Title: Ferroelectricity out of magnetic frustration

Date: Apr 24, 2008 02:00 PM

URL: http://pirsa.org/08040044

Abstract: Responding electrically to magnetic stimuli and vise versa, multiferroics offer exciting possibilities for applications and challenge our understanding of coupled lattice and spin degrees of freedom in solids. I discuss how multiferroic properties can develop in frustrated magnets where competing interactions produce non-collinear spin order and symmetry breaking lattice distortions. Our experiments in TbMnO3, Ni3V2O8, and RbFe(MoO4)2 show that when the low temperature magnetic order breaks spatial inversion symmetry it is accompanied by ferroelectricity [1-3]. Conversely, the application of an electric field favors one of the two inversion symmetry related antiferromagnetic domains. We infer that inversion symmetry breaking magnetic order acts as an effective electric field through magneto-elastic distortions that relieve frustration. We also present evidence for microscopic correspondence between the ferroelectric and the antiferromagnetic domain structure. The results presented are based on magnetic neutron diffraction, pyrocurrent measurements, and theoretical work by A. B. Harris [4]. [1] M. Kenzelmann, A. B. Harris, S. Jonas, C. Broholm, J. Schefer, S. B. Kim, C. L. Zhang, S.-W. Cheong, O. P. Vajk, and J. W. Lynn, Phys. Rev. Lett. 95, 087206 (2005). [2] G. Lawes, A. B. Harris, T. Kimura, N. Rogado, R. J. Cava, A. Aharony, O. Entin-Wohlman, T. Yildirim, M. Kenzelmann, C. Broholm, and A. P. Ramirez, Phys. Rev. Lett. 95, 087205 (2005). [3] M. Kenzelmann, G. Lawes, A.B. Harris, G. Gasparovic, C. Broholm, A.P. Ramirez, G.A. Jorge, M. Jaime, S. Park, Q. Huang, A.Ya. Shapiro, and L.A. Demianets, Phys. Rev. Lett. 98, 267205 (2007). [4] A. B. Harris, Phys. Rev. B 76 , 054447 (2007).

Ferroelectricity out of Magnetic Frustration

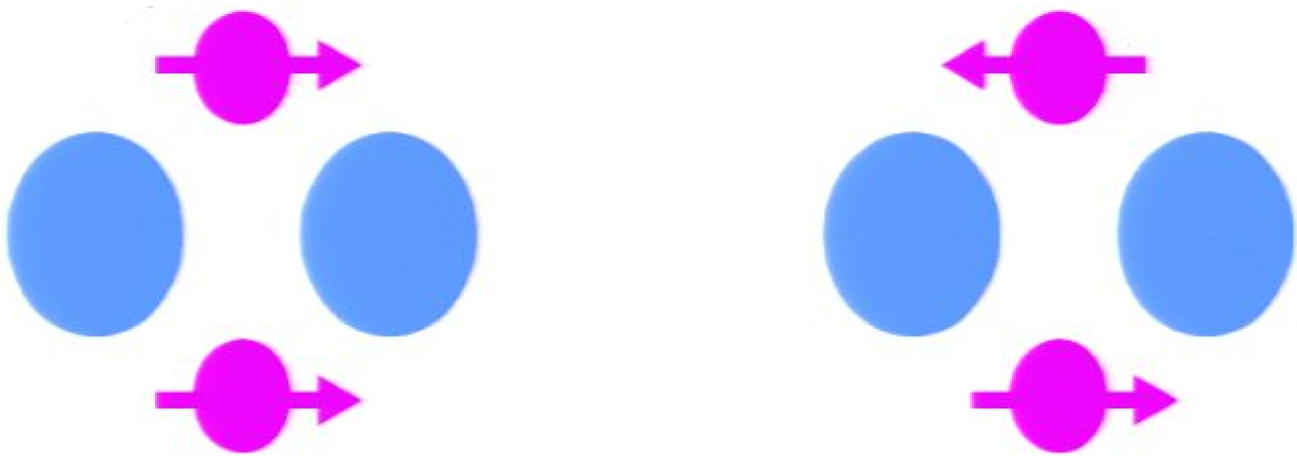
Collin Broholm
Johns Hopkins University &
NIST Center for Neutron Research

Outline

- Introduction
  - Magneto elastic effects frustrated magnets
- Inversion symmetry breaking magnetism
  - Kagome staircase magnetism $Ni_3V_2O_8$
  - Triangular lattice AFM $RbFe(MoO_4)_2$
  - Electric field control of spin chirality
- Conclusions and Outlook

Magneto-striction

$$\mathbf{F}_{12} = -\nabla\left(J_{12}\langle \mathbf{S}_1 \cdot \mathbf{S}_2 \rangle\right) = -\hat{\mathbf{r}}_{12}\frac{\partial J_{12}}{\partial r}\langle \mathbf{S}_1 \cdot \mathbf{S}_2 \rangle$$



Tchernyshyov et al. PRL (2001) and PRB (2002)

Magneto-striction

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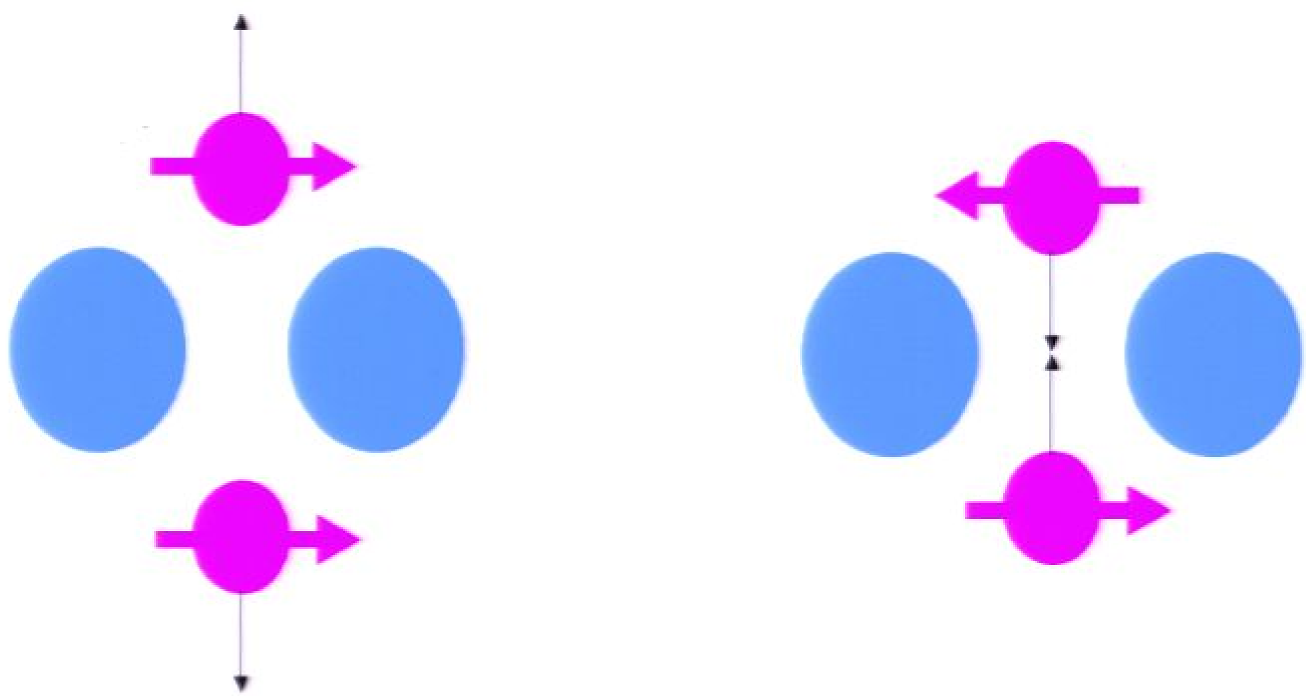
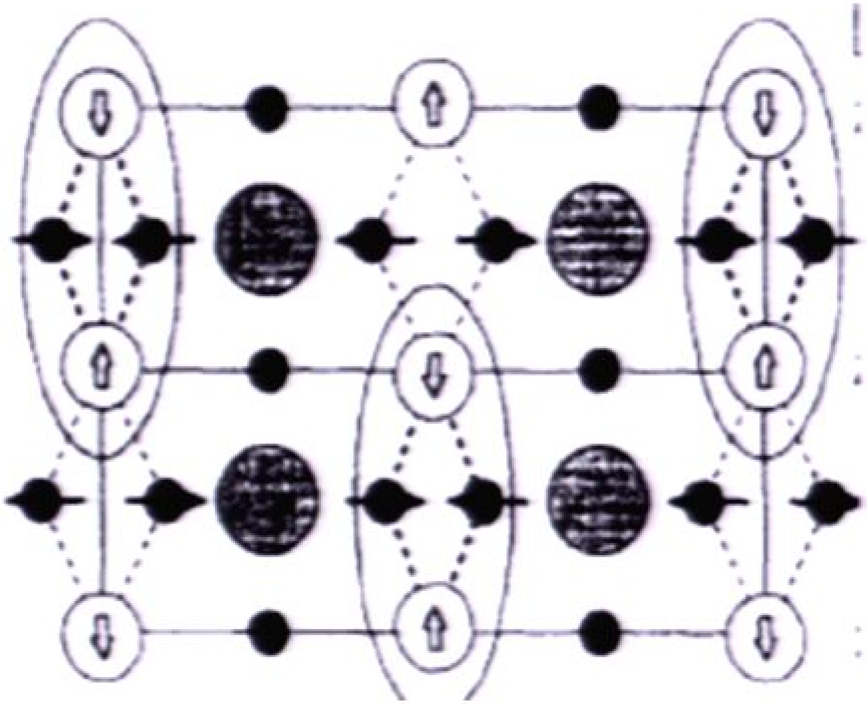
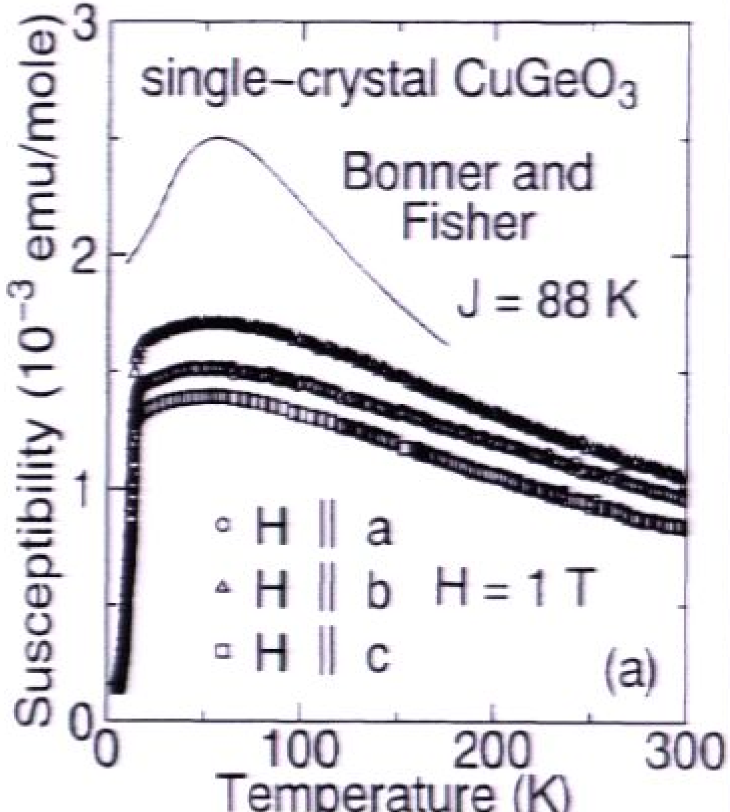


Tchernyshyov et al. PRL (2001) and PRB (2002)

Quantum criticality and magneto-striction

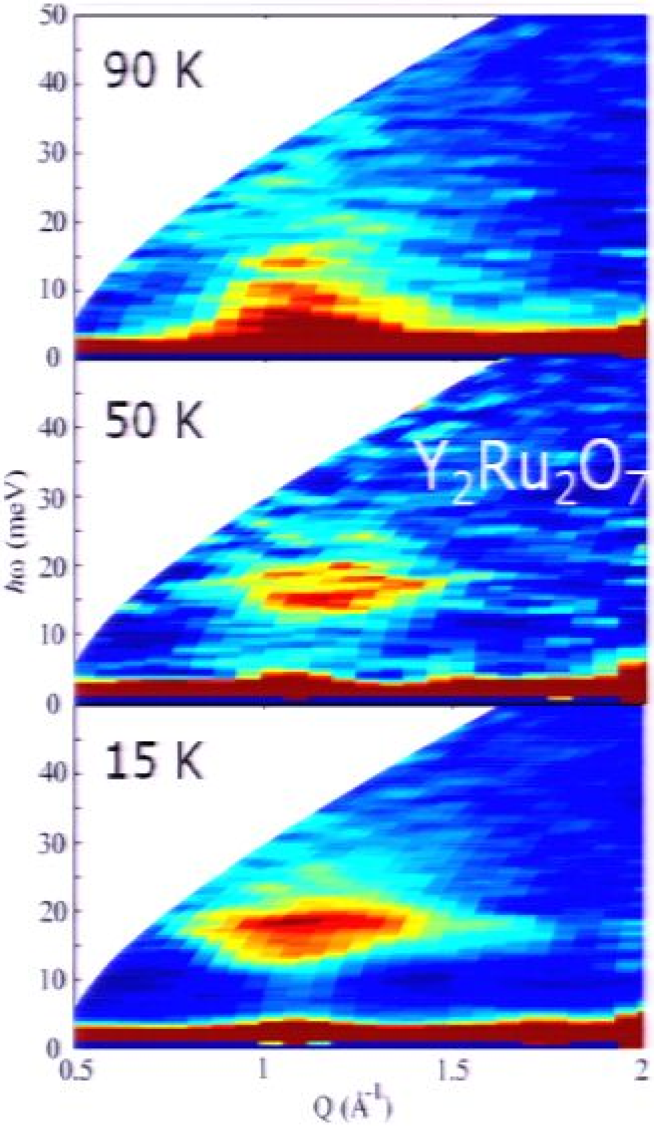


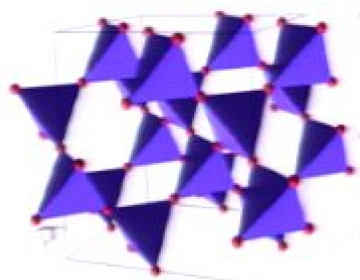
$J_2 \approx 0.36\, J_1$

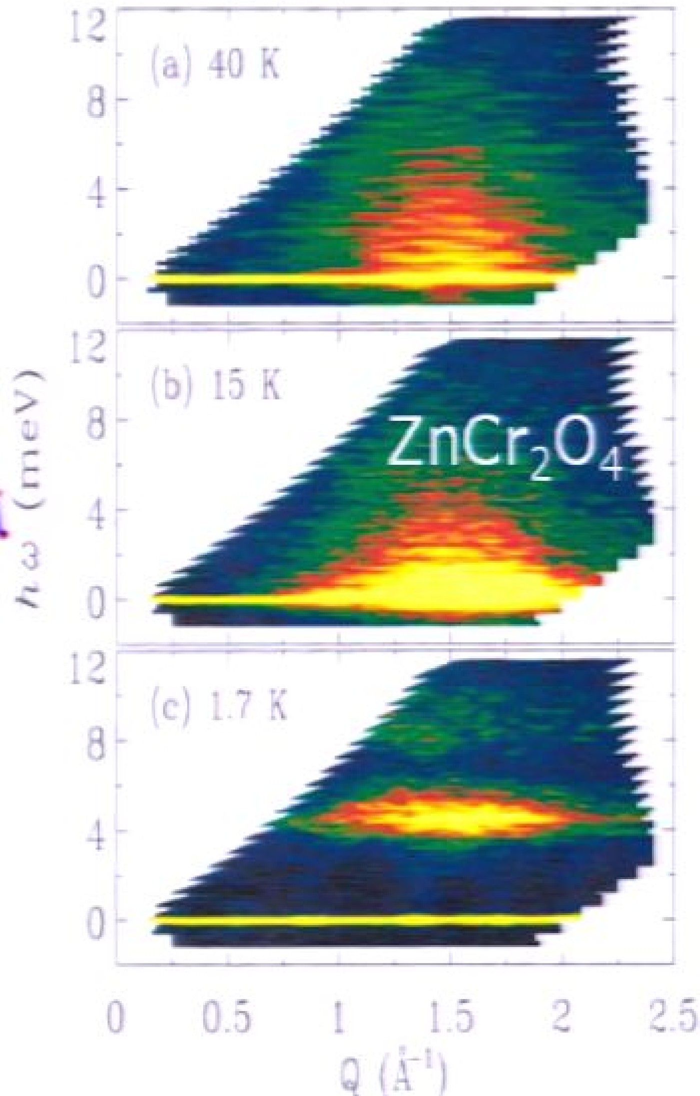


Hase et al (1993)

Resonance upon ordering: pyrochlore & spinel





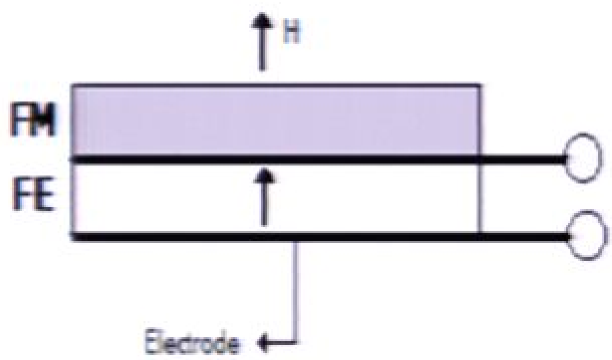


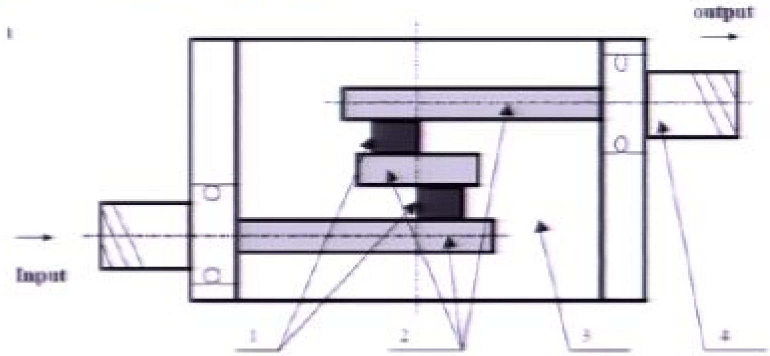
Van Duijn et al. (2007)

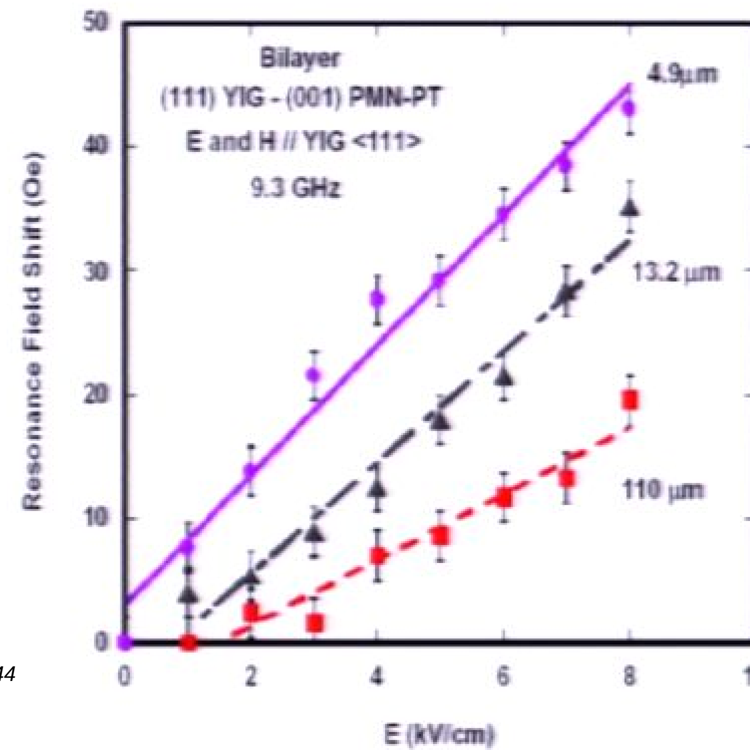
Lee et al. (2000)

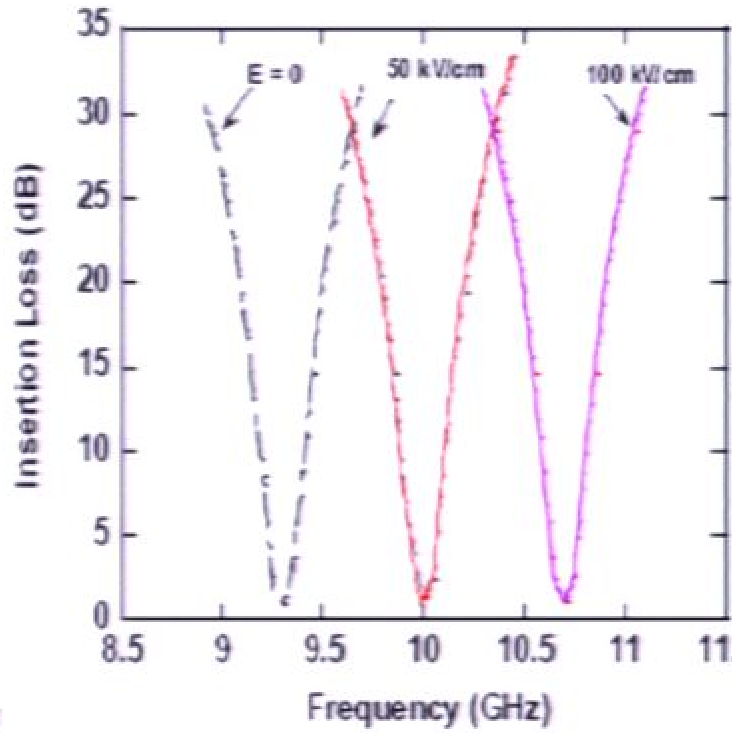
Electric Field tuned RF filter

G. Srinivasan et al Electronics Letters (2005)



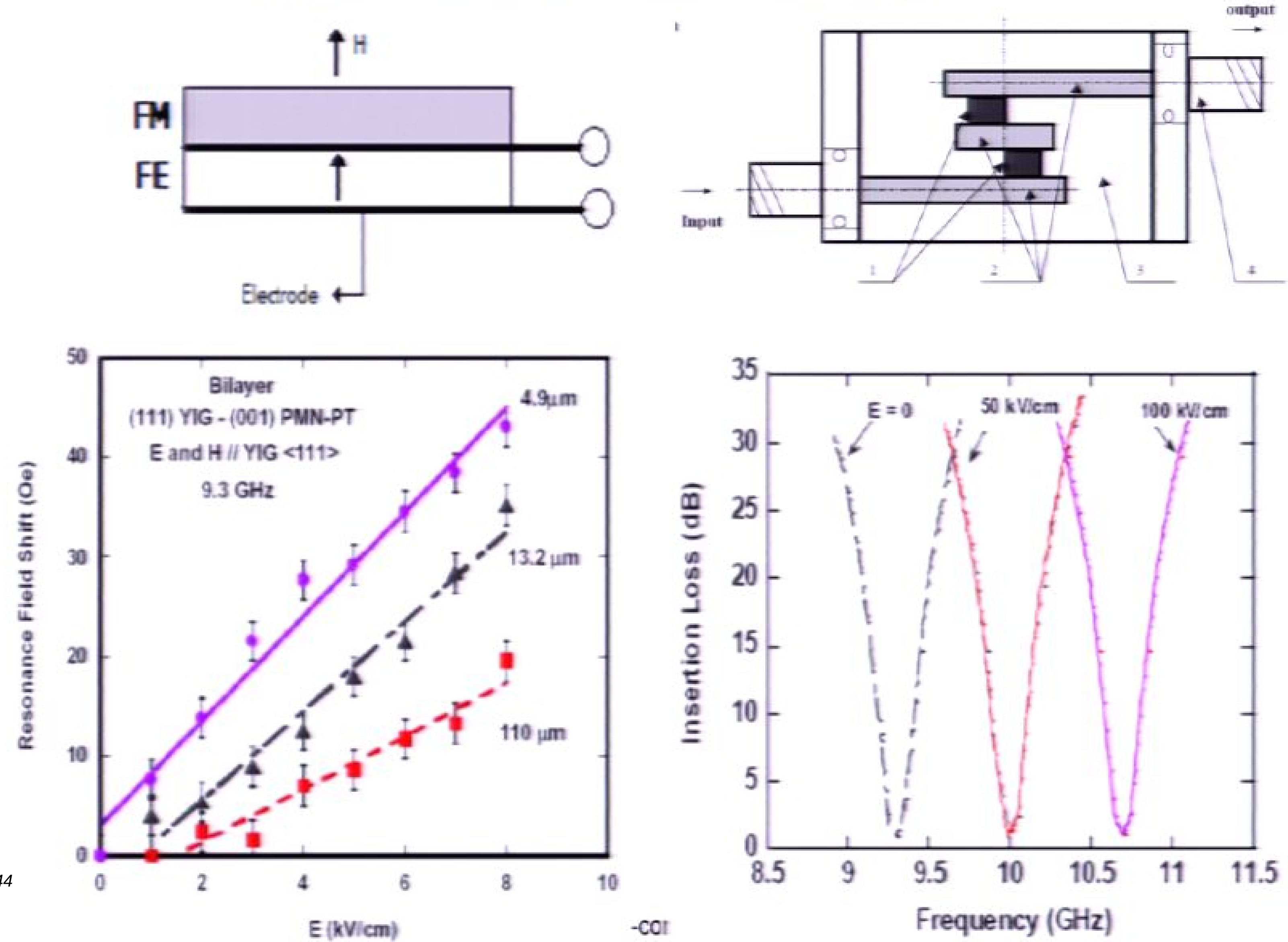






Electric Field tuned RF filter

G. Srinivasan et al Electronics Letters (2005)



Collaborators

$TbMnO_3$

M. Kenzelmann
A. B. Harris
S. Jonas
C. Broholm
J. Schefer
S. B. Kim
C. L. Zhang
S.-W. Cheong
O. P. Vajk
J. W. Lynn
T. Yildirim

$RbFe(MoO_4)_2$

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C. Broholm
A.P. Ramirez
G.A. Jorge
M. Jaime
S. Park
Q. Huang
A. Smirnov
A. Ya. Shapiro
L.A. Demianets

$Ni_3V_2O_8$

I. Cabrera
G. Lawes
A. B. Harris
T. Kimura
N. Rogado
R. J. Cava
A. Aharony
O. Entin-Wohlman
T. Yildirim
M. Kenzelmann
C. Broholm
A. P. Ramirez
W. Chen

PAUL SCHERRER INSTITUT
PSI

Collaborators

National Institute of Standards and Technology

$TbMnO_3$	$RbFe(MoO_4)_2$	$Ni_3V_2O_8$
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	L.A. Demianets	W. Chen

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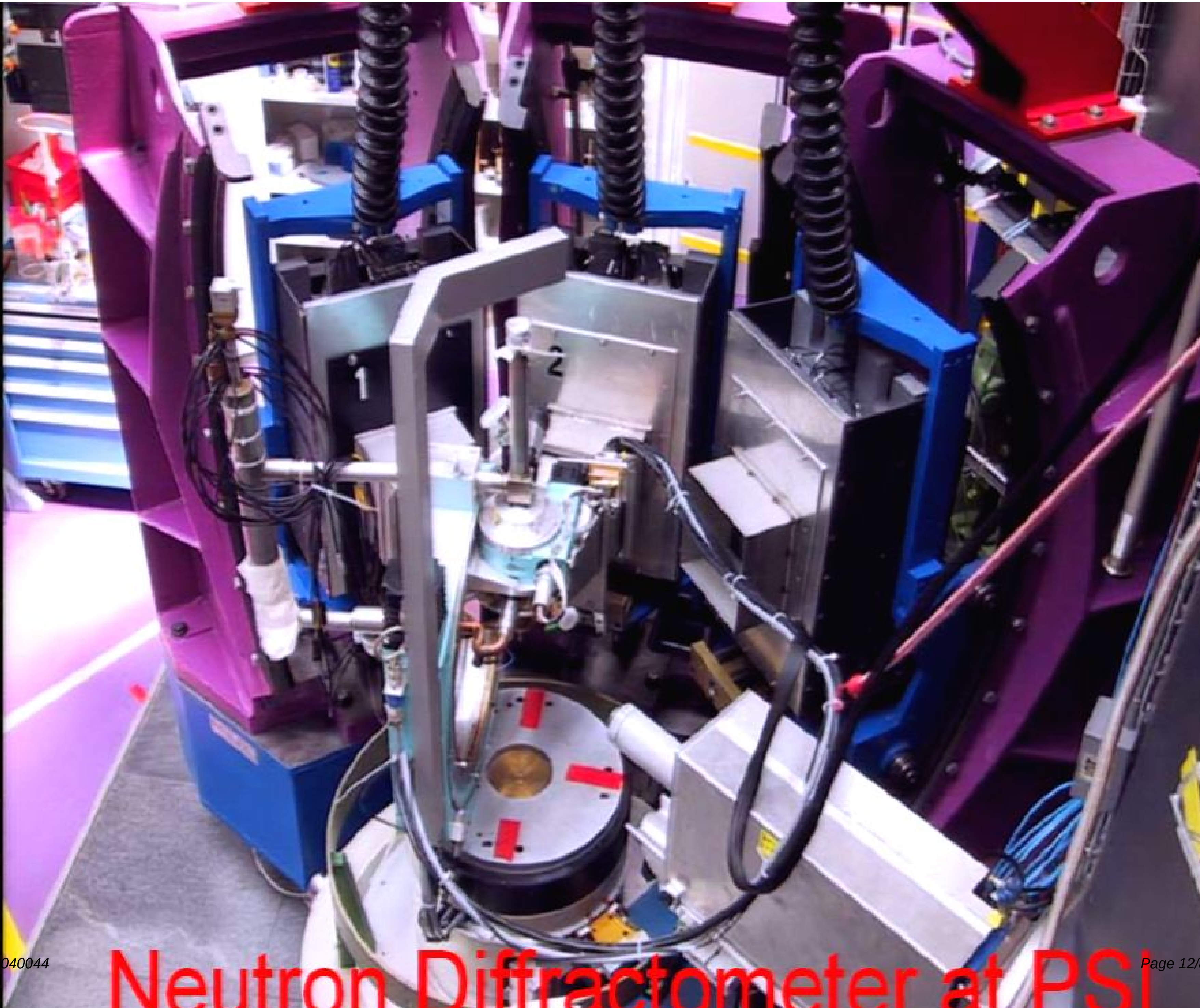
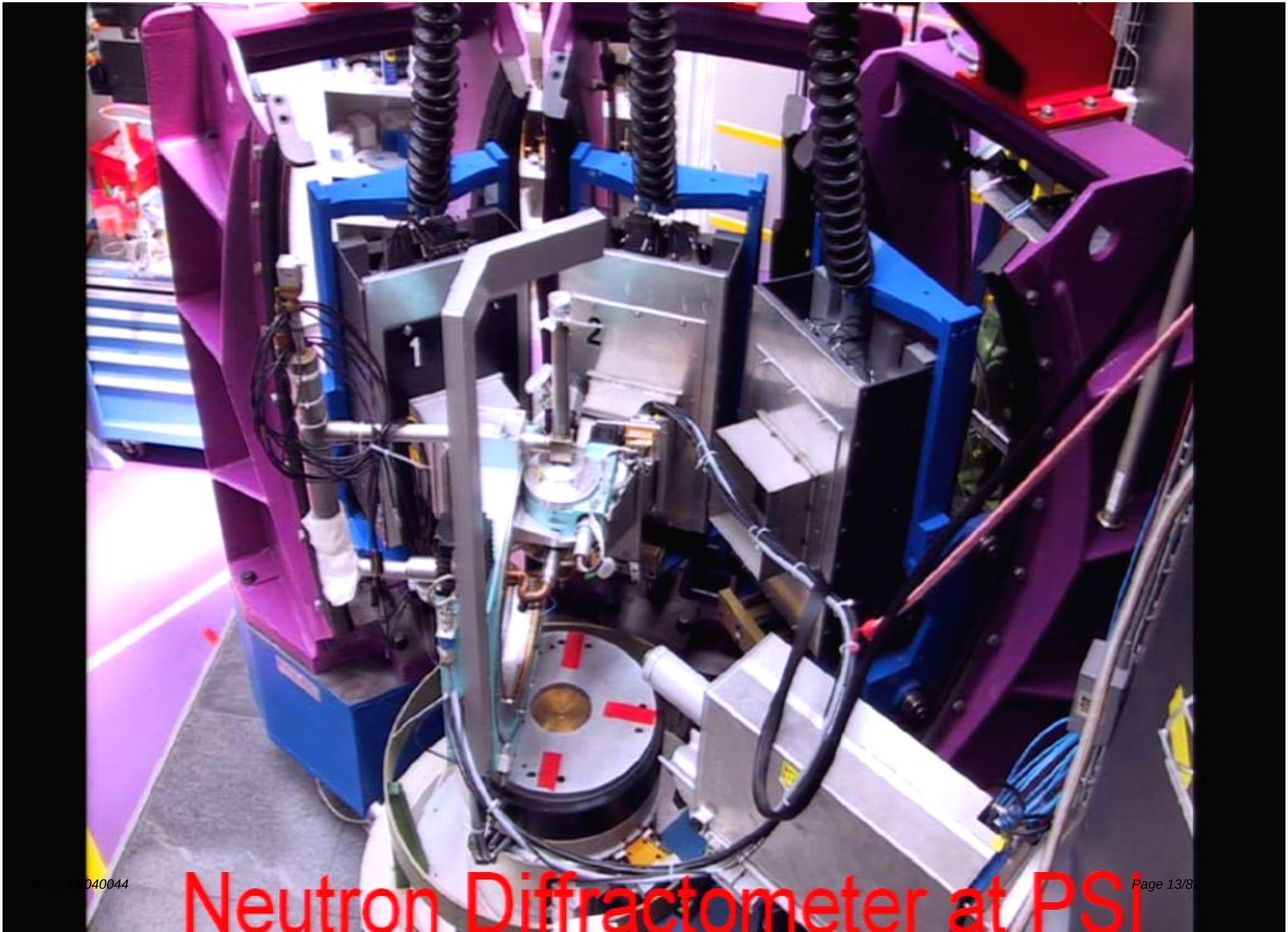


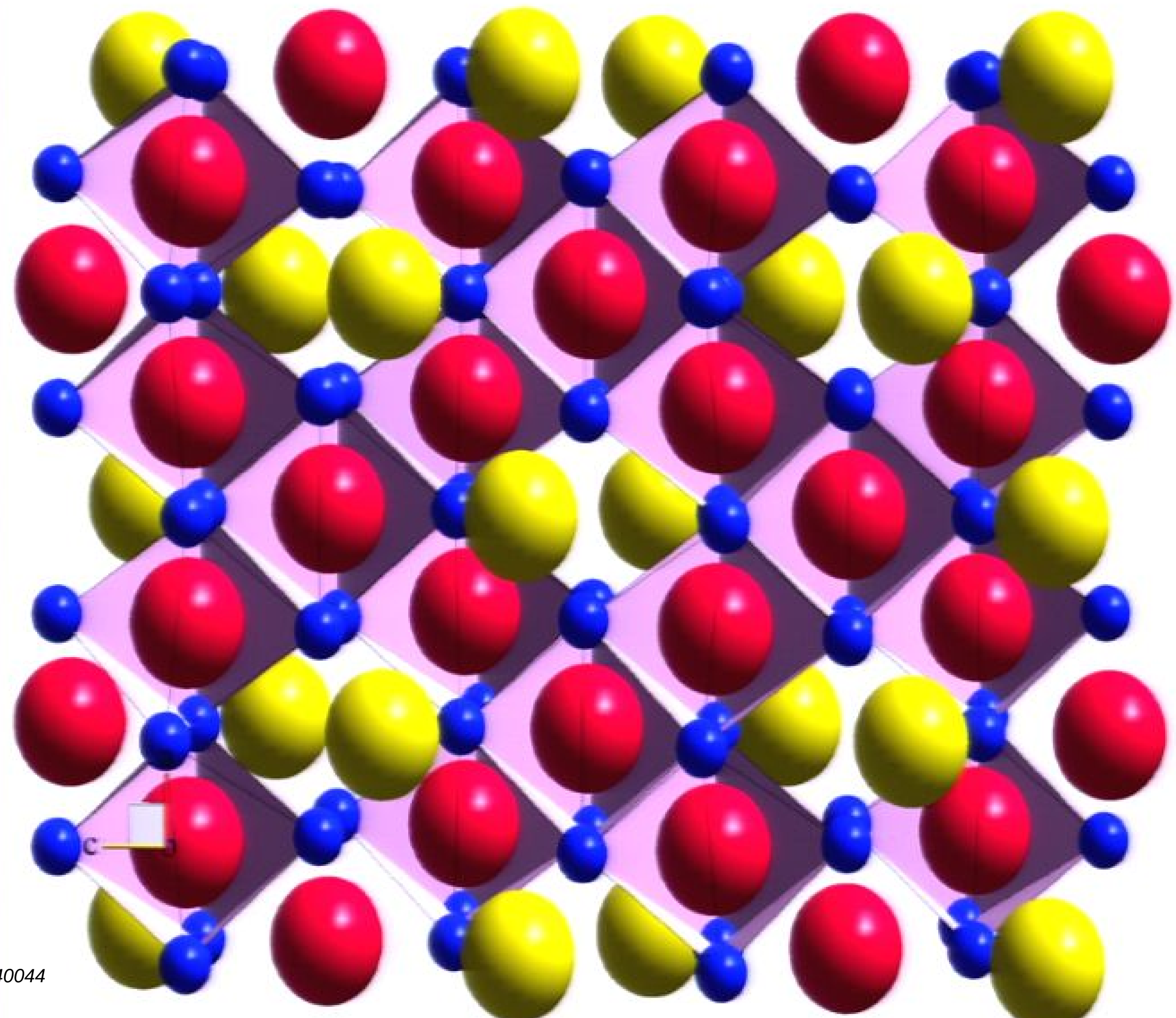
Neutron Diffractometer at PSI

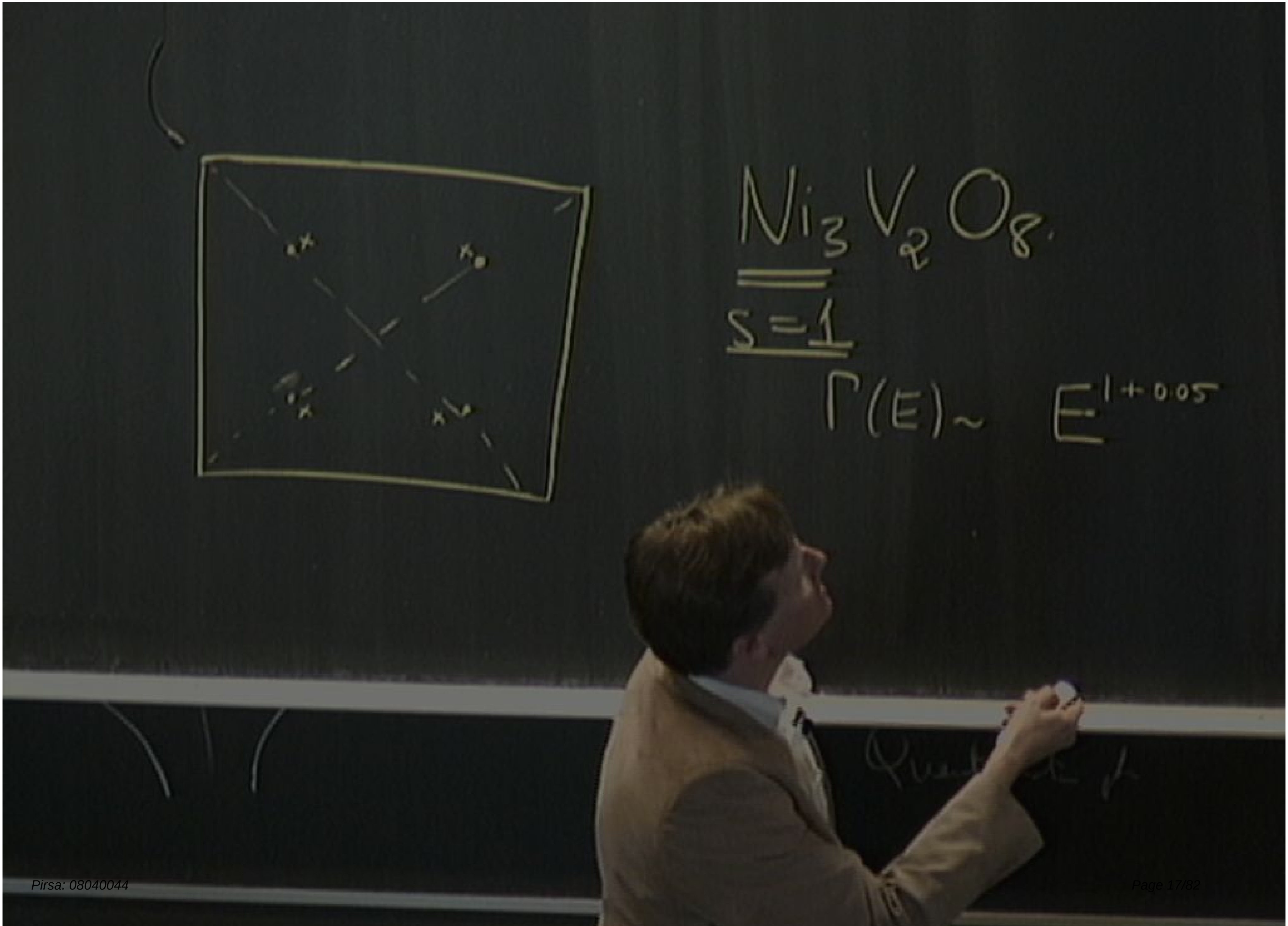

1
2
Neutron Diffractometer at PSI

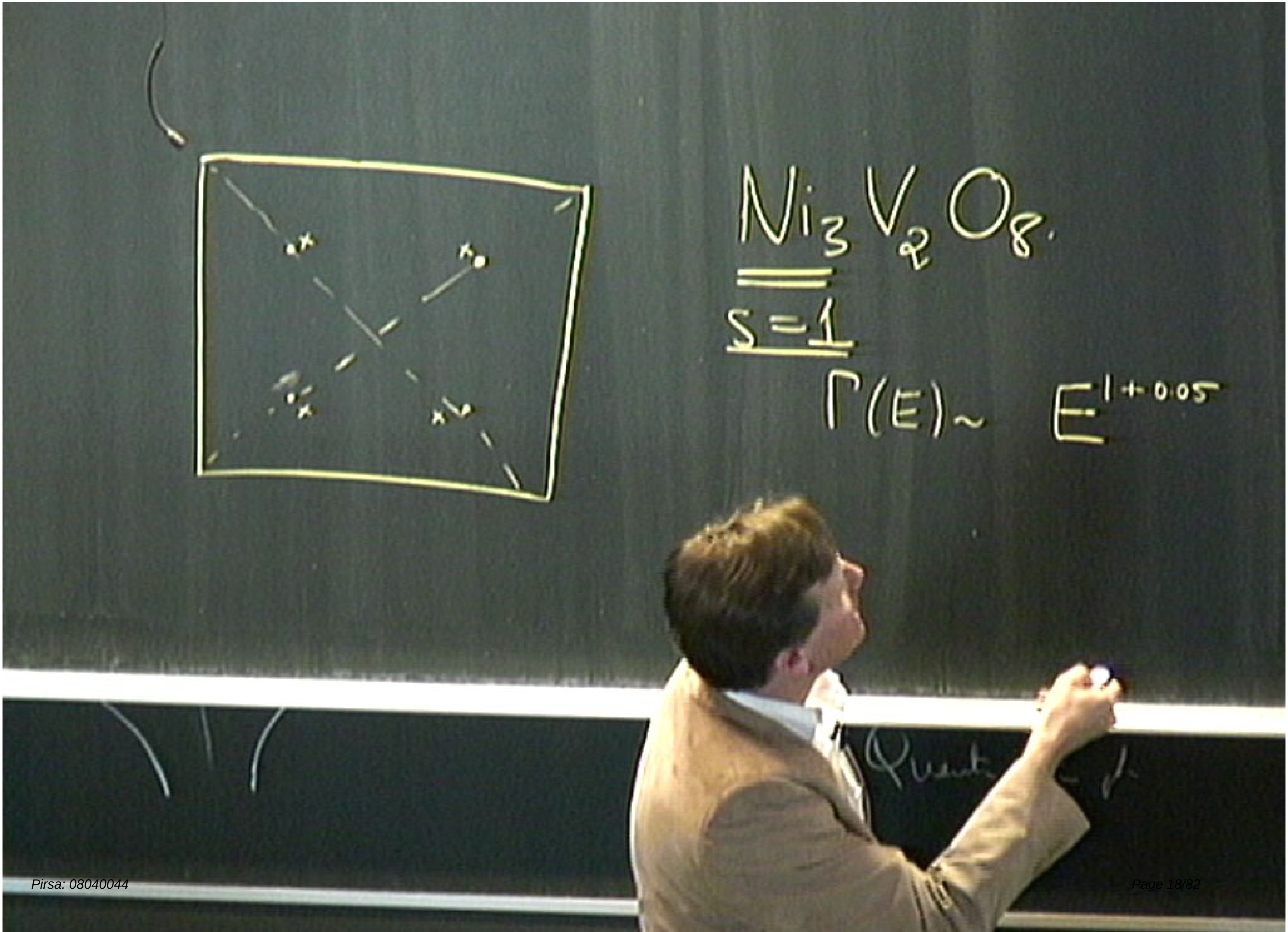
Spallation Neutron Source at ORNL, TN


Spallation Neutron Source at ORNL, TN

A Kagome Staircase AFM




Ni3V2O8.
S = 1
Γ(E) ~ E1+0.05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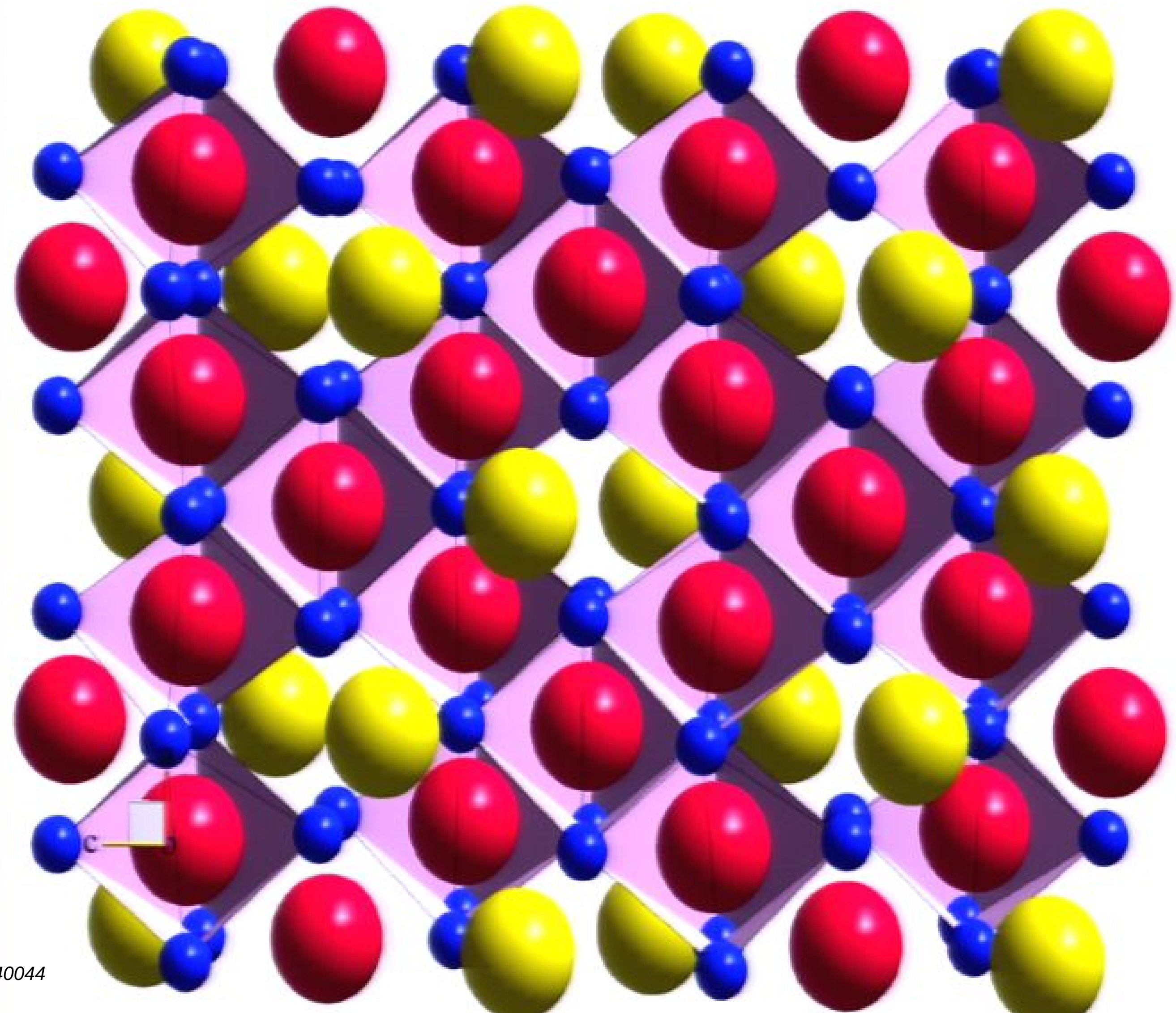
A Kagome Staircase AFM



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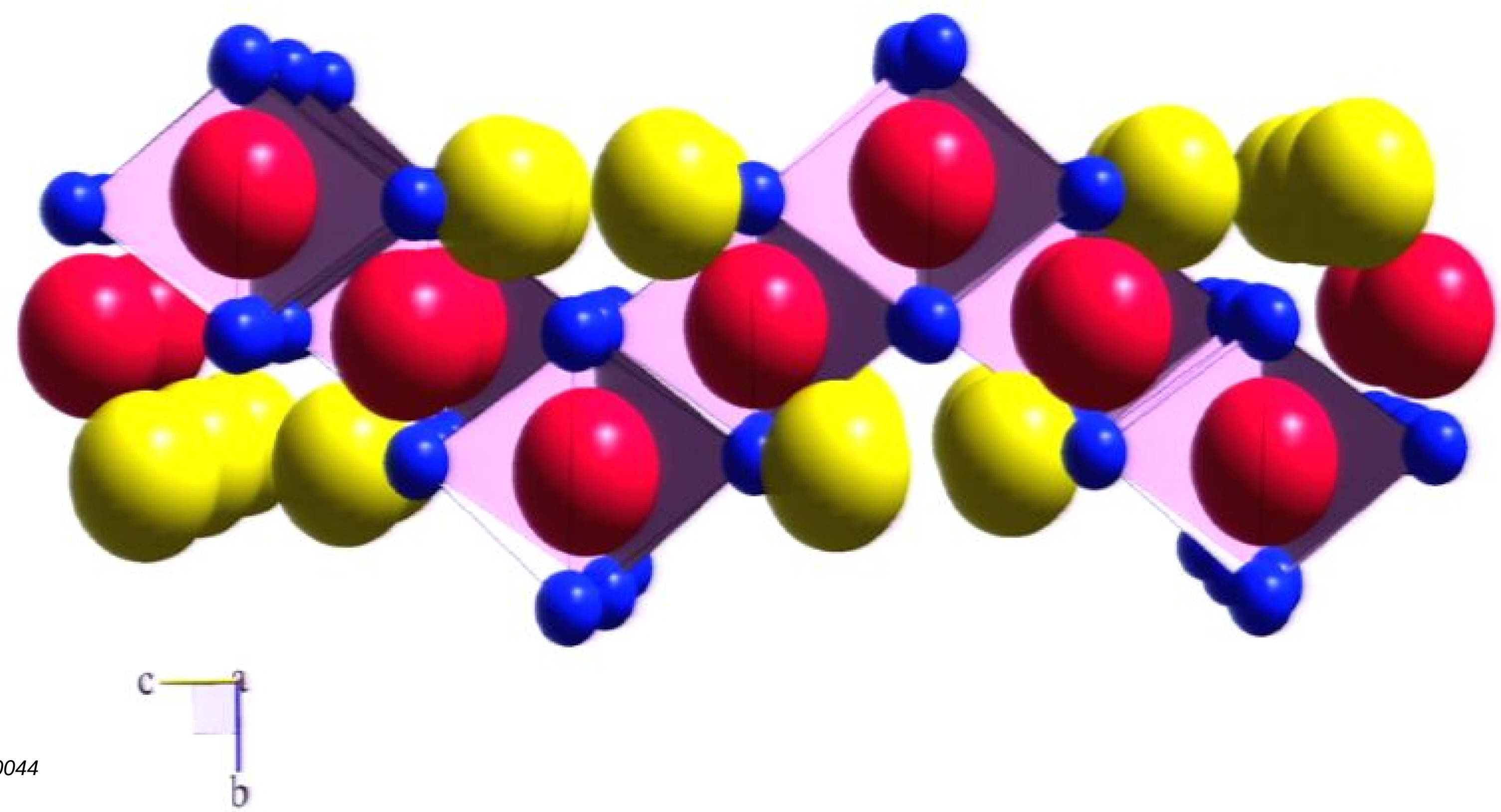
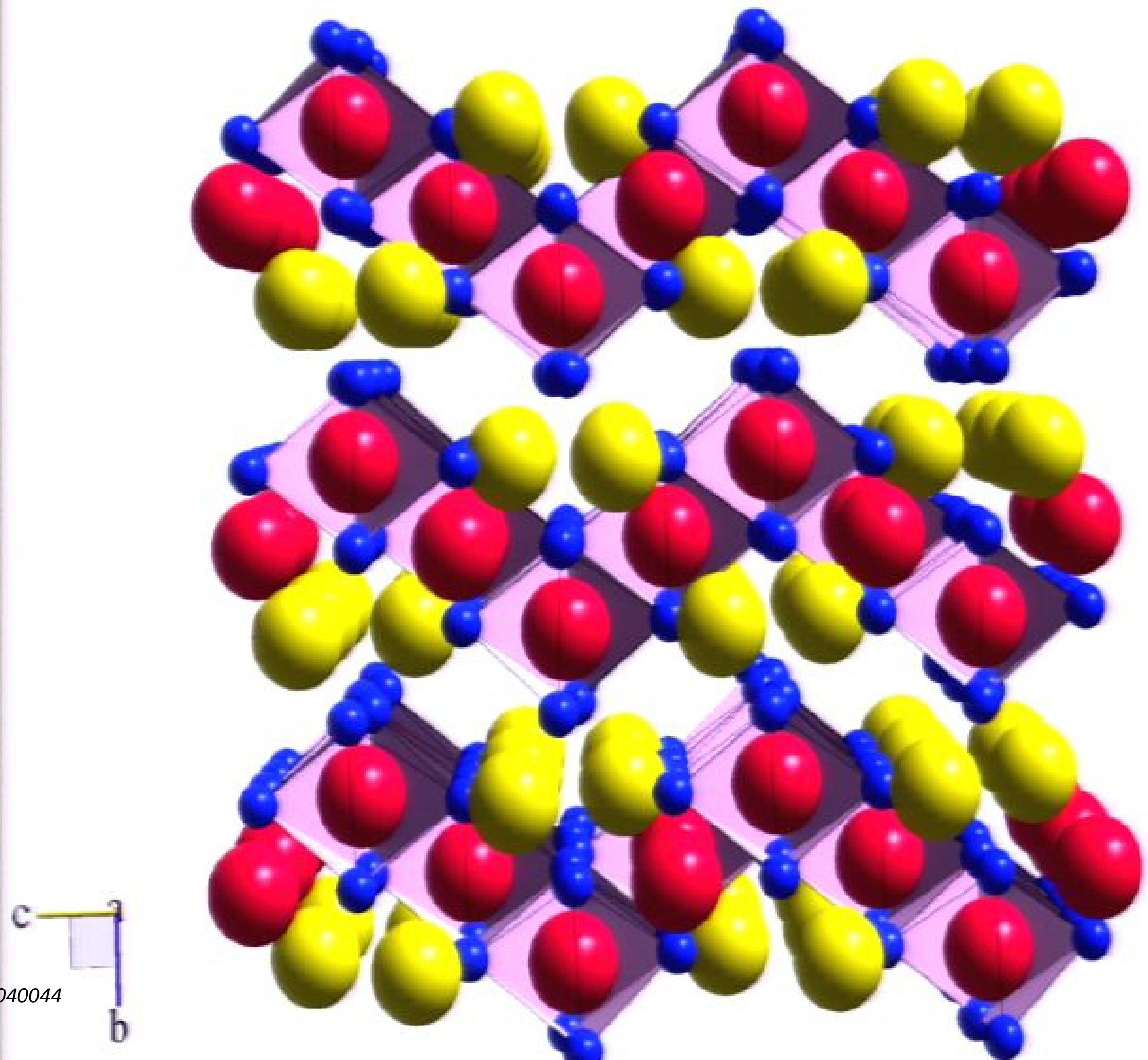
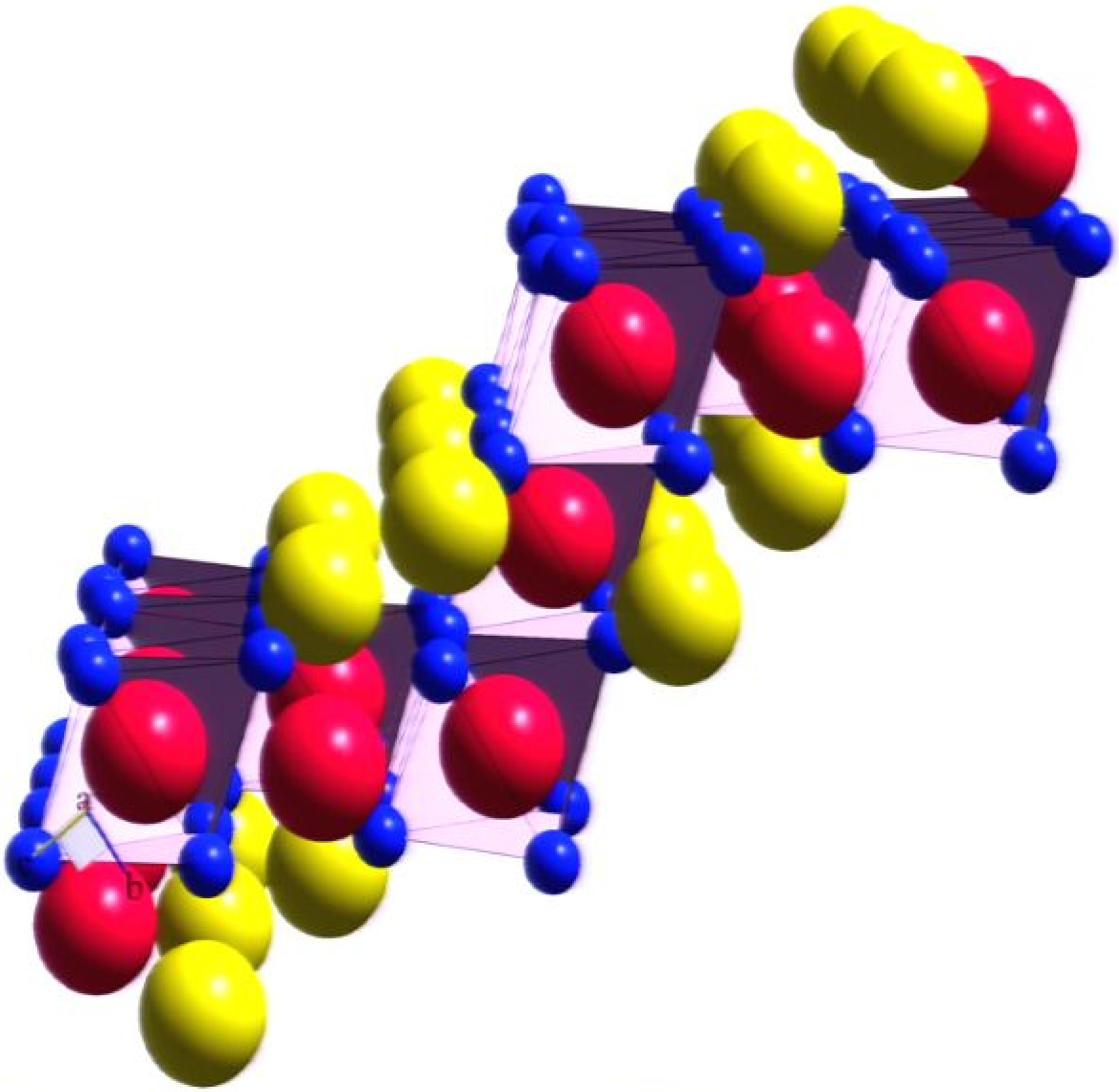
A Kagome Staircase AFM



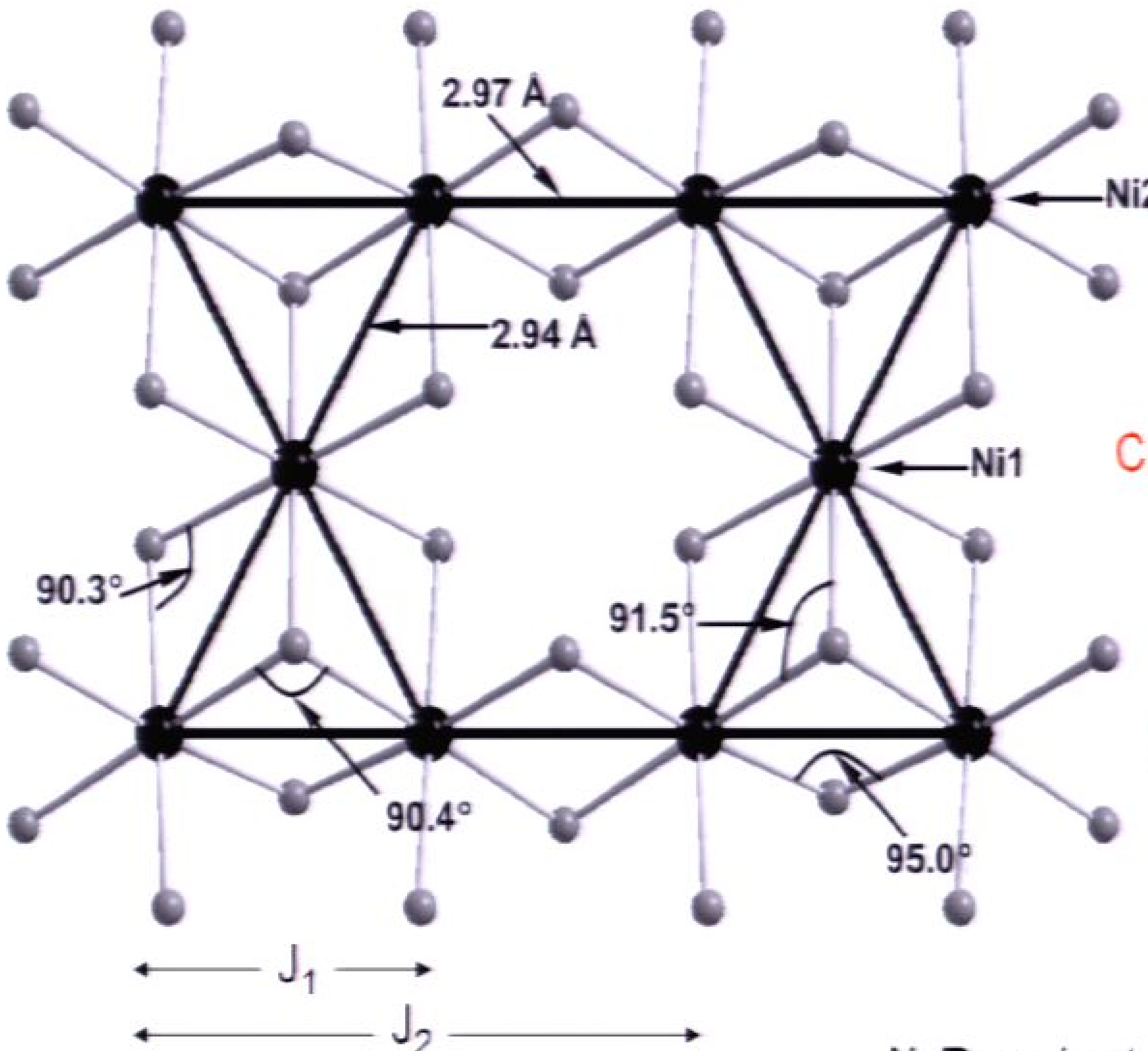
A Kagome Staircase AFM



A Kagome Staircase AFM



Exchange Interactions

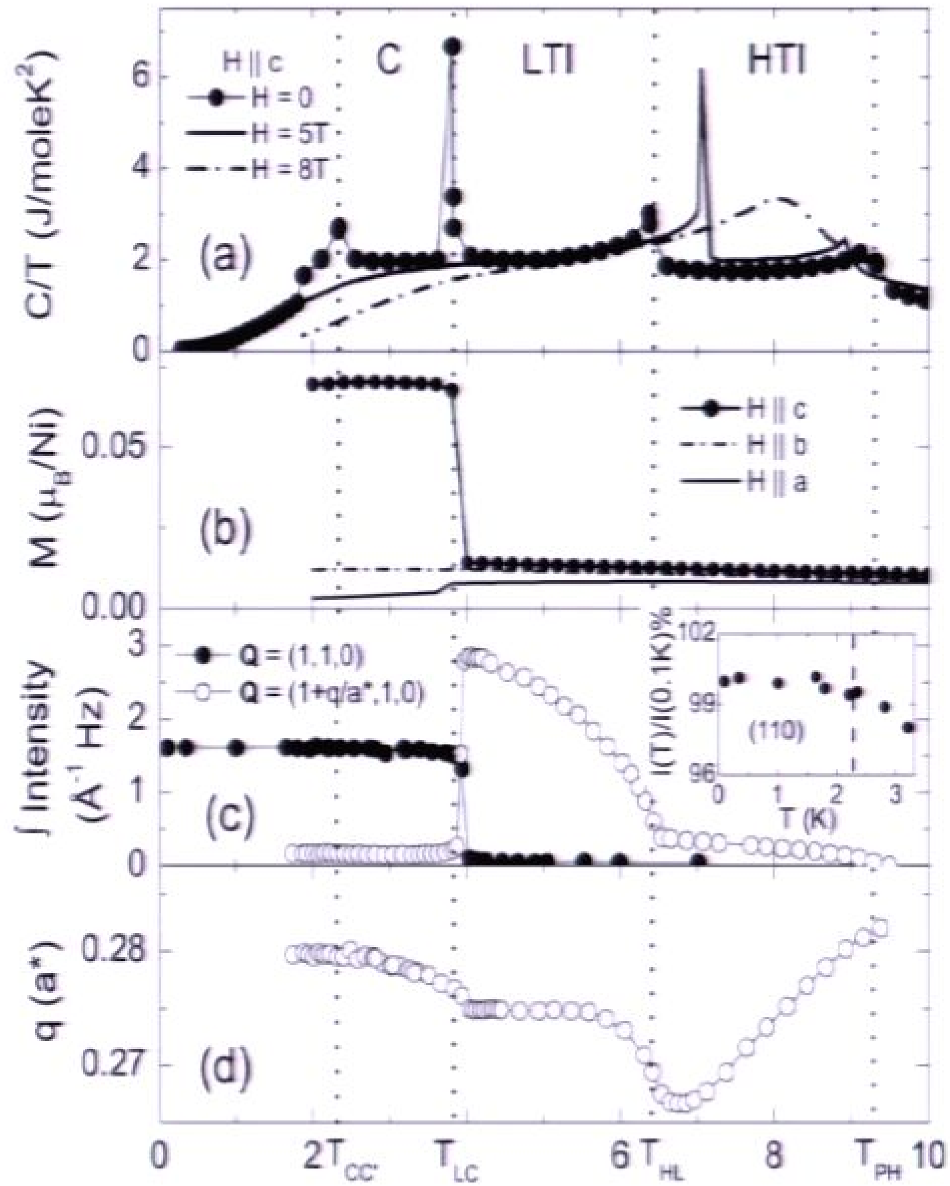


Cross tie spins

Spine spins

N. Rogado et al (2003)

Multiple Magnetic Phases



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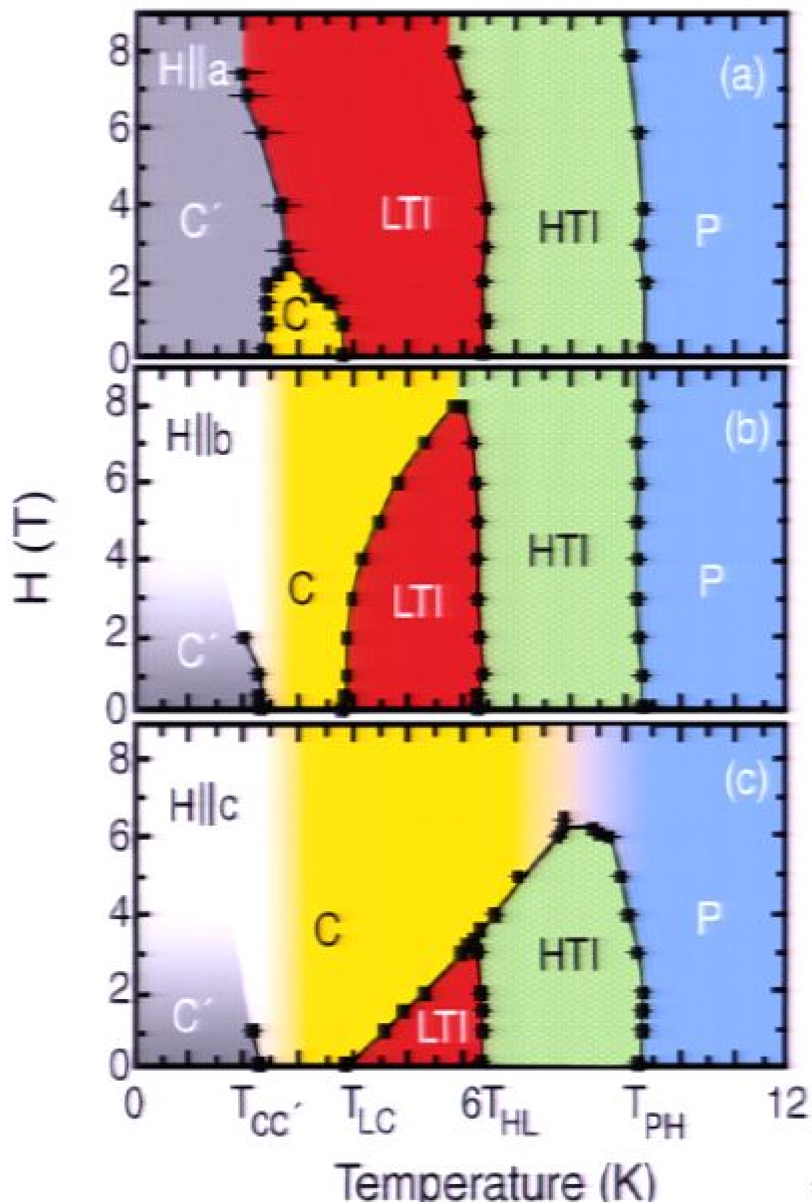
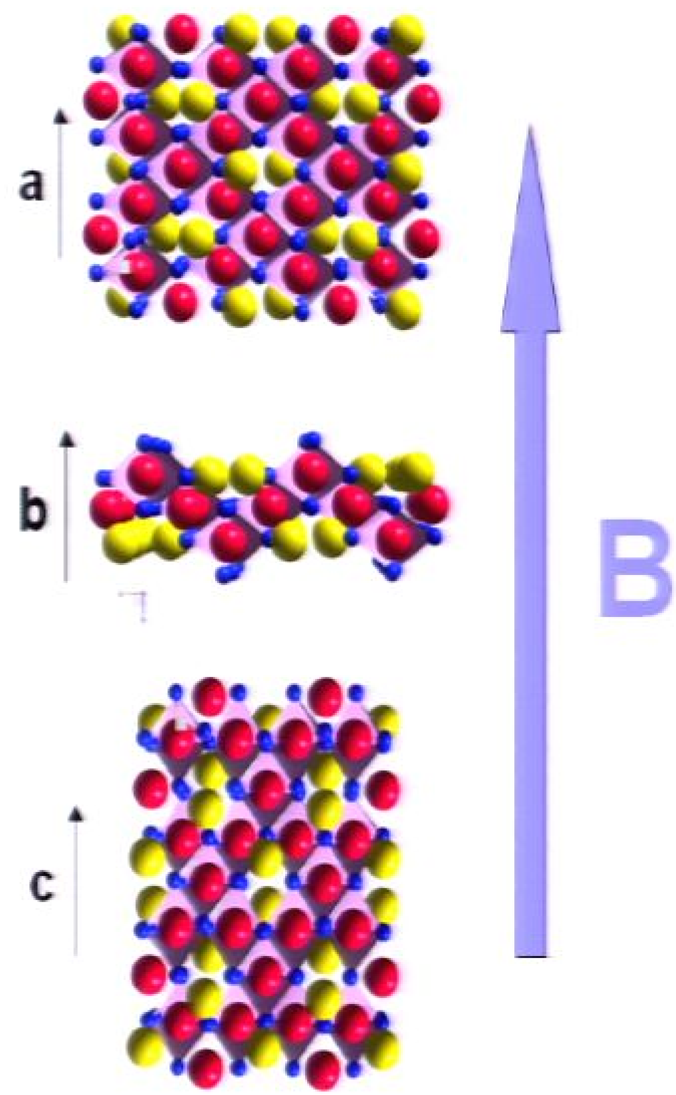
4/24/2008

Compiled Phase Diagram





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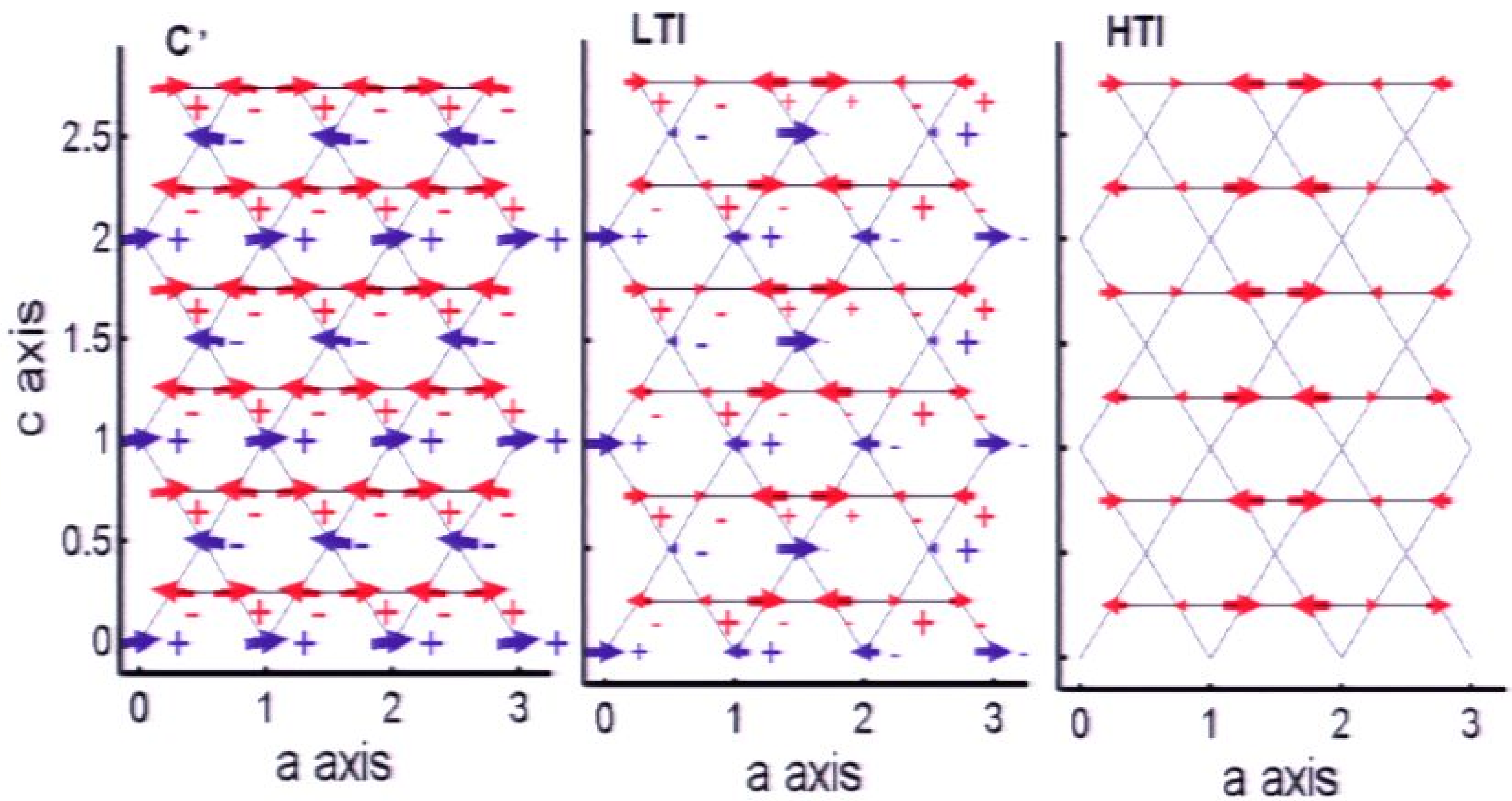
Modulated magnetic phases

2.2 K<T< 4 K | 4 K<T< 6.5 K | 6.5 K<T<9.2 K

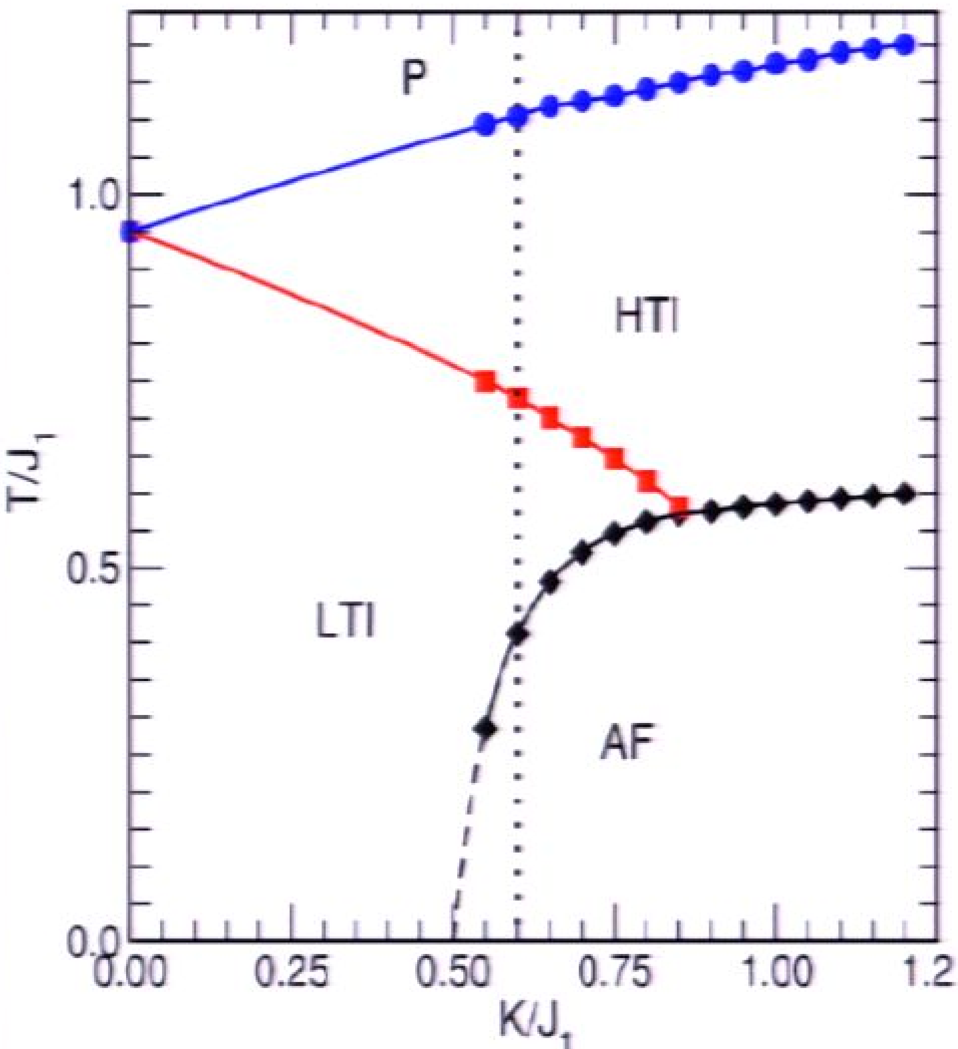


Commensurate Canted FM

Incommensurate Cycloidal

Incommensurate amplitude modulated

Mean Field "ANNNI" Phase Diagram

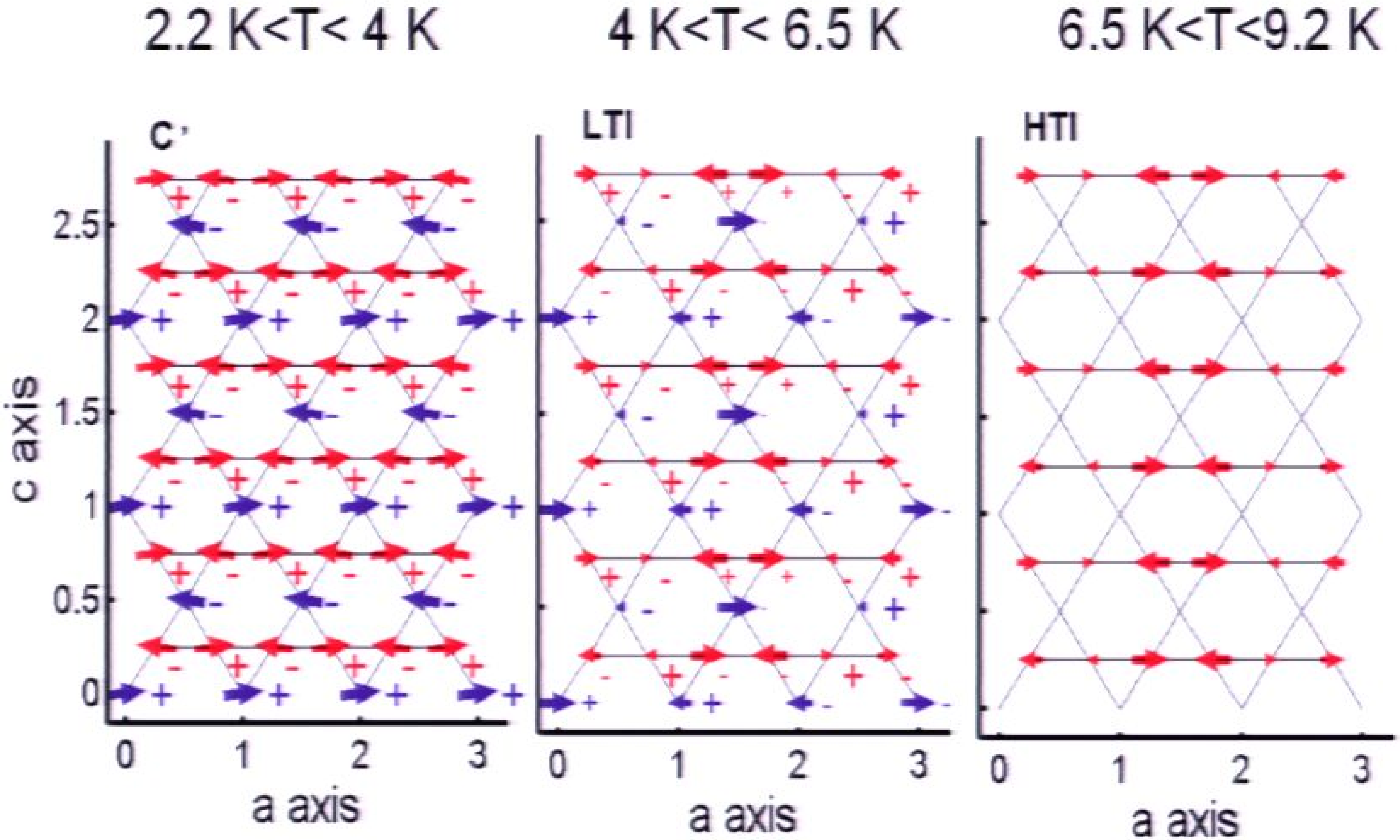


$$\mathcal{H} = -K\sum_n S_a(n)^2 + J_1\sum_n \mathbf{S}(n)\cdot\mathbf{S}(n+1) + J_2\sum_n \mathbf{S}(n)\cdot\mathbf{S}(n+2).$$

$$\cos(\pi q_{0\alpha}) = -J_{1\alpha}/(4J_{2\alpha})$$

$$J_1/J_2 = 2.56$$

Modulated magnetic phases



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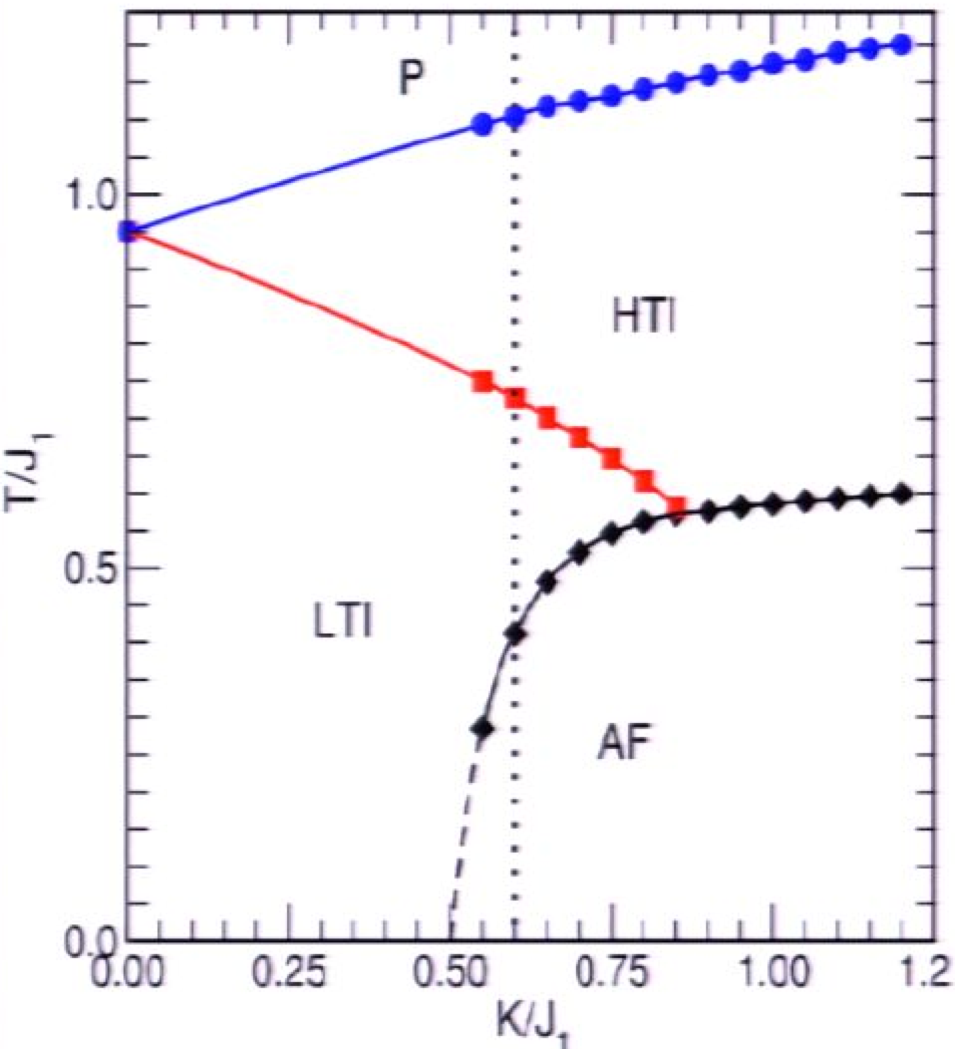

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$$\cos(\pi q_{0\alpha}) = -J_{1\alpha}/(4J_{2\alpha})$$

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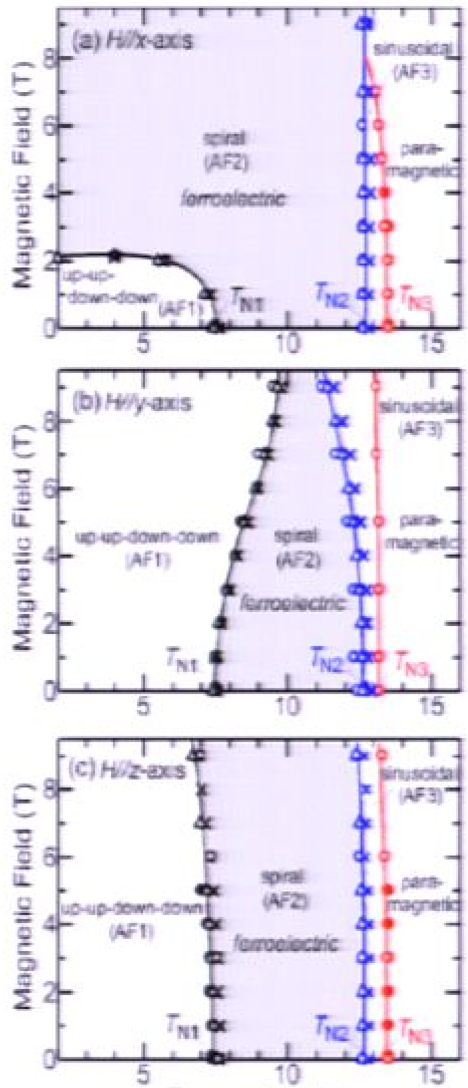
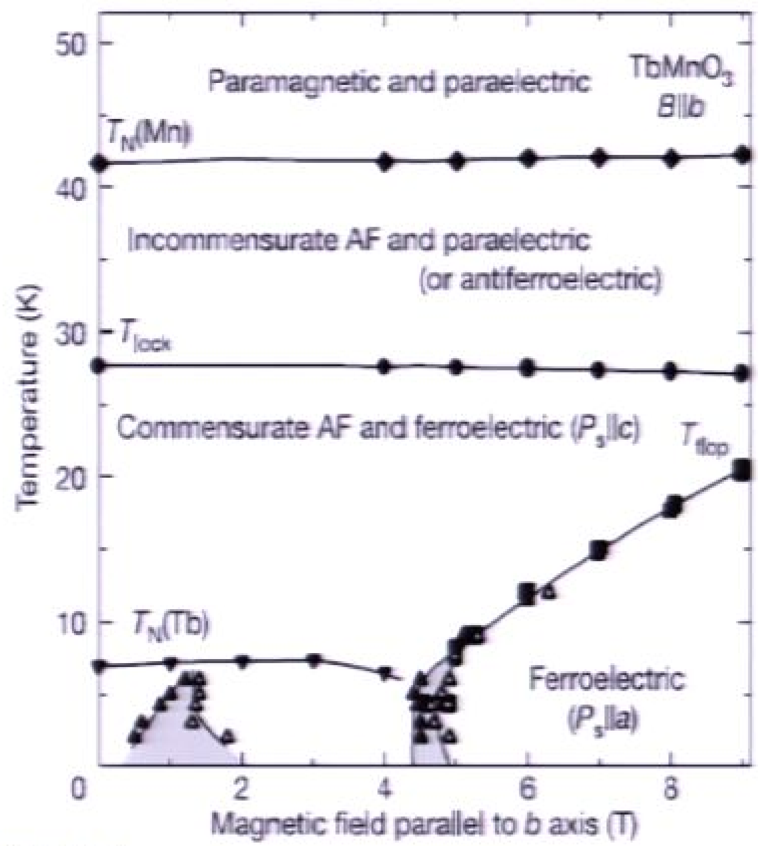
Related systems

$MnWO_4$



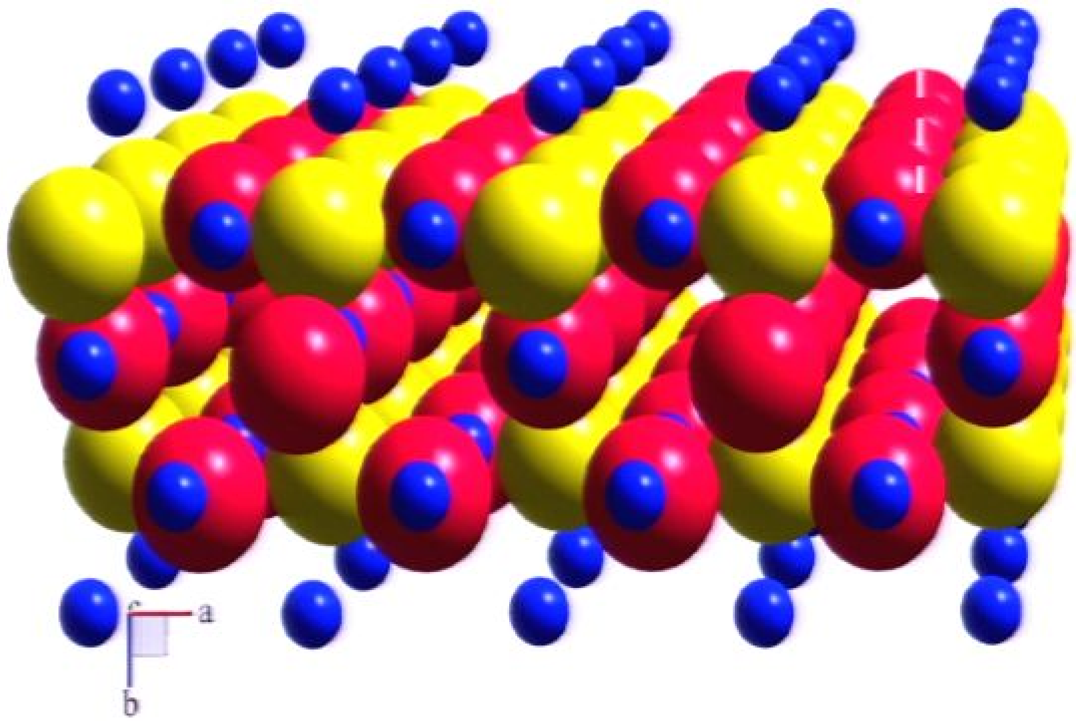
Arkenbout et al. PRB (2006)

$TbMnO_3$



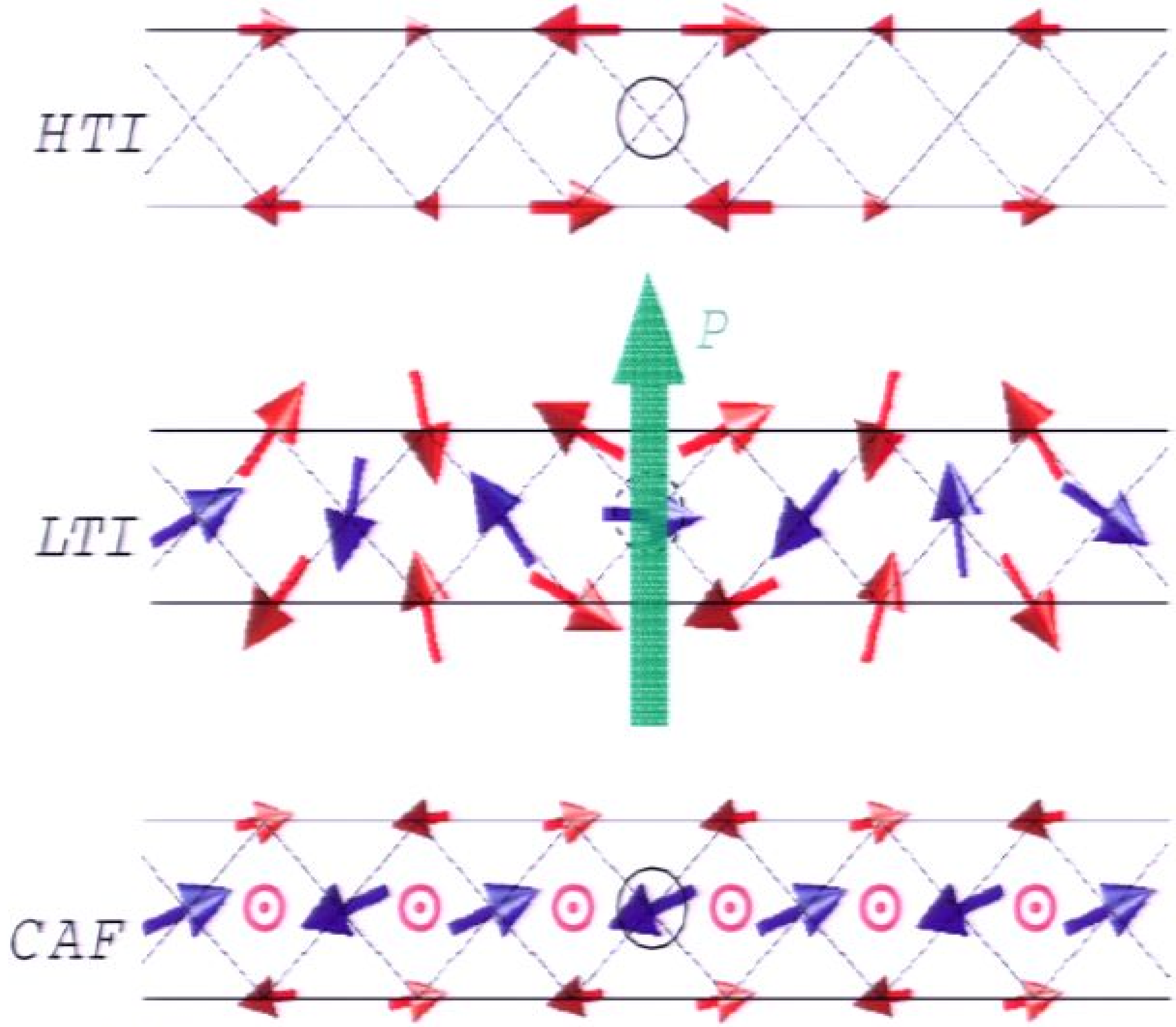
Kimura et al. Nature (2003)

Ferro-electricity on a kagome' staircase



Lawes et al (2005)

Ferro-electricity on a kagome' staircase



Lawes et al (2005)

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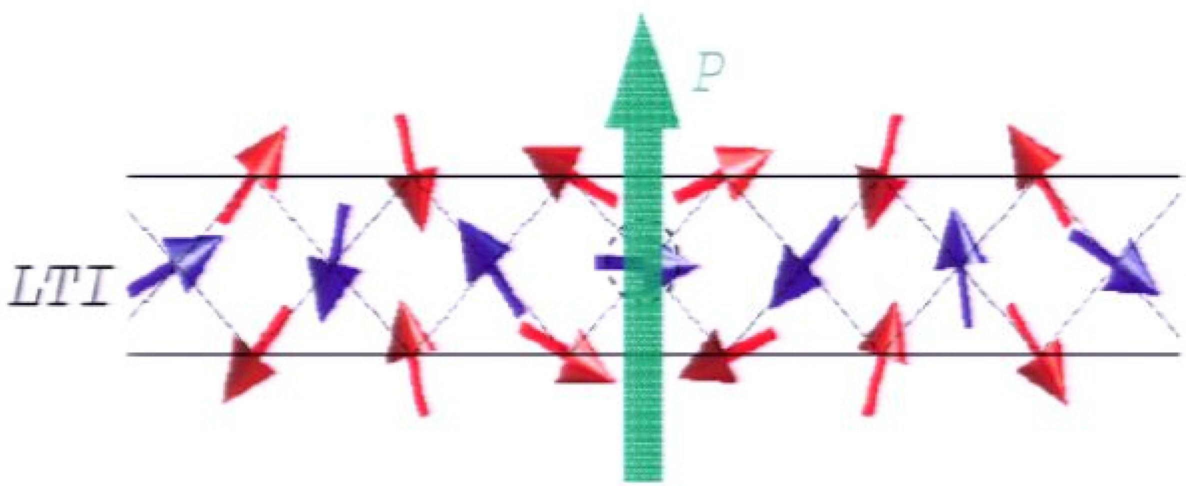

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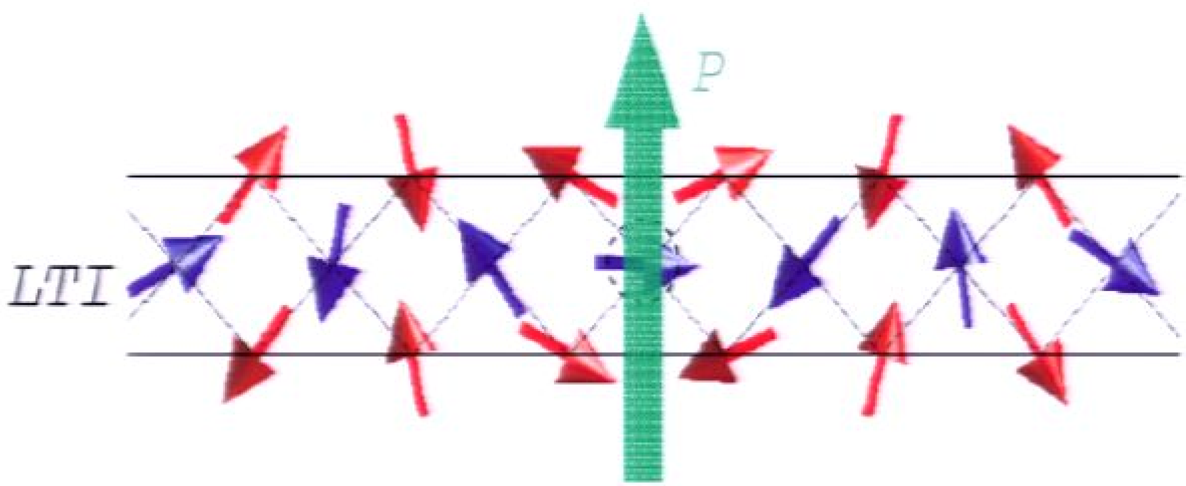
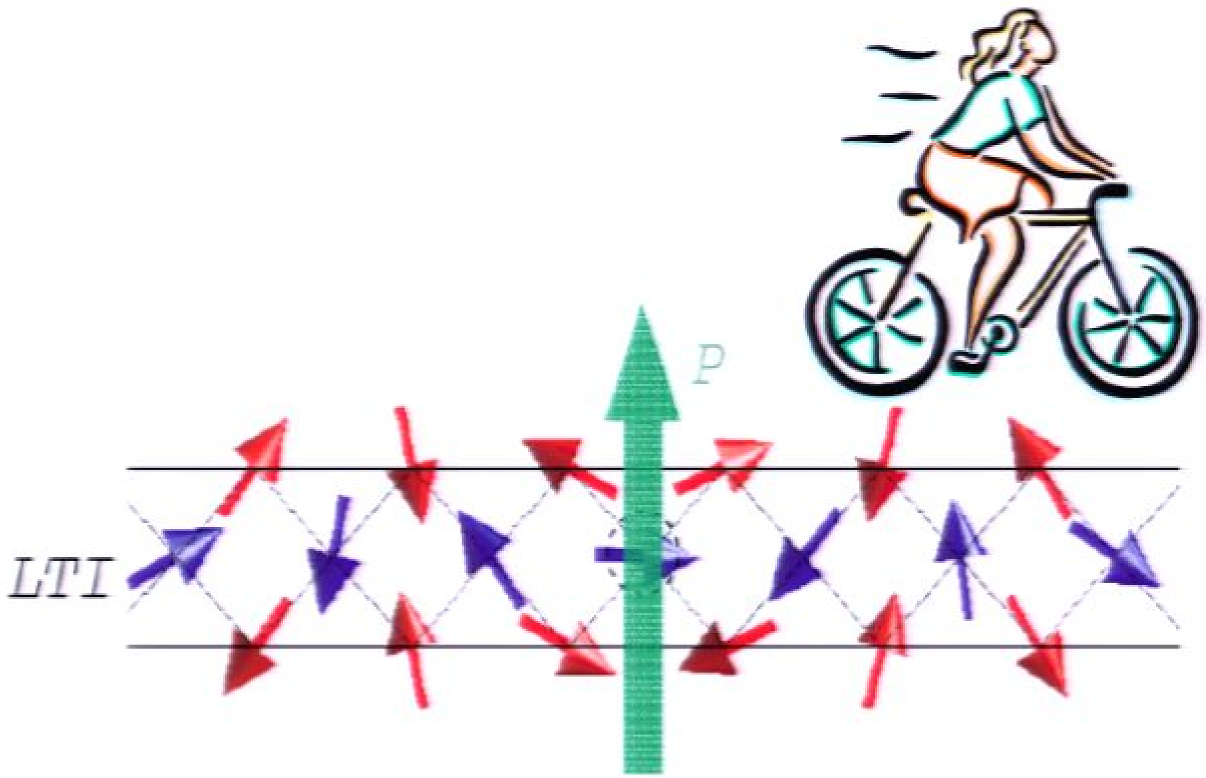


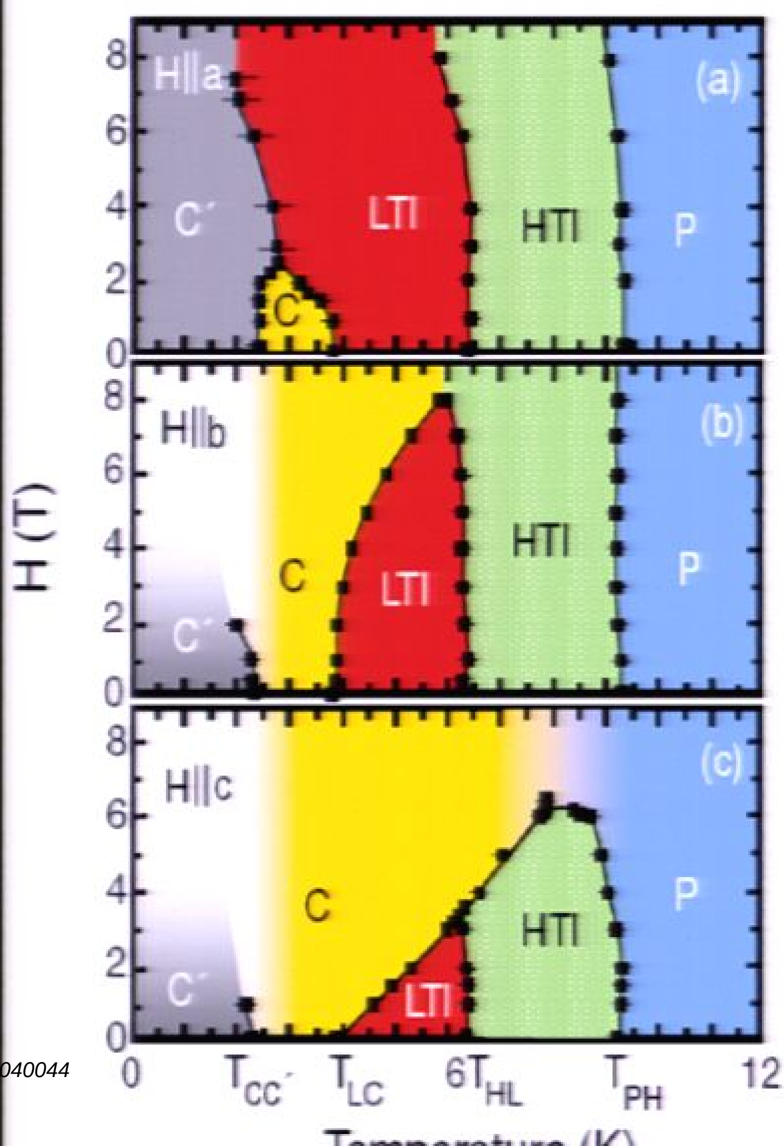
Lawes et al (2005)

Ferro-electricity on a kagome' staircase

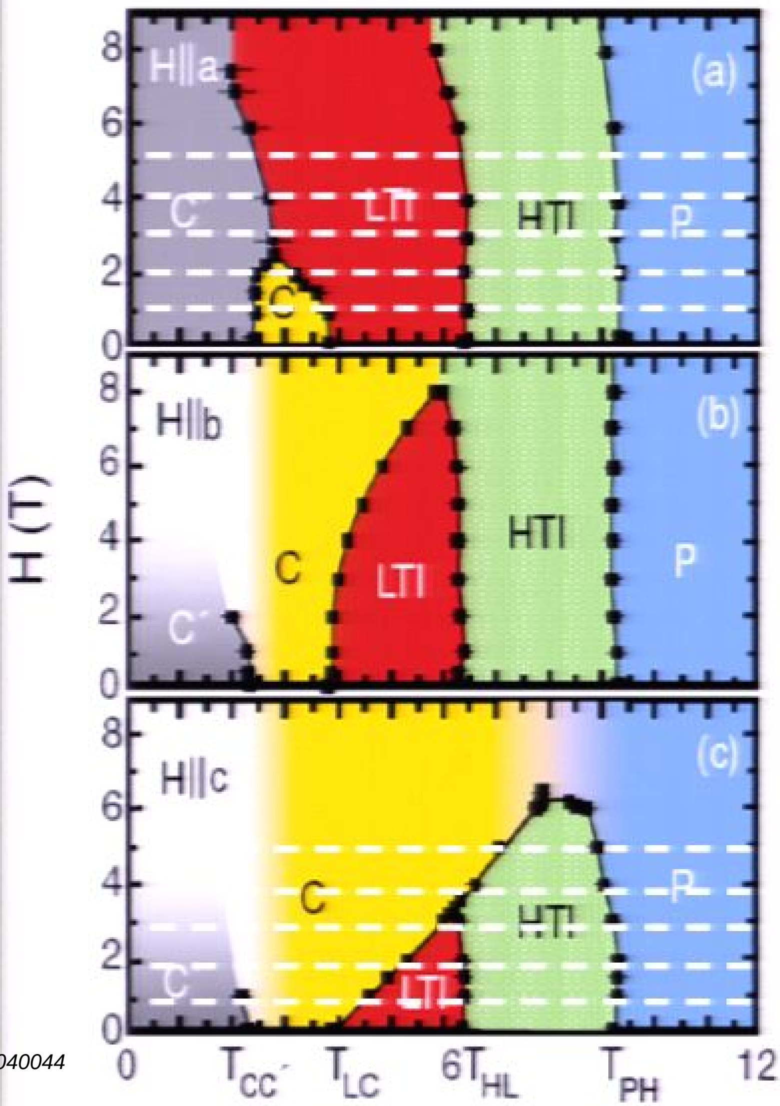


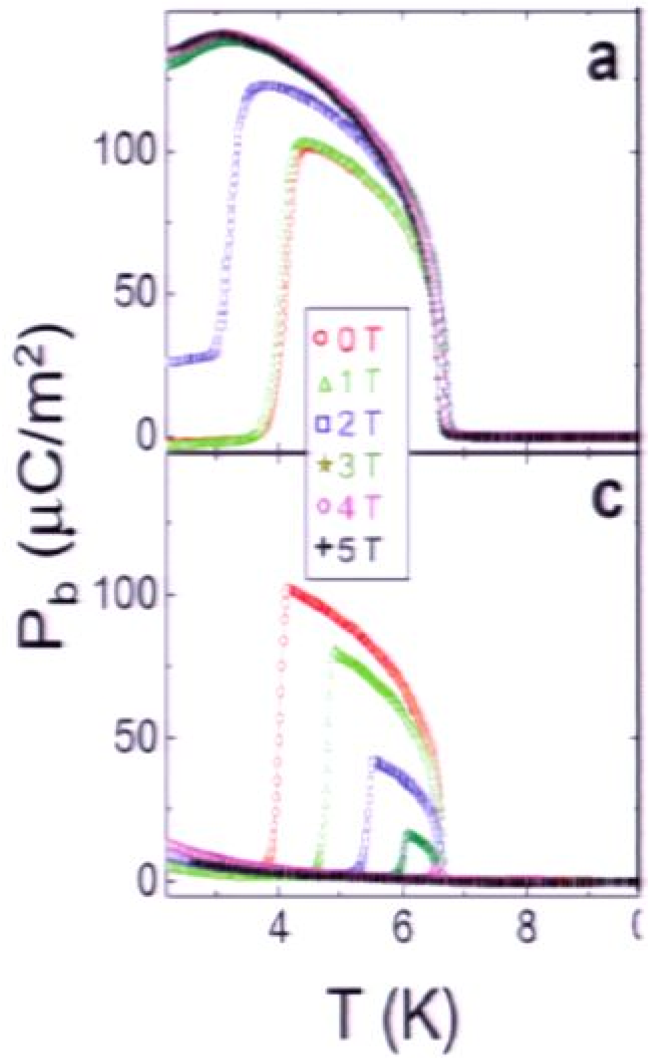
Lawes et al (2005)

Magnetism on a kagome' staircase

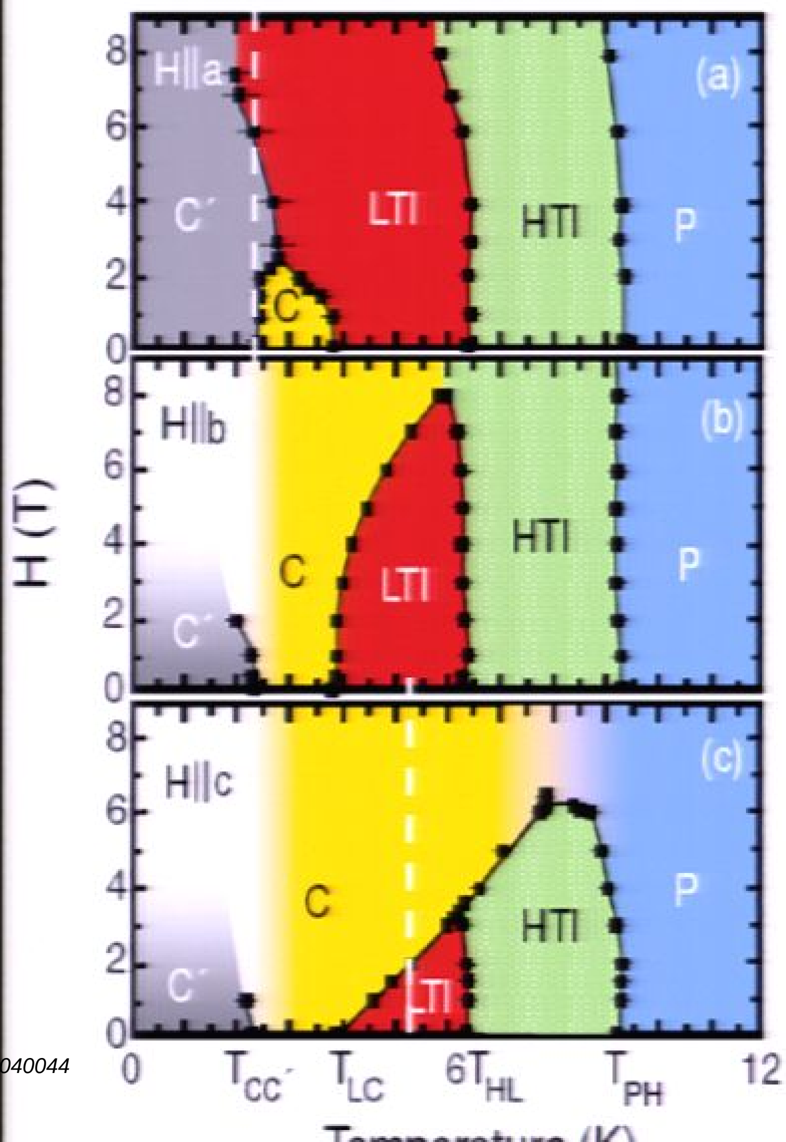


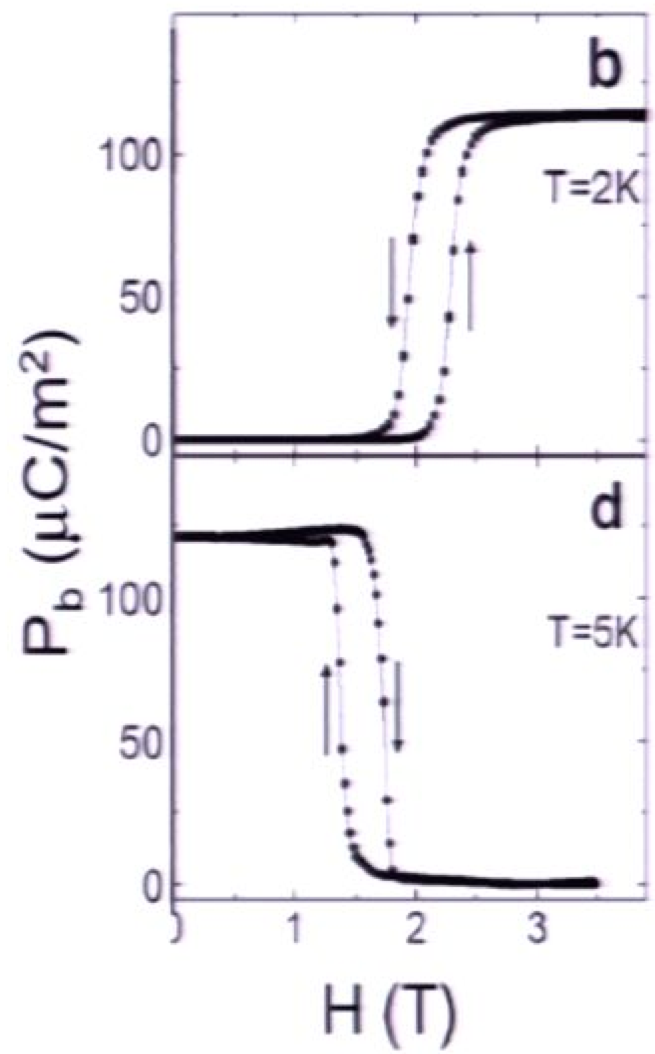
Ferro-electricity on a kagome' staircase





Ferro-electricity on a kagome' staircase





Lawes et al (2005)

Phenomenological observations

- Polarization direction is consistent with spin current model:

$$\mathbf{P} \propto \gamma\, \mathbf{e}_{ij} \times \left(\mathbf{S}_i \times \mathbf{S}_j\right)$$

- The magneto-electric phase is an incommensurate cycloid phase
- Magneto-electric phase develops from existing incommensurate order

Landau Theory of Magneto-Electricity

A. B. Harris arXiv:cond-mat/0610241

General case:

$$V = \sum_{nm\gamma} c_{nm\gamma} \sigma_n(\mathbf{q}) \sigma_m(-\mathbf{q}) P_\gamma$$

IRREP	1	2_X	$\tilde{m}_y$	$\tilde{m}_z$
Γ_1	1	1	1	1
Γ_2	1	1	-1	-1
Γ_3	1	-1	1	-1
Γ_4	1	-1	-1	1

Landau Theory of Magneto-Electricity

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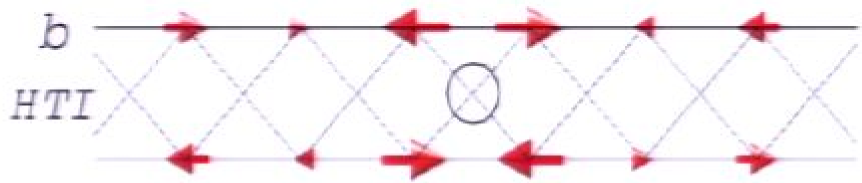
Amplitude modulated (Γ_4)

$$V_{HTI} = \sum_\gamma c_{44\gamma} |\sigma_4(\mathbf{q})|^2 P_\gamma \quad \equiv 0$$



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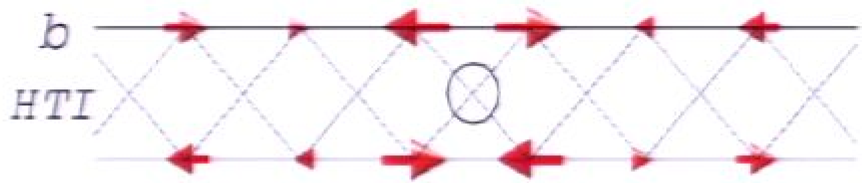
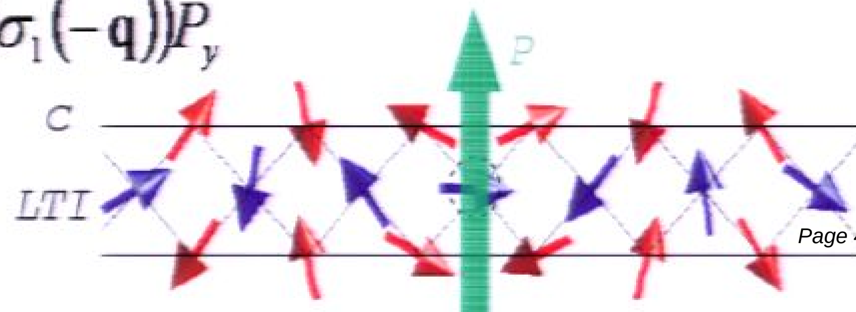
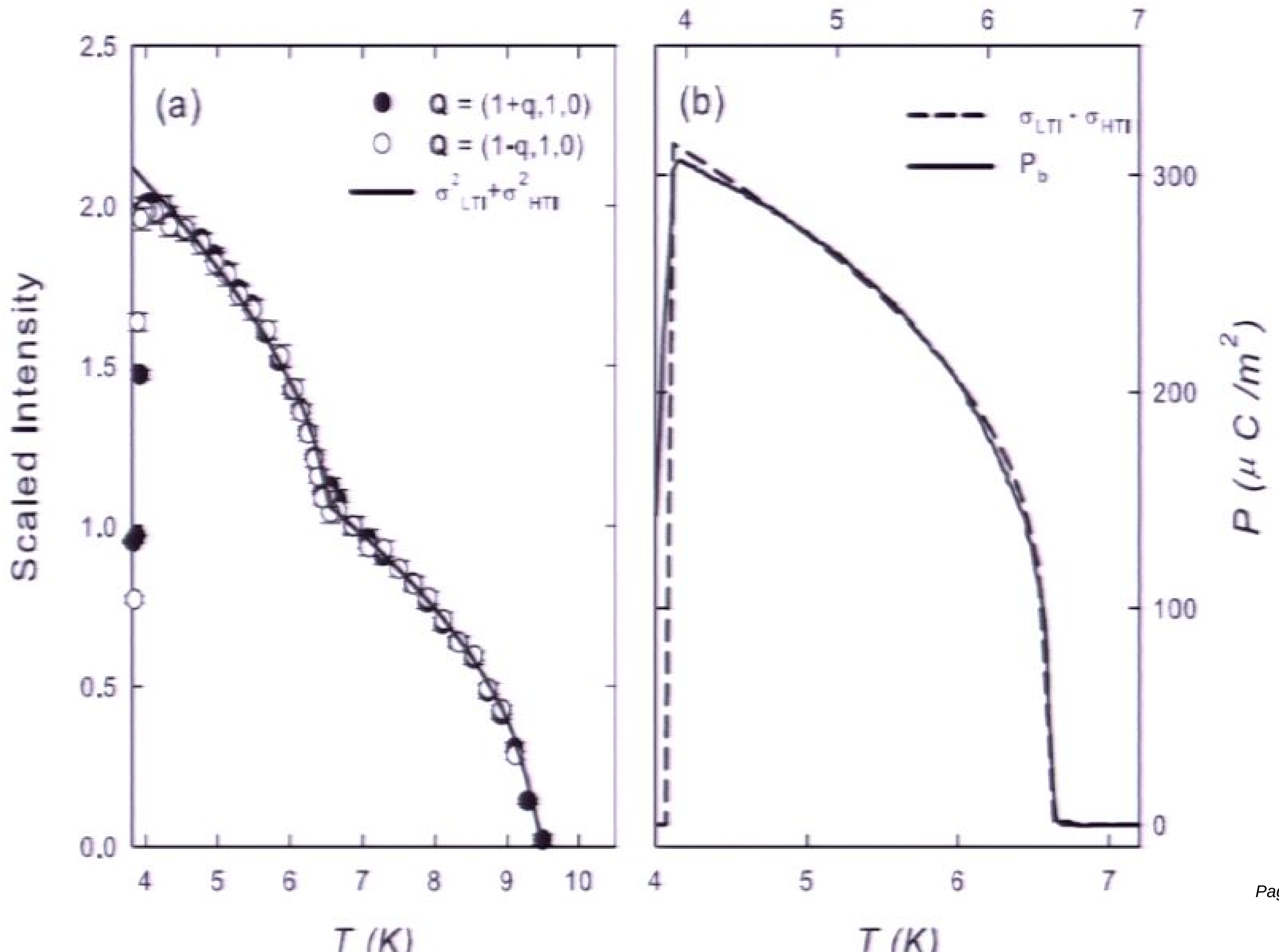


Cycloid state ($\Gamma_4+\Gamma_1$)

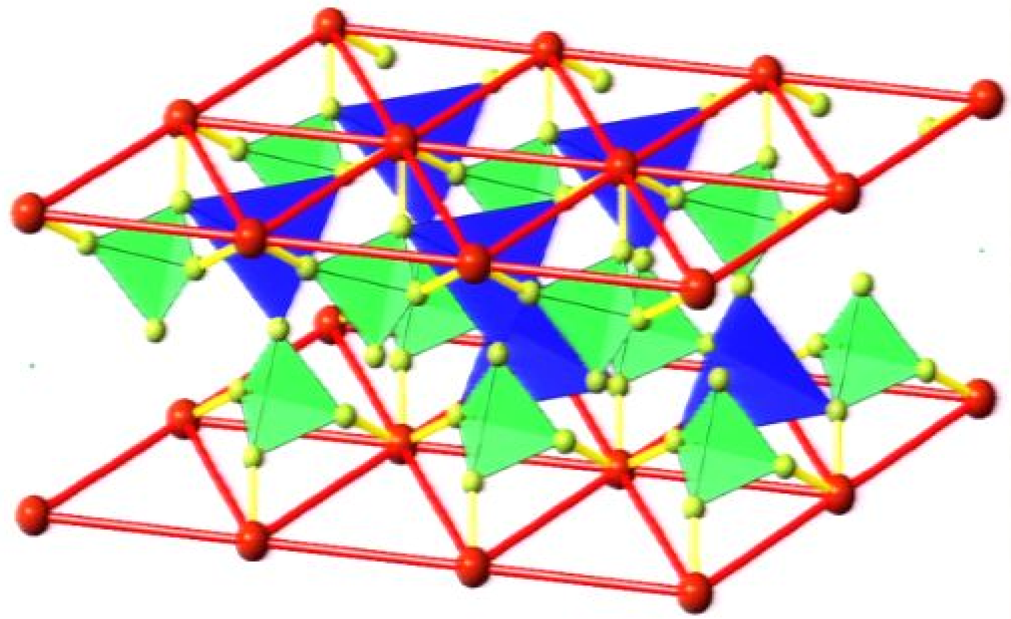
$$V_{LTI} = c_{14y}(\sigma_1(\mathbf{q})\sigma_4(-\mathbf{q}) + \sigma_4(\mathbf{q})\sigma_1(-\mathbf{q}))P_y$$



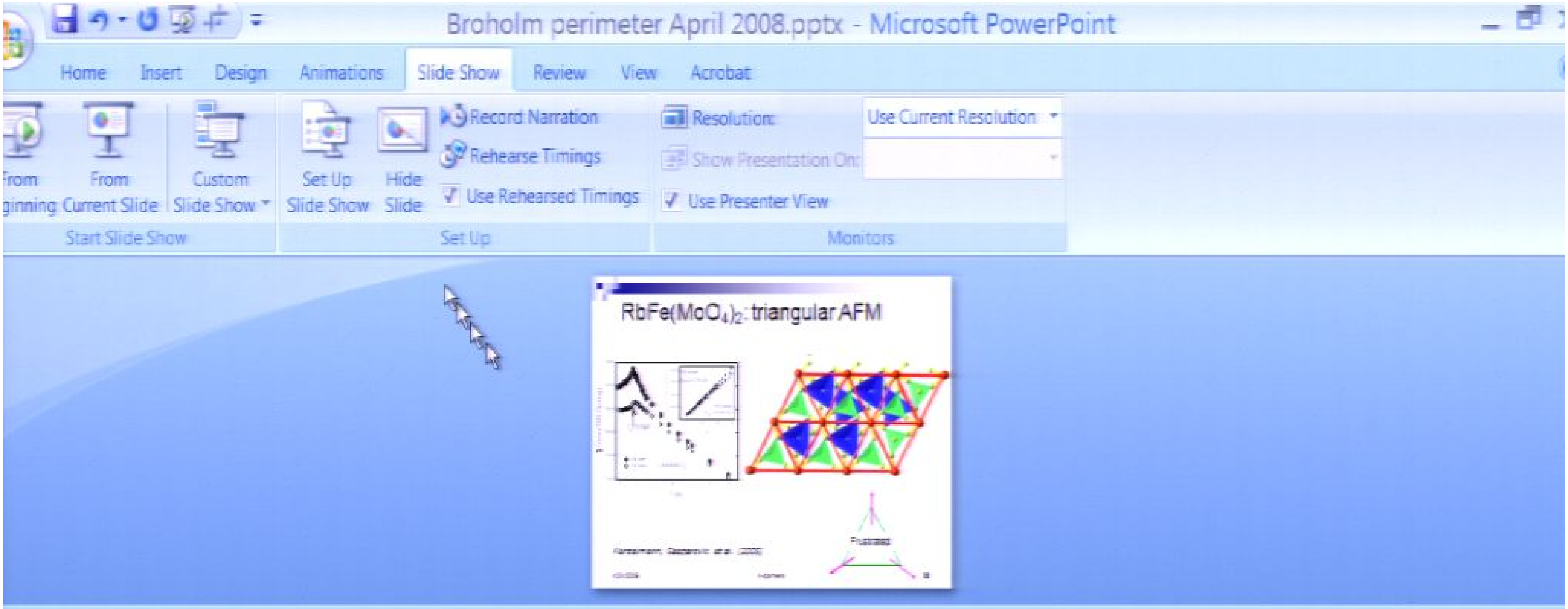
Tri-linear coupling in $Ni_3V_2O_8$



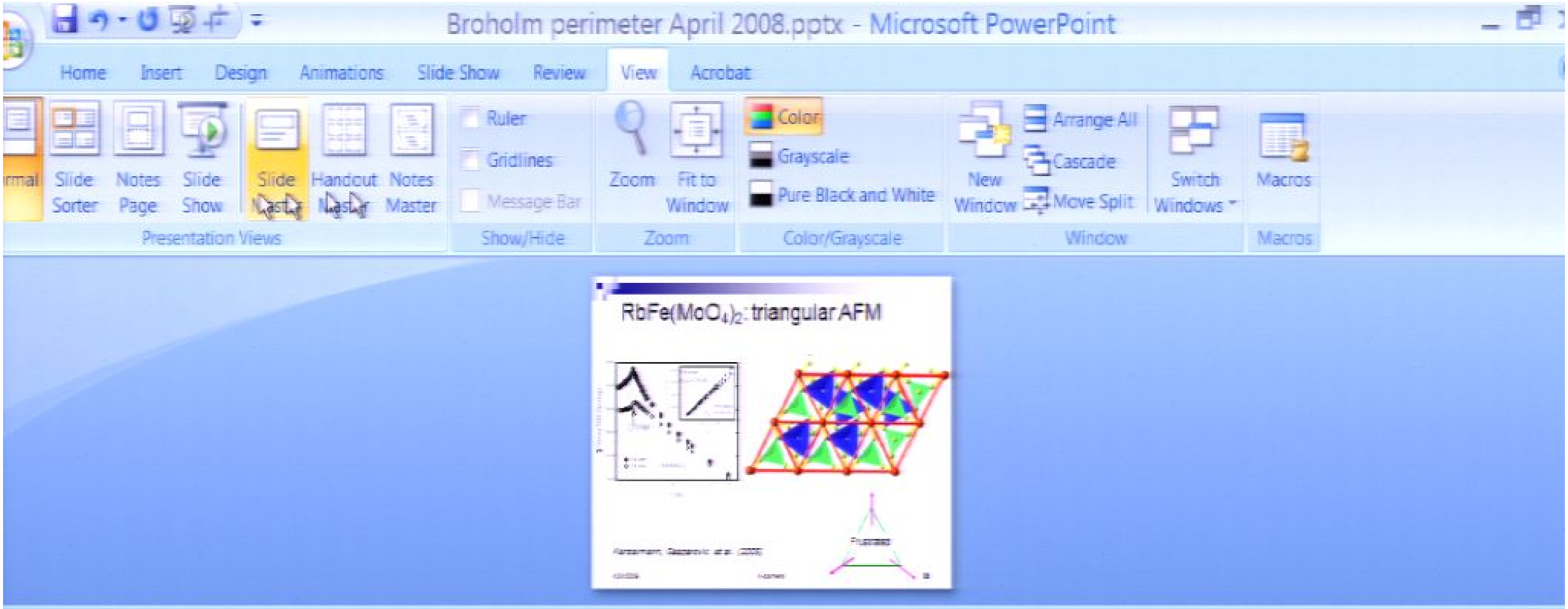
$RbFe(MoO_4)_2$: triangular AFM



Kenzelmann, Gasparovic et al. (2005)



t is a stacked triangular lattice as shown here. Delightfully simple in there being just one magnetic Fe atom per unit cell. The susceptibility data show a magnetic phase transition at a temperature that is about an order of magnitude lower than the Curie Weiss temperature. This indicates frustrated and quasi-two-dimensional magnetism and a potential for interesting lattice distortions and magneto-electricity.



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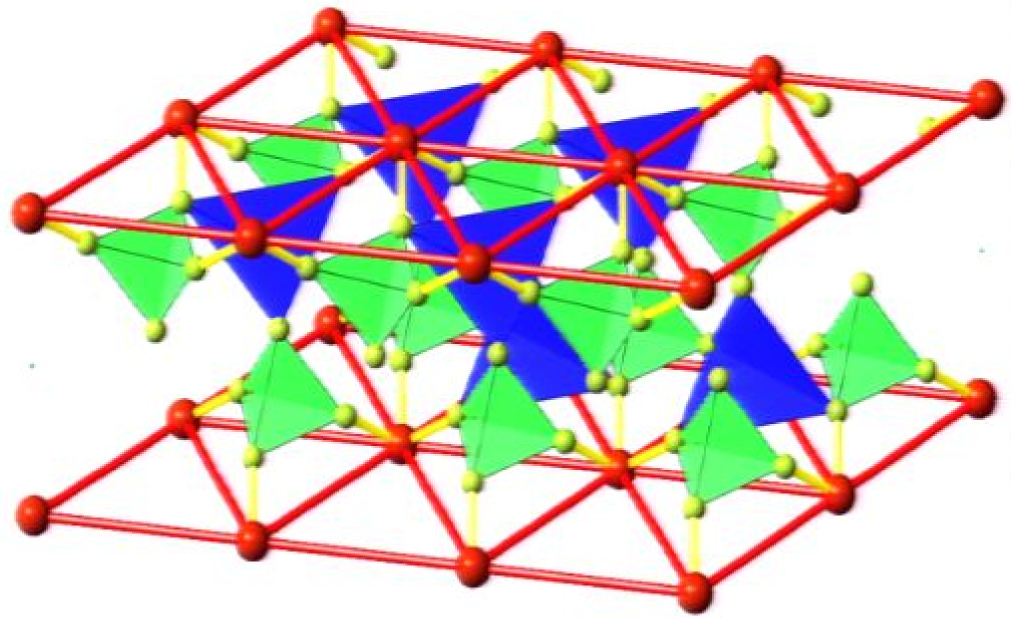

Kenzelmann, Gasparovic et al. (2005)

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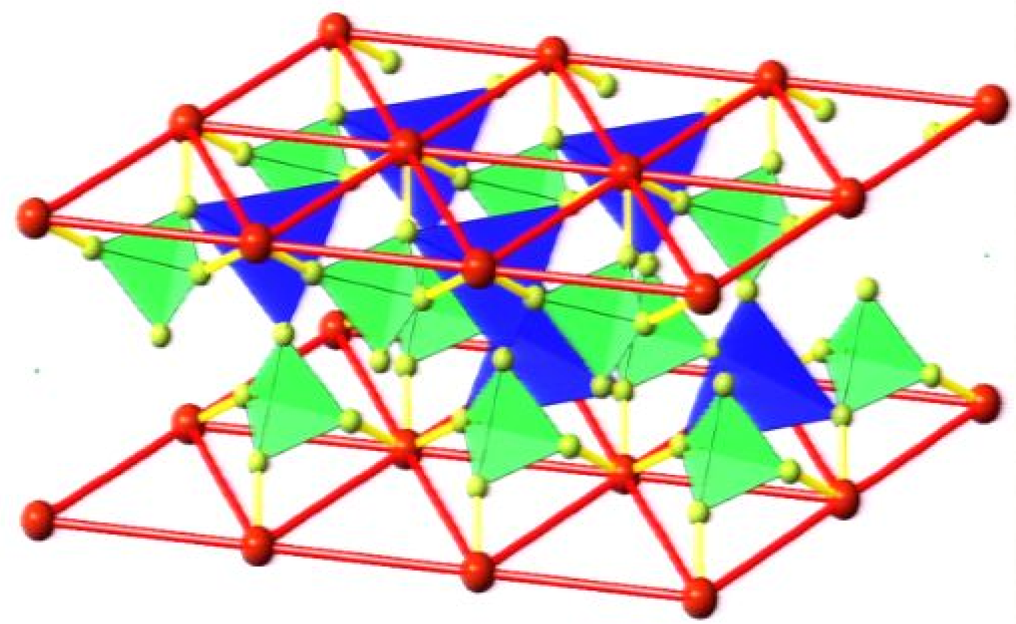

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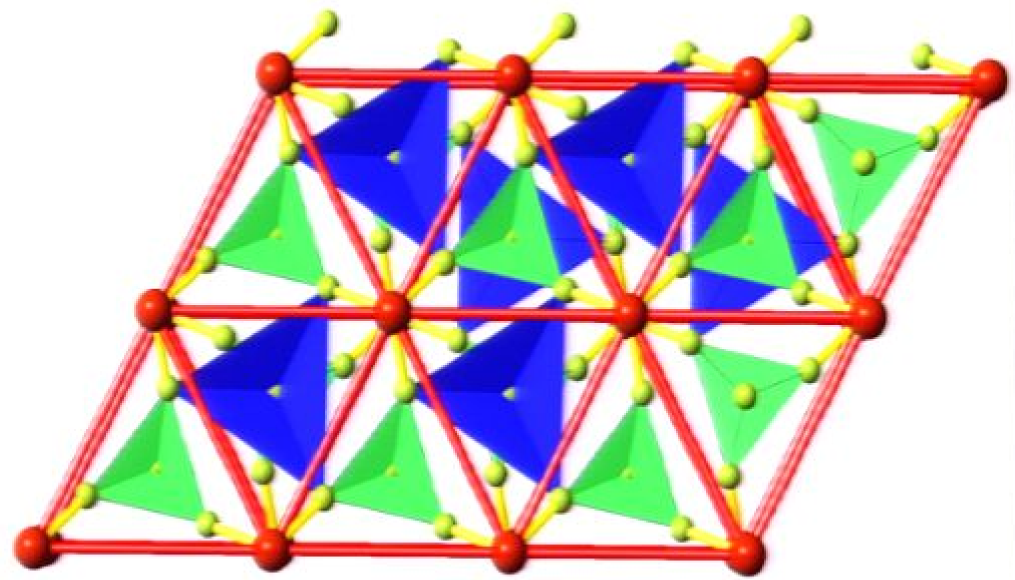

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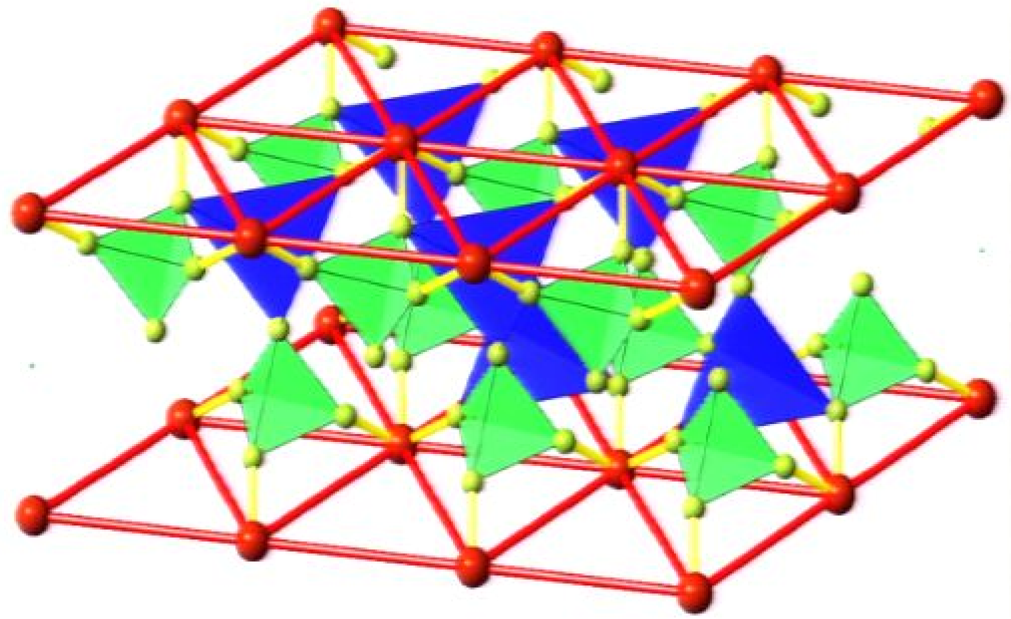

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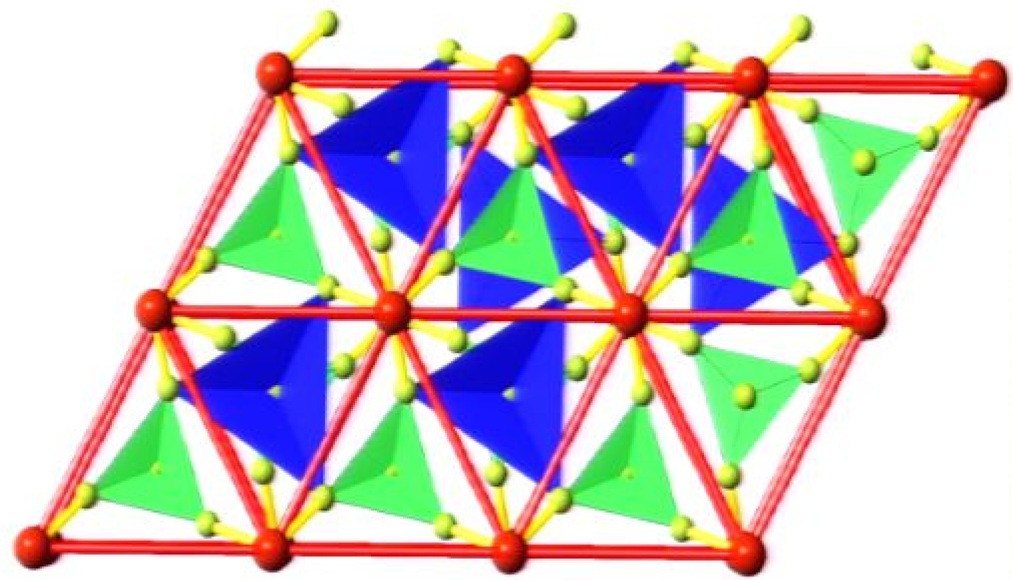

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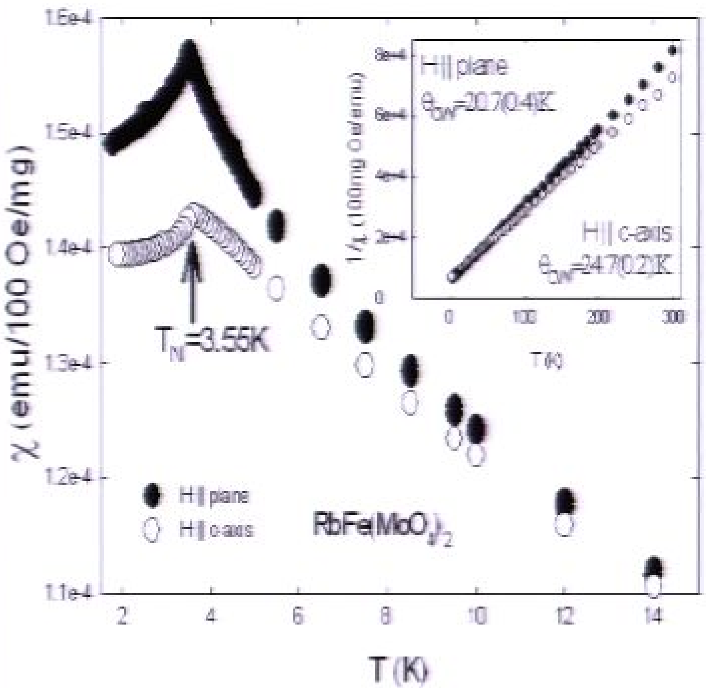
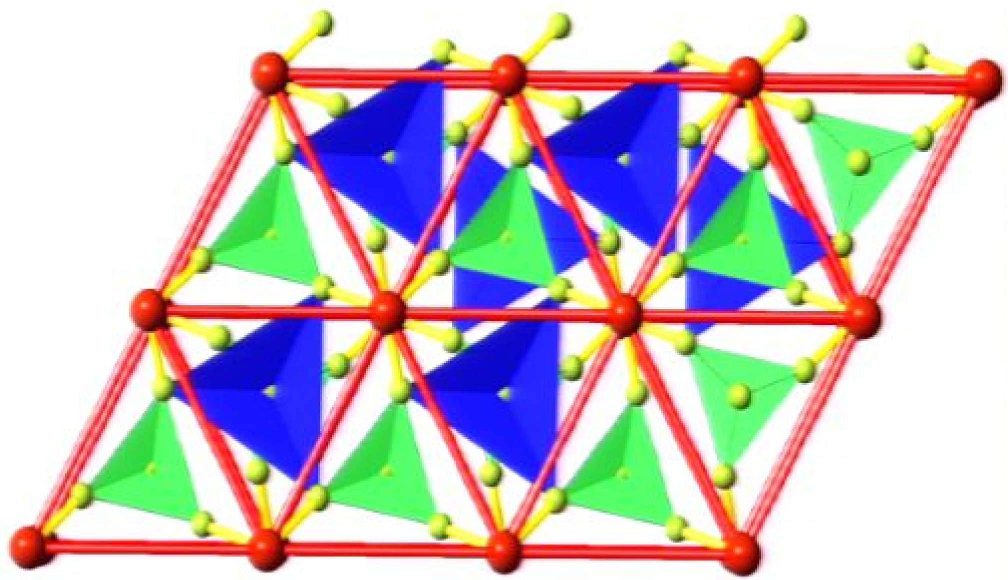
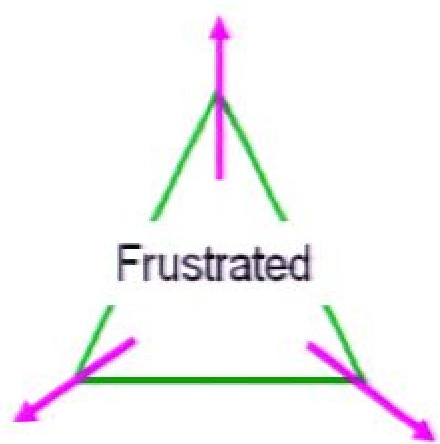
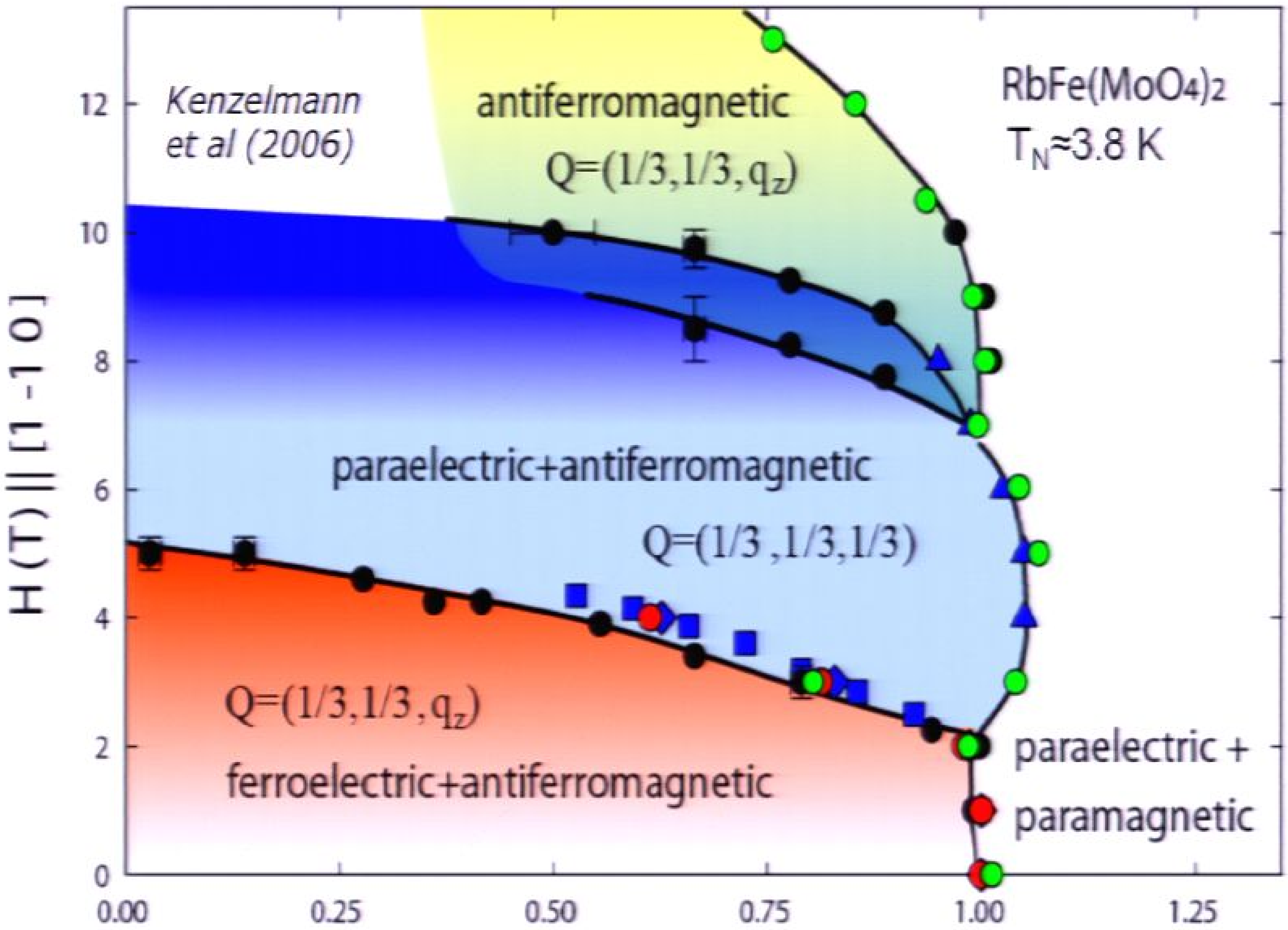






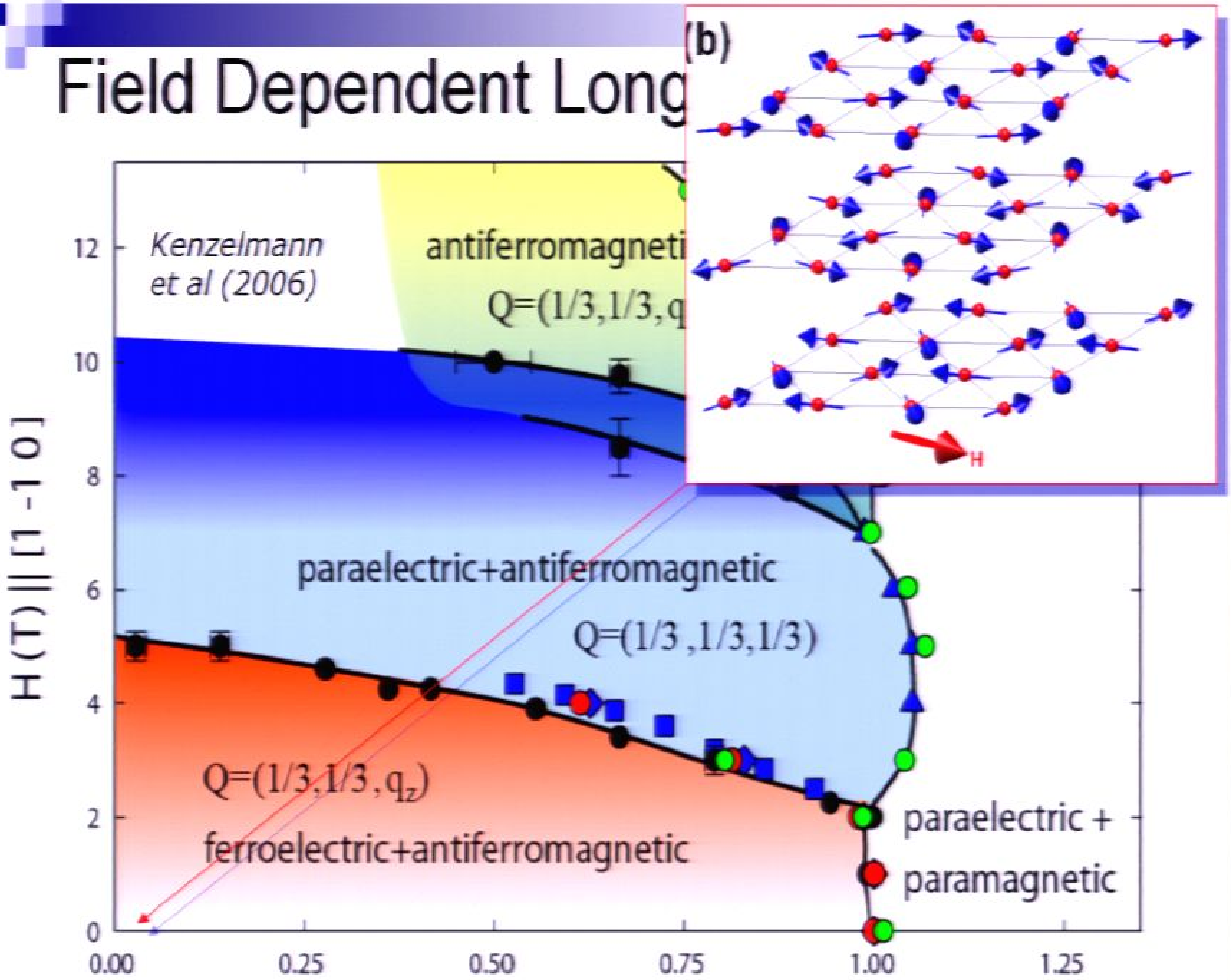
Kenzelmann, Gasparovic et al. (2005)

Field Dependent Long Range Order



Kenzelmann et al (2006)

Field Dependent Long



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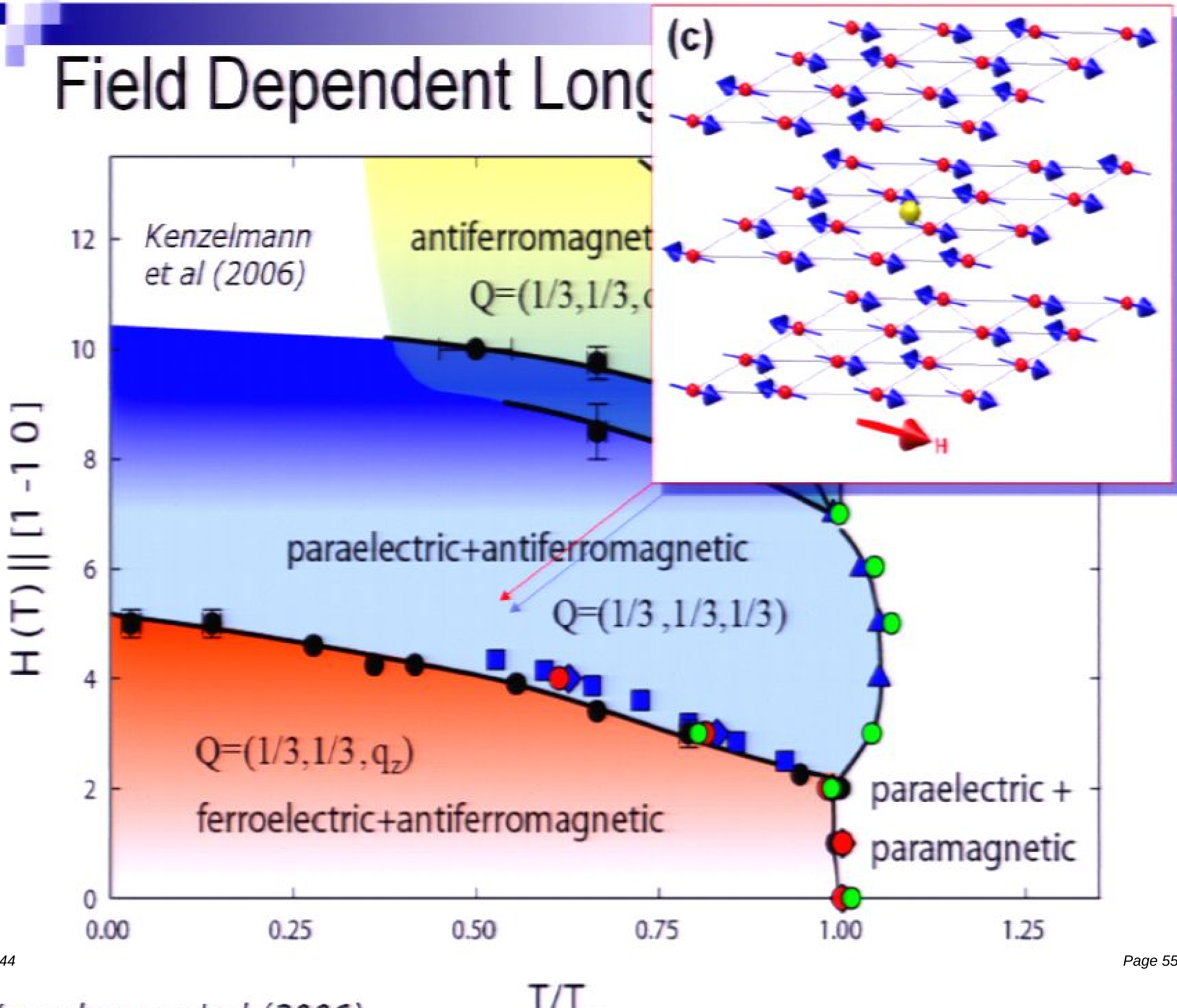
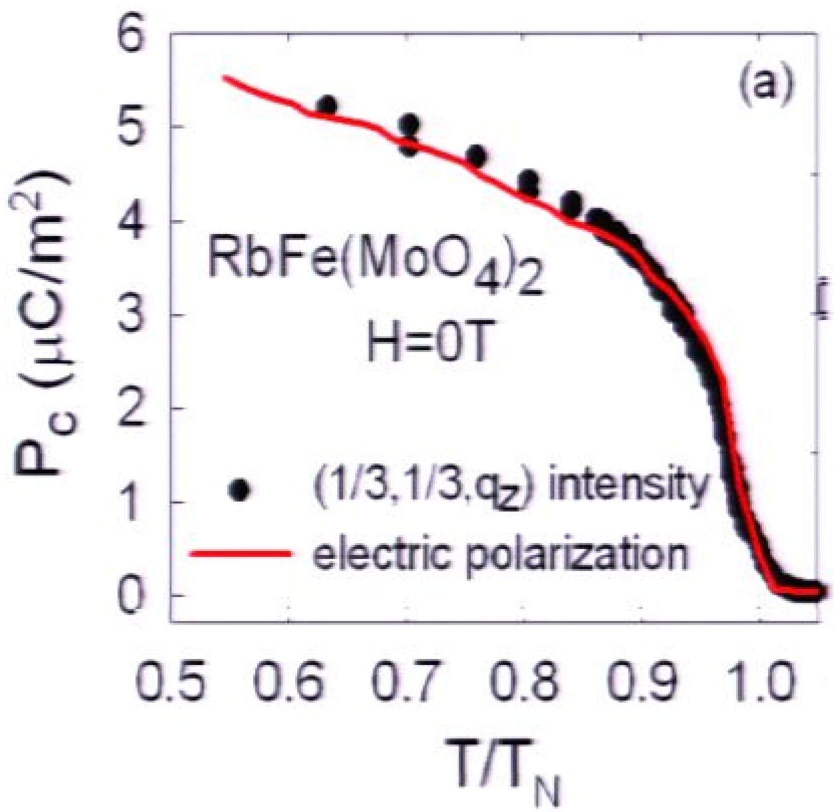
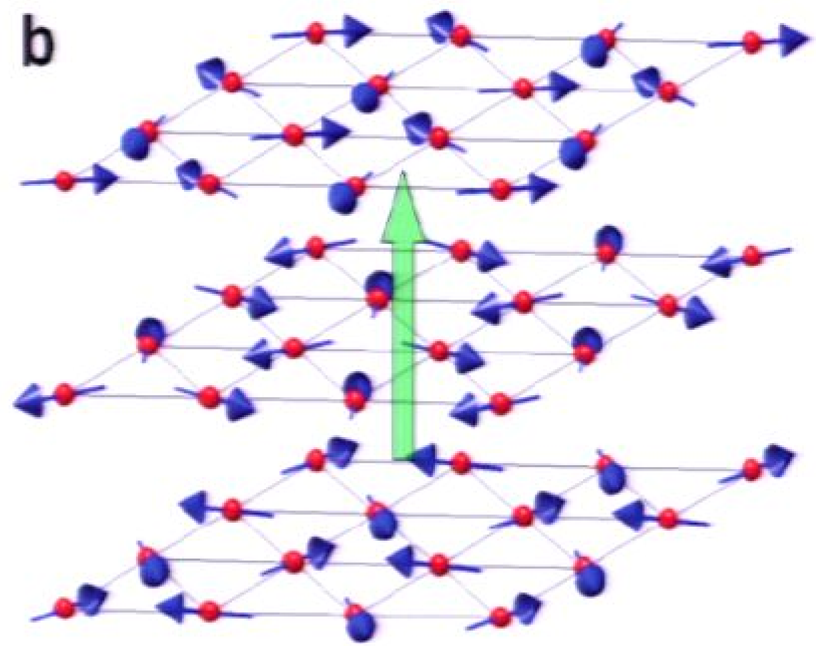


$RbFe(MoO_4)_2$: Breaking the mold





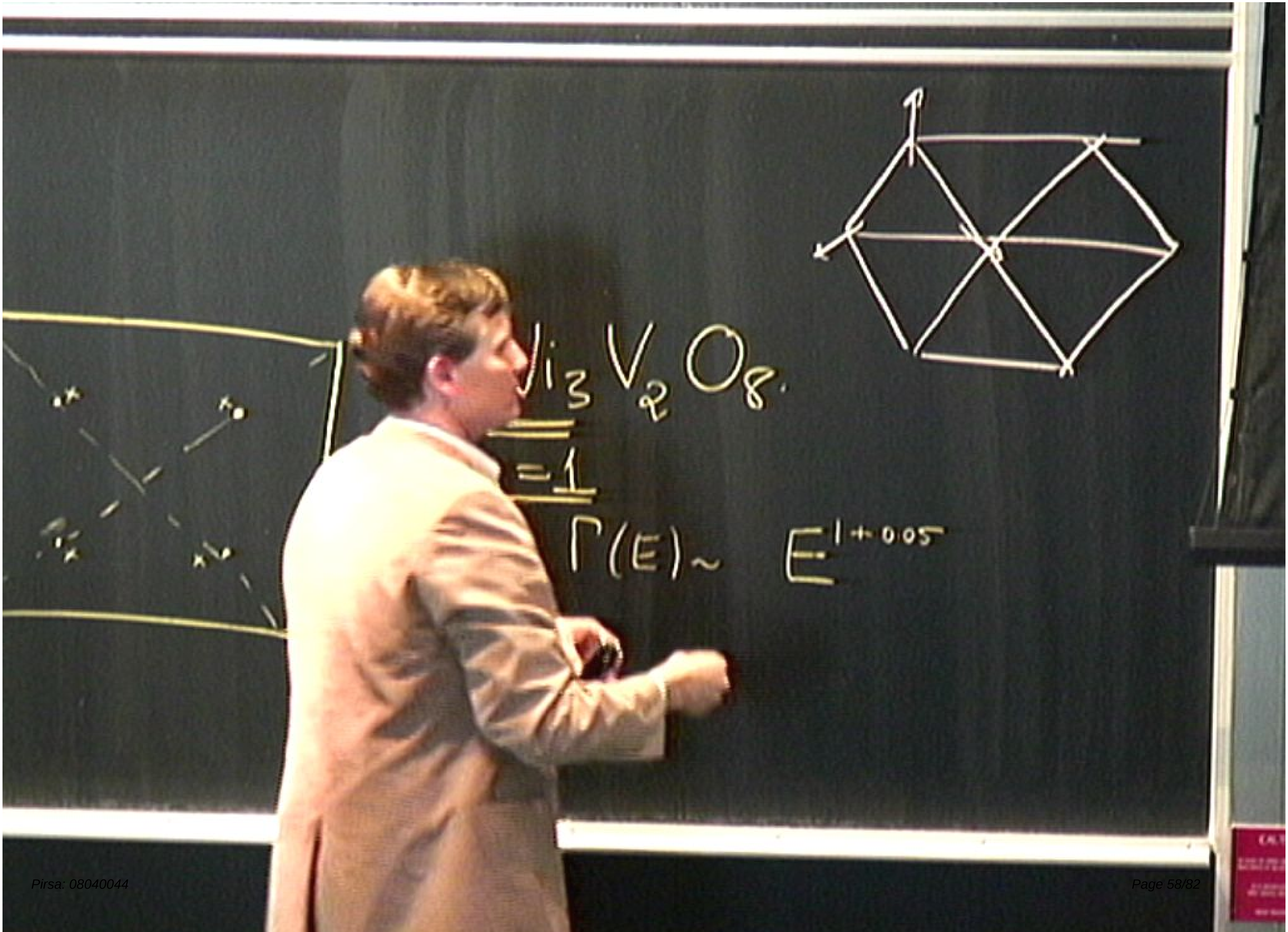
- Direct transition to magneto-electric state
- Polarization perpendicular to spin plane $\mathbf{P} \neq \gamma \mathbf{e}_{ij} \times (\mathbf{S}_i \times \mathbf{S}_j)$
- Incommensurability irrelevant

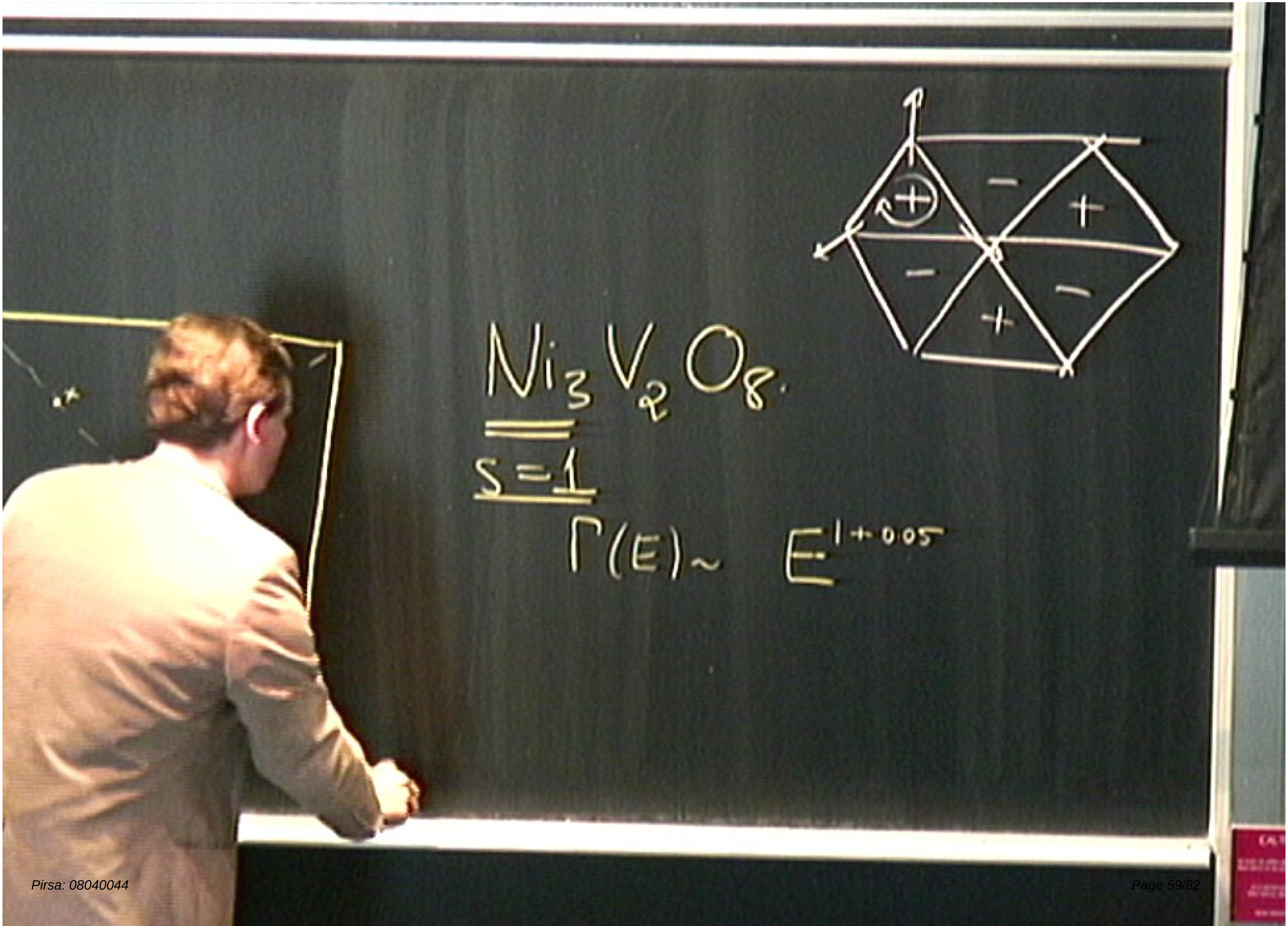
Landau theory for $RbFe(MoO_4)_2$

Spin structure expressed in terms of complex order parameters $\sigma^{(i)}$

$$\mathbf{S}(\mathbf{r}) = \left[\sigma^{(1)}(\mathbf{X}_1 + q_z\hat{\mathbf{z}})(\hat{\mathbf{x}} - i\hat{\mathbf{y}}) + \sigma^{(2)}(\mathbf{X}_1 + q_z\hat{\mathbf{z}})(\hat{\mathbf{x}} + i\hat{\mathbf{y}})\right]\exp(i(\mathbf{X}_1 + q_z\hat{\mathbf{z}})) + c.c.$$

Kenzelmann et al (2006)


i3 V2 O8.
=1
Γ(E) ~ E^{1+0.05}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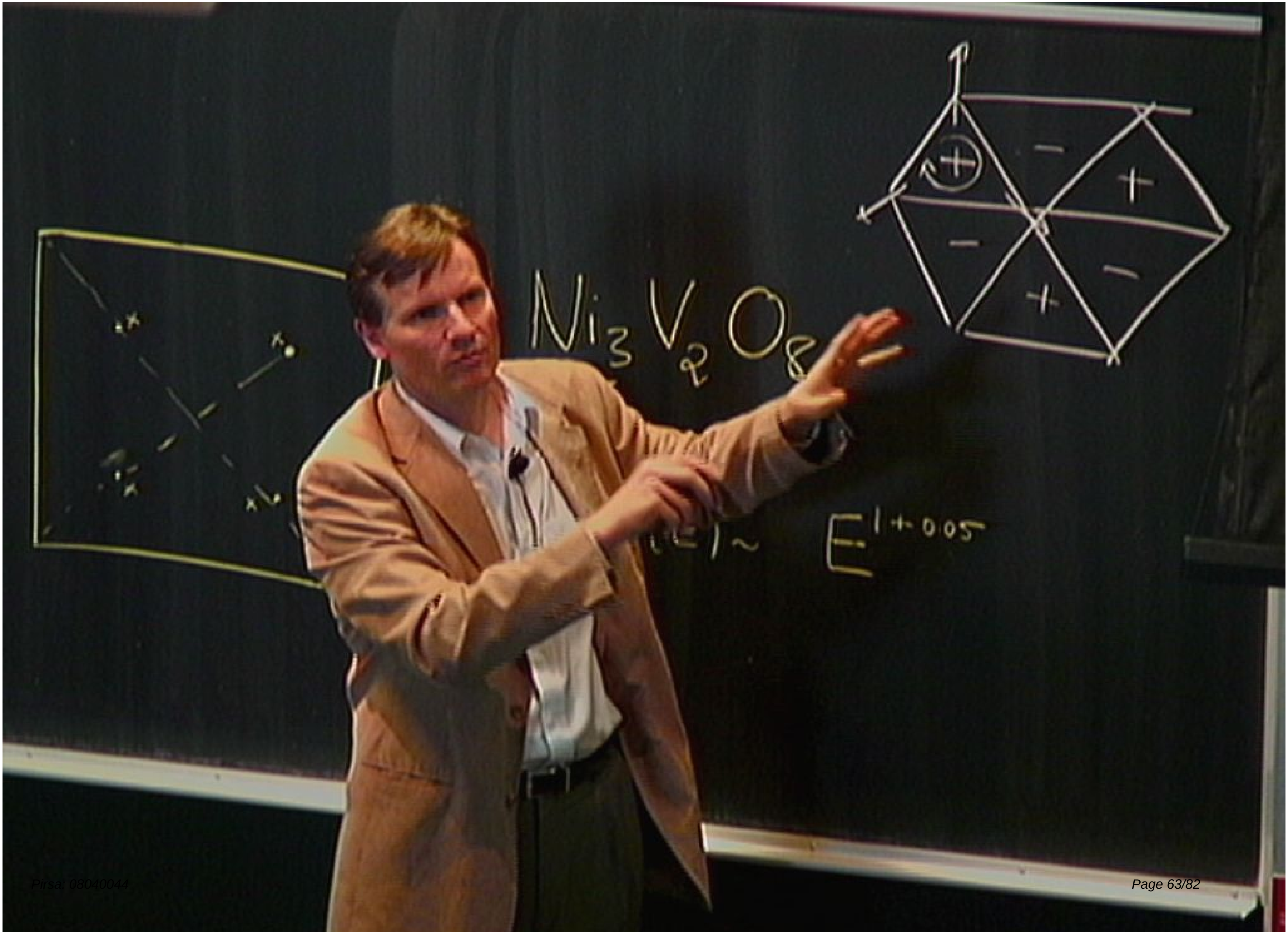
Free energy at quadratic order:

$$F = \tfrac{1}{2}\alpha(T - T_C)\left(\left|\sigma^{(1)}(\mathbf{q}_m)\right|^2 + \left|\sigma^{(2)}(\mathbf{q}_m)\right|^2\right) + \mathcal{O}(\sigma^4)$$ *Magnetic free energy*

$$+ \tfrac{1}{2}\chi^{-1}|P|^2 + \mathbf{E}\cdot\mathbf{P}$$ *Dielectric free energy*

$$+ K\left(\left|\sigma^{(1)}(\mathbf{q}_m)\right|^2 - \left|\sigma^{(2)}(\mathbf{q}_m)\right|^2\right)P_z$$ *Symmetry allowed Tri-linear interaction*

Kenzelmann et al (2006)


Ni3V2O8
E1+0.05

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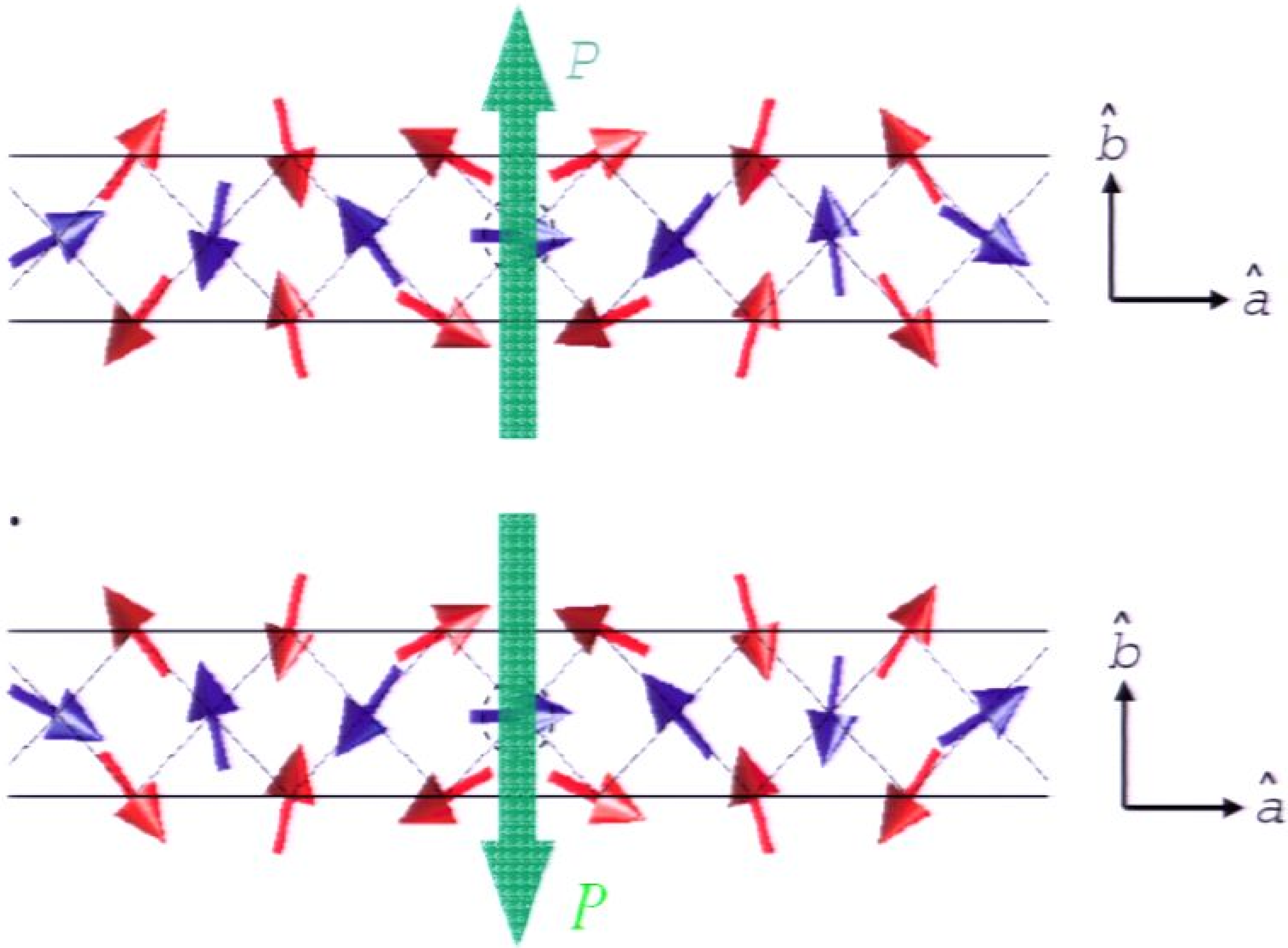
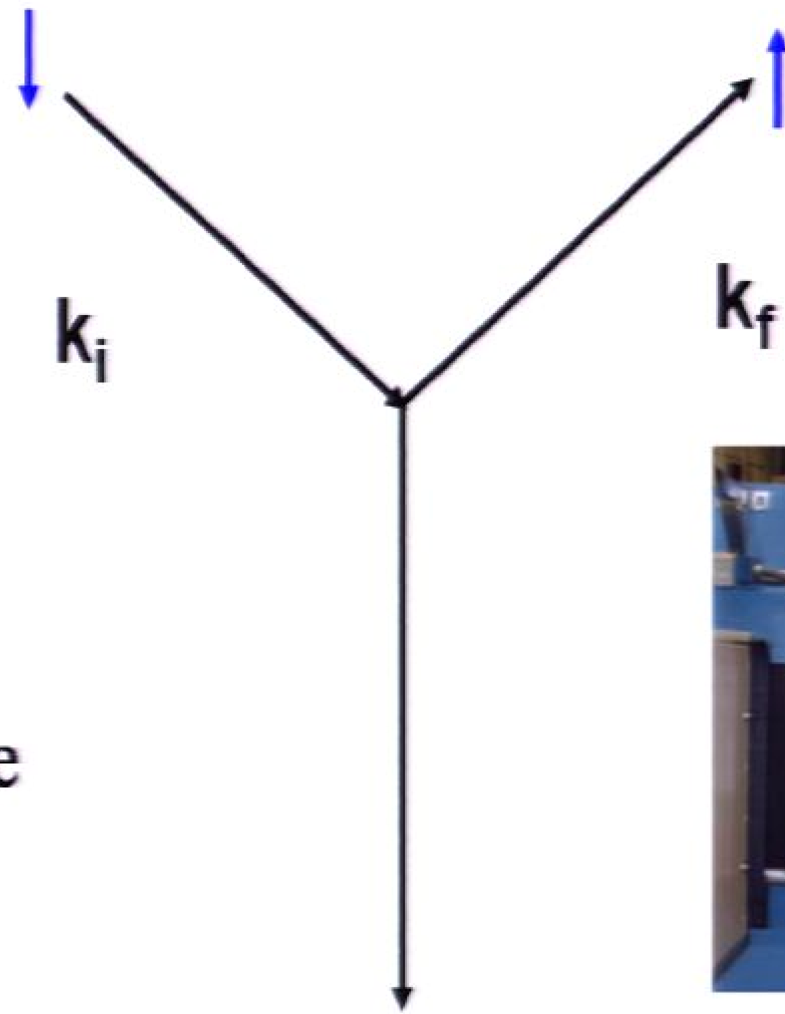
Hypothesis: Chiral FE domains



Detecting chiral domains in $Ni_3V_2O_8$



Q=(1.27,1,1)

<u>No effect if:</u>

$\mathbf{S}_n \perp \mathbf{P}_e$

$\mathbf{Q} \parallel$ spin plane

$\mathbf{S}_n \perp \mathbf{q}_m$

Polarized ^{3}He →

Polarized neutrons

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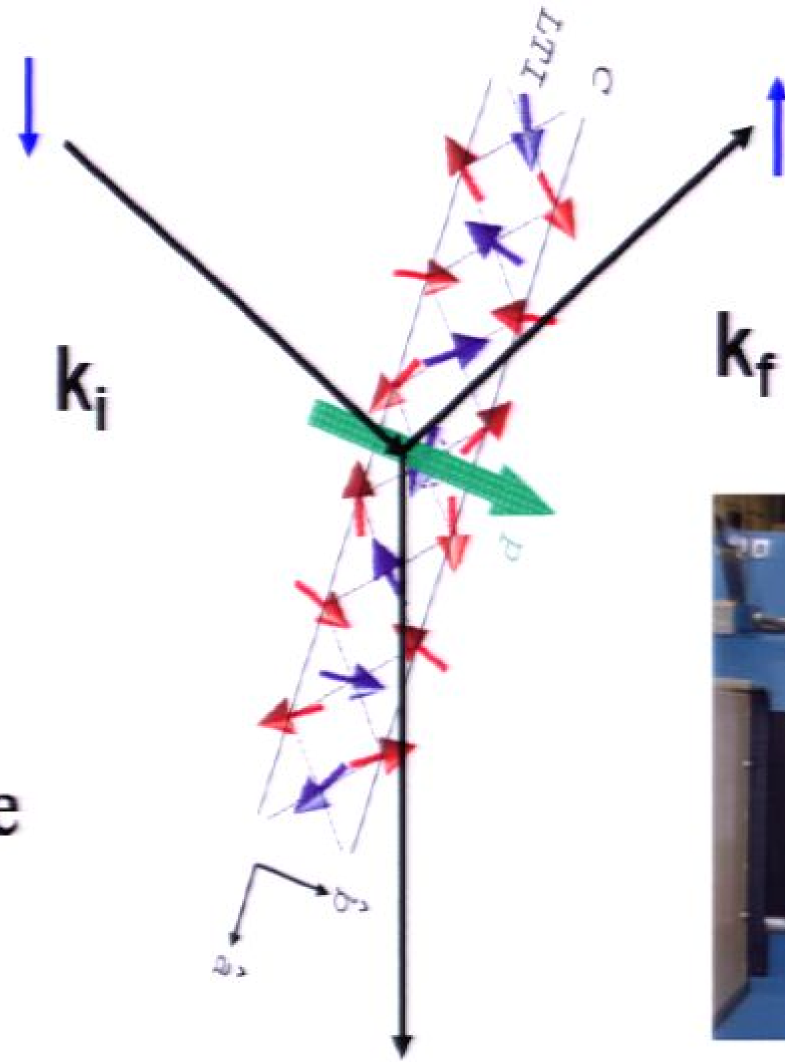

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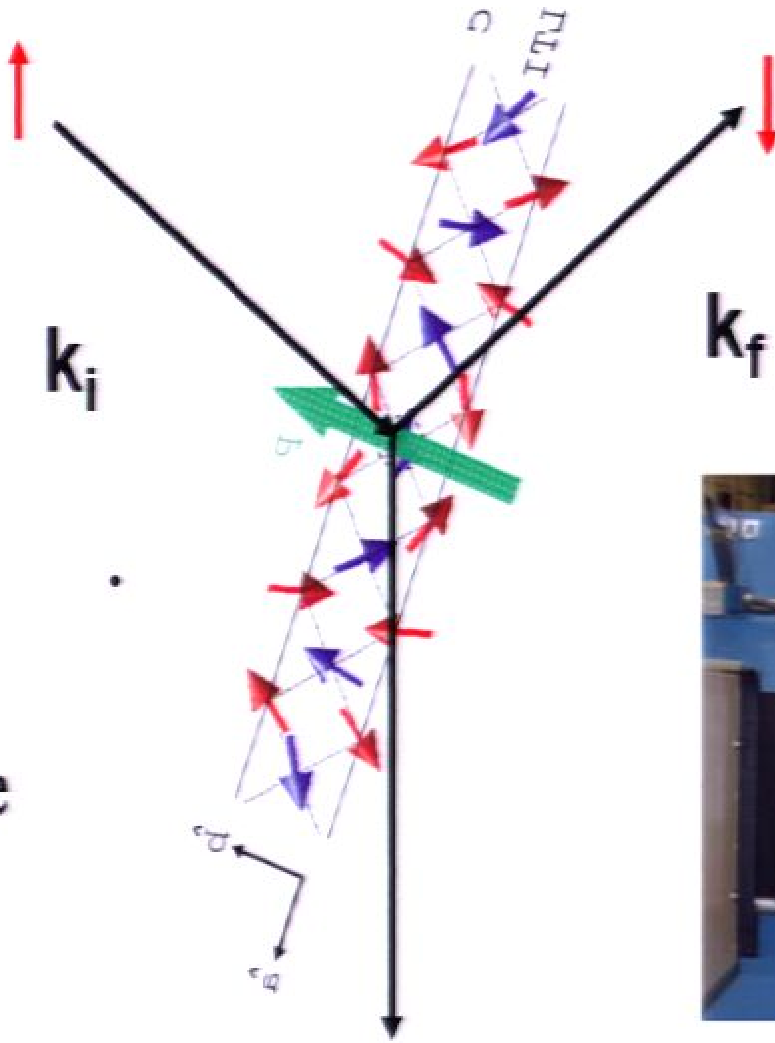

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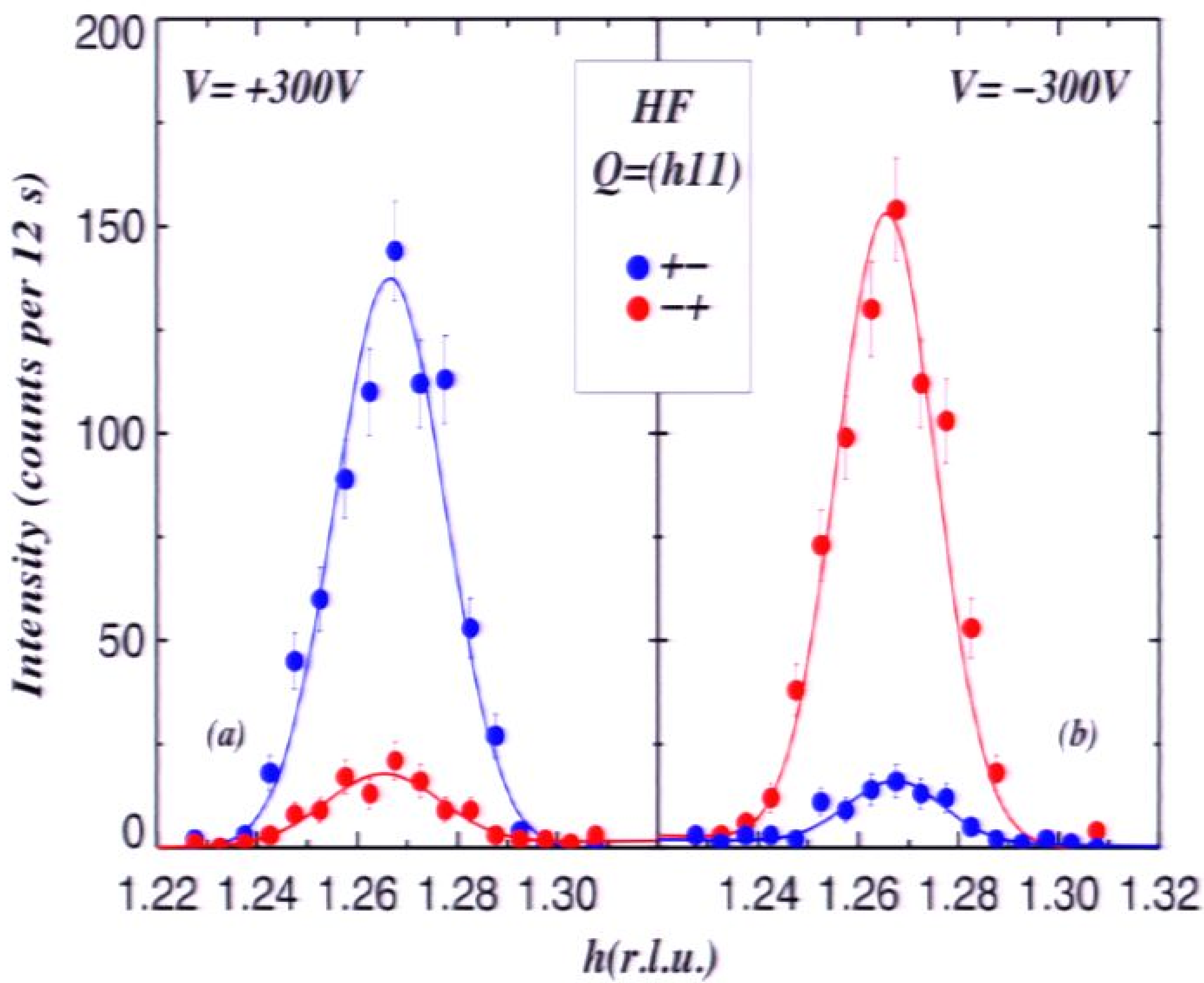
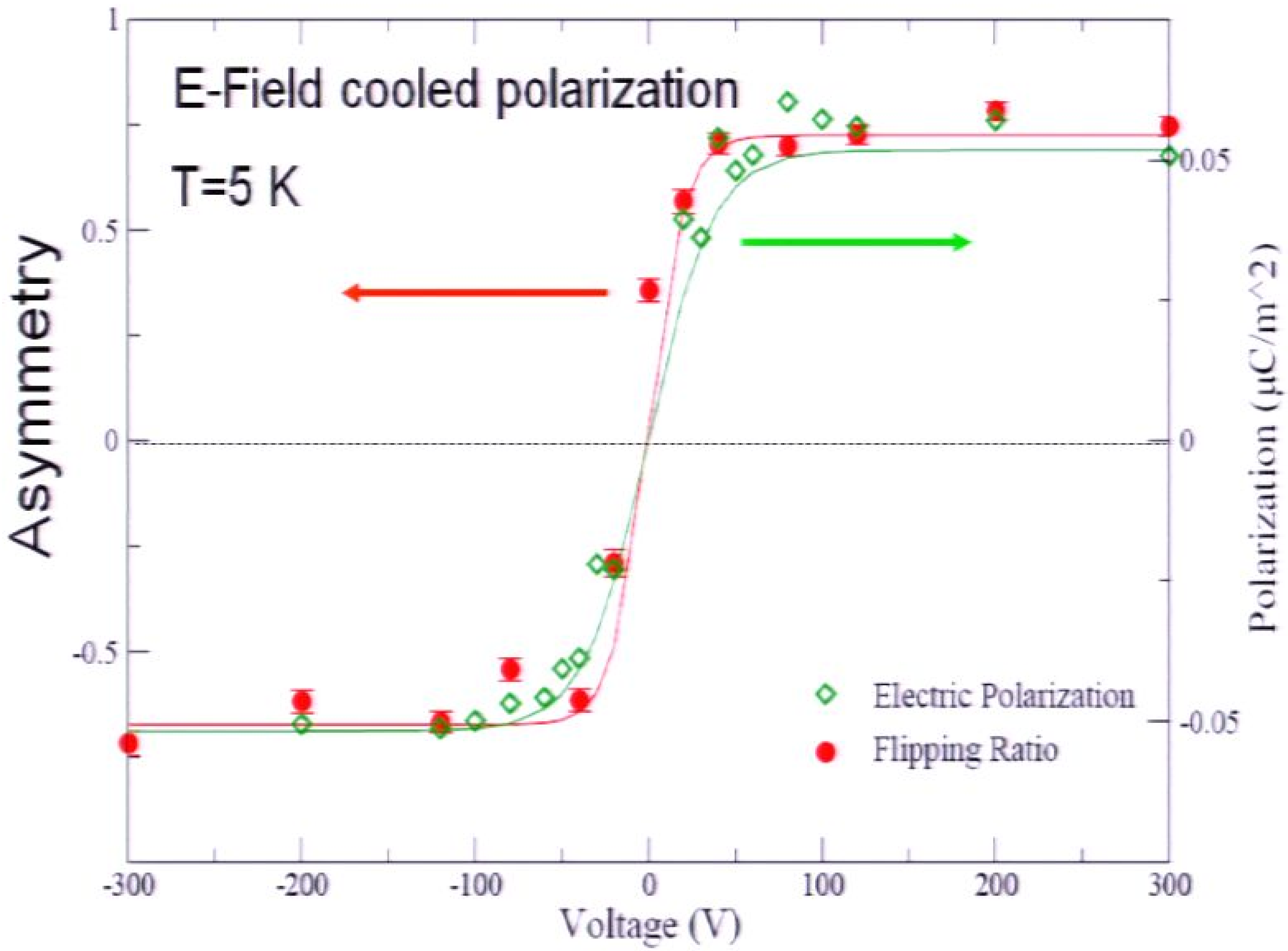
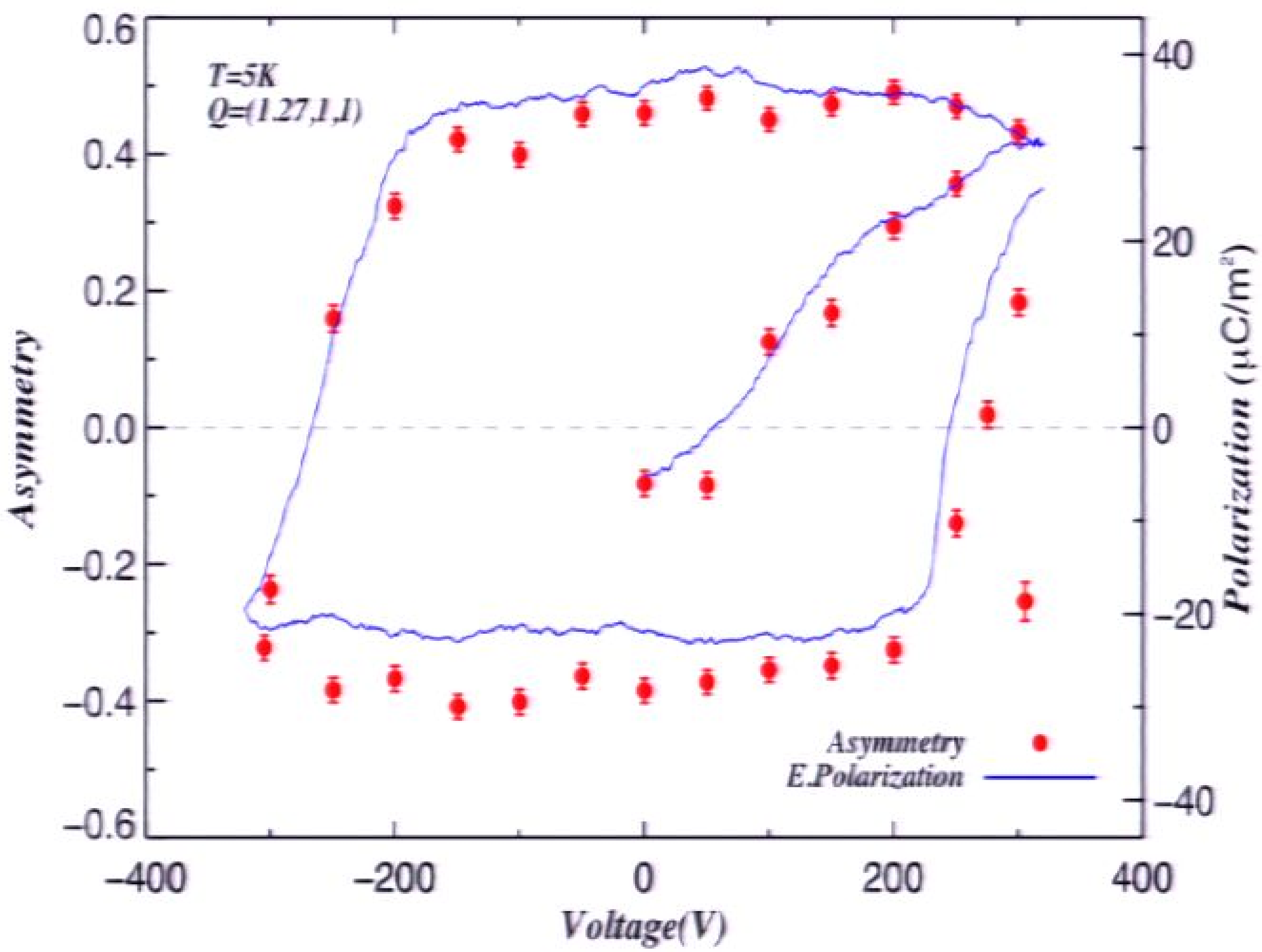
Chirality and polarization in $Ni_3V_2O_8$



Ferroelectric & Chiral domains



Chirality hysteresis in FE state



Conclusions

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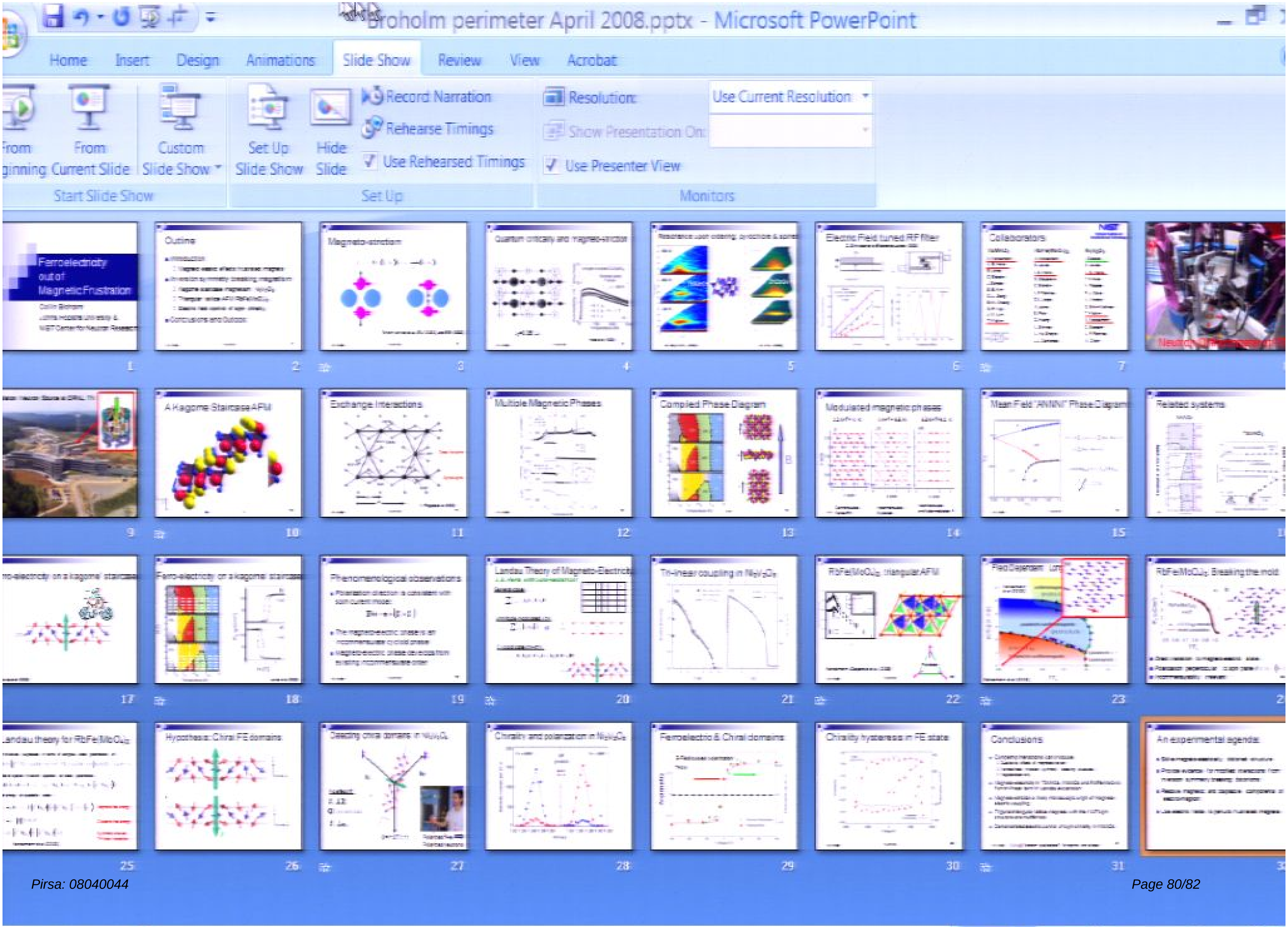
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Start Slide Show
Set Up Slide Show
Hide Slide
Record Narration
Rehearse Timings
Use Rehearsed Timings
Set Up
Resolution:
Use Current Resolution
Show Presentation On:
Use Presenter View
Monitors
Ferroelectricity out of Magnetic Frustration
Outline
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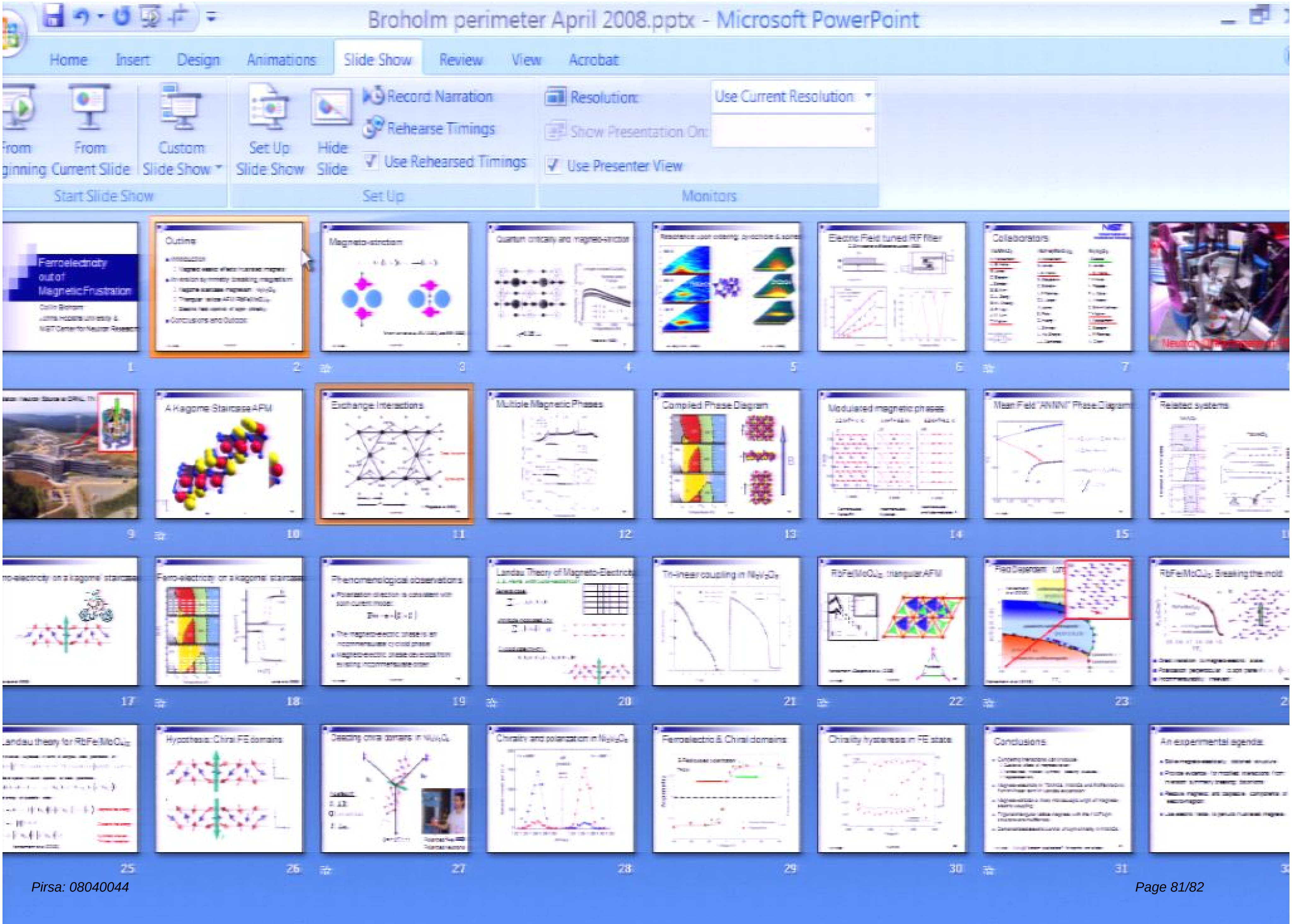
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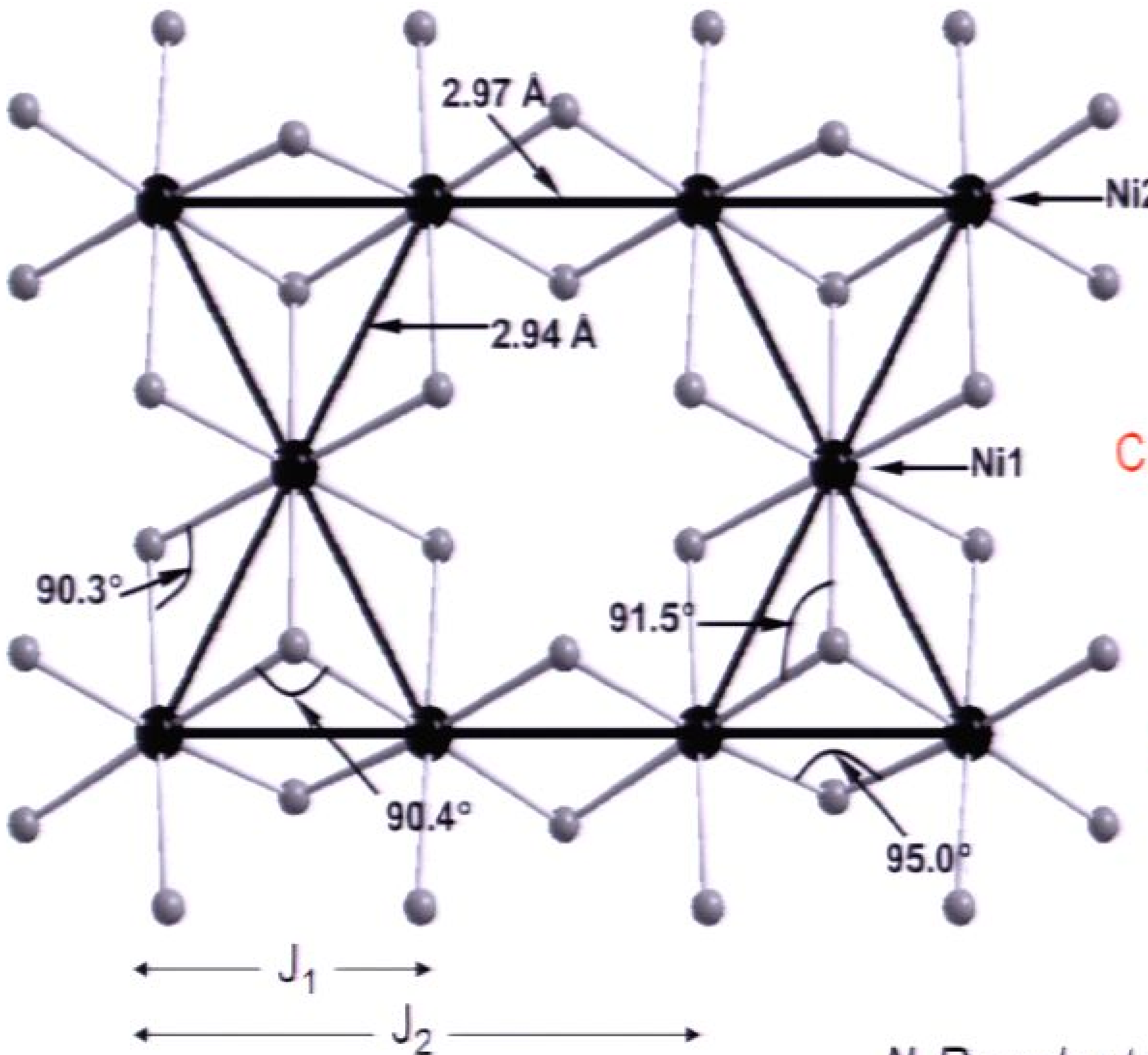
Exchange Interactions



Cross tie spins

Spine spins

N. Rogado et al (2003)