Spin current in magnetic insulators driven by stochastic fluctuations

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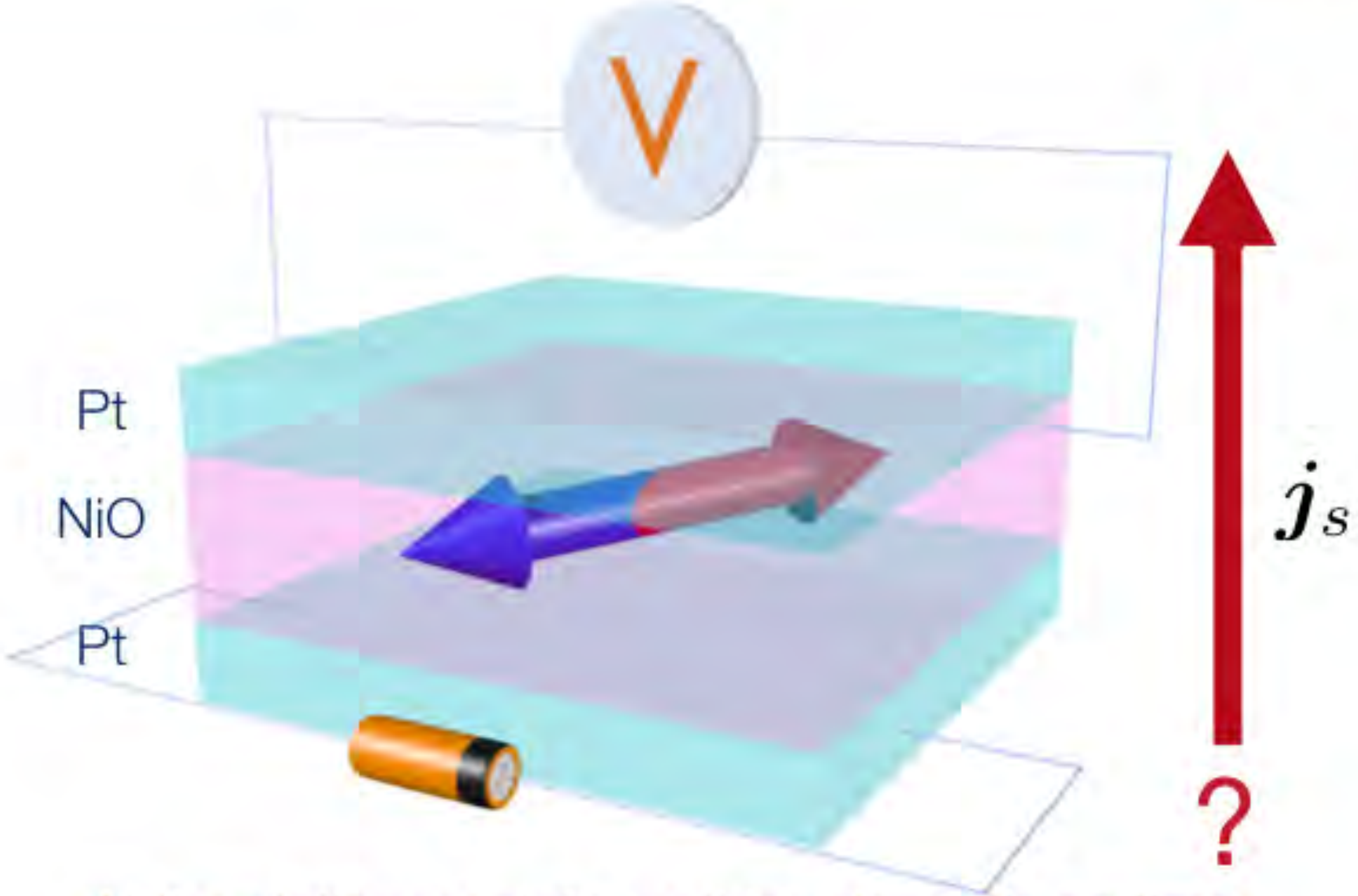
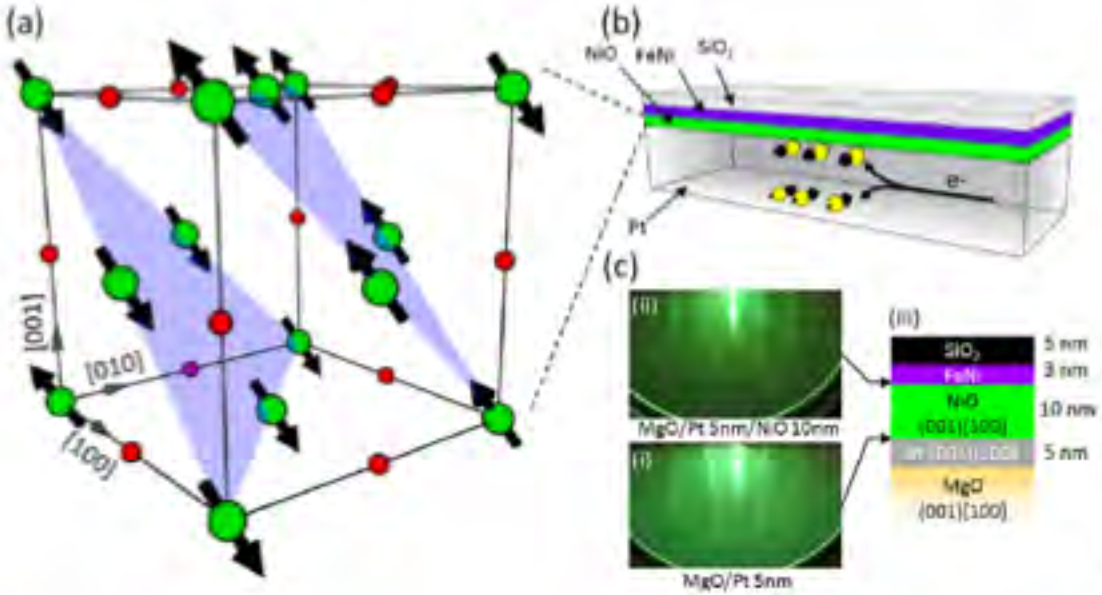
Introduction

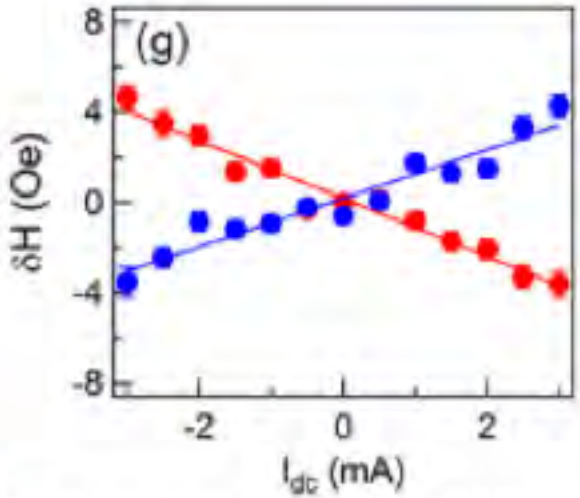


At the stationary state, nothing depends on time

What is driving the spin current through the insulator?

Experimental evidence





Moriyama et al. (2016)

Theoretical attempts so far;

1. Bulk diffusion equation approach (Rezende et al. 2016, cf. Zhang & Zhang 2012)
2. Evanescent mode (Khymyn et al. 2016)
3. Linear response to spin accumulation (Bender et al. 2017)

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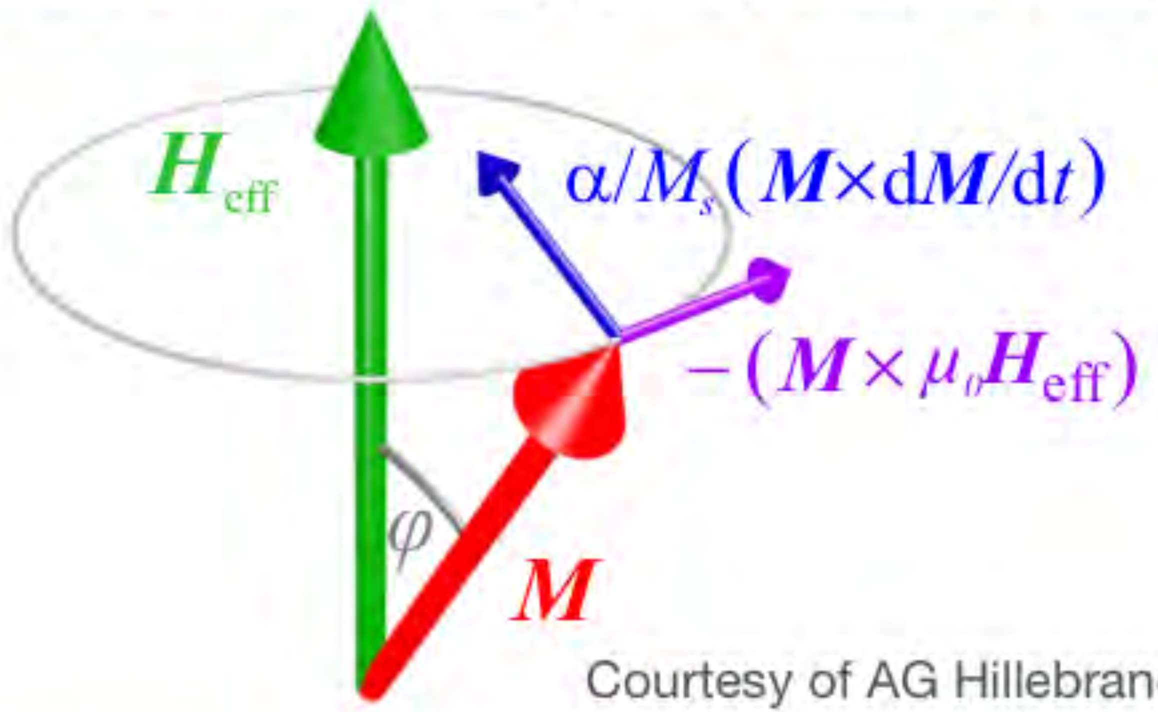
Damping-like torque + thermal fluctuation -> Spin current

Spin fluctuations and spin Seebeck effect

Precession of spins

Dynamics of spins in magnetically ordered materials



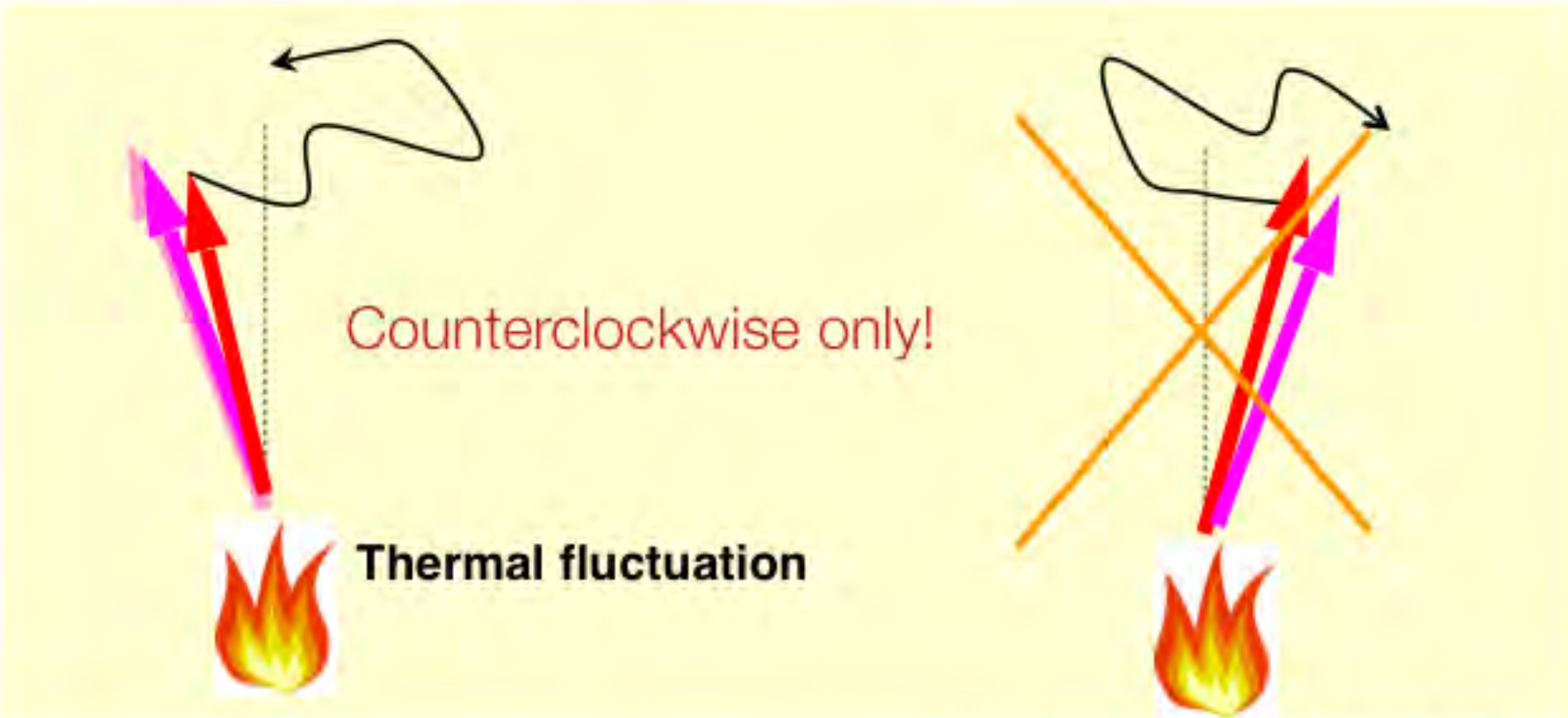
Courtesy of AG Hillebrands

Precession is always chiral and non-reciprocal

Precession -> angular momentum $\boldsymbol{L} \propto \boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}$

Ordered spin is a ratchet

Random motion of spins must also be chiral



Courtesy of Prof. Eiji Saitoh

Random motion -> Nonzero expectation value of angular momentum

Temperature induced angular momentum

- Random precession -> nonzero angular momentum on average

$$\left\langle \delta \boldsymbol{M} \times \frac{d\delta \boldsymbol{M}}{dt} \right\rangle \neq 0$$

- Higher temperature -> more fluctuations

$$\langle \delta \boldsymbol{M}^2 \rangle \propto T \quad \text{(High T approximation)}$$

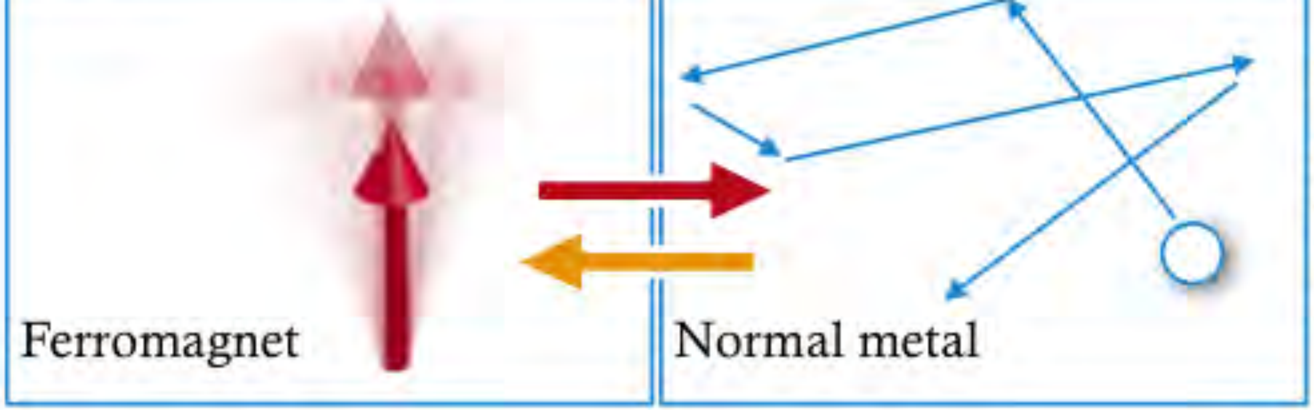
- Temperature generates angular momentum

Bloch's law

$$\langle M_s - M_z \rangle \propto T^{3/2}$$

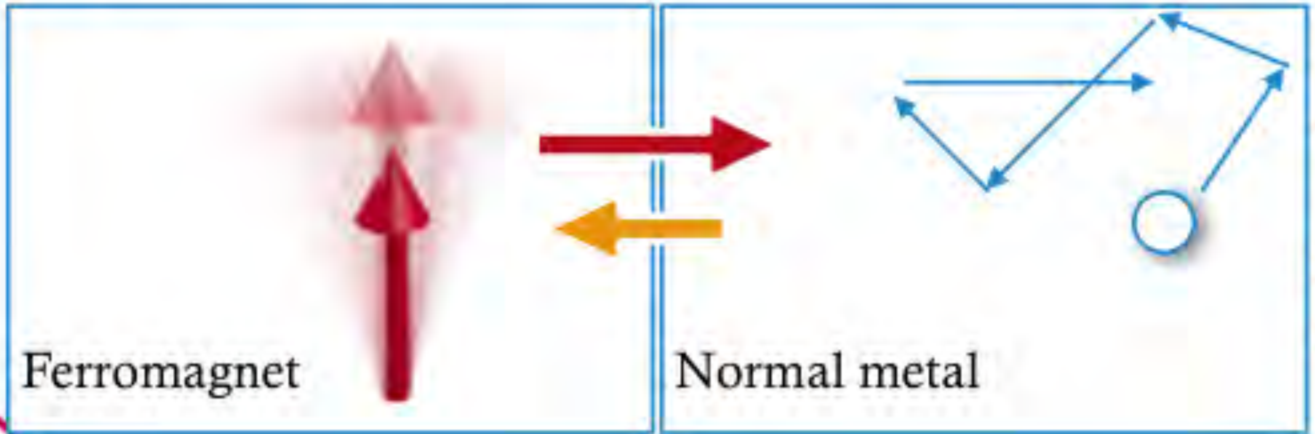
Equilibrium vs non-equilibrium

$$T_F = T_N$$



Complete compensation of incoming and outgoing spin

$$T_F \neq T_N$$



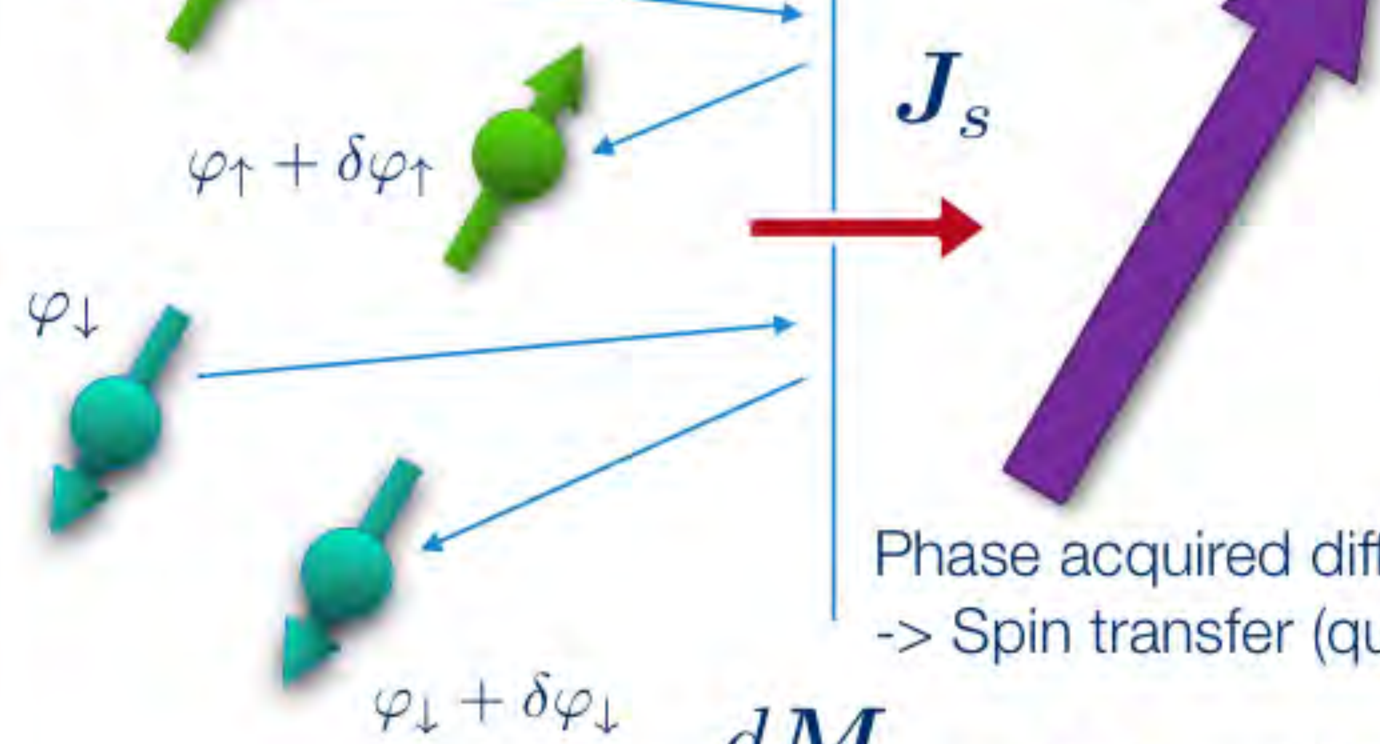
Net spin current

Spin Seebeck effect (Xiao et al.)

Spin transfer torque and damping modulation

Slonczewski's damping-like torque

Elastic spin conserving scatterings at the interface



$$\delta\varphi_\uparrow \neq \delta\varphi_\downarrow$$

Phase acquired differs between up/down
-> Spin transfer (quantum mechanical!)

$$\frac{d\boldsymbol{M}}{dt} \propto \boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{J}_s)$$

Damping modulation

Landau-Lifshitz-Gilbert equation

$$\frac{d\boldsymbol{M}}{dt} = \gamma \boldsymbol{M} \times \left(\boldsymbol{H}_{\text{eff}} + \frac{\alpha}{\gamma M_s}\frac{d\boldsymbol{M}}{dt} + \frac{\sigma}{M_s}\boldsymbol{M} \times \boldsymbol{J}_s \right)$$

Landau-Lifshitz equation

$$\frac{d\boldsymbol{M}}{dt} = \gamma \boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} + \gamma \boldsymbol{M} \times \left[\frac{\boldsymbol{M}}{M_s} \times (\alpha \boldsymbol{H}_{\text{eff}} + \sigma \boldsymbol{J}_s) \right]$$

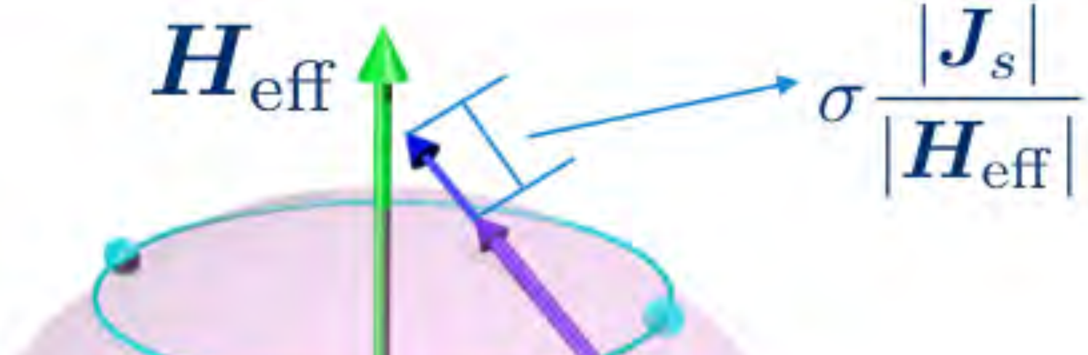
If $\boldsymbol{H}_{\text{eff}} \parallel \boldsymbol{J}_s$, the torque effectively shifts the damping by

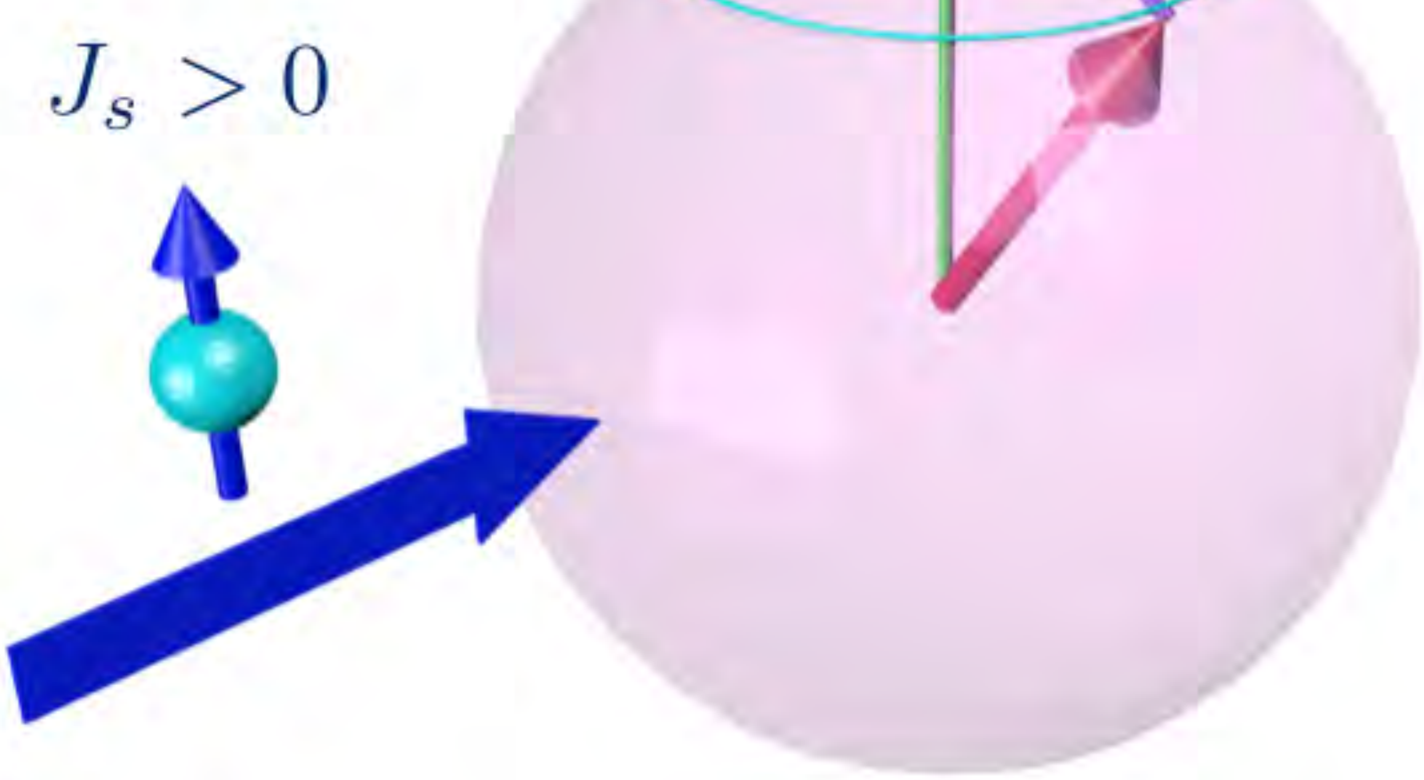
$$\alpha \to \alpha + \text{sgn}\,(J_s)\,\sigma \frac{|\boldsymbol{J}_s|}{|\boldsymbol{H}_{\text{eff}}|}$$

"Damping-like"

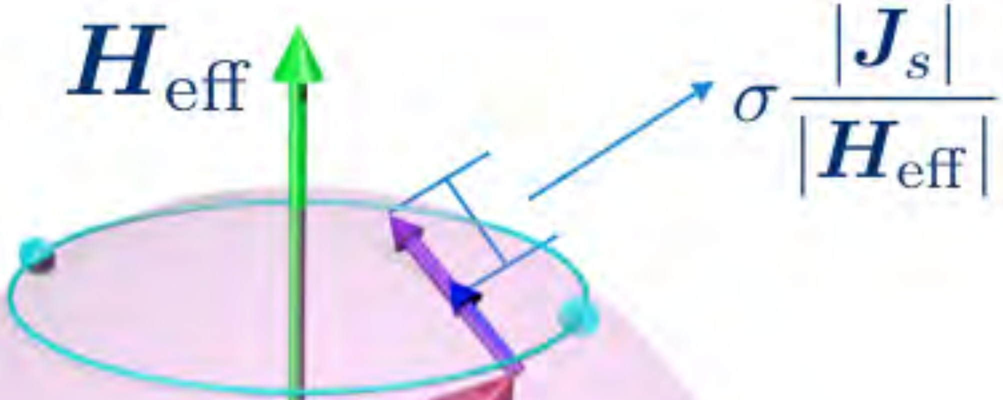
Ando et al., PRL (2008)

Damping modulation





Damping modulation



$J_s < 0$

Stochastic equation of motion

- Damping torque itself cannot induce any dynamics

Solution of LLG $\quad \boldsymbol{M} \to (\boldsymbol{M} \parallel \boldsymbol{H}_{\rm eff})$

- Temperature induces random magnetic field

$$\langle h_i(t) \rangle = 0, \quad \langle h_i(t) h_j(t') \rangle = \frac{2\alpha k_B T}{|\gamma M_s|} \delta_{ij} \delta(t - t')$$

- Langevin-type probabilistic dynamical equation

$$\frac{d\boldsymbol{M}}{dt} = \gamma \boldsymbol{M} \times \left(\boldsymbol{H}_{\text{eff}} + \boxed{\boldsymbol{h}(t)} + \frac{\alpha}{\gamma M_s} \frac{d\boldsymbol{M}}{dt} + \frac{\sigma}{M_s} \boldsymbol{M} \times \boldsymbol{J}_s \right)$$

Time dependent field -> stochastic dynamics of $\boldsymbol{M}$

Fluctuation-dissipation relation

- Solution of stochastic LLG = Probability distribution of $\boldsymbol{M}$

$$P(\boldsymbol{M}) \leftrightarrow \langle \boldsymbol{M} \rangle, \langle \boldsymbol{M}^2 \rangle, \cdots$$

- Without the torque, the solution should describe equilibrium

$$\left[\quad E(\boldsymbol{M}) \right]$$

$$P(\boldsymbol{M}) \propto \exp\left[-\frac{E(\boldsymbol{M})}{k_B T}\right]$$ Boltzmann distribution

- This is true only if the damping and random field compensate

$$\langle h_i(t)\, h_j(t')\rangle = \frac{2\alpha k_B T}{|\gamma M_s|}\delta_{ij}\delta(t-t')$$

Fluctuation-Dissipation Theorem (FDT)

Deviation from FDT

- Spin torque modifies effective damping

$$\alpha \to \alpha \pm \sigma \frac{|\boldsymbol{J}_s|}{|\boldsymbol{H}_{\text{eff}}|}$$

- Assumption: the random field is unchanged by the torque

$$\langle h_i(t)\, h_j(t')\rangle = \frac{2\alpha k_B T}{|\gamma M_s|}\delta_{ij}\delta(t-t')$$

$$\langle h_i(t) h_j(t') \rangle = \ldots \frac{\ldots}{|\gamma M_s|} \delta_{ij}\delta(t - t')$$

e.g. Apalkov-Visscher (2005)

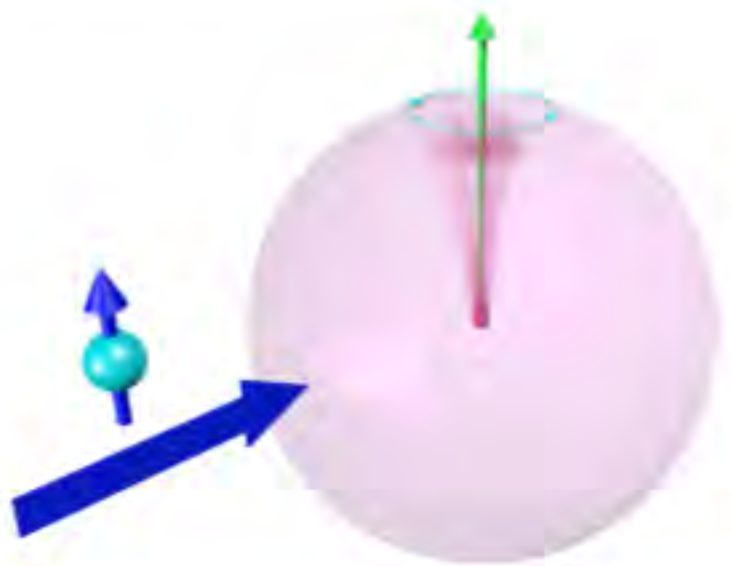
- FDT does not hold, system out of equilibrium

Caveat

Temperature here is the temperature of a heat bath.

Temperature of the magnetic system in general cannot be defined because the system is out of equilibrium.

Deviation from FDT



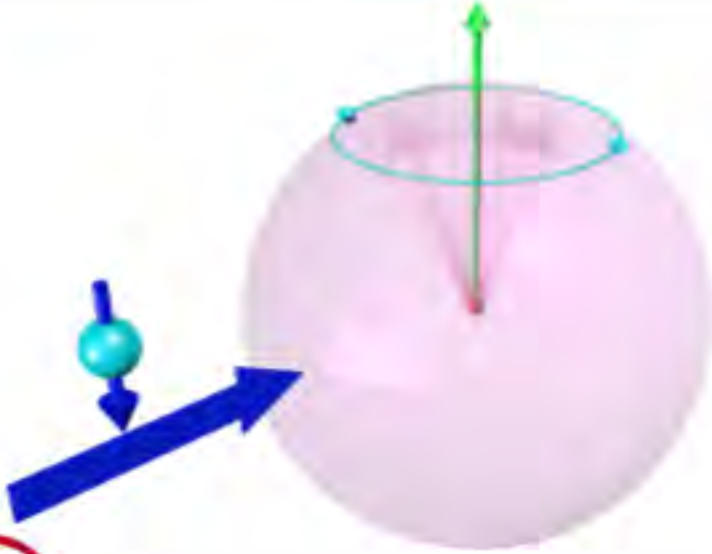
$$J_s > 0 \, (\boldsymbol{H}_{\text{eff}} \parallel \boldsymbol{J}_s)$$

Enhanced damping

Unchanged random field

Less fluctuation -> less spin

$$J_s < 0 \left(\boldsymbol{H}_{\text{eff}} \parallel -\boldsymbol{J}_s \right)$$

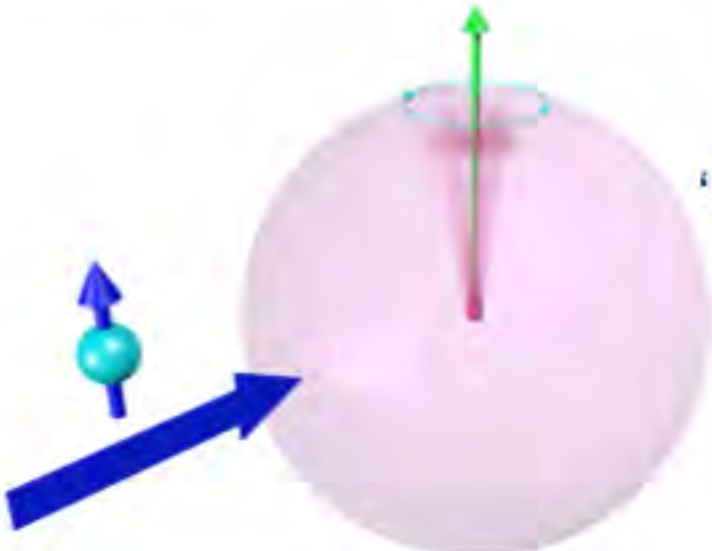


Reduced damping
Unchanged random field

More fluctuation -> more spin

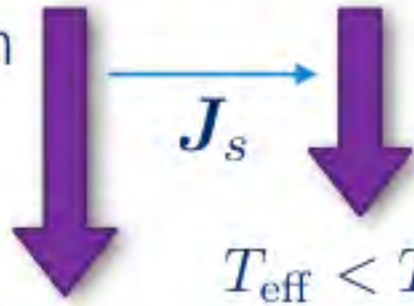
Effective temperature

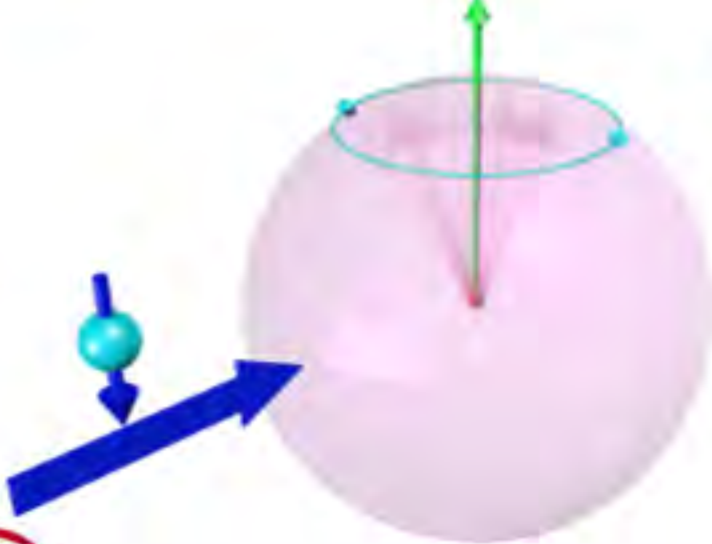
$$P\left(\boldsymbol{M}\right) \propto \exp\left[-\frac{E\left(\boldsymbol{M}\right)}{k_B\left(T-\delta T\right)}\right], \quad \delta T \propto |J_s|$$



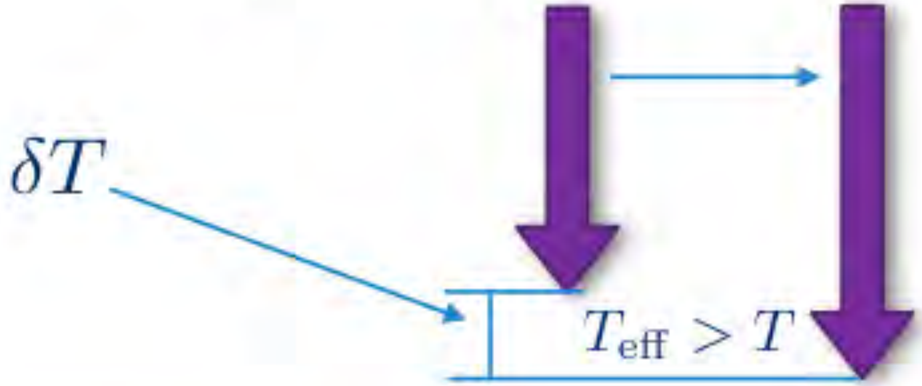
'Loose' angular momentum

$$\langle M_s - M_z \rangle$$





$$P(\boldsymbol{M}) \propto \exp\left[-\frac{E(\boldsymbol{M})}{k_B (T + \delta T)}\right], \quad \delta T \propto |J_s|$$



Spin current through antiferromagnetic insulators

Two sublattice model of AFM

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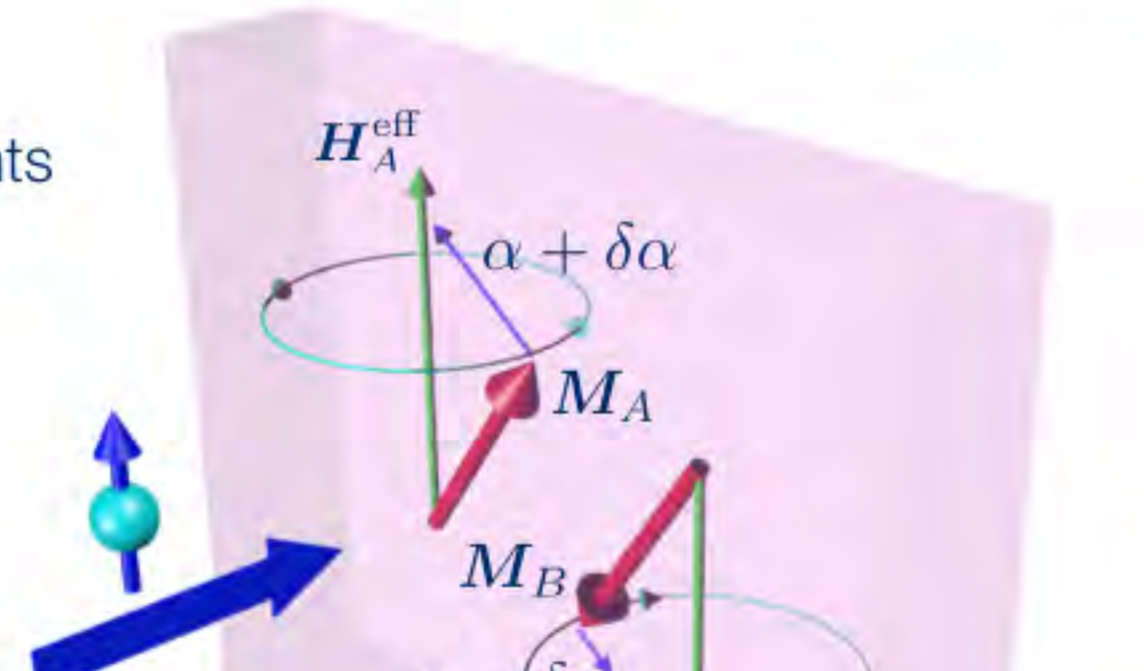
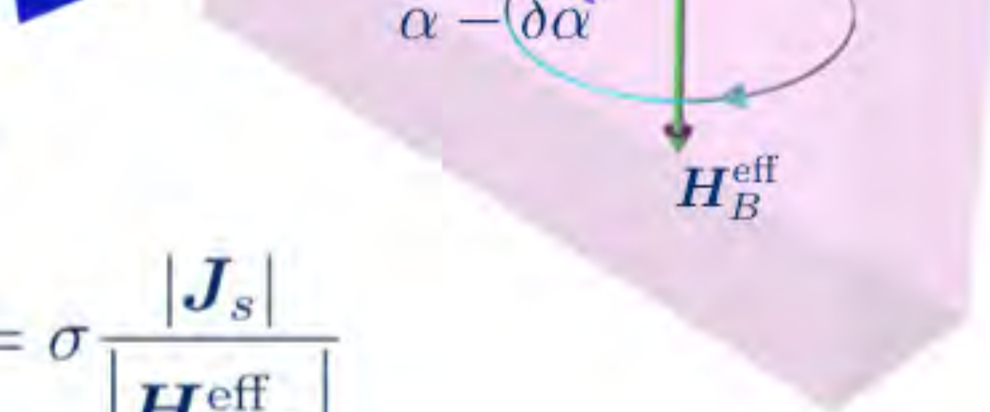
Two antiferromagnetically coupled ferromagnetic moments

$$\frac{1}{\gamma}\frac{d\boldsymbol{M}_{A,B}}{dt}$$
$$=\boldsymbol{M}_{A,B} \times \left(\boldsymbol{H}^{\mathrm{eff}}_{A,B} + \boldsymbol{h}_{A,B}\right)$$
$$+\frac{\alpha}{\ }\boldsymbol{M}_{A,B} \times \frac{d\boldsymbol{M}_{A,B}}{\ }$$



$$\gamma M_s \quad dt$$

$$+\frac{\sigma}{M_s}\boldsymbol{M}_{A,B}\times(\boldsymbol{M}_{A,B}\times\boldsymbol{J}_s)$$

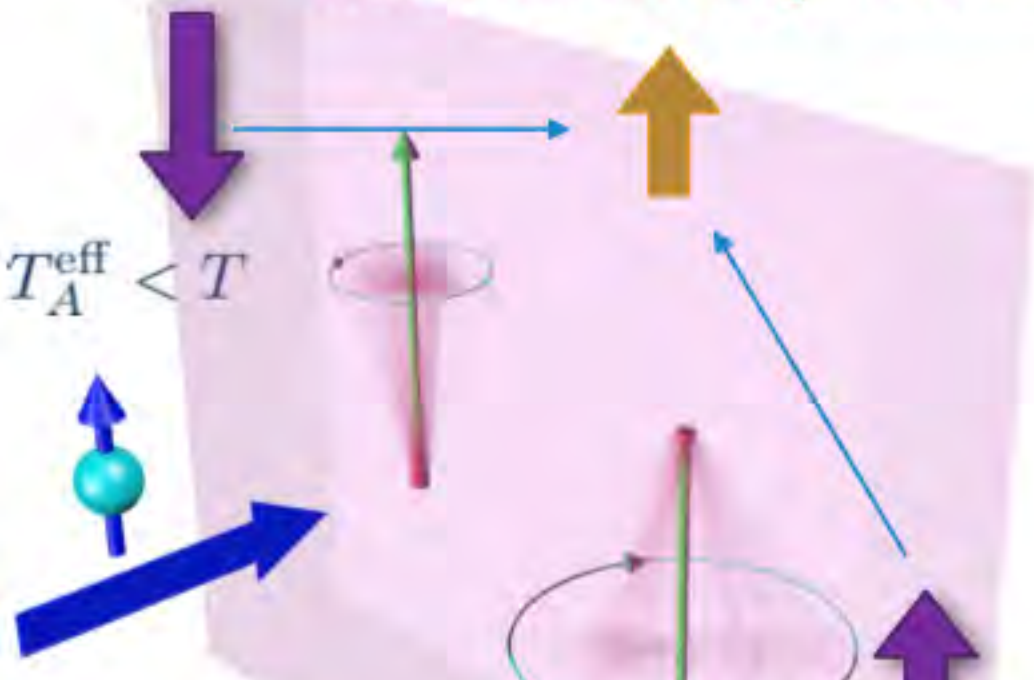


$$\boldsymbol{H}_A^{\rm eff}\sim-\boldsymbol{H}_B^{\rm eff}\qquad \delta\alpha=\sigma\frac{|\boldsymbol{J}_s|}{\left|\boldsymbol{H}_{A,B}^{\rm eff}\right|}$$

Qualitative picture

Spin transfer torque acts oppositely for the two sub lattices
-> Generate different effective temperature

Assumption: the random fields are identical and independent for the two sublattices



$$\langle h_{Ai}(t)\, h_{Aj}(t')\rangle = \langle h_{Bi}(t)\, h_{Bj}(t')\rangle = \frac{2\alpha k_B T}{\gamma M_s}\delta_{ij}\delta(t-t'),$$

$$\langle h_{Ai}(t)\, h_{Bj}(t')\rangle = 0$$

$T_B^{\rm eff} > T$

Induced magnetisation and spin pumping

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$$\langle \boldsymbol{M}_A + \boldsymbol{M}_B\rangle \sim \frac{1}{2\gamma M_s H_E}\left\langle \boldsymbol{L} \times \frac{d\boldsymbol{L}}{dt}\right\rangle, \boldsymbol{L} = \boldsymbol{M}_A - \boldsymbol{M}_B$$

$T_A^{\rm eff} < T$

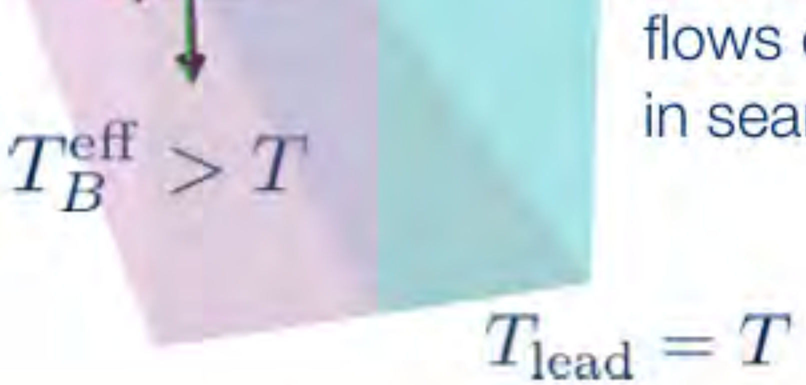
$J_s^{\rm in}$

Interface spin-pumping formula

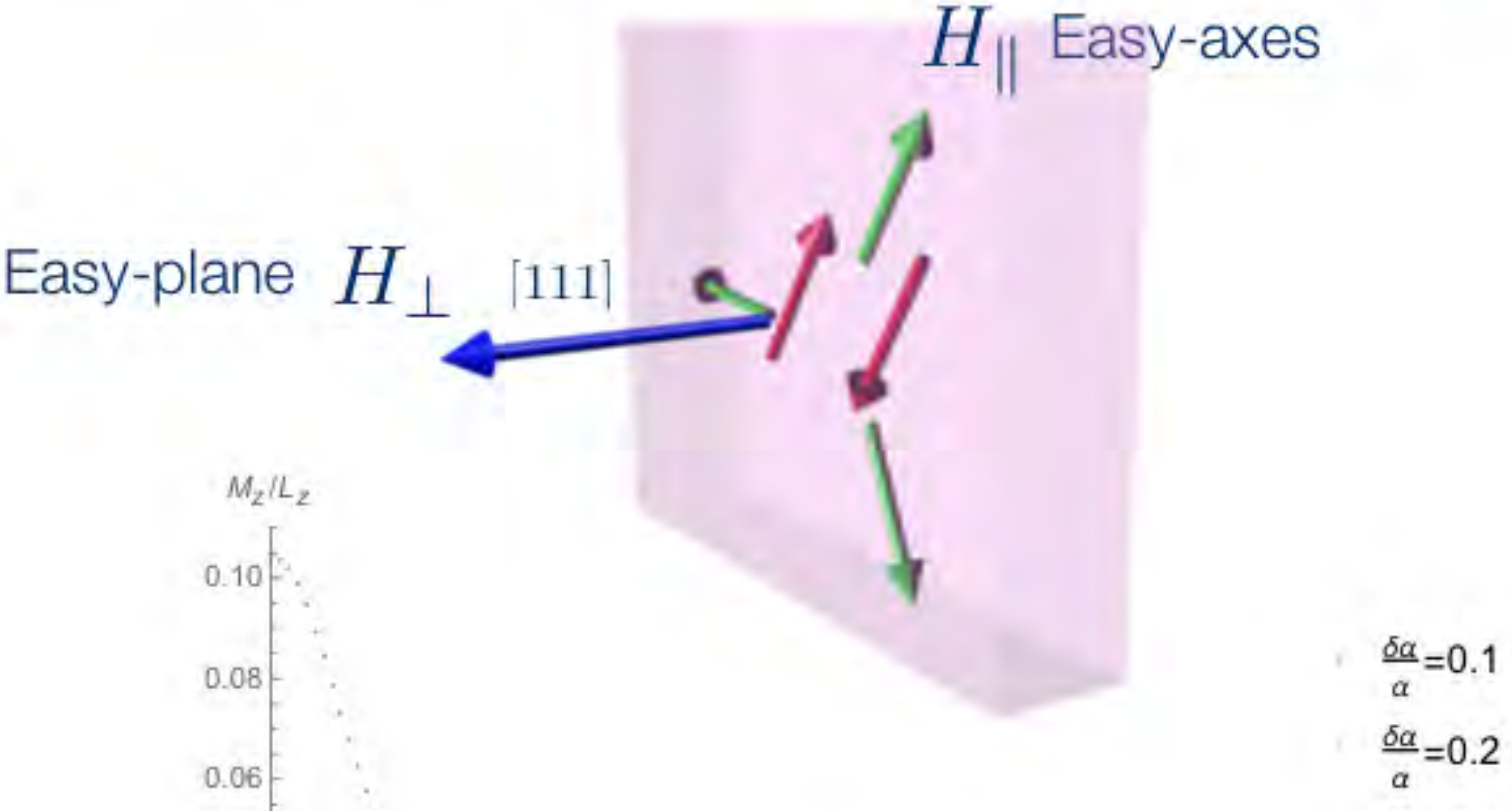
$$J_s^{\rm out} \sim g_{\uparrow\downarrow}\left\langle \boldsymbol{L} \times \frac{d\boldsymbol{L}}{dt}\right\rangle \propto -\left(T_A^{\rm eff} - T_B^{\rm eff}\right) \propto J_s^{\rm in}$$

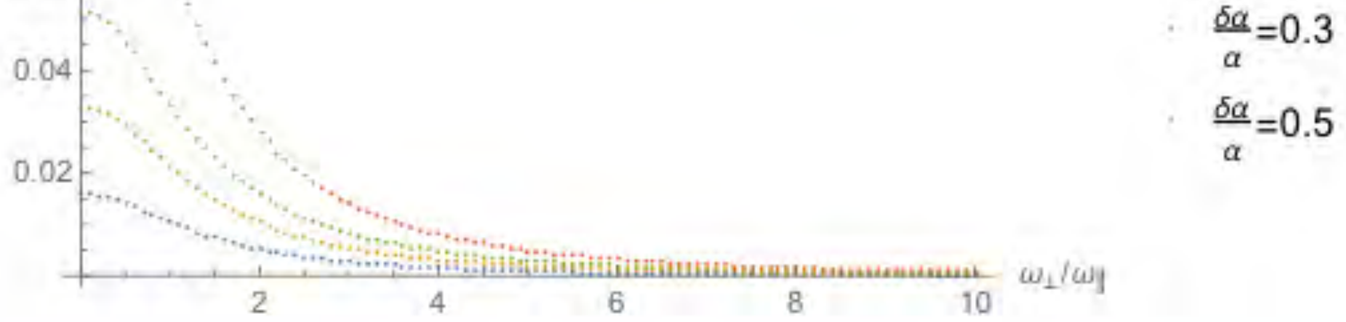
Out-of-equilibrium magnetisation

flows out into the adjacent lead
in search of equilibrium



Dependence on biaxial anisotropy





Summary

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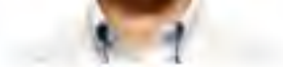
- Spin is a ratchet -> fluctuations generate loose angular momenta
- In equilibrium, there is a balance between random force fields that completely cancel any transport current (FDT)
- Damping-like torque drives system out of equilibrium by modulating the damping constants and breaking FDT
- Damping-like torque induces out-of-equilibrium net magnetisation

in AFMs, which is converted to spin current via spin-pumping

THANK YOU

Acknowledgements



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