Title: Universal Dynamic Magnetism in the Ytterbium Pyrochlores

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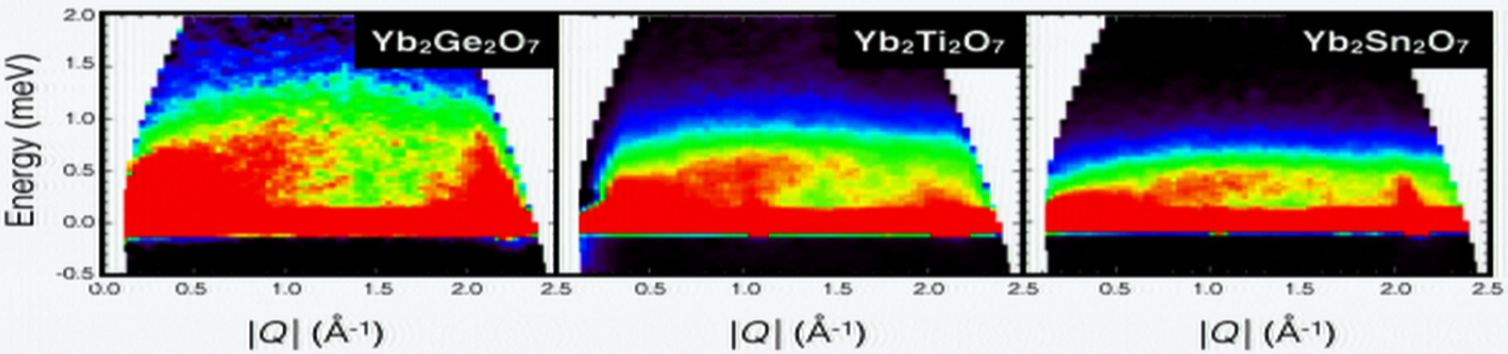
URL: http://pirsa.org/16050041

Abstract: The ytterbium pyrochlores, Yb2B2O7, are a family of materials with a remarkable diversity in their low-temperature physics. At the heart of their interesting physics is the proximity of their ground states to numerous competing phases. These proximate phases make the Yb pyrochlores very sensitive to perturbations such as pressure and off-stoichiometry. I will present a study of the effects of chemical pressure on the ytterbium pyrochlores, in which substitution of a non-magnetic constituent alters the lattice size and consequently inflicts an internal pressure on the system. We find that although each of Yb2B2O7 (B = Ge, Ti, Sn) exhibits a distinct dipole ordered state, there is a ubiquitous nature to their spin excitations. Furthermore, these spin excitations are highly unconventional in their own right and may hint at a hidden order parameter.

Universal Dynamic Magnetism in the Ytterbium Pyrochlores



Alannah Hallas,[1] Jonathan Gaudet,[1] Nick Butch,[2] Makoto Tachibana,[3] Rafael Freitas,[4] Graeme Luke,[1] Chris Wiebe,[5] and Bruce Gaulin[1]

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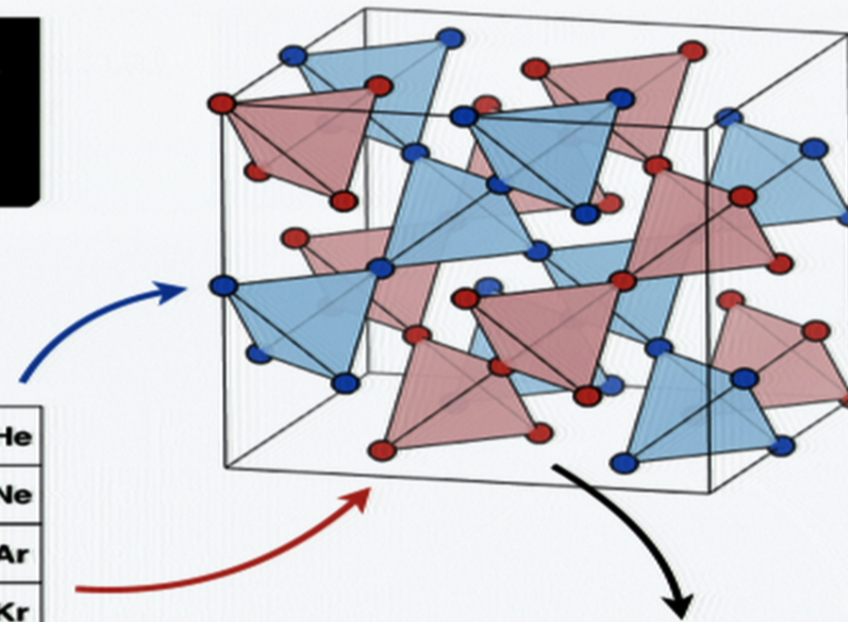
5 The University of Winnipeg

Pyrochlores have the quintessential lattice for the phenomena of magnetic frustration in 3D.

$(A^{3+})_2(B^{4+})_2O_7$

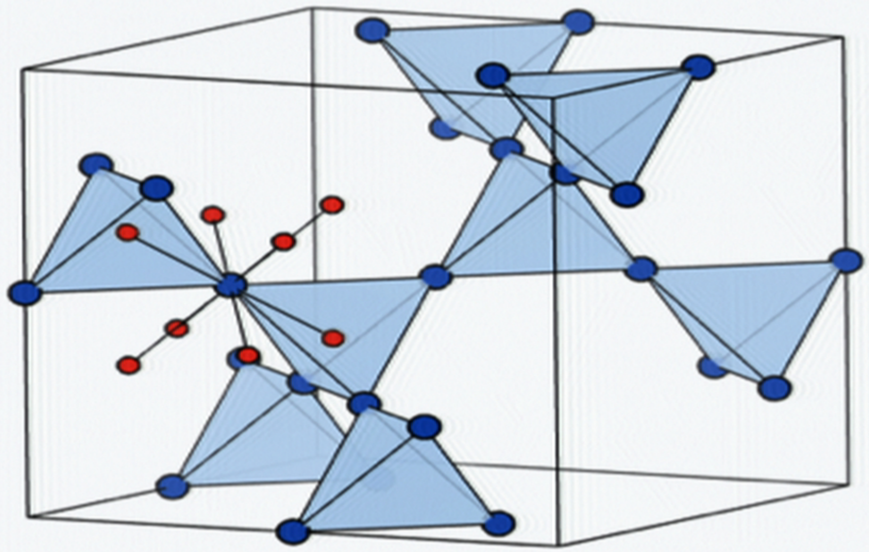
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
				Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
				Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



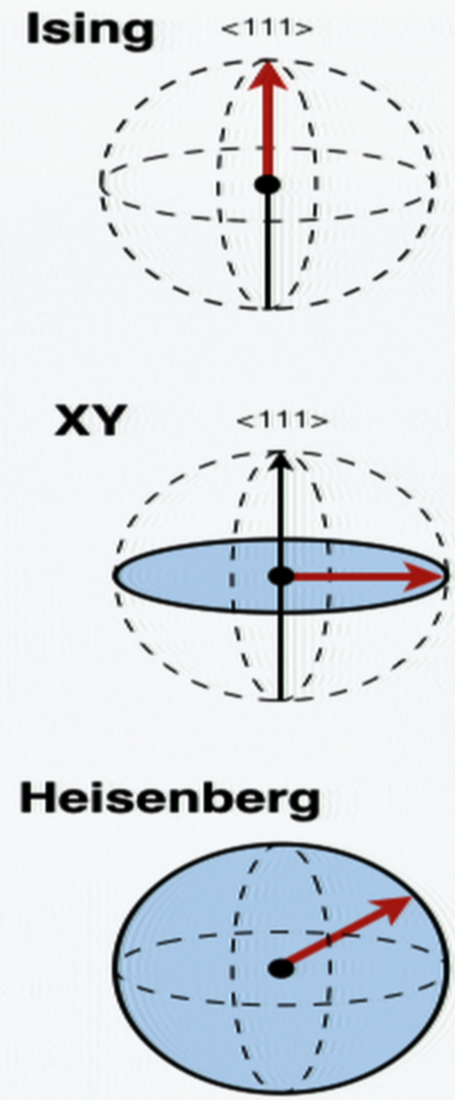
...
....
disorder-free spin glass
spin ice
metal-insulator transition
partial order
spin liquid
order-by-disorder

Gardner, Gingras, and Greedan, Rev. Mod. Phys **82**, 53 (2010)

The pyrochlore lattice can effectively realize different spin anisotropies.

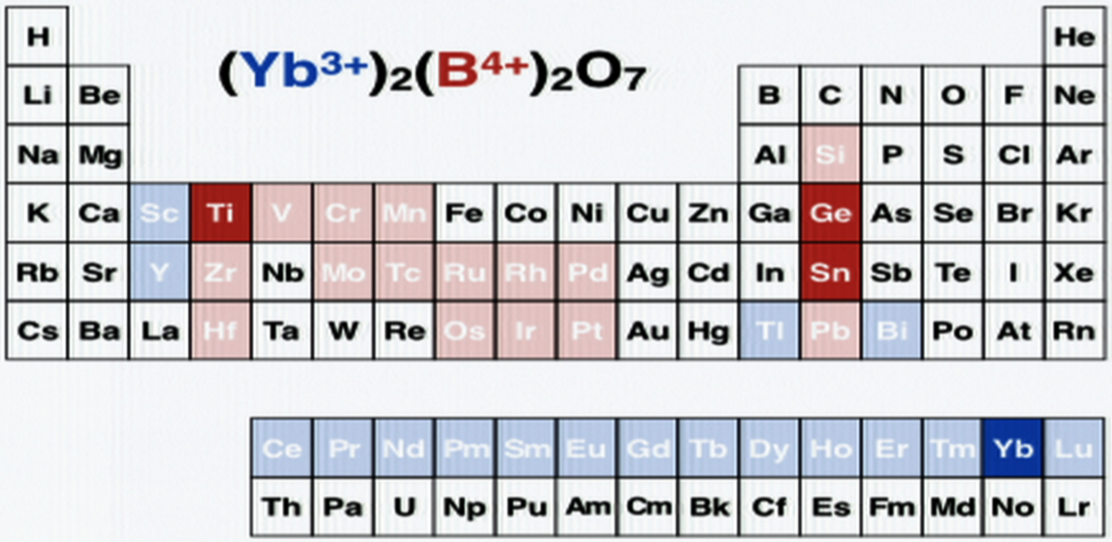


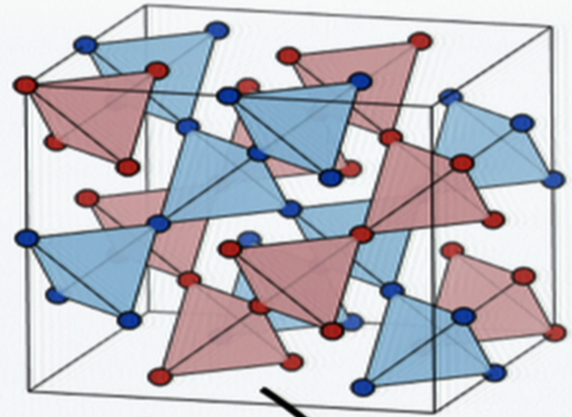
Anisotropy	Interactions		
Ising	FM	$Dy_2Ti_2O_7$	Spin Ice
XY	AFM	$Er_2Ti_2O_7$	Order-by-Disorder
Heisenberg	AFM	$Gd_2Ti_2O_7$	Partial Order

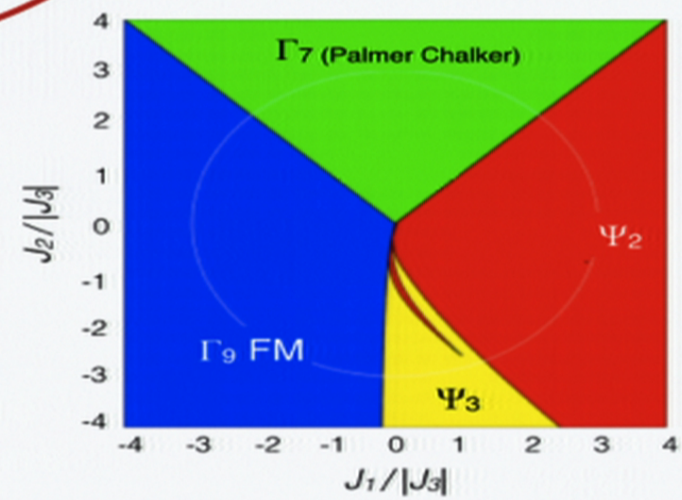


The ytterbium pyrochlores live on a rich phase diagram.

$(Yb^{3+})_2(B^{4+})_2O_7$



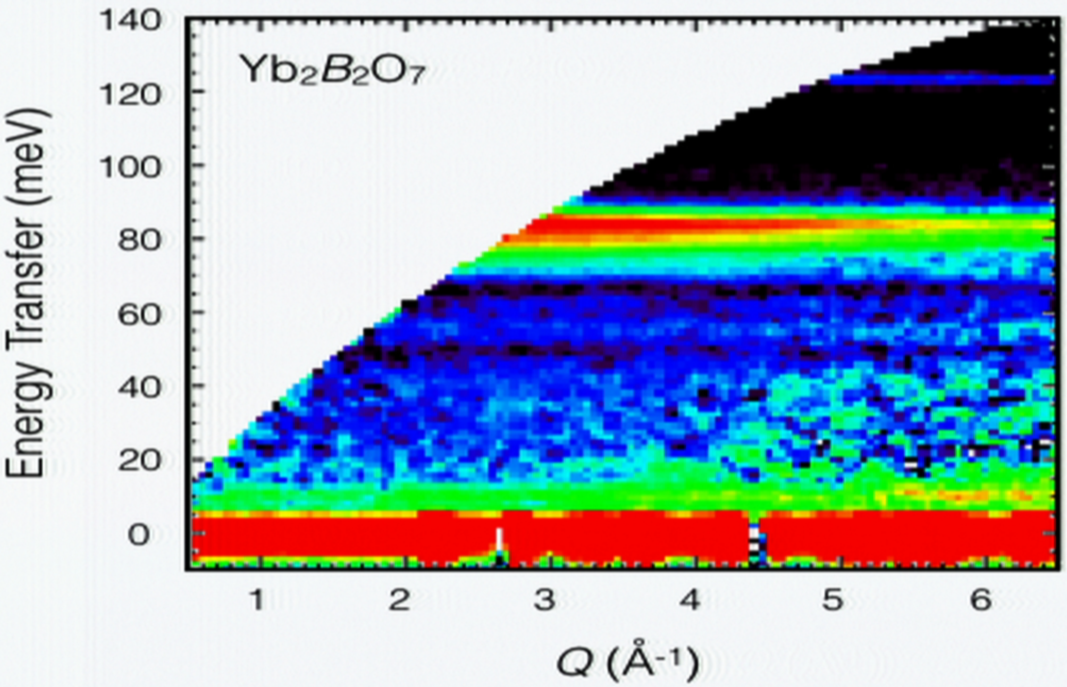




Magnetism = Single Ion Anisotropy + Exchange Interactions

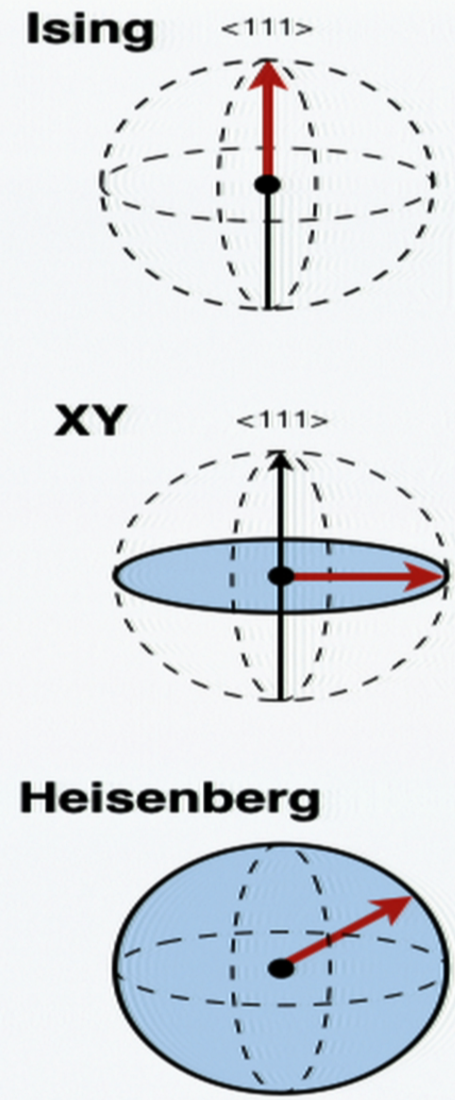
Yan *et al.*, arXiv:1603.09466 (2016)

Inelastic neutron scattering can determine the single ion anisotropy.



Yb^{3+} $J = 7/2$

4 doublets!



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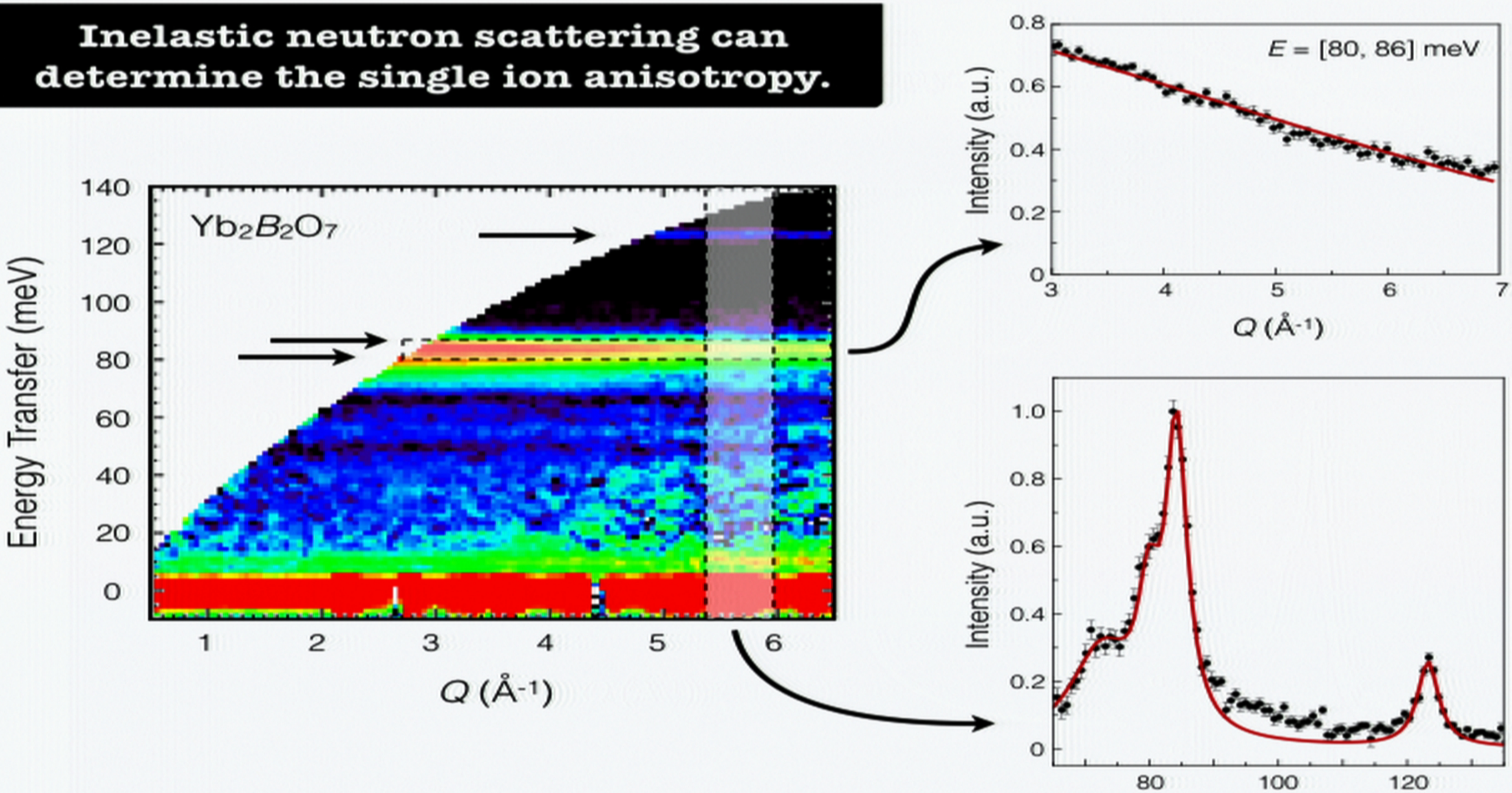
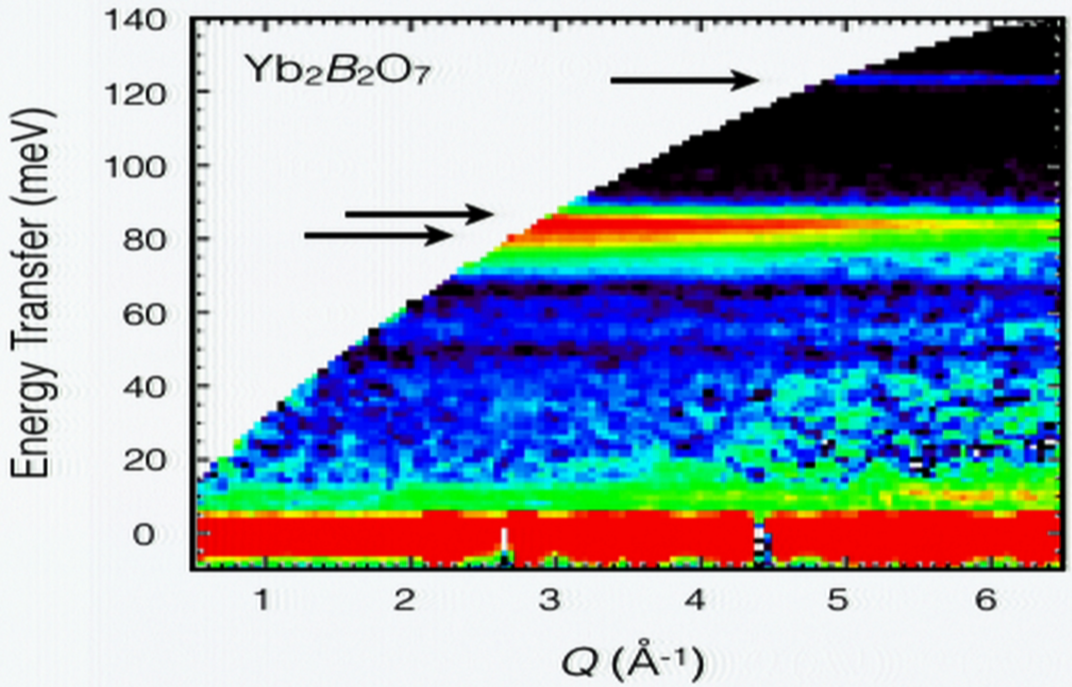
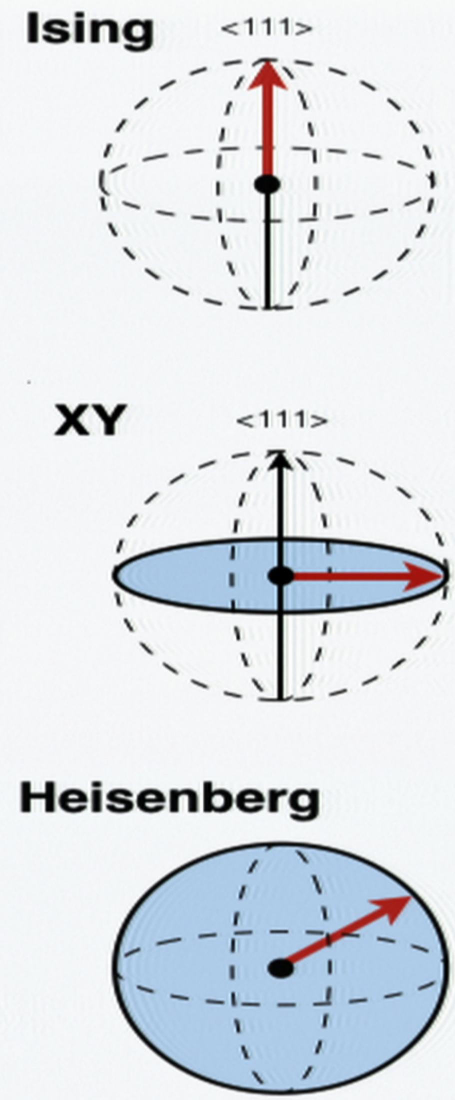


Gaudet *et al.*, Phys. Rev. B **92**, 134420 (2015)
Hallas *et al.*, Phys. Rev. B **93**, 104405 (2016)

The ytterbium pyrochlores have XY field anisotropy and effective S = ½.





$$g_z = 2.1(1)$$

$$g_\perp = 3.5(2)$$

$$|\phi^{\mp}\rangle = 0.91|\mp\tfrac{1}{2}\rangle \pm 0.40|\mp\tfrac{7}{2}\rangle \pm 0.13|\pm\tfrac{5}{2}\rangle$$

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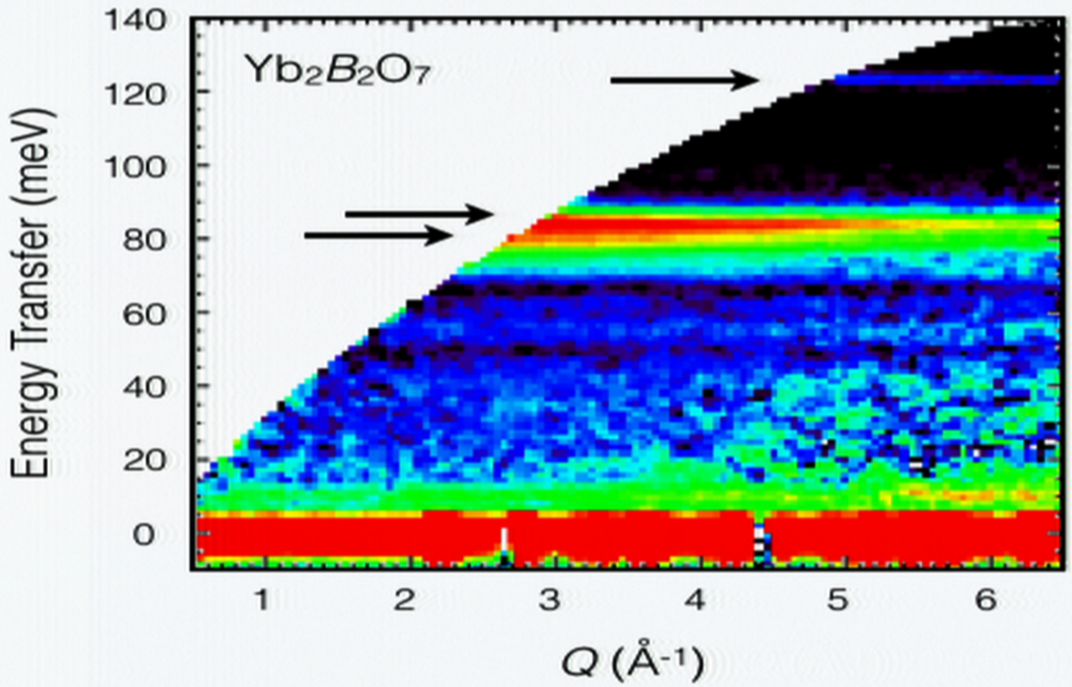

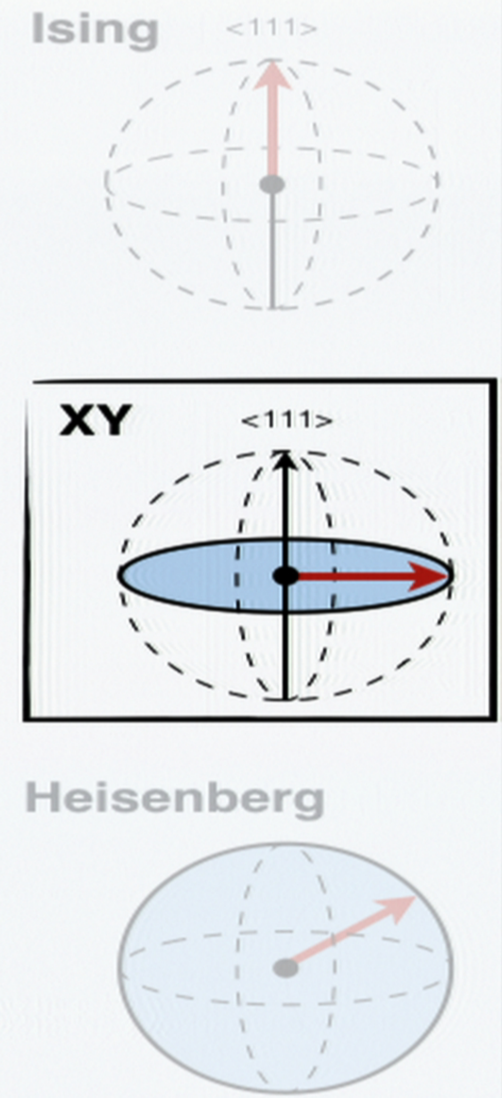

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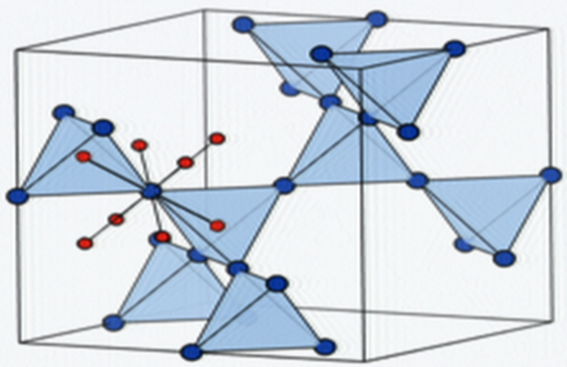
$g_\perp = 3.5(2)$

$$|\phi^{\mp}\rangle = \boxed{0.91|\mp\tfrac{1}{2}\rangle} \pm 0.40|\mp\tfrac{7}{2}\rangle \pm 0.13|\pm\tfrac{5}{2}\rangle$$

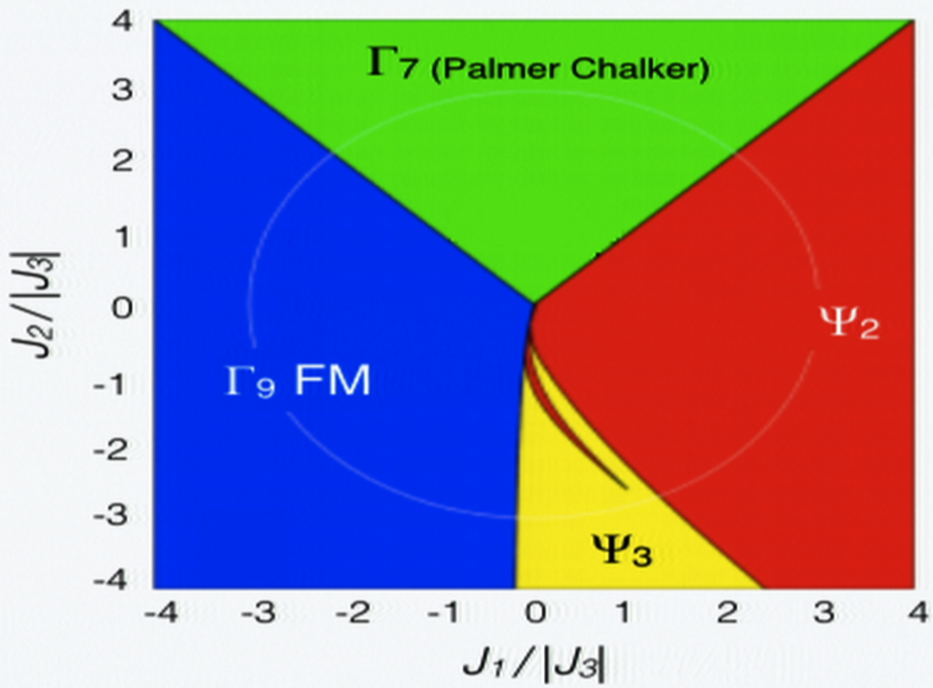
The anisotropic exchange Hamiltonian predicts a rich phase diagram for the XY pyrochlores

$$\mathcal{H} = \sum_{<ij>} \vec{S}_i \vec{J}_{ij} \vec{S}_j$$



J_1 = XY
J_2 = Ising
J_3 = Symmetric off-diagonal
J_4 = Dzyaloshinskii-Moriya

$J_3 < 0 \qquad J_4 = 0$



Wong *et al.*, Phys. Rev. B **88**, 144402 (2013)
Yan *et al.*, arXiv:1603.09466 (2016)

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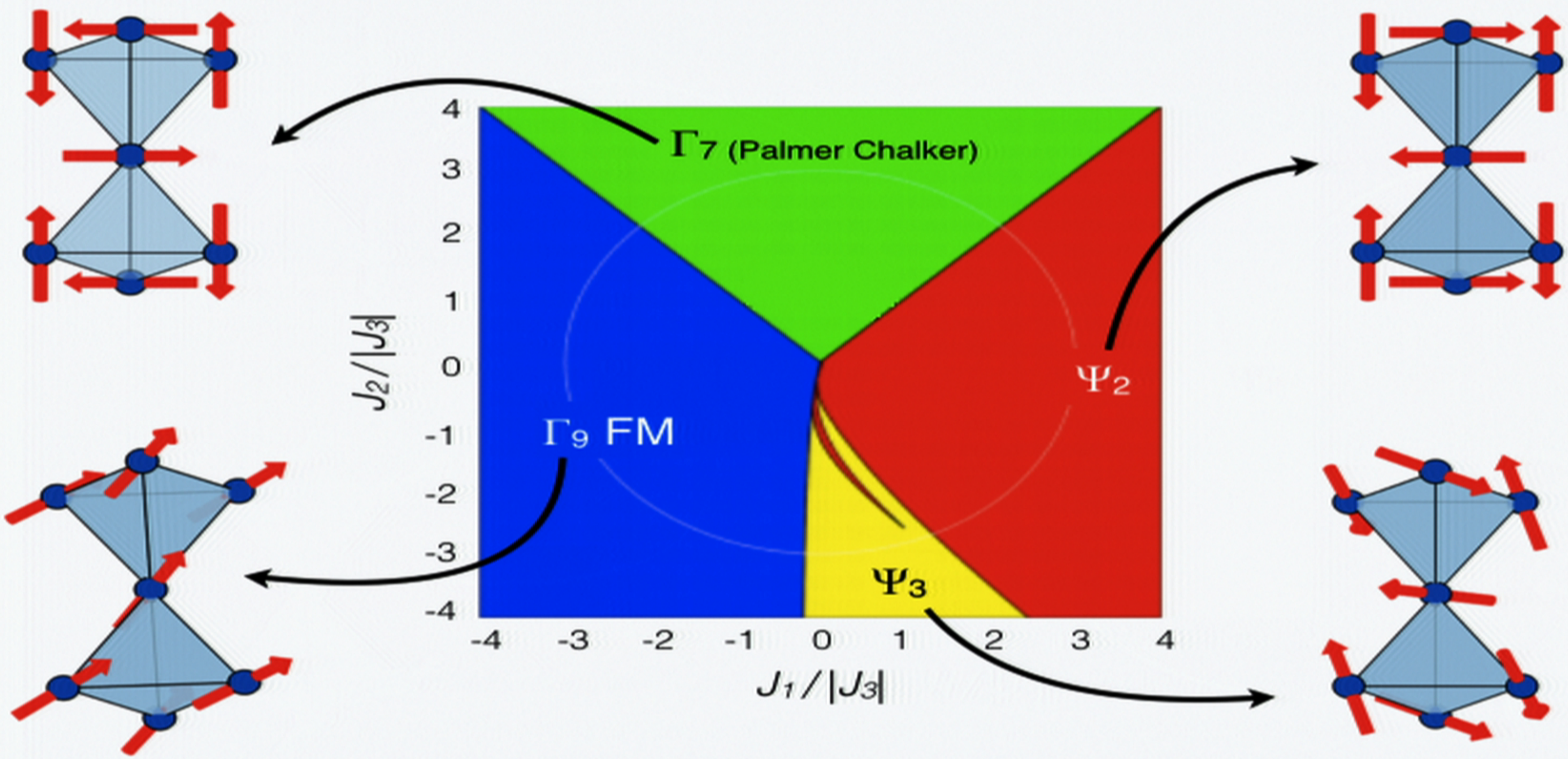
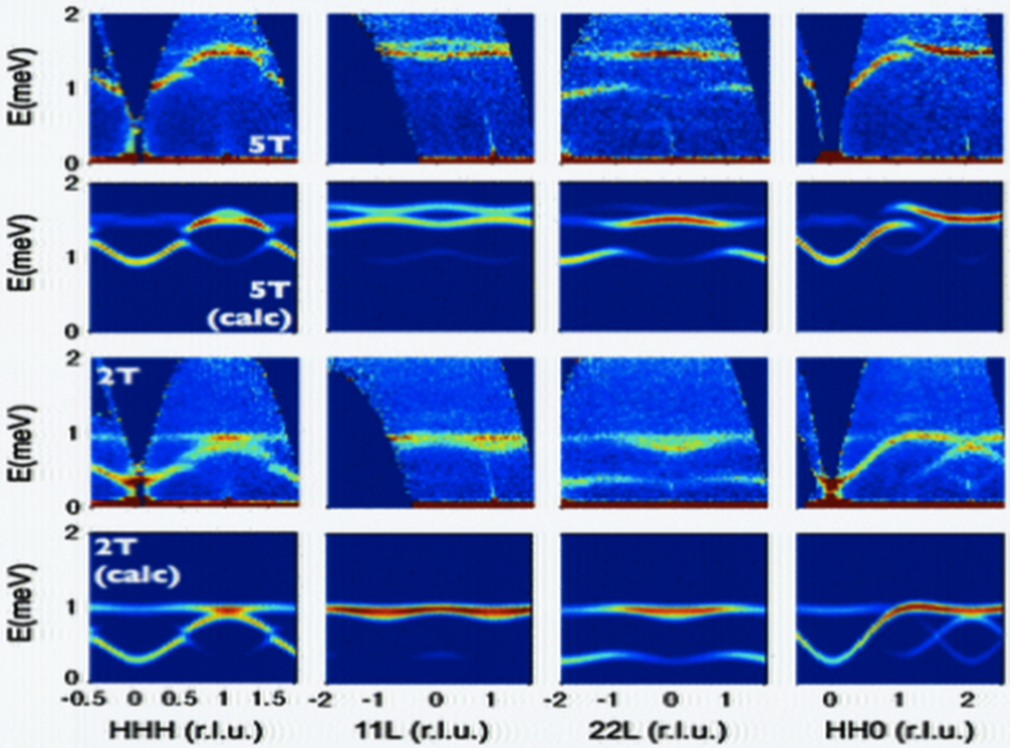
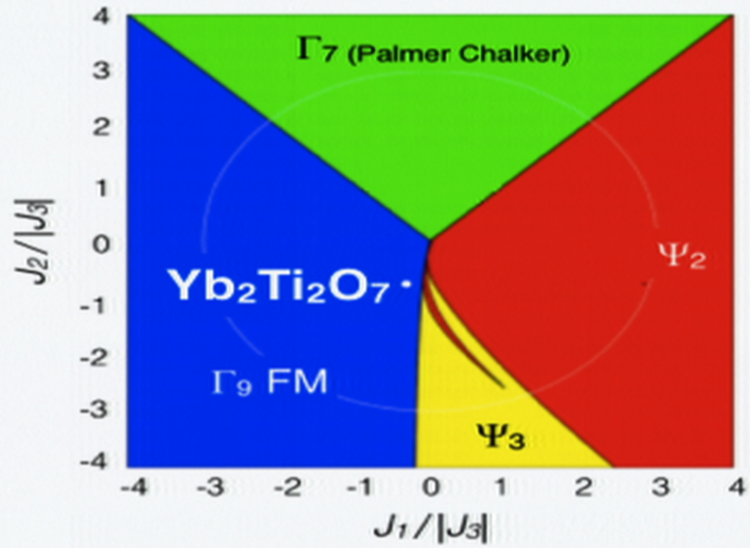


Yan *et al.*, arXiv:1603.09466 (2016)

Fits to the high field spin waves of $Yb_2Ti_2O_7$ place it in the Γ_9 ferromagnet region of the phase diagram.

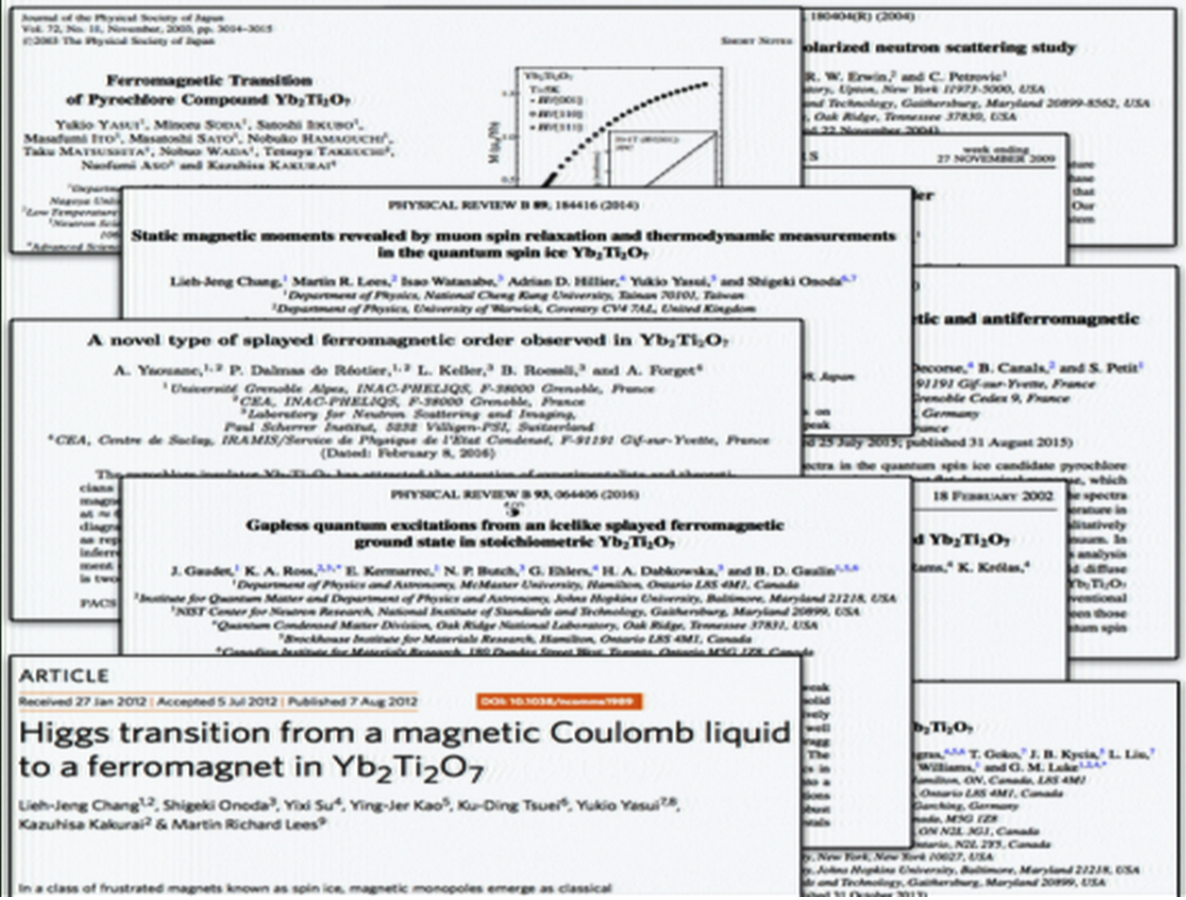




$$\mathcal{H} = \sum_{<ij>} \vec{S}_i \vec{J}_{ij} \vec{S}_j$$

Ross *et al.*, Phys. Rev. X **1**, 021002 (2011).

Sample dependence can be linked with phase competition.



Journal of the Physical Society of Japan

Ferromagnetic Transition of Pyrochlore Compound $Yb_2Ti_2O_7$

PHYSICAL REVIEW B 89, 184416 (2014)

Static magnetic moments revealed by muon spin relaxation and thermodynamic measurements in the quantum spin ice $Yb_2Ti_2O_7$

Lieh-Jeng Chang, Martin R. Lees, Isao Watanabe, Adrian D. Hillier, Yukio Yasui, and Shigeki Onoda

A novel type of splayed ferromagnetic order observed in $Yb_2Ti_2O_7$

A. Yaouanc, P. Dalmas de Réotier, L. Keller, B. Roessli, and A. Forget

PHYSICAL REVIEW B 93, 064406 (2016)

Gapless quantum excitations from an icelike splayed ferromagnetic ground state in stoichiometric $Yb_2Ti_2O_7$

J. Gaudet, K. A. Ross, E. Kermarrec, N. P. Butch, G. Ehlers, H. A. Dabkowska, and B. D. Gaulin

ARTICLE

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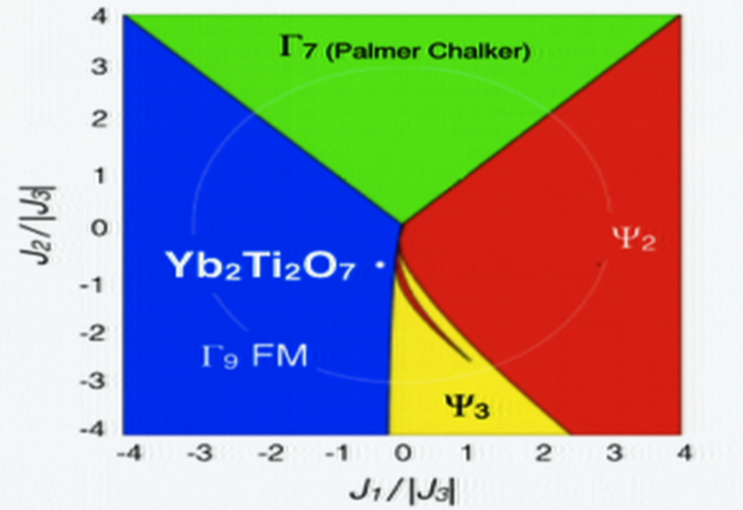
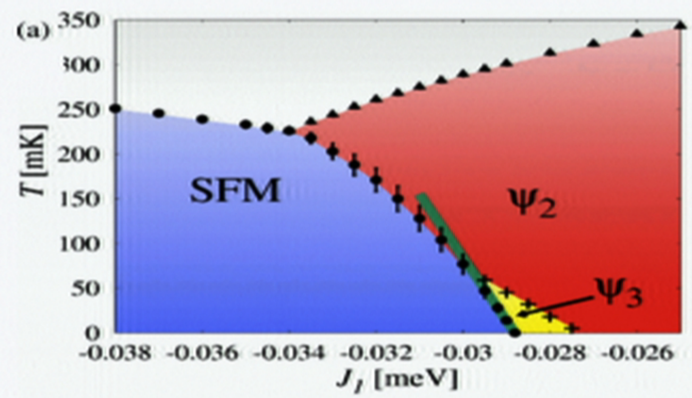
Higgs transition from a magnetic Coulomb liquid to a ferromagnet in $Yb_2Ti_2O_7$

Lieh-Jeng Chang, Shigeki Onoda, Yixi Su, Ying-Jer Kao, Ku-Ding Tsuei, Yukio Yasui, Kazuhisa Kakurai & Martin Richard Lees

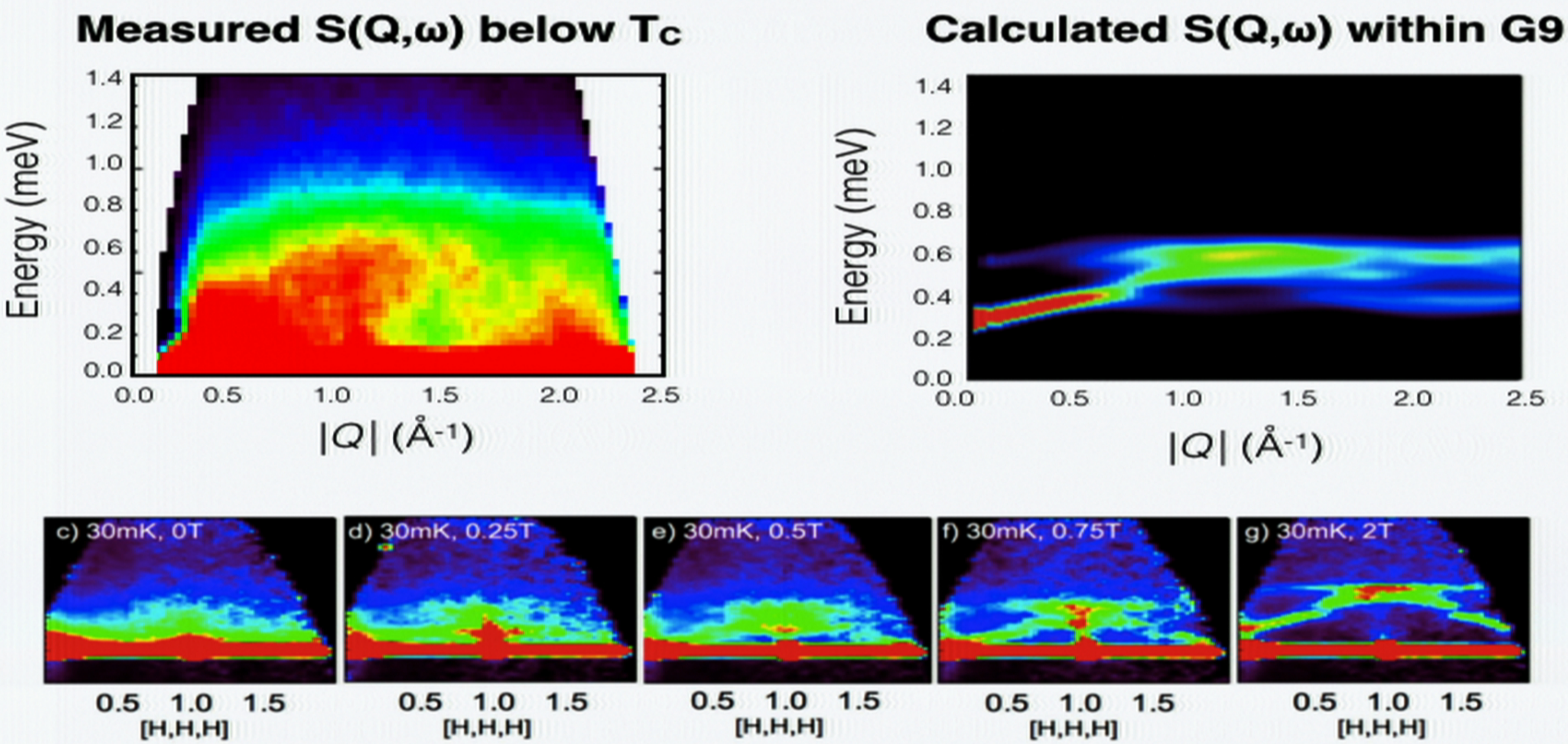
In a class of frustrated magnets known as spin ice, magnetic monopoles emerge as classical



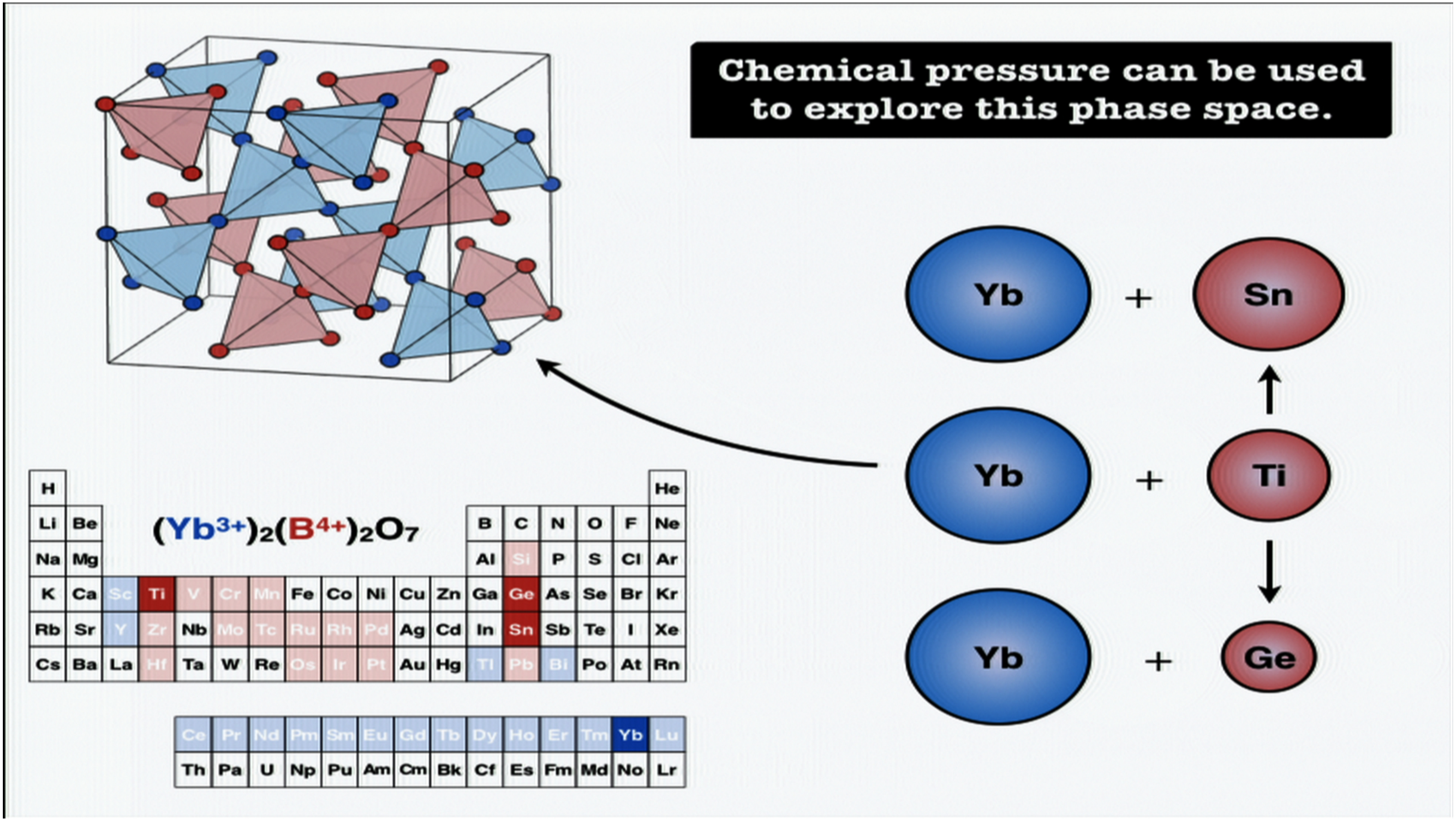


Jaubert *et al.*, Phys. Rev. Lett. **115**, 267208 (2015).

$Yb_2Ti_2O_7$ has no conventional spin waves in zero field.

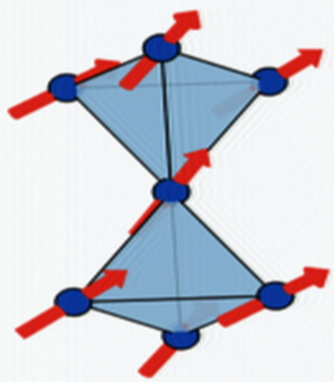


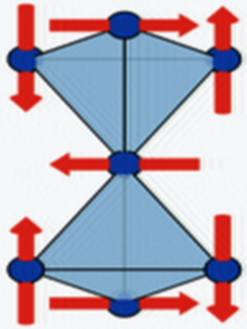
Ross *et al.*, Phys. Rev. Lett. **103**, 227202 (2009).
Gaudet *et al.*, Phys. Rev. B **93**, 064406 (2016).


Chemical pressure can be used to explore this phase space.
$(Yb^{3+})_2(B^{4+})_2O_7$
Yb + Sn
Yb + Ti
Yb + Ge
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

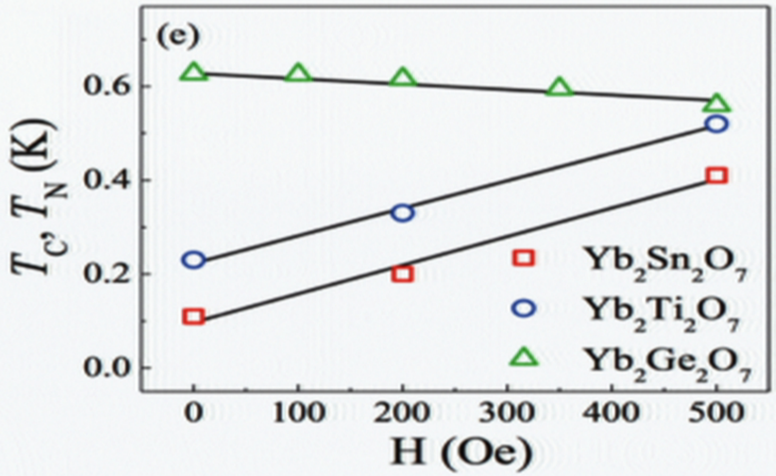
Changing the B-site cation in $Yb_2B_2O_7$ changes the ground state.

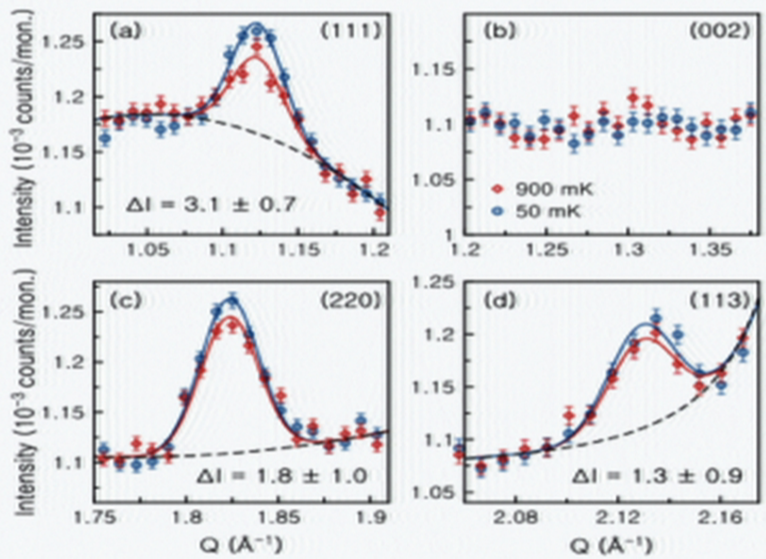
$Yb_2\mathbf{Ti}_2O_7$
$Yb_2\mathbf{Sn}_2O_7$
Γ_9 Ferromagnet





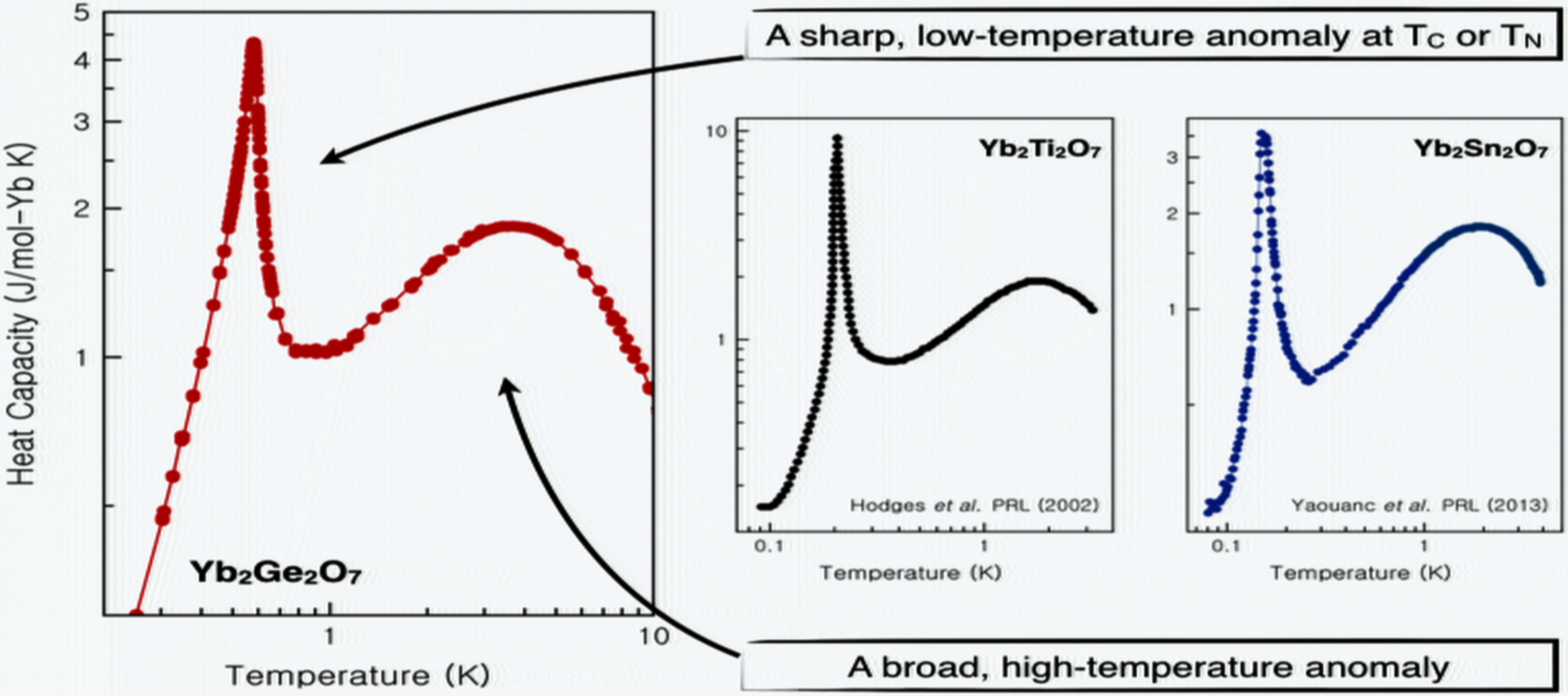
$Yb_2\mathbf{Ge}_2O_7$
Antiferromagnetic
Γ_5 (ψ_2 or ψ_3)



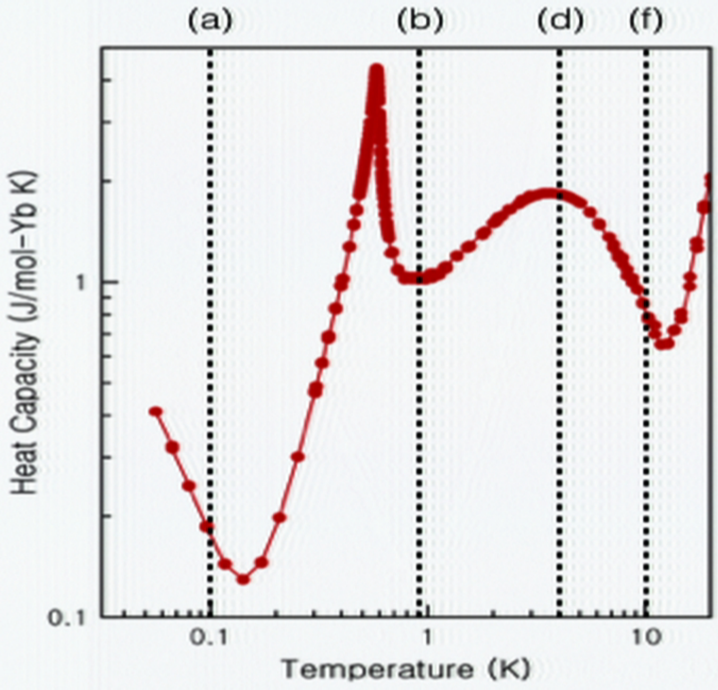


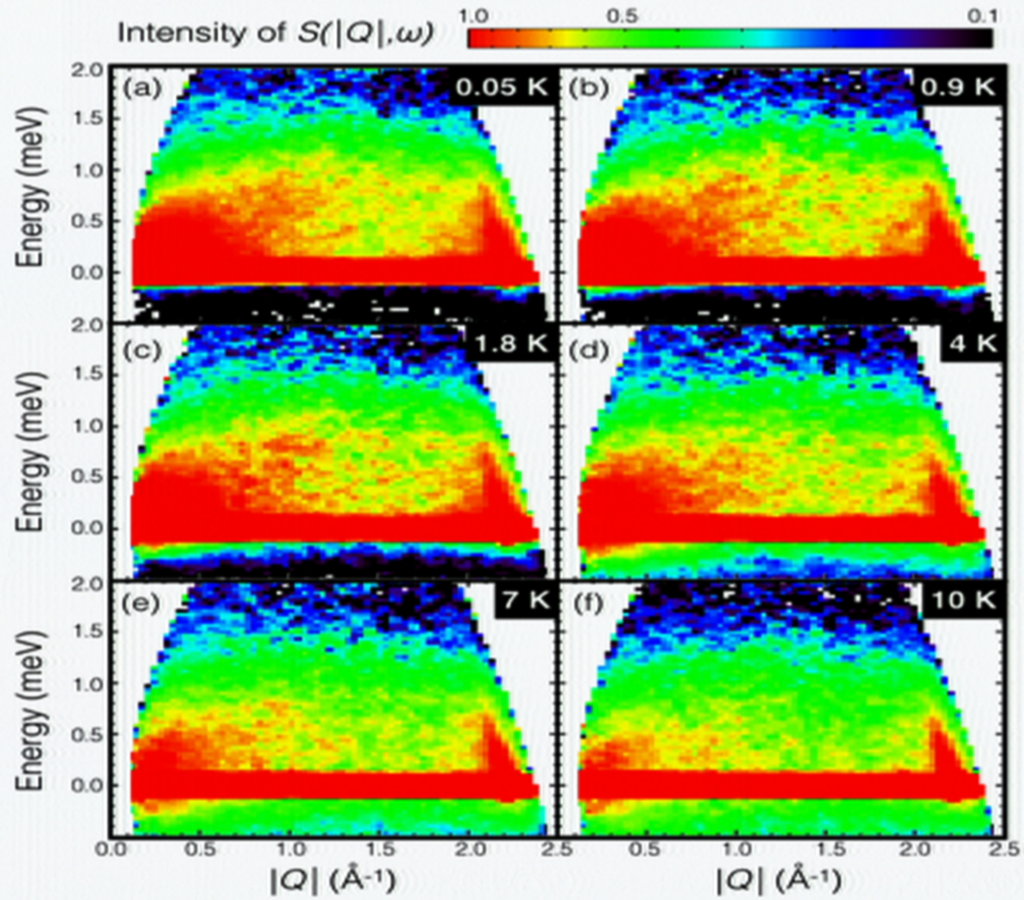
Dun *et al.*, Phys. Rev. B **89**, 064401 (2014).
Dun *et al.*, Phys. Rev. B **92**, 140407(R) (2015).
Hallas *et al.*, Phys. Rev. B **93**, 104405 (2016).

The heat capacity of the Yb pyrochlores follow a common form.

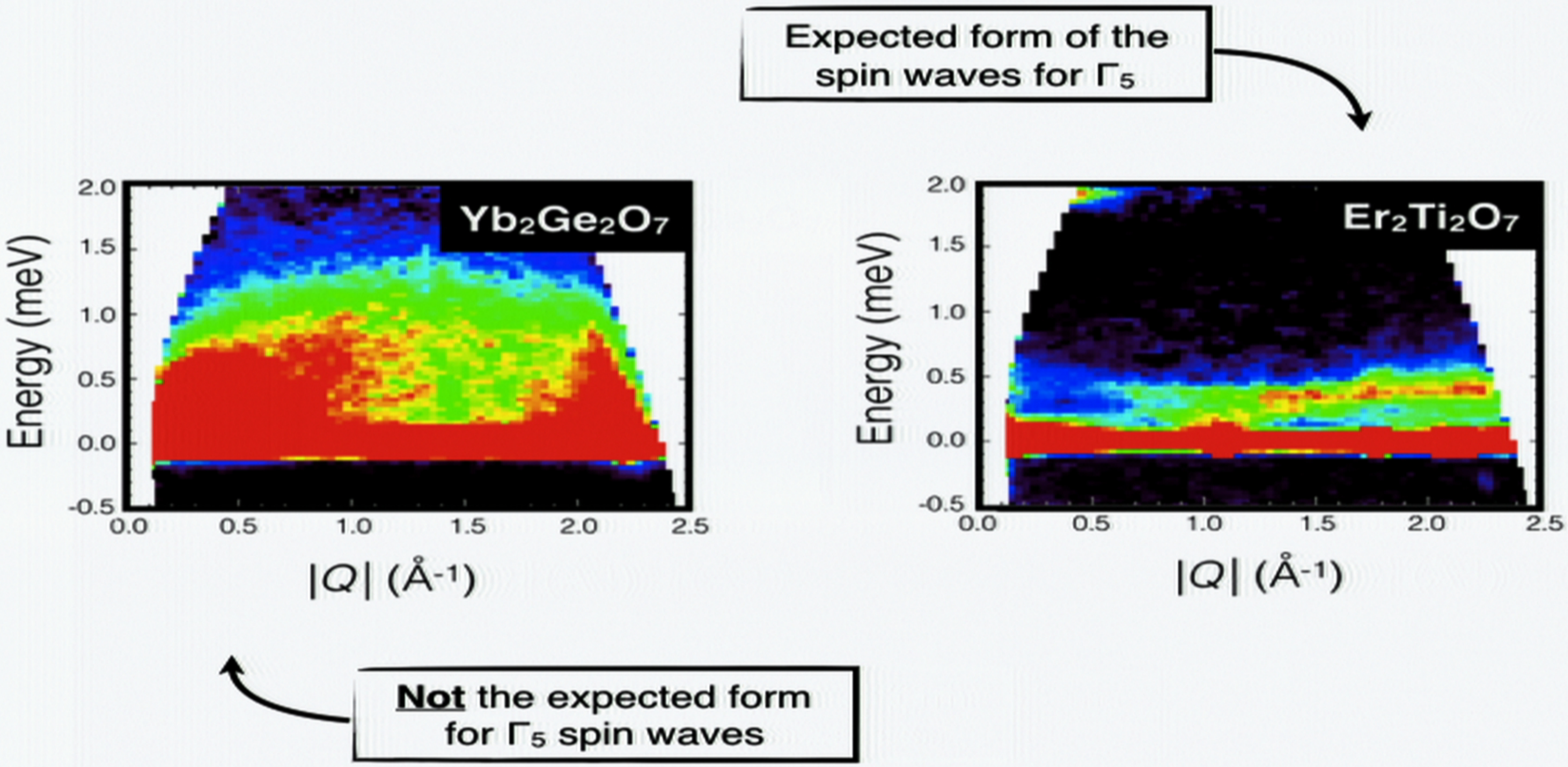


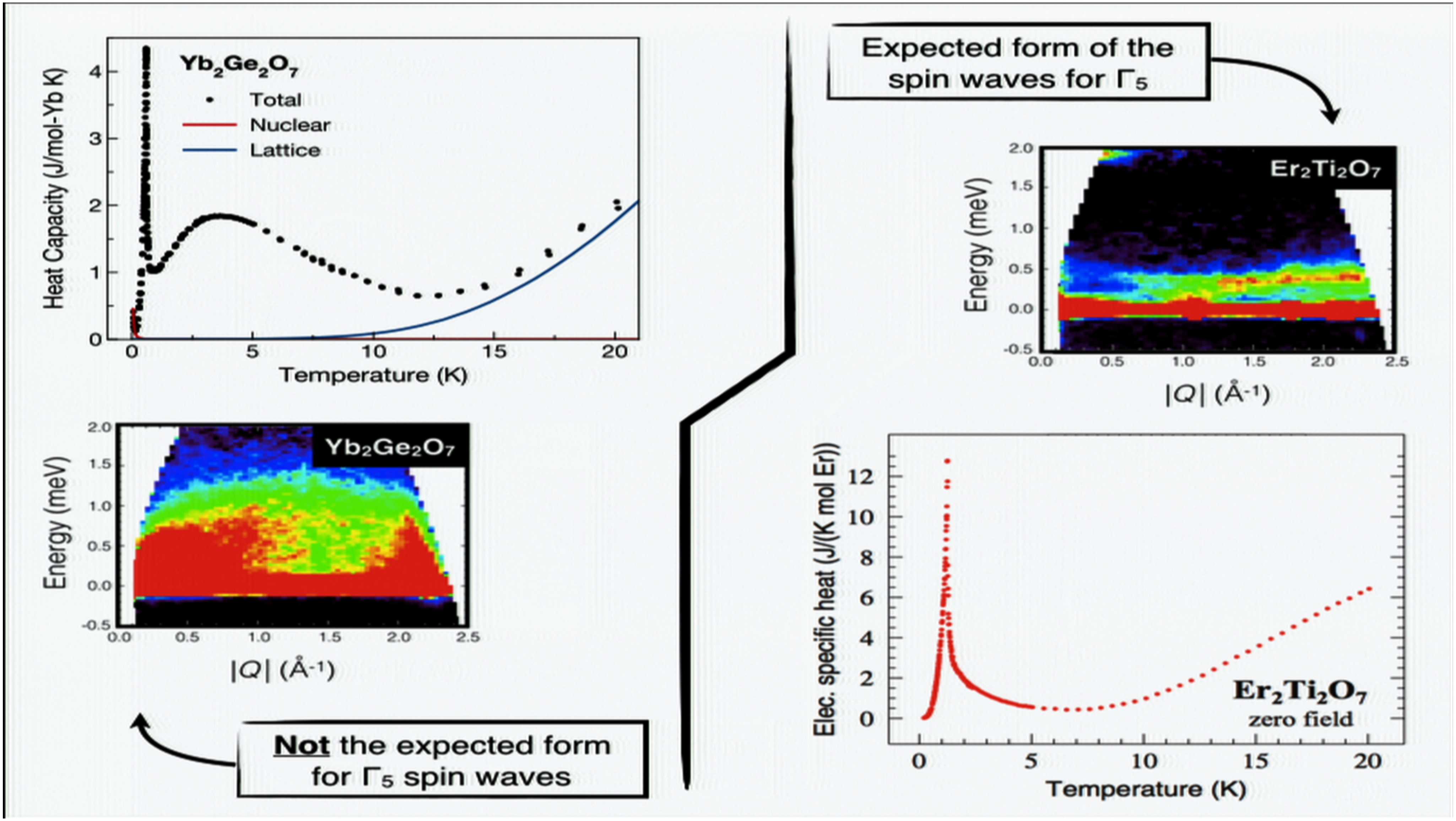
$Yb_2Ge_2O_7$'s magnetic excitations correlate with the broad specific heat anomaly only.



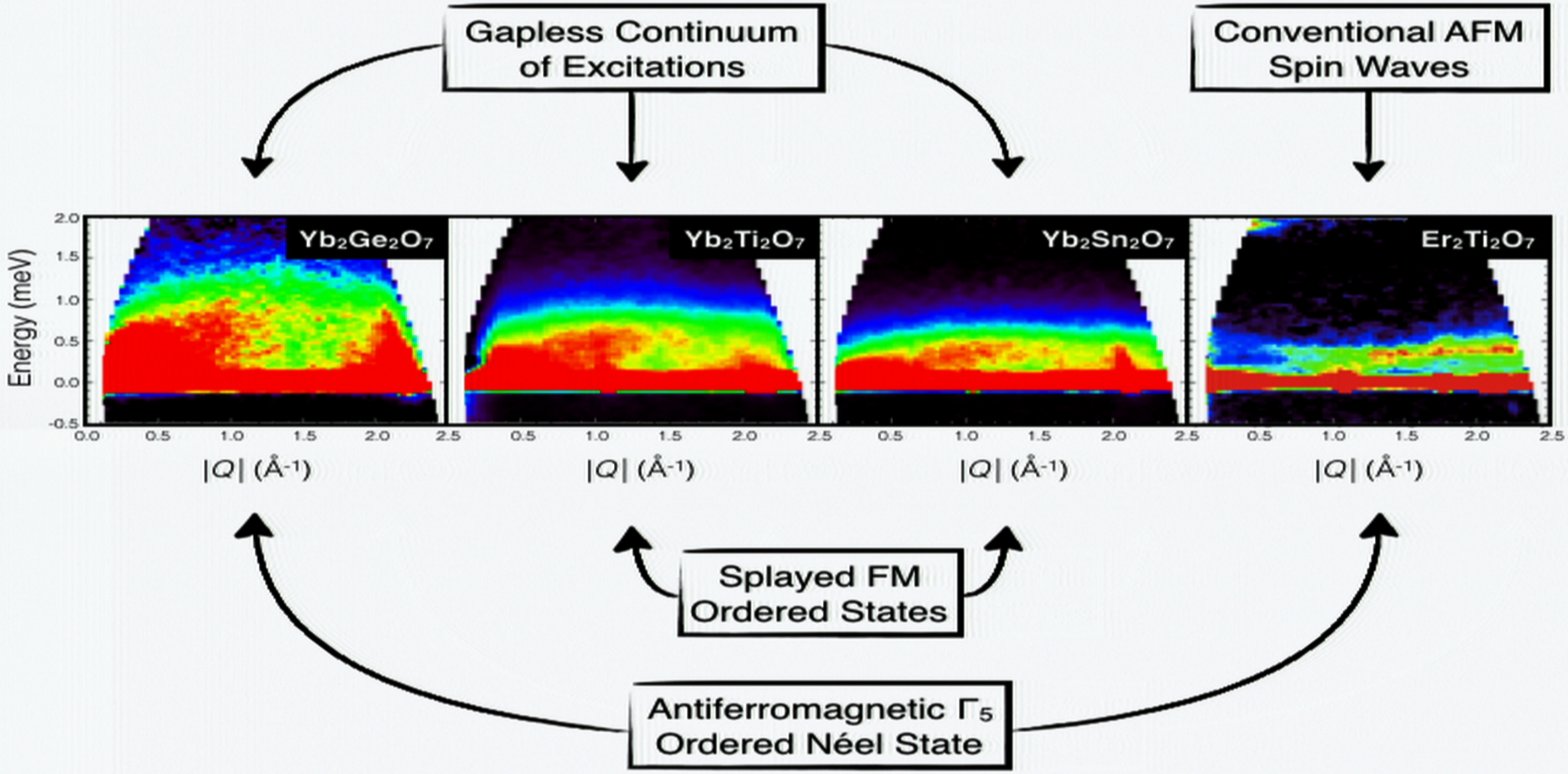


The magnetic excitations in $Yb_2Ge_2O_7$ are not related to Γ_5.

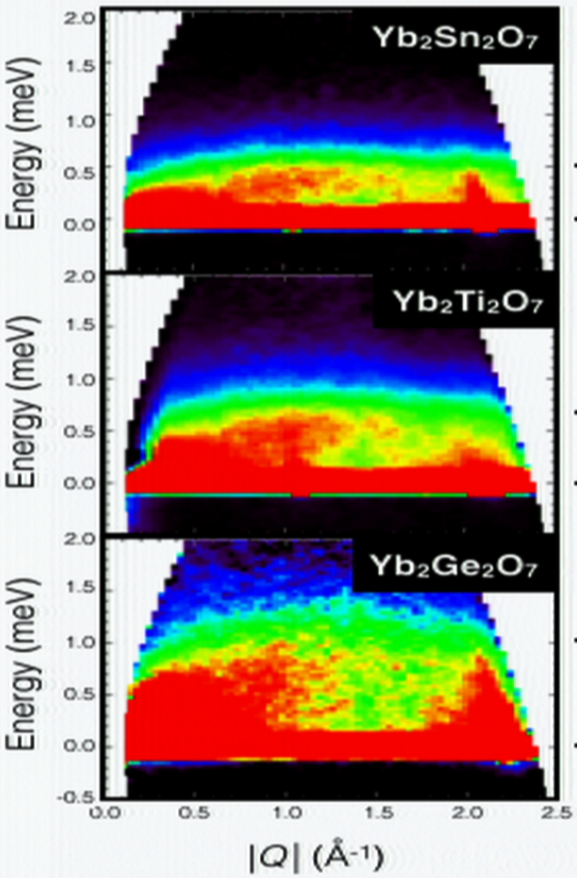


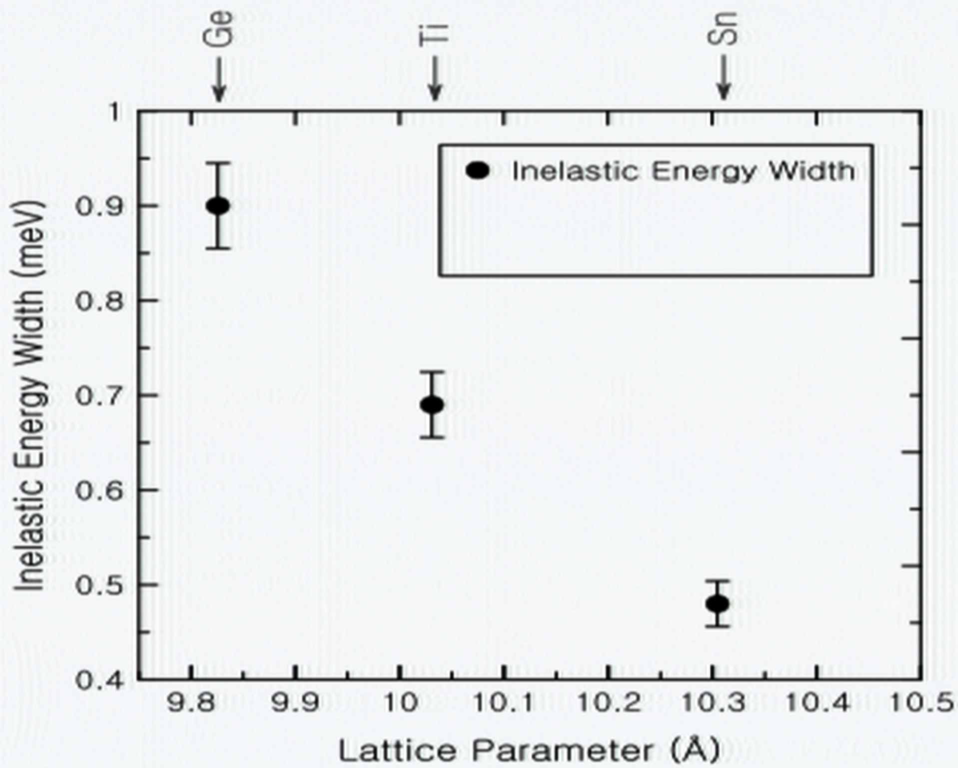

Yb₂Ge₂O₇
Total
Nuclear
Lattice
Heat Capacity (J/mol-Yb K)
Temperature (K)
Expected form of the spin waves for Γ_5
Er₂Ti₂O₇
Energy (meV)
|Q| (Å⁻¹)
Yb₂Ge₂O₇
Energy (meV)
|Q| (Å⁻¹)
Elec. specific heat (J/(K mol Er))
Er₂Ti₂O₇
zero field
Temperature (K)
Not the expected form for Γ_5 spin waves

The magnetic excitations of the Yb pyrochlores share a common form



The energy scales in the Yb pyrochlores scale with their lattice parameters





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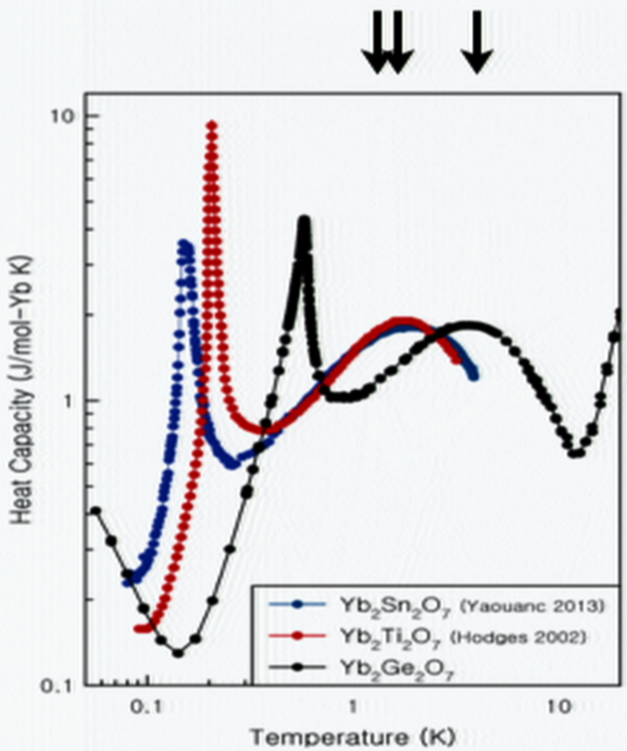

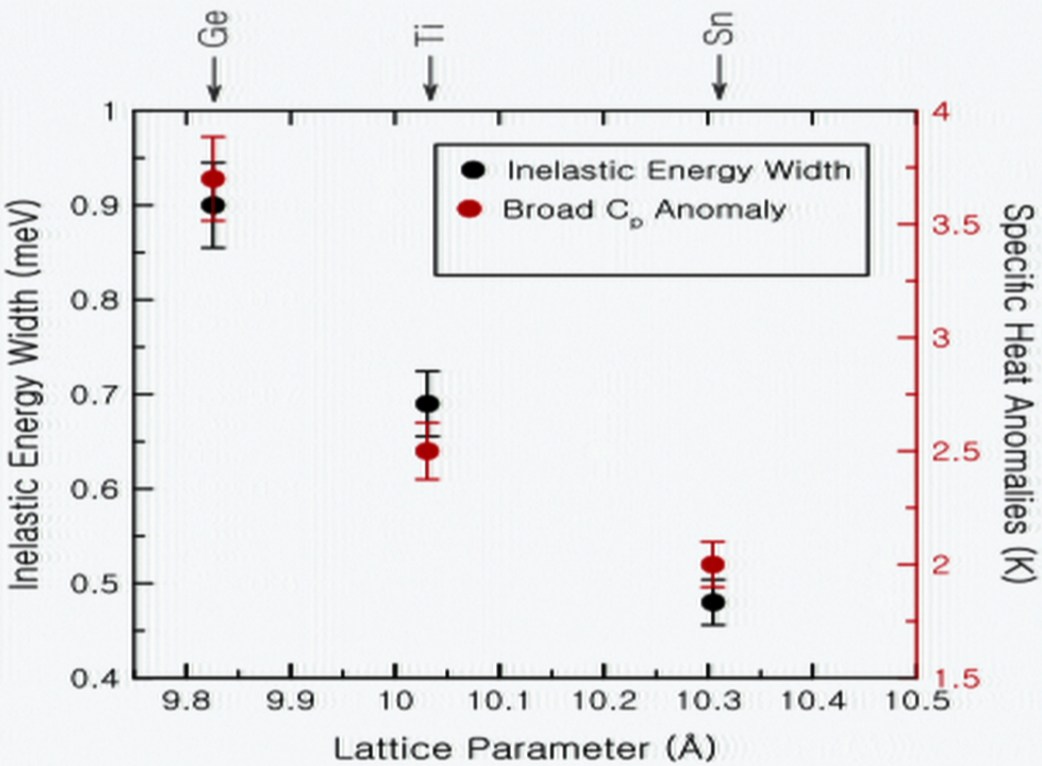

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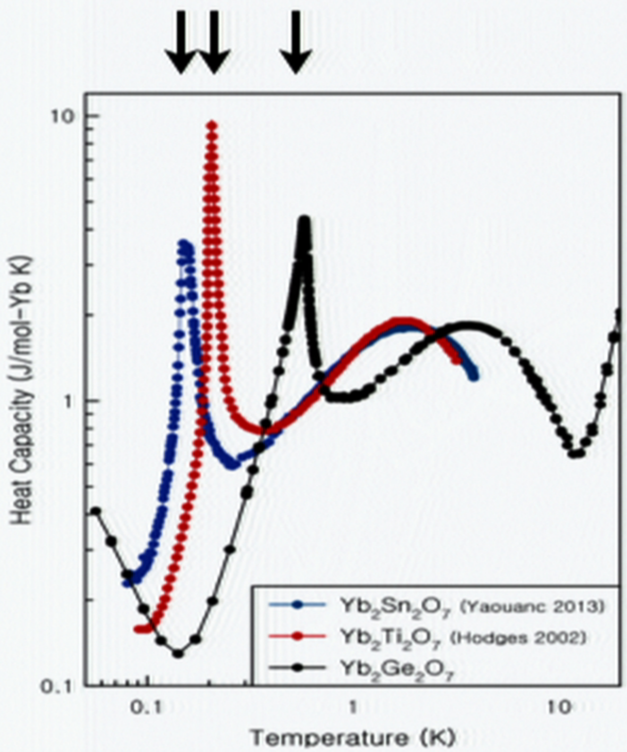
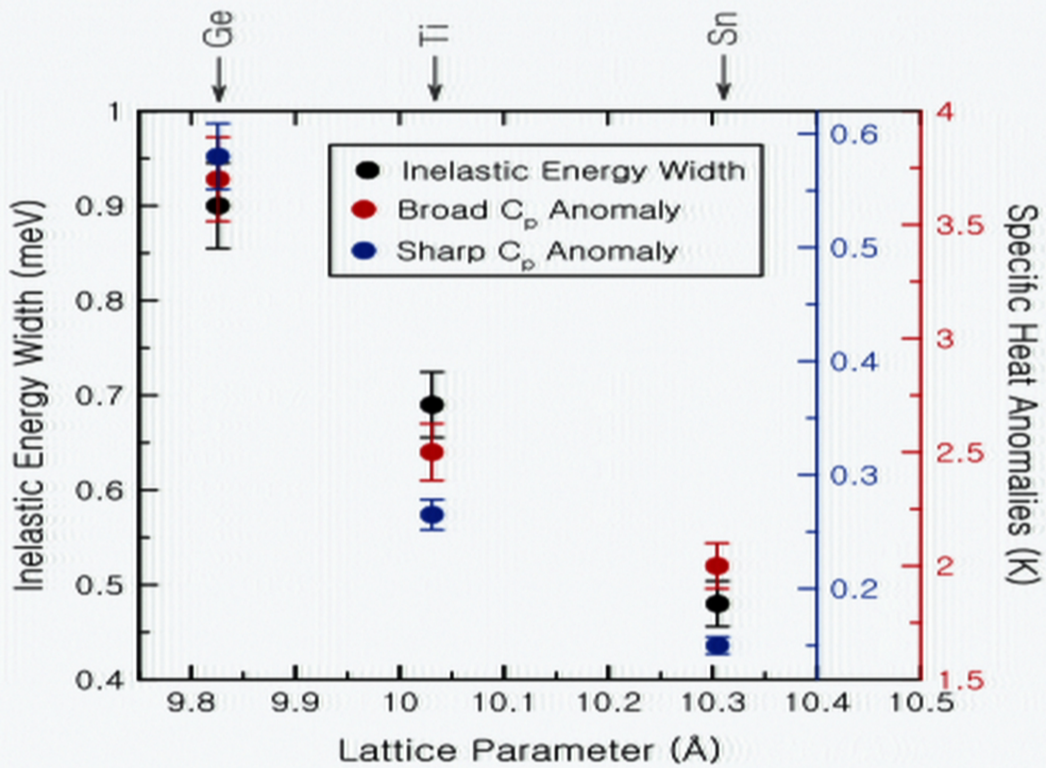
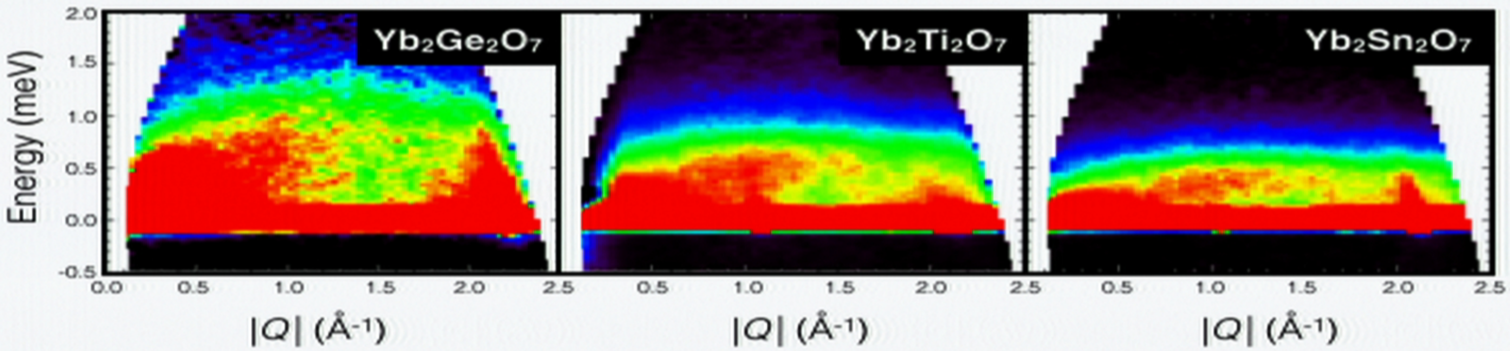




The Yb pyrochlores share a ubiquitous form to their unconventional spin excitations - unreacted to their dipole ordered states!



1. A. M. Hallas, J. Gaudet, M. N. Wilson, T. J. Munsie, A. A. Aczel, M. B. Stone, R. S. Freitas, A. M. Arevalo-Lopez, J. P. Attfield, M. Tachibana, C. R. Wiebe, G. M. Luke, and B. D. Gaulin, Phys. Rev. B **93**, 104405 (2016).

2. A. M. Hallas, J. Gaudet, N. P. Butch, M. Tachibana, R. S. Freitas, G. M. Luke, C. R. Wiebe, and B. D. Gaulin, Phys. Rev. B **93**, 100403(R) (2016)

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