Collective spin transport through antiferromagnets

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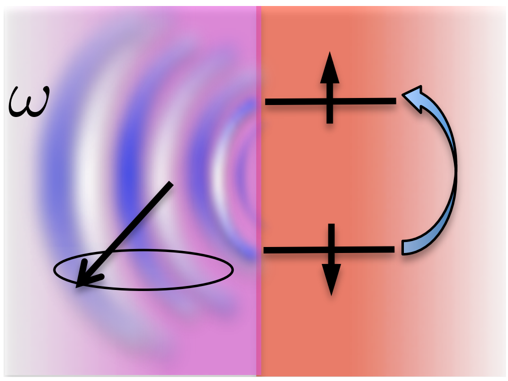
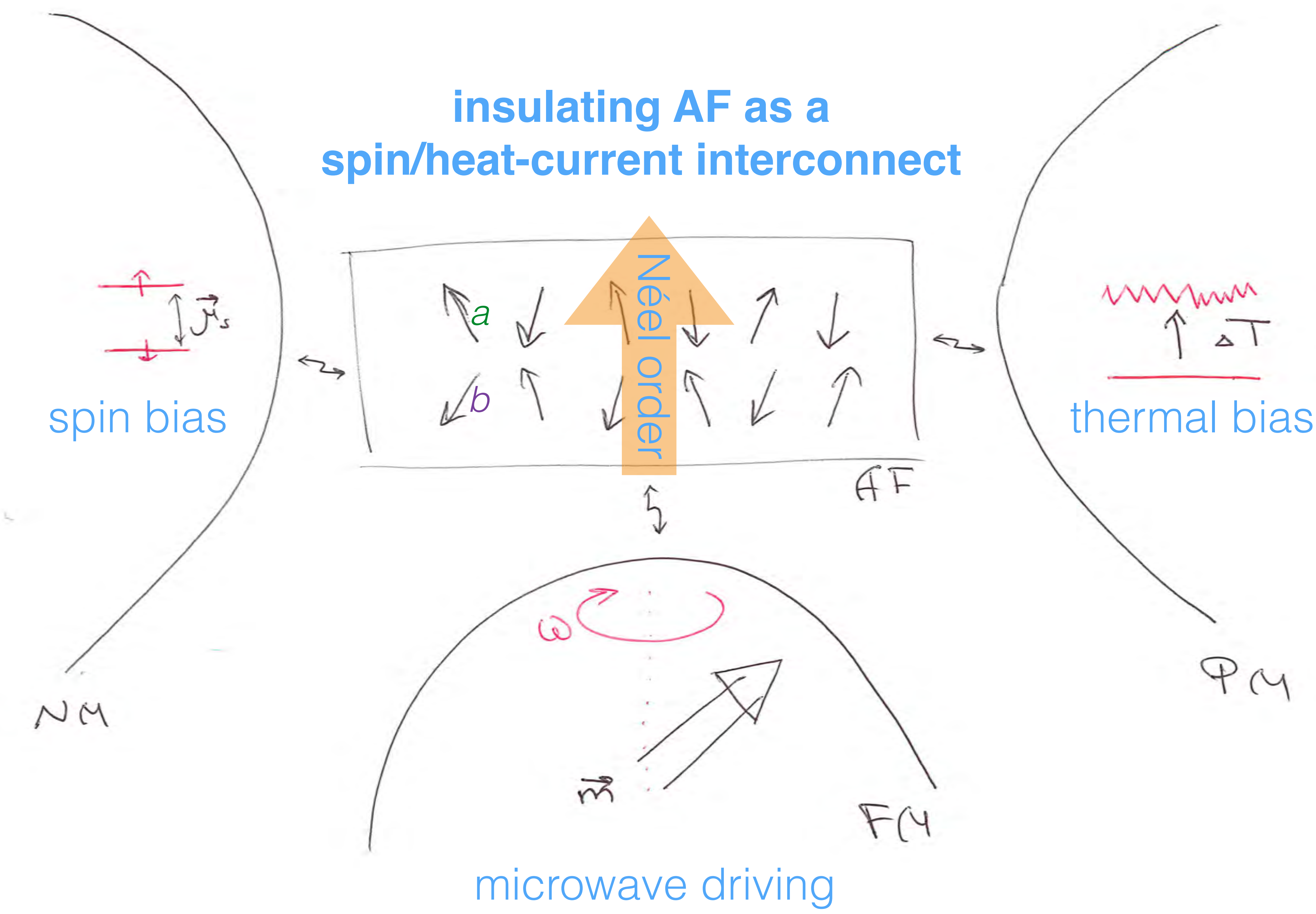


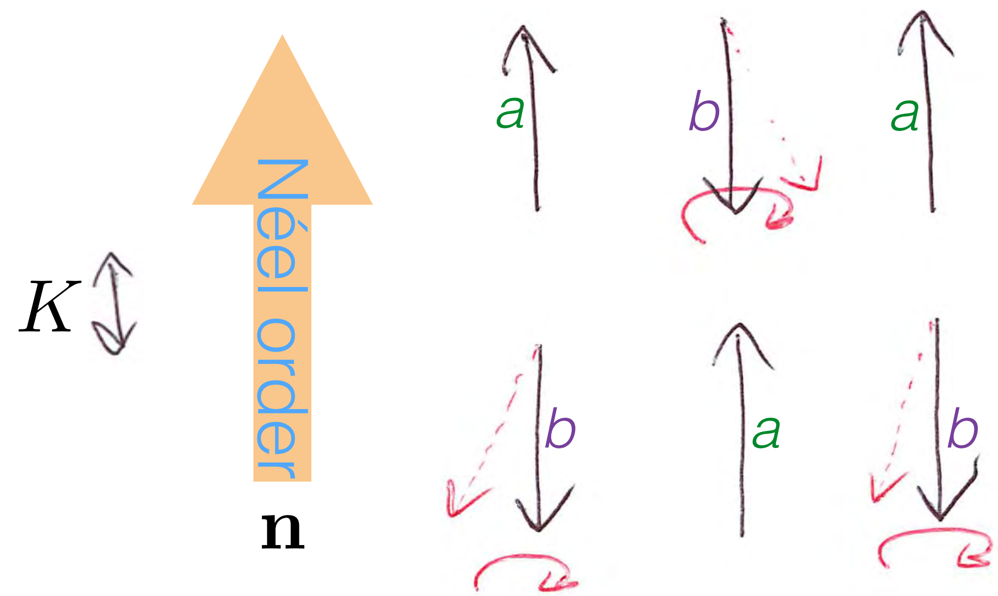
Scope

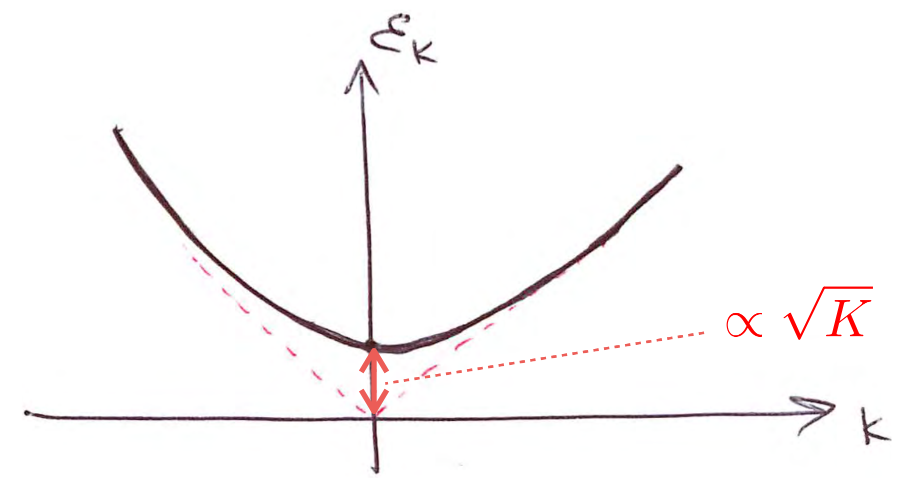


⇒ *two-“fluid” dynamics*

Two types of spin current

easy-axis AF





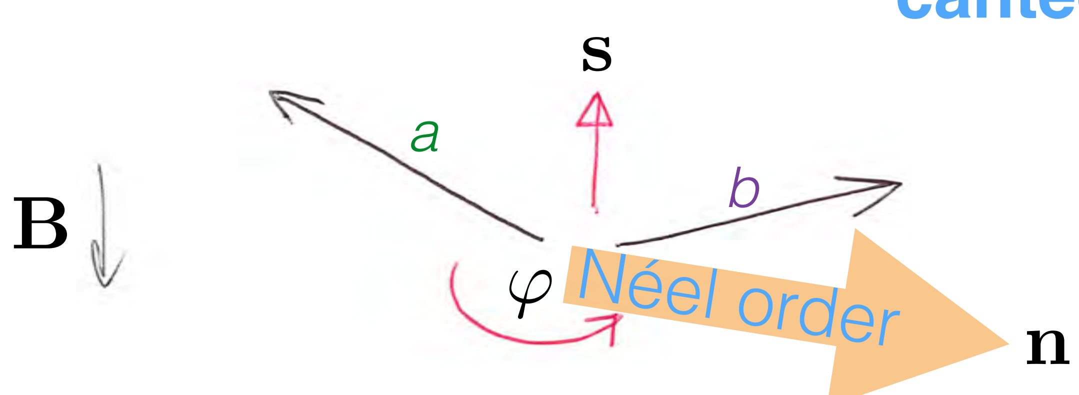
spin-degenerate spectrum

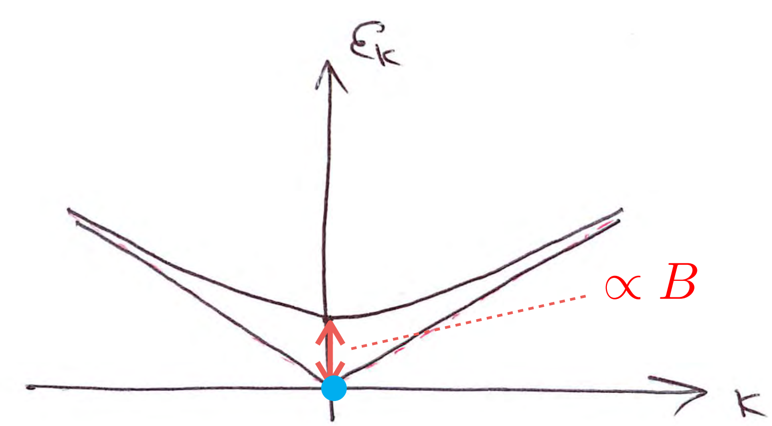
spin $+\hbar$ magnon (spin wave) along $\mathbf{n}$

thermal spin transport (vanishes at zero temperature)

See, however, Meier and Loss, *PRL* (2003) cf. spin liquids

canted AF





Goldstone mode

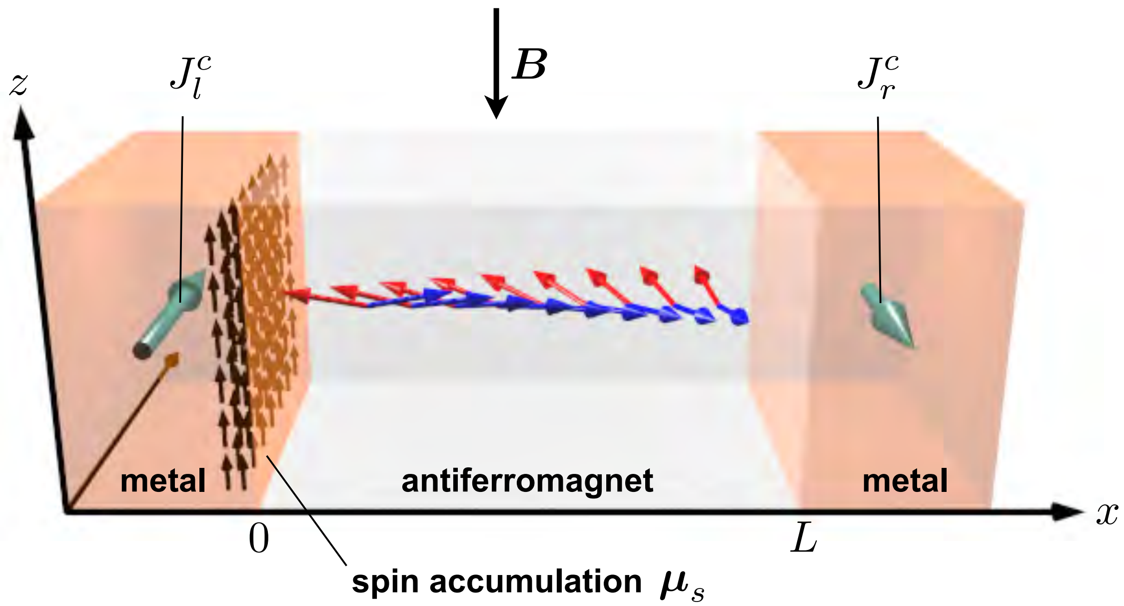
s_z is momentum canonically conjugate to φ

$s_z \propto \partial_t \varphi$ and $\mathbf{j}_z \propto -\boldsymbol{\nabla} \varphi$

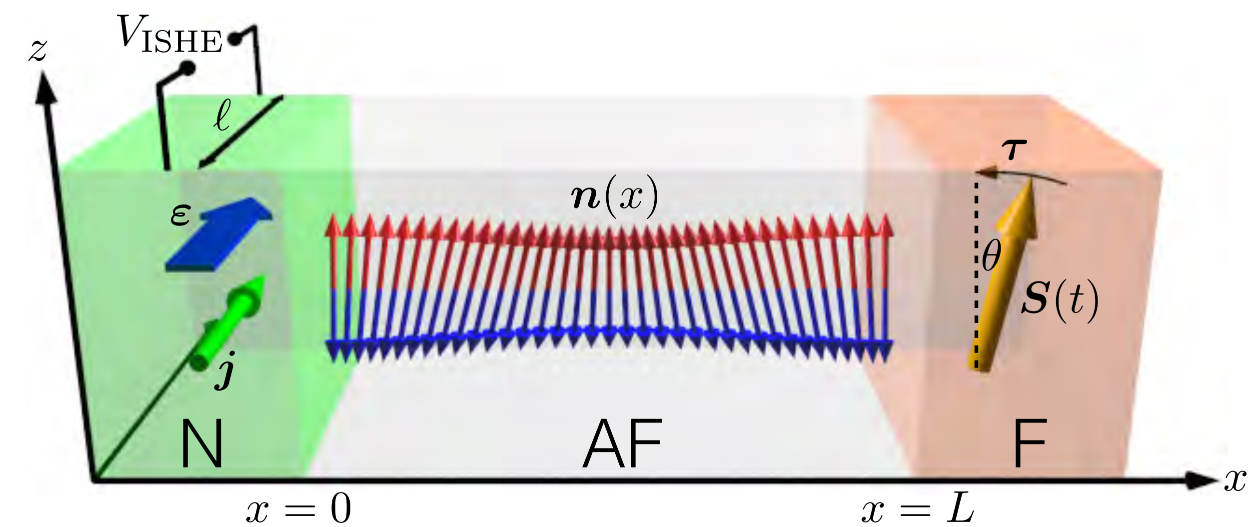
superfluid spin transport (maximized at zero temperature)

Sonin, *AP* (2010)

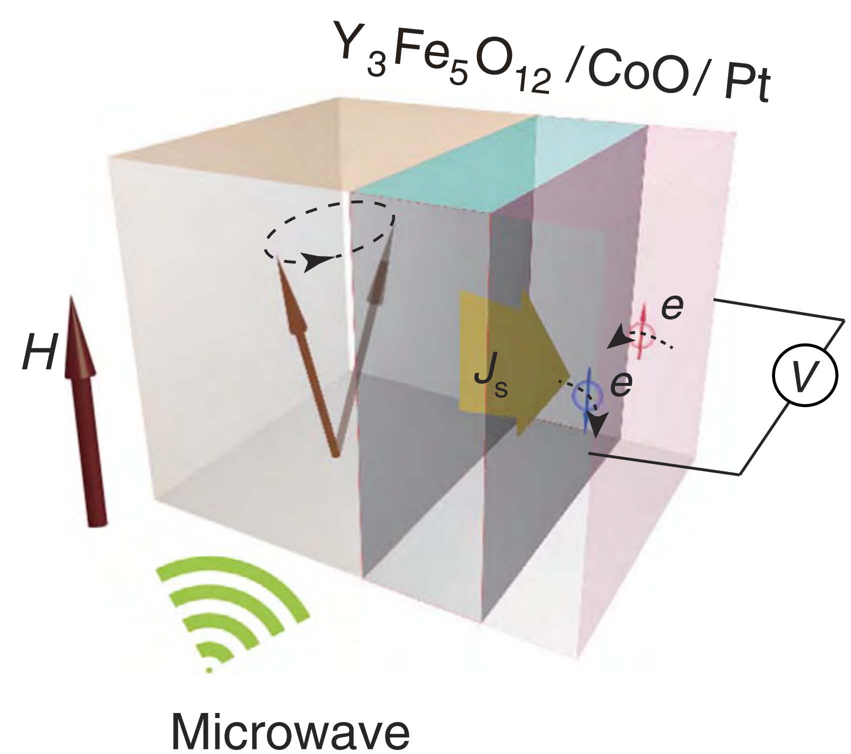
Overview



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

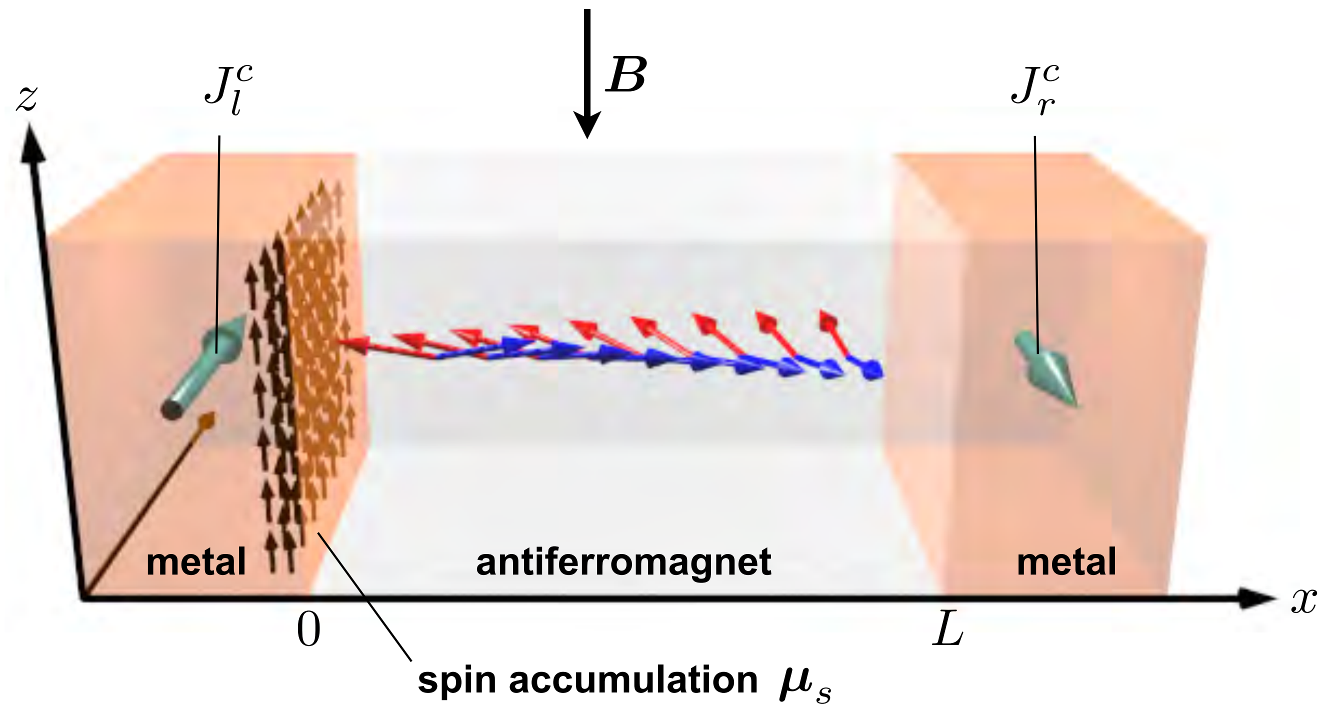


Takei, Moriyama, Ono, and YT, *PRB* (2015)



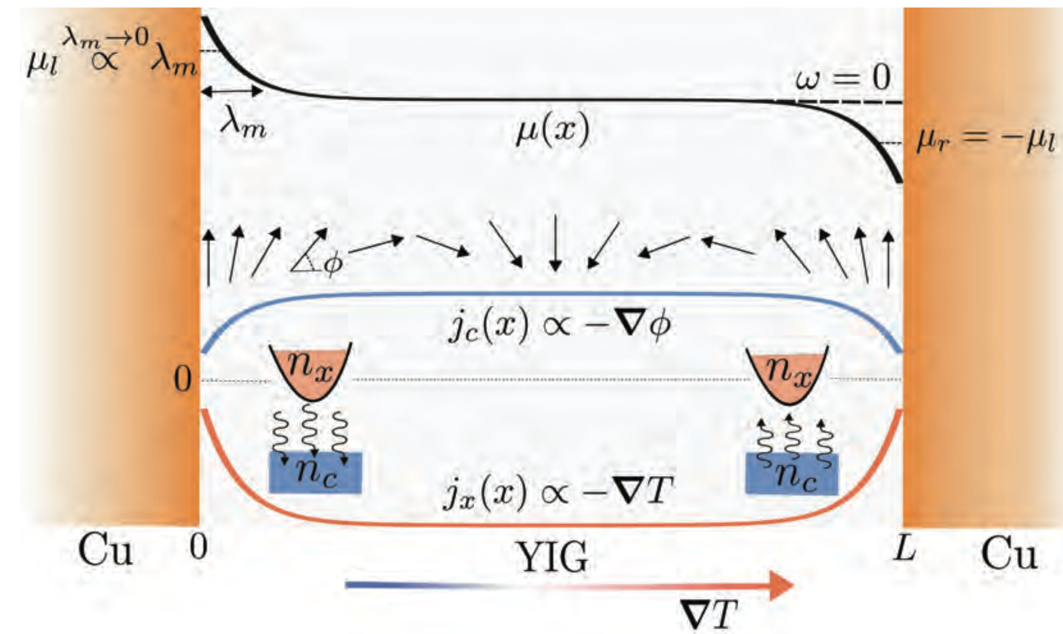
Qiu *et al.*, *Nat. Comm.* (2016)

Two-terminal spin superfluid



spin bias

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

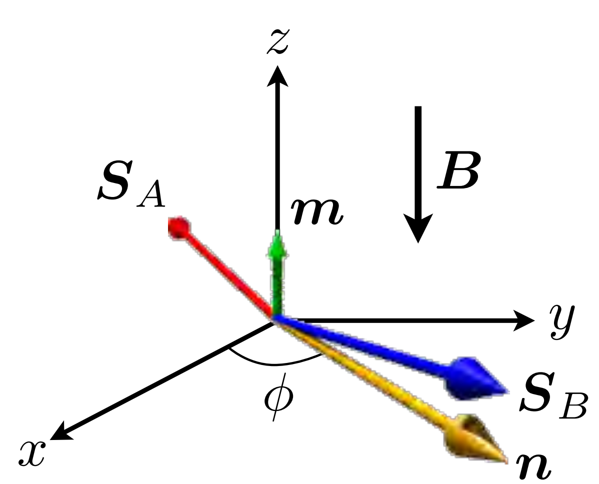


thermal bias

Flebus, Bender, YT, and Duine, *PRL* (2016)

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



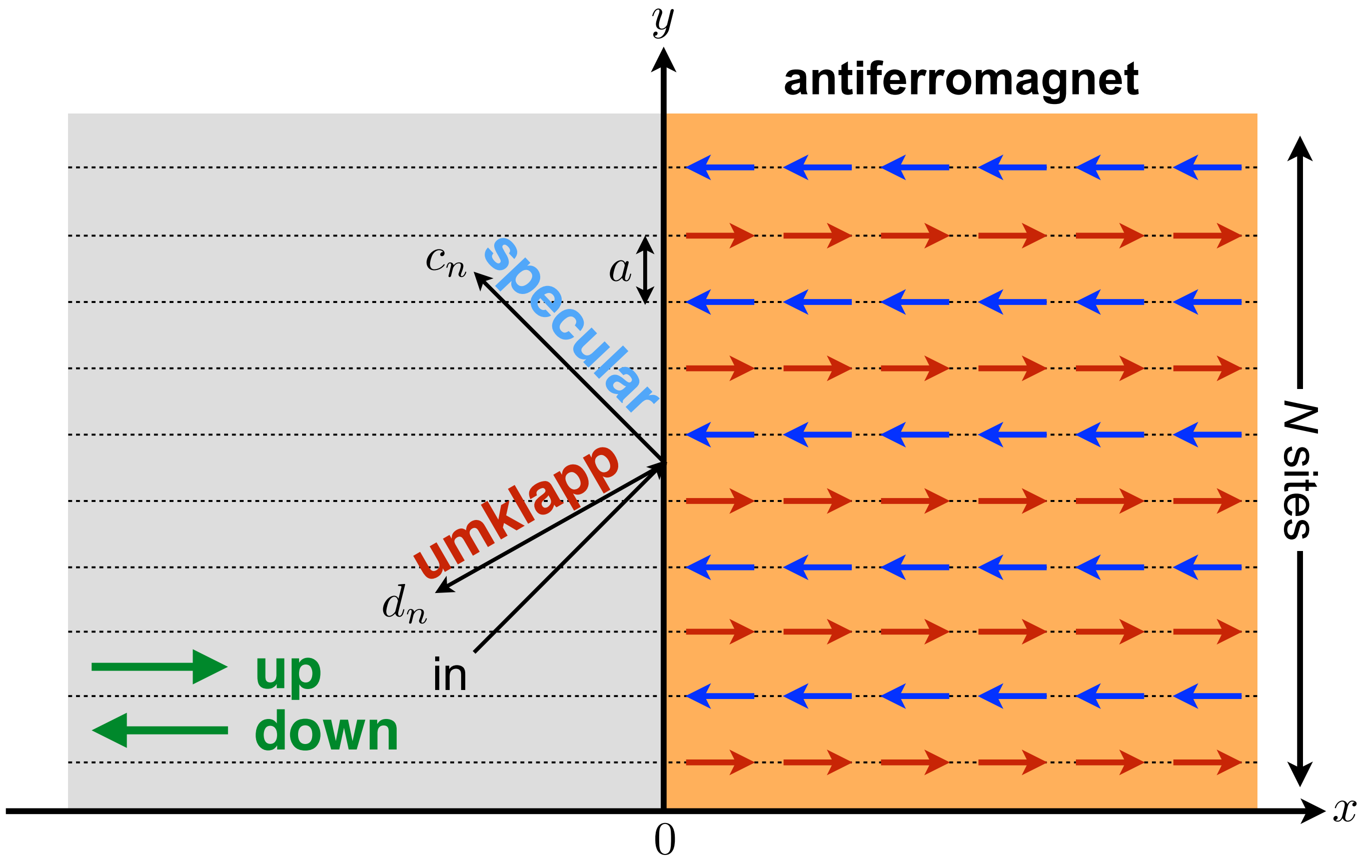
collective spin current: $$\mathbf{J}_s = -A\mathbf{n}\times\nabla\mathbf{n} \to -A\nabla\varphi$$

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)

Interfacial spin transfer

- 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:*



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

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

specular umklapp

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

the interfacial spin current density:

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

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

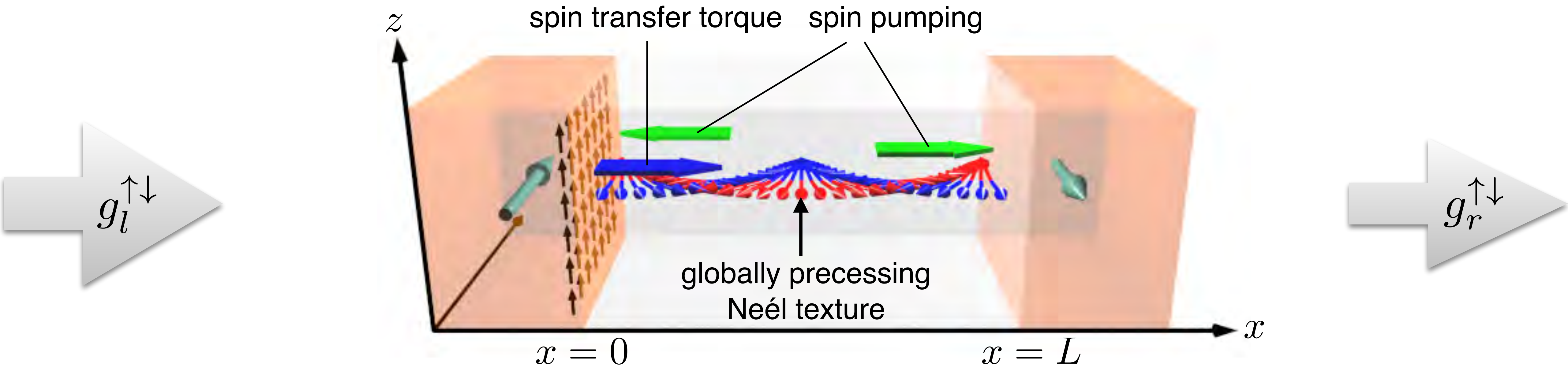
torque pumping

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

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); see also Jia, Liu, Xia, and Bauer, *EPL* (2011) for YIG

Spin-current circuit

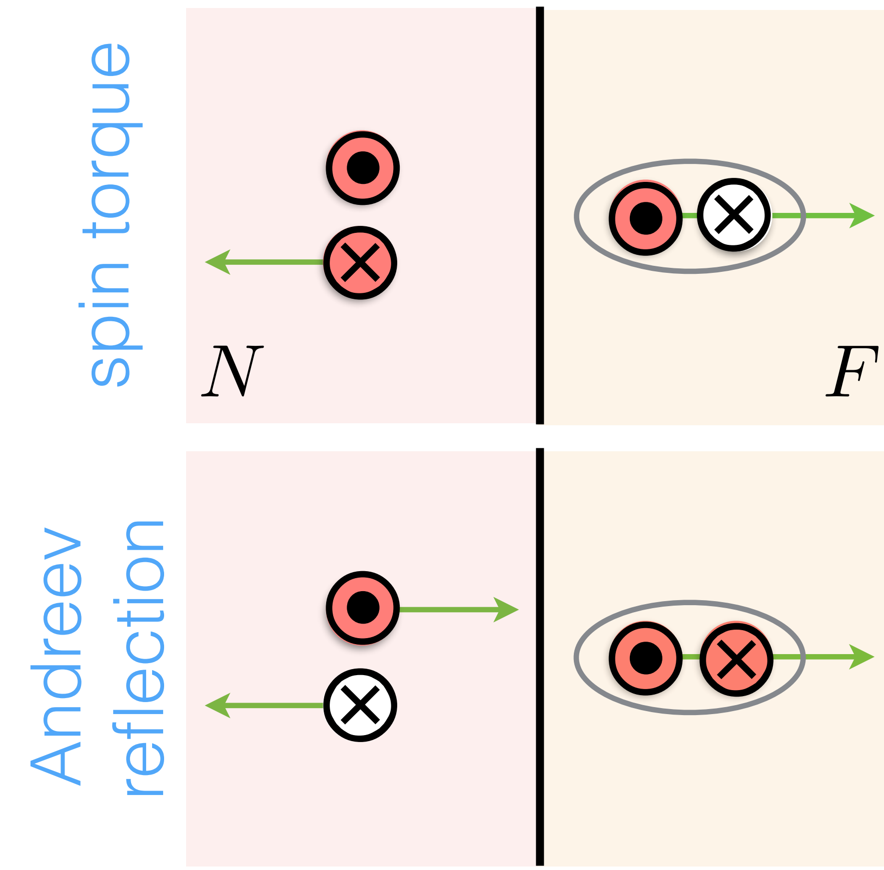


$$g_\alpha = \frac{4\pi\alpha s L}{\hbar}$$ (mechanical torque)

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

Takei and YT, *PRL* (2014)

Negative DC electron drag (revealed by SHE)



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

Onsager

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

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

assuming $L < L_\alpha \equiv \dfrac{\hbar g^{\uparrow\downarrow}}{4\pi\alpha s}$

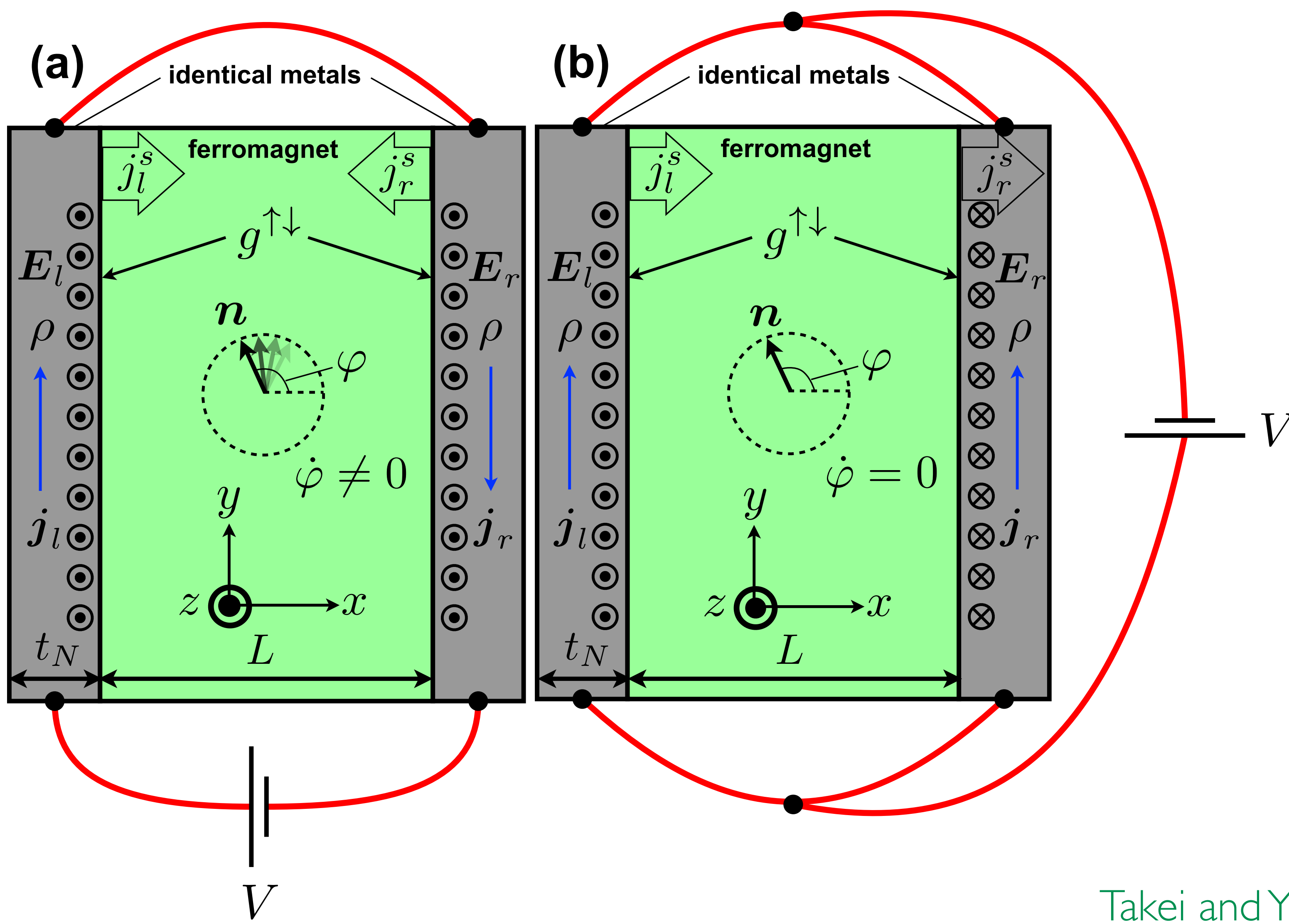
for $\rm Pt|YIG|Pt$ heterostructure: $L_\alpha \sim 1\ \mu{\rm m}$ and $\mathcal{D} \sim 0.1$

Takei and YT, *PRL* (2014)

Nonlocal magnetoresistance

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

$$\rho_m \propto -\frac{\vartheta_{\rm SH}^2}{2g^{\uparrow\downarrow} + \alpha s L}$$



$$\rho_m = 0$$

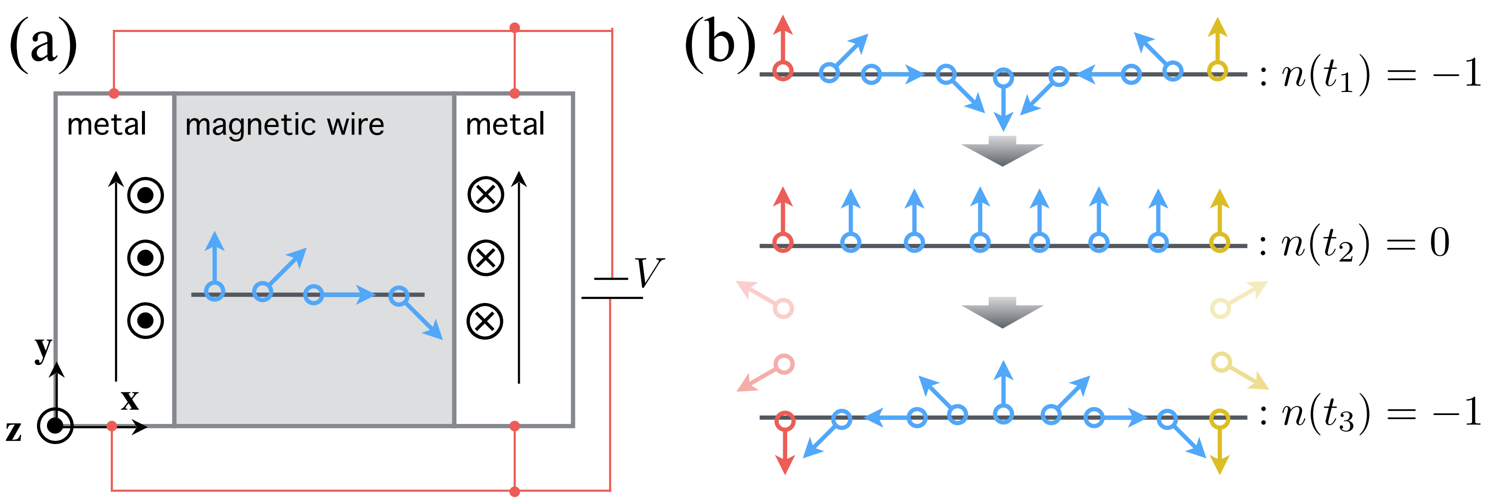
Takei and YT, *PRL* (2015)

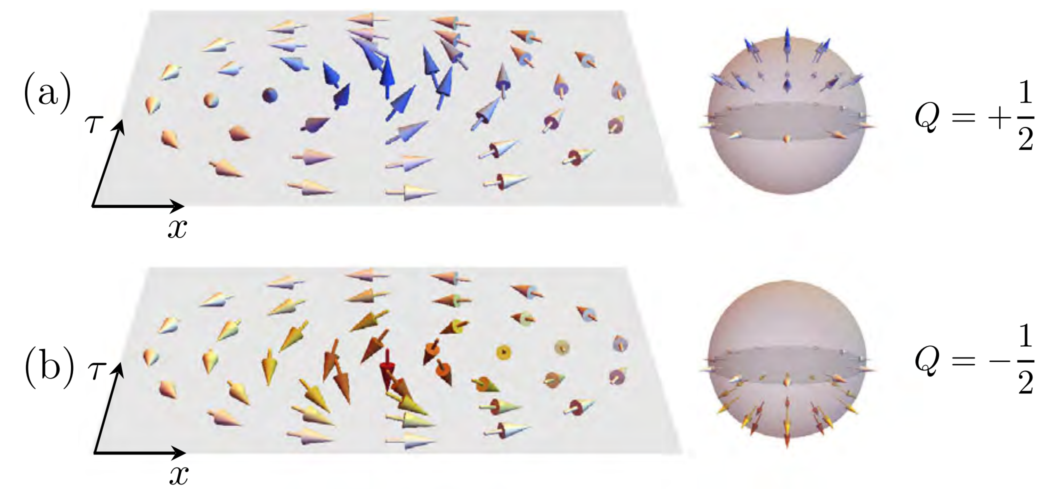
- In the parallel configuration (b), the torques are balanced, and the magnet remains stationary, causing more friction

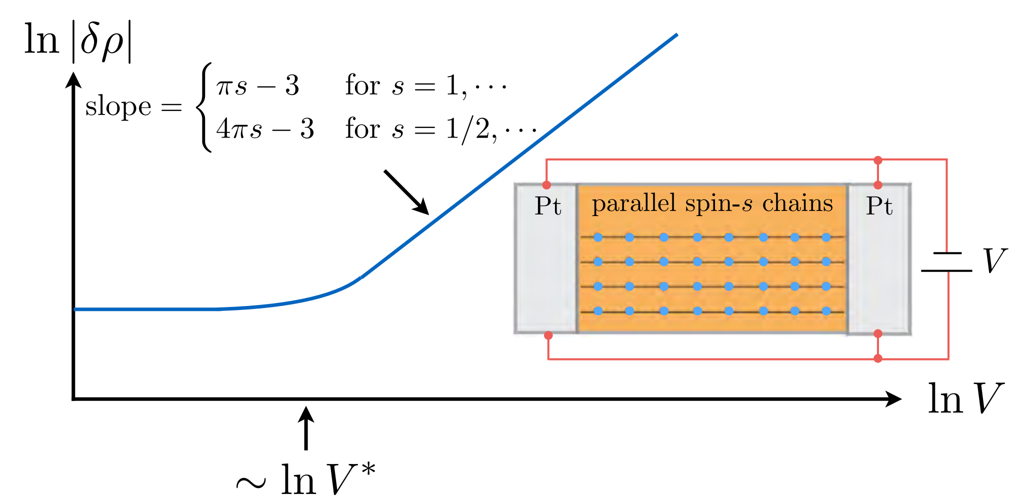
Cf. Eisenstein and MacDonald, *Nature* (2004) for *BEC of excitons in bilayer electron systems*

Quantum phase slips

- The parallel magnetoresistance geometry can be used to extract the thermal and quantum phase slip rates:







- The effective action for a gas of QPS's in the presence of a spin superflow:

$$S_{\mathrm{eff}} = nS_{\mathrm{core}} - \mu \sum_{i<j} q_i q_j \ln(d_{ij}/\lambda) + j_s \sum_i q_i \tau_i$$

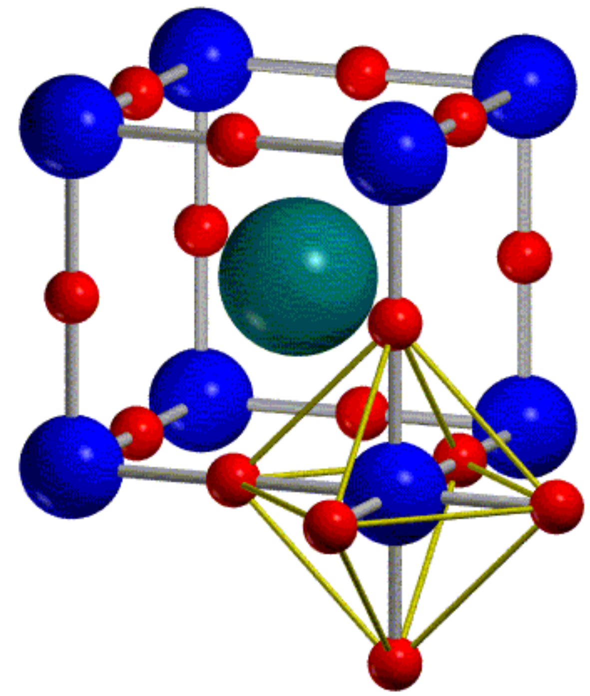
Kim and YT, *PRL* (2016)

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

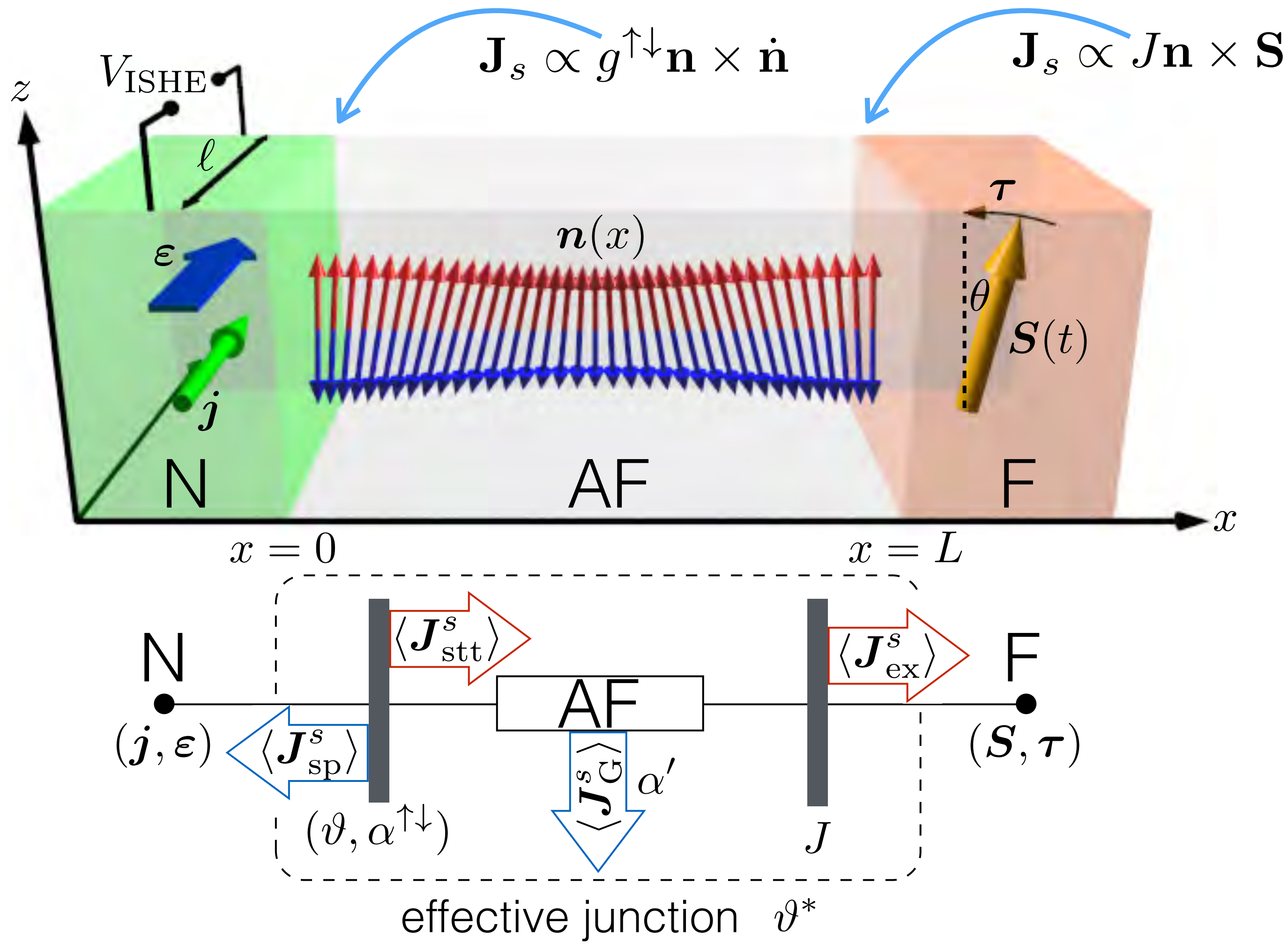
$J_c^{(s)} = \kappa L_c = \sqrt{A\kappa}$ $\rightarrow$ $J_c \sim 10^{12}$ A/m^2

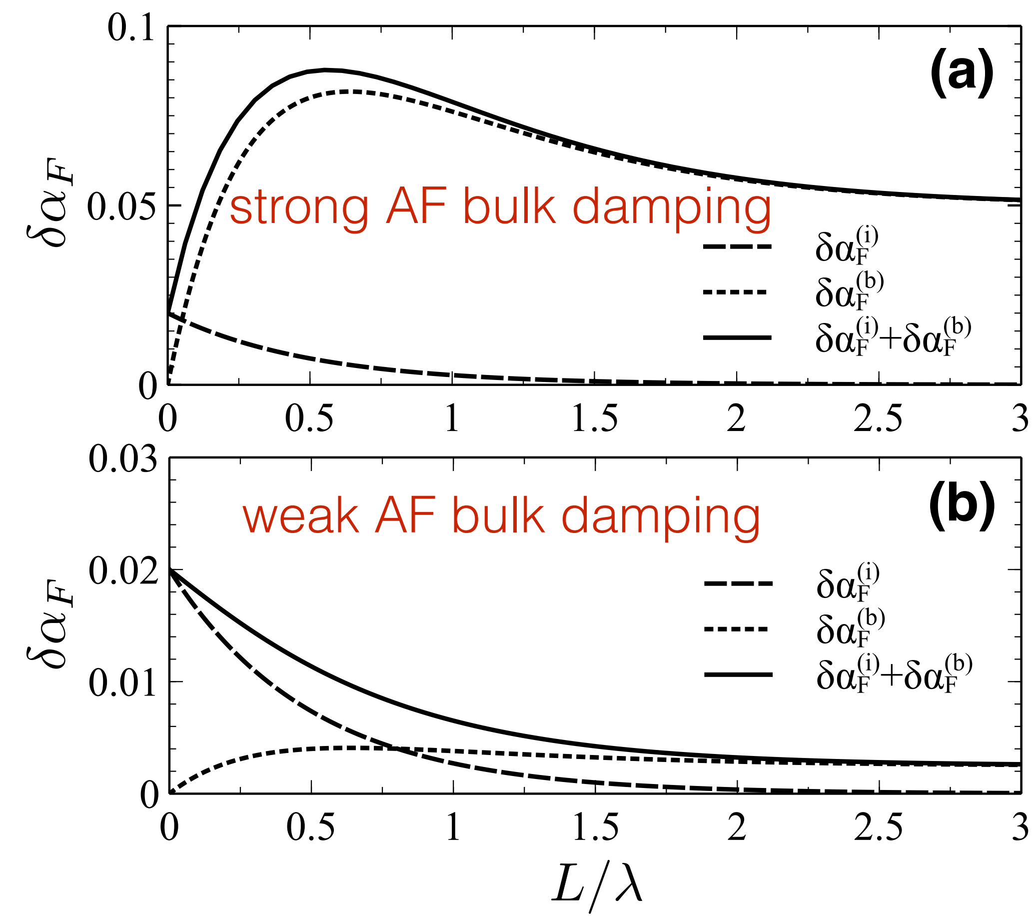
minimal magnetic field providing easy plane: $B_c = \sqrt{\kappa J} \sim 1$ T

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

AF-mediated (coherent) spin transfer

- Spin-transfer torque and spin pumping mediated by AF (NiO):





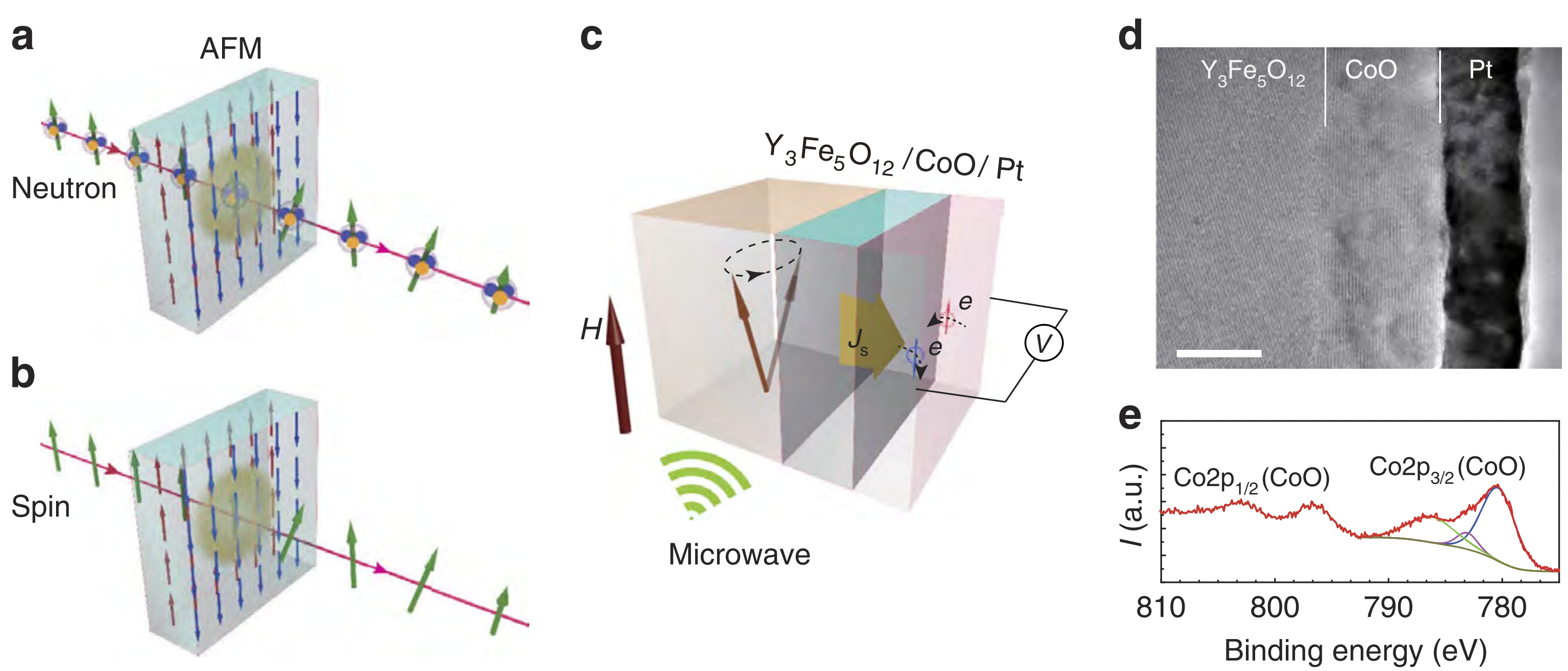
$$\alpha_F^{(i)} = \frac{1}{S}\frac{g^{\uparrow\downarrow}+\frac{\vartheta}{\omega_F}j}{\left(\cosh\frac{L}{\lambda}+\frac{1}{\eta}\sinh\frac{L}{\lambda}\right)^2} \qquad \vartheta^*$$

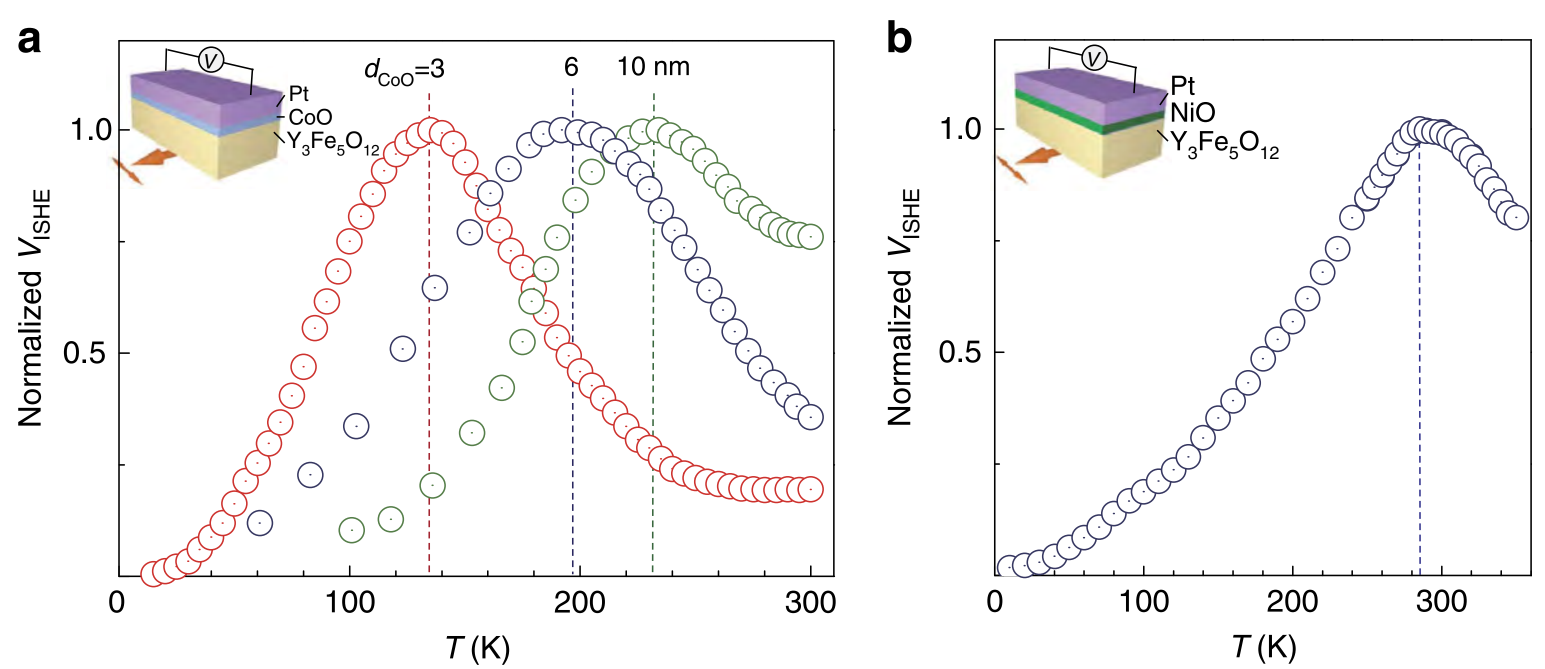
$$\alpha_F^{(b)} = \frac{\alpha_{\rm AF}}{S}\frac{\frac{L}{\lambda}+\frac{1}{2}\sinh\frac{2L}{\lambda}}{\left(\cosh\frac{L}{\lambda}+\frac{1}{\eta}\sinh\frac{L}{\lambda}\right)^2}$$

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

AF-mediated (thermal) spin transfer

- Spin pumping mediated by AF (CoO and NiO):





Qiu *et al.*, *Nat. Comm.* (2016)

Summary

- While antiferromagnets possess magnetic order that is hidden from generic electromagnetic probes, they may serve as efficient interconnects for spin transport (manifested, e.g., through spin Hall, spin Seebeck, and FMR probes)

- It is natural to invoke a two-fluid picture, with the spin superfluid taking over the transport at low temperatures and thermal magnons at elevated temperatures

- Quantum phase slips, which exhibit unique properties in the AFM materials, dominate dissipation of spin transport at low temperatures

"KITP-style" program in Natal, Brazil (~May, 2017)

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