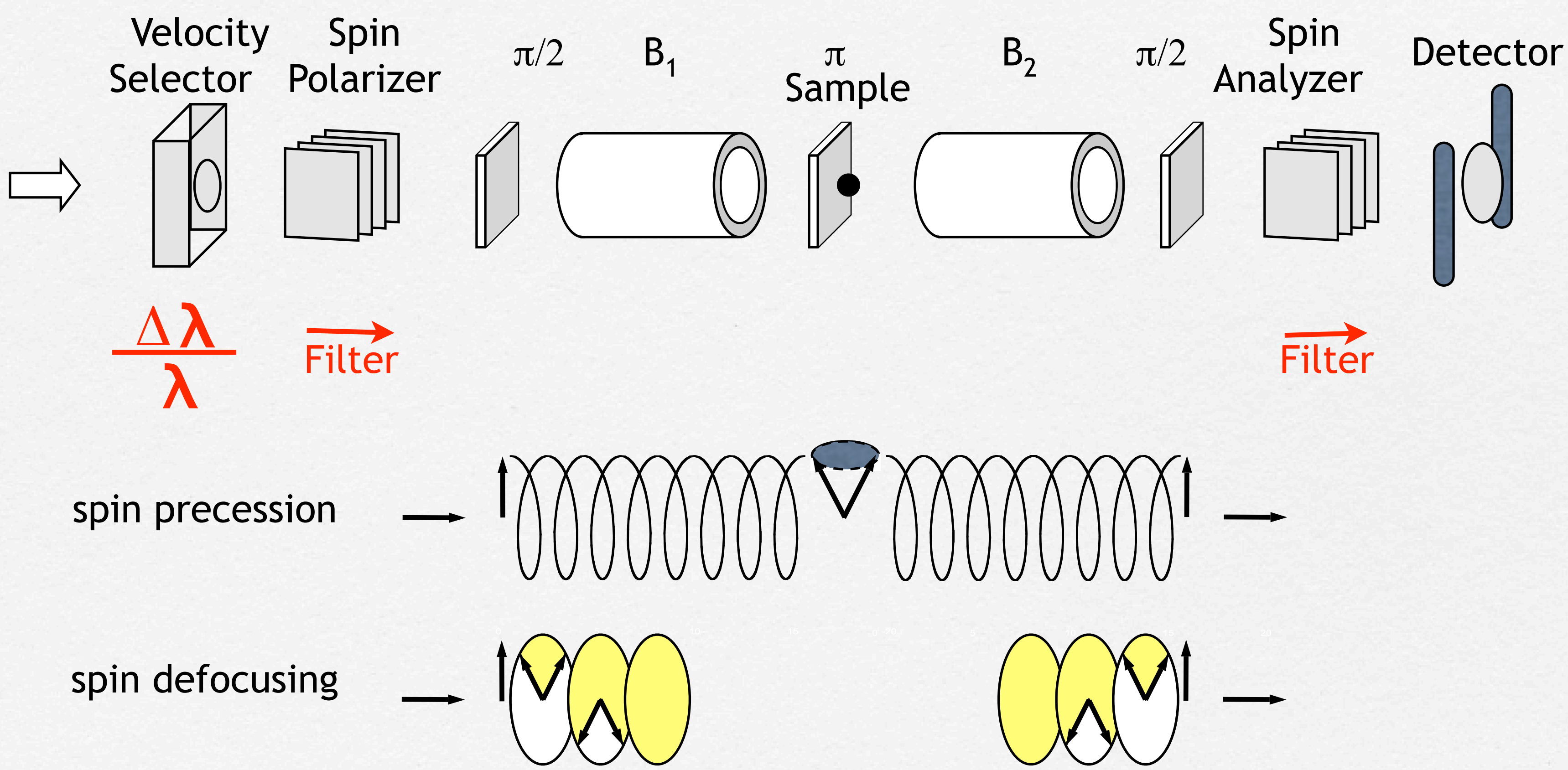
G. Ehlers, *SNS, Oak Ridge National Laboratory, Oak Ridge, TN*

S. T. Bramwell and T Fennell, *University College London, London WC1H 0AJ, UK*

R. Stewart, *ILL, Grenoble, France*

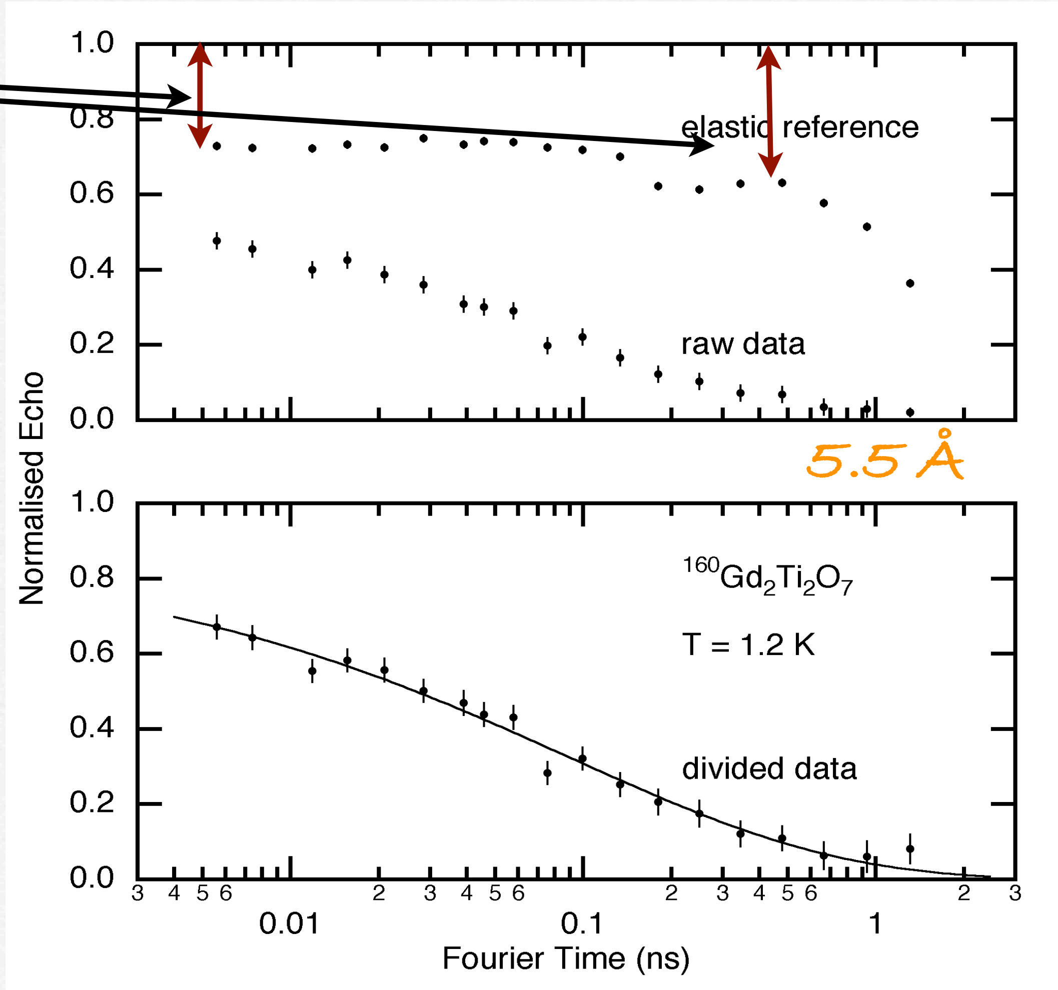
A. L. Cornelius, *University of Nevada Las Vegas, Las Vegas, NV 89154.*

Spin Echo – How does it work



Data Analysis Procedure

Imperfections in the instrument



5.5 Å

λ^3

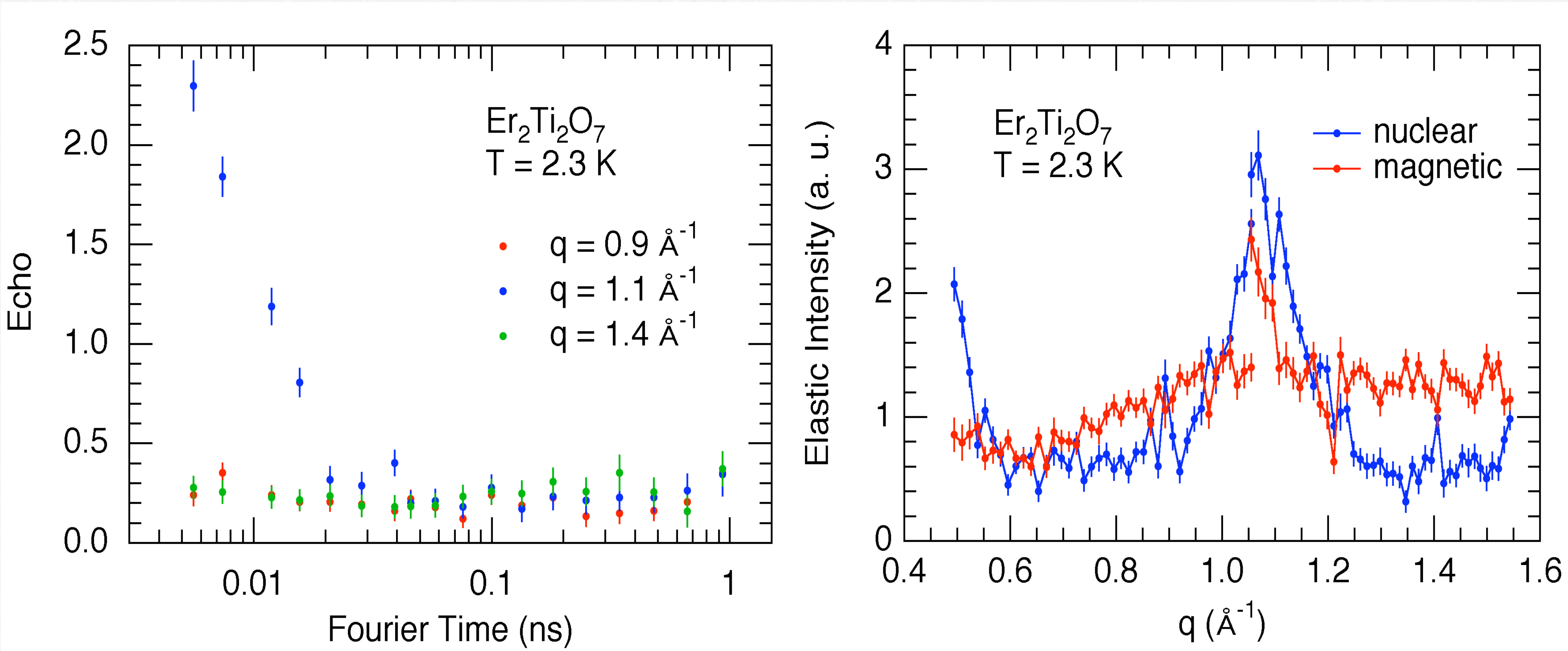
Outline

- [x] Introduction and Repetition
- [ ] Peculiar characteristics of magnetic scattering: intensity considerations and spin flip scattering
- [ ] Science examples
    - [ ] Spin Glass
    - [ ] Spin Ice
    - [ ] Partial Order
    - [ ] Spin Liquid
- [ ] Closing remarks

Magnetic Scattering

- The spin in the sample does the π flip.
  No need for the π flipper
- NEED xyz-analysis to scale data
  (need a resolution sample)
- Must be aware of magnetic excitations in the "neutron energy window" of the experiment (6Å ≅ 2.3meV ⇒ Visit DCS first)
- Polarised beam so FM correlations kill us.
- Beware of Bragg peaks

The NSE Spurions - Direct Echo



xyz Polarization Analysis - the Idea

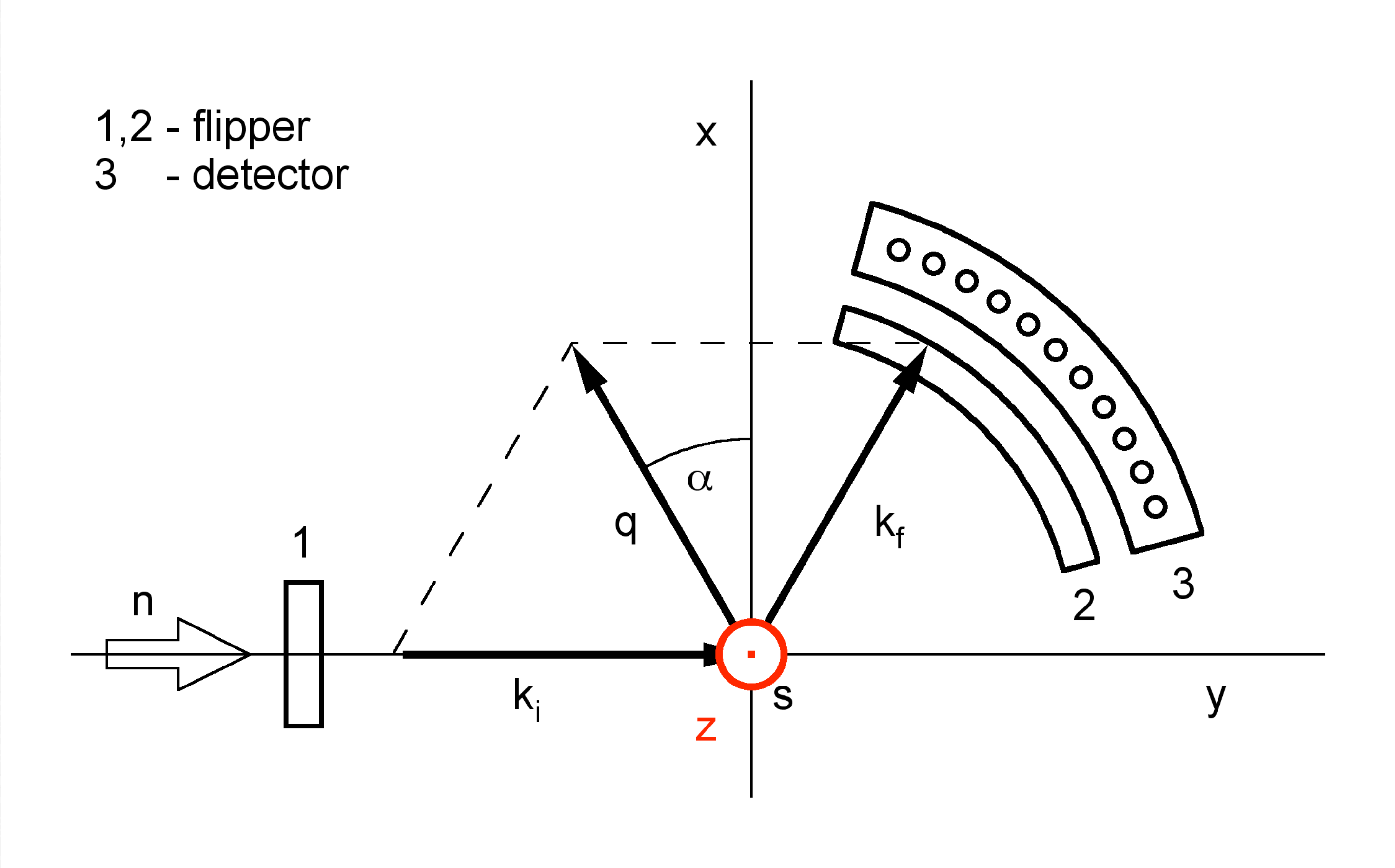
Types of scattering processes Effect on neutron spin

- nuclear coherent scattering (Bragg) no effect
- isotope incoherent scattering no effect
- spin incoherent scattering spin flip (2/3 probability)
- magnetic scattering spin rotation

in a paramagnet, magnetic moment directions are isotropically distributed

	$\boldsymbol{B}$ vertical	$\boldsymbol{B}$ horizontal ($\perp \boldsymbol{q}$)	$\boldsymbol{B}$ horizontal ($\parallel \boldsymbol{q}$)
$\boldsymbol{\mu}$ vertical	nsf	sf	sf
$\boldsymbol{\mu}$ horizontal ($\perp \boldsymbol{q}$)	sf	nsf	sf
$\boldsymbol{\mu}$ horizontal ($\parallel \boldsymbol{q}$)	0	0	0
average	50% nsf 50% sf	50% nsf 50% sf	100% sf

xyz Polarization Analysis - Reality



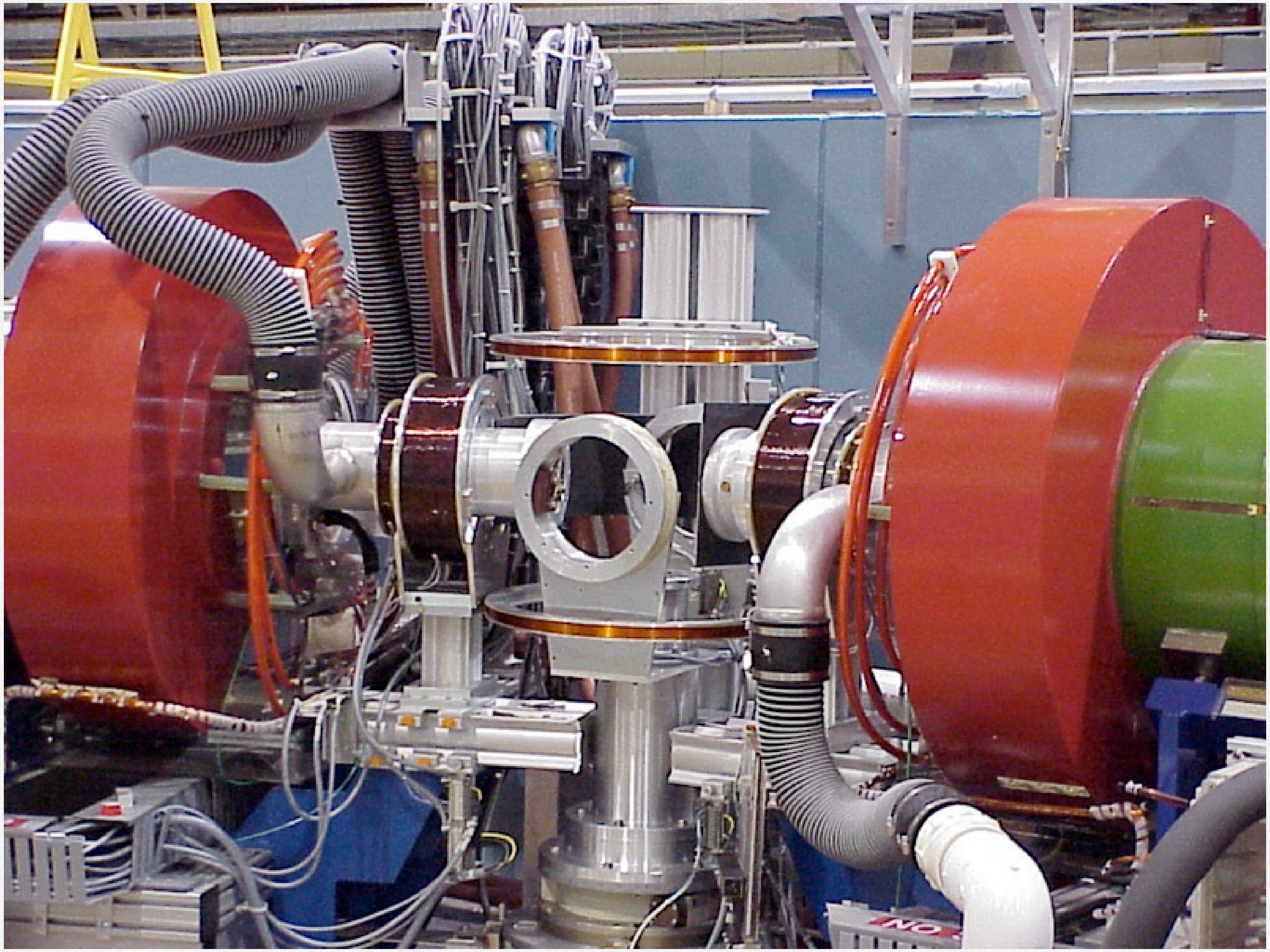
xyz Polarization Analysis - Equations

case	non spin flip ("up")	spin flip ("down")
$\vec{p} \parallel \vec{x}$	$\sigma_n \frac{1+p}{2} + \frac{1}{2}\sigma_m \cdot (1 - p \cdot \cos^2\alpha)$	$\sigma_n \frac{1-p}{2} + \frac{1}{2}\sigma_m \cdot (1 + p \cdot \cos^2\alpha)$
$\vec{p} \parallel \vec{y}$	$\sigma_n \frac{1+p}{2} + \frac{1}{2}\sigma_m \cdot \left(1 - p \cdot \sin^2\alpha\right)$	$\sigma_n \frac{1-p}{2} + \frac{1}{2}\sigma_m \cdot \left(1 + p \cdot \sin^2\alpha\right)$
$\vec{p} \parallel \vec{z}$	$\sigma_n \frac{1+p}{2} + \frac{1}{2}\sigma_m$	$\sigma_n \frac{1-p}{2} + \frac{1}{2}\sigma_m$

$$\sigma_m = \frac{2}{p} \cdot \left(-\sigma_x^{\text{up}} - \sigma_y^{\text{up}} + 2 \cdot \sigma_z^{\text{up}}\right)$$

$$\sigma_m = \frac{2}{p} \cdot \left(\sigma_x^{\text{down}} + \sigma_y^{\text{down}} - 2 \cdot \sigma_z^{\text{down}}\right)$$

NG5NSE



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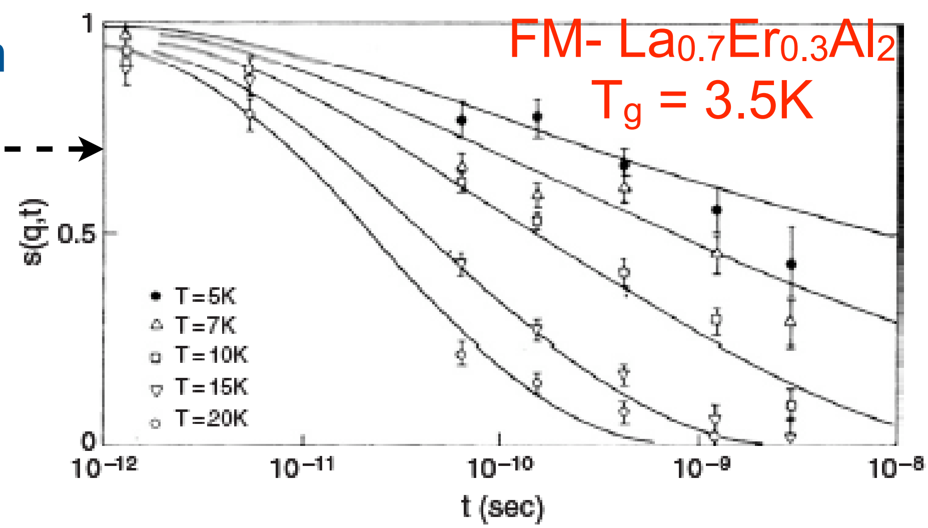
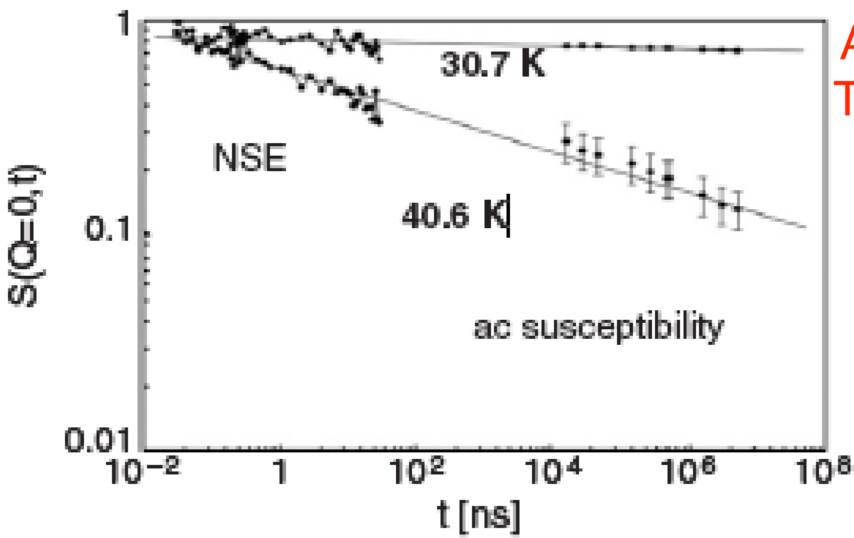
Spin Glasses

Model assuming different τ and E in different parts of the sample.
Mezei, Solid State Comm. 45 411, 1983

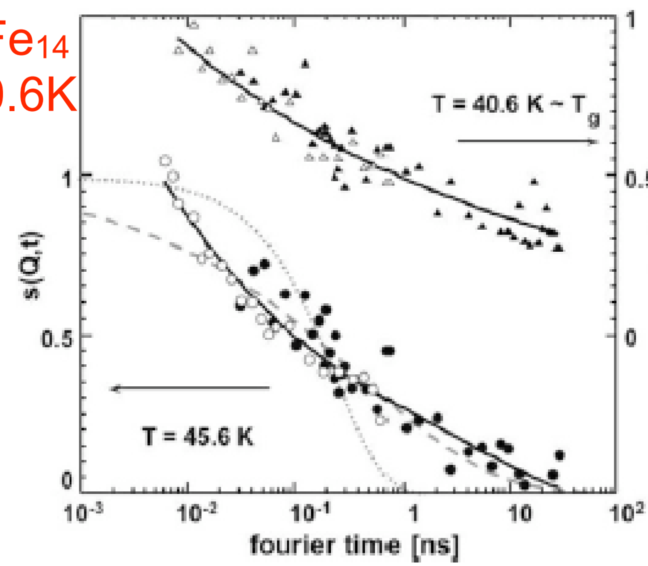
At Tg and below - power law
above Tg - Ogielski function
B increases from 1/3
Pappas, Solid State Comm. 68 054431, 2003

FM- $La_{0.7}Er_{0.3}Al_2$
T_g = 3.5K

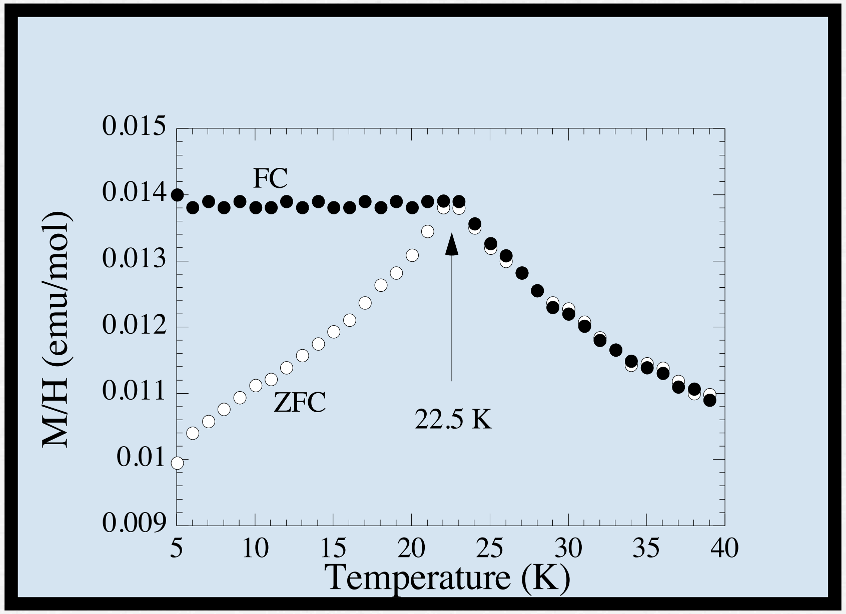


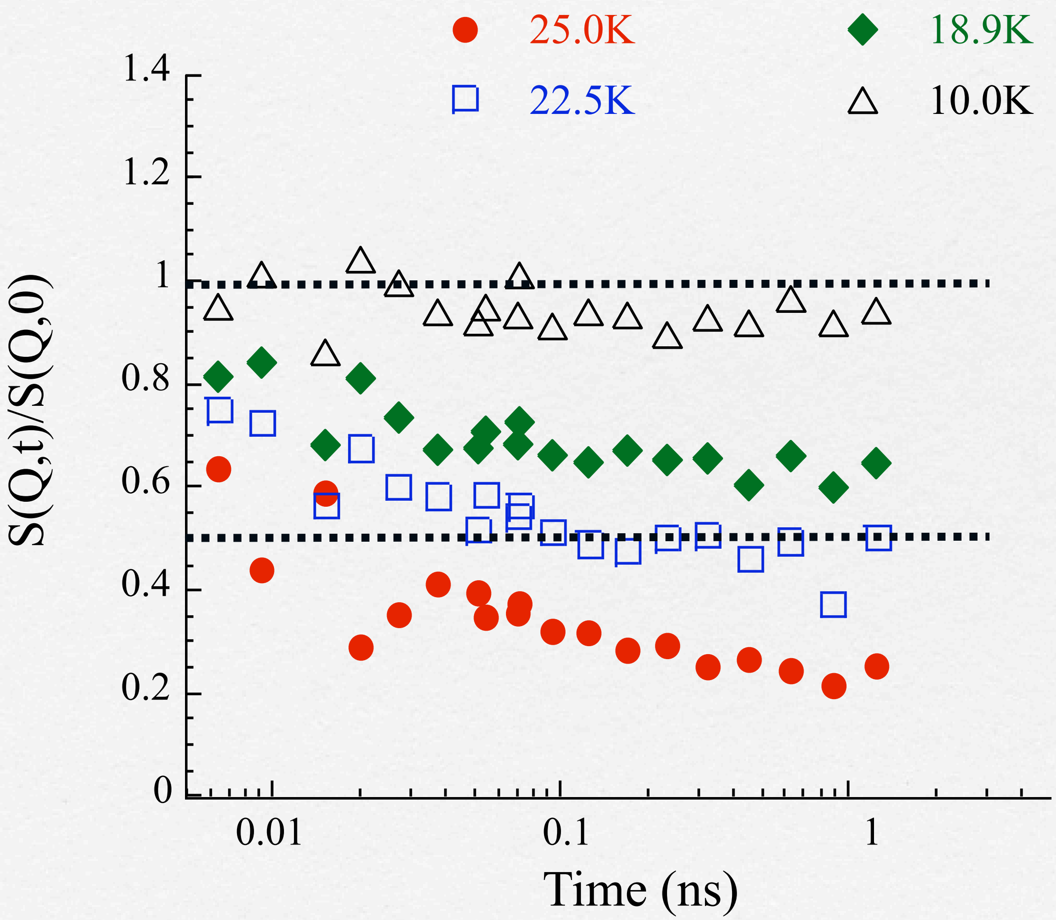


$Au_{86}Fe_{14}$
T_g=40.6K



Spin Glasses - $Y_2Mo_2O_7$





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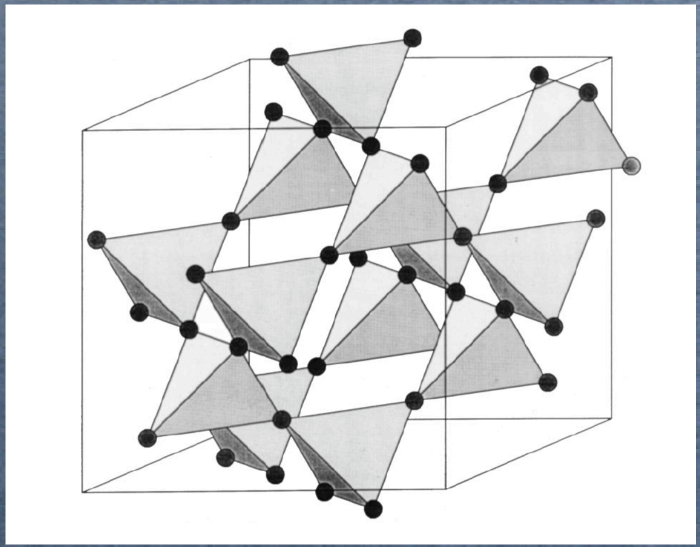
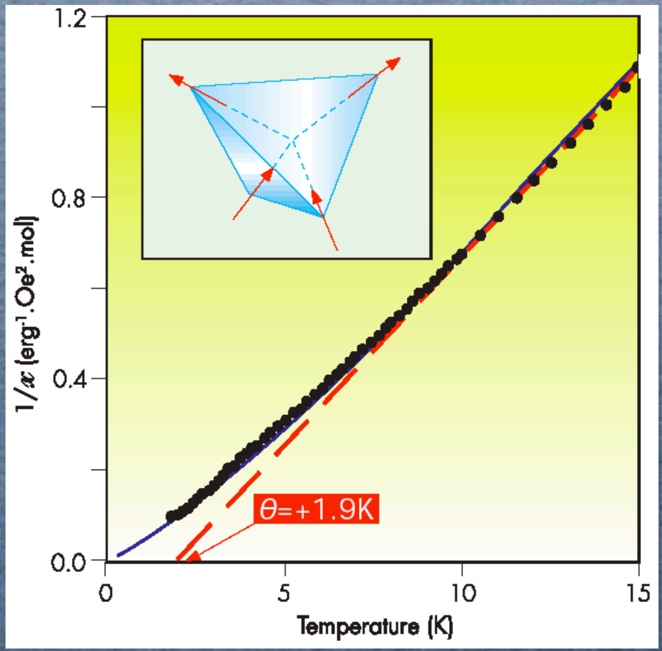
Spin Ice

Spin Ice Crystal Structure





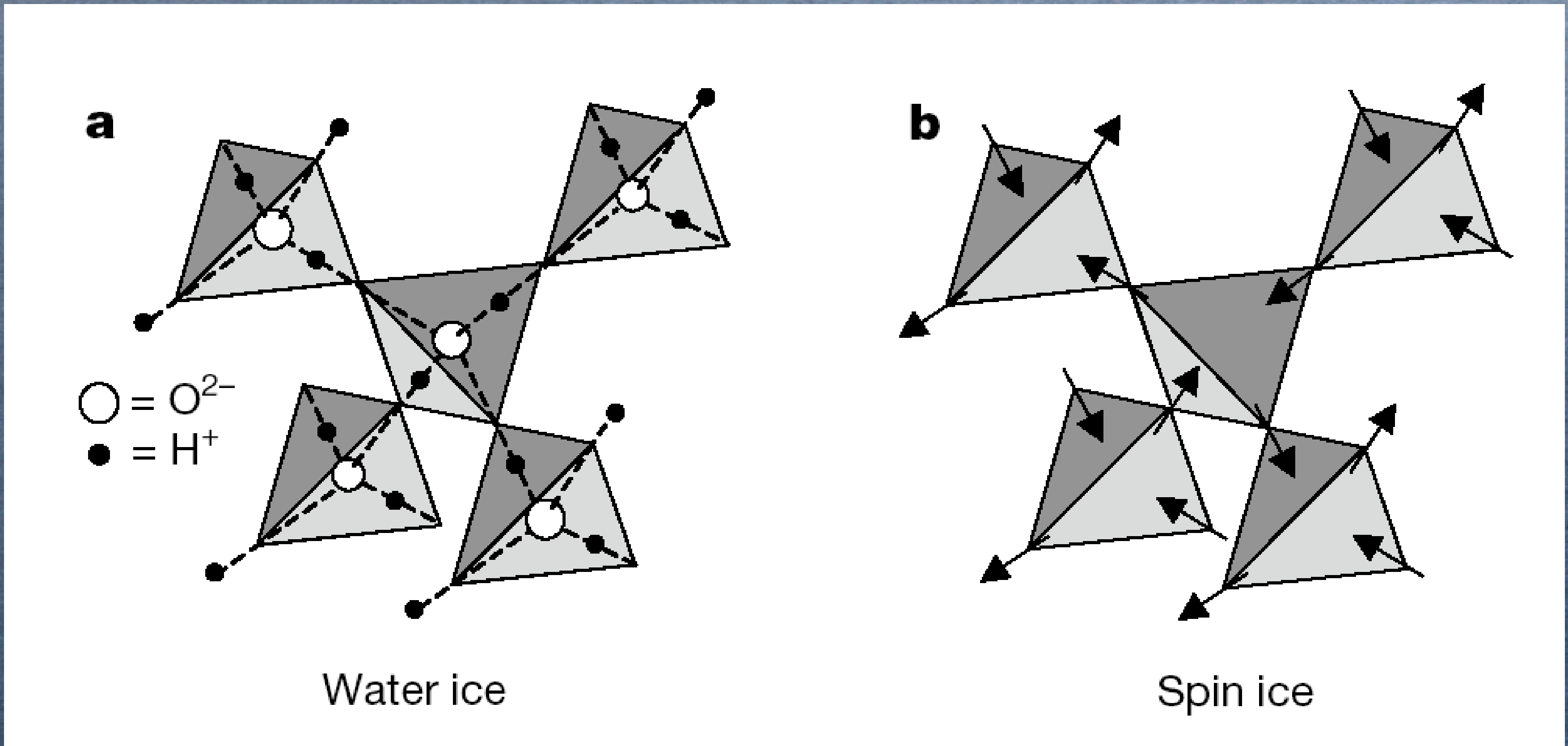
$$\chi(T) = \frac{n}{3k_B} \cdot \frac{\mu_{\text{eff}}^2}{T - \Theta}$$

$$\mu_{\text{eff}} \approx 9\mu_B \qquad \Theta \approx +1\text{K}$$

Stoichiometry

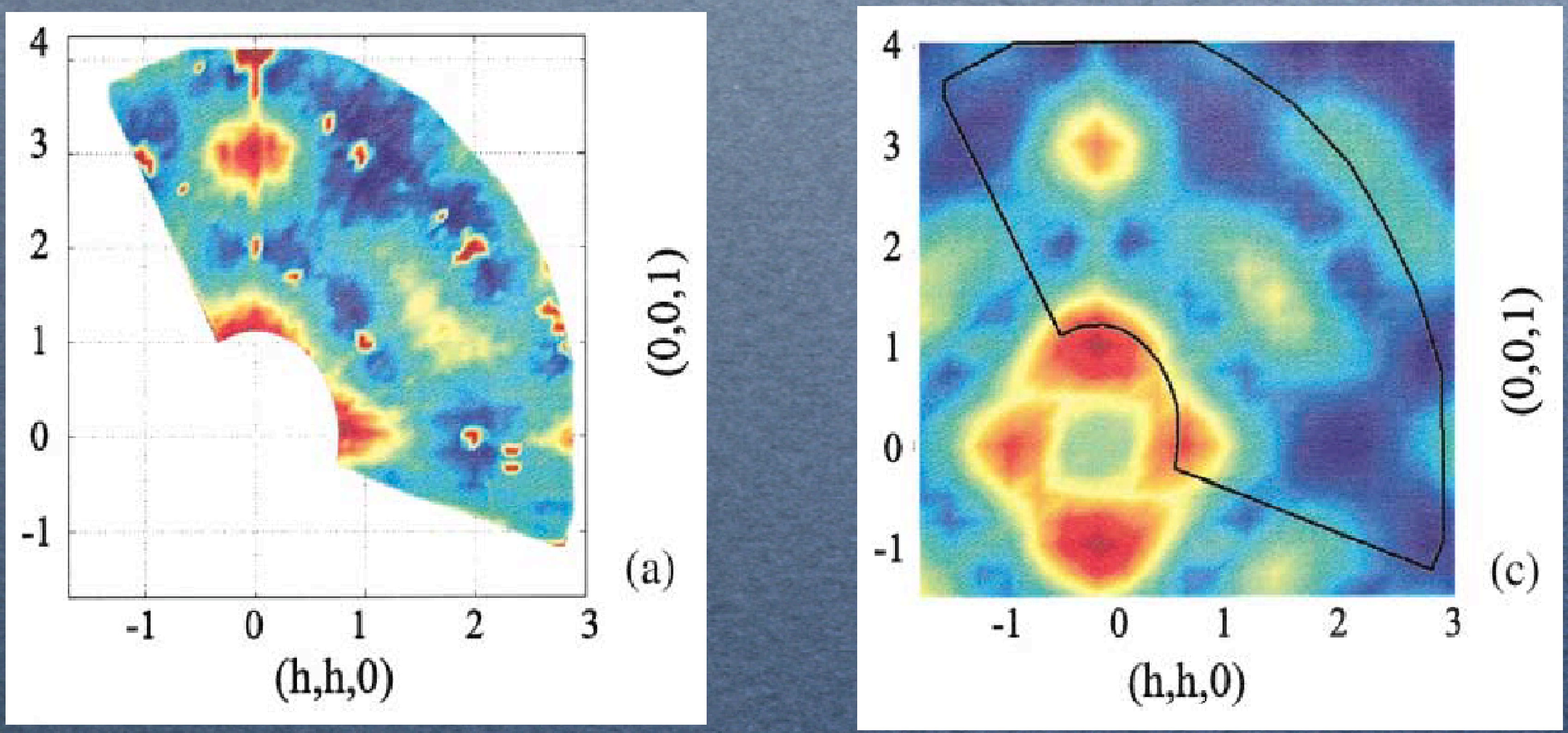
$Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$,
($Ho_2Sn_2O_7$, $Dy_2Sn_2O_7$),
$Pr_2Sn_2O_7$

Analogy to Water Ice



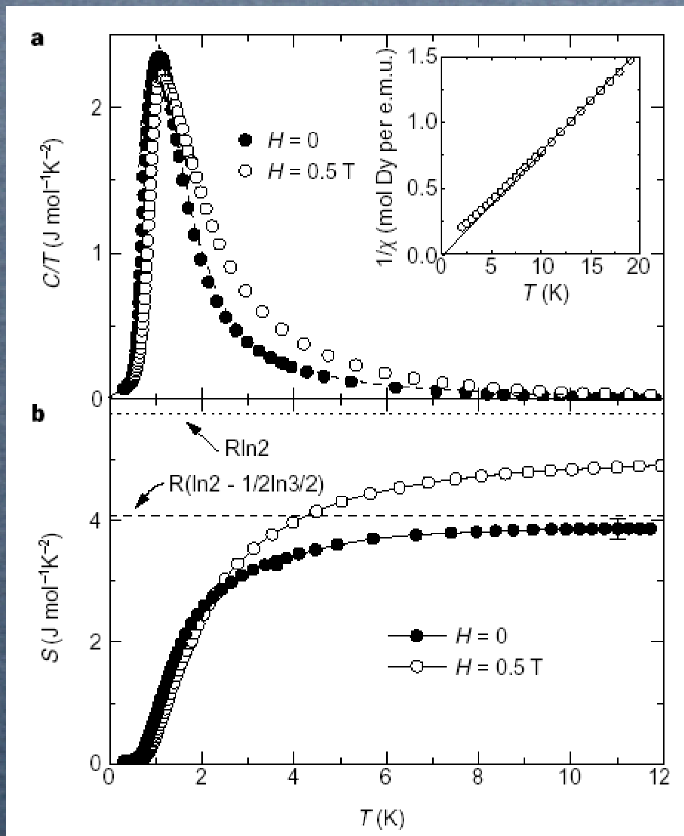
CEF constraints spins to local <111> axes

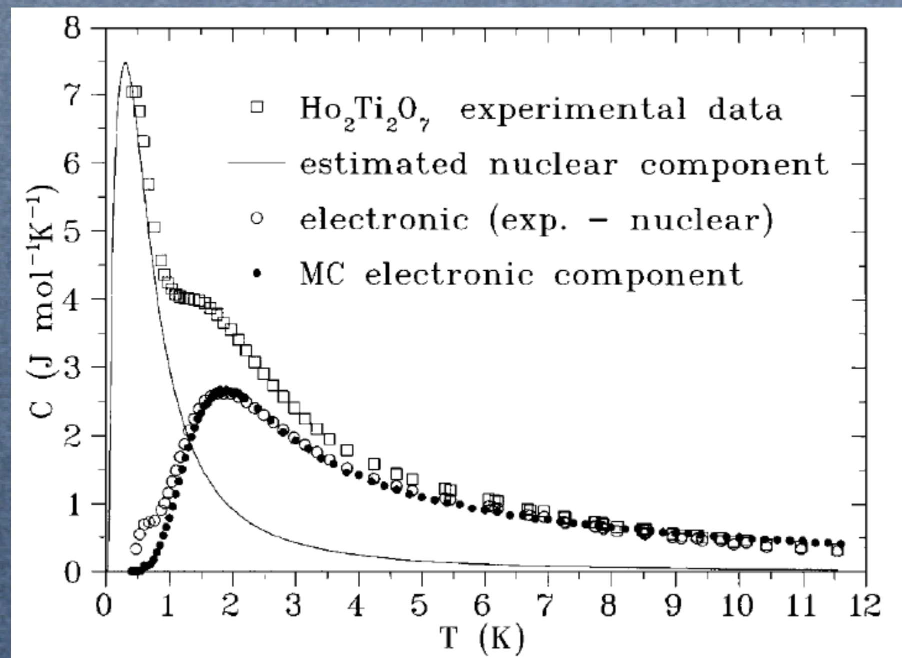
NEUTRON DIFFRACTION



PRISMA T = 50 mK S. T. Bramwell et al.,
PRL 87, 047205 (2001)

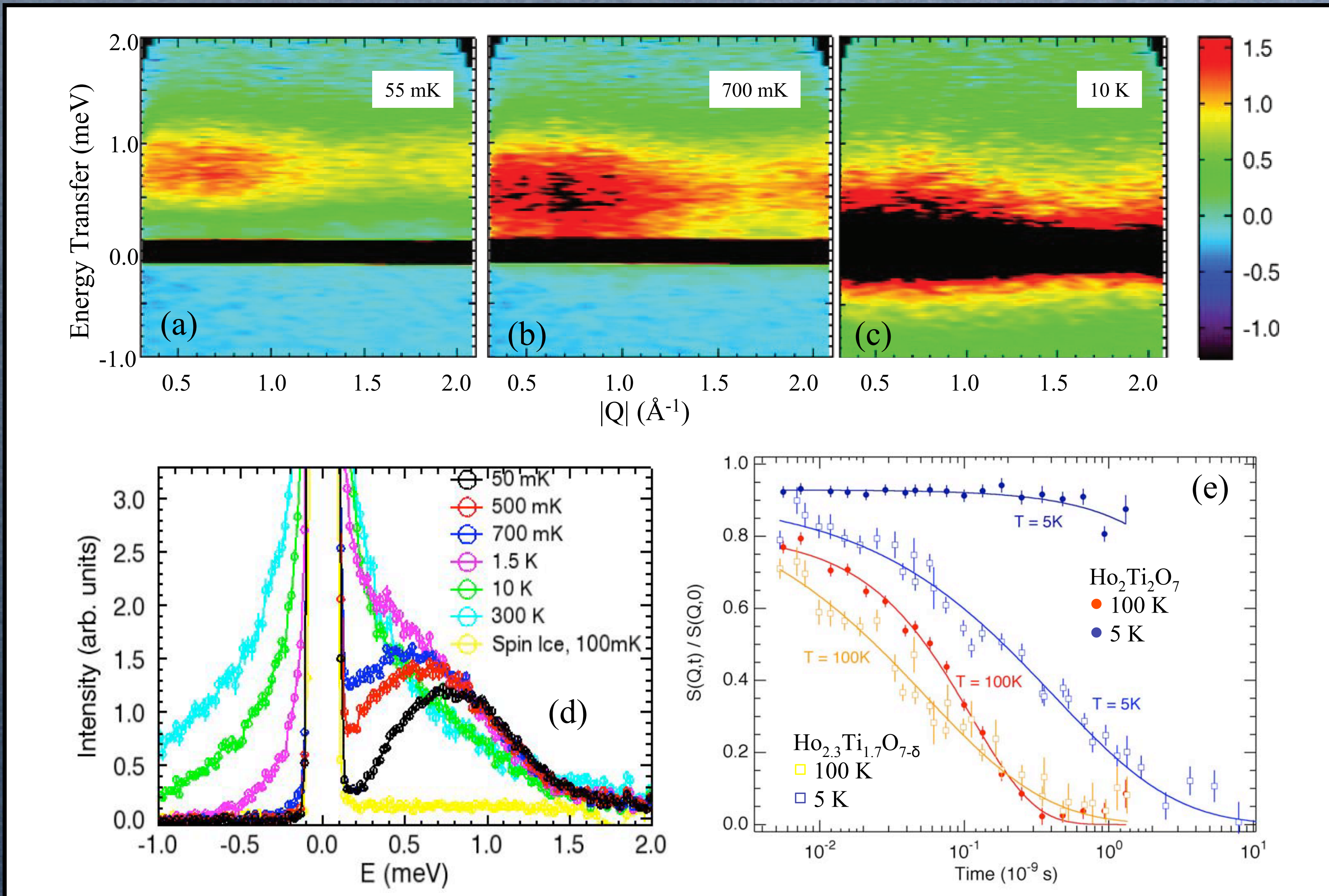
Magnetic Specific Heat





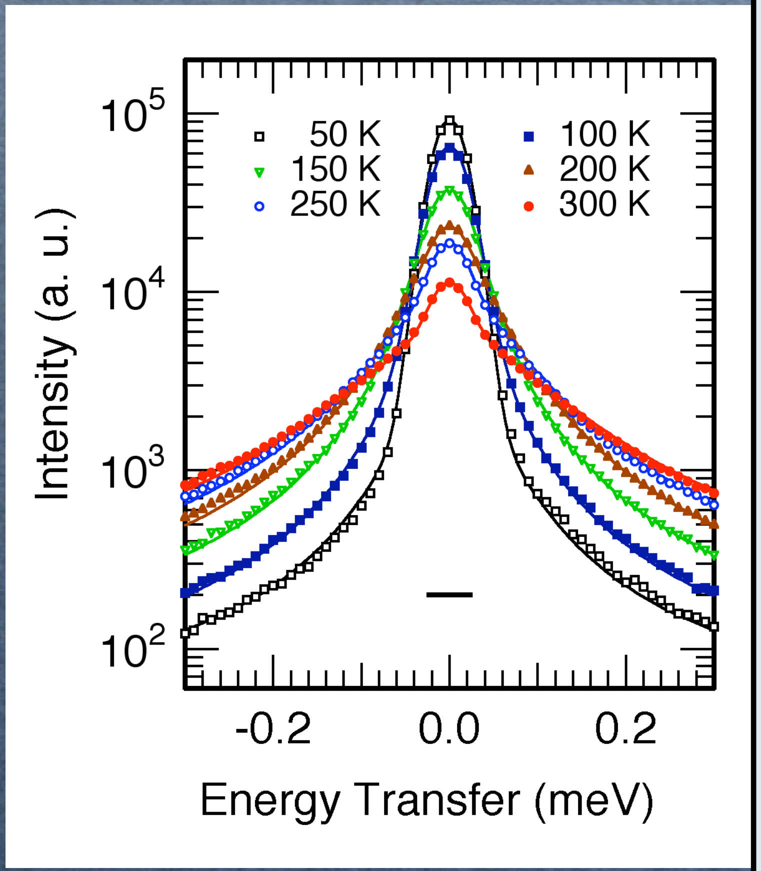
A. P. Ramirez et al., S. T. Bramwell et al.,
Nature 399, 333 (1999). PRL 87, 047205 (2001).

PREVIEW

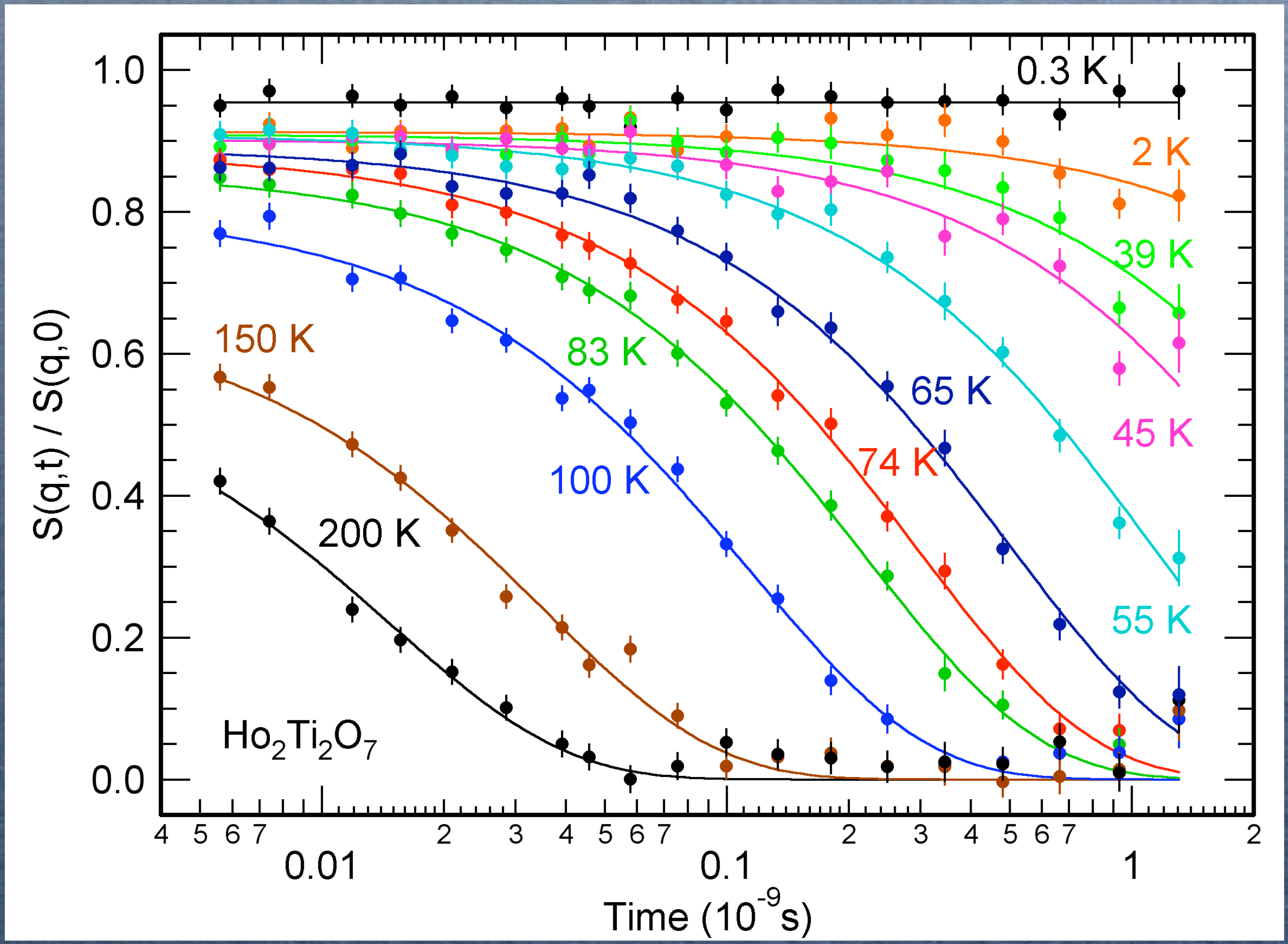


55 mK
700 mK
10 K
(a)
(b)
(c)
Energy Transfer (meV)
|Q| (Å-1)
50 mK
500 mK
700 mK
1.5 K
10 K
300 K
Spin Ice, 100mK
(d)
Intensity (arb. units)
E (meV)
(e)
T = 5K
T = 100K
T = 100K
T = 5K
Ho2Ti2O7
100 K
5 K
Ho2.3Ti1.7O7-δ
100 K
5 K
S(Q,t) / S(Q,0)
Time (10-9 s)

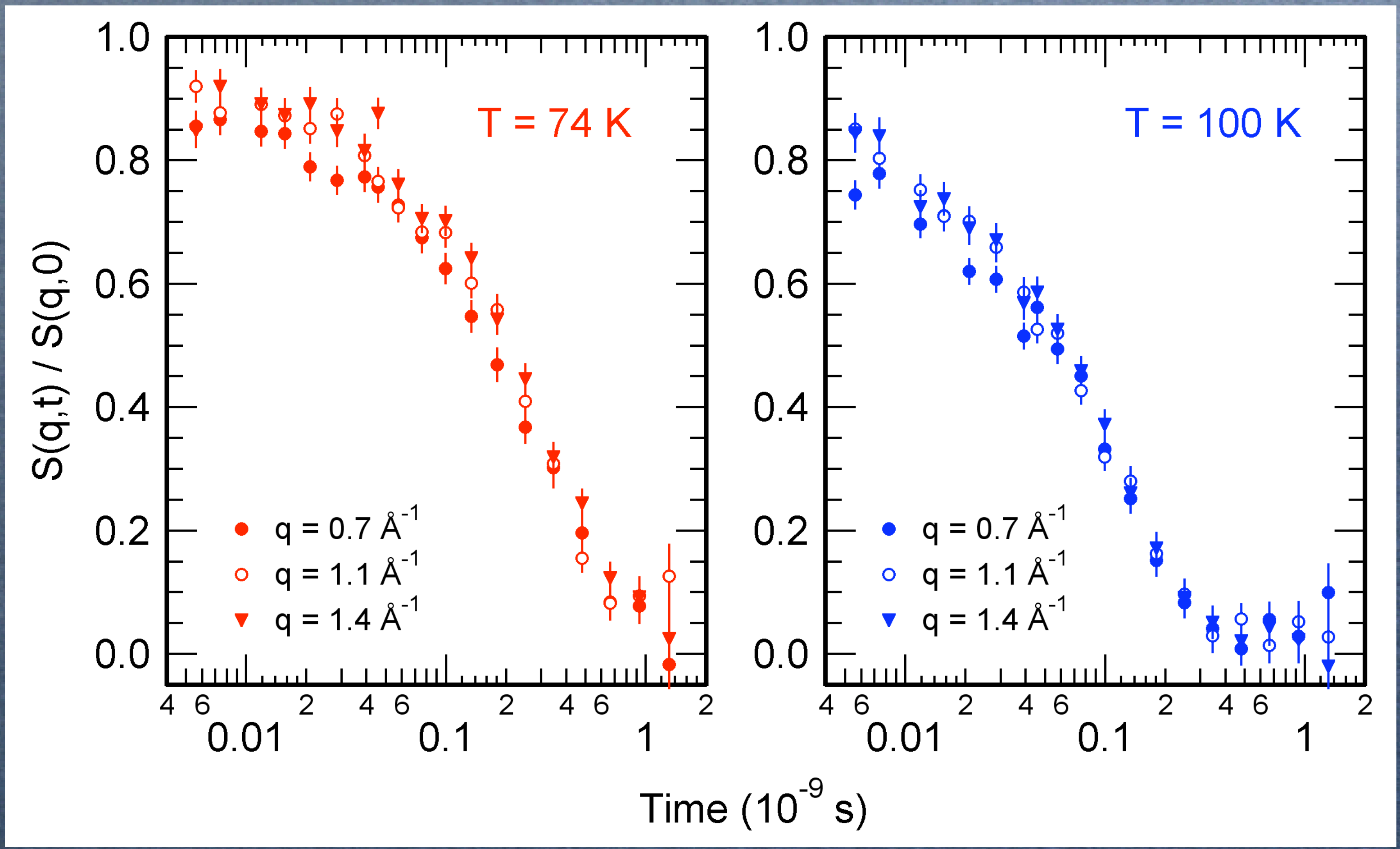
More inelastic results



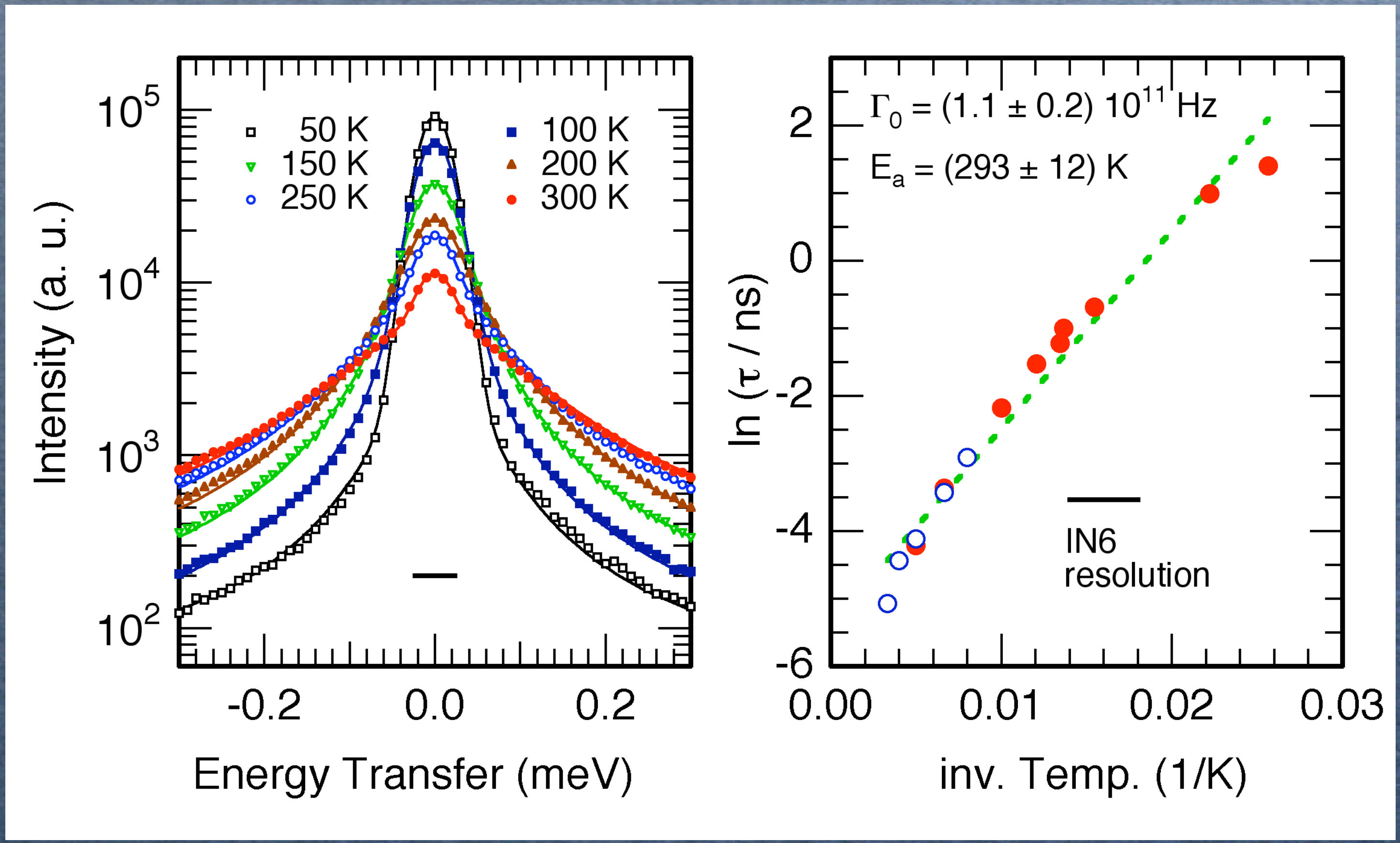
Spin echo results (1)



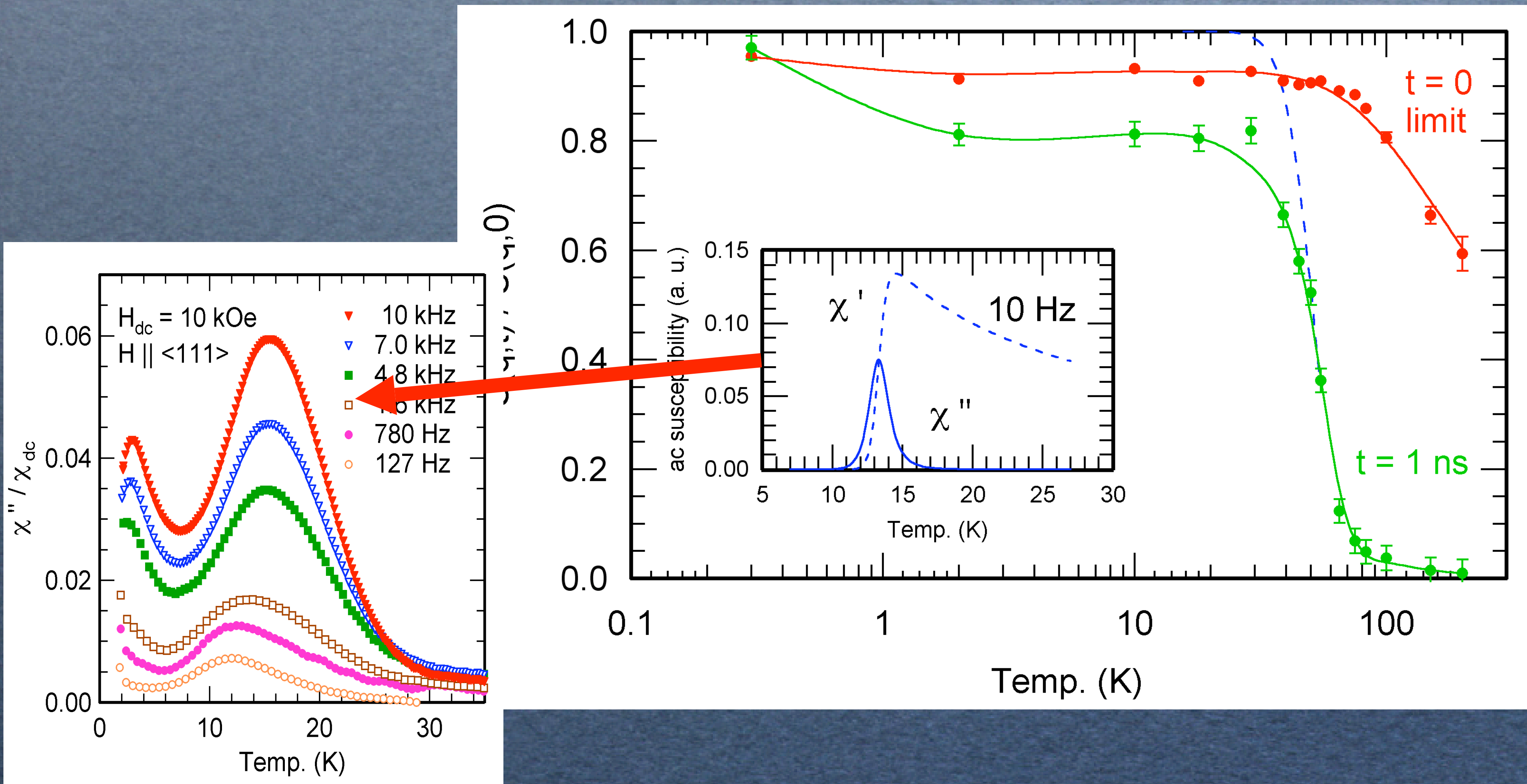
Spin Echo Results (2)



More inelastic results



Comparison with AC Susceptibility



Conclusion

NSE works perfectly to study the dynamics of spin ice:

- works in the time domain
- gives just the right time range
- q information tells it is single ion relaxation
- data is ‘clean’ because magnetic scattering is separated

NSE proves that there are TWO relaxation mechanisms in spin ice.

Consistent picture with ac susceptibility results.

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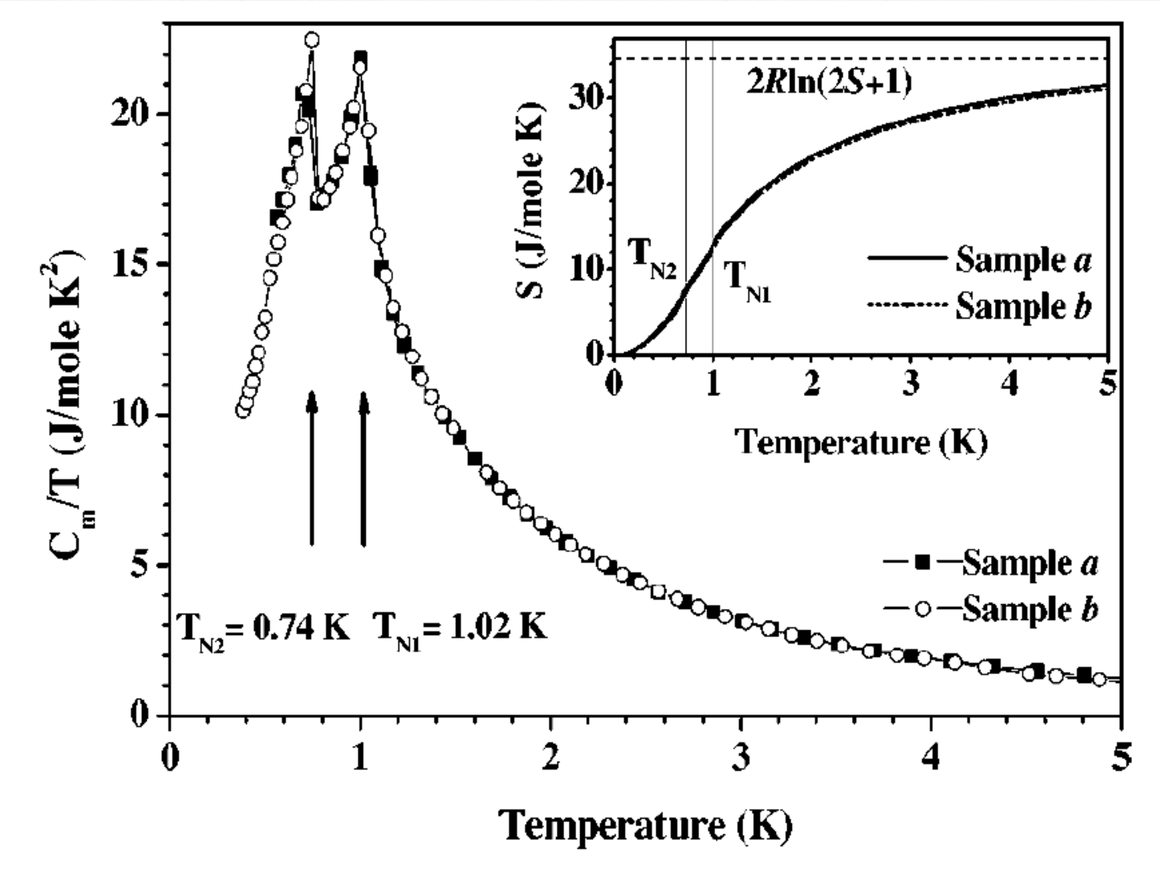
$Gd_2Ti_2O_7$

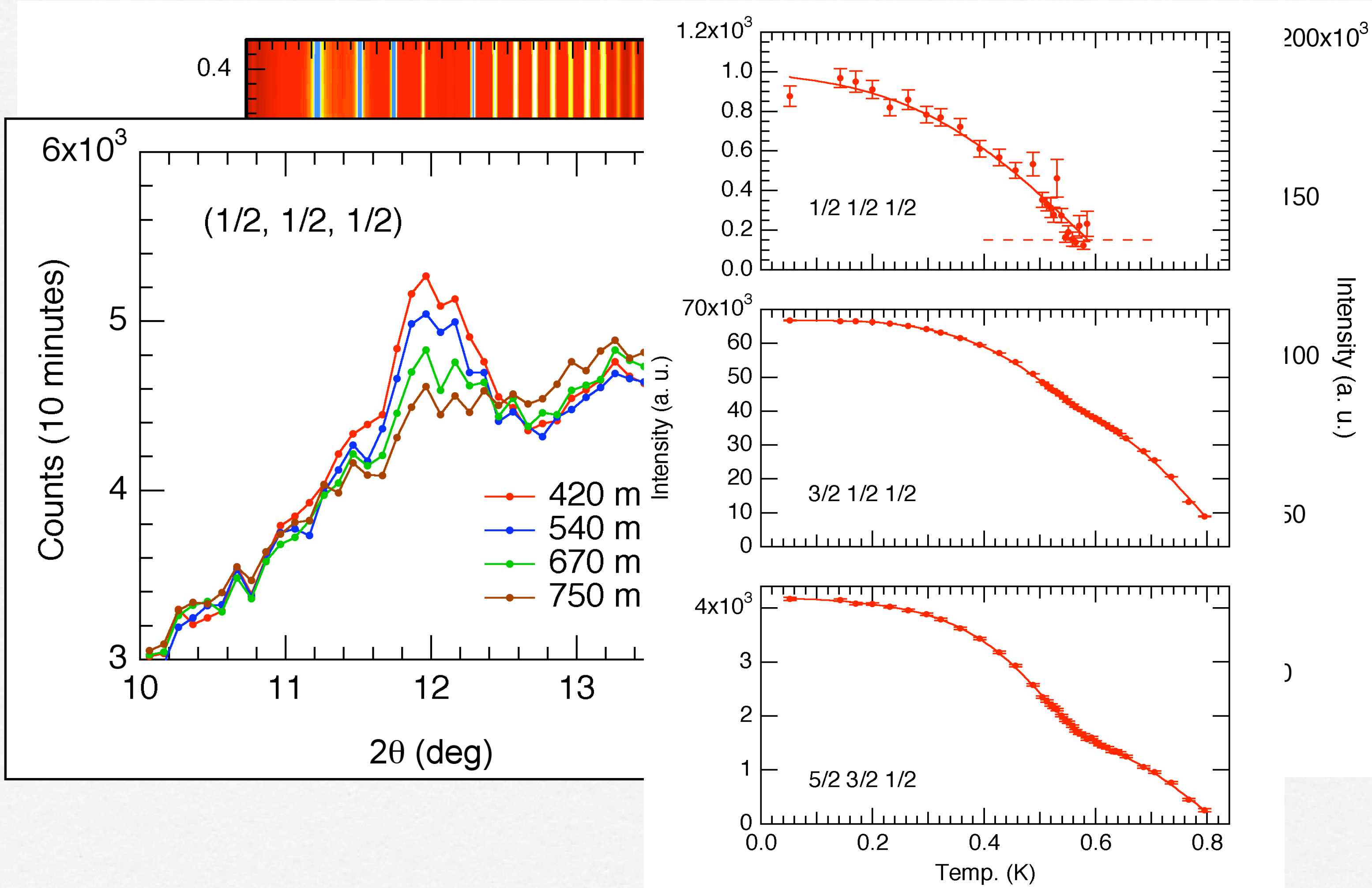


$S = 7/2 \qquad L = 0$

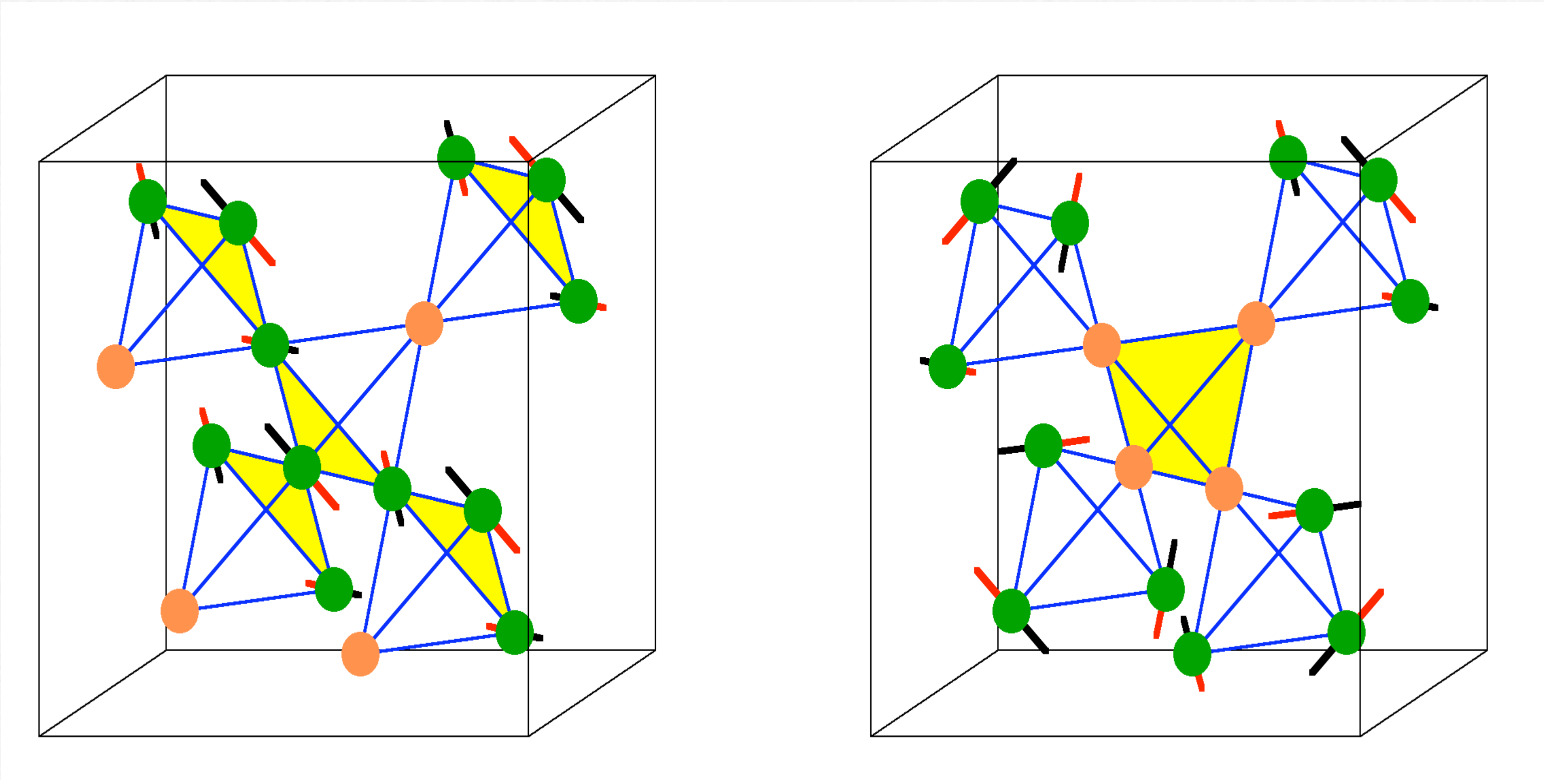
$\mu_{\text{eff}} \approx 7\mu_B \qquad \Theta \approx -10\text{K}$

O. A. Petrenko et al., PRB **70** (2004) 012402
A. P. Ramirez et al., PRL 89 (2002) 067202

$Gd_2Ti_2O_7$ - Unpolarised diffraction

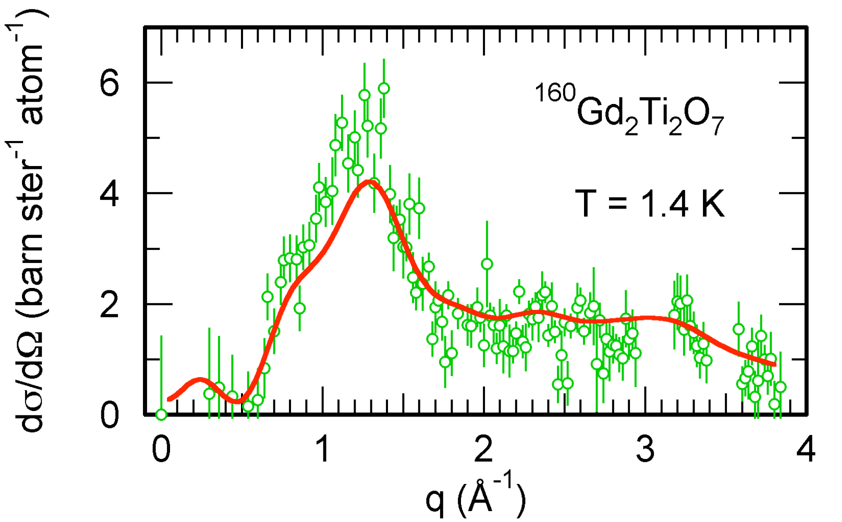


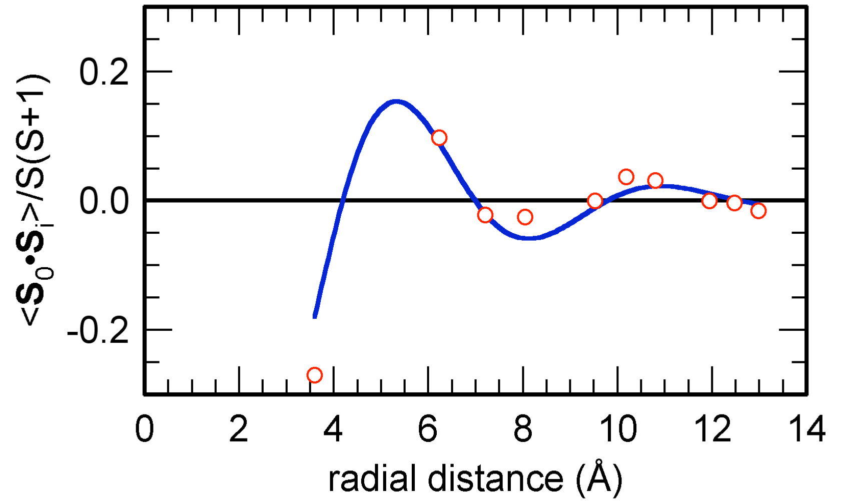
$Gd_2Ti_2O_7$ - possible structures

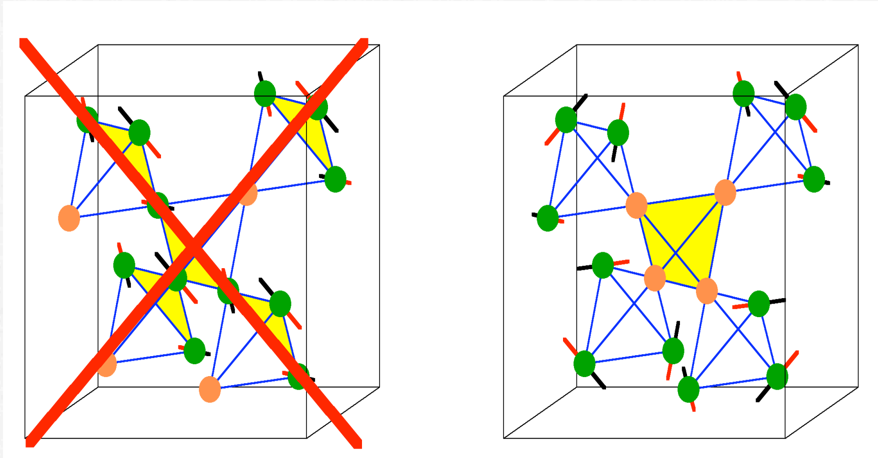


1k structure   4k structure

$Gd_2Ti_2O_7$ - polarised neutrons





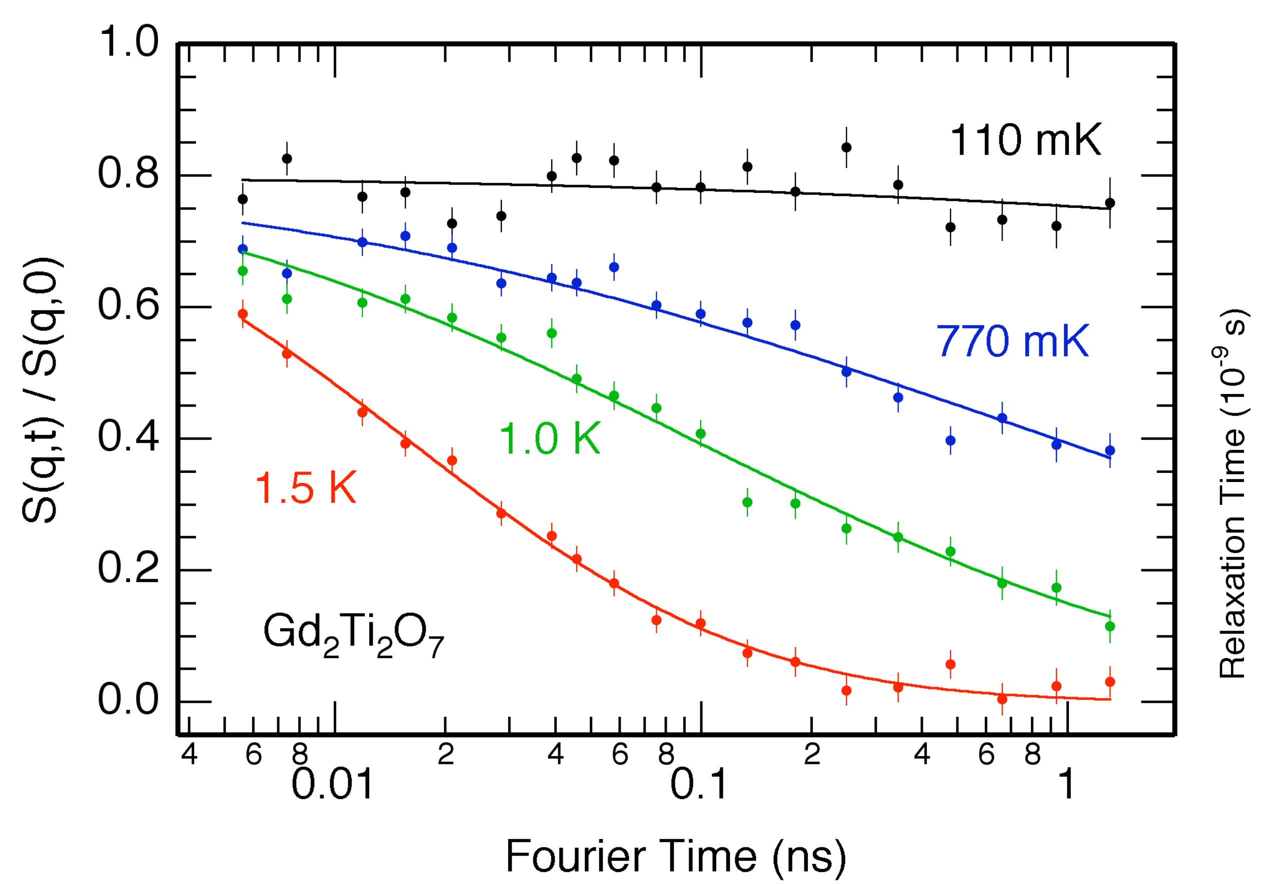


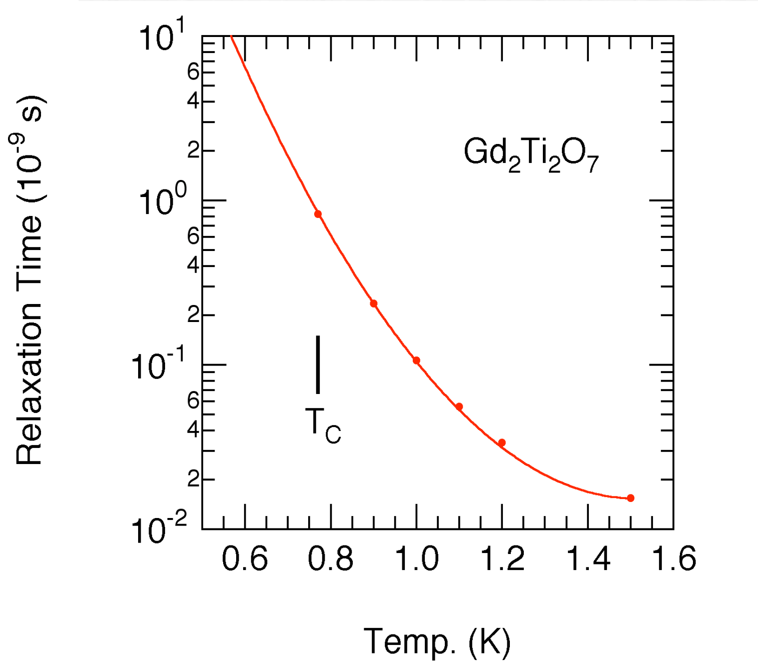
Data analysis using
Reverse Monte Carlo
Simulations

$Gd_2Ti_2O_7$ - NSE results

$I(Q,0) \Rightarrow 0.75$ above LT transition

As the last spin begins to freeze $I(Q,t)$ increases





$Gd_2Ti_2O_7$ - NSE results

- Even small samples can be measured.
  - Rem. 1/2 g sample, 7 Bohr Magnetons
- Spin Echo reveals 3/4 spins relax with a single time constant
- With more data could reveal interesting temperature dependence.

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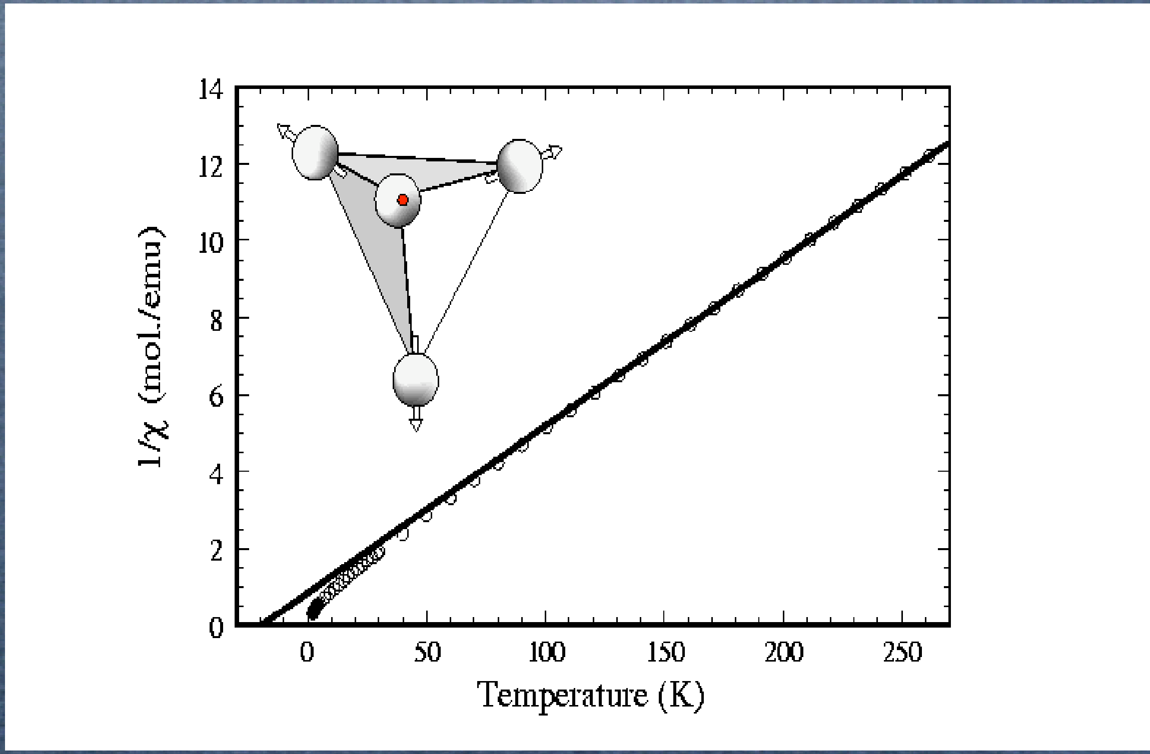
$Tb_2Ti_2O_7$ - Cooperative Paramagnet

Although there are magnetic correlations below 60 K, there is no LRO above 0.5 K.

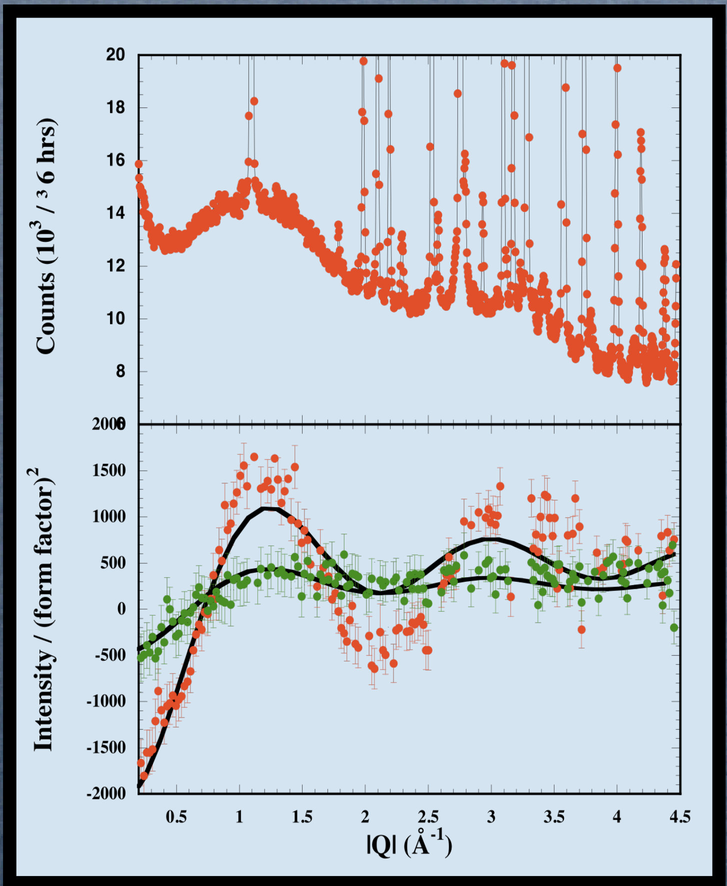
- Θ_{CW} = -19 K
- 9.4 μ_B (~ $^7F_6$ Tb^{3+} ion)
- Very linear above Θ_{CW}
- Dips below CW behaviour

Spatial magnetic correlations of ~ 5 Å at 2 K

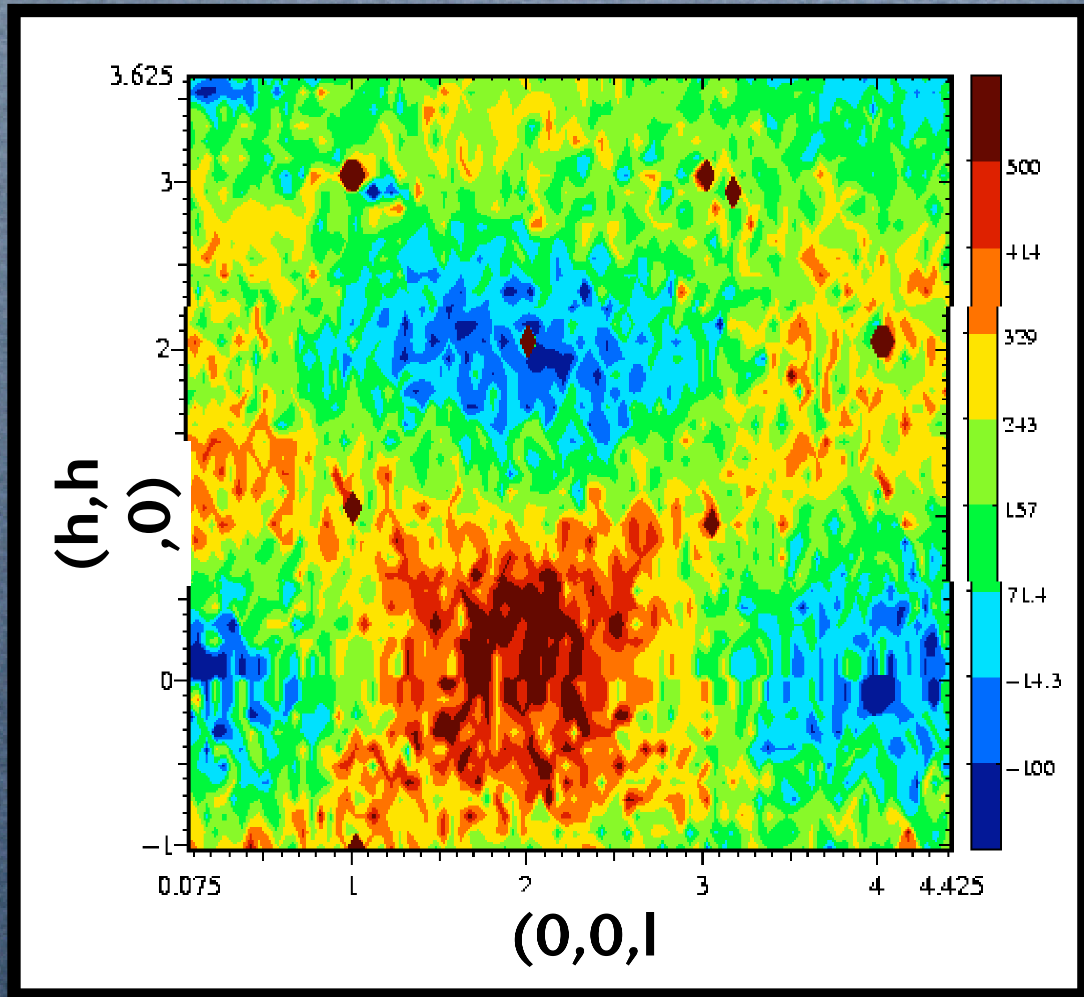
Mouns tell us its dynamic at 15 mK



$Tb_2Ti_2O_7$ - Diffraction

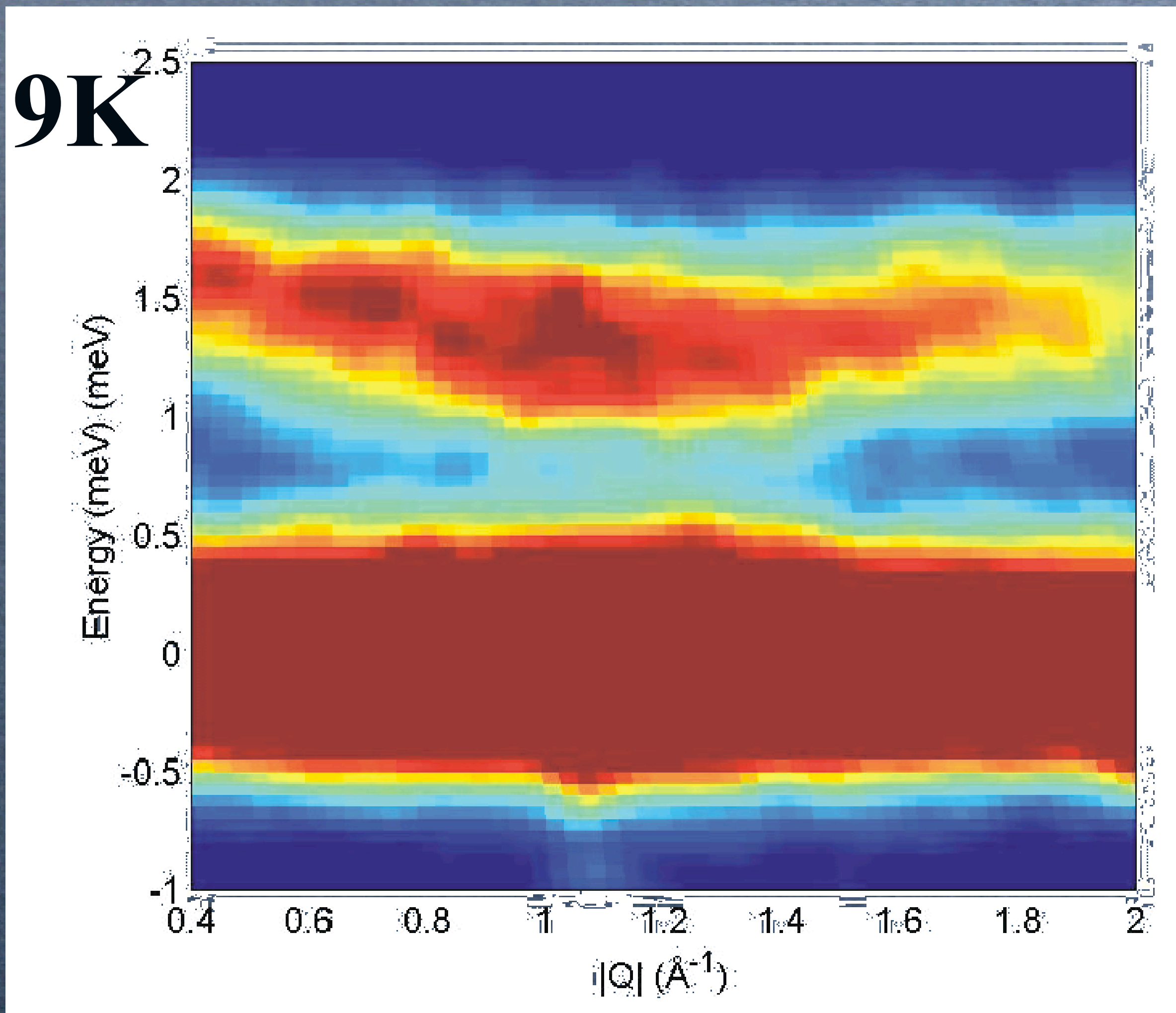


2 K



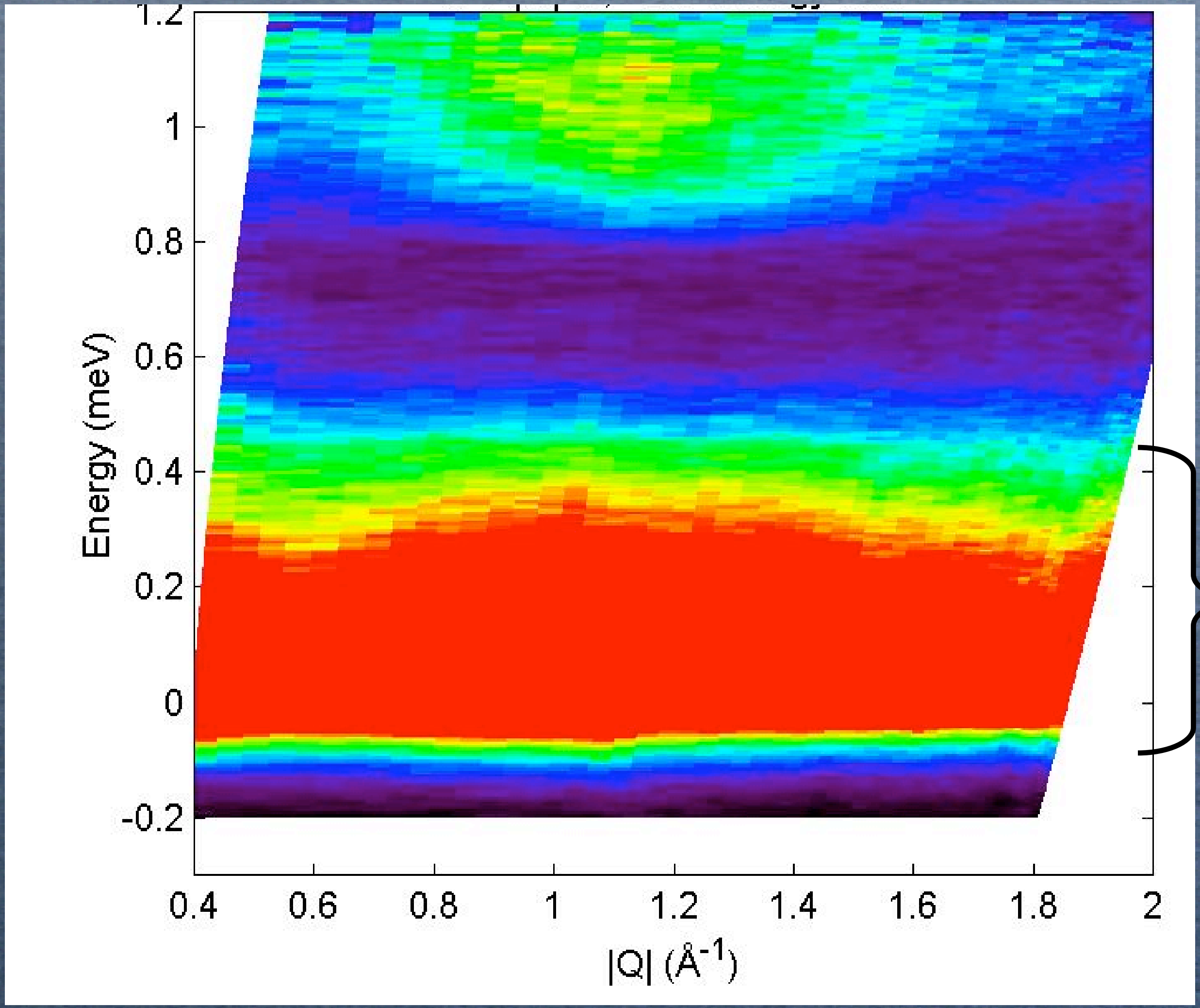
9 K

$Tb_2Ti_2O_7$ - Inelastic Scattering



Still gapped, and ....
lots of structure

$Tb_2Ti_2O_7$ - Inelastic Scattering



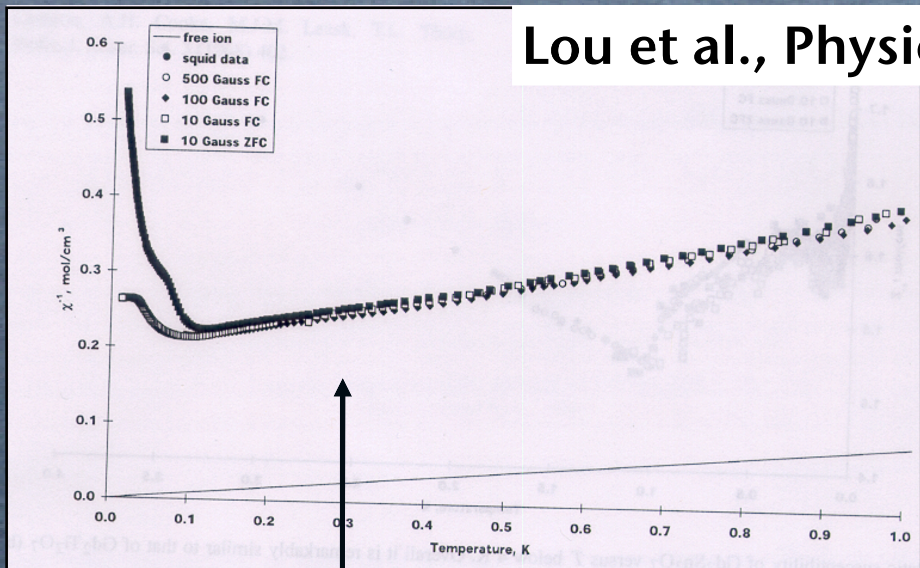
100 mK

Still Gapped

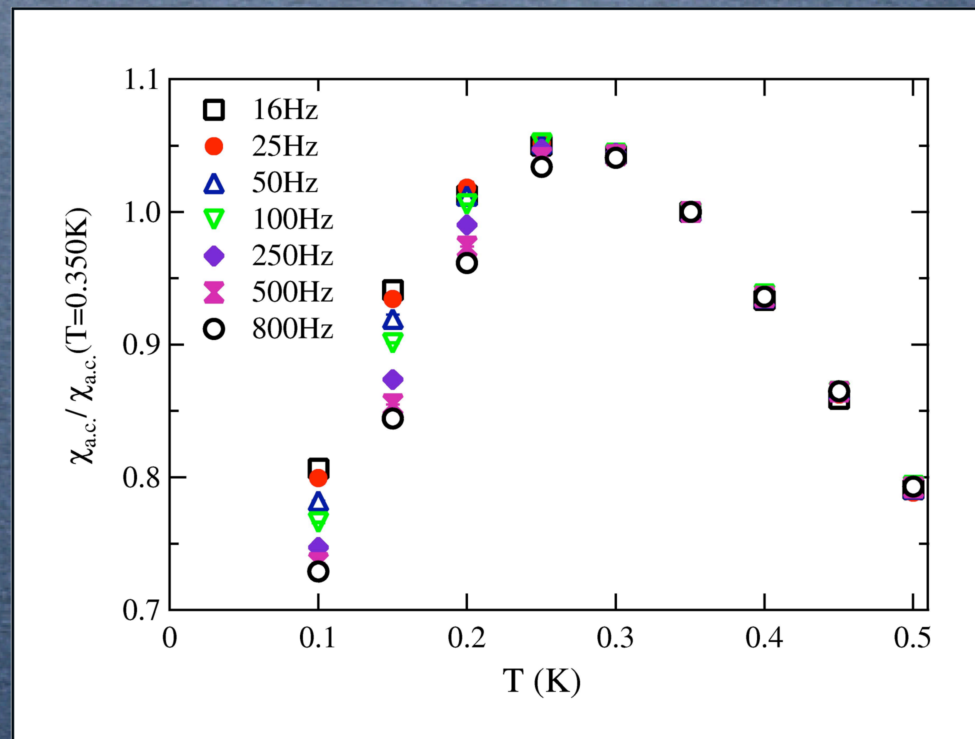
Lots of Quasielastic Scattering

A bit Glassy at low temperatures

Lou et al., Physics A 291, 306 (2001)



0.3 K



BUT.....

$Tb_2Ti_2O_7$ - the echo

Complete relaxation at 400 mK

Baseline change at (0.3±0.1) K

HOWEVER

Still a long timescale relaxation process at 50 mK

|Q| dependence