Antiferromagnetic spin-something-tronics: phenomenological models and approaches

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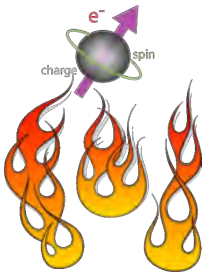
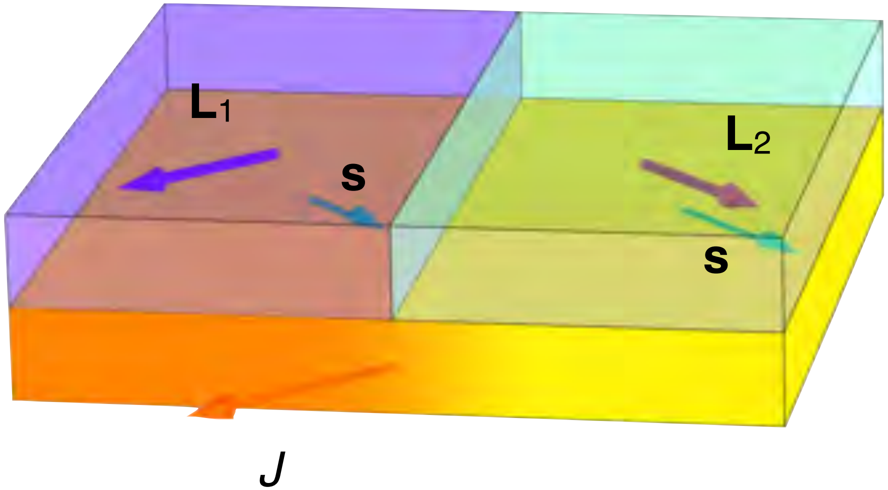
SpinCaT
Mainz

Take-home message

- Dynamics of antiferromagnets is **different** from the dynamics of ferromagnets
- Antiferromagnetic states can be **effectively** manipulated by **spin** and **charge** currents and **temperature** gradient





Motivation

FM $\Rightarrow$ AFM

Application

- High frequencies
- Zero magnetization
- Magnetomechanical coupling
- Combined with semiconductors

New physics

- Variety of structures
- Nontrivial dynamics
- Spin-orbit coupling
- Complicated, less studied

Outline

- Basics of antiferromagnetism: exchange interactions,Neel states, magnetic sublattices
- Dynamic equations. Torques and forces
- Current-induced dynamics
- Temperature effects

Outline

- **Basics of antiferromagnetism: exchange interactions,Neel states, magnetic sublattices**
- Dynamic equations. Torques and forces
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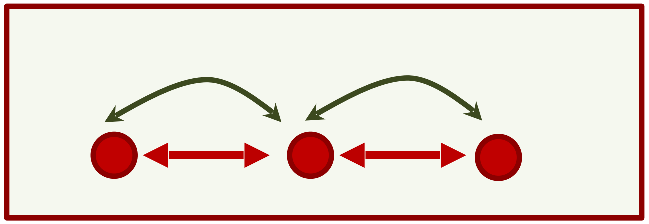
- Temperature effects

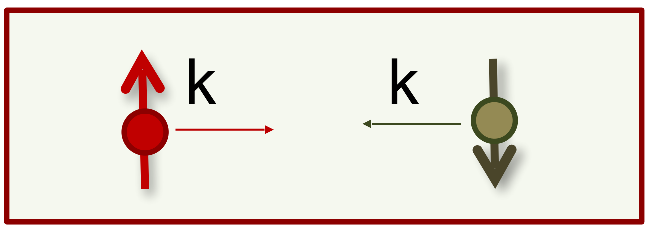
Hierarchy of atomic interactions

energy, eV



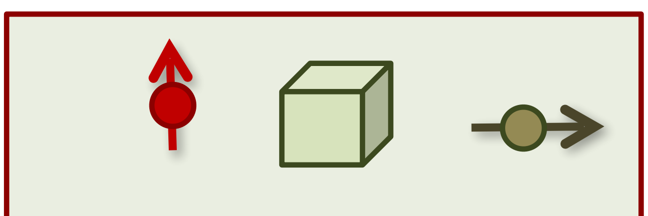
1 eV

$$\frac{e^2}{a}, \frac{\hbar^2}{ma^2}$$



1 meV

$$-\lambda_{SO}(\mathbf{SL})$$

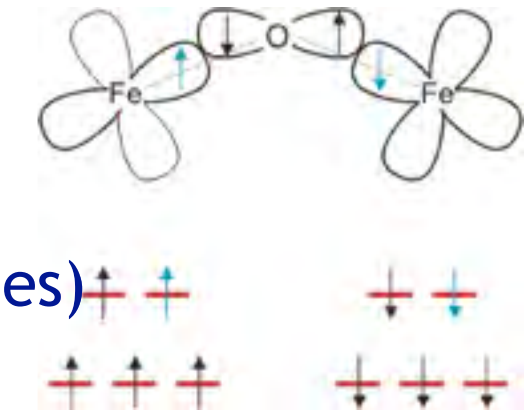


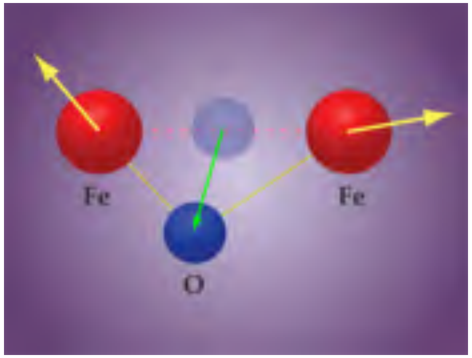
1μeV

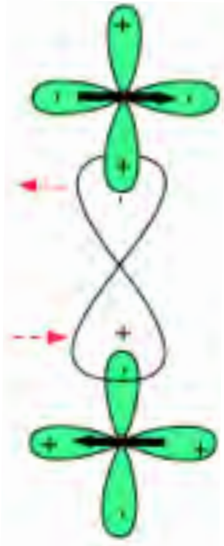
$$-K_{\mathrm{an}}S_z^2$$

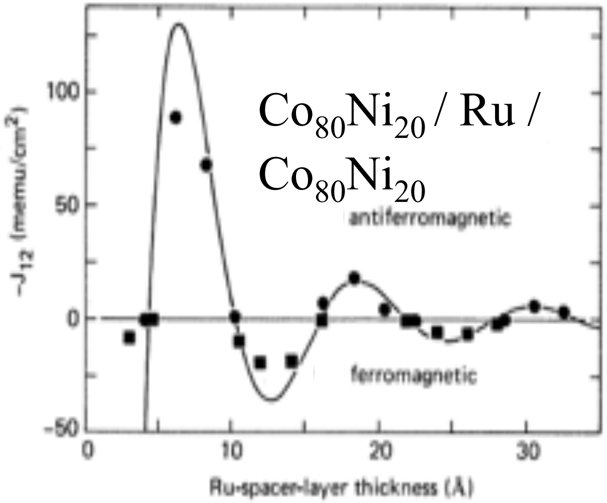
AF exchange interactions

- Superexchange (insulators)
- RKKY (4-f metals)
- Exchange in 3-d metals
- Double exchange (transition metal oxides)
- <u>**DMI**</u> (anisotropic exchange)







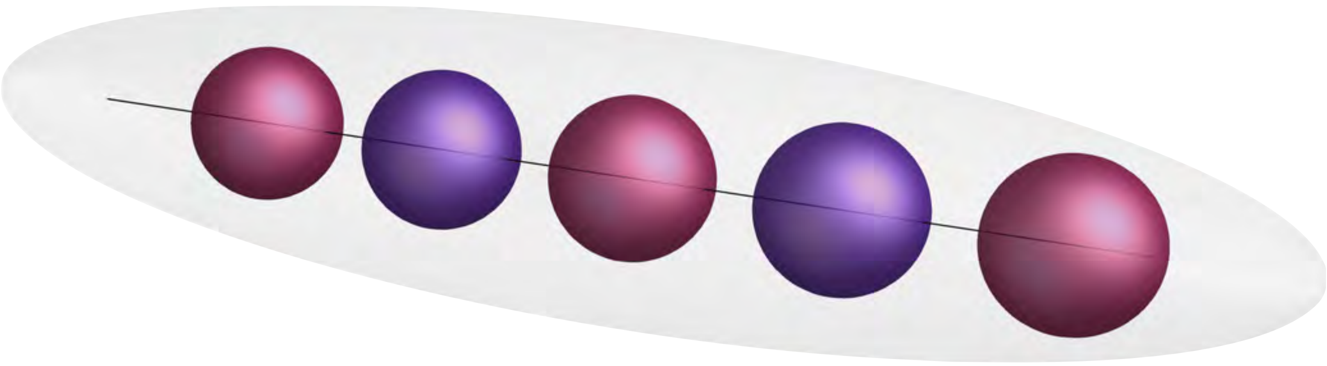


Parkin et al., Phys.Rev. B 44, 7131 (1991)

Quantum state vs Neel state

$$\hat{H} = \sum_{j,k} J_{jk} \hat{\mathbf{S}}_j \hat{\mathbf{S}}_k$$

Quantum state, *T*=0

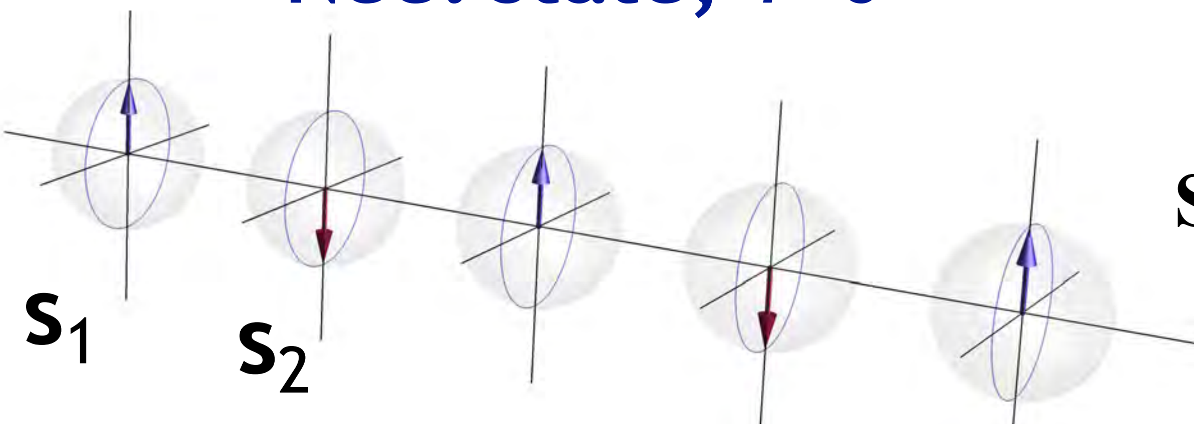


$$|\psi\rangle = \sum_{\{j\}} c_{\{j\}} |S_{z1}\rangle |S_{z2}\rangle \dots |S_{zj}\rangle |S_{zj+1}\rangle$$

Quantum state vs Neel state

$$\hat{H} = \sum_{j,k} J_{jk} \hat{\mathbf{S}}_j \hat{\mathbf{S}}_k$$

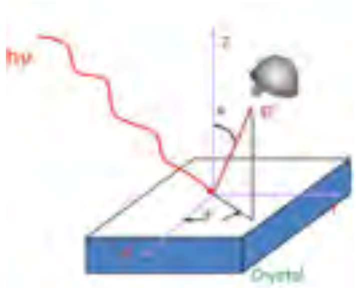
Neel state, $T \neq 0$



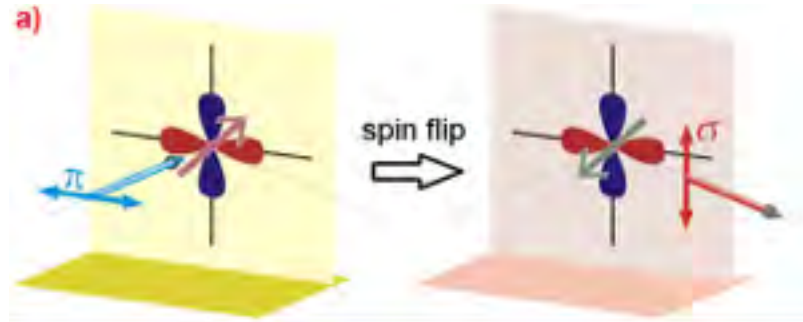
$$\mathbf{S}_1 = -\mathbf{S}_2$$

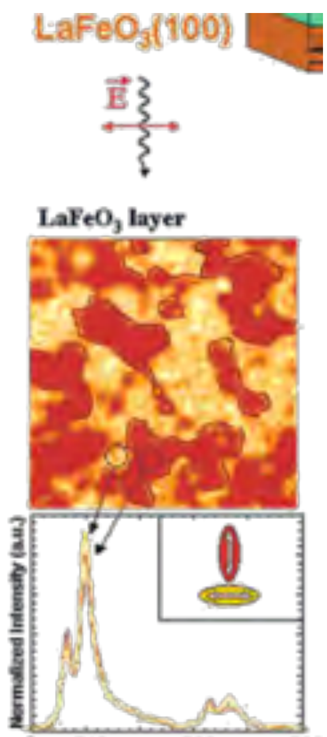
$$\{\mathbf{s}_1, \mathbf{s}_2, \ldots, \mathbf{s}_j, \mathbf{s}_{j+1}\}$$

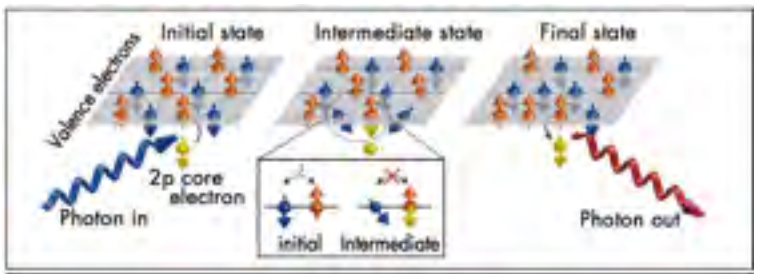
Different experimental technique



ARPES





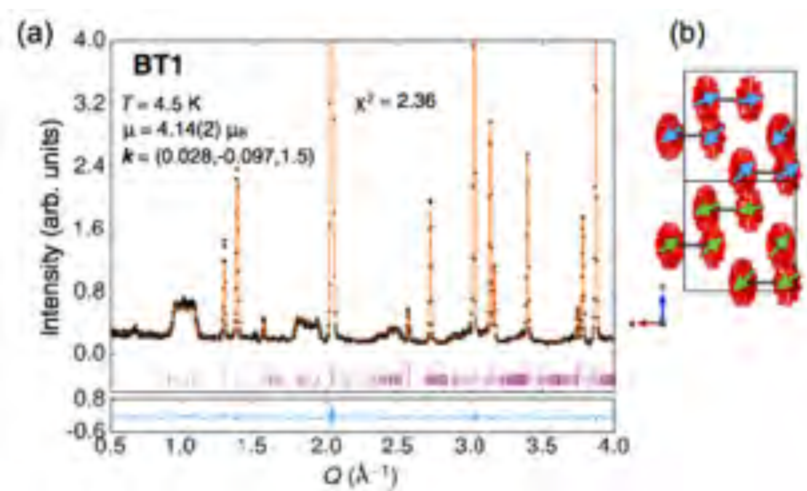


RIXS

Raman spectroscopy

XMLD

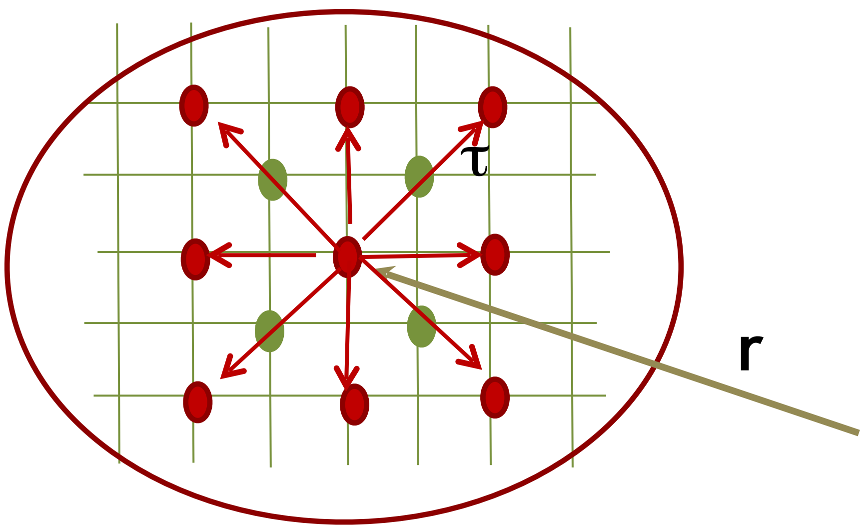
ND



Sublattices

Sublattice magnetizations (Neel, 1948)

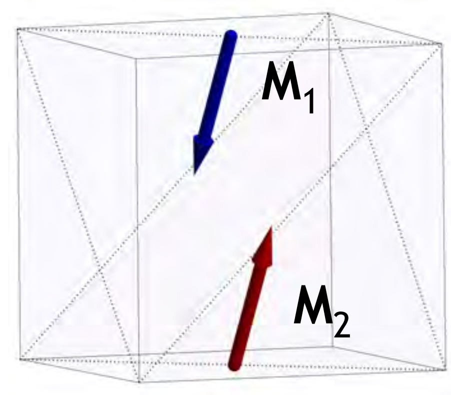
$$\mathbf{M}_k(\mathbf{r}) = \frac{g}{N}\sum_{\tau_j}\mathbf{S}_k\left(\mathbf{r}+\tau_j\right)$$



- Physically small volumes
- Macroscopic vectors
- Field variables

& order parameters

Symmetry relations: $2_{[110]}$: $\mathbf{M}_1 \leftrightarrow \mathbf{M}_2$



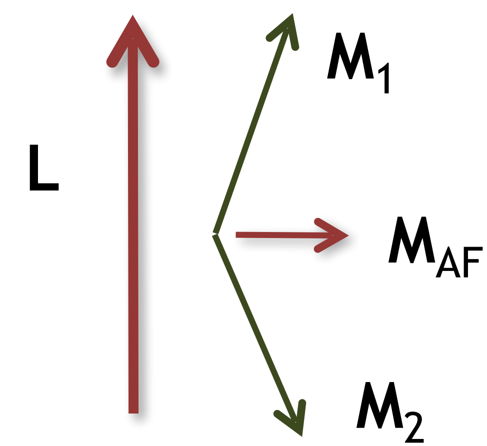
NiO, IrMn

Order parameter (Neel vector):

$$\mathbf{L} = \mathbf{M}_1 - \mathbf{M}_2$$

Magnetization: $\mathbf{M}_{AF} = \mathbf{M}_1 + \mathbf{M}_2 \approx 0$

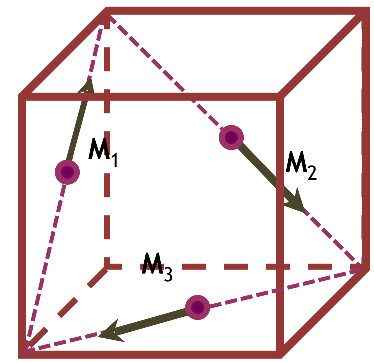
$\mathbf{L} \perp \mathbf{M}_{AF}$, $|\mathbf{L}| \approx 2\, M_s$



Noncollinear structures

$2_{[110]} : M_1 \leftrightarrow M_2,\ M_3 \leftrightarrow M_3$

$3_{[111]} : M_1 \rightarrow M_2 \rightarrow M_3$

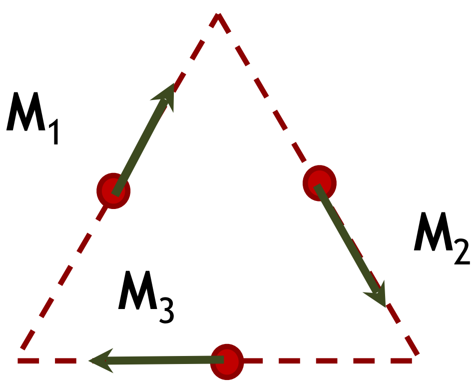


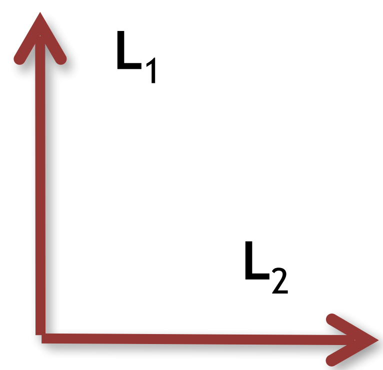
Order parameters (Neel vectors):

$L_1 = M_1 + M_2 - 2M_3 \quad L_2 = M_1 - M_2$

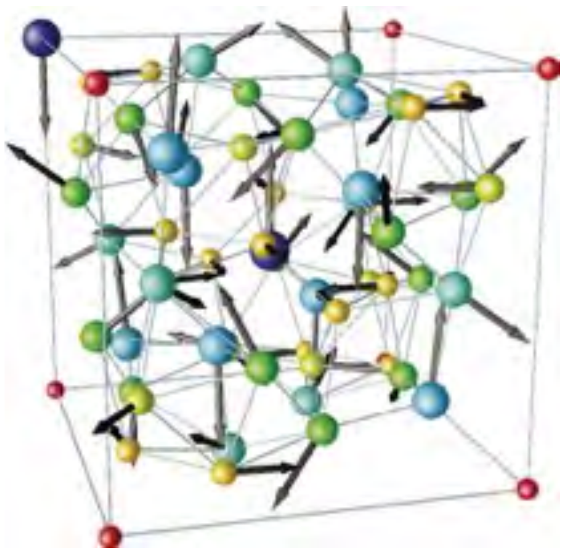
Magnetization: $M_{AF} = M_1 + M_2 + M_3 \approx 0$

IrMn, Mn_3NiN

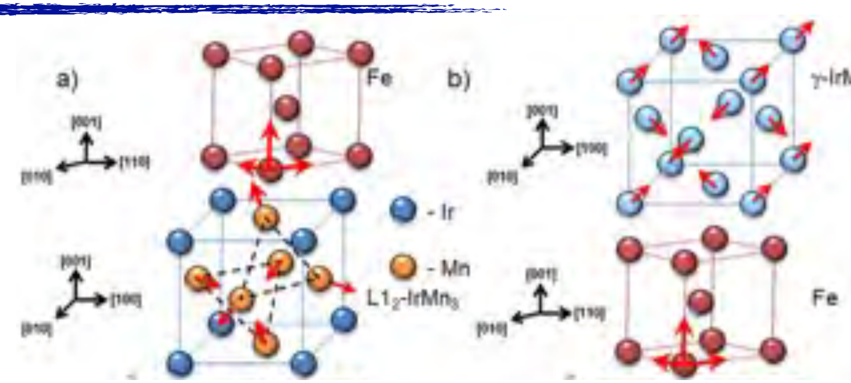


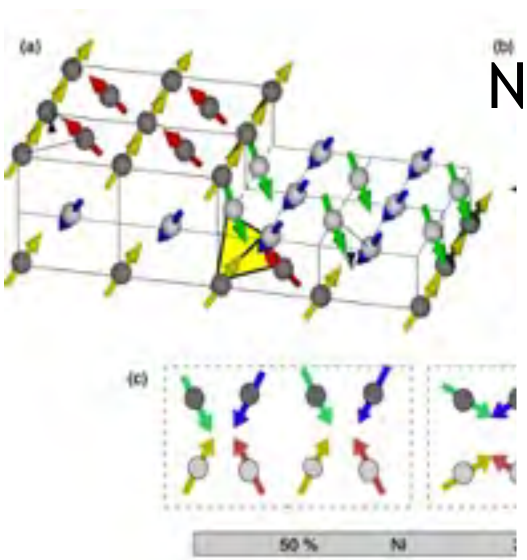


Variety of AFM structures

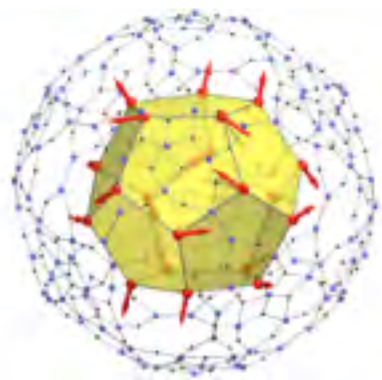


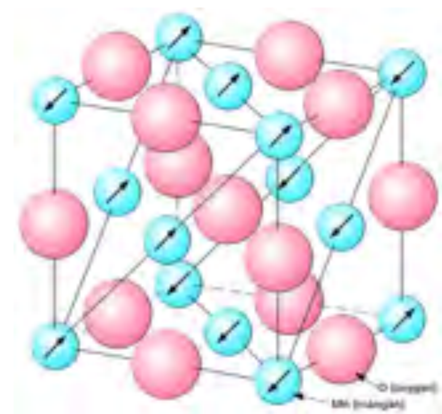
α-Mn





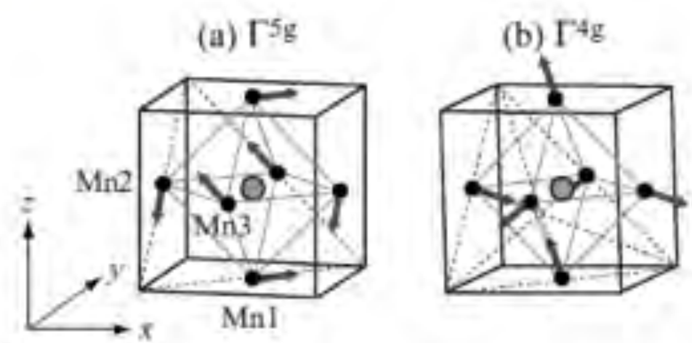
NiMn





NiO

Mn_3NiN



Take-home messages

- AF = variety of exchange mechanisms
- AF = metals,insulators and in between
- AF = variety of structures
- Macroscopic description = sublattice magnetizations

Outline

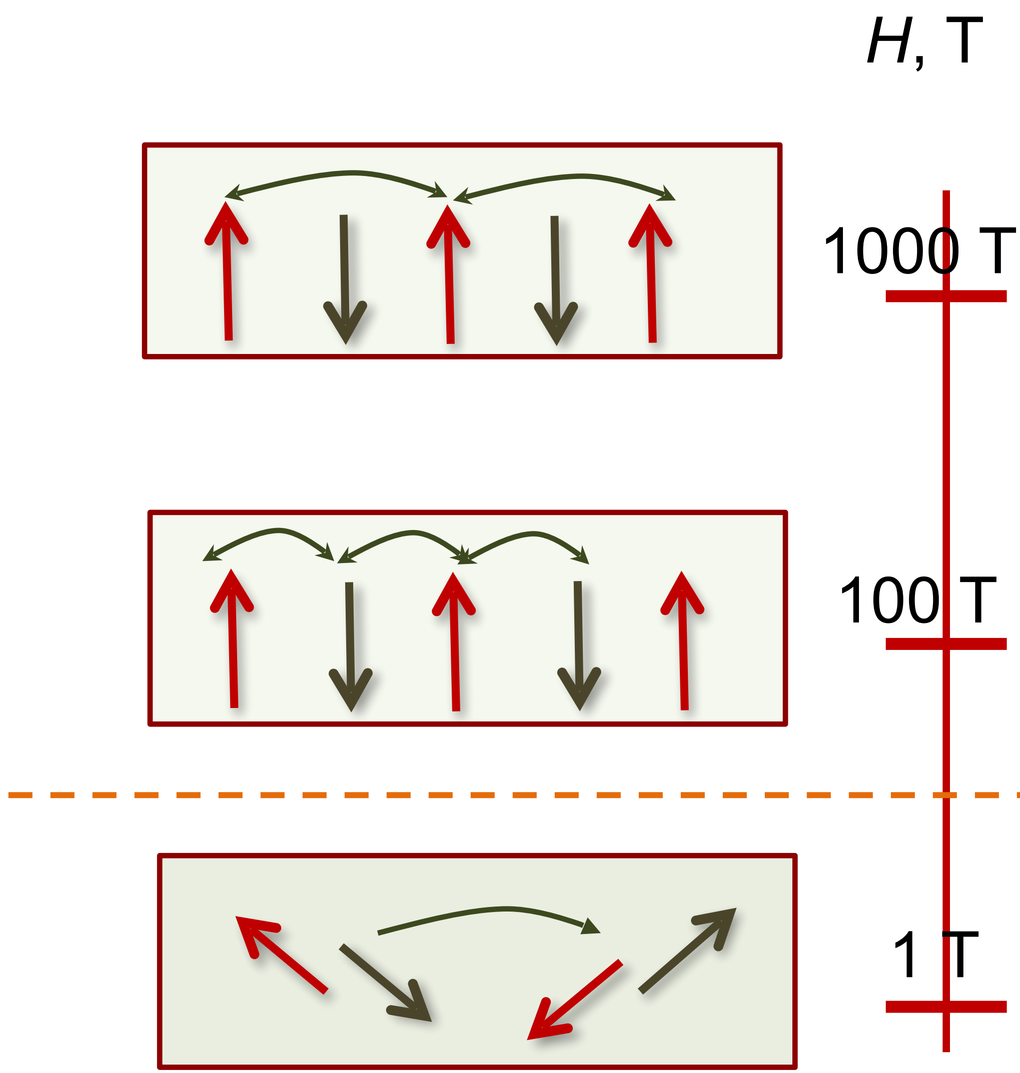
- Basics of antiferromagnetism: exchange interactions,Neel states, magnetic sublattices
- Dynamic equations. Torques and forces
- Current-induced dynamics
- Temperature effects

Spin Torques in antiferromagnet

$$\frac{d\mathbf{M}_1}{dt} = \gamma \mathbf{M}_1 \times \mathbf{H}_1 + \Lambda \mathbf{M}_1 \times \mathbf{p}_1 \times \mathbf{M}_1$$

$$\frac{d\mathbf{M}_2}{dt} = \gamma \mathbf{M}_2 \times \mathbf{H}_2 + \Lambda \mathbf{M}_2 \times \mathbf{p}_2 \times \mathbf{M}_2$$

Hierarchy of interactions

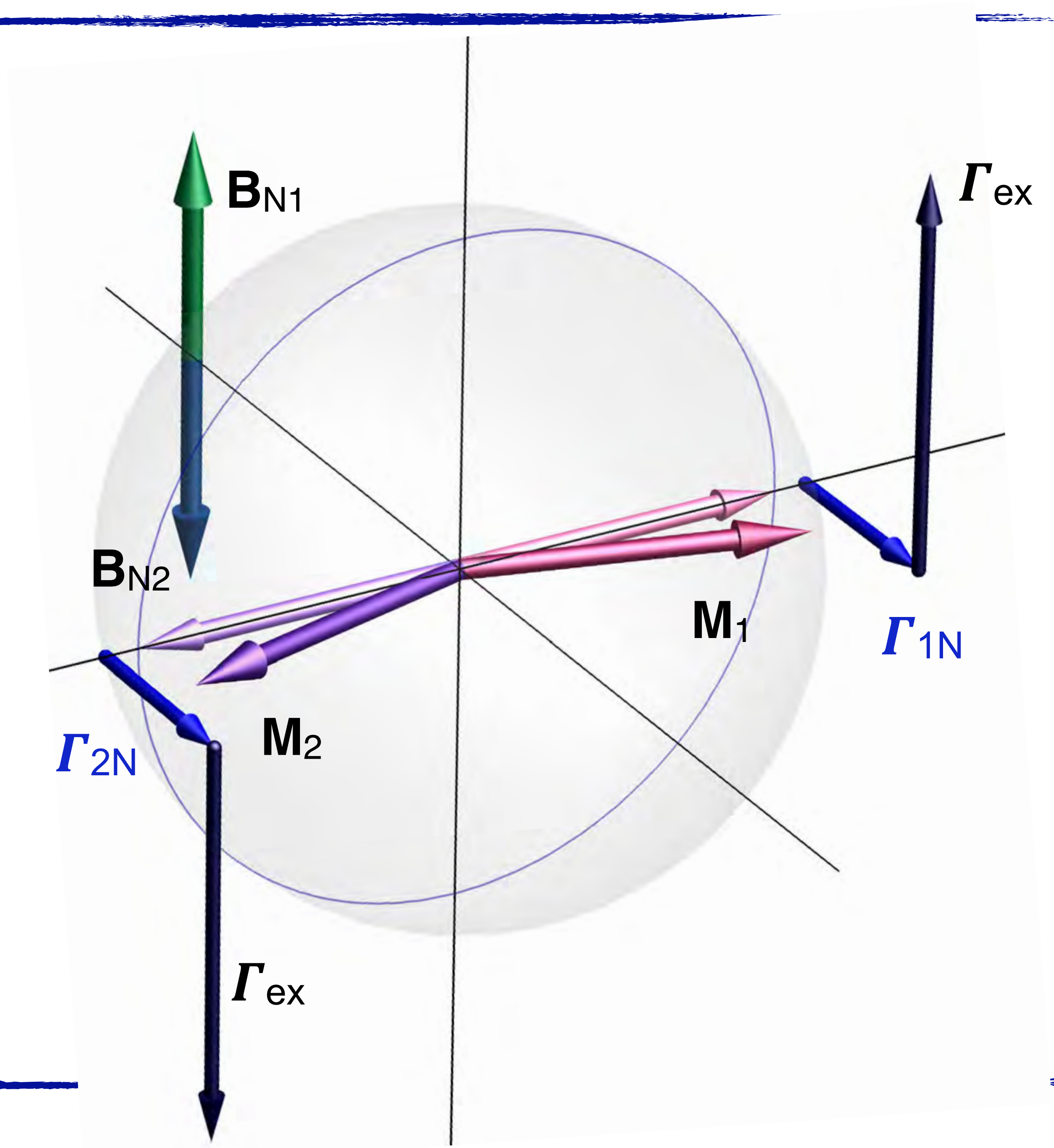


$$J_{intra} \Leftrightarrow T_N$$

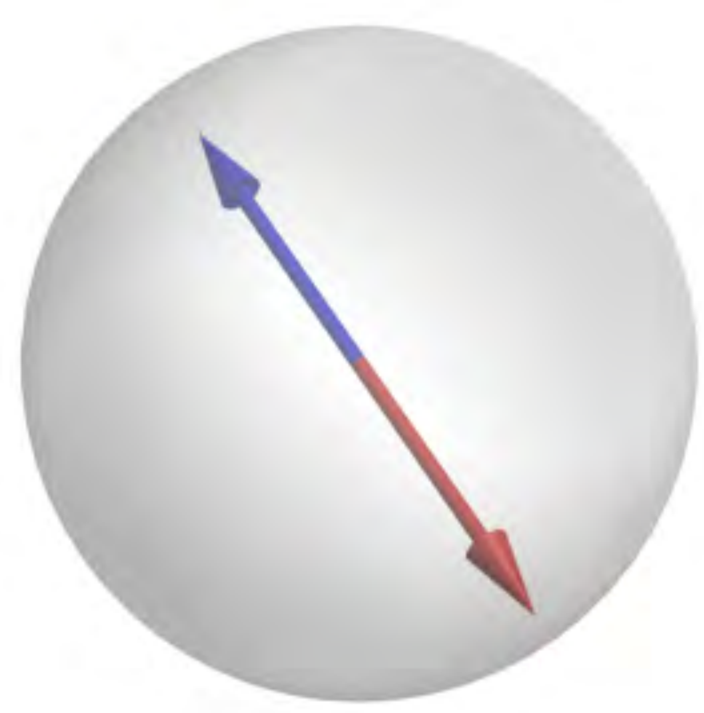
$$J_{inter} \propto 1/\chi_{\perp}$$

$$H_{s\text{-}f} \propto \sqrt{J_{inter} H_{anis}}$$

Exchange enhancement



Solid-like dynamics



$$T, H << J_{\text{inter}}$$

Equations of motion

Dynamics magnetisation

$$\mathbf{M} = \frac{1}{H_{\mathrm{ex}}} \mathbf{L} \times \dot{\mathbf{L}} + \frac{1}{H_{\mathrm{ex}}} \mathbf{L} \times \mathbf{H} \times \mathbf{L}$$

Magnetisation balance

$$\dot{\mathbf{M}} \equiv \frac{1}{H_{\mathrm{ex}}} \mathbf{L} \times \ddot{\mathbf{L}} = \gamma \mathbf{L} \times \mathbf{H}_{\mathrm{L}}$$

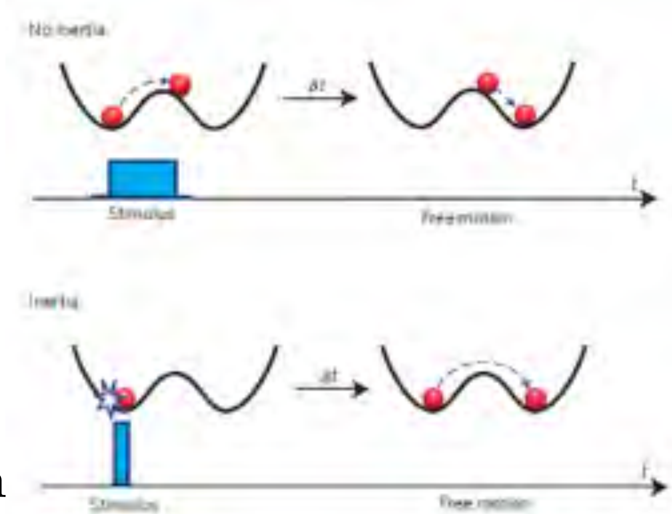
Equation of motion

AF dynamics: Newton-like

$$\underbrace{\ddot{\mathbf{L}}}_{\text{acc.}} = -\underbrace{-\gamma(\dot{\mathbf{H}} \times \mathbf{L} + 2\mathbf{H} \times \dot{\mathbf{L}})}_{\text{gyro force}} + \underbrace{\gamma^2 J_{\text{inter}} \times \mathbf{H}_L}_{\text{potential force}}$$

FM dynamics: precession

$$\underbrace{\dot{\mathbf{M}}}_{\text{ang. momentum}} = -\underbrace{\gamma \mathbf{M} \times \mathbf{H}_M}_{\text{force momentum}}$$



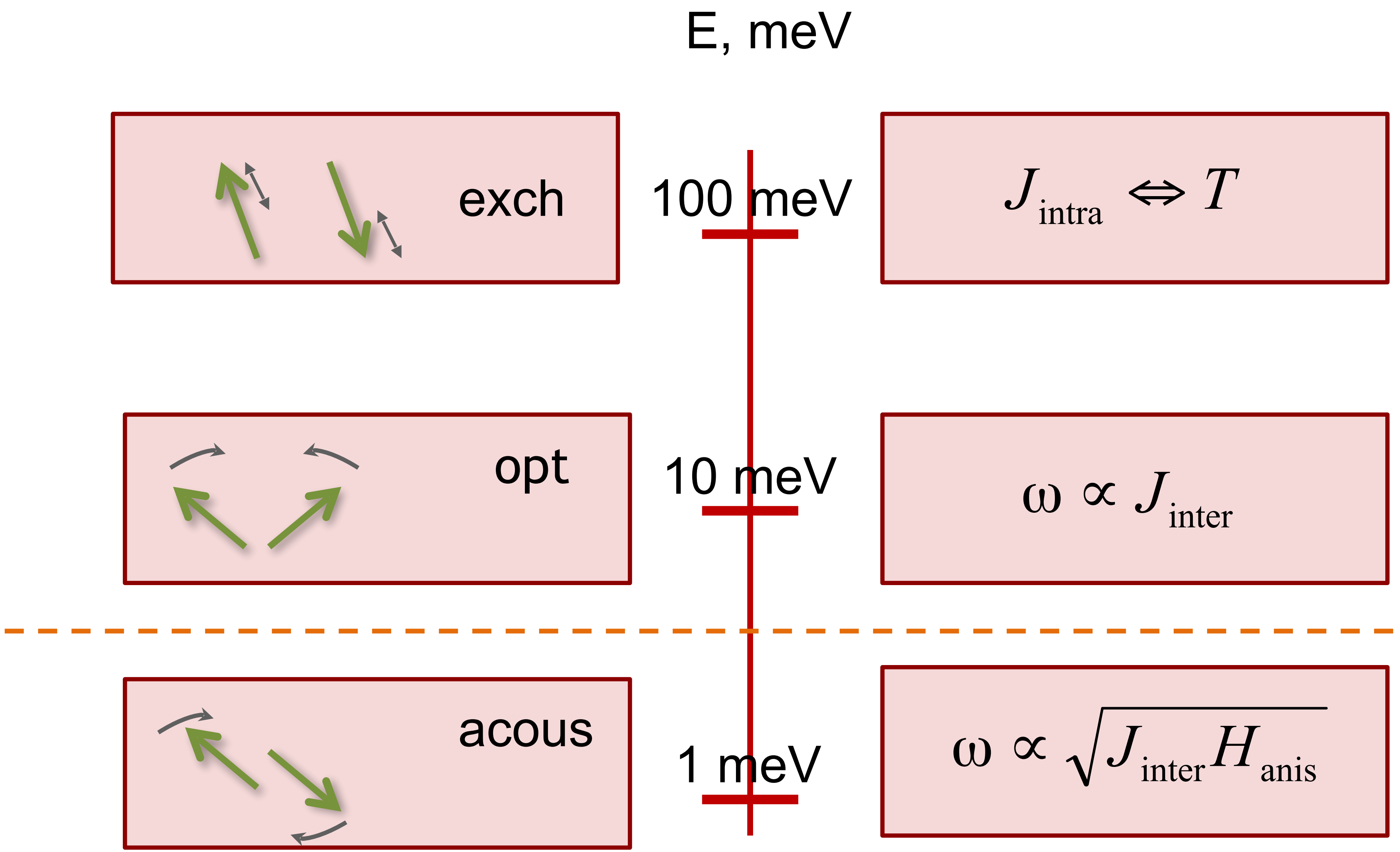
Take-home messages

- AF: dynamics magnetisation
- AF: inertia due to exchange
- Dynamics = balance equation for magnetizations

Outline

- Basics of antiferromagnetism: exchange interactions,Neel states, magnetic sublattices
- Dynamic equations. Torques and forces
- **Current-induced dynamics**
- Temperature effects

Excitations and scales

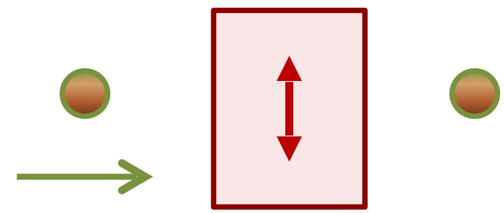


Spintronic: sd-exchange?

$$\hat{H}_{sd} = -J_{sd} \sum \hat{\mathbf{s}}_j \cdot \mathbf{S}_j \Rightarrow -J_{sd} \delta\mathbf{m} \cdot \mathbf{M}_{\mathrm{AF}}$$

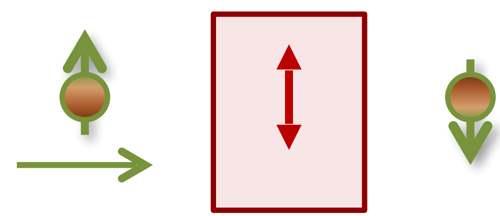
Polarization:

$$\delta\mathbf{m} \propto \langle \hat{\mathbf{s}}_j \rangle \parallel \mathbf{M}_{\mathrm{AF}} \to 0$$



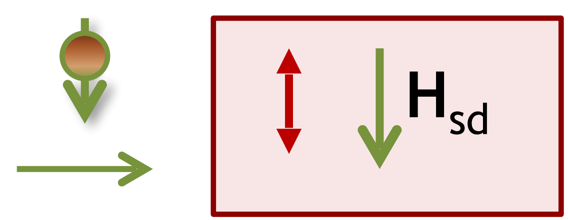
Scattering:

$$\hat{\Pi}_{in} - \hat{\Pi}_{out} \propto f(J_{sd})\delta\mathbf{m} \otimes \mathbf{j}_e$$

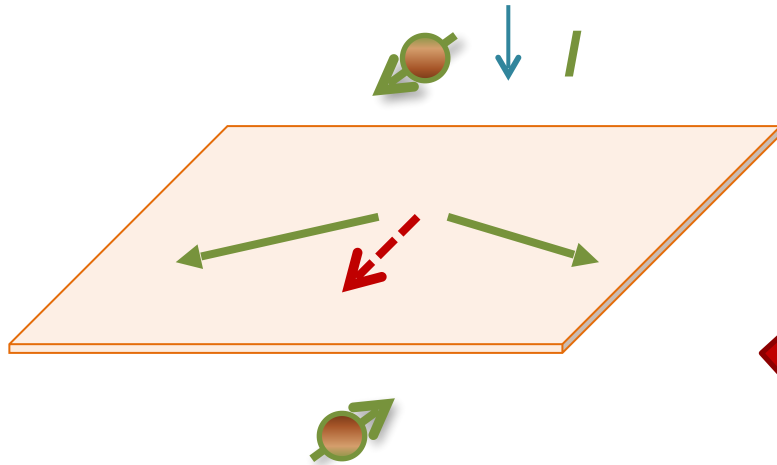


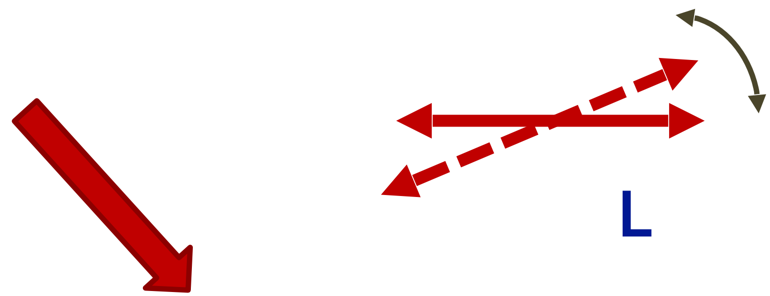
Effective field:

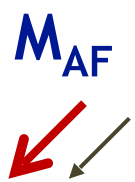
$$\mathbf{H}_{sd} = J_{sd}\delta\mathbf{m}$$



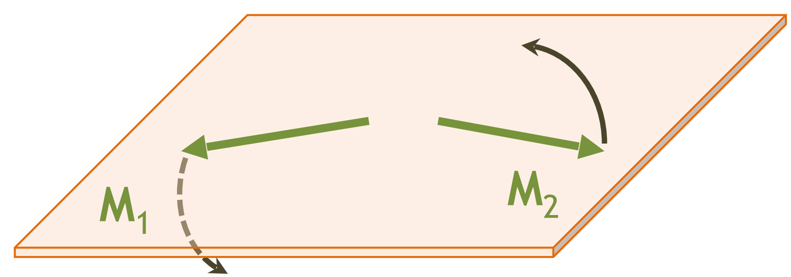
Magnetization⇒ rotation







$$\delta \mathbf{m} + \mathbf{M}_{AF} = const$$



$$\delta \mathbf{m} \rightarrow \mathbf{M}_{\mathrm{AF}} \propto \mathbf{L} \times \dot{\mathbf{L}} \rightarrow \mathbf{L}(t)$$

Spin transfer in AF & spin balance

$$\frac{d\mathbf{M}_{AF}}{dt} = \left(\hat{\Pi}_{in} - \hat{\Pi}_{out}\right)\mathbf{N} + \mathrm{sink}$$

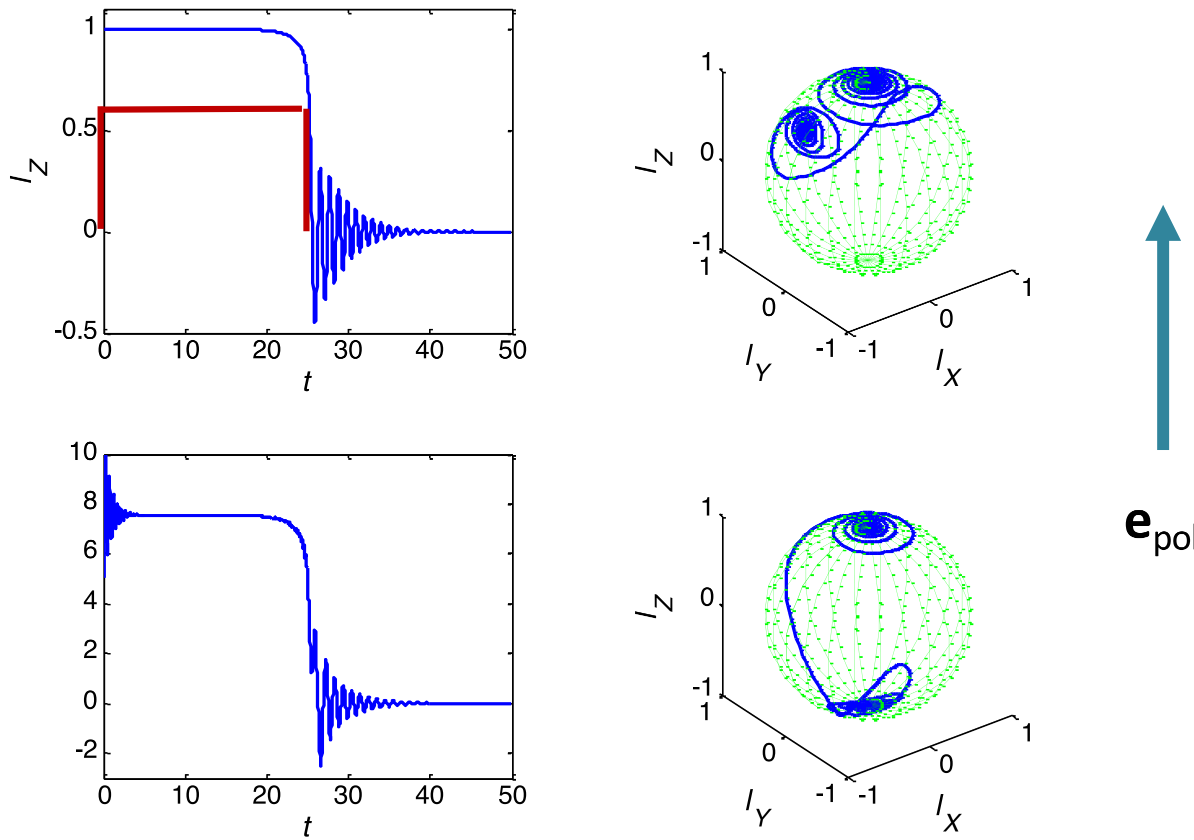
$$\ddot{\mathbf{L}} - \gamma^2 H_{\rm ex}\mathbf{H}_{\rm L} = \left(\beta\frac{dI}{dt} + H_{\rm ex}I\sigma\right)\mathbf{p}\times\mathbf{L} - \gamma_{\rm AF}\mathbf{L}\times\dot{\mathbf{L}}$$

H.Gomonay, V.Loktev,2008

$$m\ddot{x} + 2\gamma\dot{x} + \frac{dU}{dx} = F_{diss}$$

Critical current

$$I_{cr} = \frac{\gamma_{AF}\omega_{AFMR}}{\gamma\sigma J_{inter}} = \frac{\alpha}{\sigma}\gamma H_{an}$$



Critical current

FM

$$H_{STT}^{FM} = \alpha_G H_{an}$$

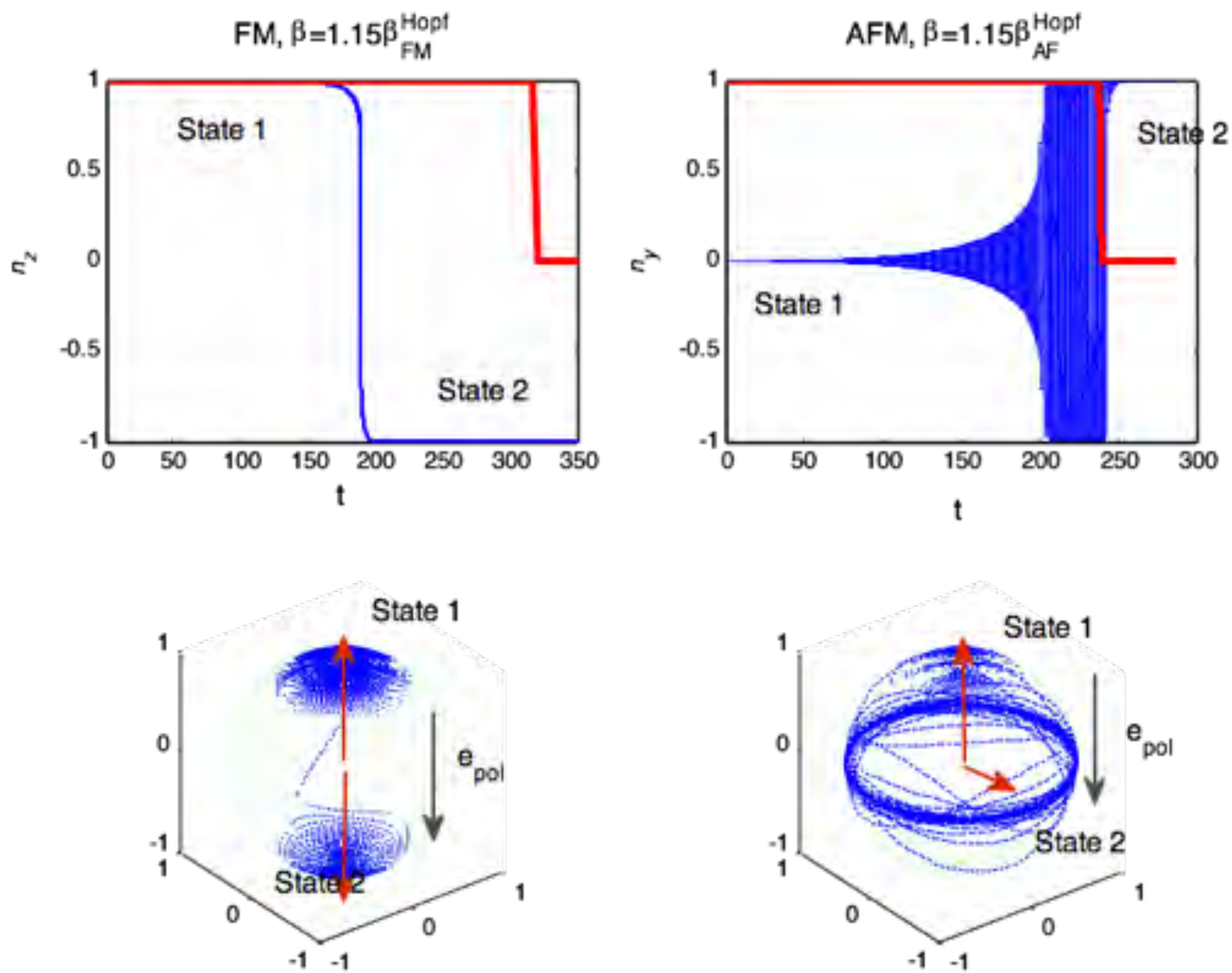
AFM, cubic

$$H_{STT}^{AF} = \alpha_G \sqrt{H_{an} H_E}$$

AFM, uniaxial

$$H_{STT}^{AF} = \sqrt{\alpha_G^2 H_{an} H_E + (H_{an1} - H_{an2})^2}$$

FM vs AFM, possible dynamics near the critical current



Take-home messages

- Spin transfer = magnetisation = dynamics
- Exchange enhancement of spin
- Different dynamics of FM and AF

Outline

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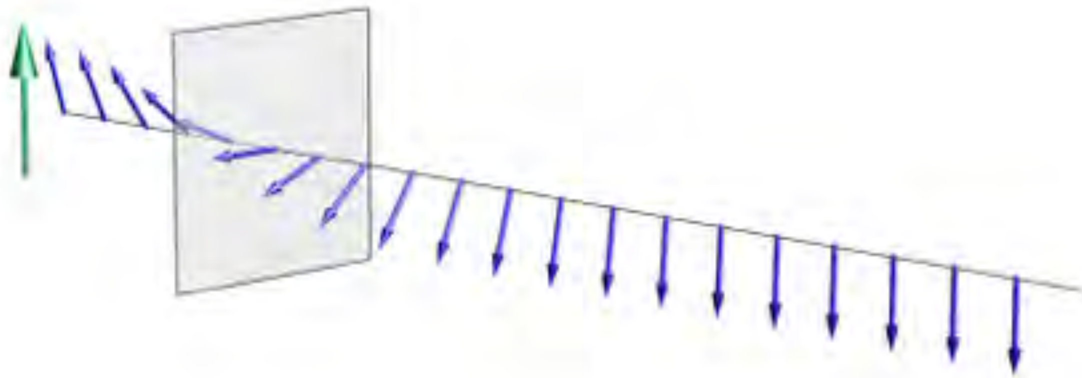
DW motion



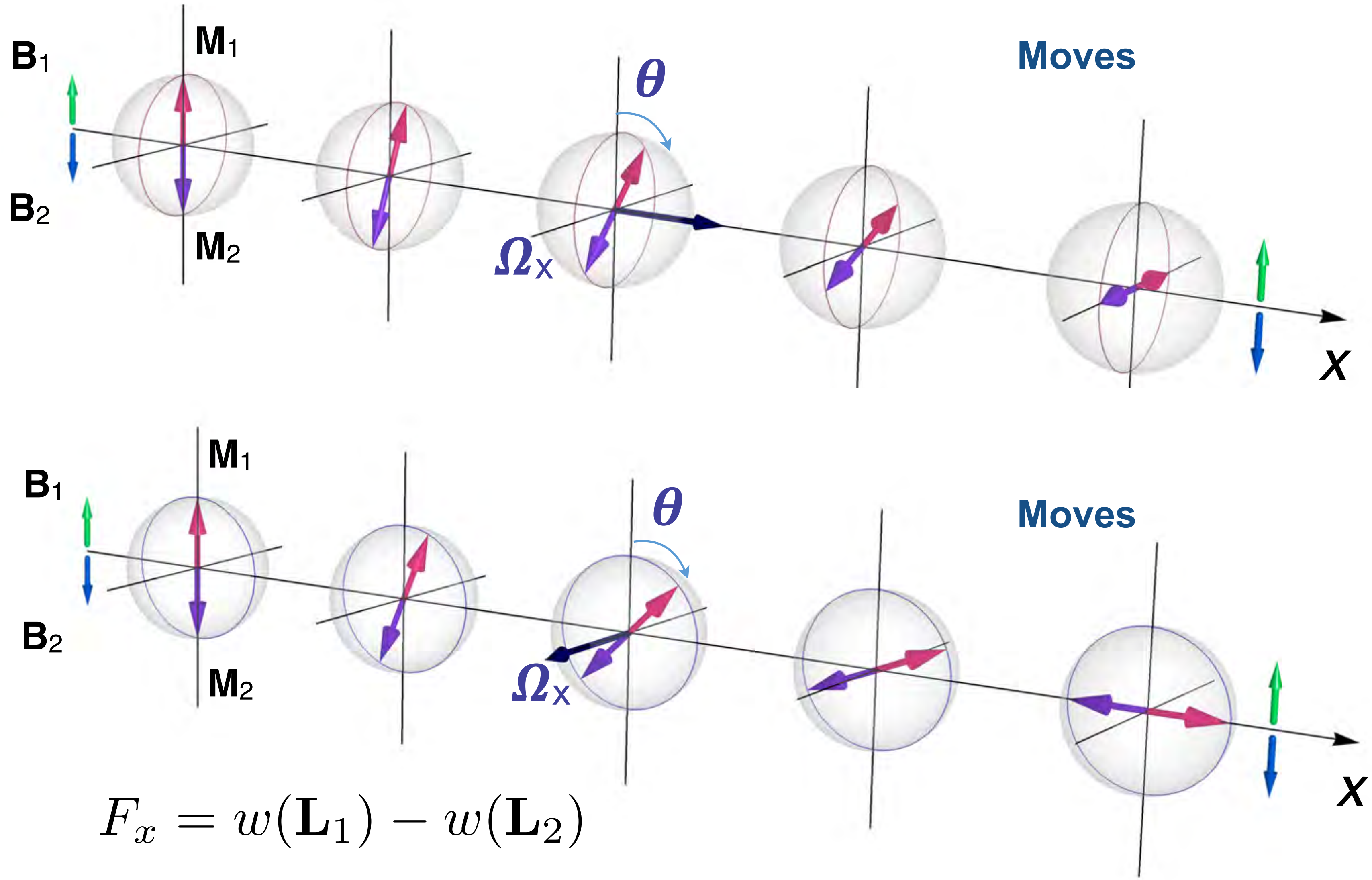
$$c^2 \frac{\partial^2 \theta}{\partial x^2} - \ddot{\theta} - \gamma^2 H_{\mathrm{ex}} H_{\mathrm{an}} \sin\theta \cos\theta = \alpha_G \gamma H_{\mathrm{ex}} \dot{\theta} + \gamma^2 H_{\mathrm{ex}} B_{\mathrm{Neel}} \sin\theta$$

$$\frac{dP_x}{dt} = -\alpha_G \gamma H_{\mathrm{ex}} P_x + F_x$$

$$P_x \propto -\int \frac{\partial \theta}{\partial x} \dot{\theta} dx$$

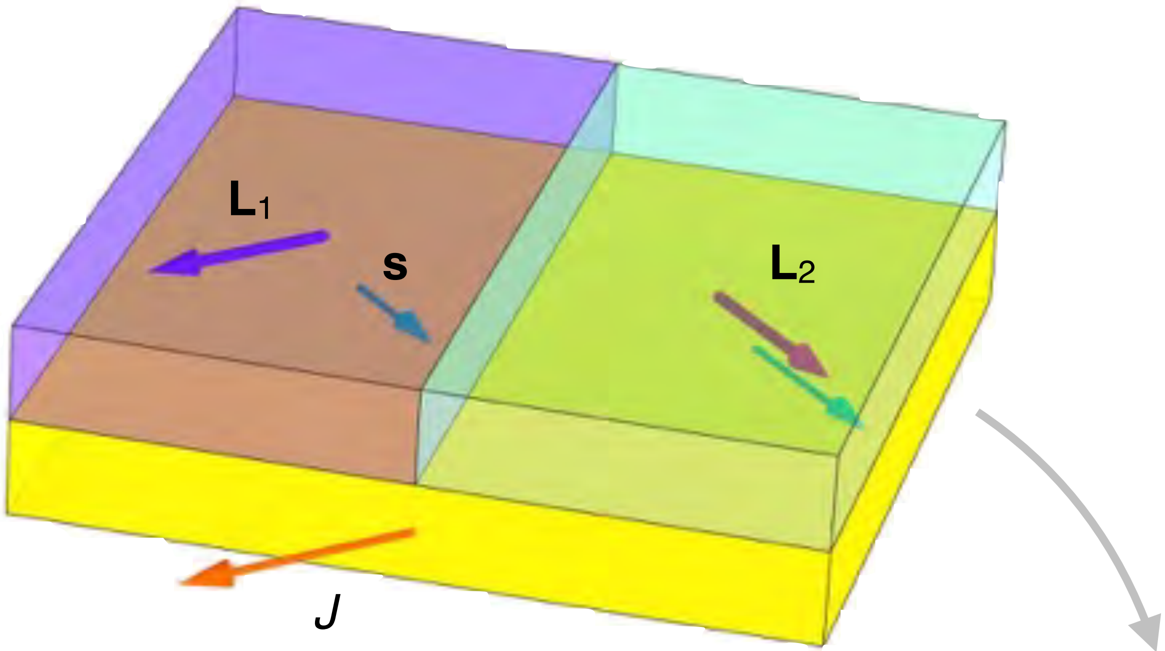
$$P_x \propto \frac{v}{\sqrt{1 - v^2/c^2}}$$

Ponderomotive force



$$F_x = w(\mathbf{L}_1) - w(\mathbf{L}_2)$$

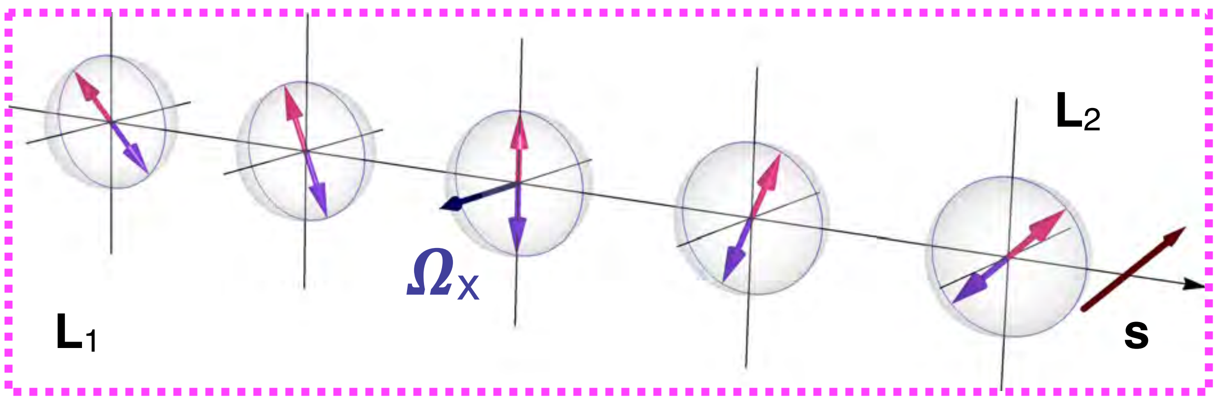
Geometry is important!



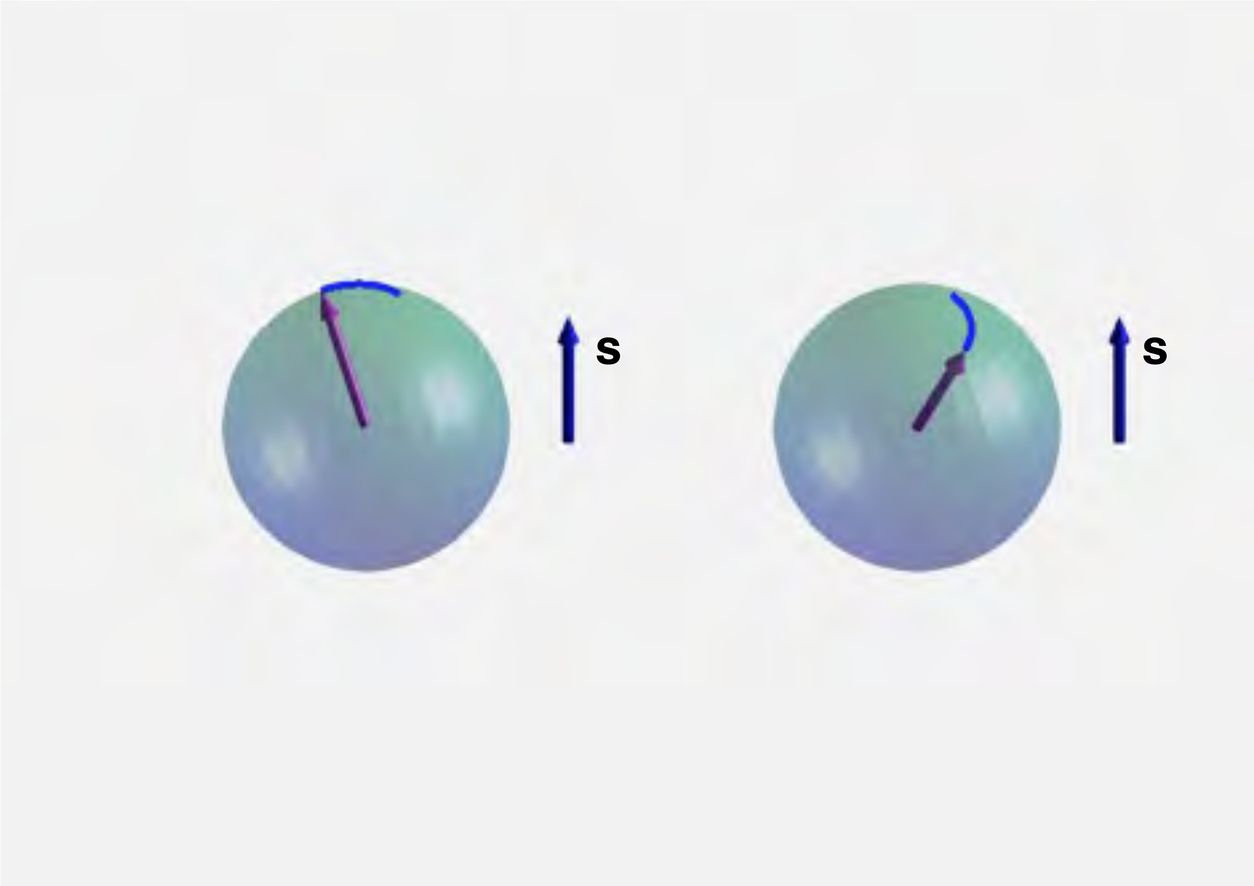
$$T = 0$$

$$\boldsymbol{\Omega}_x \perp \mathbf{s}$$

$$F_x = 0$$

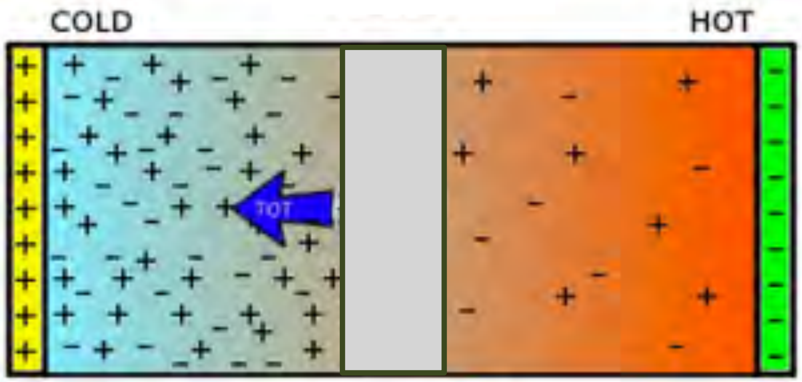


Two magnon modes



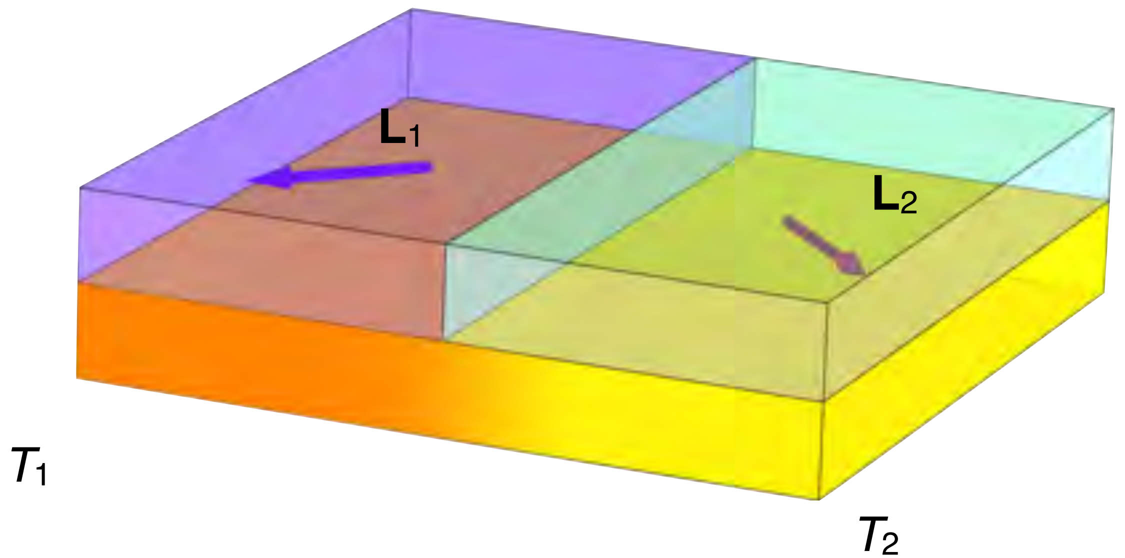
Transparent vs nontransparent DW

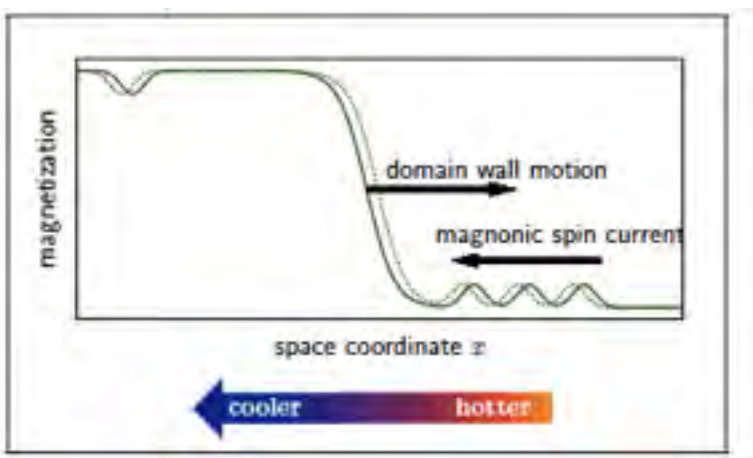
Thermophoresis

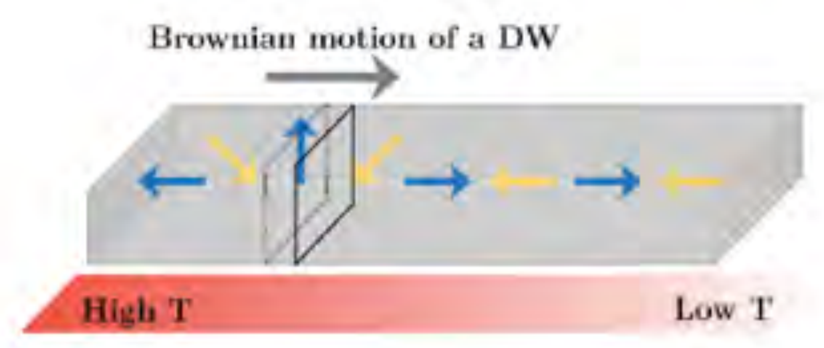


Entropic motion

Temperature gradient





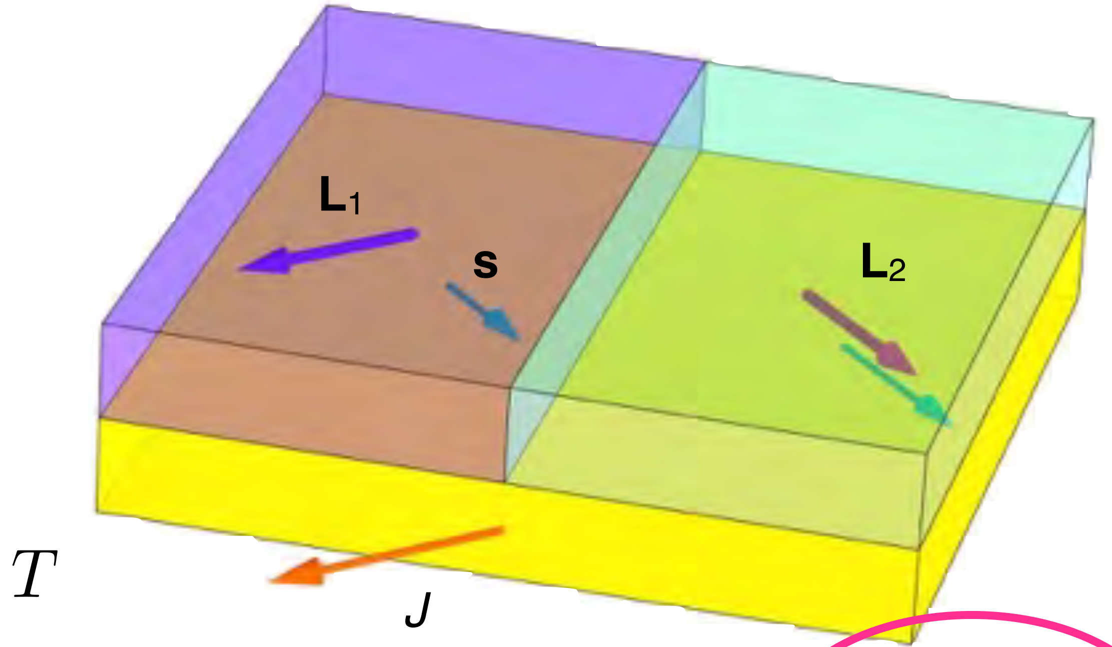


Schlickeiser, Ritzmann, Hinzke, & Nowak (2014)

Kim, Tchernyshyov, Tserkovnyak (2015)

Spin+Caloritronics

$T \neq 0$



$$\frac{T}{1-(J/J_{\rm cr})^2}$$

Two modes, two temperatures

$$T_{\mathrm{eff}}^{(-)} = \frac{T}{1 - J/J_{\mathrm{cr}}} \qquad T_{\mathrm{eff}}^{(+)} = \frac{T}{1 + J/J_{\mathrm{cr}}}$$

Fluctuations in a single AF domain

Langevin equations

$$\dot{\mathbf{M}}_j = \gamma \mathbf{M}_j \times \left(\mathbf{H}_j^{\mathrm{eff}} + \mathbf{h}\right) + \frac{\gamma \alpha_G}{M} \mathbf{M}_j \times \dot{\mathbf{M}}_j + \mathbf{\Gamma}_{\mathrm{cur}}$$

$$\langle \mathbf{h}(t) \rangle = 0, \quad \langle h_j(t_1) h_k(t_2) \rangle = 2D\delta_{jk}\delta(t_1 - t_2),$$

Fokker-Plank equation

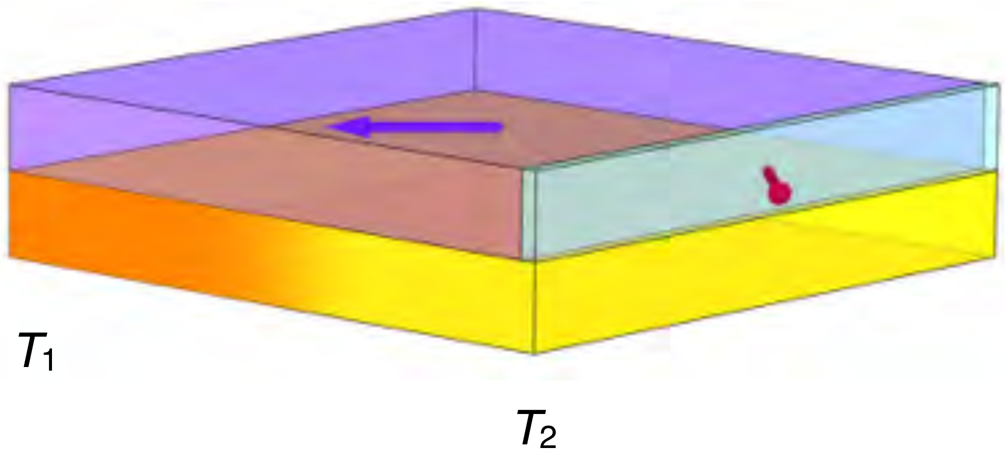
$$\frac{\partial f_\pm(E_\pm)}{\partial t} = \frac{\partial}{\partial E_\pm}\left\{\frac{2\gamma_{\mathrm{AF}}}{\gamma^2 E_0}\left[\left(1 \mp \frac{J}{J_{\mathrm{cr}}}\right) E_\pm + D E_0 \frac{\partial}{\partial E_\pm}\right] f_\pm(E_\pm)\right\}.$$

$$f(E_+, E_-) = f_0 \exp\left\{-\frac{2\gamma_{\mathrm{AF}}}{\gamma^2 D E_0}\left[\left(1 + \frac{J}{J_{\mathrm{cr}}}\right) E_+ + \left(1 - \frac{J}{J_{\mathrm{cr}}}\right) E_-\right]\right\}$$

$$D = \frac{2\gamma_{\mathrm{AF}}}{\gamma^2 E_0} T$$

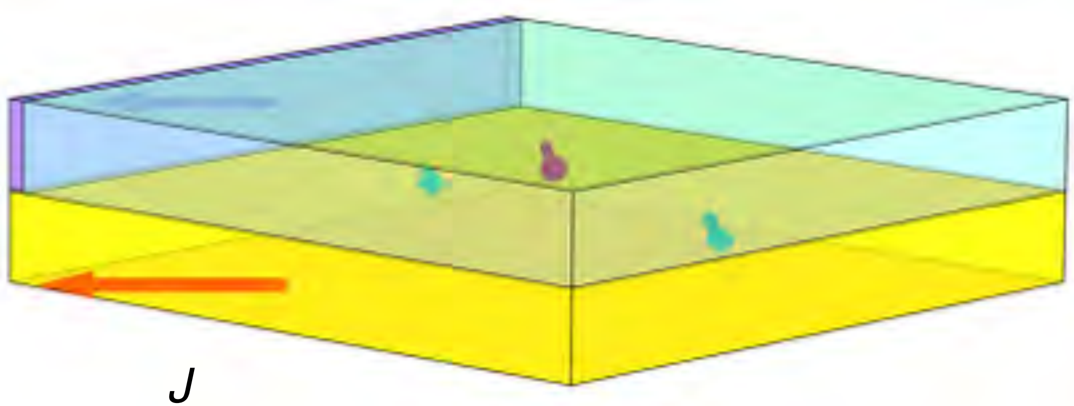
Gomonay, Loktev (2013)

Current-temperature competition

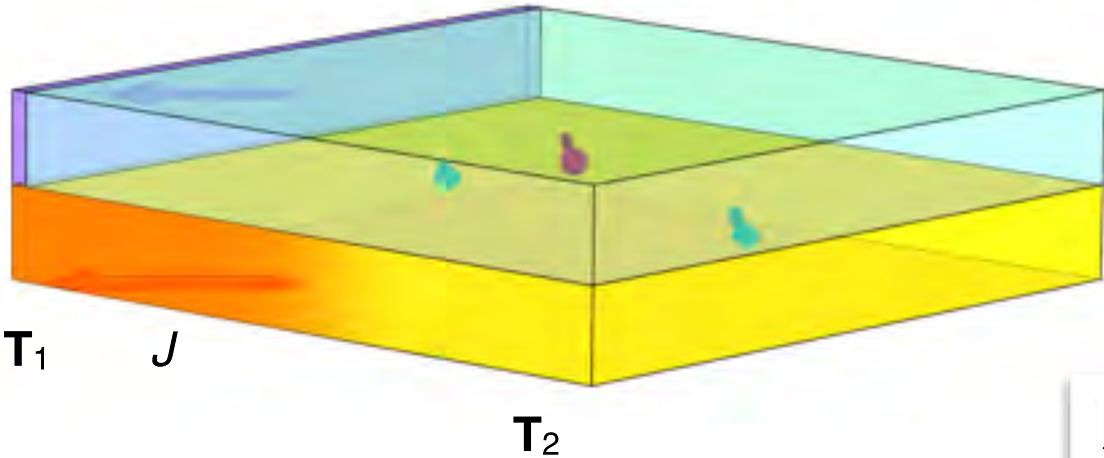


$$F_x = 2\Delta T$$

$$F_x = \frac{2T}{1-(J/J_{\rm cr})^2}$$



Manipulation of the domain wall

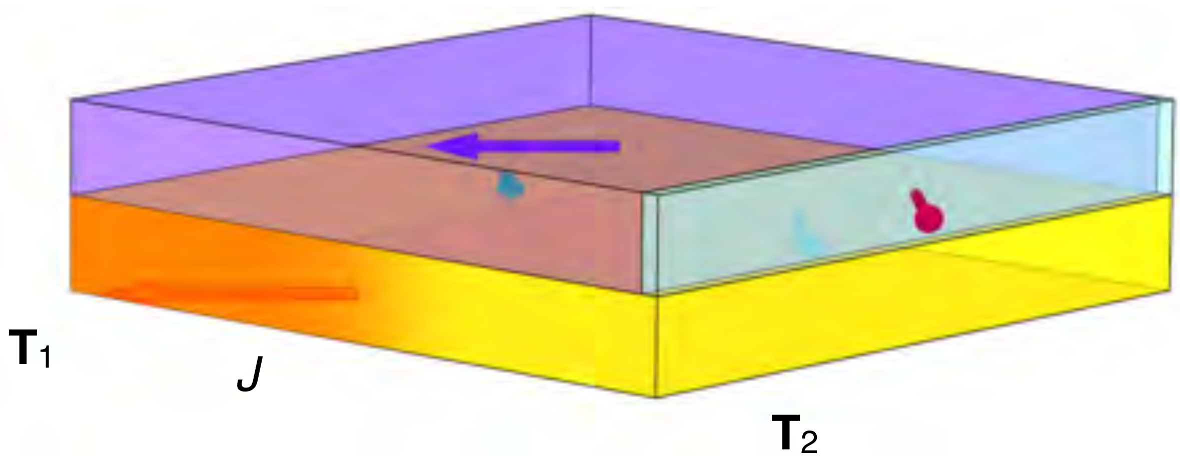


$$J > J_{\rm cont}$$

$$F_x = 2\Delta T - \frac{2T_2 (J/J_{\rm cr})^2}{1-(J/J_{\rm cr})^2}$$

$$J_{\rm cont} = J_{\rm cr}\sqrt{\frac{\Delta T}{T_1}}$$

$$J < J_{\rm cont}$$



Take-home messages

- Magnon pressure = momentum transfer
- Thermoporesis = momentum transfer
- Temperature+current => manipulation of the DW position

Conclusions

- AF different from FM
- Exchange interaction => important for dynamics
- Strong spintronic effects
- Caloritronics needs spintronics

Thank you!