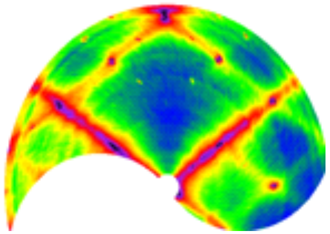
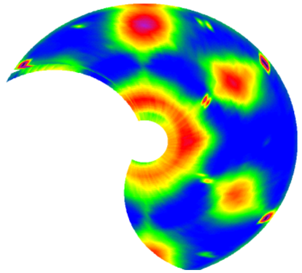
Higgs transition from a magnetic Coulomb liquid to a ferromagnet in $Yb_2Ti_2O_7$





Lieh-Jeng Chang

Department of Physics,
National Cheng Kung University
Taiwan

14th June 2013

EQPCM 2013,
Kashiwa, Japan

Collaborators :

RIKEN : S. Onoda, I. Watanabe

JCNS: Y. Su

NTU: Y.-J. Kao

U. of Warwick: M. R. Lees, G. Balakrishnan

NU: Y. Yasui

NSRRC: K. D. Tsuei, C. W. Pao, M. C. Huang, H. C. Lin

ISIS: A. D. Hillier, G. Tatiana

JAEA: K. Kakurai

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- **Sample dependent**

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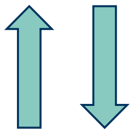
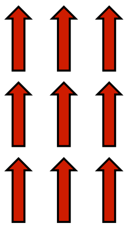


Classical Ising spins, s_i = +/- 1

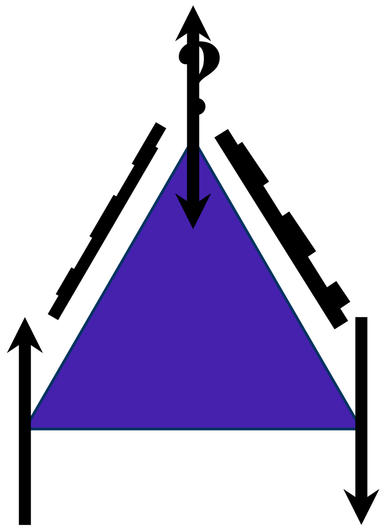


Exchange interaction, $H = J\, s_i s_j$

$J < 0$, ferromagnetic;

$J > 0$, antiferromagnetic

Geometrical Frustration: what happened?



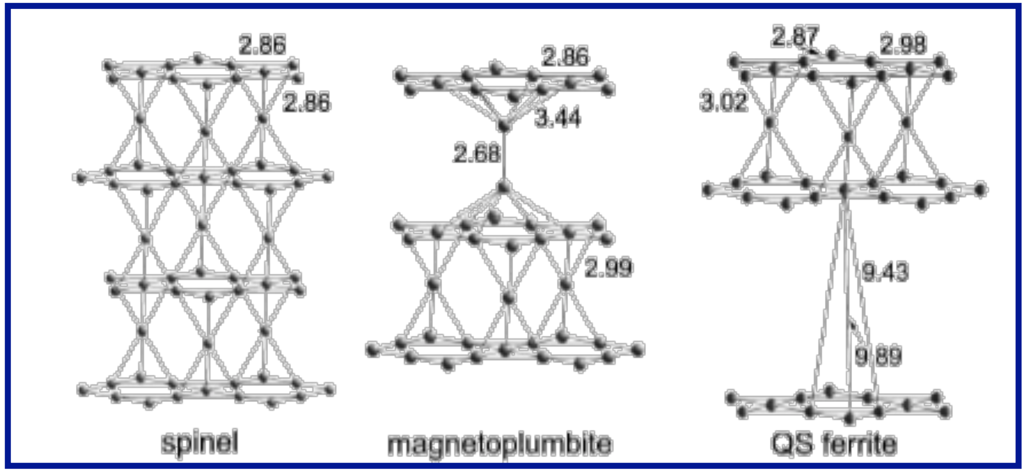
Not all the terms in H can be minimized

But $$H = J/2\left(\sum_{i=1}^{n} s_i\right)^2 + C$$

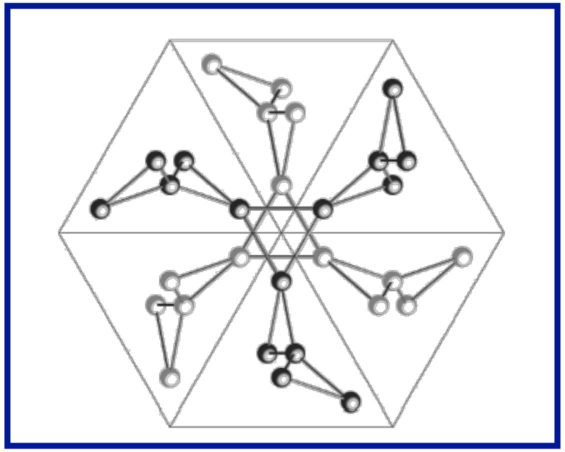
Can be minimized

→ **ground state degeneracy**

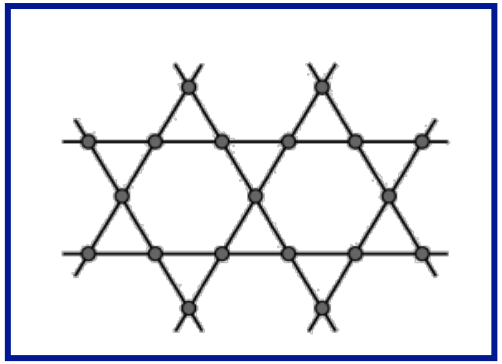
Famous Frustrated lattices



AB_2O_4



RE-Garnet ($RE_3Ga_5O_{12}$)



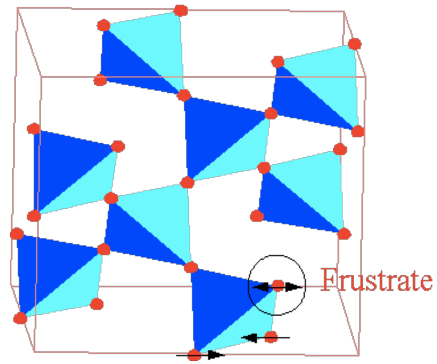
Kagomé Lattice

$SrCr_xGa_{12-x}O_{19}$

Jarosite: $AB_3(OH)_6(SO4)_2$

(A=Na, K, NH_4...., B=Fe, Cr...)

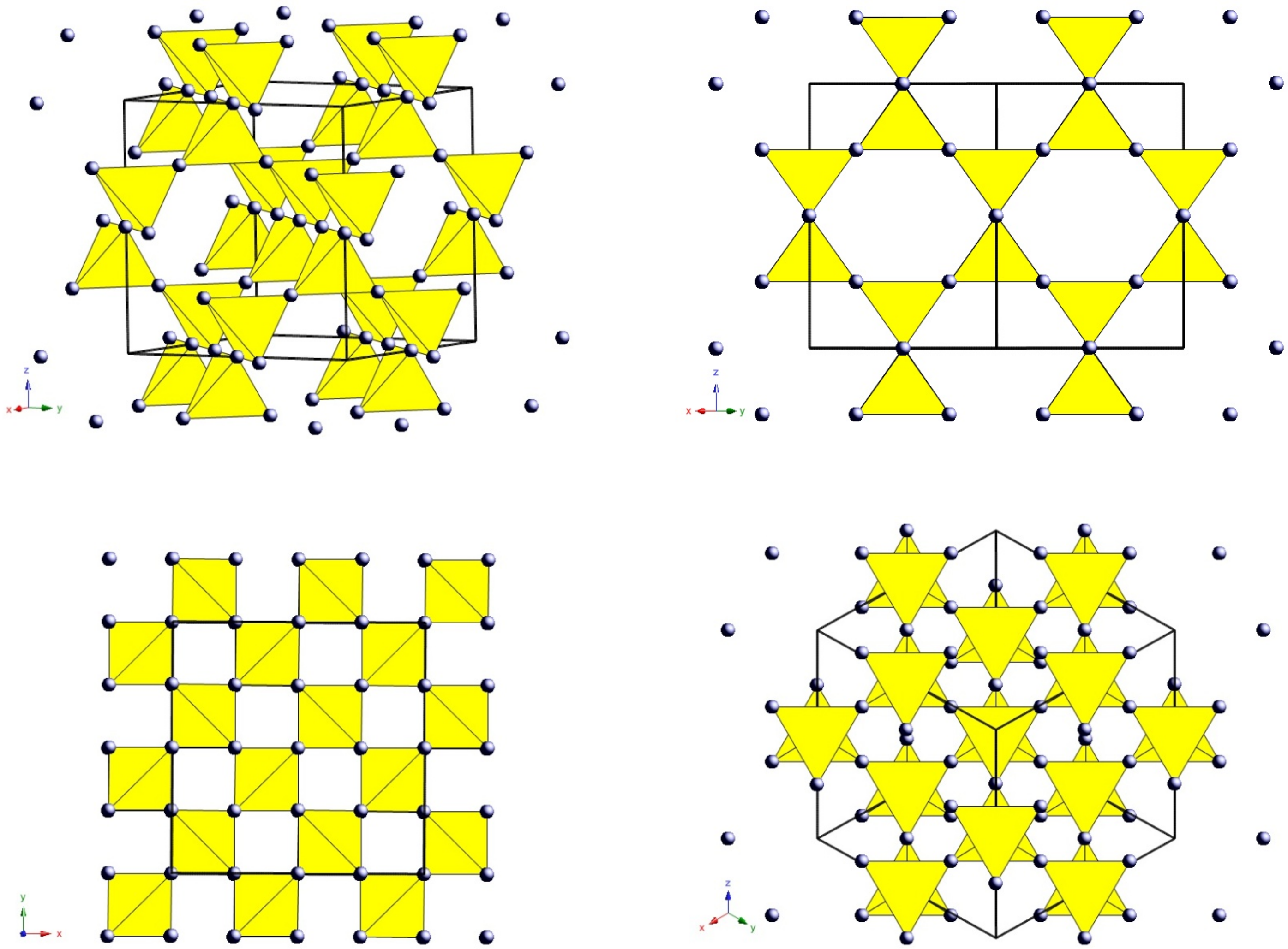
Pyrochlore Lattice



$A_2B_2O_7$

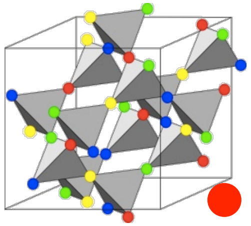
(A= Rare Earth,... ;B= Ti, Sn, Mo, Ru...)

Pyrochlore lattice

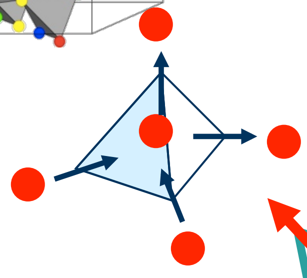


Famous examples for 3D

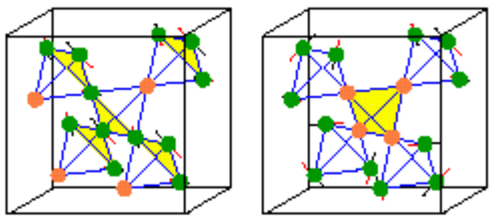
- **Spin glass**
  randomly frozen
  $Y_2Mo_2O_7$



- **Spin ice**
  frozen local order
  $Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$



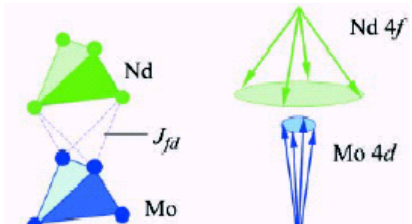
- **Spin liquid**
  (Cooperative paramagnet)
  very dynamic
  $Tb_2Ti_2O_7$



J. Phys. Cond. Matter. 16, L321 (2004)

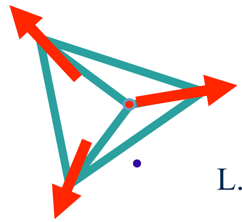
- **Spin slush**
  partially ordered
  $Gd_2Ti_2O_7$

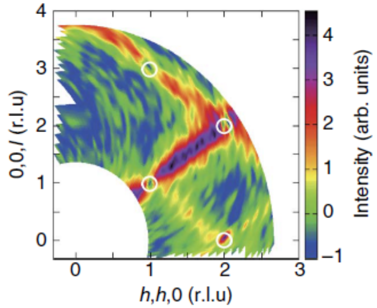
- **Spin Chirality**
  transition metal sites
  $Nd_2Mo_2O_7$

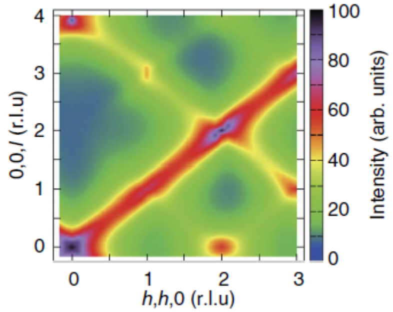


Science. 291, 2573 (2001)

- **XY pyrochlore**
  2-D
  $Yb_2Ti_2O_7$

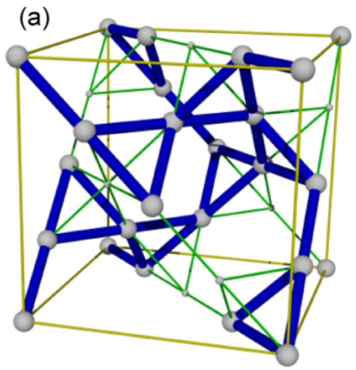






L. J. Chang/ S. Onoda *et al.*, Nat. Commun. 3, 992 (2012)

- **HyperKagome**
  $Na_4Ir_3O_7$



PRL. 105, 237202 (2010)

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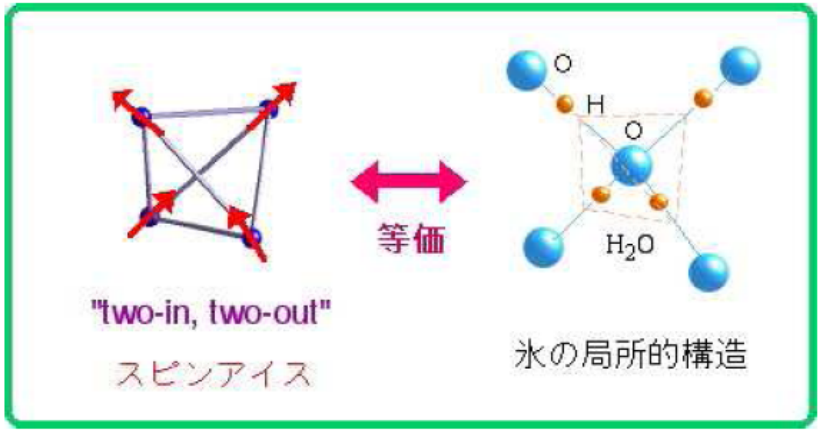
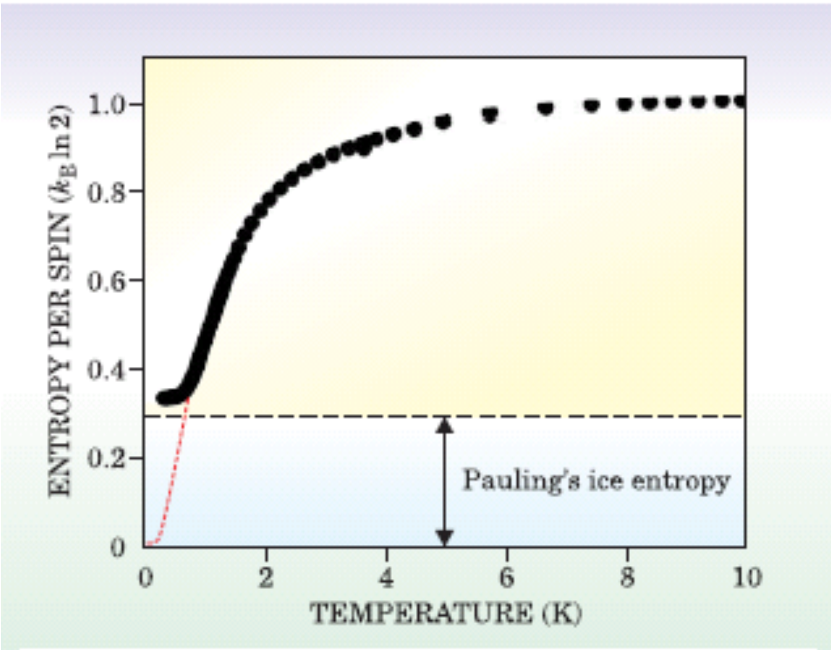
Spin Ice



150.69.54.33/takagi/matuhirasan/SpinIce.jpg



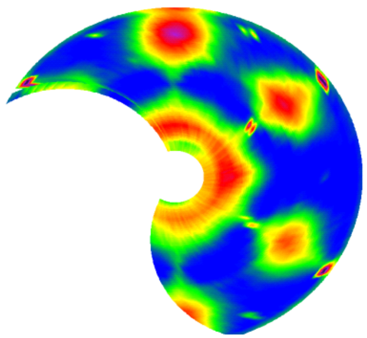
R. Moessner et al., Physics Today, **Feb.,** 24 (2006).

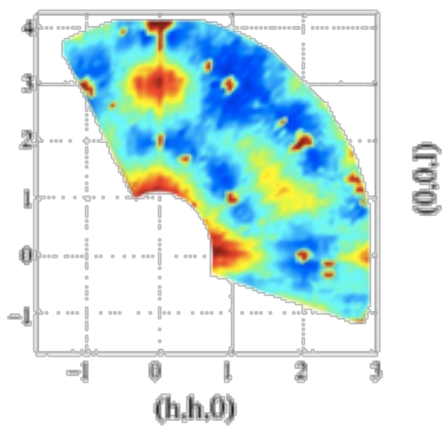
Zero point entropy:

$S/k_BN = ln2 - (1/2)ln(3/2)$

Microstates: *N* spins, *N/2* tetrahedra;
Constrains: two-in, two-out;
No. of ground state: $2^N(6/16)^{N/2}$
Entropy: 1/2 ln (3/2)

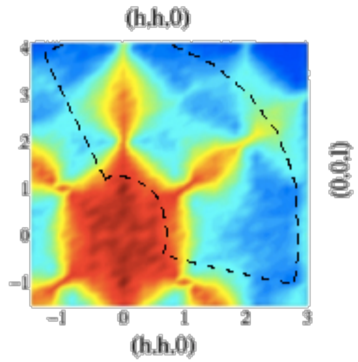
Diffuse neutron scattering for spin ice



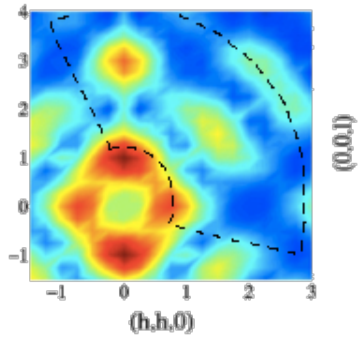


L. J. Chang et al., PRB, **82,** 172403 (2010).

nn Spin Ice

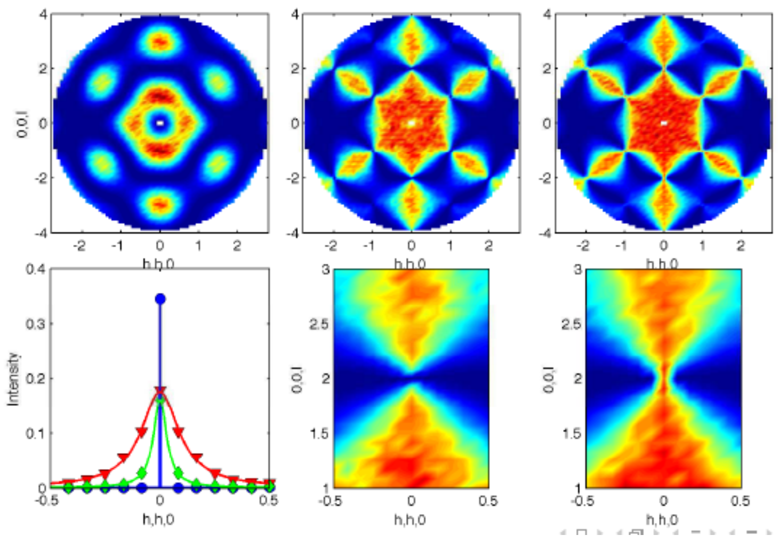


Dipolar Spin Ice



S.T. Bramwell et al., PRL, **87,** 047205 (2001).

Strings as ferromagnetic fluctuations



T. Fennell et al. Science **326**, 415 (2009)

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

$Yb_2Ti_2O_7$

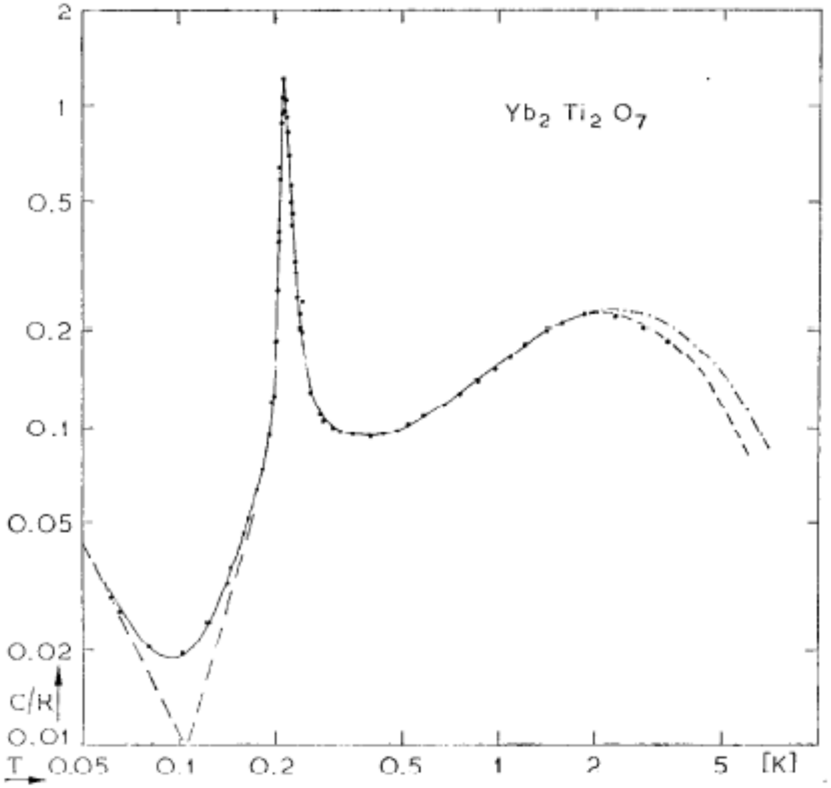


Fig. 12. Heat capacity of $Yb_2Ti_2O_7$.

H. W. J. Bloete *et al.*, *Physica* **43,** 549–568 (1969).

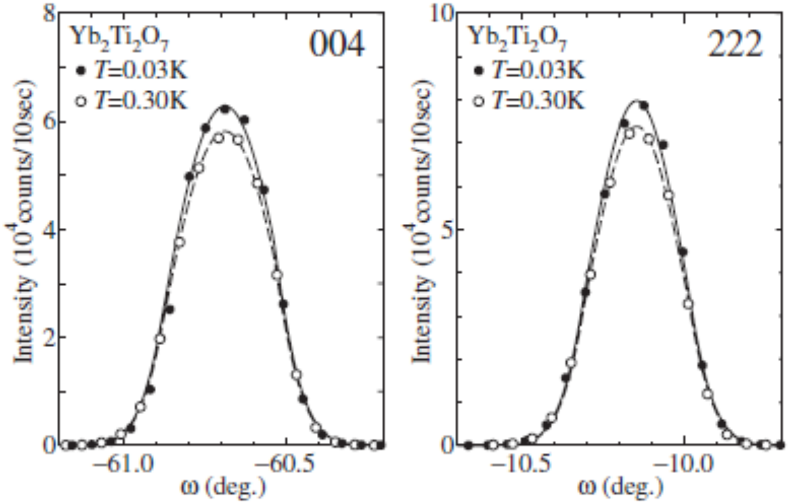


Fig. 3. Profiles of the ω-scans for 004 and 222 reflections taken at 0.03 K and 0.30 K. Solid and Broken lines are guides for the eye.

Y. Yasui *et al.*, JPSJ **72** 3014 (2003)

ferromagnetic

CW temperature ~ 0.6 K

1^{st} order transition ~ 210 mK

LRO?

Quantum spin ice approach

The Yb^{3+} 4f magnetic moment at a site *r is described with the pseudospin-1/2 operator* $\hat{\boldsymbol{S}}_{\boldsymbol{r}} = (\hat{S}^x_{\boldsymbol{r}}, \hat{S}^y_{\boldsymbol{r}}, \hat{S}^z_{\boldsymbol{r}})$

$$\boldsymbol{m}_{\boldsymbol{r}} = \mu_B \left(g_\perp (\hat{S}^x_{\boldsymbol{r}} \boldsymbol{x}_{\boldsymbol{r}} + \hat{S}^y_{\boldsymbol{r}} \boldsymbol{y}_{\boldsymbol{r}}) + g^{\parallel} \hat{S}^z_{\boldsymbol{r}} \boldsymbol{z}_{\boldsymbol{r}} \right)$$

the *g-tensor components* $g^{\perp} = 4.18$ and $g^{\parallel} = 1.77$

where the *z* direction is taken along the <111> direction

$$H_D = \frac{\mu_0}{4\pi} \sum_{\langle \boldsymbol{r}, \boldsymbol{r} \rangle} \left[\frac{\boldsymbol{m}_{\boldsymbol{r}} \cdot \boldsymbol{m}_{\boldsymbol{r}}}{(\Delta r)} - 3 \frac{(\boldsymbol{m}_{\boldsymbol{r}} \cdot \Delta \boldsymbol{r})(\Delta \boldsymbol{r} \cdot \boldsymbol{m}_{\boldsymbol{r}})}{(\Delta r)^5} \right],$$

Spin ice + Quantum fluctuations = Quantum spin Ice

$$H_{se} = J \sum_{\langle \boldsymbol{r}, \boldsymbol{r} \rangle}^{n.n.} \left[\hat{S}^z_{\boldsymbol{r}} \hat{S}^z_{\boldsymbol{r}} + \frac{\delta}{2} \left(\hat{S}^+_{\boldsymbol{r}} \hat{S}^-_{\boldsymbol{r}} + h.c. \right) + \frac{q}{2} \left(e^{2i\phi_{\boldsymbol{r},\boldsymbol{r}}} \hat{S}^+_{\boldsymbol{r}} \hat{S}^+_{\boldsymbol{r}} + h.c. \right) + \frac{K}{2} \left(e^{i\phi_{\boldsymbol{r},\boldsymbol{r}}} (\hat{S}^z_{\boldsymbol{r}} \hat{S}^+_{\boldsymbol{r}} + \hat{S}^+_{\boldsymbol{r}} \hat{S}^z_{\boldsymbol{r}}) + h.c. \right) \right].$$

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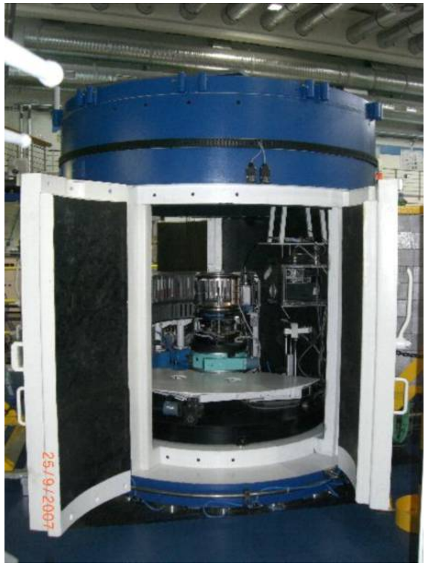
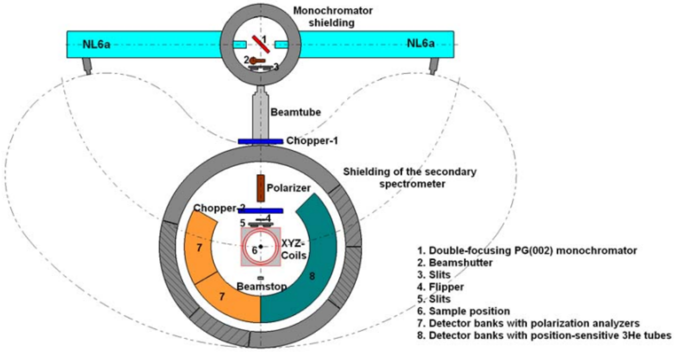
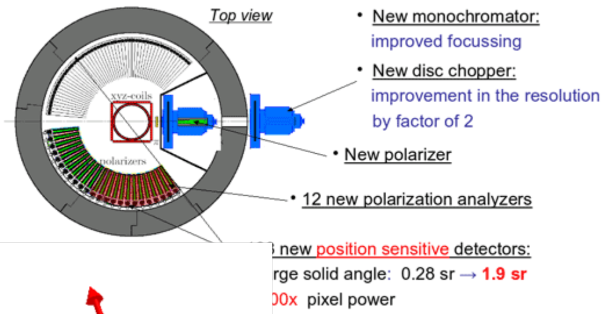
$Yb_2Ti_2O_7$

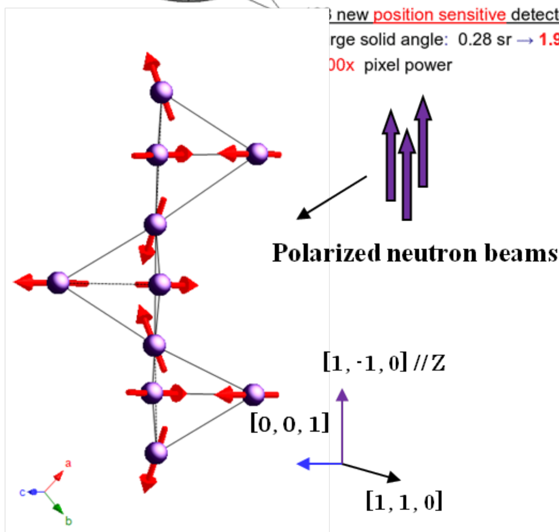
Single crystals were grown from IR furnace (Y. Yasui, Nagoya U.)

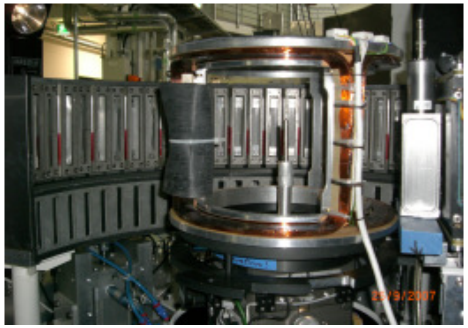
•DNS@FRM-II, Germany Diffuse Neutron Scattering







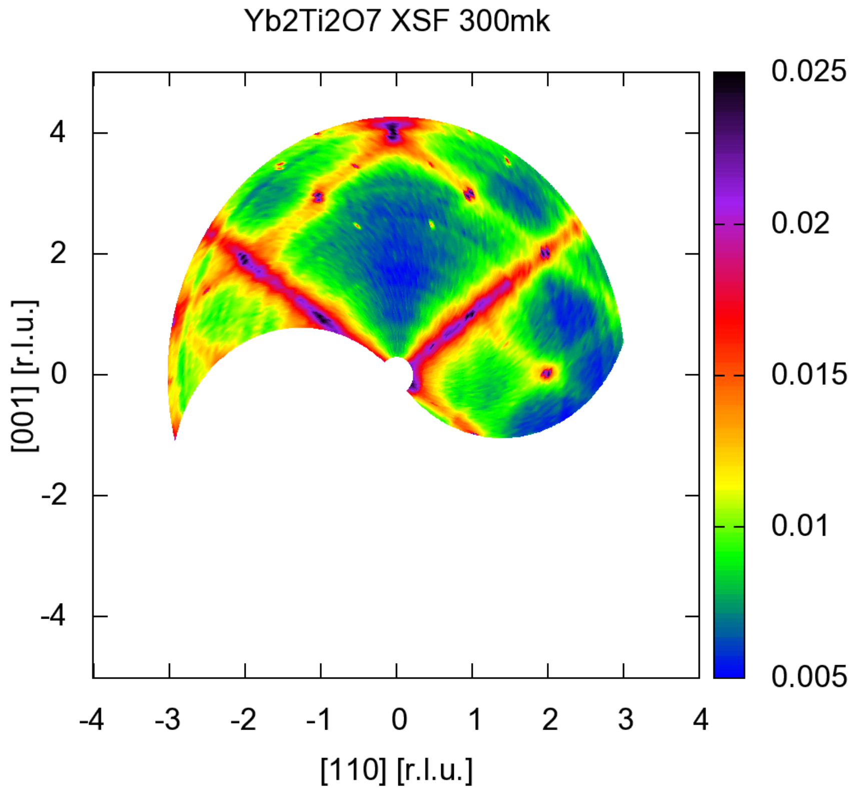




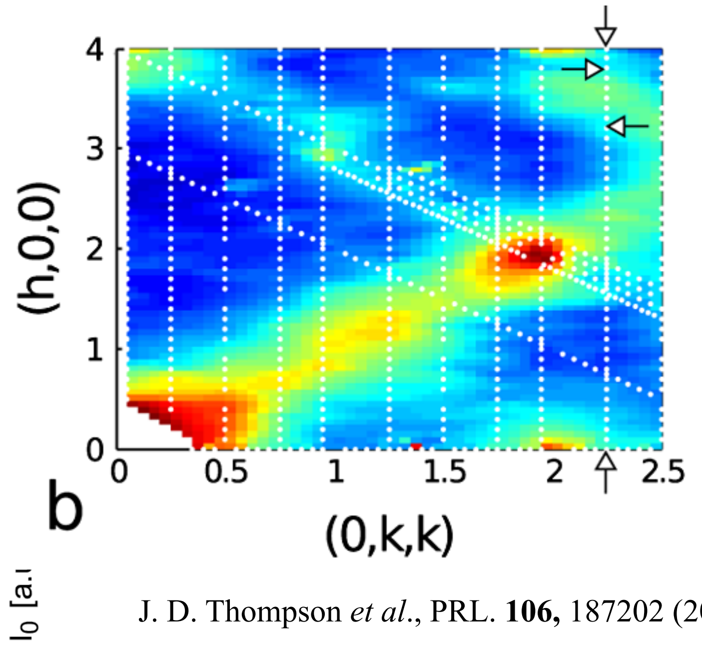
Spin-flip channel

Non-Spin-flip channel

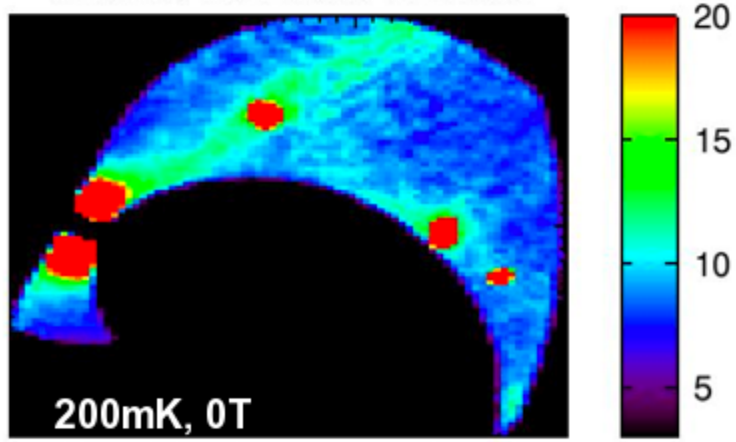
Rod structure along [111]: 2 D correlations on kagome plane above transition temperature



L. J. Chang *et al.*



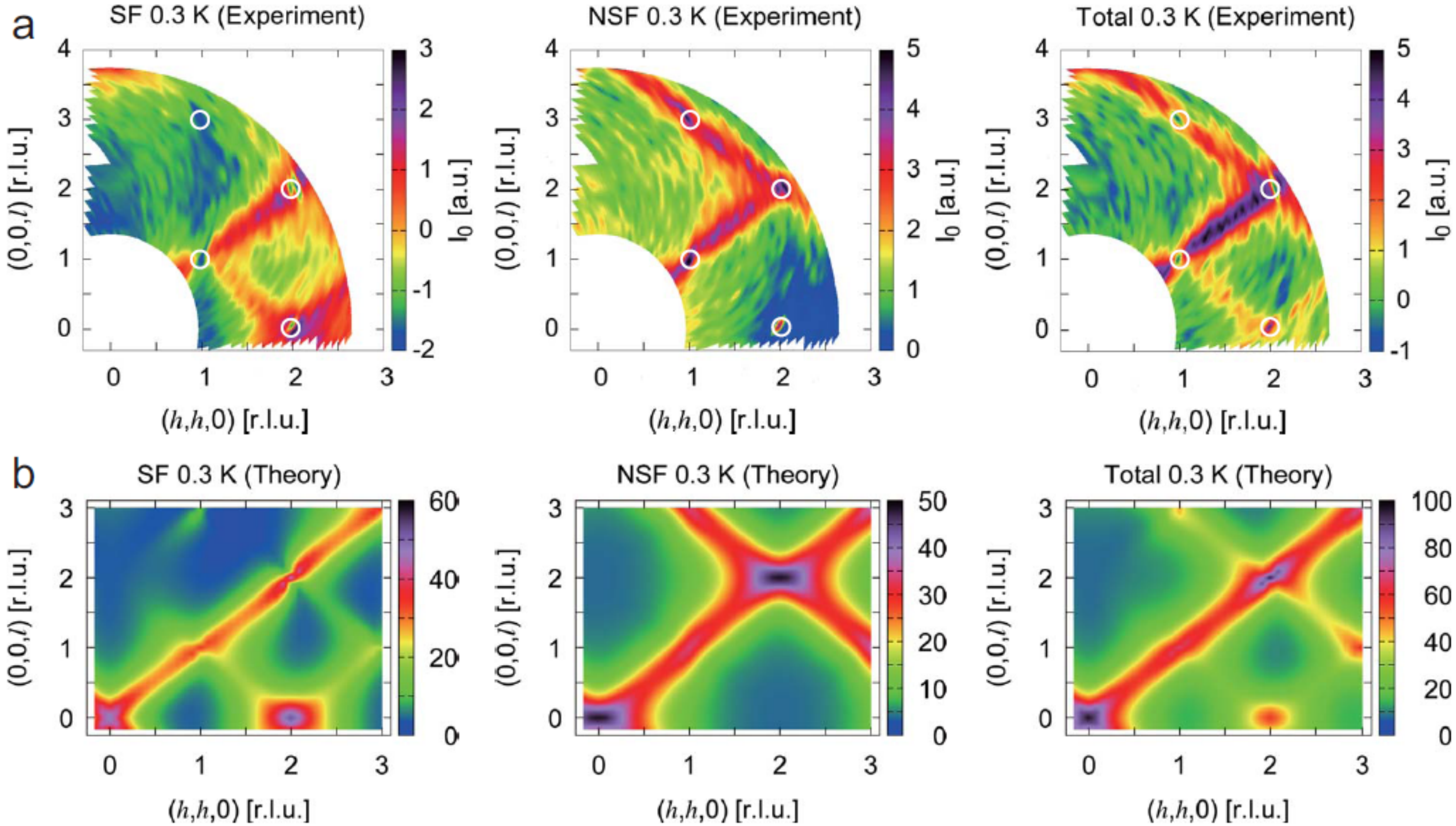
J. D. Thompson *et al.*, PRL. **106,** 187202 (2011)



K. A. Ross *et al.*, PRL **103** 227202 (2010)

Diffuse neutron scattering with polarization analysis

Calculated by RPA $$I(Q) = \sum_{n} \sum_{i,j=1}^{4} f^{\mu\nu}_{\boldsymbol{Q},i,j} \frac{\phi^{\mu}_{-\boldsymbol{Q},n,i}\phi^{\nu}_{\boldsymbol{Q},n,j}}{3+\epsilon_{\boldsymbol{Q},n}/T}.$$



$$f^{\mu\nu}_{\boldsymbol{Q},i,j} = \frac{1}{4|\boldsymbol{Q}|^4}\left[\boldsymbol{Z}\cdot(\boldsymbol{Q}\times(g_\mu \boldsymbol{e}^{\mu}_{i}\times\boldsymbol{Q}))\right]\left[\boldsymbol{Z}\cdot(\boldsymbol{Q}\times(g_\nu \boldsymbol{e}^{\nu}_{j}\times\boldsymbol{Q}))\right],$$

with $\boldsymbol{Z}=(1,-1,0)/\sqrt{2}$ for the NSF channel and $$f^{\mu\nu}_{\boldsymbol{Q},i,j} = \frac{1}{4|\boldsymbol{Q}|^4}\left[\boldsymbol{Q}\times(g_\mu \boldsymbol{e}^{\mu}_{i}\times\boldsymbol{Q})\right]\cdot\left[\boldsymbol{Q}\times(g_\nu \boldsymbol{e}^{\nu}_{j}\times\boldsymbol{Q})\right]$$

for the total. The SF channel is obtained as the difference between the above two.

L. J. Chang/ S. Onoda *et al.,* Nat. Commun. 3, 992 (2012)

Coupling constants we obtained: $(J, \delta, q, K) = (0.68\ \mathrm{K}, -0.8, 0.2, -1.0)$

Similar to the results from neutron inelastic scattering in fields

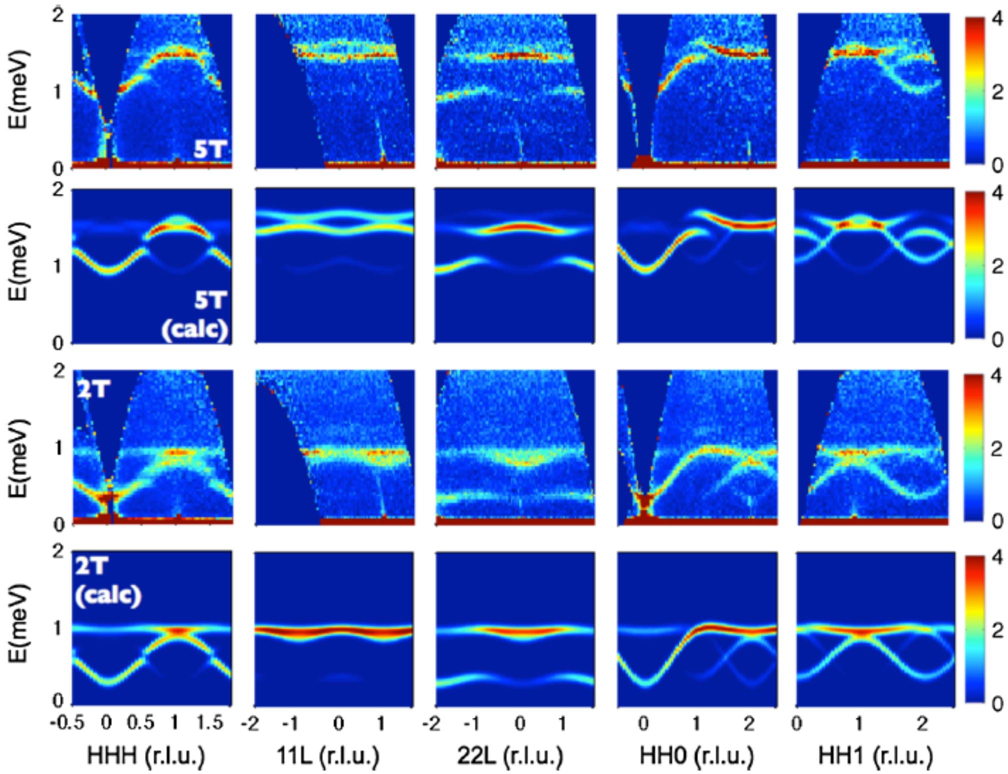
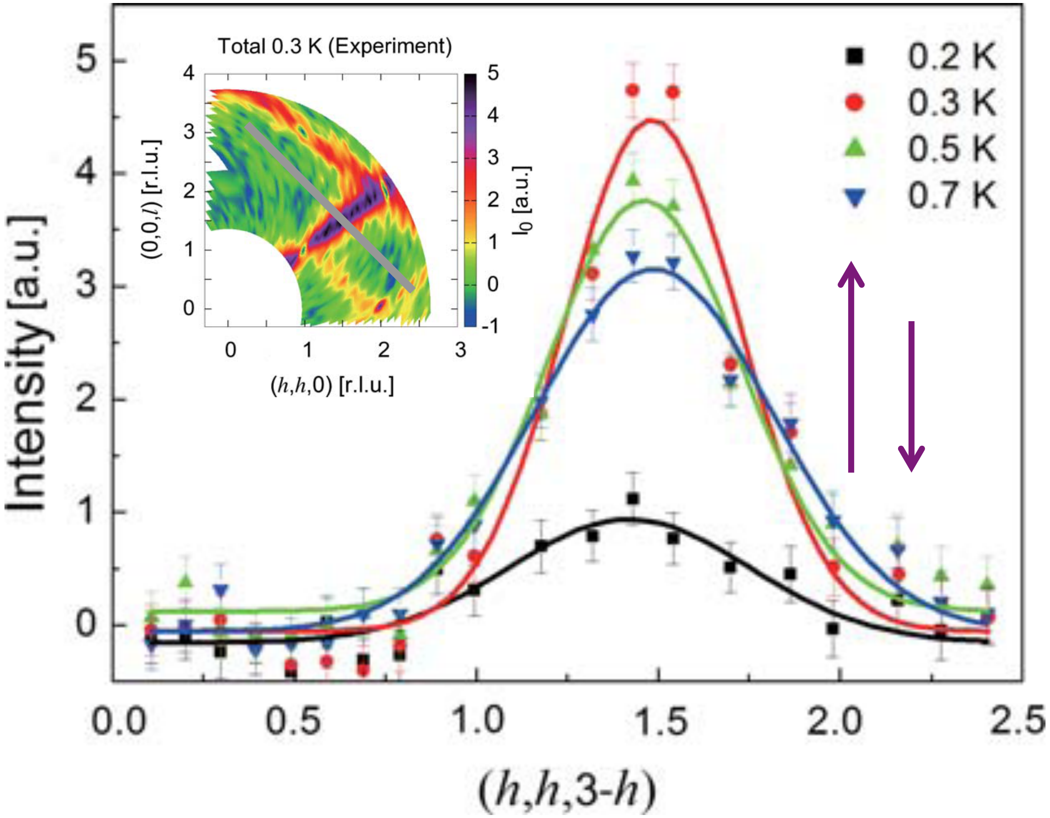


FIG. 1. The measured $S(\mathbf{Q}, \omega)$ at $T = 30$ mK, sliced along various directions in the HHL plane, for both $H = 5$ T (first row) and $H = 2$ T (third row). The second and fourth rows show the calculated spectrum for these two field strengths, based on an anisotropic exchange model with five free parameters (see text) that were extracted by fitting to the 5 T data set. For a realistic comparison to the data, the calculated $S(\mathbf{Q}, \omega)$ is convoluted with a Gaussian of full-width 0.09 meV. Both the 2 T and 5 T data sets, composed of spin wave dispersions along five different directions, are described extremely well by the same parameters. (Note that r.l.u. stands for reciprocal lattice units.)

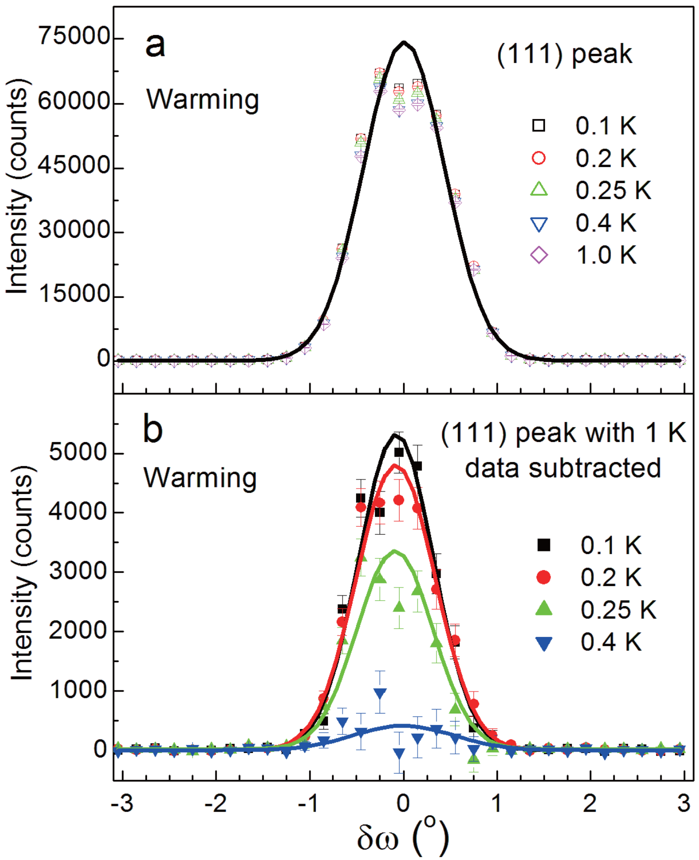
K. A. Ross *et al.*, PRX **1**, 021002 (2011)

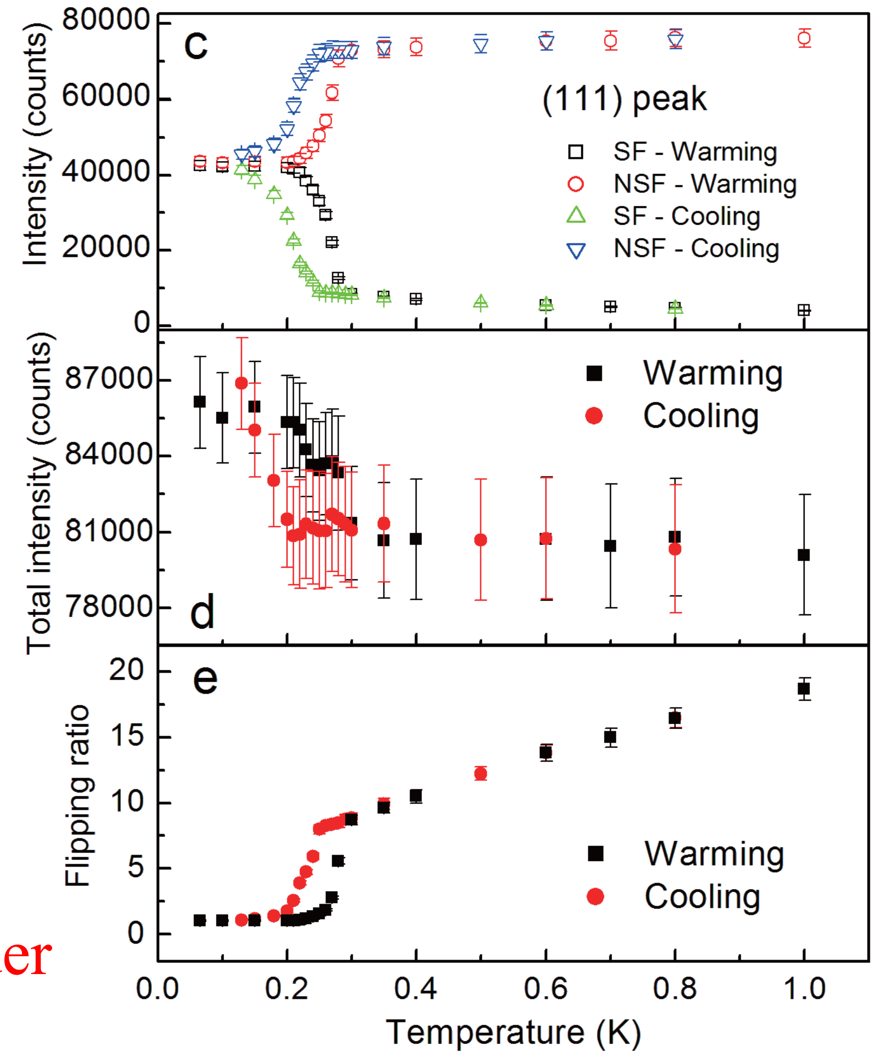
Z-TOTAL cross-section cut on rod



L. J. Chang/ S. Onoda *et al.,* Nat. Commun. 3, 992 (2012)

Peak (111) intensities

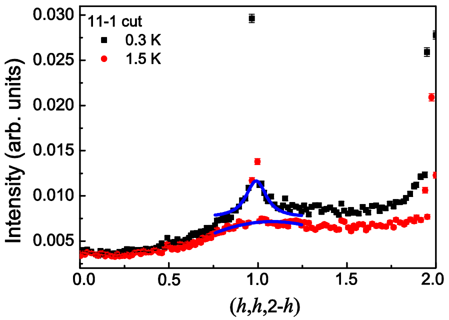


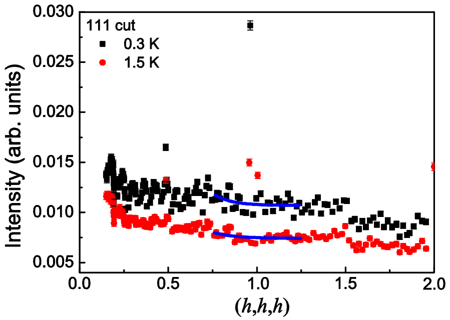


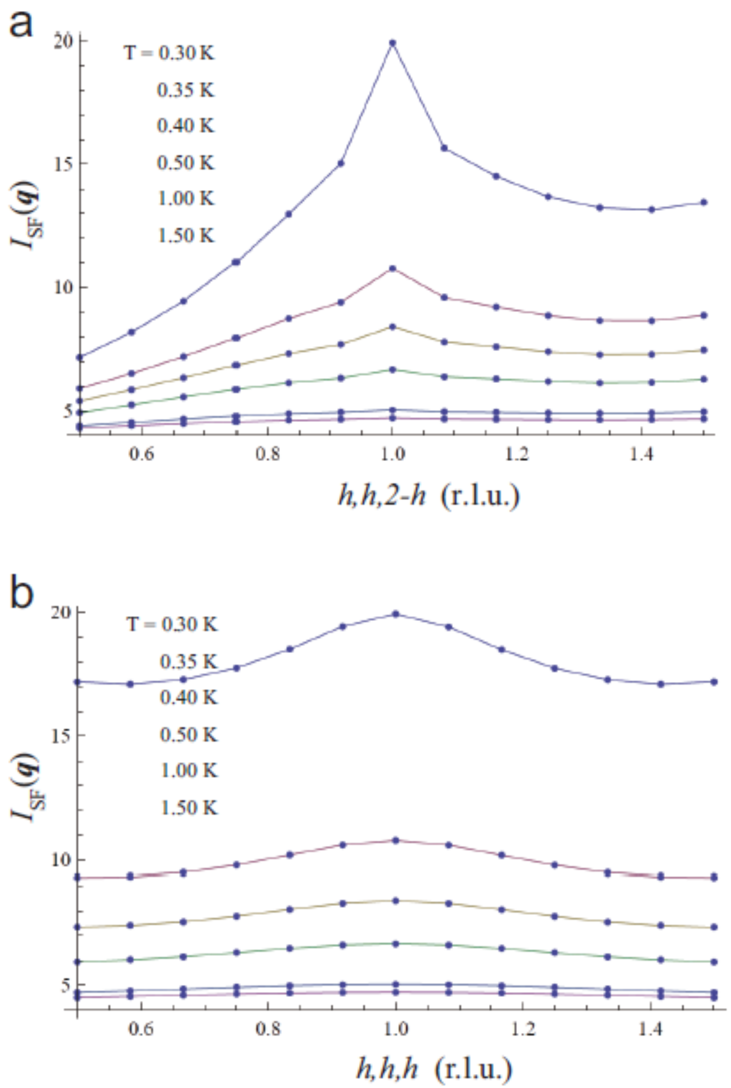
Depolarization: ferromagnetic order
First-order transition
The widths of 111 peaks are identical

L. J. Chang/ S. Onoda *et al.*, Nat. Commun. 3, 992 (2012)

Pinch point cut







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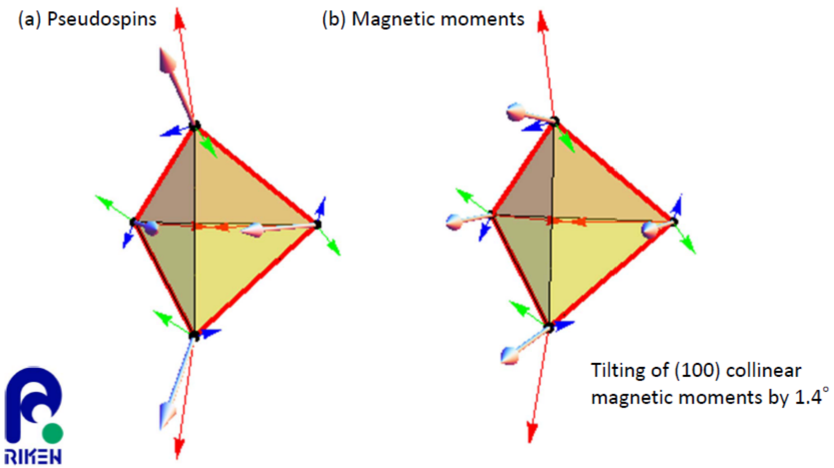
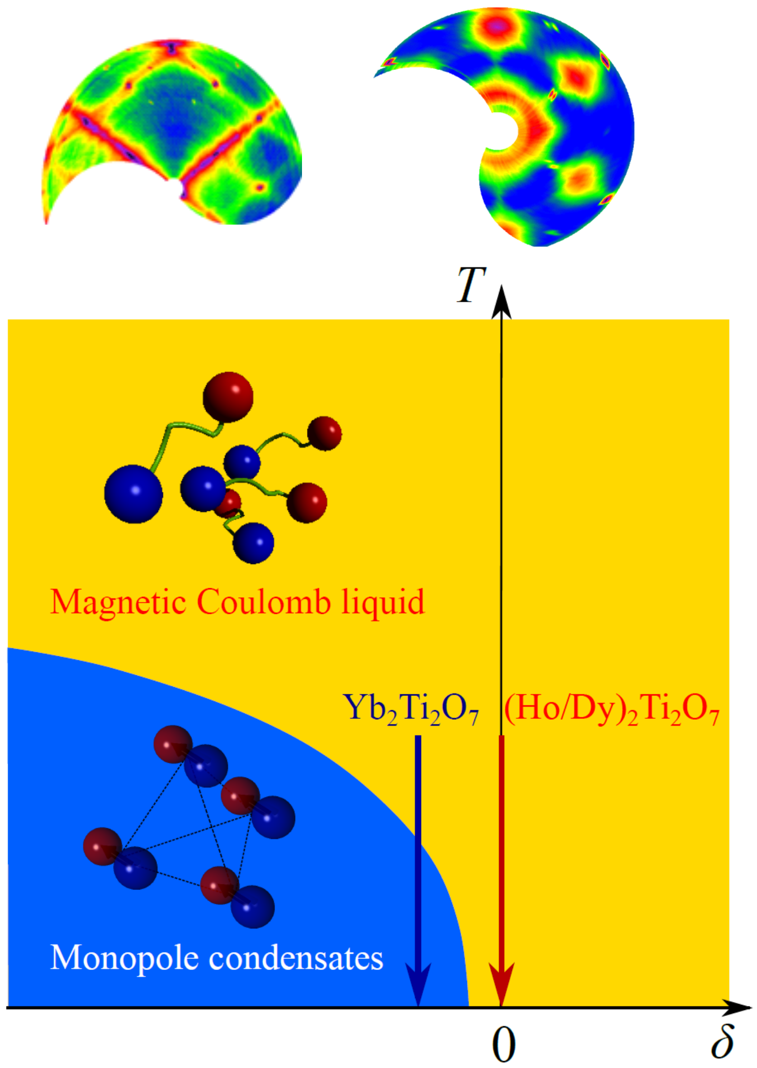
Phase diagram

Ground-state pseudospins and magnetic moments

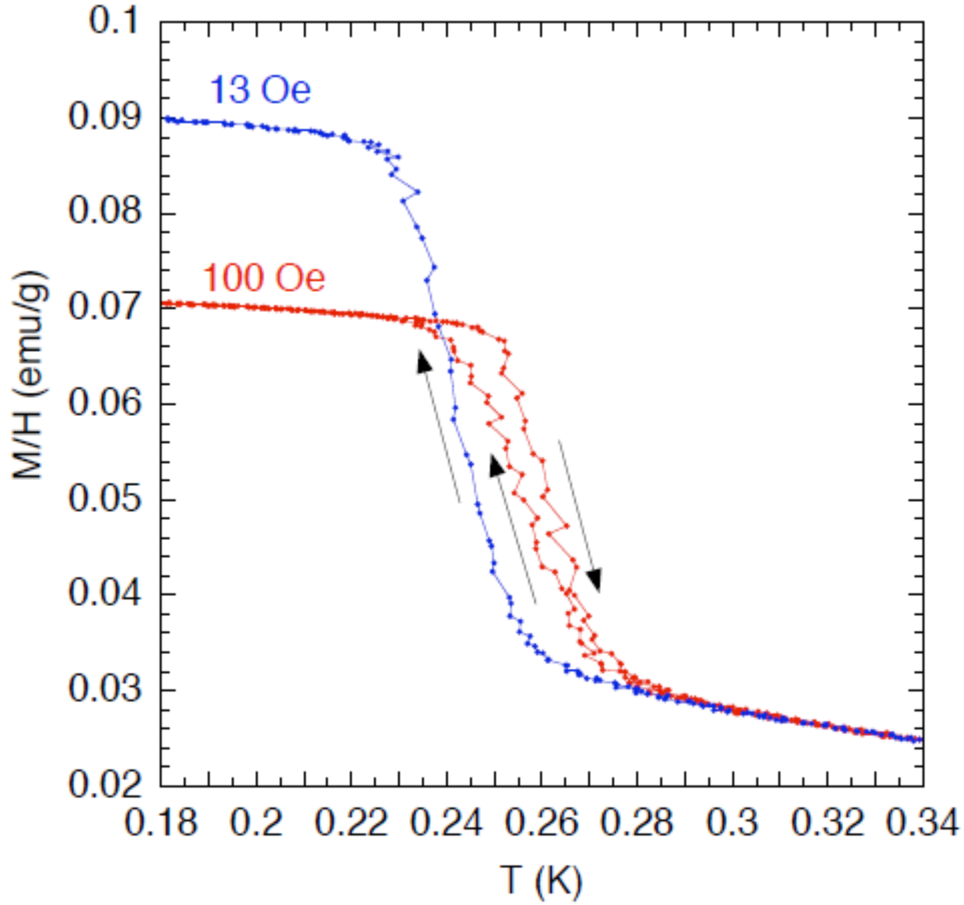


moment amplitude $1.3\mu_B$



L. J. Chang/ S. Onoda *et al.,* Nat. Commun. 3, 992 (2012)

Low Temperature Magnetization of $Yb_2Ti_2O_7$ powder



L.J. Chang *et al*., unpublished

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Summary

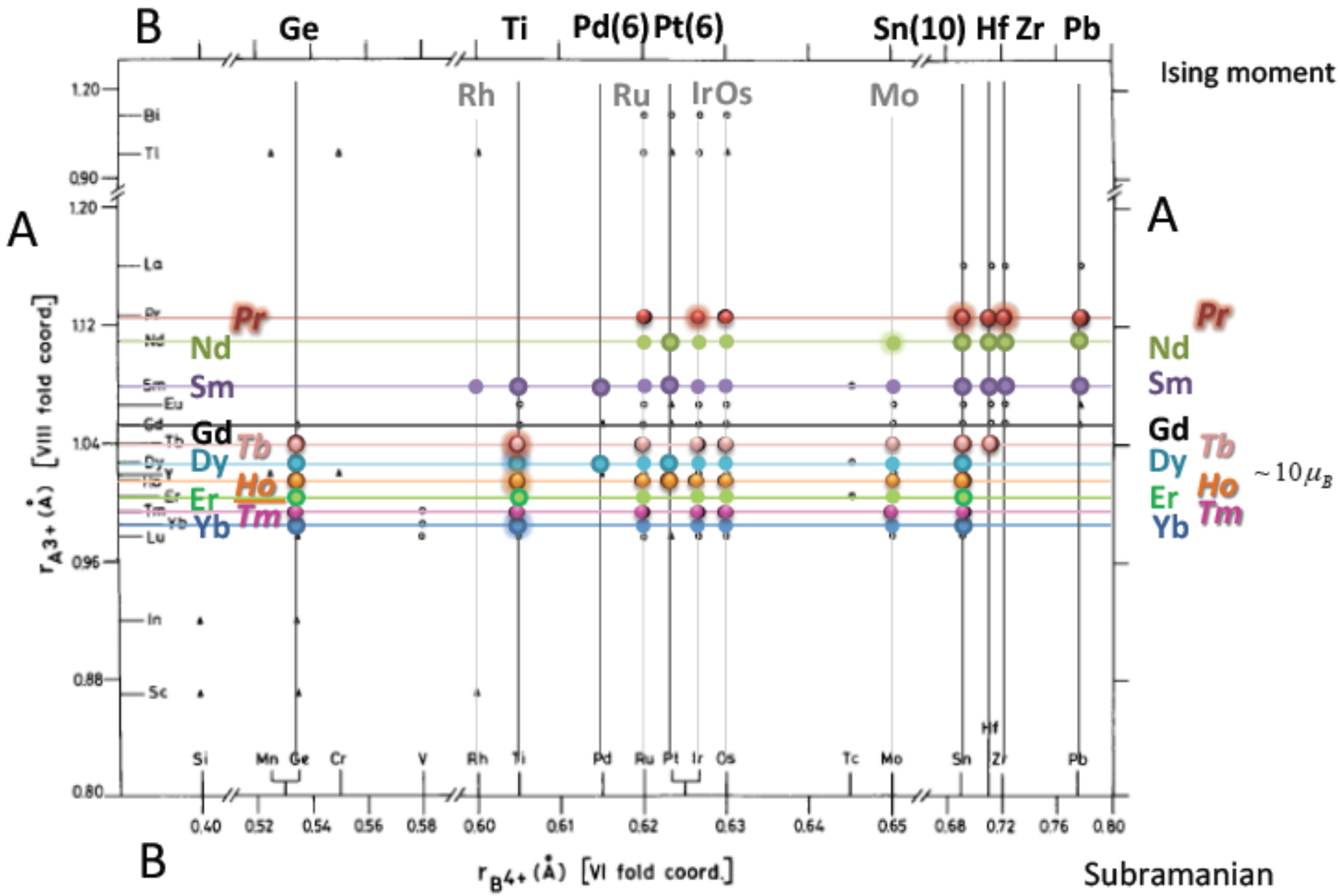
- $Yb_2Ti_2O_7$, a quantum spin ice, first CEF ~ 620 K
- Pinch points
- Ferromagnetic order at ~ 0.21 K for crystal: neutron depolarization, hysteresis.
- Quantum critical points: magnetic Coulomb phase to Higgs phase, or quantum spin liquid phase etc.???

Future plans:

- Quantum excitations: 3D spinon excitations, Higgs-boson
- Search for quantum phase transitions: by mean of pressure or substitutions
- Other pyrochlores

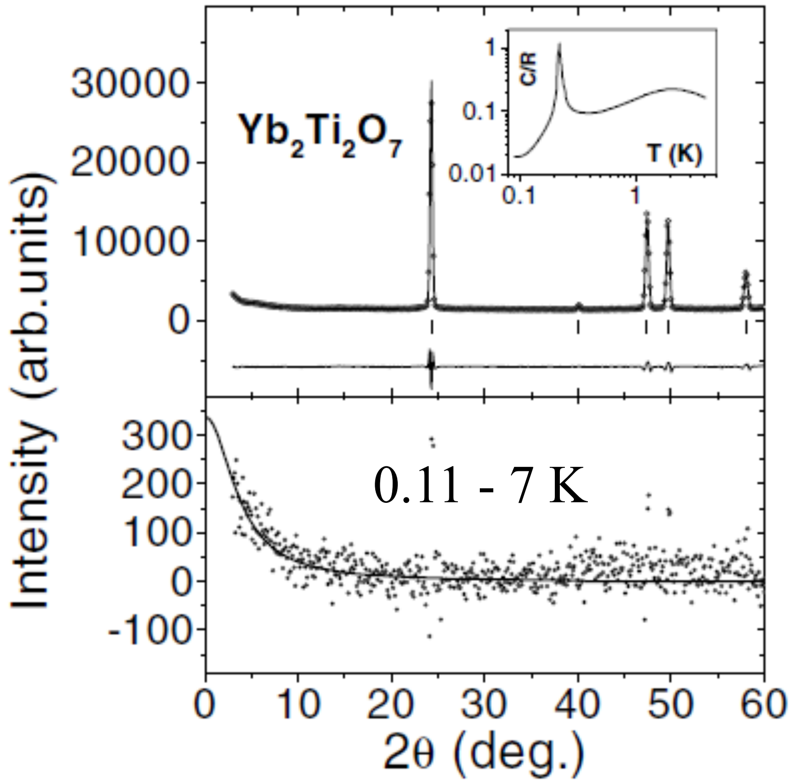
Future plans for other pyrochlores

Magnetic pyrochlore oxides $A_2B_2O_7$



Modified by: S. Onoda

Sample dependent



J. A. Hodges *et al*., PRL **88** 077204 (2002)

No magnetic peaks

CW temperature ~ 0.6 K

1st order transition ~ 210 mK

LRO?

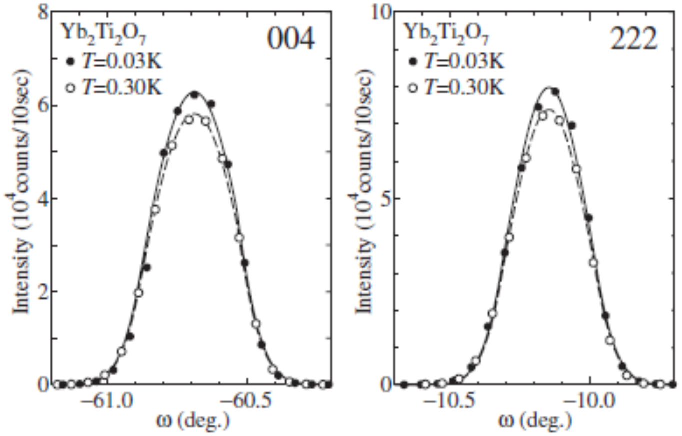


Fig. 3. Profiles of the ω-scans for 004 and 222 reflections taken at 0.03 K and 0.30 K. Solid and Broken lines are guides for the eye.

Y. Yasui *et al*., JPSJ **72** 3014 (2003)

ferromagnetic

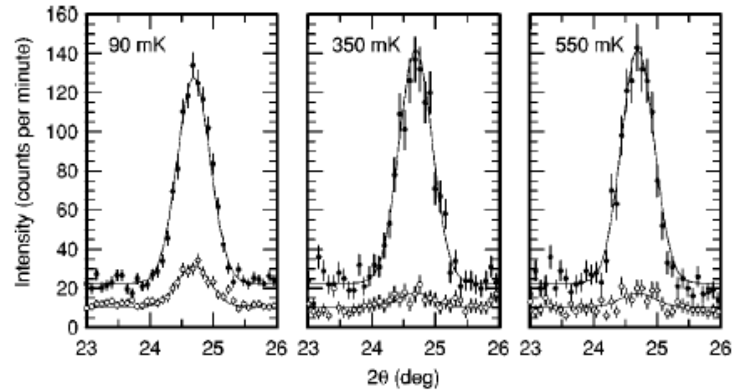
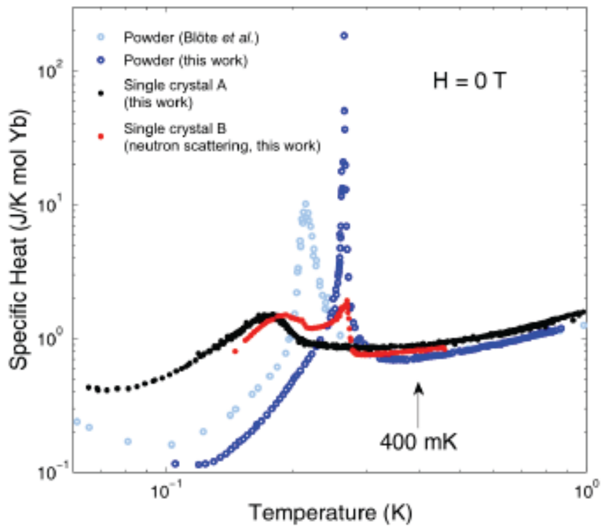


FIG. 3. Spin-flip (open circles) and non-spin-flip (closed circles) scattering at the (111) Bragg position. Above 240 mK there is only a small amount feed through due to incomplete polarization. At 90 mK, a peak is clearly seen in the spin-flip data.

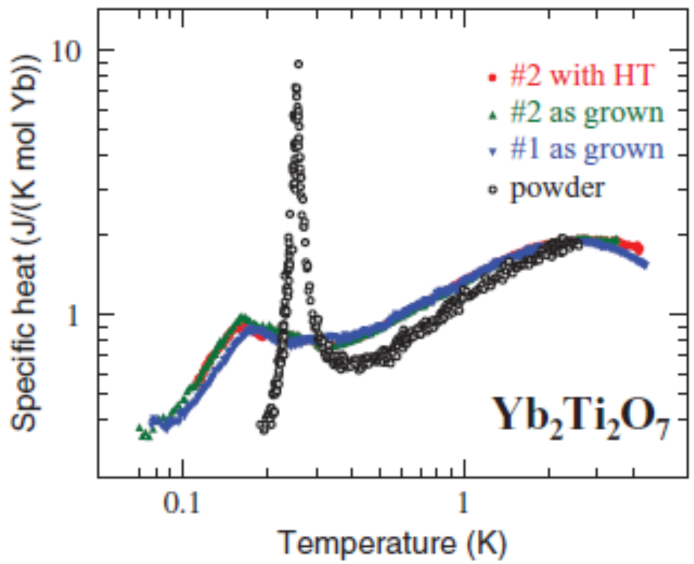
J. S. Gardner *et al*., PRB 70 180404(R) (2004)

No neutron depolarization

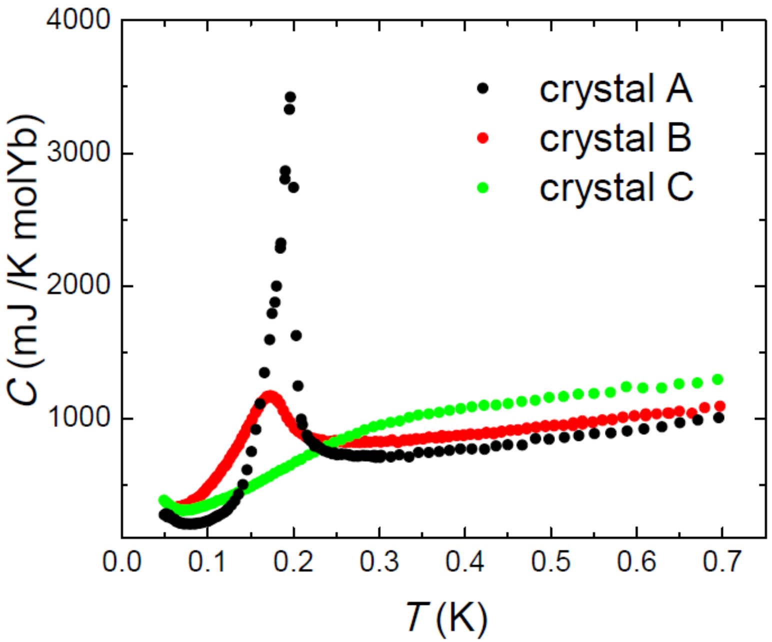
Sample dependent



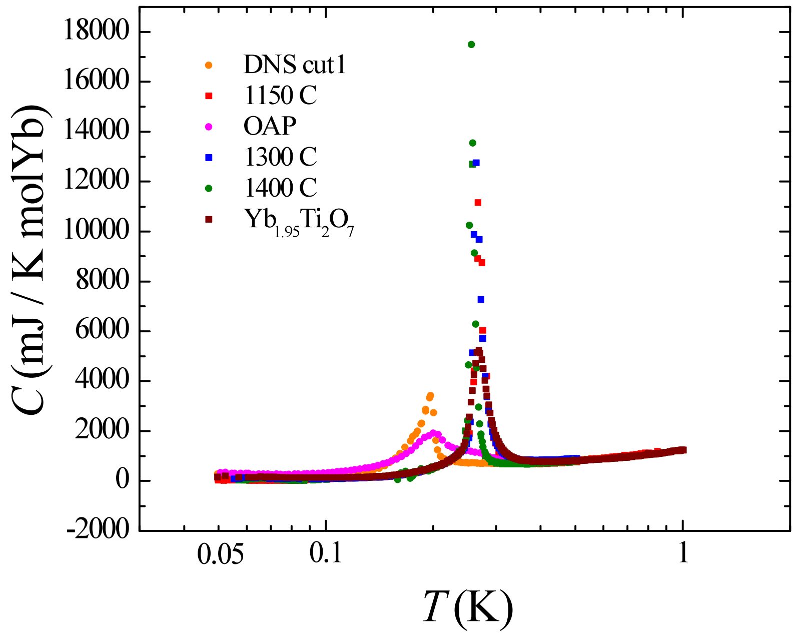
K. A. Ross *et al.*, PRB **84**, 174442 (2011)



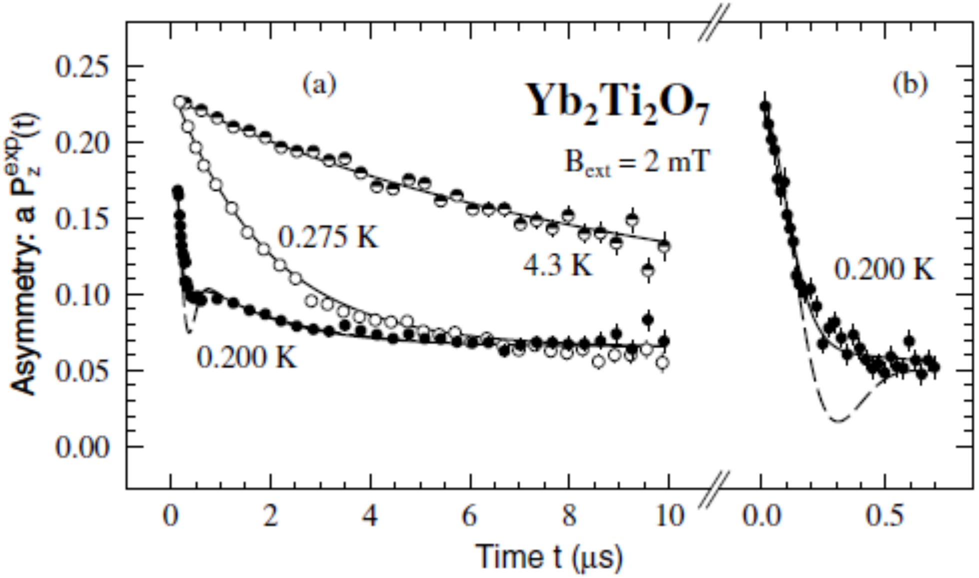
A.Yaouanc *et al.*, PRB **84**, 172408 (2011)

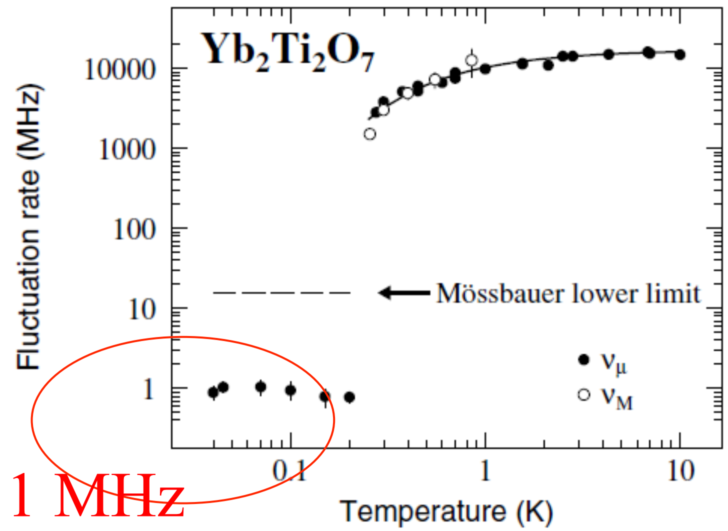


L. J. Chang/ S. Onoda *et al.*, Nat. Commun. 3, 992 (2012)

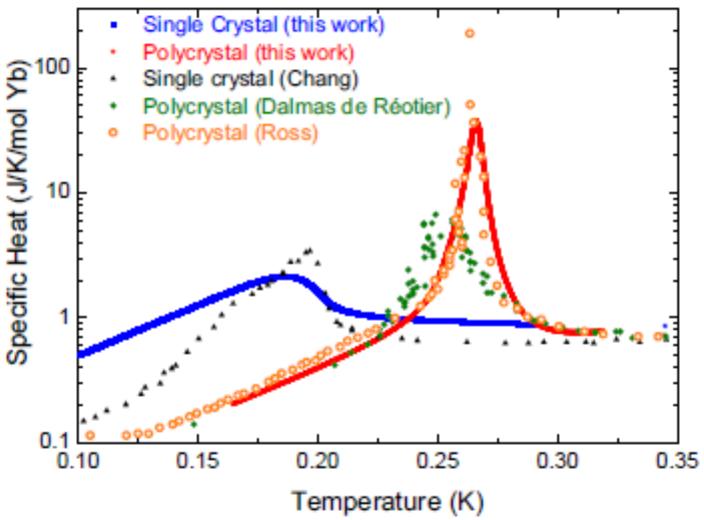


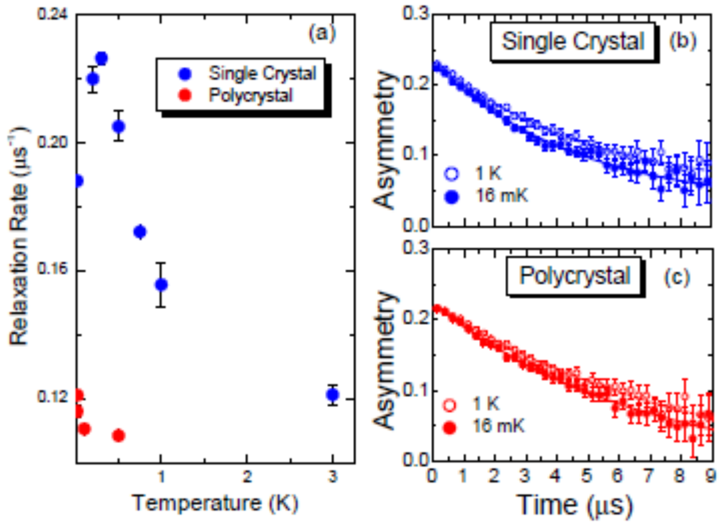
M. R. Lees/ L.J. Chang *et al.*, unpublished





J. A. Hodges *et al.,* PRL **88**, 077204 (2002)





D. M. D'Ortenzio *et al.*, arXiv:1303.3850

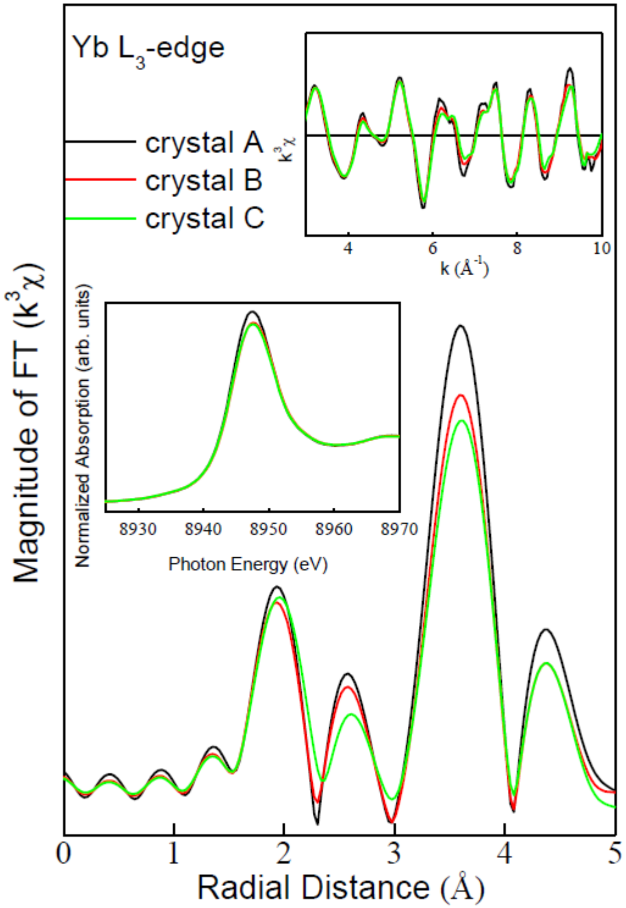
Comments on the NMR results

We had carried out MuSR experiments on powder sample, long-ranged order crystal, and a crystal without HC peak.

- Emergence of static (<1 MHz) internal magnetic moments observed for powder and long-ranged order crystal.

- Temperature vs relaxation rate of the crystal without HC peak is close to that reported in the D. M. D'Ortenzio paper. → magnetic interaction is weaker in this sample (small fraction of the crystal contributed to magnetic order)

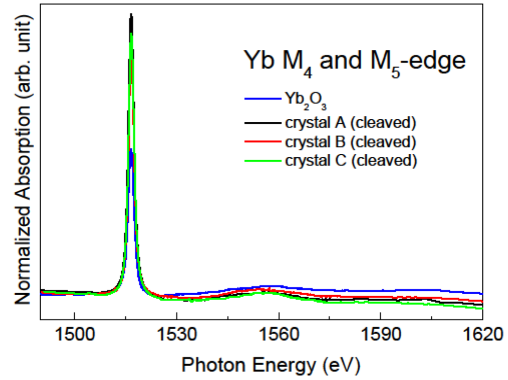
EXAFS

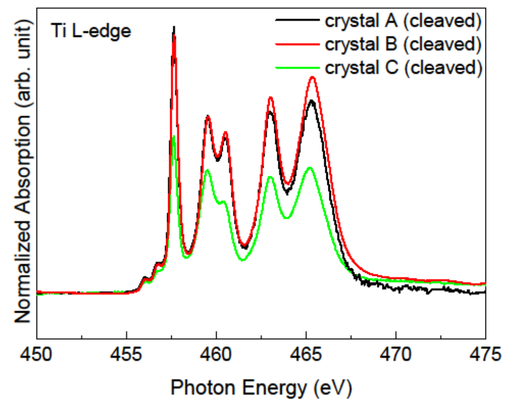


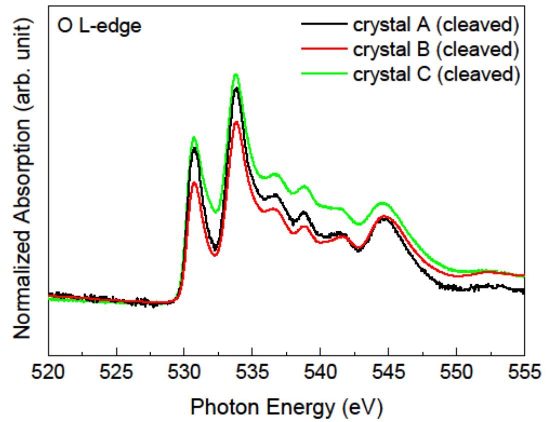
L. J. Chang/ S. Onoda *et al.,* Nat. Commun 3, 992 (2012).

K.A. Ross *et al.,* proposed "stuffed" $Yb_2(Ti_{2-x}Yb_x)O_{7-x/2}$ with x = 0.046
PRB 86, 174424 (2012)

Sample dependent







No charge state variations