Spin Transport Through Antiferromagnetic Insulators

(upcoming publication)

Scott Bender (UU)
Hans Skarsvag (NTNU)
Arne Brataas (NTNU)
Rembert Duine (UU)

SPICE Young Leaders Workshop

Thursday, August 3, 2017

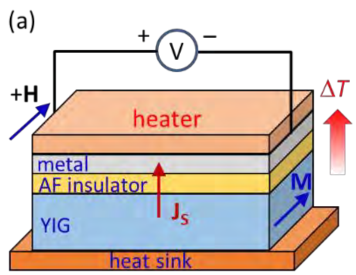
Why *anti*ferromagnets?

- Fast magnetic dynamics
- Radiation hard/less susceptible to external fields
- No pesky internal magnetic fields!
- Linear magnon dispersion

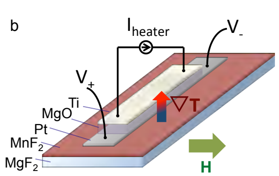
Spin Transport in AFs

Enhancement of Thermally Injected Spin Current through an Antiferromagnetic Insulator

Weiwei Lin,[1,*] Kai Chen,[2] Shufeng Zhang[2] and C. L. Chien[1,†]



Antiferromagnetic spin Seebeck effect

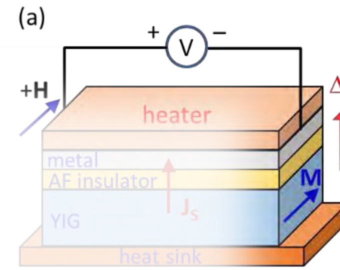


Stephen M. Wu,[1,*] Wei Zhang,[1] Amit KC,[2] Pavel Borisov,[2] John E. Pearson,[1] J. Samuel Jiang,[1] David Lederman,[2] Axel Hoffmann,[1] and Anand Bhattacharya[1]

Spin Transport in AFs

Enhancement of Thermally Injected Spin Current through an Antiferromagnetic Insulator

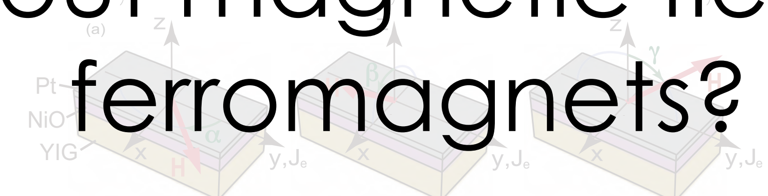
Weiwei Lin,[1,*] Kai Chen,[2] Shufeng Zhang[2] and C. L. Chien[1,†]

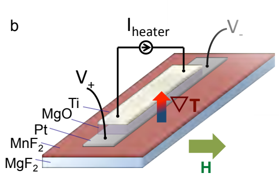


Tunable sign change of spin Hall magnetoresistance in Pt/NiO/YIG structures

Dazhi Hou,[1,2] Zhiyong Qiu,[1,2,*] Joseph Barker,[3] Koji Sato,[1] Kei Yamamoto,[3,4,5] Saül Vélez,[6] Juan M. Gomez-Perez, Luis E. Hueso, Felix Casanova, and Eiji Saitoh[1,2,3,8]

Thermal magnon transport without magnetic fields or ferromagnets?





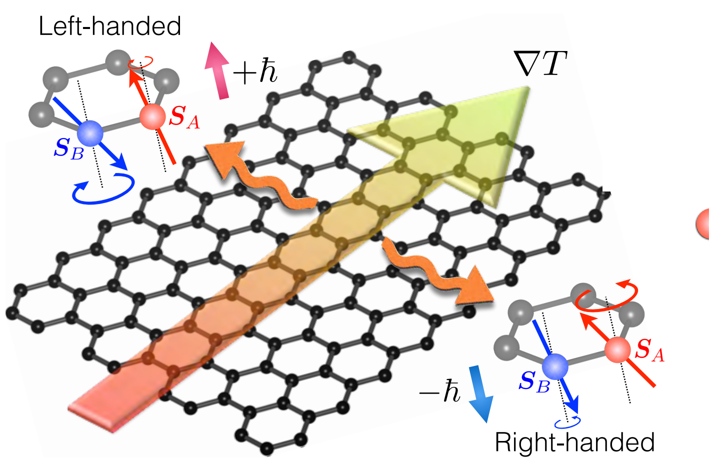
Antiferromagnetic spin Seebeck effect

Stephen M. Wu,[1,*] Wei Zhang,[1] Amit KC,[2] Pavel Borisov,[2] John E. Pearson,[1] J. Samuel Jiang,[1] David Lederman,[2] Axel Hoffmann,[1] and Anand Bhattacharya[1]

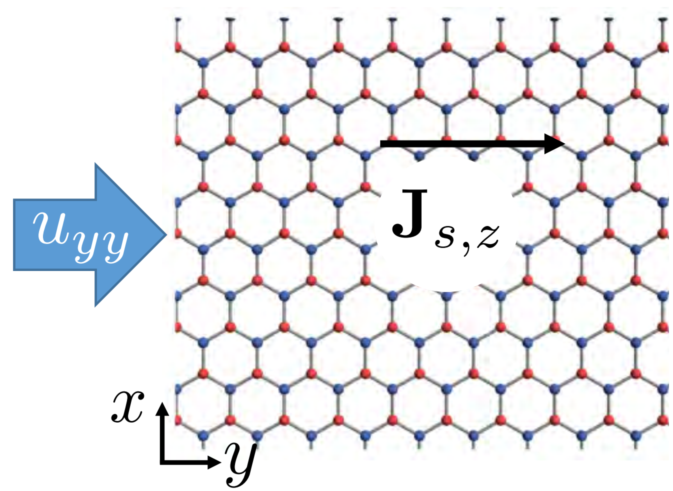
Spin Transport in AFs

Spin Nernst Effect of Magnons in Colliner Antiferromagnets

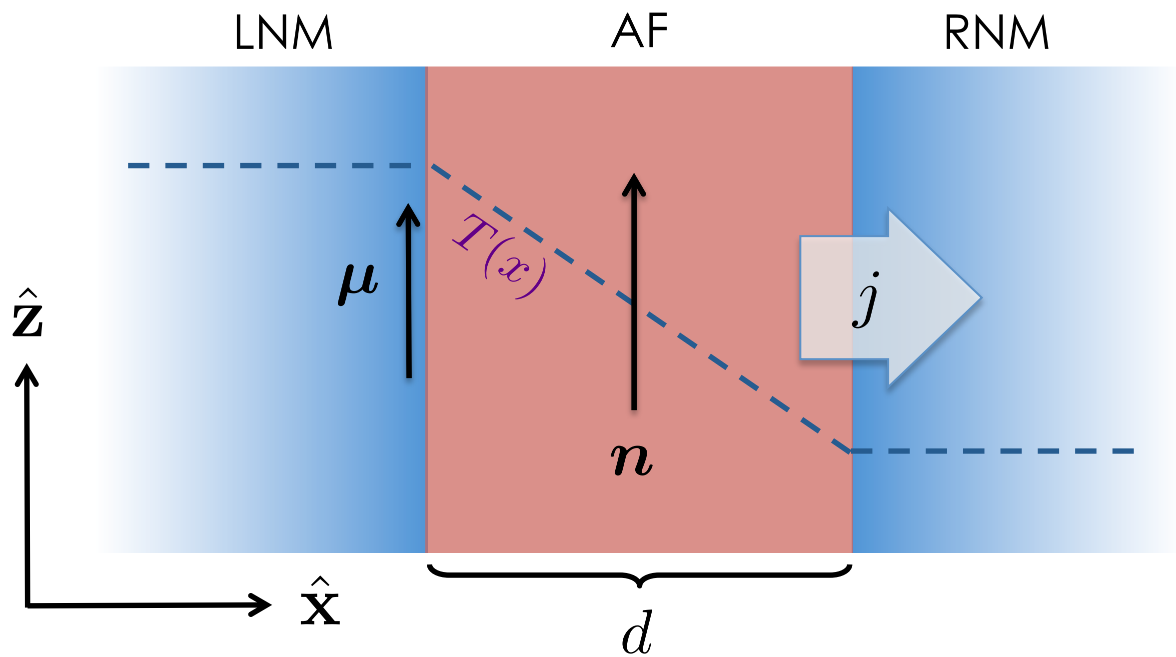
Cheng *et al.* PRL 117, 217202 (2016)



Piezospintronic effect antiferromagnetic honeycombs
Ulloa *et al.* arXiv:1707:08895



Magnonic transport



$$j = S\Delta T$$

$$j = G\mu$$

Magnonic transport

Take home messages:

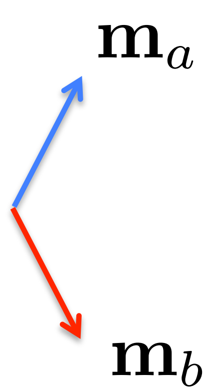
(1) Spin Seebeck effect can arise without magnetic field via symmetry breaking at interfaces

(2) Magnon conductance strongly enhanced near spin-flop transition

Outline

- Brief overview of antiferromagnets
- Classical AF dynamics
- Ballistic transport

Antiferromagnetic basics



$$\mathbf{m} = \frac{1}{2}\left(\mathbf{m}_a + \mathbf{m}_b\right)$$

$$\mathbf{l} = l\mathbf{n} = \frac{1}{2}\left(\mathbf{m}_a - \mathbf{m}_b\right)$$

time-reversal symmetry:

$$\mathbf{n} \to -\mathbf{n}$$

$$\mathbf{m} \to -\mathbf{m}$$

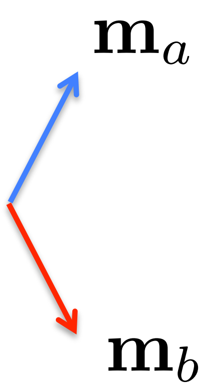
sublattice symmetry

$$\mathbf{n} \to -\mathbf{n}$$

$$\mathbf{m} \to \mathbf{m}$$

$$U = s\int_{\mathcal{V}} d^3r \left(\frac{\mathbf{m}^2}{2\chi} + \frac{A}{2}\sum_{i=1}^{3}\left(\partial_i \mathbf{n}\right)^2 - \frac{1}{2}Kn_z^2\right)$$

Antiferromagnetic basics



$$\mathbf{m} = \frac{1}{2}(\mathbf{m}_a + \mathbf{m}_b)$$

$$\mathbf{l} = l\mathbf{n} = \frac{1}{2}(\mathbf{m}_a - \mathbf{m}_b)$$

~~time-reversal symmetry:~~

$$\cancel{\mathbf{n} \to -\mathbf{n}}$$

$$\cancel{\mathbf{m} \to -\mathbf{m}}$$

sublattice symmetry

$$\mathbf{n} \to -\mathbf{n}$$

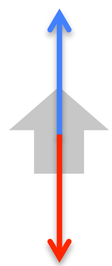
$$\mathbf{m} \to \mathbf{m}$$

$$U = s\int_{\mathcal{V}} d^3r \left(\frac{\mathbf{m}^2}{2\chi} + \frac{A}{2}\sum_{i=1}^{3}(\partial_i \mathbf{n})^2 - \frac{1}{2}K n_z^2 - \underline{\mathbf{H}\cdot\mathbf{m}} \right)$$

Antiferromagnetic basics

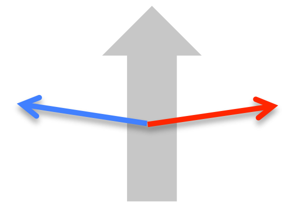
$H < H_c$

antiferromagnetic phase

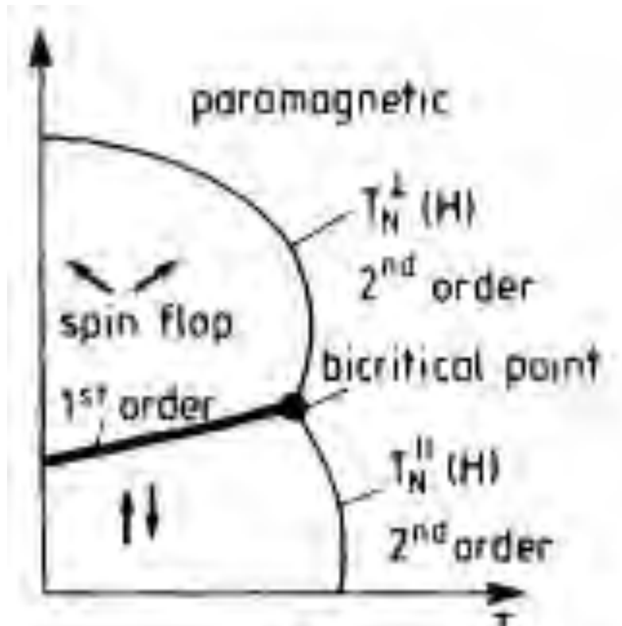


$H > H_c$

spin flop phase



$$H_c = \sqrt{K/\chi}$$

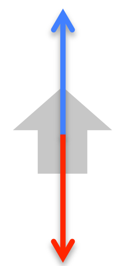


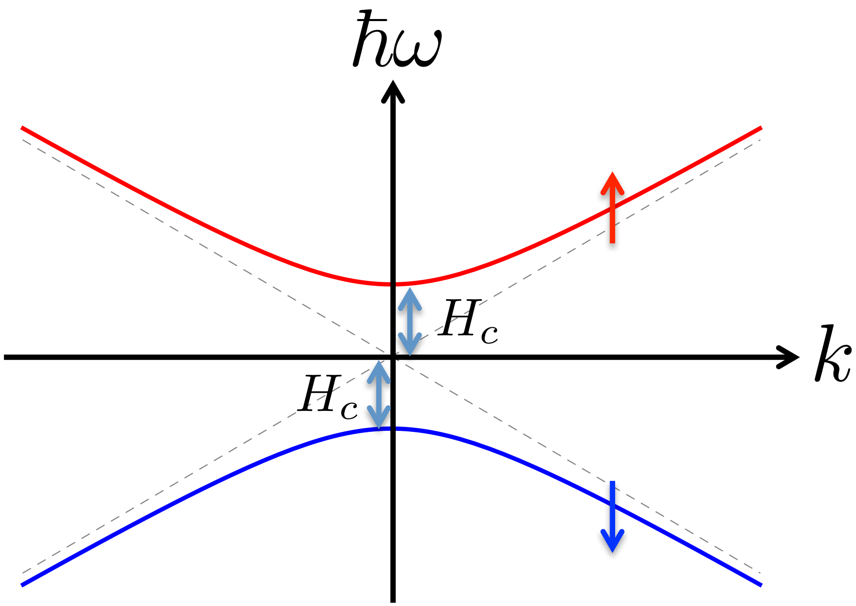
(a)

Antiferromagnetic basics

$H < H_c$

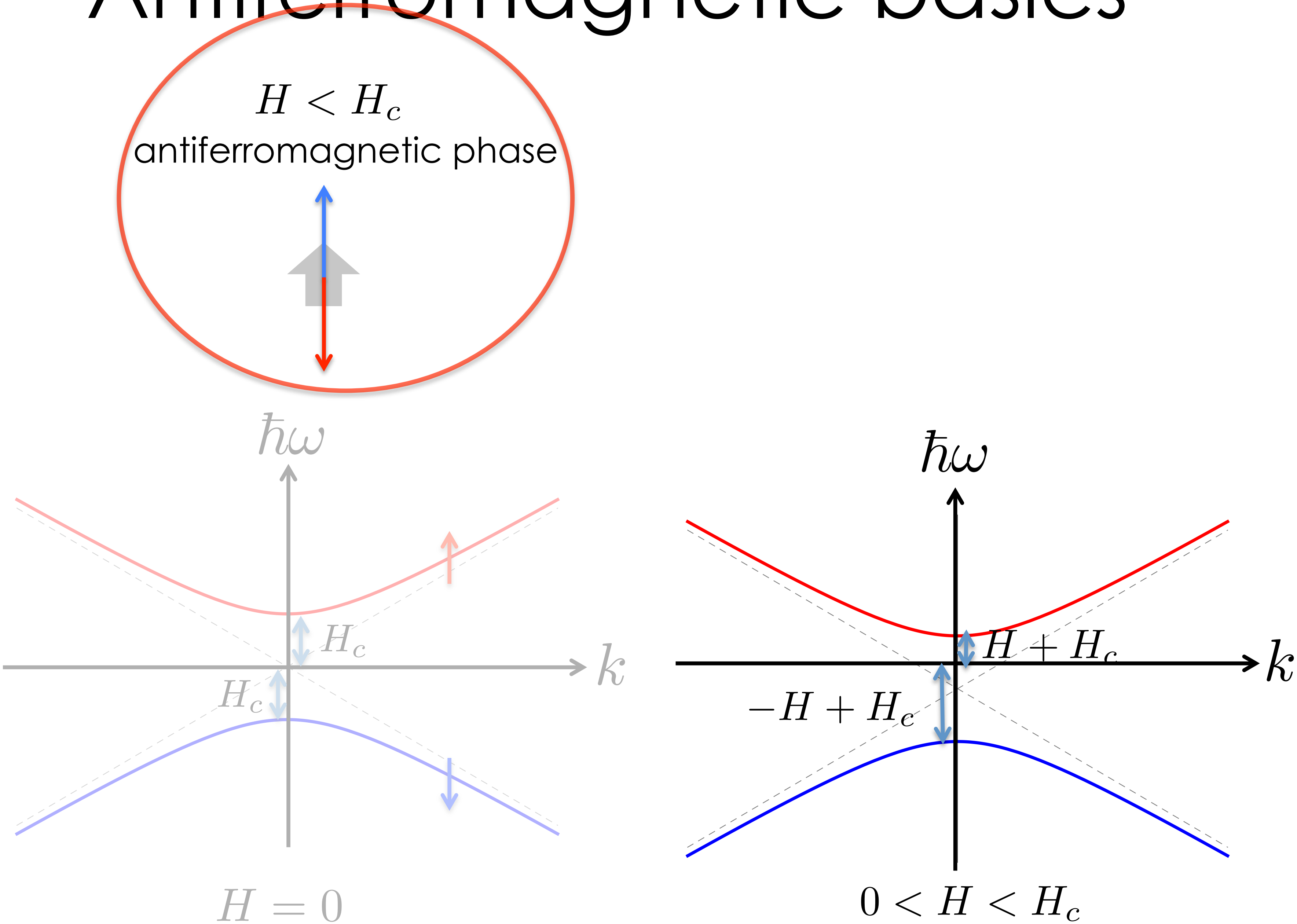
antiferromagnetic phase





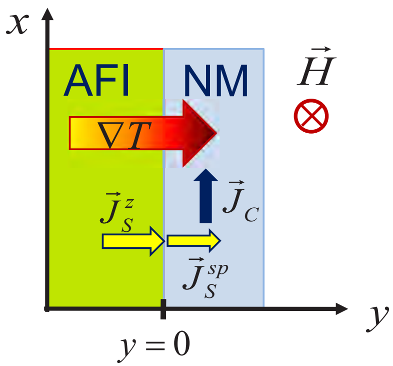
$H = 0$

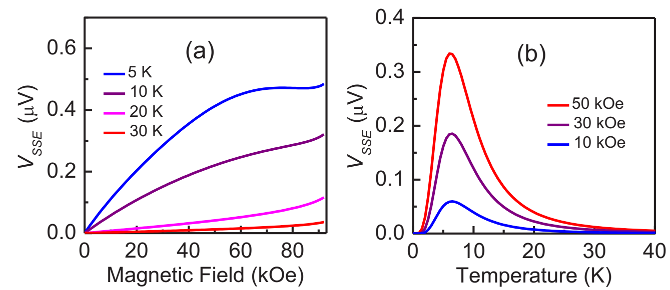
Antiferromagnetic basics



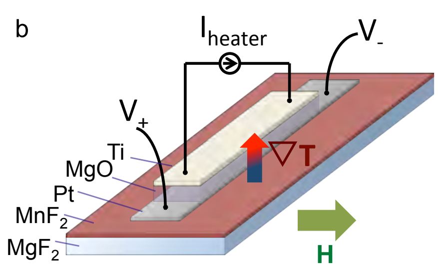
Spin seebeck effect in AF

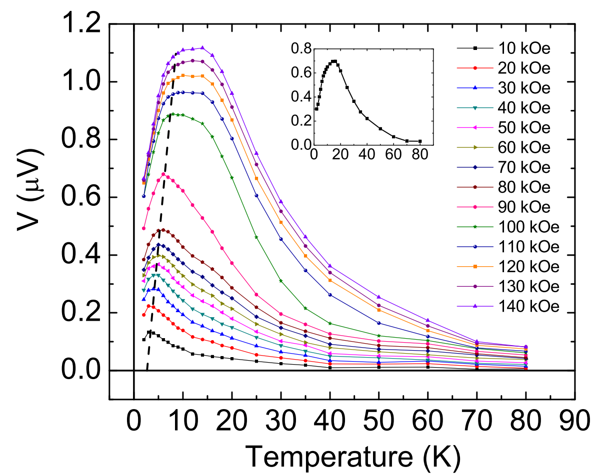
Theory: Rezende *et al.* PRB **93,** 014425 (2016)





Experiment: Wu *et al*. PRL **116,** 097204 (2016)





Outline

- ~~Brief overview of antiferromagnets~~
- Classical AF dynamics
- Ballistic transport

Stochastic LLG approach

(bulk)

$$\hbar\dot{\mathbf{n}} = \mathbf{F}_m \times \mathbf{n}$$

$$\hbar\dot{\mathbf{m}} = \mathbf{F}_m \times \mathbf{m} + \mathbf{F}_n \times \mathbf{n}$$

Stochastic LLG approach

(bulk)

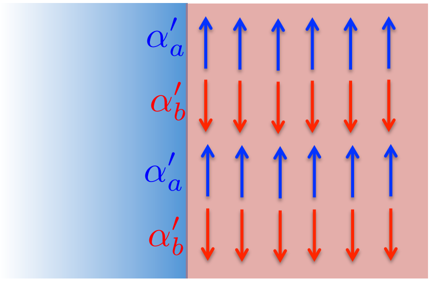
$$\hbar\dot{\mathbf{n}} = \mathbf{F}_m \times \mathbf{n} + \boldsymbol{\tau}_n$$

$$\hbar\dot{\mathbf{m}} = \mathbf{F}_m \times \mathbf{m} + \mathbf{F}_n \times \mathbf{n} + \boldsymbol{\tau}_m$$

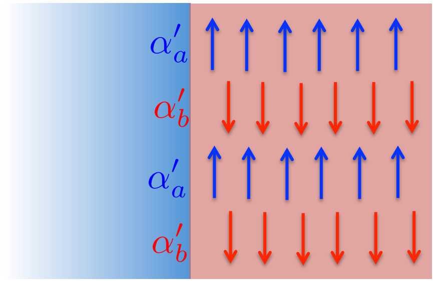
$$\text{FDT} \quad \begin{cases} \boldsymbol{\tau}_m = (\mathbf{f}_m - \alpha\hbar\dot{\mathbf{m}}) \times \mathbf{m} + (\mathbf{f}_n - \alpha\hbar\dot{\mathbf{n}}) \times \mathbf{n}\,, \\ \boldsymbol{\tau}_n = (\mathbf{f}_m - \alpha\hbar\dot{\mathbf{m}}) \times \mathbf{n} \end{cases}$$

AF/NM coupling

compensated interface
(unbroken lattice symmetry)

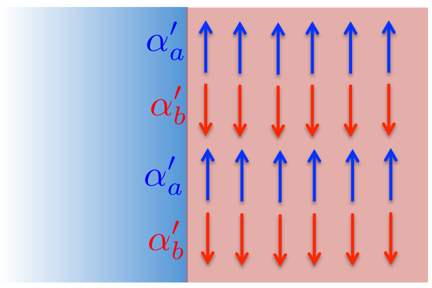


uncompensated interface
(broken lattice symmetry)

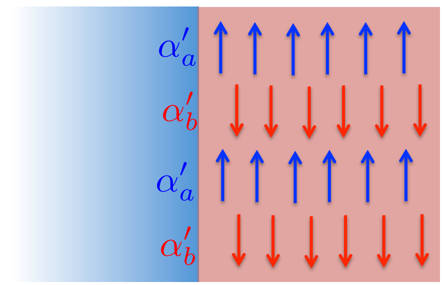


AF/NM coupling

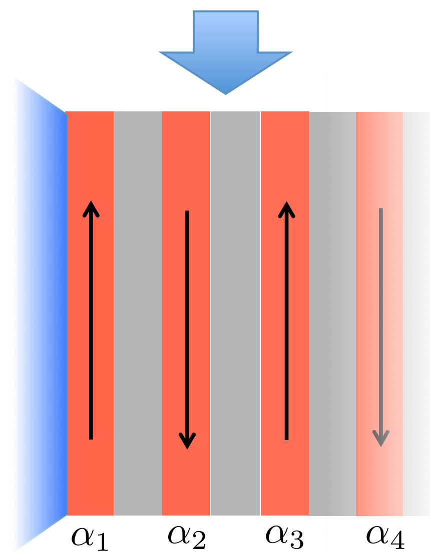
compensated interface
(unbroken lattice symmetry)



uncompensated interface
(broken lattice symmetry)



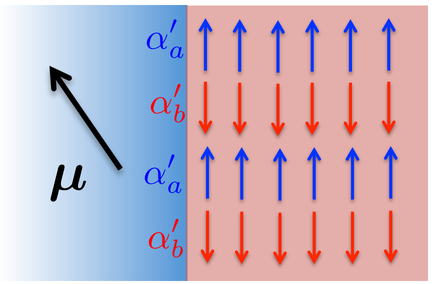
synthetic AF:



AF/NM coupling

(zero temperature)

compensated interface
(unbroken lattice symmetry)

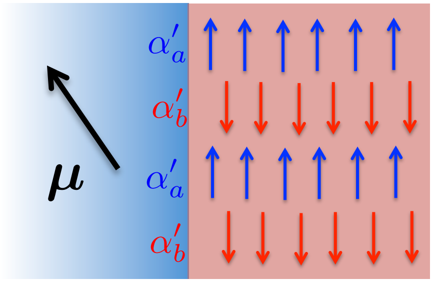


$$j_s = \frac{Re[g^{\uparrow\downarrow}]}{4\pi}\mathbf{n} \times (\boldsymbol{\mu} \times \mathbf{n} - \hbar\dot{\mathbf{n}})$$

AF/NM coupling

(zero temperature)

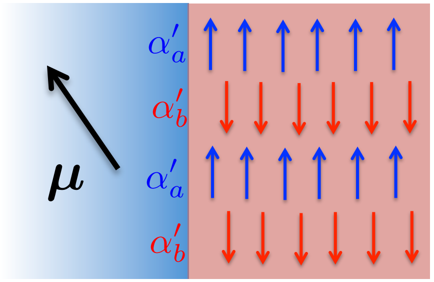
uncompensated interface
(broken lattice symmetry)



$$j_s = \frac{Re[g^{\uparrow\downarrow}]}{4\pi}\mathbf{n} \times (\boldsymbol{\mu} \times \mathbf{n} - \hbar\dot{\mathbf{n}}) + \frac{Im[g^{\uparrow\downarrow}]}{4\pi}(\boldsymbol{\mu} \times \mathbf{n} - \hbar\dot{\mathbf{n}}) + C\mathbf{n} \times \dot{\mathbf{m}}$$

AF/NM coupling
(finite temperature)

uncompensated interface
(broken lattice symmetry)



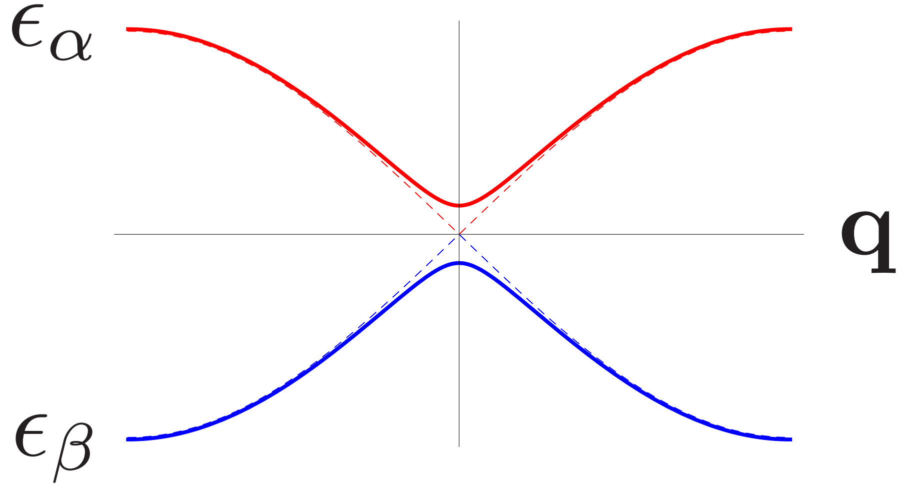
$$j_s = \frac{Re[g^{\uparrow\downarrow}]}{4\pi}\mathbf{n}\times(\boldsymbol{\mu}\times\mathbf{n}-\hbar\dot{\mathbf{n}})+\frac{Im[g^{\uparrow\downarrow}]}{4\pi}(\boldsymbol{\mu}\times\mathbf{n}-\hbar\dot{\mathbf{n}})+C\mathbf{n}\times\dot{\mathbf{m}}$$

+stochastic terms

Antiferromagnetic Magnons

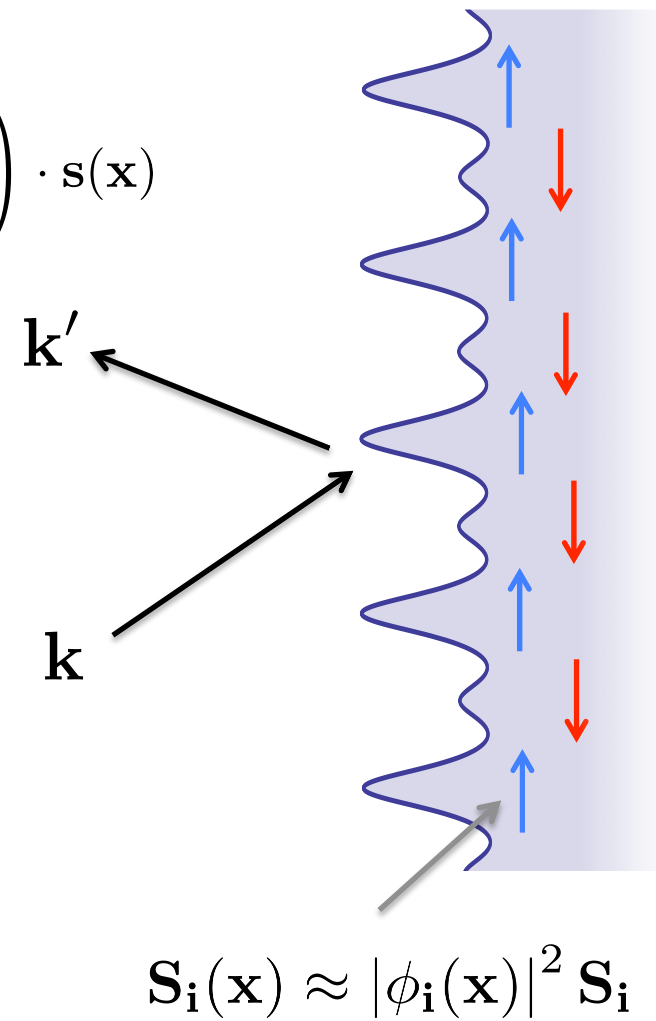
$$\hat{H}_{AF} = J\sum_{\langle \mathbf{ij}\rangle} \hat{\mathbf{s}}_{\mathbf{i}} \cdot \hat{\mathbf{s}}_{\mathbf{j}} - H\sum_{\mathbf{i}} \hat{s}_{\mathbf{i}z} + \frac{\kappa}{2S}\sum_{\mathbf{i}} \left(\hat{\mathbf{s}}_{\mathbf{i}x}^2 + \hat{\mathbf{s}}_{\mathbf{i}y}^2\right)$$

$$\hat{H}_{AF} = \sum_{\mathbf{q}} \left[\epsilon_\alpha(\mathbf{q})\hat{\alpha}_{\mathbf{q}}^\dagger \hat{\alpha}_{\mathbf{q}} + \epsilon_\beta(\mathbf{q})\hat{\beta}_{\mathbf{q}}^\dagger \hat{\beta}_{\mathbf{q}}\right]$$



AF/NM coupling (microscopics)

$$\hat{H}_I = -\int d^3x \left(J_a \sum_{\mathbf{i}\in a} \mathbf{S}_\mathbf{i}(\mathbf{x}) + J_b \sum_{\mathbf{i}\in b} \mathbf{S}_\mathbf{i}(\mathbf{x}) \right) \cdot \mathbf{s}(\mathbf{x})$$



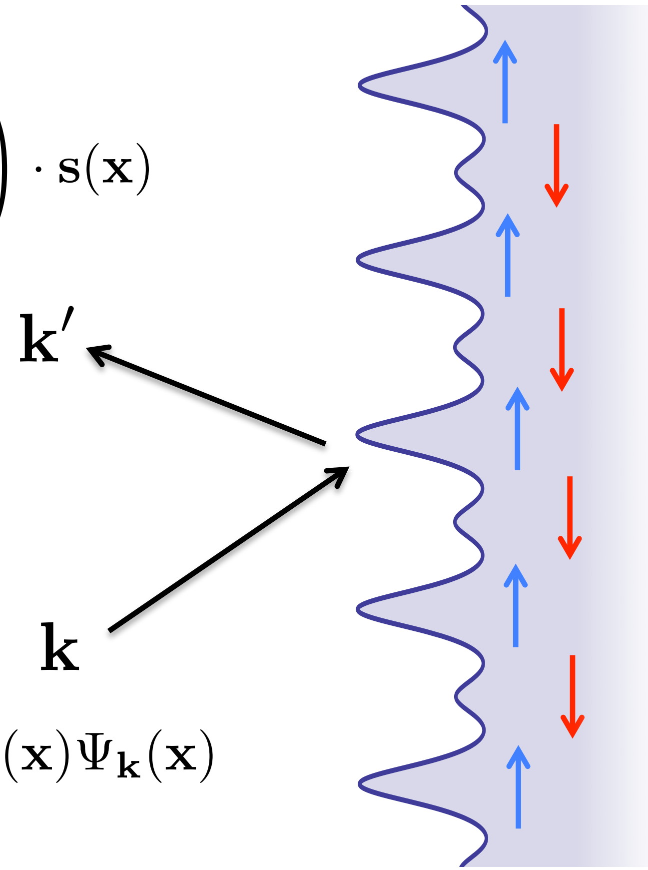
AF/NM coupling (microscopics)

$$\hat{H}_I = -\int d^3x \left(J_a \sum_{\mathbf{i}\in a} \mathbf{S_i}(\mathbf{x}) + J_b \sum_{\mathbf{i}\in b} \mathbf{S_i}(\mathbf{x}) \right) \cdot \mathbf{s}(\mathbf{x})$$

$$= \hat{H}_\perp + \hat{H}_\parallel$$

$$\hat{H}_\perp = U_{\mathbf{kk'}} \left(\hat{c}^\dagger_{\mathbf{k'}\uparrow} \hat{c}_{\mathbf{k}\uparrow} - \hat{c}^\dagger_{\mathbf{k'}\downarrow} \hat{c}_{\mathbf{k}\downarrow} \right) + H.c.$$

$$U_{\mathbf{kk'}} = -S\frac{\hbar}{2} \int d^3x \left(J_a \rho_a(\mathbf{x}) - J_b \rho_b(\mathbf{x}) \right) \Psi^*_{\mathbf{k'}}(\mathbf{x}) \Psi_{\mathbf{k}}(\mathbf{x})$$



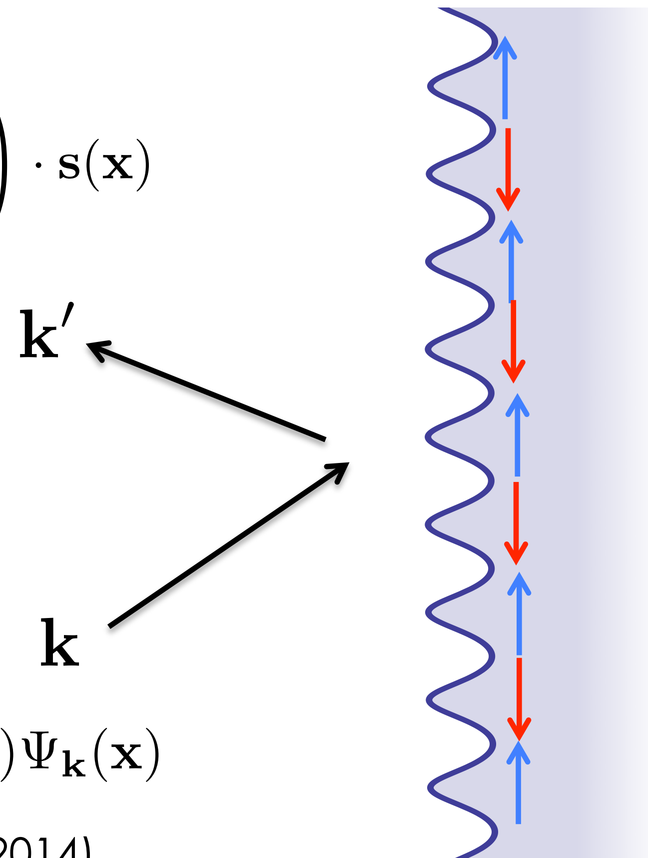
AF/NM coupling (microscopics)

$$\hat{H}_I = -\int d^3x \left(J_a \sum_{\mathbf{i}\in a} \mathbf{S_i}(\mathbf{x}) + J_b \sum_{\mathbf{i}\in b} \mathbf{S_i}(\mathbf{x}) \right) \cdot \mathbf{s}(\mathbf{x})$$

$$= \hat{H}_\perp + \hat{H}_{||}$$

$$\hat{H}_\perp = U_{\mathbf{kk}'} \left(\hat{c}^\dagger_{\mathbf{k}'\uparrow}\hat{c}_{\mathbf{k}\uparrow} - \hat{c}^\dagger_{\mathbf{k}'\downarrow}\hat{c}_{\mathbf{k}\downarrow} \right) \text{+H.c.}$$

$$U_{\mathbf{kk}'} = -S\frac{\hbar}{2}\int d^3x J\left(\rho_a(\mathbf{x}) - \rho_b(\mathbf{x})\right)\Psi^*_{\mathbf{k}'}(\mathbf{x})\Psi_{\mathbf{k}}(\mathbf{x})$$



Umklapp channel: (Takei *et al* PRB 094408 2014)

$$\mathbf{k}'_{||} - \mathbf{k}_{||} = \mathbf{G}$$

$$\Rightarrow \quad j_s = \frac{Re[g^{\uparrow\downarrow}]}{4\pi}\mathbf{n}\times(\boldsymbol{\mu}\times\mathbf{n} - \hbar\dot{\mathbf{n}})$$

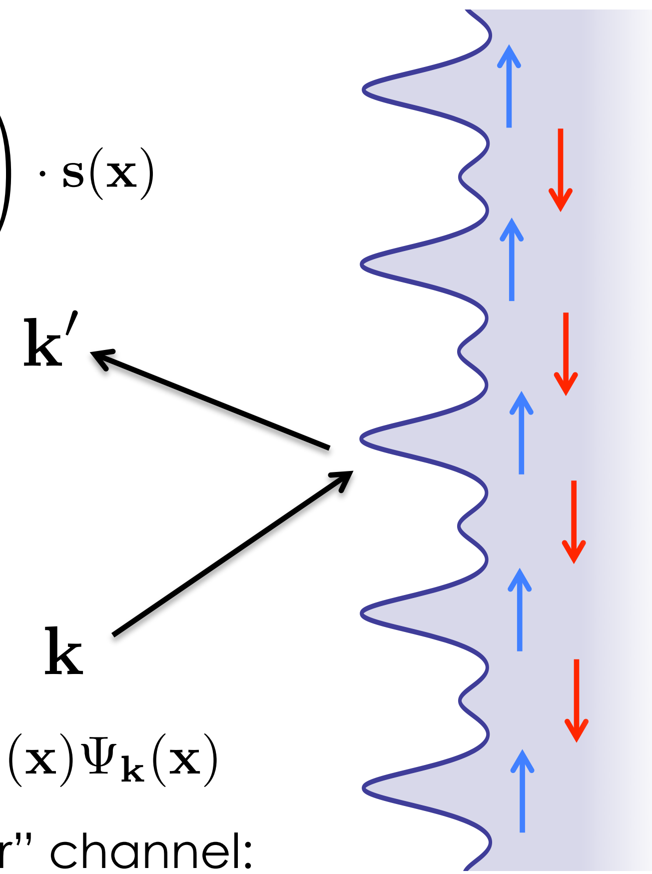
AF/NM coupling (microscopics)

$$\hat{H}_I = -\int d^3x \left(J_a \sum_{\mathbf{i}\in a} \mathbf{S_i}(\mathbf{x}) + J_b \sum_{\mathbf{i}\in b} \mathbf{S_i}(\mathbf{x}) \right) \cdot \mathbf{s}(\mathbf{x})$$

$$= \hat{H}_\perp + \hat{H}_\parallel$$

$$\hat{H}_\perp = U_{\mathbf{kk'}} \left(\hat{c}^\dagger_{\mathbf{k'}\uparrow} \hat{c}_{\mathbf{k}\uparrow} - \hat{c}^\dagger_{\mathbf{k'}\downarrow} \hat{c}_{\mathbf{k}\downarrow} \right) + \text{H.c.}$$

$$U_{\mathbf{kk'}} = -S\frac{\hbar}{2} \int d^3x \left(J_a \rho_a(\mathbf{x}) - J_b \rho_b(\mathbf{x}) \right) \Psi^*_{\mathbf{k'}}(\mathbf{x}) \Psi_{\mathbf{k}}(\mathbf{x})$$



Umklapp channel:
$\mathbf{k}'_\parallel - \mathbf{k}_\parallel = \mathbf{G}$

"specular" channel:
$\mathbf{k}'_\parallel - \mathbf{k}_\parallel = 0$

$$j_s = \frac{Re[g^{\uparrow\downarrow}]}{4\pi} \mathbf{n} \times (\boldsymbol{\mu} \times \mathbf{n} - \hbar\dot{\mathbf{n}}) + \frac{Im[g^{\uparrow\downarrow}]}{4\pi} (\boldsymbol{\mu} \times \mathbf{n} - \hbar\dot{\mathbf{n}})$$

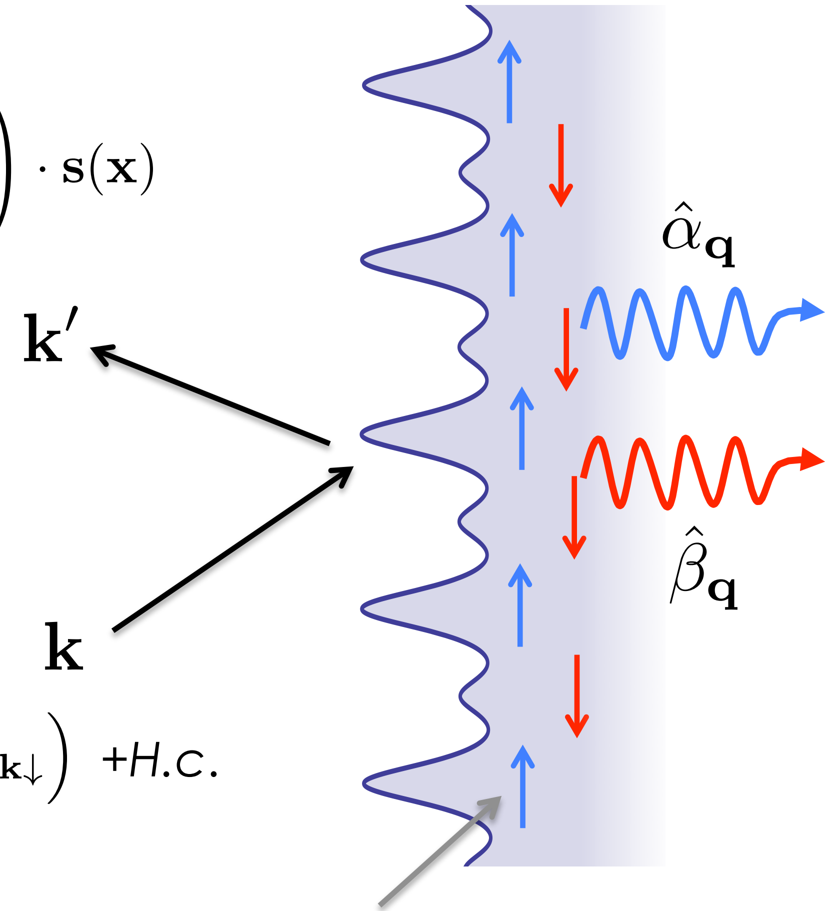
AF/NM coupling (microscopics)

$$\hat{H}_I = -\int d^3x \left(J_a \sum_{\mathbf{i}\in a} \mathbf{S}_\mathbf{i}(\mathbf{x}) + J_b \sum_{\mathbf{i}\in b} \mathbf{S}_\mathbf{i}(\mathbf{x}) \right) \cdot \mathbf{s}(\mathbf{x})$$

$$= \hat{H}_\perp + \hat{H}_\parallel$$

$$\hat{H}_\parallel = \sum_{\mathbf{qk}'} \left(V_{\alpha\mathbf{qkk}'} \hat{\alpha}^\dagger_\mathbf{q} \hat{c}^\dagger_{\mathbf{k}'\downarrow} \hat{c}_{\mathbf{k}\uparrow} + V_{\beta\mathbf{qkk}'} \hat{\beta}^\dagger_\mathbf{q} \hat{c}^\dagger_{\mathbf{k}'\uparrow} \hat{c}_{\mathbf{k}\downarrow} \right) + H.c.$$

Umklapp+specular channels!

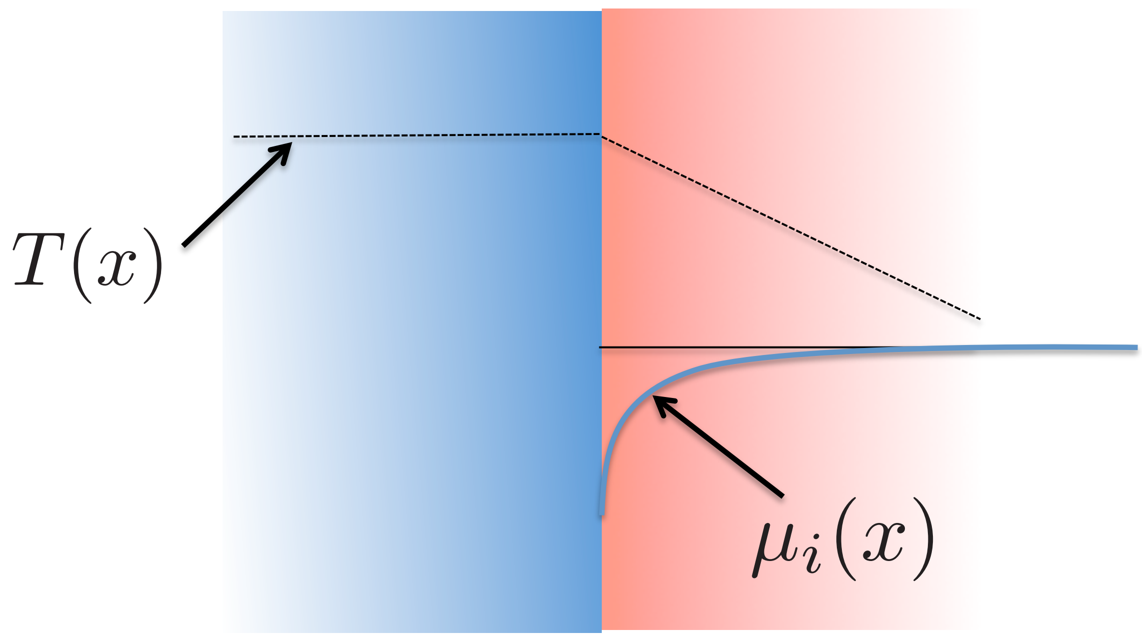


$$\mathbf{S}_\mathbf{i}(\mathbf{x}) \approx |\phi_\mathbf{i}(\mathbf{x})|^2 \, \mathbf{S}_\mathbf{i}$$

AF/NM coupling (microscopics)

$$j_\alpha = G_\alpha\left(-\mu_\alpha\right) \qquad j_\beta = -G_\beta\left(-\mu_\beta\right)$$

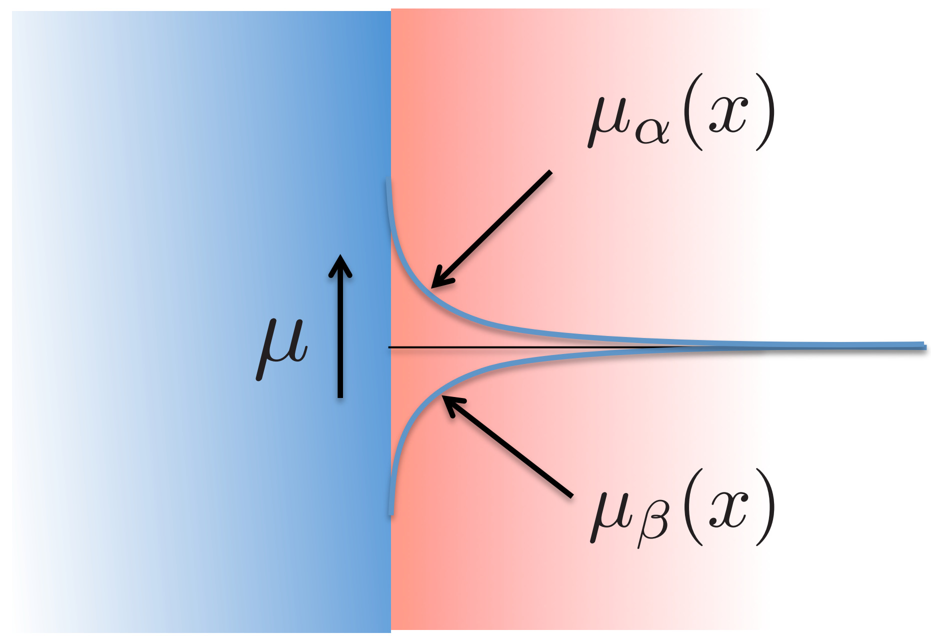
(diffusive regime)



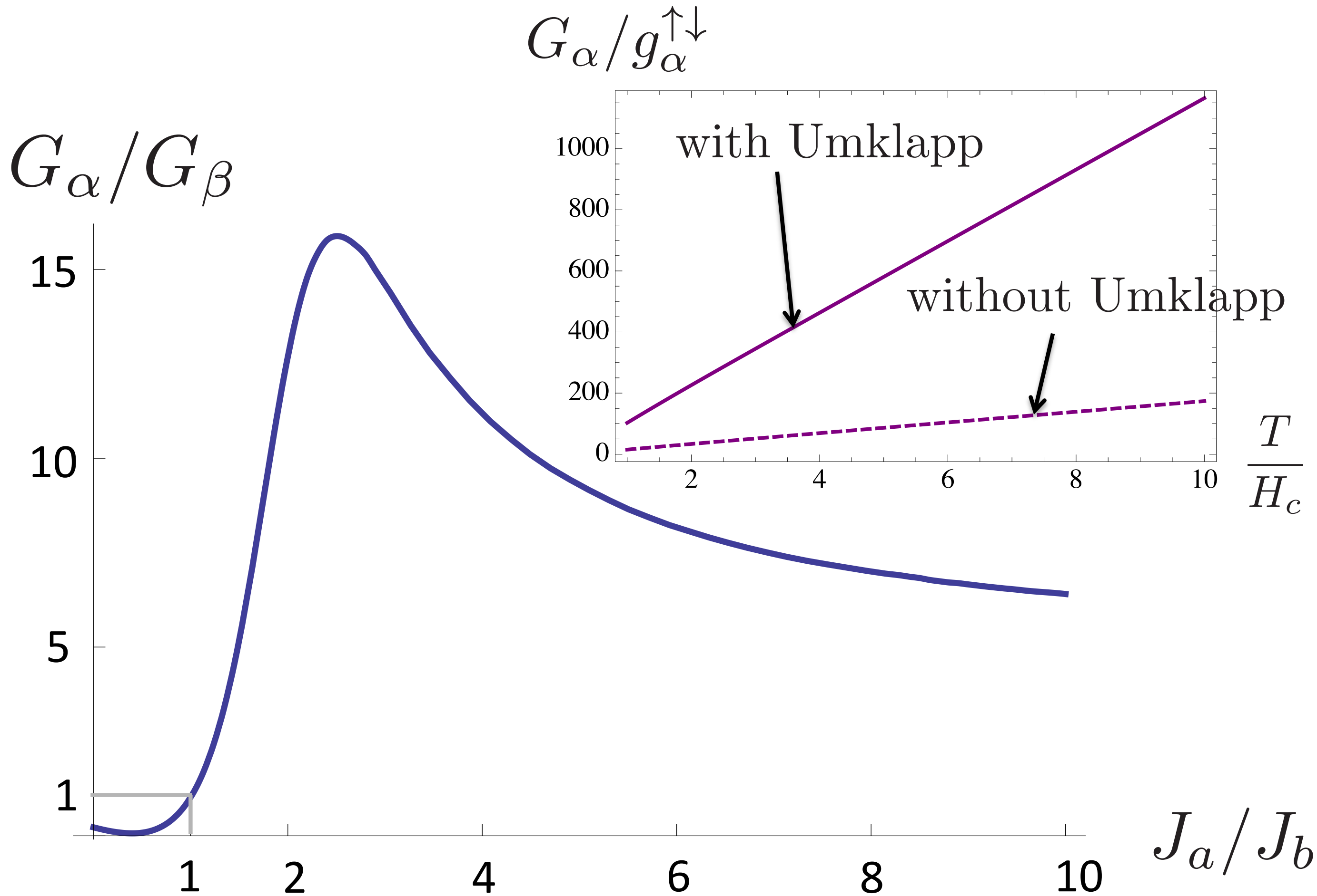
AF/NM coupling (microscopics)

$$j_\alpha = G_\alpha \left(\mu - \mu_\alpha\right) \qquad j_\beta = -G_\beta \left(\mu - \mu_\beta\right)$$

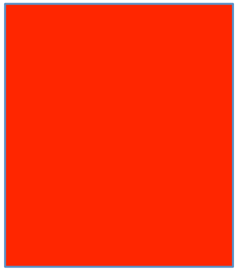
(diffusive regime)



AF/NM coupling (microscopics)



Stochastic LLG approach



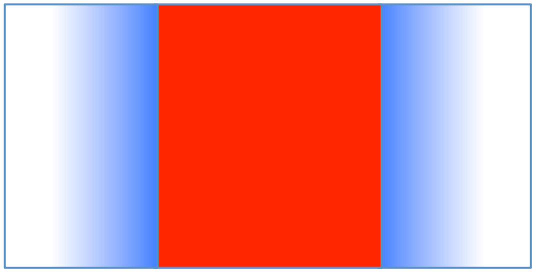
$$\hbar\dot{\mathbf{n}} = \mathbf{F}_m \times \mathbf{n} + \boldsymbol{\tau}_n$$

$$\hbar\dot{\mathbf{m}} = \mathbf{F}_m \times \mathbf{m} + \mathbf{F}_n \times \mathbf{n} + \boldsymbol{\tau}_m$$

$$\boldsymbol{\tau}_m = (\mathbf{f}_m - \alpha\hbar\dot{\mathbf{m}}) \times \mathbf{m} + (\mathbf{f}_n - \alpha\hbar\dot{\mathbf{n}}) \times \mathbf{n}\,,$$

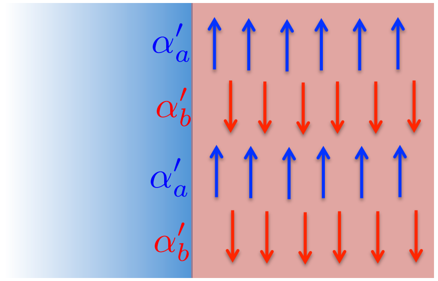
$$\boldsymbol{\tau}_n = (\mathbf{f}_m - \alpha\hbar\dot{\mathbf{m}}) \times \mathbf{n}$$

Stochastic LLG approach



$$\hbar\dot{\mathbf{n}} = \mathbf{F}_m \times \mathbf{n} + \boldsymbol{\tau}_n$$
$$\hbar\dot{\mathbf{m}} = \mathbf{F}_m \times \mathbf{m} + \mathbf{F}_n \times \mathbf{n} + \boldsymbol{\tau}_m$$

$$\boldsymbol{\tau}_m = (\mathbf{f}_m - \alpha_S\hbar\dot{\mathbf{m}} - \alpha_A\hbar\dot{\mathbf{n}}) \times \mathbf{m} + (\mathbf{f}_n - \alpha_A\hbar\dot{\mathbf{m}} - \alpha_S\hbar\dot{\mathbf{n}}) \times \mathbf{n}\,,$$
$$\boldsymbol{\tau}_n = (\mathbf{f}_m - \alpha_S\hbar\dot{\mathbf{m}}) \times \mathbf{n} - \alpha_A\left(\hbar\dot{\mathbf{n}} \times \mathbf{n} + \hat{P}\hbar\dot{\mathbf{m}} \times \mathbf{m}\right)$$

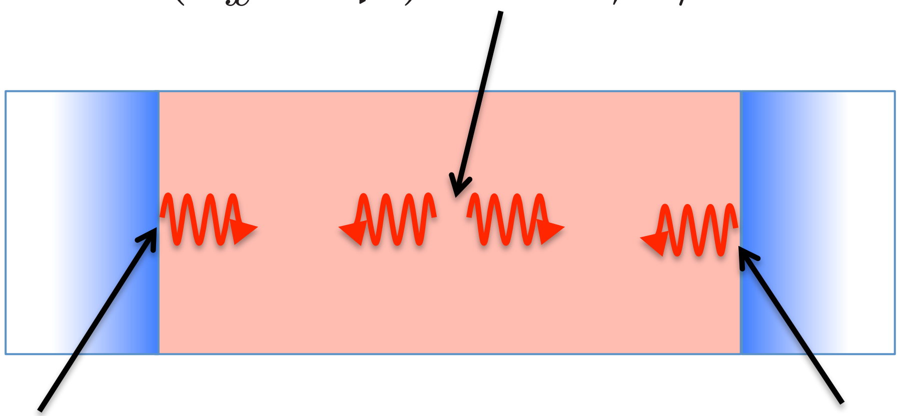


$$\alpha' = \frac{1}{2}(\alpha'_a + \alpha'_b) \longleftarrow \text{“symmetric”}$$

$$\tilde{\alpha}' = \frac{1}{2}(\alpha'_a - \alpha'_b) \longleftarrow \text{“antisymmetric”}$$

Stochastic LLG approach

$$(\partial_x^2 + \mathfrak{q}^2)n = -\mathfrak{f}_B/A$$

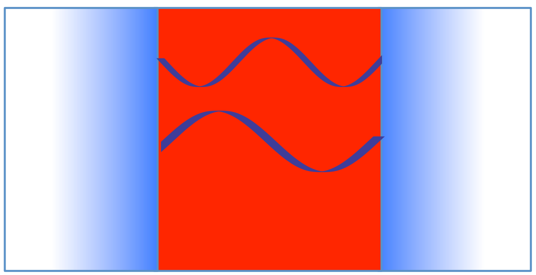


$$A\partial_x n + i\alpha'_\omega d(\hbar\omega - \mu)n = -\mathfrak{f}_L \qquad -A\partial_x n + i\alpha'_\omega d\hbar\omega n = -\mathfrak{f}_R$$

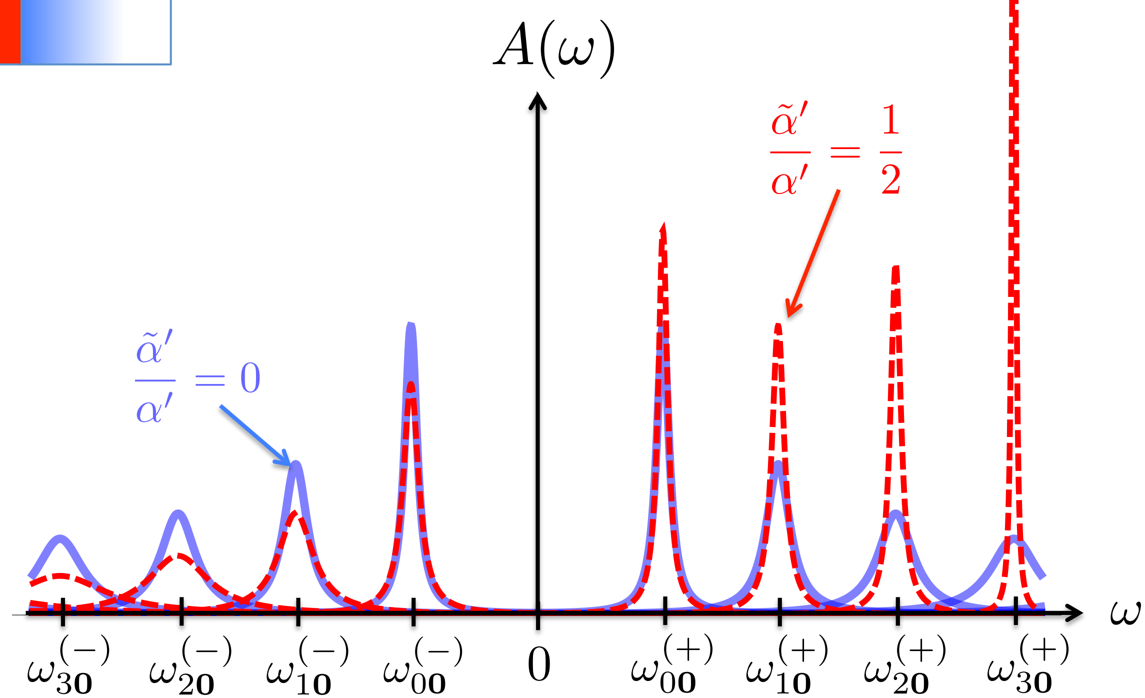
$$j \equiv \langle \hat{\mathbf{z}} \cdot \mathbf{j} \rangle = As\mathrm{Im}\langle n^*(\mathbf{r})\partial_x n(\mathbf{r})\rangle_{x=\frac{d}{2}}$$

Equilibrium

$$M_z = \sum_{n=0,1,2,\ldots} \int \frac{d\omega}{2\pi} \frac{d^2}{(2\pi)^2} \left[A^{(+)}_{n\mathbf{q}}(\hbar\omega - \epsilon^{(+)}_{n\mathbf{q}}) - A^{(-)}_{n\mathbf{q}}(\hbar\omega - \epsilon^{(-)}_{n\mathbf{q}}) \right] \frac{1}{e^{\hbar\omega/T} - 1} \, ,$$



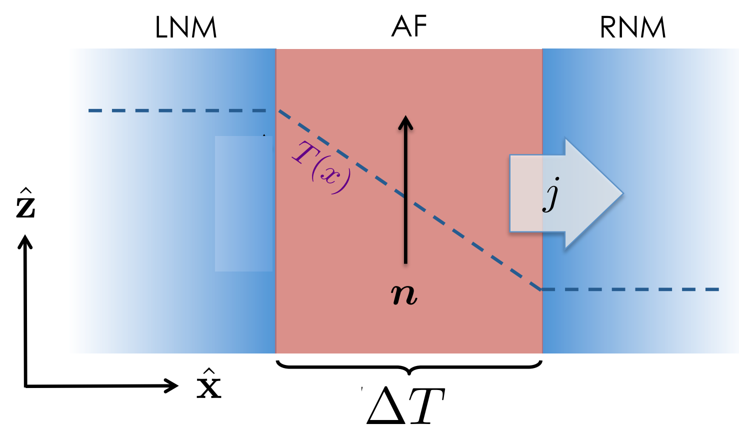
$$A^{(\pm)}_{n\mathbf{q}}(E) \equiv \frac{\Gamma^{(\pm)}_{n\mathbf{q}}}{E^2 + (\Gamma^{(\pm)}_{n\mathbf{q}}/2)^2}$$



Outline

- ~~Brief overview of antiferromagnets~~
- ~~Classical AF dynamics~~
- Ballistic transport

Spin seebeck effect



$$j = S\Delta T$$

$$S = \sum_{n=0,1,2\ldots} \int \frac{d^2q}{(2\pi)^2} \left(S^{(\mathrm{S})}_{n\mathbf{q}} + S^{(\mathrm{A})}_{n\mathbf{q}} \right)$$

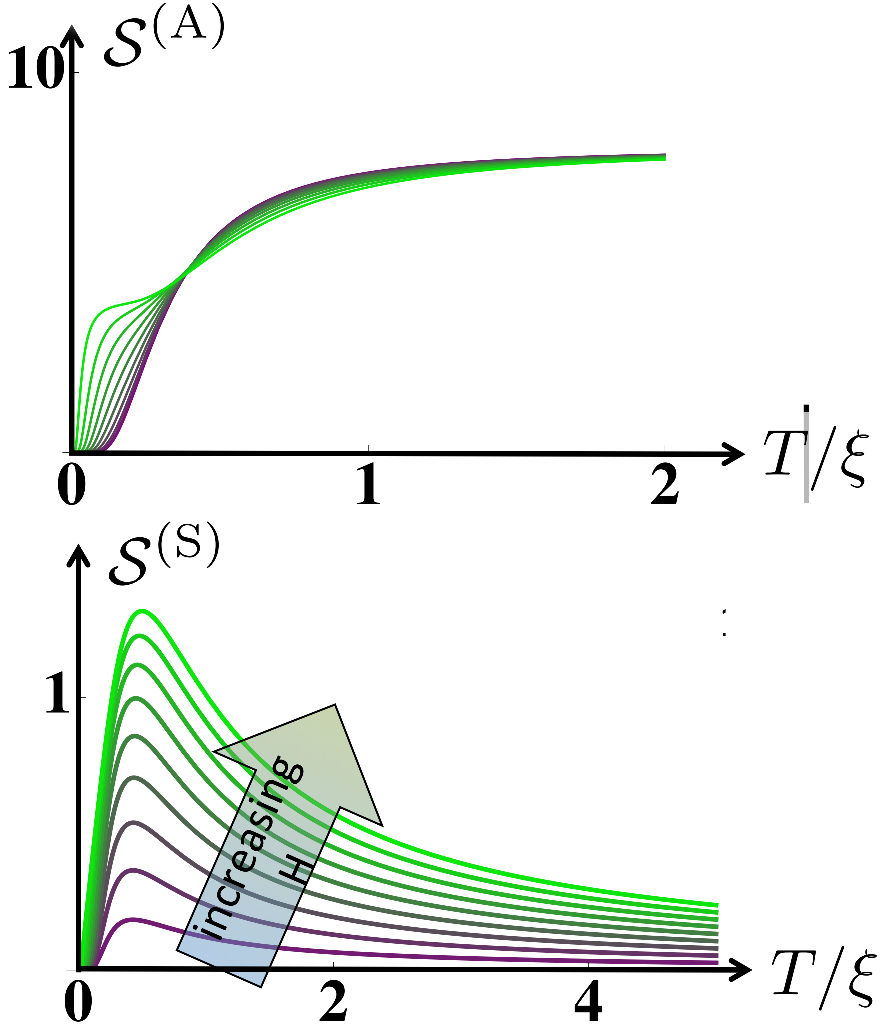
$\propto \alpha'$

$$S^{(\mathrm{S})}_{n\mathbf{q}}(-H) = -S^{(\mathrm{S})}_{n\mathbf{q}}(H)$$

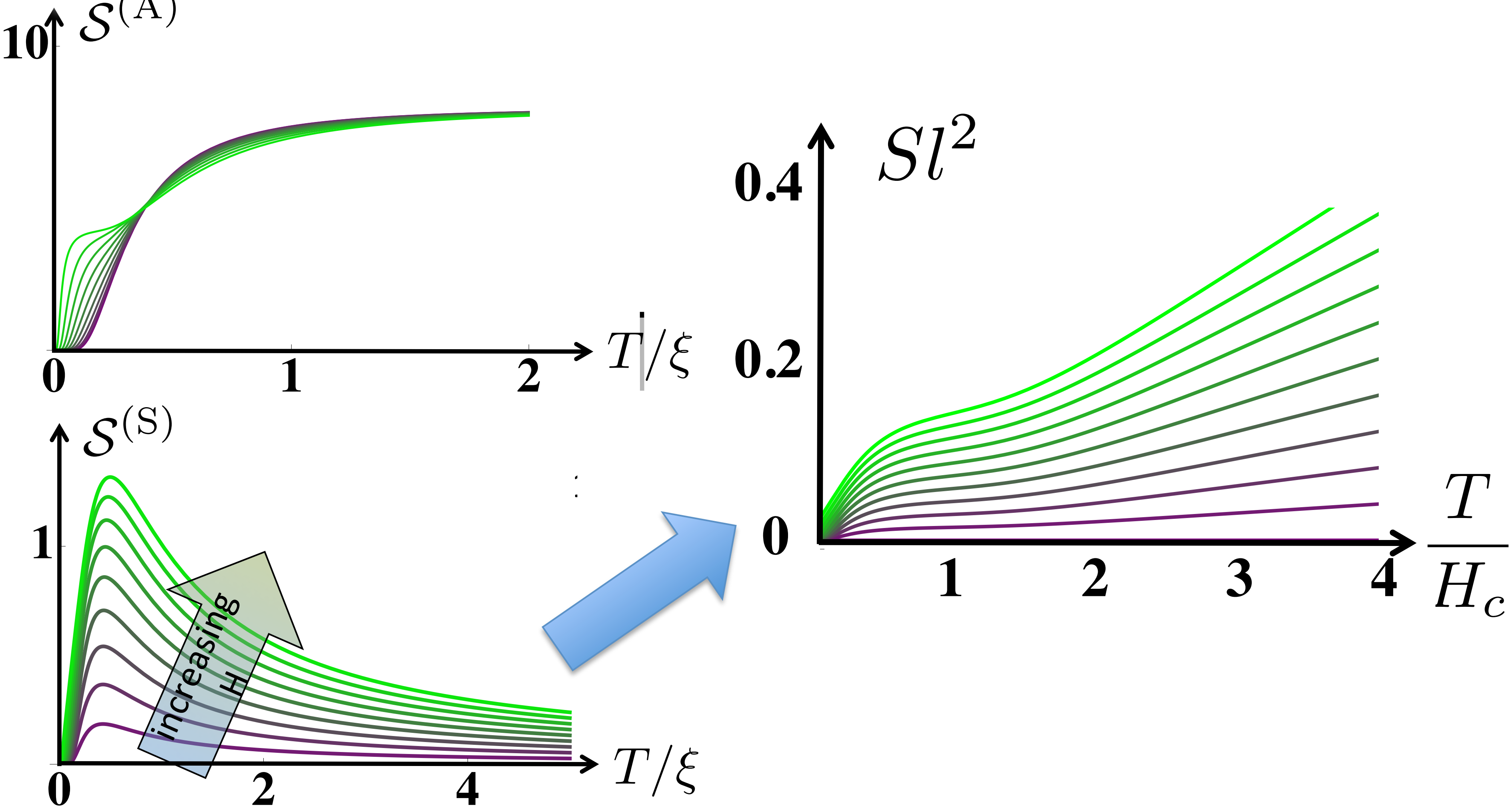
$\propto \tilde{\alpha}'$

$$S^{(\mathrm{A})}_{n\mathbf{q}}(-H) = S^{(\mathrm{A})}_{n\mathbf{q}}(H)$$

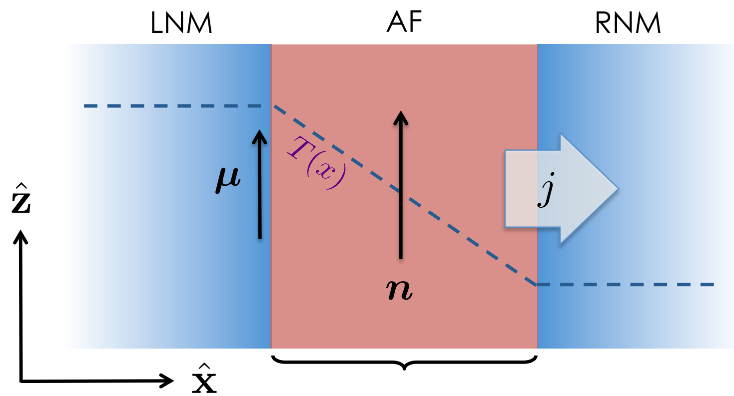
Spin seebeck effect



Spin seebeck effect



Spin biasing



$$j = G\mu$$

$$G = \sum_{n=0,1,2\ldots} \int \frac{d^2q}{(2\pi)^2} \left(G^{(\mathrm{S})}_{n\mathbf{q}} + G^{(\mathrm{A})}_{n\mathbf{q}} \right)$$

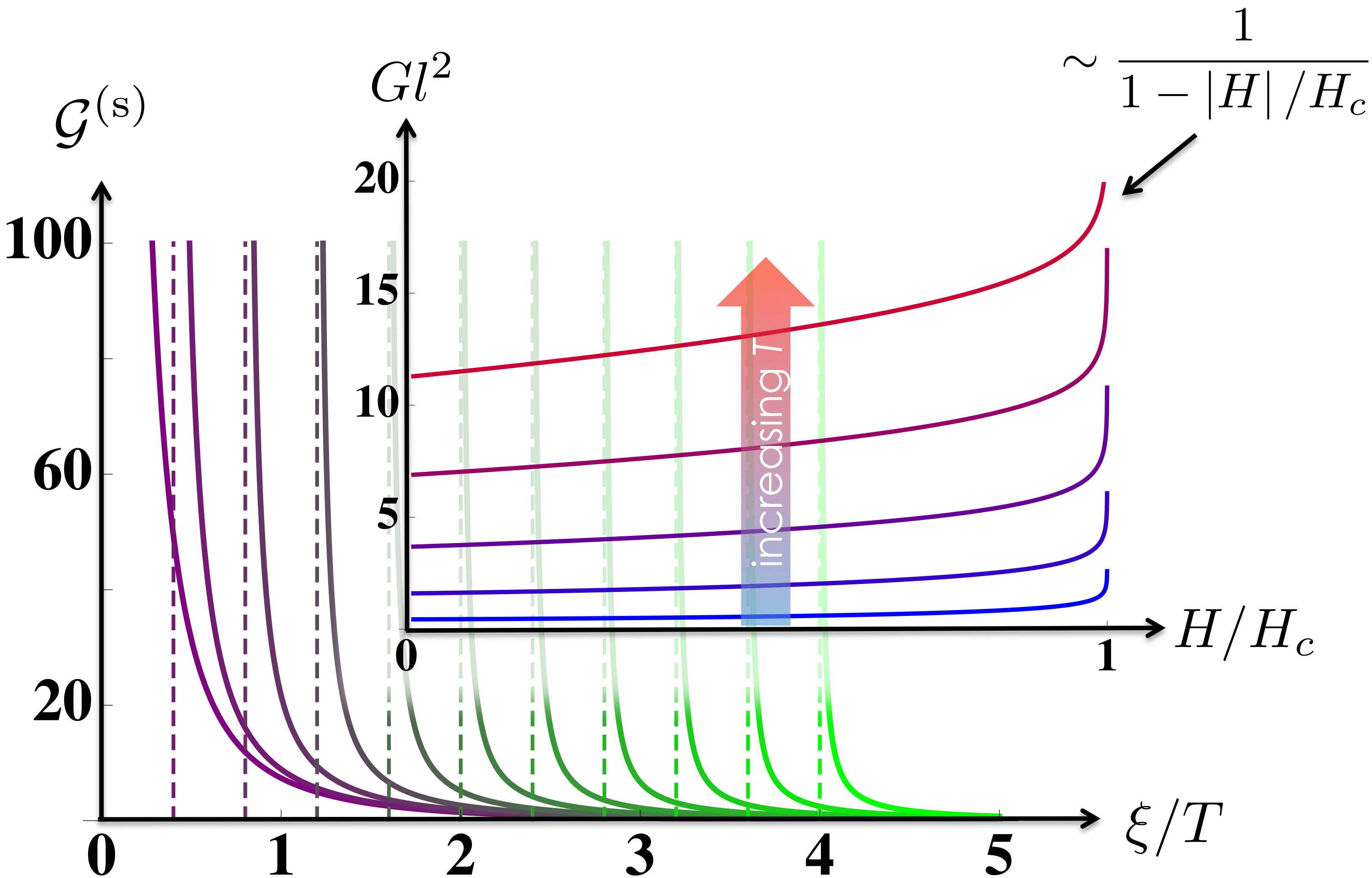
$\propto \alpha'$

$\propto \tilde{\alpha}'$

$$G^{(\mathrm{S})}_{n\mathbf{q}}(-H) = G^{(\mathrm{S})}_{n\mathbf{q}}(H)$$

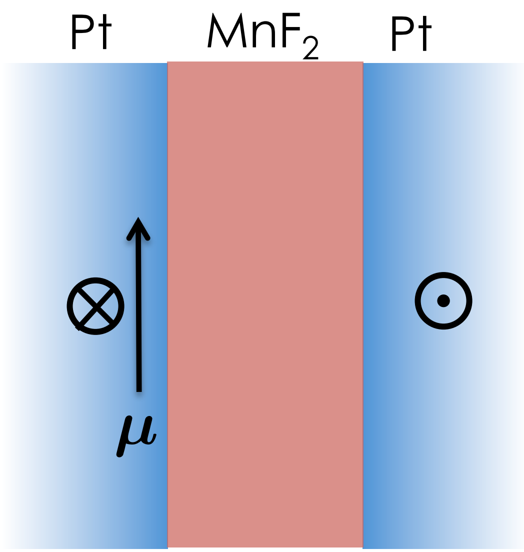
$$G^{(\mathrm{A})}_{n\mathbf{q}}(-H) = -G^{(\mathrm{A})}_{n\mathbf{q}}(H)$$

Spin biasing



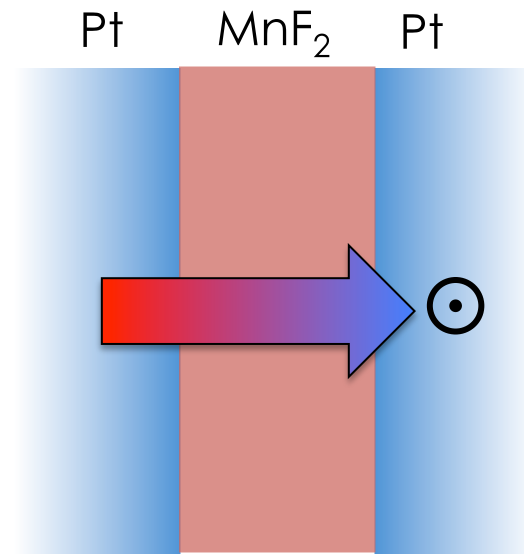
Experimental estimates

Spin Biasing



$$R = \frac{V}{I} \sim \mathrm{m}\Omega$$

Spin Seebeck



$$V \sim \mu\mathrm{V}$$

Conclusion

- Both symmetric and antisymmetric electron scattering at N/AF interfaces contribute
- Enhanced magnon conductance near spin flop transition
- Current work: magnon-magnon, magnon-phonon scattering, elastic disorder scattering for thicker films