Spin Nernst Effect of Magnons in Antiferromagnet

(accepted by PRL, preprint arXiv:1606.01952)

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Why Magnonics?

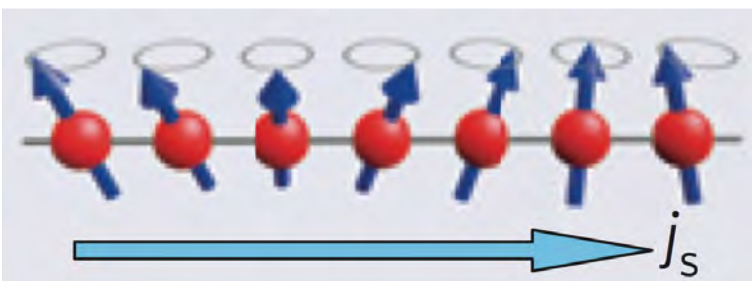
nature physics

REVIEW ARTICLE

PUBLISHED ONLINE: 2 JUNE 2015 | DOI: 10.1038/NPHYS3347

Magnon spintronics

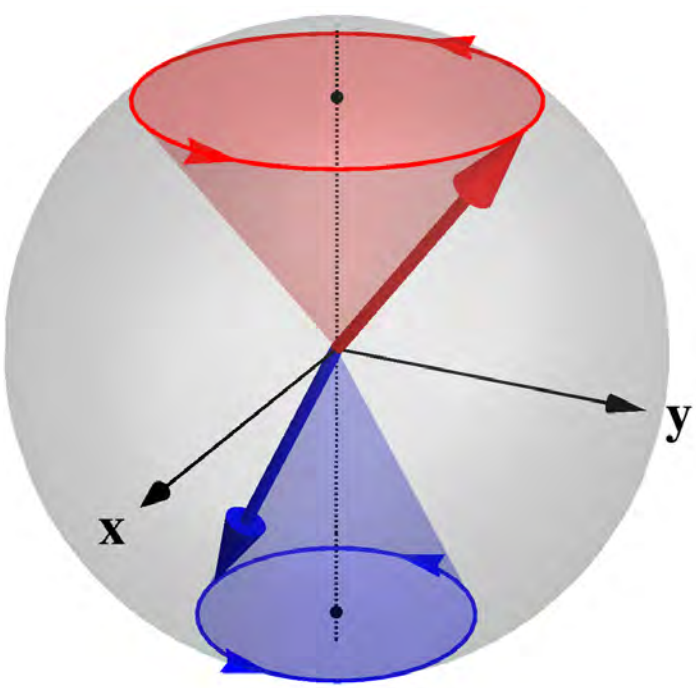
A. V. Chumak*, V. I. Vasyuchka, A. A. Serga and B. Hillebrands



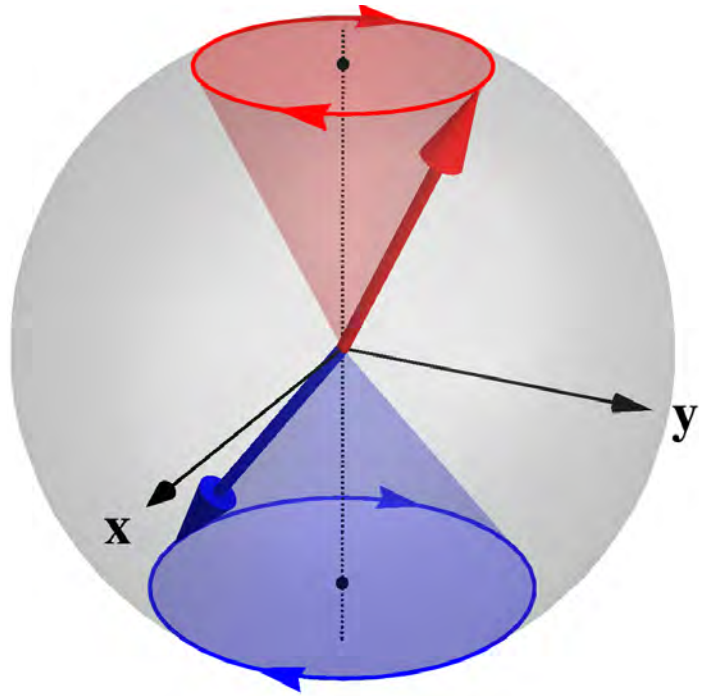
right-handed chirality

- Carry angular momentum
- No Joule heating
- Bose-Einstein statistics
- Magnon # does not conserve
- **Caveat**: only spin-down

Why Antiferromagnet?



Right-handed mode
(a)



Left-handed mode
(b)

$-\hbar$

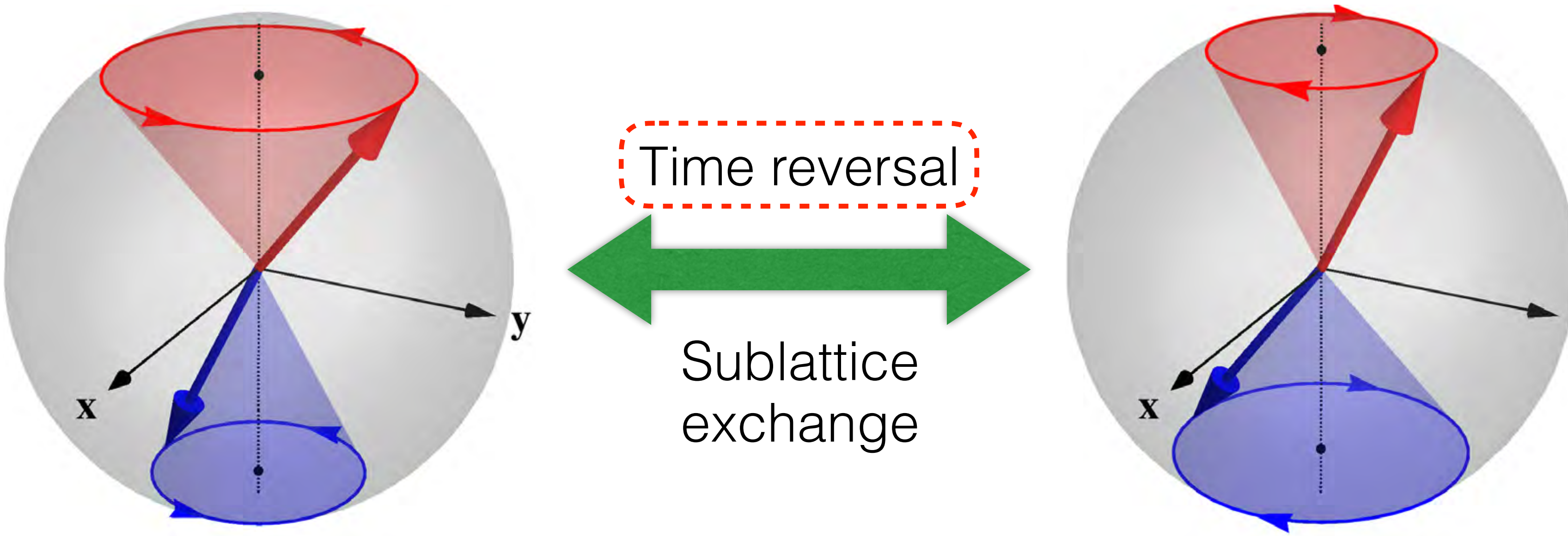
NiO, MnO ✗

MnF_2, FeF_2 ✓

$+\hbar$

Keffer & Kittel 1952
Keffer, Kaplan & Yafet 1952

Magnon Spin Current?

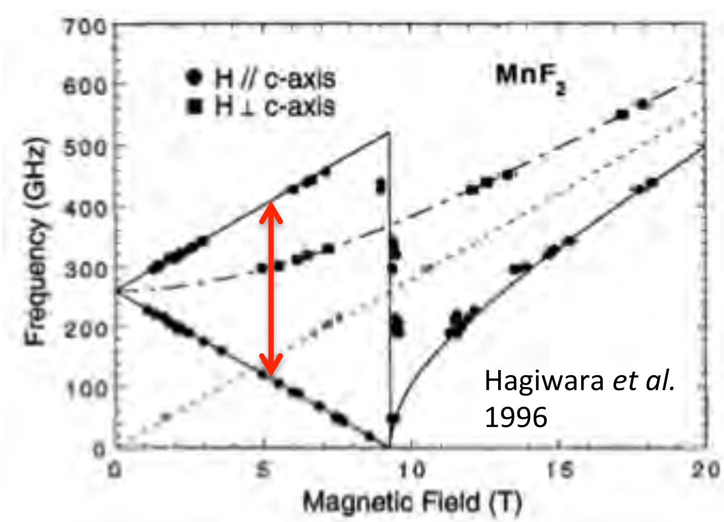


Right-handed mode
(a)

Left-handed mode
(b)

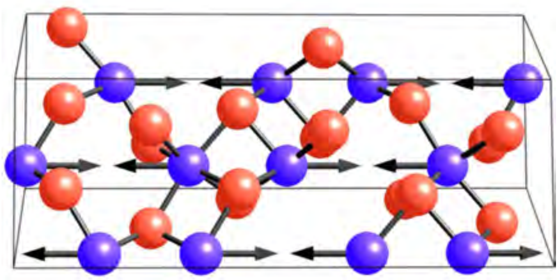
- Optical: chirality **selective**
- Electron: chirality **selective**
- Thermal: chirality <u>**non-selective**</u>!

break the degeneracy



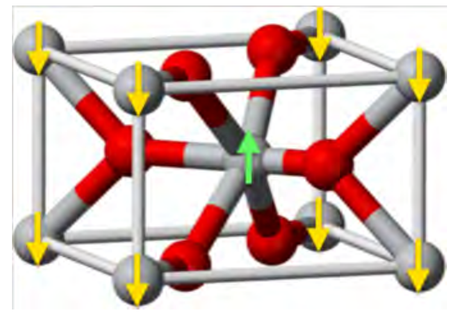
Example: Spin Seebeck Effect

Cr_2O_3



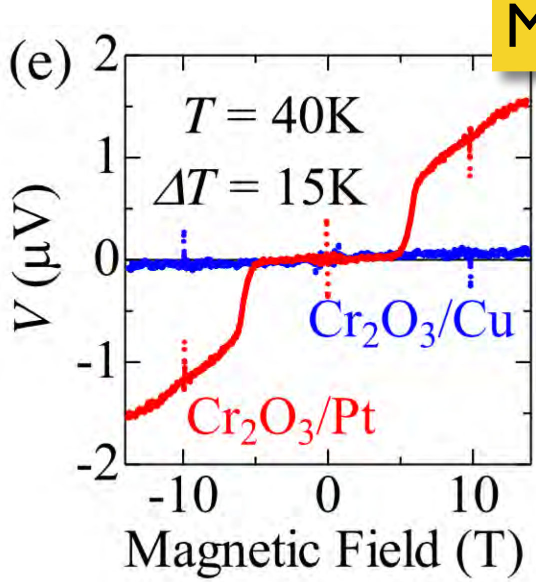
Corundum

MnF_2

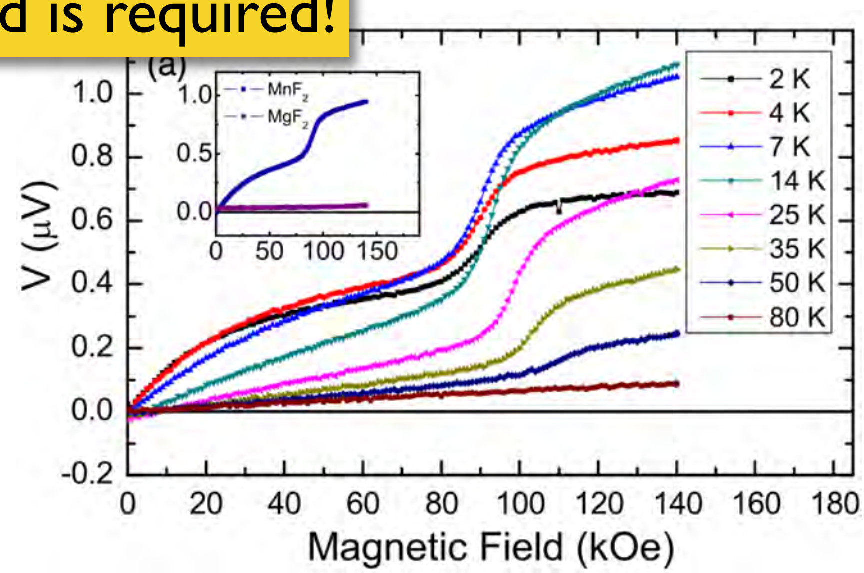


Rutile

<u>Adversity</u>:
Magnetic field is required!

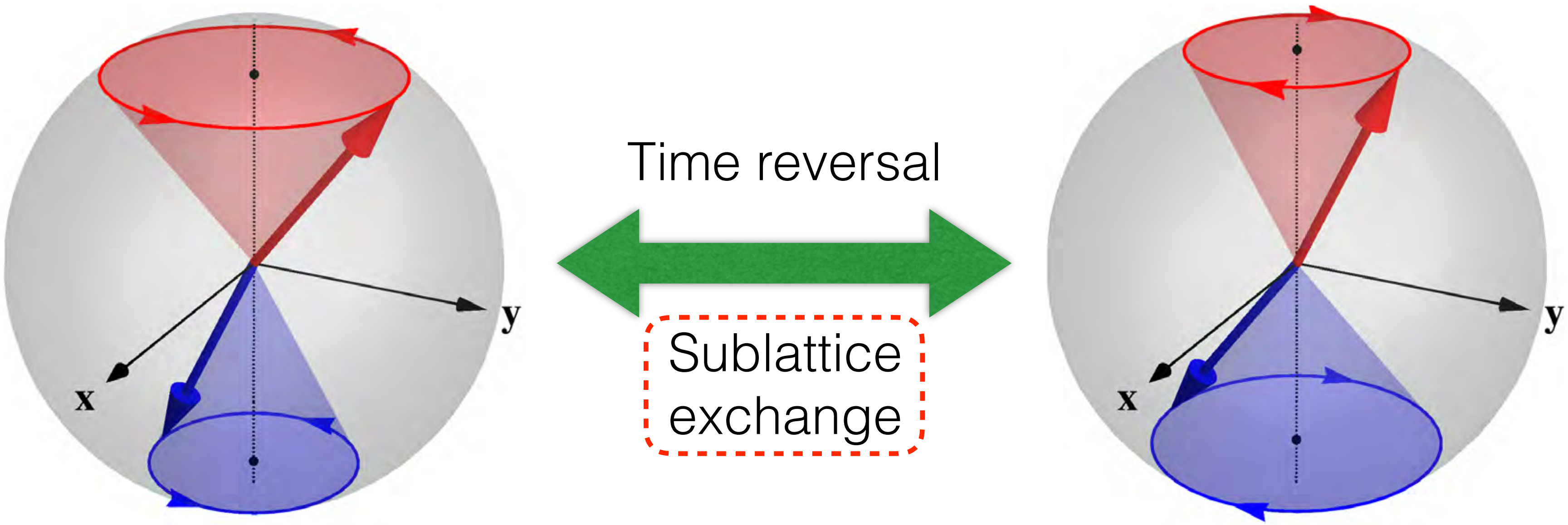


S. Seki *et al.*, PRL **115**, 266601 (2015)



S. M. Wu *et al.*, PRL **116**, 097204 (2016)

Alternative Choice?

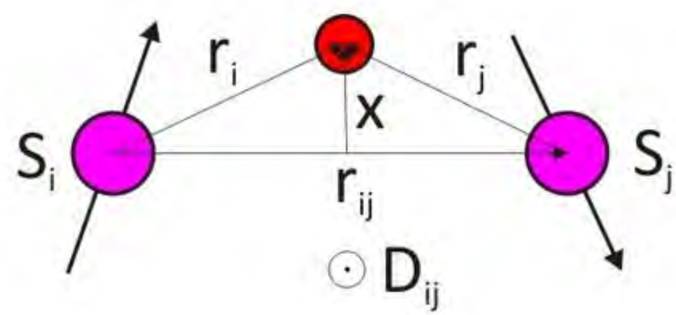


Right-handed mode
(a)

Left-handed mode
(b)

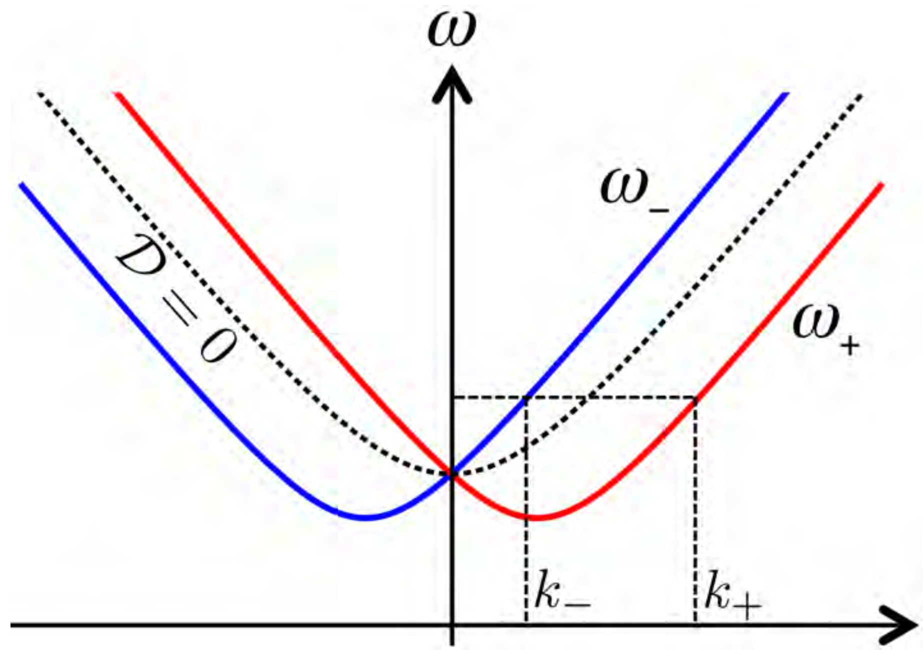
Dzyaloshinskii-Moriya Interaction

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



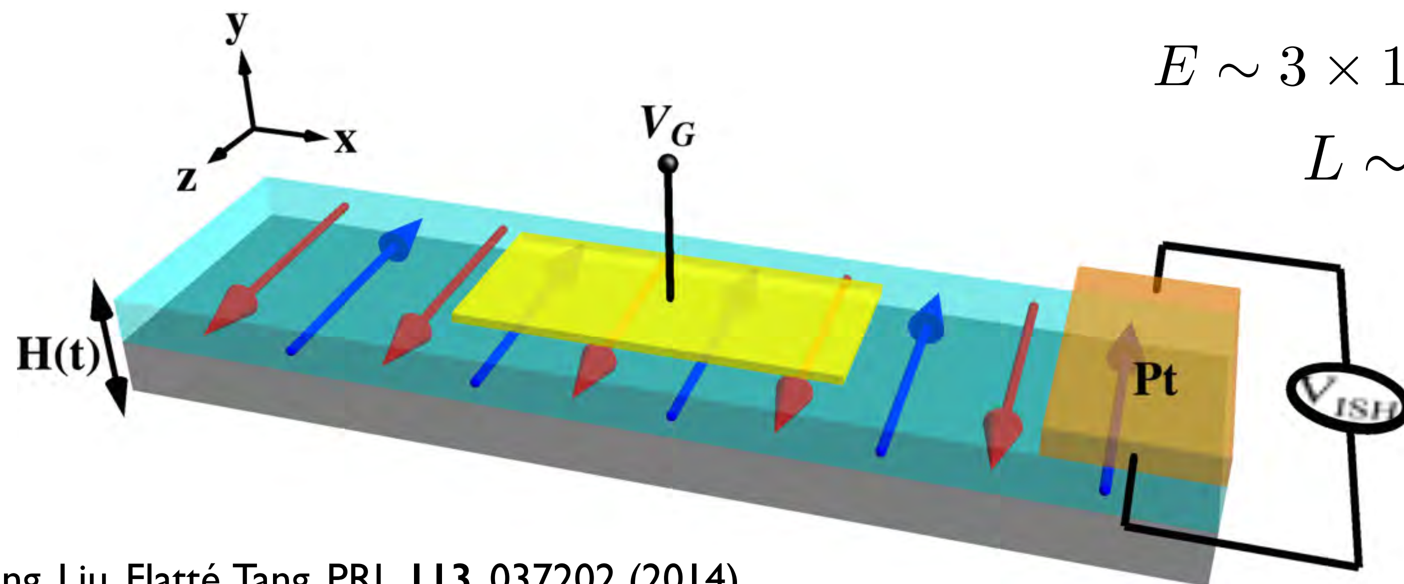
Effective Spin-orbit Coupling

$$H = \sum_{ij} J_{AF} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + K S_{i,z}^2 + \boldsymbol{D}_{ij} \cdot \boldsymbol{S}_i \times \boldsymbol{S}_j$$



A Rashba-like spectrum

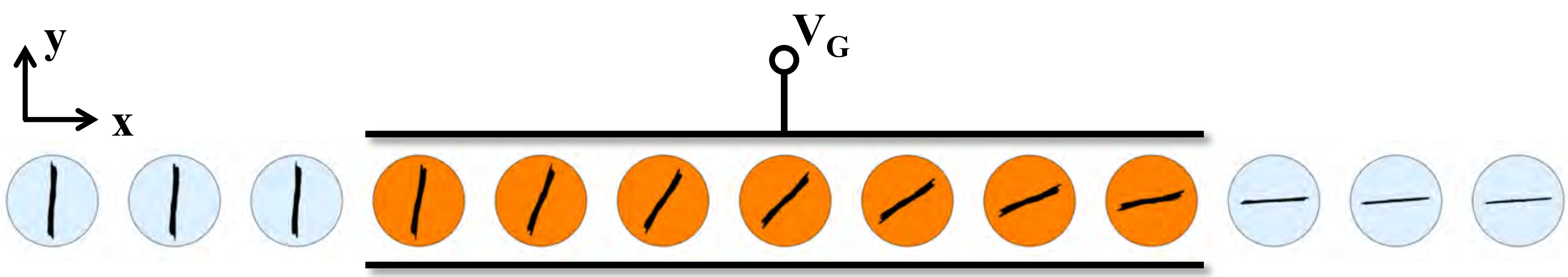
Example: Magnon Faraday Effect



$$E \sim 3 \times 10^5 V/m$$

$$L \sim 10 \mu m$$

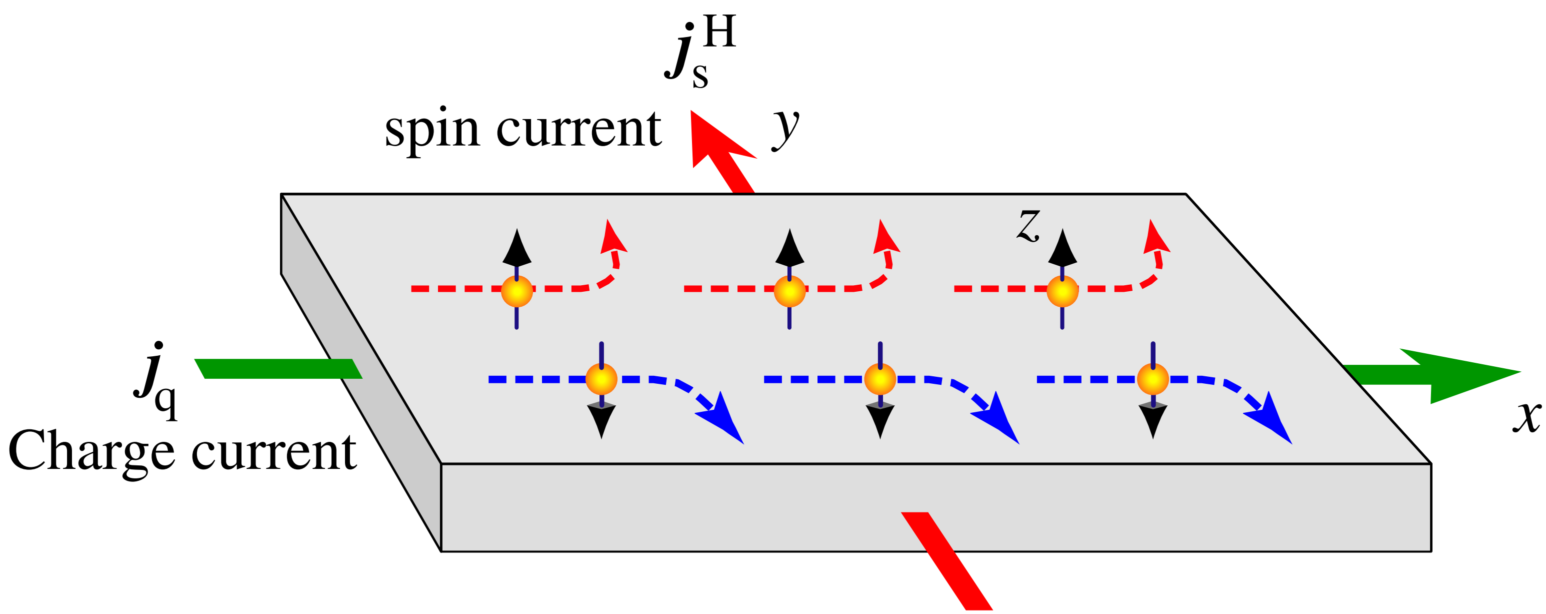
Zhang, Liu, Flatté, Tang, PRL **113**, 037202 (2014)



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

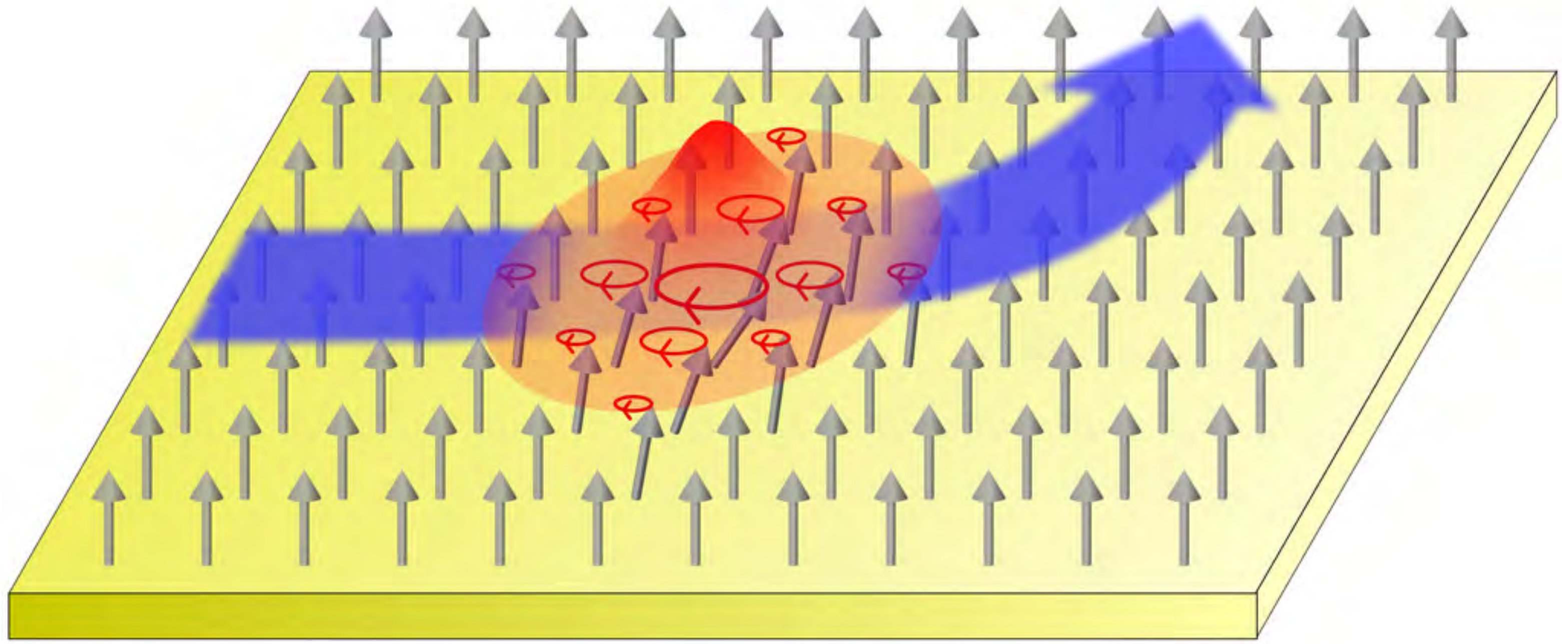
2-dimensional Manifestation

Spin Hall effect
—the most celebrated spin phenomenon



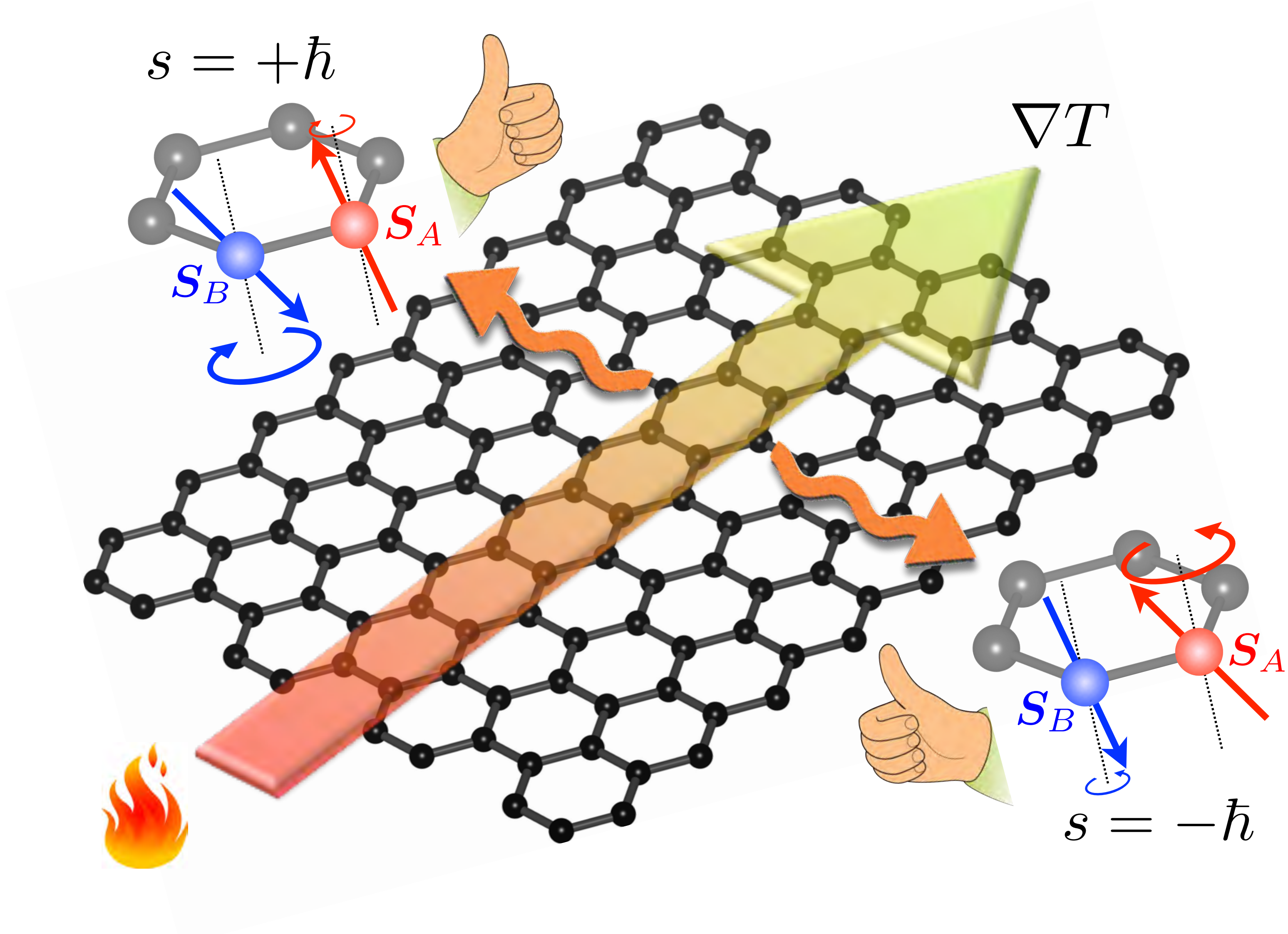
Q: can **magnon** do a similar job ?

Magnon (thermal) Hall Effect



Katsura, Nagaosa, & Lee, PRL (2010);
Matsumoto & Murakami, PRL (2011);
Onose *et al,* Science (2010);
Hirschberger *et al*, PRL (2015); Science (2015)

Magnon Spin Hall Effect



R. Cheng, S. Okamoto, and D. Xiao, accepted by PRL, arXiv:1606.01952

Spin-Chirality Locking

$$S^z = \sum_k S_k^z = \sum_k (-a_k^\dagger a_k + b_k^\dagger b_k)$$

spin-z is conserved: $[S_k^z, \mathcal{H}_k] = 0$

Bogoliubov transformation

$$\alpha_k = u_k a_k - v_k b_k^\dagger \text{ and } \beta_k = u_k b_k - v_k a_k^\dagger$$

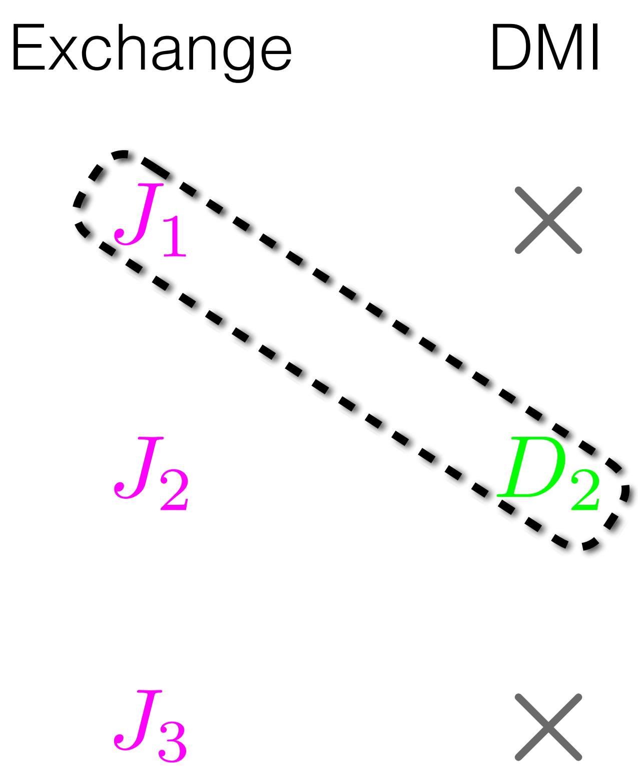
right-handed mode left-handed mode

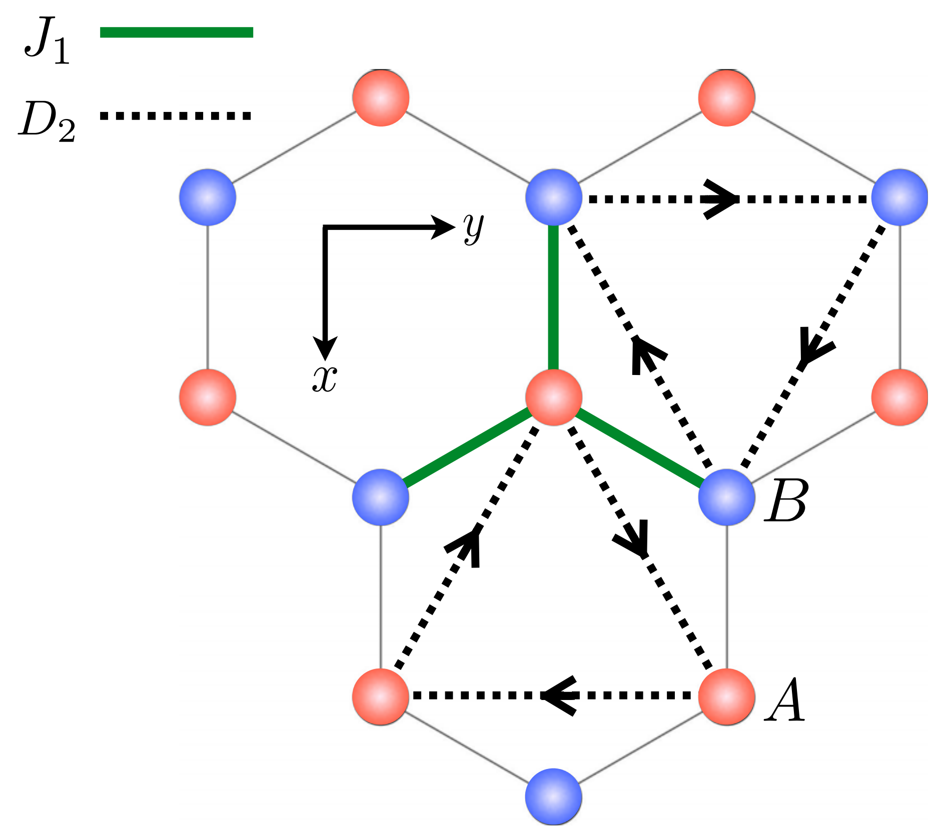
$$\boxed{S^z = \sum_k (-\alpha_k^\dagger \alpha_k + \beta_k^\dagger \beta_k)}$$

$$\langle 0|\alpha_k S^z \alpha_k^\dagger|0\rangle = -1 \text{ and } \langle 0|\beta_k S^z \beta_k^\dagger|0\rangle = +1$$

Realization: Honeycomb AF

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





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Realization: Honeycomb AF

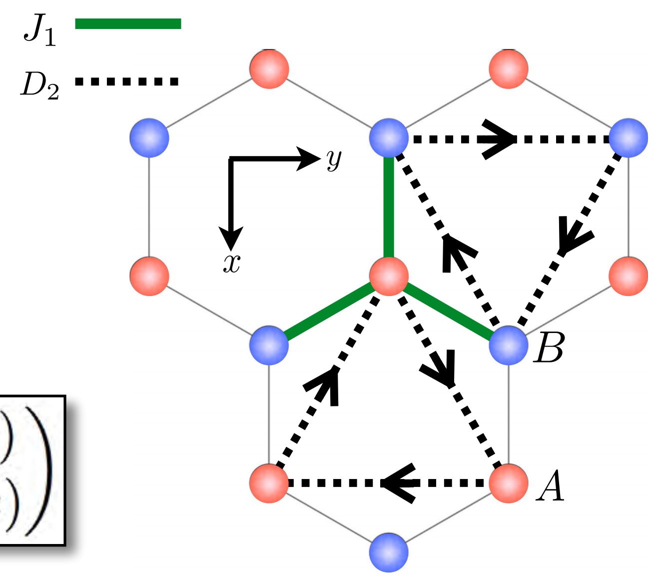
Bosonic normalize

$$\langle\Psi|\sigma_z|\Psi\rangle = 1$$

$$\boxed{H_{\mathrm{AFM}} = -3J_1 + K + \begin{pmatrix} D_2 A(\boldsymbol{k}) & -J_1 V(\boldsymbol{k}) \\ -J_1 V^*(\boldsymbol{k}) & -D_2 A(\boldsymbol{k}) \end{pmatrix}}$$

$$V(\boldsymbol{k}) = 1 + e^{i\boldsymbol{k}\cdot\boldsymbol{a}_1} + e^{i\boldsymbol{k}\cdot\boldsymbol{a}_2}$$

$$A(\boldsymbol{k}) = 2\sum_{i\in\mathrm{odd}} \sin(\boldsymbol{k}\cdot\boldsymbol{a}_i)$$



<u>magnon Haldane's model?</u>

Valid for both classical (LLG) and quantum (Holstein-Primakoff) models

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Hyperbolic Geometry

$$i\sigma_z \frac{d}{dt}\Psi = H\Psi = (dI_2 + a\sigma_x + b\sigma_y + c\sigma_z)\Psi$$

$$\boxed{d = h\cosh\theta\,, \quad a = h\sinh\theta\cos\phi\,, \quad b = h\sinh\theta\sin\phi}$$

$$E = \frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\sigma_z|\Psi\rangle} = c + h$$

$$|u_-\rangle = \begin{pmatrix} \sinh\frac{\theta}{2} e^{-i\phi} \\ -\cosh\frac{\theta}{2} \end{pmatrix}, \quad |u_+\rangle = \begin{pmatrix} \cosh\frac{\theta}{2} e^{-i\phi} \\ -\sinh\frac{\theta}{2} \end{pmatrix}$$

Relation to a spin-1/2 system:

Bloch sphere $\rightarrow$ pseudo-sphere

Radius R = -1

Hyperbolic geom.

Semiclassical Dynamics

$$i\sigma_z \frac{d}{dt}\begin{pmatrix}\Psi_A \\ \Psi_B\end{pmatrix} = H\begin{pmatrix}\Psi_A \\ \Psi_B\end{pmatrix}$$

Common structure of BdG equation

$$\boldsymbol{\Omega}(\boldsymbol{k}) = -\mathrm{Im}\langle \boldsymbol{\nabla}\Psi_+(\boldsymbol{k})| \times \sigma_z |\boldsymbol{\nabla}\Psi_+(\boldsymbol{k})\rangle$$

Berry curvature

$$\dot{\boldsymbol{r}}_c = \frac{\partial \omega(\boldsymbol{k}_c)}{\partial \boldsymbol{k}_c} + \boxed{\frac{1}{\hbar}\boldsymbol{\nabla}U(\boldsymbol{r}_c) \times \boldsymbol{\Omega}(\boldsymbol{k}_c)}$$

Anomalous velocity

Symmetry:

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

For a review of Berry phase, see Xiao, Chang & Niu, RMP (2010)

Symmetry

Expand the spin Hamiltonian up to **quadratic order** in spin deviations from the Néel ground state

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

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

Breaks inversion (I)

DMI $$H_D = D_2(\delta S_A^x \delta S_{A'}^y - \delta S_A^y \delta S_{A'}^x) - (A \to B)$$

Breaks time-reversal (T) + rotation about x in spin-space (c_x)

Symmetry

$$Tc_x : \boldsymbol{k} \Rightarrow -\boldsymbol{k} \quad \uparrow \Rightarrow \uparrow$$

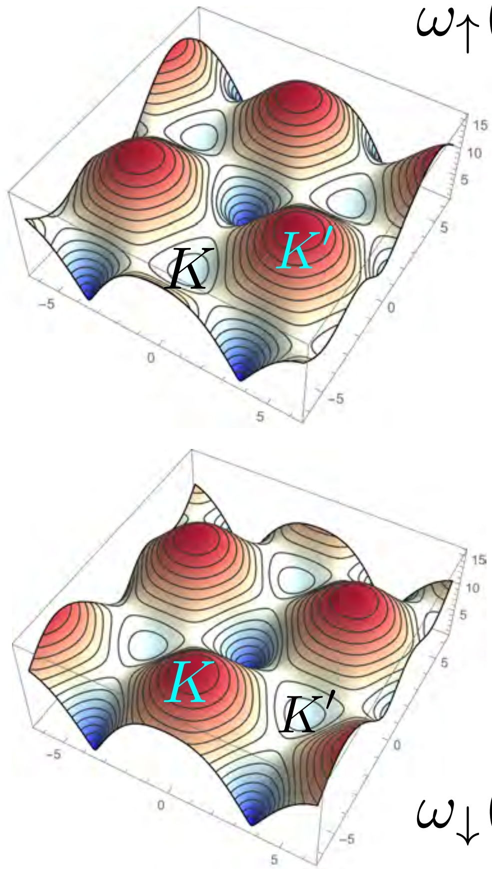
acting on EOM

$$\omega_\sigma(\boldsymbol{k}) = \omega_\sigma(-\boldsymbol{k})$$

DMI will break the degeneracy between $\omega_\uparrow(\boldsymbol{k})$ and $\omega_\downarrow(\boldsymbol{k})$.

Symmetry

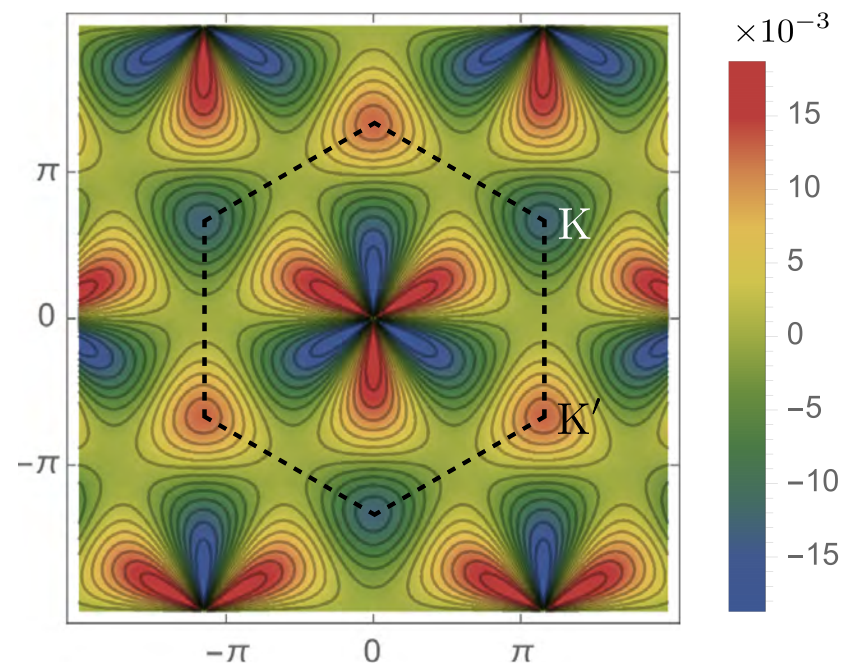
$\omega_{\uparrow}(\boldsymbol{k})$



$\omega_{\downarrow}(\boldsymbol{k})$

Spectrum

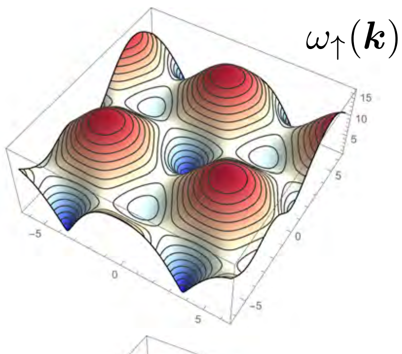
$$\boldsymbol{\Omega}_{\sigma}(\boldsymbol{k}) = -\boldsymbol{\Omega}_{\sigma}(-\boldsymbol{k})$$



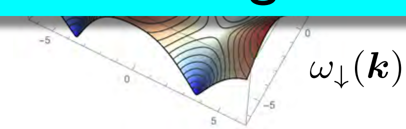
Berry curvature

Symmetry

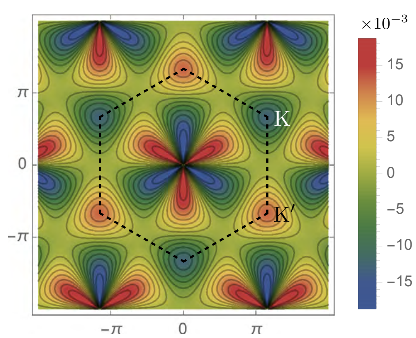
Antiferromagnet



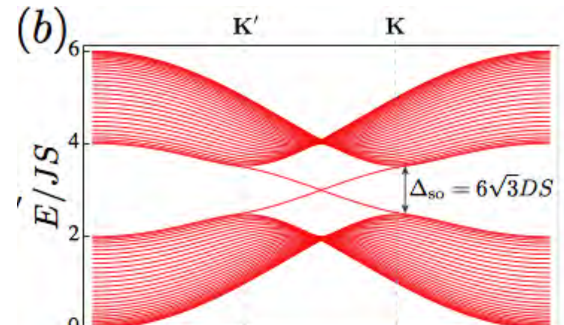
- Without D_2: I ✗ Tc_x ✓
- D_2 lifts the degeneracy



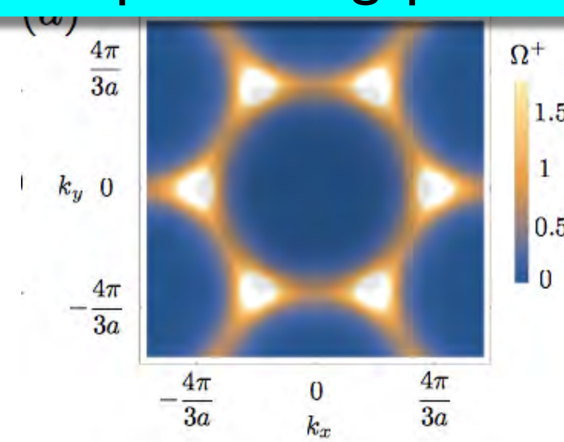
$\boldsymbol{\Omega}_\sigma(\boldsymbol{k}) = -\boldsymbol{\Omega}_\sigma(-\boldsymbol{k})$



Ferromagnet

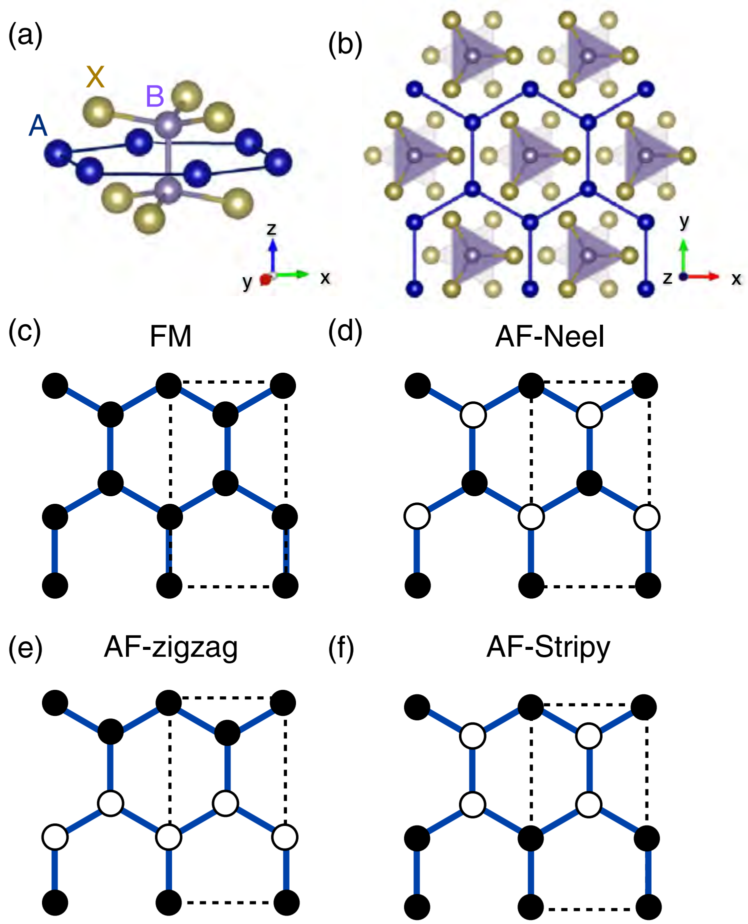


- Without D_2: I ✓ Tc_x ✓
- D_2 opens the gap!

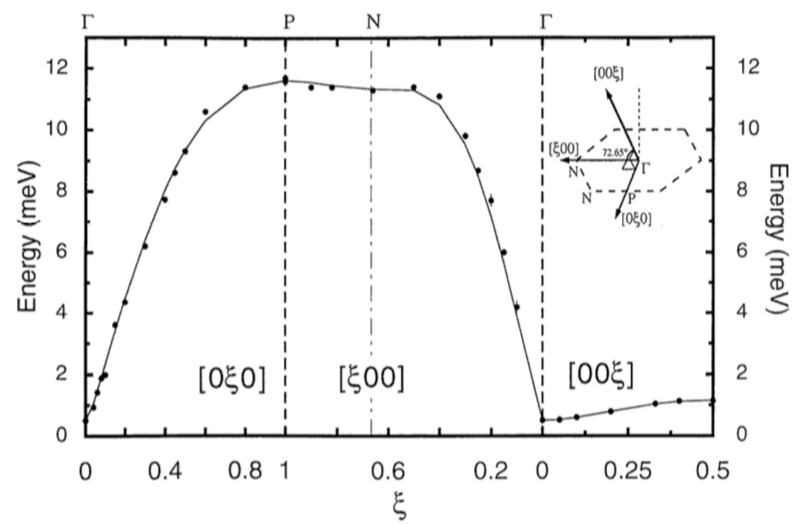


Kim, Ochoa, Zarzuela, &Tserkovnyak
arXiv:1603.04827

Material Candidates



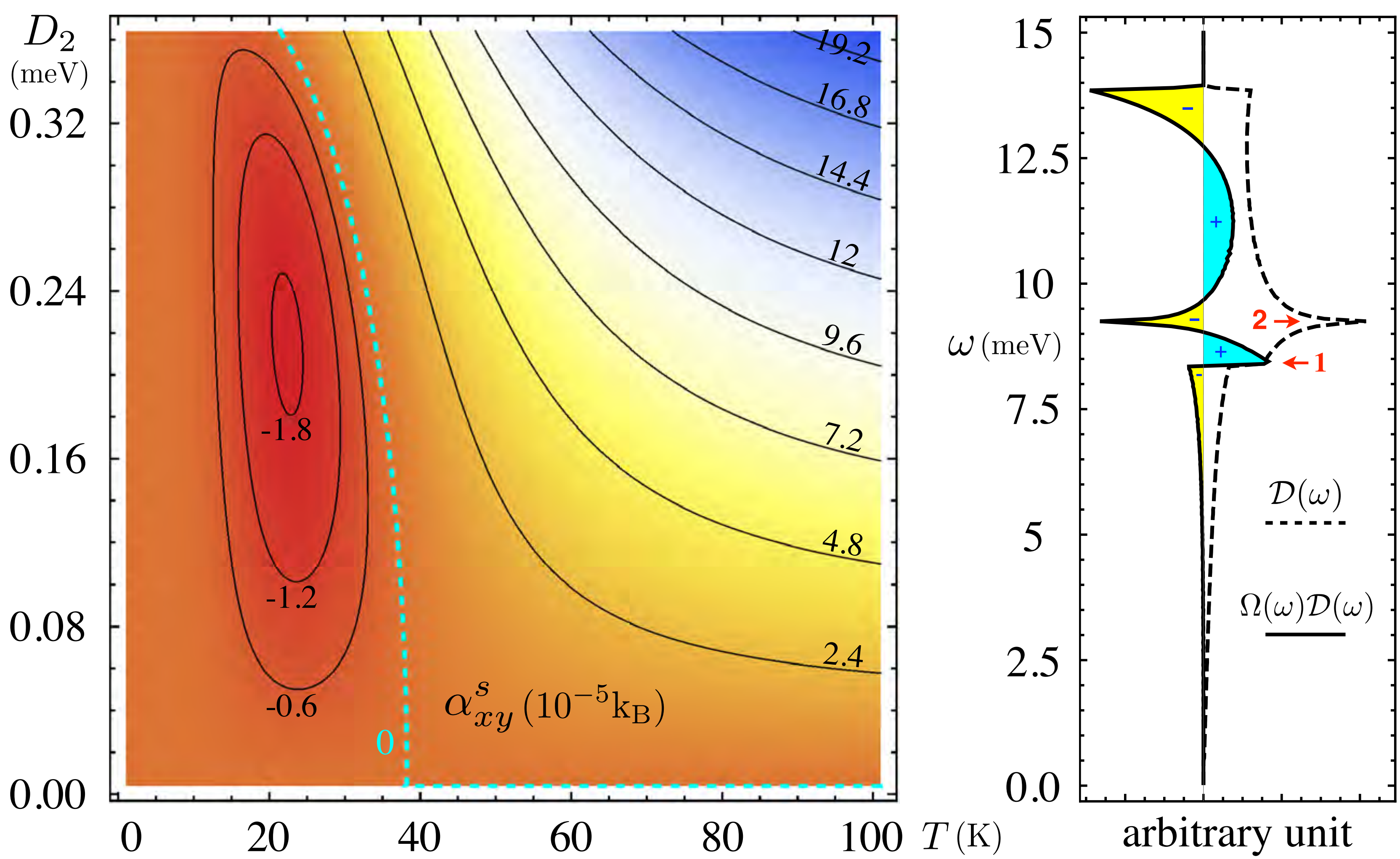
$MnPS_3$



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

Experiment: Wildes, Roessli, Lebech & Godfrey, JCM (1998)
DFT Study: Sivadas, Daniels, Swendsen, Okamoto & Xiao, PRB (2015)

Magnon Spin Nernst Effect



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Analogy

Electrons (fermions)	Magnons (Bosons)
$i\partial_t \psi = H\psi$	$\partial_t \boldsymbol{m} = \gamma \boldsymbol{H}_{\text{eff}} \times \boldsymbol{m}$
SOC: $\nabla V \cdot (\boldsymbol{\sigma} \times \boldsymbol{p})$	DMI: $\boldsymbol{\mathcal{D}}_{ij} \cdot (\boldsymbol{S}_i \times \boldsymbol{S}_j)$
Electron spin:	Magnon chirality:
"Spintronics"	"Chiralitronics"

Summary

- Easy-axis antiferromagnet: magnon chirality → spin
- Dzyaloshinskii-Moriya interaction: spin-orbit coupling
- 1-d: Magnon Faraday Effect
- 2-d: Magnon Spin Nernst Effect

Thermal generation of magnon spin current
in antiferromagnet **without** magnetic field

R. Cheng, S. Okamoto, and D. Xiao, accepted by PRL, arXiv:1606.01952
R. Cheng, M.W. Daniels, J.-G. Zhu, and Xiao, Sci. Rep. **6**, 24223 (2016)