Title: Frozen Spin Ice Ground States in the Pyrochlore Magnet Tb2 Ti2 O7

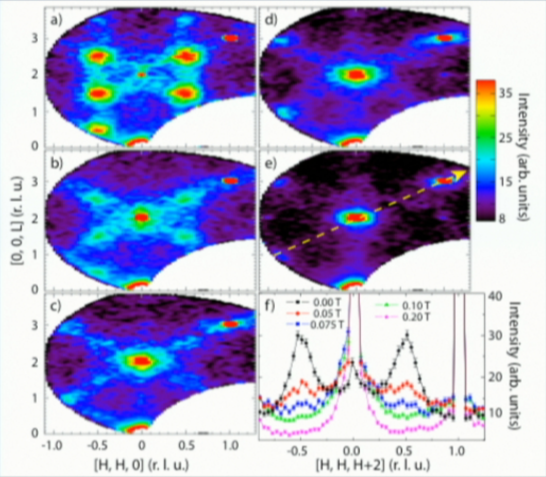
Date: May 01, 2014 05:20 PM

URL: http://pirsa.org/14050019

Abstract: Tb2Ti2O7 was one of the first pyrochlore magnets to be studied as a candidate for a spin liquid or cooperative paramagnet, and its ground state has remained enigmatic for fifteen years. Recent time-of-flight neutron scattering studies have shown that it enters a glassy Spin Ice ground state, characterized by frozen short range order over about 8 conventional unit cells, and the formation of a ~ 0.08 meV gap in its spin excitation spectrum at the appropriate quasi-Bragg wave vectors. I will introduce the relevant Spin Ice physics background, and describe how the experiments are performed. The new H-T phase diagram for Tb2Ti2O7 in a [110] magnetic field will be presented. This shows that its frozen (i.e. glassy) Spin Ice ground state (at low temperature and zero field) and its conventional field-induced ordered phase (at low temperature and high fields) bracket the cooperative paramagnetic phase which generated the original interest in this fascinating magnet.

Disney FROZEN

Spin Ice Ground States in the Pyrochlore Magnet $Tb_2Ti_2O_7$



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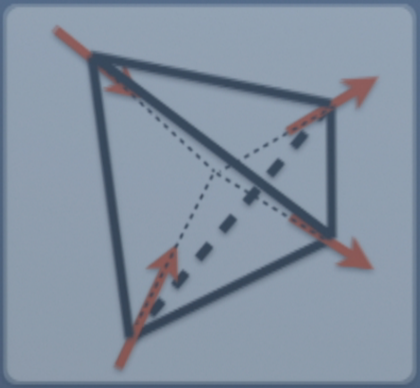
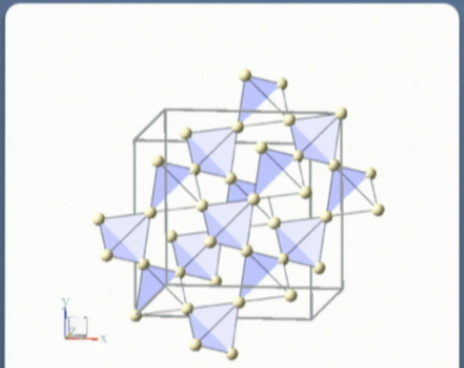
Geometric Frustration from Tetrahedra

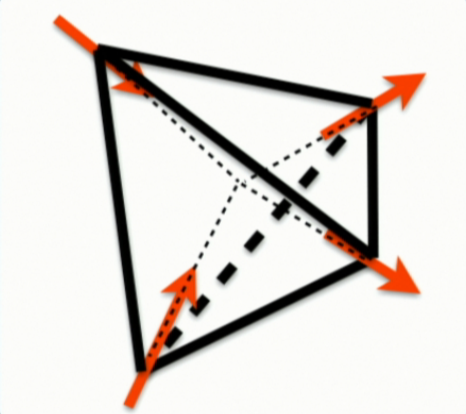


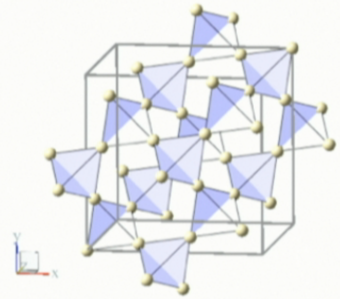


Pyrochlore

freedom of choice for each tetrahedron leads to a macroscopic degeneracy: **NO Long Range Order**

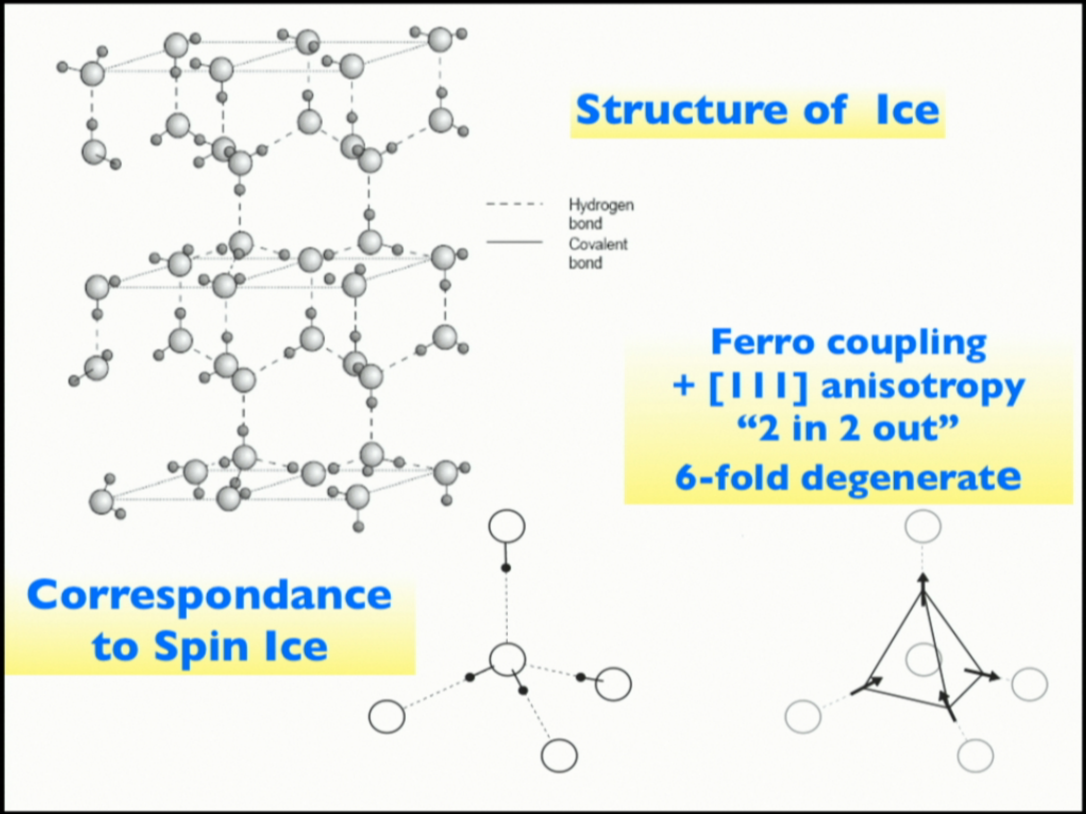
Geometric Frustration from Tetrahedra





Pyrochlore

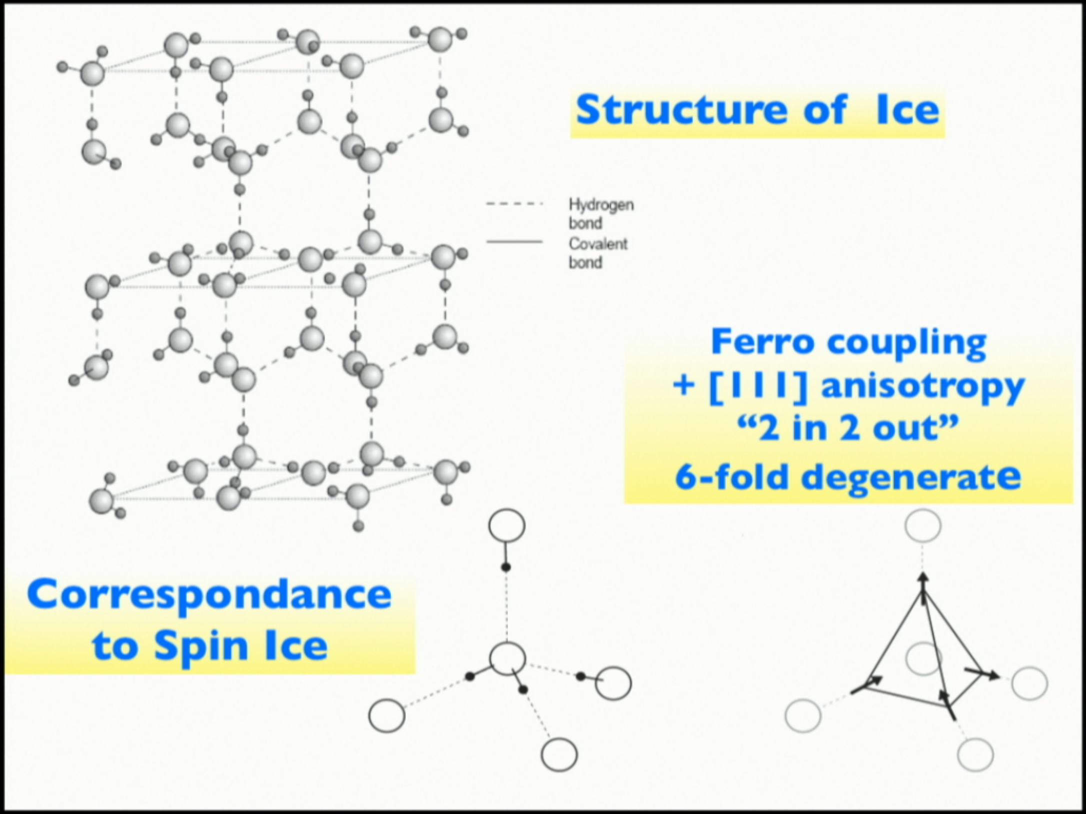
freedom of choice for each tetrahedron leads to a macroscopic degeneracy: **NO Long Range Order**



Structure of Ice

Ferro coupling
+ [111] anisotropy
“2 in 2 out”
6-fold degenerate

Correspondance to Spin Ice



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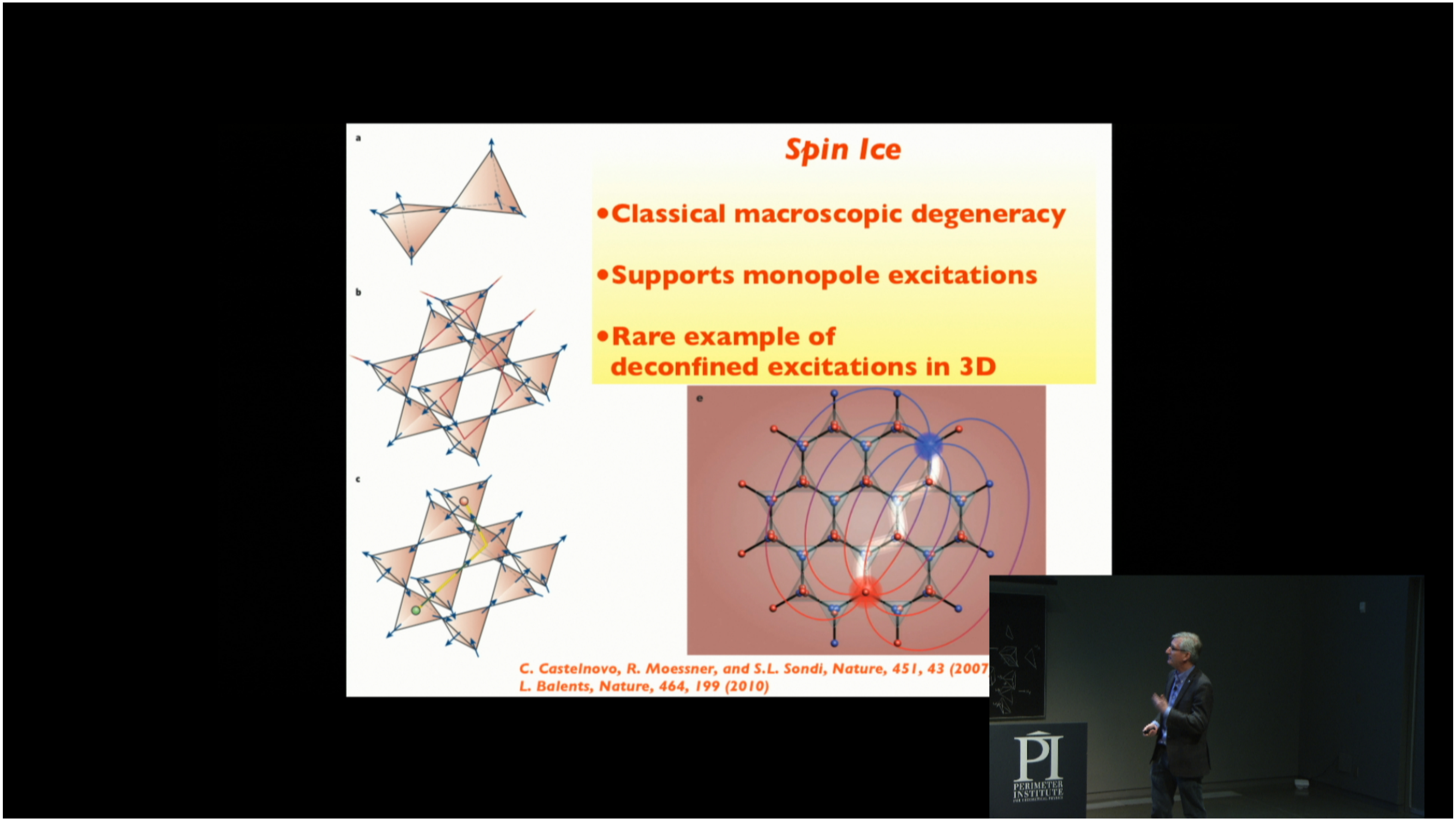

Spin Ice

- Classical macroscopic degeneracy
- Supports monopole excitations
- Rare example of deconfined excitations in 3D

C. Castelnovo, R. Moessner, and S.L. Sondi, Nature, 451, 43 (2007
L. Balents, Nature, 464, 199 (2010)


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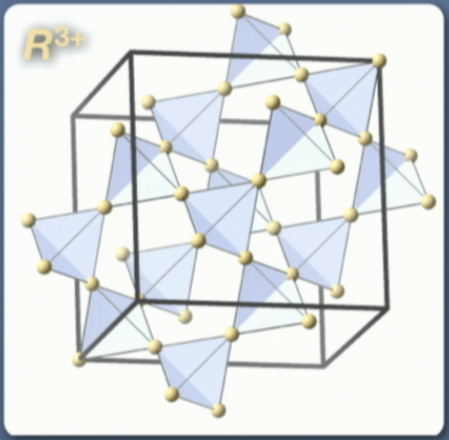
Real Pyrochlores

$R_2Ti_2O_7$

"Rare earth titanates"

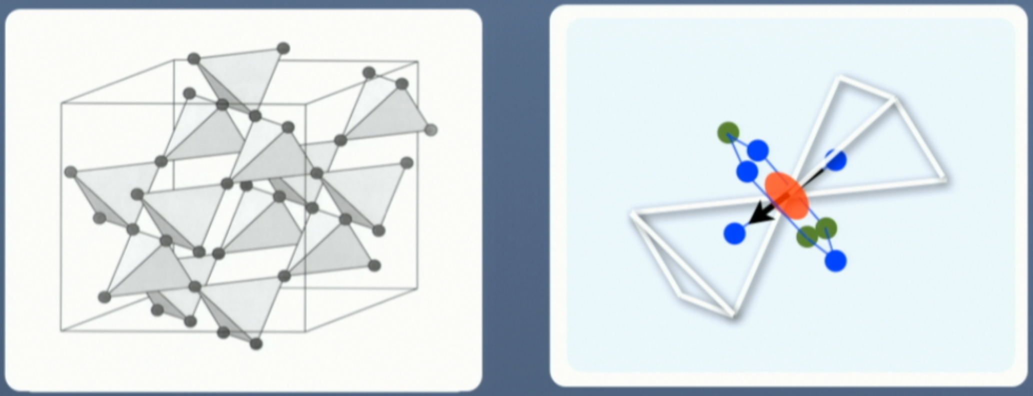
<u>Single-ion Anisotropy</u>:
Crystal Field Effects

<u>Exchange Anisotropy</u>:
Spin orbit coupling



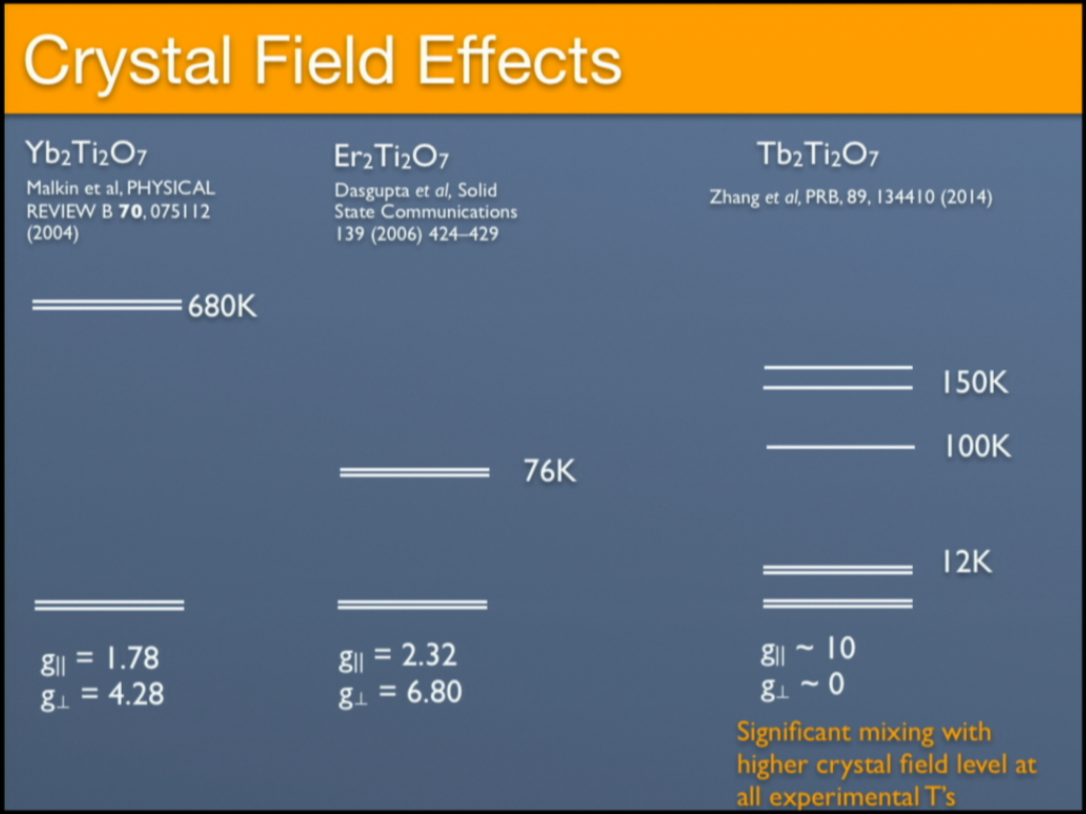
$R^{3+} =$
Ho, Dy → Spin Ice, "Magnetic Monopoles", Coulomb phase
Er → Long range order, Quantum critical point, Order by Disorder
Tb → Spin Liquid (?) ; Cooperative paramagnet (?)
Gd → Partial Ordering
Yb → Quantum Spin Ice, Coulomb phase?

Crystal Field Environment at the RE Site



(2J+1) degenerate multiplet splits in presence of strong crystalline electric field from O^{2-} neighbours

Crystal Field Effects



$Yb_2Ti_2O_7$

Malkin et al, PHYSICAL REVIEW B **70**, 075112 (2004)

$g_{||} = 1.78$
$g_{\perp} = 4.28$

$Er_2Ti_2O_7$

Dasgupta *et al*, Solid State Communications 139 (2006) 424–429

$g_{||} = 2.32$
$g_{\perp} = 6.80$

$Tb_2Ti_2O_7$

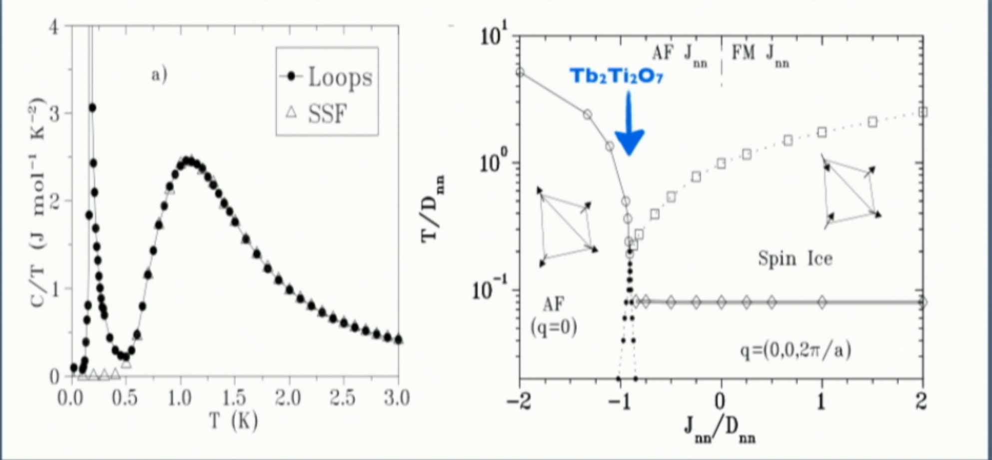
Zhang *et al*, PRB, 89, 134410 (2014)

$g_{||} \sim 10$
$g_{\perp} \sim 0$

Significant mixing with higher crystal field level at all experimental T's

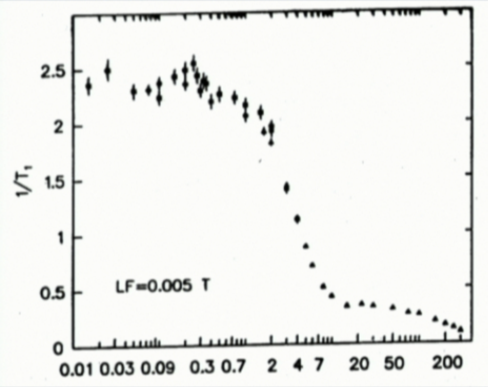
Minimal dipolar spin ice Hamiltonian

$$H = -J \sum_{\langle ij \rangle} \mathbf{S}_i^{z_i} \cdot \mathbf{S}_j^{z_j} + D r_{nn}^3 \sum_{i>j} \frac{\mathbf{S}_i^{z_i} \cdot \mathbf{S}_j^{z_j}}{|\mathbf{r}_{ij}|^3} - \frac{3(\mathbf{S}_i^{z_i} \cdot \mathbf{r}_{ij})(\mathbf{S}_j^{z_j} \cdot \mathbf{r}_{ij})}{|\mathbf{r}_{ij}|^5}$$

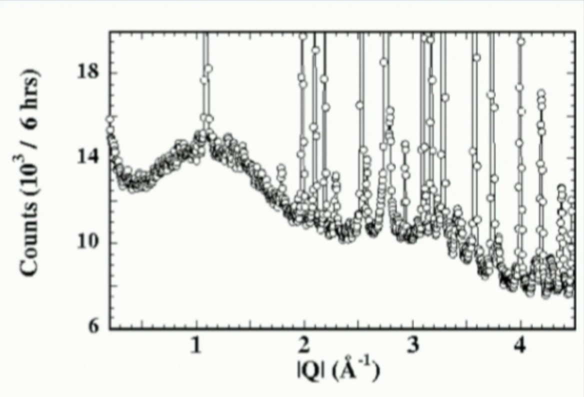


R. G. Melko et al, Phys. Rev. Lett, 87, 067203, 2001

but, $Tb_2Ti_2O_7$ *doesn't* order at low T (~ 20 mK)

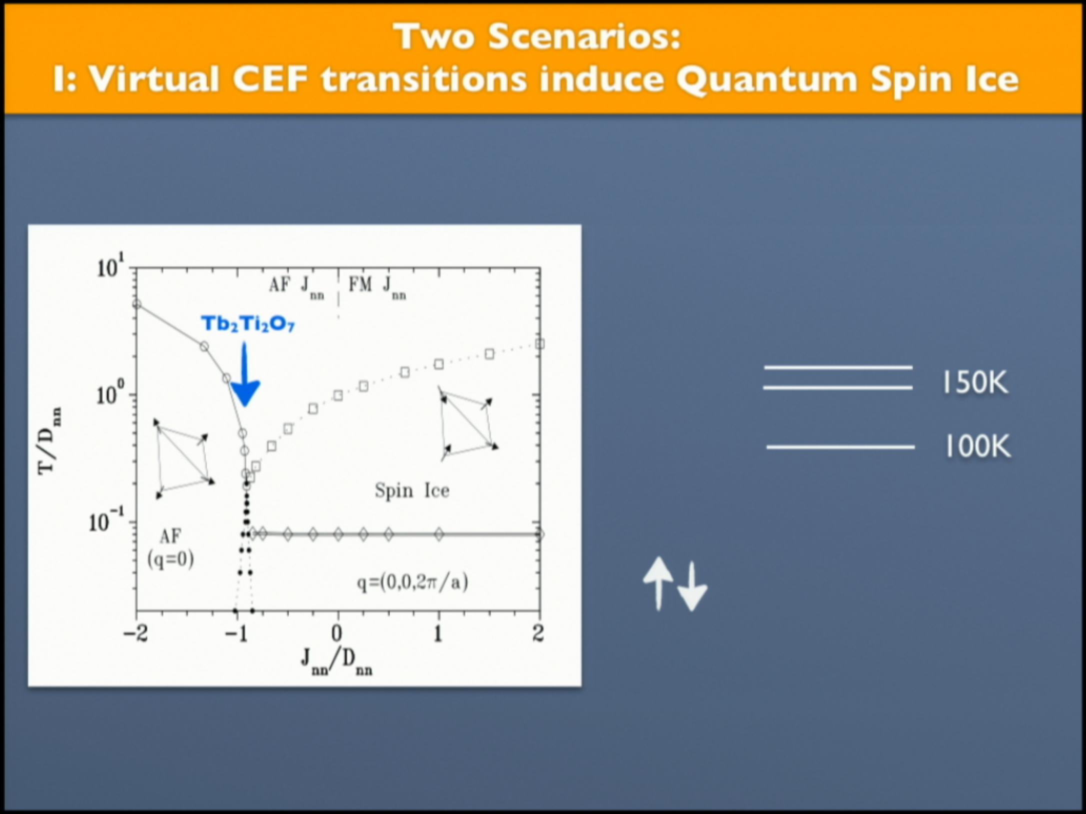


$1/T_1$ relaxation rate
muSR



Low T powder
neutron diffraction

J.S. Gardner et al, Phys. Rev. Lett, 82, 1012, 1999



Two Scenarios:
I: Virtual CEF transitions induce Quantum Spin Ice

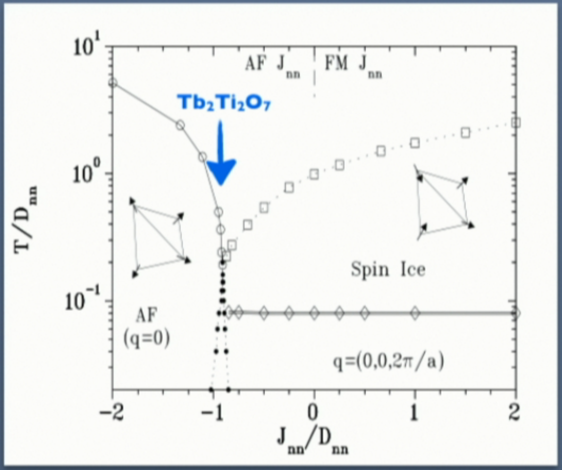
150K

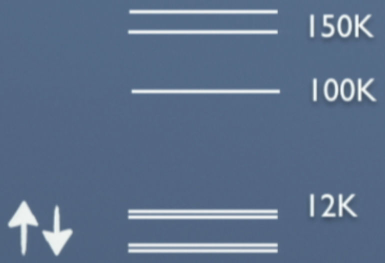
100K

Two Scenarios:
I: Virtual CEF transitions induce Quantum Spin Ice

$Tb_2Ti_2O_7$

Zhang *et al*, PRB, 89, 134410 (2014)





$g_{||} \sim 10$
$g_{\perp} \sim 0$

Significant mixing with higher crystal field level at all experimental T's

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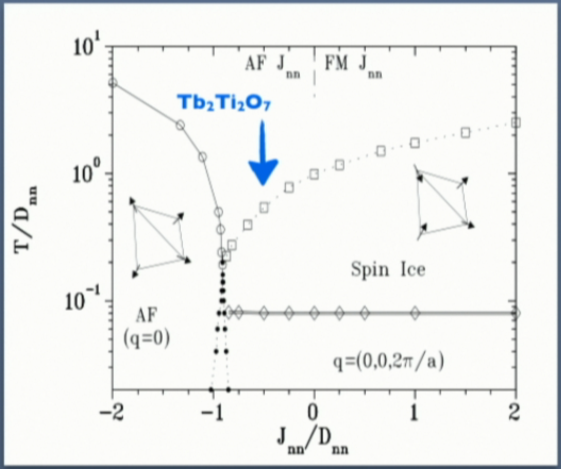

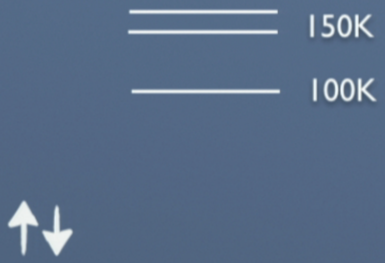

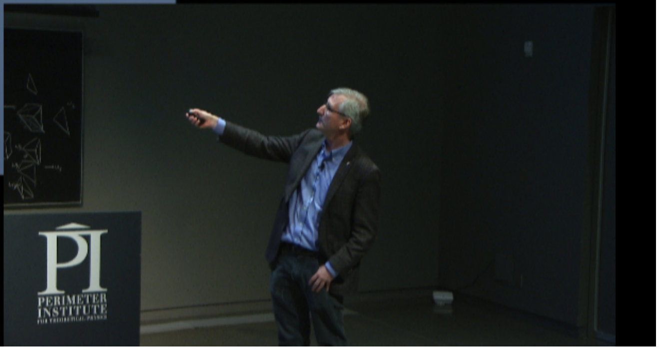

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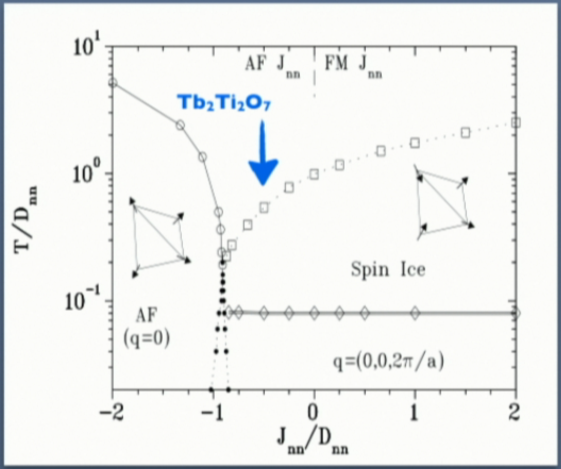
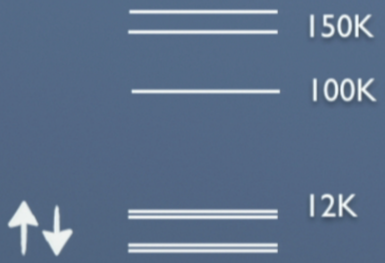
$Tb_2Ti_2O_7$

Zhang *et al*, PRB, 89, 134410 (2014)





$g_{\|} \sim 10$
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Significant mixing with higher crystal field level at all experimental T's

Two Scenarios:
II: Tb^{3+} ground state is a non-magnetic singlet

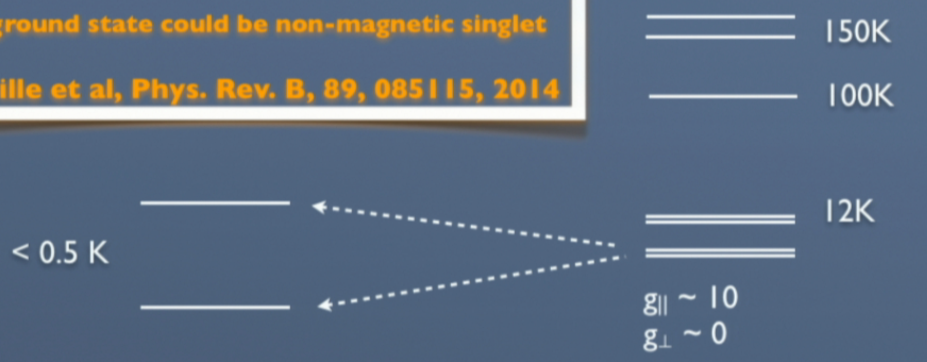
$Tb_2Ti_2O_7$

Zhang *et al*, PRB, 89, 134410 (2014)

Doublet nature of Tb^{3+} CEF eigenvalues *not* protected by Kramer's theorem

Tb^{3+} ground state could be non-magnetic singlet

Bonville et al, Phys. Rev. B, 89, 085115, 2014



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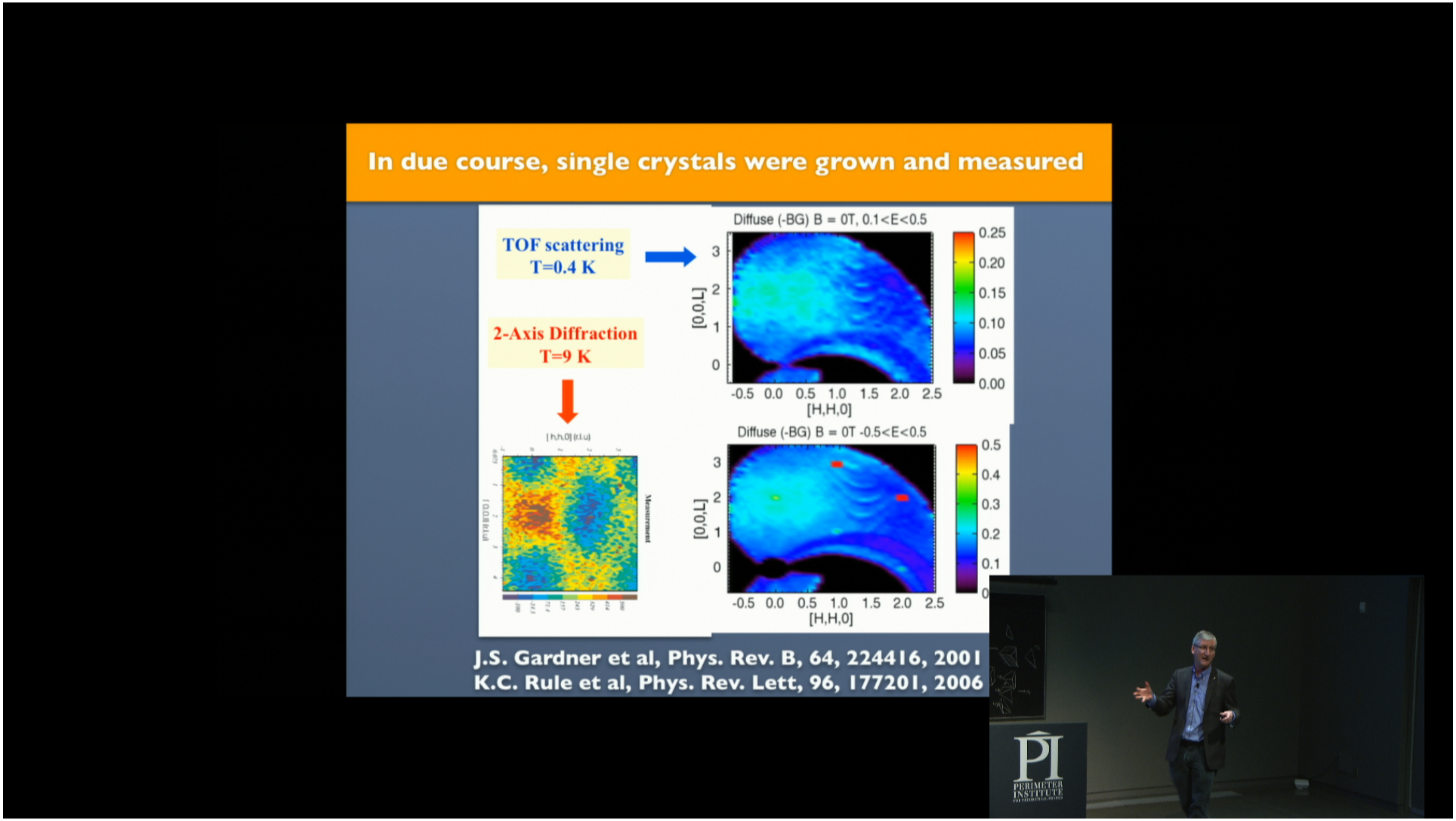
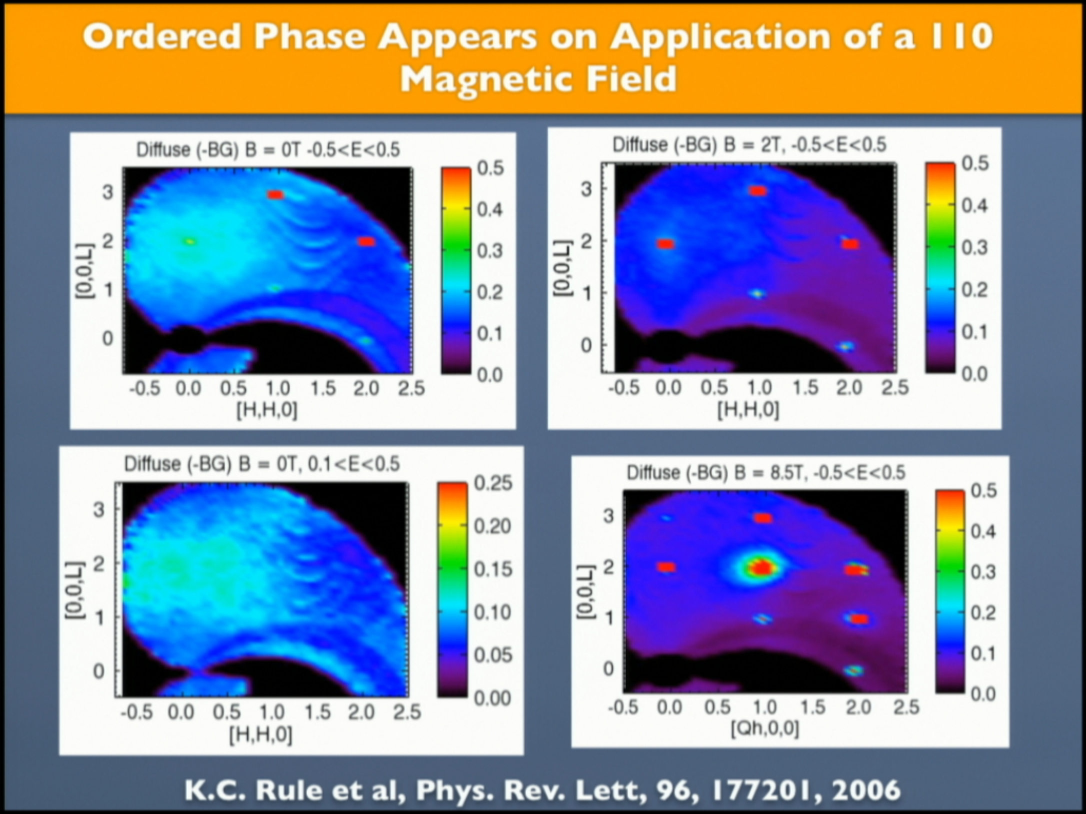


In due course, single crystals were grown and measured

TOF scattering
T=0.4 K

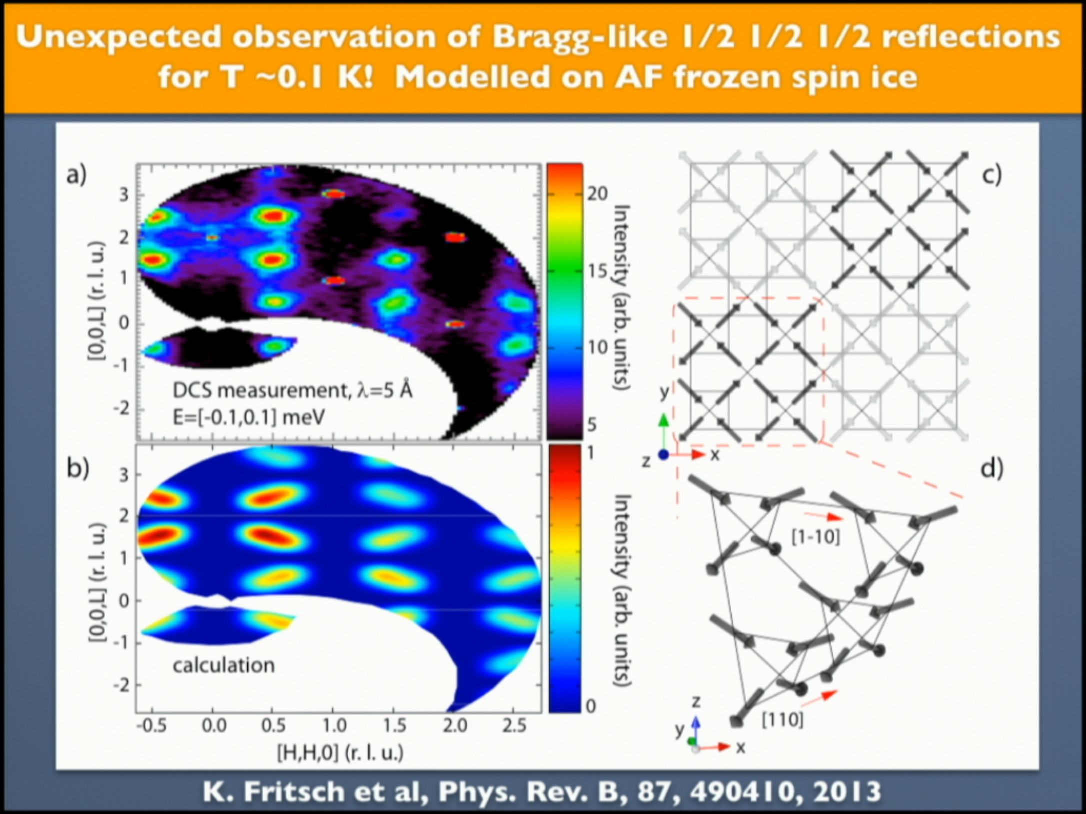
2-Axis Diffraction
T=9 K

J.S. Gardner et al, Phys. Rev. B, 64, 224416, 2001
K.C. Rule et al, Phys. Rev. Lett, 96, 177201, 2006



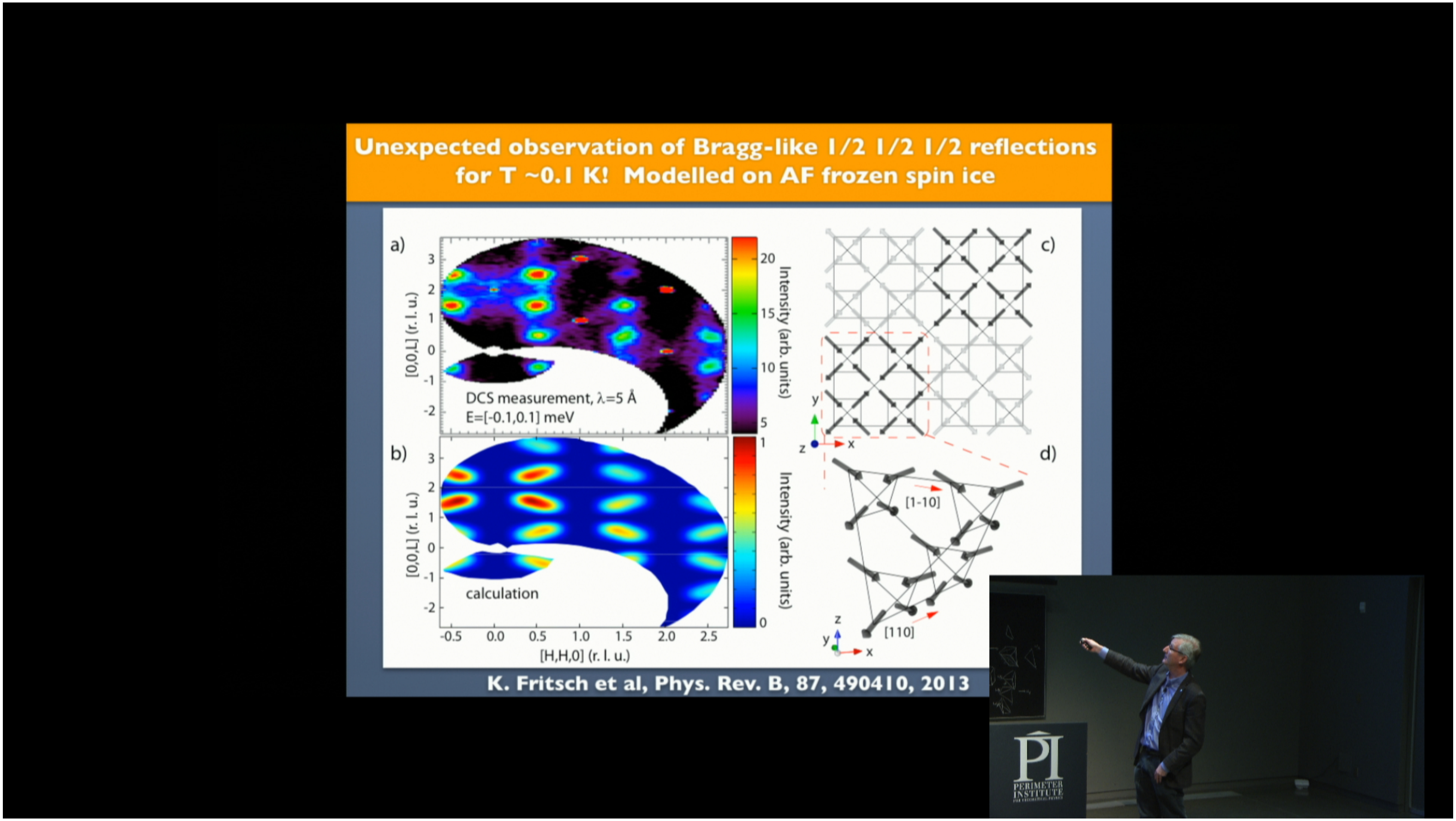
Ordered Phase Appears on Application of a 110 Magnetic Field

K.C. Rule et al, Phys. Rev. Lett, 96, 177201, 2006



Unexpected observation of Bragg-like 1/2 1/2 1/2 reflections for T ~0.1 K! Modelled on AF frozen spin ice

K. Fritsch et al, Phys. Rev. B, 87, 490410, 2013



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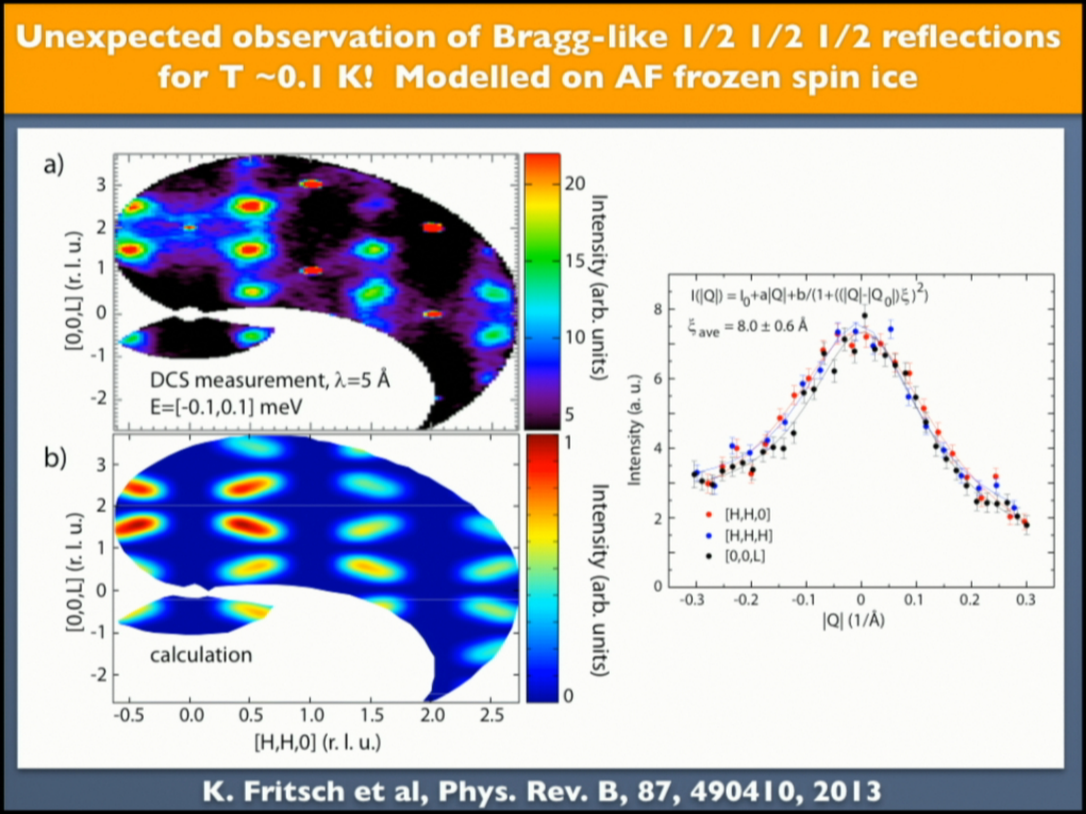

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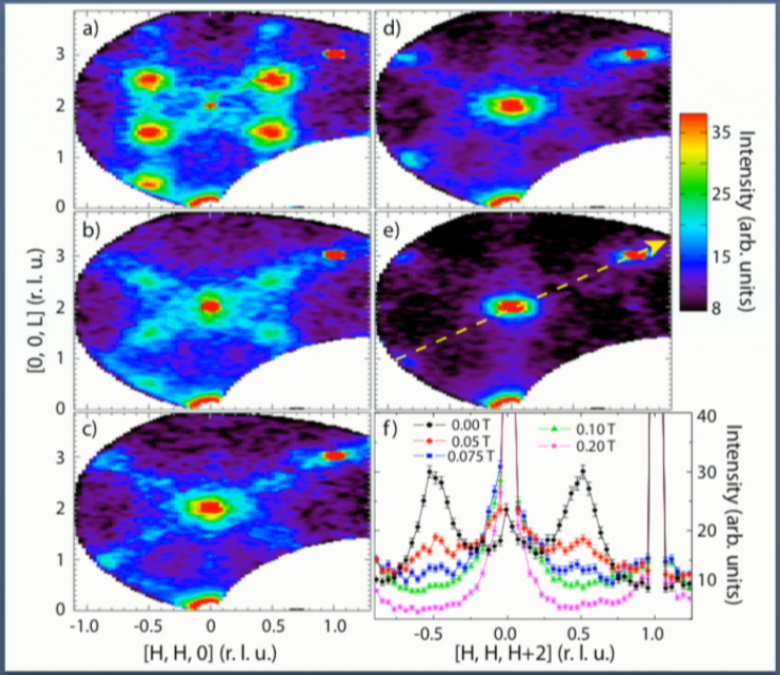
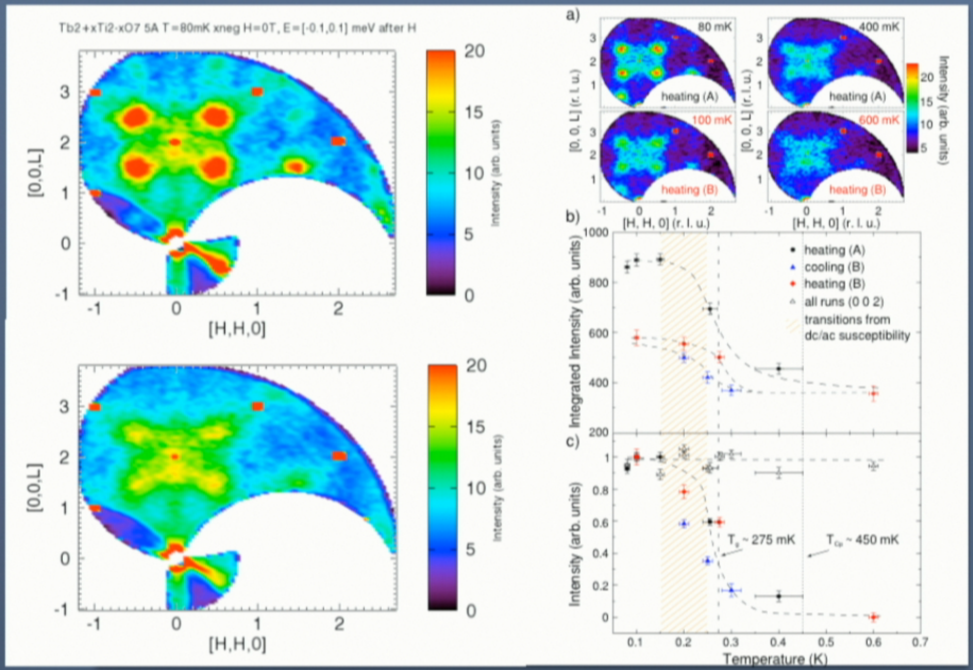
K. Fritsch et al, Phys. Rev. B, 87, 490410, 2013

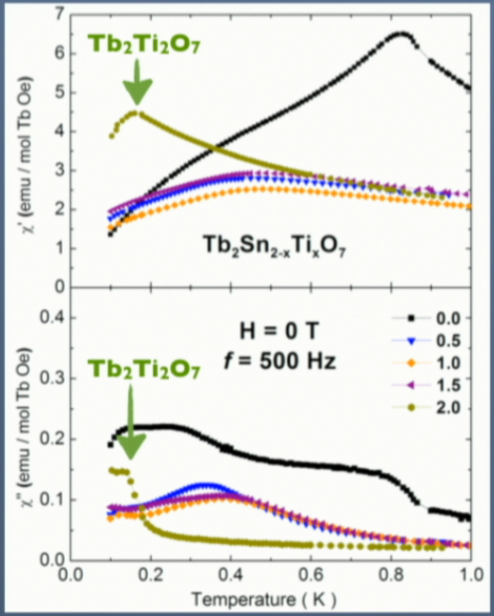
Frozen Spin Ice Structure Polarized by ~ 0.075 T (110) Magnetic Field

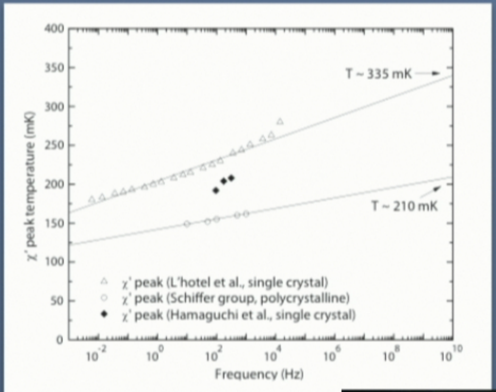


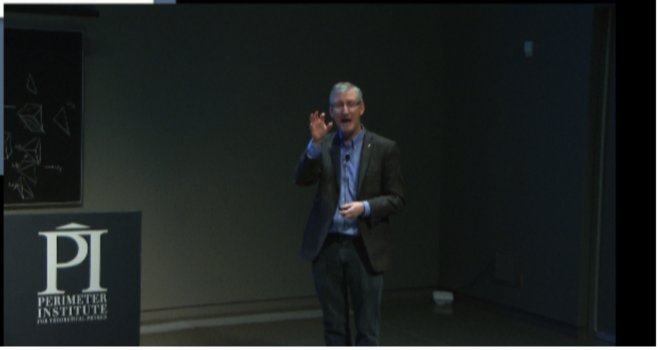
Low T Spin Ice Phase is History Dependent

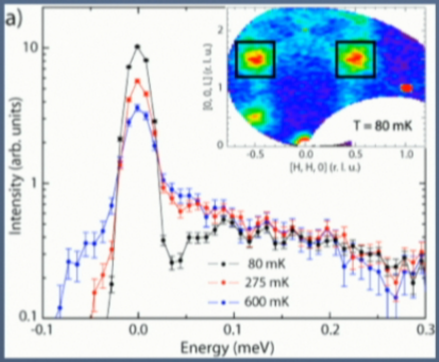


Glassy-behaviour seen below ~ 0.25 K in $Tb_2Ti_2O_7$

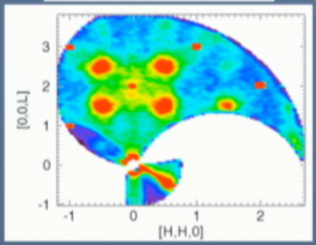




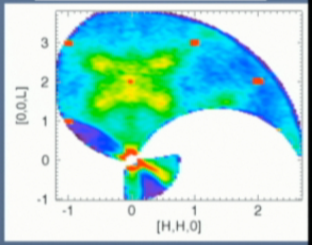


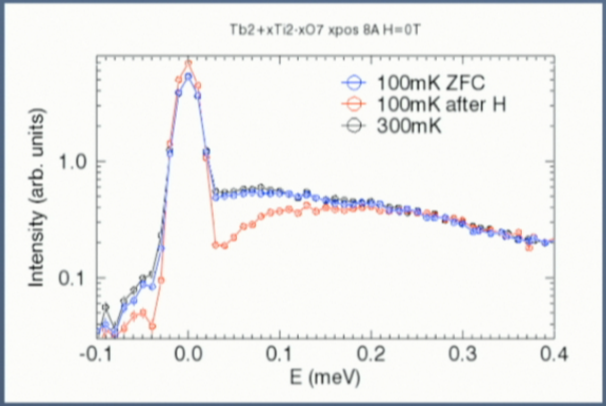


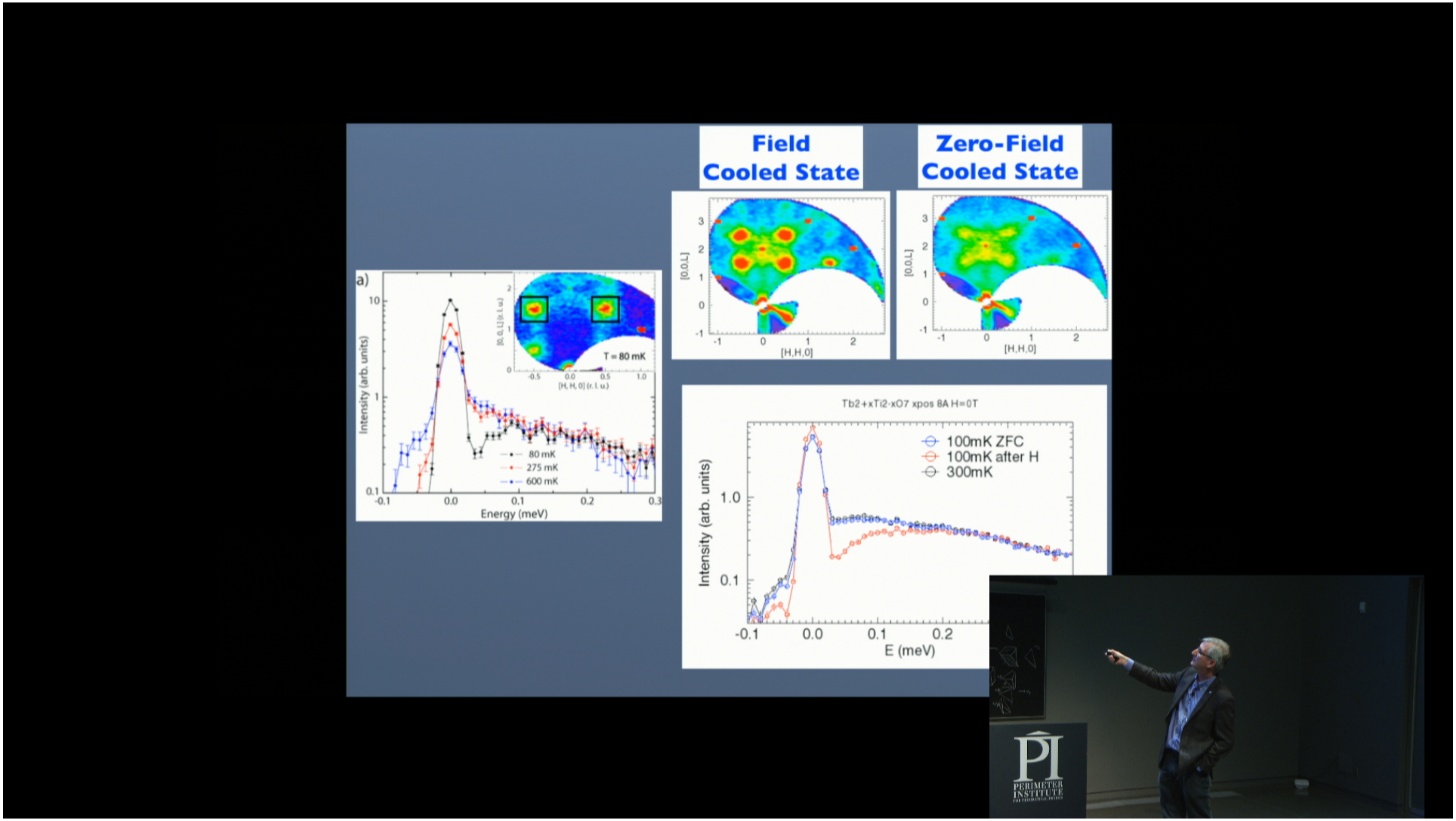
Field Cooled State



Zero-Field Cooled State

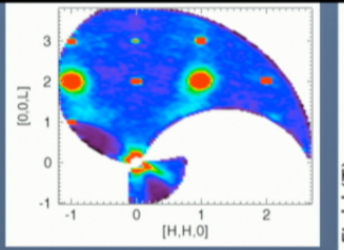


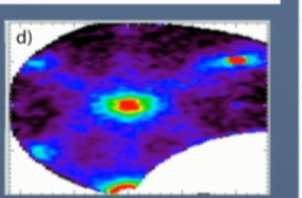


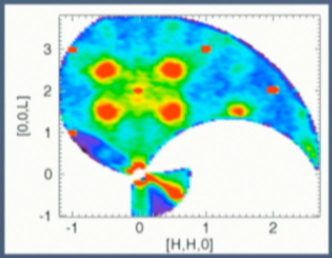


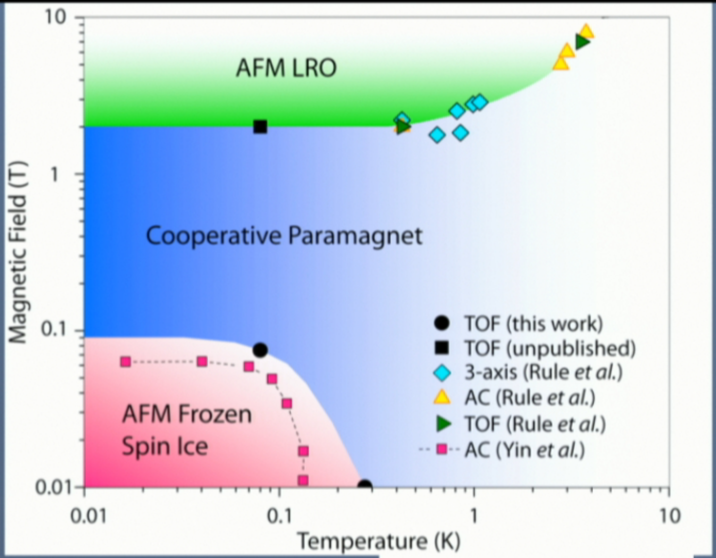
Field Cooled State

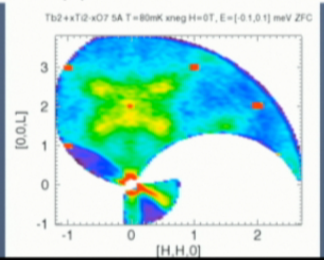
Zero-Field Cooled State


[0,0,L]
3
2
1
0
-1
-1
0
1
2
[H,H,0]


d)


[0,0,L]
3
2
1
0
-1
-1
0
1
2
[H,H,0]


10
1
0.1
0.01
Magnetic Field (T)
AFM LRO
Cooperative Paramagnet
AFM Frozen
Spin Ice
● TOF (this work)
■ TOF (unpublished)
◆ 3-axis (Rule et al.)
▲ AC (Rule et al.)
▶ TOF (Rule et al.)
■ AC (Yin et al.)
0.01
0.1
1
10
Temperature (K)


Tb2+xTi2-xO7 5A T=80mK xneg H=0T, E=[-0.1,0.1] meV ZFC
[0,0,L]
3
2
1
0
-1
-1
0
1
2
[H,H,0]

Conclusions

- *TOF techniques well suited to exotic magnetism as it measures very effectively across wide dynamic range in Q and energy*
- *$Tb_2Ti_2O_7$ displays frozen AF spin ice state at low temperatures (< 0.25 K) and fields (< 0.075 T)*
- *FC state shows 1/2 1/2 1/2 short range (~ 8 unit cell) correlations and an ~ 0.1 meV ~ 1 K gap*
- *ZFC state is gapless and shows "checkerboard" correlations*


EXIT
EXIT
RESERVED
RESERVED
RESERVED
RESERVED


EXIT
RESERVED
RESERVED
RESERVED
RESERVED