Magnon-Mediated Interlayer Coupling and Spin-Transfer Torques

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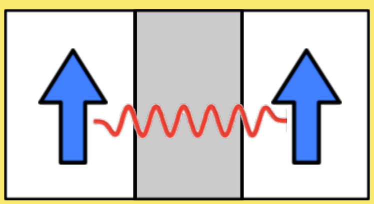
Moving to: ECE, University of California – Riverside

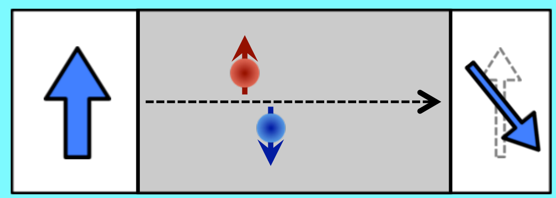
Roadmap

- ❑ Magnons
- ❑ Antiferromagnets

Interlayer Coupling



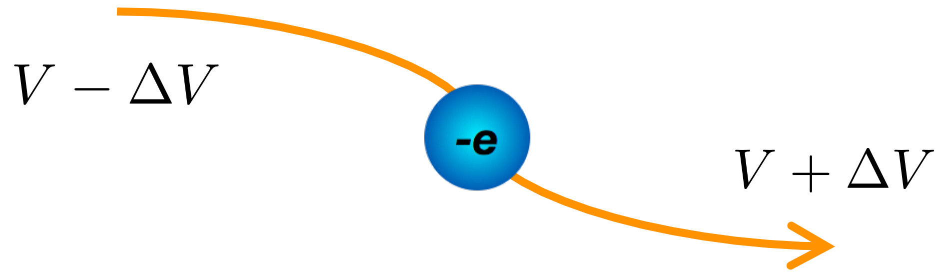
STT and Switching



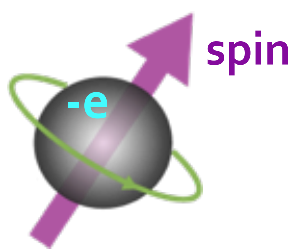
- ➢ Spin Nernst Effect
- ➢ Data Modulation
- ➢ Outlook

Challenge

- ✓ Soaring power consumption
- ✓ Waste heat

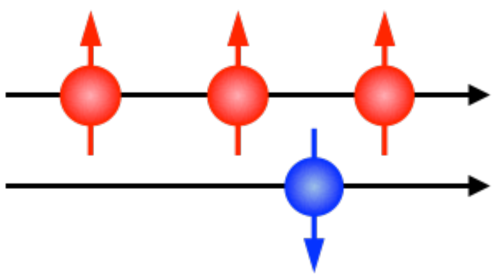


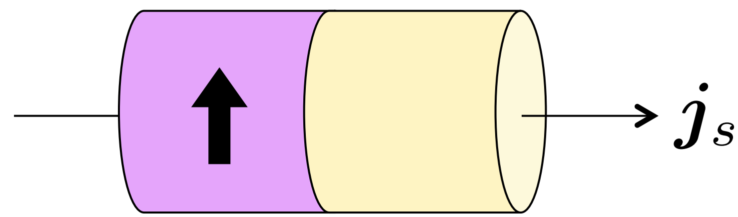
- ✓ Spin logic



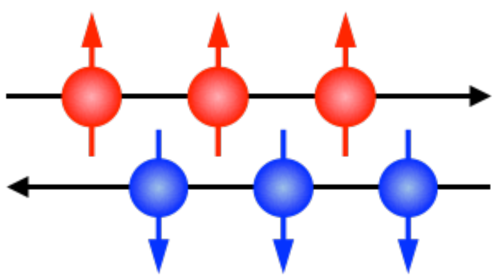
Challenge

✓ Spin-polarized current

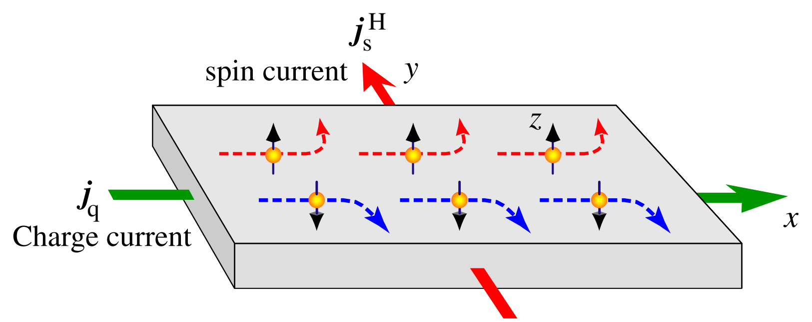




✓ Pure spin current



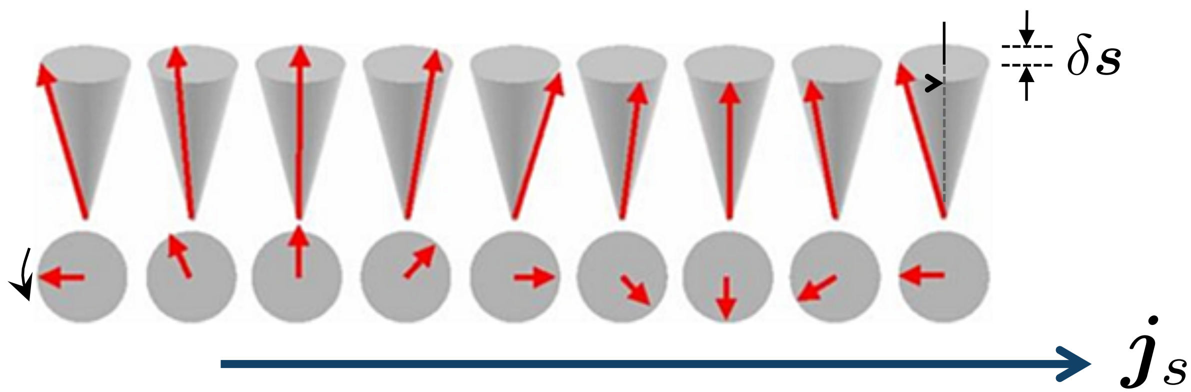
$j_c = 0$



Spin Hall Effect

Magnonics

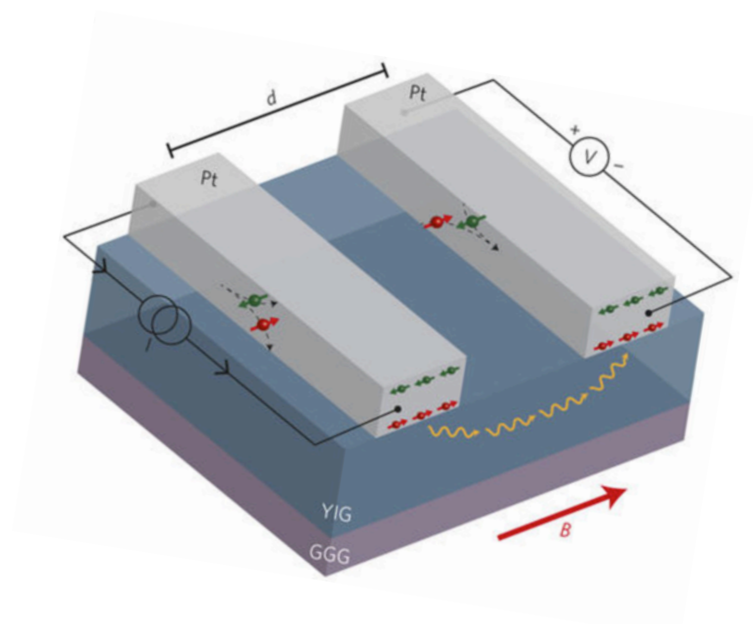
- ✓ Spin-wave (magnon) spin current



- ✓ Thermal transport

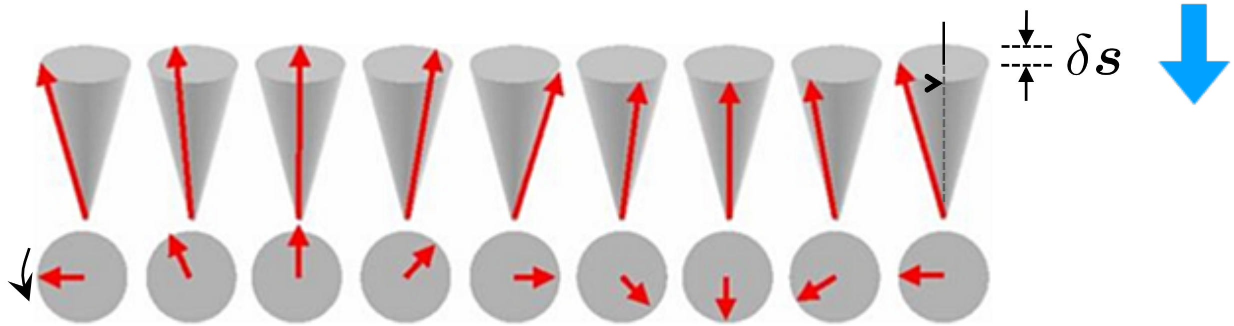
$$j_s = \sigma_m \nabla \mu + L \nabla T$$
$$j_Q = L T \nabla \mu + \kappa \nabla T$$

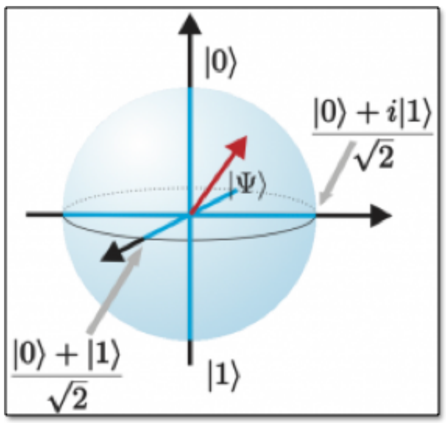
Cornelissen, Liu, Duine, Ben Youssef & van Wees, Nat. Phys. **11**, 1022 (2015)



Magnonics

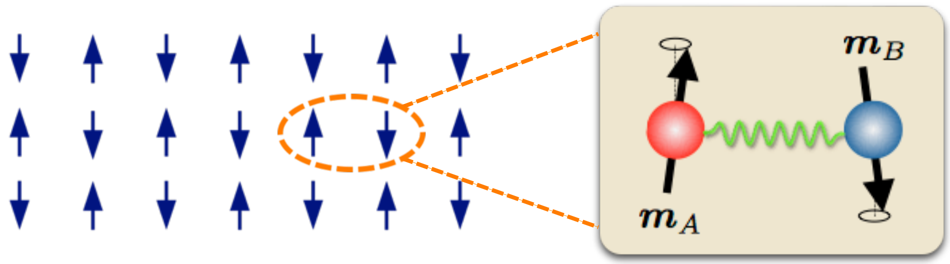
- **Caveat!**





Intrinsic degree of freedom?

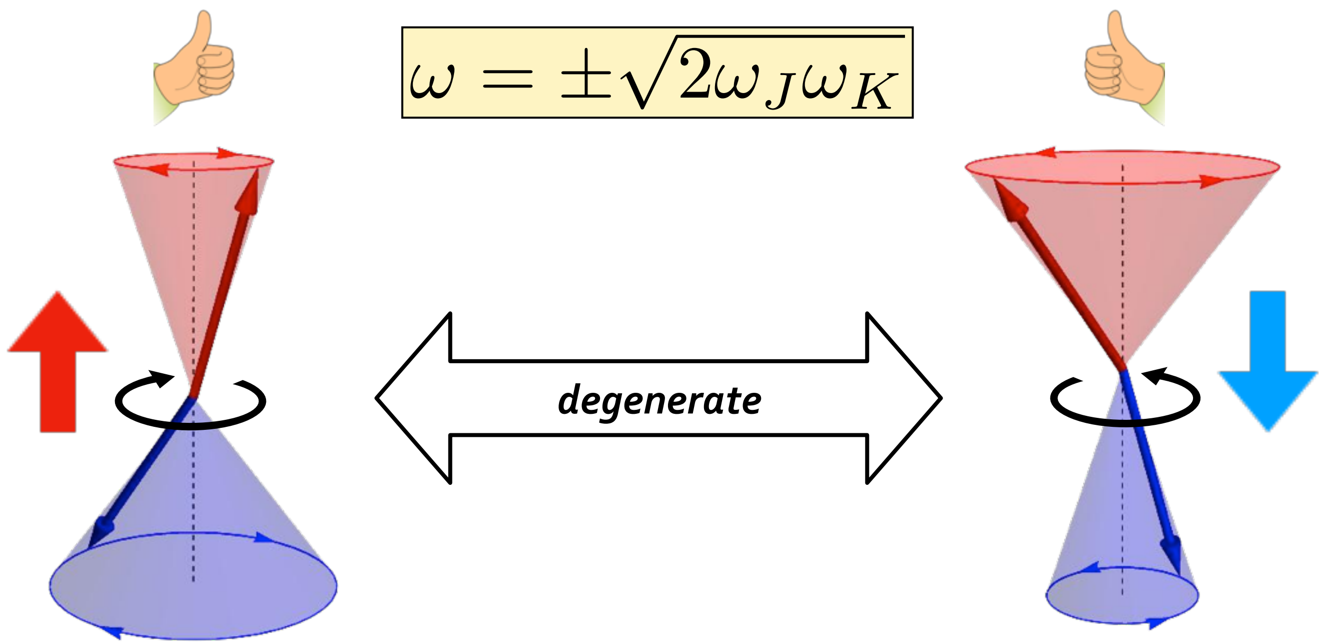
Antiferromagnet



$$\frac{\partial \boldsymbol{m}_A}{\partial t} = \boldsymbol{m}_A \times (-\omega_J \boldsymbol{m}_B + \omega_K \hat{\boldsymbol{z}})$$

$$\frac{\partial \boldsymbol{m}_B}{\partial t} = \boldsymbol{m}_B \times (-\omega_J \boldsymbol{m}_A - \omega_K \hat{\boldsymbol{z}})$$

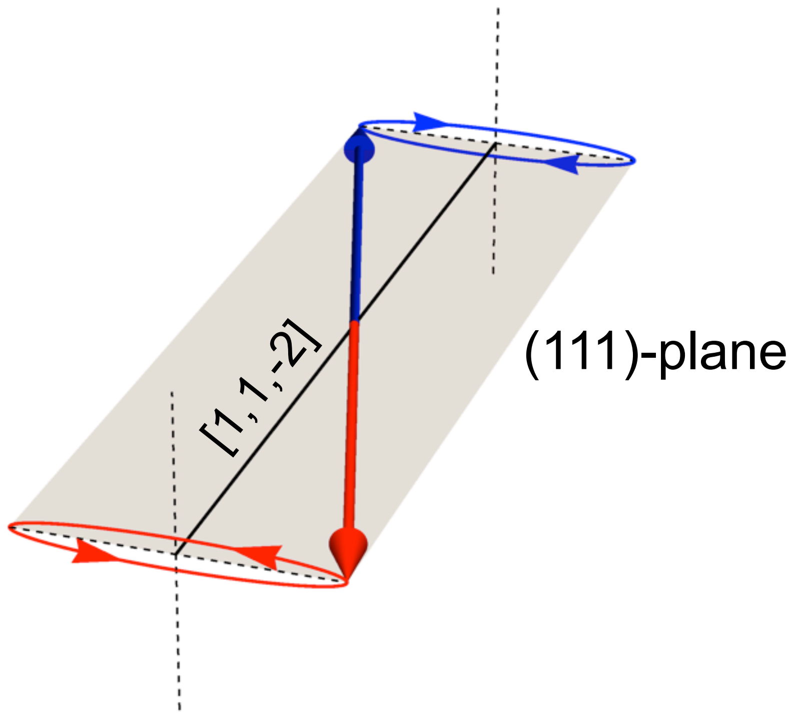
$$\omega = \pm\sqrt{2\omega_J \omega_K}$$



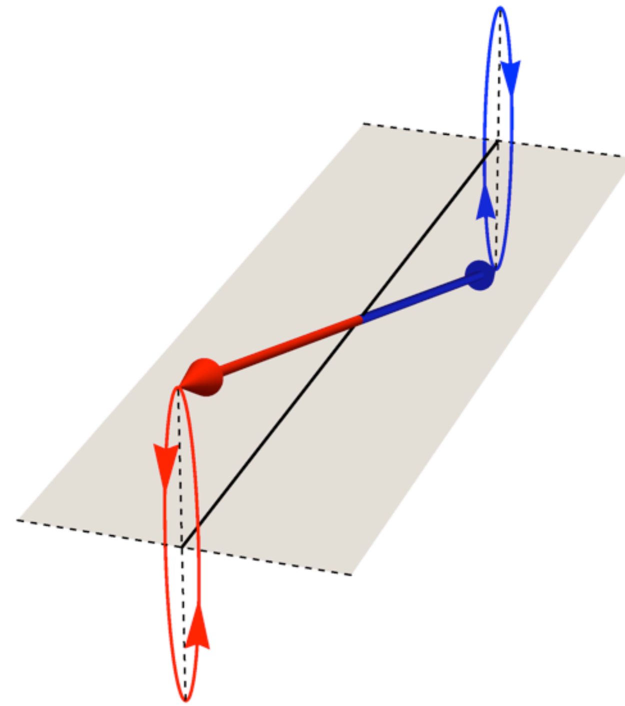
Left-handed ✓ MnF_2, FeF_2, Cr_2O_3 Right-handed

Antiferromagnet

✓ Hard-axis & Easy-axis (NiO, MnO)



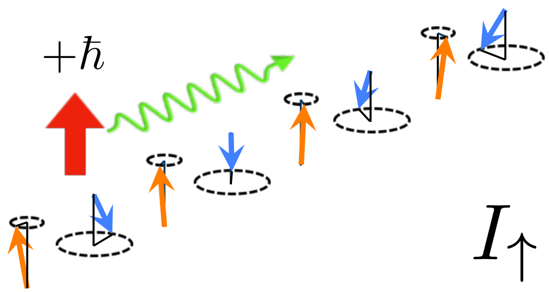
Acoustic (0.14 THz)

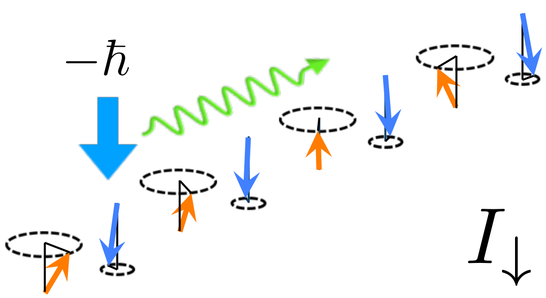


Optical (1.1 THz)

Magnon Spin Current

✓ Spin <u>conductor</u>





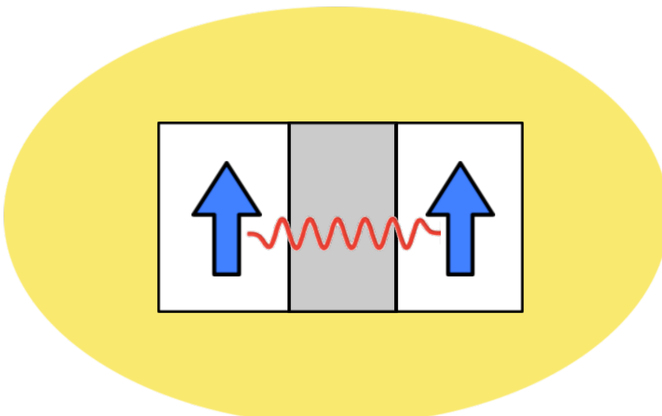
Spin

Charge

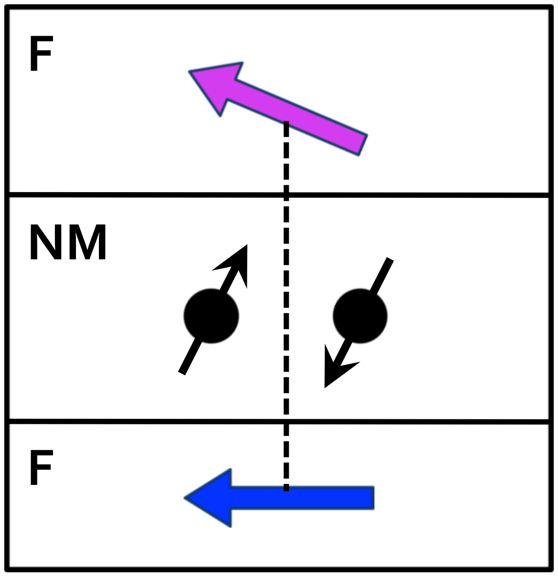
System	Magnon current
Antiferromagnet ↑ ↓ ↑ ↓	$I_Q = I_\uparrow + I_\downarrow$ $I_s = I_\uparrow - I_\downarrow$
Ferrimagnet ↑ ↓ ↑ ↓	$I_\downarrow > I_\uparrow$
Ferromagnet ↑ ↑ ↑ ↑	$I_\uparrow = 0$

Roadmap

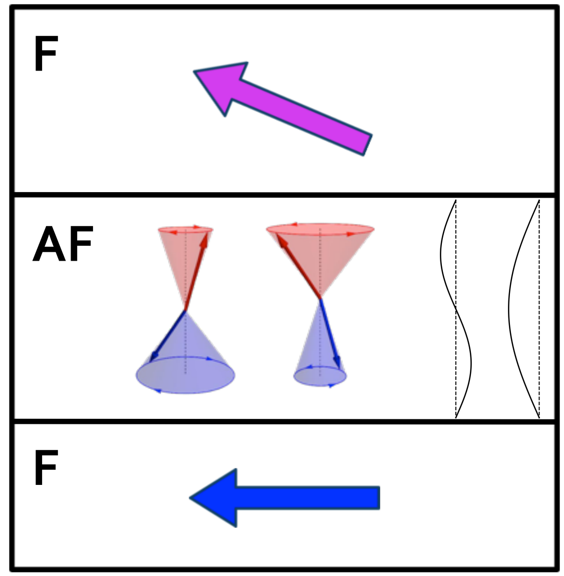
Interlayer Coupling



Interlayer Coupling



Interlayer RKKY

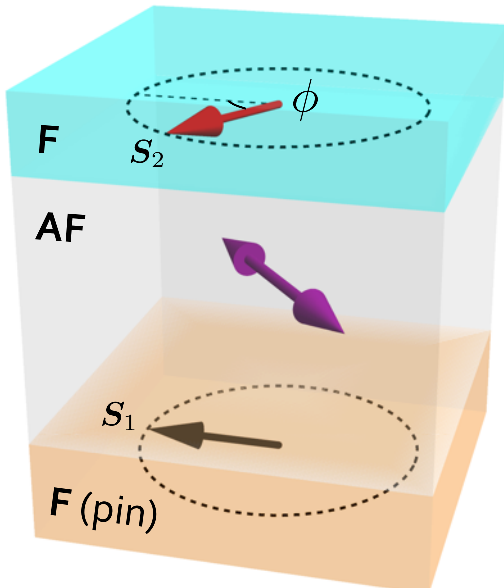


A similar effect?

Review:
P. Bruno, Phys. Rev. B **52**, 411 (1995)

- Bose-Einstein Statistics

Interlayer Coupling

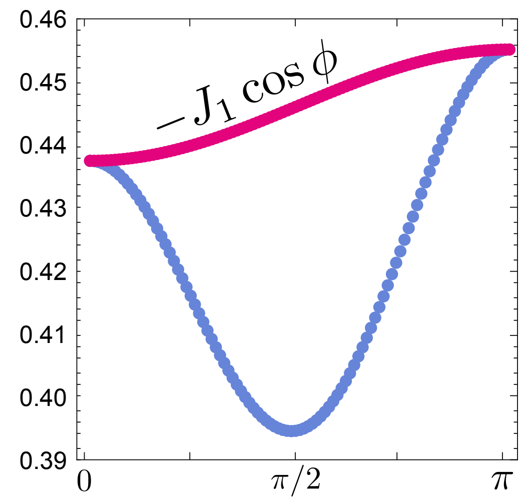


Magnon Thermal Energy

$$U(\phi) = \sum_i \int d^2\boldsymbol{k}_\parallel \frac{\varepsilon_i(\phi, \boldsymbol{k}_\parallel)}{\exp[\varepsilon_i(\phi, \boldsymbol{k}_\parallel)/k_B T] - 1}$$

Polycrystal Averaged

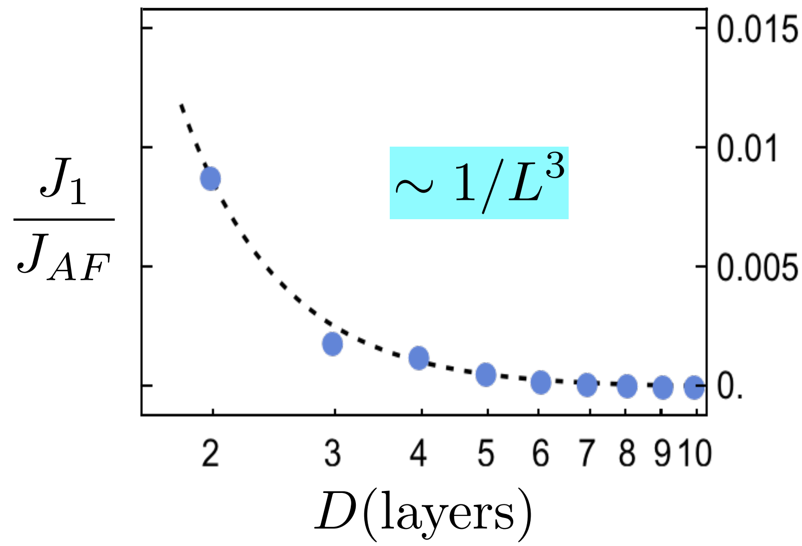
$$U = -J_1 \cos\phi - J_2 \cos 2\phi$$



RC, D. Xiao & J. Zhu, arXiv:1802.07867

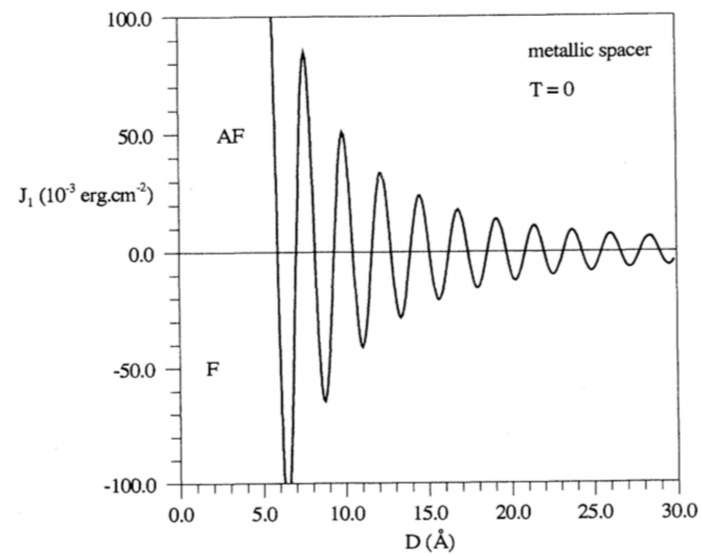
Interlayer Coupling

- ✓ Dependence on AF thickness



$k_B T = 0.6 J_{AF}$

Electron-mediated

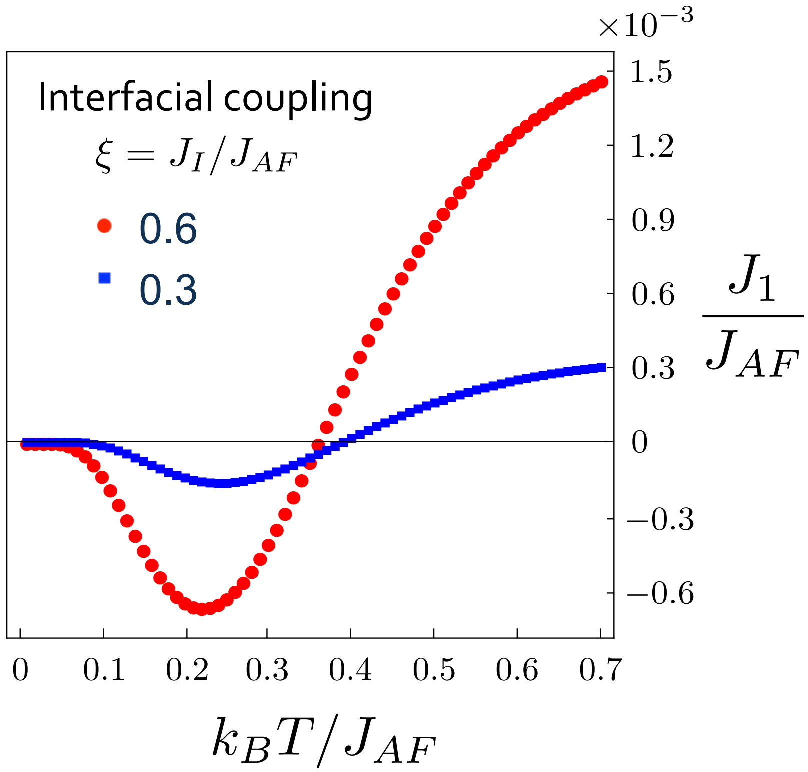


$k_B T = 0$

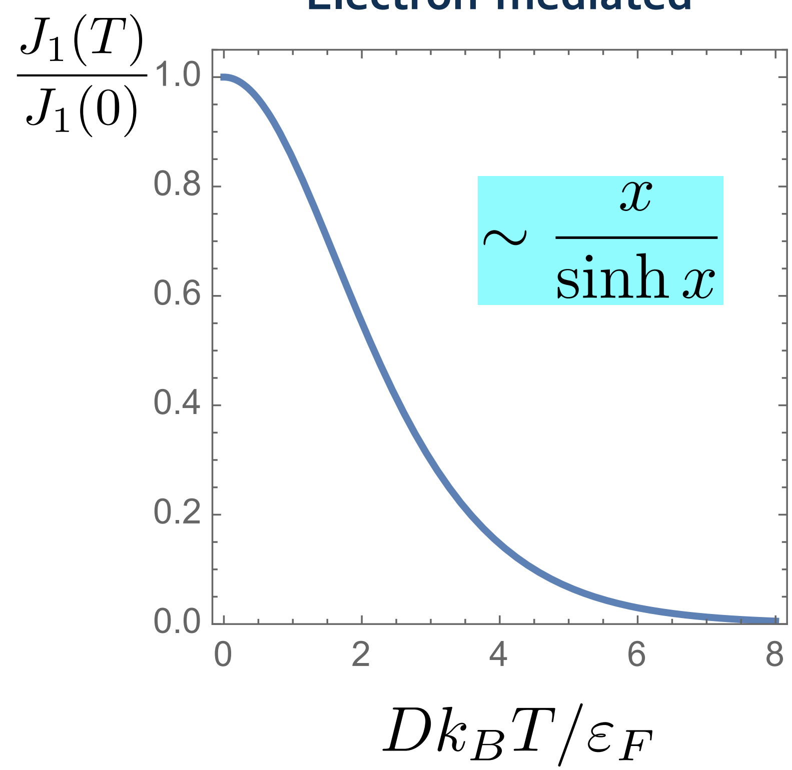
P. Bruno, Phys. Rev. B **52**, 411 (1995)

Interlayer Coupling

✓ Dependence on temperature

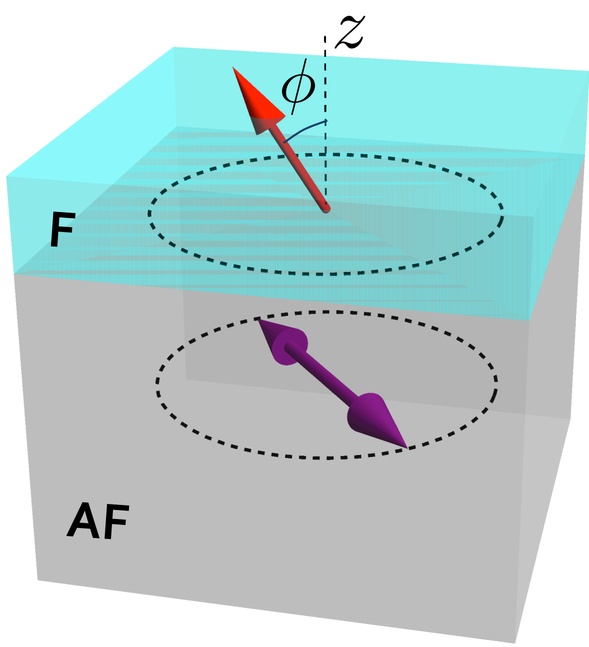


Electron-mediated



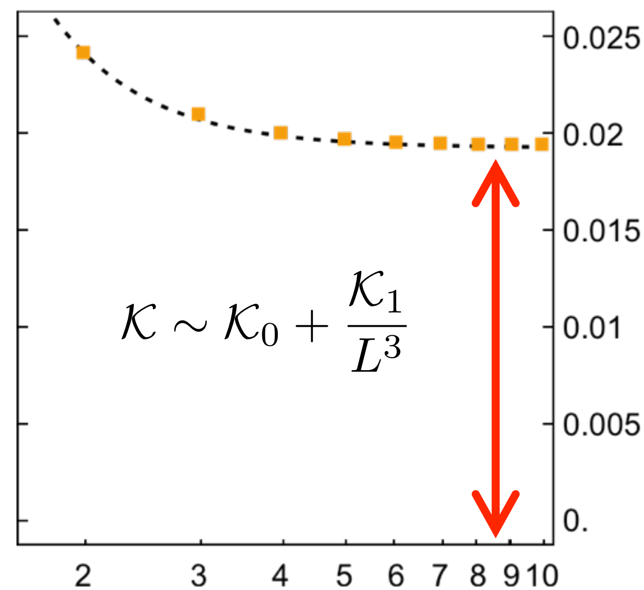
Bilayer Effect

✓ Magnon-induced anisotropy



Polycrystal AF
(random in-plane Néel vectors)

$$U = -\mathcal{K}\cos 2\phi$$

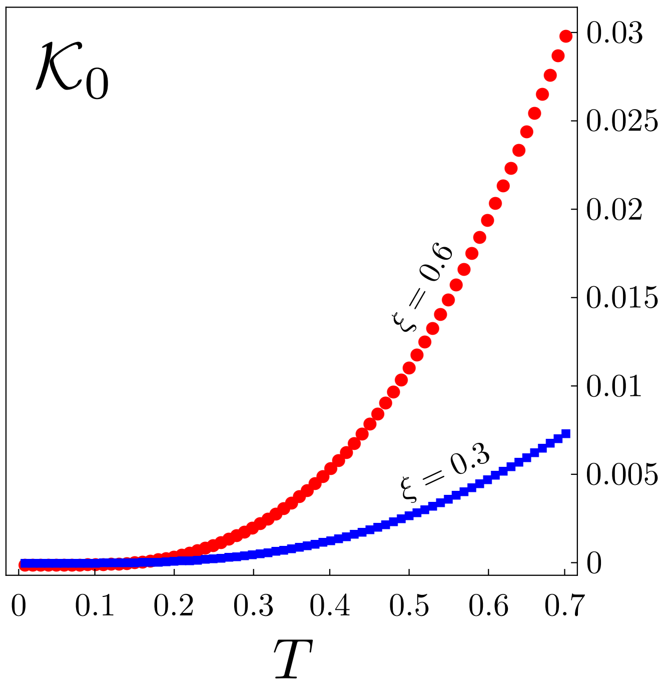


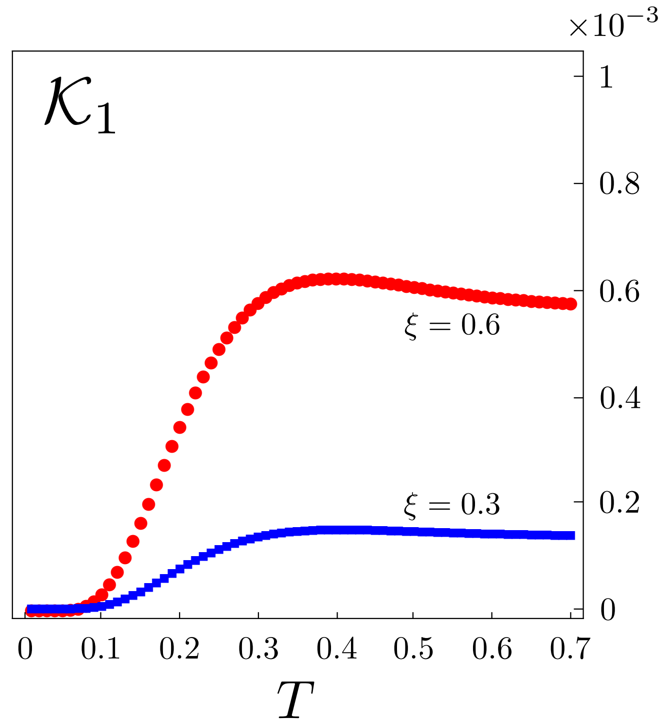
$\mathcal{K}_0$ ***Surface*** magnons (bilayer effect)

$\mathcal{K}_1$ ***Bulk*** magnons (trilayer effect)

Bilayer Effect

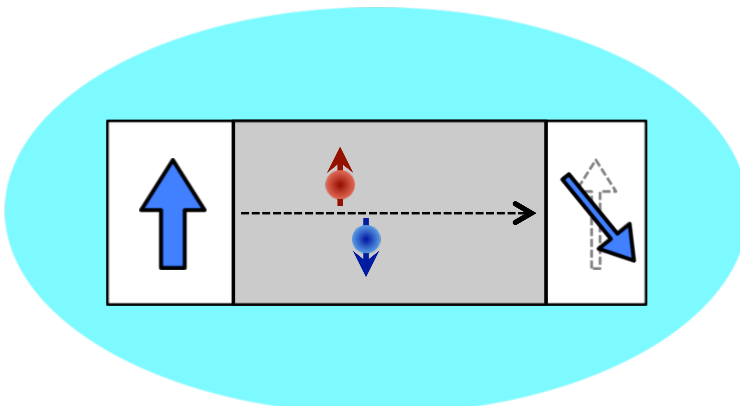
$$\mathcal{K} \sim \mathcal{K}_0 + \frac{\mathcal{K}_1}{L^3}$$



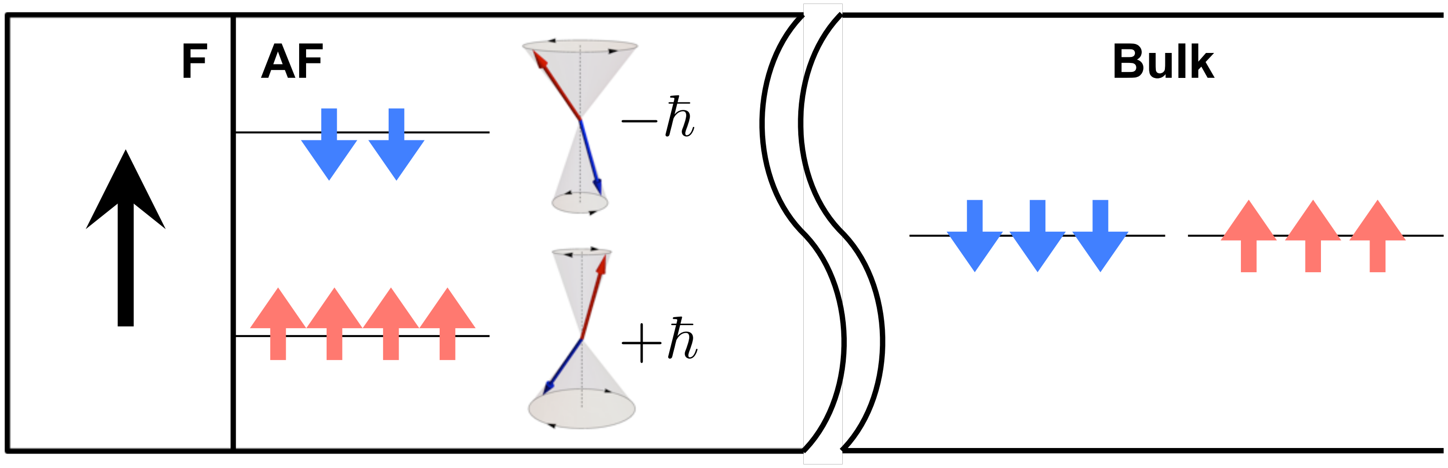


Roadmap

STT
Switching



Magnonic Spin-Transfer Torque



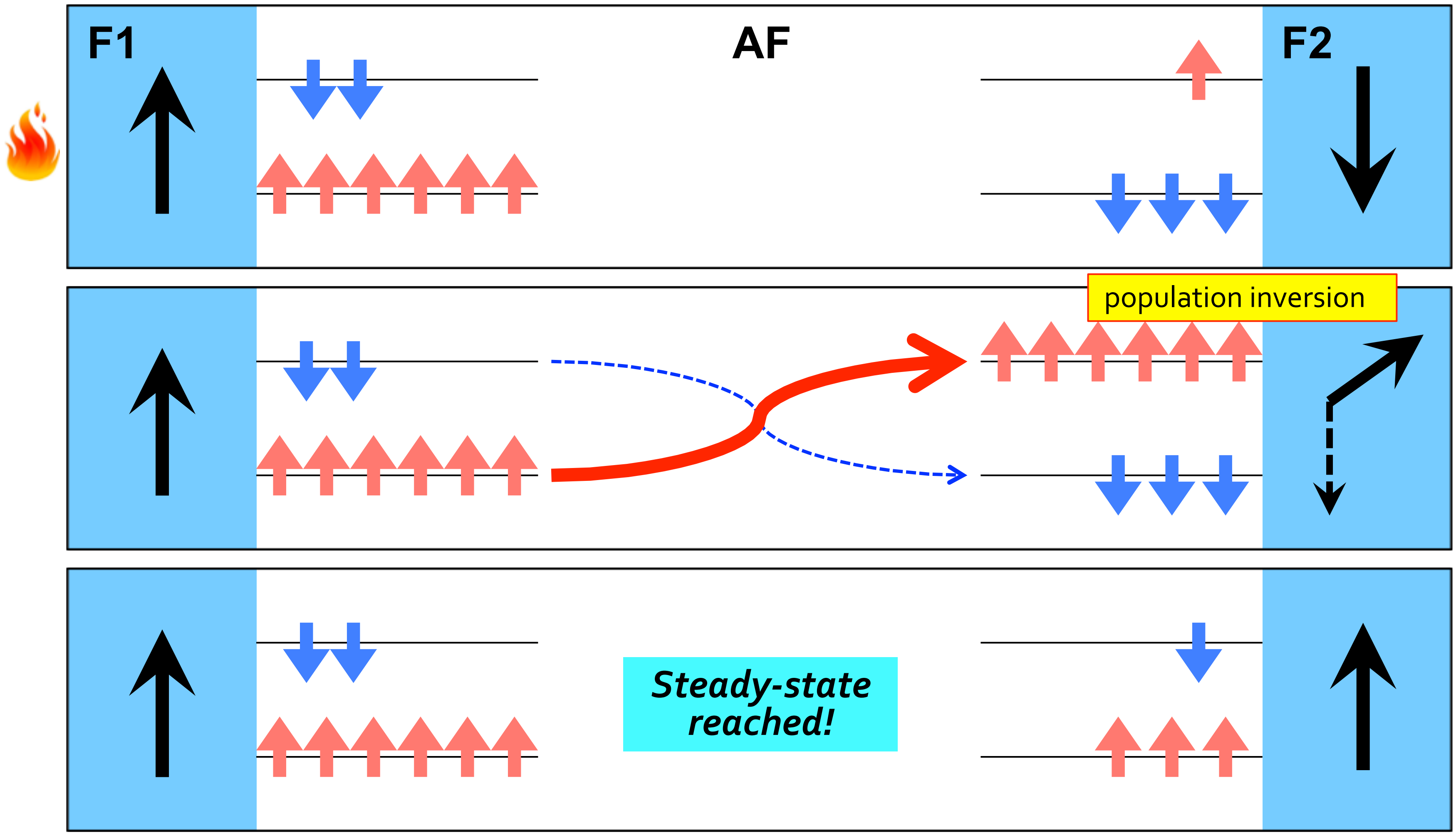
$$n(\varepsilon) = \frac{1}{\exp(\frac{\varepsilon \pm J}{k_B T}) - 1}$$

$$n(\varepsilon) = \frac{1}{\exp(\frac{\varepsilon}{k_B T}) - 1}$$

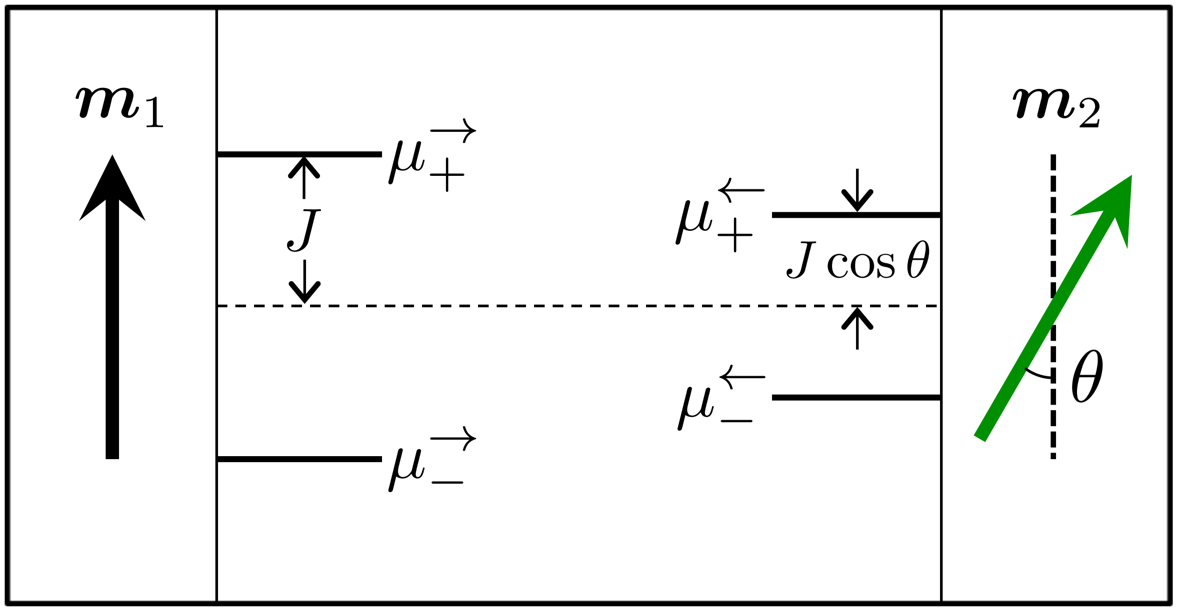
Exchange Split

Degenerate

All-Magnonic Switching



Theoretical Model



$$\boldsymbol{j}_s = \hbar \int_{v_x>0} dk v_x \left[f_+^{\rightarrow} - f_-^{\rightarrow}\right] + \hbar \int_{v_x<0} dk v_x \left[f_+^{\leftarrow} - f_-^{\leftarrow}\right]$$

$$\frac{\partial \boldsymbol{m}}{\partial t} = \gamma \boldsymbol{H}_{eff} \times \boldsymbol{m} + \alpha \boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t} + \boldsymbol{j}_s$$

Theoretical Model

$$\frac{\partial \delta f_\sigma^v}{\partial x} + \frac{\delta f_\sigma^v}{v_x \tau_m} = (\varepsilon - \mu_\sigma^v) \frac{\partial \bar{f}_\sigma^v}{\partial \varepsilon} \frac{\partial_x T}{T} + \frac{f_0 - \bar{f}_\sigma^v}{v_x \tau_{\text{th}}}$$

$\tau_m \ll \tau_{\text{th}}$

momentum relaxation
(conserve magnon #)

thermal relaxation
(kills magnons)

$$\bar{f}_\sigma^v = \frac{1}{e^{(\varepsilon - \mu_\sigma^v)/k_B T} - 1}$$

$$f_0 = \frac{1}{e^{\varepsilon / k_B T} - 1}$$

Local equilibrium

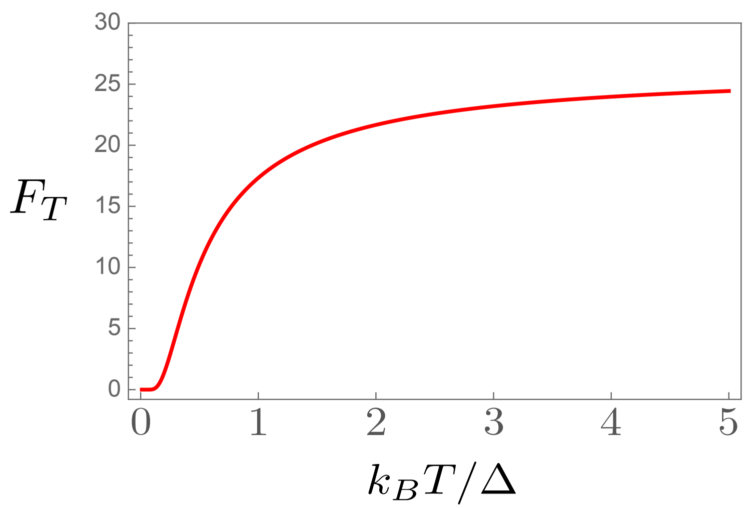
Global equilibrium

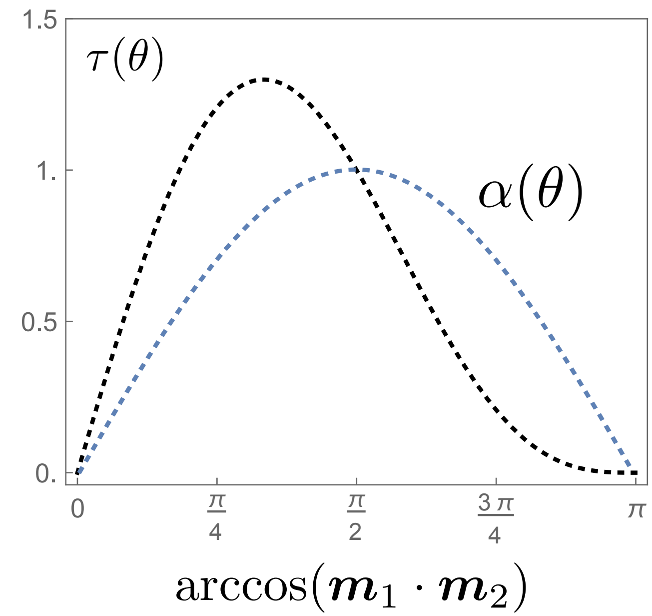
Zhang & Zhang, PRL **109**, 096603 (2012)

Central Results

✓ Damping-like torque

$$\boldsymbol{\tau} = \frac{-\lambda\partial_x T}{T}\frac{2\pi J(k_B T)^2}{3\hbar^2 v_s^2} F\left(\frac{k_B T}{\Delta}\right) g(\theta) \boldsymbol{m}_2 \times (\boldsymbol{m}_1 \times \boldsymbol{m}_2)$$





Δ : AFMR frequency

RC, D. Xiao & J. Zhu, arXiv:1802.07709

Central Results

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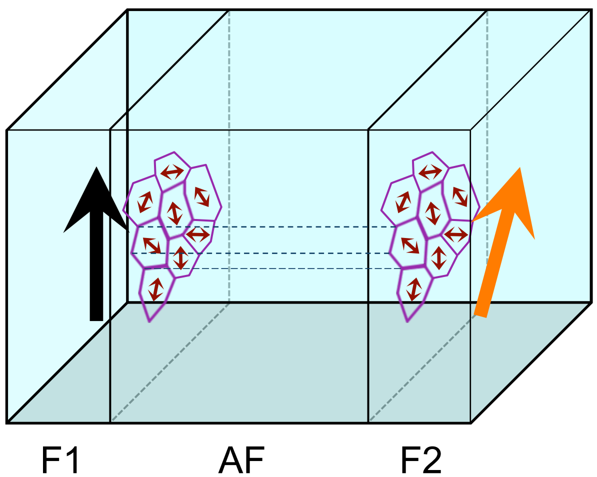
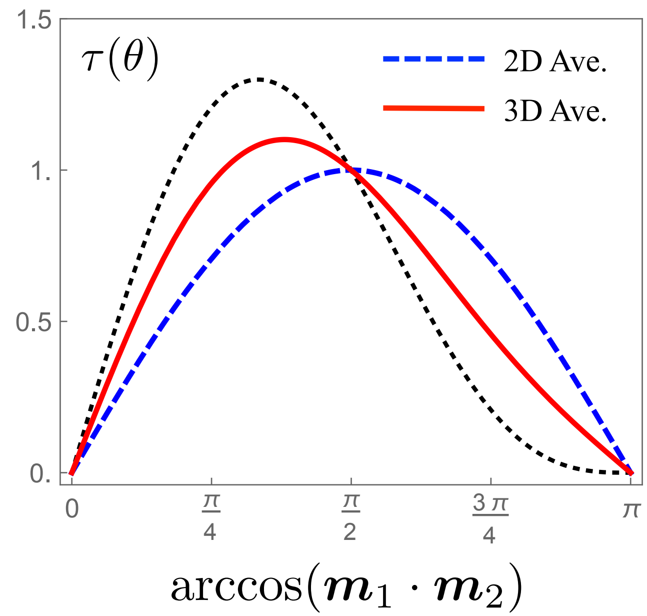
$$\boldsymbol{\tau} = \frac{-\lambda\partial_x T}{T}\frac{2\pi J(k_B T)^2}{3\hbar^2 v_s^2} F\left(\frac{k_B T}{\Delta}\right) g(\theta)\boldsymbol{m}_2 \times (\boldsymbol{m}_1 \times \boldsymbol{m}_2)$$



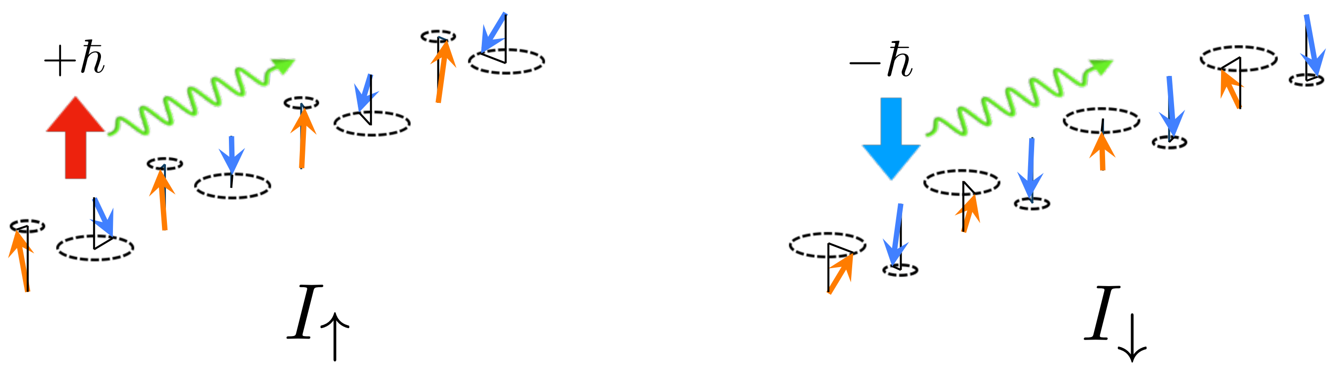


Threshold: $\nabla T \sim 1K/nm$

RC, D. Xiao & J. Zhu, arXiv:1802.07709

Roadmap

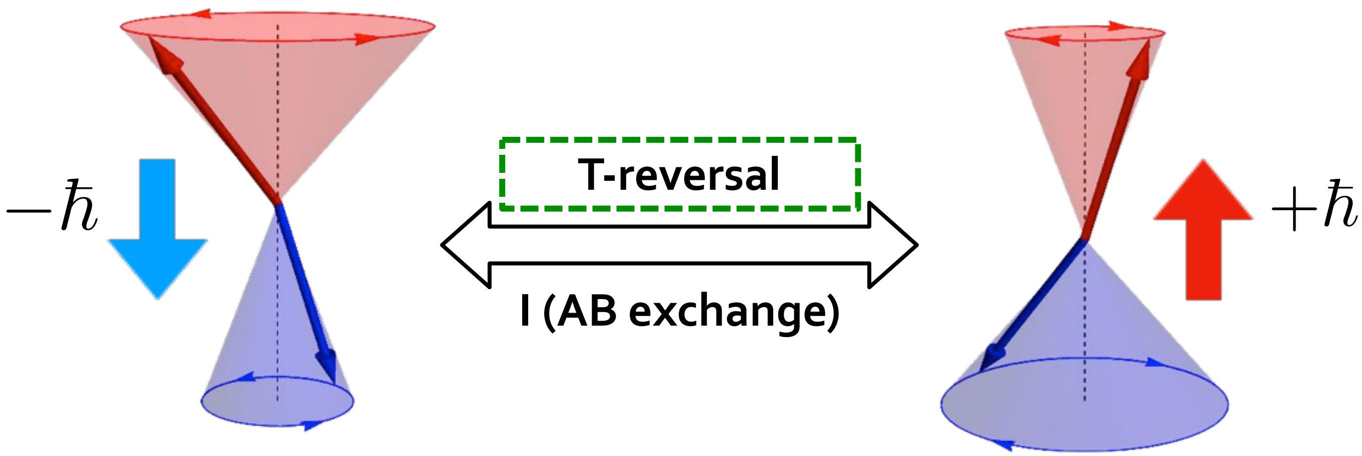
- Spin Nernst Effect
- Data Modulation
- Outlook



$$I_Q = I_\uparrow + I_\downarrow$$

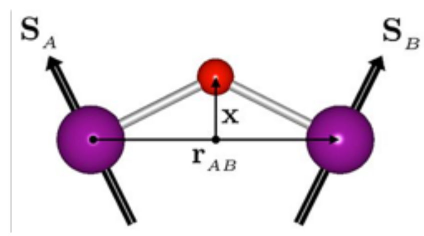
$$I_s = I_\uparrow - I_\downarrow$$

Symmetry



$$\boxed{\boldsymbol{\mathcal{D}}_{AB} \cdot \boldsymbol{S}_A \times \boldsymbol{S}_B}$$

Dzyaloshinskii-Moriya Interaction (DMI)

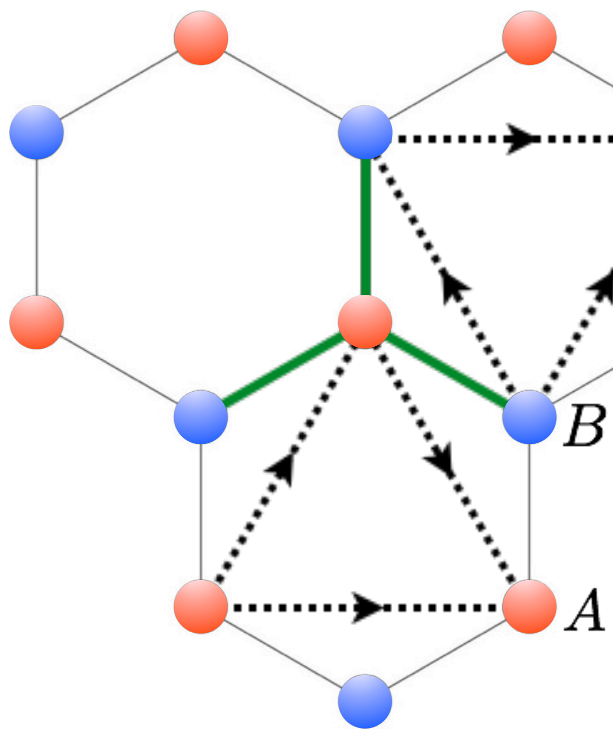


$$\left.\begin{aligned} \delta \boldsymbol{S}_A &= \boldsymbol{S}_A - \hat{\boldsymbol{z}} \\ \delta \boldsymbol{S}_B &= \boldsymbol{S}_B + \hat{\boldsymbol{z}} \end{aligned}\right\}$$

Spin-Orbit Coupling

Spin Nernst Effect

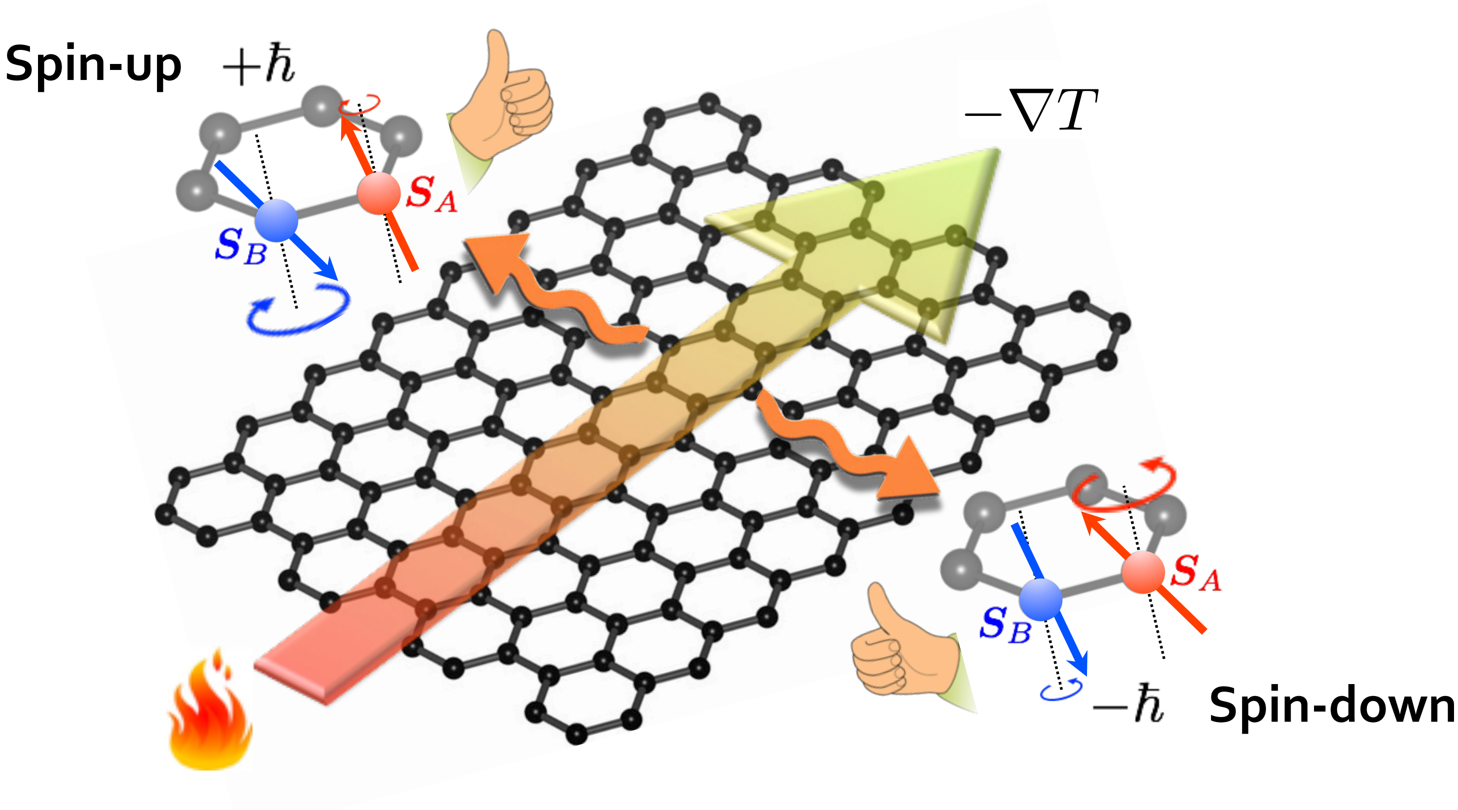
$$H = J_1 \sum_{\langle ij \rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + D_2 \sum_{\langle\langle ij \rangle\rangle} \boldsymbol{\xi}_{ij} \cdot \boldsymbol{S}_i \times \boldsymbol{S}_j + \mathcal{K} \sum_i S_{iz}^2$$



Exchange	DMI
J_1	×
J_2	D_2
J_3	×

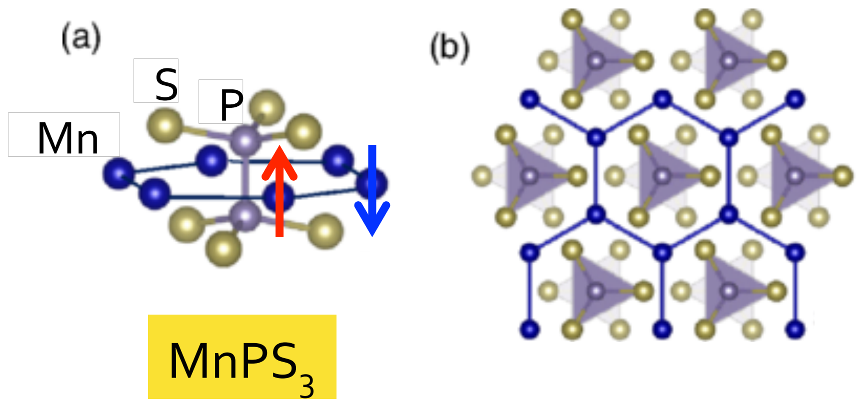
Spin Nernst Effect

$$H = J_1 \sum_{\langle ij \rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + D_2 \sum_{\langle\langle ij \rangle\rangle} \boldsymbol{\xi}_{ij} \cdot \boldsymbol{S}_i \times \boldsymbol{S}_j + \mathcal{K} \sum_i S_{iz}^2$$



RC, Okamoto & Xiao, PRL **117**, 217202 (2016)

Spin Nernst Effect



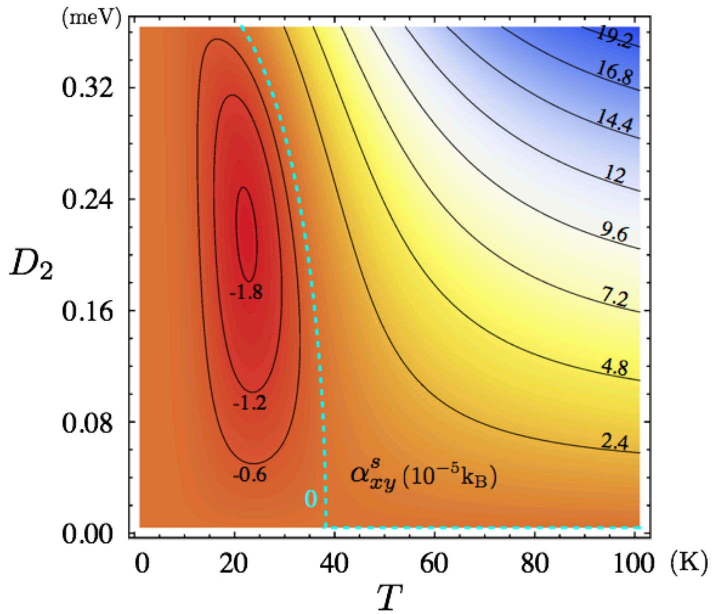
S	J_1 (meV)	J_2 (meV)	J_3 (meV)	J' (meV)	$g\mu_B H_A$ (meV)
2.5	−0.77 ±0.09	−0.07 ±0.03	−0.18 ±0.01	0.0019 ±0.0002	0.0086 ±0.0009

Neutron Scattering: Wildes, Roessli, Lebech & Godfrey, JCM 1998
DFT: Sivadas, Daniels, Swendsen, Okamoto & Xiao, PRB 2015

Spin Nernst Effect

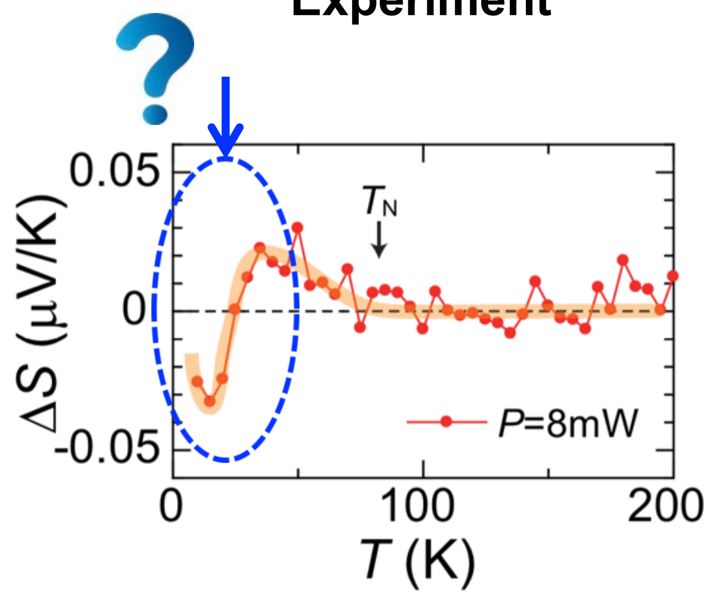
$$\boldsymbol{j}_{SN} = \hbar(\boldsymbol{j}_{\uparrow} - \boldsymbol{j}_{\downarrow}) \equiv \alpha^{s}_{xy} \hat{\boldsymbol{z}} \times \boldsymbol{\nabla} T$$

Theory



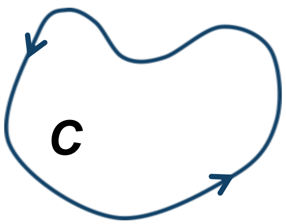
RC, Okamoto & Xiao,
PRL **117**, 217202 (2016)

Experiment

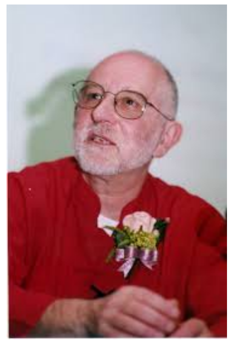


Shiomi, Takashima & Saitoh
PRB **96**, 134425 (2017)

Berry Phase Effect

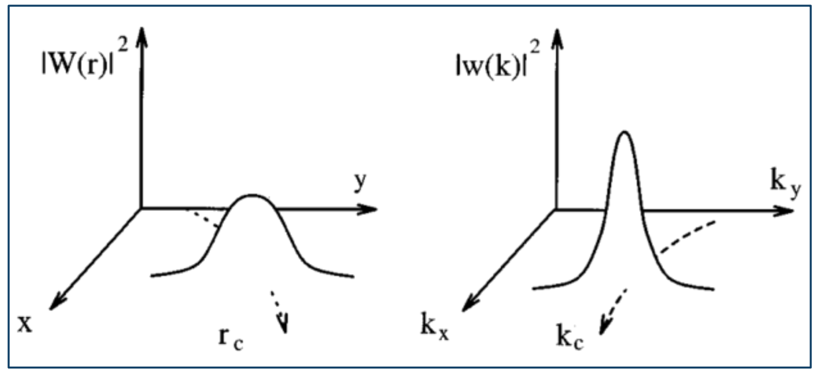


$$\gamma(C) = \iint d\boldsymbol{s} \cdot \boldsymbol{\mathcal{B}}$$



M. V. Berry 1984

$$\dot{\boldsymbol{r}}_c = \boldsymbol{\nabla}\omega(\boldsymbol{k}_c) - \dot{\boldsymbol{k}}_c \times \boldsymbol{\mathcal{B}}(\boldsymbol{k}_c)$$



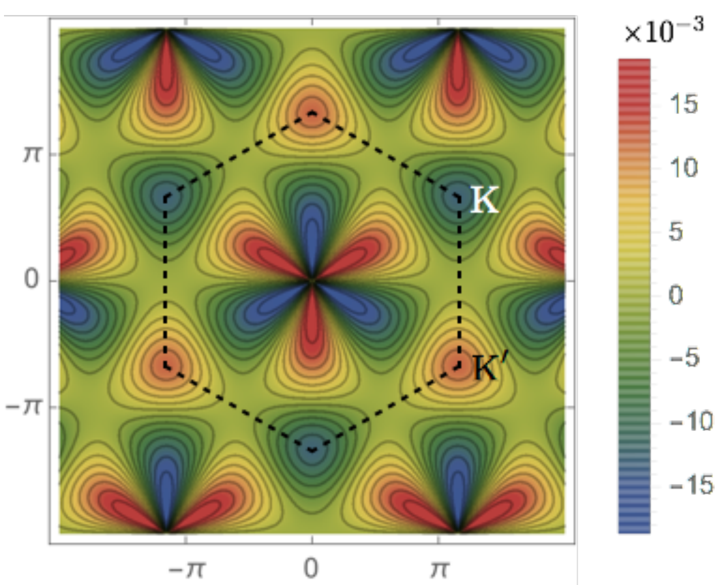
Sundaram & Niu, 1999; Xiao, Chang & Niu 2010

D. J. Thouless F.D.M. Haldane J. M. Kosterlitz

Nobel Prize in Physics, 2016

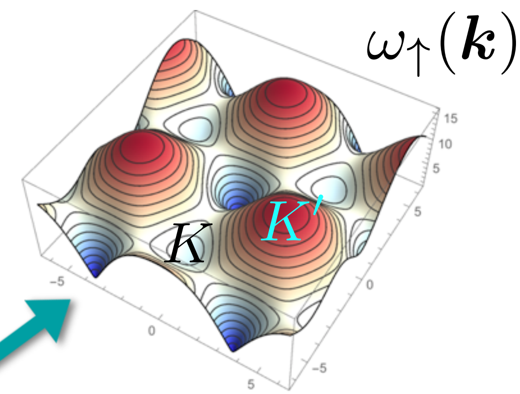
Berry Phase Effect

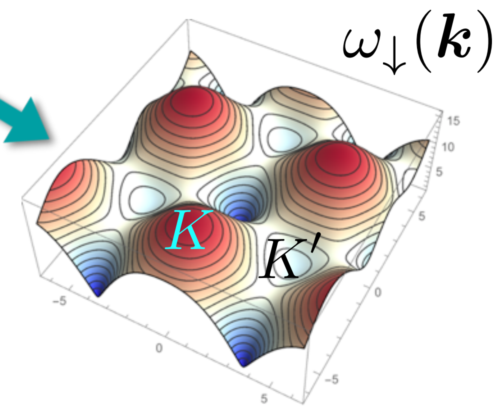
<u>Effective</u> ‘Lorentz’ Force $\dot{\boldsymbol{r}}_c = \boldsymbol{\nabla}\omega(\boldsymbol{k}_c) - \dot{\boldsymbol{k}}_c \times \boldsymbol{\mathcal{B}}(\boldsymbol{k}_c)$



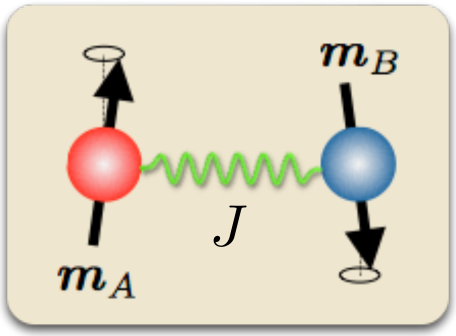
$$\boldsymbol{\mathcal{B}}_\uparrow(\boldsymbol{k}) = \boldsymbol{\mathcal{B}}_\downarrow(\boldsymbol{k})$$
$$\boldsymbol{\mathcal{B}}_\sigma(\boldsymbol{k}) = -\boldsymbol{\mathcal{B}}_\sigma(-\boldsymbol{k})$$

DMI breaks degeneracy!





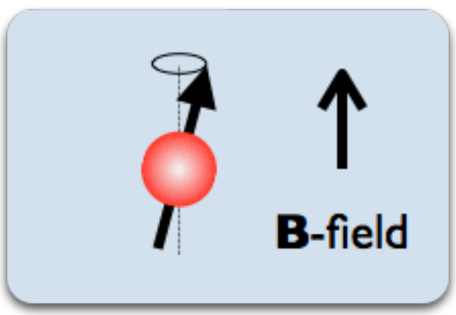
Terahertz Spin Dynamics



$$\omega(\boldsymbol{k}) = \pm\sqrt{2\omega_J\omega_K + c^2\boldsymbol{k}^2}$$

$$\omega_J \gg \omega_K$$

Terahertz



ferromagnet

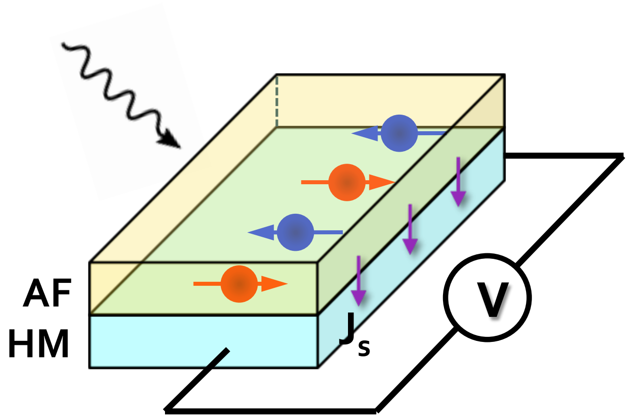
$$\omega(\boldsymbol{k}) = \omega_A + c\boldsymbol{k}^2$$

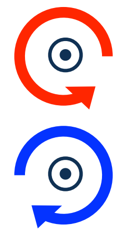
Anisotropy / Zeeman / Demagnetization

at most **100 GHz**

Terahertz Spin Dynamics

✓ Spin pumping



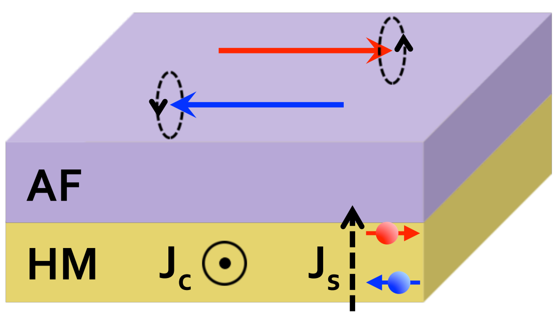


right-handed photon: **V>0**

left-handed photon: **V<0**

RC, Xiao, Niu & Brataas, PRL **113**, 057601 (2014)

✓ Spin-transfer torques



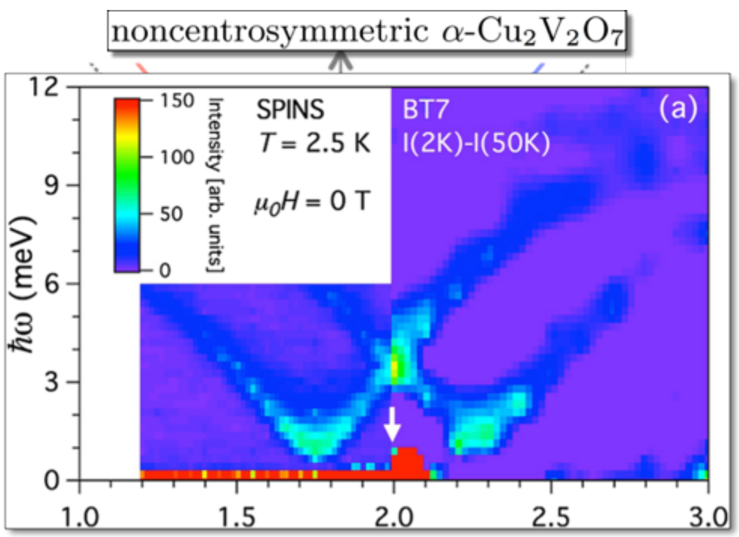
$J_c > 0$: excite right-handed mode

$J_c < 0$: excite left-handed mode

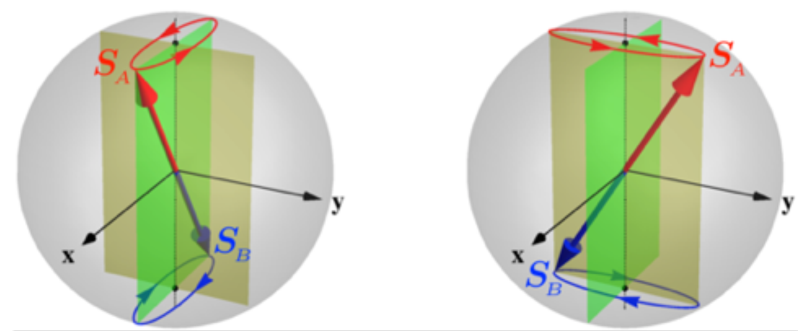
RC, Xiao & Brataas, PRL **116**, 207603 (2016)
RC, Zhu & Xiao, PRL **117**, 097202 (2016)

One-Dimensional AF Chain

$$H = \sum_i \left[J \boldsymbol{S}_i \cdot \boldsymbol{S}_{i+1} + K(\hat{\boldsymbol{z}} \cdot \boldsymbol{S}_i)^2 \right] + \sum_{ij} \boldsymbol{D}_{ij} \cdot \boldsymbol{S}_i \times \boldsymbol{S}_j$$



G. Gitgeatpong *et al.*, Phys. Rev. Lett. **119**, 047201 (2017)

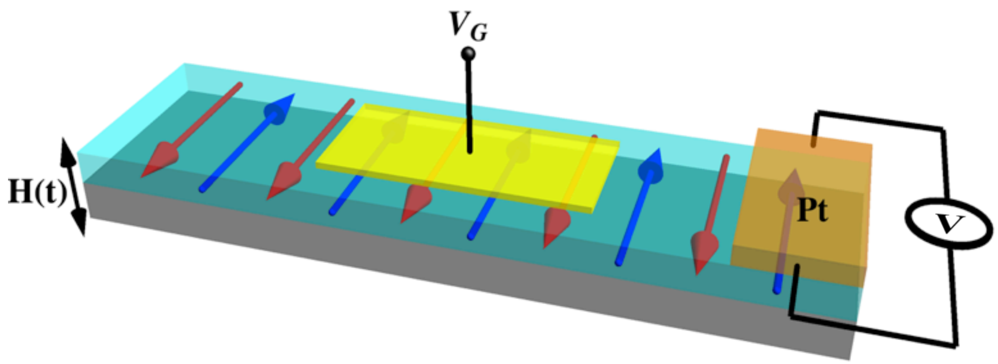


$|L\rangle + i|R\rangle$ $\quad$ $|L\rangle - i|R\rangle$

Faraday Rotation

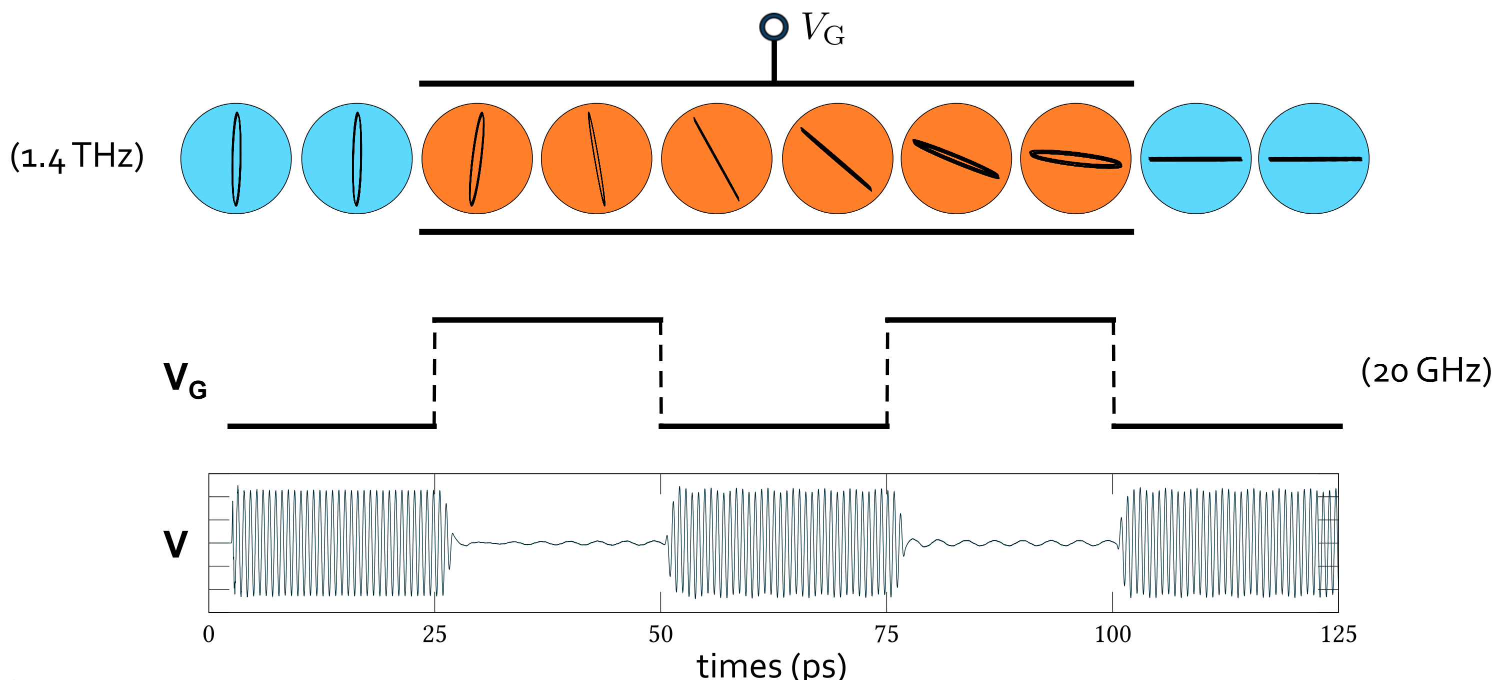
RC, Daniels, Zhu & Xiao, Sci. Rep. **6**, 24223 (2016)

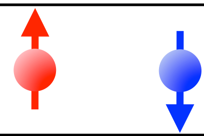
Data Modulation



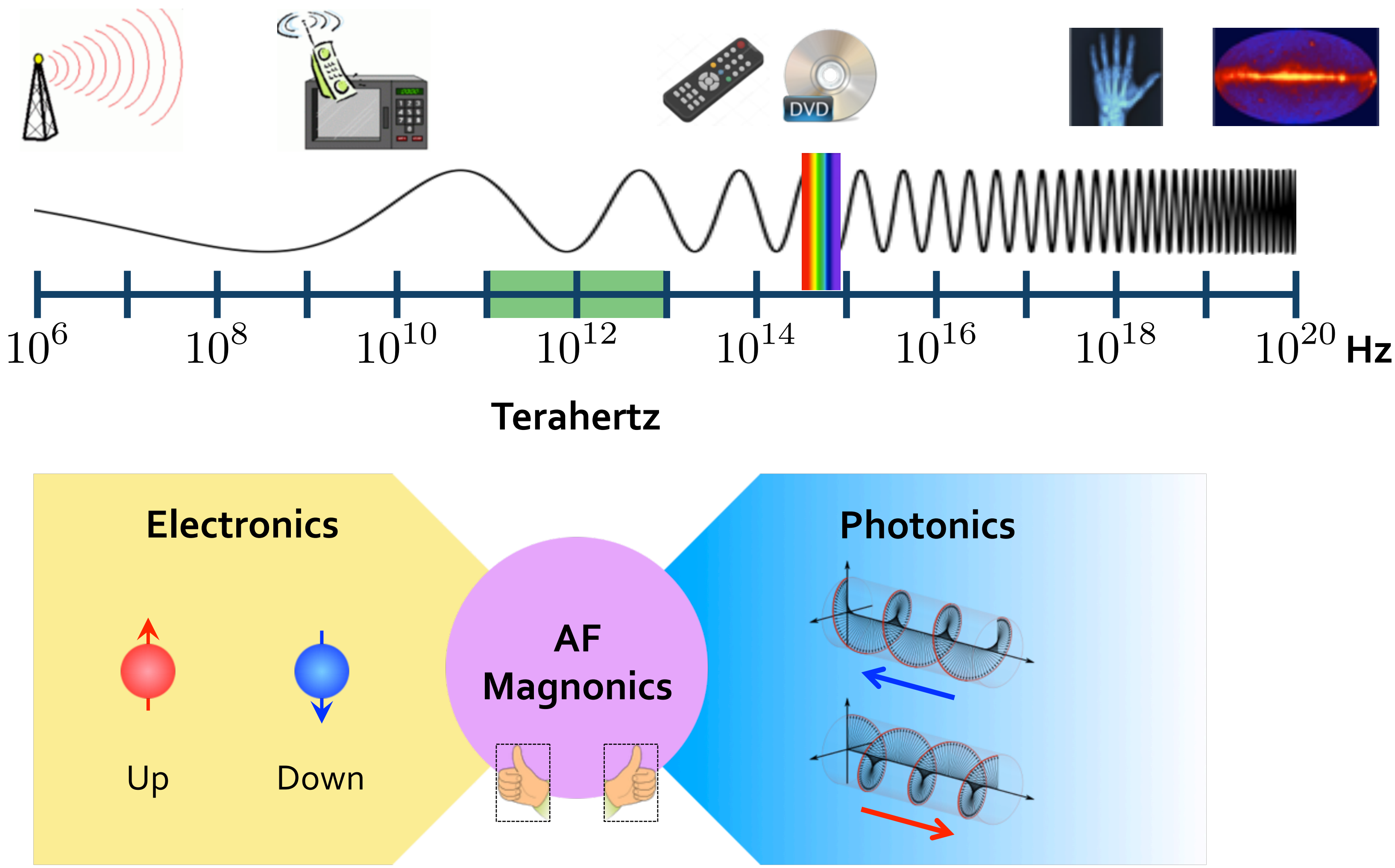
RC, Daniels, Zhu & Xiao,
Sci. Rep. **6**, 24223 (2016);

Daniels, RC, Yu, Xiao & Xiao,
arXiv:1801.06535



Electron (fermion)	Magnon (Boson)
$i\partial_t \psi = H\psi$	$\partial_t \boldsymbol{S} = \gamma \boldsymbol{H} \times \boldsymbol{S}$
Spin 	Chirality 
SOC: $\boldsymbol{\nabla} V \cdot (\boldsymbol{\sigma} \times \boldsymbol{p})$	DMI: $\boldsymbol{D}_{ij} \cdot (\boldsymbol{S}_i \times \boldsymbol{S}_j)$
Spin-FET	Magnon spin-FET
Spin Hall effect	Spin Nernst effect
Oscillatory RKKY	Non-oscillatory RKKY
Spin-transfer torque	Magnon-transfer torque

Antiferromagnetics

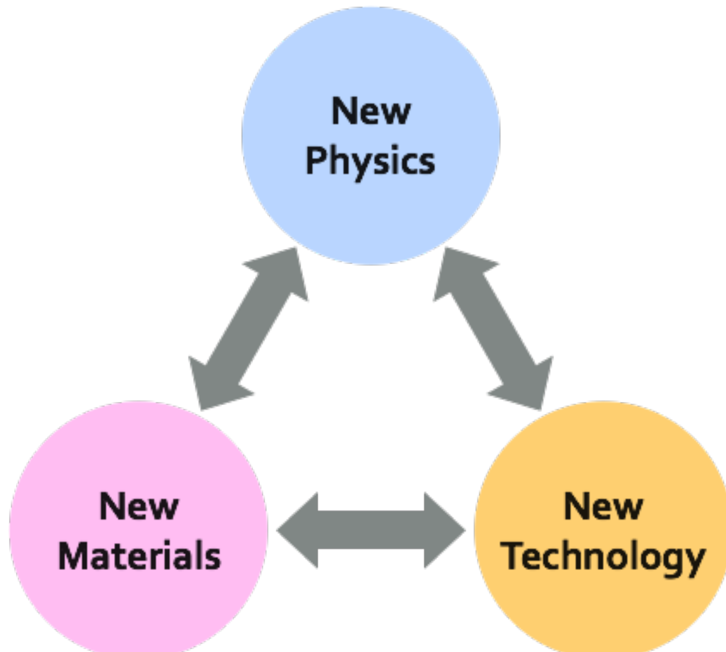


Starting in September
at UC-Riverside

- ✓ Physics beyond Néel order
- ✓ Information beyond binary
- ✓ Magnetoelastic Spintronics

<u>Opening</u>:

1 Postdoc
1 Student (Physics or ECE)

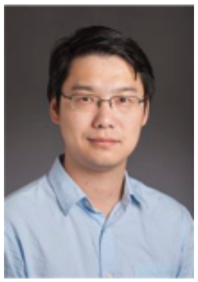


- ✓ 2-D magnets ($Cr_2Ge_2Te_6$, CrI_3, $MnPS_3$)
- ✓ Metals (Mn_2Au, CuMnAs)
- ✓ Insulators (MnF_2, Cr_2O_3)
- ✓ Heterostructures (AF/TI, AF/WSM)

- ✓ Ultrafast data processing
- ✓ Low-dissipation memory
- ✓ M-bit (vs. Q-bit)

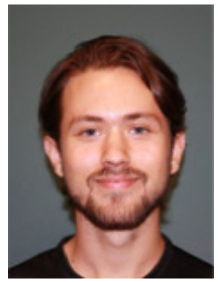
Acknowledgements

- Carnegie Mellon University



Prof. Di Xiao
Physics, CMU

Prof. Jimmy Zhu
ECE, CMU



Dr. Matthew Daniels
(Postdoc @ NIST)

Mr. Xiaochuan Wu
(PhD @ UCSB)

Mr. Abir Shadman
(PhD, ECE, CMU)

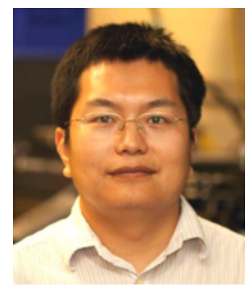
- International

Prof. Qian Niu
Physics, UT-Austin

Prof. Arne Brataas
Physics, NTNU

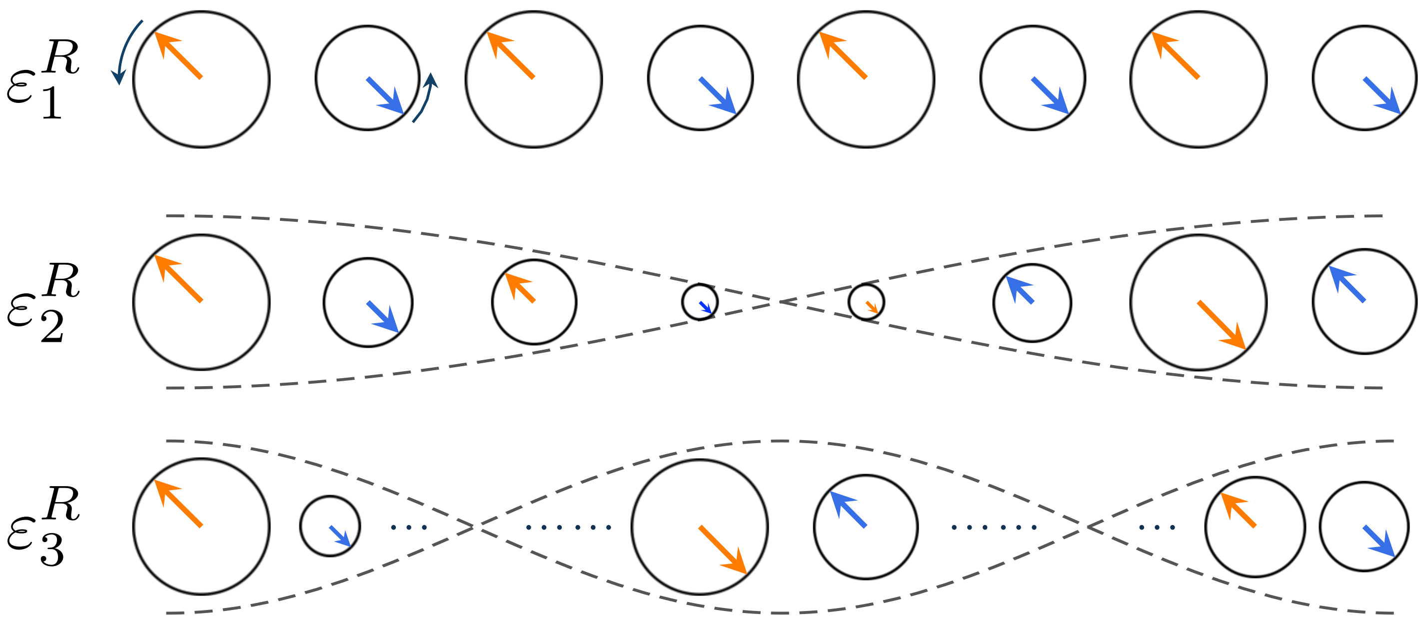
Dr. Satoshi Okamoto
Oak Ridge N. L.

Prof. Jiang Xiao
Physics, Fudan

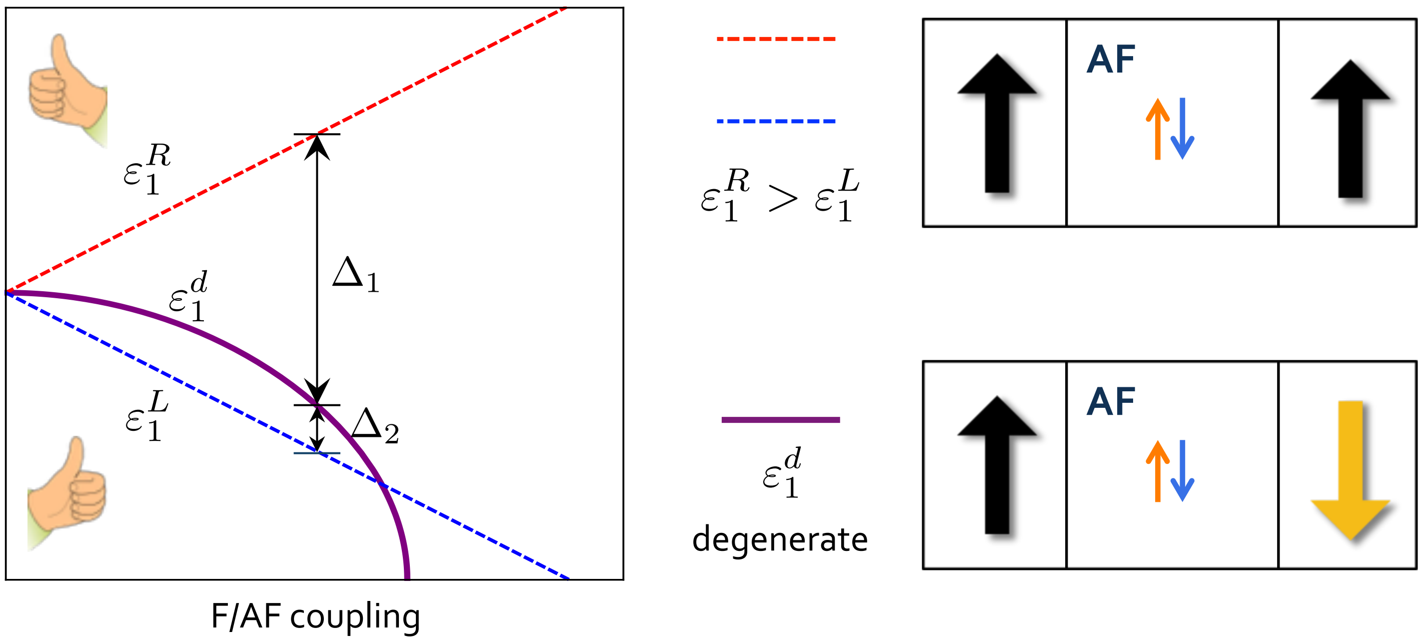


Prof. Xiaodong Xu
Physics, UW-Seattle

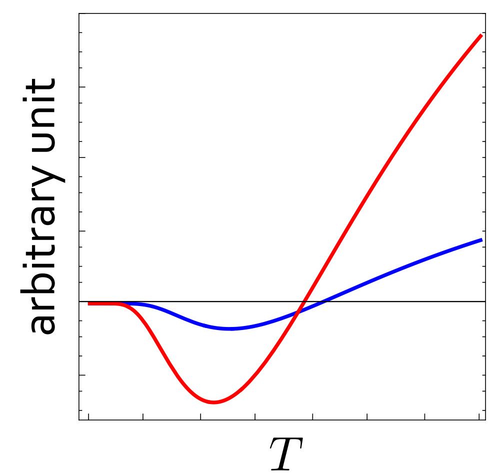
Low-lying modes



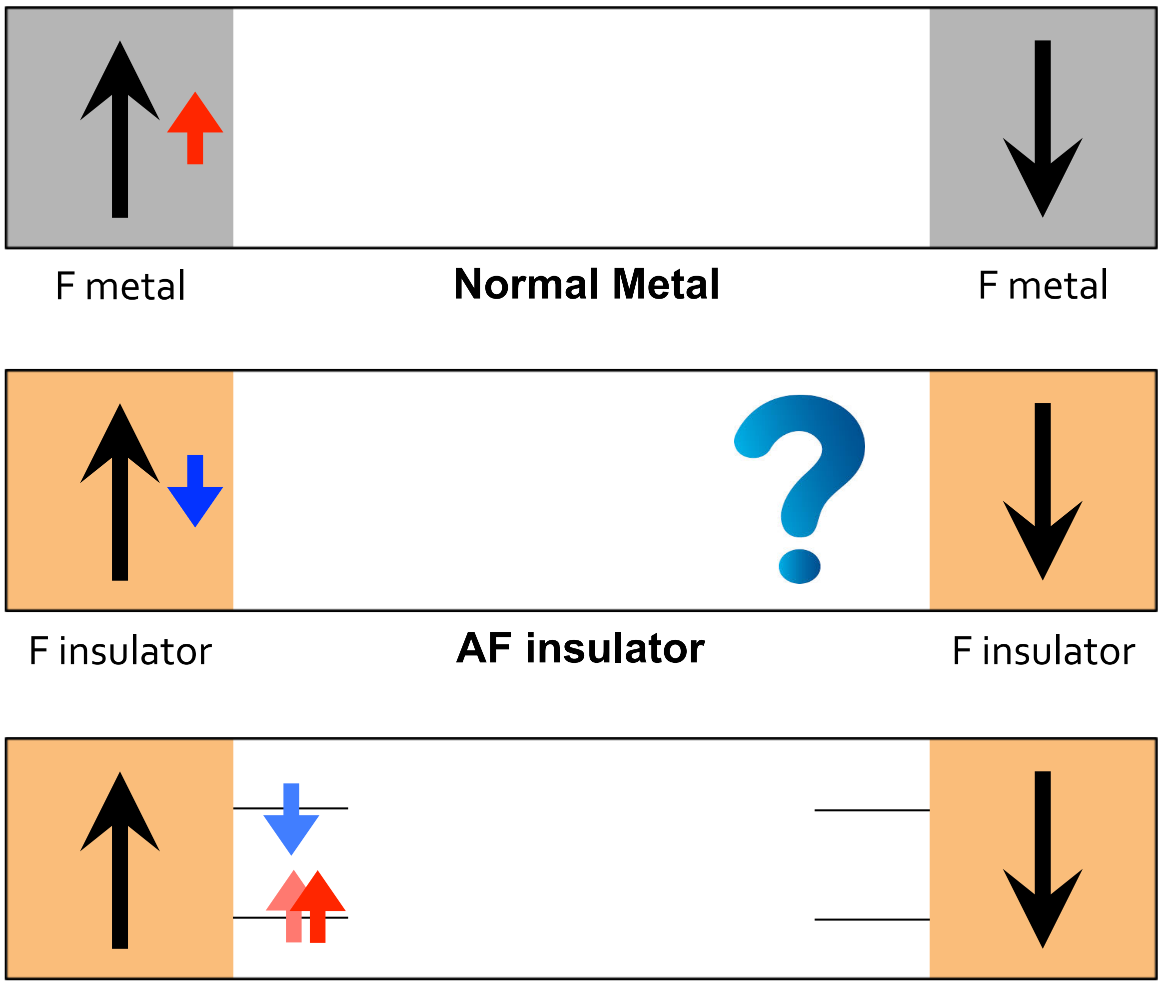
(Right-handed components)



$$
\begin{aligned}
\Delta U =& U_{\uparrow\downarrow} - U_{\uparrow\uparrow} \\
=& \frac{2\varepsilon_1^d}{\exp(\varepsilon_1^d/k_BT)-1} - \frac{\varepsilon_1^d+\Delta_1}{\exp[(\varepsilon_1^R+\Delta_1)/k_BT]-1} \\
&- \frac{\varepsilon_1^d-\Delta_2}{\exp[(\varepsilon_1^R-\Delta_2)/k_BT]-1}.
\end{aligned}
$$



Magnonic Spin-Transfer Torque



Cheng, Chen & Zhang, Appl. Phys. Lett. **112**, 052405 (2018)

RC, D. Xiao & J. Zhu, arXiv:1802.07709

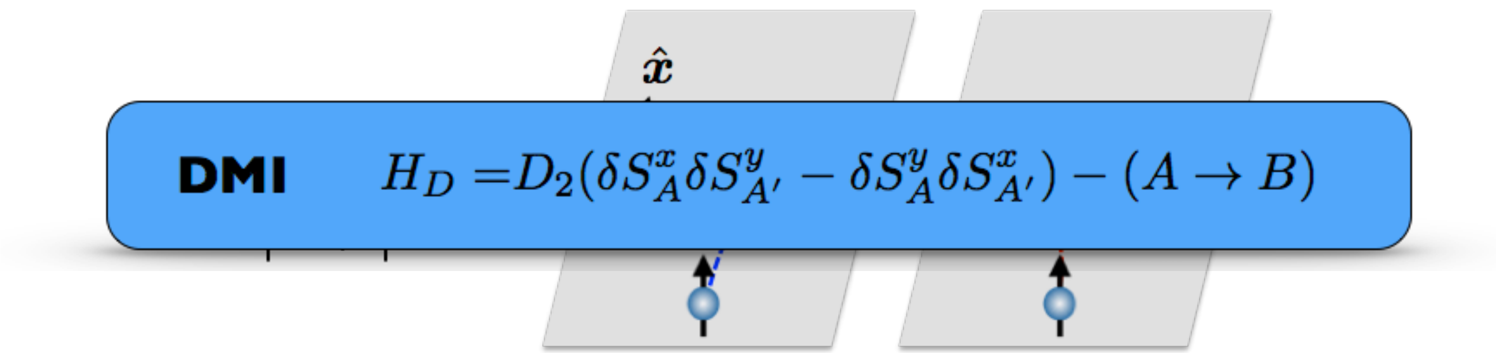
Spin Nernst Effect

Expand the spin Hamiltonian up to quadratic order in:

$$\delta \boldsymbol{S}_A = \boldsymbol{S}_A - \hat{\boldsymbol{z}} \text{ and } \delta \boldsymbol{S}_B = \boldsymbol{S}_B + \hat{\boldsymbol{z}}$$

Exchange $H_J = J_1(1 - \delta S^z_A + \delta S^z_B + \delta \boldsymbol{S}_A \cdot \delta \boldsymbol{S}_B)$

T: No! **I (AB exchange): No!** **T-I combined: Yes!**



DMI $H_D = D_2(\delta S^x_A \delta S^y_{A'} - \delta S^y_A \delta S^x_{A'}) - (A \to B)$