Title: Berry-curvature physics of magnons and magnon-polarons

Speakers: Se Kwon Kim

Collection/Series: Quantum Matter

Subject: Condensed Matter

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Berry-curvature physics of magnons and magnon-polarons

Se Kwon Kim
Department of Physics, KAIST

Perimeter Institute, April 2025

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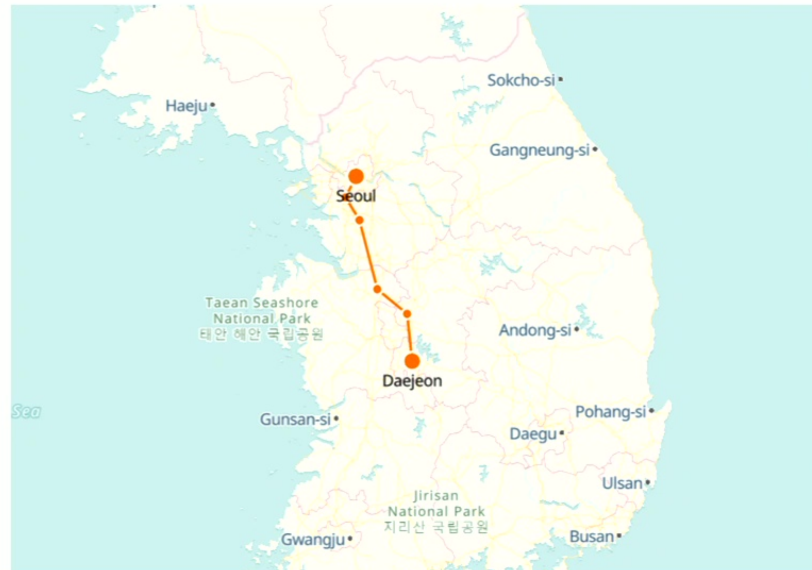
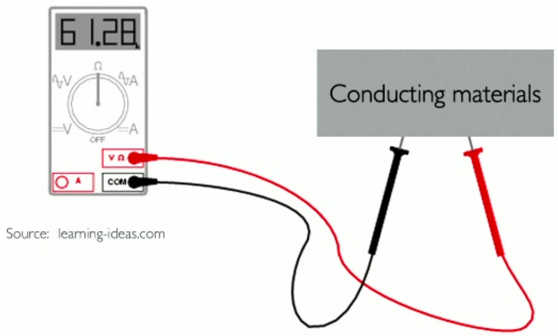
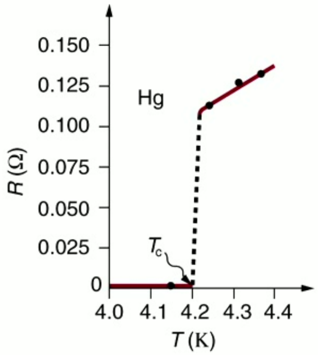


Charge transport measurement

Charge transport measurement has been a central probe of **conducting** materials.

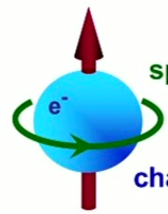




superconducting phase transition

However, **it cannot be used for insulating materials**, which are abundant in nature.

Spintronics = Spin + electronics

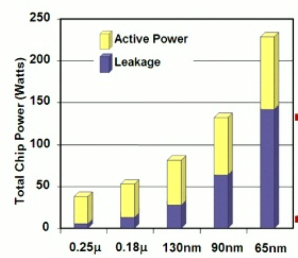


spin $\mathbf{S} = (S_x, S_y, S_z)$

charge $e^- \approx -1.6 \times 10^{-19}\mathrm{C}$

Spintronics vision: computing based on **spin** in addition to charge of electrons

Credit: Gene Siegel, Shiang Teng



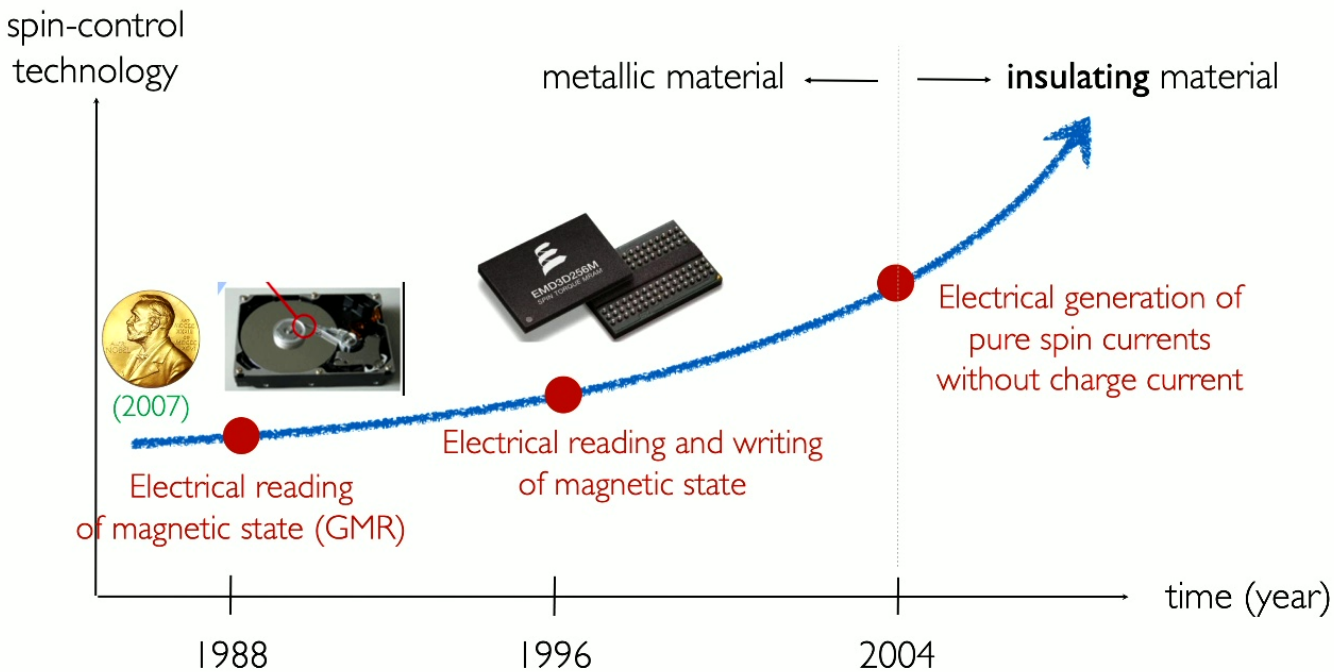
Energy waste !!

Source: Cadence Design Systems

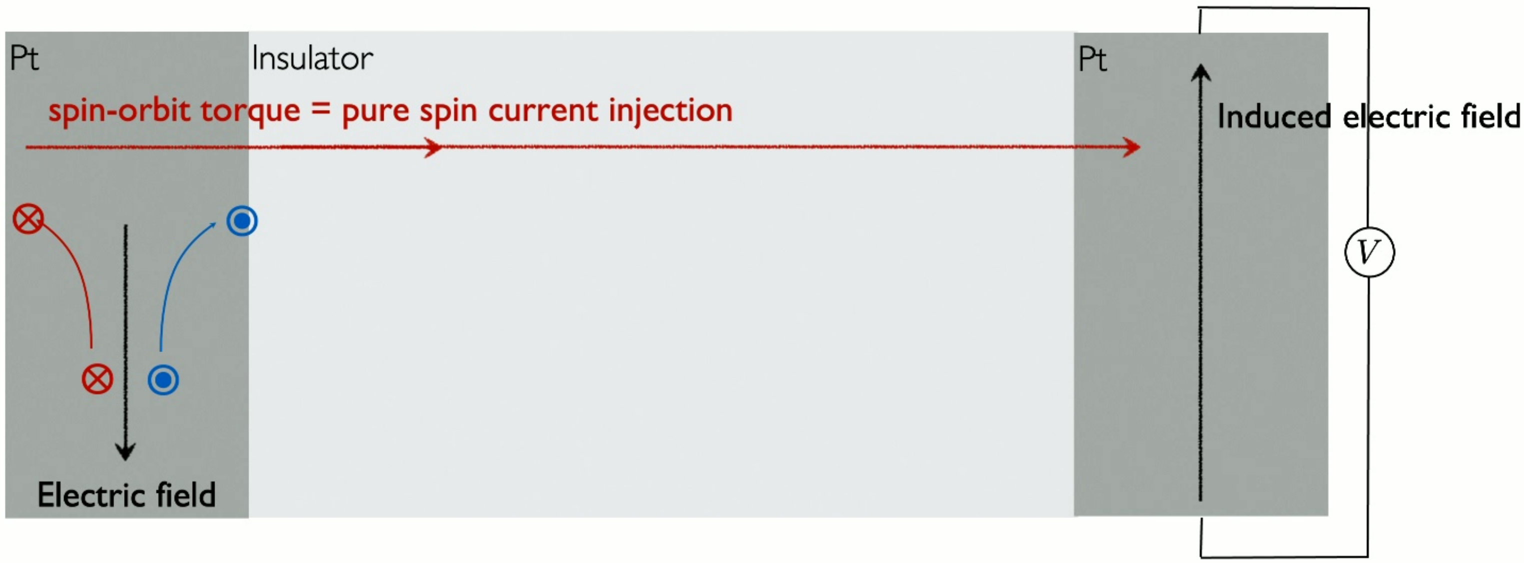
Challenge: **significant energy loss in conventional electronics**

Spintronics = Spin + electronics

Our ability to control **spin** has been improved tremendously, driven by practical motivations to advance **spintronics**.



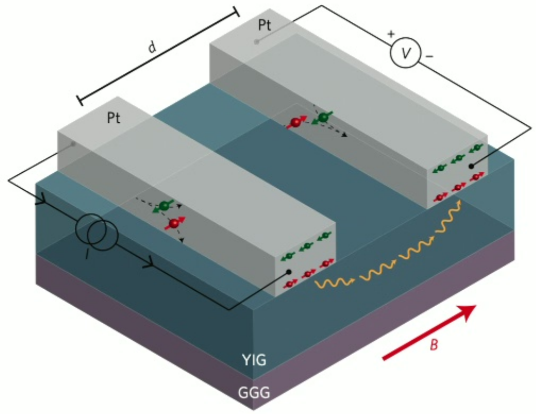
Technology for pure spin-current manipulation

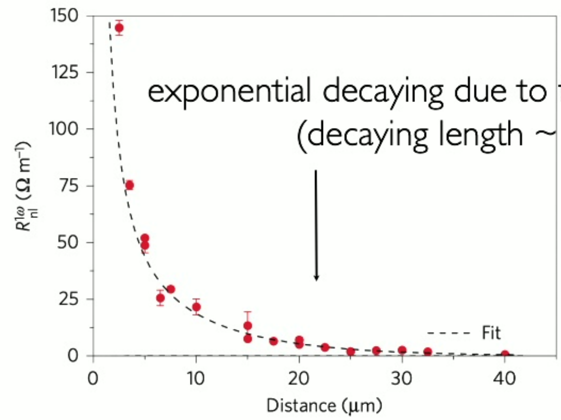


Generation: spin Hall effects

Detection: inverse spin Hall effects

Spin transport in insulating ferromagnets





exponential decaying due to finite spin lifetime
(decaying length ~ 9 μm)

Exponential spin-current decaying in a magnetic insulator, yttrium-iron-garnet

Cornelissen, van Wees, et al, ***Nat. Phys.*** (2015)

One of the clearest signatures of exponential decaying of diffusive spin currents !!

Spin transport through quantum materials

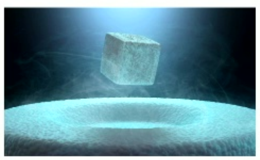
Novel spin transport in quantum materials ??

New spin physics from Berry curvatures ??

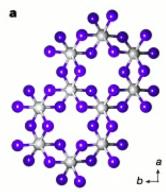
Quantum materials

Quantum materials are material systems
where quantum effects remain manifest over a wider range of energy and length scales.

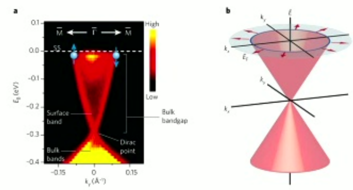
Keimer and Moore, ***Nat. Phys.*** (2017)



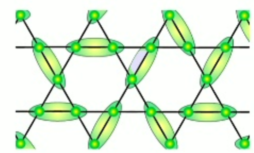
Superconductors



2D materials/magnets



Topological insulators



Quantum spin liquids

Quantum spintronics

charge e^- + spin $\mathbf{S}$

electronics

spintronics

spin

charge e^-

lattice

orbital

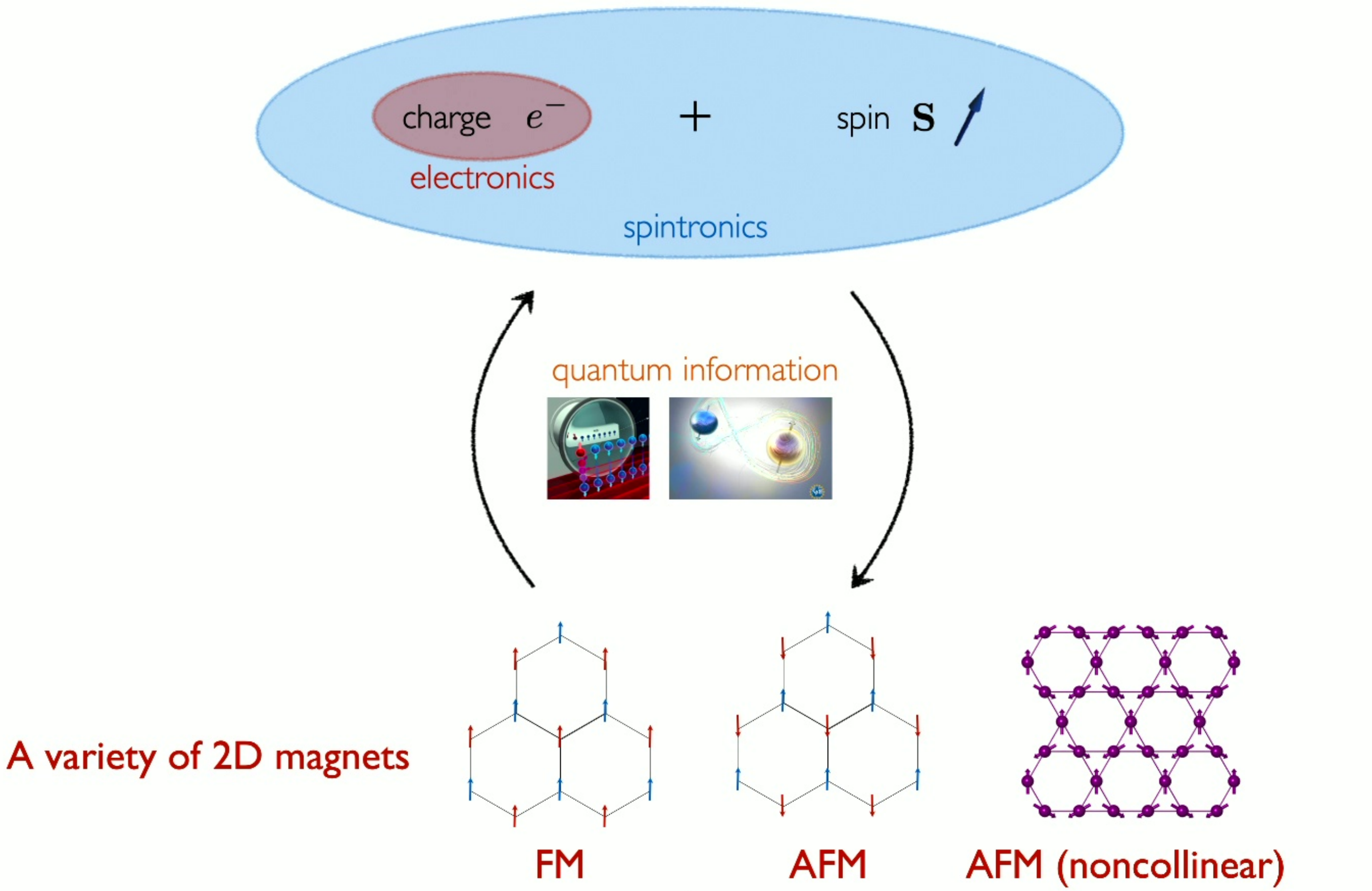
quantum materials

topology

entanglement

frustration

Quantum spintronics



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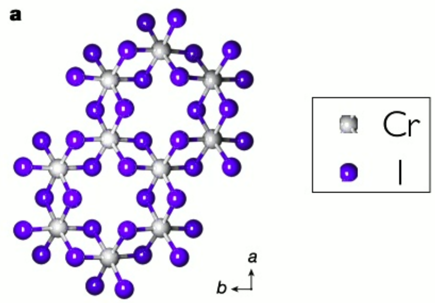
Discovery of monolayer ferromagnetism, CrI_3



LETTER

doi:10.1038/nature22391

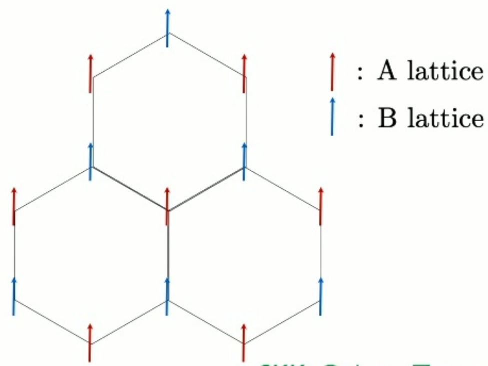
Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit

Bevin Huang[1]*, Genevieve Clark[2]*, Efrén Navarro-Moratalla[3]*, Dahlia R. Klein[3], Ran Cheng[4], Kyle L. Seyler[1], Ding Zhong[1], Emma Schmidgall[1], Michael A. McGuire[5], David H. Cobden[1], Wang Yao[6], Di Xiao[4], Pablo Jarillo-Herrero[3] & Xiaodong Xu[1,2]

Huang, Xu, et al., ***Nature*** (2017)

The first material realization of *monolayer* 2D ferromagnets !!

2D honeycomb ferromagnet



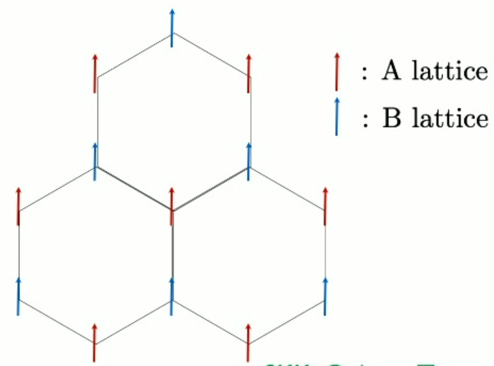
SKK, Ochoa, Zarzuela, and Tserkovnyak., ***PRL*** 117, 227201 (2016)

$$H = -J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + D \sum_{\langle\langle i,j \rangle\rangle} \nu_{ij} \hat{\mathbf{z}} \cdot \mathbf{S}_i \times \mathbf{S}_j - B \sum_i S_i^z$$

ferromagnetic exchange

spin-orbit coupling
[Dzyaloshinskii-Moriya (DM) interaction]

2D honeycomb ferromagnet

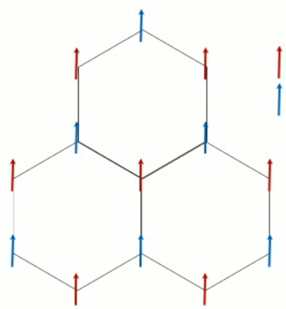


SKK, Ochoa, Zarzuela, and Tserkovnyak., ***PRL*** 117, 227201 (2016)

$$H = -J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + D \sum_{\langle\langle i,j \rangle\rangle} \nu_{ij} \hat{\mathbf{z}} \cdot \mathbf{S}_i \times \mathbf{S}_j - B \sum_i S_i^z$$

ferromagnetic exchange — spin-orbit coupling [Dzyaloshinskii-Moriya (DM) interaction] — Zeeman coupling

Magnon Hamiltonian



$$H = -J\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j + D\sum_{\langle\langle i,j\rangle\rangle}\nu_{ij}\hat{\mathbf{z}}\cdot\mathbf{S}_i\times\mathbf{S}_j - B\sum_i S_i^z$$

Holstein-Primakoff transformation

$$H_{\rm m} = (3JS+B)\sum_i d_i^\dagger d_i$$ ← on-site term

$$-JS\sum_{\langle i,j\rangle}(d_i^\dagger d_j + \mathrm{H.c.})$$ ← hopping term (exchange energy)

$$-DS\sum_{\langle\langle i,j\rangle\rangle}(i\nu_{ij}d_i^\dagger d_j + \mathrm{H.c.})$$ ← hopping term (spin-orbit coupling)

Haldane's mass term for electrons in a honeycomb lattice [Haldane, *PRL* (1988)]

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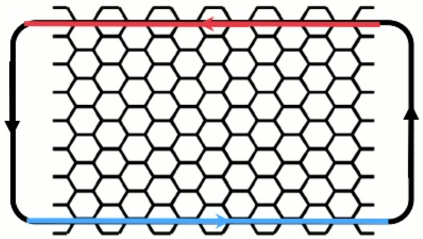
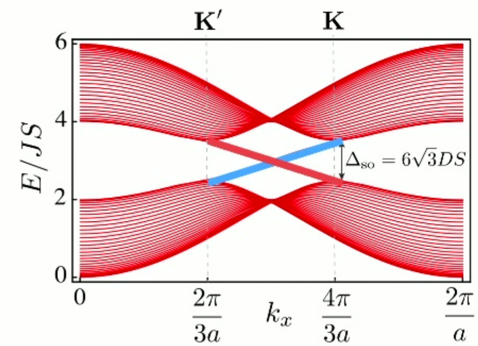
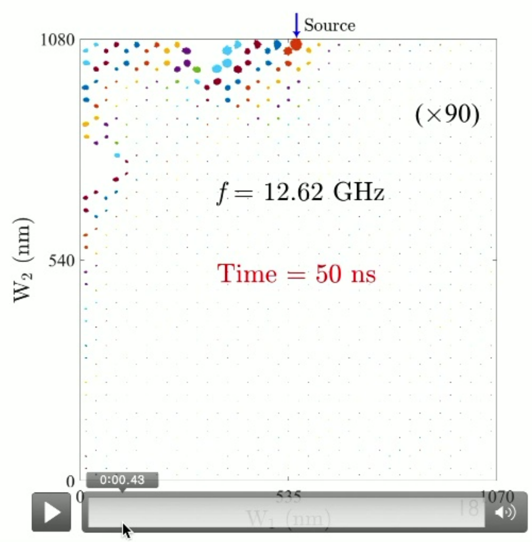
Magnon bands with edge modes



Finite sample



Magnon bands

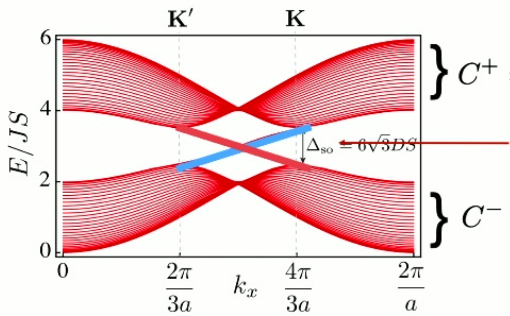


Numerical simulation:

1. **Localized along the edge**
2. **Fixed chirality**
3. **Backward scattering free**

Li, Yan, et al., ***PRB*** (2018)

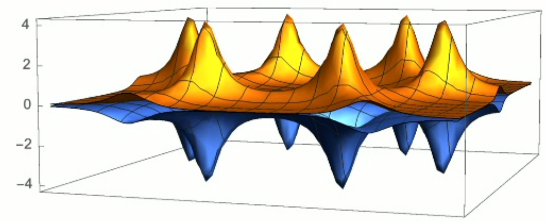
Magnonic topological insulator



$$C^{+} = \int_{\mathrm{BZ}} \frac{d^2k}{(2\pi)^2}\Omega^{+} = 1$$

edge mode !

$$C^{-} = \int_{\mathrm{BZ}} \frac{d^2k}{(2\pi)^2}\Omega^{-} = -1$$

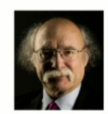


Ω^{+} (upper band)

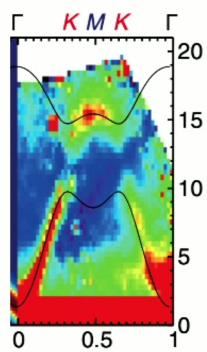
Ω^{-} (lower band)

Berry curvature: $\mathbf{\Omega}_n(\boldsymbol{q}) = \boldsymbol{\nabla}_{\boldsymbol{q}} \times \langle u_n(\boldsymbol{q})|i\boldsymbol{\nabla}_{\boldsymbol{q}}|u_n(\boldsymbol{q})\rangle.$ ***SKK*** et al., ***PRL*** (2016) ; Owerre JPCM (2016)

Magnonic topological insulator !! : analogous to Haldane's topological (Chern) insulator



Haldane, ***PRL*** (1988) (2016)



Neutron scattering on CrI_3

Chen, Dai, et al., ***PRX*** (2018)

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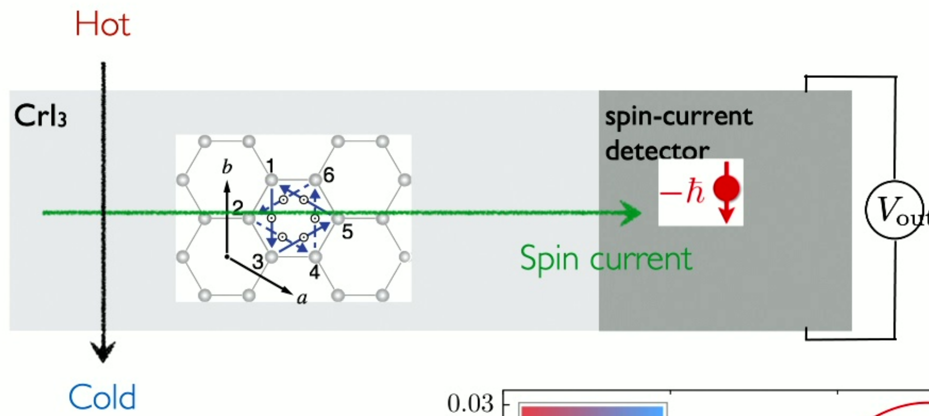
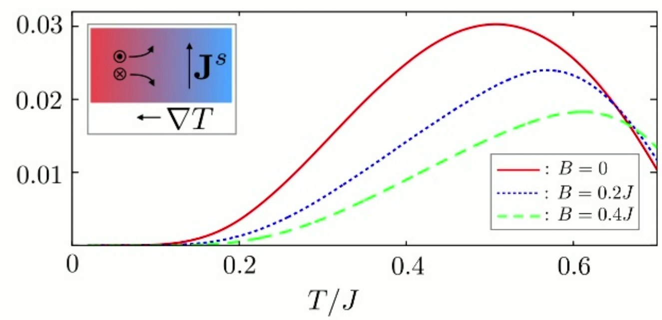
Spin transport of magnonic topological insulators

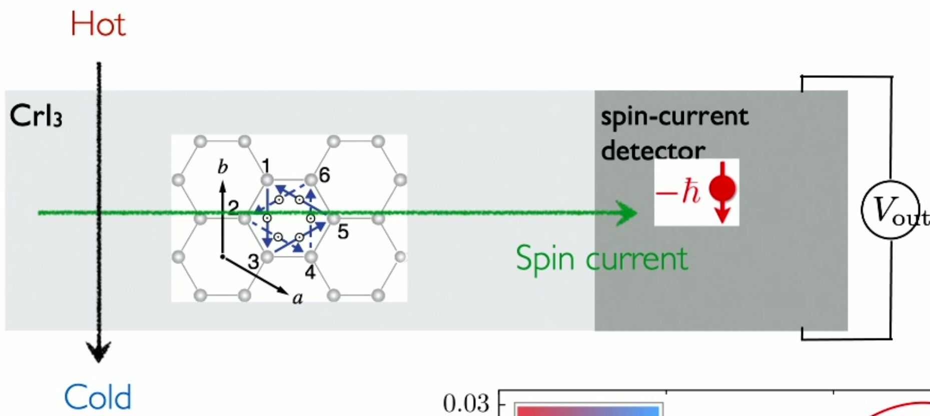


SKK et al., ***PRL*** (2016)

Spin Nernst conductivity $\alpha^s_{yx} = -\dfrac{J^s_y}{\partial_x T}$

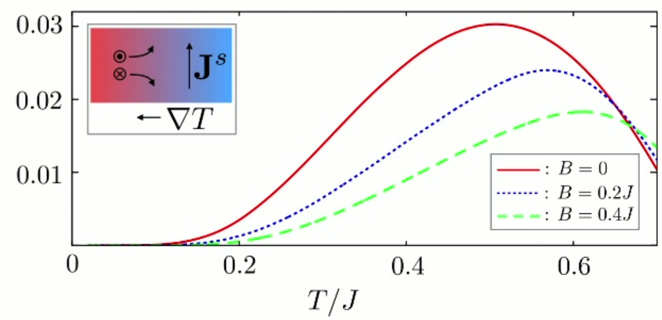


Spin transport of magnonic topological insulators



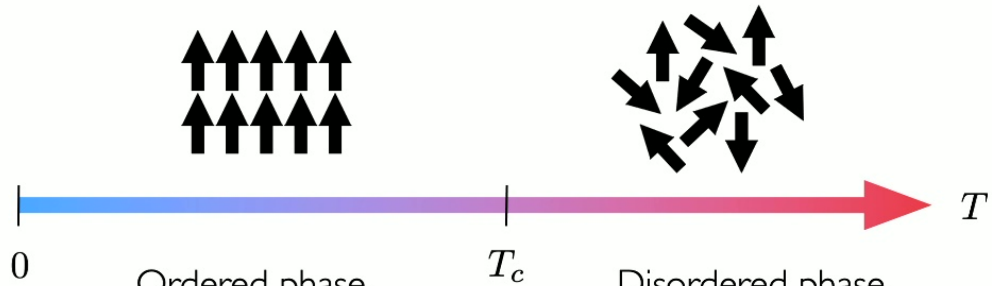
SKK et al., *PRL* (2016)

Spin Nernst conductivity $\alpha_{yx}^s = -\frac{J_y^s}{\partial_x T}$



The magnon picture for the spin Nernst effect is valid only for low temperatures, i.e., ordered phases.

How about above the Curie temperature ?



Ordered phase.
Magnons are well defined.

Disordered phase.
Magnons are not defined.

Spin Nernst effect: YES.

Spin Nernst effect: YES or NO ??

* the figure is taken from https://en.wikipedia.org/wiki/Curie_temperature.

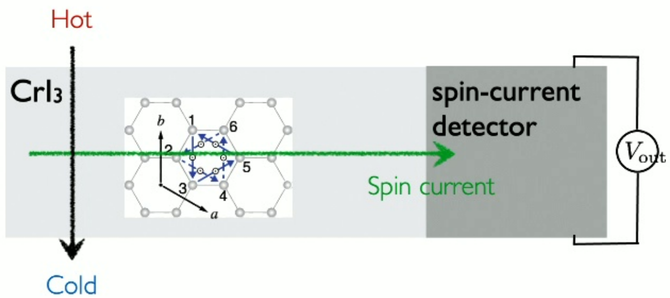
Spin Nernst effect in a disordered phase?

A spin current is even under time reversal.

$$J_i^\alpha = v_i s^\alpha \quad \xrightarrow{\text{time reversal}} \quad J_i^\alpha = (-v_i)(-s^\alpha) = v_i s^\alpha$$

velocity spin

This indicates that the spin current does not need breaking of time-reversal symmetry, and therefore, the spin Nernst effect may exist even when there is no magnetic ordering.



Does the spin Nernst effect exist even above the Curie temperature?

Schwinger spinons

$$S^+ = c_\uparrow^\dagger c_\downarrow$$
$$S^- = c_\downarrow^\dagger c_\uparrow$$
$$S^z = (c_\uparrow^\dagger c_\uparrow - c_\downarrow^\dagger c_\downarrow)/2$$

spin-up spinon   spin-up spinon

with the local number constraint

$$\sum_s c_{i,s}^\dagger c_{i,s} = 2S$$

Arovos and Auerbach, ***PRB*** (1988)
Auerbach and Arovos, ***PRL*** (1988)

The Schwinger spinon representation does not need information about a ground state.

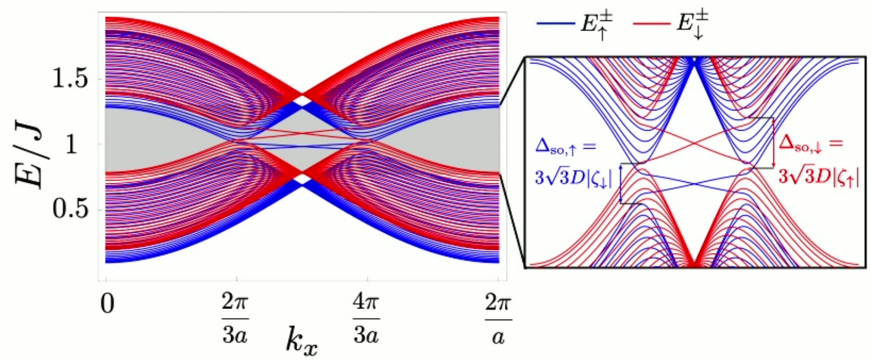
Spinon Hamiltonian

$$H = -J\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j + D\sum_{\langle\langle i,j\rangle\rangle}\nu_{ij}\hat{\mathbf{z}}\cdot\mathbf{S}_i\times\mathbf{S}_j - B\sum_i S_i^z$$

Schwinger representation & mean-field approach

$$\begin{aligned} H_\mathrm{s} =& -\eta J\sum_{\langle i,j\rangle,s}\left[c_{i,s}^\dagger c_{j,s} + \mathrm{h.c.}\right] \\ &+ \frac{D}{2}\sum_{\langle\langle i,j\rangle\rangle,s}\left[i\nu_{ij}s\zeta_{-s}\, c_{i,s}^\dagger c_{j,s} + \mathrm{h.c.}\right] \\ &+ \frac{D}{2}\sum_{\langle\langle i,j\rangle\rangle,s}\left[s\xi_{-s}\, c_{i,s}^\dagger c_{j,s} + \mathrm{h.c.}\right] \\ &+ \sum_{i,s}\left(\lambda - s\frac{B}{2}\right)c_{i,s}^\dagger c_{i,s}\,. \end{aligned}$$

Topological spinon bands

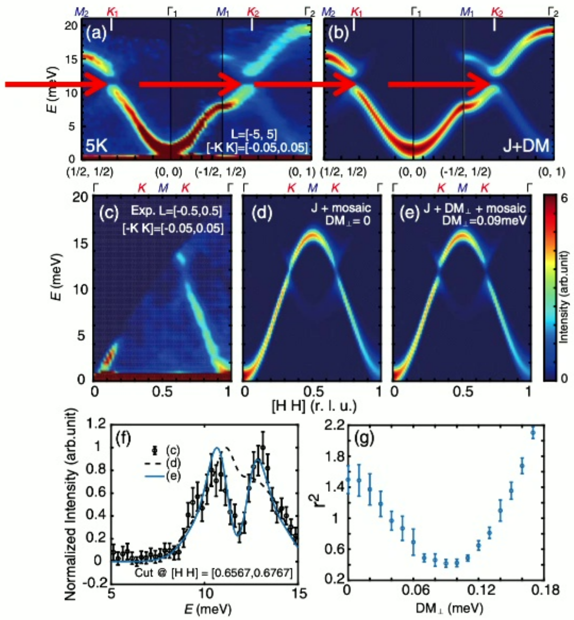


Both spin-up and spin-down spinons have the topological bands !!!

The spin Nernst effect should exist even above the Curie temperature !!!, albeit decreasing with increasing temperature.

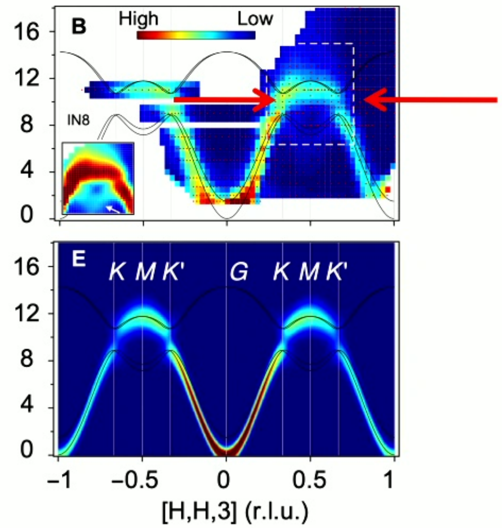
SKK, Ochoa, Zarzuela, and Tserkovnyak., ***PRL*** 117, 227201 (2016)

Experimental status of searching for topological magnons



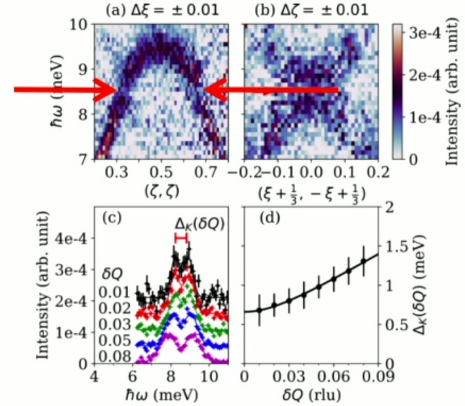
Neutron scattering on CrI_3

Chen, Dai, et al., ***PRX*** (2021)



Neutron scattering on $CrSiTe_3$

Zhu, Bruckel et al., ***Sci. Adv.*** (2022)

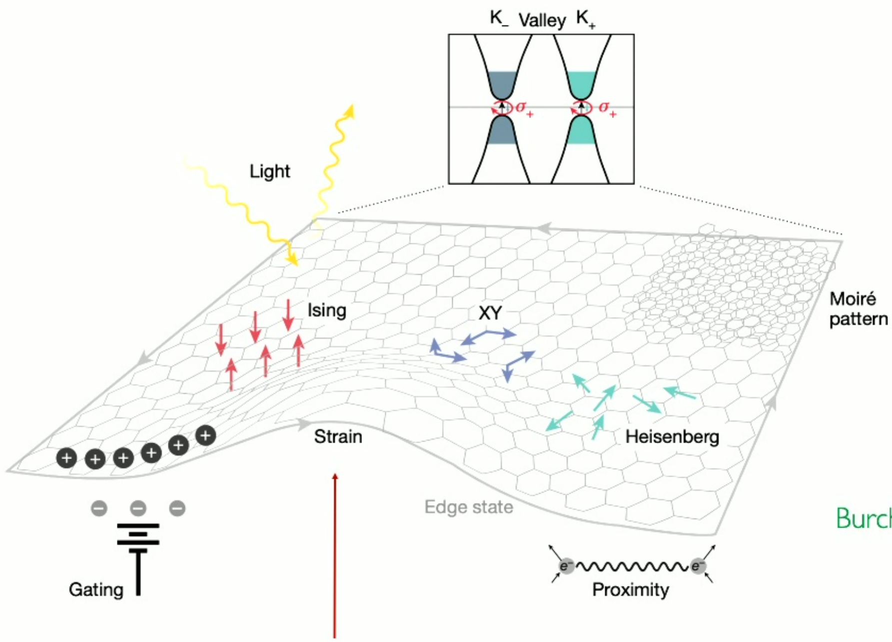


Neutron scattering on $CoTiO_3$

Yuan, Kim et al., ***PRB*** (2024)

Neutron scattering experiments demonstrate finite gaps at K points, but there is no experimental proof showing that the gaps are topological.

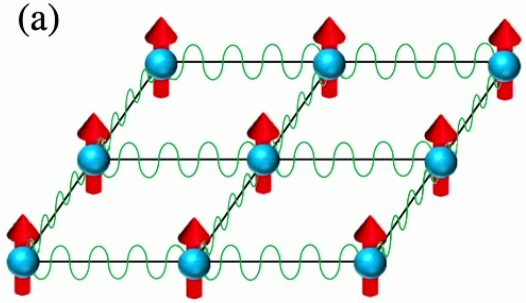
Phonons are important in 2D materials.



Burch, Mandrus, and Park., ***Nature*** (2018)

2D materials including 2D magnets are easy to bend, which indicates the importance of lattice vibrations, i.e., phonons, in their properties.

Magnon-phonon hybridized mode = magnon-polaron



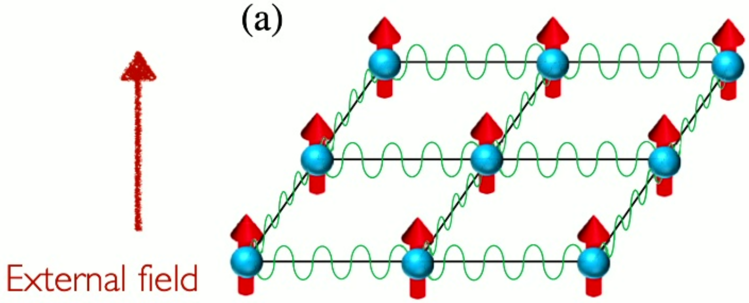
Go, **SKK**, and Lee., ***PRL*** (2020)

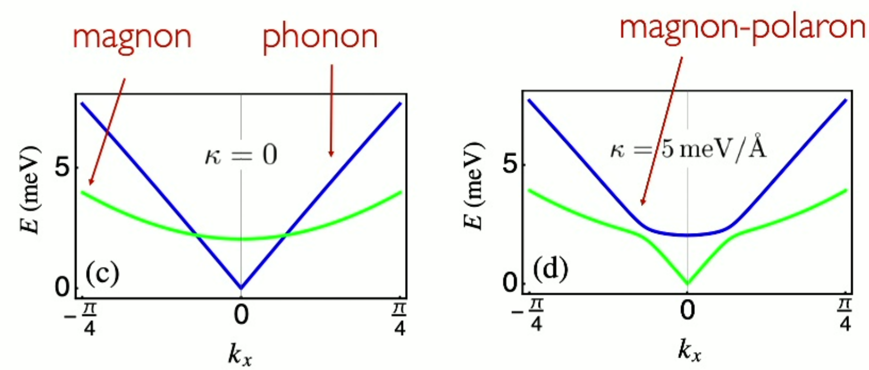
The number of magnon bands is one, thus topologically trivial.

Phonons are also topologically trivial.

Can magnon-polarons be topological ??

Topological magnon-polarons





Go, **SKK**, and Lee., ***PRL*** (2020)

Magnetic sector: $$H_{\rm mag} = -J\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j - \frac{K_z}{2}\sum_i S_{i,z}^2 - \mathcal{B}\sum_i S_{i,z},$$

Lattice sector: $$H_{\rm ph} = \sum_i \frac{\mathbf{p}_i^2}{2M} + \frac{1}{2}\sum_{i,j,\alpha,\beta} u_i^\alpha \Phi_{i,j}^{\alpha,\beta} u_j^\beta,$$

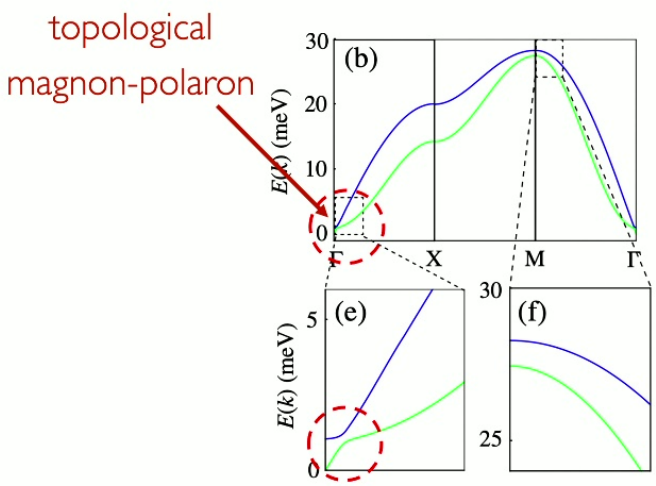
Magnetoelastic coupling: $$H_{\rm mp} = \kappa\sum_i\sum_{\mathbf{e}}(\mathbf{S}_i\cdot\mathbf{e})(u_i^z - u_{i+\mathbf{e}}^z),$$ (first discussed by Kittel in 1958)

C. Kittel, ***Phys. Rev.*** 110, 836 (1958).

continuum

$$H_{\rm mp} \propto (\mathbf{S}\cdot\nabla u^z - u_z\nabla\cdot\mathbf{S})$$

Berry curvature of magnon-polarons

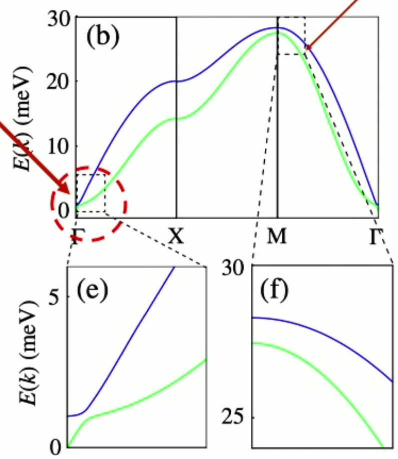


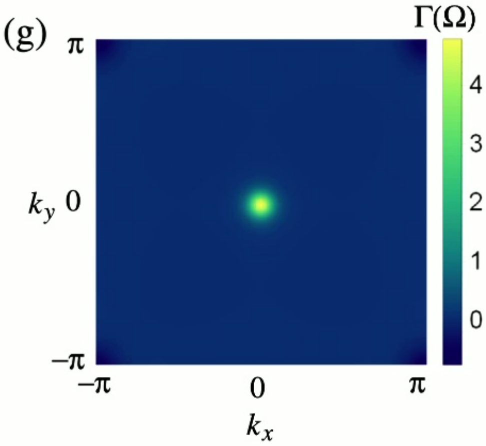
Go, **SKK**, and Lee., ***PRL*** (2020)

Berry curvature of magnon-polarons

magnon. We can move this band up uniformly by the field.

topological magnon-polaron





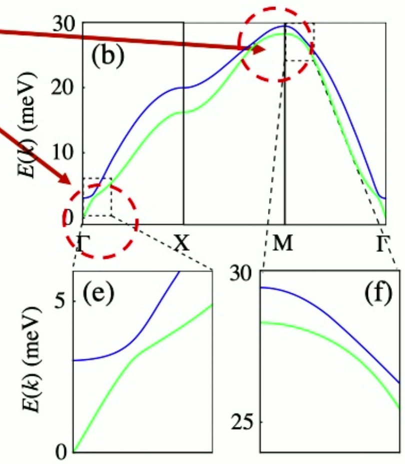
Finite Berry curvature near Γ point.

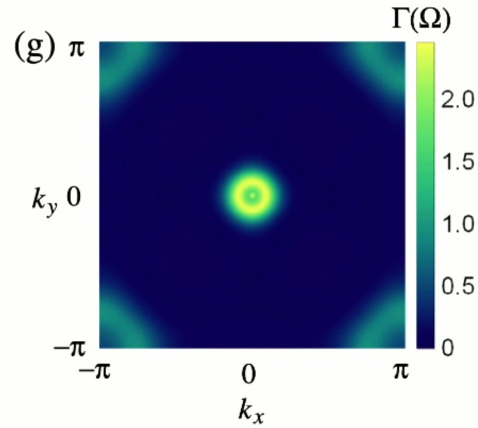
The Chern number (of the upper band) is one.

Go, **SKK**, and Lee., ***PRL*** (2020)

Berry curvature of magnon-polarons

topological
magnon-polaron



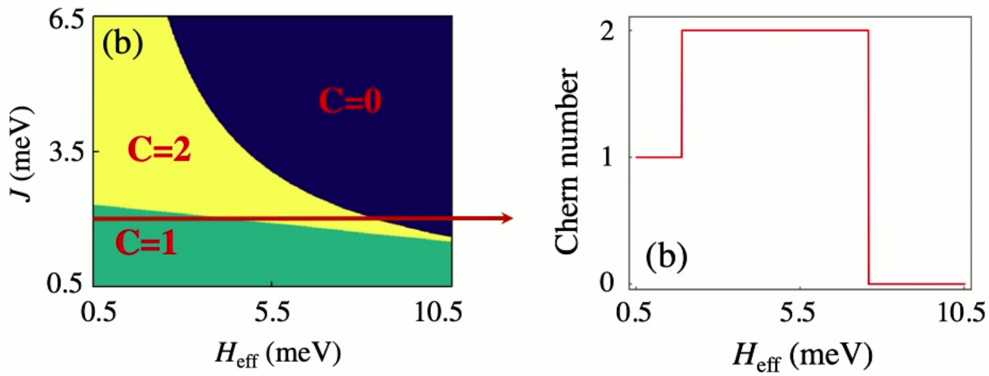


Finite Berry curvature near Γ & **M** points.

The Chern number (of the upper band) is two.

Go, **SKK**, and Lee., ***PRL*** (2020)

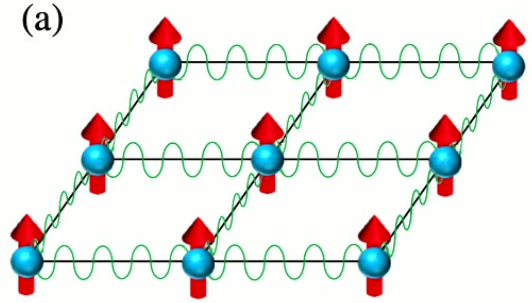
Topological magnon-polarons



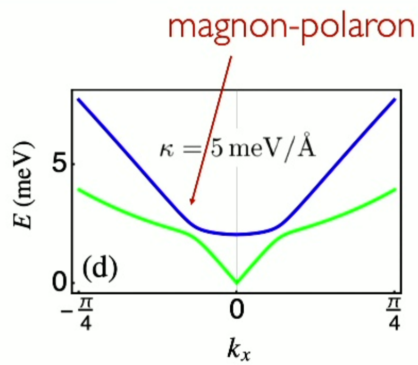
The Chern number can be controlled by varying an external field !!

Go, **SKK**, and Lee., ***PRL*** (2020)

Unsolved: spin transfer between magnon and phonon?



Go, **SKK**, and Lee., ***PRL*** (2020)



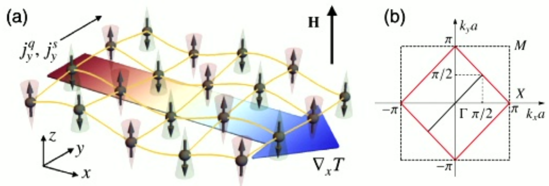
Magnetic sector: $$H_{\mathrm{mag}} = -J\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j - \frac{K_z}{2}\sum_i S_{i,z}^2 - \mathcal{B}\sum_i S_{i,z},$$

Lattice sector: $$H_{\mathrm{ph}} = \sum_i \frac{\mathbf{p}_i^2}{2M} + \frac{1}{2}\sum_{i,j,\alpha,\beta} u_i^\alpha \Phi_{i,j}^{\alpha,\beta} u_j^\beta,$$

Magnetoelastic coupling: $$H_{\mathrm{mp}} = \kappa\sum_i\sum_{\mathbf{e}}(\mathbf{S}_i\cdot\mathbf{e})(u_i^z - u_{i+\mathbf{e}}^z),$$ (first discussed by Kittel in 1958)

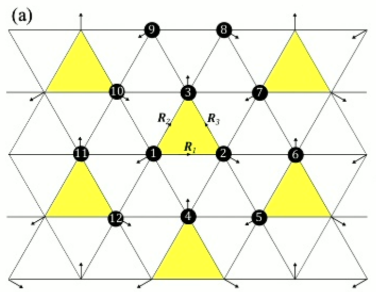
C. Kittel, ***Phys. Rev.*** 110, 836 (1958).

A variety of topological magnon-polarons



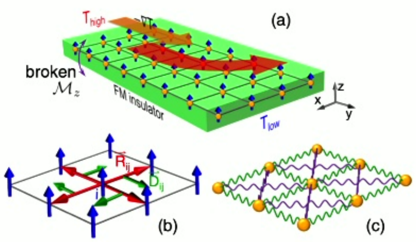
SU(3) topology of magnon-polaron in 2D antiferromagnets

Zhang, **SKK**, et al., ***PRL*** (2020)



2D triangular antiferromagnet

Park and Yang, ***PRB*** (2019)

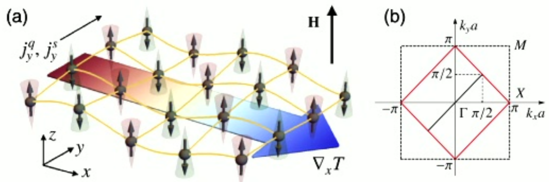


Inversion-symmetry-broken 2D ferromagnet

(With Dzyaloshinskii-Moriya interaction)

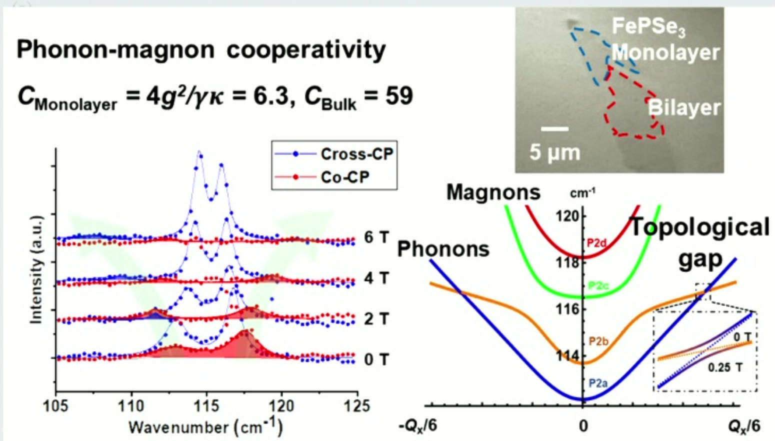
Zhang, Xiao, et al., ***PRL*** (2019)

A variety of topological magnon-polarons



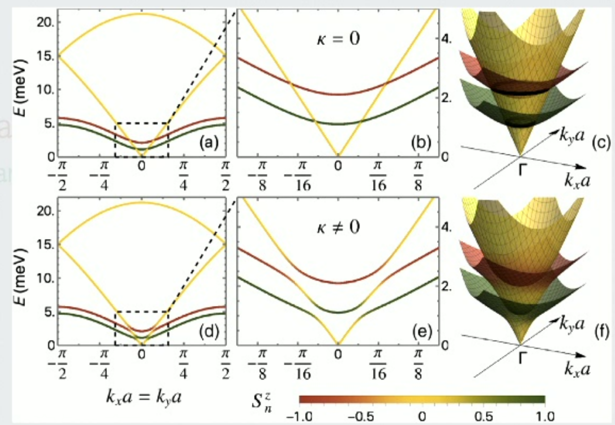
SU(3) topology of magnon-polaron in 2D antiferromagnets

Zhang, **SKK**, et al., ***PRL*** (2020)



Experimental confirmation of a topological magnon-phonon coupling in a 2D magnet FePSe3 !!

Luo, Zhu et al., ***Nano Lett.*** (2023)



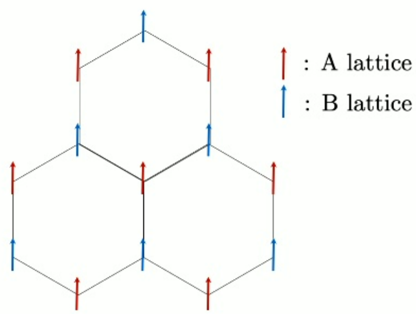
Zhang, **SKK**, et al., ***PRL*** (2020)

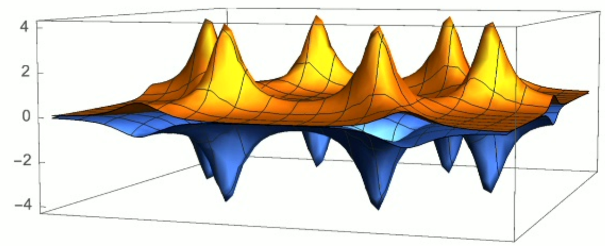
Wait!

All the known Hall effects of magnons require spin-orbit coupling.

Is spin-orbit coupling essential for Hall effects?

The known magnon Hall effects require spin-orbit coupling.



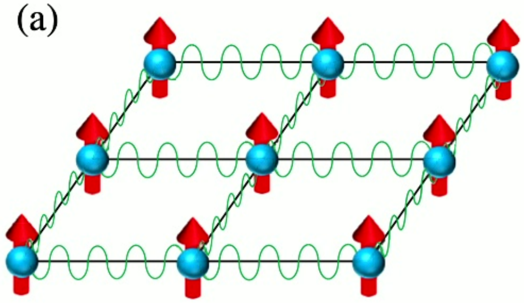


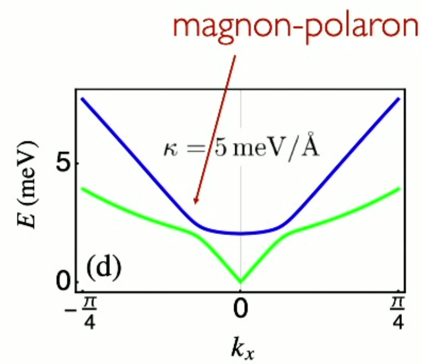
$$H = -J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + D \sum_{\langle\langle i,j \rangle\rangle} \nu_{ij} \hat{\mathbf{z}} \cdot \mathbf{S}_i \times \mathbf{S}_j - B \sum_i S_i^z$$

spin-orbit coupling (DMI)

In the example of a honeycomb ferromagnet,
DMI gives rise to the Berry curvature and thus the spin Nernst effect.

The known magnon Hall effects require spin-orbit coupling.





Magnetic sector: $$H_{\mathrm{mag}} = -J\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j - \frac{K_z}{2}\sum_i S_{i,z}^2 - \mathcal{B}\sum_i S_{i,z},$$

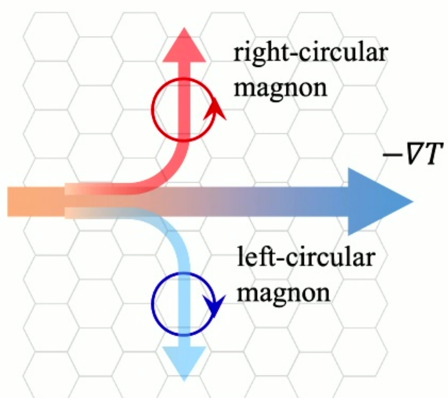
Lattice sector: $$H_{\mathrm{ph}} = \sum_i \frac{\mathbf{p}_i^2}{2M} + \frac{1}{2}\sum_{i,j,\alpha,\beta} u_i^\alpha \Phi_{i,j}^{\alpha,\beta} u_j^\beta,$$

Magnetoelastic coupling: $$H_{\mathrm{mp}} = \kappa\sum_i\sum_{\mathbf{e}}(\mathbf{S}_i\cdot\mathbf{e})(u_i^z - u_{i+\mathbf{e}}^z),$$

spin-orbit coupling (magnon-phonon coupling)

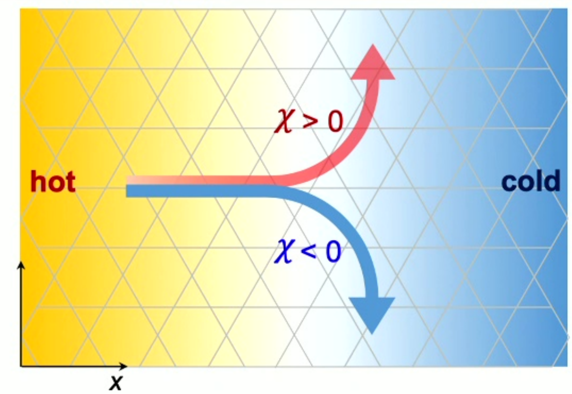
The magnon-phonon coupling (effective spin-orbit coupling) gives rise to the Berry curvature and thus the thermal Hall effect.

Is it possible for magnets to exhibit a Hall effect without SOC?



Magnon orbital Hall effect

Go, **SKK**, et al., Nano Lett. (2024)

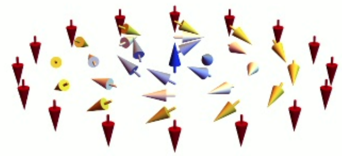


Scalar spin chirality Hall effect

Go, Prasad Goli, Esaki, Tserkovnyak, and SKK, arXiv:2411.03679

Scalar spin chirality: an elementary unit of skyrmions

Skyrmion:



Skyrmion's topological charge:

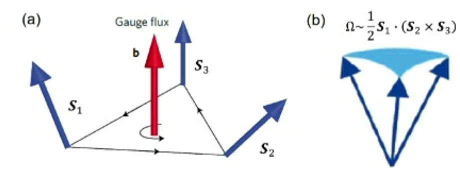
$$Q = \frac{1}{4\pi} \int dxdy\, \mathbf{n}_0 \cdot (\partial_x \mathbf{n}_0 \times \partial_y \mathbf{n}_0)$$

$$= \pm 1 \text{ for a full skyrmion}$$

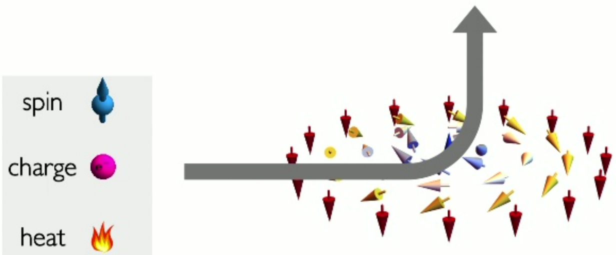
lattice version

$$Q = \frac{1}{4\pi} \sum_{\triangle} \mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k) \approx \pm 1$$

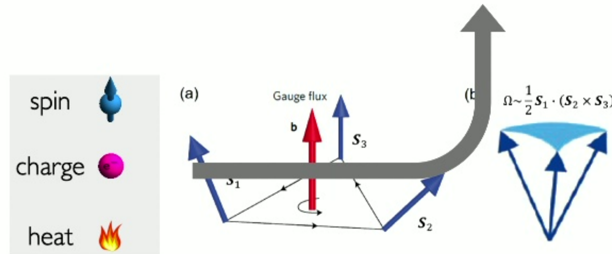
Scalar spin chirality:



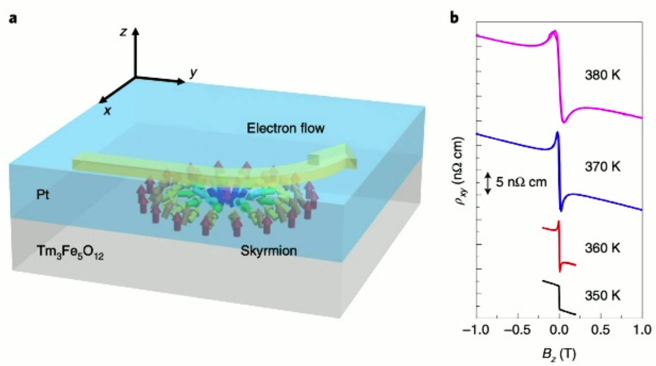
Hall effect due to spin textures



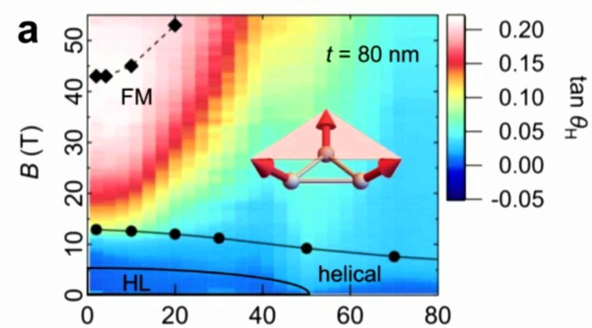
Topological Hall effect due to *static* skyrmions



Topological Hall effect due to the *static* scalar spin chirality



Topological Hall resistivity of Pt | TmIG
Shao, SKK, et al. Nat. Electron. (2019)



Topological Hall angle of MnGe thin films
Fujishiro, Tokura et al., Nat. Commun. (2021)

Scalar spin chirality: known source of the various Hall effects

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RESEARCH ARTICLE | PHYSICS

Spin chirality induced skew scattering and anomalous Hall effect in chiral magnets

HIROAKI ISHIZUKA AND NAOTO NAGAOSA — Authors Info & Affiliations

SCIENCE ADVANCES · 9 Feb 2018 · Vol 4, Issue 2

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Article | Open access | Published: 12 January 2021

Giant anomalous Hall effect from spin-chirality scattering in a chiral magnet

Yukako Fujishiro, Naoya Kanazawa, Ryosuke Kurihara, Hiroaki Ishizuka, Tomohiro Hori, Fehmi Sami Yasin, Xiuzhen Yu, Atsushi Tsukazaki, Masakazu Ichikawa, Masashi Kawasaki, Naoto Nagaosa, Masashi Tokunaga & Yoshinori Tokura

Nature Communications **12**, Article number: 317 (2021) | Cite this article

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Letter | Published: 12 August 2019

Spin chirality fluctuation in two-dimensional ferromagnets with perpendicular magnetic anisotropy

Wenbo Wang, Matthew W. Daniels, Zhaoliang Liao, Yifan Zhao, Jun Wang, Gertjan Koster, Guus Rijnders, Cui-Zu Chang, Di Xiao & Weida Wu

Nature Materials **18**, 1054–1059 (2019) | Cite this article

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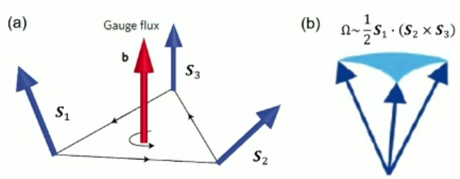
Article | Open access | Published: 24 March 2023

Field-linear anomalous Hall effect and Berry curvature induced by spin chirality in the kagome antiferromagnet Mn_3Sn

Xiaokang Li, Jahyun Koo, Zengwei Zhu, Kamran Behnia & Binghai Yan

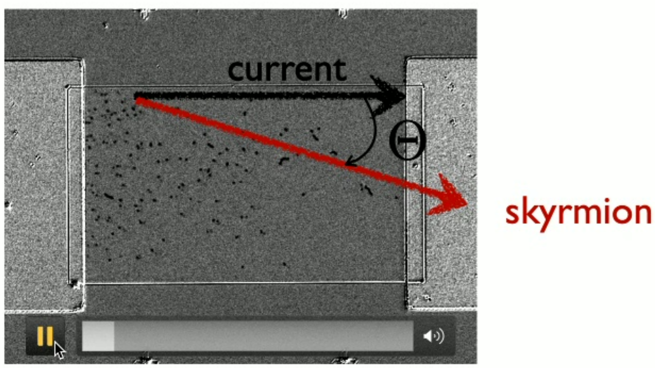
Nature Communications **14**, Article number: 1642 (2023) | Cite this article



The scalar spin chirality generates an effective magnetic field for electrons, whereby inducing various Hall effects.

In all the previous studies, the scalar spin chirality is assumed to be static.

Hall effect of mobile spin textures



Skyrmion Hall effect in Ta | CoFeB | MgO
Yu, SKK, et al. Nano Lett. (2016)

45

Hall effect of mobile spin textures

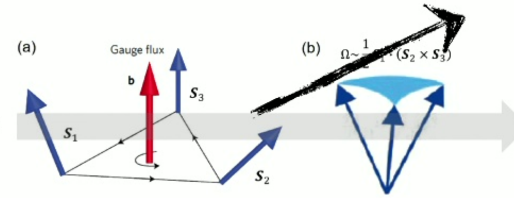
Skyrmion motion

Charge/heat flow

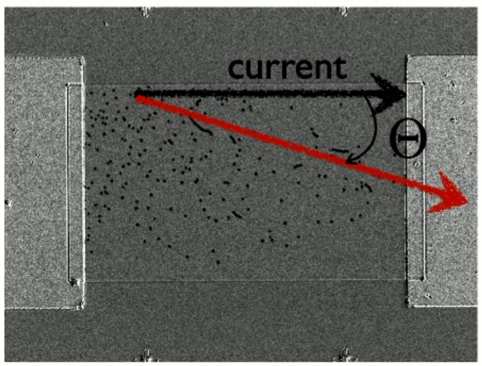
Skyrmion Hall effect

Spin chirality motion ???

Charge/heat flow



Open question: If we allow the spin chirality to move, would there be the <u>scalar spin chirality Hall effect</u> ???



skyrmion

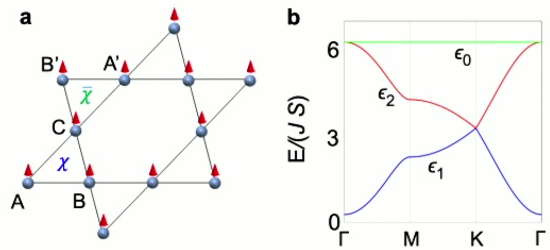
Skyrmion Hall effect in Ta | CoFeB | MgO
Yu, SKK, et al. Nano Lett. (2016)

45

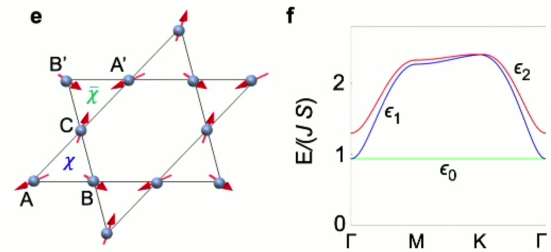
Scalar-spin-chirality Nernst effect in FM/AFM Kagome lattices

$$H = -J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - K \sum_i (\mathbf{S}_i \cdot \mathbf{e}_i)^2,$$ No spin-orbit coupling !!

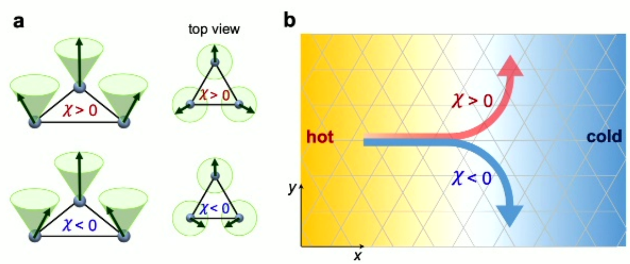
Ferromagnet (FM)



Antiferromagnet (AFM)



Both systems exhibit finite Nernst effect of the scalar spin chirality !!



Go, Prasad Goli, Esaki, Tserkovnyak, and SKK, arXiv:2411.03679

Scalar-spin-chirality Nernst effect in FM Kagome lattices

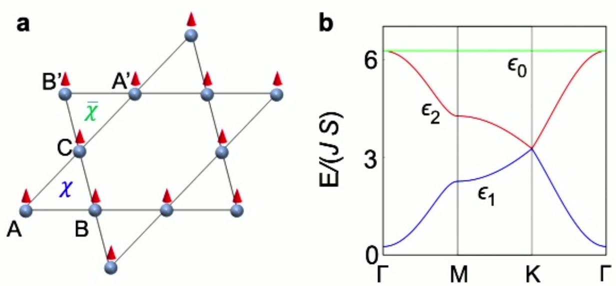
How can we describe the transport of the scalar spin chirality ? In terms of magnons !

$$H = -J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - K \sum_i (S_{i,z})^2 + \sum_{\langle i,j \rangle} \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j) - g\mu_B B \sum_i S_{i,z},$$

$$H = \sum_{\mathbf{k}} \Psi^\dagger_{\mathbf{k}} h_{\mathbf{k}} \Psi_{\mathbf{k}}, \qquad \Psi_{\mathbf{k}} = (a_{\mathbf{k}}, b_{\mathbf{k}}, c_{\mathbf{k}})^T \,,$$

$$h_{\mathbf{k}} = \bar{\epsilon} - 2S\sqrt{J^2 + D^2} \begin{pmatrix} 0 & \cos(\mathbf{k}\cdot\mathbf{a}_1)e^{i\phi} & \cos(\mathbf{k}\cdot\mathbf{a}_2)e^{-i\phi} \\ \cos(\mathbf{k}\cdot\mathbf{a}_1)e^{-i\phi} & 0 & \cos(\mathbf{k}\cdot\mathbf{a}_3)e^{i\phi} \\ \cos(\mathbf{k}\cdot\mathbf{a}_2)e^{i\phi} & \cos(\mathbf{k}\cdot\mathbf{a}_3)e^{-i\phi} & 0 \end{pmatrix},$$

$$\epsilon^1_{\mathbf{k}} = \bar{\epsilon} - JS(\sqrt{1+4f_{\mathbf{k}}} + 1), \qquad \epsilon^2_{\mathbf{k}} = \bar{\epsilon} + JS(\sqrt{1+4f_{\mathbf{k}}} - 1), \qquad \epsilon^0_{\mathbf{k}} = \bar{\epsilon} + 2JS,$$



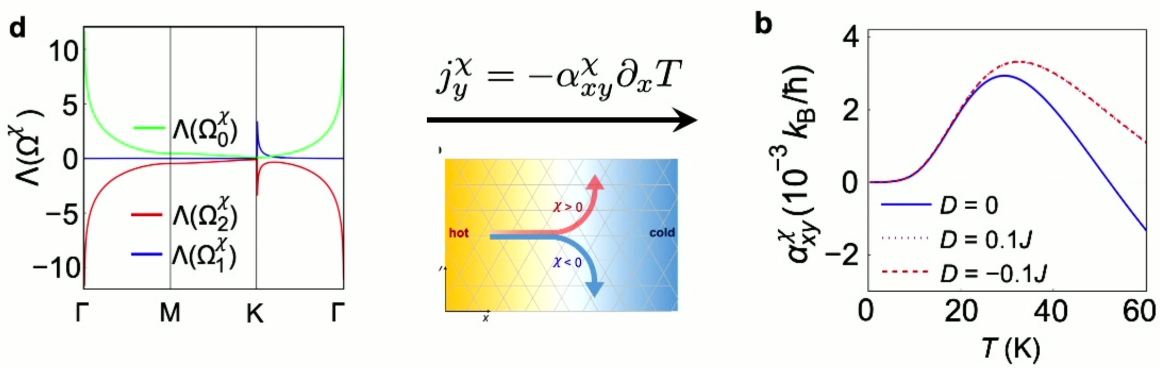
Scalar-spin-chirality Nernst effect in FM Kagome lattices

How can we describe the transport of the scalar spin chirality ? In terms of magnons !

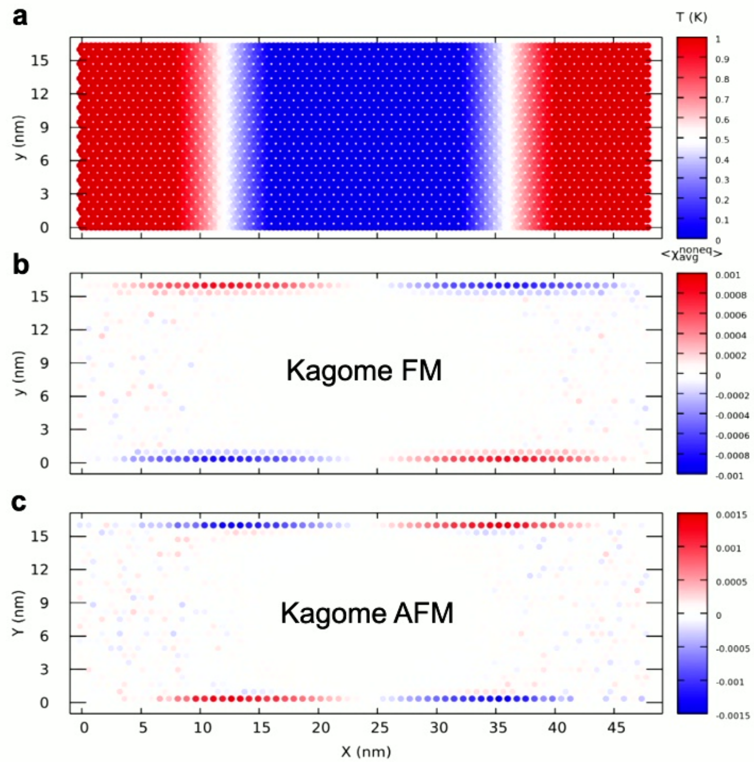
$$\chi_i = \hat{\mathbf{S}}^A_{\mathbf{r}_i} \cdot (\hat{\mathbf{S}}^B_{\mathbf{r}_i} \times \hat{\mathbf{S}}^C_{\mathbf{r}_i}) = -\frac{i}{S}\left(a^\dagger_{\mathbf{r}_i} b_{\mathbf{r}_i+\mathbf{a}_1} + b^\dagger_{\mathbf{r}_i+\mathbf{a}_1} c_{\mathbf{r}_i+\mathbf{a}_1+\mathbf{a}_2} + c^\dagger_{\mathbf{r}_i+\mathbf{a}_1+\mathbf{a}_2} a_{\mathbf{r}_i}\right) + \text{h.c.} = \Psi(\mathbf{r}_i)^\dagger \hat{\chi}_{\mathbf{r}} \Psi(\mathbf{r}_i),$$

$$\hat{\chi}_{\mathbf{k}} = -\frac{i}{S}\begin{pmatrix} 0 & e^{i\mathbf{k}\cdot\mathbf{a}_1} & -e^{-i\mathbf{k}\cdot\mathbf{a}_3} \\ -e^{-i\mathbf{k}\cdot\mathbf{a}_1} & 0 & e^{i\mathbf{k}\cdot\mathbf{a}_2} \\ e^{i\mathbf{k}\cdot\mathbf{a}_3} & -e^{-i\mathbf{k}\cdot\mathbf{a}_2} & 0 \end{pmatrix}$$

$$\Omega^{\chi(\bar{\chi})}_{n,\mathbf{k}} = -\sum_{m\neq n} \frac{2\hbar^2 \text{Im}\langle n|j^{\chi(\bar{\chi})}_{y,\mathbf{k}}|m\rangle\langle m|v_x|n\rangle}{(\epsilon_{n,\mathbf{k}} - \epsilon_{m,\mathbf{k}})^2}. \qquad j^{\chi}_{y,\mathbf{k}} = \frac{1}{2}(v_y\hat{\chi}_{\mathbf{k}} + \hat{\chi}_{\mathbf{k}}v_y),\ j^{\bar{\chi}}_{y,\mathbf{k}} = \frac{1}{2}(v_y\hat{\bar{\chi}}_{\mathbf{k}} + \hat{\bar{\chi}}_{\mathbf{k}}v_y)$$

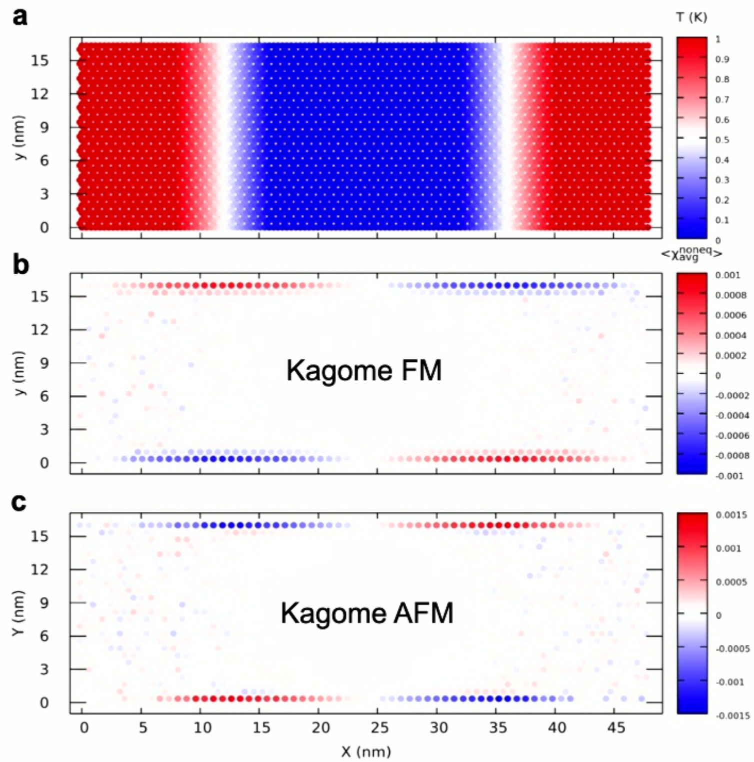


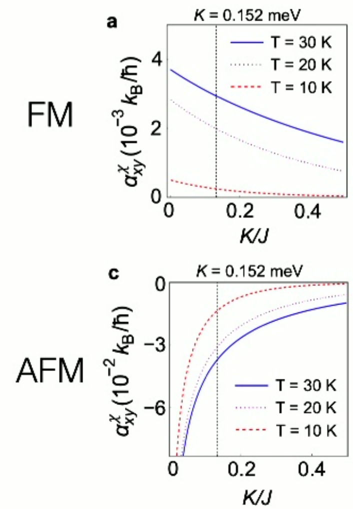
Scalar-spin-chirality Nernst effect in FM/AFM Kagome lattices



Go, Prasad Goli, Esaki, Tserkovnyak, and SKK, arXiv:2411.03679

Scalar-spin-chirality Nernst effect in FM/AFM Kagome lattices





FM and AFM systems exhibit the opposite signs of the scalar-spin-chirality Nernst conductivities.

Go, Prasad Goli, Esaki, Tserkovnyak, and SKK, arXiv:2411.03679

Detection of the scalar spin chirality

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https://doi.org/10.1038/s42005-020-00490-3 OPEN

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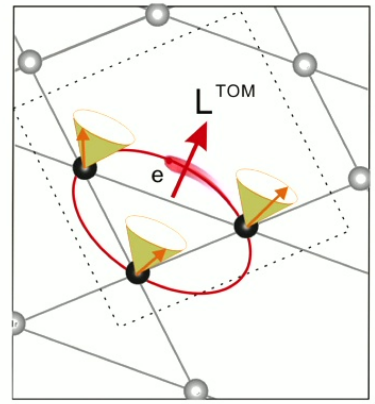
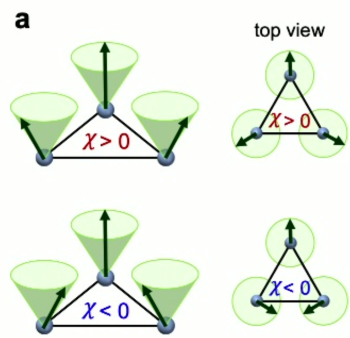
Imprinting and driving electronic orbital magnetism using magnons

Li-chuan Zhang[1,2], Dongwook Go[1,3], Jan-Philipp Hanke[1], Patrick M. Buhl[3], Sergii Grytsiuk[1], Stefan Blügel[1], Fabian R. Lux[1,2] & Yuriy Mokrousov[1,3]✉





$\longrightarrow L_z > 0$

$\longrightarrow L_z < 0$

Scalar spin chirality

topological orbital magnetization,
which can be detected by MOKE.

Take-home message

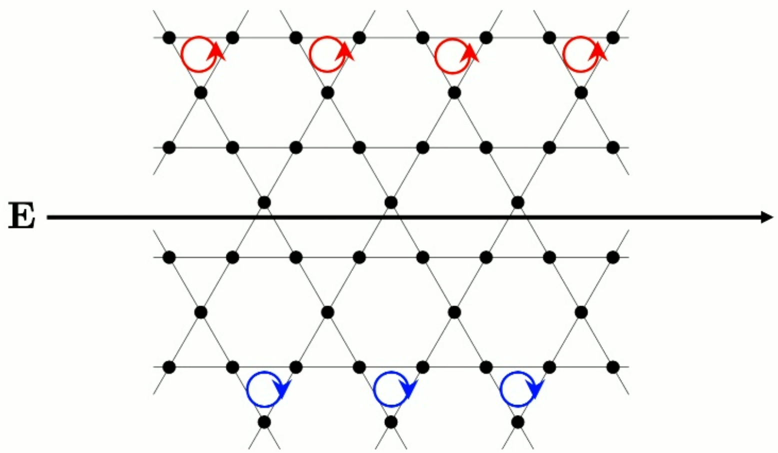
So far, only magnons or solitons such as skyrmions have been considered as a transportable quantity in magnetic insulators.

Go, Prasad Goli, Esaki, Tserkovnyak, and SKK, arXiv:2411.03679

Future investigations

Future investigations

- The S=1/2 limit of topological magnon physics.
- The S=1/2 limit of topological magnon-polaron physics.
- The possibility of the scalar-spin-chirality Hall effect in S=1/2 Kagome systems (*quantum spin liquids*?).
- The possibility of analogous Hall effects of *a charge loop current* in itinerant systems without spin-orbit coupling.



Thank you !!