Multiferroic and magnetoelectric materials

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ICMR Summer School
on Multiferroics

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Outline

- Ferroelectric properties of magnetic defects
- Toroidal moment and magnetoelectric effect
- Electromagnons

Electrostatics of magnetic defects

Easy plane spins: $$\mathbf{M} = M\left[\mathbf{e}_1 \cos\varphi + \mathbf{e}_2 \sin\varphi\right]$$

Polarization: $$P_a = -\gamma\chi_e M^2 \varepsilon_{3ab}\partial_b\varphi$$

Total polarization of domain wall:

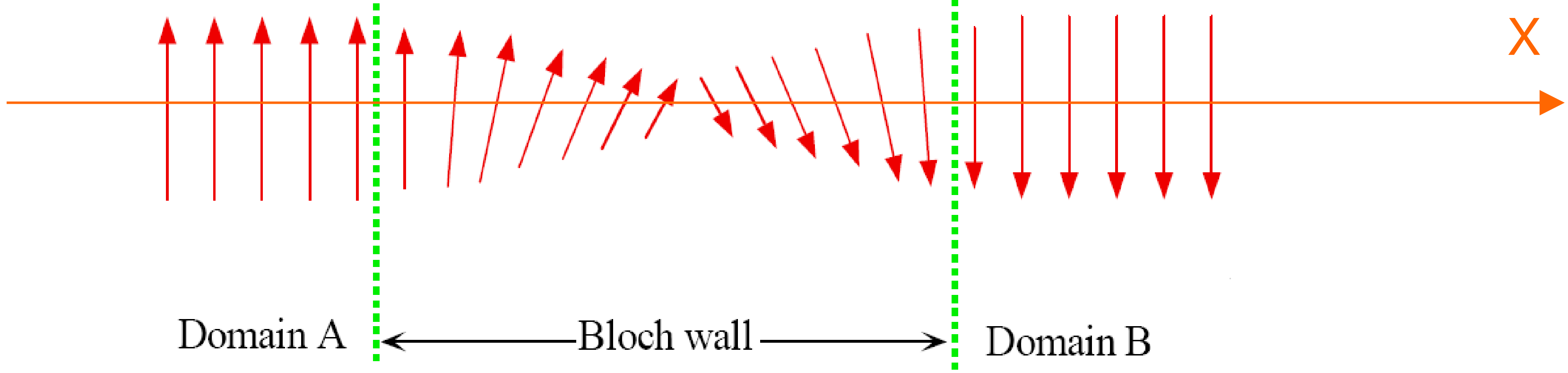
$$\int dx P_y = \gamma\chi_e M^2\left[\varphi(+\infty) - \varphi(-\infty)\right]$$

Charge density: $$\rho = -\mathrm{div}\mathbf{P} = 2\pi\gamma\chi_e M^2\Gamma\delta^{(2)}(\mathbf{x}_\perp)$$

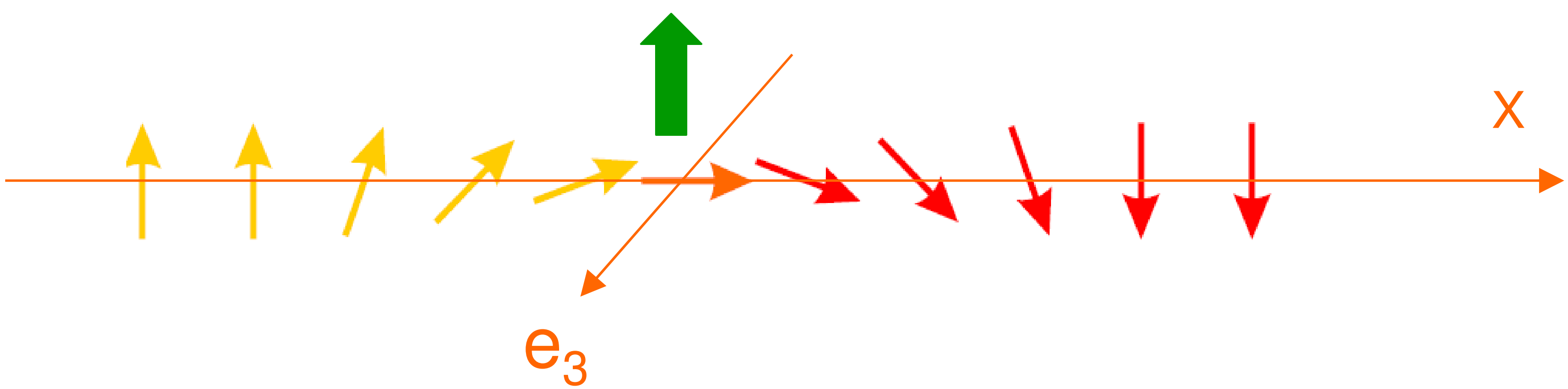
Vortex charge: $$Q \propto \Gamma = \frac{1}{2\pi}\oint_C d\mathbf{x}\cdot\nabla\varphi$$ **winding number**

Polarization of domain walls

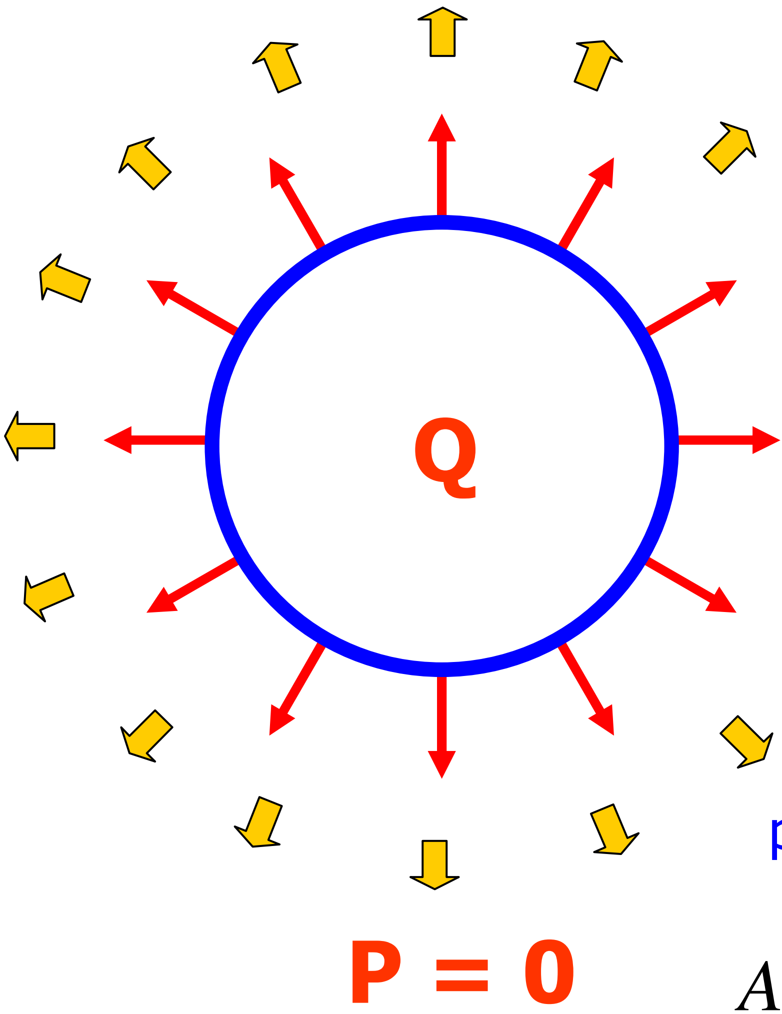
Bloch wall $\mathbf{P}=0$ $\mathbf{e}_3 \parallel \hat{\mathbf{x}}$



Néel wall $\mathbf{P} \parallel [\mathbf{e}_3 \times \hat{\mathbf{x}}]$ $\mathbf{e}_3 \perp \hat{\mathbf{x}}$

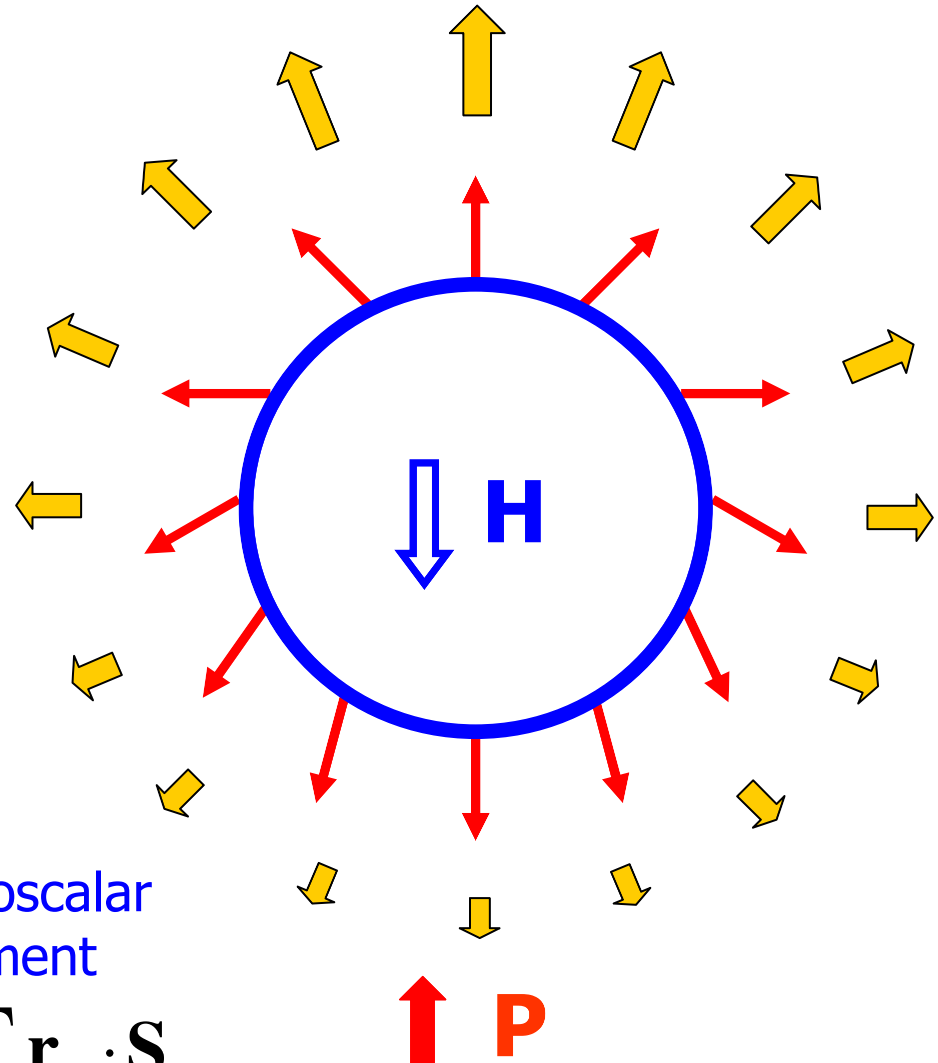


Magnetic vortex in magnetic field

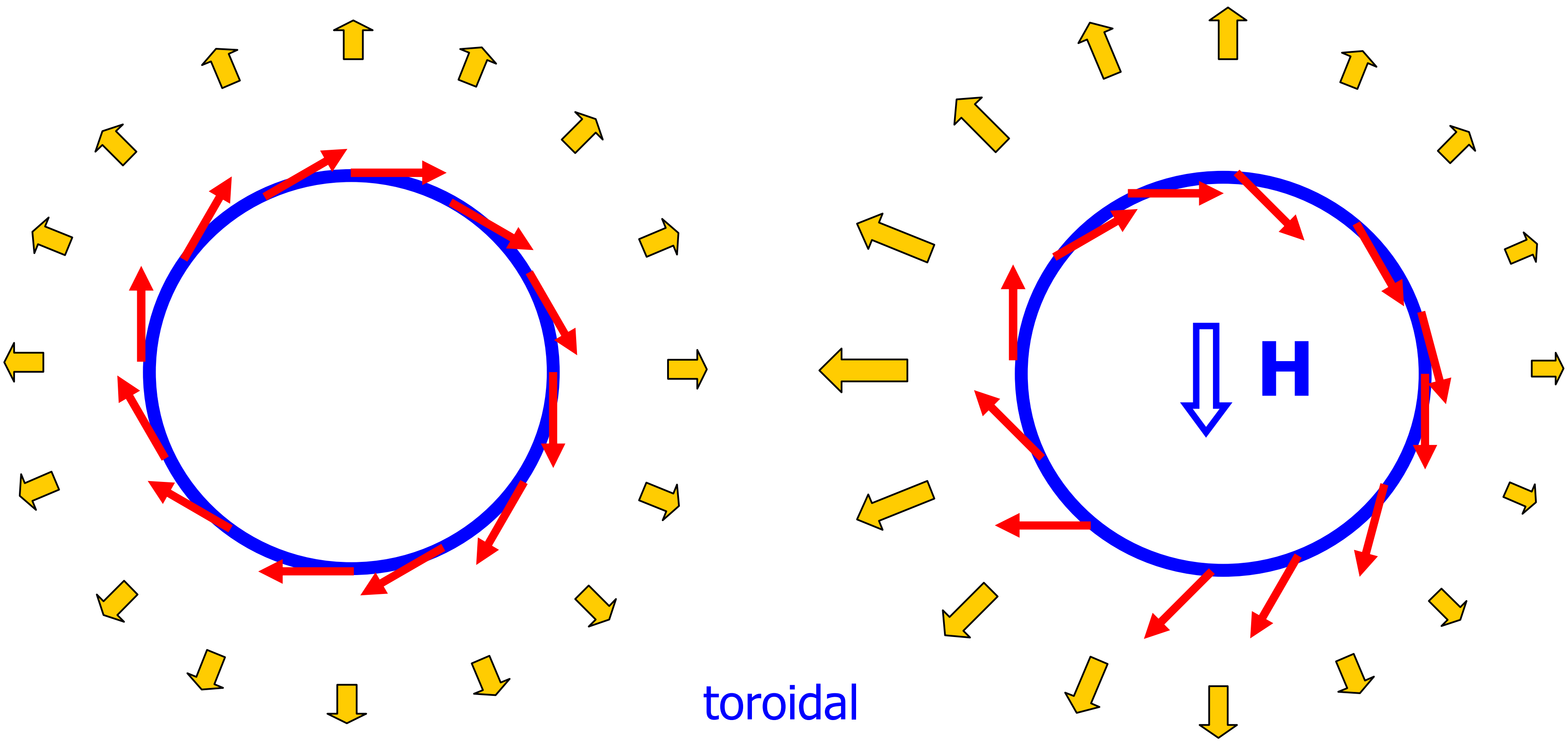


pseudoscalar moment

$$A \propto \sum_{\alpha} \mathbf{r}_\alpha \cdot \mathbf{S}_\alpha$$



Magnetic vortex in magnetic field



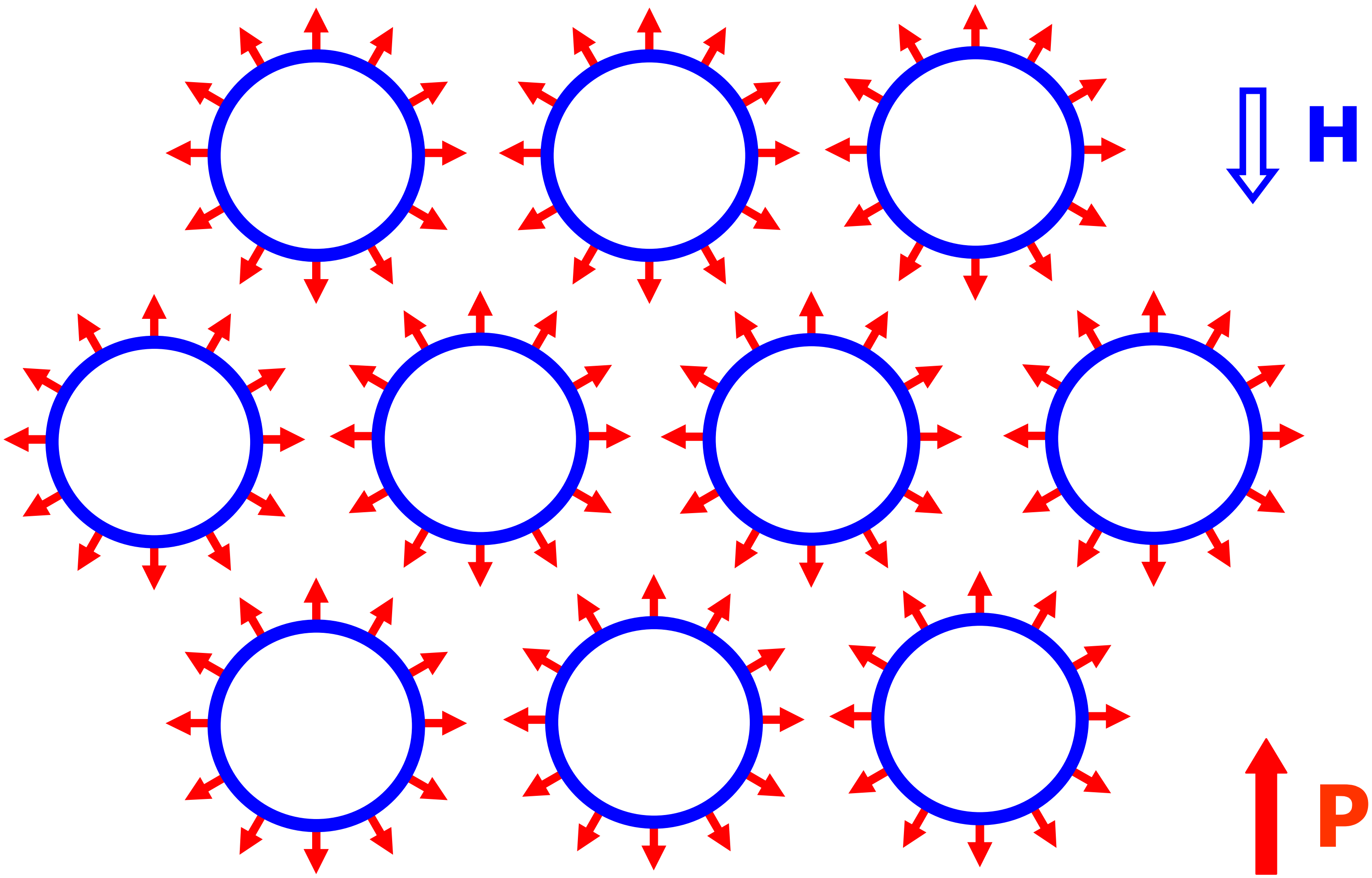
toroidal moment

P = 0

$$\mathbf{T} \propto \sum_{\alpha} \mathbf{r}_{\alpha} \times \mathbf{S}_{\alpha}$$

P

Array of magnetic vortices is magnetoelectric



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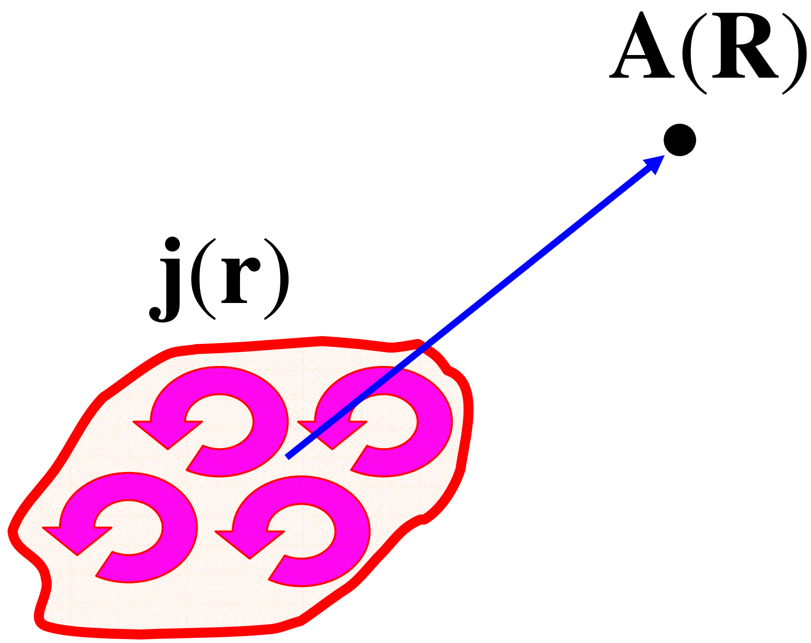
Multipole expansion

Average vector potential



$$\mathbf{A}(\mathbf{R}) = \frac{1}{c}\int d^3r\, \frac{\mathbf{j}(\mathbf{r})}{|\mathbf{r}-\mathbf{R}|}$$

Magnetic dipole moment

$$\mathbf{A}^{(1)} = -\mathbf{M}\times\nabla\frac{1}{R} \qquad \mathbf{M} = \frac{1}{2c}\int d^3r\, \mathbf{r}\times\mathbf{j}$$

Quadrupole and toroidal moments

Quadrupole moment

$$A_i^{(2)} = -\varepsilon_{ijk} Q_{kl} \partial_j \partial_l \frac{1}{R}$$

$$Q_{ij} = \frac{1}{6c} \int d^3r \left([\mathbf{r} \times \mathbf{j}]_i r_j + [\mathbf{r} \times \mathbf{j}]_j r_i \right)$$

Toroidal moment (not in textbooks)

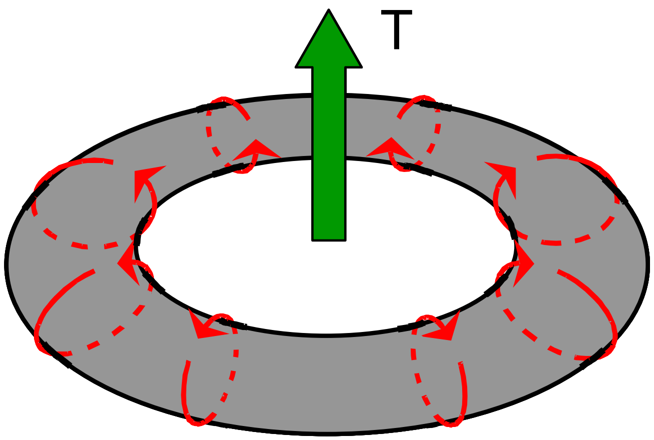
$$\mathbf{A}^{(2)} = \nabla (\mathbf{T} \cdot \nabla) \frac{1}{R} + 4\pi \mathbf{T} \delta(\mathbf{R})$$

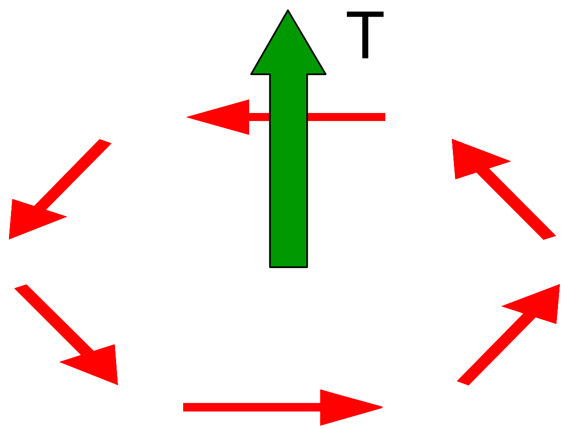
$$\mathbf{T} = \frac{1}{6c} \int d^3r \, \mathbf{r} \times [\mathbf{r} \times \mathbf{j}]$$

Meaning of toroidal moment

$$\mathbf{T} = \frac{1}{6c}\int d^3r\, \mathbf{r}\times[\mathbf{r}\times\mathbf{j}]$$

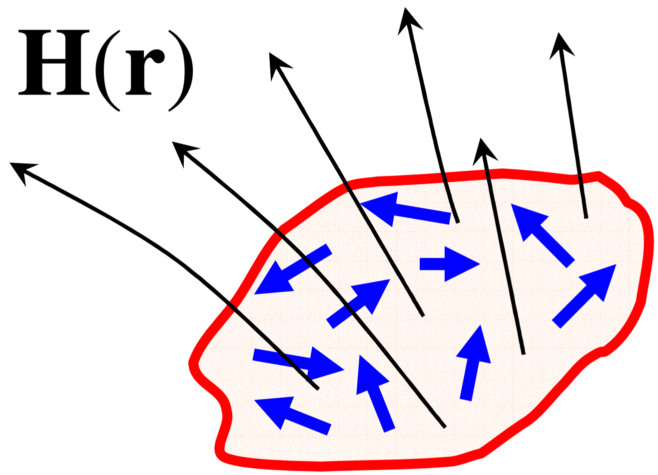
$$\mathbf{T} = \mu_B \sum_{\alpha} \mathbf{r}_\alpha \times \mathbf{S}_\alpha$$





Spins interacting with inhomogeneous magnetic field

$$E = -2\mu_B \sum_\alpha \mathbf{S}_\alpha \cdot \mathbf{H}(\mathbf{r}_\alpha)$$



Gradient expansion

$$E^{(0)} = -\mathbf{M} \cdot \mathbf{H}(0)$$

$$E^{(1)} = -A\nabla \cdot \mathbf{H} - \mathbf{T} \cdot \nabla \times \mathbf{H} - Q_{ij}\left(\partial_i H_j + \partial_j H_i\right)$$

$$A = -\frac{2}{3}\mu_B \sum_\alpha \mathbf{r}_\alpha \cdot \mathbf{S}_\alpha$$

Magnetoelectric properties of magnetic multipoles

$$\Phi_{\text{me}} = -a\,\mathbf{E}\cdot\mathbf{H} - \mathbf{t}\cdot\mathbf{E}\times\mathbf{H} - q_{ij}\left(E_i H_j + E_j H_i\right)$$

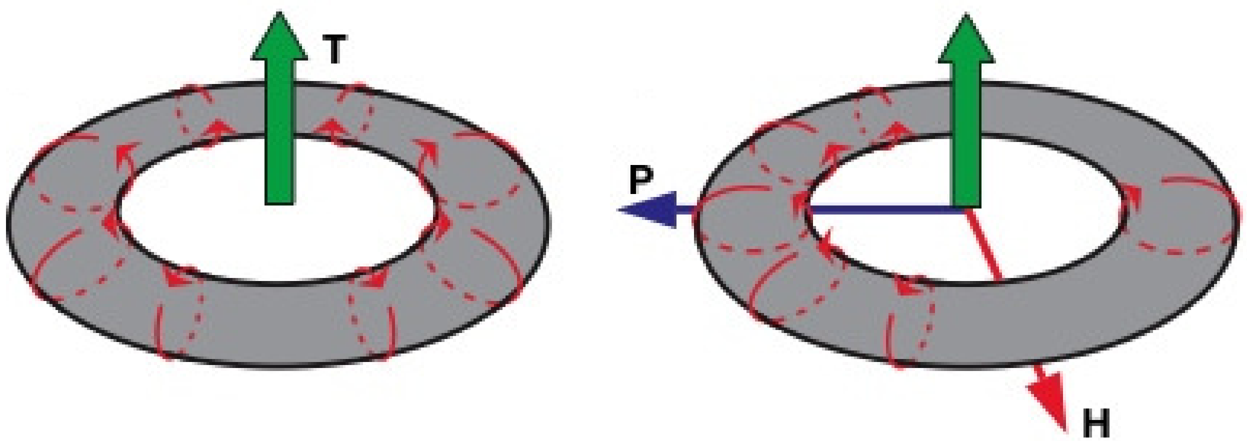
$$\Phi_H = -A\nabla\cdot\mathbf{H} - \mathbf{T}\cdot\nabla\times\mathbf{H} - Q_{ij}\left(\partial_i H_j + \partial_j H_i\right)$$

The magnetic multipoles have the same symmetry as magnetoelectric tensor

$$a \propto A \qquad \mathbf{t} \propto \mathbf{T} \qquad q_{ij} \propto Q_{ij}$$

Magnetoelectric effect

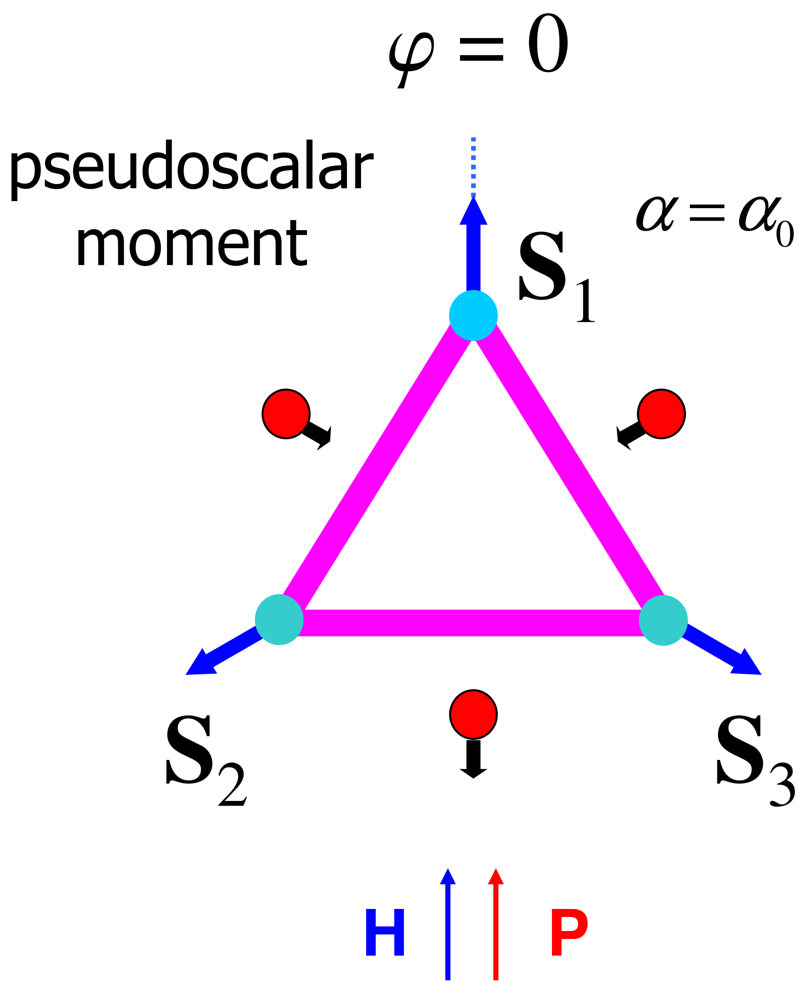
$$\Phi_{me} = -\lambda \mathbf{T} \cdot \mathbf{E} \times \mathbf{H}$$



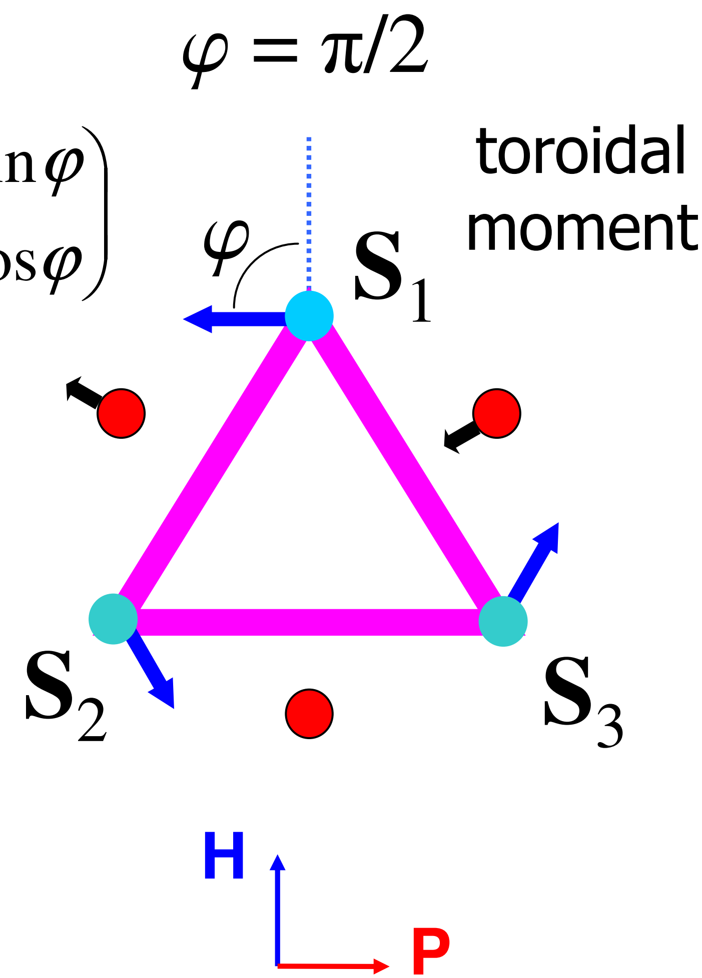
$$\mathbf{P} = -\frac{\partial \Phi_{me}}{\partial \mathbf{E}} = -\mathbf{T} \times \mathbf{H}$$

$$\mathbf{M} = -\frac{\partial \Phi_{me}}{\partial \mathbf{H}} = +\mathbf{T} \times \mathbf{E}$$

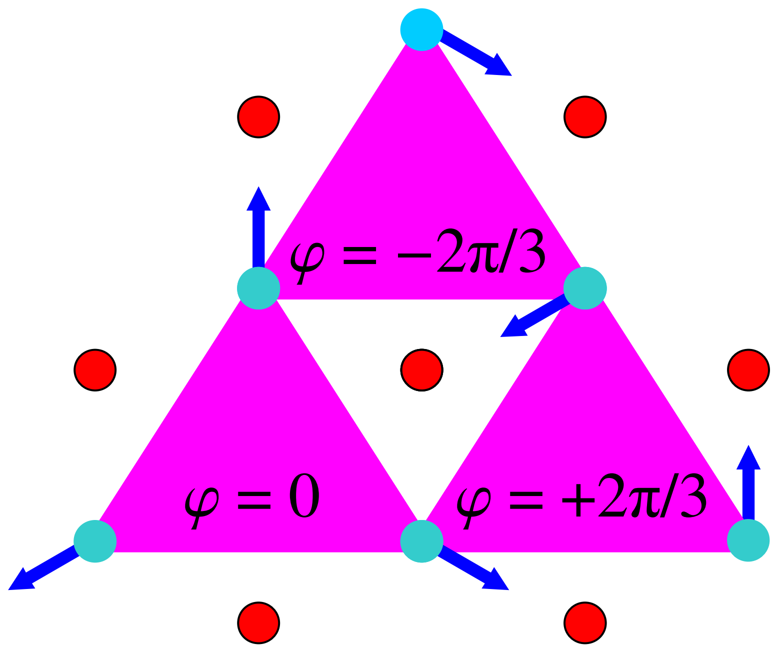
Magnetoelectric effect in spin triangle



$$\alpha = \alpha_0 \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix}$$

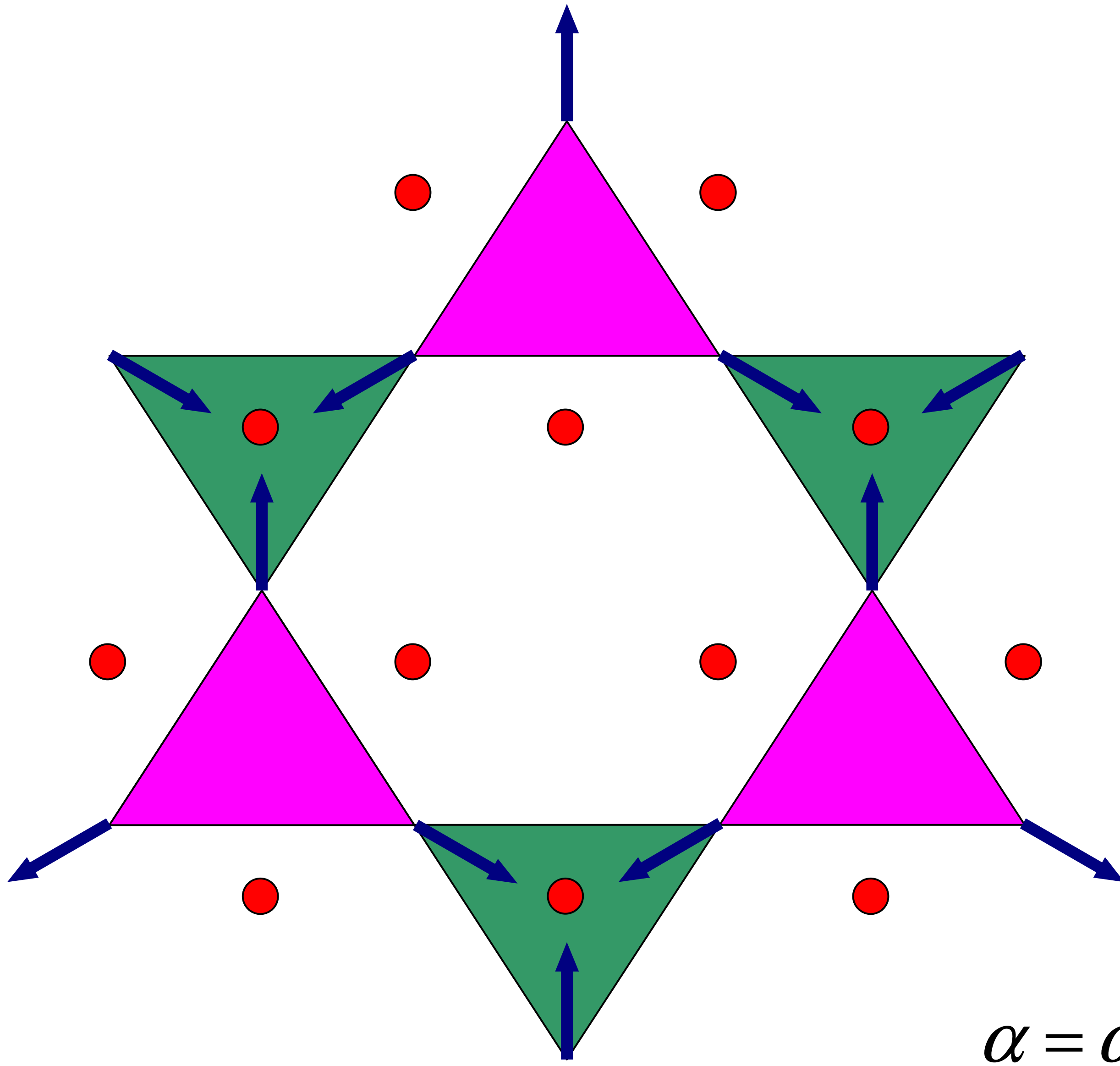


Triangular lattice



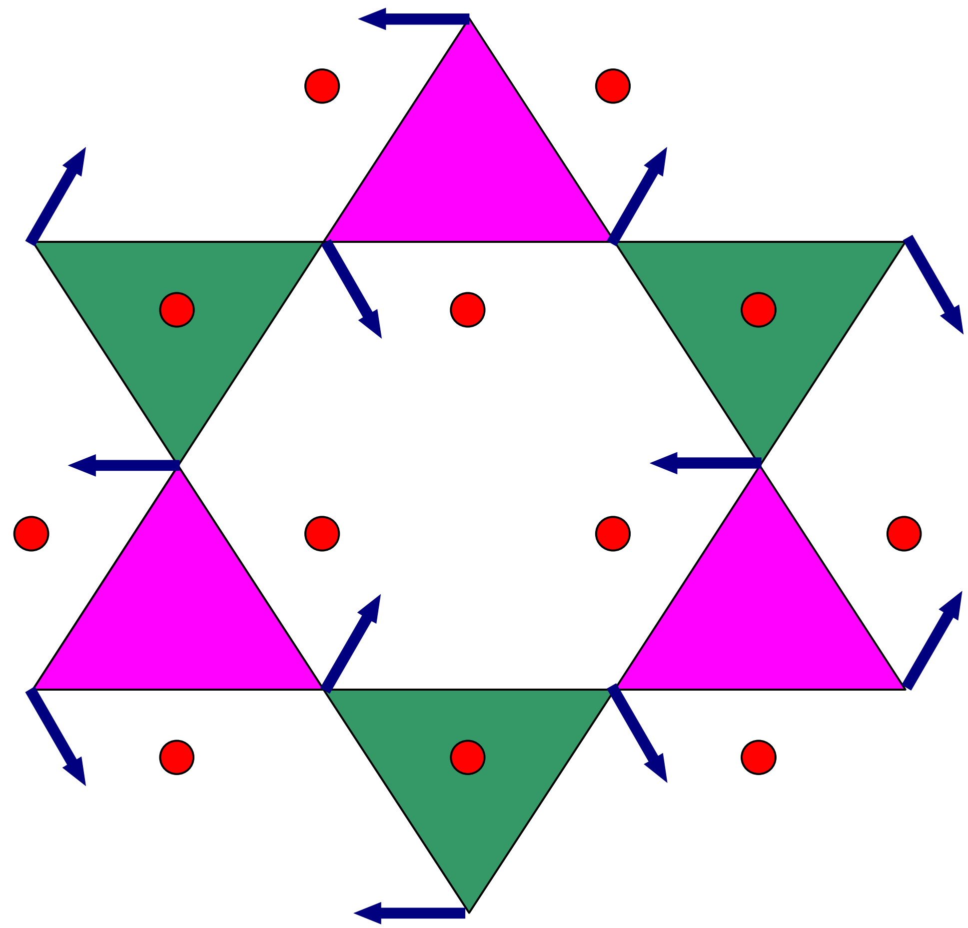
Cancellation of
magnetoelectric
effect

Pseudoscalar Kagome



$$\alpha = \alpha_0 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Toroidal Kagome

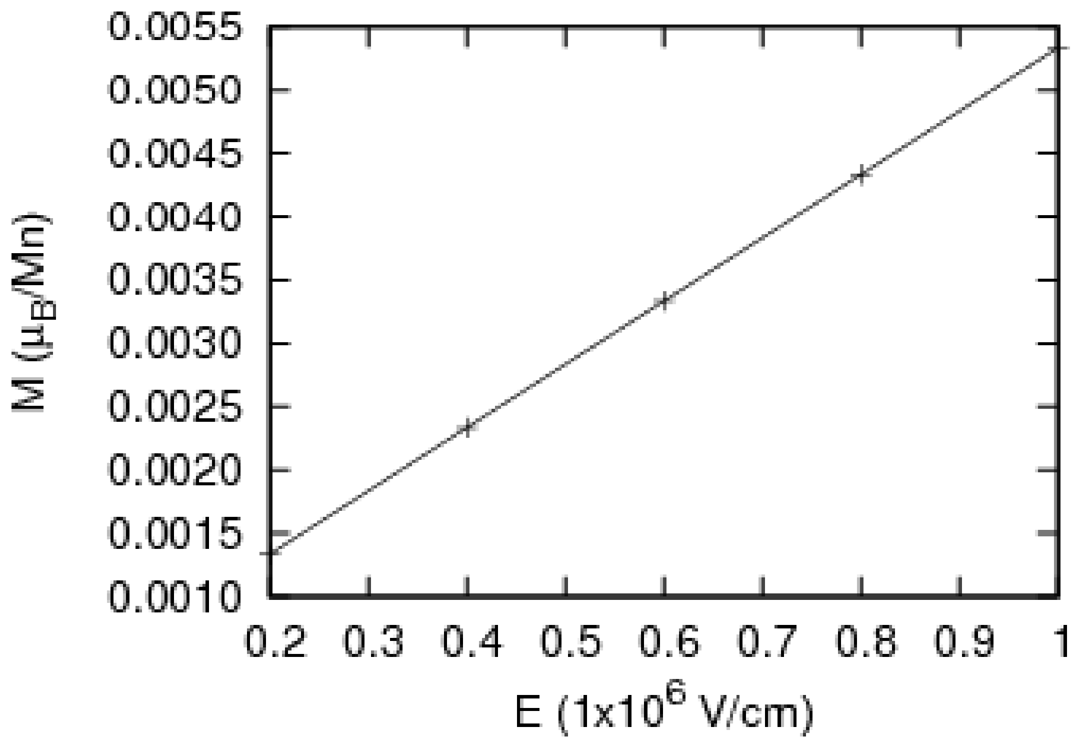


layered
Kagomé lattice

$$\alpha = \alpha_0 \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Magnetoelectric Coupling

- KITPITE: $\alpha = 3 \cdot 10^{-3}$ Gaussian units)



LDA+U
Cris Delaney &
Nicola Spaldin

- Cr_2O_3 $\alpha = 1 \cdot 10^{-4}$

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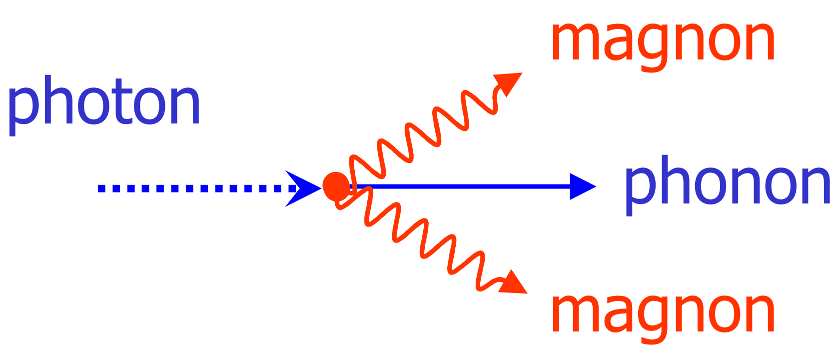
Phonon-magnon continuum

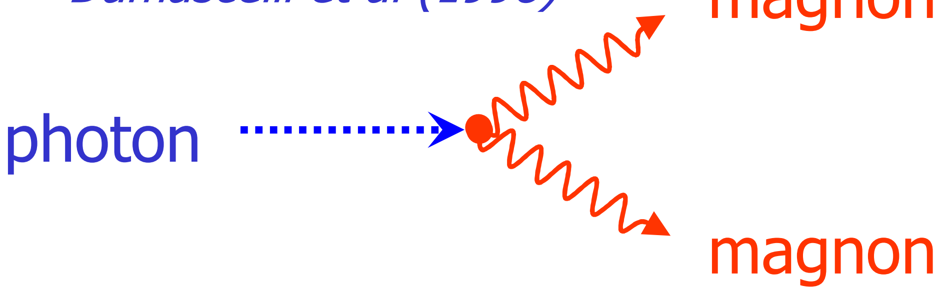
$$H_{me} = -\mathbf{P}\sum_{ijk}\lambda_{ijk}\mathbf{u}_i\left(\mathbf{S}_j\cdot\mathbf{S}_k\right)$$

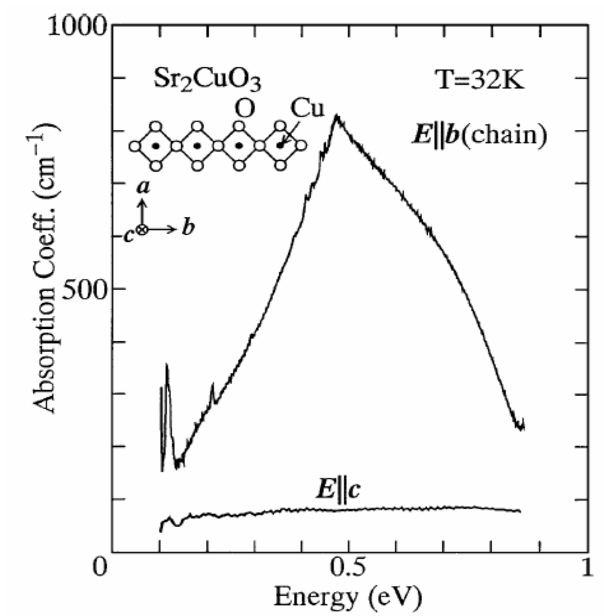
Lorenzana & Sawatzky (1995)



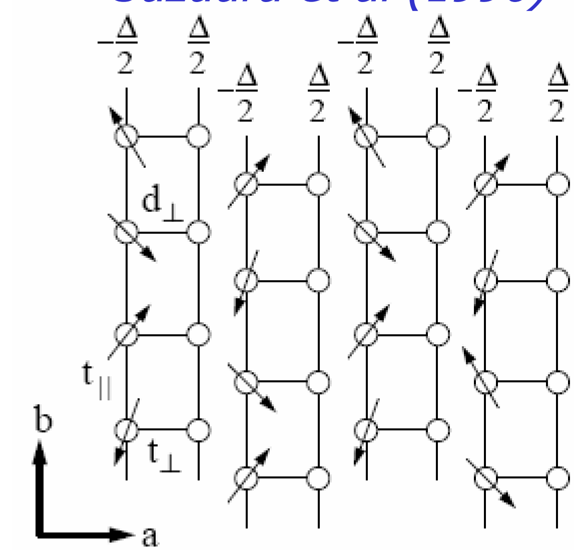
‘Charged magnons’ in NaV_2O_5

Damascelli et al (1998)



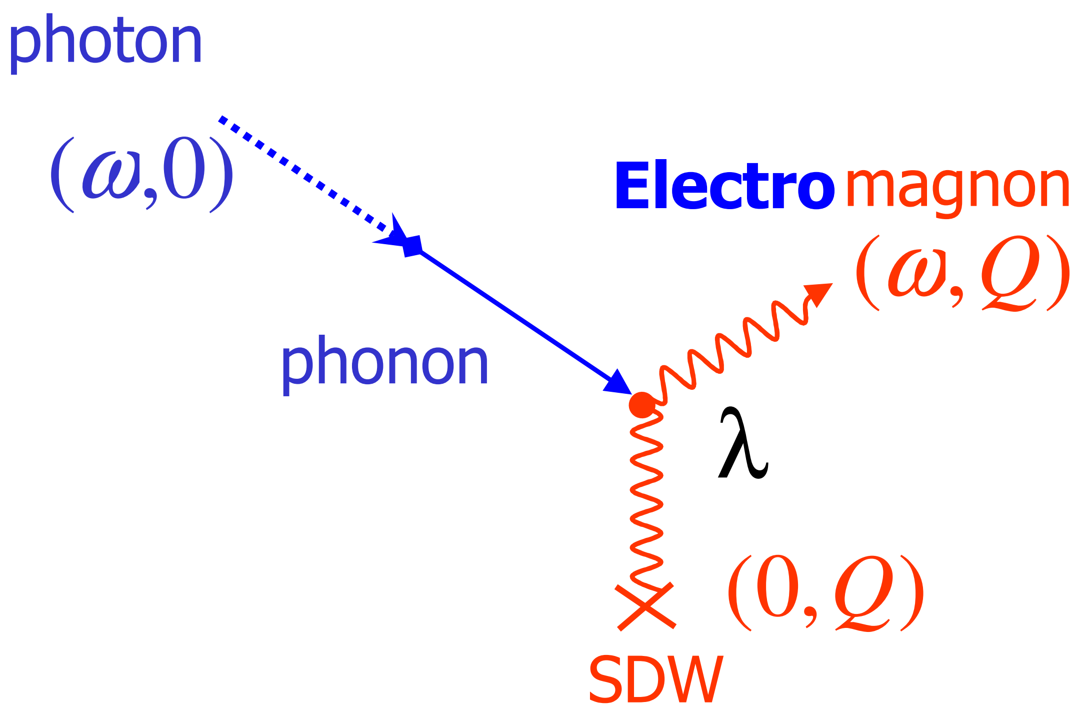


Suzuura et al (1996)



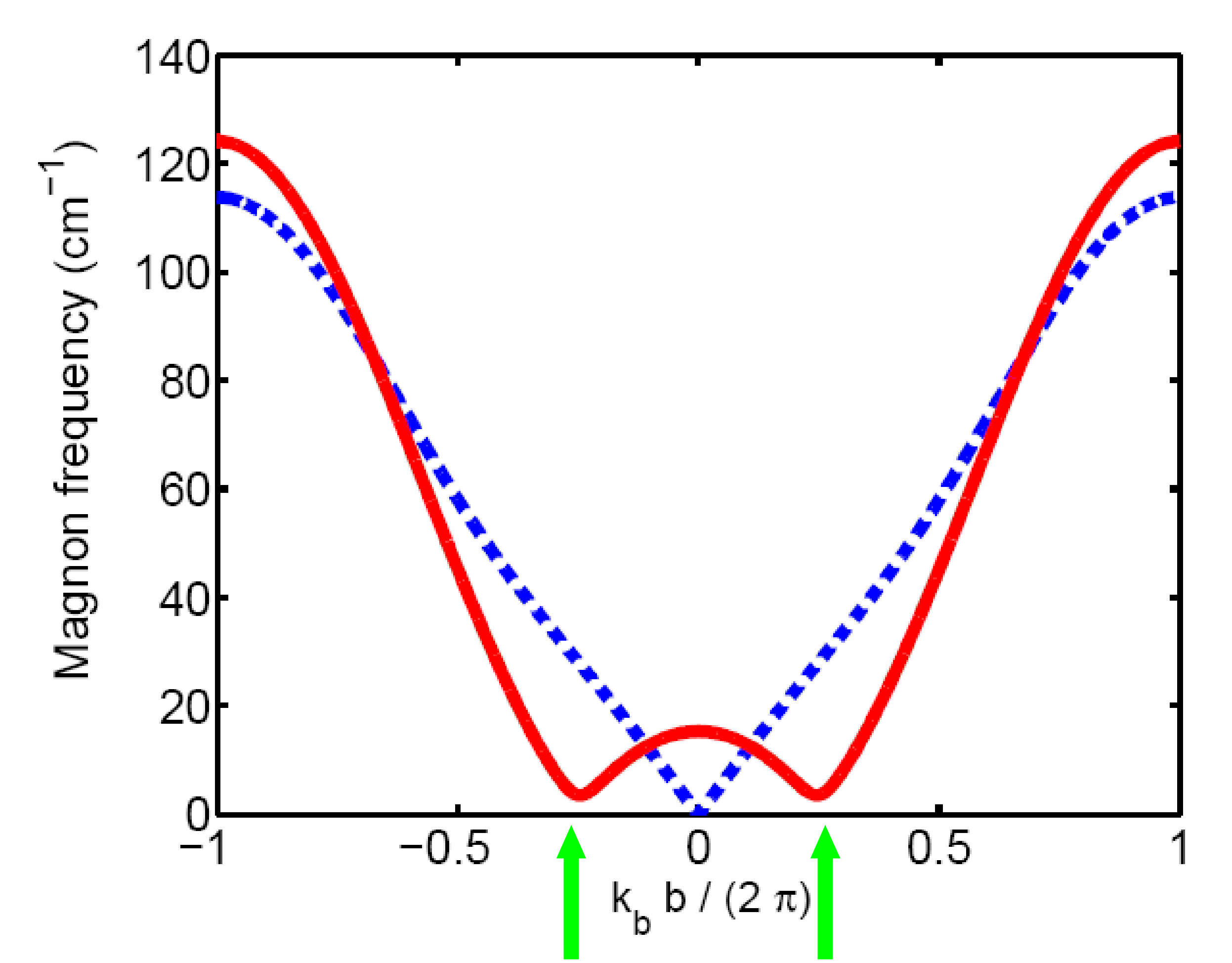
Photoexitation of magnons

$$PL\partial L$$



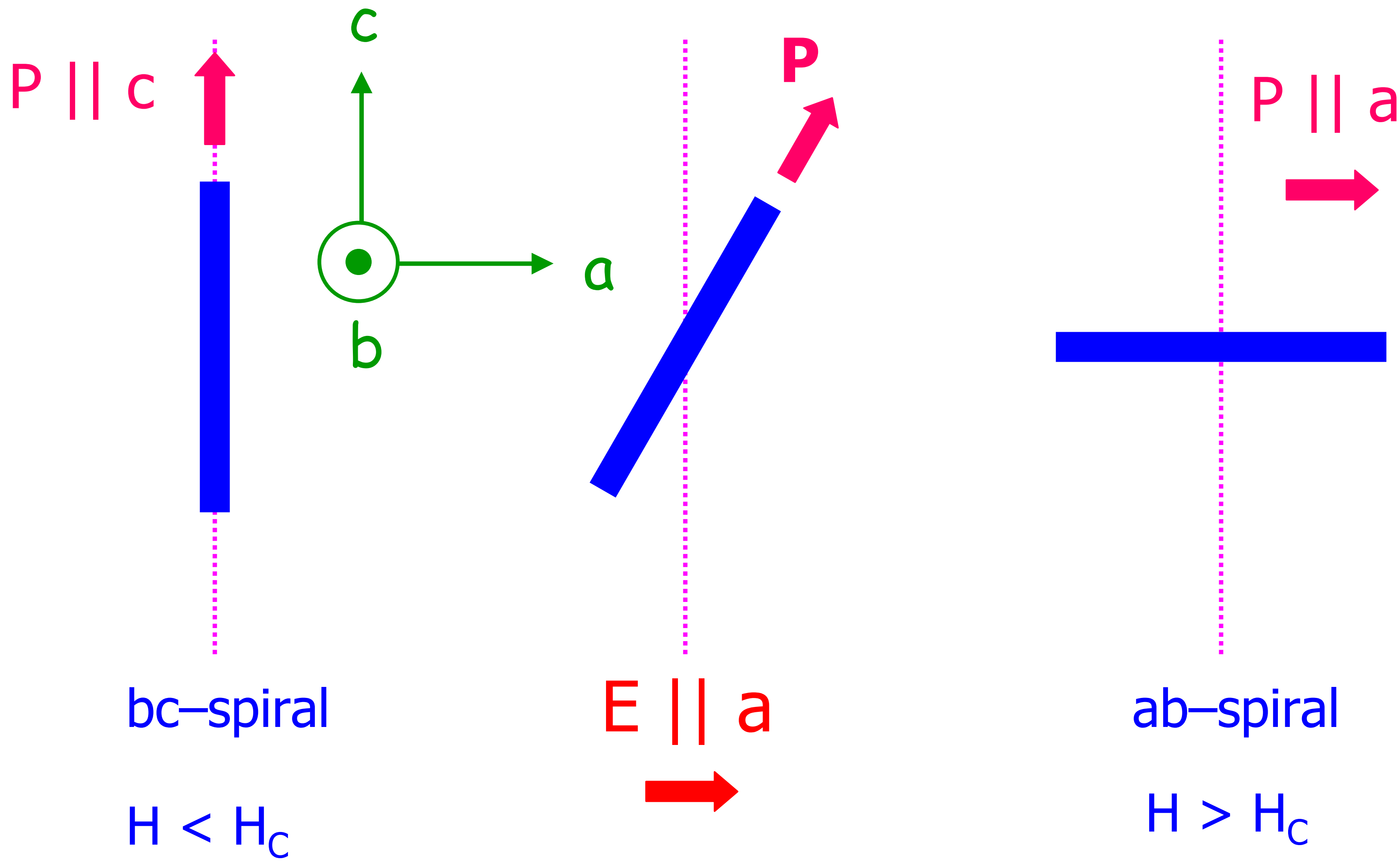
H. Katsura et al. (2006)

Magnons in spiral state of $RMnO_3$



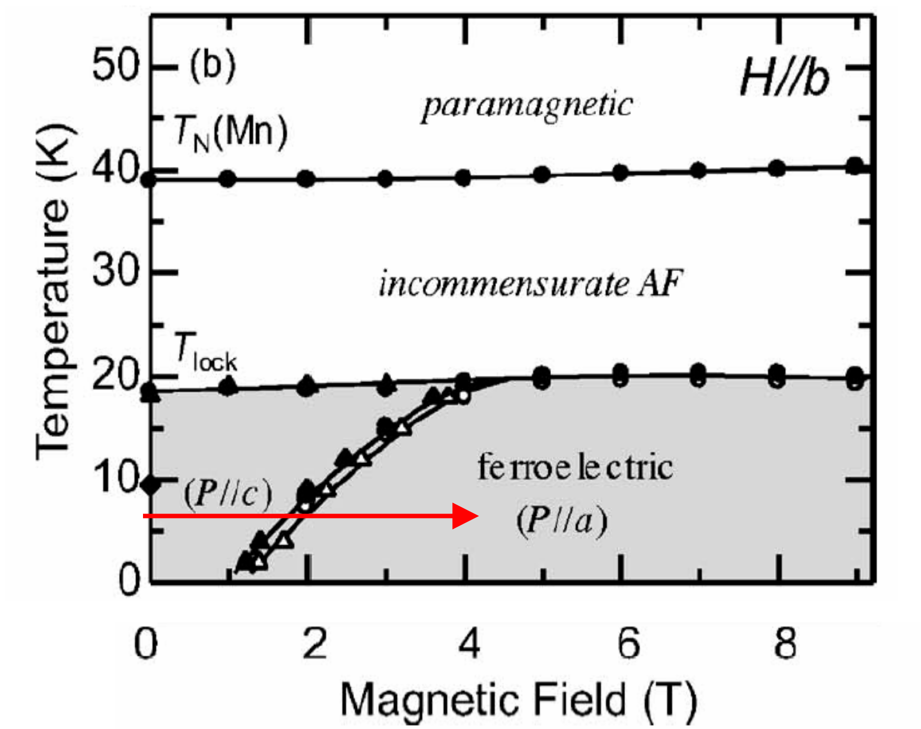
electromagnon

Electromagnon mode

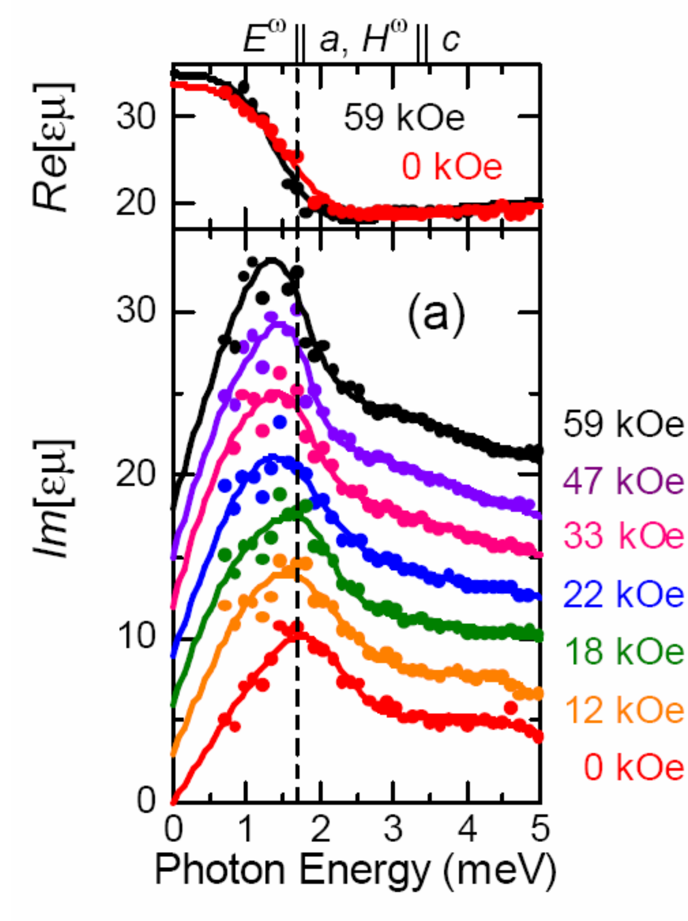


Softening at H_C ~ divergent ε_a

Magnetic field dependence



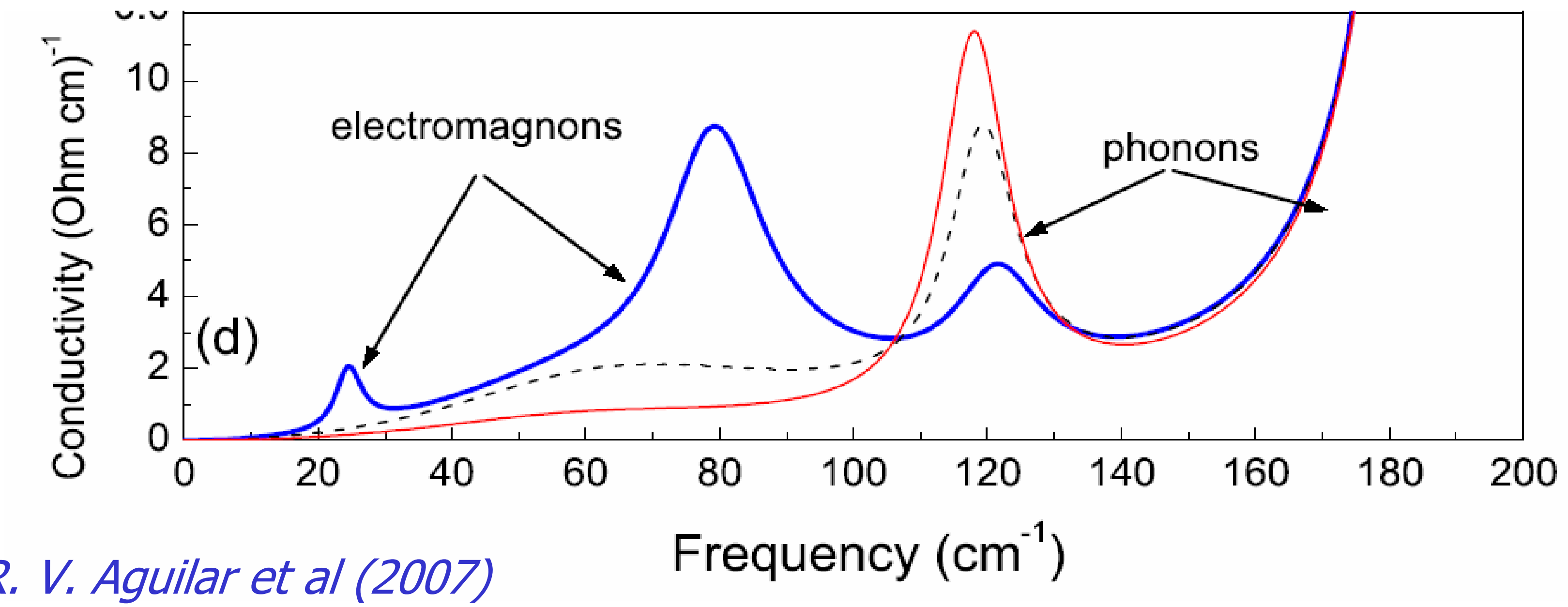
T. Kimura et al (2005)



N. Kida et al (2008)

$Eu_{1-x}Y_xMnO_3$

ab spiral $E \parallel a$



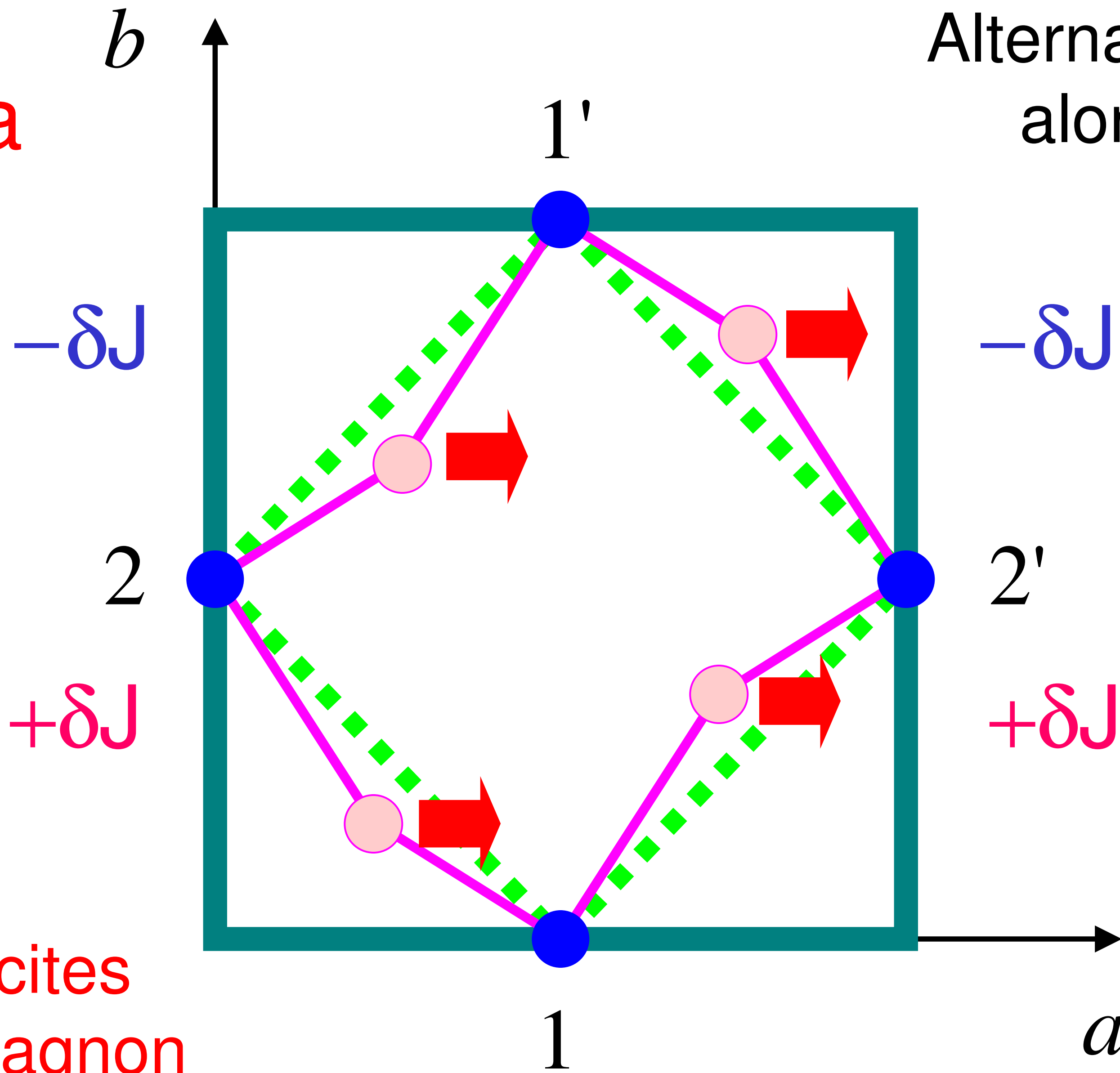
R. V. Aguilar et al (2007)

$RMnO_3$

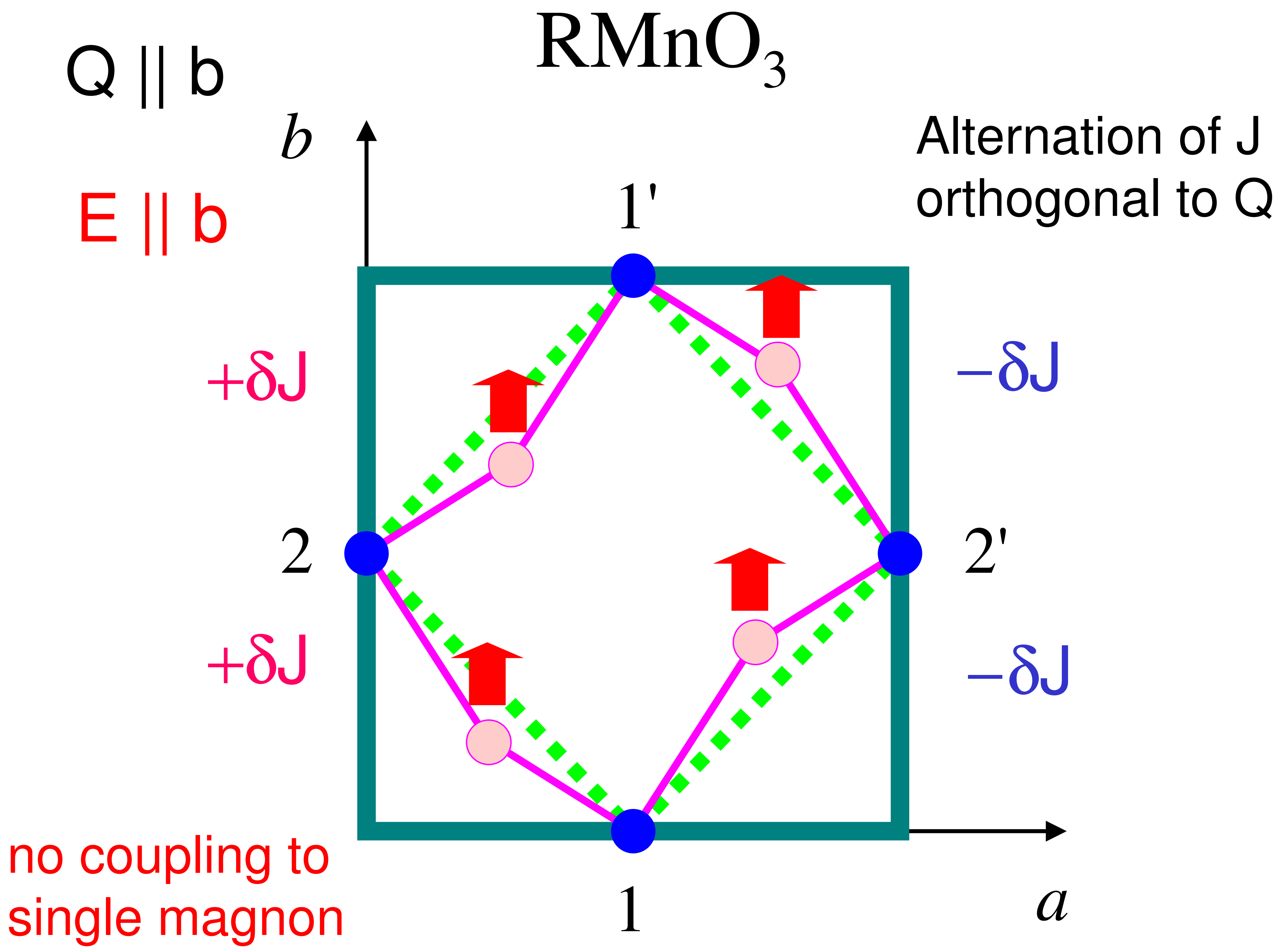
Q || b

E || a

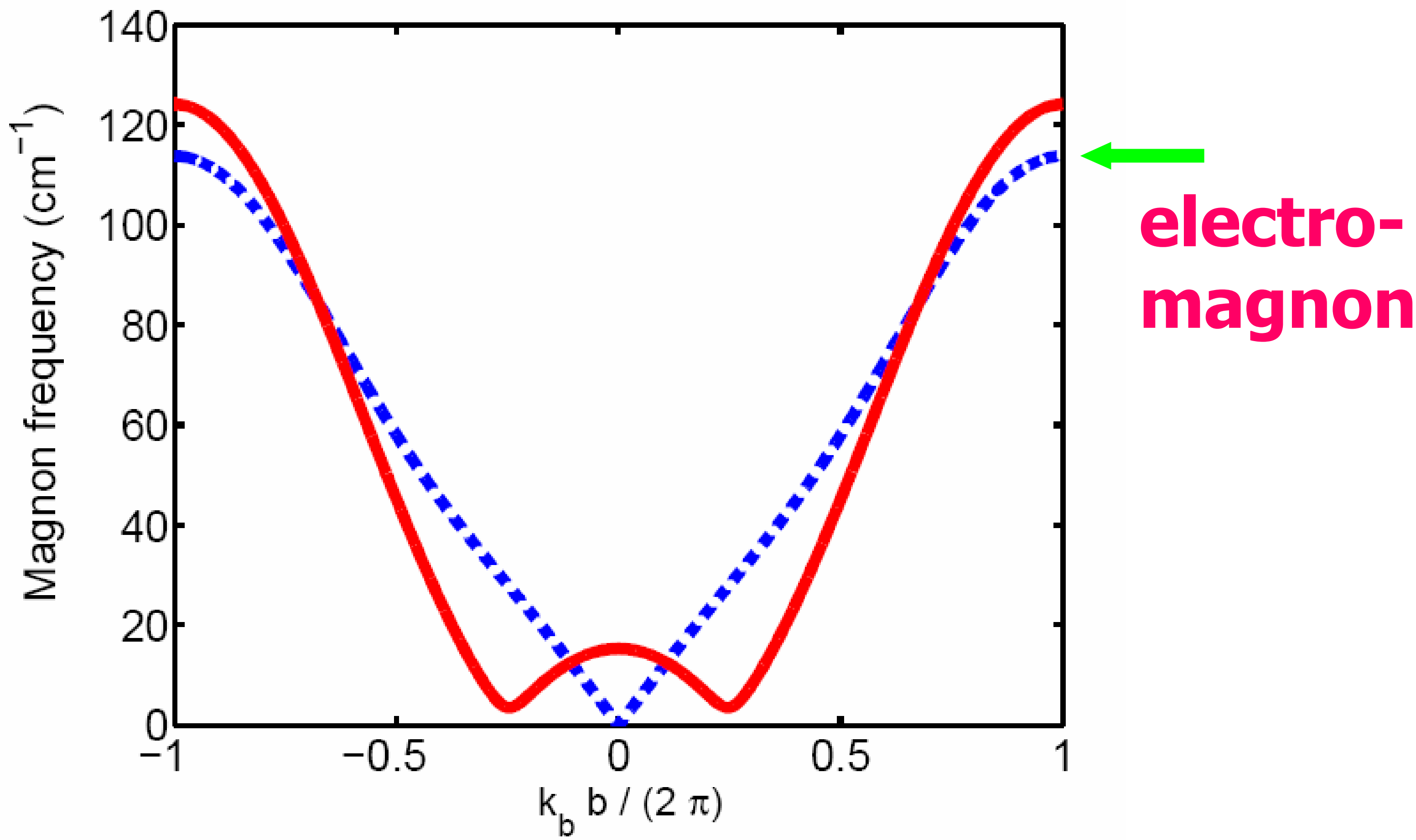
Alternation of J along Q



E || a excites single magnon

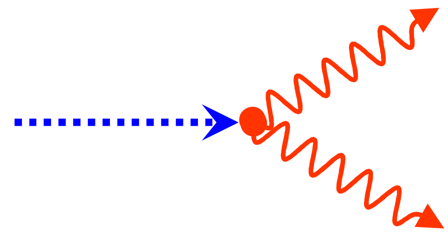

RMnO3
Q || b
E || b
b
Alternation of J
orthogonal to Q
1'
+δJ
−δJ
2
2'
+δJ
−δJ
no coupling to
single magnon
1
a

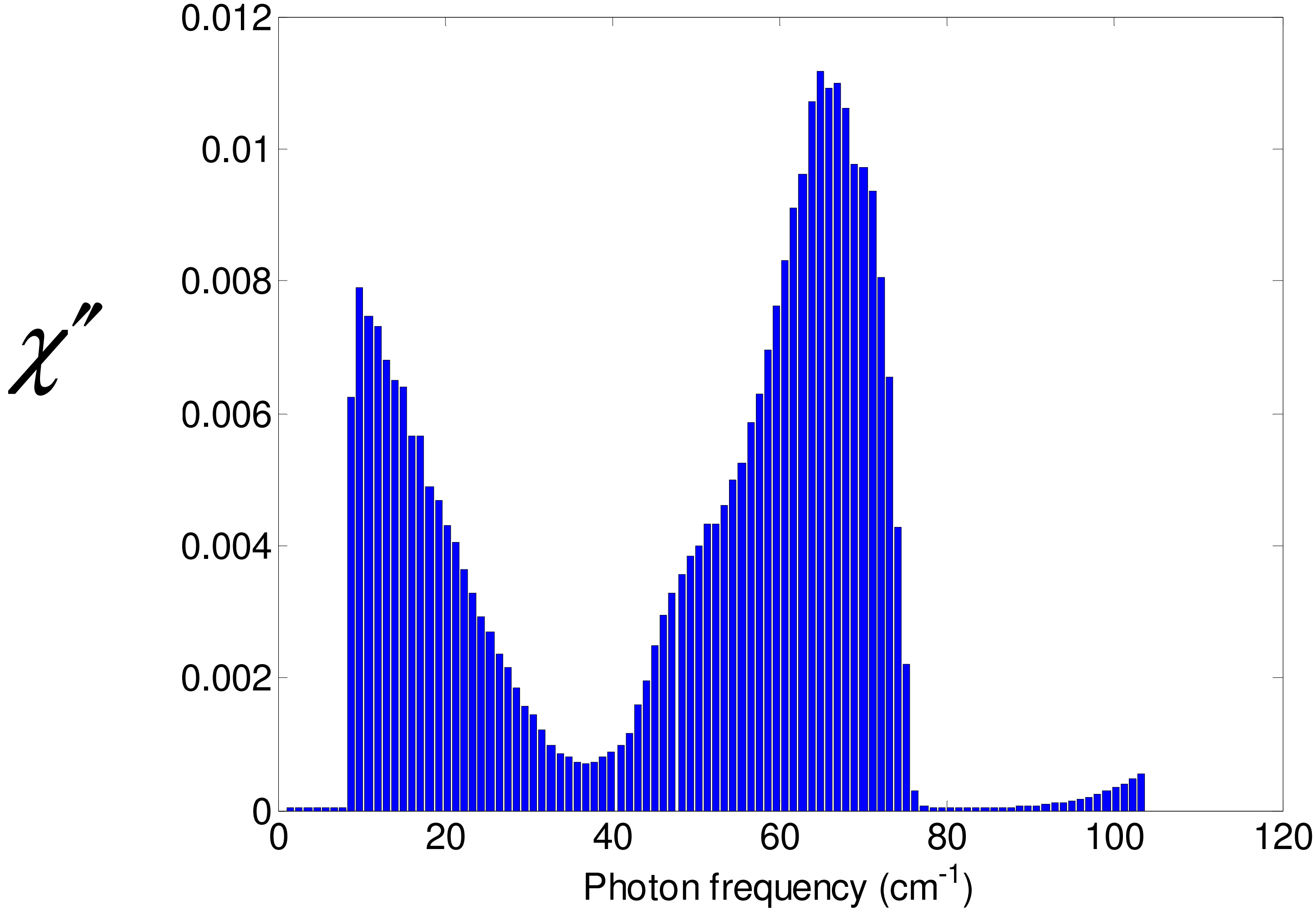
Magnons in spiral state of $RMnO_3$



Bi-magnon continuum

e || a





Conclusions

- Magnetic frustration gives rise to unusual spin orders that break inversion symmetry and give rise to multiferroic behavior and linear magnetoelectric effect