Dynamic magnetoelectric coupling in Mott insulators

Maxim Mostovoy

University of Groningen
Zernike Institute for Advanced Materials

Modern Trends in Magnetism
Grenoble
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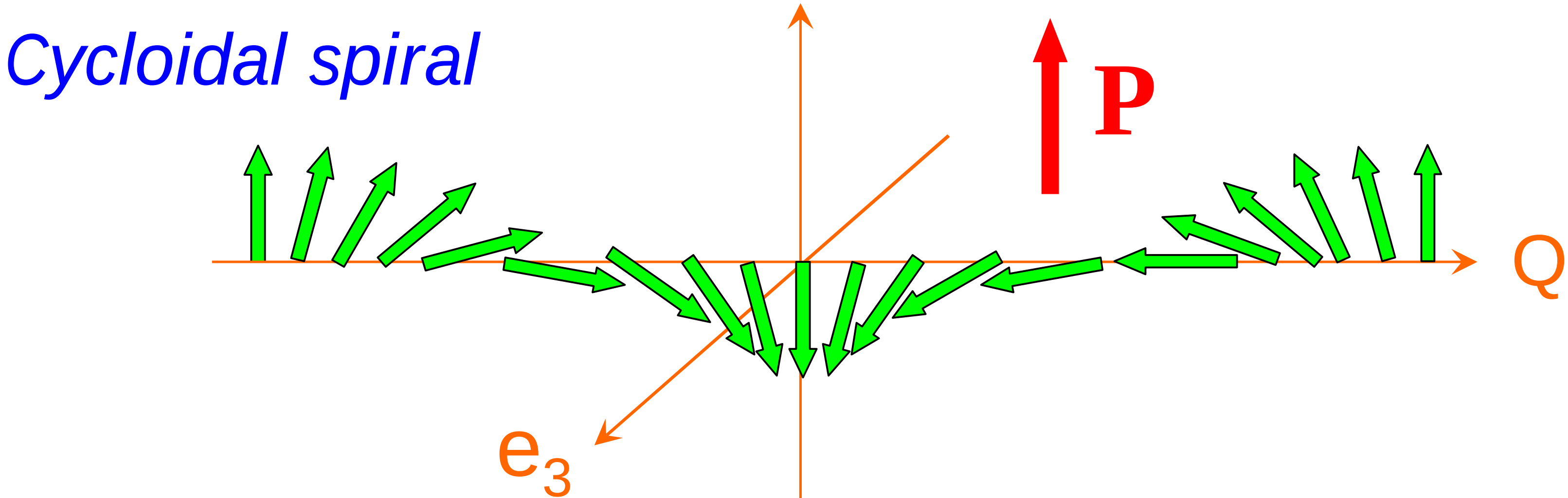
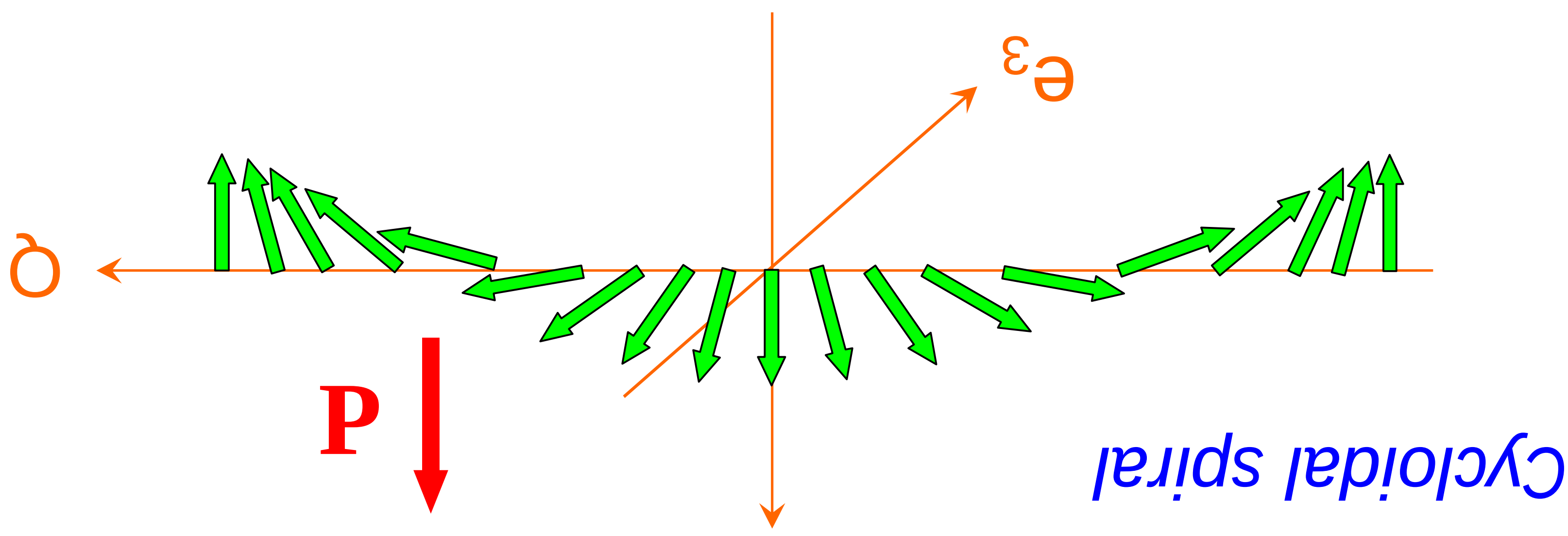
Outline

- **Dynamic magnetoelectric coupling**
- **Solitonic array and Yukawa forces in $TbFeO_3$**

Breaking of inversion symmetry by spin ordering



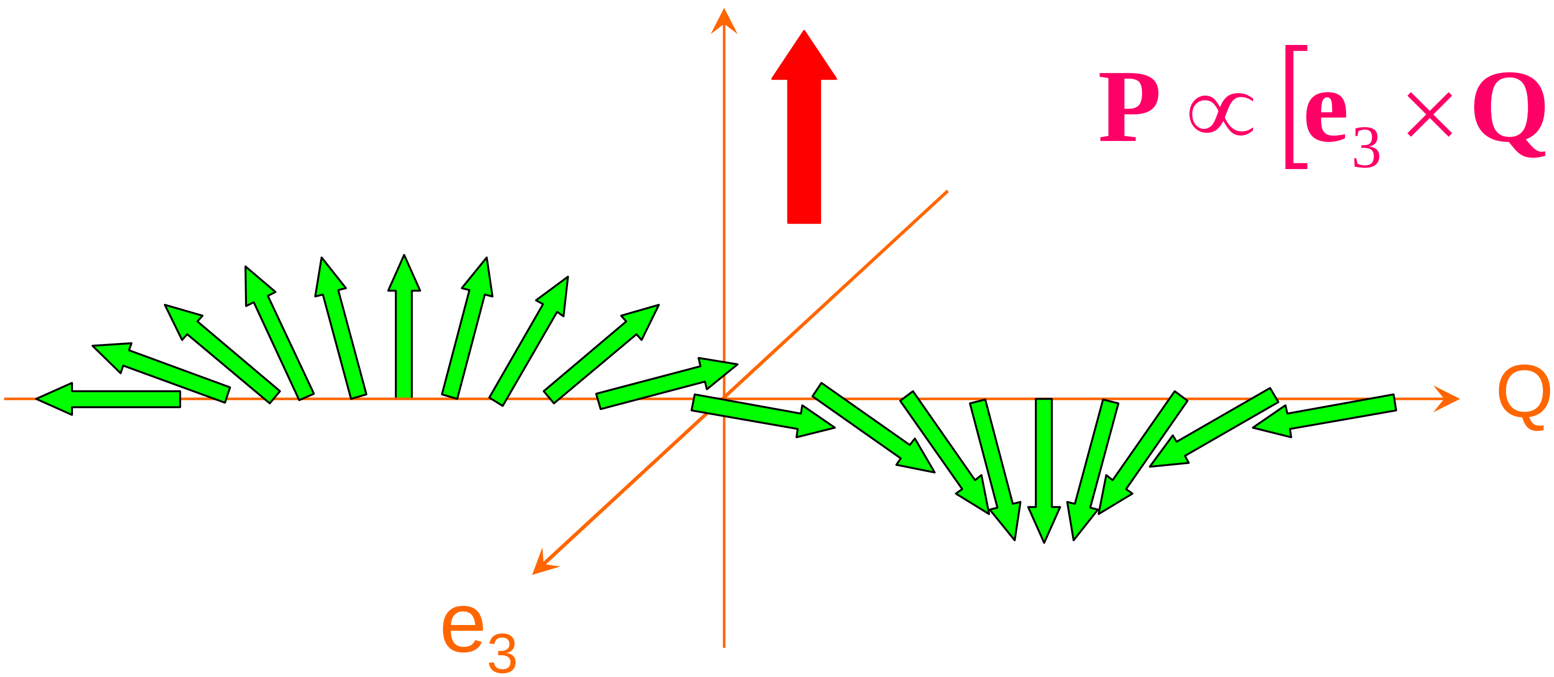
Inversion I: $(x,y,z) \longrightarrow (-x,-y,-z)$



Induced Polarization

H. Katsura et al PRL (2005), Sergienko & Dagotto PRB (2006), M.M. PRL (2006)

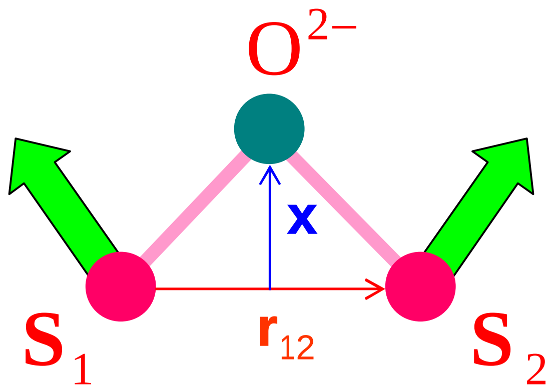
$$P_y\left(M_x\partial_x M_y - M_y\partial_x M_x\right)$$



$$\mathbf{P} \propto \left[\mathbf{e}_3 \times \mathbf{Q}\right]$$

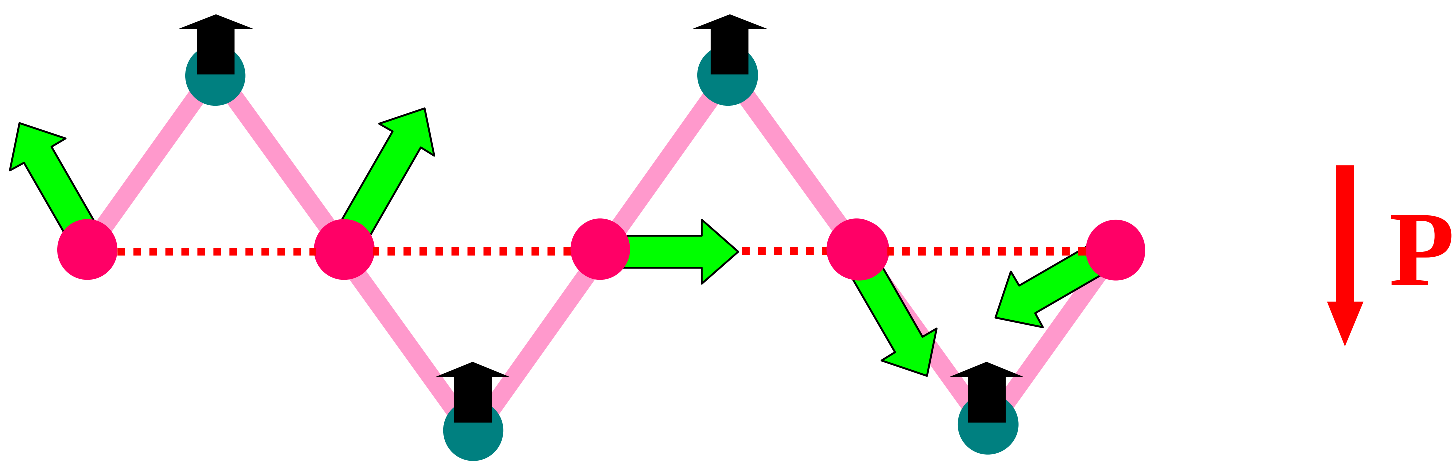
I. Dzyaloshinskii, Theory of helical structures in antiferromagnets, Sov. Phys. JETP ***19****, 960-971 (1964)*

Inverse Dzyaloshinskii-Moriya mechanism



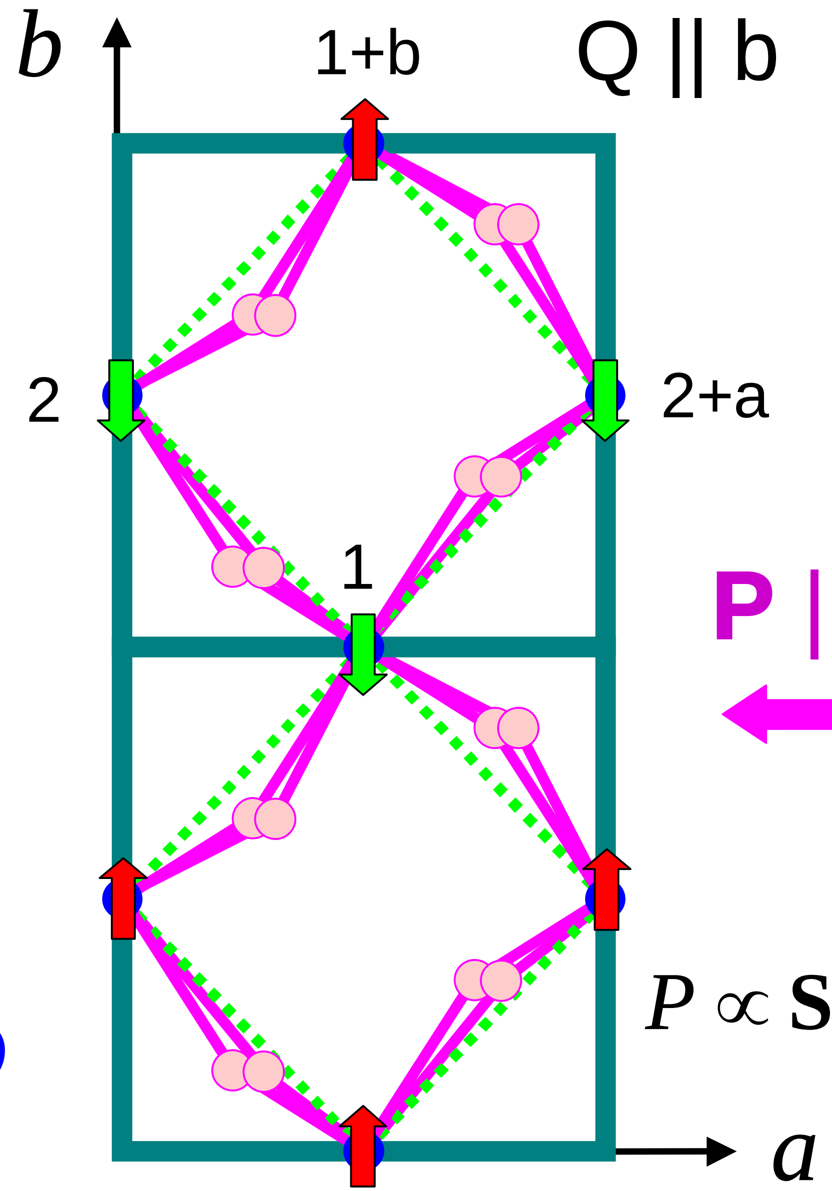
$$E_{DM} = \mathbf{D}_{12} \cdot [\mathbf{S}_1 \times \mathbf{S}_2]$$

$$\mathbf{D}_{12} \propto \lambda\, \mathbf{x} \times \hat{\mathbf{r}}_{12}$$



P induced by Heisenberg exchange

RMnO$_3$



P || a

$$P \propto \mathbf{S}_1 \cdot \mathbf{S}_2 - \mathbf{S}_2 \cdot \mathbf{S}_{1+b}$$

Lorenz et al (2004)

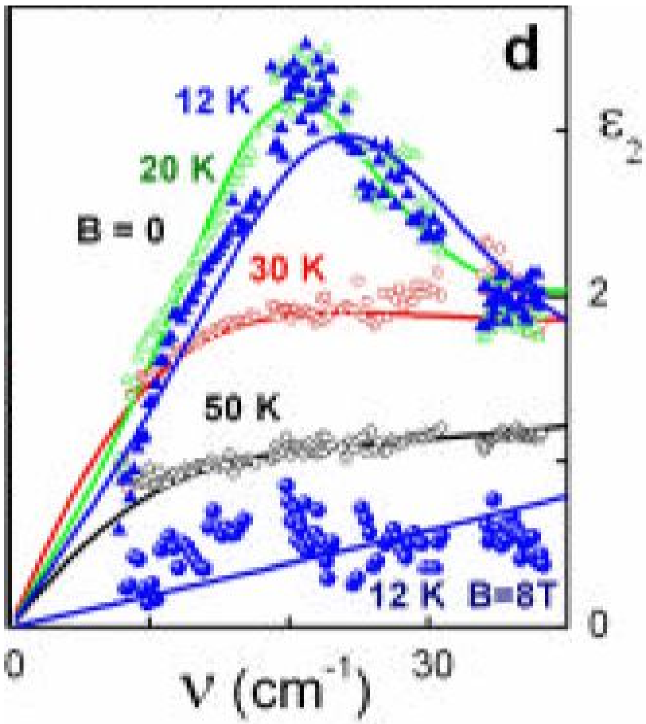
Sergienko et al (2006)

Electromagnons

magnons excited by the electric field of light wave

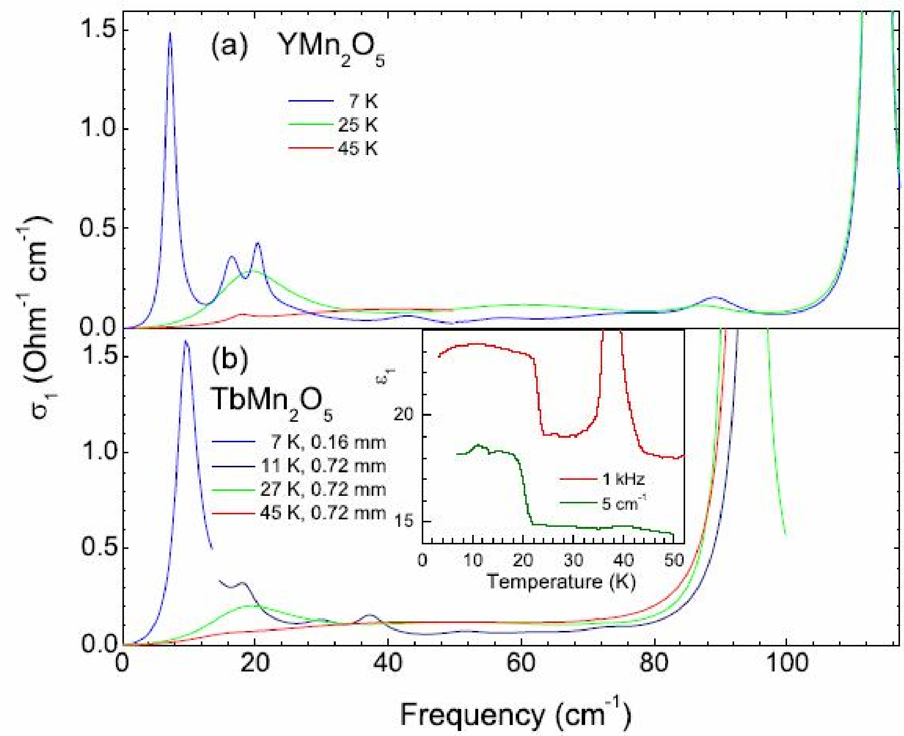
Electromagnons in spiral multiferroics

$TbMnO_3$

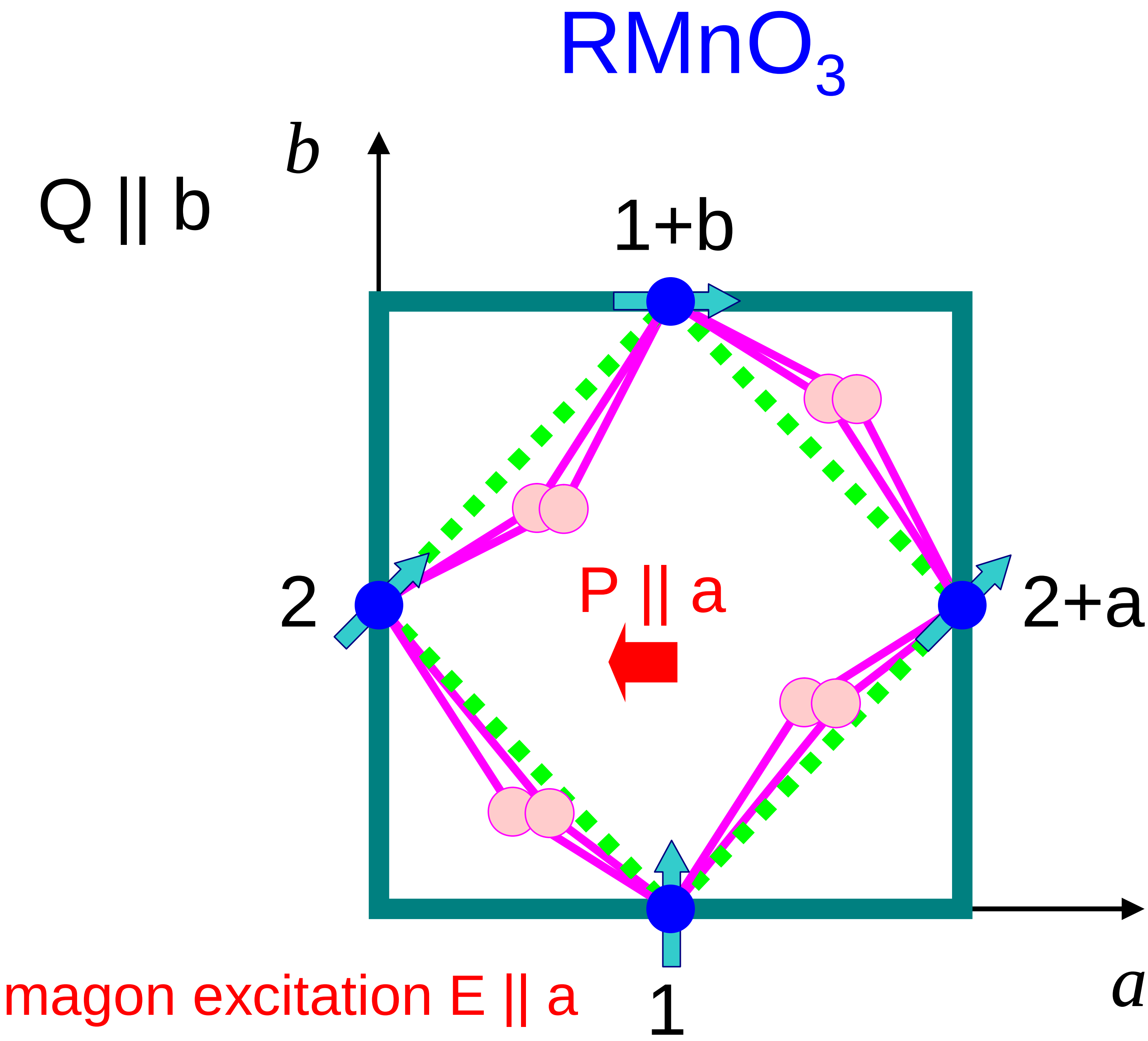


A. Pimenov et al
Nature Mat. (2006)

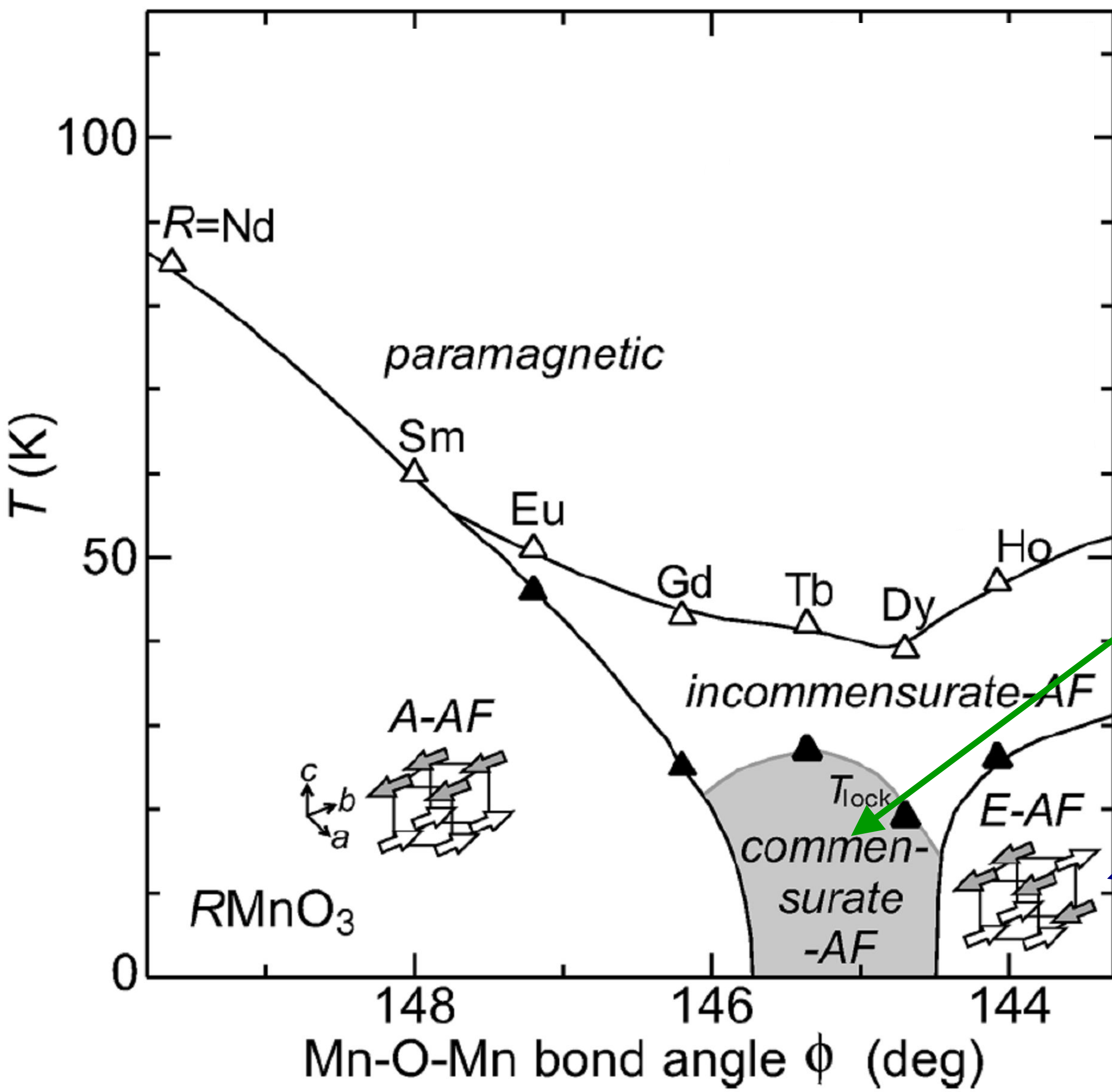
YMn_2O_5 & $TbMn_2O_5$



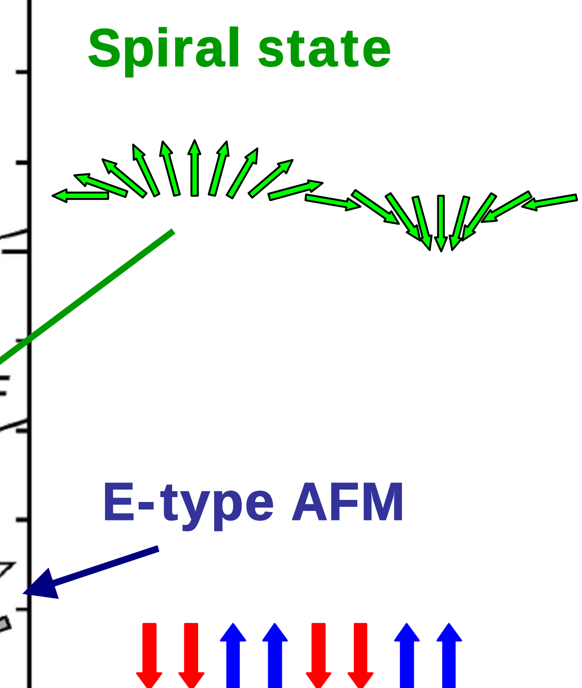
A.B. Sushkov et al (2006)


RMnO3
Q || b
b
1+b
2
P || a
2+a
1
a
magon excitation E || a

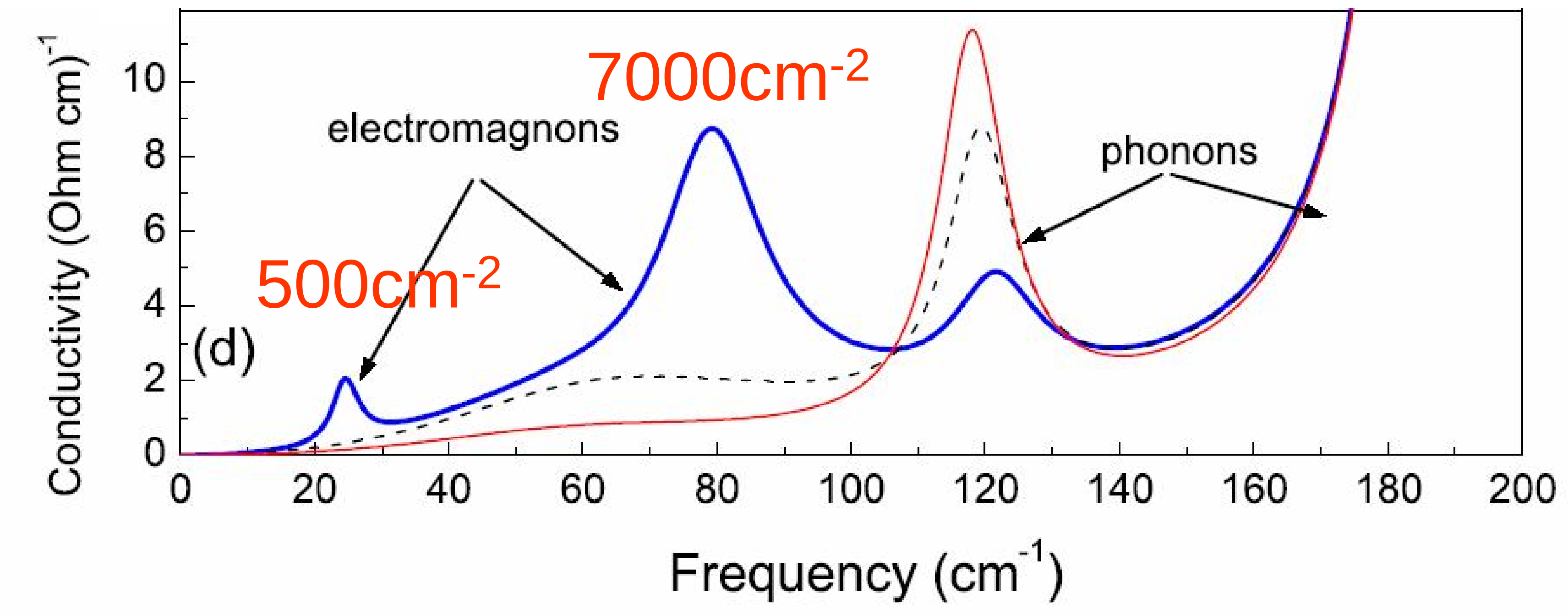
Orthorombic $RMnO_3$



T. Kimura et al
PRB (2003)



$Eu_{1-x}Y_xMnO_3$



From the spectral weight of the giant electromagnon peak S ~ 7000 cm^{-2} **we obtain the polarization in the E-phase** P ~ 1 μC·cm^{-2}

R. Valdés-Aguilar et al, PRL 102 (2009)

Paramagnetism of ferroelectrics

I. E. Dzyaloshinskii & D. E. Mills (2009)

Interaction of magnetic field with the soft ferroelectric mode

$$\mathbf{H} \cdot \left[\mathbf{P} \times \frac{\partial \mathbf{P}}{\partial t} \right]$$

$$H \parallel \langle P_z \rangle \neq 0 \qquad \delta P_x \pm i \delta P_y \propto L_z$$

$$H_{\text{int}} = -\mu H_z L_z$$

Dynamic magnetoelectric coupling

*MM, K. Nomura and N. Nagaosa, PRL **106**, 047204 (2011)*

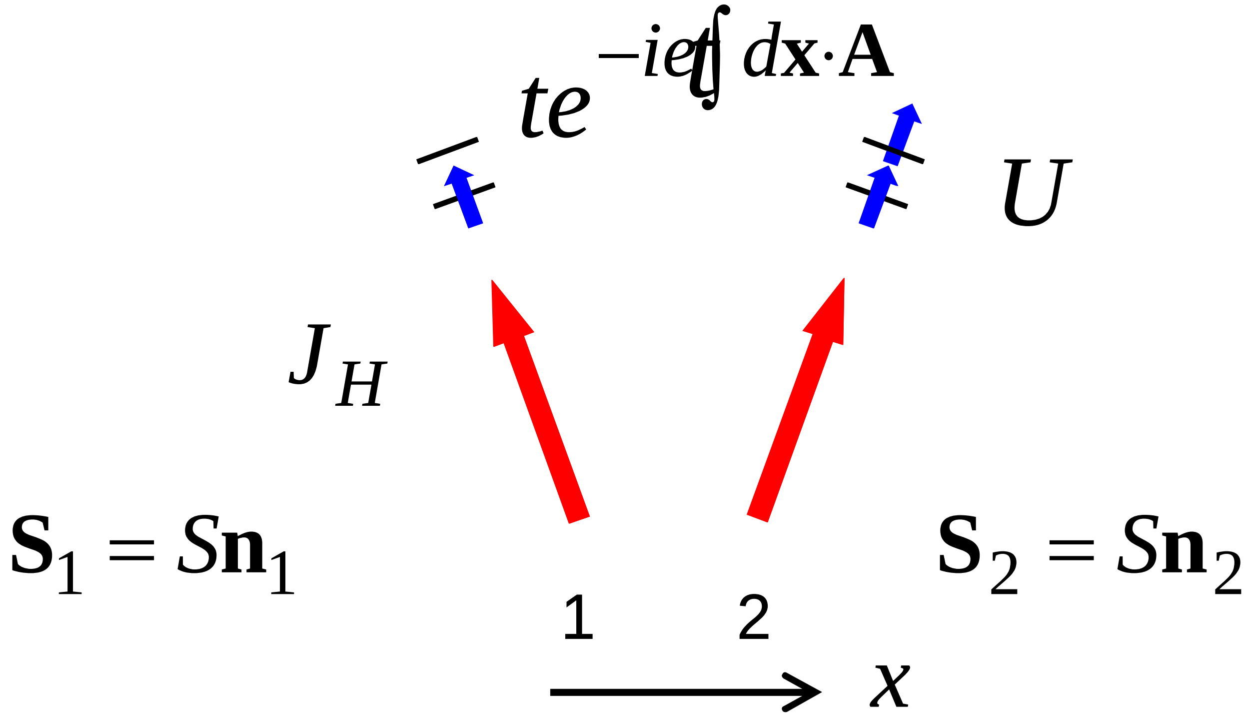
Mechanisms of magnetoelectric coupling

Relativistic IDM mechanism $$\mathbf{P}_{12} \propto \left[\mathbf{r}_{12} \times \left[\mathbf{S}_1 \times \mathbf{S}_2\right]\right]$$

Heisenberg exchange $$\mathbf{P}_{12} = \boldsymbol{\pi}_{12}\left(\mathbf{S}_1 \cdot \mathbf{S}_2\right)$$

Dynamical ME coupling $$\mathbf{P}_{12} \propto \mathbf{r}_{12}\left(\left[\mathbf{S}_1 \times \mathbf{S}_2\right] \cdot \left(\dot{\mathbf{S}}_1 + \dot{\mathbf{S}}_2\right)\right)$$

Exchange in multi-orbital Mott insulator



Dynamical ME coupling

$$\varepsilon[\mathbf{n}_1 \times \mathbf{n}_2] \cdot (\dot{\mathbf{n}}_1 + \dot{\mathbf{n}}_2)$$

$$\varepsilon = \left(\frac{t}{U}\right)^2 \frac{eaE_x}{U}$$

Continuum limit

$$E_i \left(\mathbf{n} \cdot \partial_i \mathbf{n} \times \partial_t \mathbf{n} \right) \propto \mathbf{E} \cdot \mathbf{e}$$

Internal electric field

Adiabatic motion

$$i\hbar\frac{\partial\psi}{\partial t} = \left(\frac{\mathbf{p}^2}{2m} - J\boldsymbol{\sigma}\cdot\mathbf{n}\right)\psi \qquad \mathbf{n} = \mathbf{n}(\mathbf{x}, t)$$

Adiabatic projection

$$\psi = \chi|\mathbf{n}\rangle \qquad \boldsymbol{\sigma}\cdot\mathbf{n}|\mathbf{n}\rangle = |\mathbf{n}\rangle$$

$$i\hbar\frac{\partial\chi}{\partial t} = \left(-ea_0 + \frac{\left(\mathbf{p} + \frac{e}{c}\mathbf{a}\right)^2}{2m} - J\right)\chi$$

Effective gauge potentials (*M. Berry*)

$$\begin{cases} a_0 = -\frac{\hbar}{2e}(1-\cos\theta)\dot{\varphi}, \\ \mathbf{a} = \frac{\hbar c}{2e}(1-\cos\theta)\boldsymbol{\nabla}\varphi \end{cases}$$

Effective gauge fields

$$\begin{cases} e_i &= -\partial_i a_0 - \frac{1}{c}\dot{a}_i = \frac{\hbar}{2e}\left(\mathbf{n}\cdot\partial_i\mathbf{n}\times\dot{\mathbf{n}}\right), \\ h_i &= [\boldsymbol{\nabla}\times\mathbf{a}]_i = \frac{\hbar c}{2e}\delta_{iz}\left(\mathbf{n}\cdot\partial_x\mathbf{n}\times\partial_y\mathbf{n}\right) \end{cases}$$

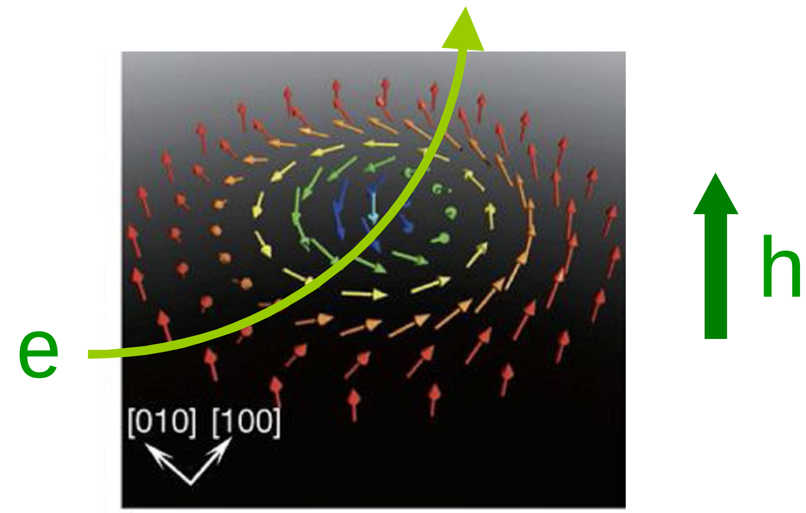
Force on spin-polarized electron

$$\Delta\mathbf{F} = -e\,\mathbf{e} - \frac{e}{c}[\mathbf{v}\times\mathbf{h}]$$

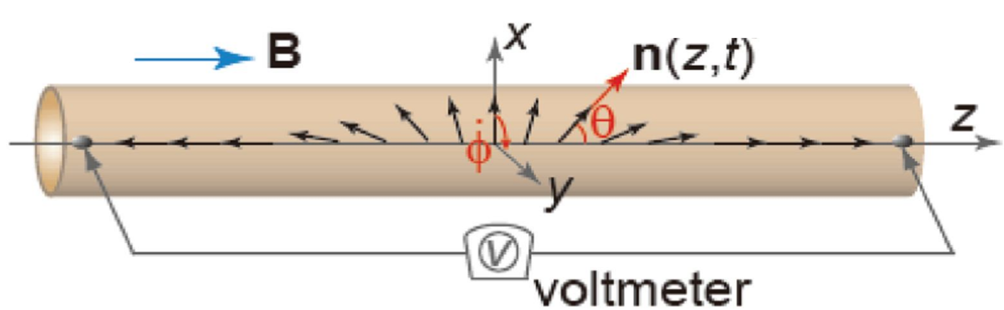
Effects of internal gauge fields

Topological Hall effect

A. Neubauer et. al. PRL (2009)



Spinmotive force: $$\nabla \times \mathbf{e} = -\frac{1}{c}\frac{\partial \mathbf{h}}{\partial t}$$



S. Barnes and S. Maekawa, PRL (2007)

Effects of dynamic coupling

$$L_{\text{int}} = -g\int d^3x\,\mathbf{E}\cdot\mathbf{e}$$

The meaning of **e** in insulators is the electric polarization induced by time-dependent spins

Shift of spin texture in external electric field

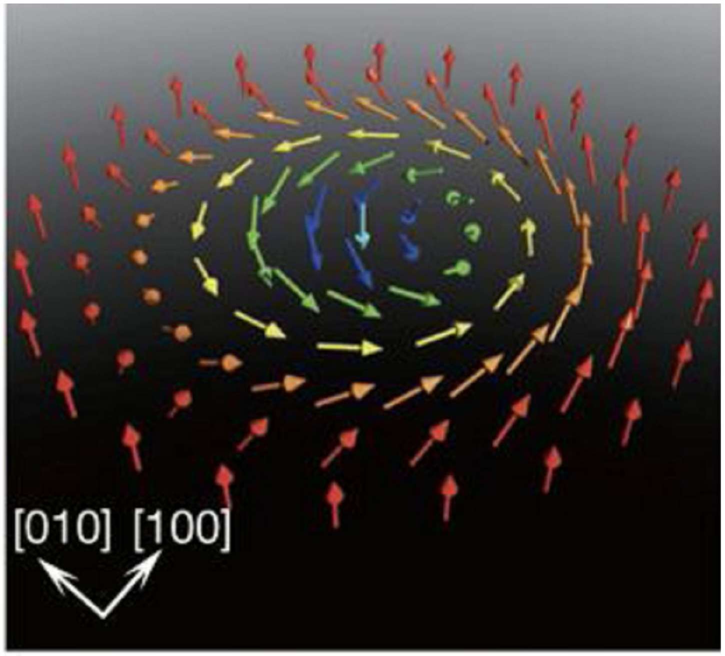
$$\mathbf{n}(\mathbf{x},t) \rightarrow \mathbf{n}\left(\mathbf{x} + \frac{g}{S}\mathbf{E}, t\right)$$

tiny effect

Topological textures

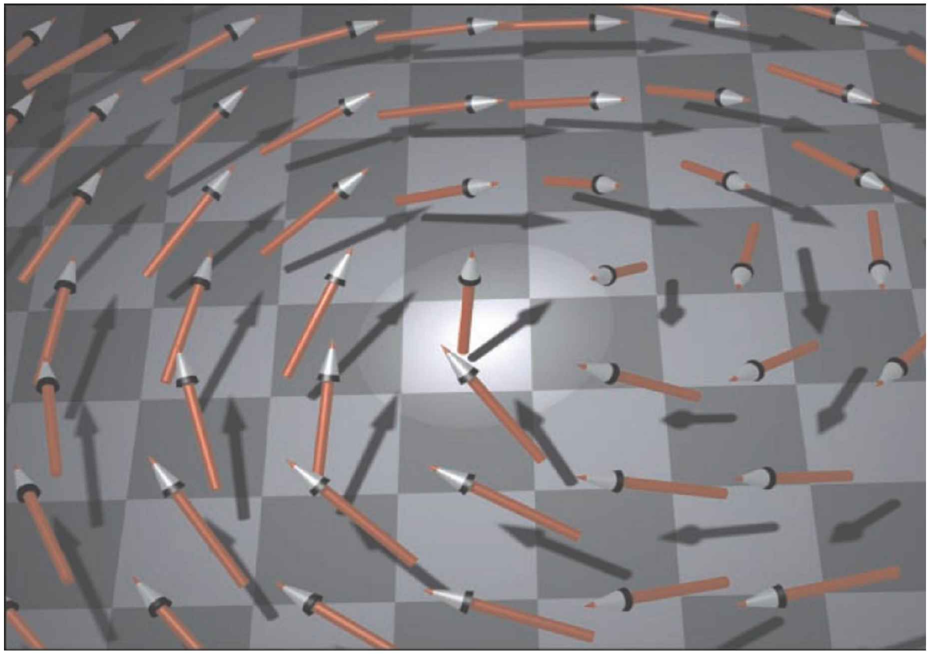
Topological charge: $$Q = \frac{1}{4\pi}\int d^2x\left(\mathbf{n}\cdot\left[\partial_x\mathbf{n}\times\partial_y\mathbf{n}\right]\right)$$

Skyrmion



integer Q

Vortex



half-integer Q

Interaction with topological textures in thin films

Static skyrmion/vortex carries a flux of internal magnetic field

$$\Phi = \int d^2 x h_z = Q\Phi_0 \qquad \Phi_0 = \frac{hc}{e}$$

Moving Skyrmion/vortex induces internal electric field

$$\mathbf{e} = -\frac{1}{c}[\mathbf{V} \times \mathbf{h}]$$

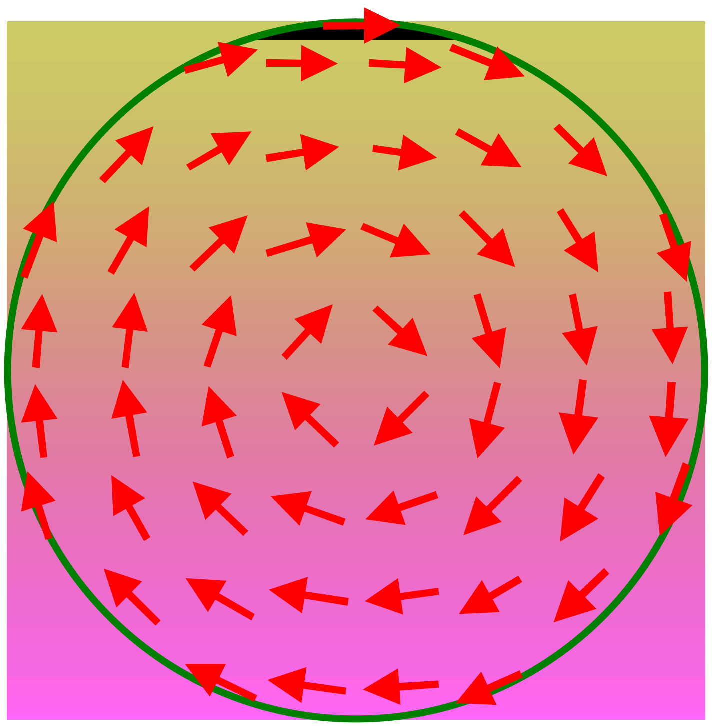
Jiadong Zhang, MM, Yung Hoon Han and Naoto Nagaosa, arXiv: 1102.5384

$$\mathbf{n}(x, y, t) = \mathbf{n}(x - X(t), y - Y(t))$$

$$L_{\text{int}} = -gQ\int d^2 x \left(E_x \dot{Y} - E_y \dot{X}\right)$$

Magnetic vortex in a disk

Lowest-energy model: Rotation of the vortex center



$$\mathbf{R}(t) = R(\cos\Omega t, \sigma \sin\Omega t)$$

Chirality: $\sigma = \pm 1$

Excitation by rotating electric field

$$\mathbf{E}(t) = E(\cos\Omega t, \nu \sin\Omega t)$$

Circular polarization: $\nu = \pm 1$

$$\frac{R}{gE} \approx \begin{cases} 1, & \nu = -\sigma \\ \frac{4\pi}{\alpha}, & \nu = \sigma \end{cases}$$

Gilbert damping → α

Resonant enhancement

Solitonic array and Yukawa force in $TbFeO_3$

http://arxiv.org/abs/1103.4275

Collaborators

Helmholtz Zentrum Berlin
Dimitri Argyriou (ESS)
Duc Le
Andrey Malyuk
Karel Prokes
Vinicus Paula
Heloisa Bordallo
Sven Landsgesell
Hanjo Ryll
Bastian Klemke
Sebastian Paeckel
Klaus Kiefer

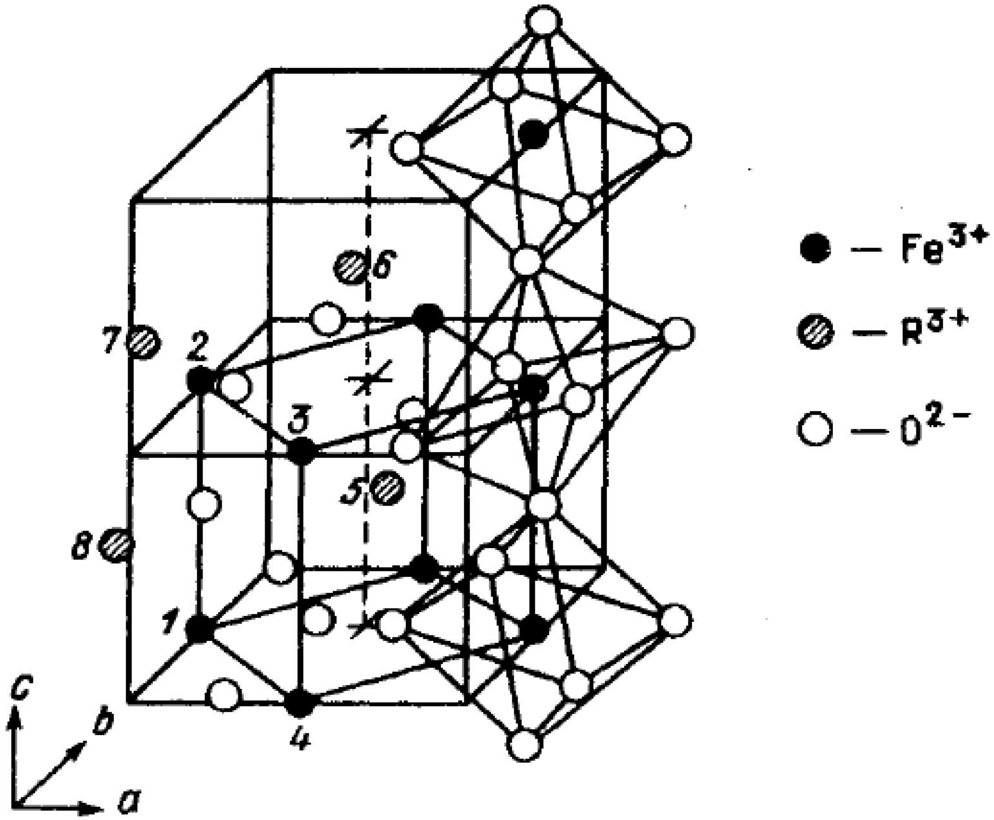
Risø National Lab
Niels Paduraru Jensen
Luise Theil Kuhn

Niels Bohr Institute
Kim Lefmann

University of Groningen
Sergey Artyukhin

Orthoferrites

Fe^{3+} S=5/2



1. T_{Fe} ~ 650K G-type AFM M ~ 0.1 μ_B

2. T_R ~ 10-100K $G_z \rightarrow G_x$ $G_z \rightarrow G_y$

3. T_{RE} < 5K

Representations of *Pbnm*

	Fe	RE	$\tilde{m}_x$	$\tilde{m}_y$	m_z
Γ_1	A_x **G_y** C_z	C'_z	+	+	+
Γ_2	F_x C_y **G_z**	$F'_x C'_y$	+	−	−
Γ_3	C_x F_y A_z	$C'_x F'_y$	−	+	−
Γ_4	**G_x** A_y F_z	F'_z	−	−	+
Γ_5		$G'_x A'_y$	−	−	−
Γ_6		A'_z	−	+	+
Γ_7		G'_z	+	−	+
Γ_8		$A'_x G'_y$	+	+	−

Magnetic orders in $GdFeO_3$

Fe^{3+} S=5/2
T_N = 661K

Γ_4	$G_x A_y F_z$

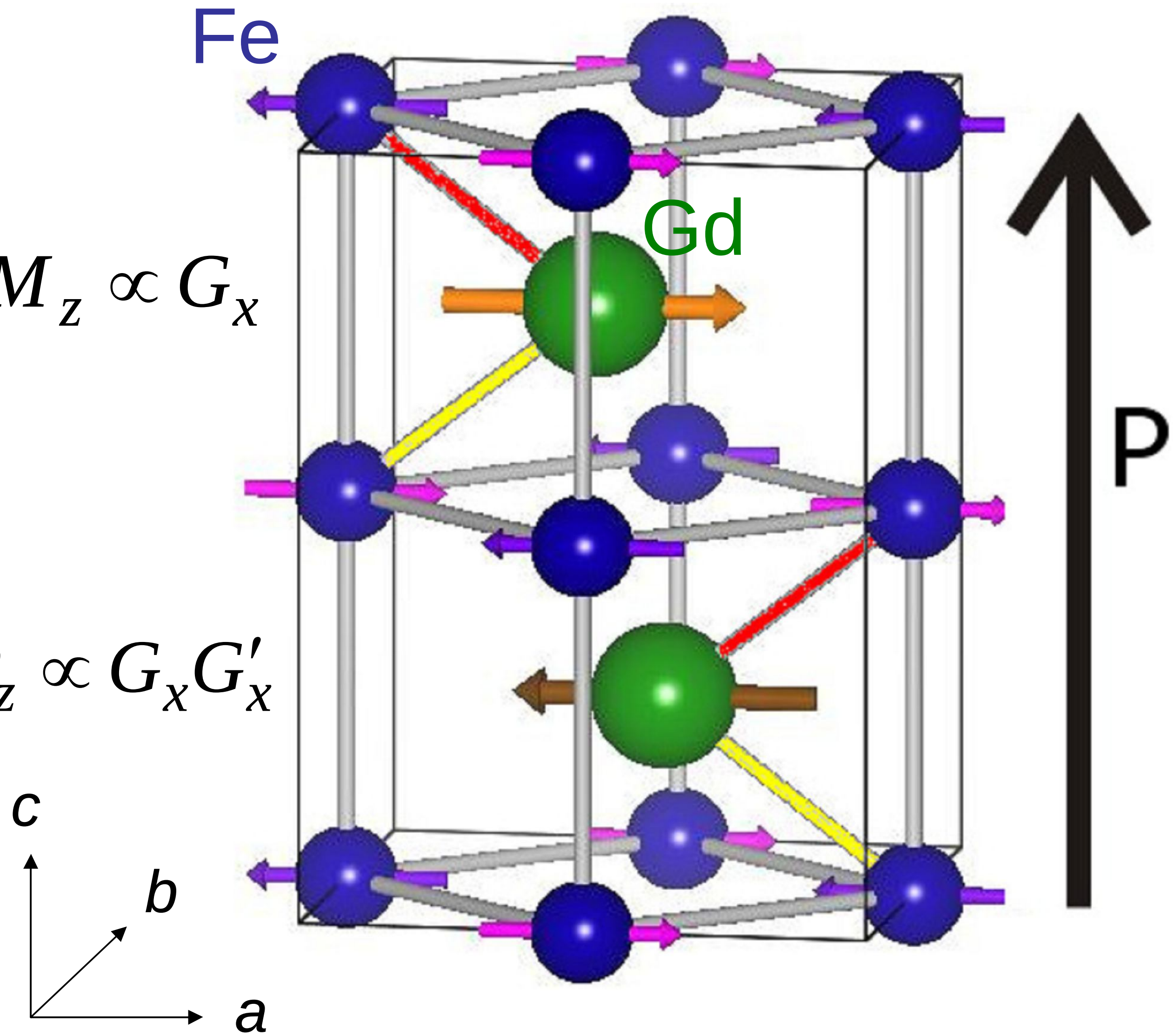
$$M_z \propto G_x$$

Gd^{3+} S=7/2
T'_N = 2.5K

Γ_5	$G'_x A'_y$

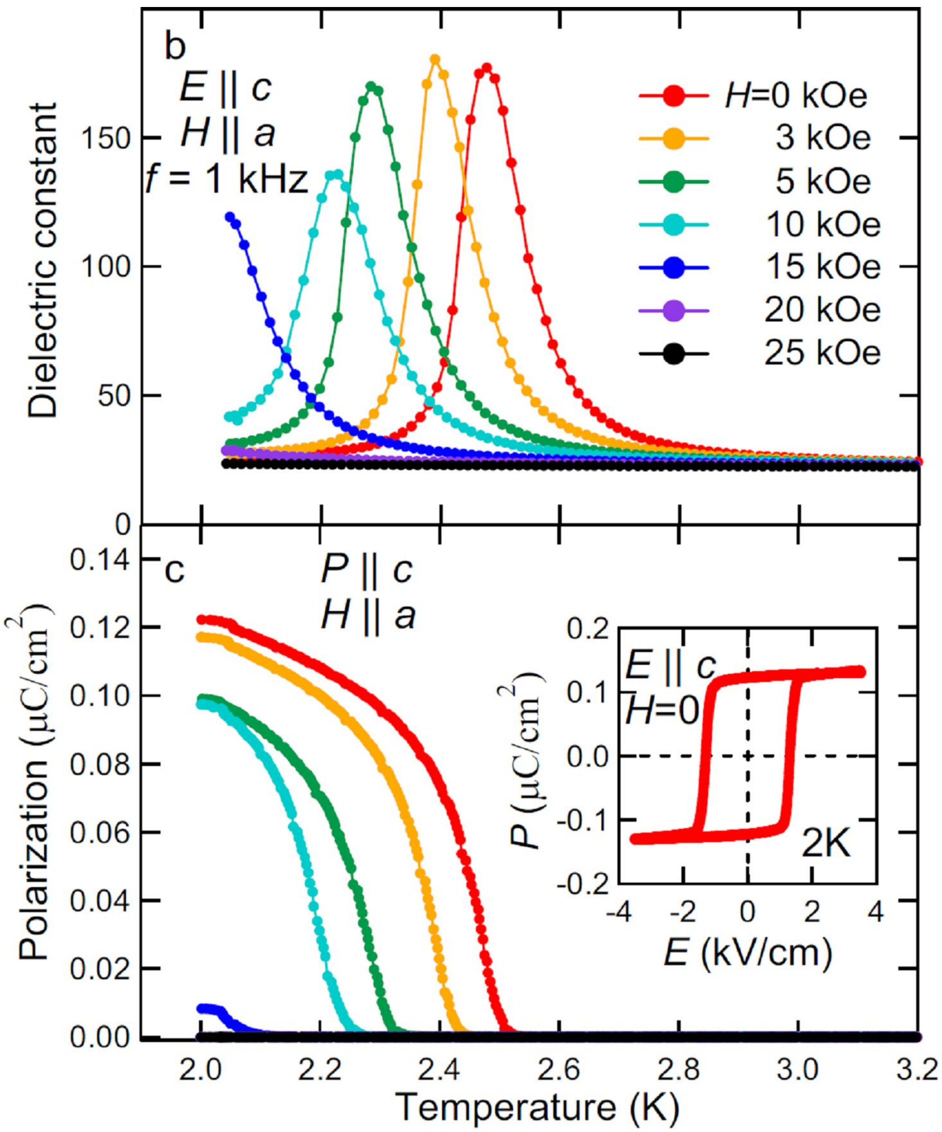
$$P_z \propto G_x G'_x$$

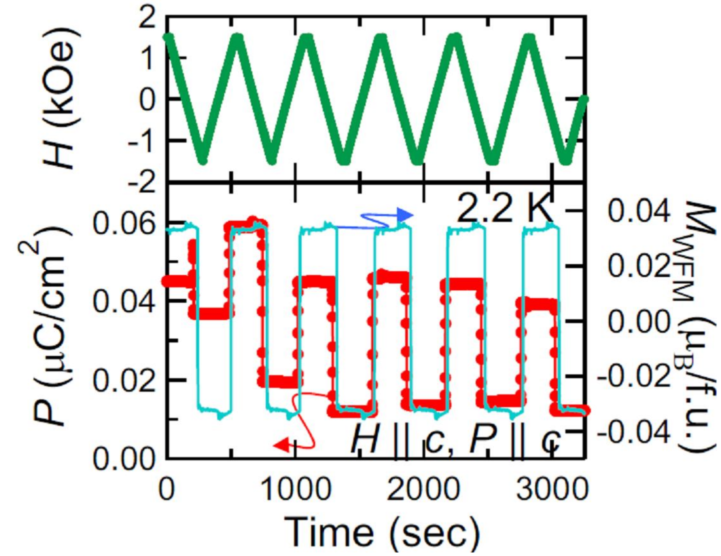
$T < T'_N$
$P_z \sim 0.1 \mu C\ cm^{-2}$

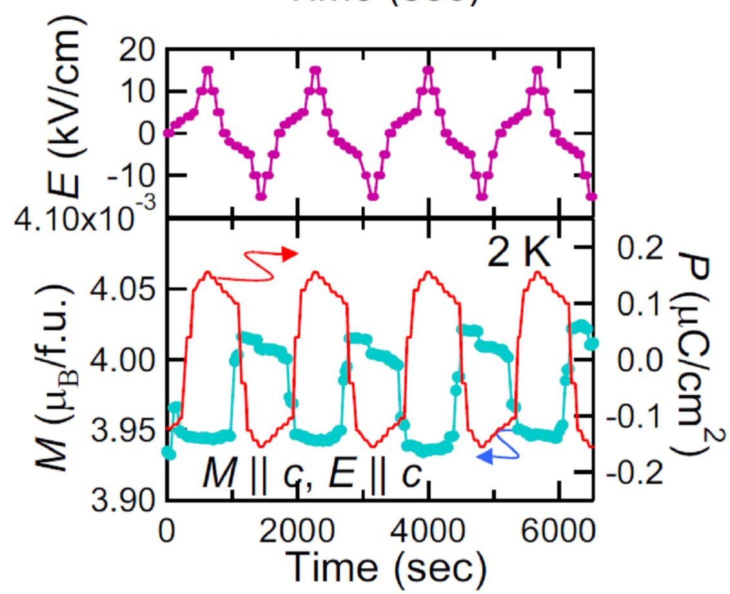


Magnetoelectric effects in $GdFeO_3$

Y. Tokunaga et al Nature Materials ***8****, 558 (2009)*



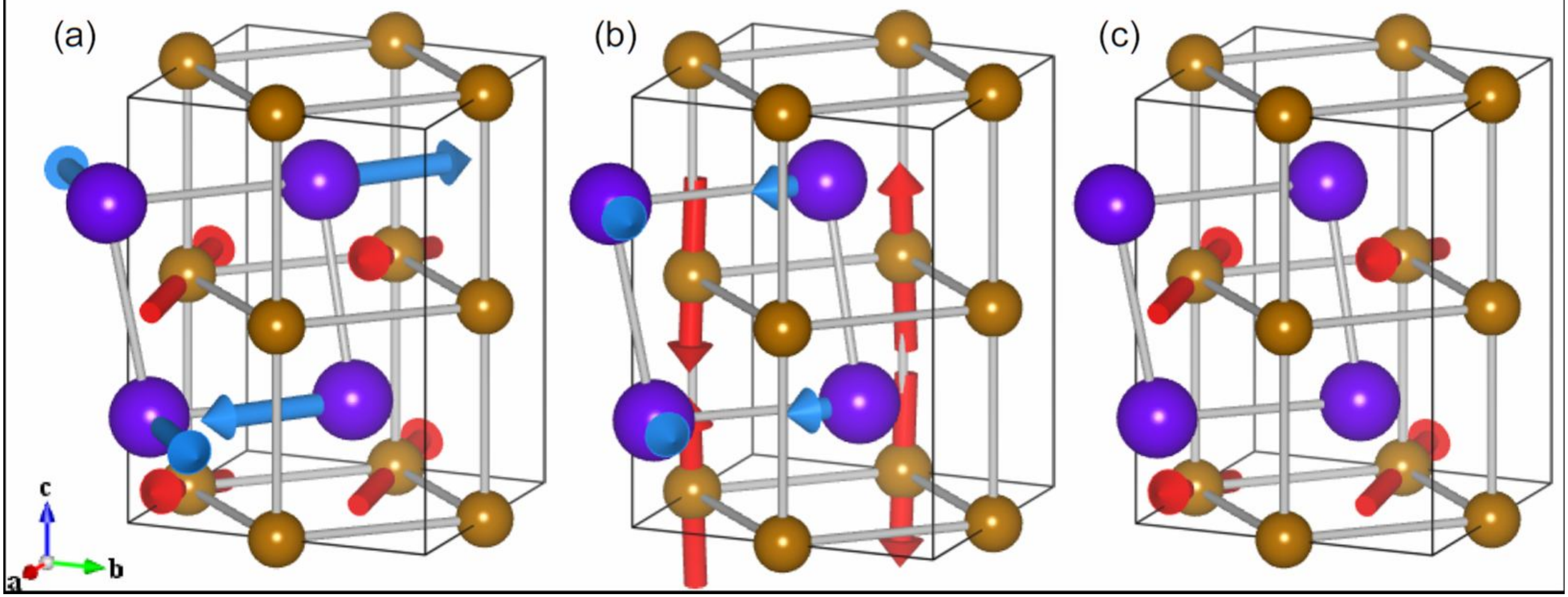




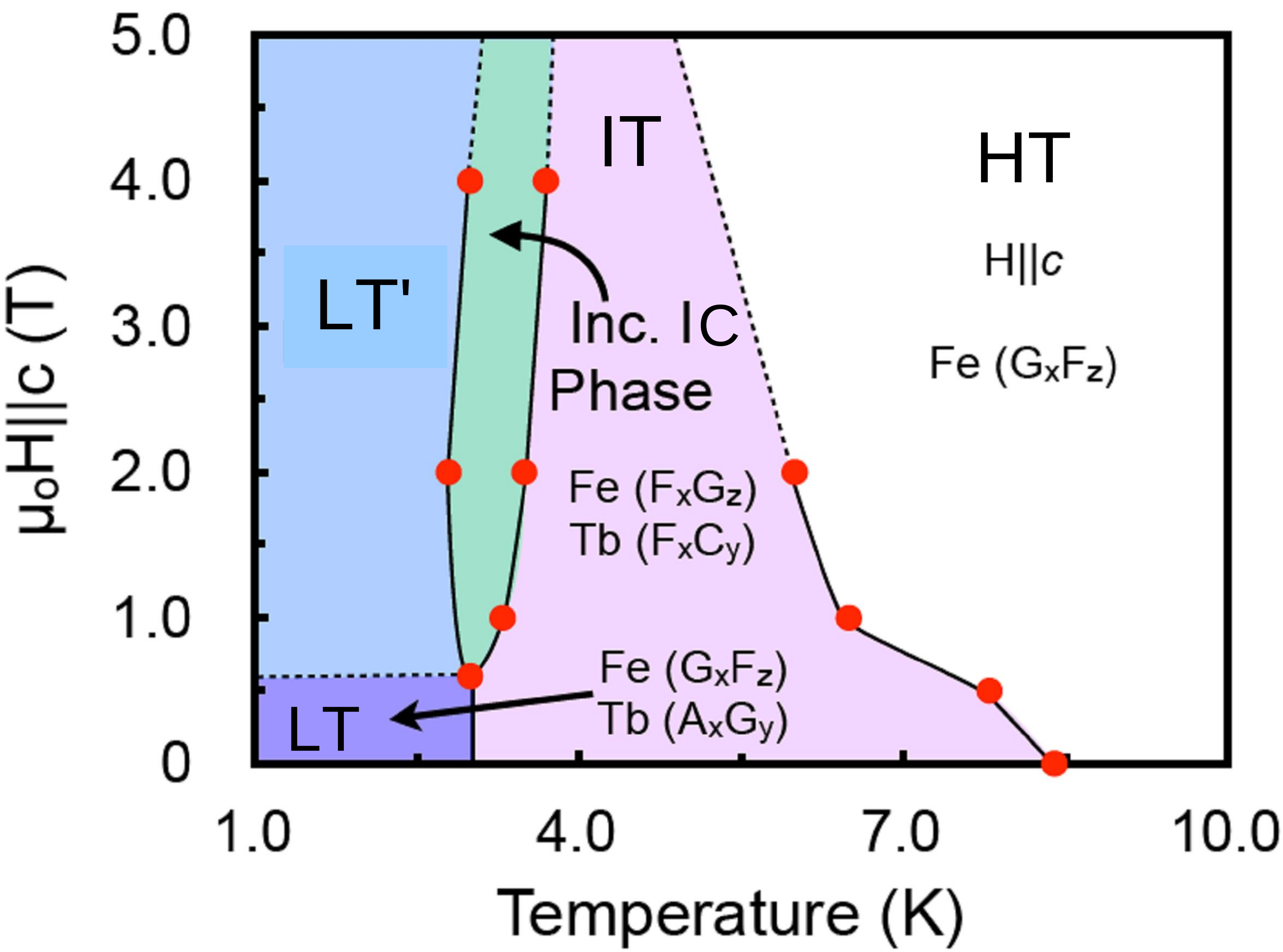
$TbFeO_3$

E. F. Bertaut et al. (1967) K. P. Belov, A. K. Zvezdin, and A. A. Mukhin (1979)

T(K)	T<3K	3K<T<8.5K	8.5K<T<650K
Fe	Gx=5μ_B Fz=0.15μ_B ξ_1 Γ_4	Gz=5μ_B Fx=0.15μ_B ξ_2 Γ_2	Gx=5μ_B Fz=0.15μ_B ξ_1 Γ_4
Tb	A'x=6.5μ_B G'y=5μ_B η_1 Γ_8	F'x=2.6 μ_B C'y=1.8 μ_B η_2 Γ_2	

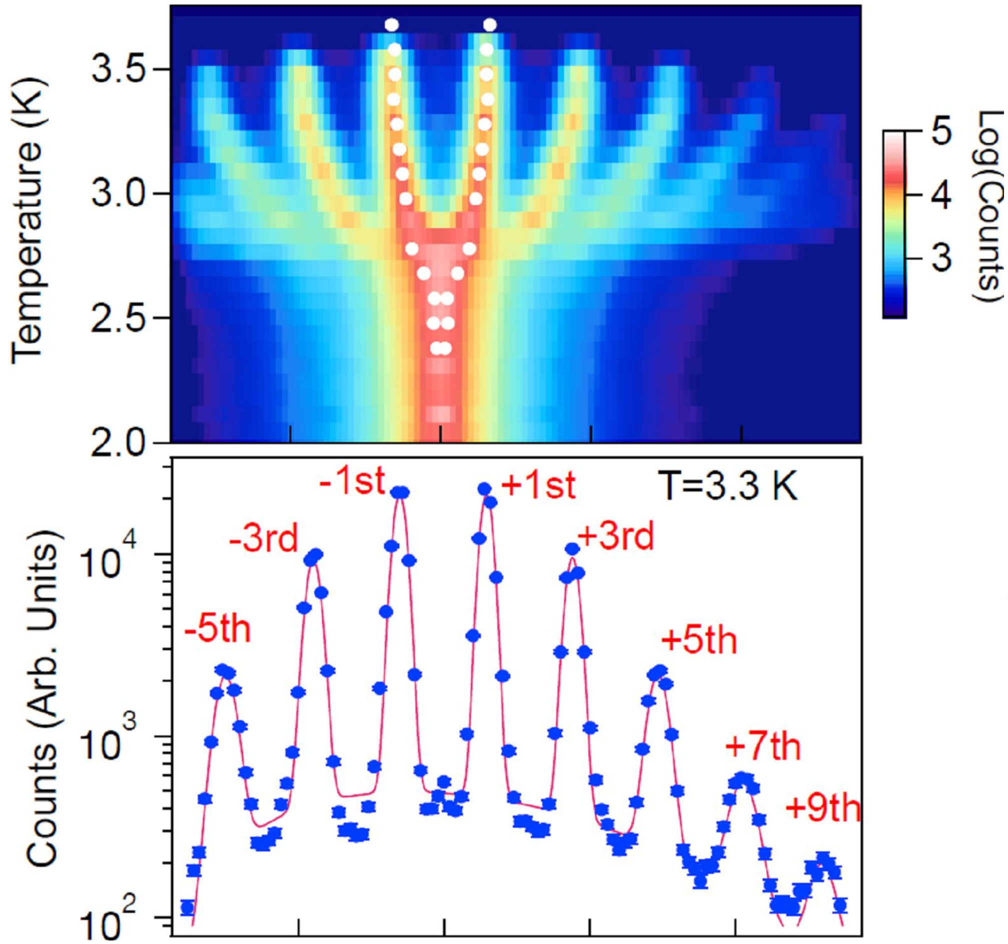


Magnetic field phase diagram



Incommensurate state

A-type reflection



Sharp domain walls in Tb spin ordering separated by d = 170 Å

Solitonic array

Landau theory

Fe $$f_{\rm Fe} = \frac{c}{2}\left(\frac{d\theta}{dy}\right)^2 + \frac{K}{2}\sin^2\theta - h\cos\theta$$

$$\Gamma_4: \ \xi_1 = \cos\theta$$
$$\Gamma_2: \ \xi_2 = \sin\theta$$

Tb $\Gamma_8: \eta_1$ $\Gamma_2: \eta_2$

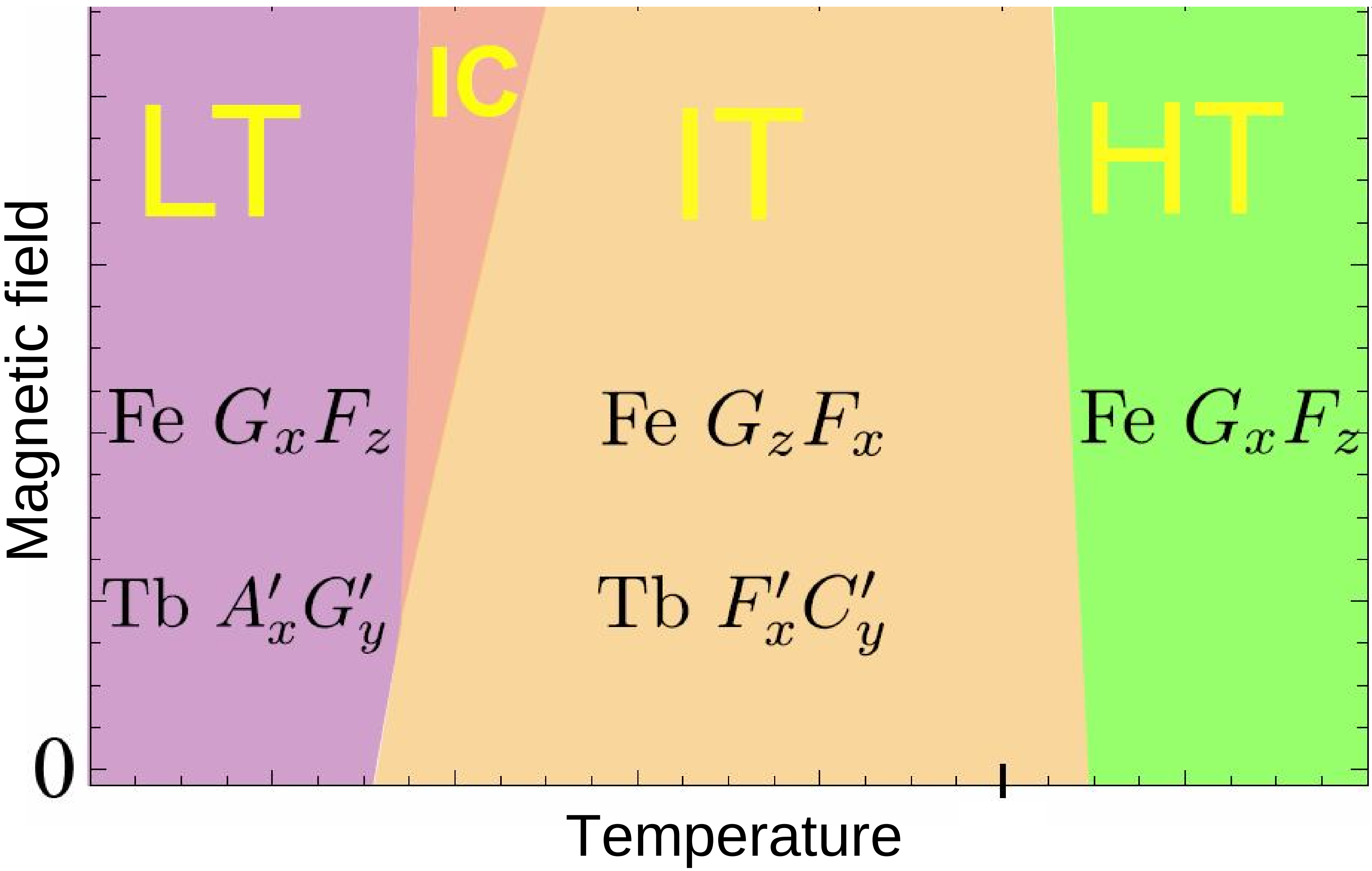
$$f_{\rm Tb} = \frac{c_1}{2}\left(\frac{d\eta_1}{dy}\right)^2 + \frac{c_2}{2}\left(\frac{d\eta_2}{dy}\right)^2 + \frac{a_1}{2}\eta_1^2 + \frac{a_2}{2}\eta_2^2 + \frac{b_1}{4}\eta_1^4 + \frac{b_{12}}{2}\eta_1^2\eta_2^2 + \frac{b_2}{4}\eta_2^4$$

Fe-Tb $$f_{\rm Fe-Tb} = -\lambda\xi_2\eta_2$$

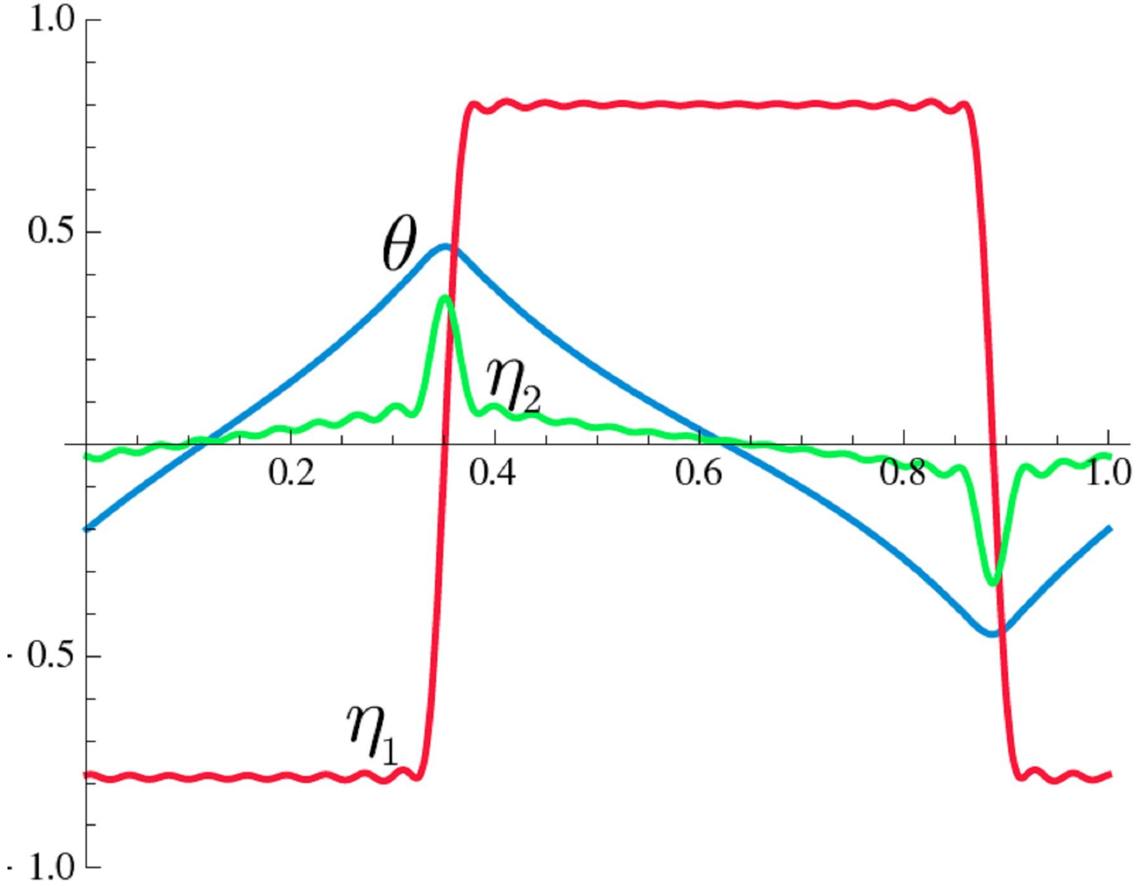
Lifshitz invariant (cancelation of frustration)

$$f_{\rm L} = g_1\left(\eta_1\partial_y\xi_2 - \xi_2\partial_y\eta_1\right) + g_2\left(\eta_1\partial_y\eta_2 - \eta_2\partial_y\eta_1\right)$$

Theoretical phase diagram



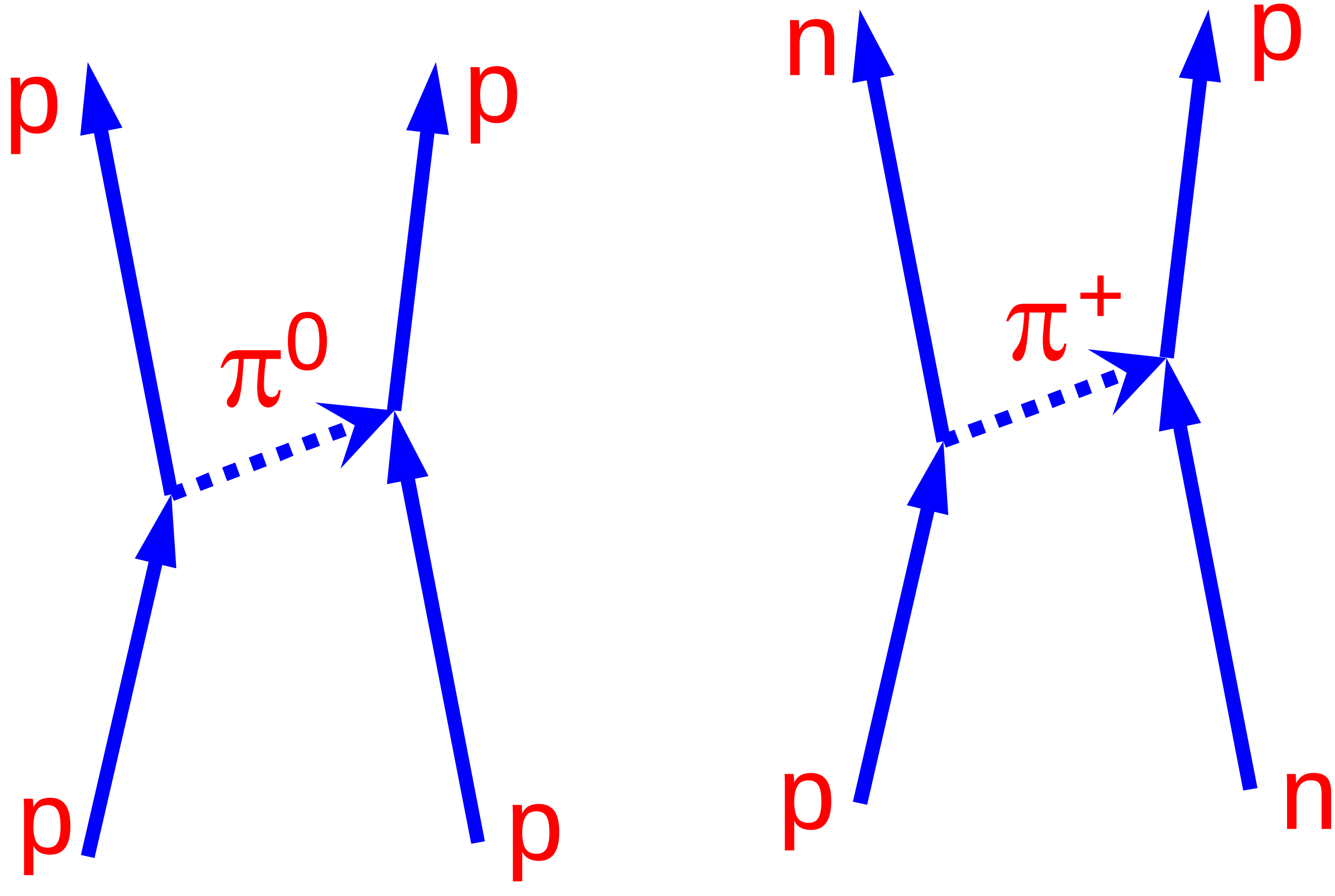
Solitonic lattice



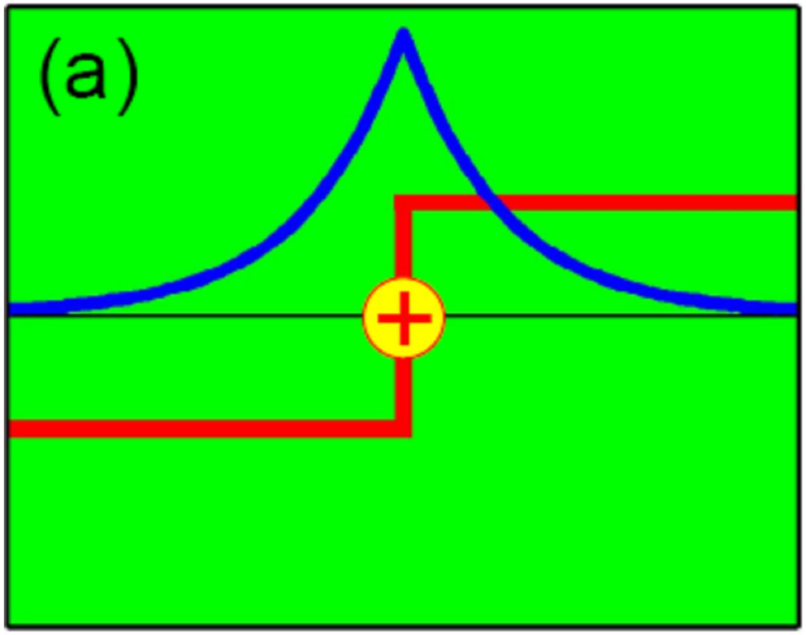
Yukawa force

$$U(x) \propto e^{-\frac{x}{l}}$$

$$l = \frac{\hbar}{m_\pi c}$$



Fe spin distortion around Tb domain wall



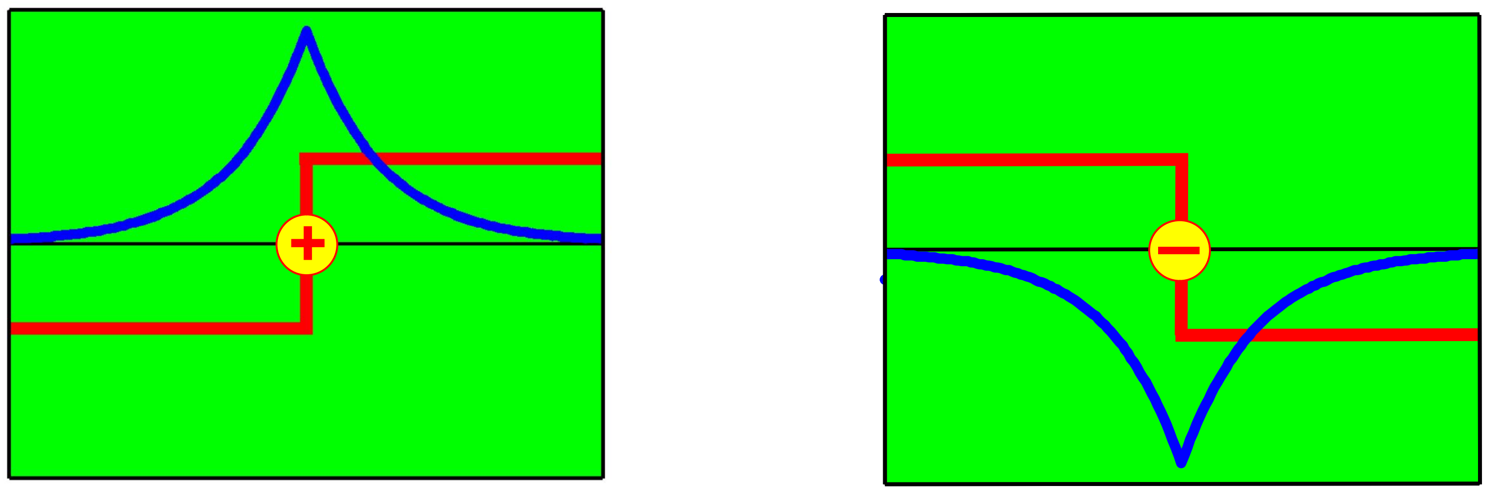
$$\theta(y) = \frac{Qg}{\sqrt{c(K+h)}} e^{-\frac{|y|}{l}}$$

$$l = m^{-1} = \sqrt{\frac{c}{K+h}}$$

$$F_\theta = -2g\theta(0)Q + \frac{1}{2}\int dy \left[c\left(\frac{d\theta}{dy}\right)^2 + (K+h)\,\theta^2 \right]$$

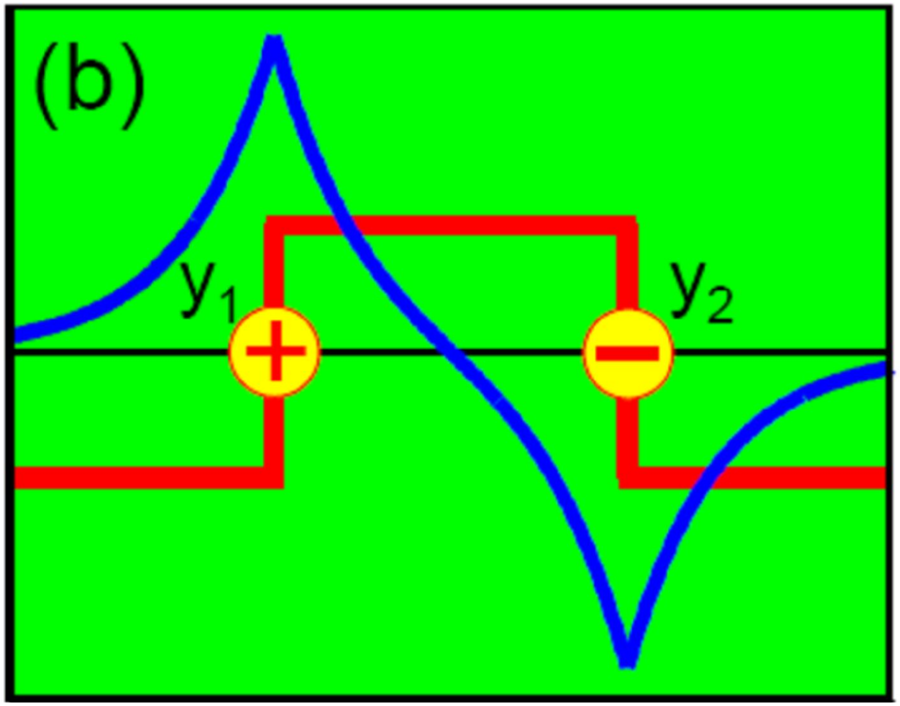
$$F_{DW} = F_{DW}^{(0)} - \frac{g^2}{\sqrt{c(K+h)}}$$

Fe spin distortion around Tb domain wall



Q = +1　　　　　　Q = −1

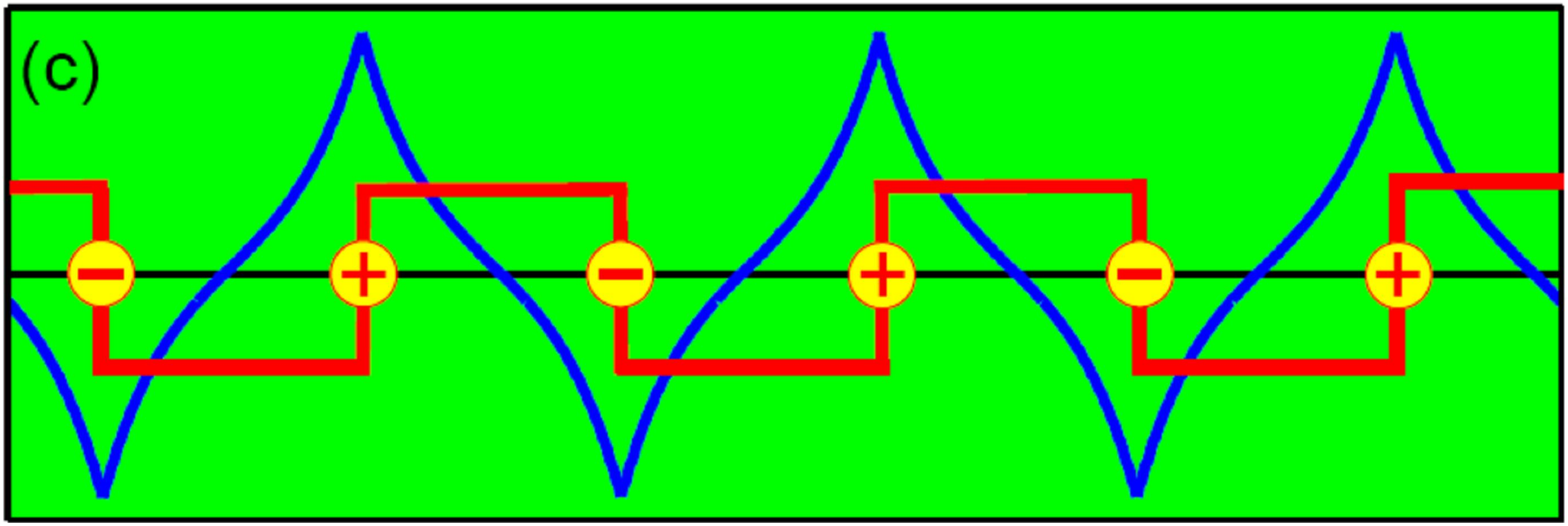
Yukawa potential



Repulsion between neighboring domain walls

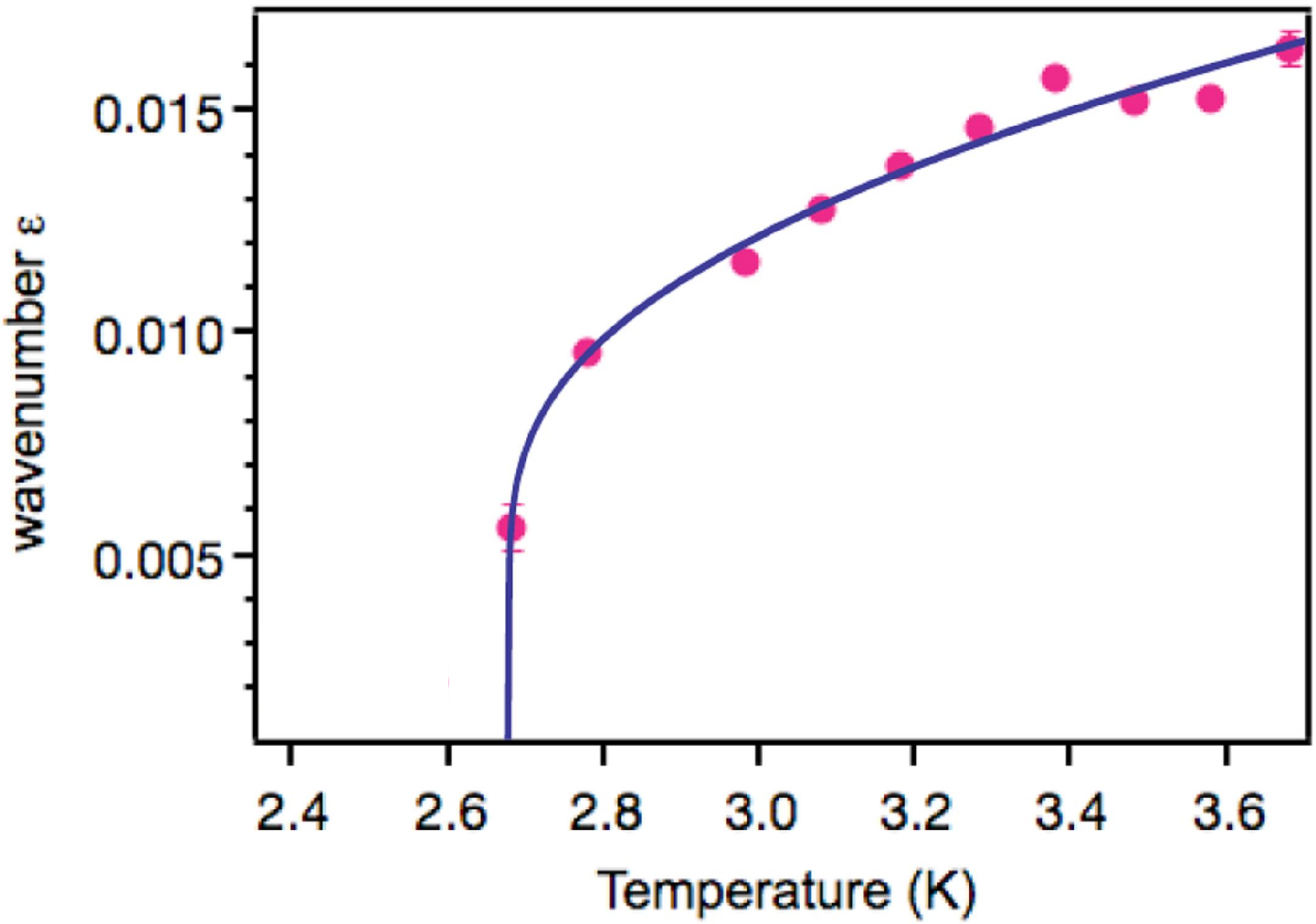
$$U(y_2 - y_1) = \frac{g^2}{\sqrt{c(K+h)}} e^{-\frac{|y_2 - y_1|}{l}}$$

Solitonic array



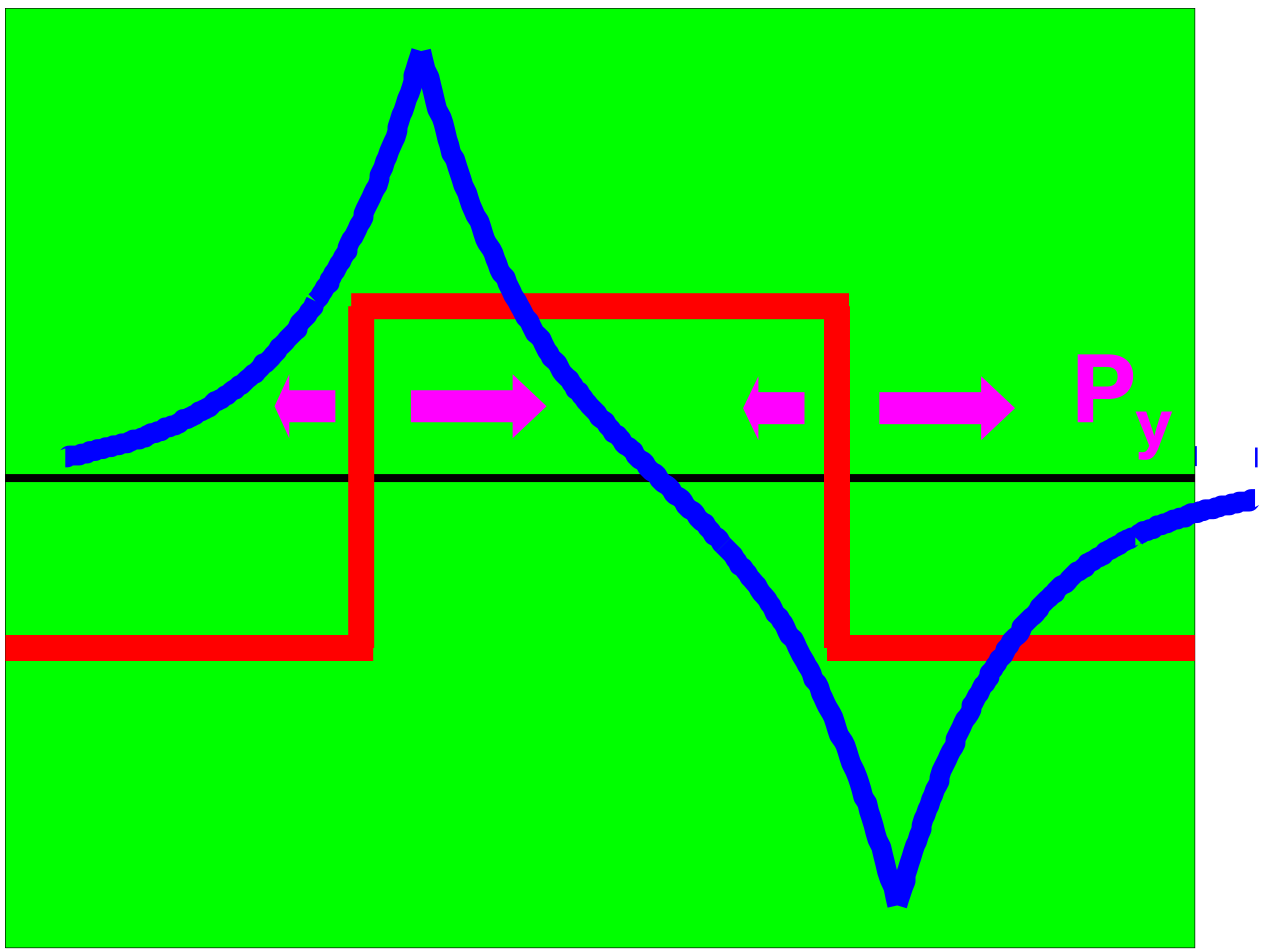
$$F_\theta = -\sum_{n,m} Q_n U(y_n - y_m) Q_m$$

T-dependence of wave vector



Phason-electromagnon

$$\Gamma_8 \partial_y \Gamma_2 - \Gamma_2 \partial_y \Gamma_8 \qquad P_y \Gamma_8 \Gamma_2 \qquad E_y(t) \Gamma_8 \delta\Gamma_2(t)$$



Conclusions

- Symmetry arguments make possible to predict new effects and understand the common origin of apparently different phenomena

- Advances in microscopic theory

  $\alpha_{||} = 10^{-4}$ for Cr_2O_3 (*Scaramucci et al, 2010)*