Spin transport through antiferromagnets

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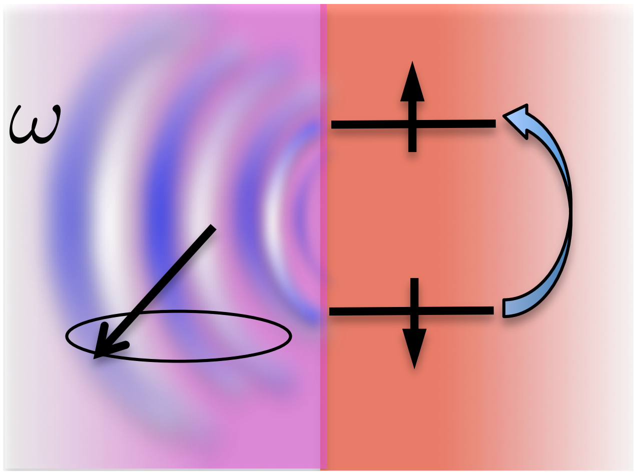
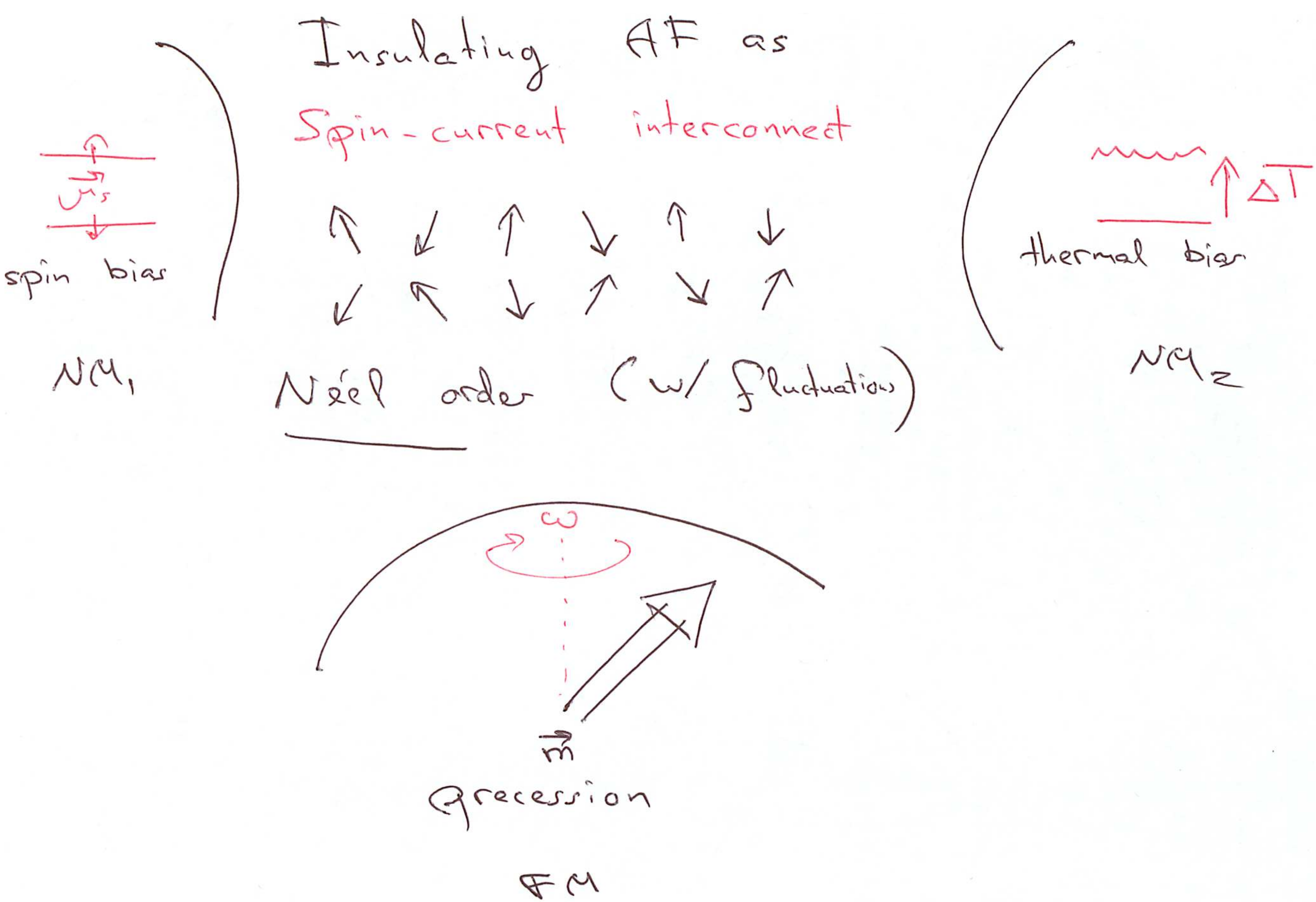
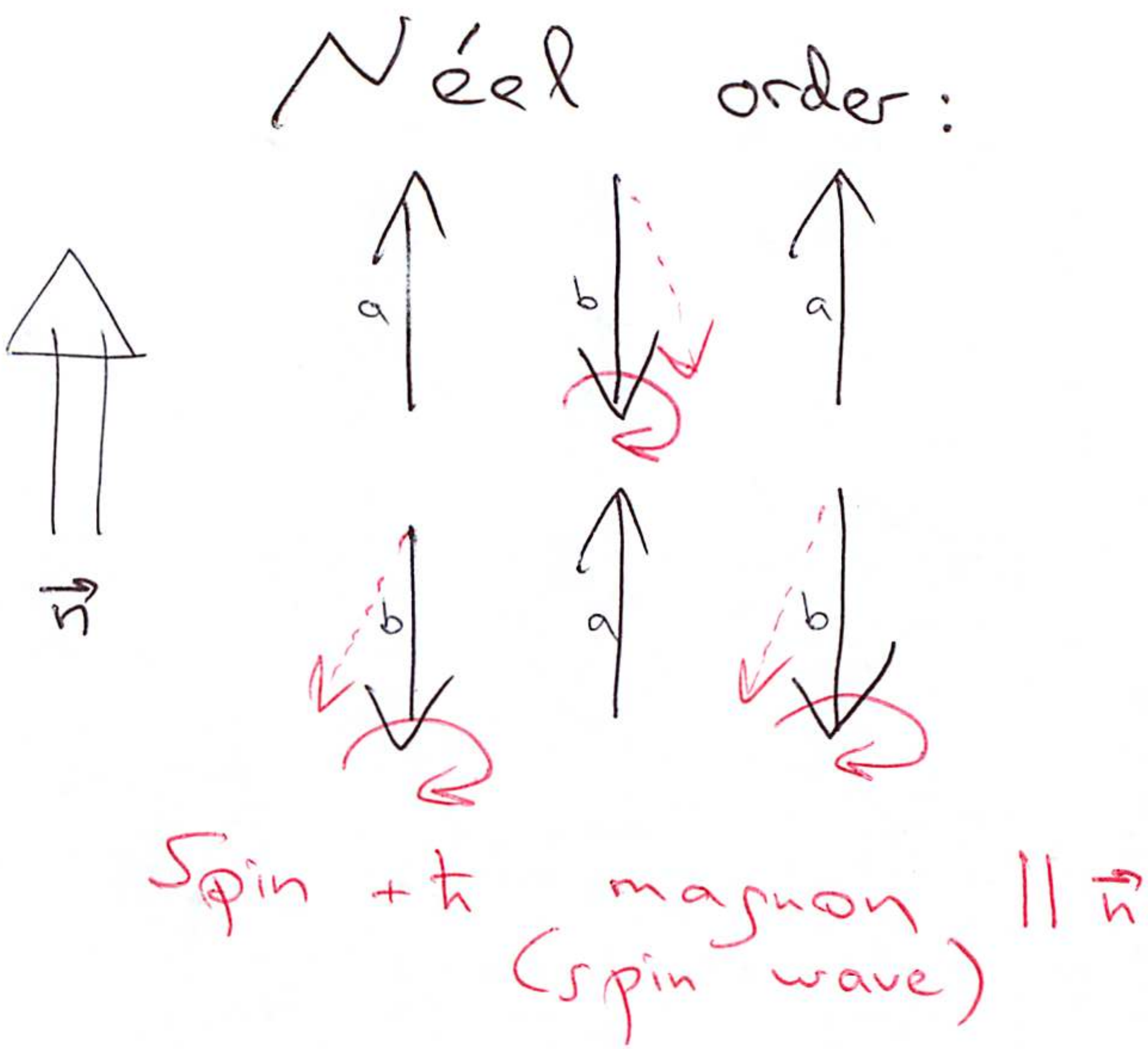


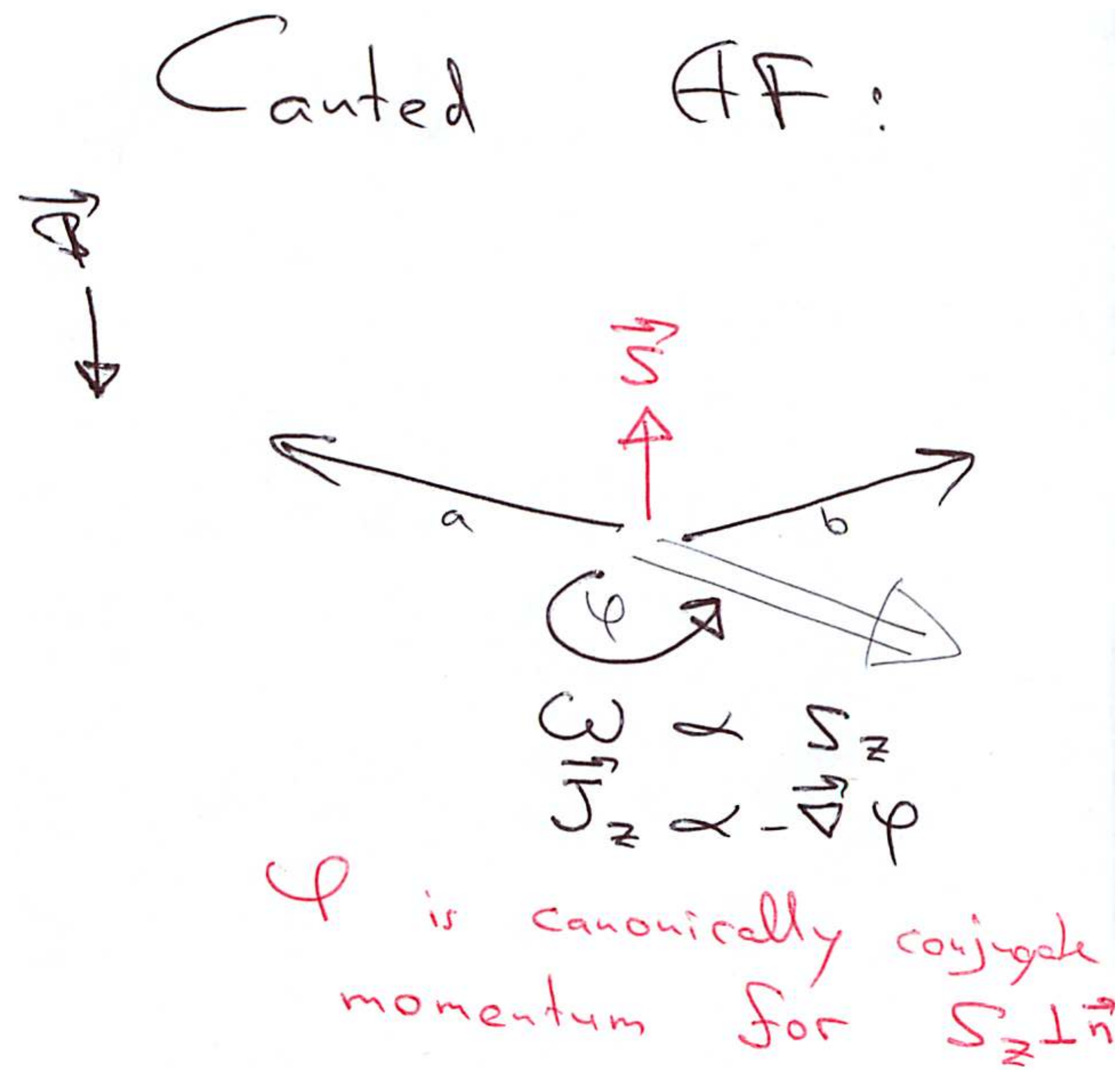
Scope


Insulating AF as
Spin-current interconnect
$\vec{\mu}_s$
spin bias
NM$_1$
Néel order (w/ fluctuation)
ΔT
thermal bias
NM$_2$
ω
$\vec{m}$
precession
FM

Two types of spin current

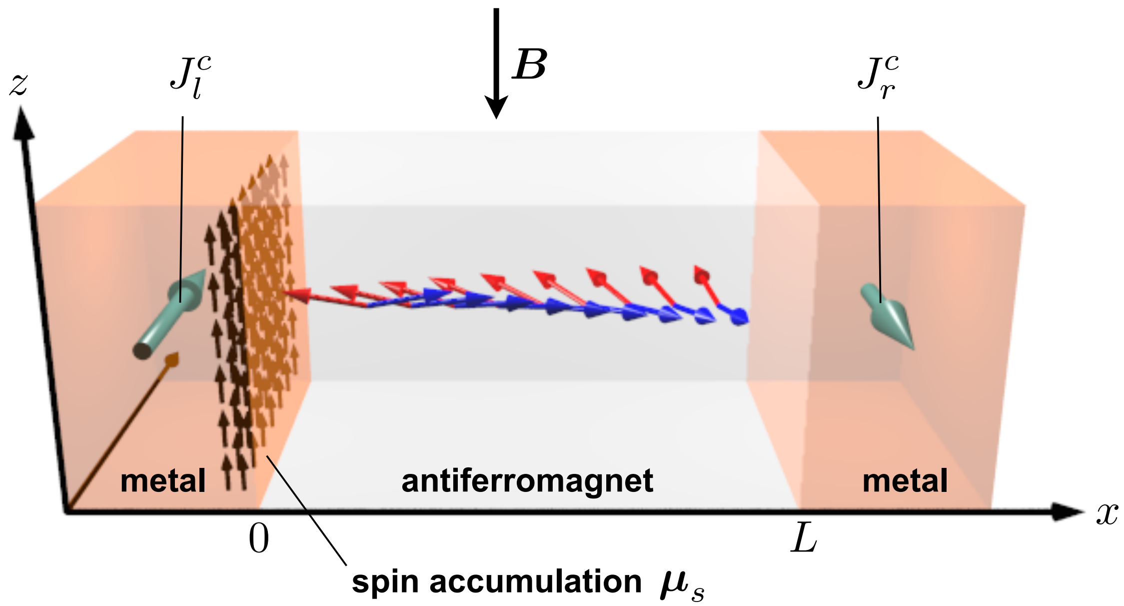


thermal spin transport
(vanishes at zero temperature)
See, however, Meier and Loss, *PRL* (2003)

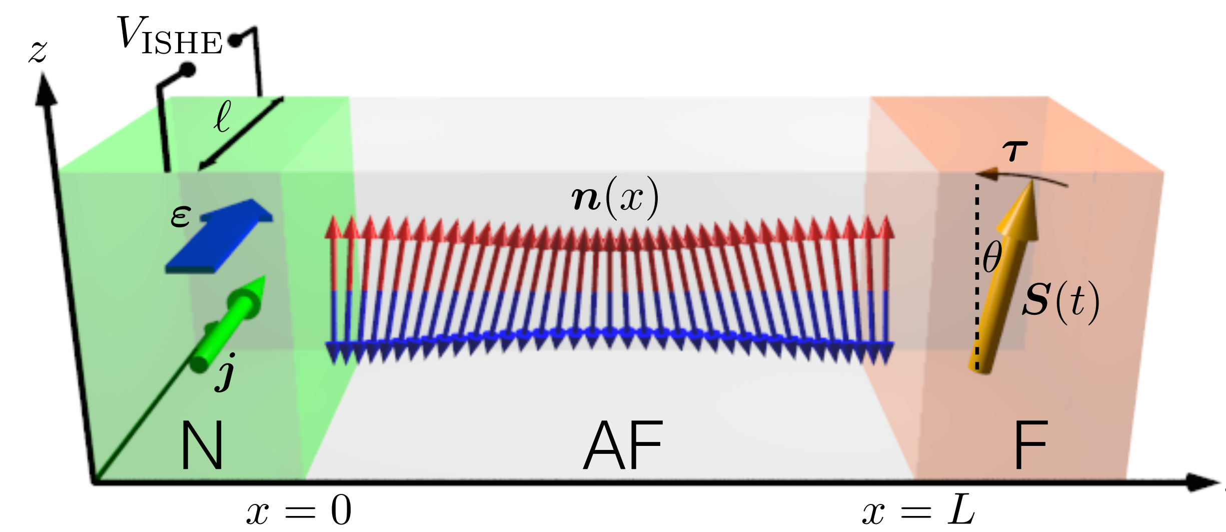


superfluid spin transport
(largest at zero temperature)
Sonin, *AP* (2010)

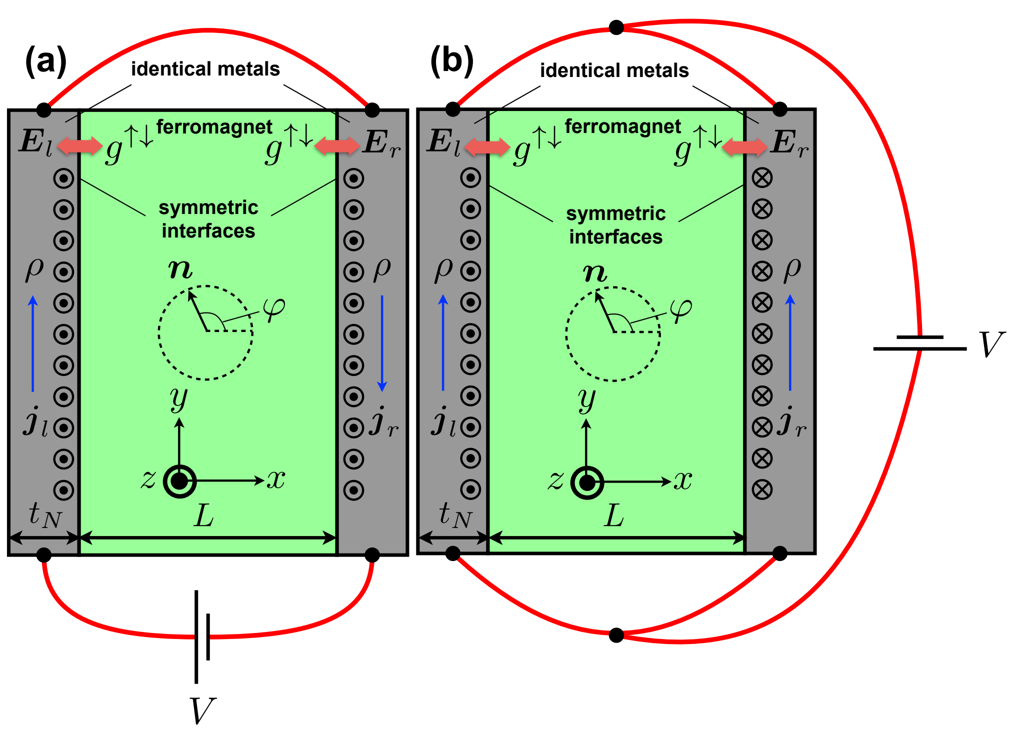
Overview



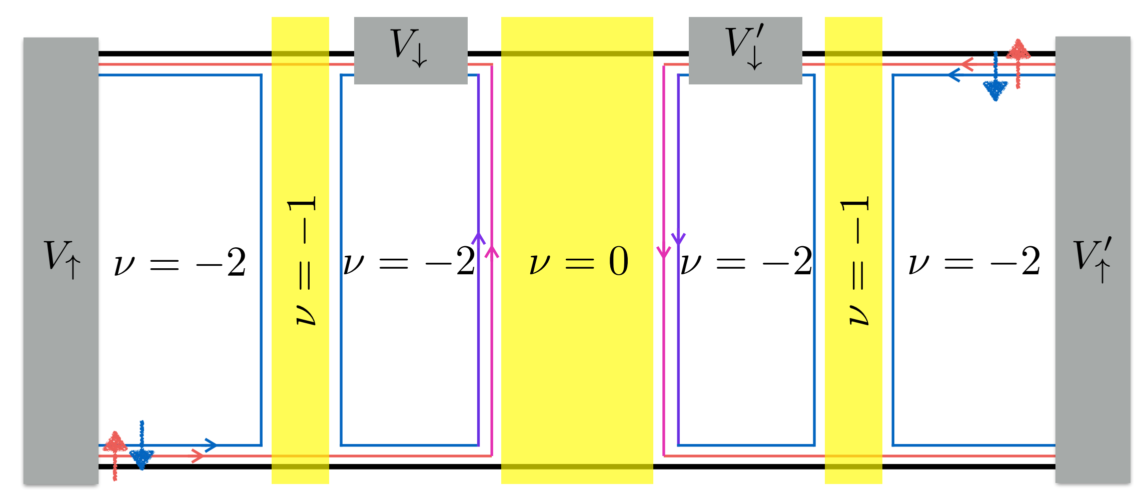
Takei, Halperin, Yacoby, and YT, *PRB* (2014)



Takei, Moriyama, Ono, and YT, *arXiv* (2015)



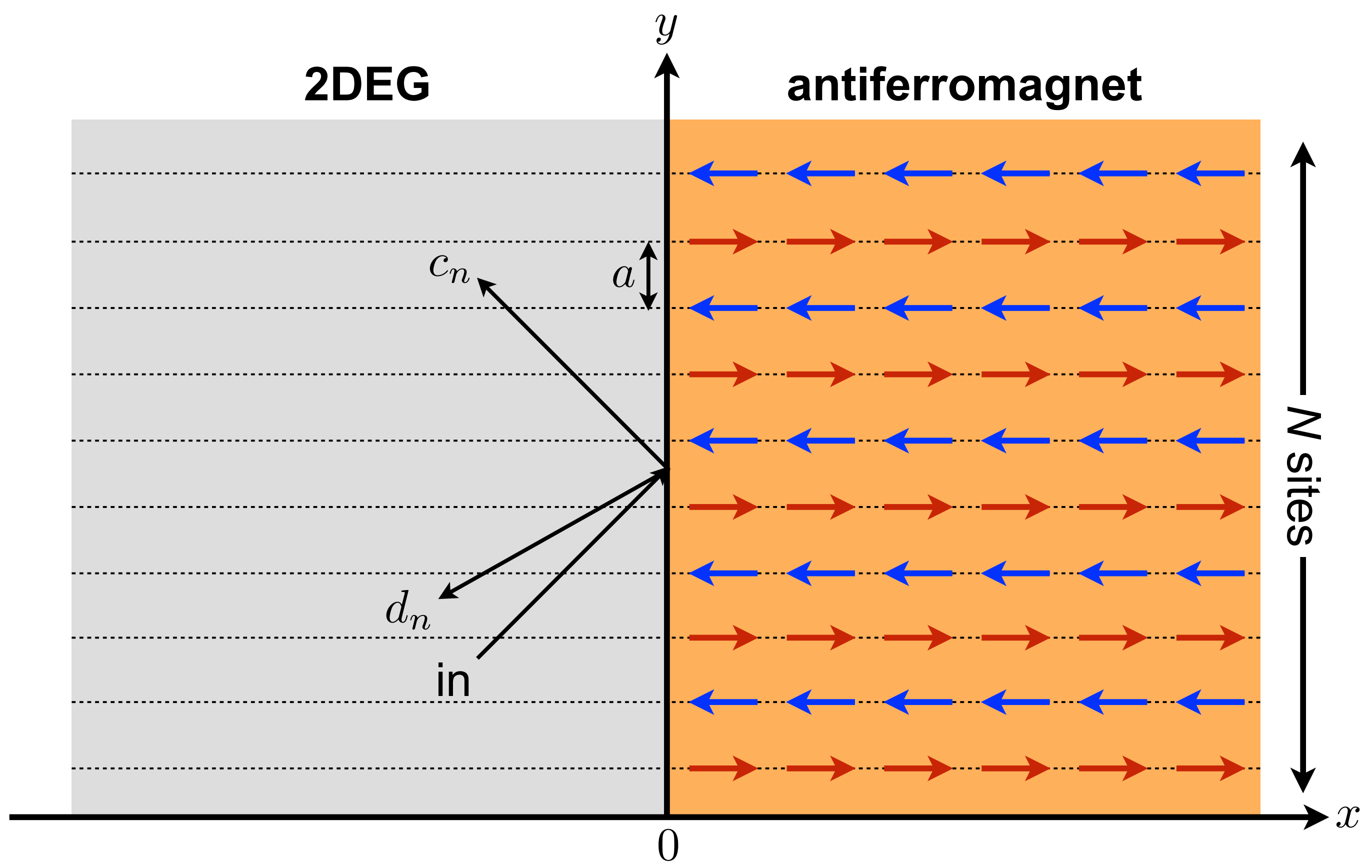
Takei and YT, *arXiv* (2015)



Takei, Yacoby, Halperin, and YT, *arXiv* (2015)

Low-temperature interfacial torque

- In the absence of spin-orbit interactions and spin-order inhomogeneities, the collinear spin of scattered electrons is conserved; the phase shift governs the *spin-mixing conductance:*



$$r^{\sigma}_{n'n} = \underbrace{c_n \delta_{n'n}}_{\text{specular}} + \underbrace{\sigma d_n \delta_{\bar{n}'n}}_{\text{umklapp}}$$

$$\bar{n} = (n + N/2) \bmod N$$

$$g^{\uparrow\downarrow} = \sum_{nm} \left(\delta_{nm} - r^{\uparrow}_{nm} r^{\downarrow *}_{nm}\right)$$

the interfacial spin current density:

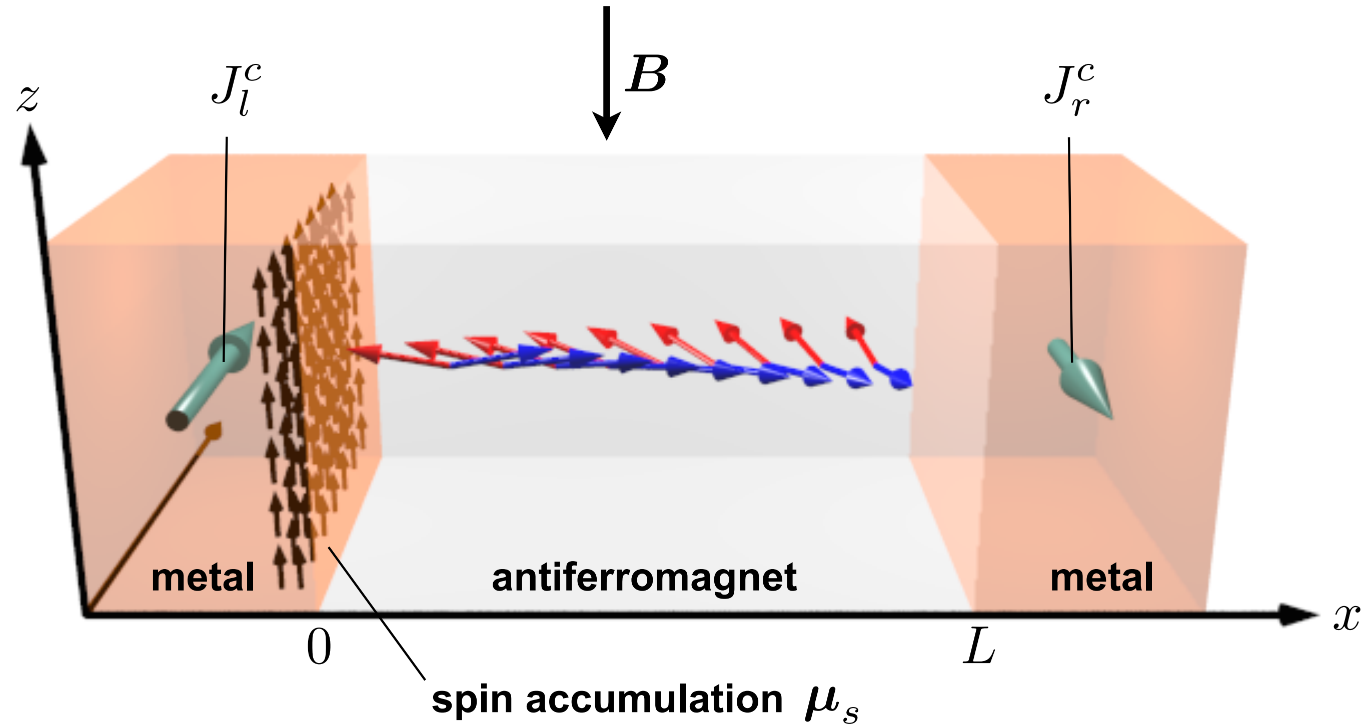
$$\mathbf{J}_s = \frac{\mathrm{Re}\, g^{\uparrow\downarrow}}{4\pi} \mathbf{n} \times \tilde{\boldsymbol{\mu}}_s \times \mathbf{n} + \frac{\mathrm{Im}\, g^{\uparrow\downarrow}}{4\pi} \tilde{\boldsymbol{\mu}}_s \times \mathbf{n}$$

$$\tilde{\boldsymbol{\mu}}_s \equiv \underbrace{\boldsymbol{\mu}_s}_{\text{torque}} - \underbrace{\hbar \mathbf{n} \times \dot{\mathbf{n}}}_{\text{pumping}}$$

Unitarity: $|c_n|^2 + |d_n|^2 = 1 \quad \Rightarrow \quad g^{\uparrow\downarrow} = 2 \sum_n |d_n|^2$

Takei, Halperin, Yacoby, and YT, *PRB* (2014)

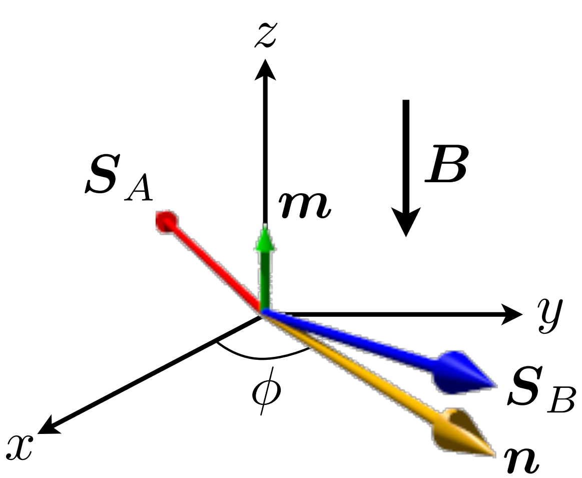
Two-terminal spin superfluid



Takei, Halperin, Yacoby, and YT, *PRB* (2014)

nonlinear σ model: $$\mathcal{L}_{\mathrm{AF}}[\mathbf{m},\mathbf{n}] = \mathcal{L}_k - \frac{A}{2}(\partial_\mu \mathbf{n})^2 - \frac{\mathbf{m}^2}{2\chi} - \mathbf{b}\cdot\mathbf{m}$$

kinetic term (Berry phase): $$\mathcal{L}_k = s\mathbf{m}\cdot(\mathbf{n}\times\partial_t\mathbf{n})$$



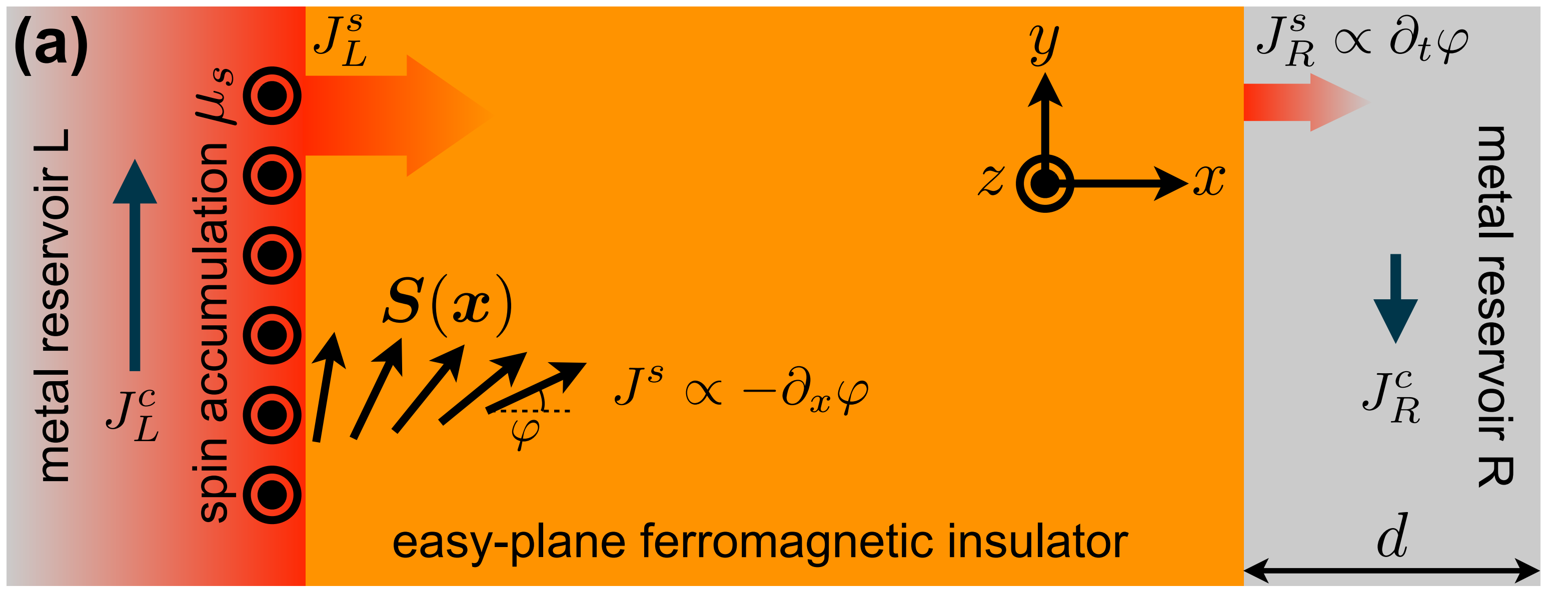
collective spin current: $$\mathbf{J}_s = -A\mathbf{n}\times\boldsymbol{\nabla}\mathbf{n} \to -A\boldsymbol{\nabla}\phi$$

Gilbert damping: $$s\dot{\mathbf{m}} = -\alpha\mathbf{n}\times\dot{\mathbf{n}} + \cdots$$

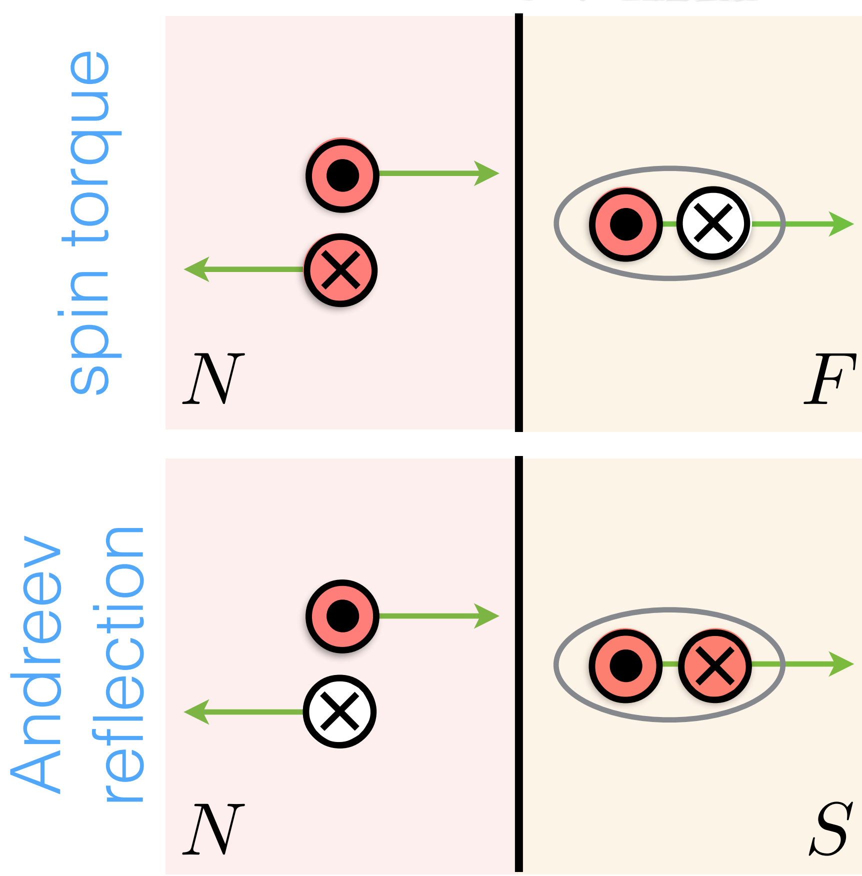
Halperin and Hohenberg, *PR* (1969); Sonin, *JETP* (1978) and *AP* (2010); König, Bønsager, and MacDonald, *PRL* (2001)

Ferromagnetic analog

- Low-energy dynamics of easy-plane ferromagnet is fully equivalent:



Takei and YT, *PRL* (2014)



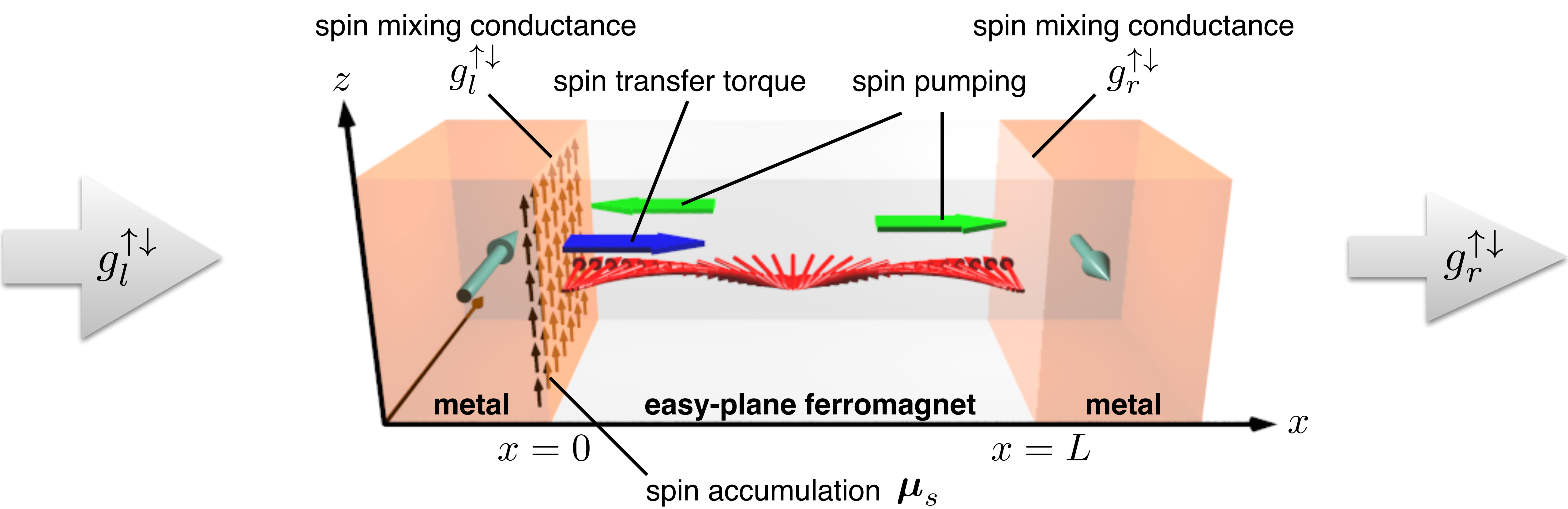
$$\mathbf{J}_s = \frac{\mathrm{Re}\, g^{\uparrow\downarrow}}{4\pi} \mathbf{n} \times \tilde{\boldsymbol{\mu}}_s \times \mathbf{n} + \frac{\mathrm{Im}\, g^{\uparrow\downarrow}}{4\pi} \tilde{\boldsymbol{\mu}}_s \times \mathbf{n}$$

$$\tilde{\boldsymbol{\mu}}_s \equiv \boldsymbol{\mu}_s - \hbar \mathbf{n} \times \dot{\mathbf{n}}$$

effective voltage difference

YT, Brataas, Bauer, and Halperin, *RMP* (2005)

Spin-current circuit

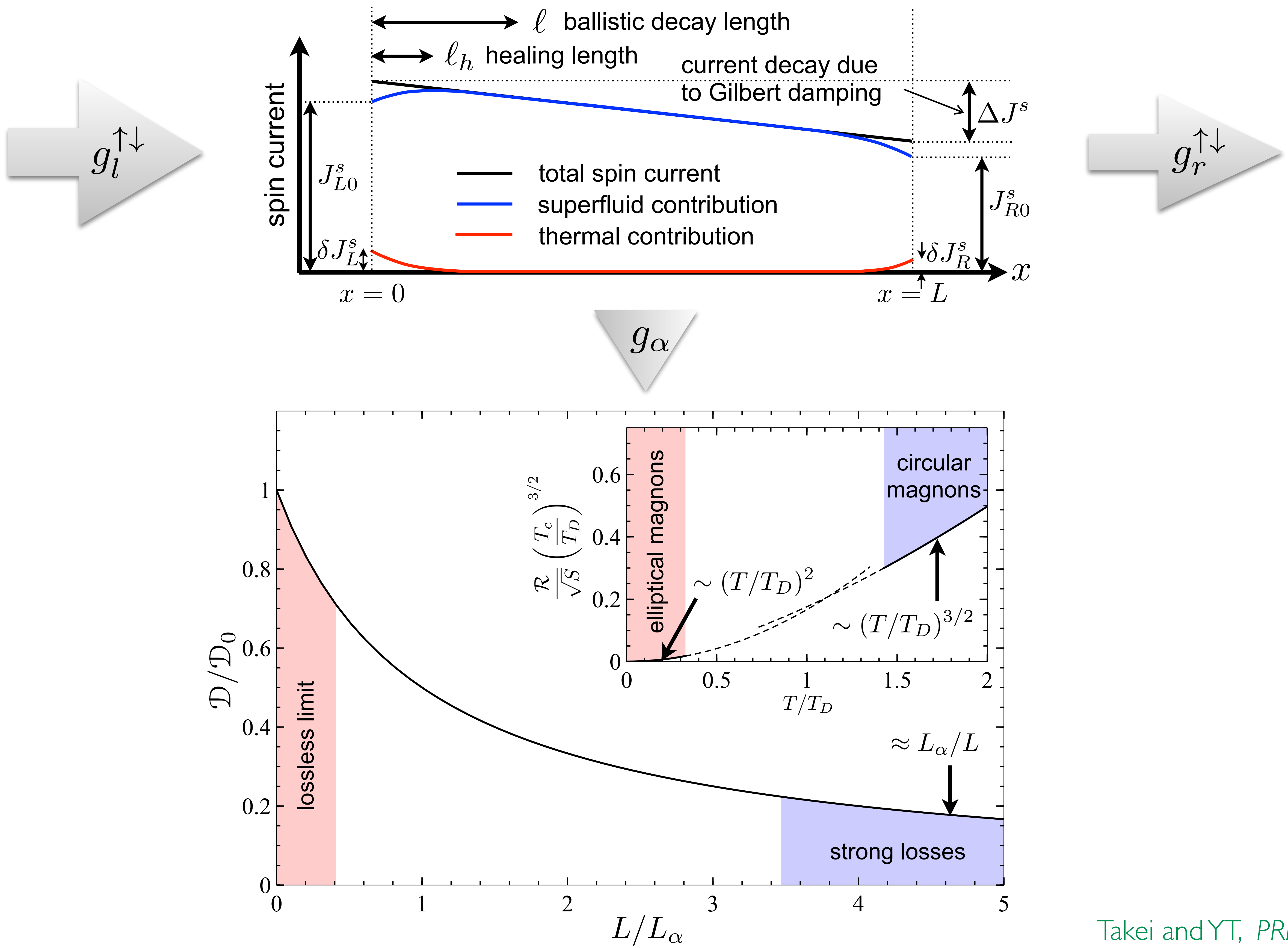


$$g_\alpha = \frac{4\pi\alpha s L}{\hbar}$$

$$\Omega = \frac{\mu_s}{\hbar}\frac{g_l^{\uparrow\downarrow}}{g_l^{\uparrow\downarrow} + g_r^{\uparrow\downarrow} + g_\alpha}\,, \quad J_r^s = \frac{\mu_s}{4\pi}\frac{g_l^{\uparrow\downarrow} g_r^{\uparrow\downarrow}}{g_l^{\uparrow\downarrow} + g_r^{\uparrow\downarrow} + g_\alpha}$$

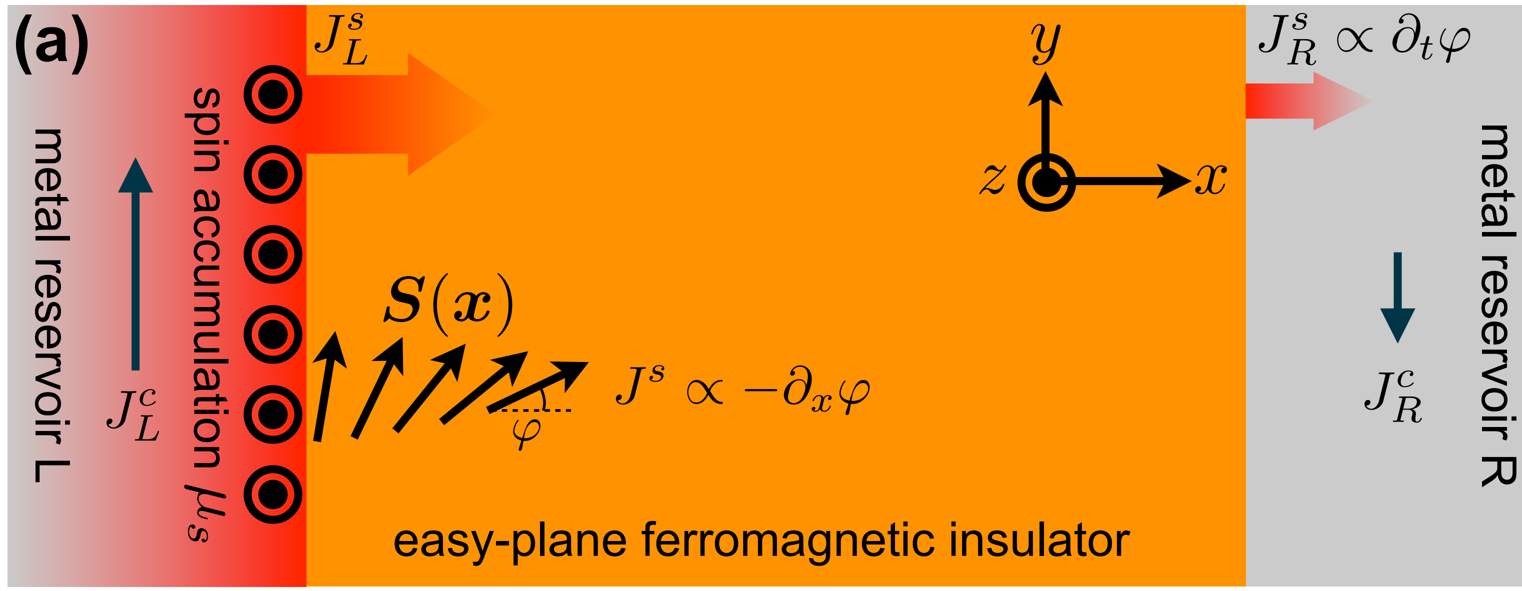
Takei and YT, *PRL* (2014)

Role of thermal magnons



Takei and YT, *PRL* (2014)

Negative DC electron drag



$$J^s_{\mathrm{SH}} = \frac{\hbar}{2e}\theta_{\mathrm{SH}} J^c_l$$

Onsager

$$J^c_r = -\frac{\hbar}{2e}\theta_{\mathrm{SH}}\frac{\sigma}{d}\Omega$$

$$\mathcal{D} \equiv -\frac{J^c_r}{J^c_l} = \frac{h}{4e^2}\left(\frac{\theta^2_{\mathrm{SH}}}{g^{\uparrow\downarrow}}\right)_{N|F}\left(\frac{\sigma}{\lambda_s}\right)_N$$

assuming

$$L < l_\alpha \equiv \frac{\hbar g^{\uparrow\downarrow}}{4\pi\alpha s}$$

for $\mathrm{Pt|YIG|Pt}$ heterostructure: $l_\alpha \sim 1\ \mu\mathrm{m}$ and $\mathcal{D} \sim 0.1$

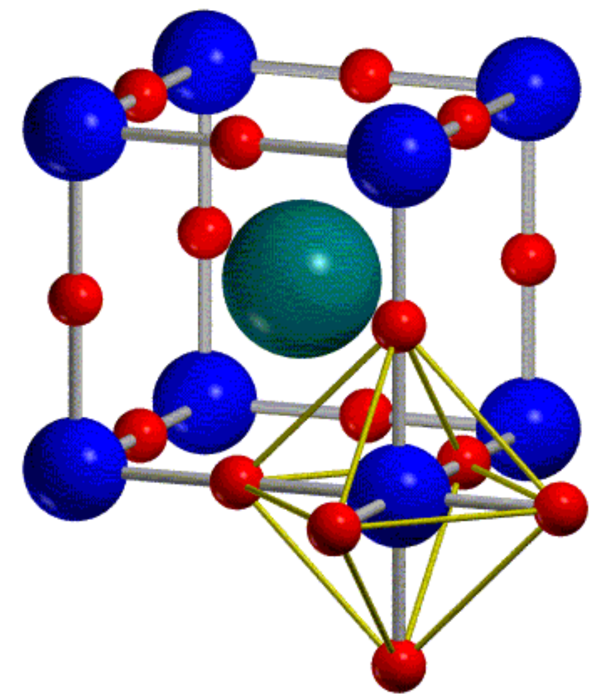
See also Eisenstein and MacDonald, *Nature* (2004) on *BEC of excitons in bilayer electron systems*

Possible materials: Perovskites

$RbMnF_3$

$S = 5/2$

$T_N \approx 83$ K



$KNiF_3$

$S = 1$

$T_N \approx 275$ K

$\alpha \sim 10^{-4}$ $\rightarrow$ damping length $L_\alpha \sim 100$ nm

anisotropy: $K/J \sim 10^{-5}$ $\rightarrow$ critical length $L_c = \sqrt{A/K} \sim 100$ nm

$J_c^{(s)} = KL_c = \sqrt{AK}$ $\rightarrow$ $J^{(c)} \sim 10^{12}$ A/m^2

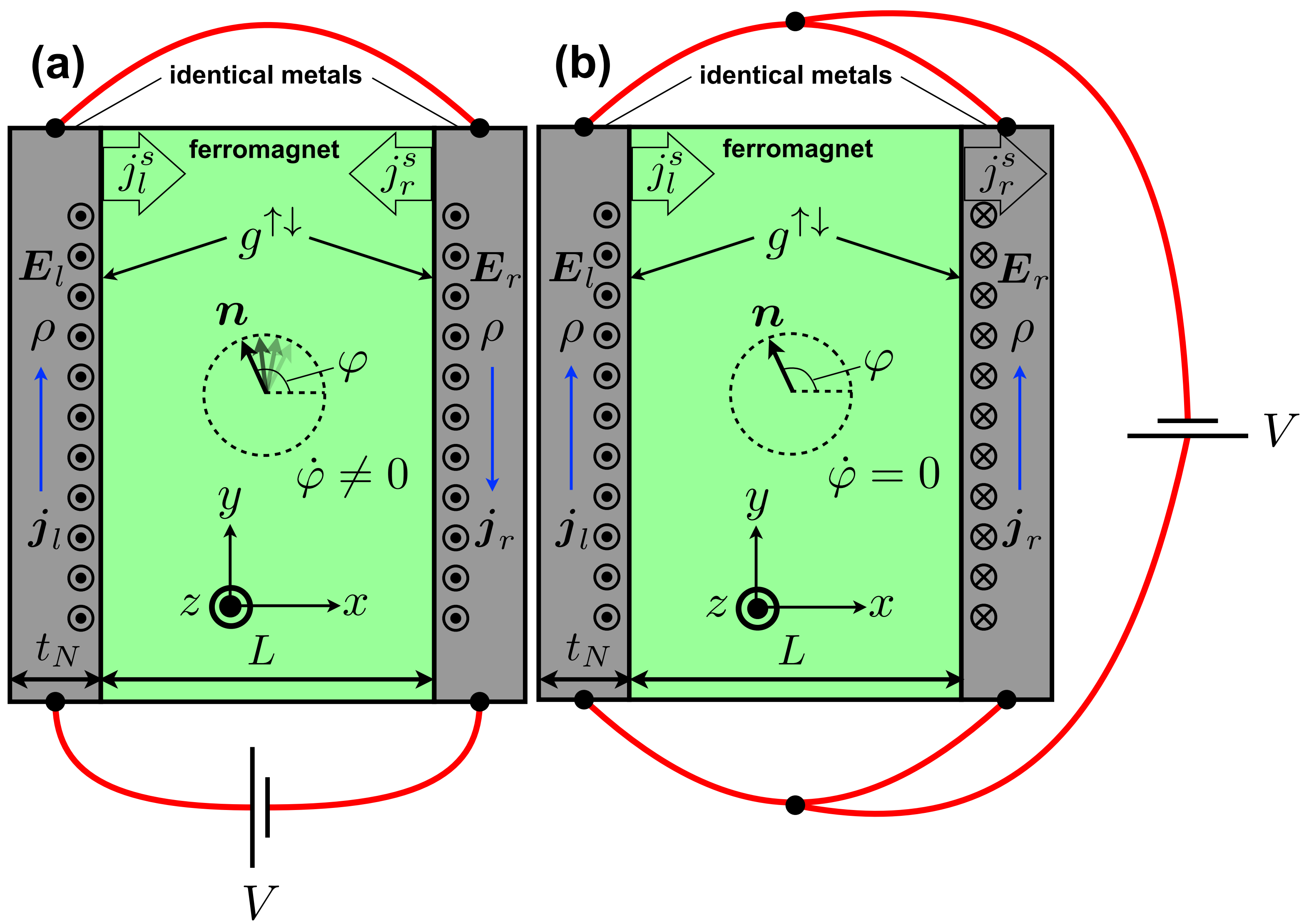
minimal magnetic field providing easy plane: $B_c = \sqrt{KJ} \sim 1$ T

Takei, Halperin, Yacoby, and YT, *PRB* (2014)

Topological magnetoresistance

- Circulating current through two metal films in series (a) spins the order, reducing the overall dissipation

$$\rho_m = -\frac{\vartheta^2}{g^{\uparrow\downarrow} + g_\alpha/2}$$



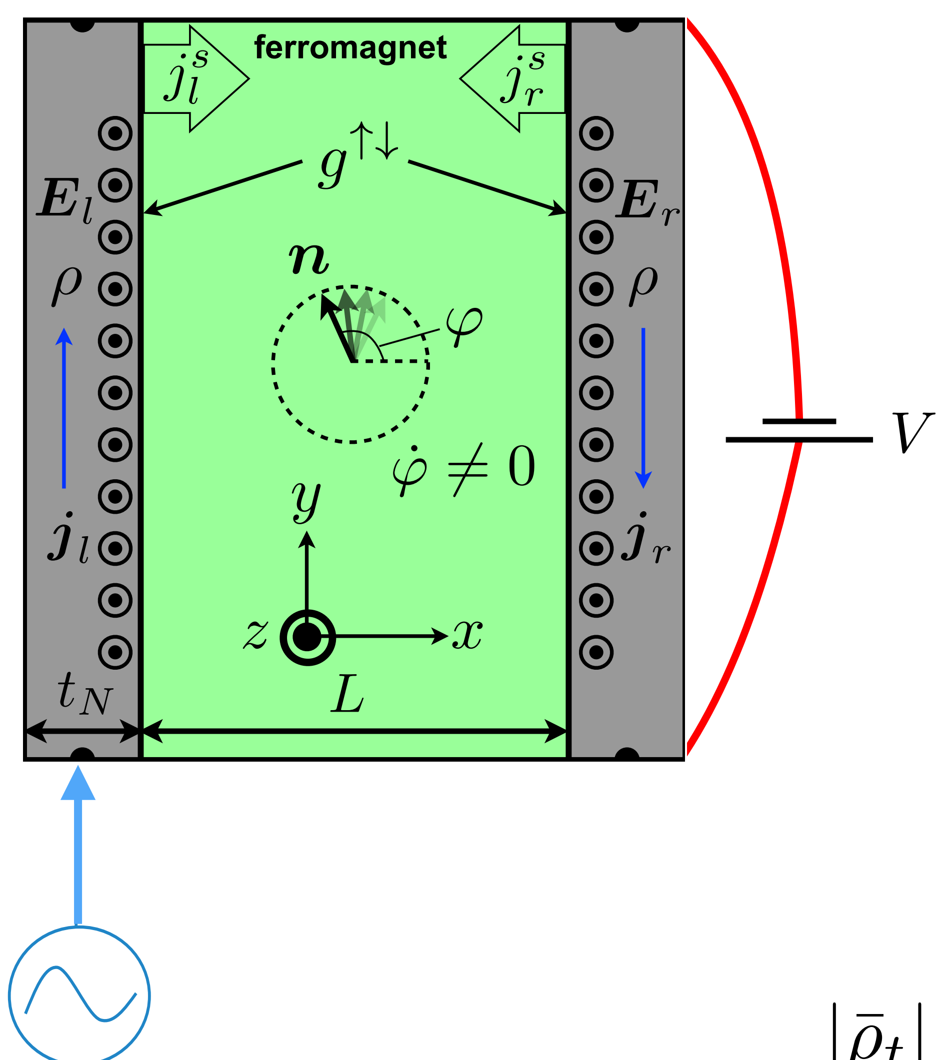
$$\rho_m = 0$$

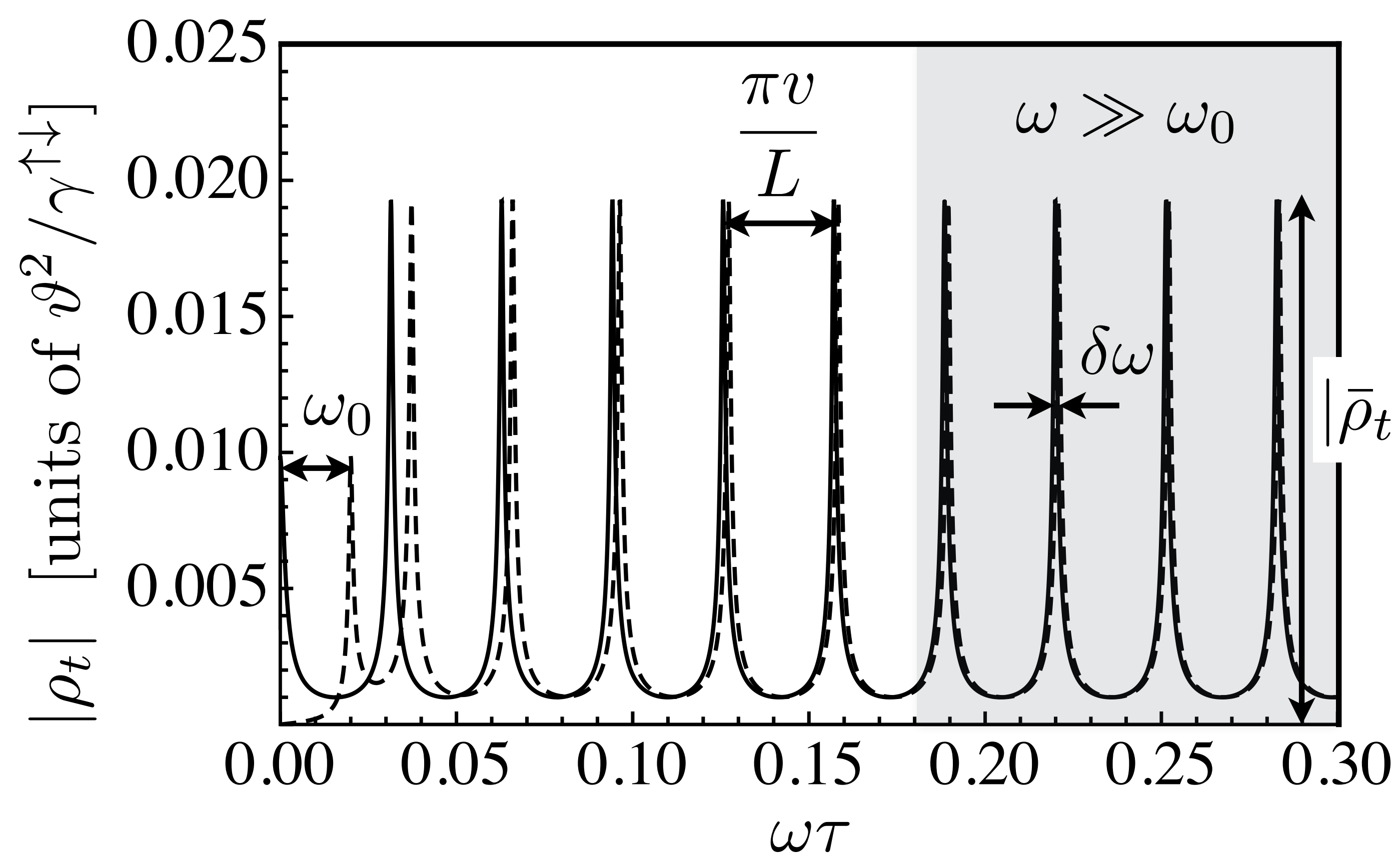
- In the parallel configuration, the torques are balanced, and the magnet remains stationary, causing more friction

Takei and YT, *arXiv* (2015)

AC transresistance

- While the DC spin supercurrent (and corresponding drag) can be quenched by an in-plane anisotropy, the AC transresistance is still fully operative on spin-wave resonances:



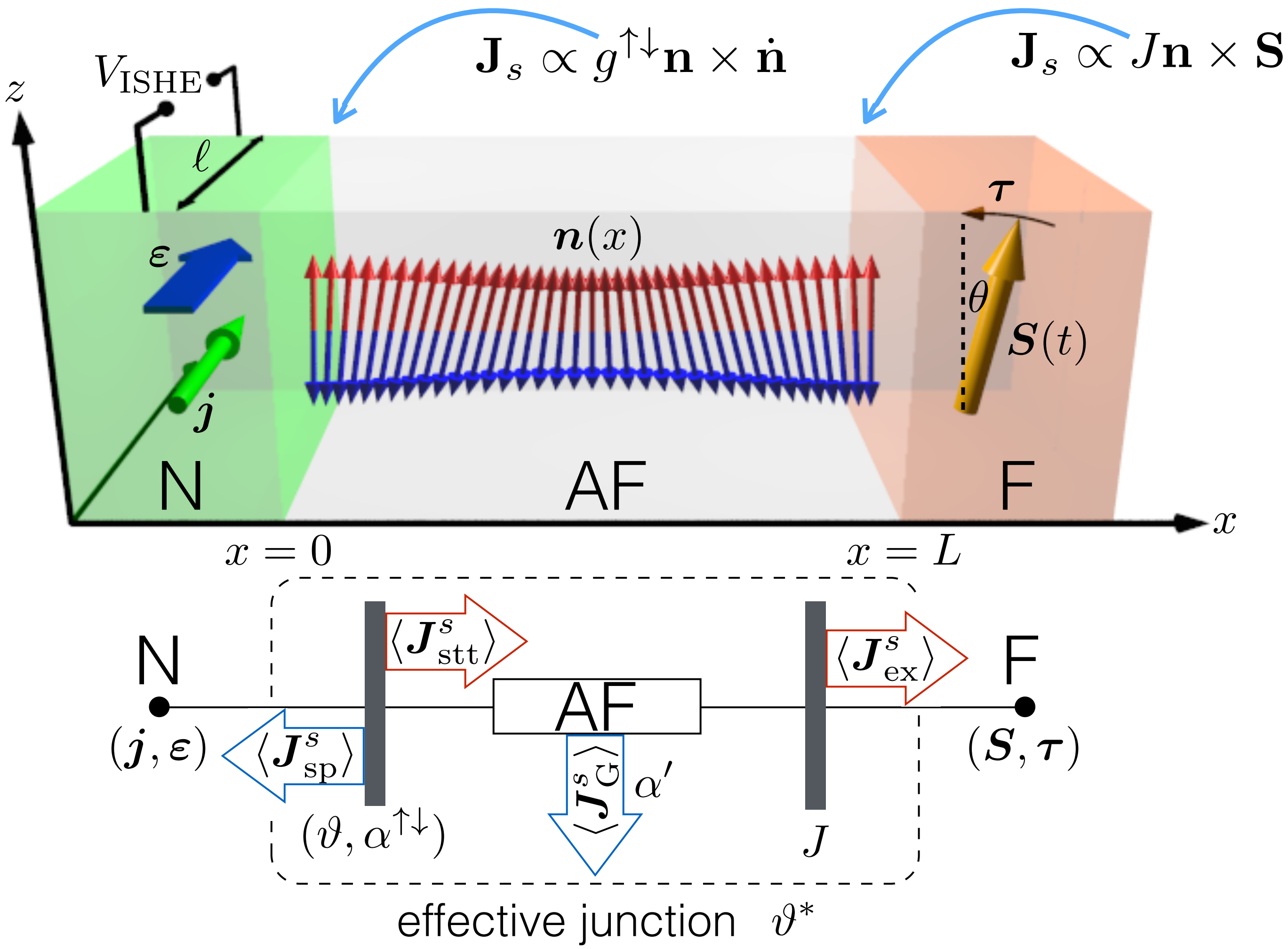


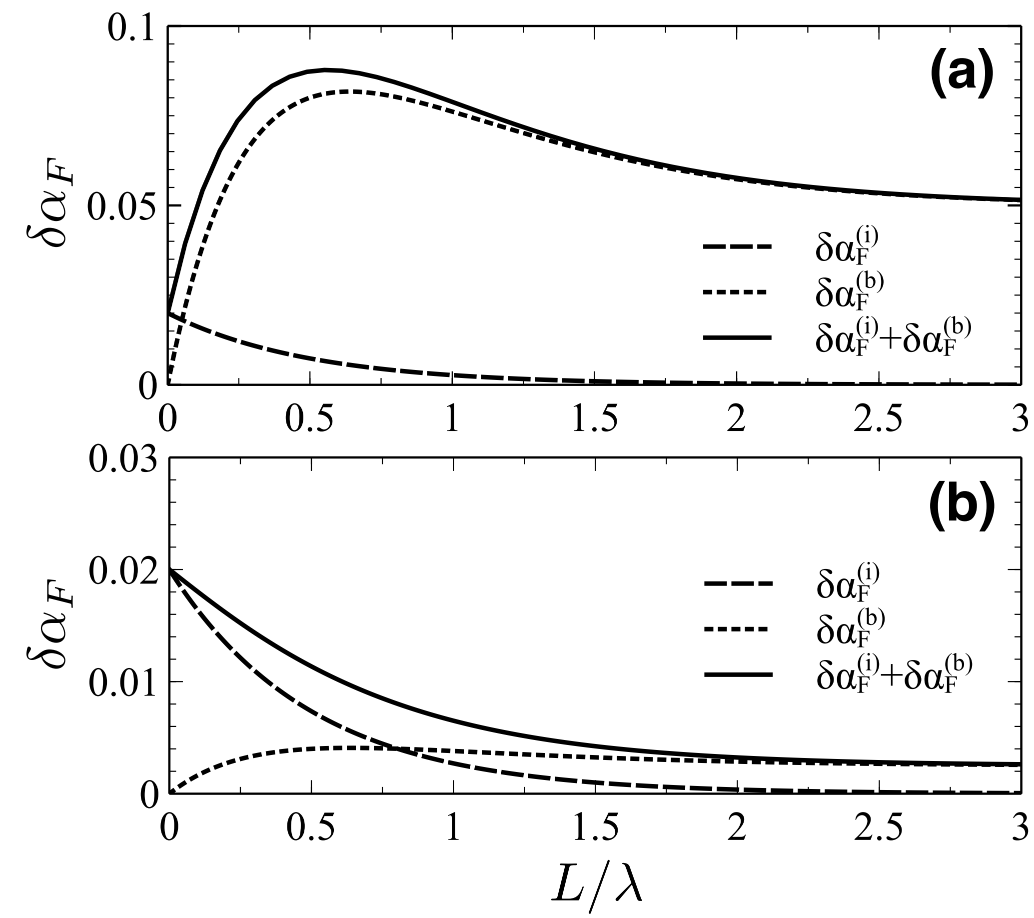
$$|\bar{\rho}_t| = \frac{\vartheta^2}{2g^{\uparrow\downarrow} + g_\alpha/2}$$

Takei and YT, *arXiv* (2015)

AF-mediated spin transfer

- Spin transfer torque and spin pumping mediated by AF:



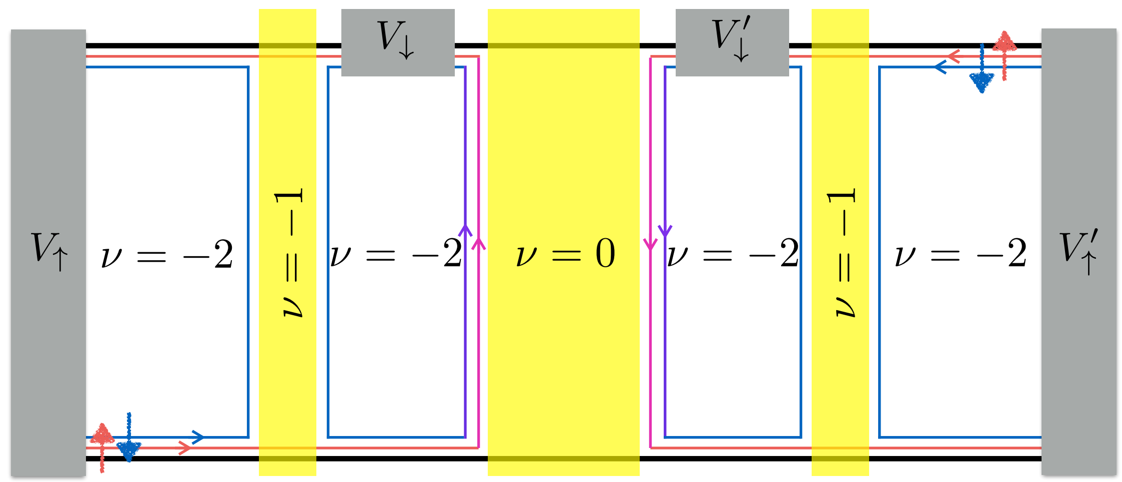


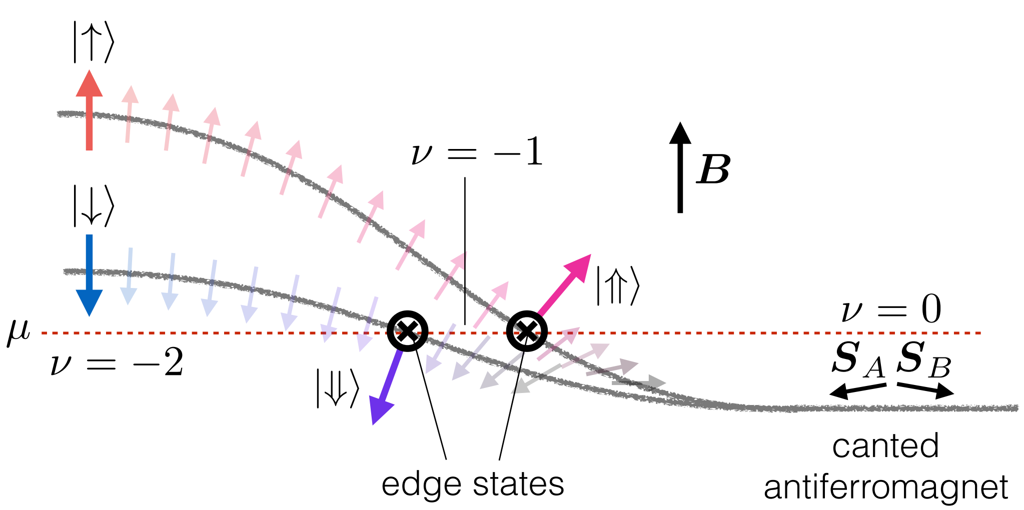
$$\alpha_F^{(i)} = \frac{1}{S}\frac{g^{\uparrow\downarrow}+\frac{\vartheta}{\omega_F}j}{\left(\cosh\frac{L}{\lambda}+\frac{1}{\eta}\sinh\frac{L}{\lambda}\right)^2}$$

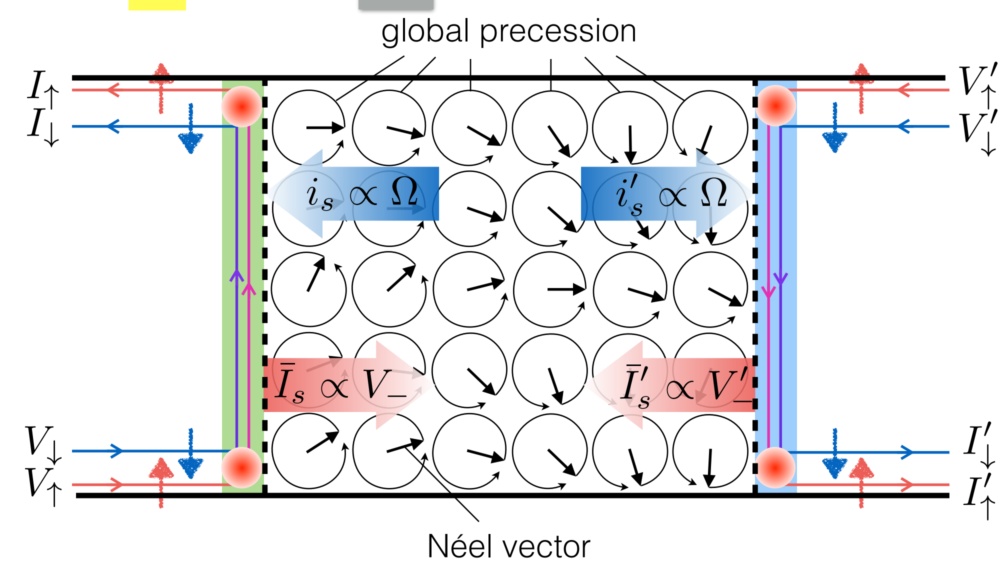
$$\alpha_F^{(b)} = \frac{\alpha_{\mathrm{AF}}}{S}\frac{\frac{L}{\lambda}+\frac{1}{2}\sinh\frac{2L}{\lambda}}{\left(\cosh\frac{L}{\lambda}+\frac{1}{\eta}\sinh\frac{L}{\lambda}\right)^2}$$

Exp: Hahn *et al.*, *EPL* (2014), Wang *et al.*, *PRL* (2014), Moriyama *et al.*, *APL* (2015)   Takei, Moriyama, Ono, and YT, *arXiv* (2015)

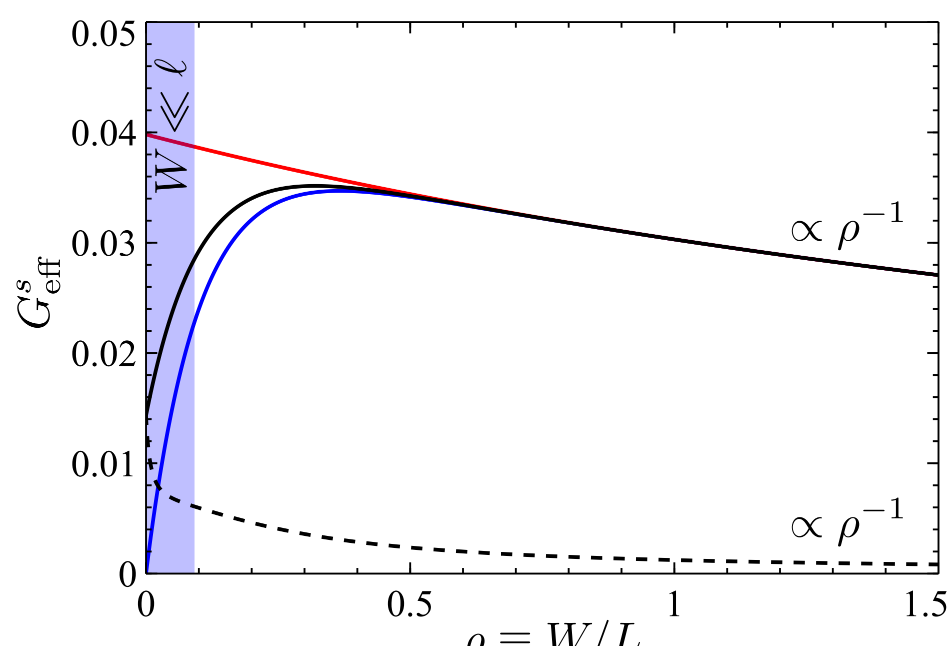
Spin transport through 0LL in graphene







interplay between damping, vertex scattering, and interedge scattering:



Takei, Yacoby, Halperin, and YT, *arXiv* (2015)

Summary

- While antiferromagnets possess magnetic order that is hidden from generic electromagnetic probes, they appear as potentially efficient interconnects for spin transport
- It is natural to invoke a two-fluid picture, with the spin superfluid dominating transport at low temperatures (compared to T_N)
- Spin transport can be transmitted through interfaces with normal metals and ferromagnets, and thus manifested through spin Hall and FMR probes; exhibiting long-ranged and topological characteristics
- Intriguing prospects for edge transport in strongly-correlated symmetry-broken graphene under strong magnetic field