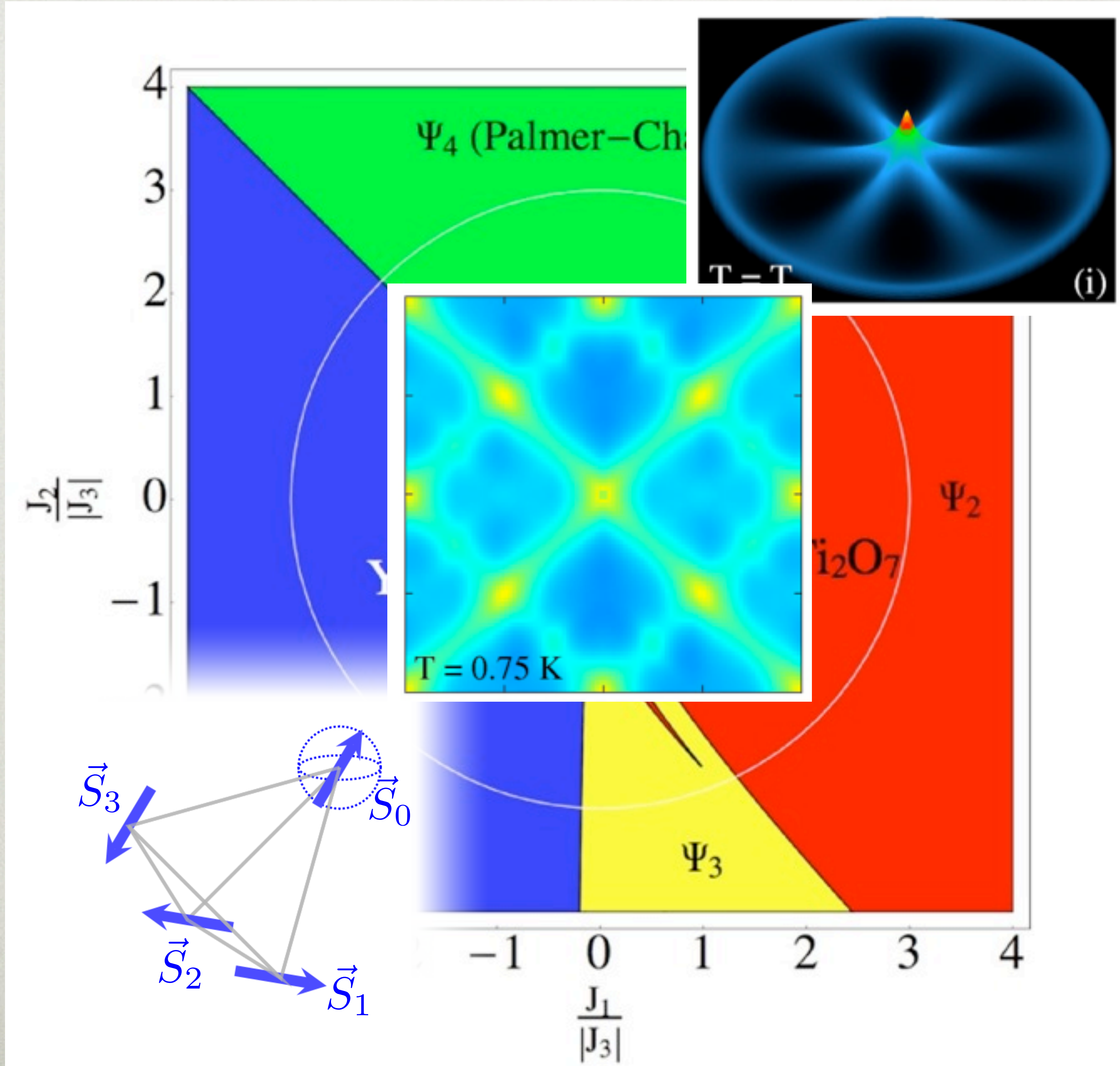
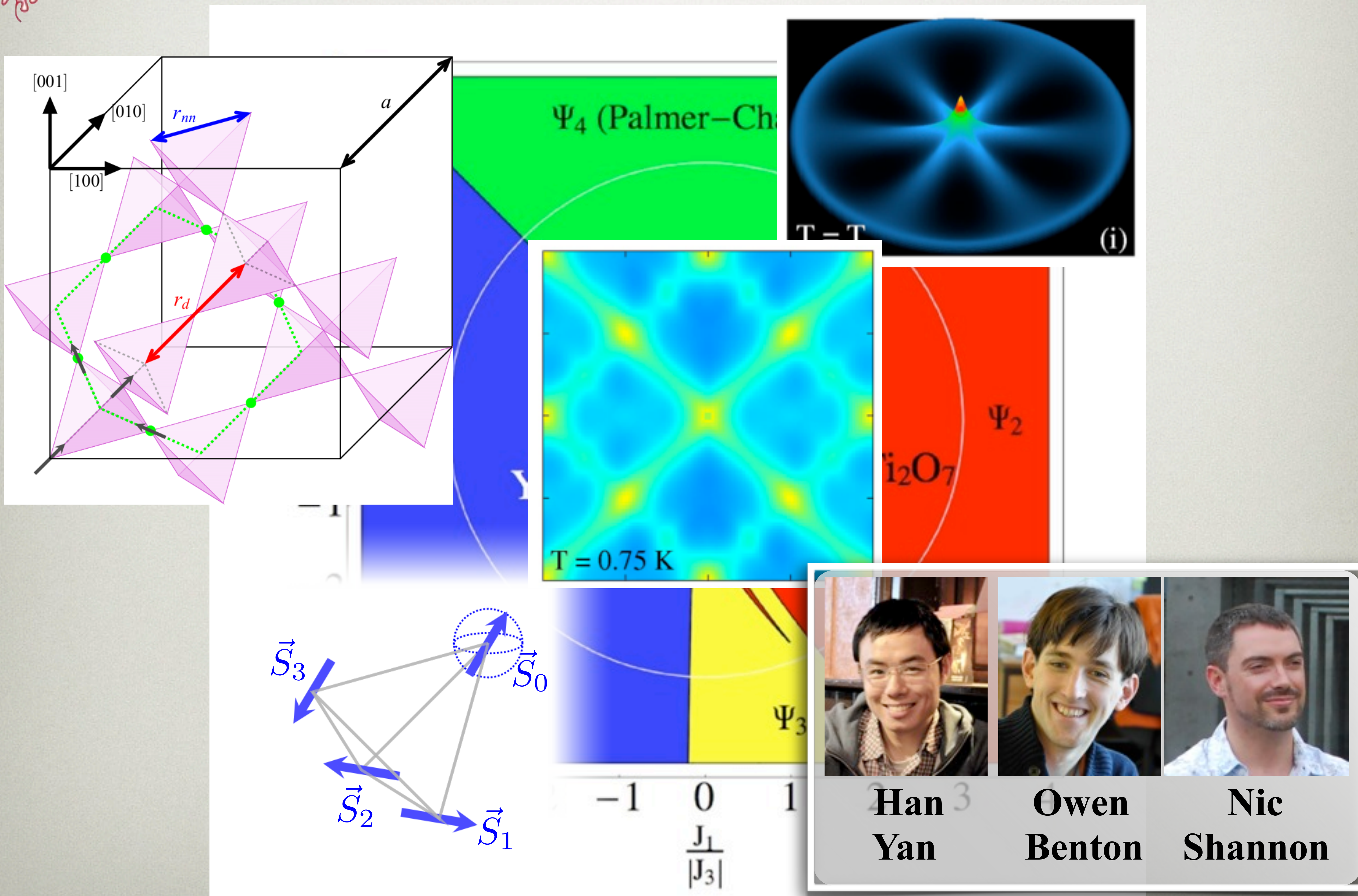
Towards a general theory for pyrochlores

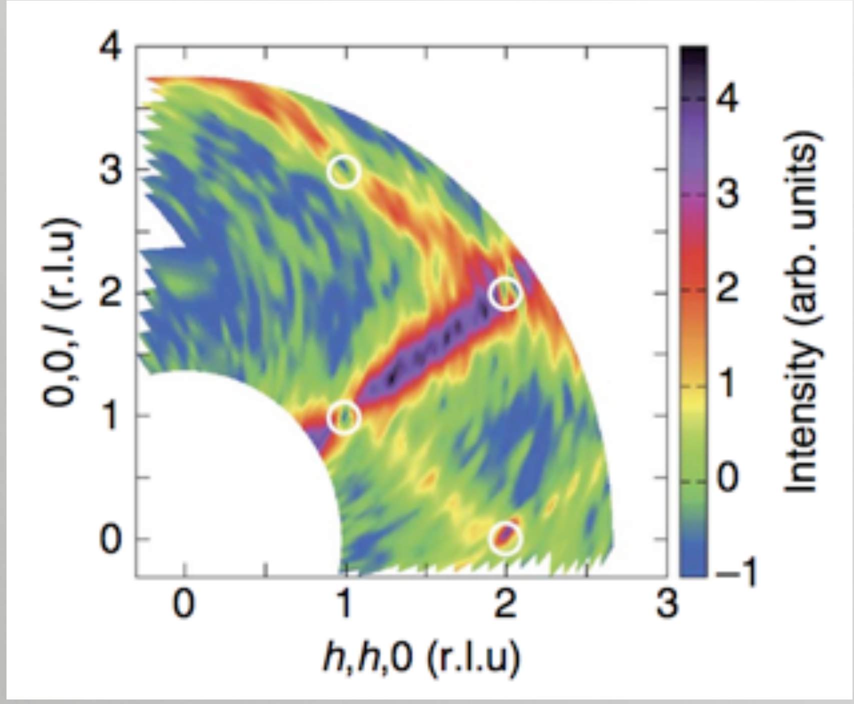


Towards a general theory for pyrochlores

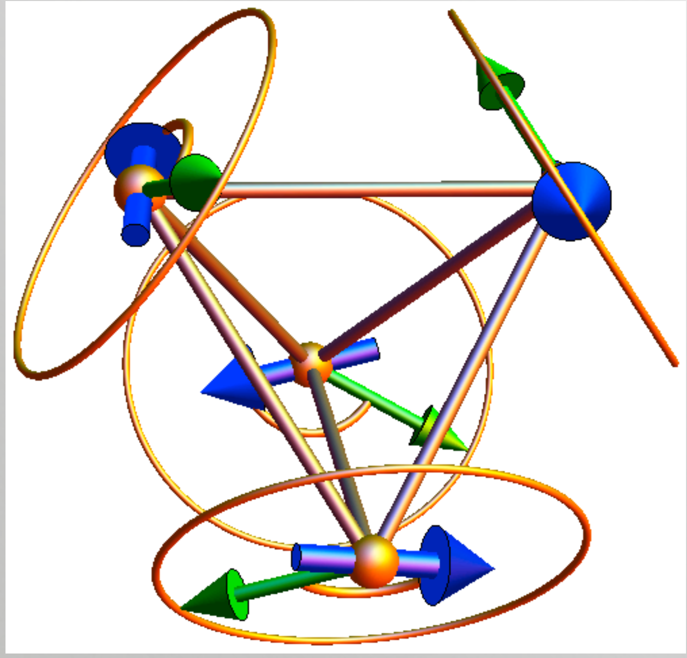


One theory ⇨ three stories

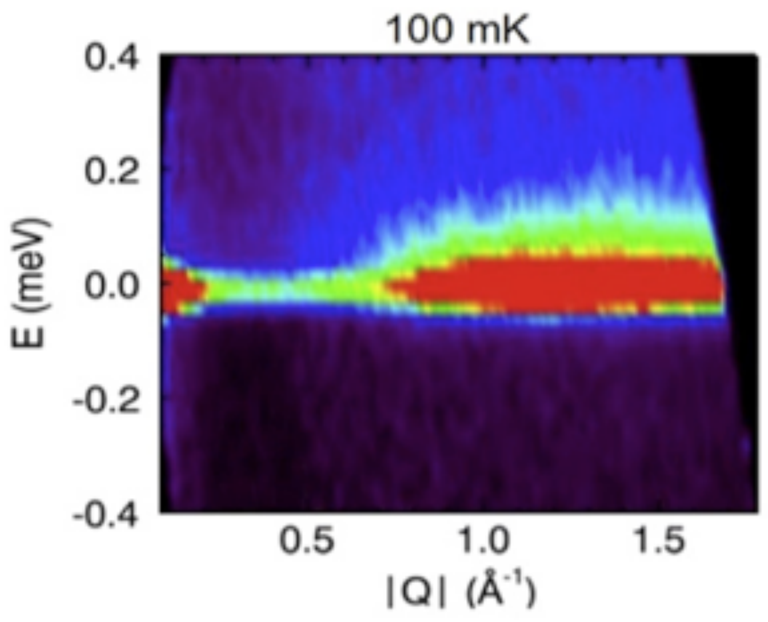
General Phase Diagram of Pyrochlores



Dimensional reduction
($Yb_2Ti_2O_7$)



Order by disorder
($Er_2Ti_2O_7$)

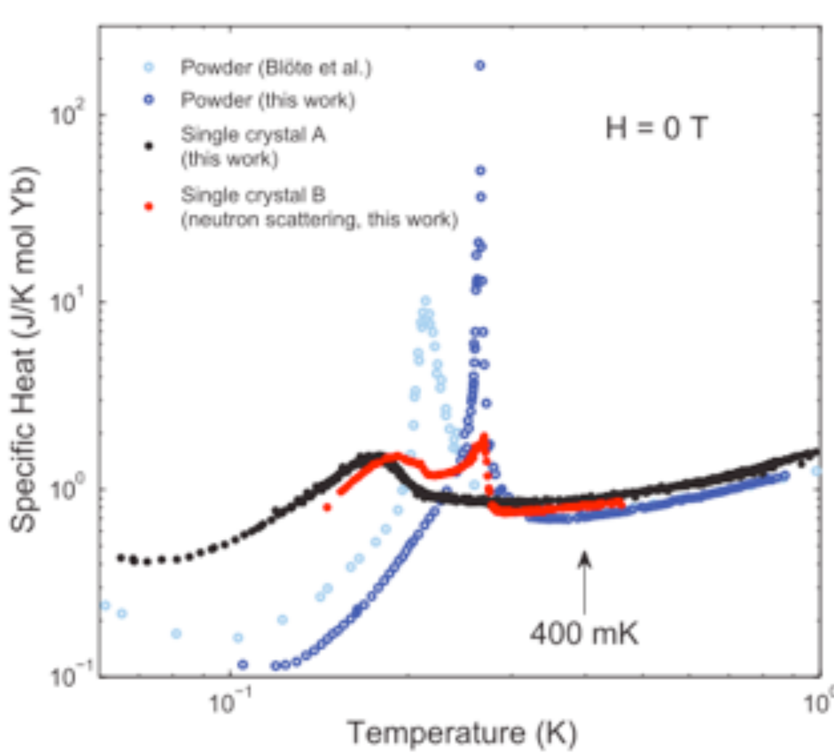


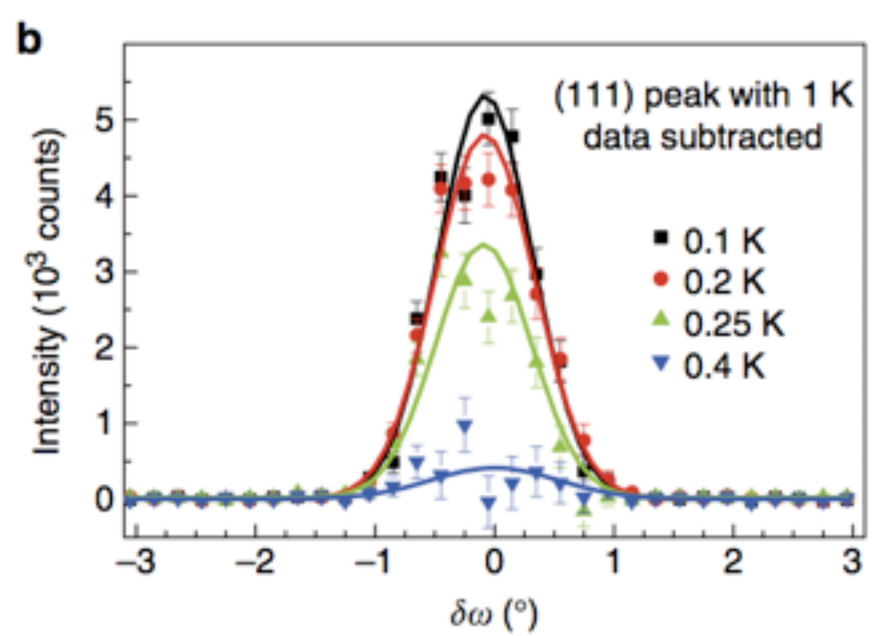
Spin liquid ?
($Er_2Sn_2O_7$)

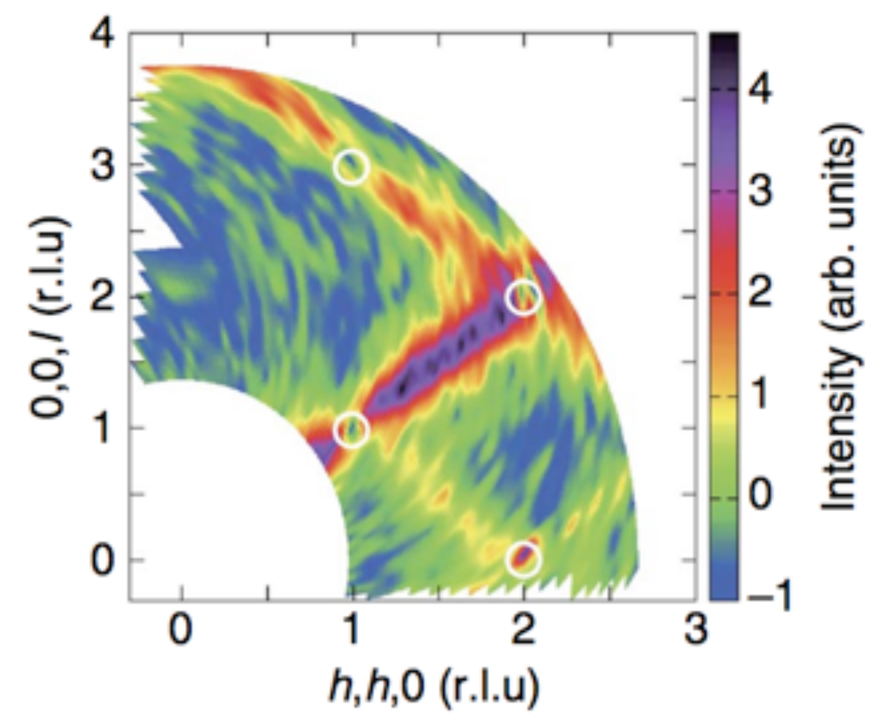
Dimensional reduction in $Yb_2Ti_2O_7$

- phase transition at $T_c \sim 240$ mK
- ferromagnetic order, but sample dependence
- Higgs mechanism (?)
- rods of scattering = dimensional reduction

Hodges et al. PRL 2002
Yasui et al. JPSJ 2003
Cao et al. JPCM 2009
Cao et al. PRL 2009
Ross et al. PRL 2009
Onoda PRB 2011
Ross et al. PRX 2011
Savary, Balents, PRL 2012
Savary, Balents, PRB 2013
Thompson et al. PRL 2011
Applegate et al. PRL 2012
Chang et al. Nat. Com. 2012
Hayre et al. arXiv 2012
D'Ortenzio et al. PRB 2013



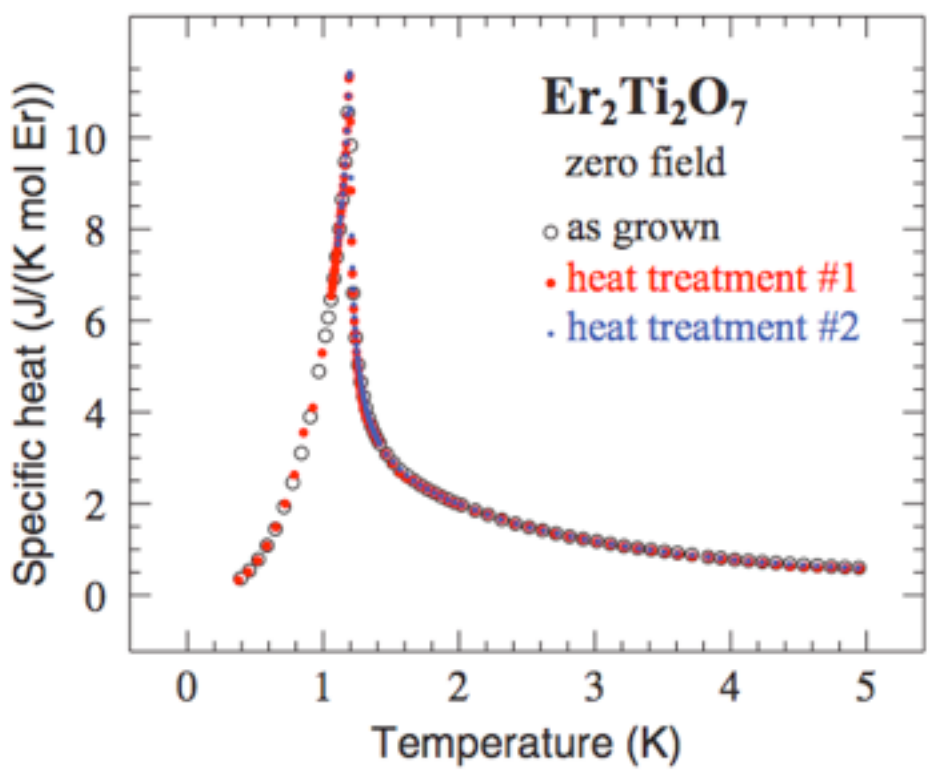


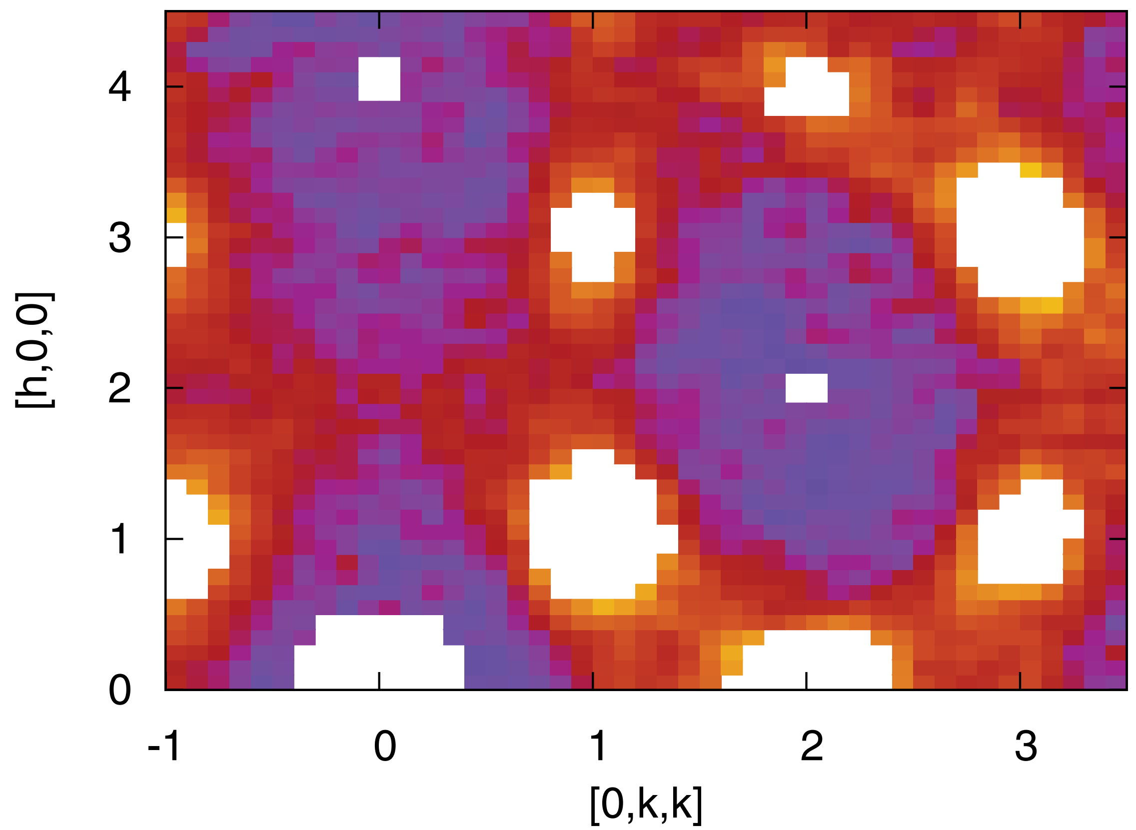


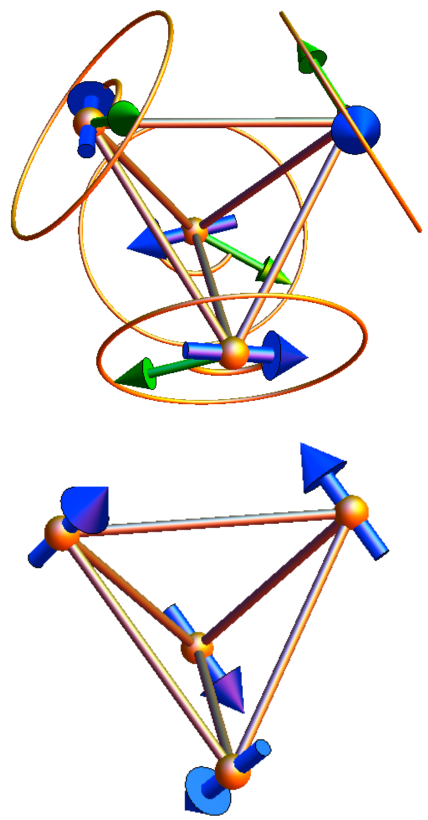
Order by disorder in $Er_2Ti_2O_7$

- phase transition at $T_c \sim 1.2$ K
- thermal & quantum order by disorder transition
- physical mechanism of the selection process ?

Champion et al. PRB 2003
Champion et al. JPCM 2004
McClarty et al. JPCS 2009
Sosin et al. PRB 2010
Zhitomirsky et al. PRL 2012
Bonville et al. JPCM 2013
Dalmas de Réotier et al. PRB 2012
Ruff et al. PRL 2008
Cao et al. PRL 2009
Stasiak et al. arXiv 2011
Savary et al. PRL 2012
Wong et al. PRB 2013



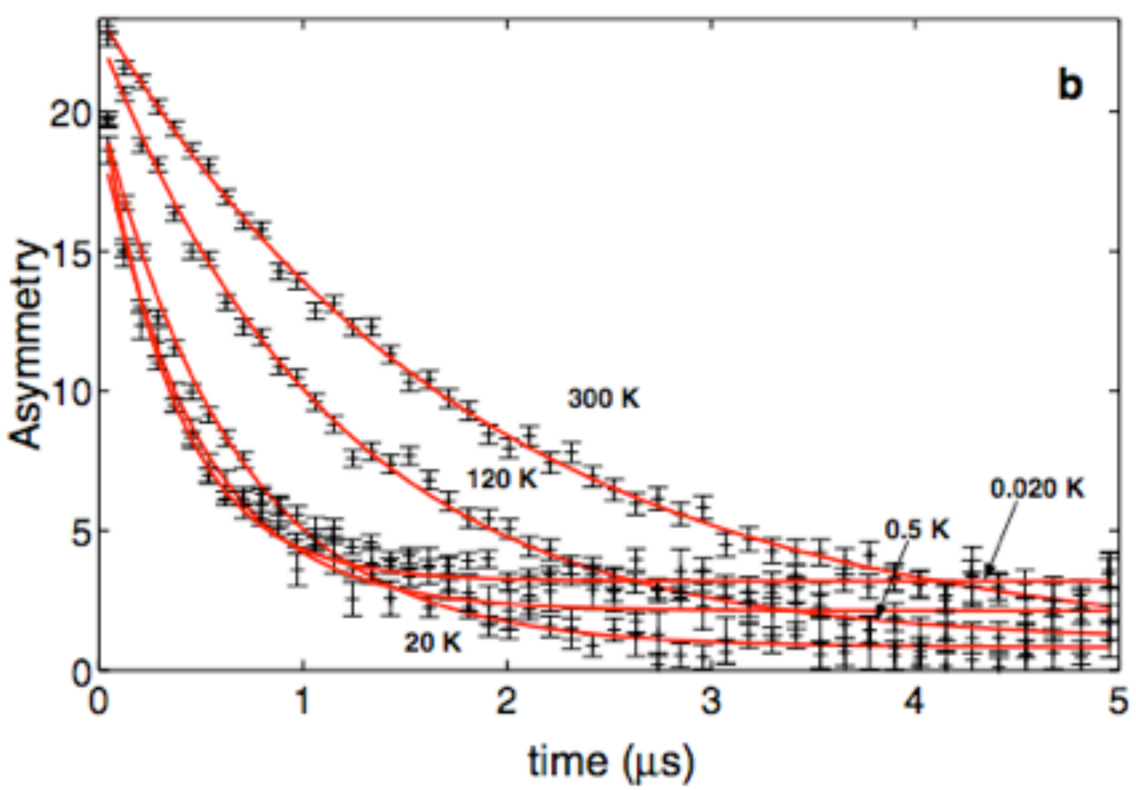


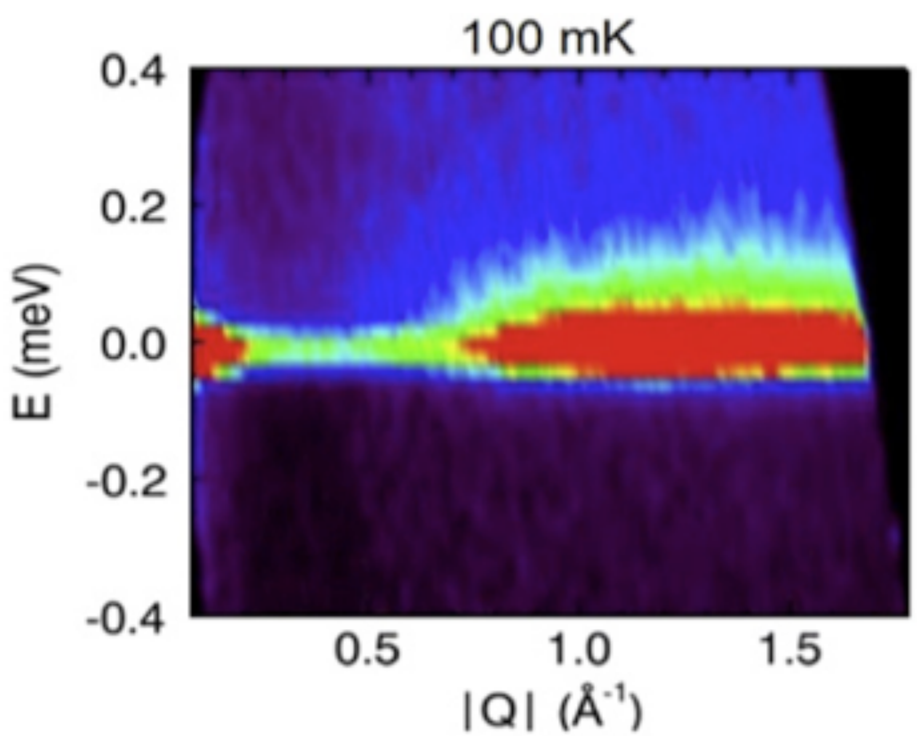


Possible spin liquid in $Er_2Sn_2O_7$

- no transition
- Palmer-Chalker correlations
- what's going on ?

Matsuhira et al. JPSJ 2002
Lago et al. JPCM 2005
Sarte et al. JPCM 2011
Guitteny et al. arXiv 2013





Methodology

quantum fluctuations
=
semi-classical
spin wave calculations

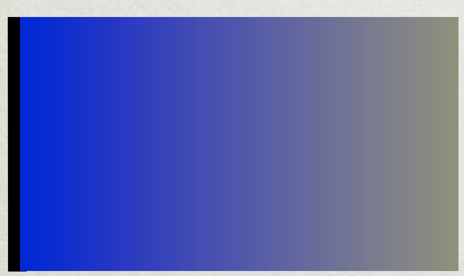
exact phase diagram
via group theory

$T = 0$

Methodology

quantum fluctuations
=
semi-classical
spin wave calculations

exact phase diagram
via group theory



T = 0

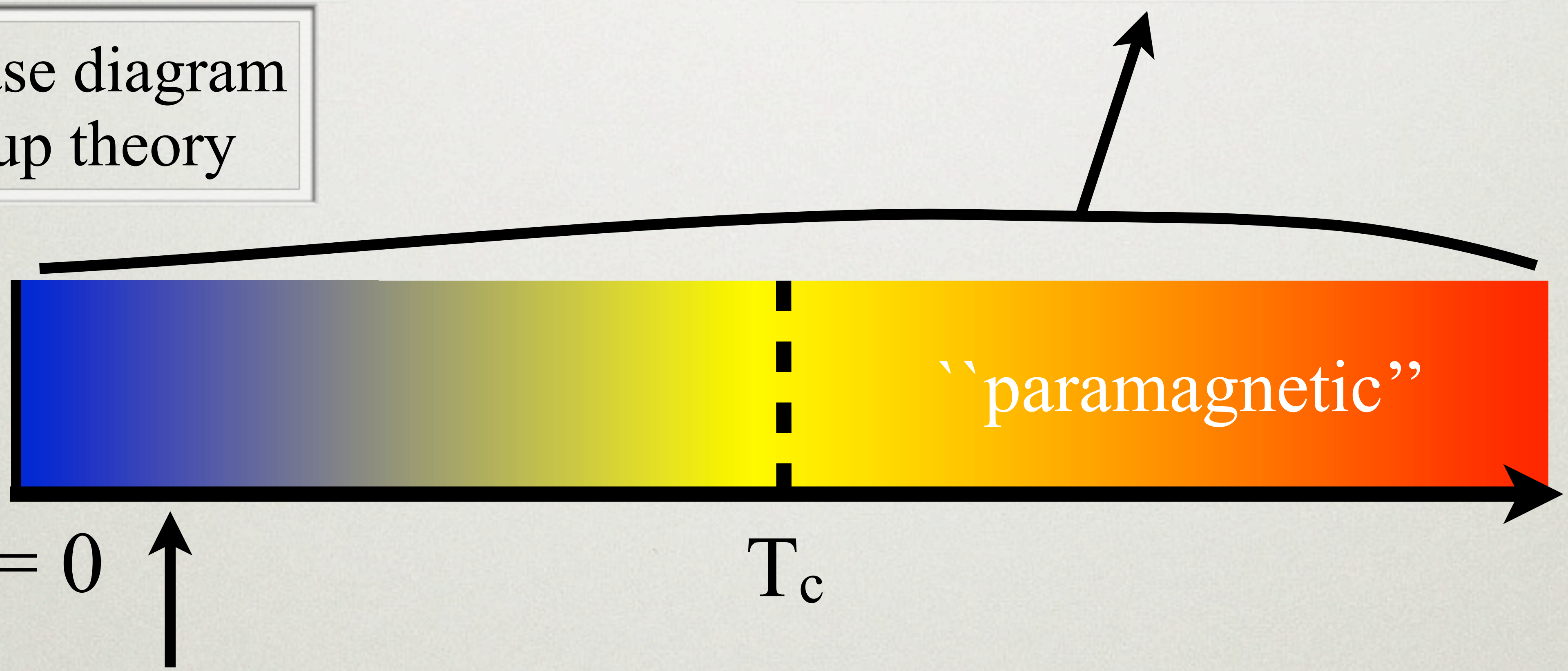
thermal fluctuations
=
spin wave calculations

Methodology

quantum fluctuations
=
semi-classical
spin wave calculations

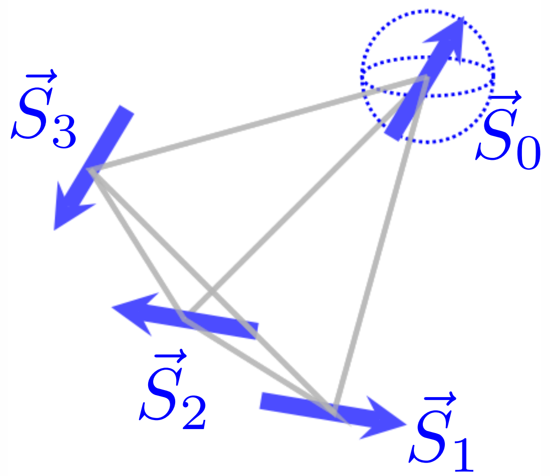
exact phase diagram
via group theory

for all temperatures
=
Monte Carlo simulations



thermal fluctuations
=
spin wave calculations

The model



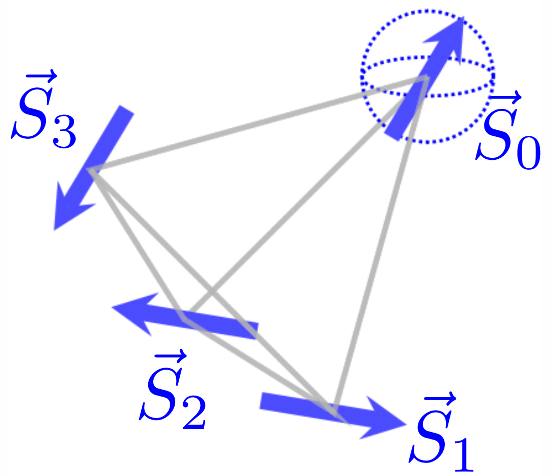
All possible nearest neighbor interactions

$$\mathcal{H} = \frac{1}{2} \sum_{<ij>} \vec{S}_i \; \hat{J}_{ij} \; \vec{S}_j$$

$$\hat{J}_{01} = \begin{bmatrix} J_2 & J_4 & J_4 \\ -J_4 & J_1 & J_3 \\ -J_4 & J_3 & J_1 \end{bmatrix}$$

Curnoe PRB 2007
McClarty et al. JPCS 2009
Ross et al. PRX 2011

The model



All possible nearest neighbor interactions

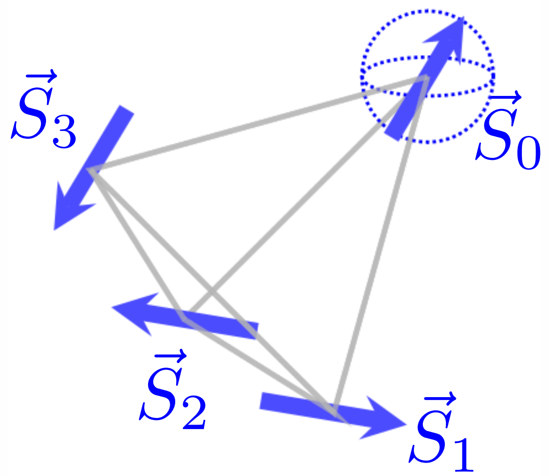
$$\mathcal{H} = \frac{1}{2} \sum_{<ij>} \vec{S}_i \; \hat{J}_{ij} \; \vec{S}_j$$

$$\hat{J}_{01} = \begin{bmatrix} J_2 & J_4 & J_4 \\ -J_4 & J_1 & J_3 \\ -J_4 & J_3 & J_1 \end{bmatrix}$$

Heisenberg - like

Curnoe PRB 2007
McClarty et al. JPCS 2009
Ross et al. PRX 2011

The model



All possible nearest neighbor interactions

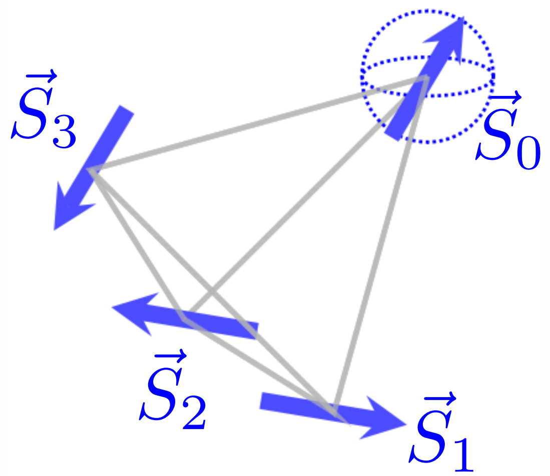
$$\mathcal{H} = \frac{1}{2} \sum_{<ij>} \vec{S}_i \, \hat{J}_{ij} \, \vec{S}_j$$

$$\hat{J}_{01} = \begin{bmatrix} J_2 & J_4 & J_4 \\ -J_4 & J_1 & J_3 \\ -J_4 & J_3 & J_1 \end{bmatrix}$$

dipolar - like

Curnoe PRB 2007
McClarty et al. JPCS 2009
Ross et al. PRX 2011

The model



<u>All</u> possible nearest neighbor interactions

$$\mathcal{H} = \frac{1}{2} \sum_{<ij>} \vec{S}_i \; \hat{J}_{ij} \; \vec{S}_j$$

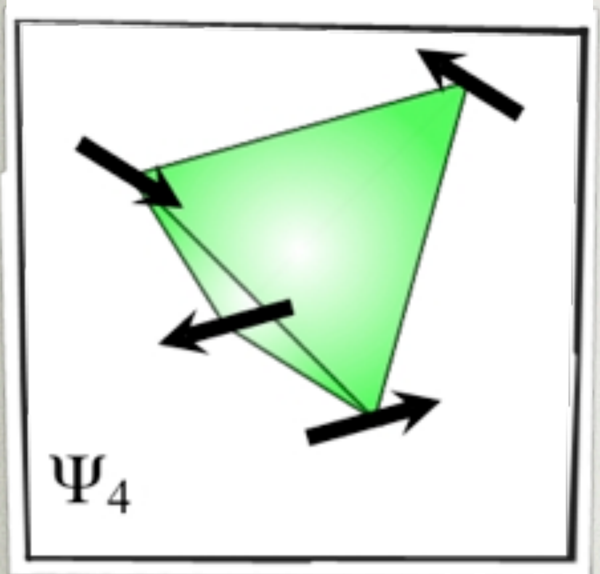
Dzyaloshinskii–Moriya

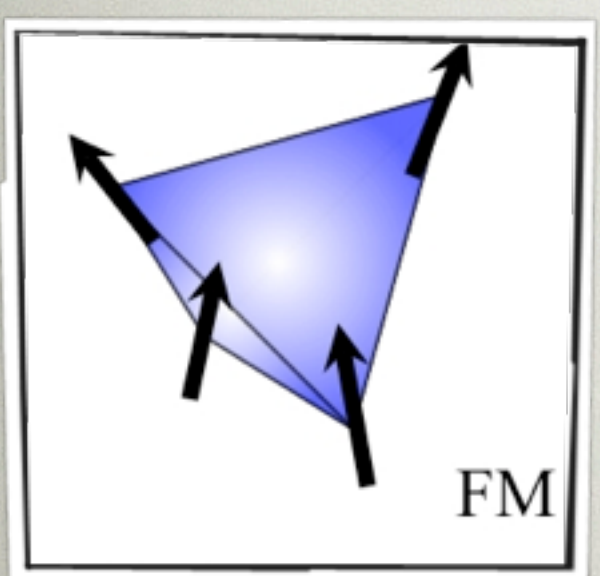
$$\hat{J}_{01} = \begin{bmatrix} J_2 & J_4 & J_4 \\ -J_4 & J_1 & J_3 \\ -J_4 & J_3 & J_1 \end{bmatrix}$$

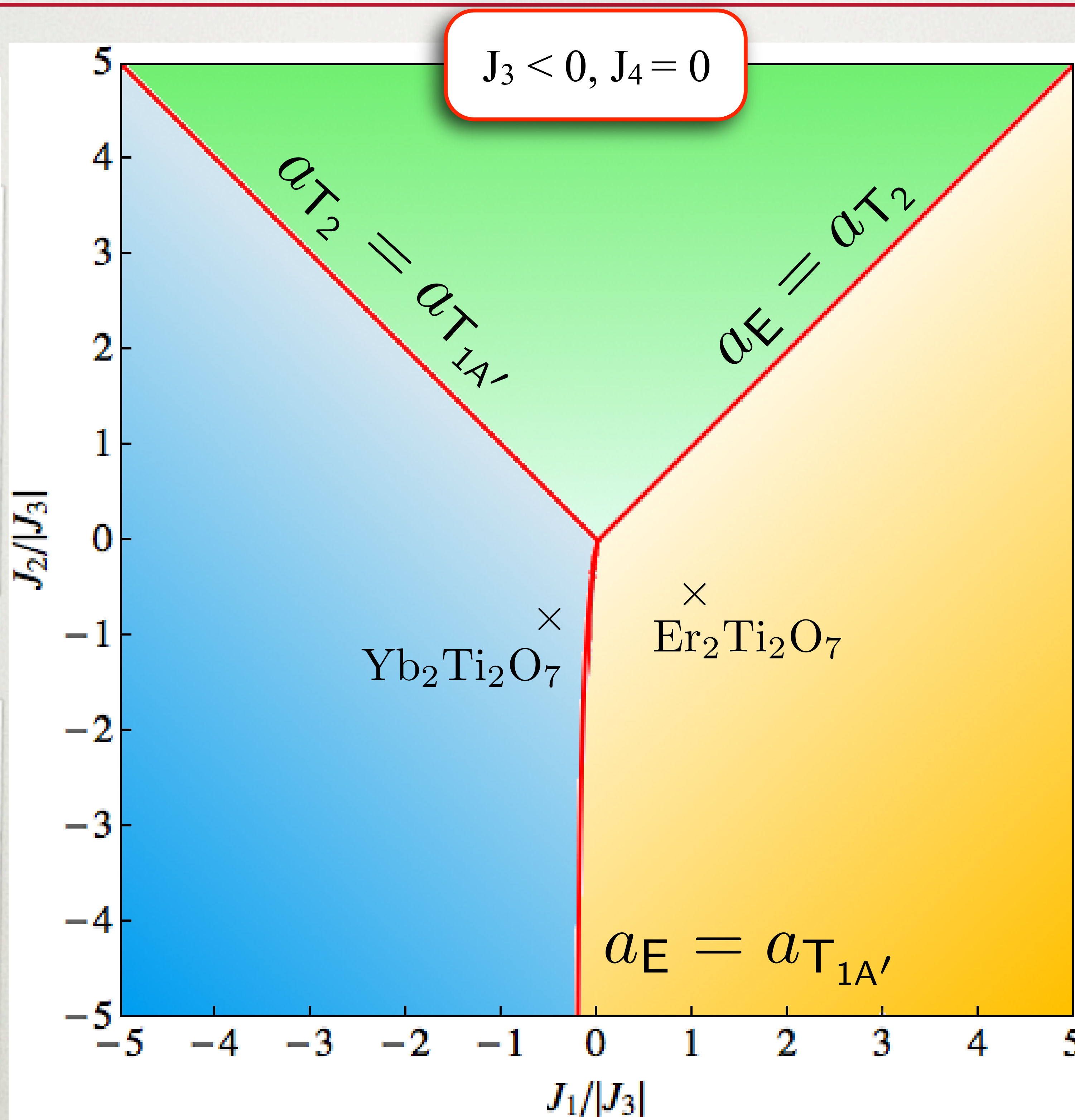
Curnoe PRB 2007
McClarty et al. JPCS 2009
Ross et al. PRX 2011

What happens at 0 K ?

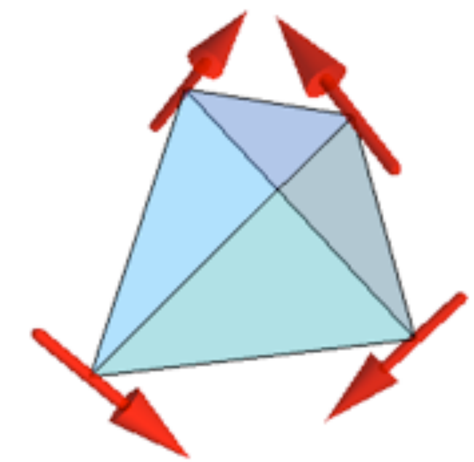
"Palmer - Chalker"







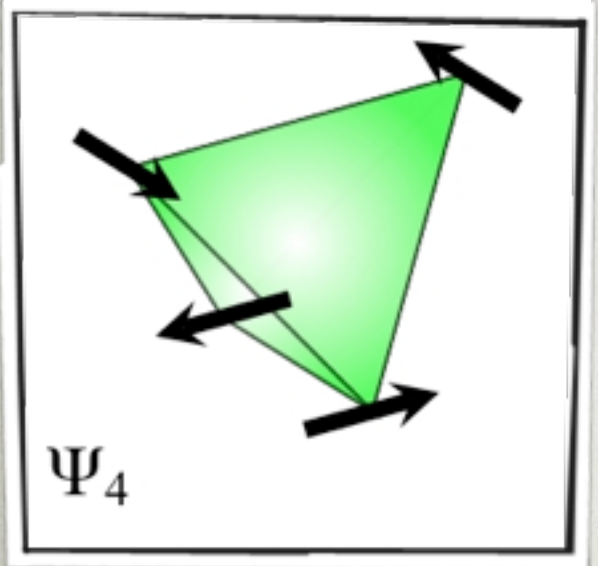
Global U(1) manifold

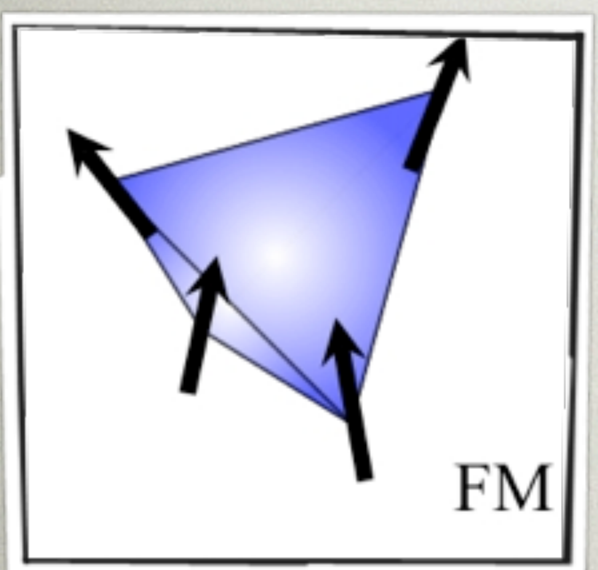


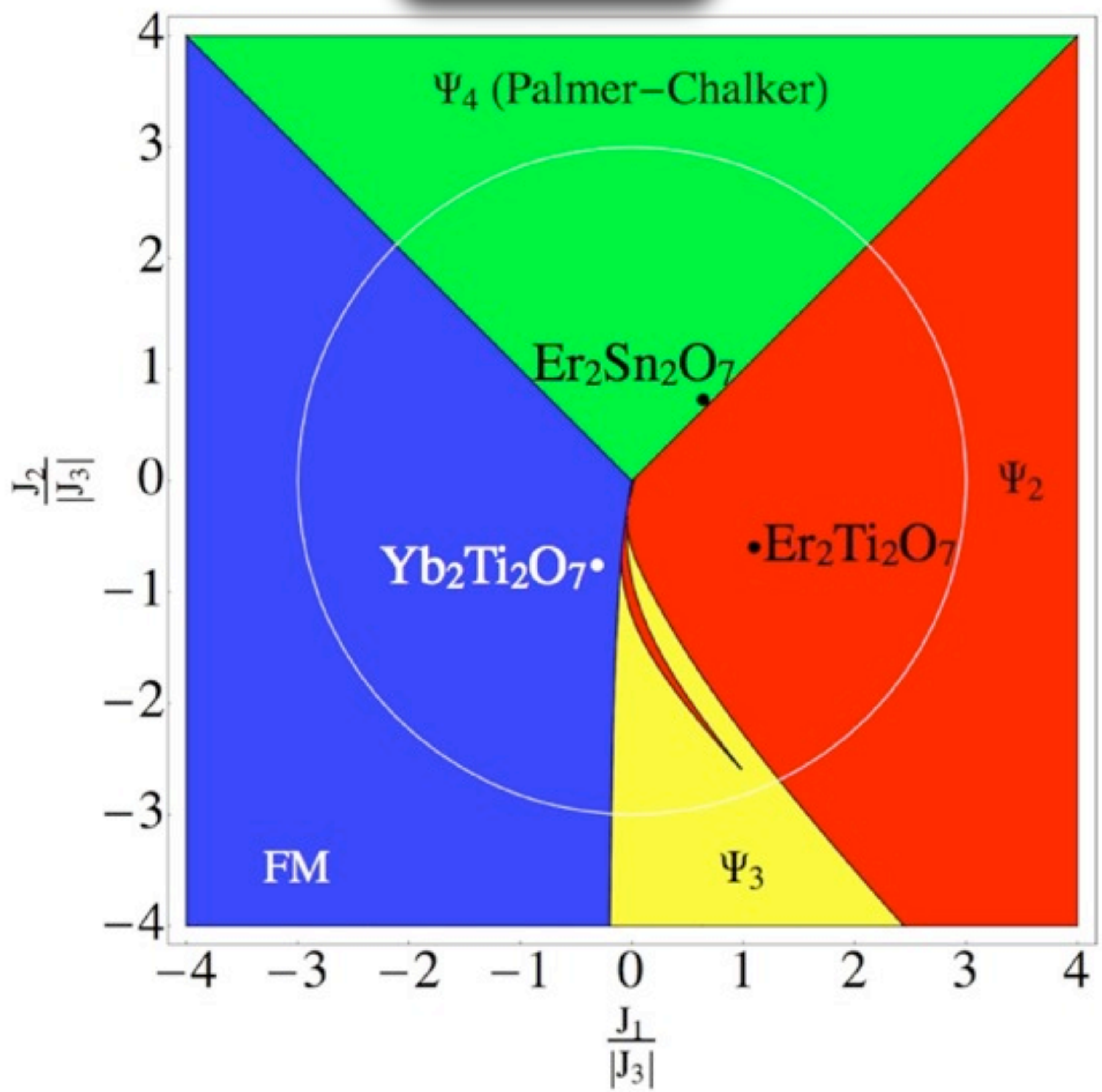
What happens just above 0 K ?

$J_3 < 0, J_4 = 0$

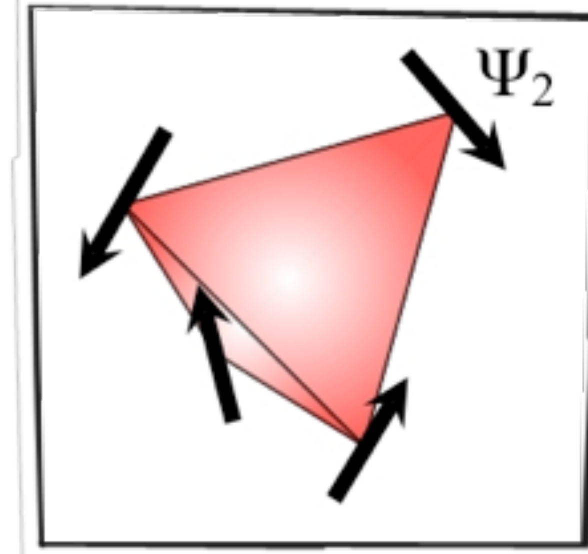
"Palmer - Chalker"

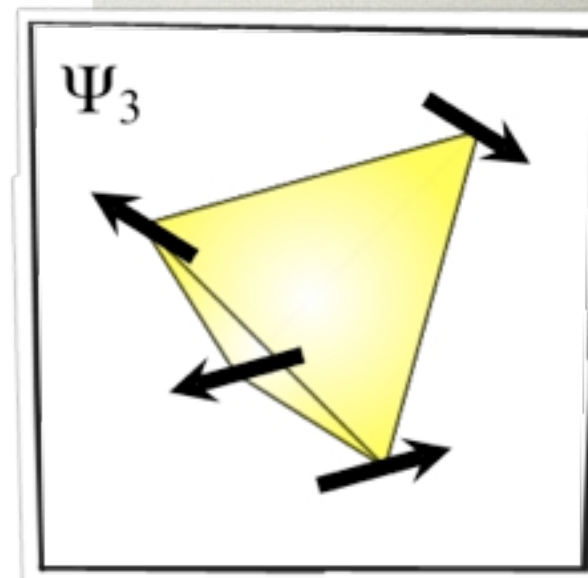




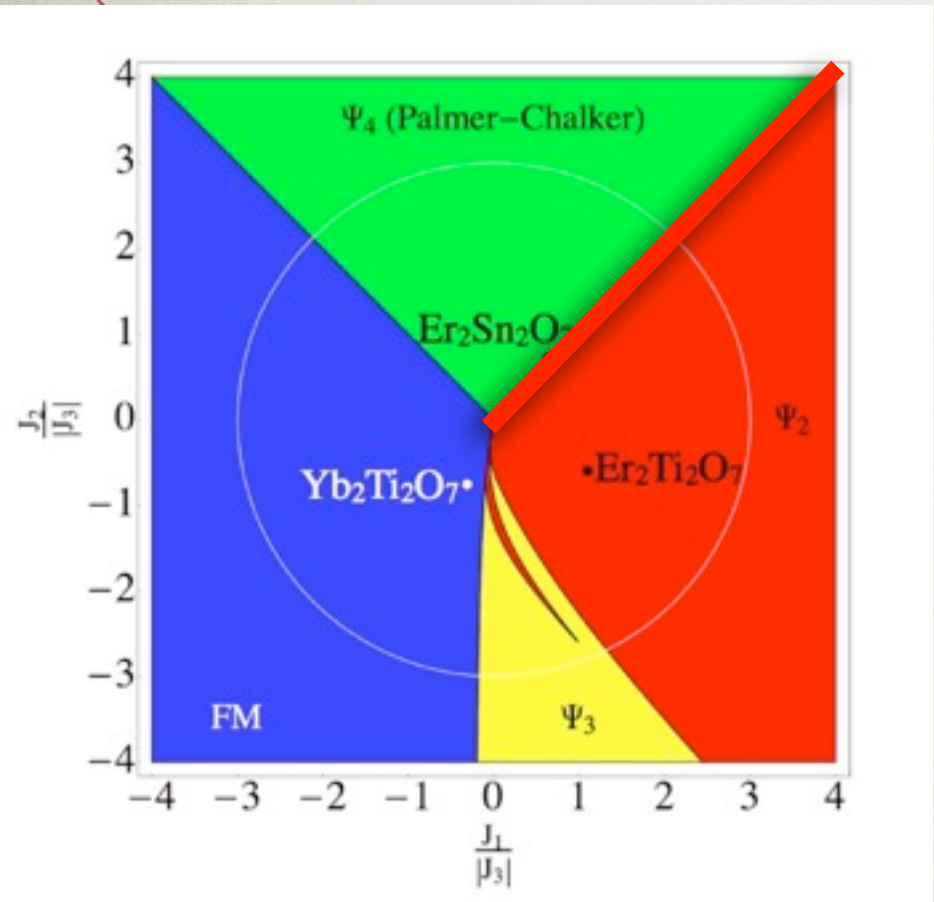


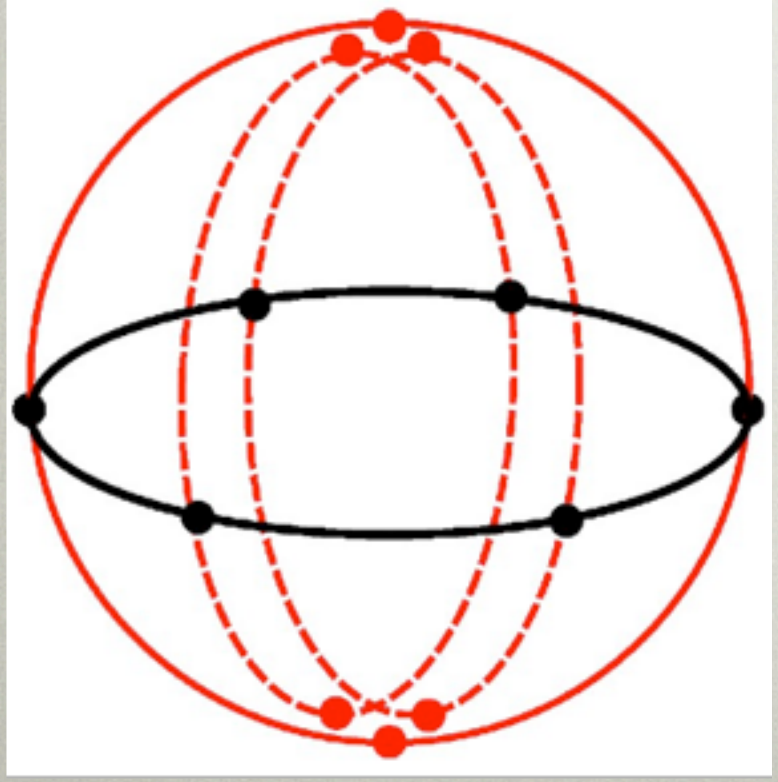
"Champion - Holdsworth"



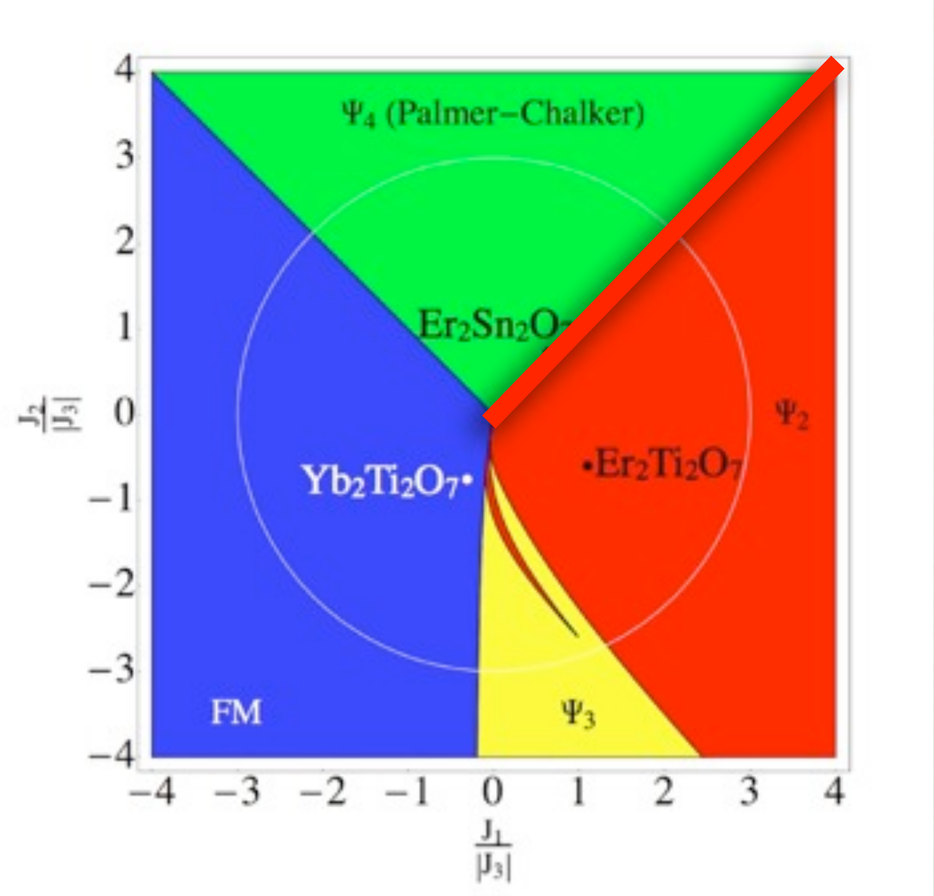


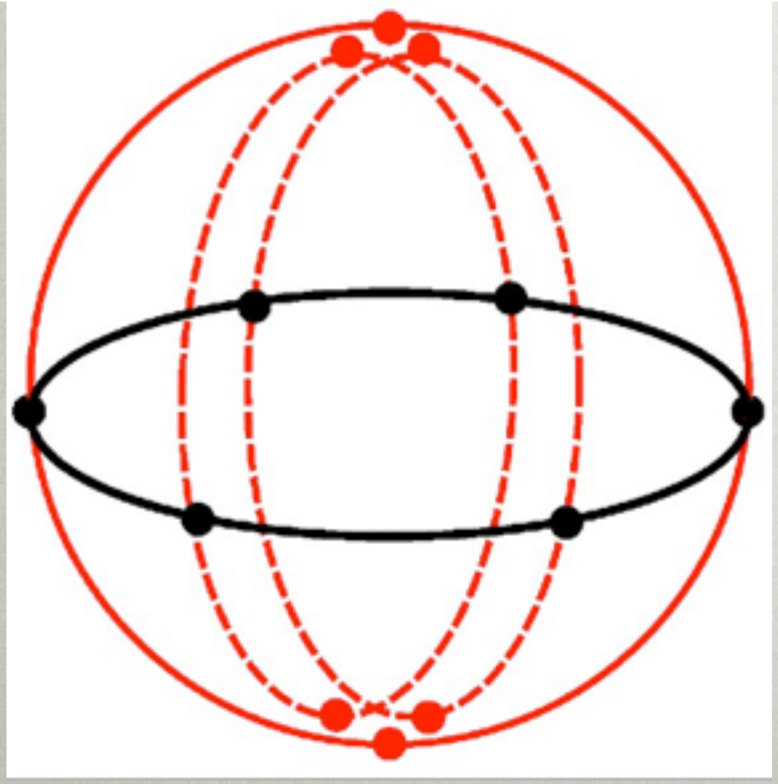
Distribution of order parameter m_E

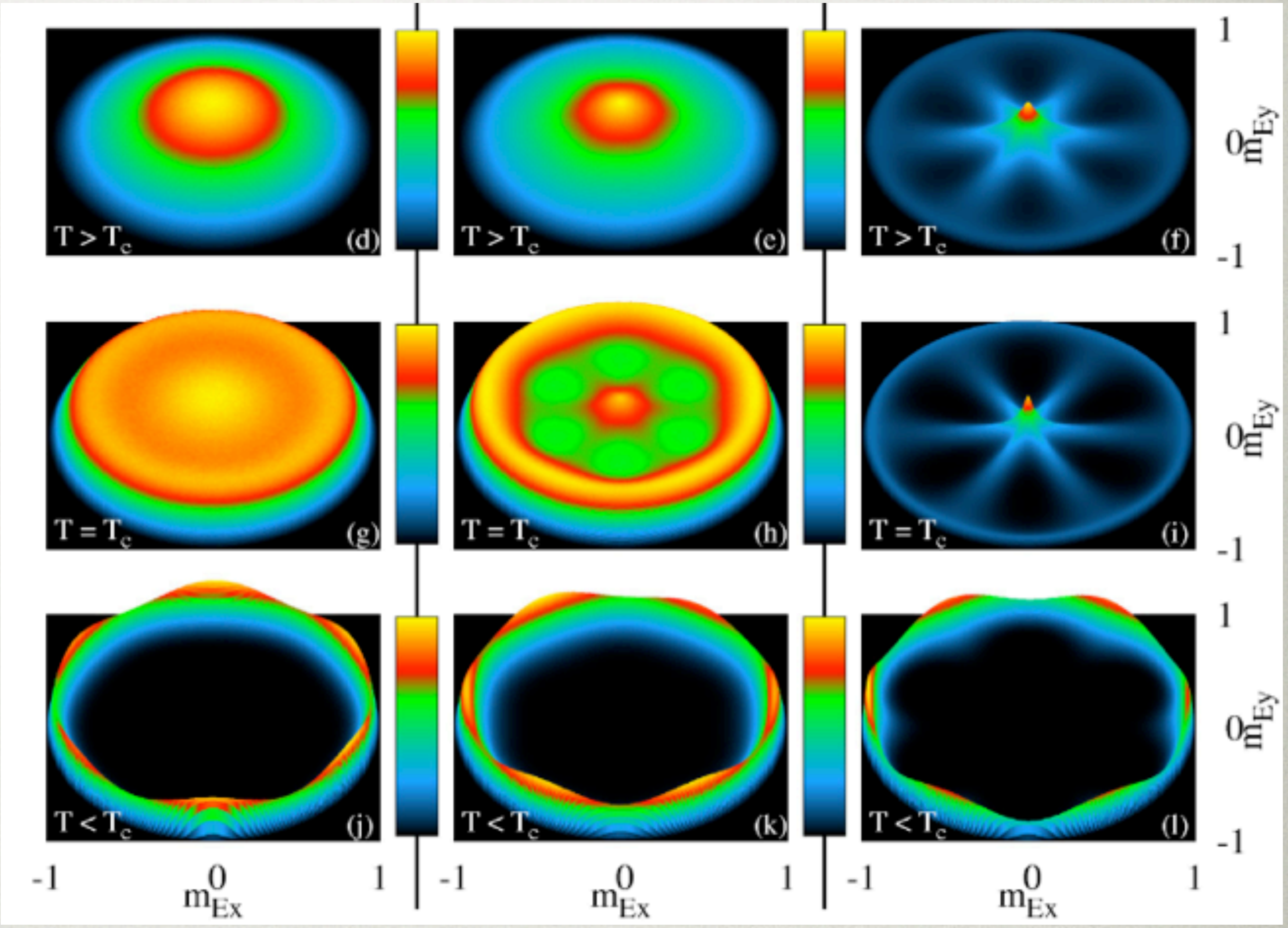




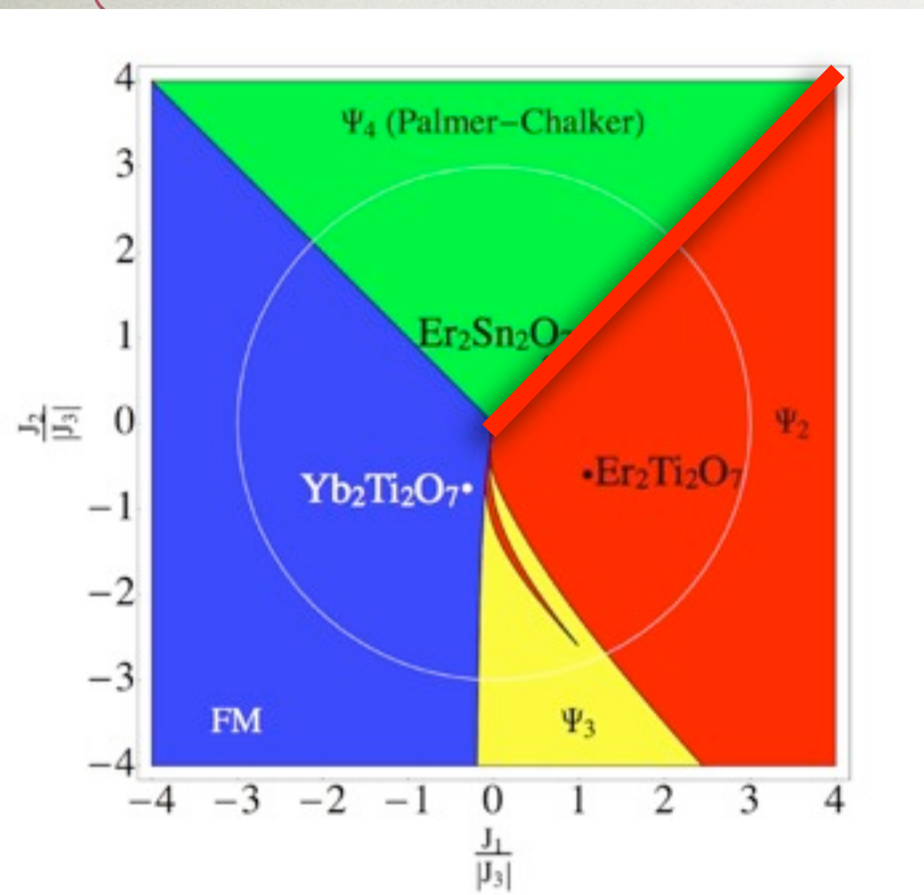
Distribution of order parameter m_E

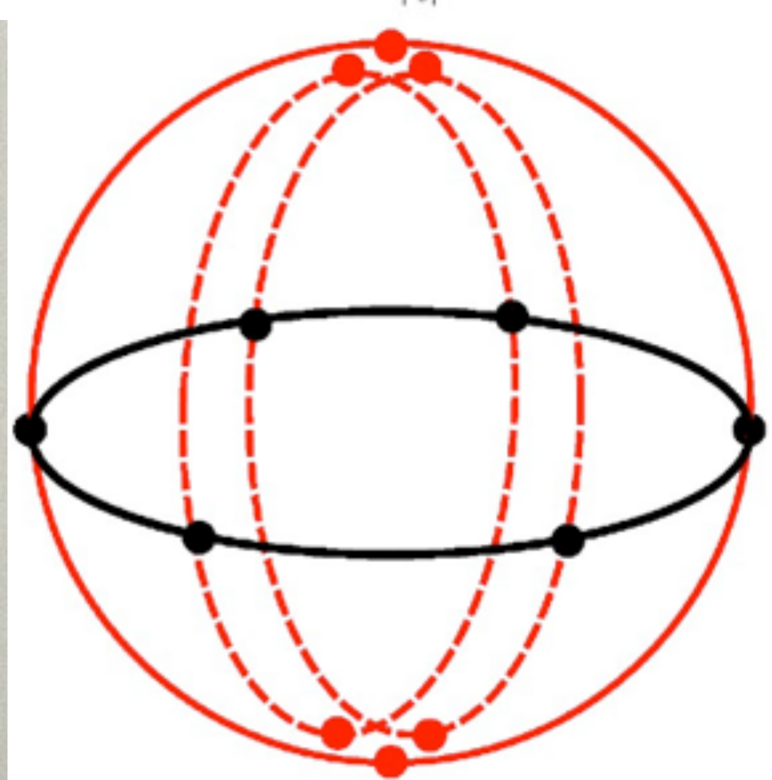


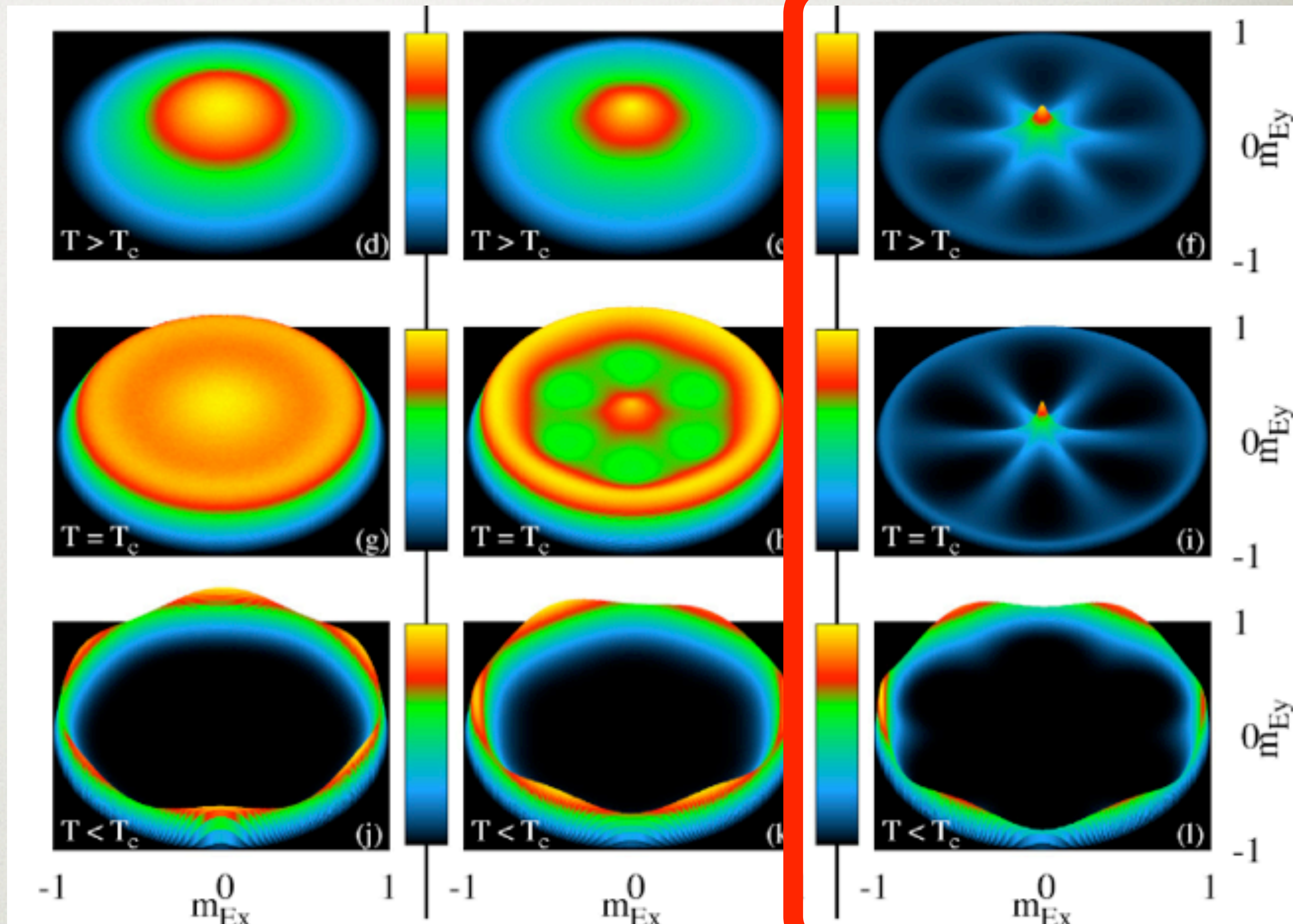




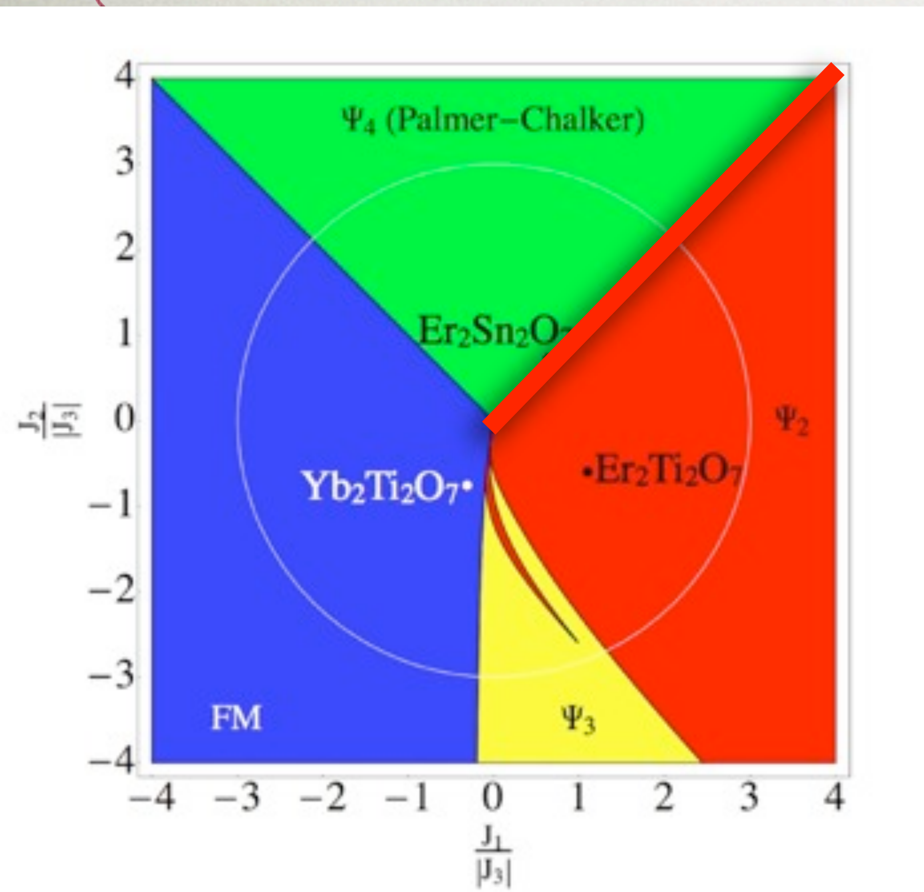
Distribution of order parameter m_E

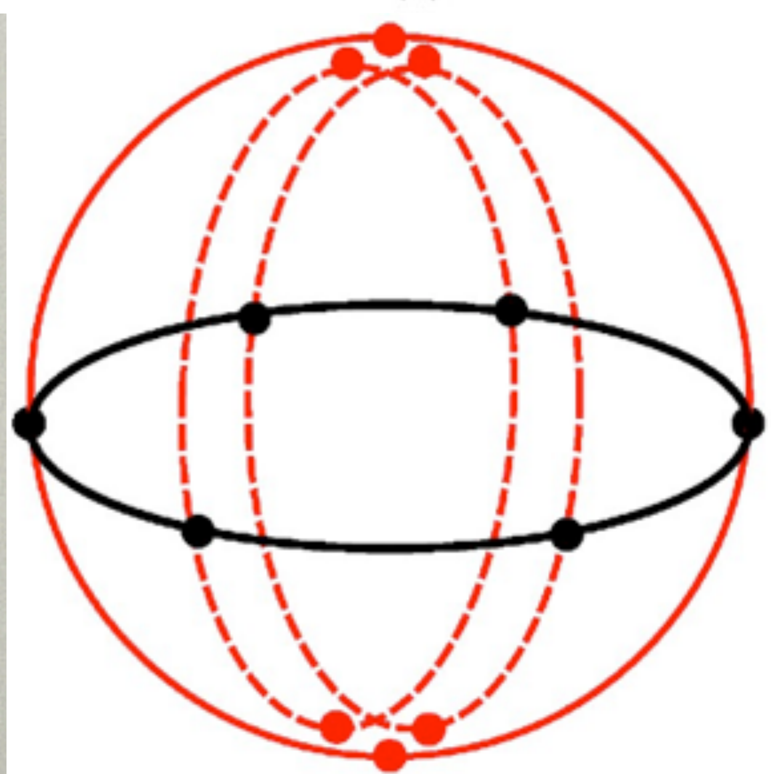


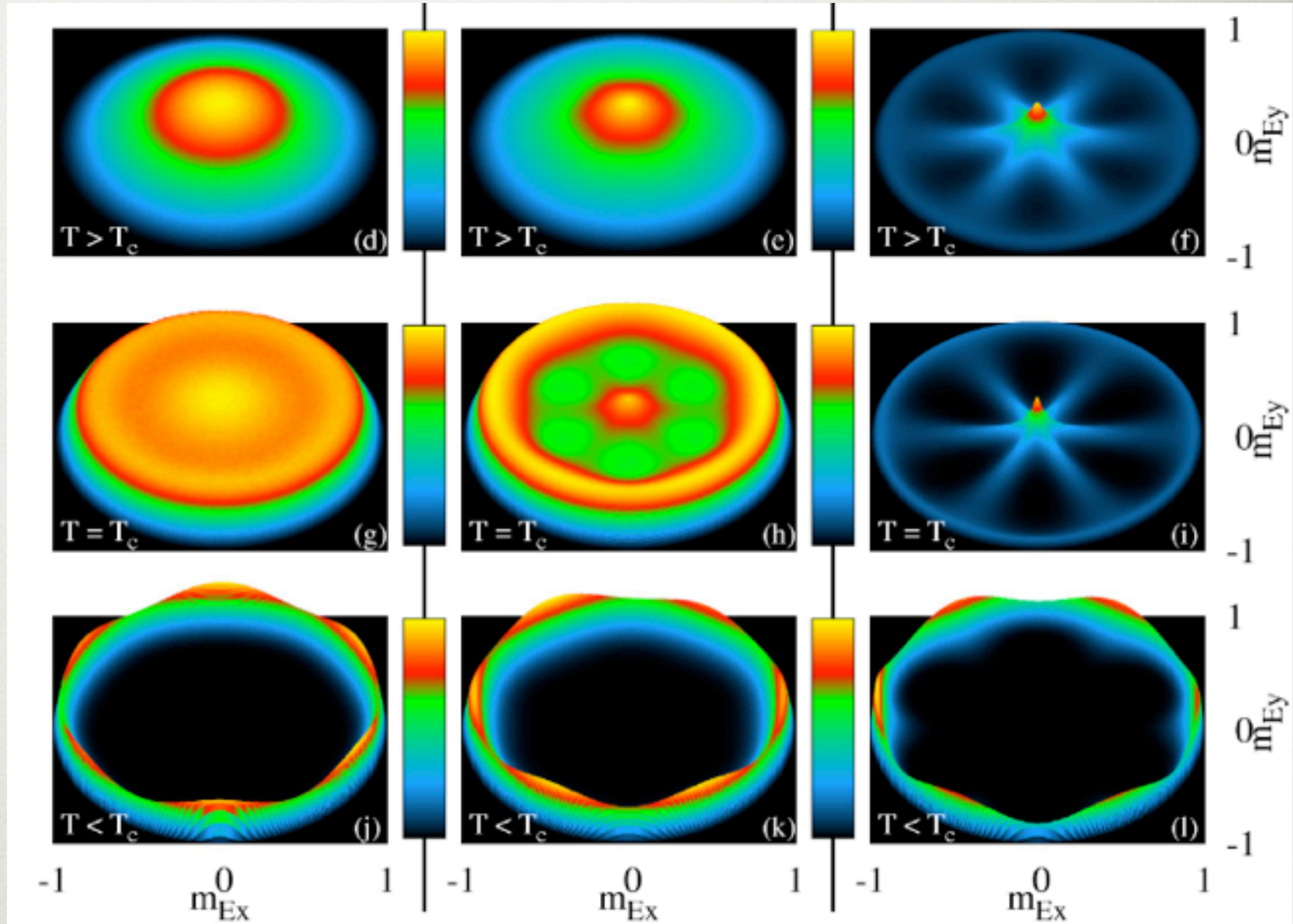




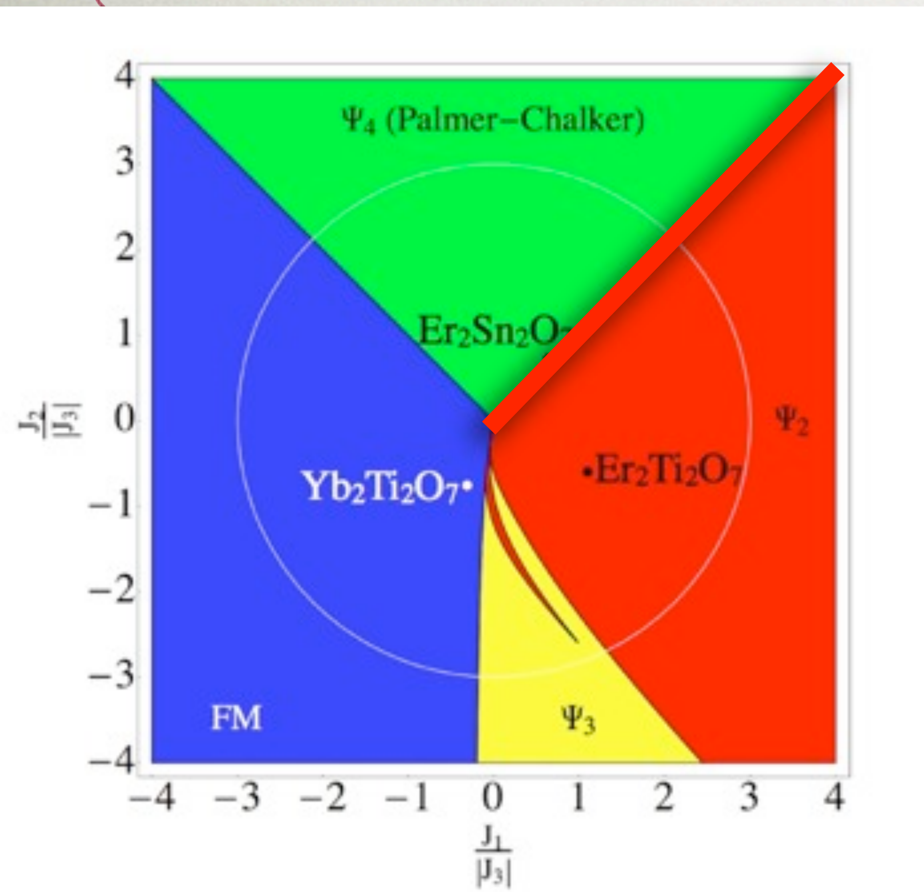
Distribution of order parameter m_E

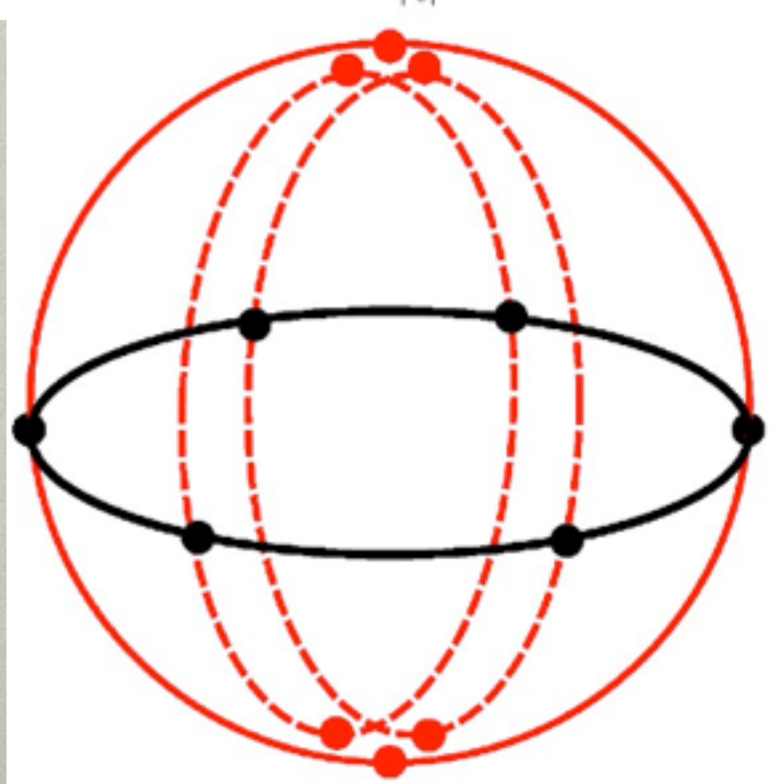


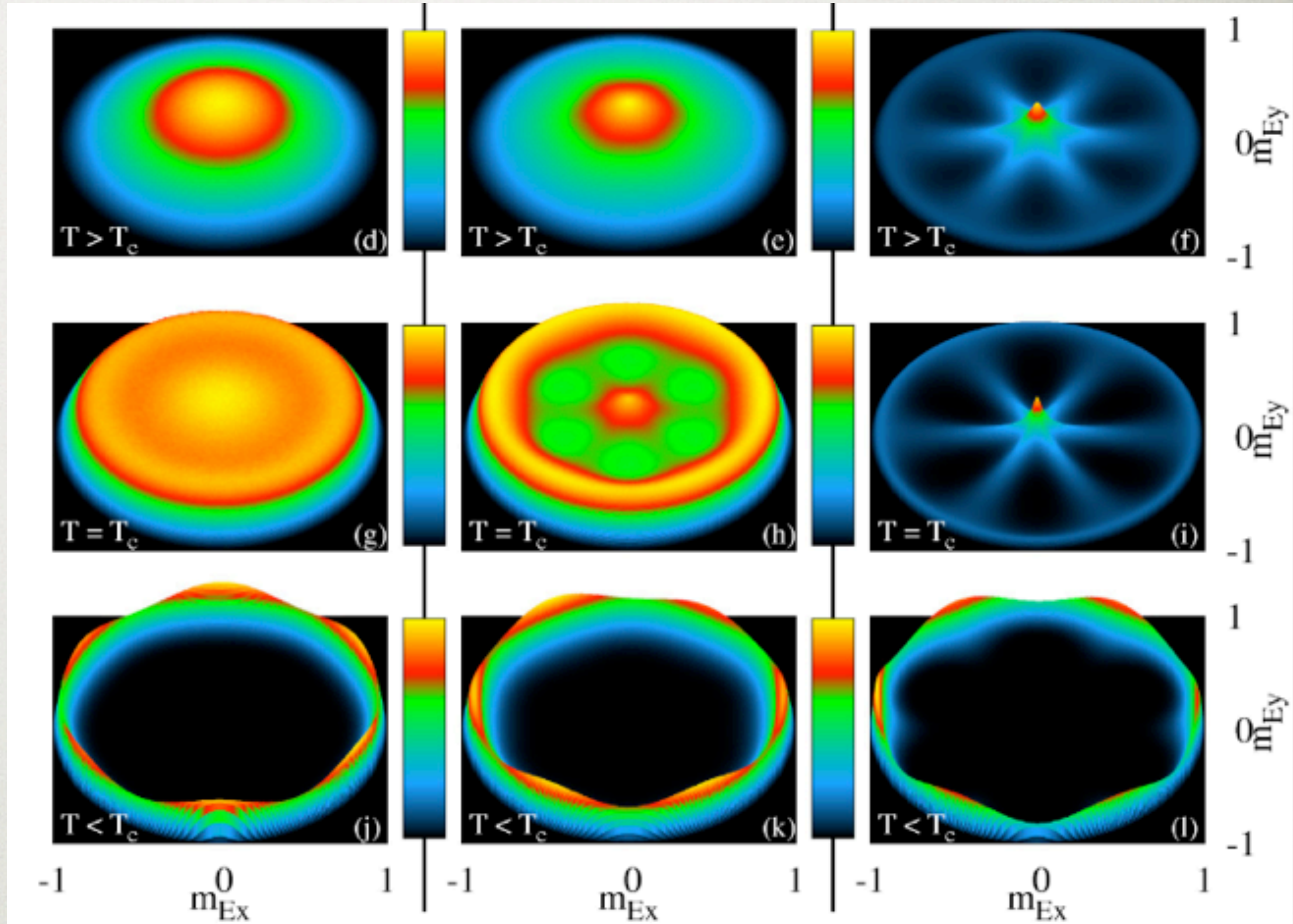




Distribution of order parameter m_E



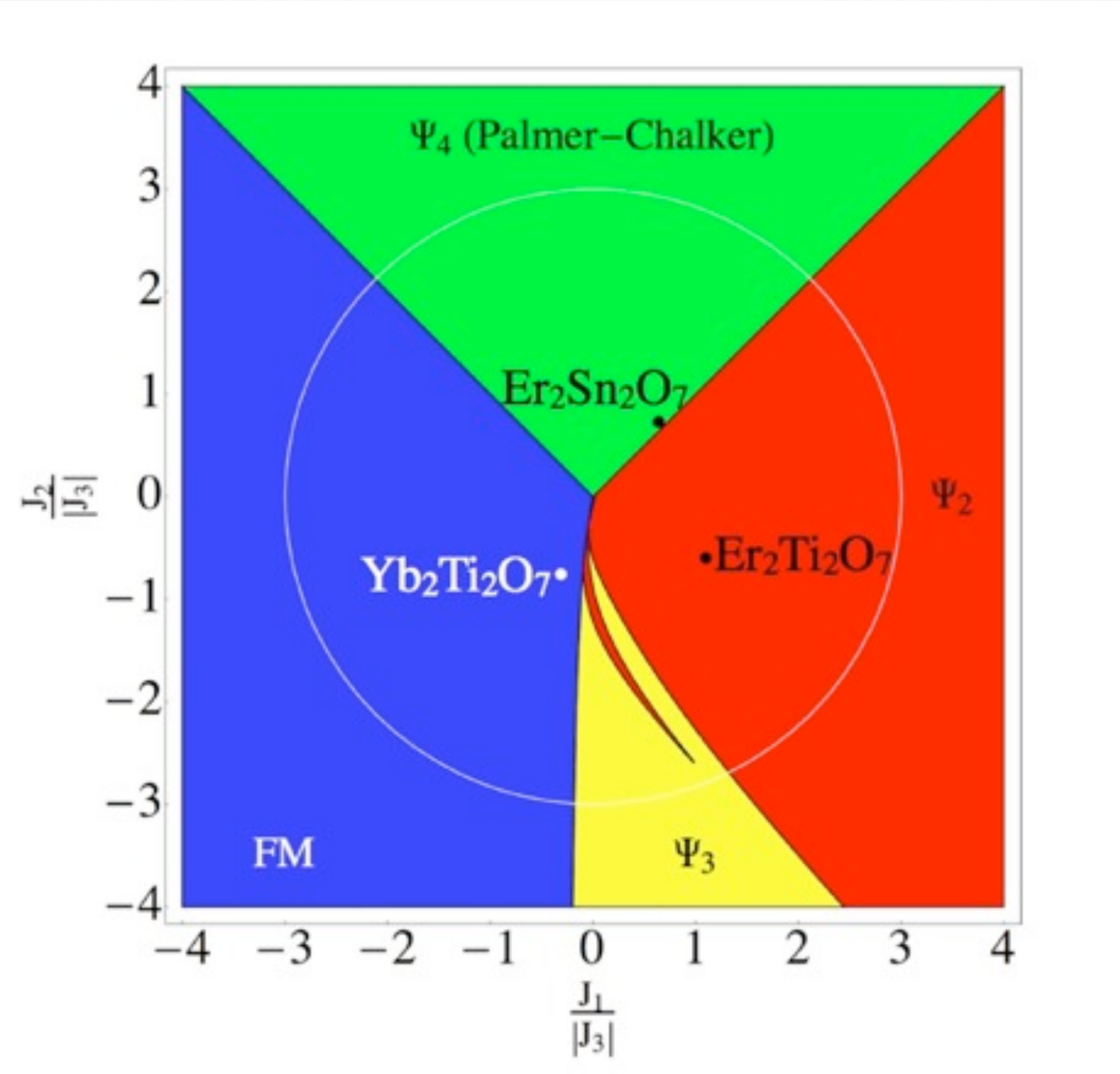




Origin of Champion-Holdsworth phase in $Er_2Ti_2O_7$ is proximity to Palmer - Chalker phase

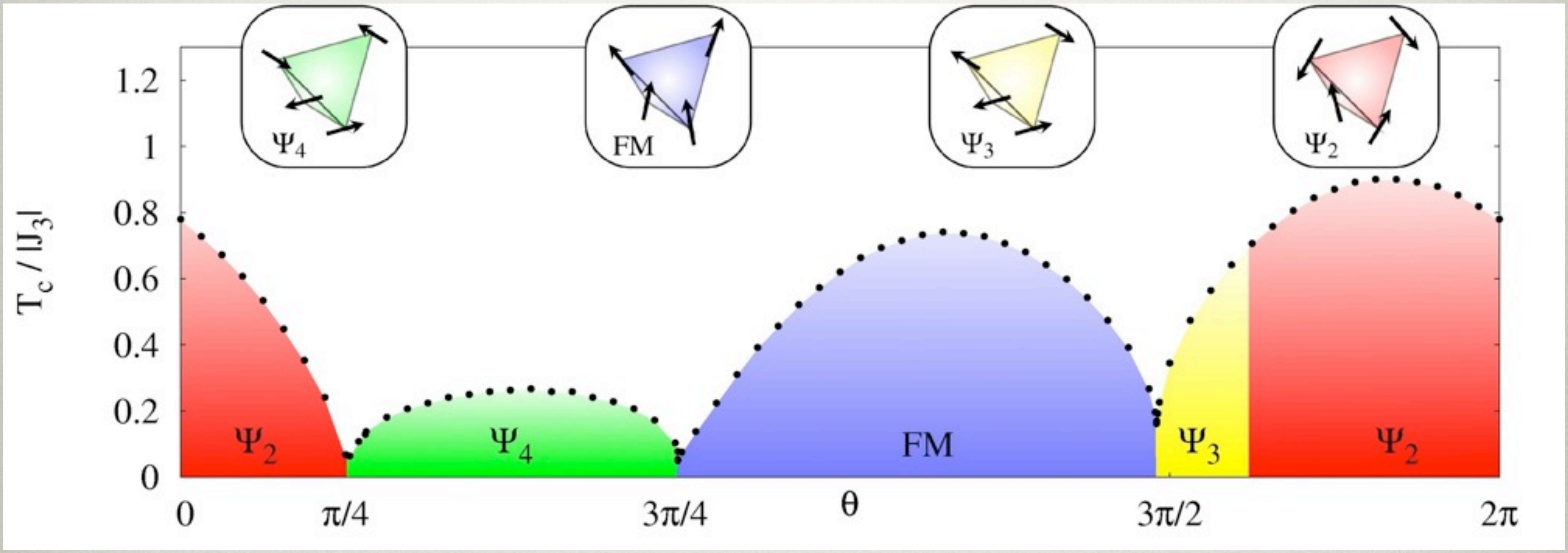
What happens at finite temperature ?

$J_3 < 0$, $J_4 = 0$

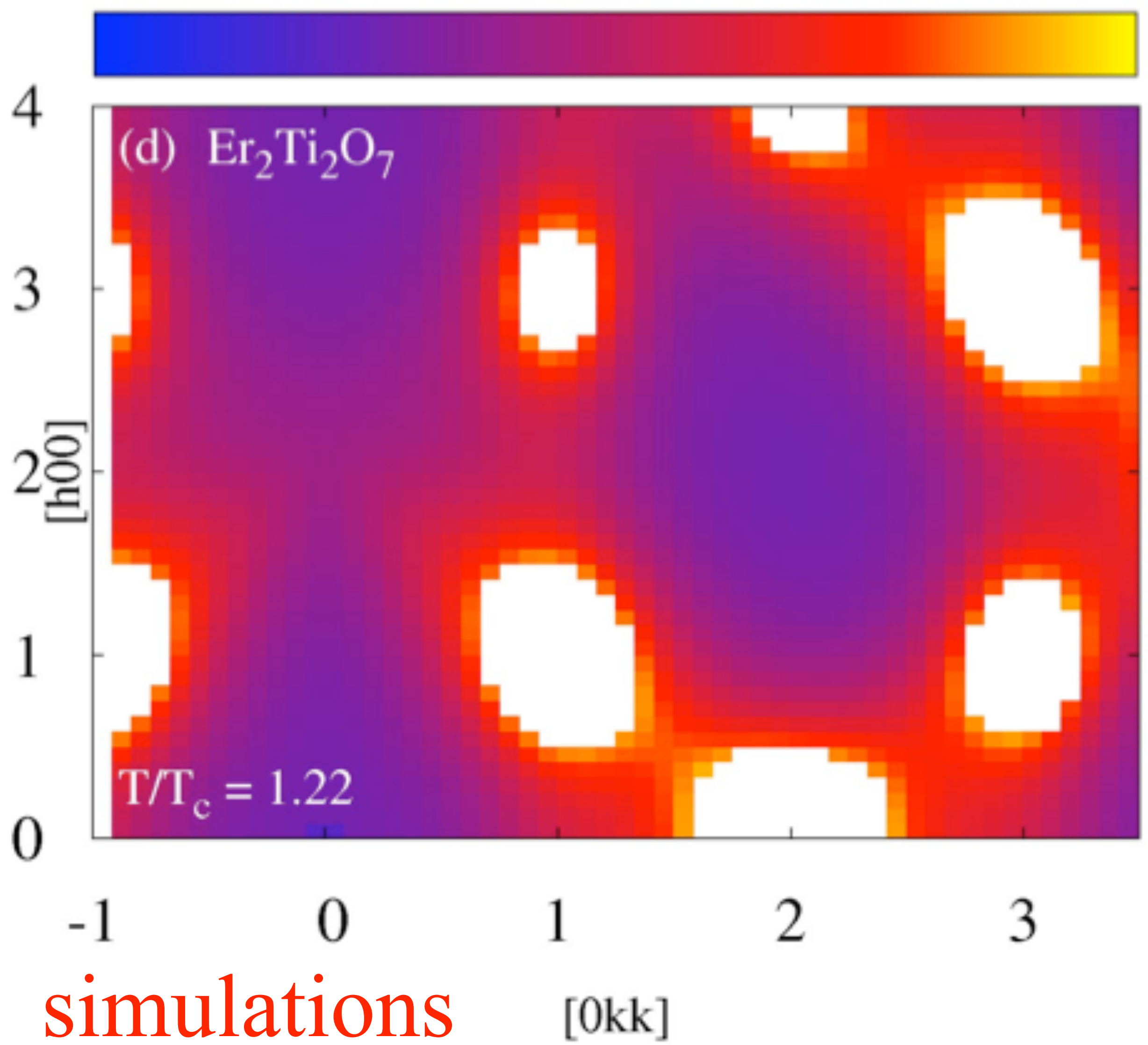


What happens at finite temperature ?

$J_3 < 0,\ J_4 = 0$

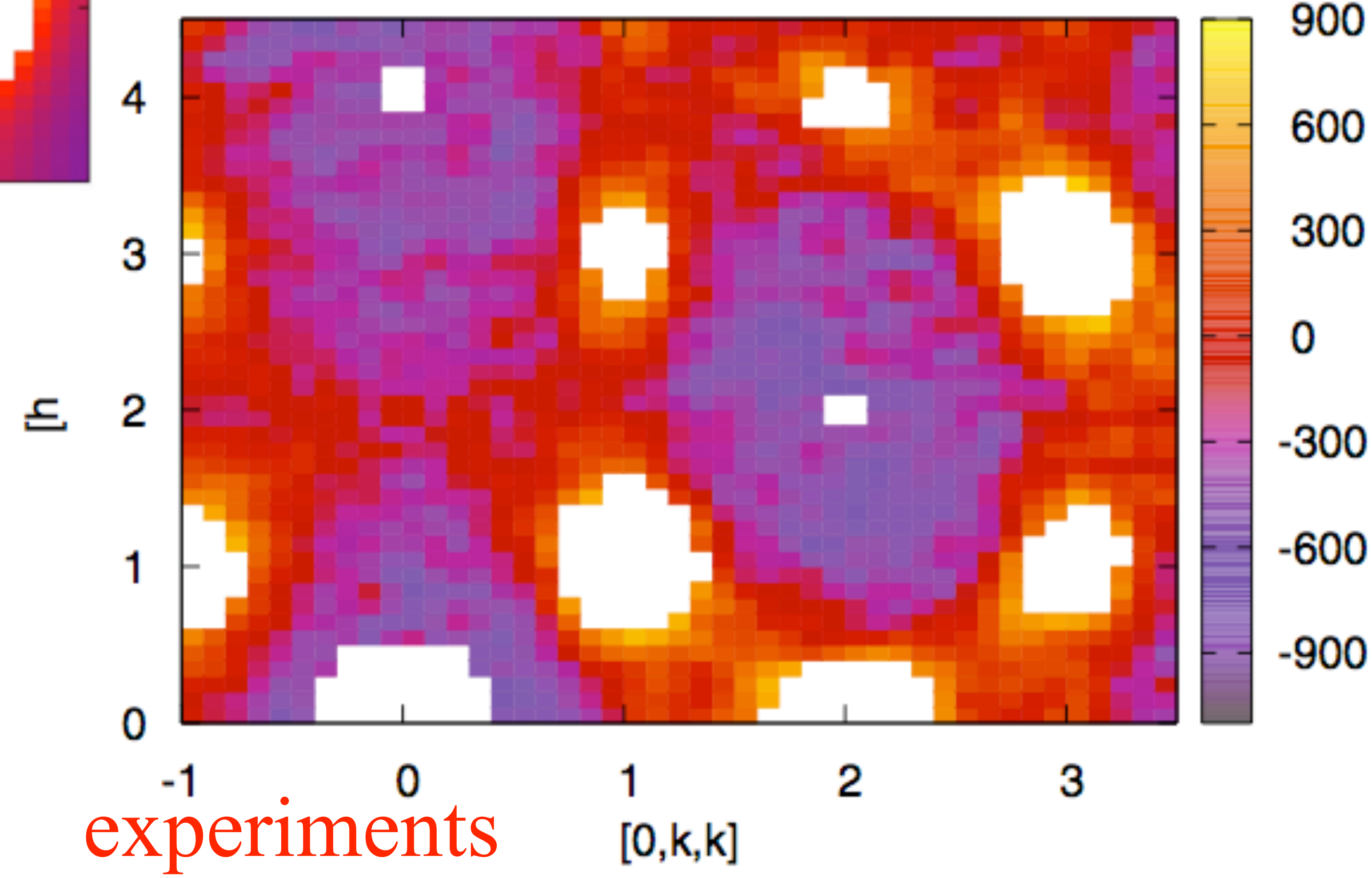


Comparison to experiments in $Er_2Ti_2O_7$



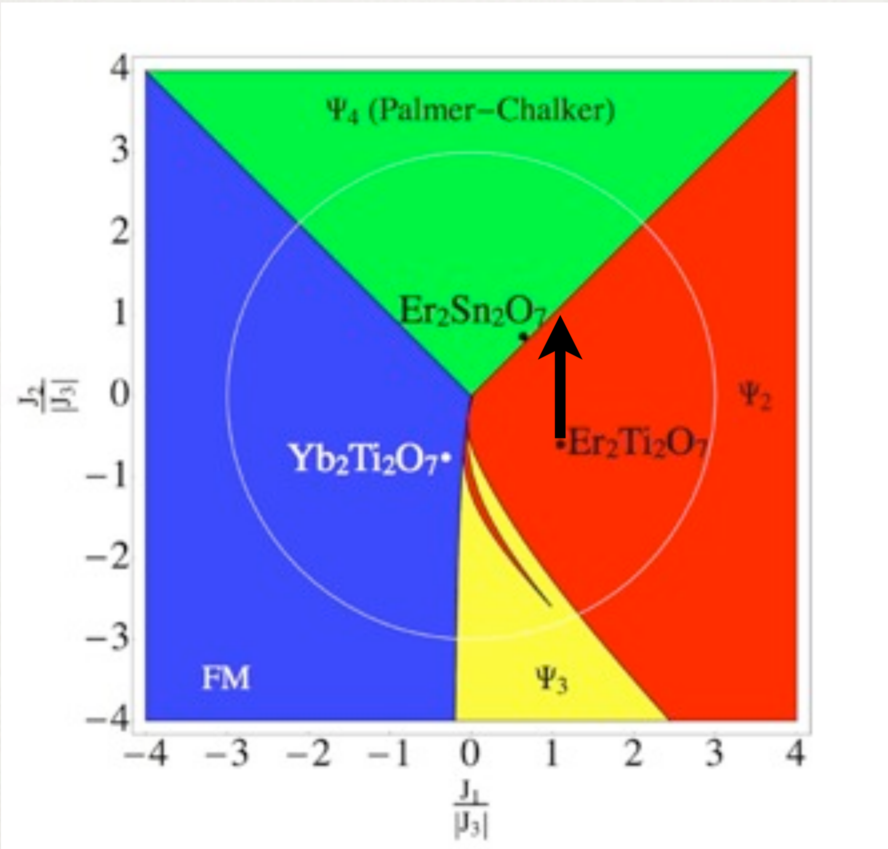
simulations

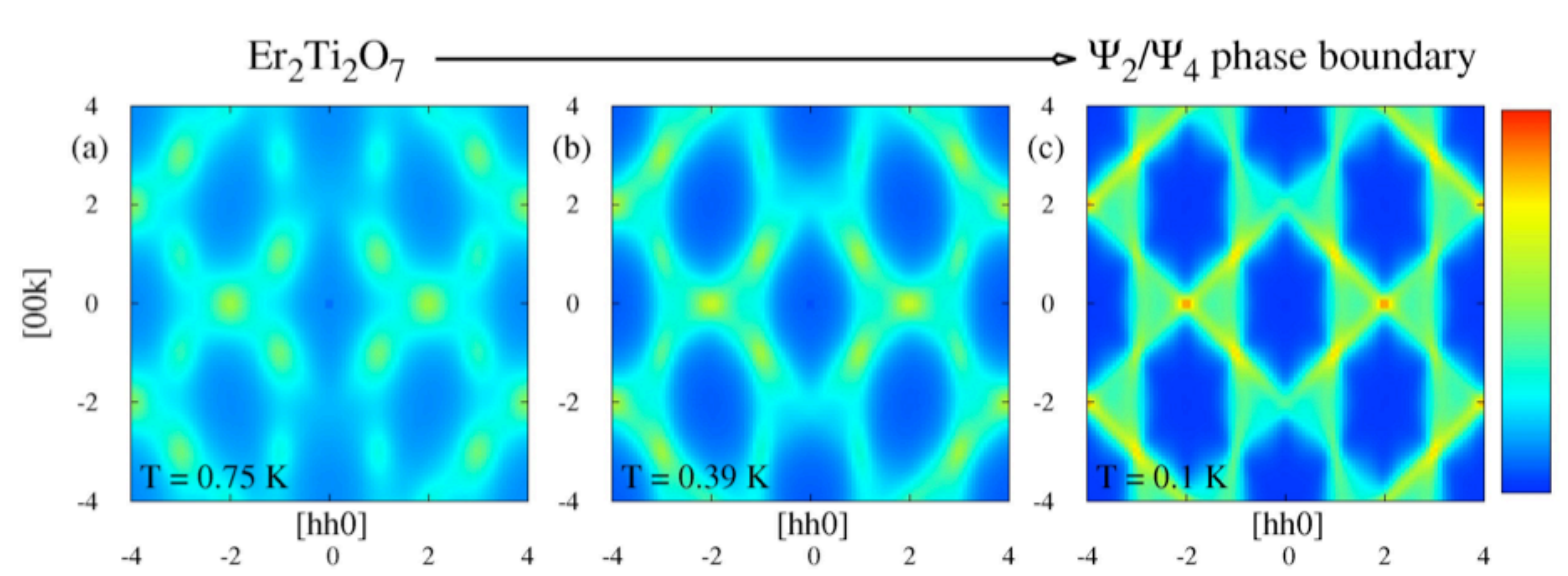
Dalmas de Réotier et al. PRB 2012



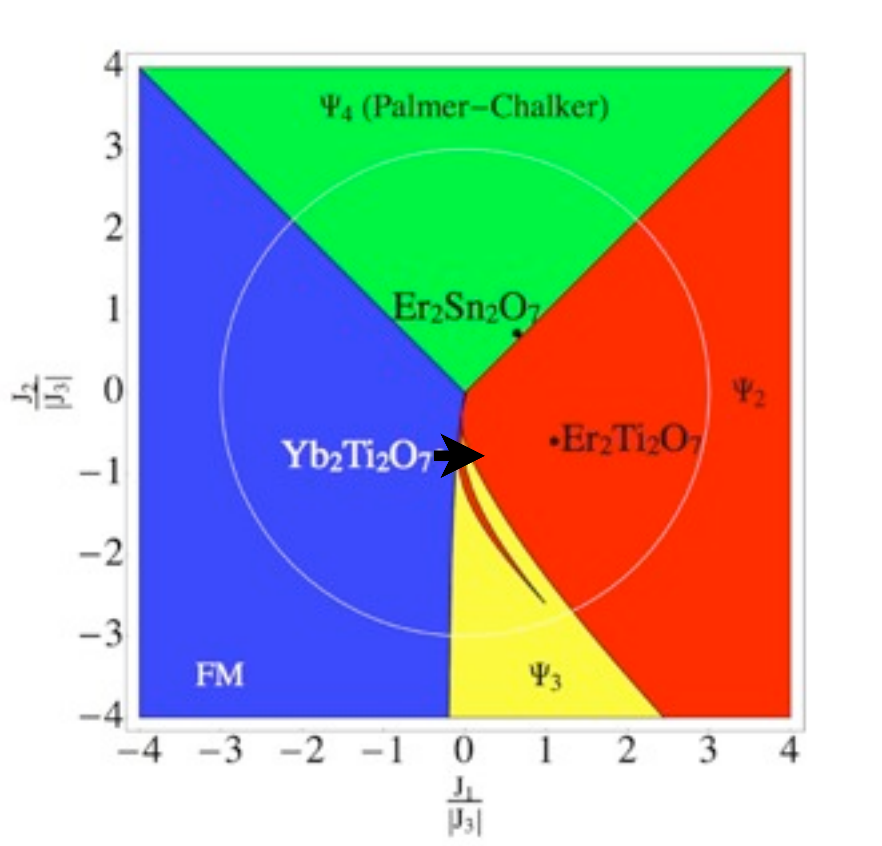
experiments

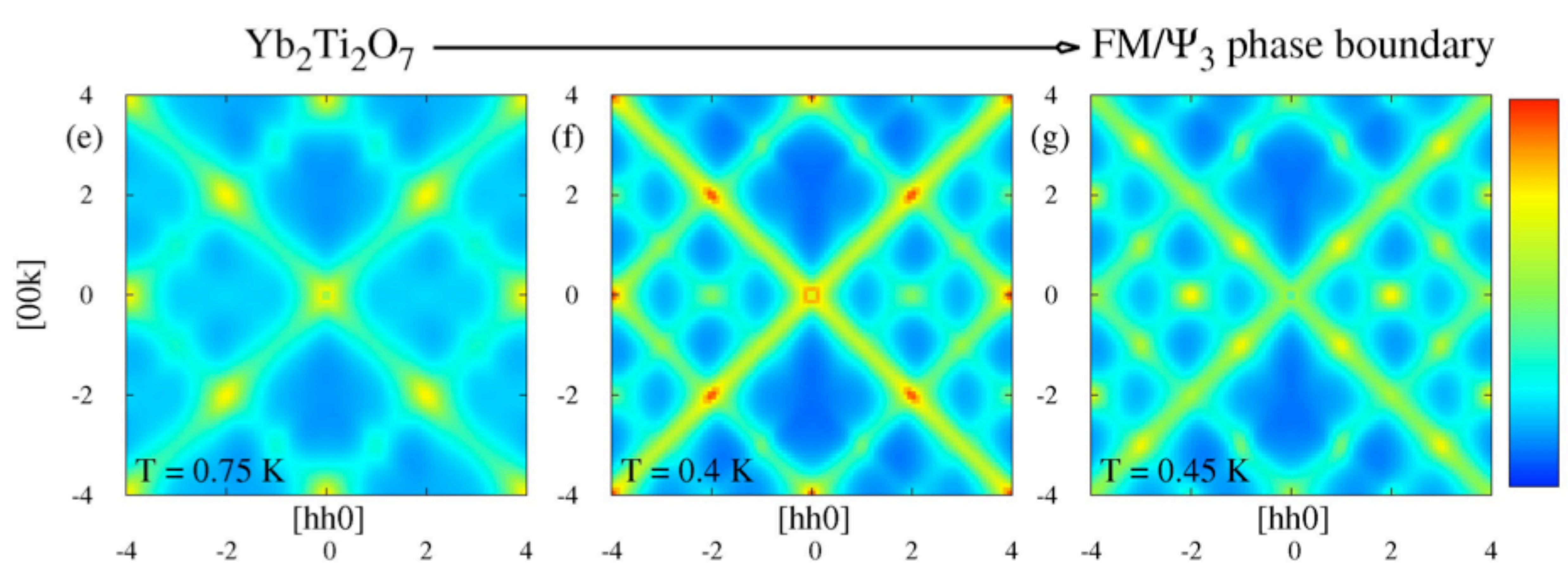
Vanishing pinch points in $Er_2Ti_2O_7$



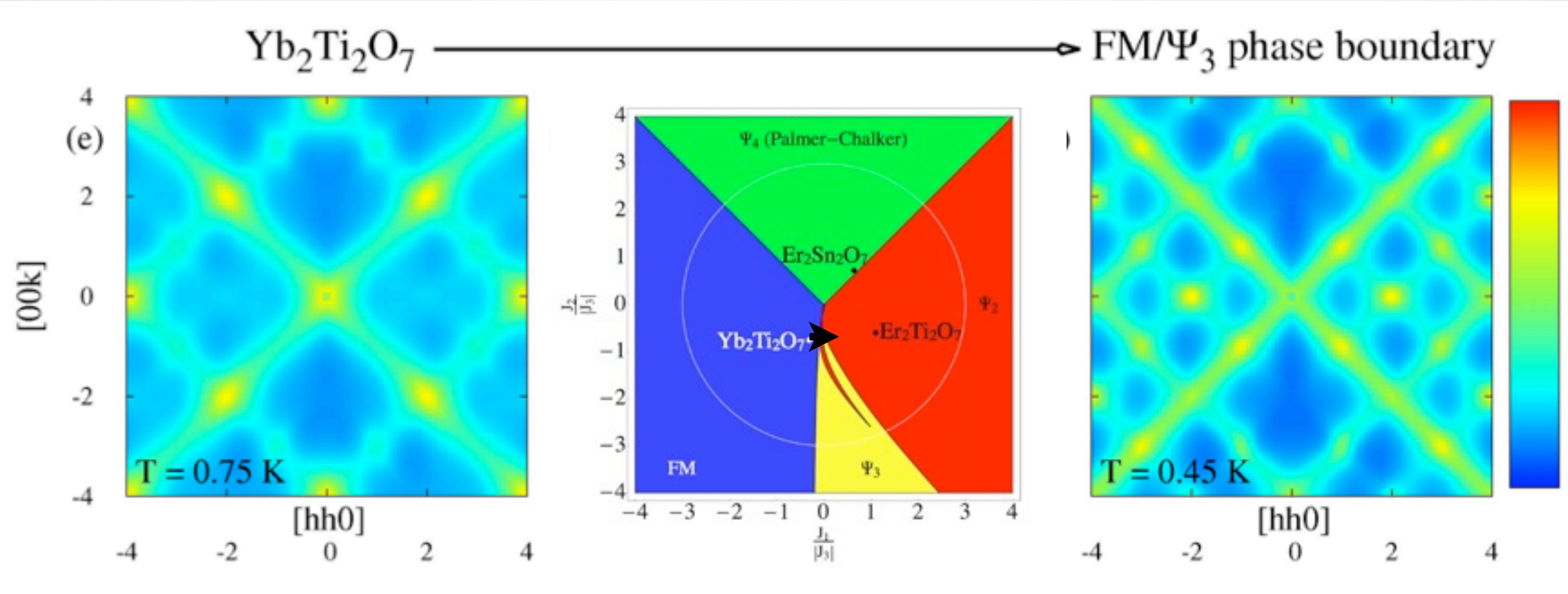


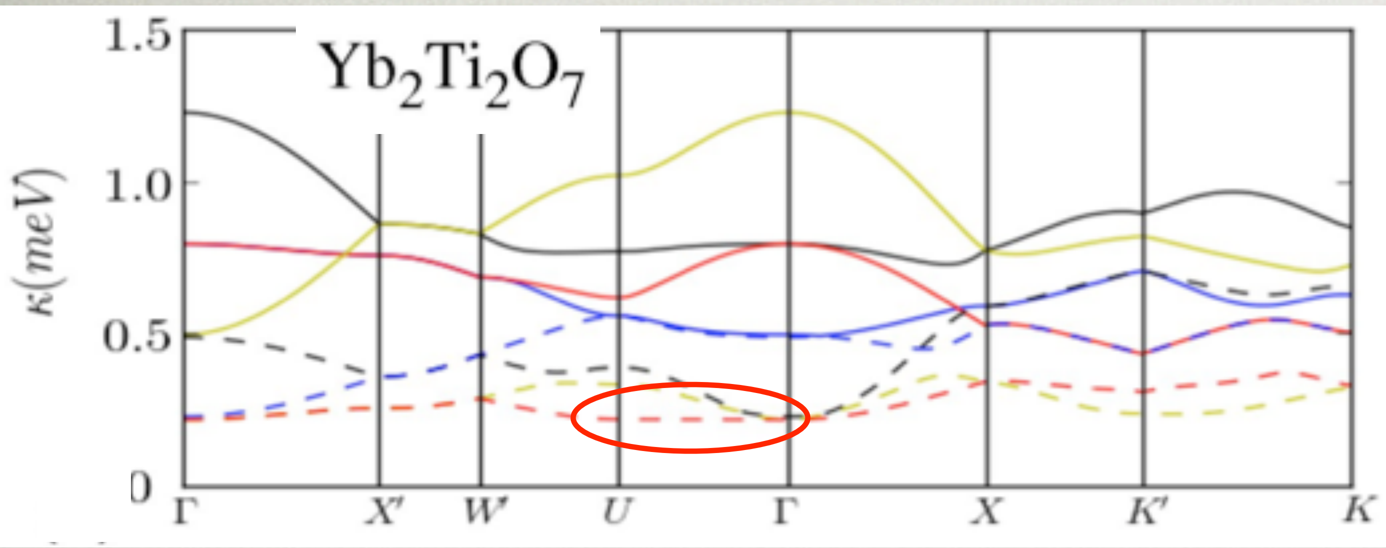
Dimensional crossover in $Yb_2Ti_2O_7$

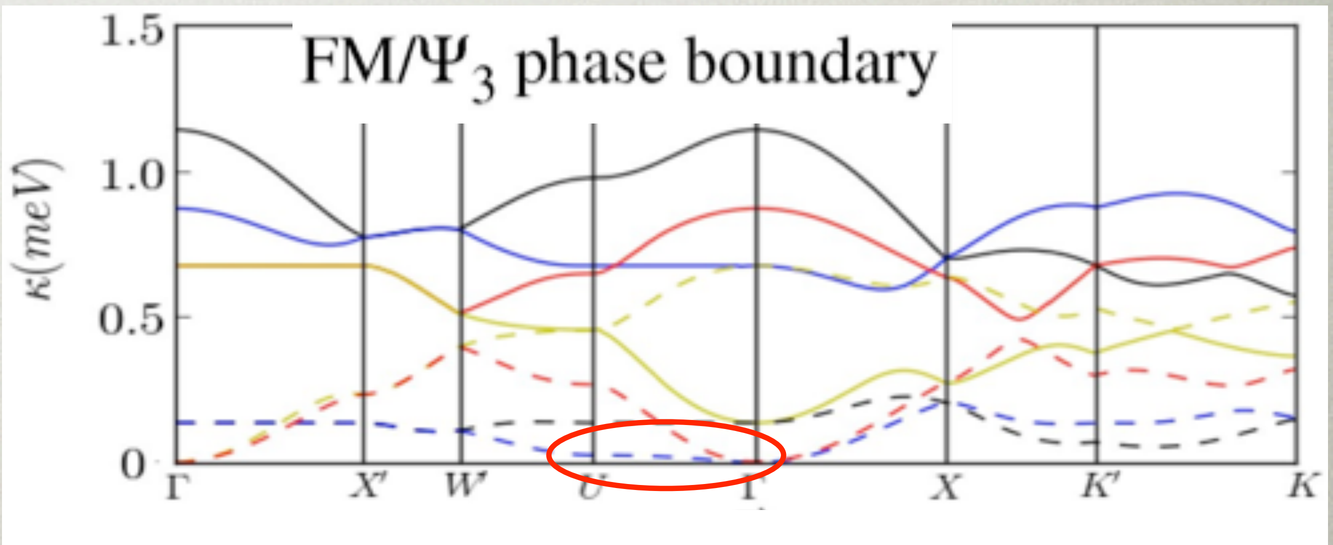




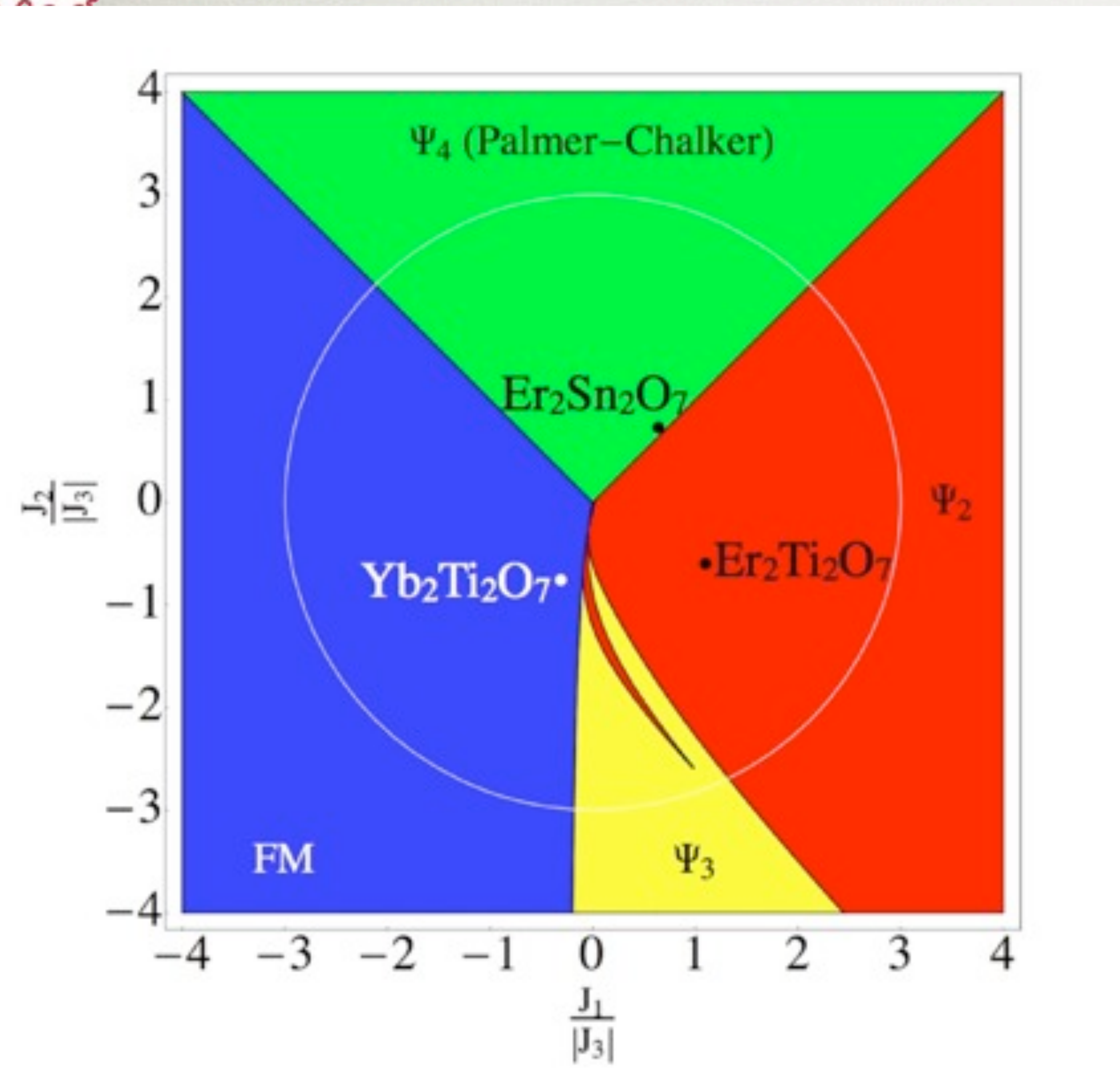
Dimensional crossover in $Yb_2Ti_2O_7$

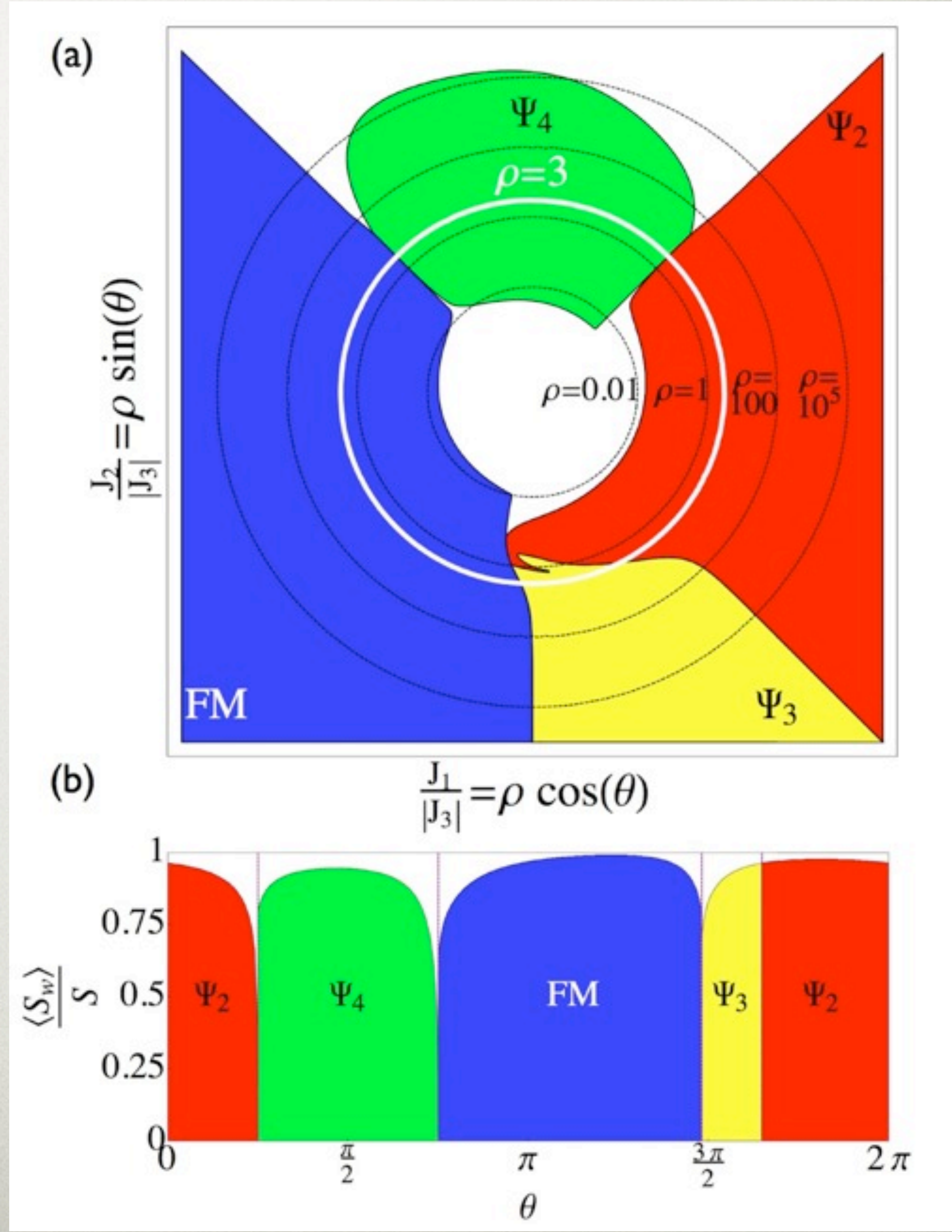






Quantum spin liquid for $Er_2Sn_2O_7$





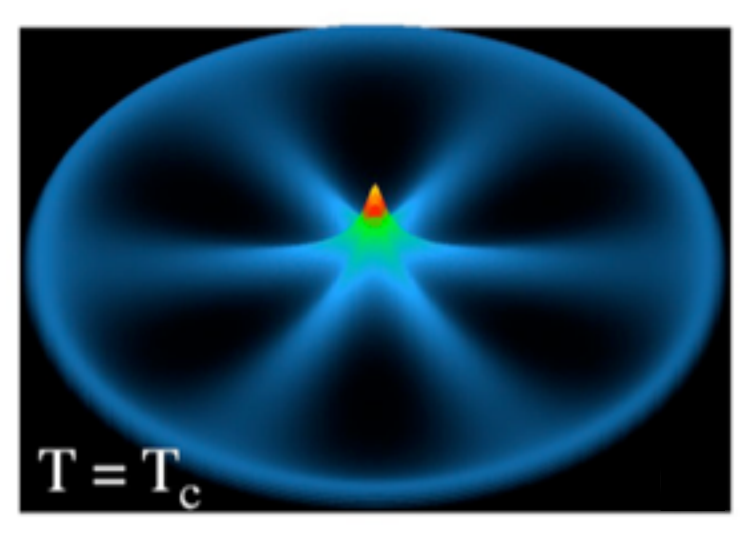
Conclusion

Towards a general theory for pyrochlores

development of an exact quadratic field theory based on group theory

crucial importance of the phase boundaries with extra continuous degeneracies

responsible for
dimensional reduction ($Yb_2Ti_2O_7$)
ground state selection ($Er_2Ti_2O_7$)
quantum spin liquid ($Er_2Sn_2O_7$)
and much more ...



OIST