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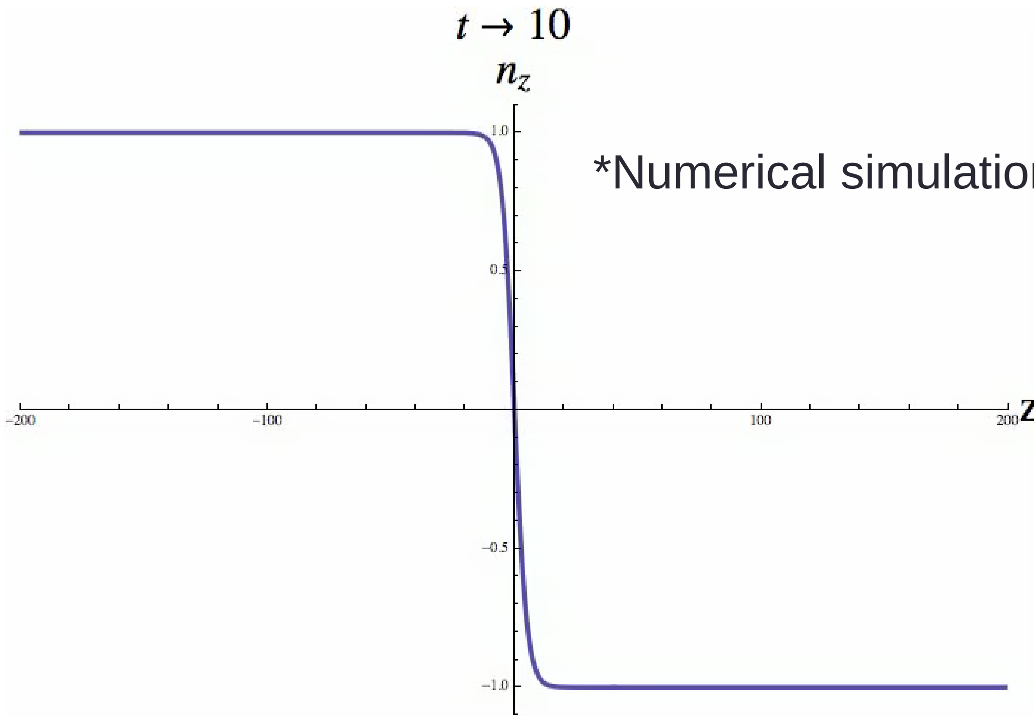
SPIN WAVES AND DOMAIN WALL MOTION IN ANTIFERROMAGNETS

arXiv:1311.4328



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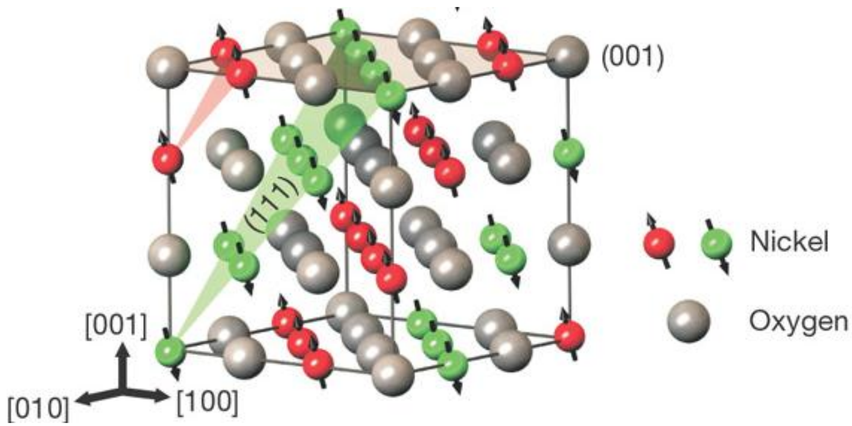
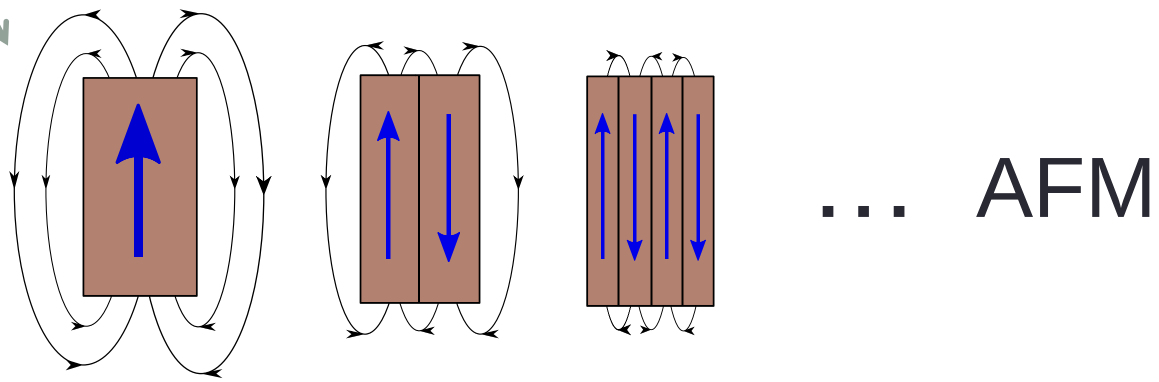
Why antiferromagnets (AFMs)?

- Highly ordered spin systems.
- Current-induced torques.
  [Wei et al. PRL 98, 116603 (2007)]
- Insulating, semiconducting, or metallic.
- Rich spin wave phenomena.
- Have no stray fields.



[Nature **446**, 522-525 (2007)]

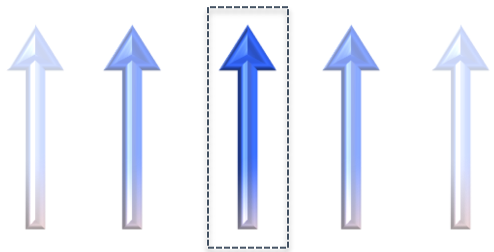


The AFM Staggered Field

$$\mathcal{H} = -\sum_{<i,j>} \mathcal{J}_{ij} \vec{s}_i \cdot \vec{s}_j$$

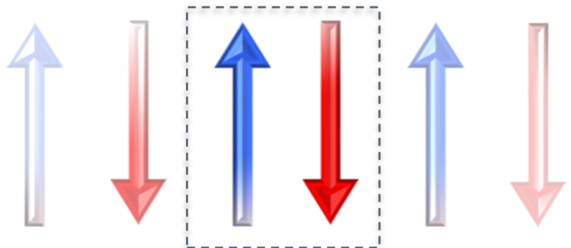
$\mathcal{J}_{ij} > 0$

Ferromagnets



$\mathcal{J}_{ij} < 0$

Antiferromagnets



$$\mathbf{m} = \mathbf{M} / M_s$$

Magnetization field

$$\mathbf{n} = \frac{\mathbf{m}_1 - \mathbf{m}_2}{|\mathbf{m}_1 - \mathbf{m}_2|}$$

“Staggered” field

$$\mathbf{m} = \mathbf{m}_1 + \mathbf{m}_2$$

AFM equations of motion

Gilbert damping parameters

$$\dot{\mathbf{n}} = (\gamma \mathbf{f}_m - G_1 \dot{\mathbf{m}}) \times \mathbf{n}$$

$$\dot{\mathbf{m}} = (\gamma \mathbf{f}_n - G_2 \dot{\mathbf{n}}) \times \mathbf{n} + (\gamma \mathbf{f}_m - G_1 \dot{\mathbf{m}}) \times \mathbf{m}$$

[Hals et al. PRL 106, 107207 (2011)]

$\mathbf{m}_1 \mathbf{m}_2$

$\mathbf{n}$

$$\mathbf{n} = \frac{\mathbf{m}_1 - \mathbf{m}_2}{|\mathbf{m}_1 - \mathbf{m}_2|}$$

$$|\mathbf{n}| = 1$$

$$\mathbf{m} = \mathbf{m}_1 + \mathbf{m}_2$$

$$\mathbf{m} \cdot \mathbf{n} = 0$$

Effective fields:

$$\mathbf{f}_m = -\frac{\partial U}{\partial \mathbf{m}} \qquad \mathbf{f}_n = -\frac{\partial U}{\partial \mathbf{n}}$$

U – Free energy

➢ **Landau-Lifshitz-Gilbert**

$$\dot{\mathbf{m}} = \gamma \mathbf{m} \times \mathbf{H}_{eff} - \alpha \mathbf{m} \times \dot{\mathbf{m}}$$

Without damping and ext. fields:

$$\dot{\mathbf{n}} = \gamma \mathbf{m} \times \mathbf{n}$$

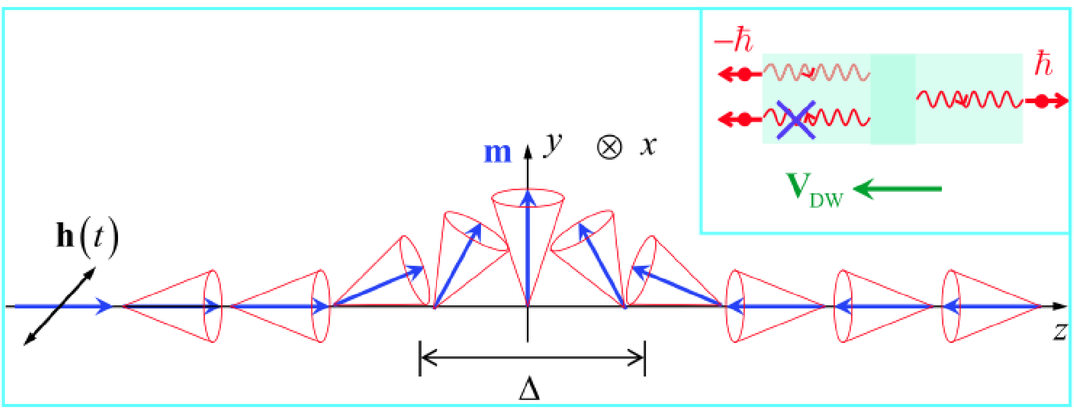
$$\dot{\mathbf{m}} = \gamma \mathbf{f}_n \times \mathbf{n}$$

$$\Rightarrow \ddot{\mathbf{n}} \propto \mathbf{f}_n$$

NB: Different from ferromagnets.
Second order in time derivatives.

Motivation

- Magnonic torque in ferromagnets

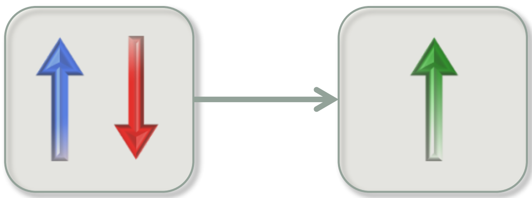


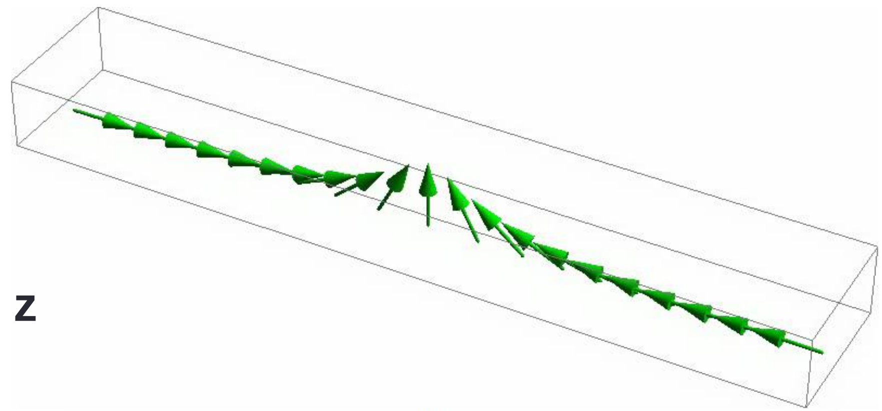
$$V_{DW} = - r^{2} A k$$

[P. Yan et al. PRL 107, 177207 (2011)]

- Is this effect present in AFMs as well?

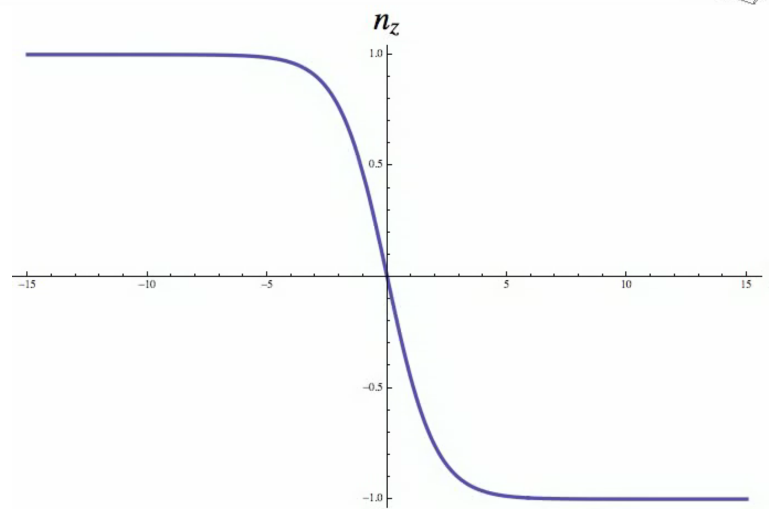
Antiferromagnetic domain wall





- **Our model: 1D AFM insulator along z**

$$U = \frac{1}{2}\int dV(a\,\mathbf{m}^2 + A(\nabla\mathbf{n})^2 - K_z n_z^2)$$



- **Walker's ansatz**

$$\mathbf{n}_{dw} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$$

$$\frac{\theta}{2} = \arctan[\exp(\frac{z - r_w}{\lambda})]$$

$$\lambda = \sqrt{\frac{A}{K_z}}$$

$\varphi_w(t), r_w(t)$: Dynamical variables

Spin waves + domain wall

$$\dot{\mathbf{n}} = (\gamma \mathbf{f}_m - G_1 \dot{\mathbf{m}}) \times \mathbf{n}$$

$$\dot{\mathbf{m}} = (\gamma \mathbf{f}_n - G_2 \dot{\mathbf{n}}) \times \mathbf{n} + (\gamma \mathbf{f}_m - G_1 \dot{\mathbf{m}}) \times \mathbf{m}$$

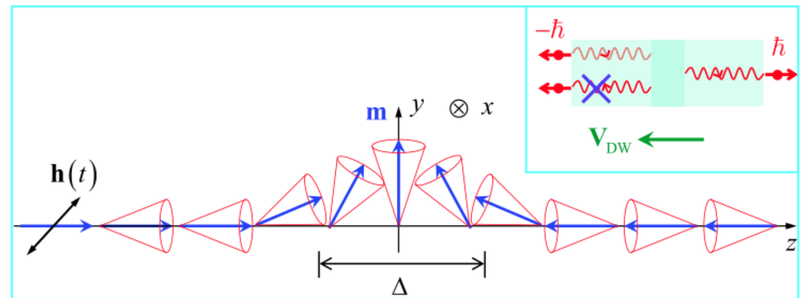
- Expansion in small excitations h

$$\mathbf{n}(z,t) = \mathbf{n}_{dw} + h\,\mathbf{n}_1 + h^2\,\mathbf{n}_2$$

$$\mathbf{m}(z,t) = h\,\mathbf{m}_1 + h^2\,\mathbf{m}_2$$

- Ferromagnets

$$\mathbf{m}_{SW} \rightarrow \rho(\cos(kz - \omega t)\hat{x} + \sin(kz - \omega t)\hat{y})$$



- To order h we find wave equations:

$$\frac{\ddot{\mathbf{n}}_1}{\gamma^2 a} = A\,\partial_z^2 \mathbf{n}_1 + K_z[2\,\mathrm{sech}^2(\frac{z - r_w}{\lambda}) - 1]\mathbf{n}_1$$

Dispersion

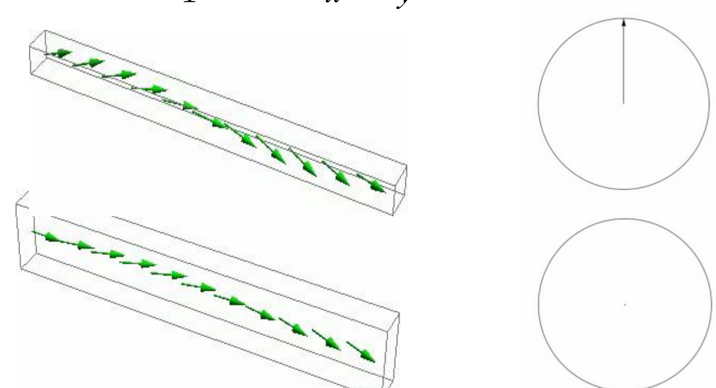
$$\omega^2 = \gamma^2 a A(k^2 + \frac{1}{\lambda^2})$$

Homogeneous system

$$\omega = \gamma\sqrt{aA}k$$

- Antiferromagnets

$$\mathbf{n}_1 \rightarrow (\mathbf{n}_x, \mathbf{n}_y)$$



Spin waves + domain wall

- Ansatz: SW-DW interaction is of order h^2:

- After doing time averaging:

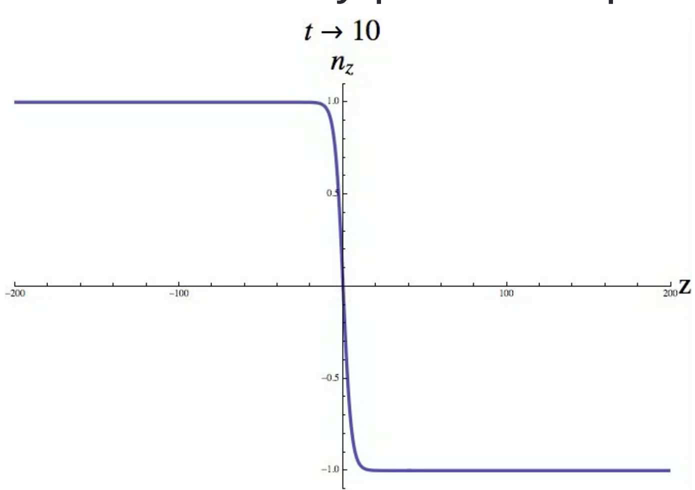
$$\ddot{r}_w + \alpha\gamma G_2 \dot{r}_w = \frac{\alpha\gamma^2 K_z}{\pi} \int dz [\langle \mathbf{n}_1^2 \rangle \mathrm{sech}(\frac{z - r_w}{\lambda}) \tanh(\frac{z - r_w}{\lambda})]$$

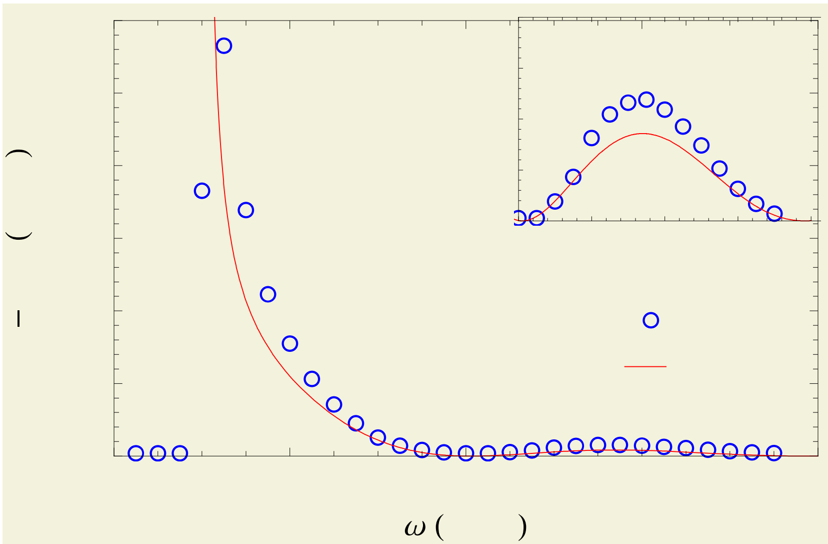
$$[\ldots] \Rightarrow \dot{r}_w \to V_{DW} = -\rho^2 e^{-Q|z_0 - r_w|} \frac{(1 + 3k^2\lambda^2)\omega}{6k} \approx -\frac{\rho^2 \omega}{6k}$$

Force on the domain wall

~~Divergent~~ (Edit: Resonance) in long-wavelength limit

- Transverse linearly polarized spin waves





What about circularly polarized waves?

$$\dot{\mathbf{n}} = (\gamma \mathbf{f}_m - G_1 \dot{\mathbf{m}}) \times \mathbf{n}$$

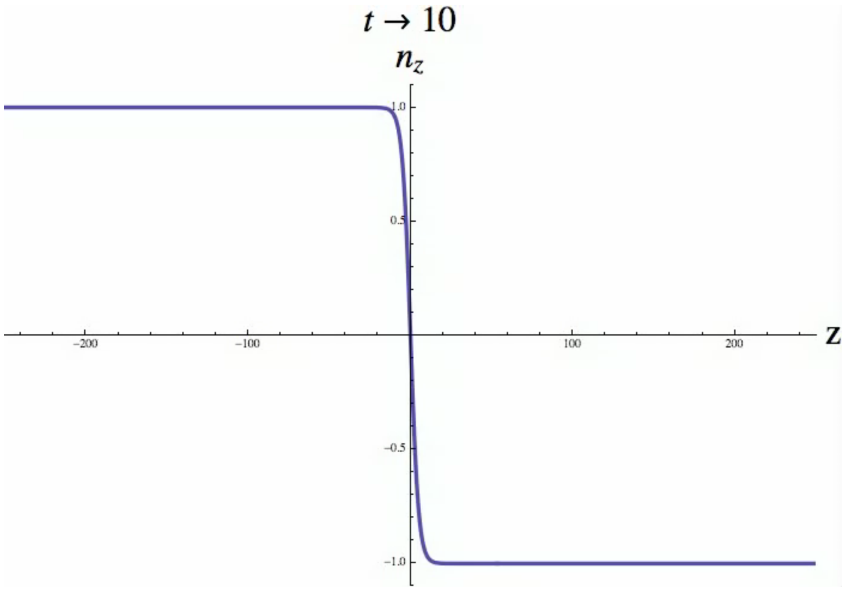
$$\dot{\mathbf{m}} = (\gamma \mathbf{f}_n - G_2 \dot{\mathbf{n}}) \times \mathbf{n} + (\gamma \mathbf{f}_m - G_1 \dot{\mathbf{m}}) \times \mathbf{m}$$

- Waves carry angular momentum.

$$\dot{m}_z + \partial_z J_z = 0$$

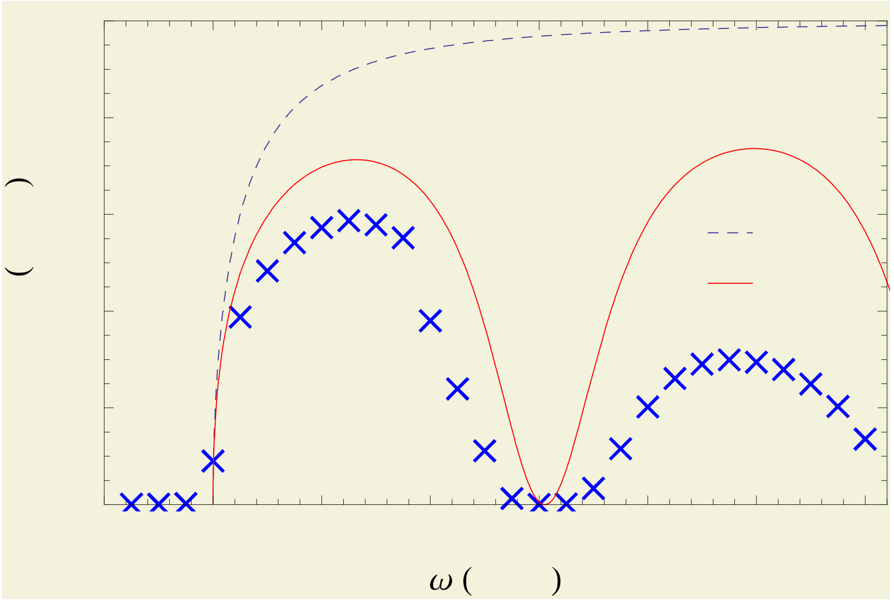
$$J_z = \gamma A (n_x \partial_z n_y - n_y \partial_z n_x) = \pm \rho^2 \gamma A k$$

J_z- "Spin wave spin current"



- Strong exchange interaction in the AFM counteracts build-up of local magnetic moment.
- Spin waves reflect from the domain wall.
- Spin waves transfer linear momentum to domain wall.

Circularly polarized waves



- Assume "total reflection" and linear momentum transfer:

$$V_{DW} = \frac{v_g}{1 + \dfrac{\alpha \gamma G_2}{\rho^2 k / \omega}}$$

- For low damping the domain wall can be accelerated up to the spin wave group velocity v_g.

- Velocity potentially very high. V_{circ}/V_{lin}~10. Example: V_g~500 m/s for NiO.
- Oppositely directed than for linear polarization (away from spin wave source).