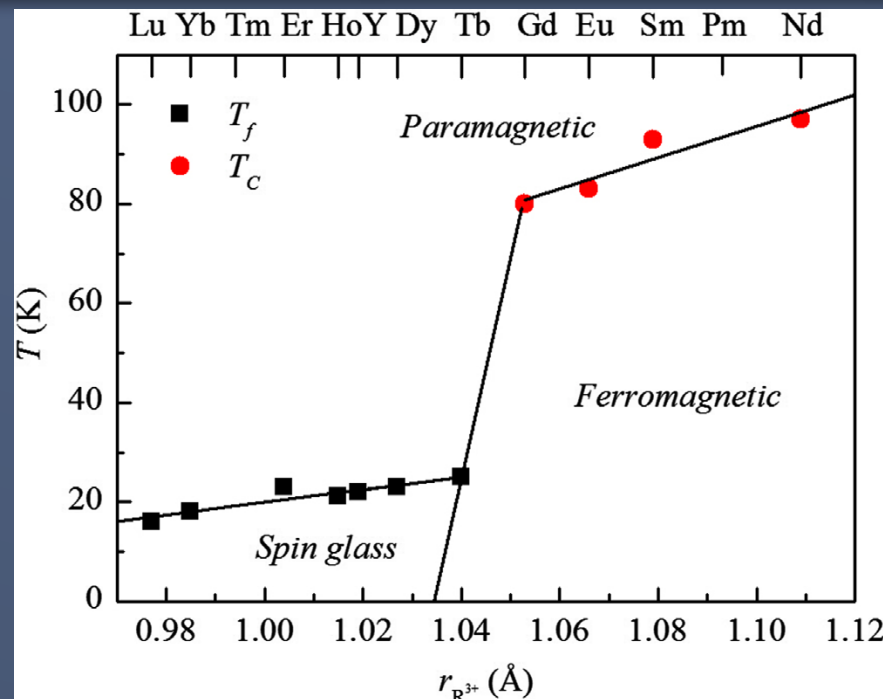
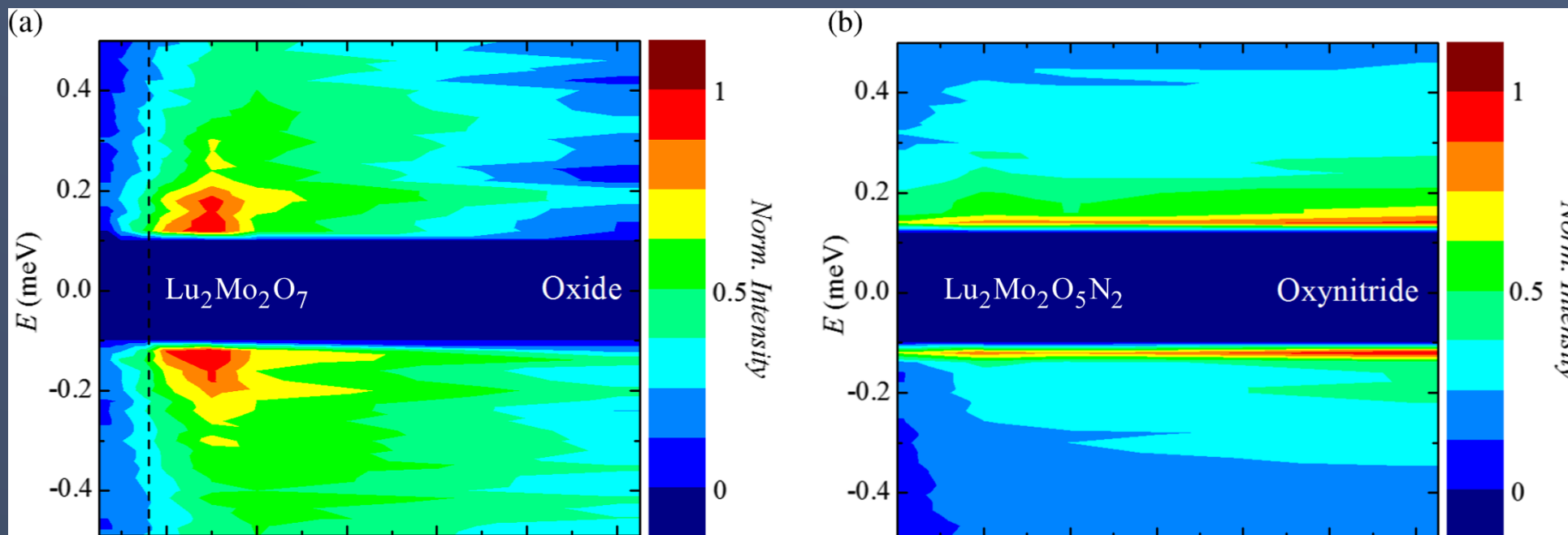


From Spin Glass to Spin Liquid Ground States in Molybdate Pyrochlores

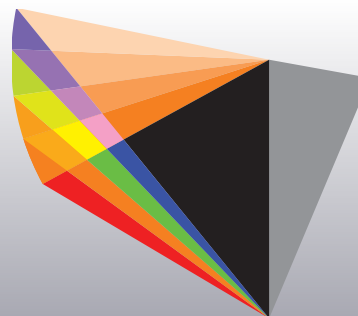


L. Clark ^{1, 2}
 E. Kermarrec ^{1, 3}
 K. Fritsch ^{1, 4}
 G. J. Nilsen ⁵
 J. P. Attfield ⁶
 A. Harrison ^{5, 6}
 H. J. Silverstein ^{7, 8}
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⁵ Institut Laue Langevin
⁶ Edinburgh University
⁷ University of Winnipeg
⁸ Stanford University
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¹⁰ NSRRC, Taiwan
¹¹ University of Waterloo

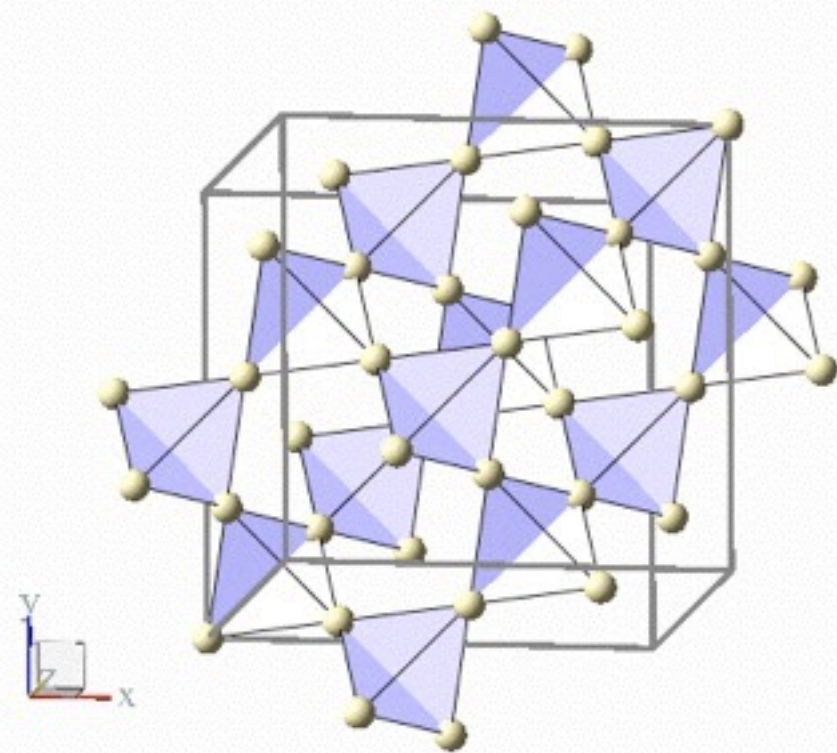


Bruce D. Gaulin
 McMaster University



Brockhouse Institute
 for Materials Research

Geometric Frustration from Tetrahedra

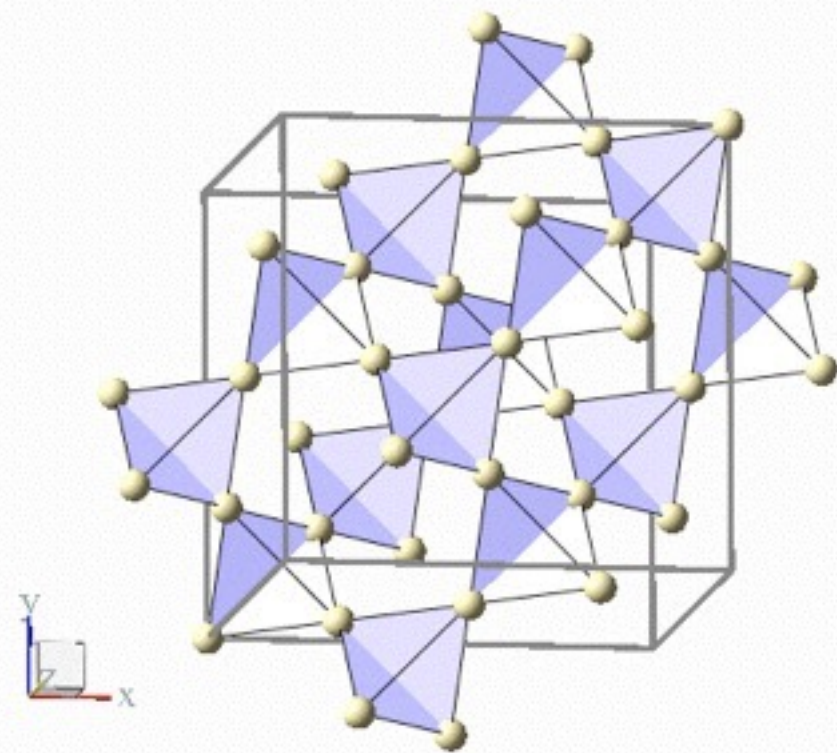
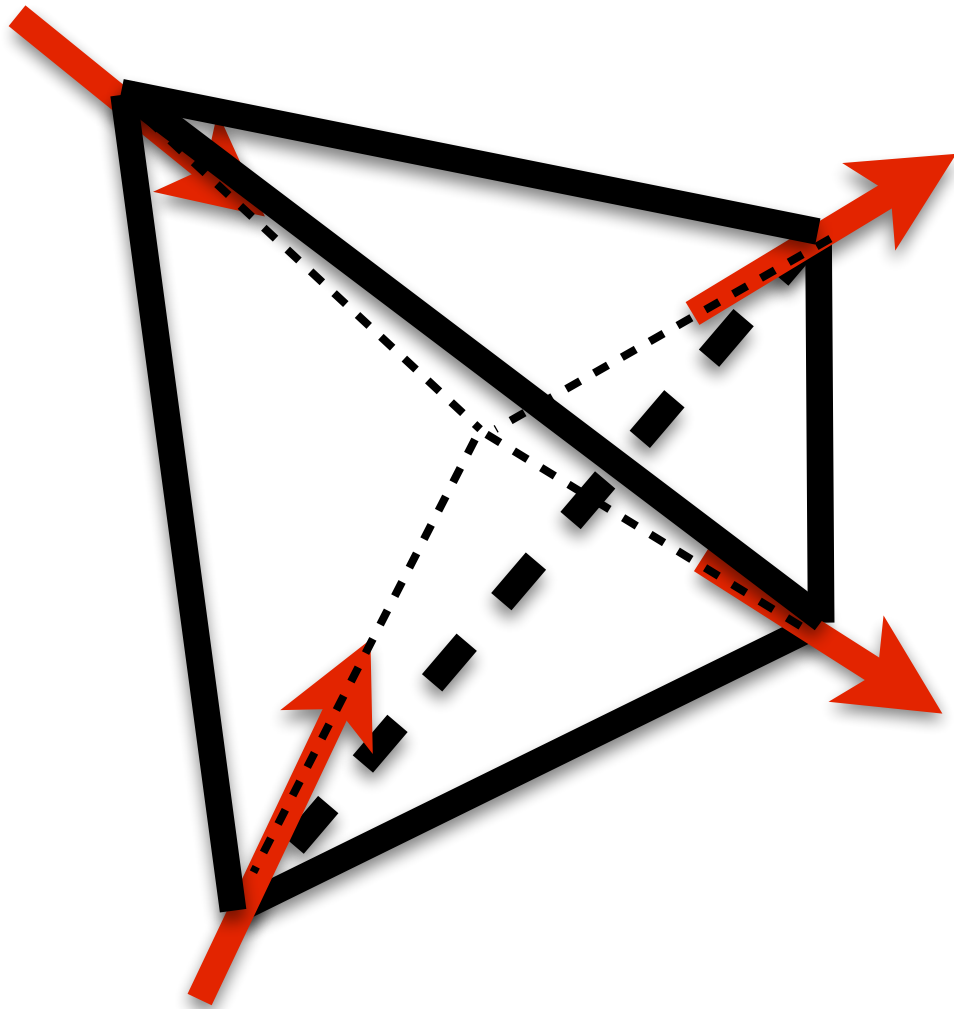


Pyrochlore

Spin Ice: FM near-neighbour coupling + local Ising anisotropy leads to 6-fold degenerate “ice states” for a single tetrahedron.

Macroscopic degeneracy for network of corner-sharing tetrahedra.

Geometric Frustration from Tetrahedra



Pyrochlore

Spin Ice: FM near-neighbour coupling + local Ising anisotropy leads to 6-fold degenerate “ice states” for a single tetrahedron.

Macroscopic degeneracy for network of corner-sharing tetrahedra.

Cubic Pyrochlores: $A_2B_2O_7$



Hydrogen 1 H 1.008																		Helium 2 He 4.0026																			
Lithium 3 Li 6.94		Beryllium 4 Be 9.0122																Boron 5 B 10.81		Carbon 6 C 12.011		Nitrogen 7 N 14.007		Oxygen 8 O 15.999		Fluorine 9 F 18.998		Neon 10 Ne 20.180									
Sodium 11 Na 22.990		Magnesium 12 Mg 24.305																Aluminium 13 Al 26.982		Silicon 14 Si 28.085		Phosphorus 15 P 30.974		Sulfur 16 S 32.06		Chlorine 17 Cl 35.45		Argon 18 Ar 39.948									
Potassium 19 K 39.098		Calcium 20 Ca 40.078(4)		Scandium 21 Sc 44.956		Titanium 22 Ti 47.867		Vanadium 23 V 50.942		Chromium 24 Cr 51.996		Manganese 25 Mn 54.938		Iron 26 Fe 55.845(2)		Cobalt 27 Co 58.933		Nickel 28 Ni 58.693		Copper 29 Cu 63.546(3)		Zinc 30 Zn 65.38(2)		Gallium 31 Ga 69.723		Germanium 32 Ge 72.63		Arsenic 33 As 74.922		Selenium 34 Se 78.96(3)		Bromine 35 Br 79.904		Krypton 36 Kr 83.798(2)			
Rubidium 37 Rb 85.468		Strontium 38 Sr 87.62		Yttrium 39 Y 88.906		Zirconium 40 Zr 91.224(2)		Niobium 41 Nb 92.906(3)		Molybdenum 42 Mo 95.96(2)		Technetium 43 Tc [97.91]		Ruthenium 44 Ru 101.07(2)		Rhodium 45 Rh 102.91		Palladium 46 Pd 106.42		Silver 47 Ag 107.87		Cadmium 48 Cd 112.41		Indium 49 In 114.82		Tin 50 Sn 118.71		Antimony 51 Sb 121.76		Tellurium 52 Te 127.60(3)		Iodine 53 I 126.90		Xenon 54 Xe 131.29			
Caesium 55 Cs 132.91		Barium 56 Ba 137.33		57-70 *		Lutetium 71 Lu 174.97		Hafnium 72 Hf 178.49(2)		Tantalum 73 Ta 180.95		Tungsten 74 W 183.84		Rhenium 75 Re 186.21		Osmium 76 Os 190.23(2)		Iridium 77 Ir 192.22		Platinum 78 Pt 195.08		Gold 79 Au 196.97		Mercury 80 Hg 200.59		Thallium 81 Tl 204.38		Lead 82 Pb 207.2		Bismuth 83 Bi 208.98		Polonium 84 Po [208.98]		Astatine 85 At [209.99]		Radon 86 Rn [222.02]	
Francium 87 Fr [223.02]		Radium 88 Ra [226.03]		89-102 **		Lawrencium 103 Lr [262.11]		Rutherfordium 104 Rf [265.12]		Dubnium 105 Db [268.13]		Seaborgium 106 Sg [271.13]		Bohrium 107 Bh [270]		Hassium 108 Hs [277.15]		Meitnerium 109 Mt [276.15]		Darmstadtium 110 Ds [281.16]		Roentgenium 111 Rg [280.16]		Copernicium 112 Cn [285.17]		Ununtrium 113 Uut [284.18]		Flerovium 114 Fl [289.19]		Ununpentium 115 Uup [288.19]		Livermorium 116 Lv [293]		Ununseptium 117 Uus [294]		Ununoctium 118 Uuo [294]	

Key:

Element Name

Atomic number

Symbol

Atomic weight (mean relative mass)

SOC



~ Z^4

*lanthanoids

**actinoids

Lanthanum 57 La 138.91	Cerium 58 Ce 140.12	Praseodymium 59 Pr 140.91	Neodymium 60 Nd 144.24	Promethium 61 Pm [144.91]	Samarium 62 Sm 150.36(2)	Europium 63 Eu 151.96	Gadolinium 64 Gd 157.25(3)	Terbium 65 Tb 158.93	Dysprosium 66 Dy 162.50	Holmium 67 Ho 164.93	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.05
Actinium 89 Ac [227.03]	Thorium 90 Th 232.04	Protactinium 91 Pa 231.04	Uranium 92 U 238.03	Neptunium 93 Np [237.05]	Plutonium 94 Pu [244.06]	Americium 95 Am [243.06]	Curium 96 Cm [247.07]	Berkelium 97 Bk [247.07]	Californium 98 Cf [251.08]	Einsteinium 99 Es [252.08]	Fermium 100 Fm [257.10]	Mendelevium 101 Md [258.10]	Nobelium 102 No [259.10]

Cubic Pyrochlores: $A_2B_2O_7$



Hydrogen																		Helium																	
1 H 1.008																		2 He 4.0026																	
Lithium 3 Li 6.94																		Beryllium 4 Be 9.0122																	
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Lanthanum 57 La [262.11]																		Cerium 58 Ce [262.11]																	
Praseodymium 59 Pr [263.10]																		Neodymium 60 Nd [263.10]																	
Europium 62 Eu [263.10]																		Gadolinium 64 Gd [263.10]																	
Terbium 63 Tb [263.10]																		Dysprosium 65 Dy [263.10]																	
Erbium 64 Er [263.10]																		Ytterbium 70 Yb [263.10]																	
Lutetium 71 Lu [263.10]																		Hafnium 72 Hf [263.10]																	
Yttrium 39 Y [263.10]																		Zirconium 40 Zr [263.10]																	
Scandium 21 Sc [263.10]																		Titanium 22 Ti [263.10]																	
Vanadium 23 V [263.10]																		Chromium 24 Cr [263.10]																	
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Tellurium 52 Te [263.10]																		Antimony 51 Sb [263.10]																	
Polonium 84 Po [263.10]																		Bismuth 83 Bi [263.10]																	
Astatine 85 At [263.10]																		Radon 86 Rn [263.10]																	
Ununseptium 117 Uus [263.10]																		Livermorium 116 Lv [263.10]																	
Ununoctium 118 Uuo [263.10]																		Flerovium 114 Fl [263.10]																	
Ununpentium 115 Uup [263.10]																		Ununtrium 113 Uut [263.10]																	
Copernicium 112 Cn [263.10]																		Roentgenium 111 Rg [263.10]																	
Darmstadtium 110 Ds [263.10]																		Meitnerium 109 Mt [263.10]																	
Hassium 108 Hs [263.10]																		Bohrium 107 Bh [263.10]																	
Seaborgium 106 Sg [263.10]																		Dubnium 105 Db [263.10]																	
Rutherfordium 104 Rf [263.10]																		Lawrencium 103 Lr [263.10]																	
* 57-70																		* 57-70																	
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Atomic number																		Atomic number																	
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Atomic weight (mean relative mass)																		Atomic weight (mean relative mass)																	

Key:

Element Name

Atomic number

Symbol

Atomic weight (mean relative mass)

SOC



~ Z^4

*lanthanoids

**actinoids

Lanthanum 57 La 138.91	Cerium 58 Ce 140.12	Praseodymium 59 Pr 140.91	Neodymium 60 Nd 144.24	Promethium 61 Pm [144.91]	Samarium 62 Sm 150.36(2)	Europium 63 Eu 151.96	Gadolinium 64 Gd 157.25(3)	Terbium 65 Tb 158.93	Dysprosium 66 Dy 162.50	Holmium 67 Ho 164.93	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.05
Actinium 89 Ac [227.03]	Thorium 90 Th 232.04	Protactinium 91 Pa 231.04	Uranium 92 U 238.03	Neptunium 93 Np [237.05]	Plutonium 94 Pu [244.06]	Americium 95 Am [243.06]	Curium 96 Cm [247.07]	Berkelium 97 Bk [247.07]	Californium 98 Cf [251.08]	Einsteinium 99 Es [252.08]	Fermium 100 Fm [257.10]	Mendelevium 101 Md [258.10]	Nobelium 102 No [259.10]

Cubic Pyrochlores: $A_2B_2O_7$



Hydrogen																		Helium																	
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Lanthanum 57 La 138.905																		Cerium 58 Ce 140.12																	
Praseodymium 59 Pr 140.908																		Neodymium 60 Nd 144.24																	
Europium 63 Eu 151.964																		Gadolinium 64 Gd 157.25																	
Terbium 65 Tb 158.925																		Dysprosium 66 Dy 162.50																	
Erbium 68 Er 167.259																		Ytterbium 70 Yb 173.054																	
Lutetium 71 Lu 174.967																		Hafnium 72 Hf 178.49																	
Yttrium 39 Y 88.906																		Zirconium 40 Zr 91.224																	
Scandium 21 Sc 44.956																		Titanium 22 Ti 47.867																	
Vanadium 23 V 50.942																		Chromium 24 Cr 51.996																	
Manganese 25 Mn 54.938																		Iron 26 Fe 55.845																	
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Tellurium 52 Te 127.60																		Antimony 51 Sb 121.76																	
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Zirconium 40 Zr 91.224																		Yttrium 39 Y 88.906																	
Titanium 22 Ti 47.867																		Scandium 21 Sc 44.956																	
Chromium 24 Cr 51.996																		Vanadium 23 V 50.942																	
Iron 26 Fe 55.845																		Manganese 25 Mn 54.938																	
Nickel 28 Ni 58.693																		Cobalt 27 Co 58.933																	
Copper 29 Cu 63.546																		Zinc 30 Zn 65.38																	
Gallium 31 Ga 69.723																		Germanium 32 Ge 72.63																	
Arsenic 33 As 74.922																		Selenium 34 Se 78.96																	
Bromine 35 Br 79.904																		Krypton 36 Kr 83.798																	
Iodine 53 I 126.90																		Xenon 54 Xe 131.29																	
Tellurium 52 Te 127.60																		Antimony 51 Sb 121.76																	
Tin 50 Sn 118.71																		Indium 49 In 114.82																	
Cadmium 48 Cd 112.41																		Silver 47 Ag 107.87																	
Palladium 46 Pd 106.42																		Rhodium 45 Rh 102.91																	
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Iodine 53 I 126.90																		Xenon 54 Xe 131.29																	
Tellurium 52 Te 127.60																		Antimony 51 Sb 121.76																	
Tin 50 Sn 118.																																			

Key:

Element Name

Atomic number

Symbol

Atomic weight (mean relative mass)

SOC

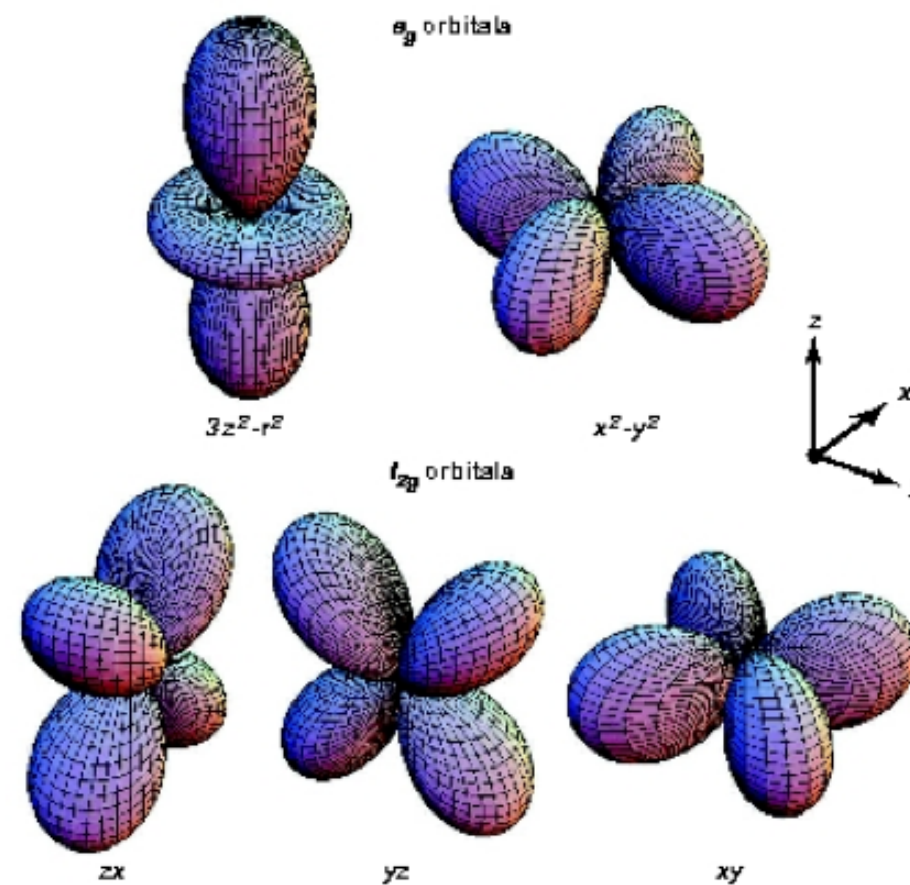
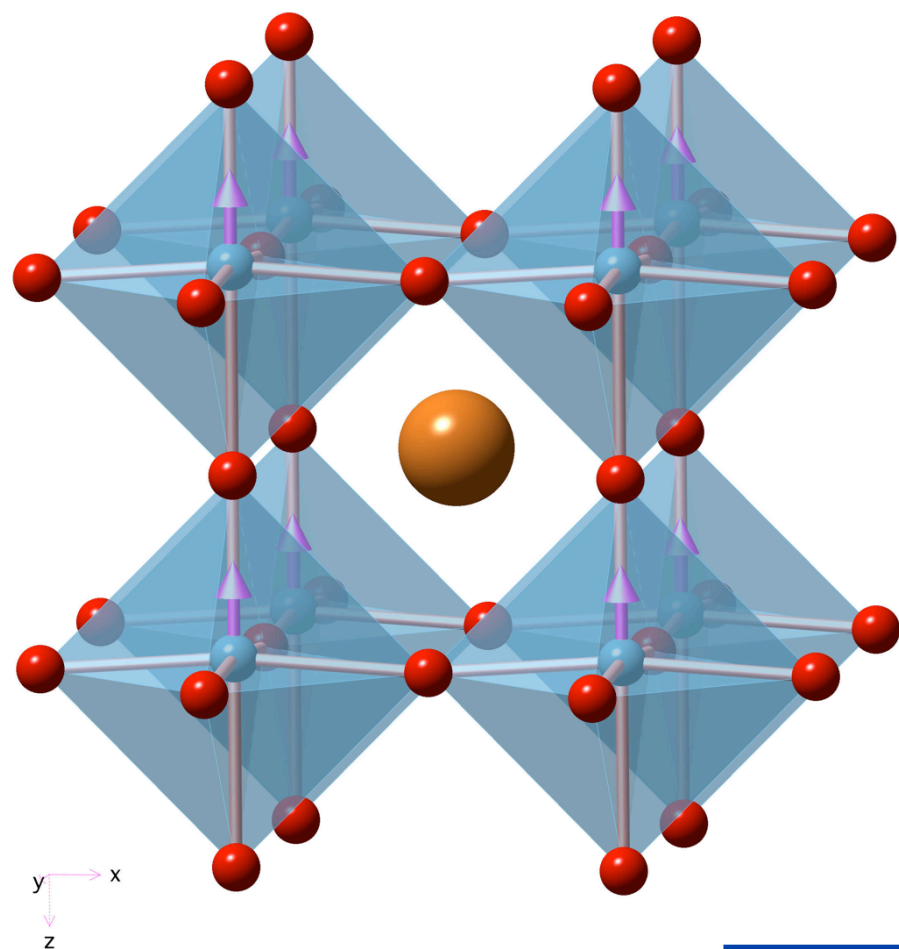


~ Z^4

*lanthanoids

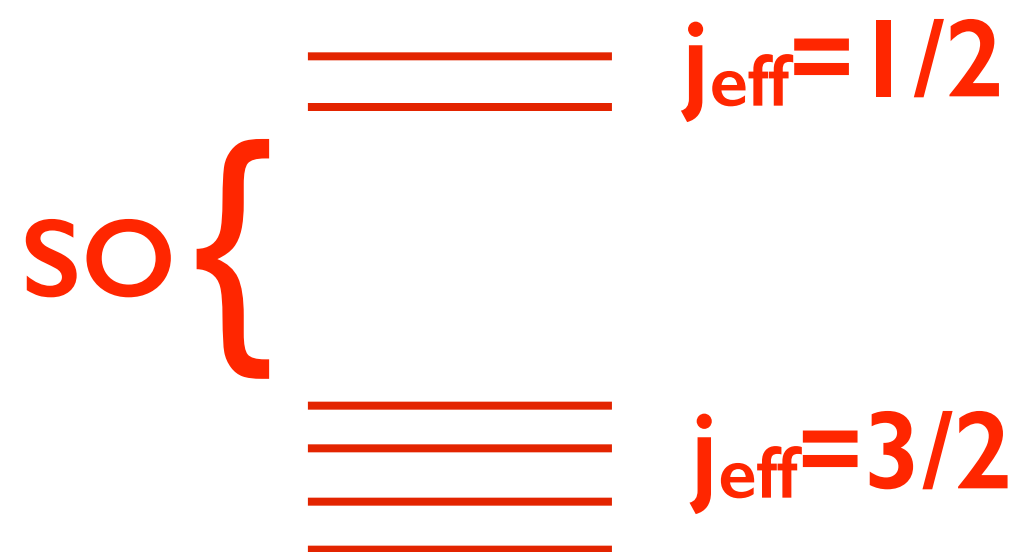
**actinoids

Lanthanum 57 La 138.91	Cerium 58 Ce 140.12	Praseodymium 59 Pr 140.91	Neodymium 60 Nd 144.24	Promethium 61 Pm [144.91]	Samarium 62 Sm 150.36(2)	Europium 63 Eu 151.96	Gadolinium 64 Gd 157.25(3)	Terbium 65 Tb 158.93	Dysprosium 66 Dy 162.50	Holmium 67 Ho 164.93	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.05
Actinium 89 Ac [227.03]	Thorium 90 Th 232.04	Protactinium 91 Pa 231.04	Uranium 92 U 238.03	Neptunium 93 Np [237.05]	Plutonium 94 Pu [244.06]	Americium 95 Am [243.06]	Curium 96 Cm [247.07]	Berkelium 97 Bk [247.07]	Californium 98 Cf [251.08]	Einsteinium 99 Es [252.08]	Fermium 100 Fm [257.10]	Mendelevium 101 Md [258.10]	Nobelium 102 No [259.10]

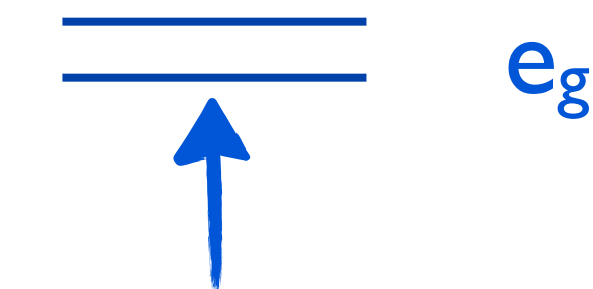
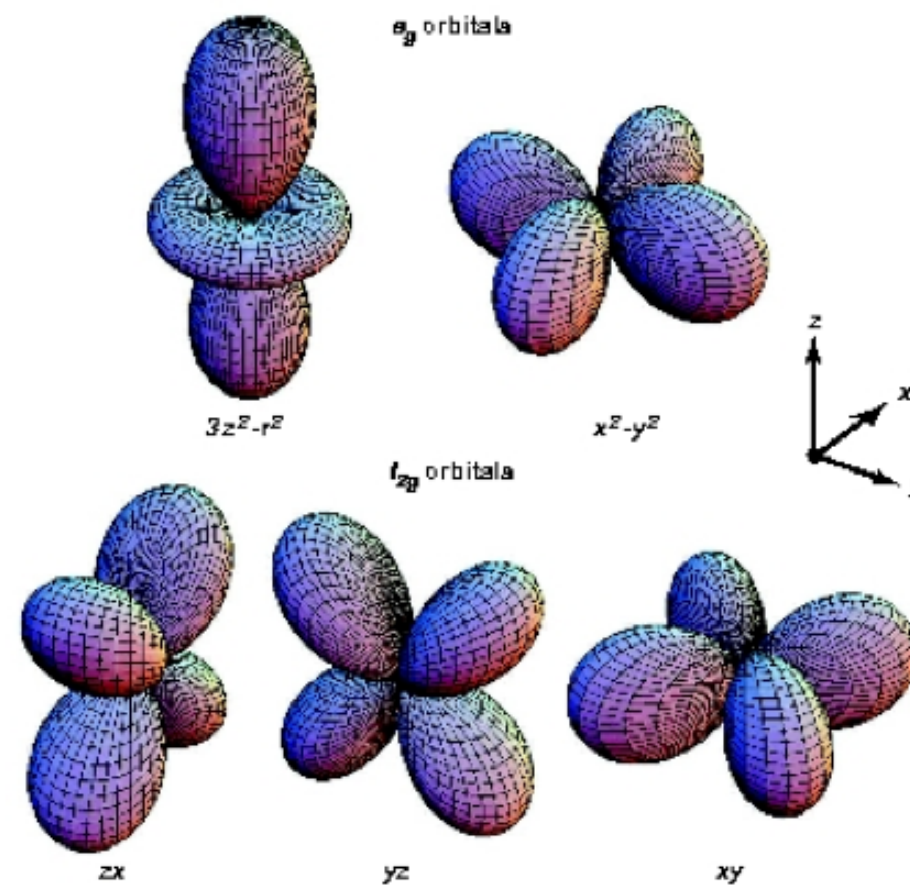
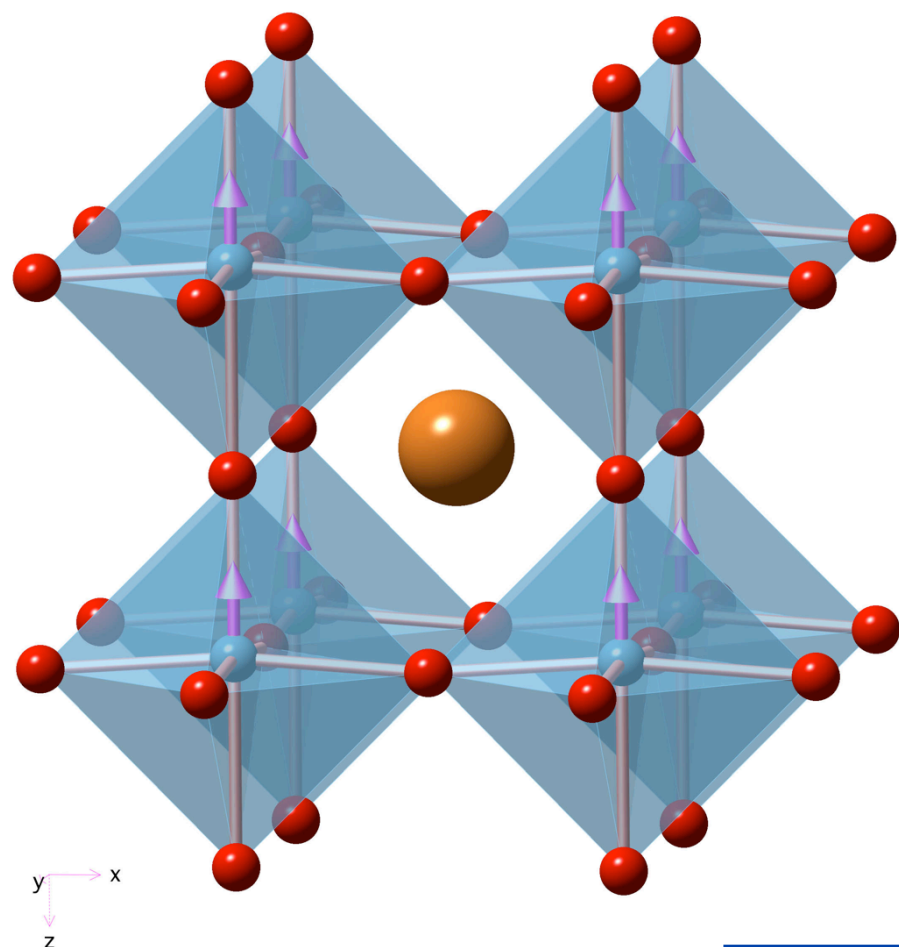


e_g

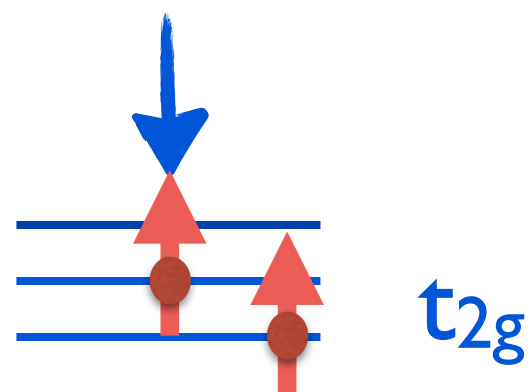
t_{2g}



5 d levels

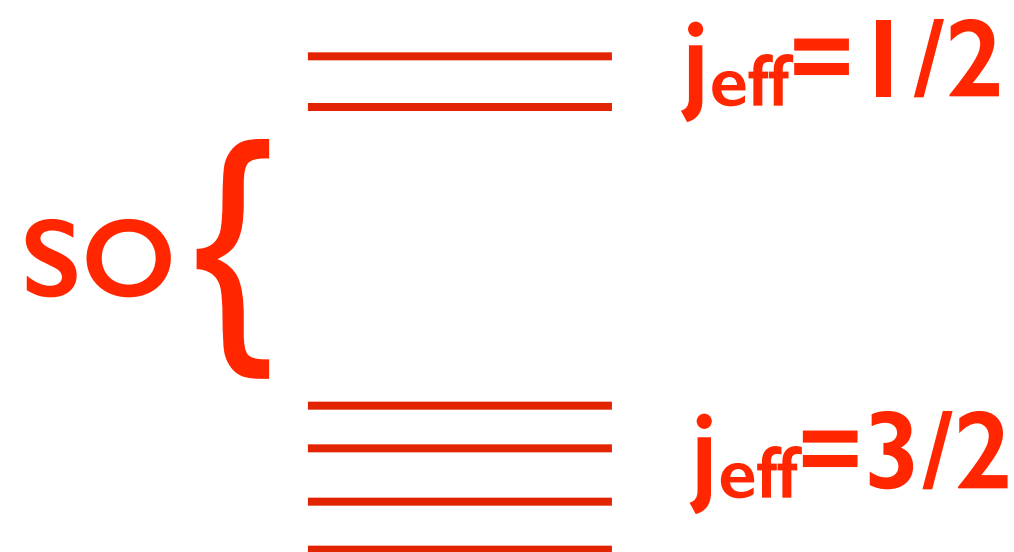


Octahedral
CEF

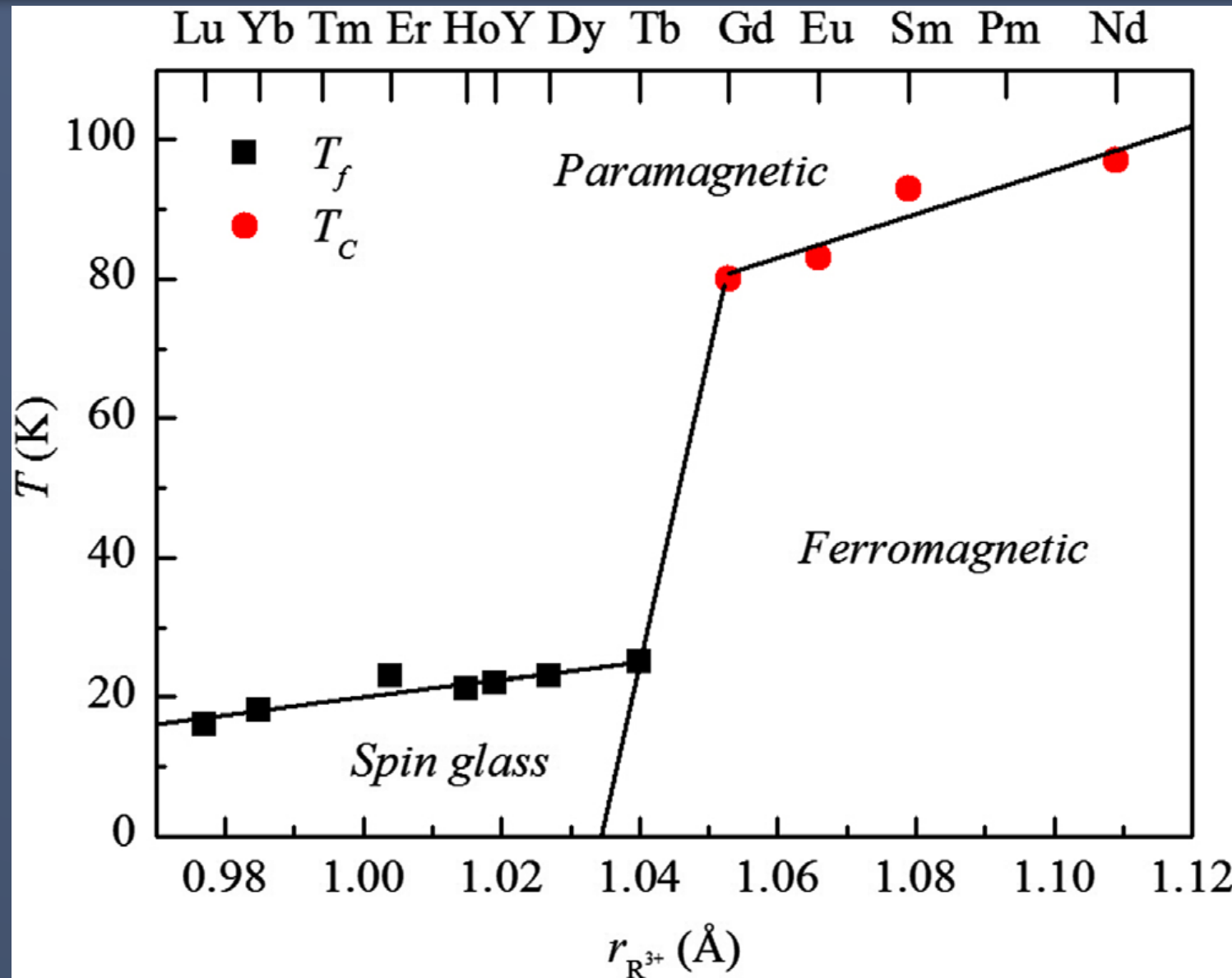


$\text{Mo}^{4+} 4d^2 S=1$

5 d levels

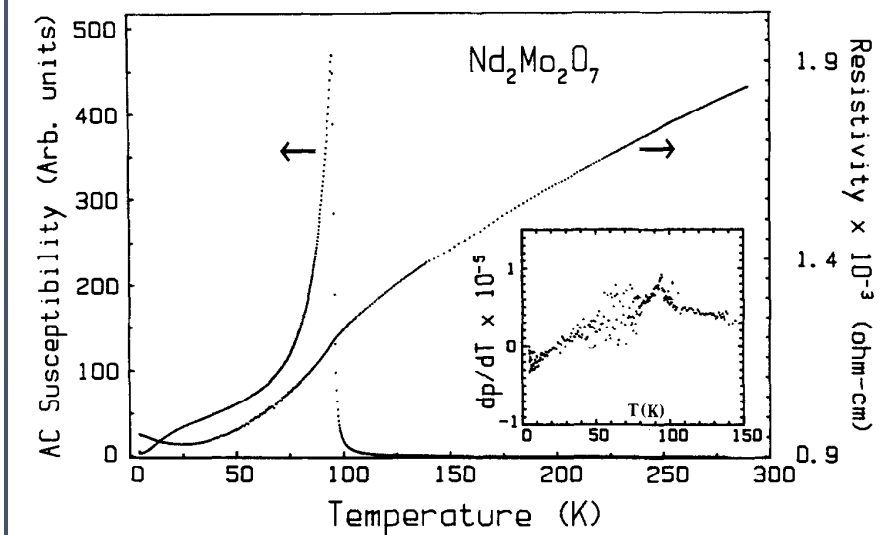
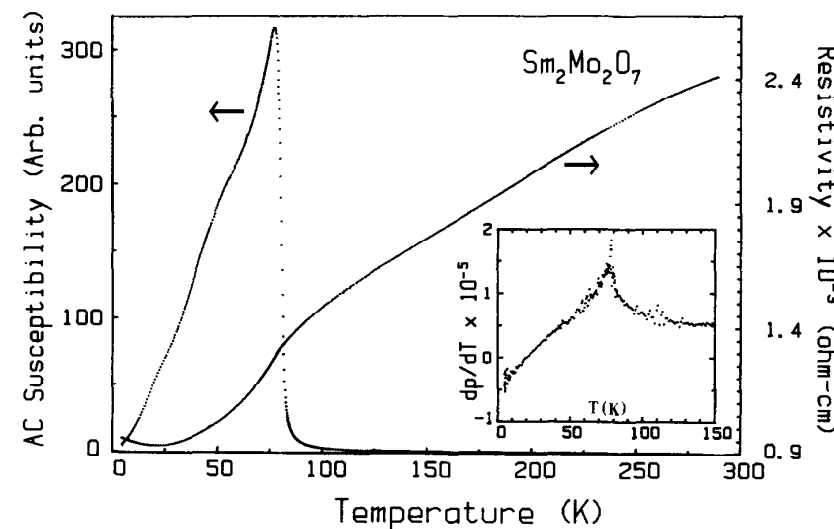
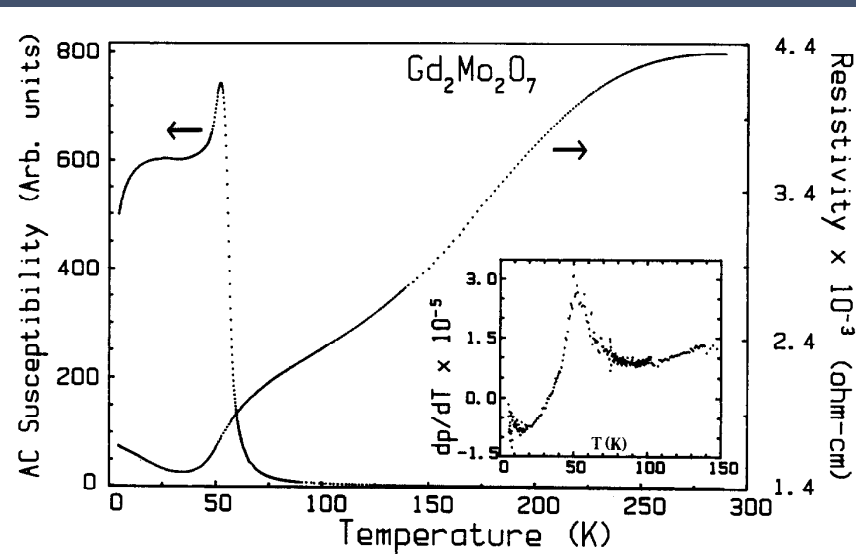


MIT in Rare Earth Molybdate Pyrochlores

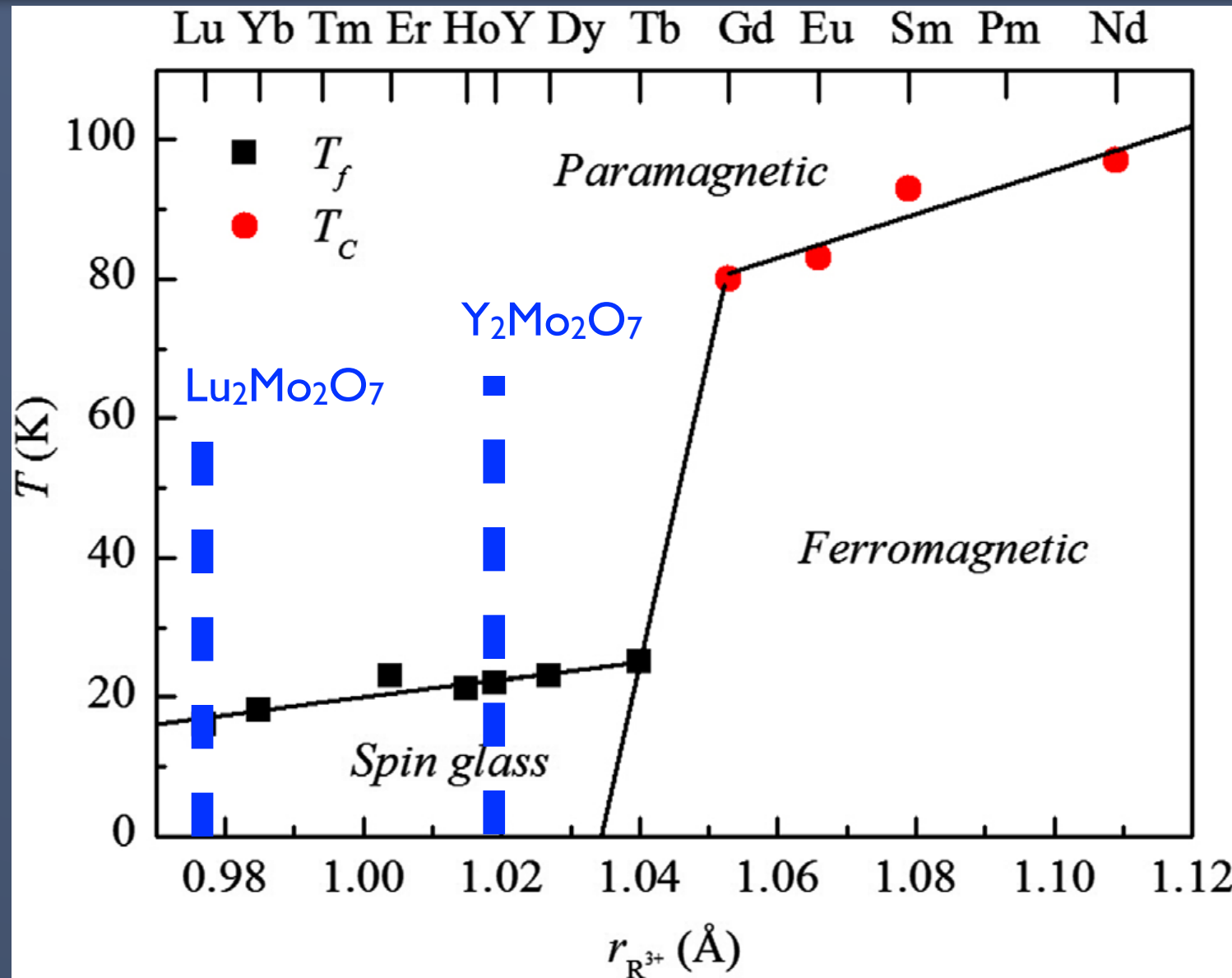


L. Clark et al.,
J. Sol. State Chem, 203, 199, 2013

N. Ali et al.,
J. Sol. State Chem, 83, 178, 1989

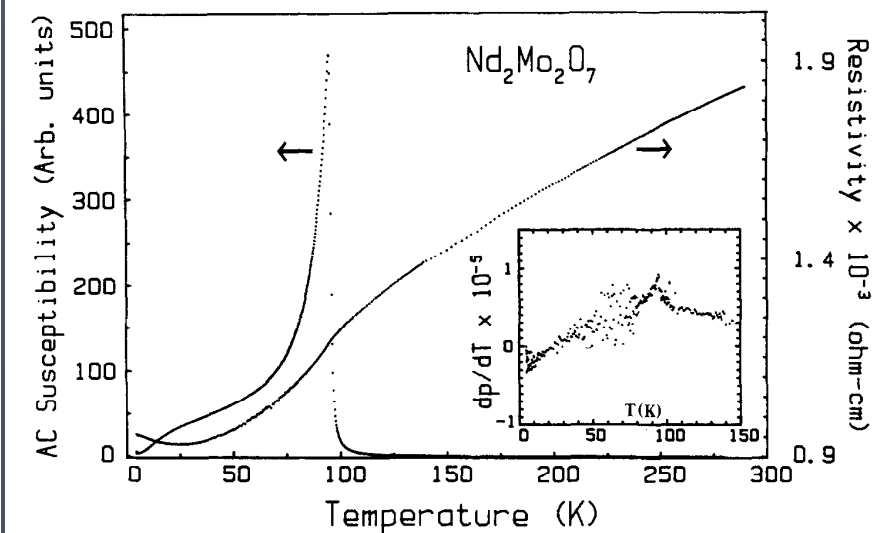
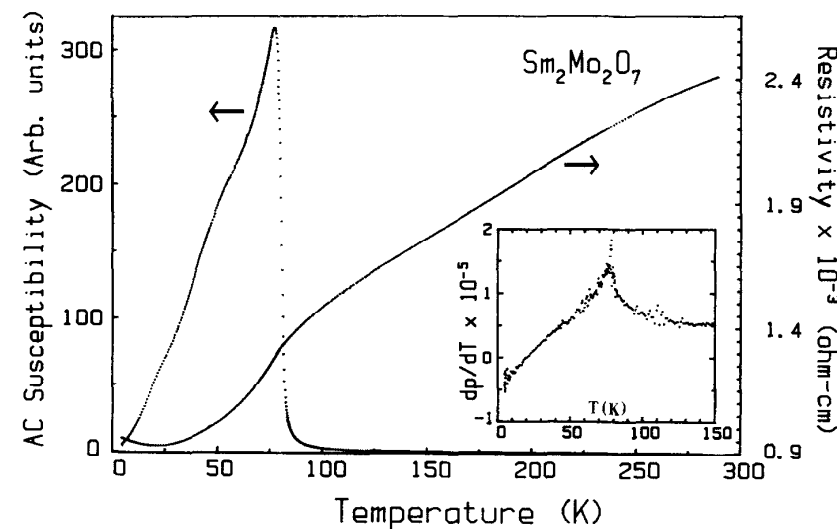
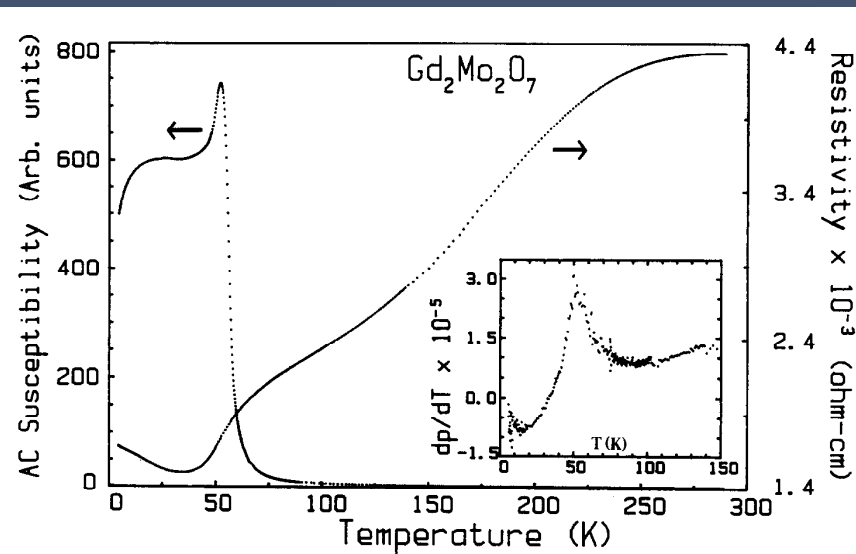


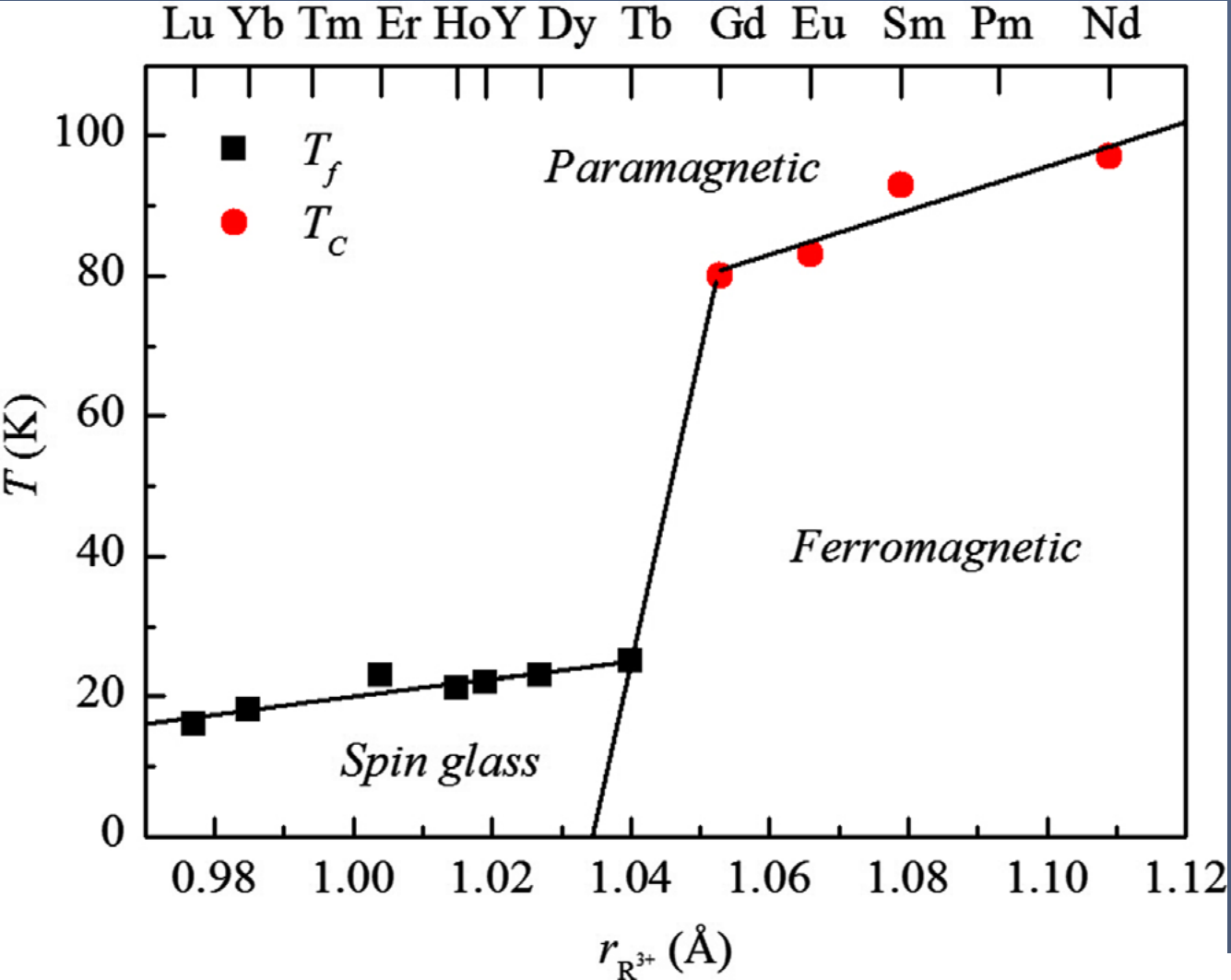
MIT in Rare Earth Molybdate Pyrochlores



L. Clark et al.,
J. Sol. State Chem, 203, 199, 2013

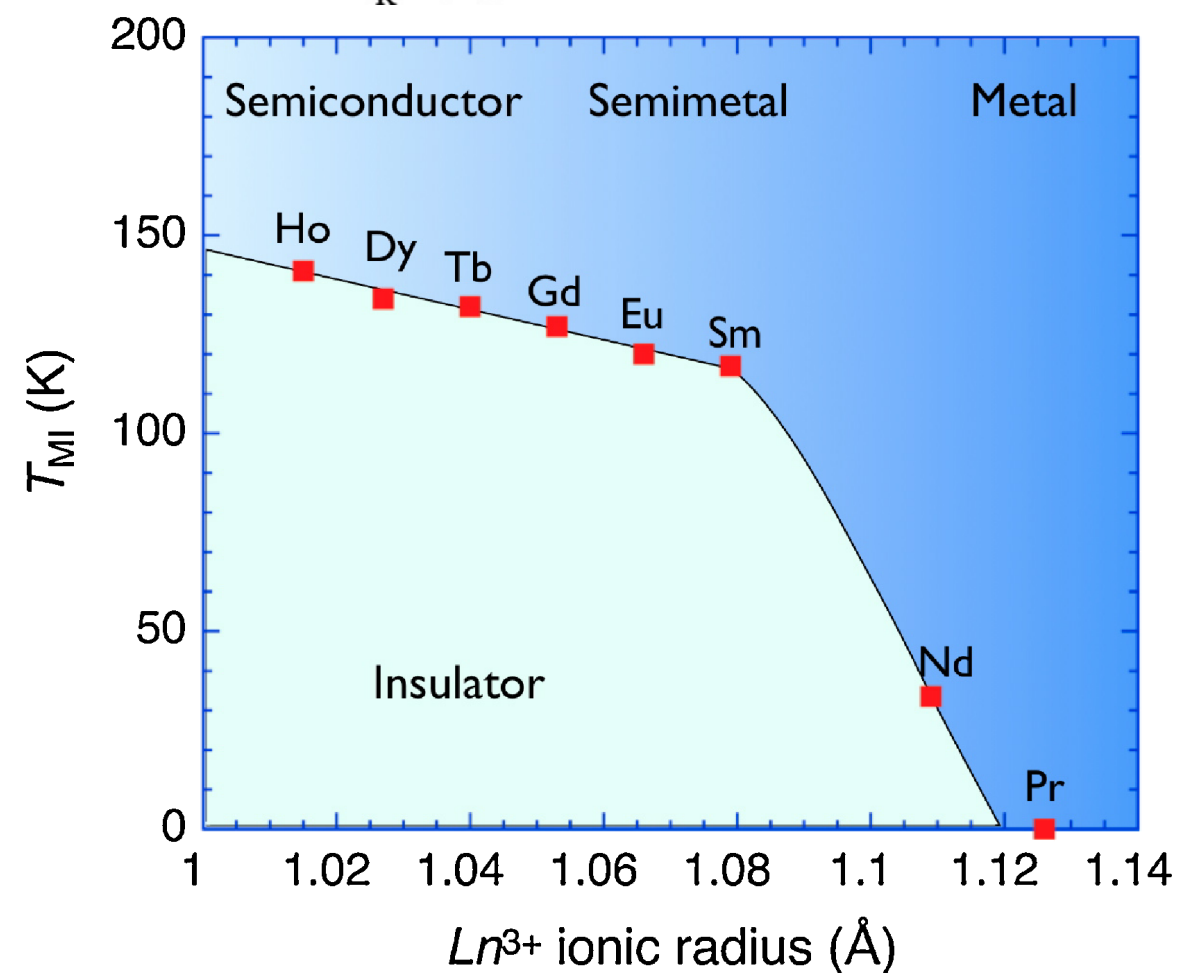
N. Ali et al.,
J. Sol. State Chem, 83, 178, 1989



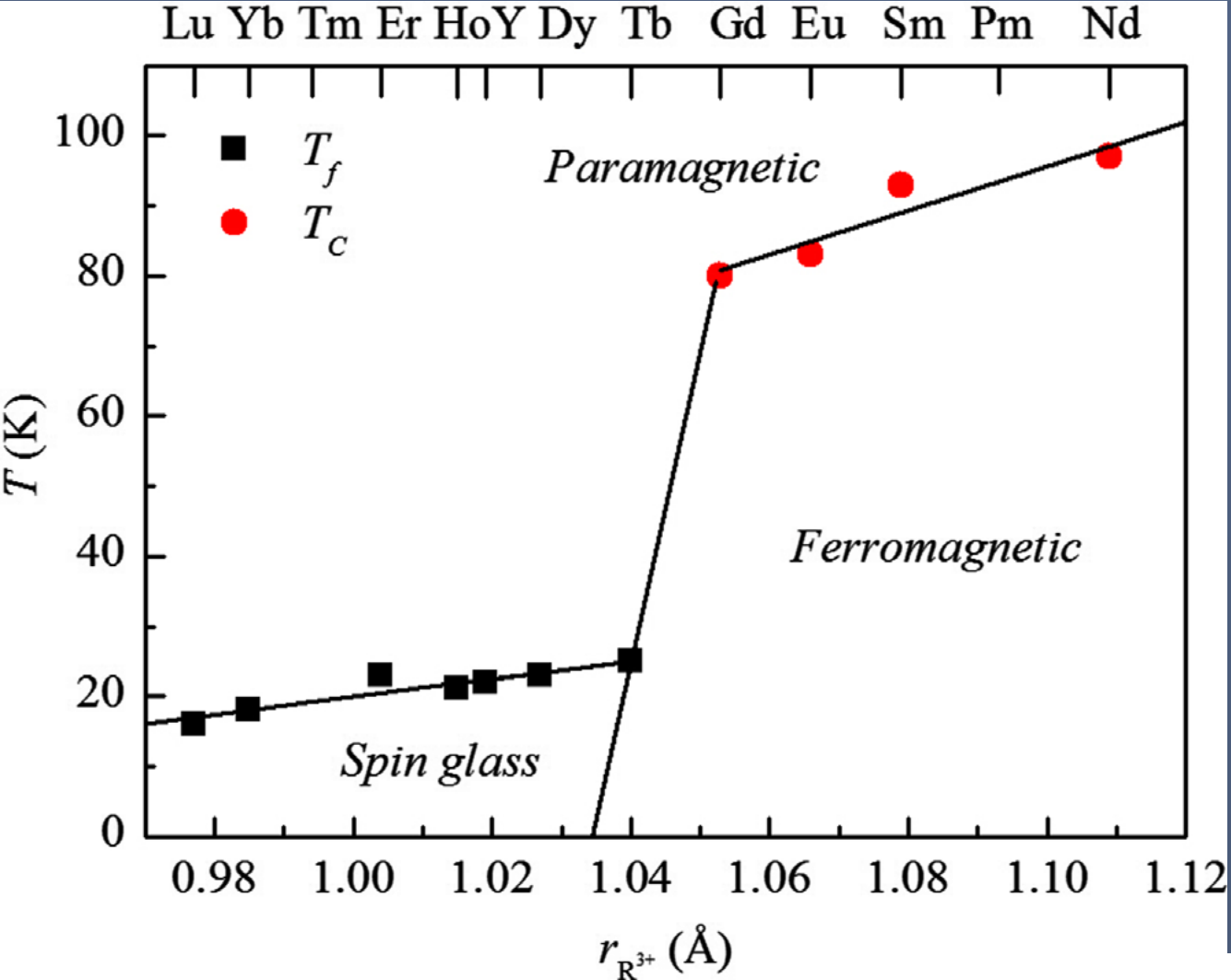


Rare Earth Molybdates
 $4d^2$

Comparing
Cubic Pyrochlore
Molybdates
and
Iridates

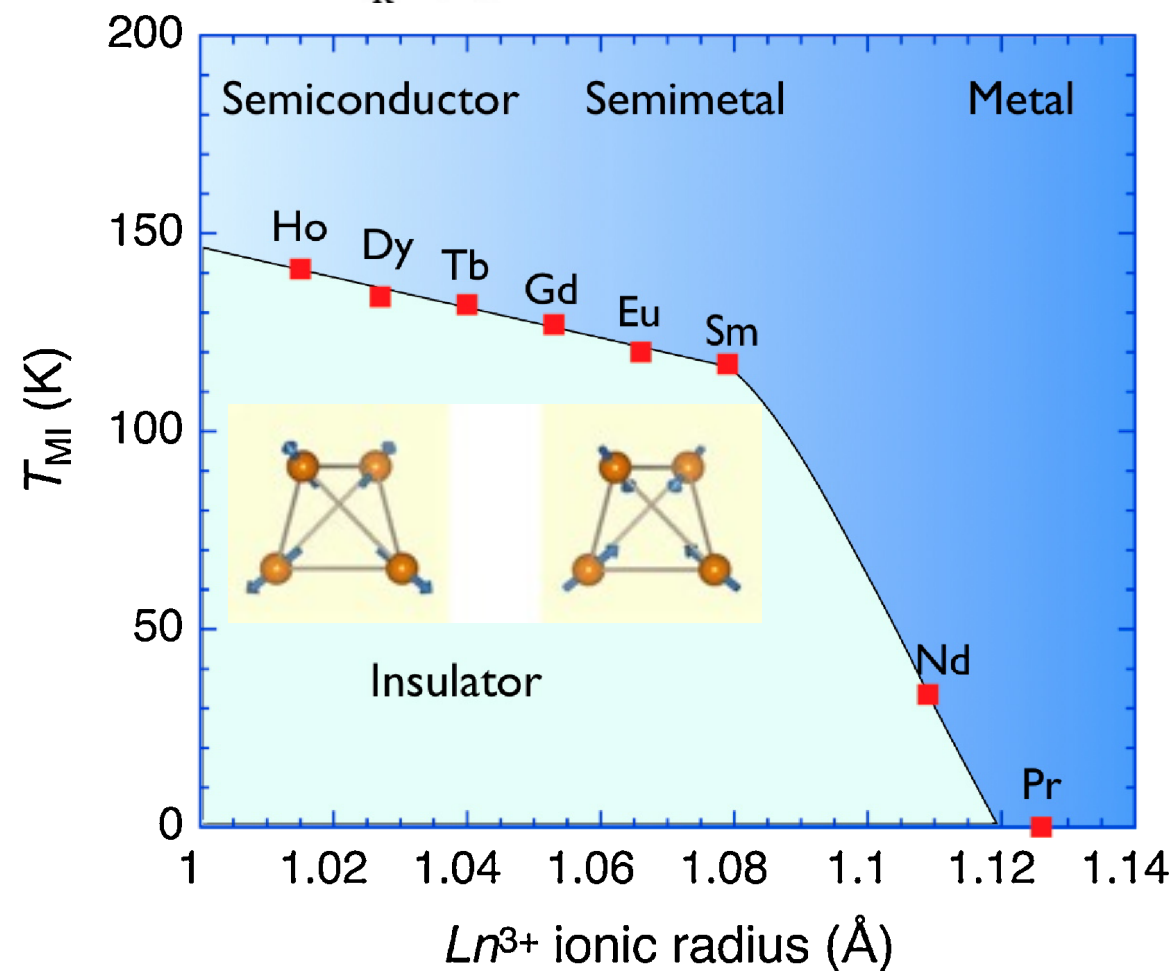


Rare Earth Iridates
 $5d^5$



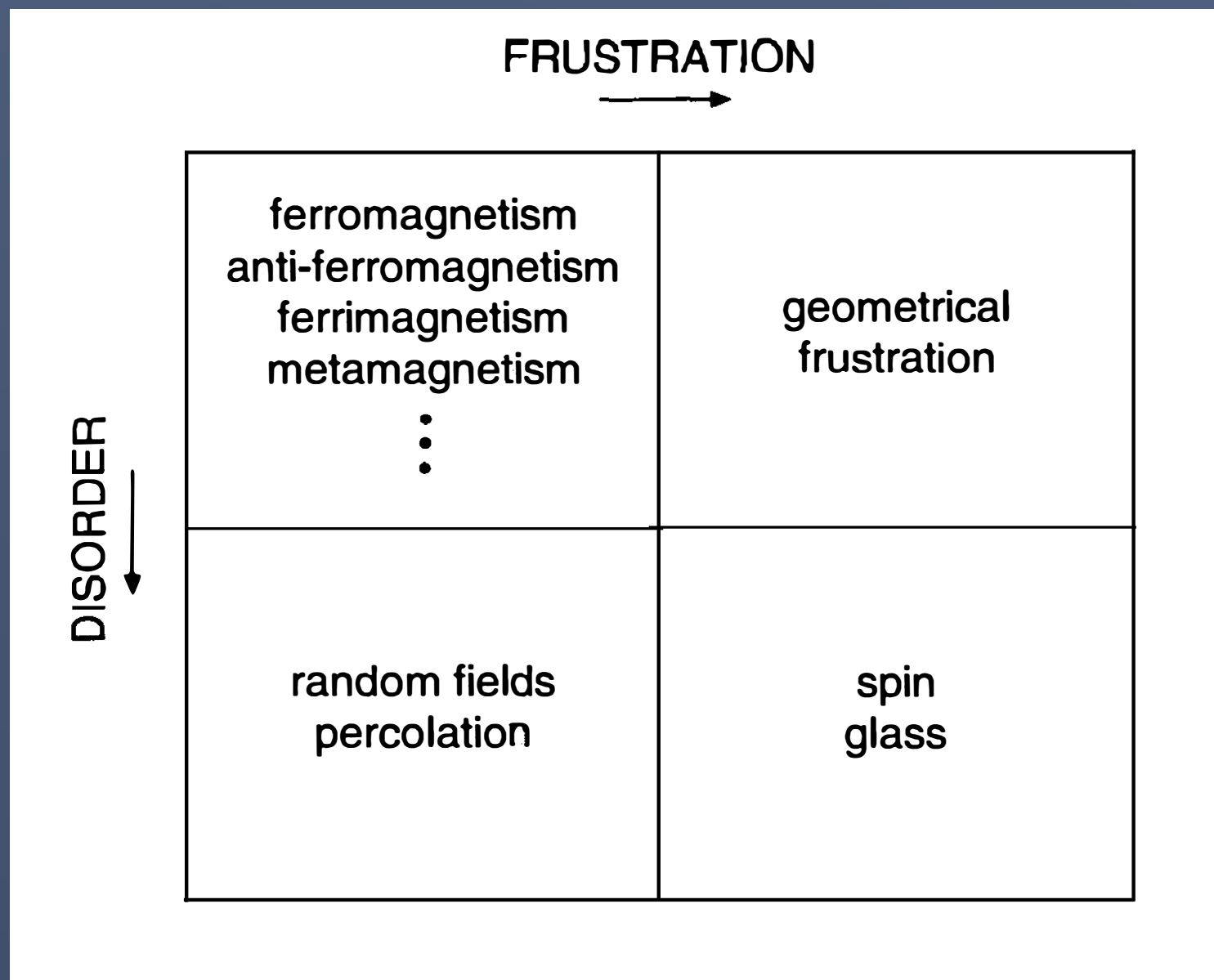
Rare Earth Molybdates
 $4d^2$

Comparing
Cubic Pyrochlore
Molybdates
and
Iridates

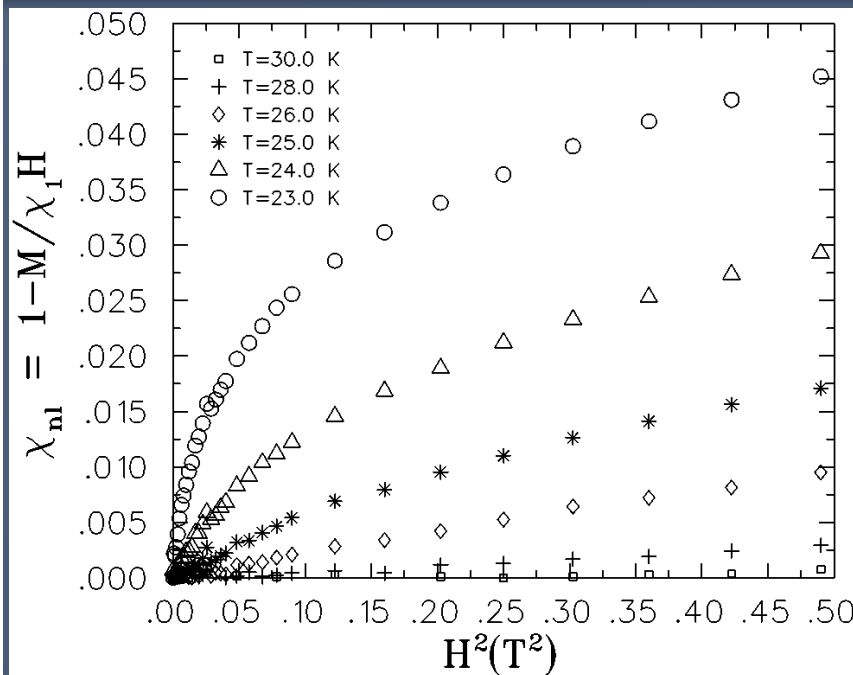
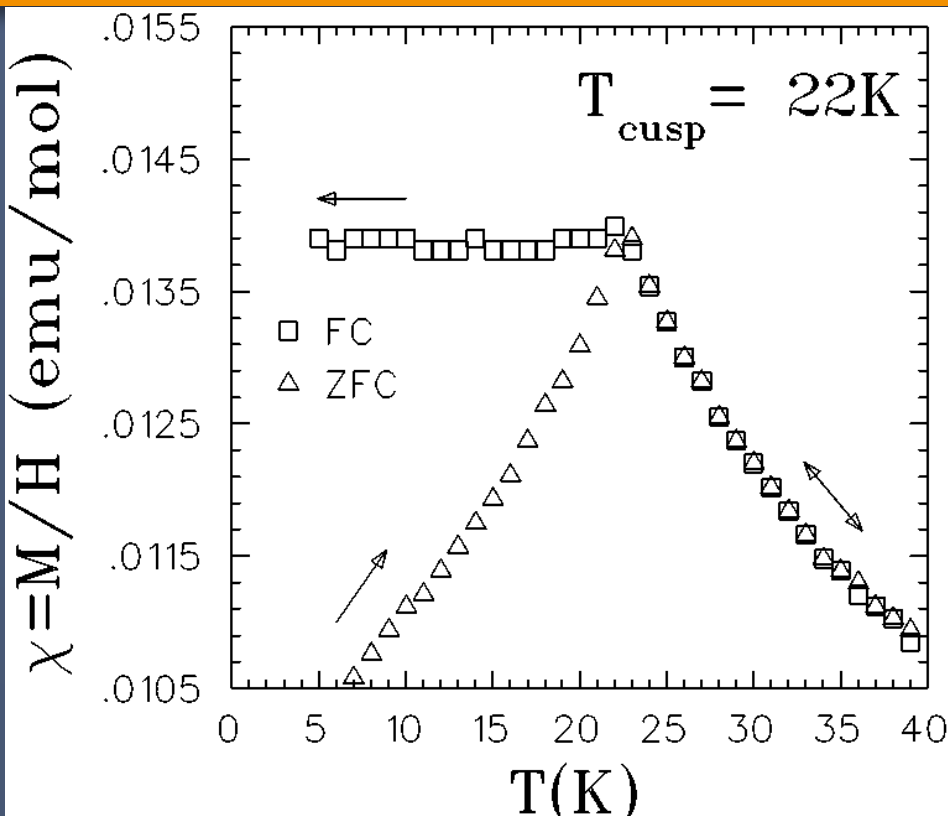


Rare Earth Iridates
 $5d^5$

Conventional View of Magnetic Ground States Selected by Frustration and Disorder

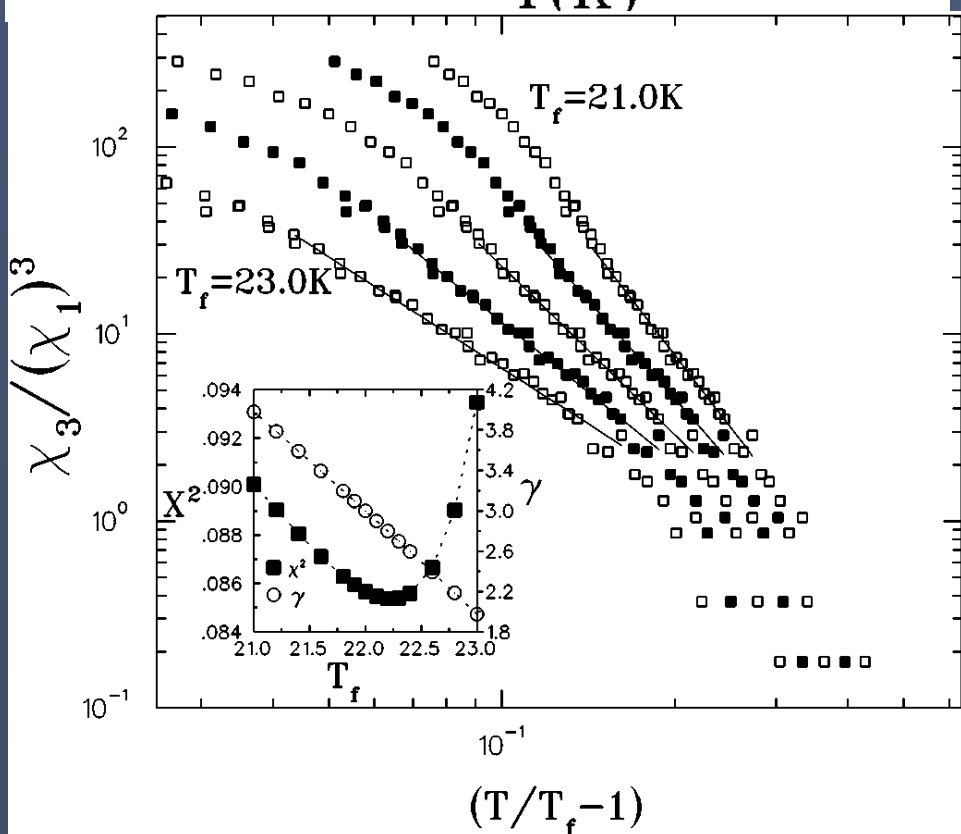


Spin Glass Transition at $T_f \sim 22$ K in $Y_2Mo_2O_7$

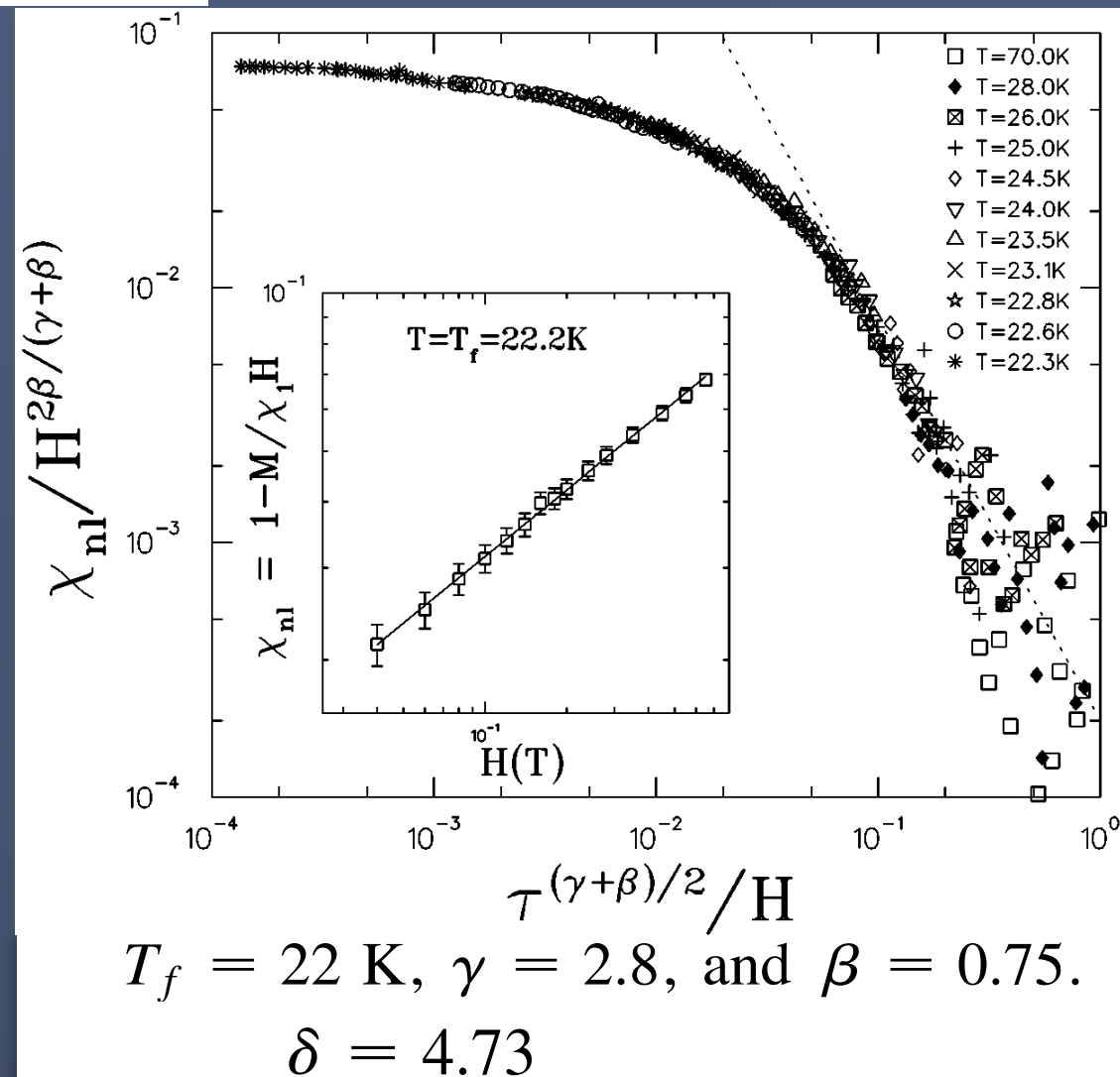


Thermodynamic
phase transition
at $T_f \sim 22$ K

Criticality typical of
random spin glasses

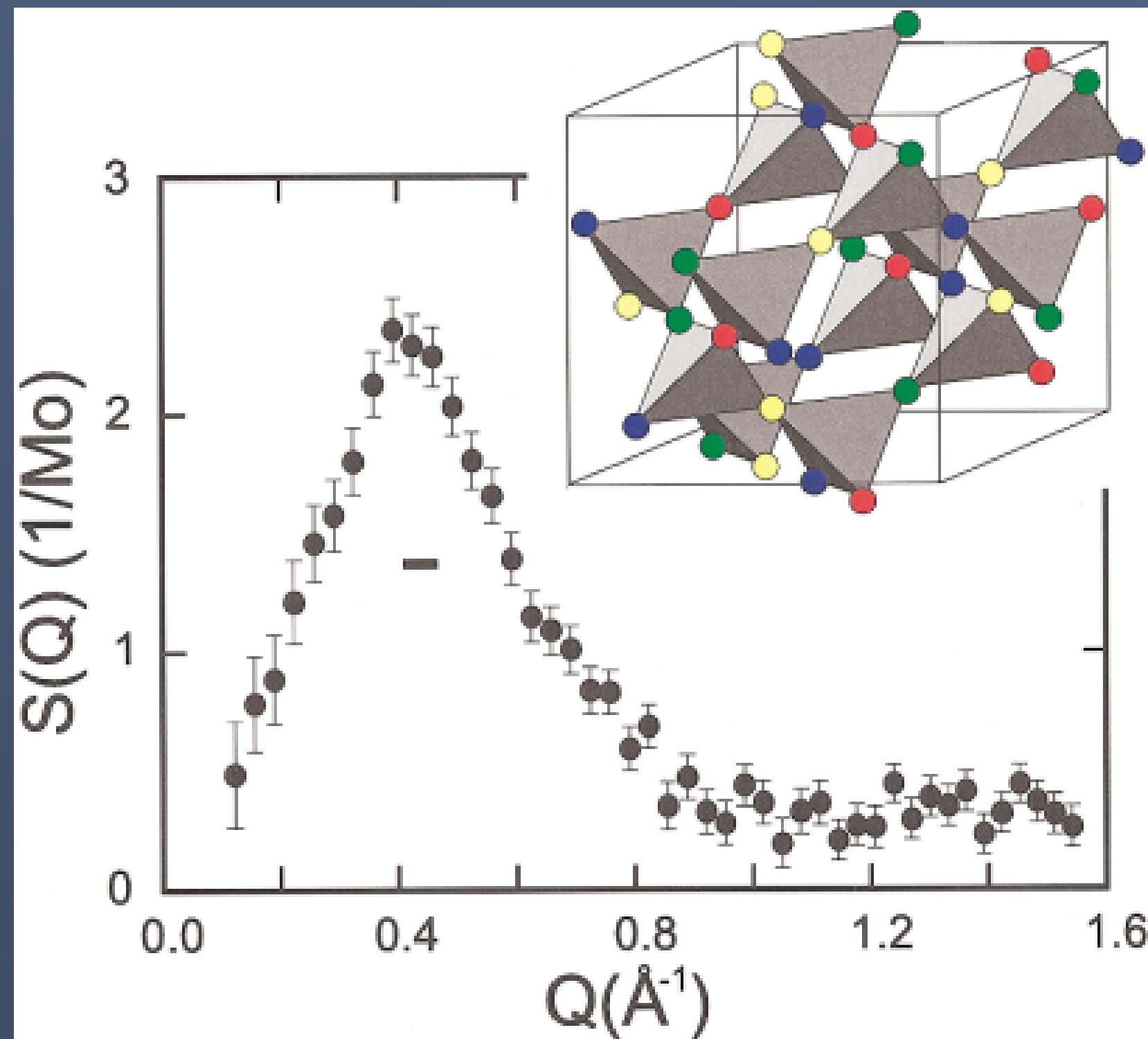


$T_{\text{CW}} \sim -200$ K
 $\mu_{\text{eff}} \sim 2.5 \mu_B$
 $S=1$ $\mu_{\text{eff}} = 2.83 \mu_B$



Elastic Neutron Scattering from $\text{Y}_2\text{Mo}_2\text{O}_7$

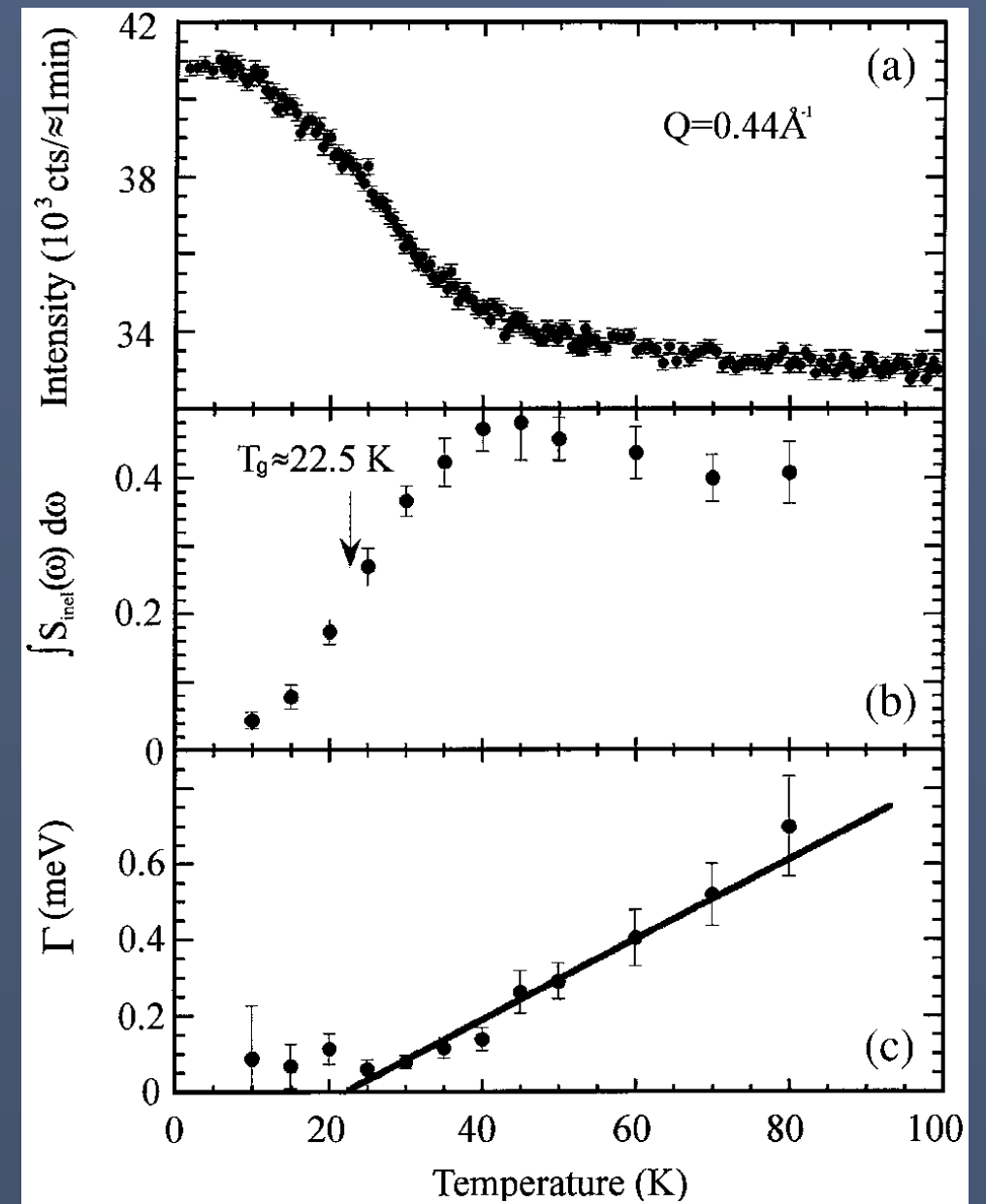
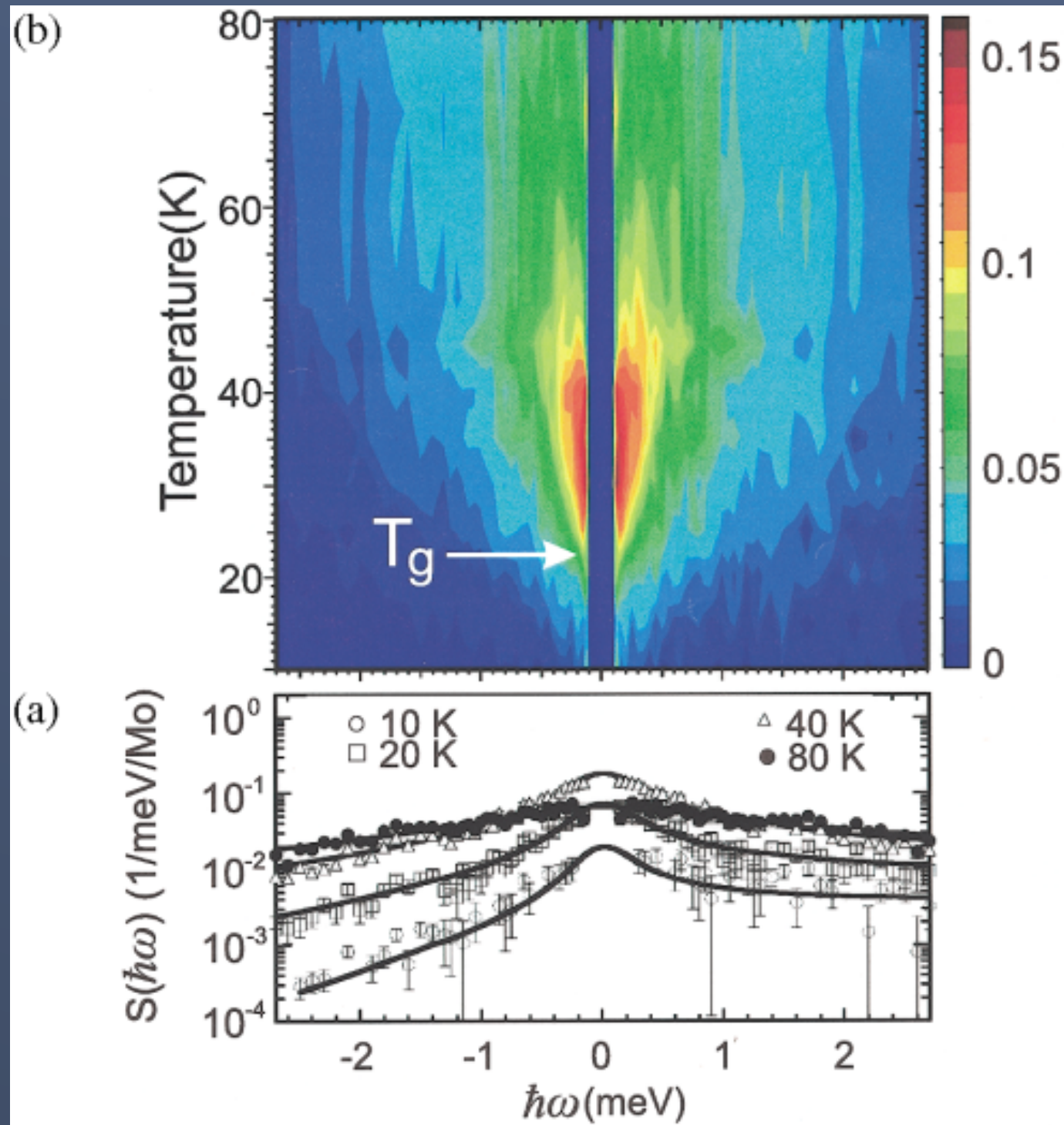
“Cluster Glass” with $Q_{\text{max}} \sim 0.44 \text{ \AA}^{-1}$



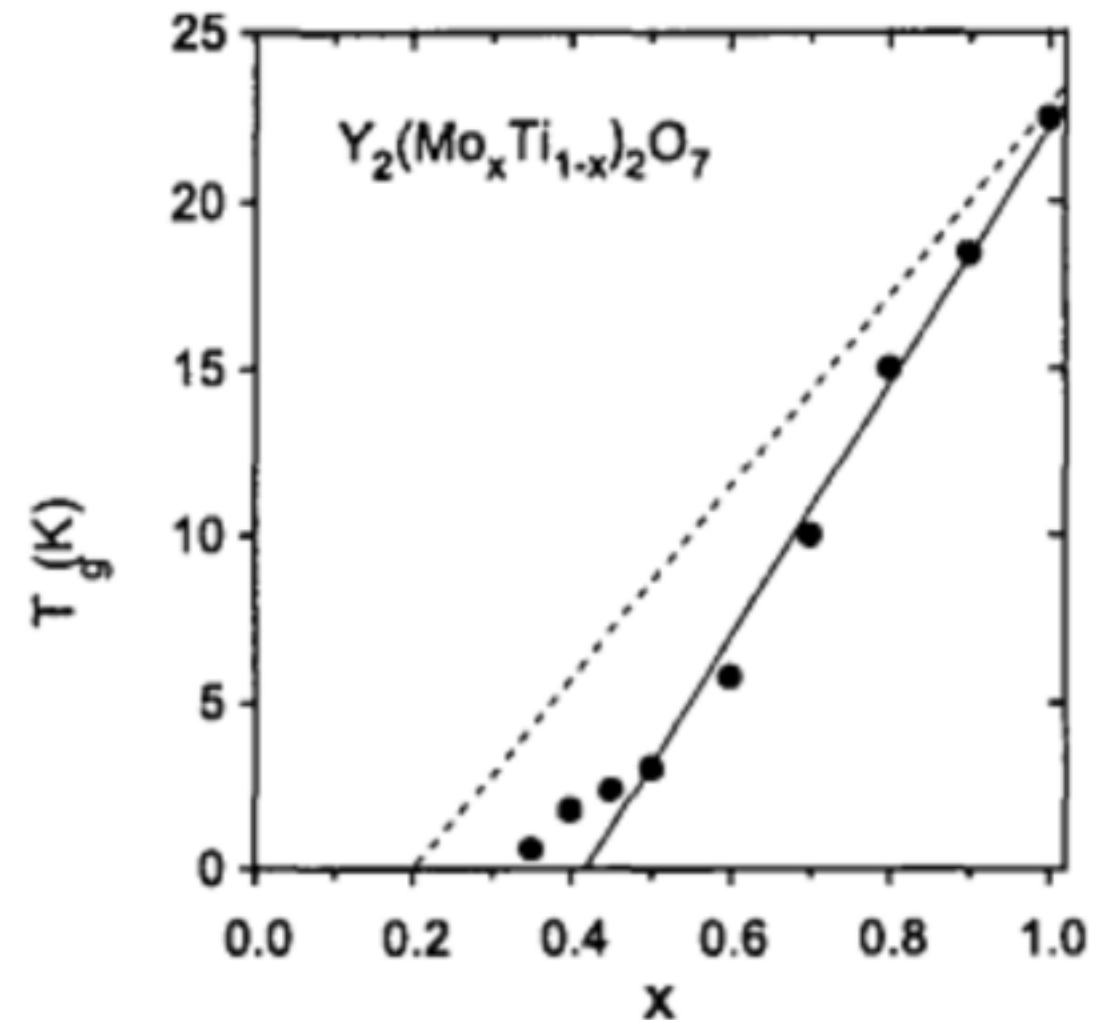
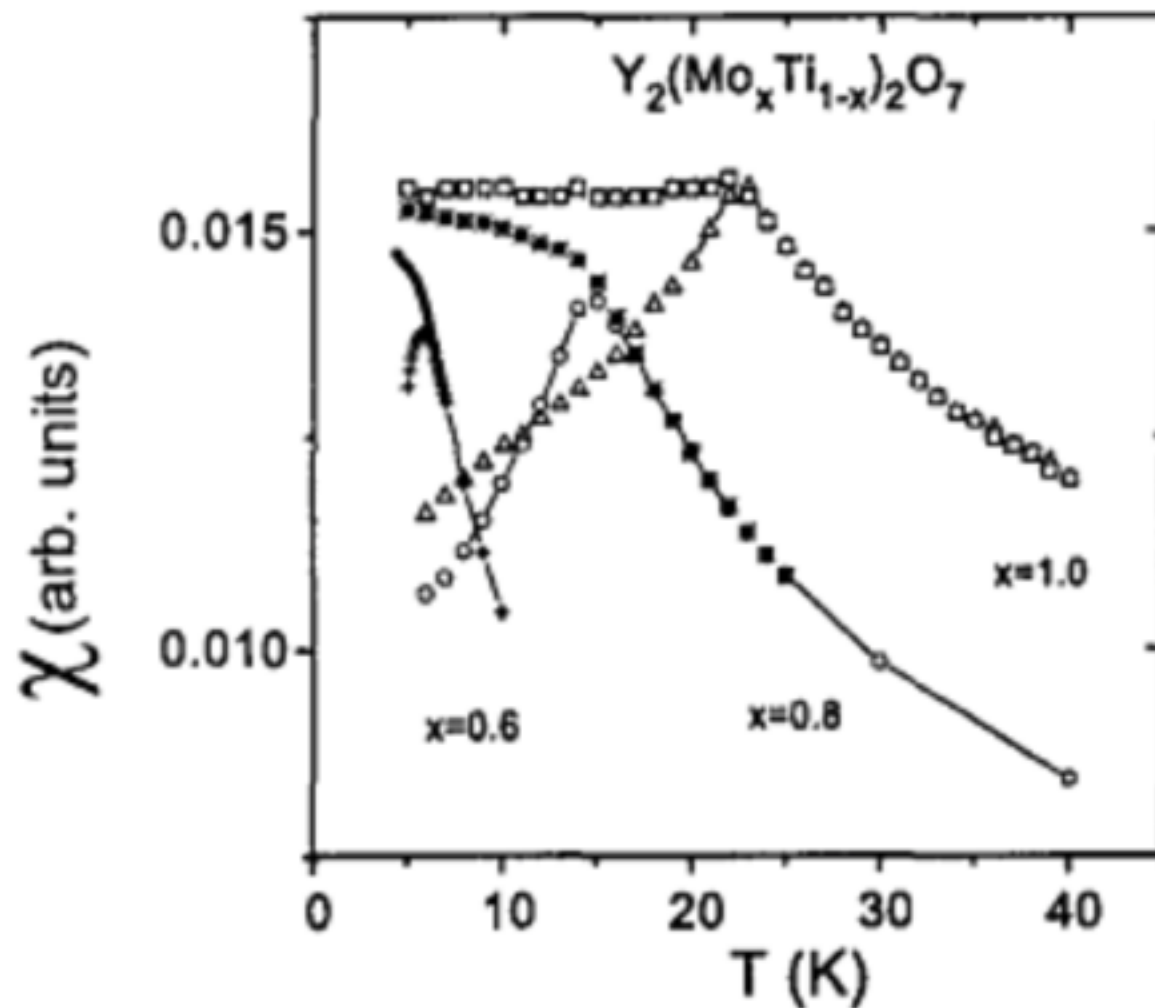
$T = 1.4 \text{ K} - 50 \text{ K}$

$$\xi \approx 1/\text{HWHM} \approx 5 \text{ \AA},$$

Inelastic Neutron Scattering from $\text{Y}_2\text{Mo}_2\text{O}_7$



3D Percolation: Just another ordered state?



Site substitution with non-magnetic Ti^{4+}

Structural Disorder in $\text{Y}_2\text{Mo}_2\text{O}_7$ definitely low, but is it measurable?

PHYSICAL REVIEW B **79**, 014427 (2009)



Local and average structures of the spin-glass pyrochlore $\text{Y}_2\text{Mo}_2\text{O}_7$ from neutron diffraction and neutron pair distribution function analysis

J. E. Greedan,¹ Delphine Gout,² A. D. Lozano-Gorrin,¹ Shahab Derahkshan,¹ Th. Proffen,³ H.-J. Kim,³ E. Božin,⁴ and S. J. L. Billinge⁴

Neutron PDF

- Weak Y-O' disorder
- No Mo-Mo disorder

RAPID COMMUNICATION

PHYSICAL REVIEW B

VOLUME 62, NUMBER 2

1 JULY 2000-II

Local lattice disorder in the geometrically frustrated spin-glass pyrochlore $\text{Y}_2\text{Mo}_2\text{O}_7$

C. H. Booth,^{1,2} J. S. Gardner,² G. H. Kwei,² R. H. Heffner,² F. Bridges,³ and M. A. Subramanian⁴

XAFS

- Weak Mo-Mo disorder

VOLUME 87, NUMBER 17

PHYSICAL REVIEW LETTERS

22 OCTOBER 2001

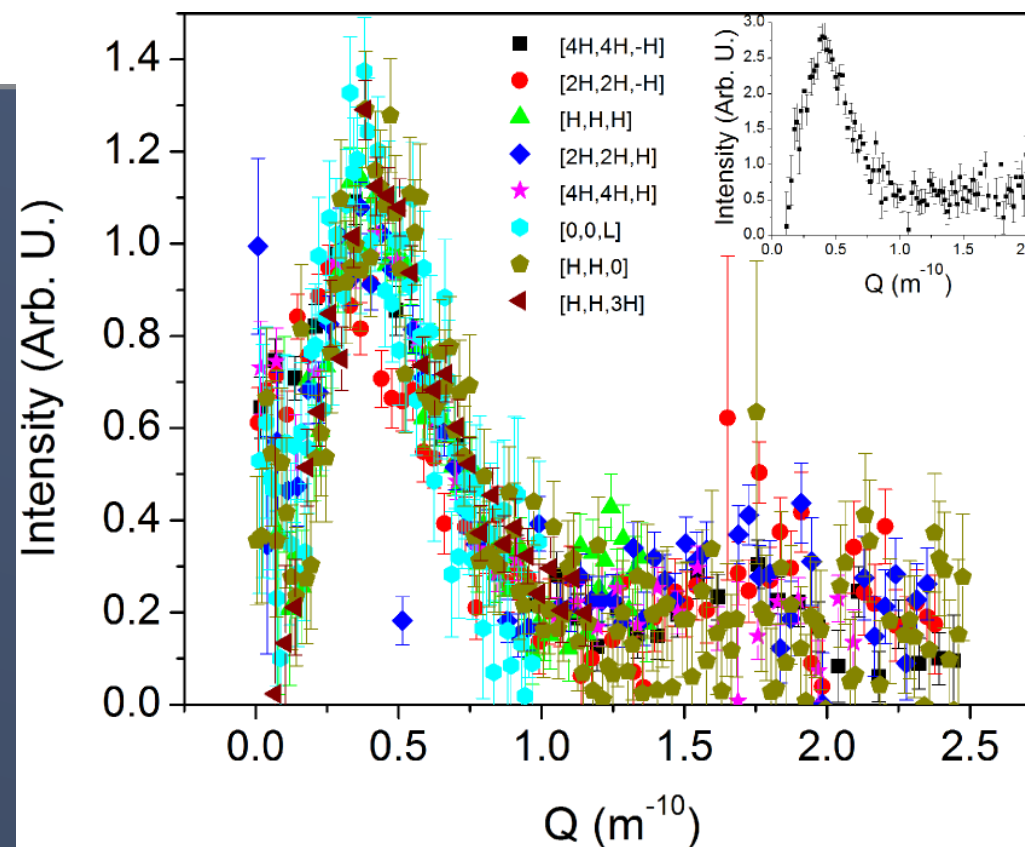
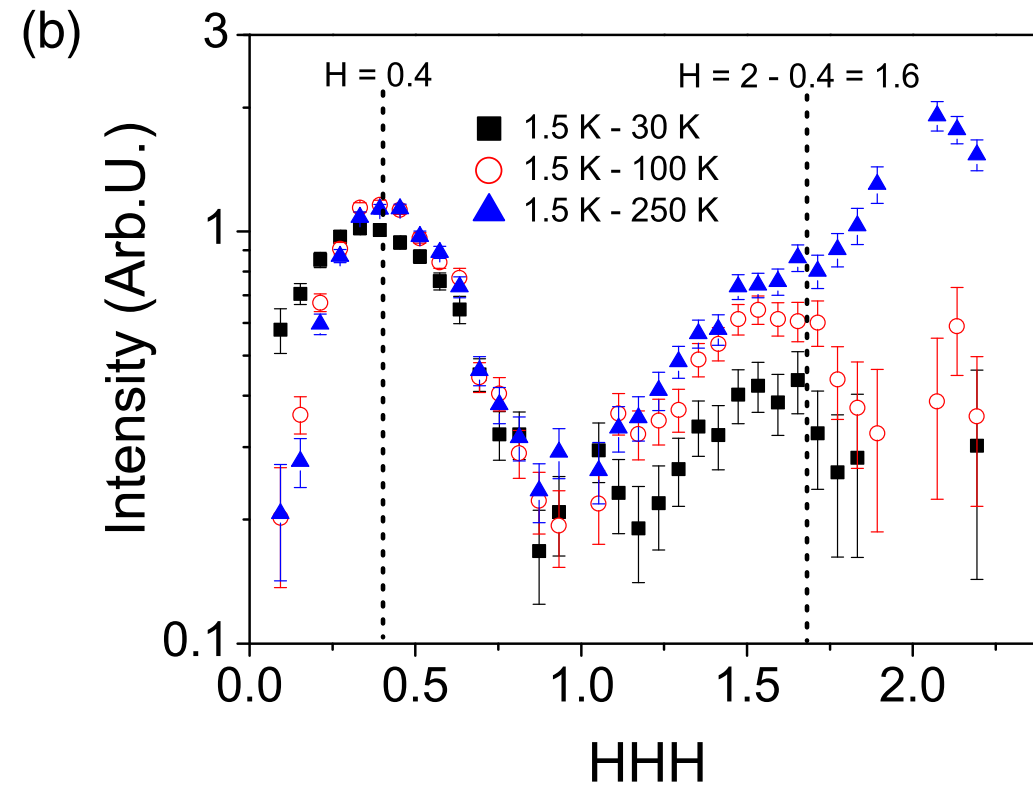
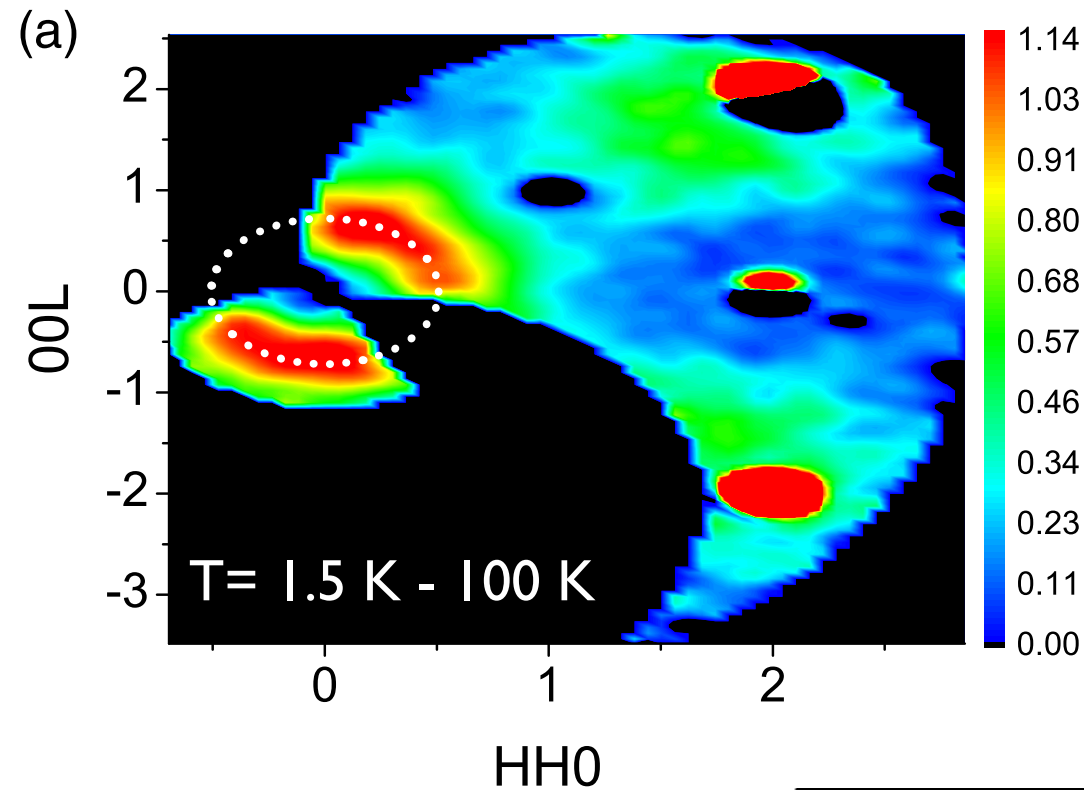
Frustration Driven Lattice Distortion: An NMR Investigation of $\text{Y}_2\text{Mo}_2\text{O}_7$

Amit Keren¹ and Jason S. Gardner²

^{89}Y NMR

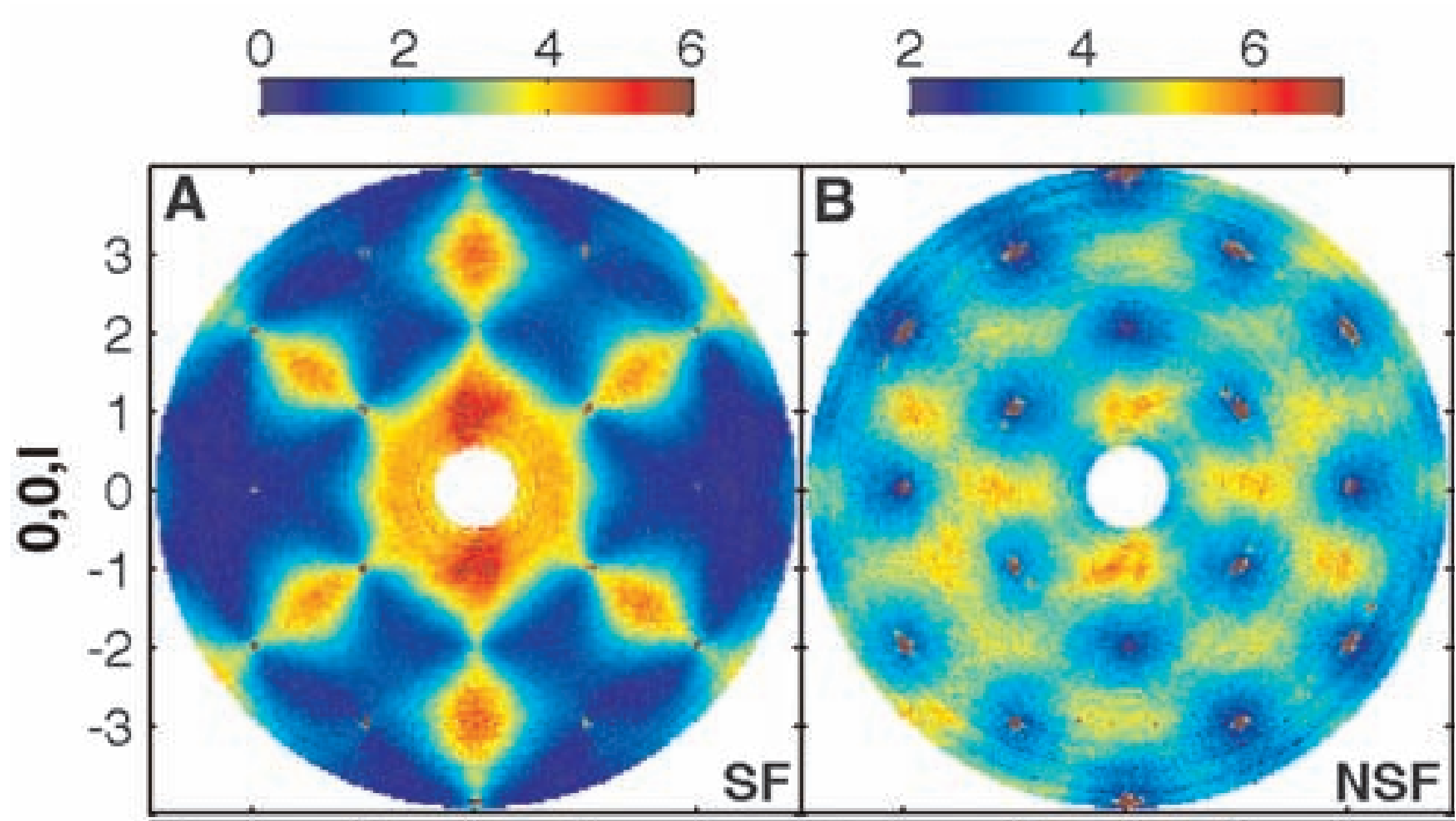
- Weak Mo-Mo disorder

Single Crystal Samples: Real Liquid Correlations!



Silverstein et al.,
PRB, 89, 054433, 2014

Spin Ice Ground State in $\text{Ho}_2\text{Ti}_2\text{O}_7$



T. Fennell et al., Science, 326 (5951): 415-417 (2009)

Oxygen miscibility gap in $\text{Lu}_2\text{Mo}_2\text{O}_7$

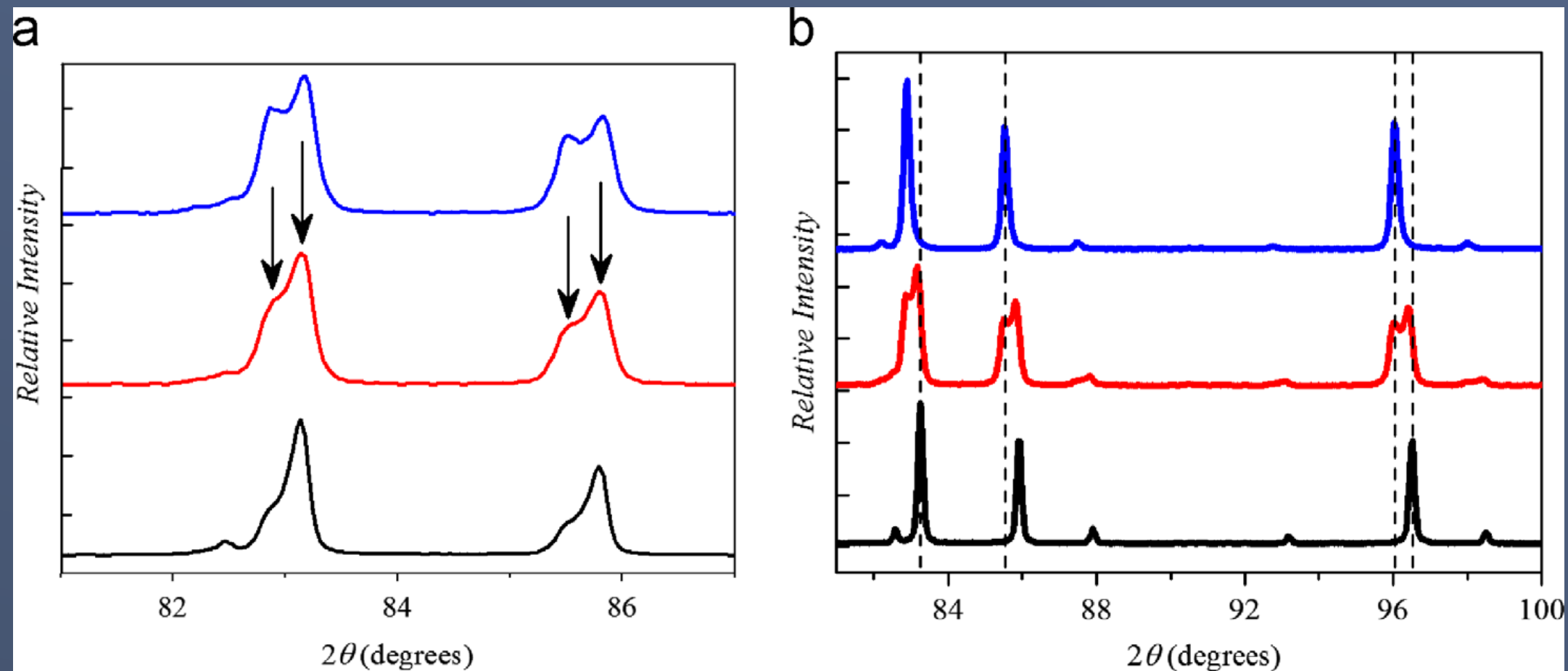
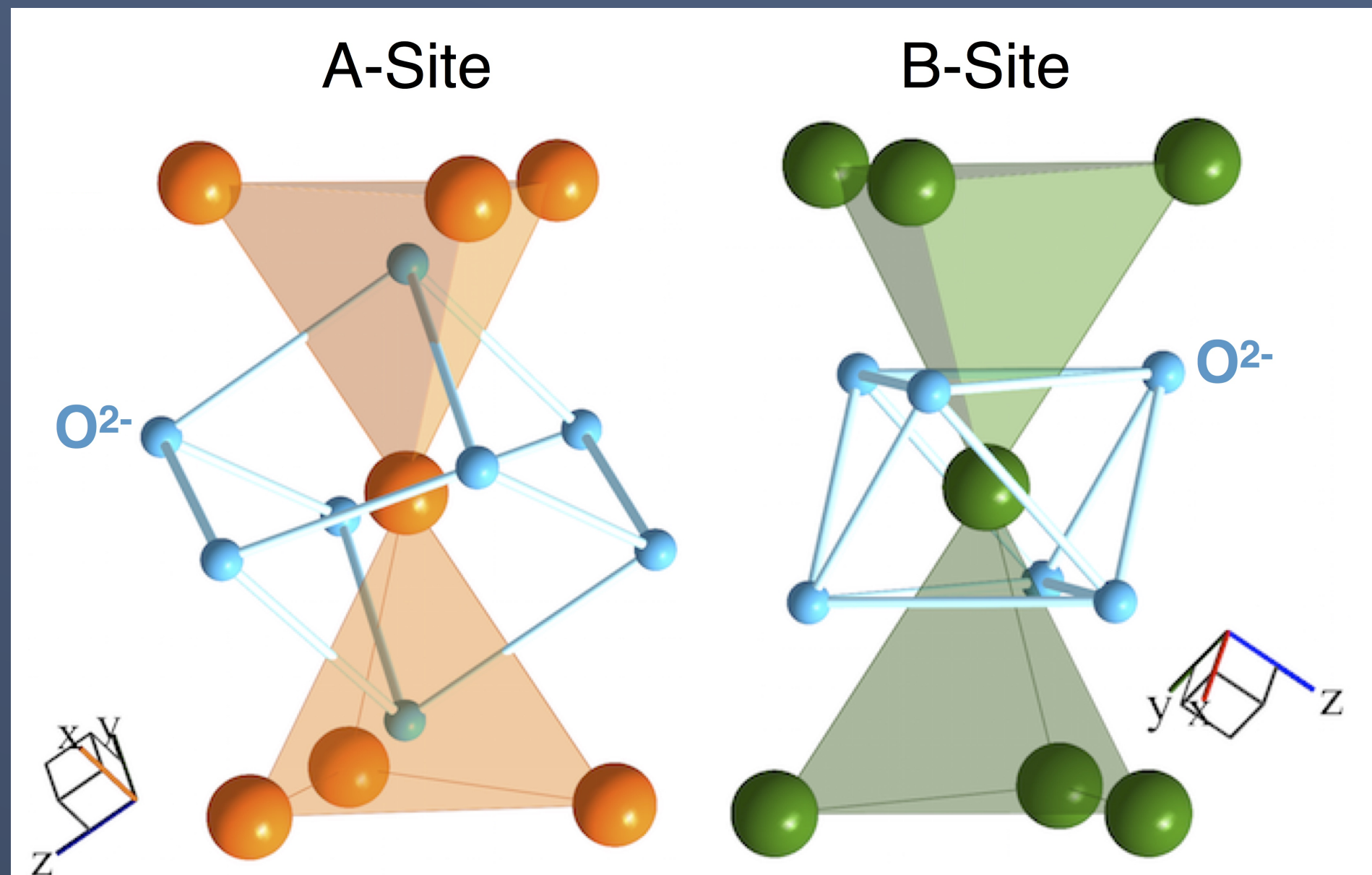


Table 1
 Refined atomic coordinates and occupancies for $\text{Lu}_2\text{Mo}_2\text{O}_7$ ($a=10.1478(1) \text{ \AA}$) and $\text{Lu}_2\text{Mo}_2\text{O}_{6.69(6)}$ ($a=10.1789(1) \text{ \AA}$). Isotropic U-factors were $0.0091(2) \text{ \AA}^2$ for metal cations and $0.0152(3) \text{ \AA}^2$ for oxygen sites. Residuals for the combined refinement were $R_{wp}=5.83\%$, and $\chi^2=6.9$.

Atom	Site	<i>x</i>	<i>y</i>	<i>z</i>	Occupancy
Lu	16 <i>d</i>	0.5	0.5	0.5	1.0
Mo	16 <i>c</i>	0.0	0.0	0.0	1.0
O	48 <i>f</i>	0.3417(1)	0.125	0.125	1.0
		0.3477(1)			0.97(1)
O'	8 <i>b</i>	0.375	0.375	0.375	1.0
					0.87(2)

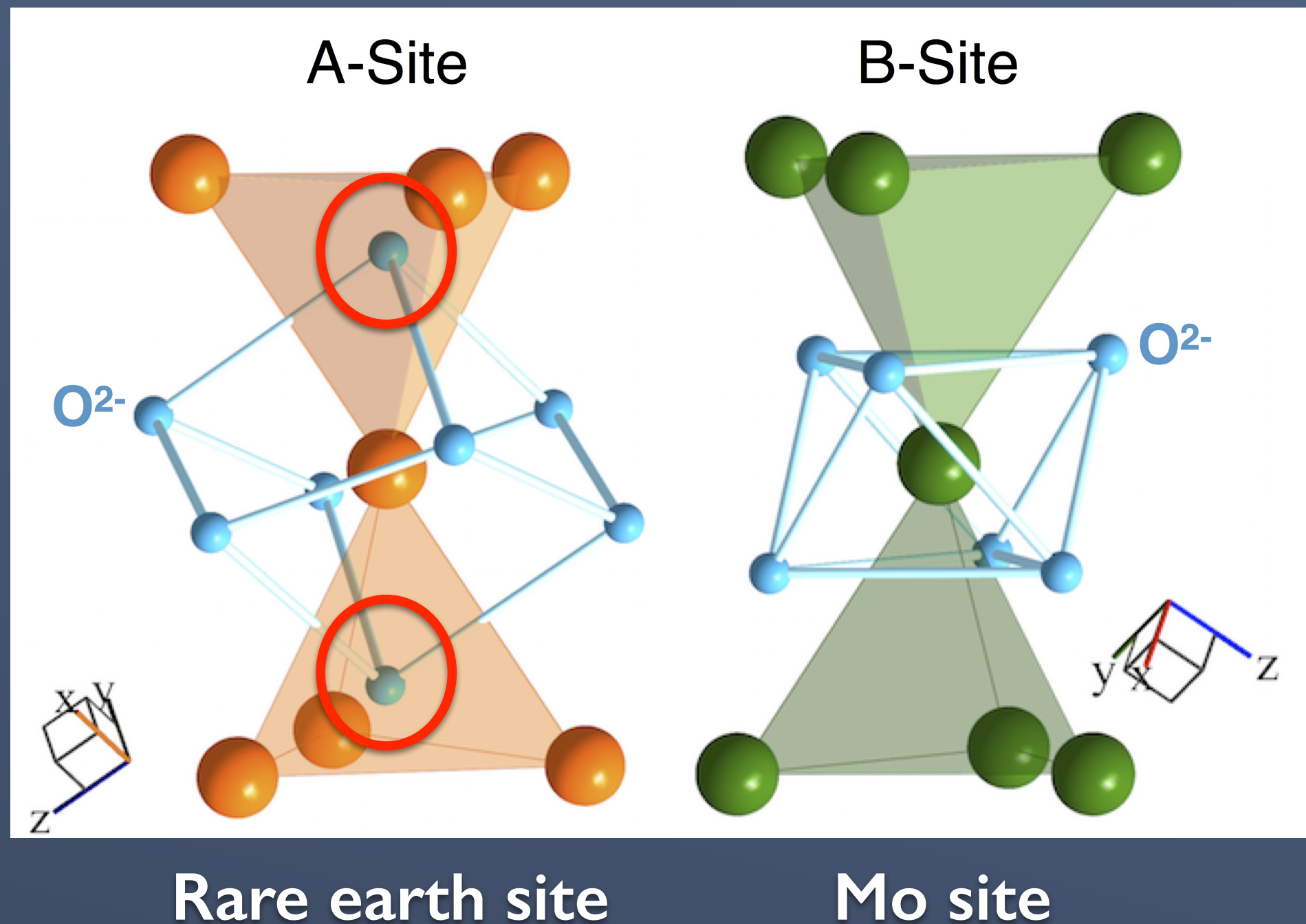
L. Clark et al.,
 J. Sol. State Chem, 203, 199, 2013

Local environments at the A^{3+} and B^{4+} sites:

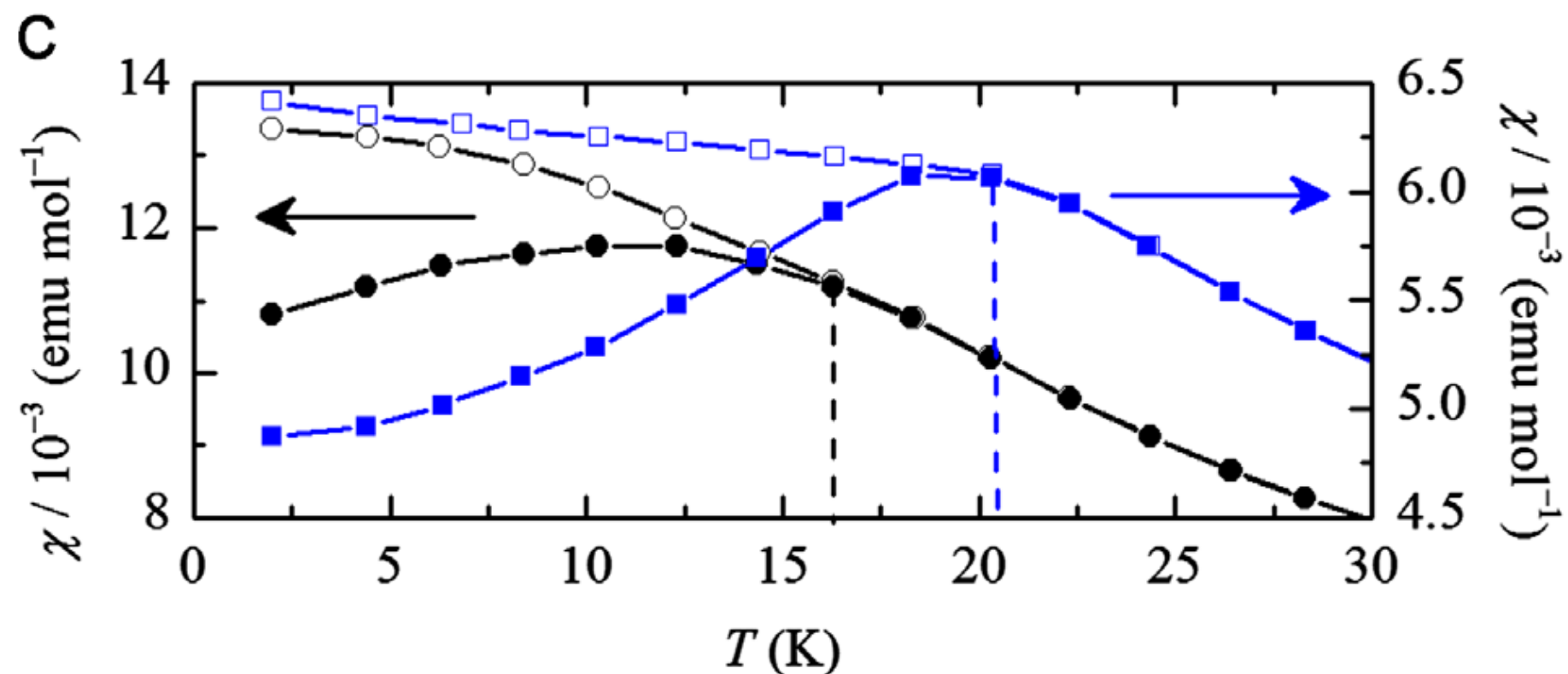
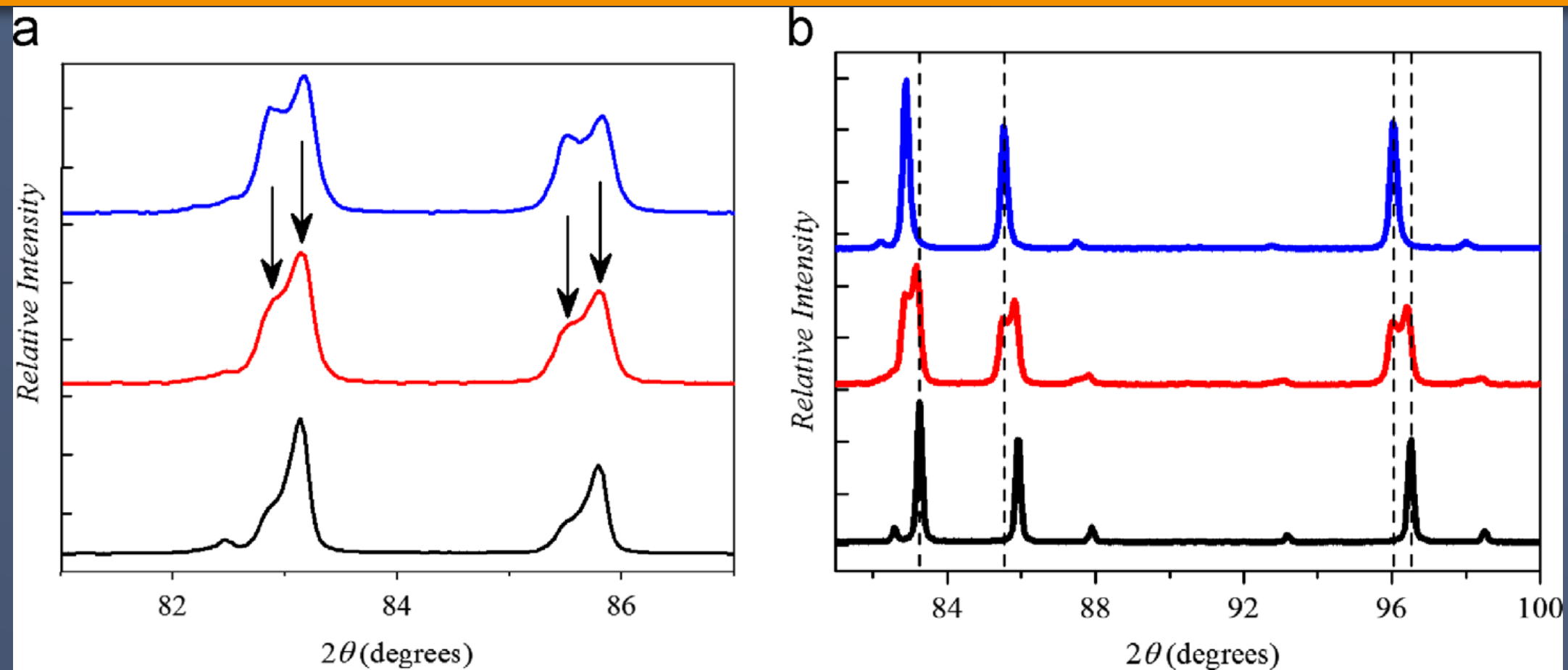


Local environments at the A^{3+} and B^{4+} sites:

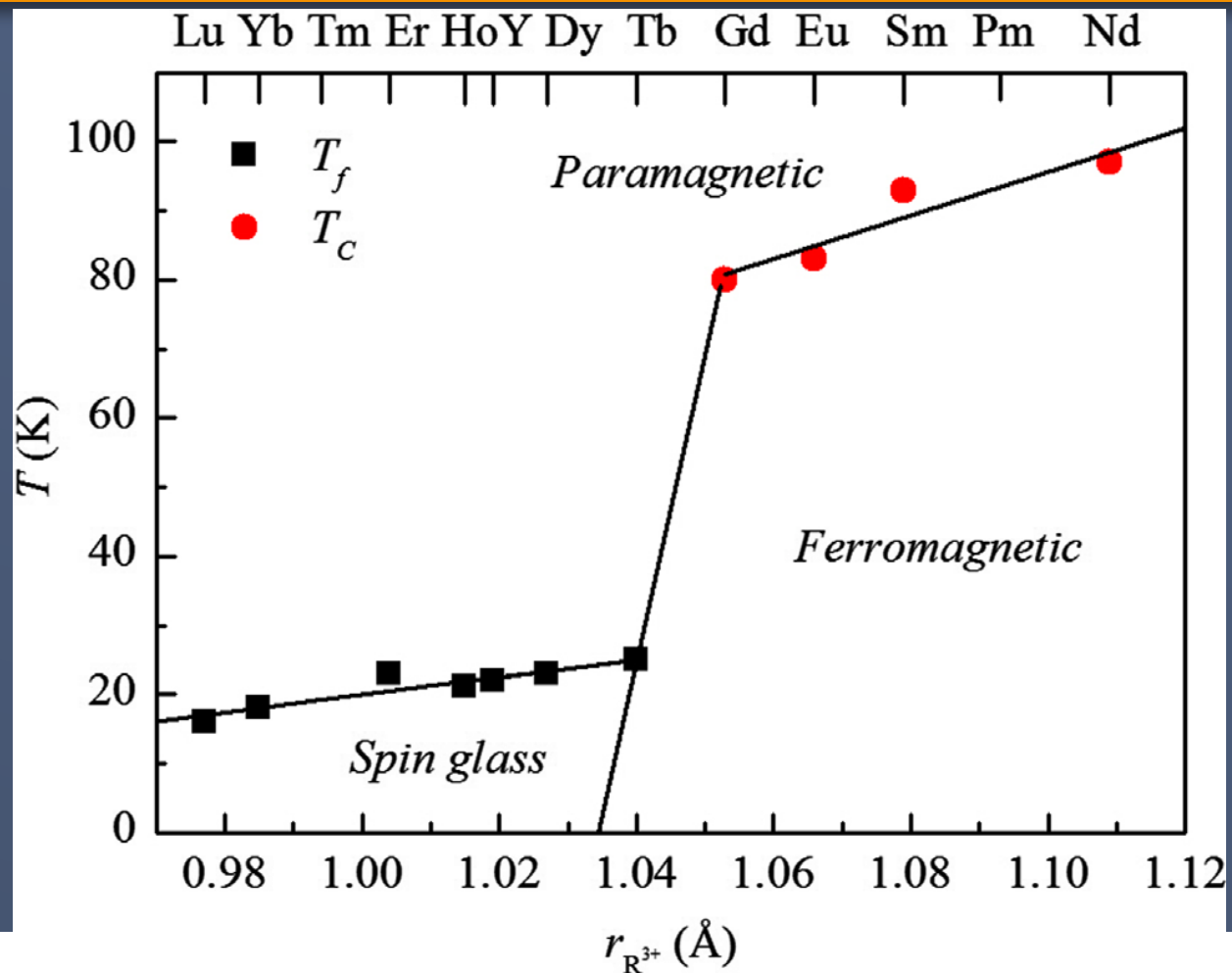
$\text{Lu}_2\text{Mo}_2\text{O}_{6.7}$ oxygen deficiency is primarily at the O' site



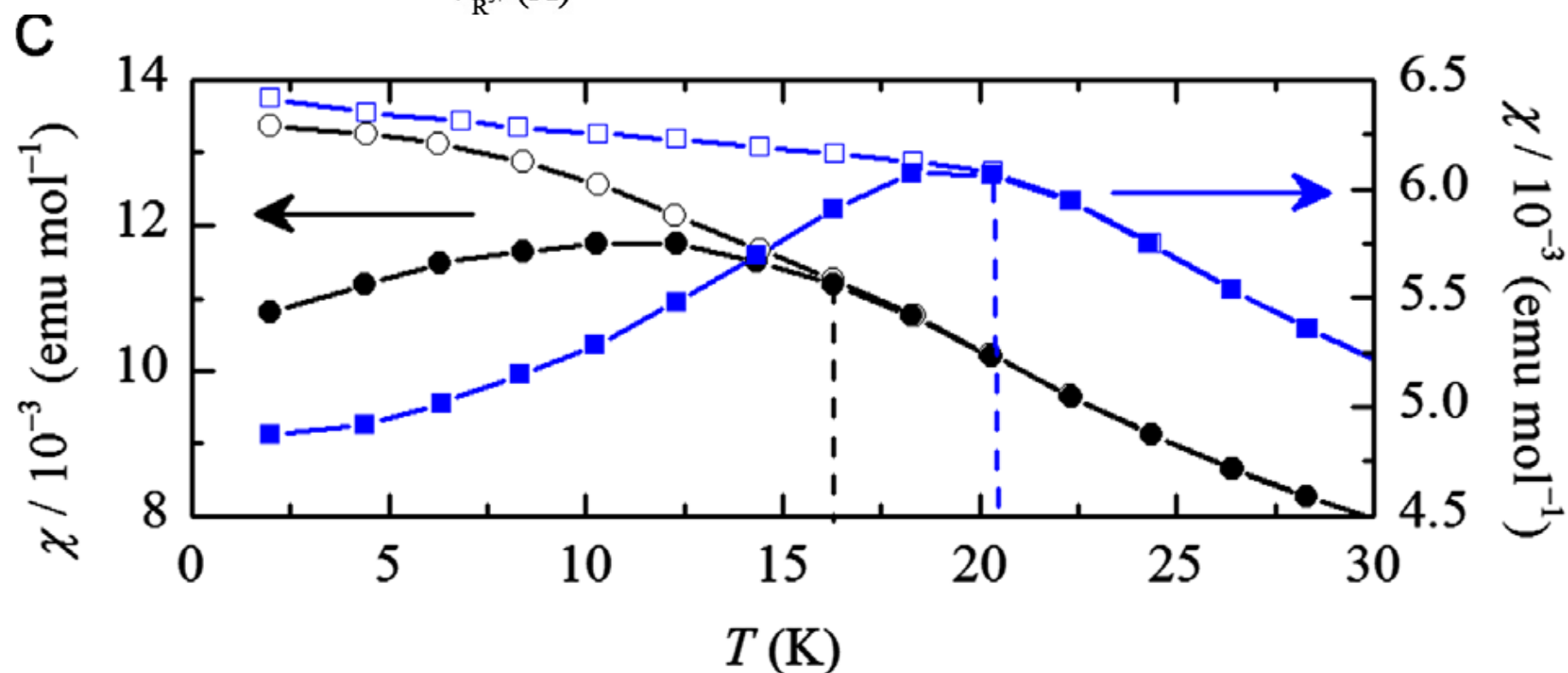
Synthesize either $\text{Lu}_2\text{Mo}_2\text{O}_7$ or $\text{Lu}_2\text{Mo}_2\text{O}_{6.7}$



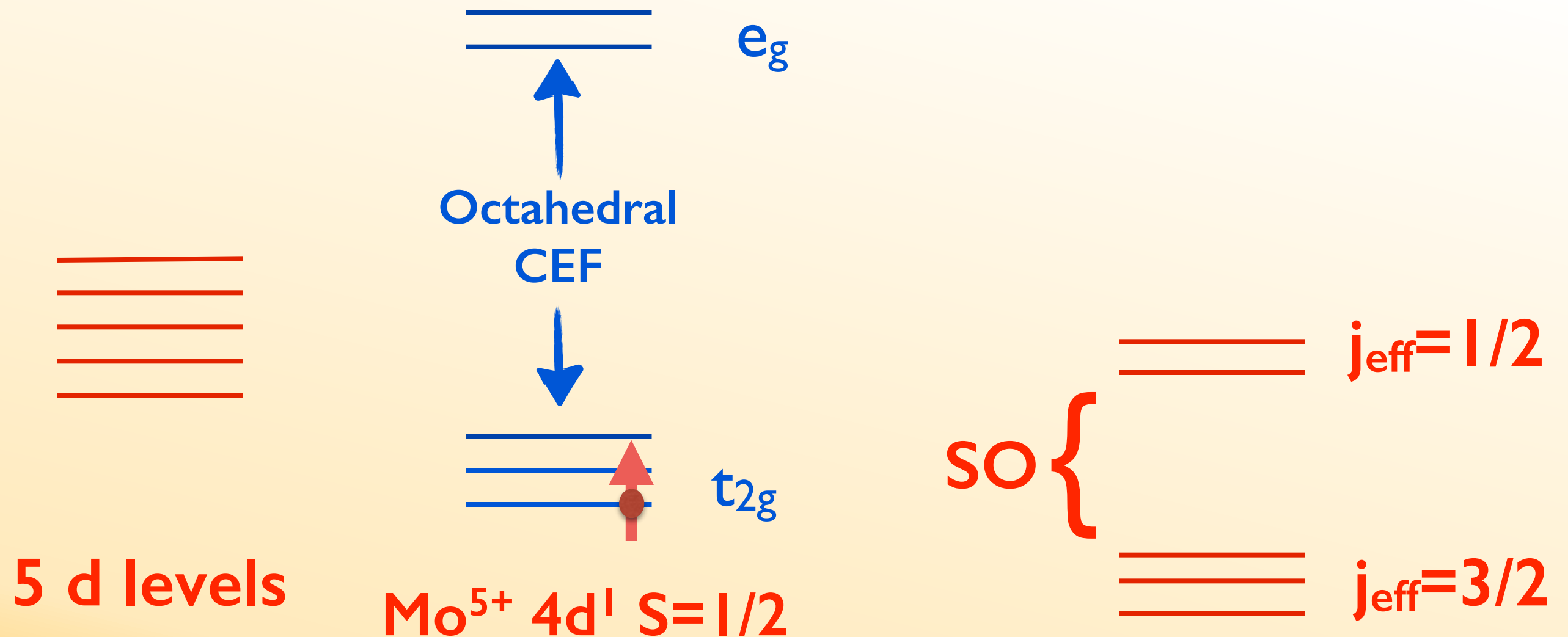
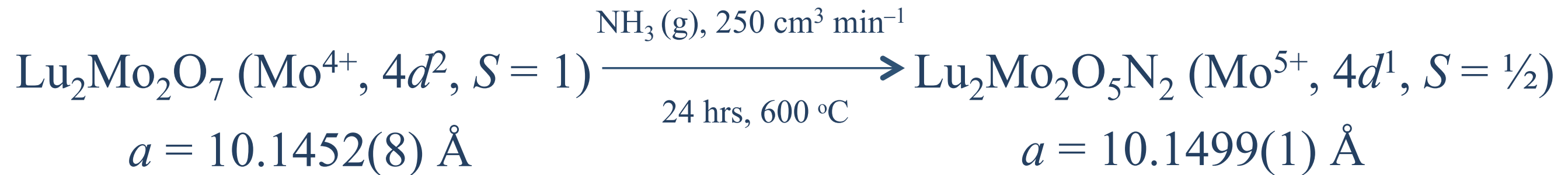
Lu₂Mo₂O₇ vs Lu₂Mo₂O_{6.7}



Increase in T_f due
in part
to expansion of the lattice



Topochemical nitration of $\text{Lu}_2\text{Mo}_2\text{O}_7$



Topochemical nitration of Lu₂Mo₂O₇

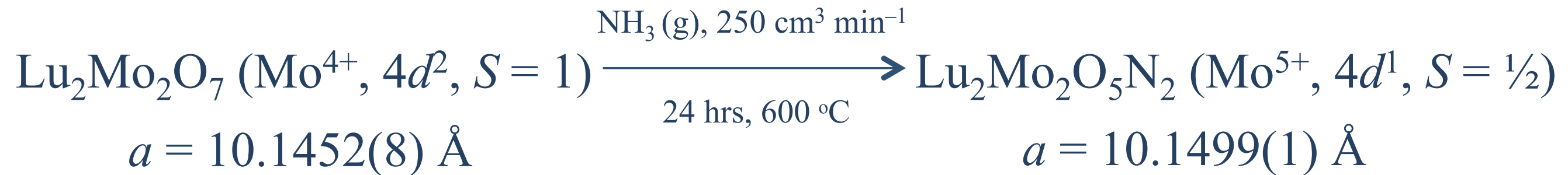


TABLE I. Refined atomic coordinates and occupancies for Lu₂Mo₂O_{4.8}N_{1.7} ($a = 10.1428(2) \text{ \AA}$). Isotropic thermal parameters were $0.0337(6) \text{ \AA}^2$ for metal cations and $0.0398(6) \text{ \AA}^2$ for anion sites. Total $R_{wp} = 2.21 \%$, $\chi^2 = 14.58$ for 64 variables.

Atom	Site	x	y	z	Occupancy
Lu	16 <i>d</i>	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1.0
Mo	16 <i>c</i>	0	0	0	1.0
O/N	48 <i>f</i>	0.3477(1)	$\frac{1}{8}$	$\frac{1}{8}$	0.663(2)/0.257
O'/N'	8 <i>b</i>	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	0.831/0.169

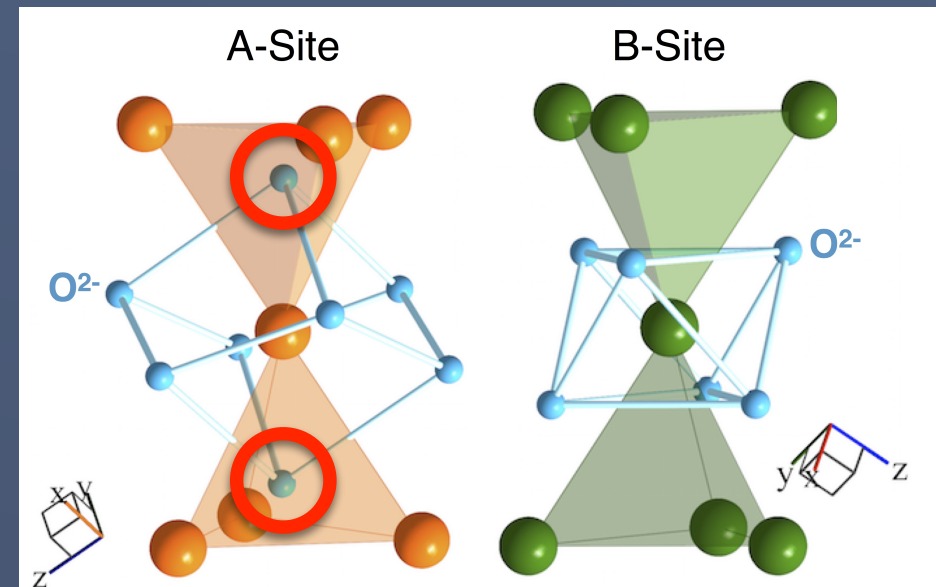
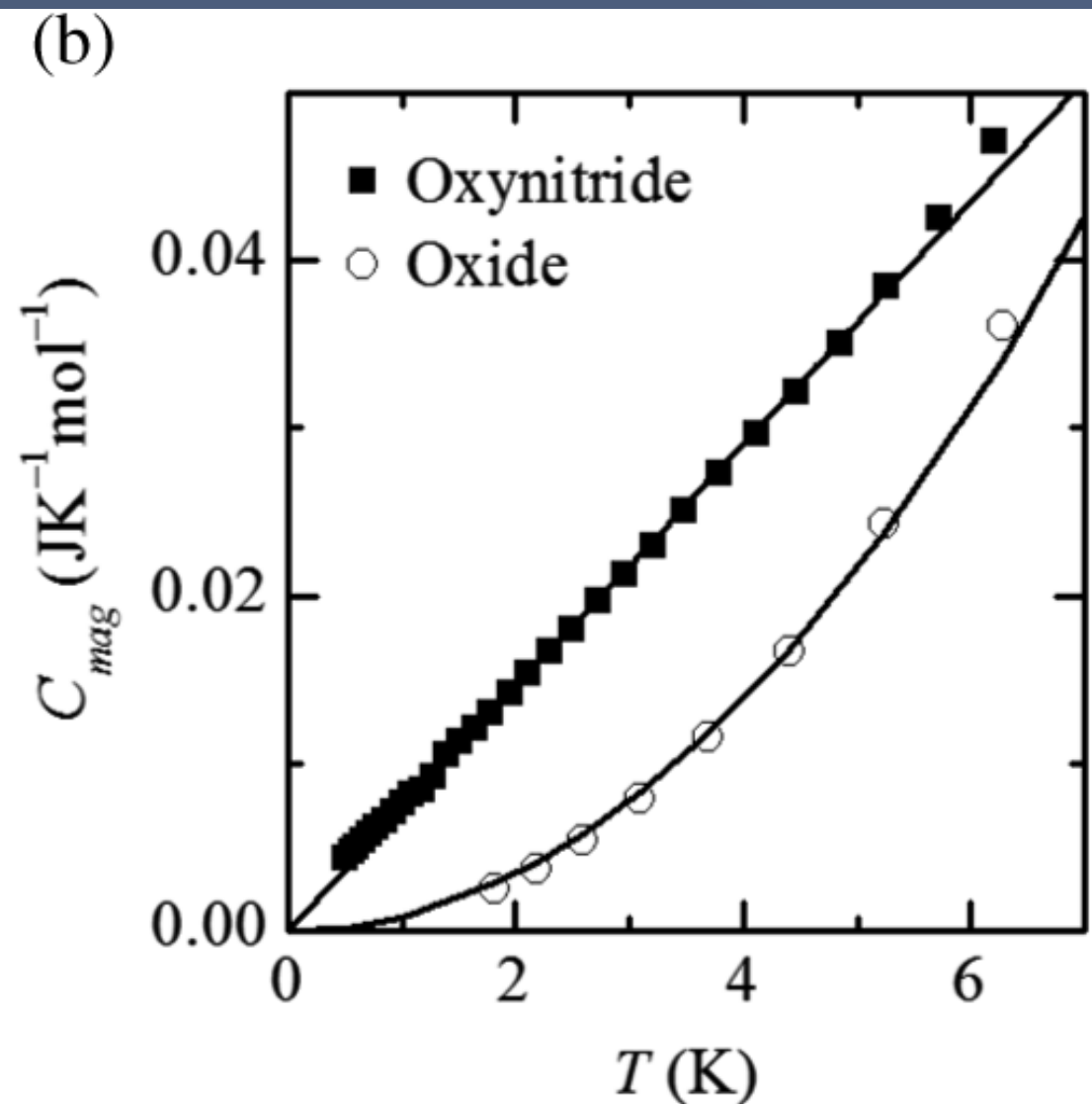
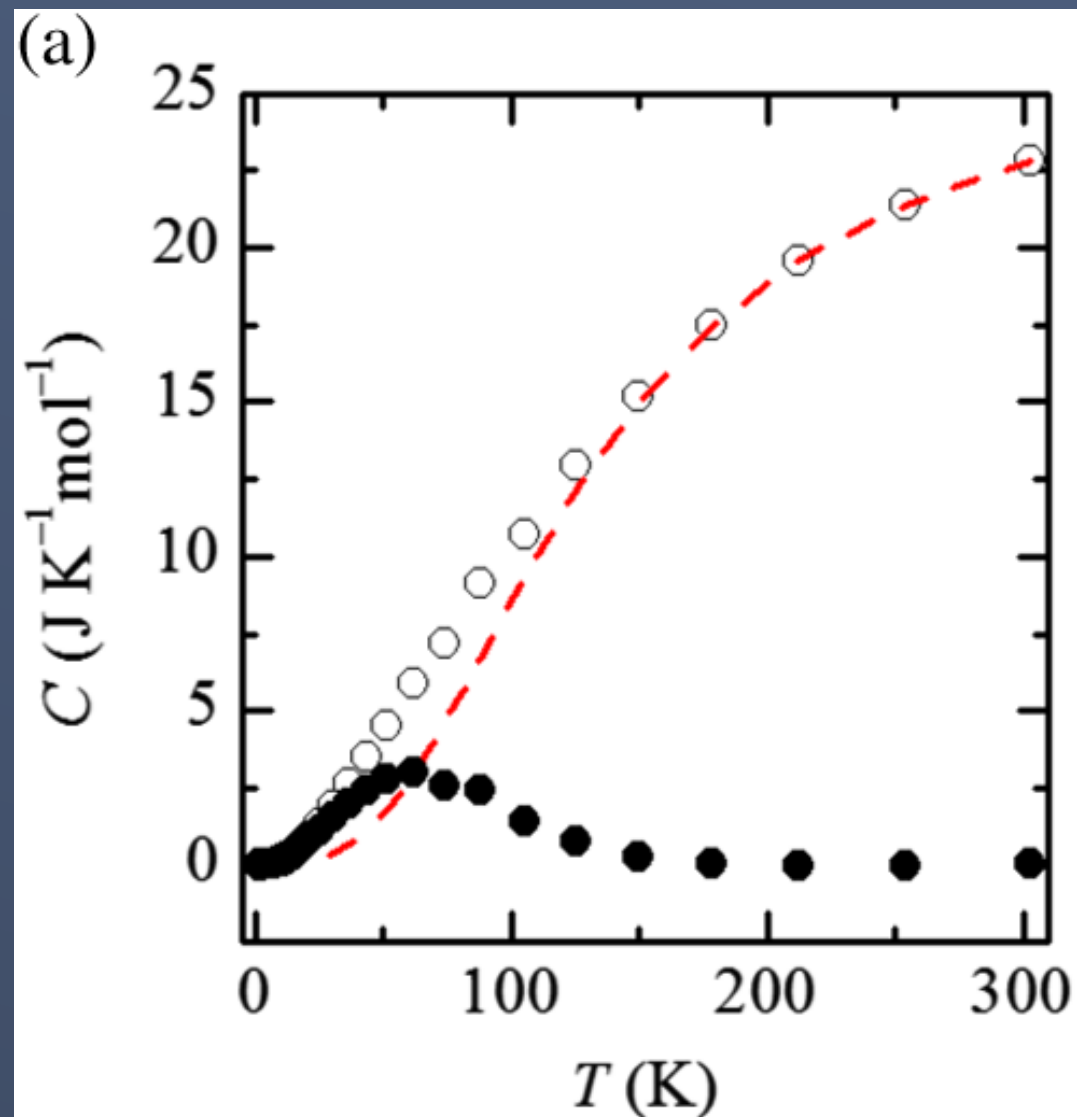
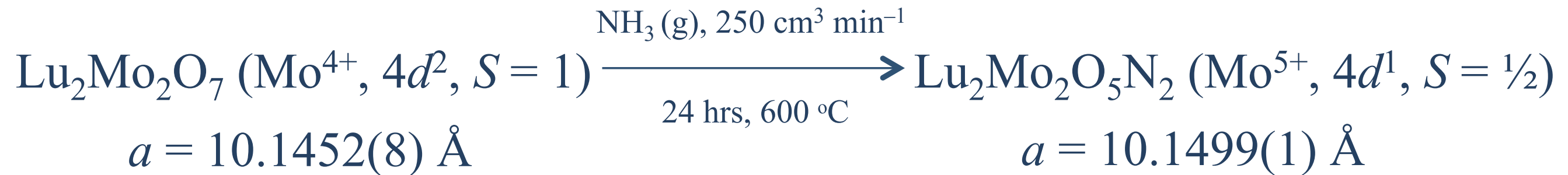


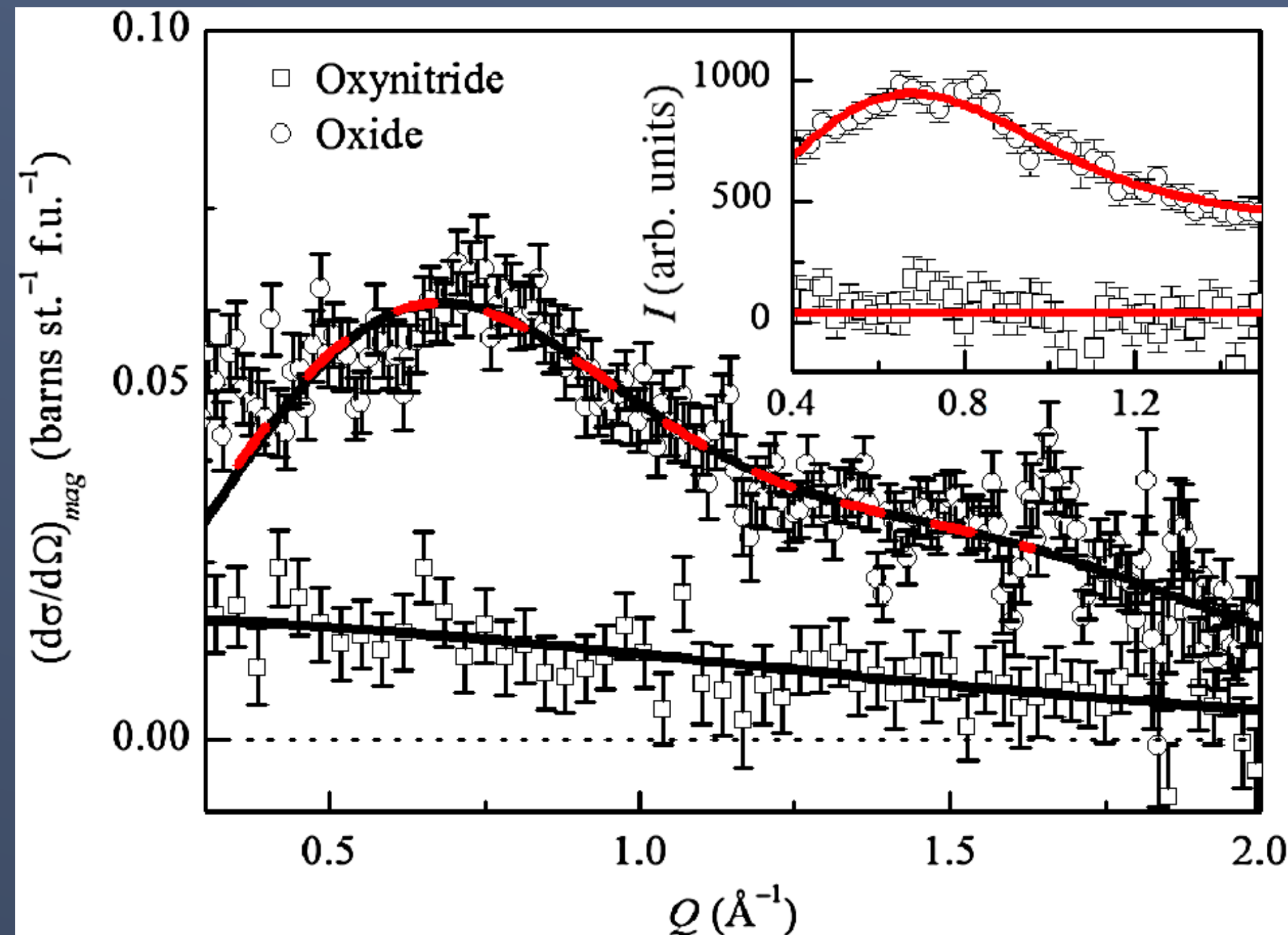
TABLE II. Results from the Curie Weiss fit to magnetic susceptibilities of the oxide and oxynitride pyrochlores.

Sample	Fit region / K	$-\theta$ / K	μ_{eff} / μ_B
Lu ₂ Mo ₂ O ₇	150 – 300	158(1)	1.89(1)
	200 – 300	171(1)	1.92(1)
	250 – 300	184(2)	1.85(1)
Lu ₂ Mo ₂ O ₅ N ₂	150 – 300	121(1)	1.11(1)
	200 – 300	135(1)	1.13(1)
	250 – 300	152(2)	1.16(1)

Topochemical nitration of $\text{Lu}_2\text{Mo}_2\text{O}_7$



Elastic Neutron Scattering: $\text{Lu}_2\text{Mo}_2\text{O}_7$ vs $\text{Lu}_2\text{Mo}_2\text{O}_5\text{N}_2$

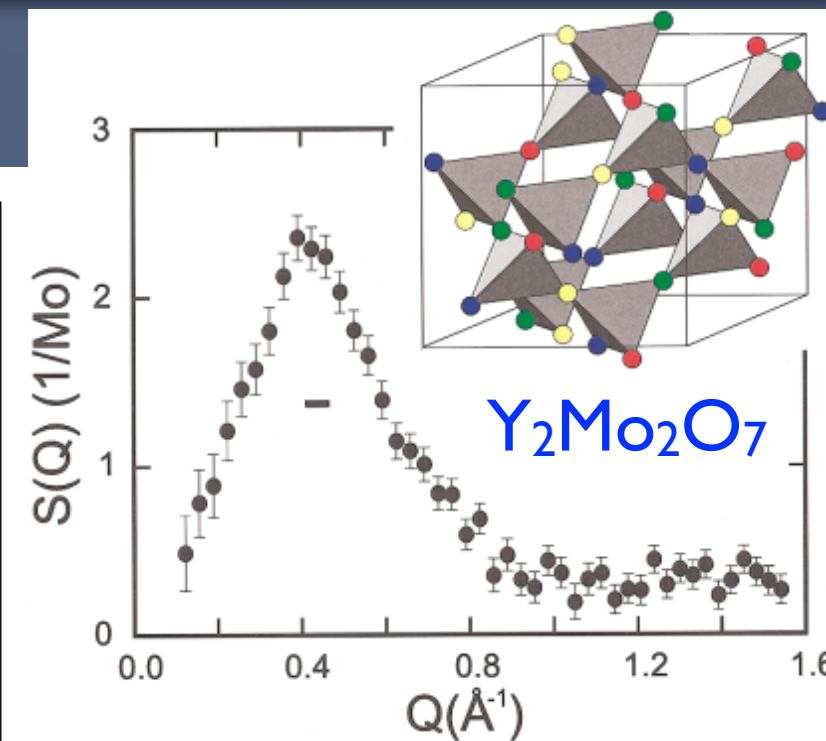
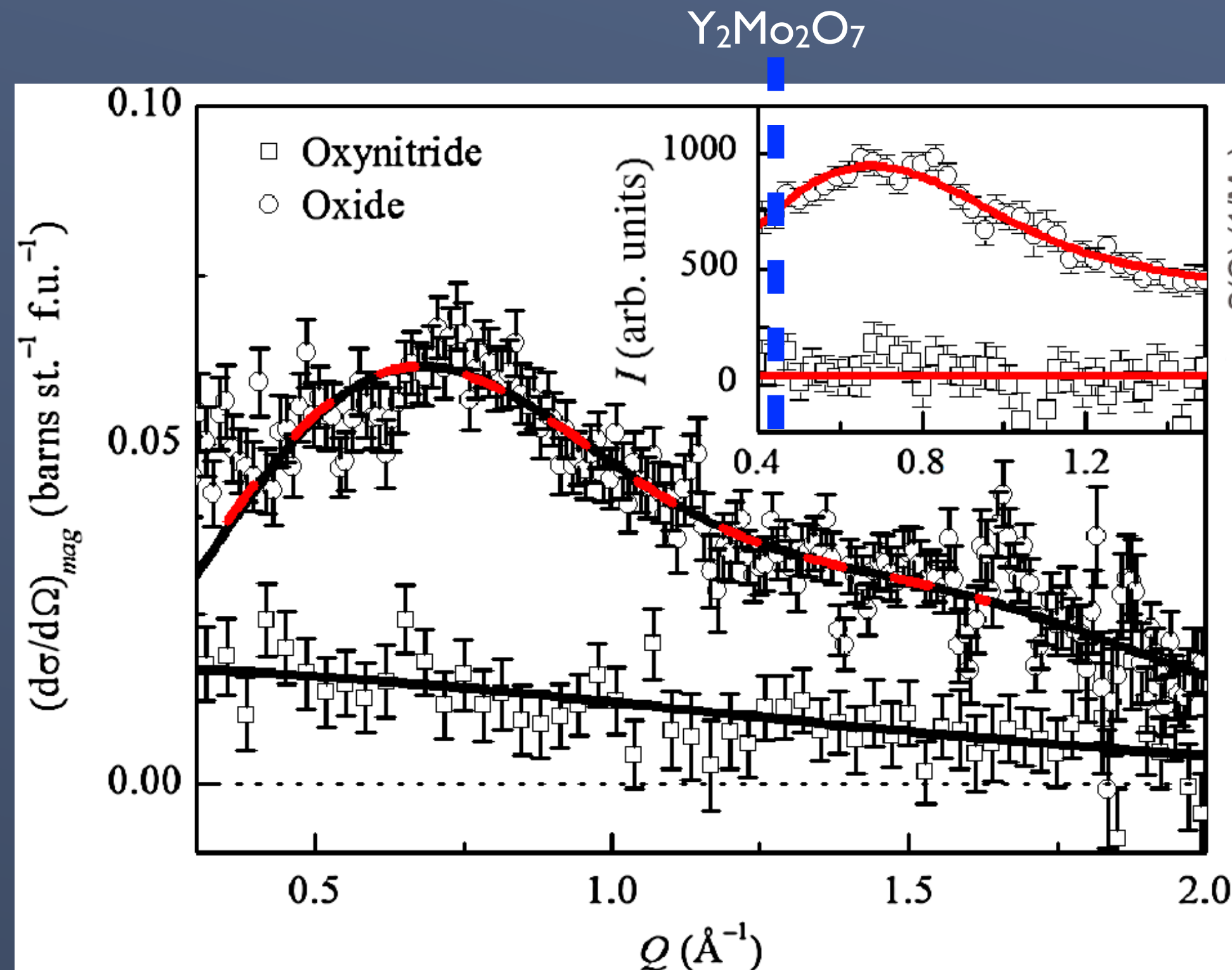


High
resolution
inelastic
scattering
res $\pm 0.1 \text{ meV}$

Polarized
Neutron
Diffraction

$T = 1.5 \text{ K}$

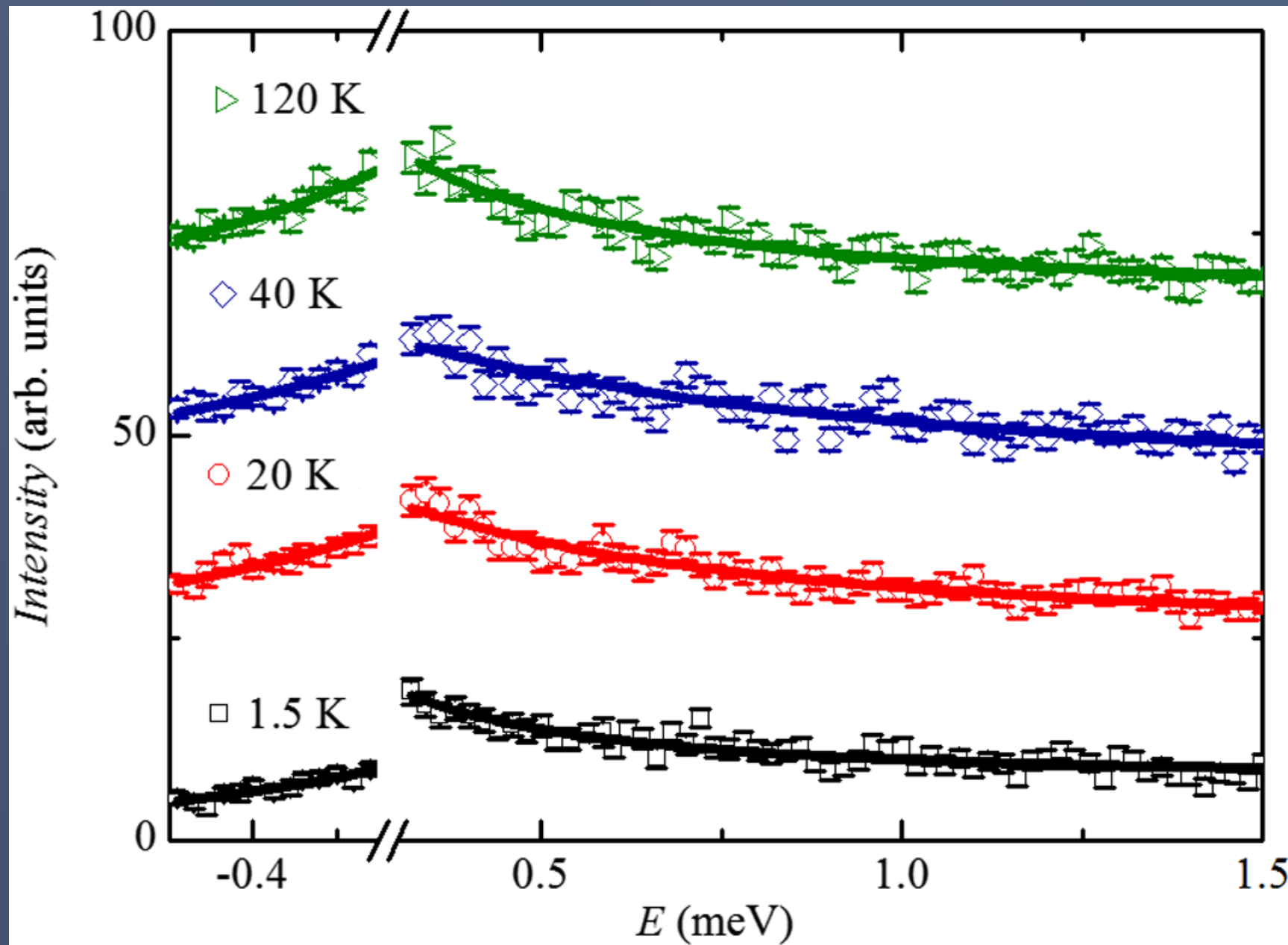
Elastic Neutron Scattering: $\text{Lu}_2\text{Mo}_2\text{O}_7$ vs $\text{Y}_2\text{Mo}_2\text{O}_7$ vs $\text{Lu}_2\text{Mo}_2\text{O}_5\text{N}_2$



Polarized
Neutron
Diffraction

$T=1.5$ K

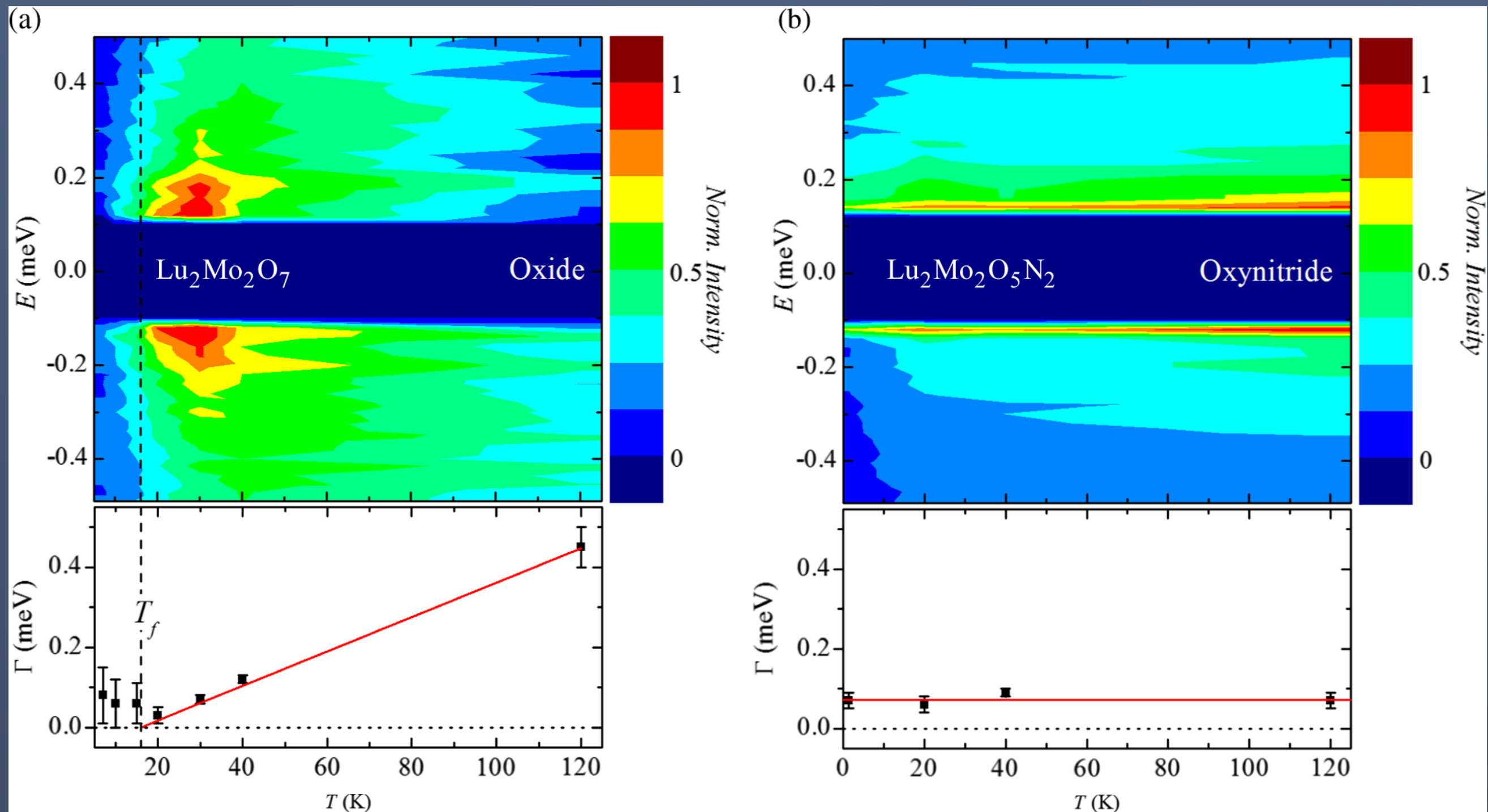
Modeling the inelastic scattering



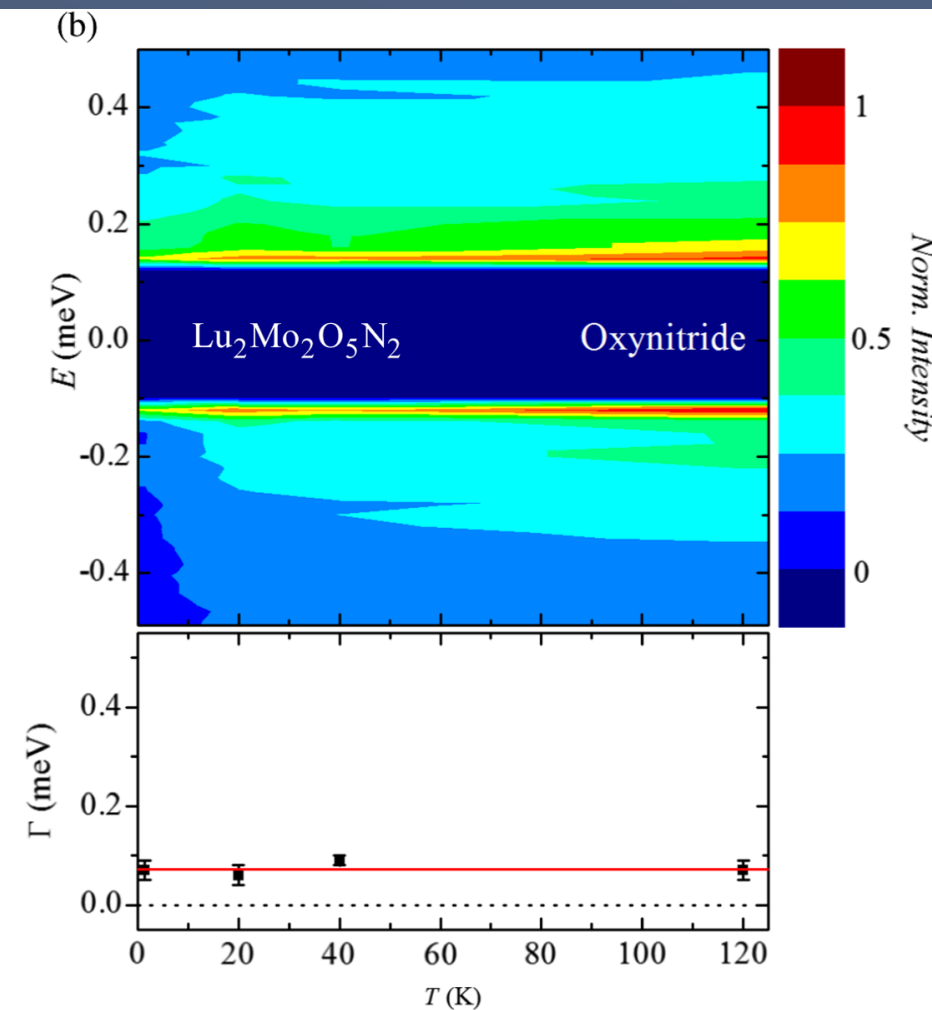
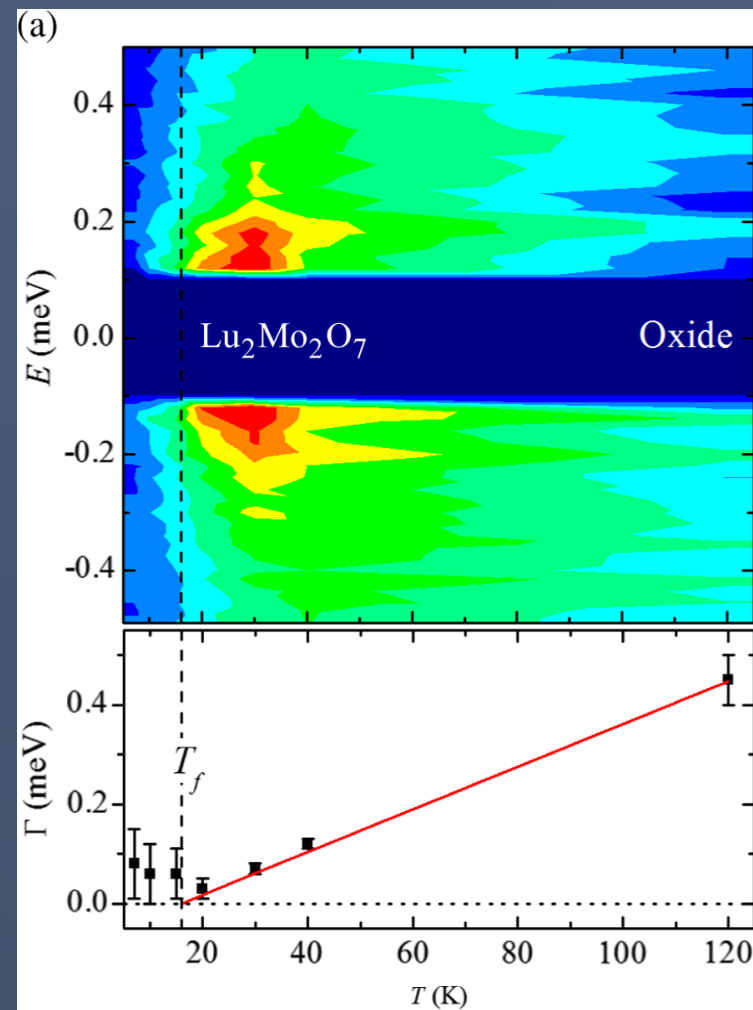
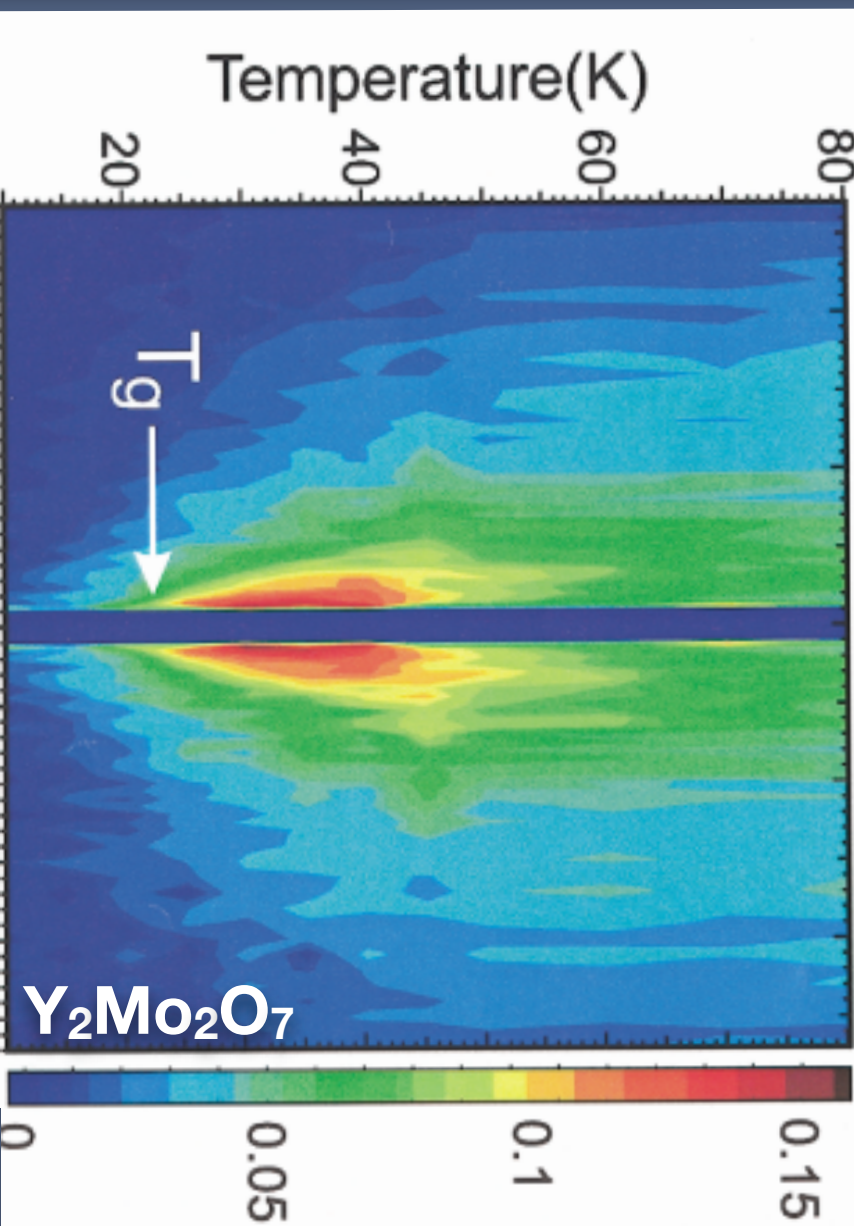
$\text{Lu}_2\text{Mo}_2\text{O}_5\text{N}_2$

$$S(E) = \frac{1}{\pi} \chi''(E) [1 + n(E)], \quad \chi''(E) = \chi_0 \arctan\left(\frac{E}{\Gamma}\right)$$

Inelastic Neutron Scattering: $\text{Lu}_2\text{Mo}_2\text{O}_7$ vs $\text{Lu}_2\text{Mo}_2\text{O}_5\text{N}_2$



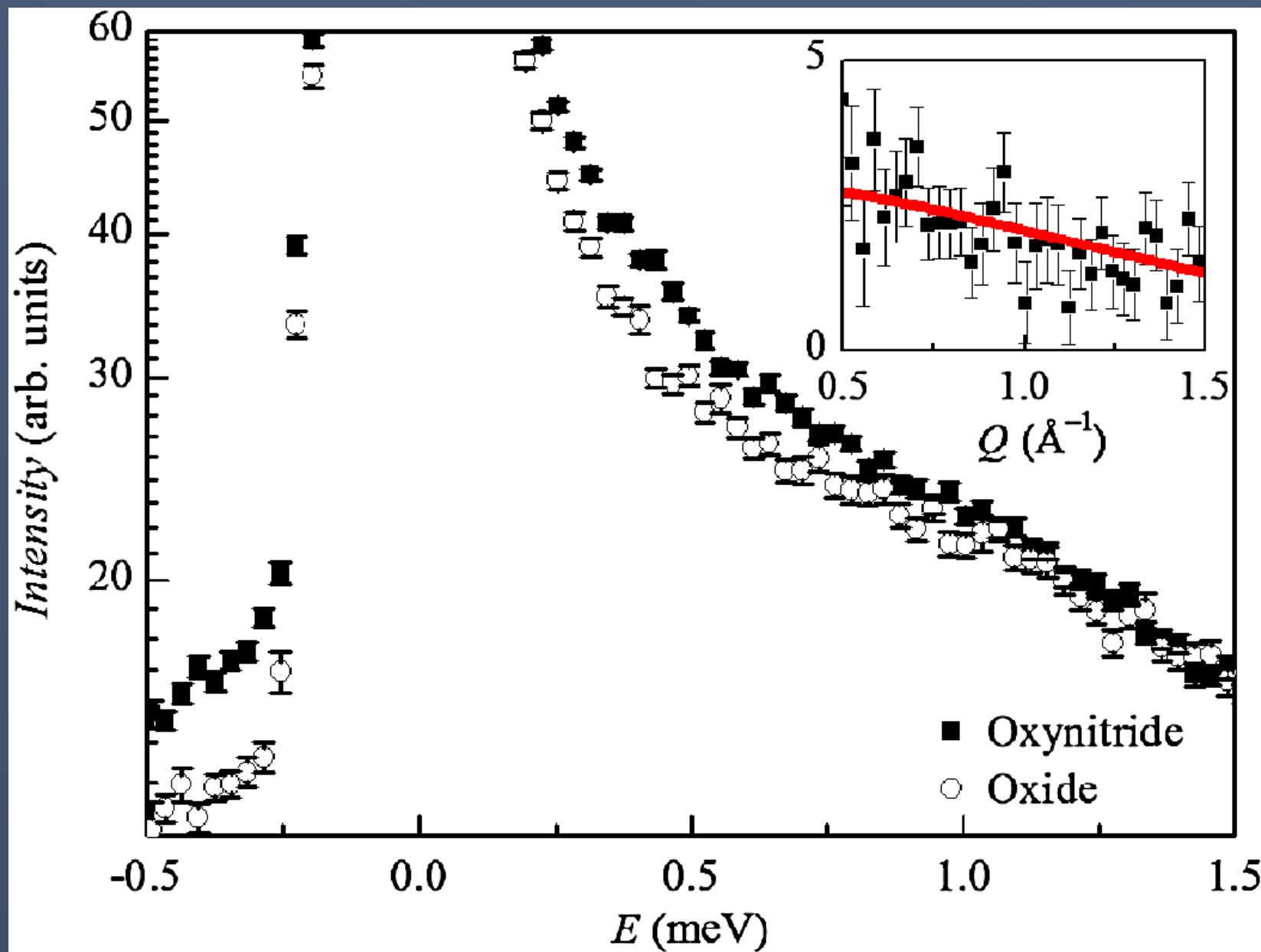
Inelastic Neutron Scattering: $\text{Y}_2\text{Mo}_2\text{O}_7$ vs $\text{Lu}_2\text{Mo}_2\text{O}_7$ vs $\text{Lu}_2\text{Mo}_2\text{O}_5\text{N}_2$



**$S=1$ Moly Oxides
freeze at $T_f \sim 20$ K**

**$S=1/2$ Oxynitride
doesn't freeze!**

Inelastic Neutron Scattering: $\text{Lu}_2\text{Mo}_2\text{O}_7$ vs $\text{Lu}_2\text{Mo}_2\text{O}_5\text{N}_2$



$S=1/2$ degrees of freedom
are strongly fluctuating at
 $T=1.5 \text{ K} \sim 0.012 T_{\text{CW}}$

Gapless - with gap $<$

$$\Delta \sim 0.05 \text{ meV or } \Delta/|\theta| \sim 0.004$$

Scattering follows $F(Q)^2$
for Mo^{5+} only

Conclusions:

- *TOF neutron techniques have made great recent advances, and are well suited to exotic magnetism as they measure very effectively across wide dynamic range in Q and energy*
- *$R_2Mo_2O_7$ with heavy R^{3+} displays robust spin glass phase below ~ 20 K*

*Disorder-free glassiness or role of weak disorder?
Isotropic static, short range correlations at low T - why?*

- *Topochemical nitration of $Lu_2Mo_2O_7$ yields $Lu_2Mo_2O_5N_2$
Variation of $S=1/2$ pyrochlore antiferromagnet?
Gapless, strongly fluctuating ground state - no freezing!*

Collaboration:

