Title: Experimental evidence for field induced emergent clock anisotropies in the XY pyrochlore Er2Ti2O7

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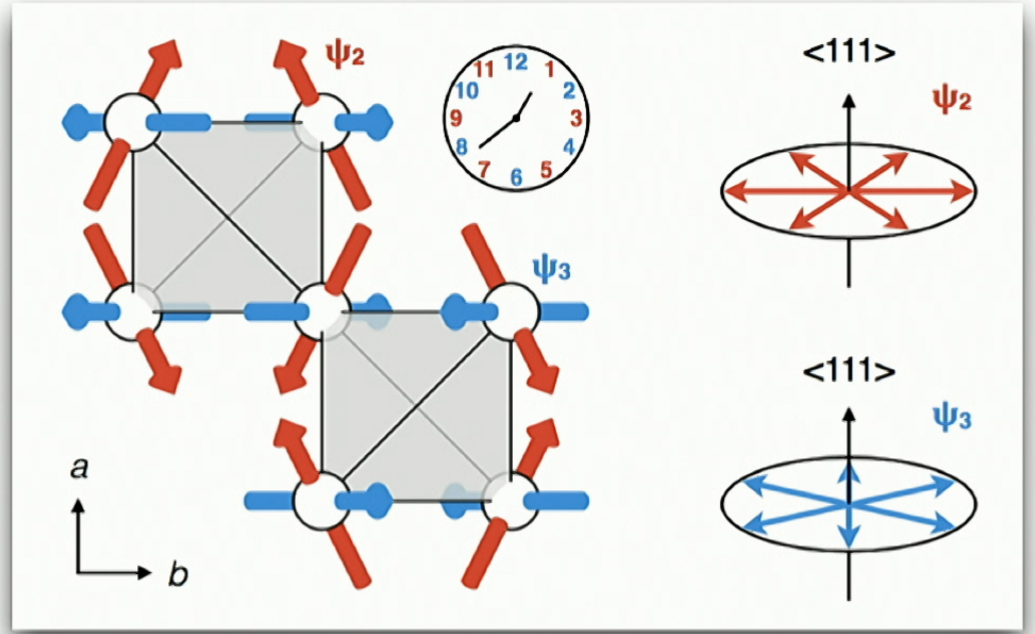
Abstract: The XY pyrochlore Er2Ti2O7 has garnered much attention due to the possibility that its ground state selection could originate from an order-by-disorder mechanism [1,2]. However, recently, theoretical work has exploited the fact that the symmetry breaking in this system is a rare case of high discrete symmetry (Z6) [3]. This work studied the effect of a magnetic field on the Z6 symmetry breaking and predicted rich and controllable magnetothermodynamic properties. Indeed, the authors predict numerous domains transitions in the low field regime that strongly depends on the field direction. In this talk, I will present neutron scattering data on Er2Ti2O7 with a magnetic field applied along different high symmetry directions which provides the first experimental evidence for this rich Z6 domain phase behavior [4].

Experimental evidence for field induced emergent clock anisotropies in the XY pyrochlore $Er_2Ti_2O_7$



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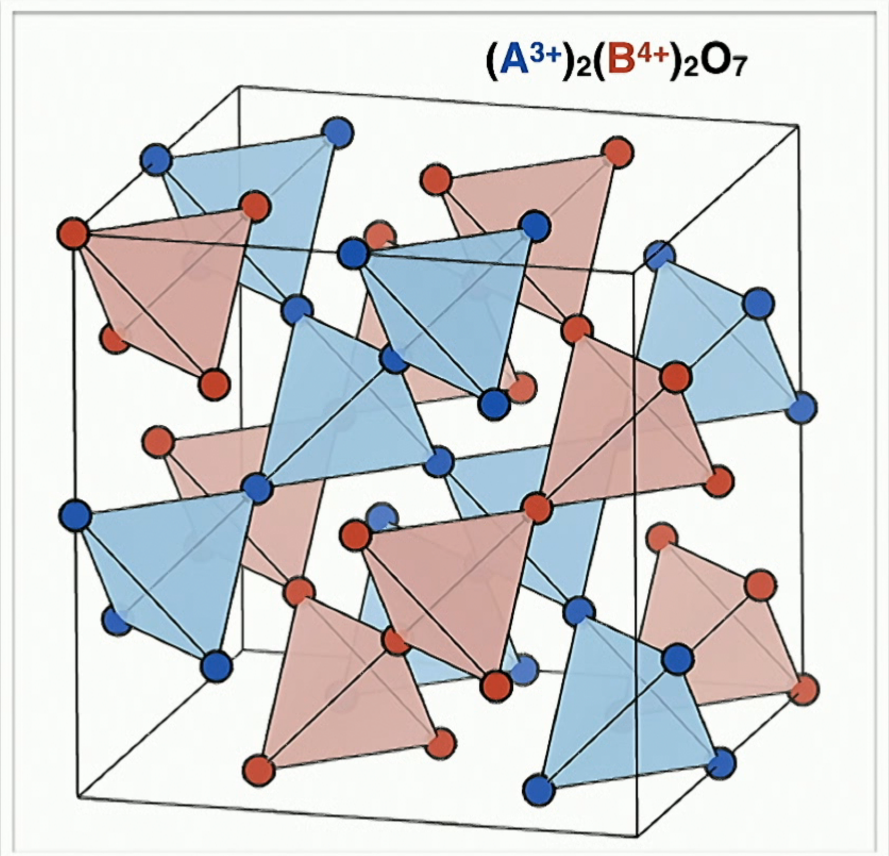
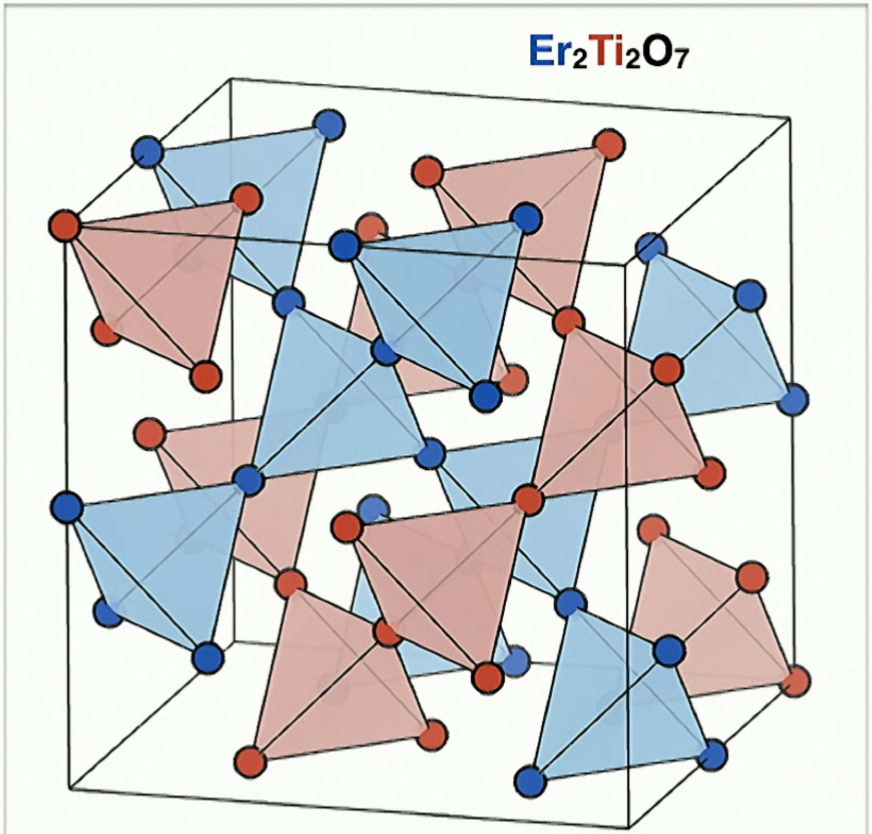
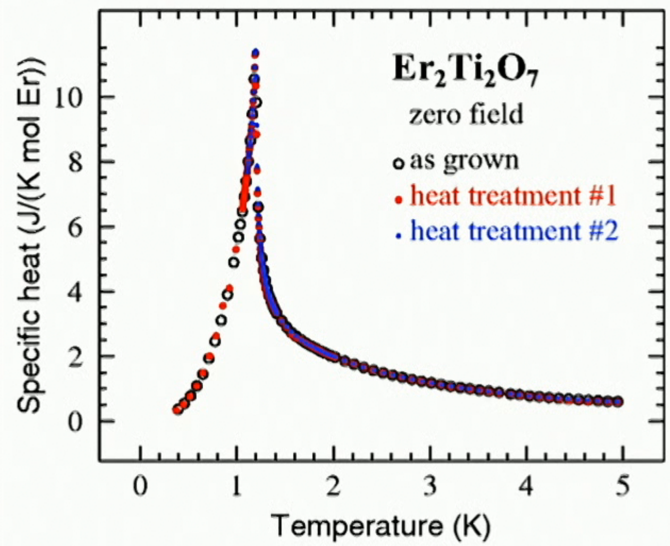
The pyrochlore lattice is renowned for the study of magnetic frustration in 3D



- Spin ice
- Spin liquid
- Multiphase competition
- Disorder-free spin glass
- Partial order
- Order-by-disorder
- Metal-insulator transition
- Magnetic fragmentation
- ....

$Er_2Ti_2O_7$ has an antiferromagnetic transition near 1.2K

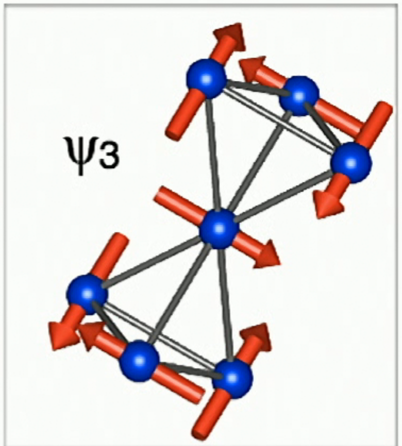


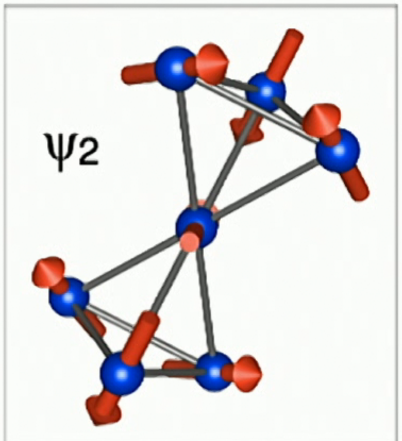


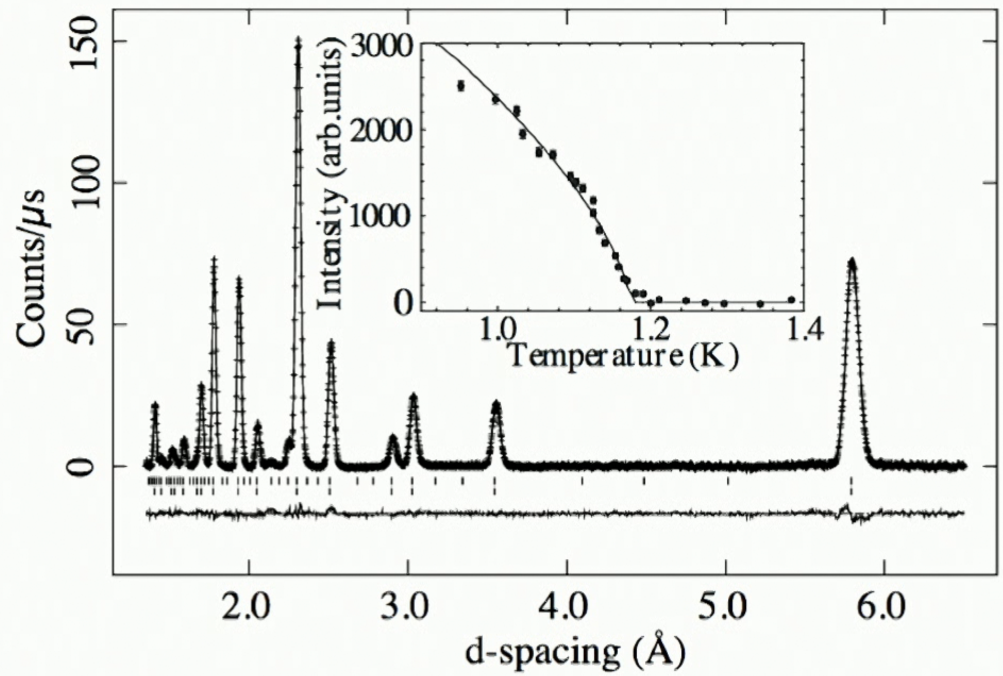
$\theta_{cw} \sim -22K \qquad T_N \sim 1.2K$

PD de Réotier et al, Phys. Rev. B. 86, 104424 (2012)

$Er_2Ti_2O_7$ orders into a k=0, Γ_5 magnetic structure.

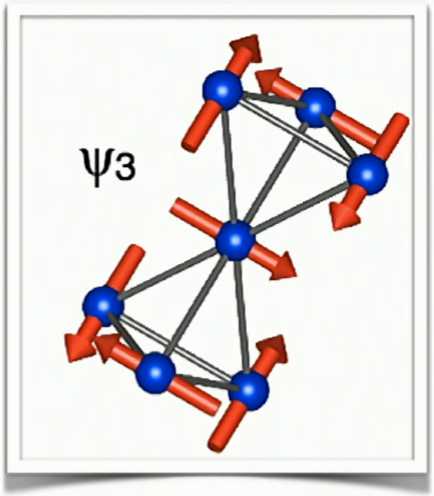


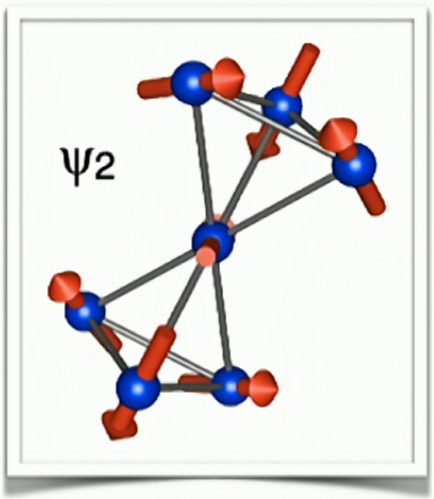


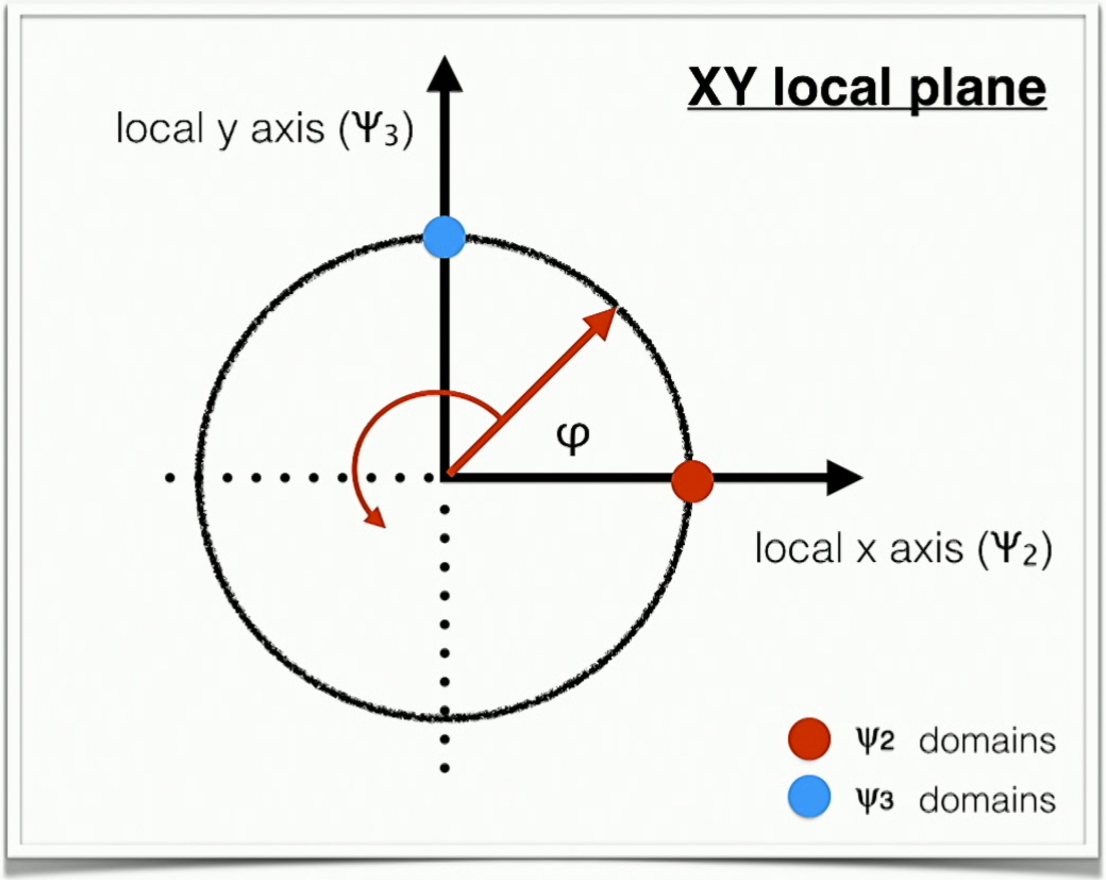


J. D. M. Champion et al, Phys. Rev. B. 68, 020401 (2003)

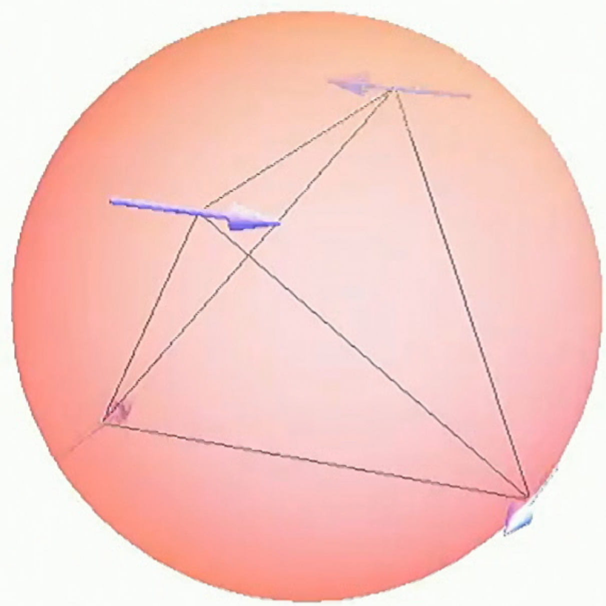
Local spin orientation in a k=0, Γ_5 magnetic structure





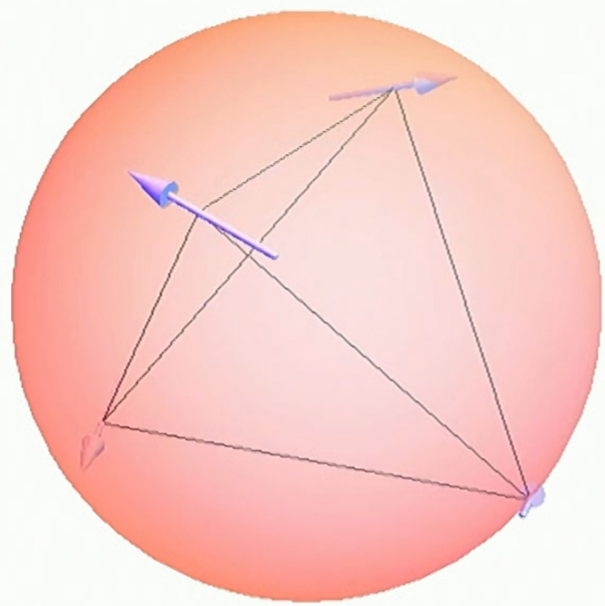


Local spin orientation in a k=0, Γ_5 magnetic structure



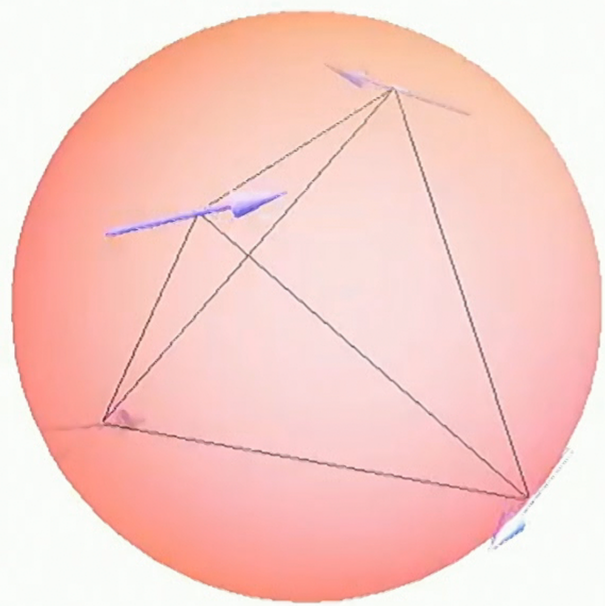
Video : O. Tchernyshev

Local spin orientation in a k=0, Γ_5 magnetic structure



Video : O. Tchernyshev

Local spin orientation in a k=0, Γ_5 magnetic structure



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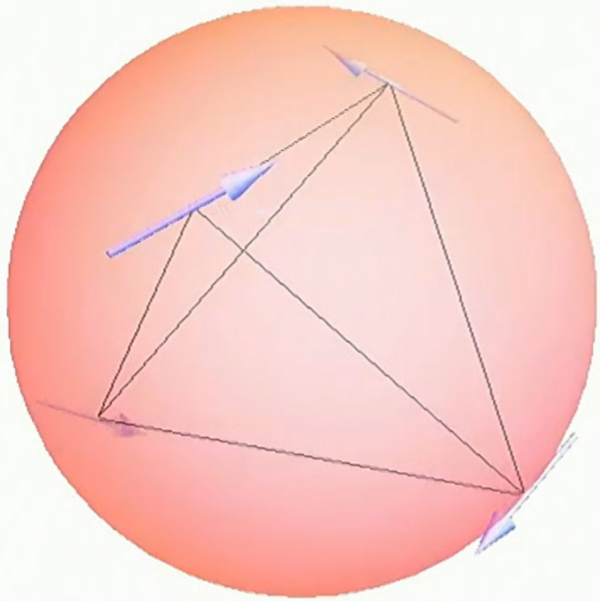
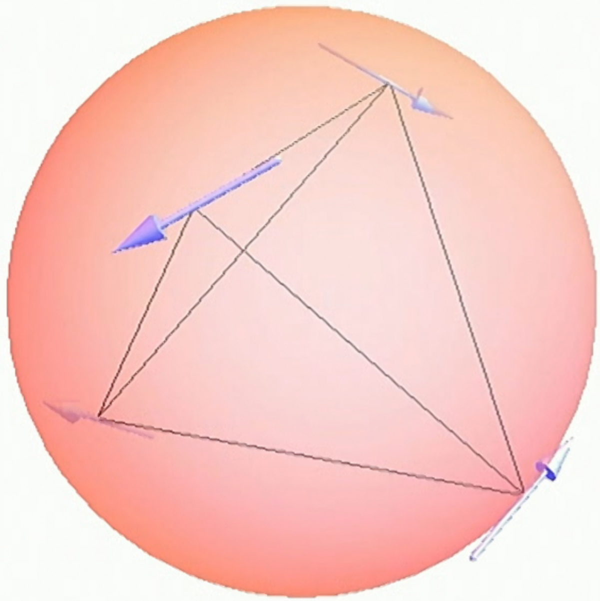
Local spin orientation in a k=0, Γ_5 magnetic structure



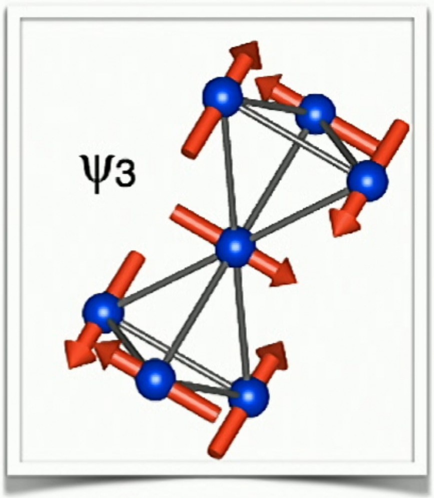
Video : O. Tchernyshev

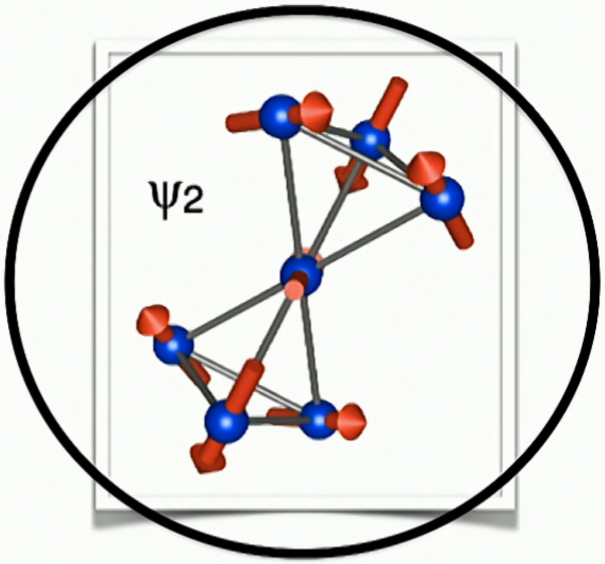
Local spin orientation in a k=0, Γ_5 magnetic structure

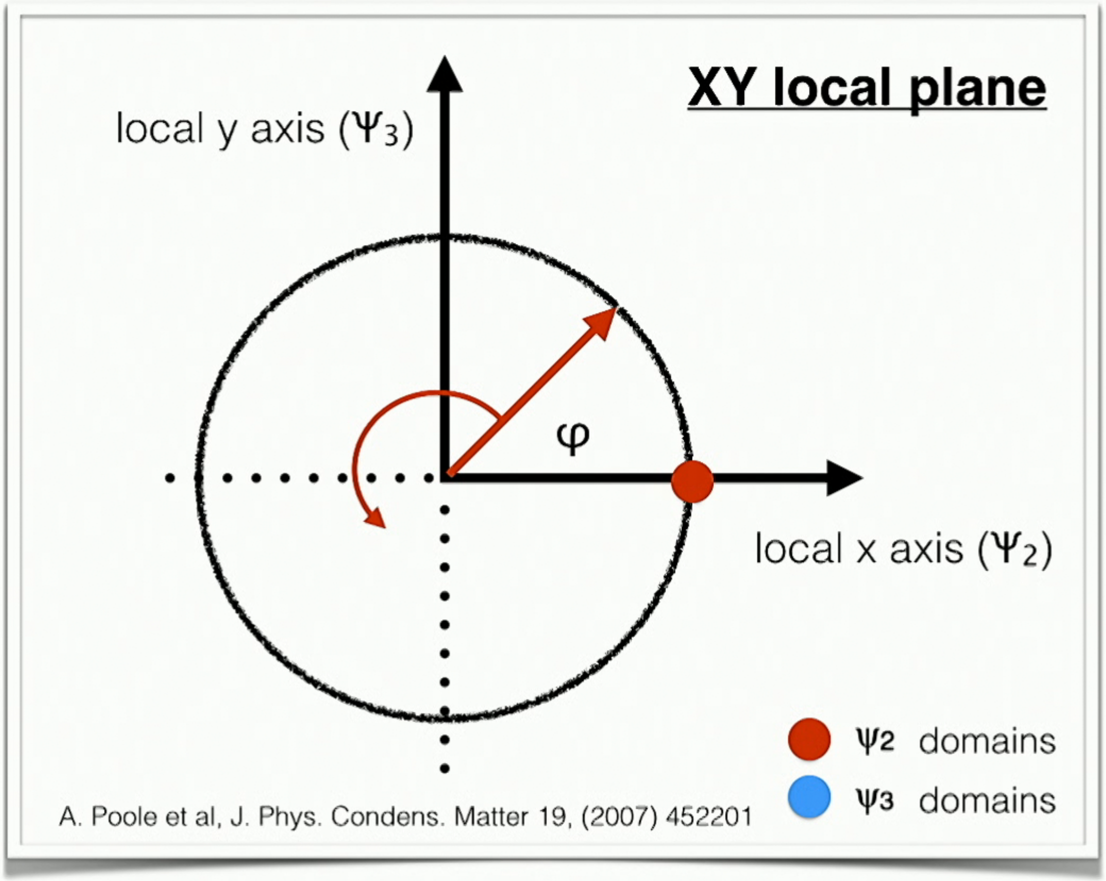


Video : O. Tchernyshev

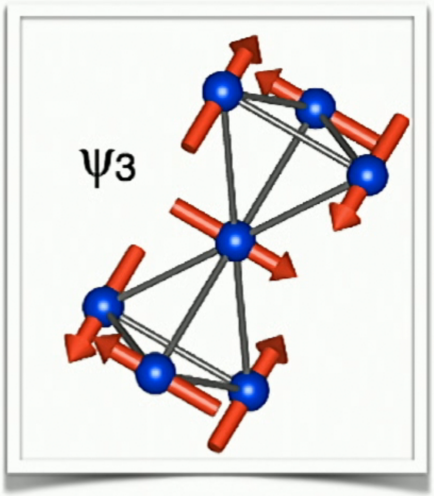
Polarized neutron diffraction revealed that $Er_2Ti_2O_7$ orders into a pure Ψ_2 state

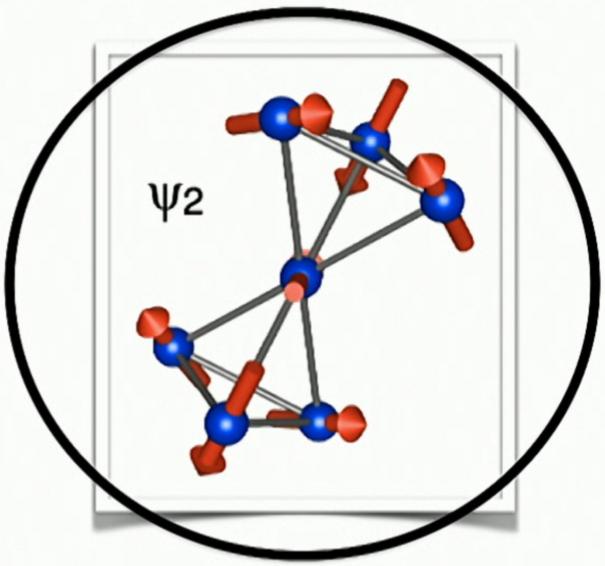


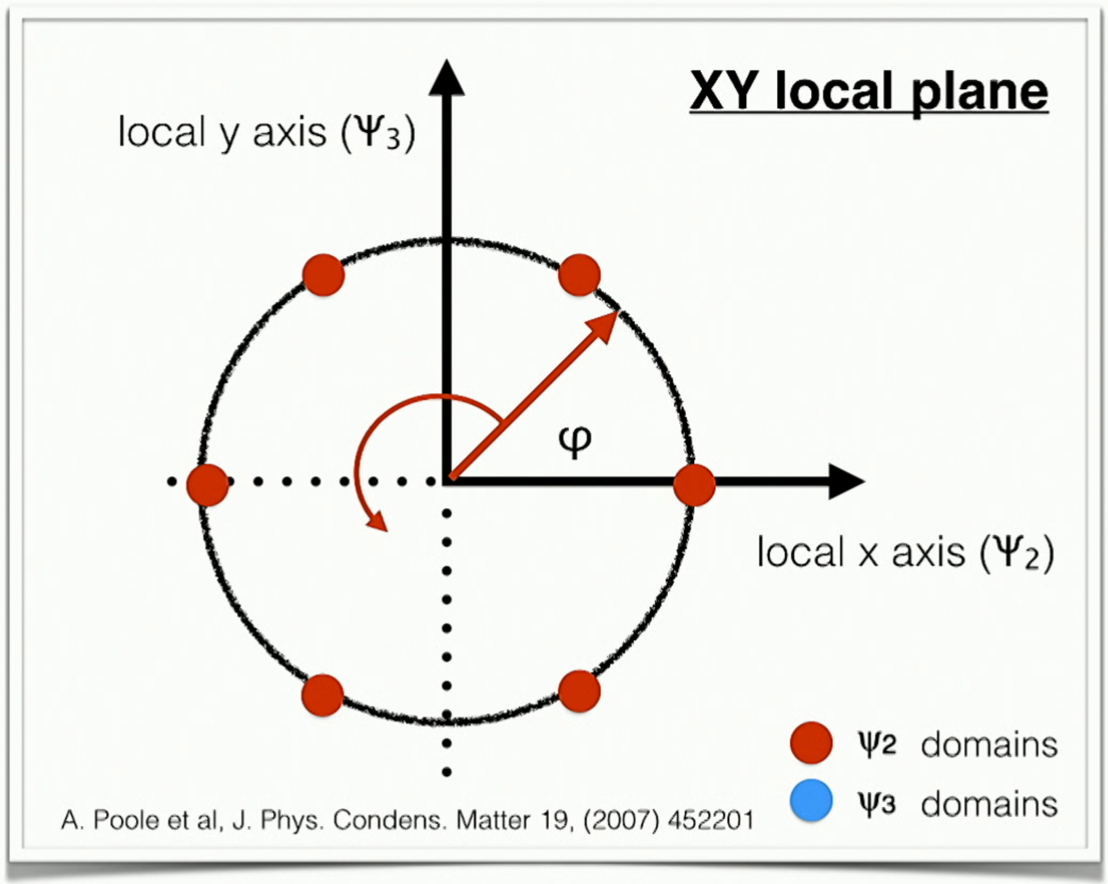




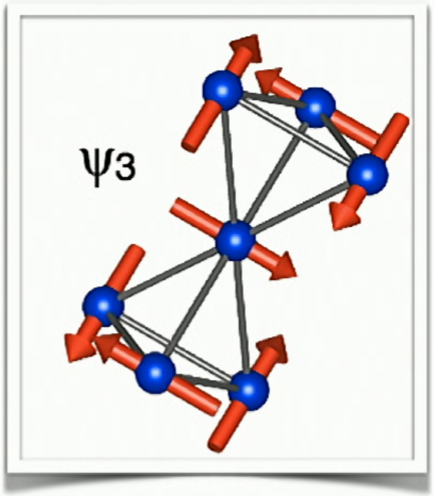
Due to 3-fold rotation symmetry and time-reversal symmetry, the Ψ_2 state is 6 times degenerate

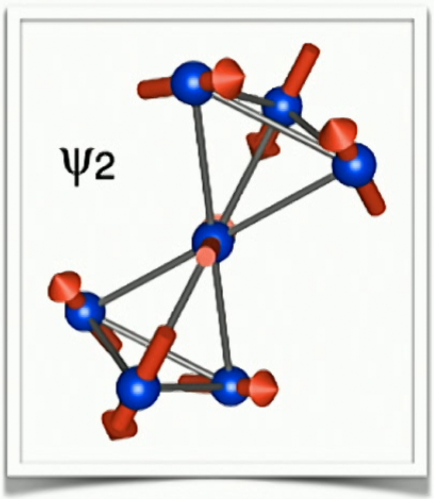


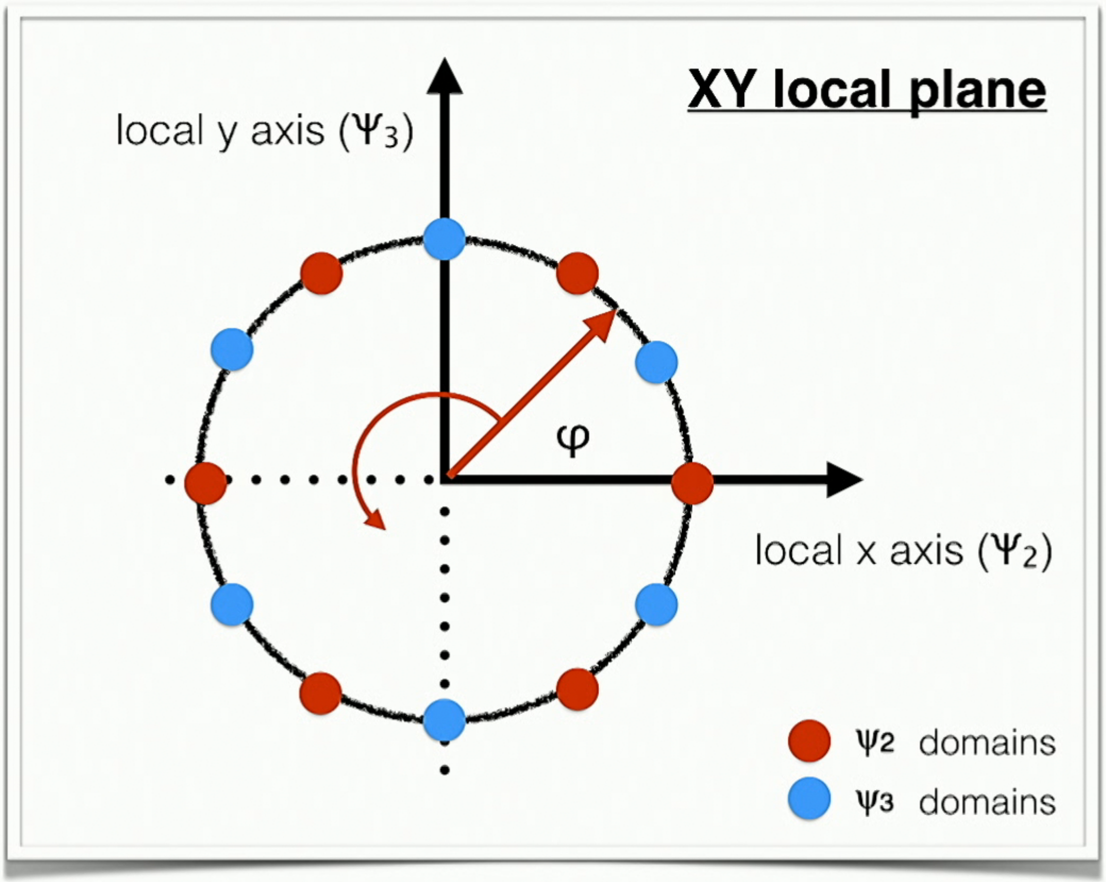




The full Ψ_2 and Ψ_3 manifold can be mapped onto the 12 hours of a clock

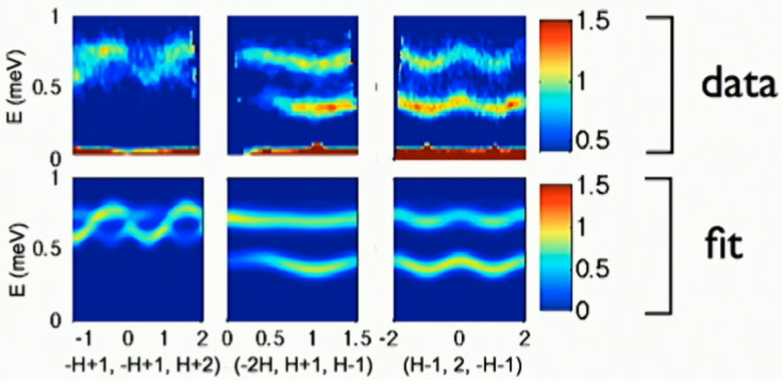






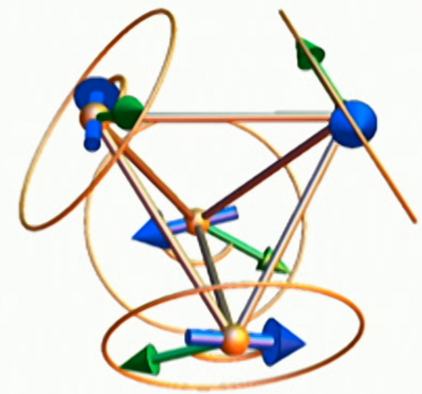
The spin Hamiltonian of $Er_2Ti_2O_7$ has a U(1) degeneracy

L. Savary et al., Phys. Rev. Lett. 109, 167201 (2012)



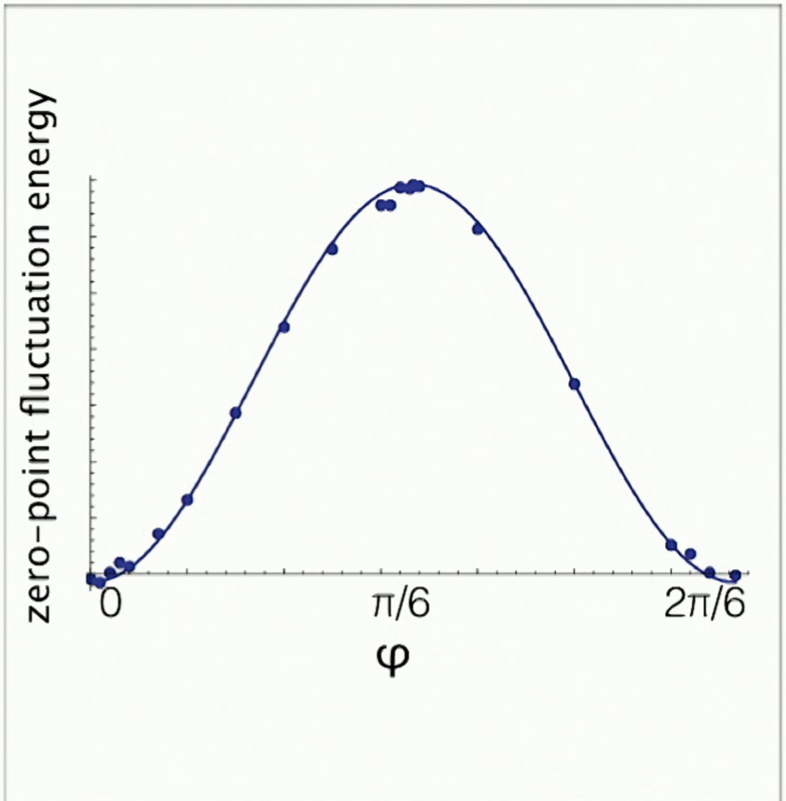
$J_{zz} = -2.5{\times}10^{-2} \pm 1.8{\times}10^{-2}, J_{\pm} = 6.5{\times}10^{-2} \pm 7.5{\times}10^{-3}$

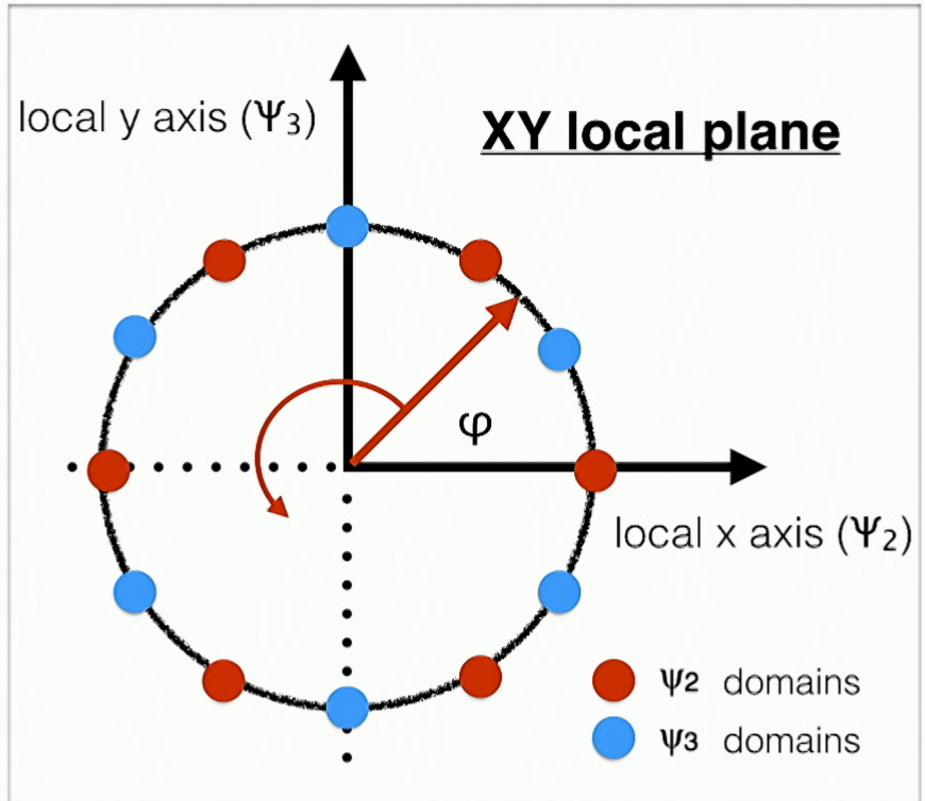
$J_{\pm\pm} = 4.2{\times}10^{-2} \pm 5.0{\times}10^{-3}, J_{z\pm} = -8.8{\times}10^{-3} \pm 1.5{\times}10^{-2}$ (meV)



- $E(\varphi)=E_0$

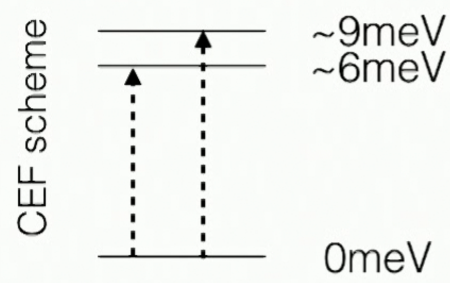
Proposed Ground State Selection Mechanism 1: Order-by-Disorder (entropic selection)





L. Savary et al., Phys. Rev. Lett. 109, 167201 (2012)
M. Zhitomirsky et al., Phys. Rev. Lett. 109, 077204 (2012)

Proposed Ground State Selection Mechanism 2: Virtual crystal electric field transitions (energetic selection)

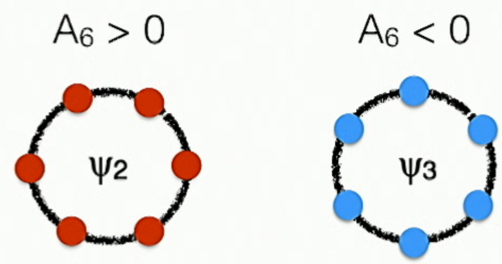


P. A. McClarty. et al., JPCS, 145, 012032 (2009)
Petit S. et al., Phys. Rev. B., 90, 060410 (2014)
Rau J. G. et al., Phys. Rev. B., 93, 184408 (2016)

$Er_2Ti_2O_7$ is a rare case of a $Z_{N>2}$ symmetry breaking system

Zero field (quantum order-by-disorder term, virtual crystal field, etc..)

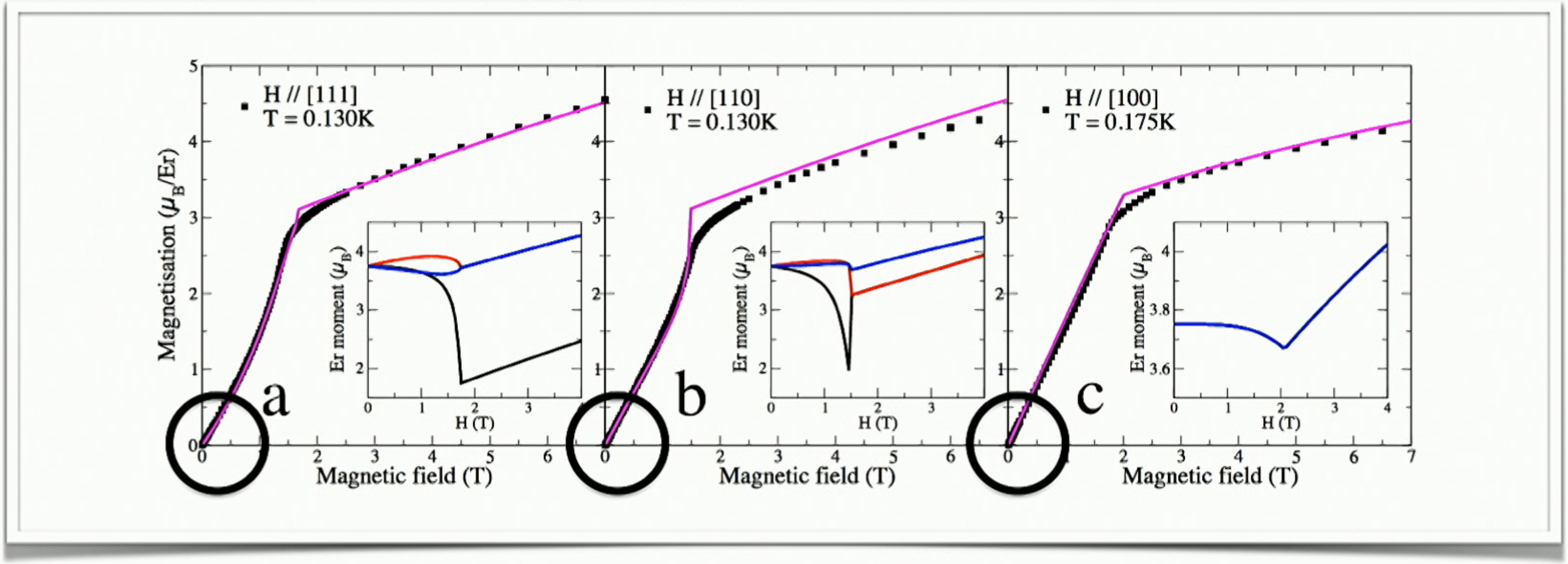
$$E_6[\mathbf{m}] = -\frac{a_6}{2}(m_+^6 + m_-^6) = -A_6 \cos 6\varphi .$$



Maryasin V. S. et al., Phys. Rev. B. 93, 100406(R) (2016)

This study is focused on the *low field behaviour that reveals domain redistribution and reorientation*

P. Bonville et al, J. Phys. Cond. Mat, 25(27), 275601(2013)

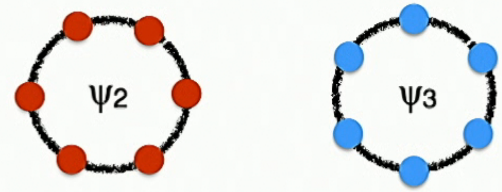


Two-fold Zeeman clock term emerging in a [110] and [001] field

Zero field (quantum order-by-disorder term, virtual crystal field, etc..)

$$E_6[\mathbf{m}] = -\frac{a_6}{2}(m_+^6 + m_-^6) = -A_6 \cos 6\varphi$$

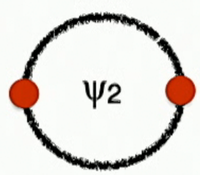
$A_6 > 0$ $\qquad$ $A_6 < 0$



Field along the [110] direction

$$E_2^{[110]} = -\tfrac{1}{2} A_2 H^2 \cos 2\varphi$$

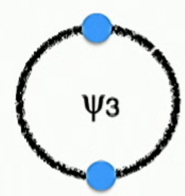
Selects:



Field along the [001] direction

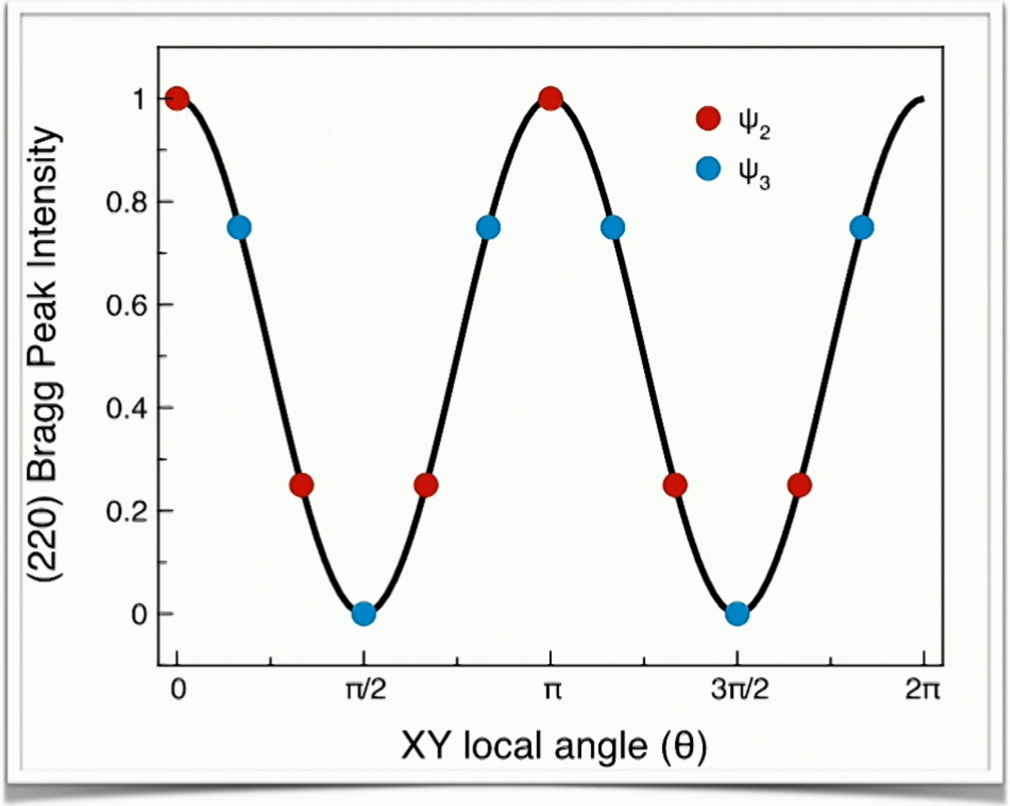
$$E_2^{[001]} = A_2 H^2 \cos 2\varphi$$

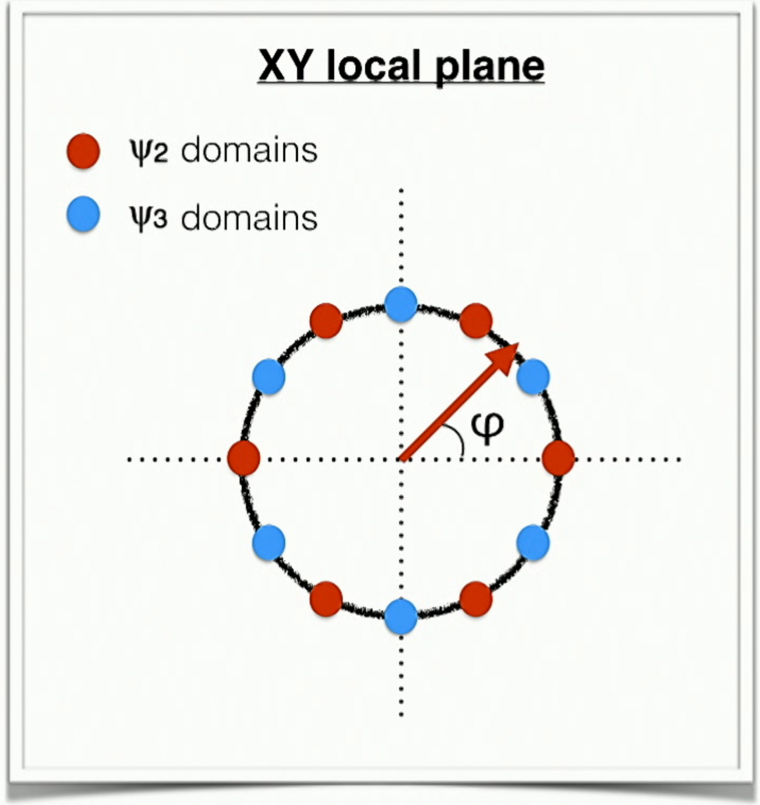
Selects:



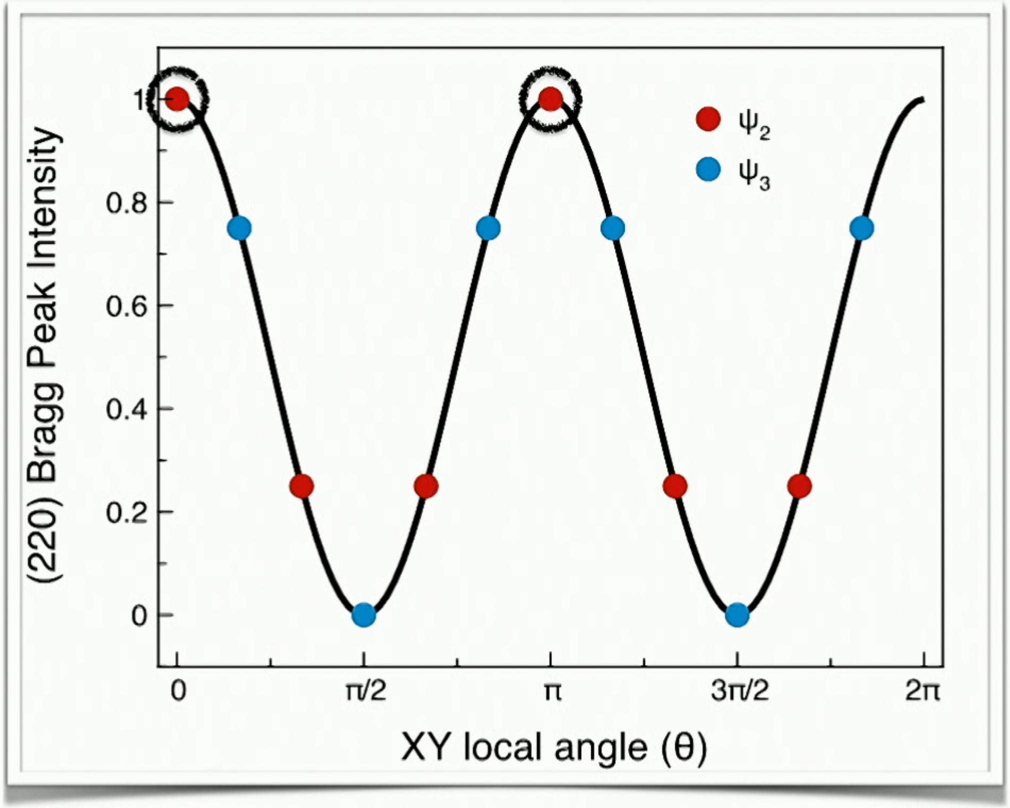
Maryasin V. S. et al., Phys. Rev. B. 93, 100406(R) (2016)

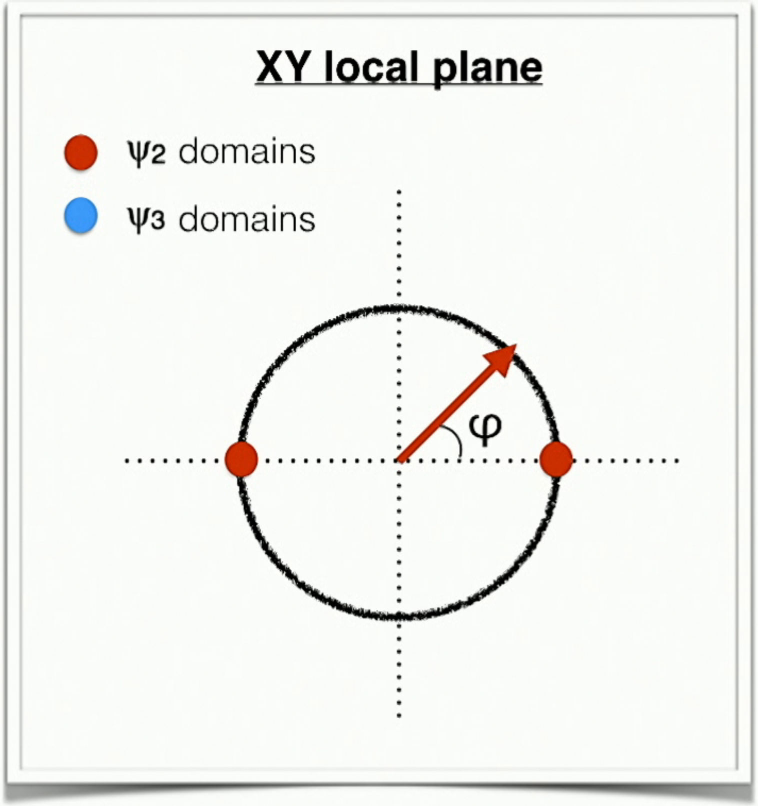
Neutron scattering can probe the predicted domain effects



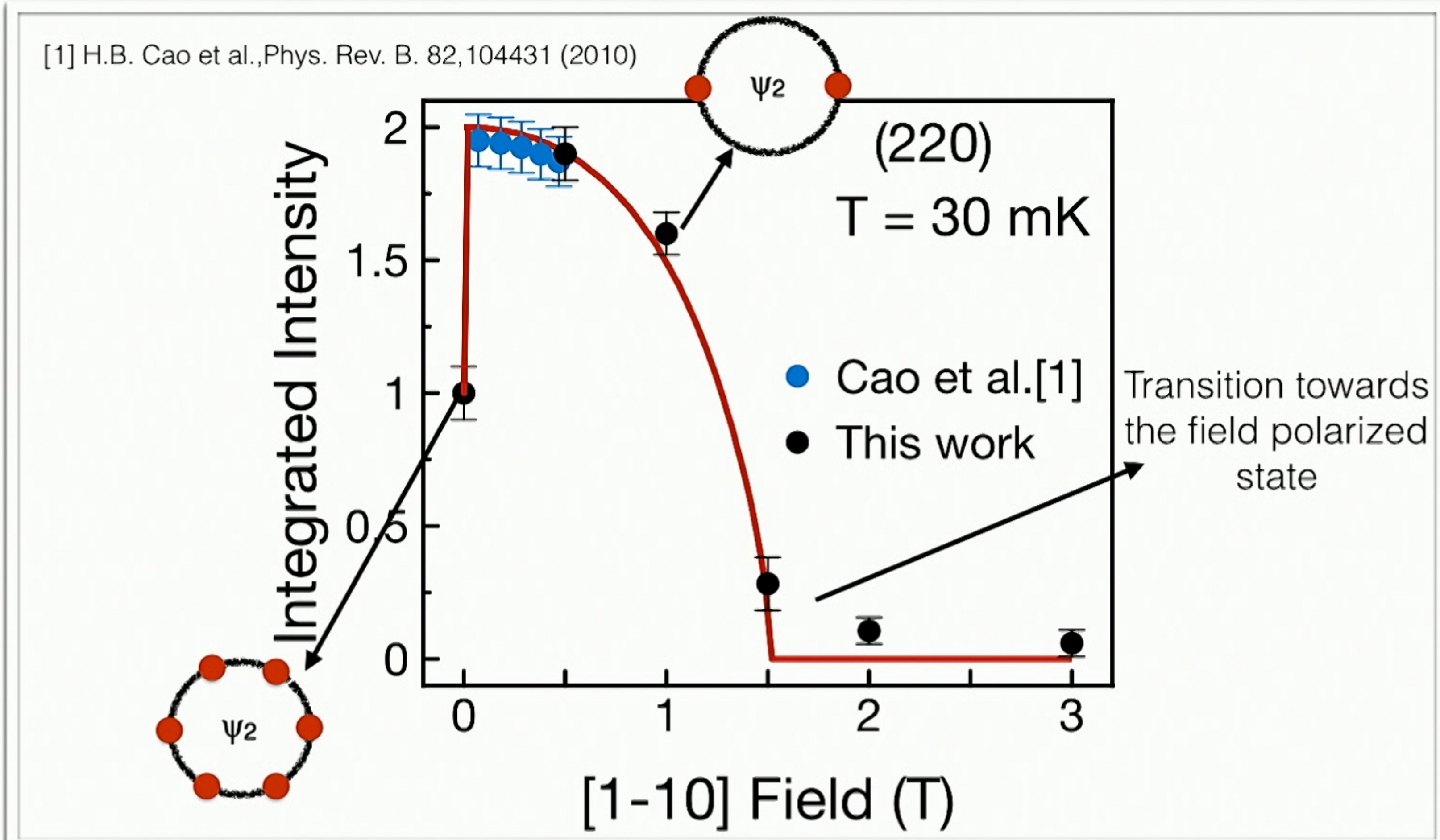


Domains selected in a [110] field should give a two-fold increase at the (220) magnetic Bragg position relative to 0T

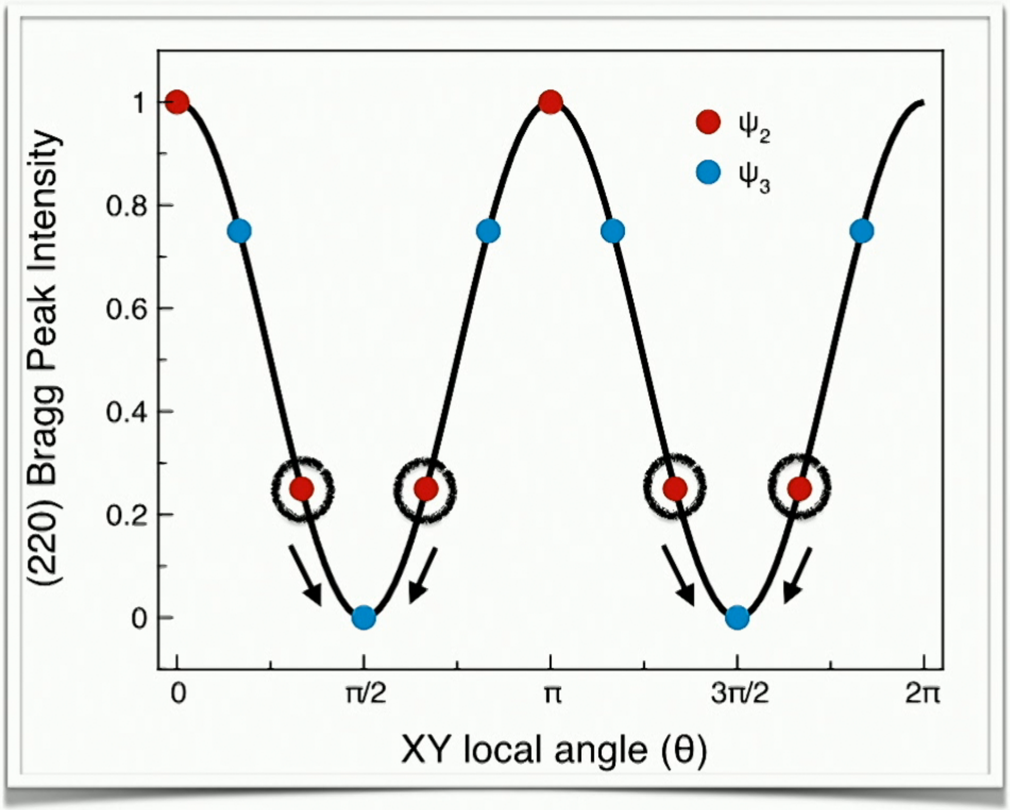


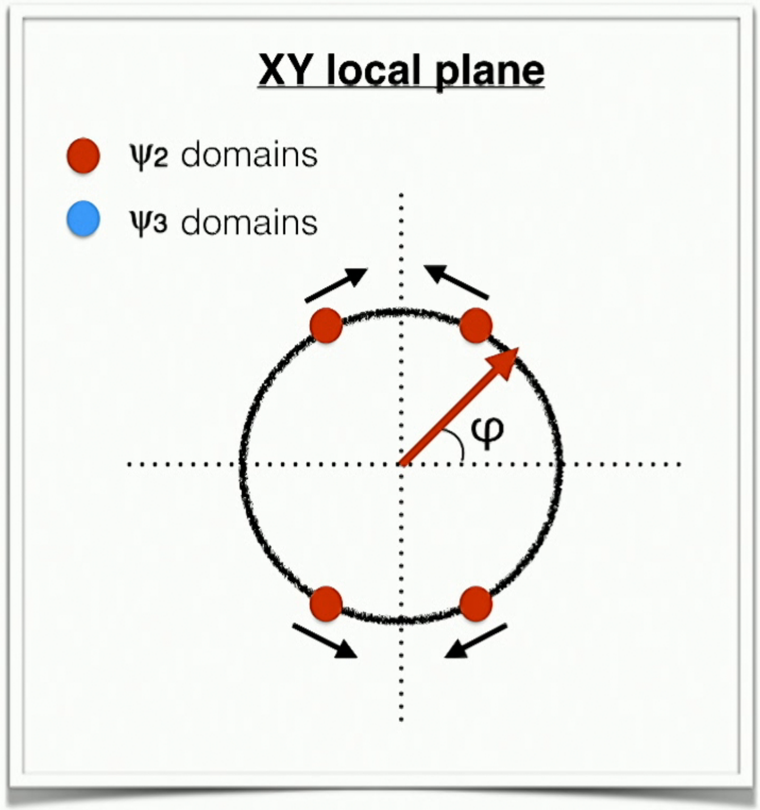


Two fold increase of the (220) magnetic Bragg peak intensity observed experimentally in a [110] field

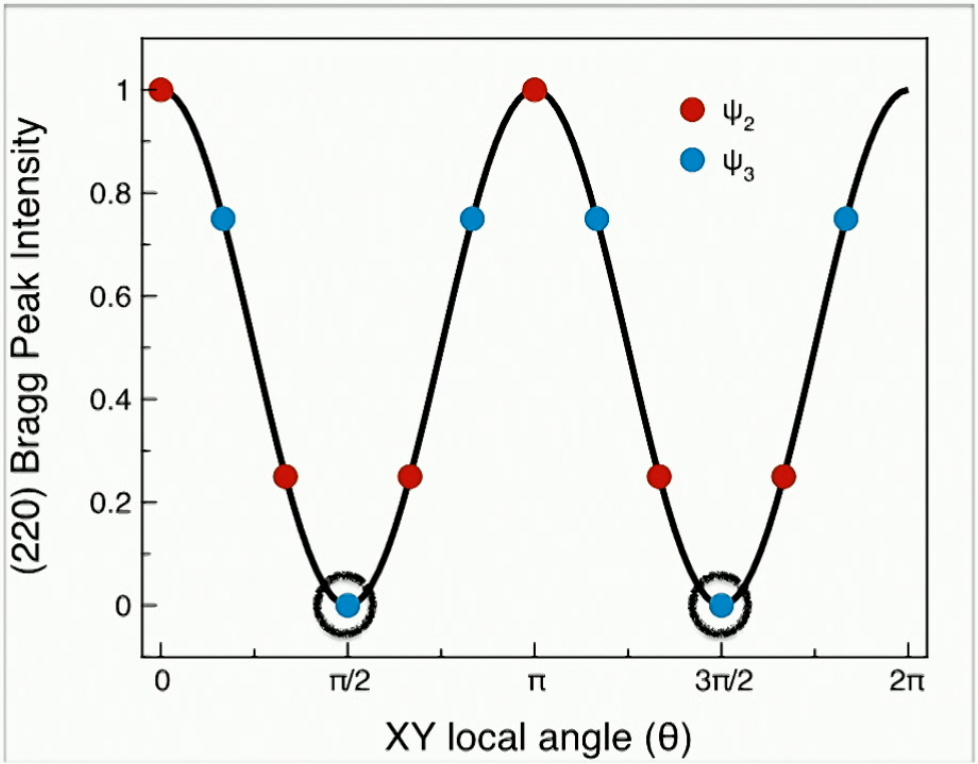


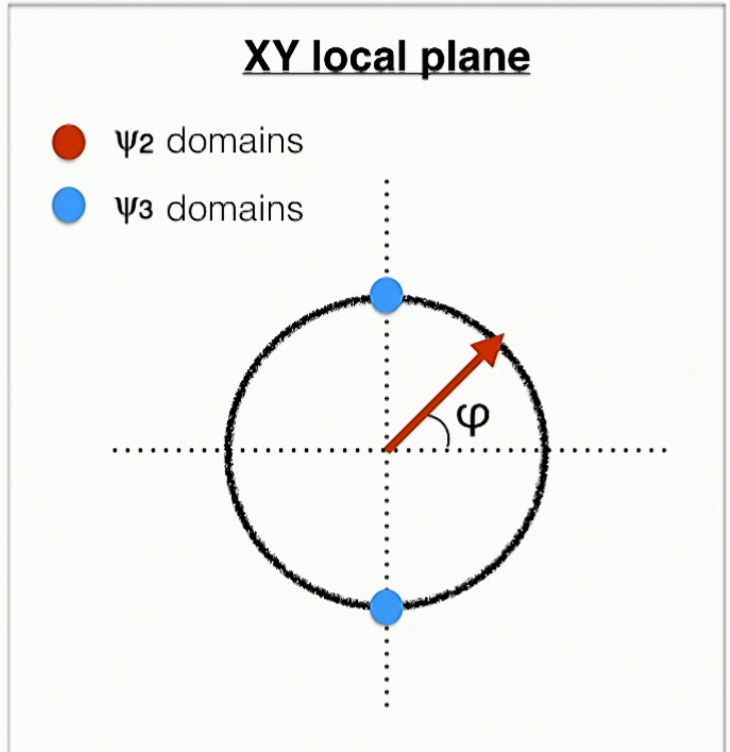
Domain selection in a [001] field should give a two-fold decrease of the (220) magnetic Bragg intensity



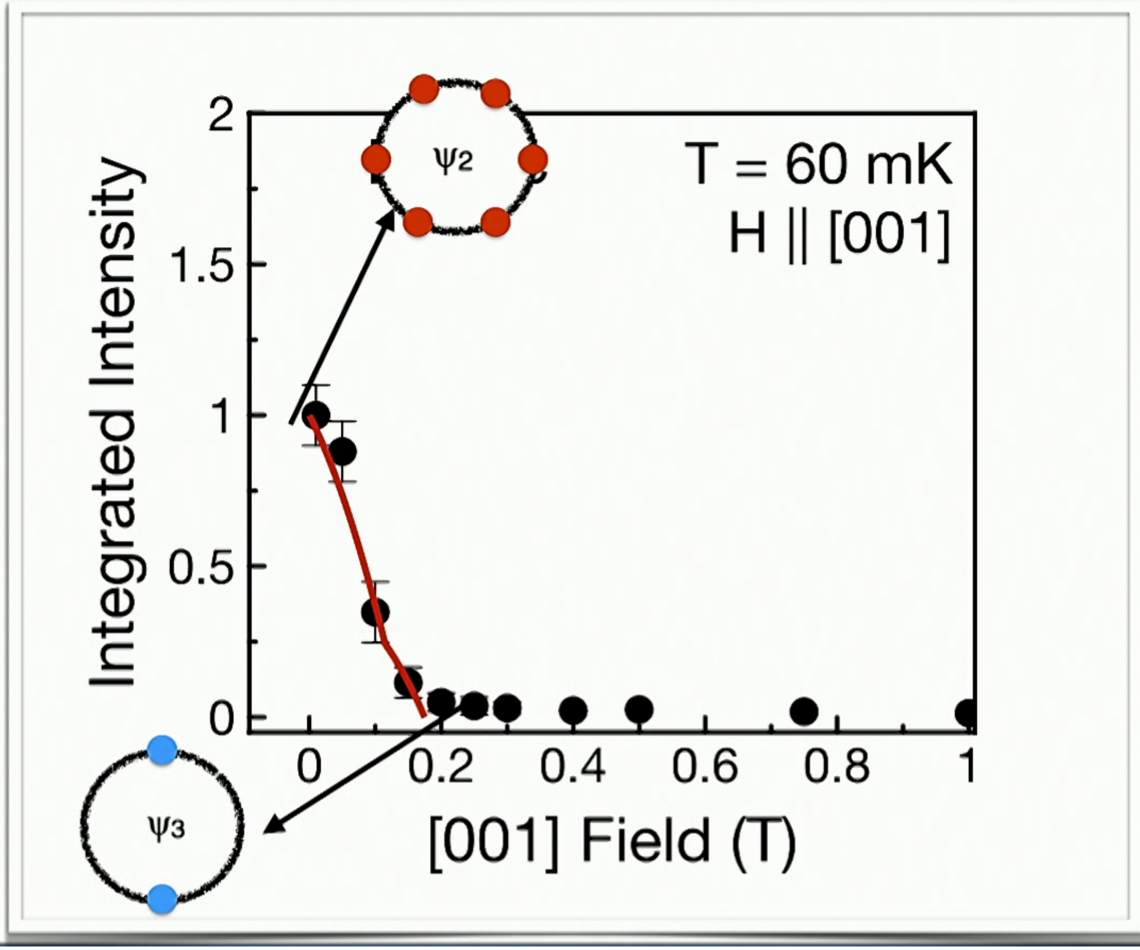


Upon further increasing the field, there is a spin re-orientation that completely eliminates the (220) Bragg intensity





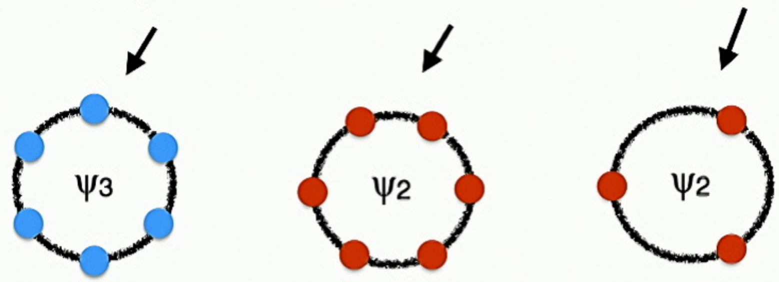
Complete decrease of the (220) magnetic Bragg peak intensity observed experimentally in a [001] field



A [111] field is predicted to lead to a six-fold and a three-fold clock term

Predicted emerging Zeeman clock terms for a [111] field

$$E(\varphi) = (A_6' H^2 - A_6) \cos 6\varphi + A_3 H^3 \cos 3\varphi$$

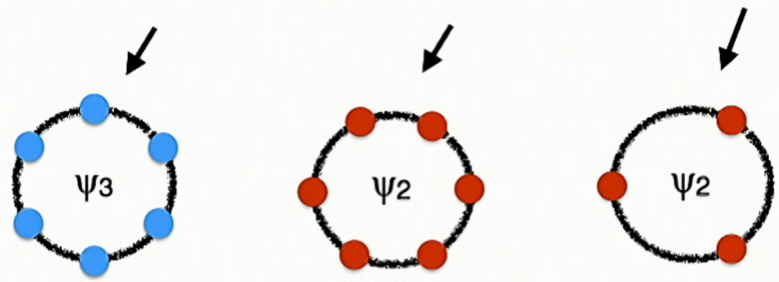


Maryasin V. S. et al., Phys. Rev. B. 93, 100406(R) (2016)

Two domain transitions predicted to occur in $Er_2Ti_2O_7$ under a [111] field

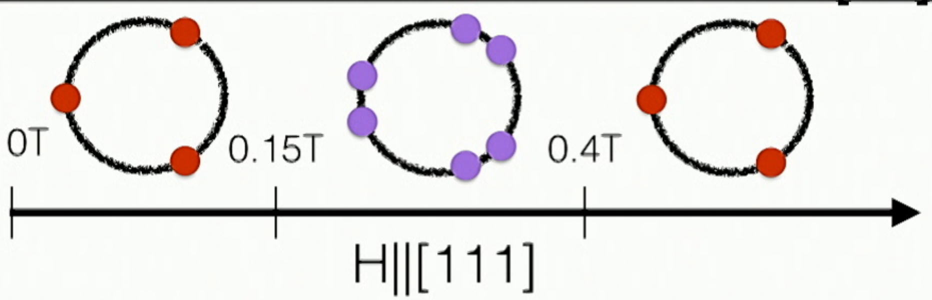
Predicted emerging Zeeman clock terms for a [111] field

$$E(\varphi) = (A_6' H^2 - A_6) \cos 6\varphi + A_3 H^3 \cos 3\varphi$$

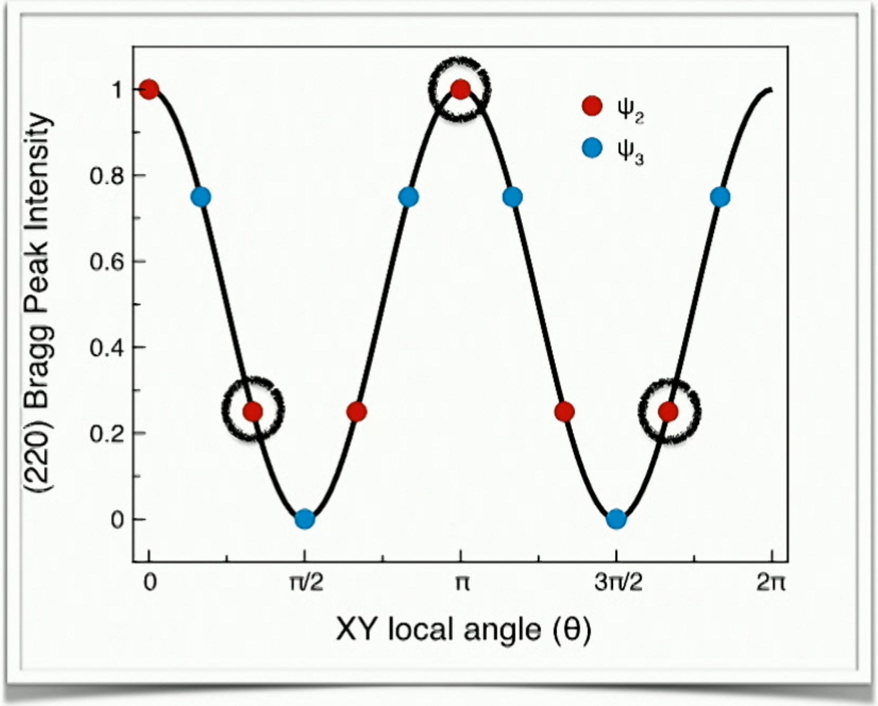


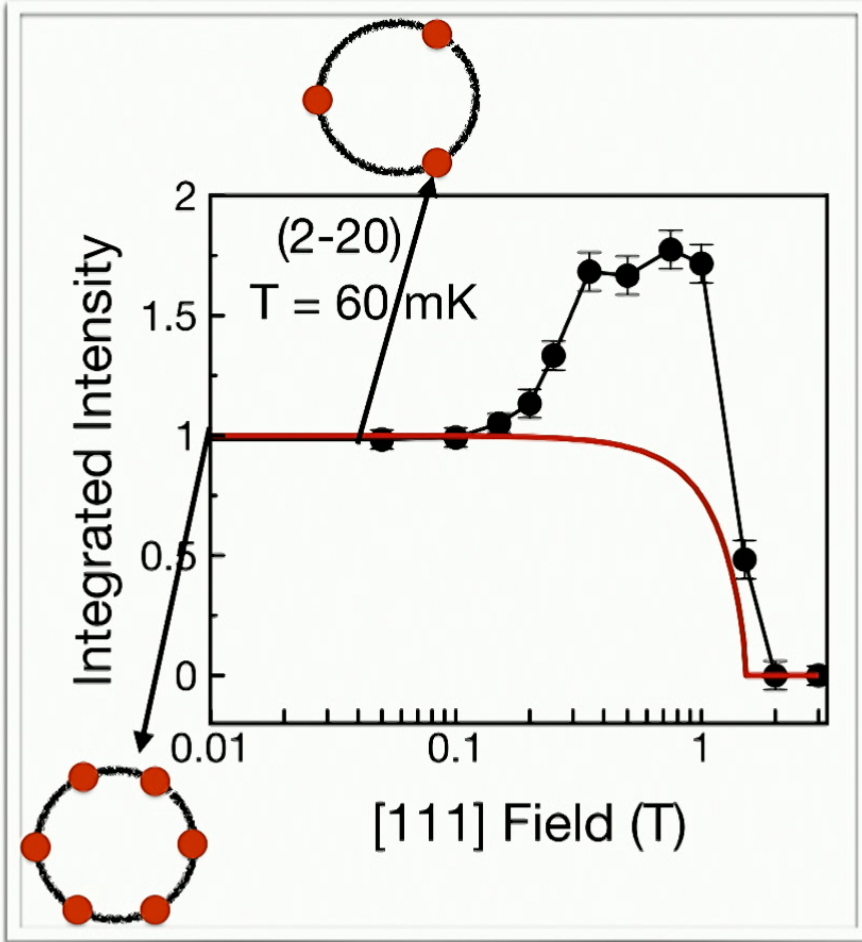
Maryasin V. S. et al., Phys. Rev. B. 93, 100406(R) (2016)

Predicted domain behaviour for Er2Ti2O7 in a [111] field

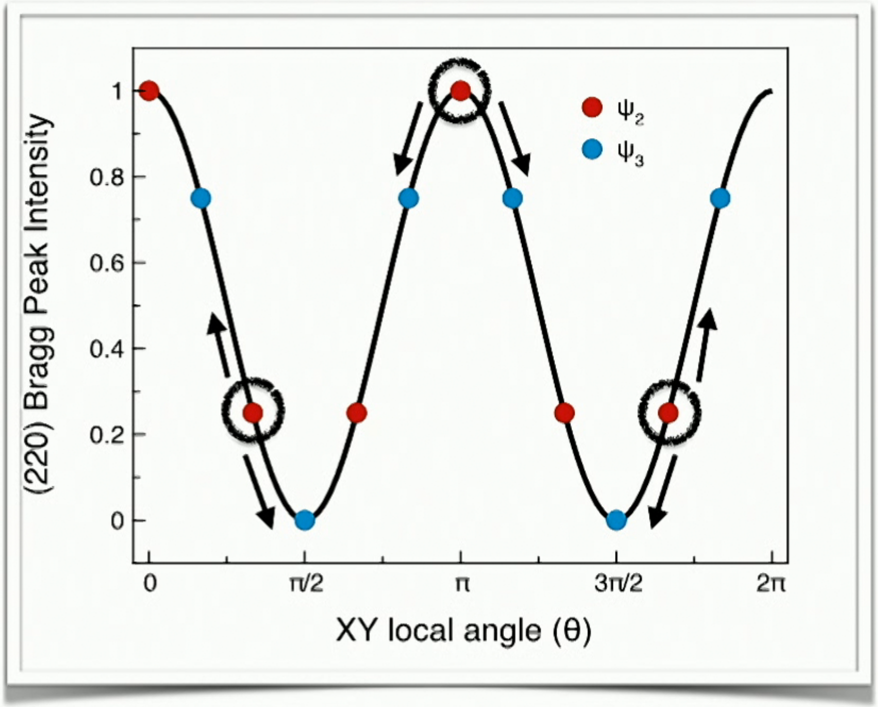


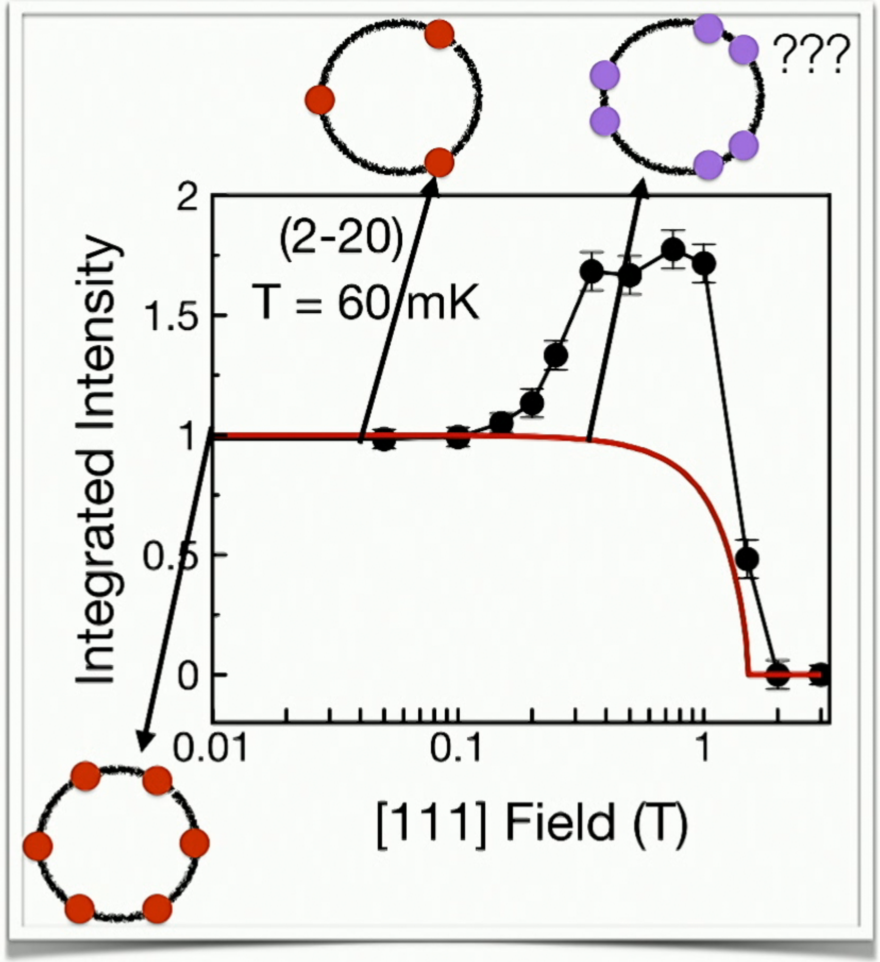
The [111] low field data is consistent with the emergence of a three-fold Zeeman clock term





The [111] field data is not consistent with the proposed intermediate domain state





Conclusion: Emergent clock terms in $Er_2Ti_2O_7$

J. Gaudet et al, Phys. Rev. B. 95, 054407 (2017)