Detecting, imprinting and switching spin chirality in magnetic materials

Yuriy Mokrousov

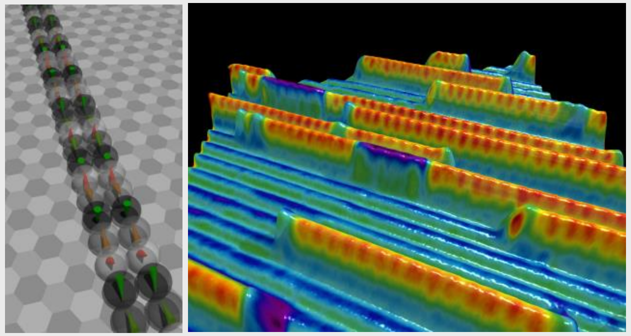
Peter Grünberg Institute, Forschungszentrum Jülich, Germany

Institute of Physics, University of Mainz, Germany

Rich world of chiral states

Menzel *et al.* PRL **108**, 197204 (2012)

Spirals, Domain walls

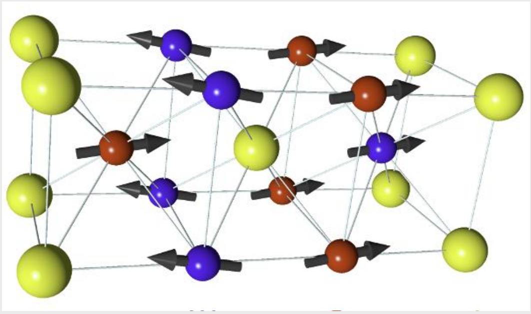


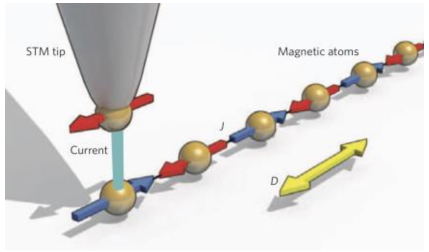
vector spin chirality

$$\chi_{ij} = \mathbf{S}_i \times \mathbf{S}_j$$

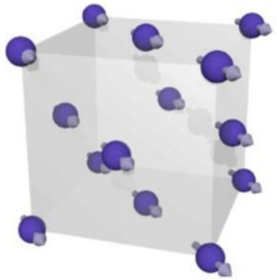
Yang *et al.* PRL **124**, 137201 (2020)

Canted Magnets





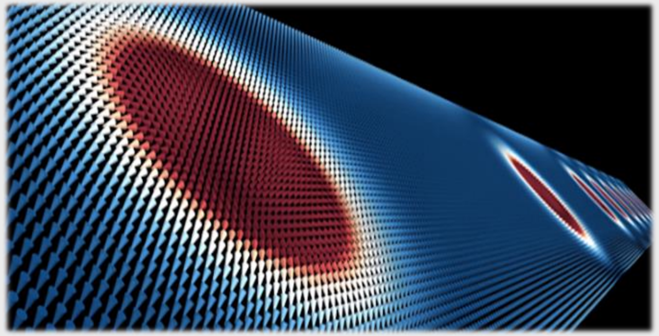
Ferromagnets



Antiferromagnets

Fert *et al.* Nat. Nano. **8**, 152 (2013)

Topological spin textures



scalar spin chirality

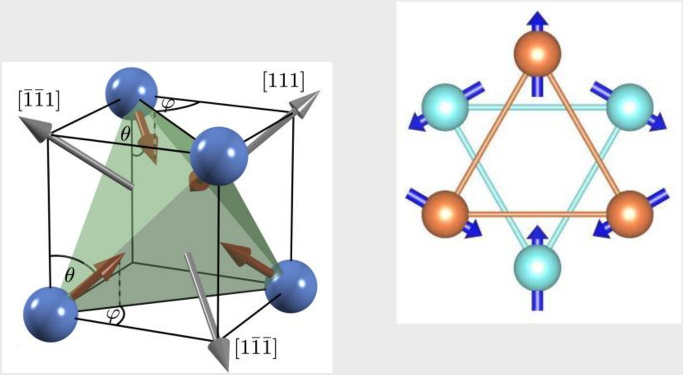
$$\chi_{ijk} = \mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k)$$

"octupolar" chirality

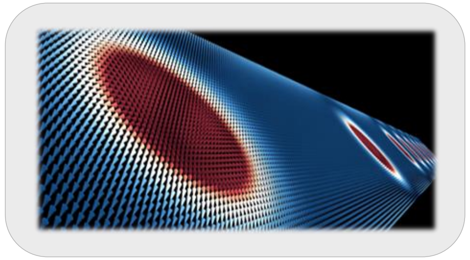
$$\mathcal{O} = \mathbf{S}_1 \times (\mathbf{S}_2 \times \mathbf{S}_3)$$

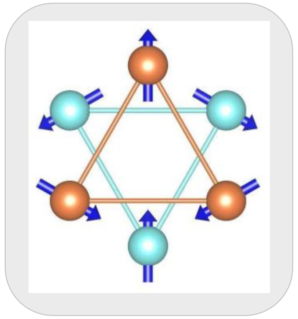
Smejkal *et al.*, Nat. Phys. **14**, 242 (2018)

Frustrated Magnets



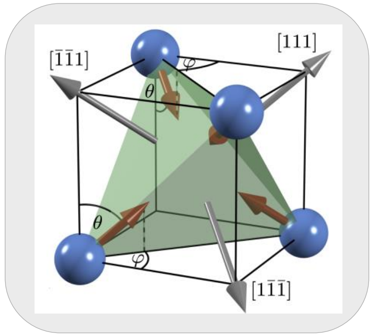
Why chirality?

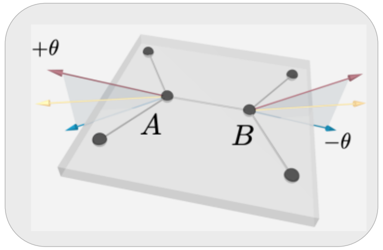




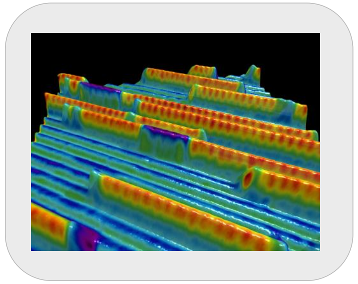
- There is a zoo of chiral states out there!

  You have to deal with them!





- We have to learn how to manipulate them
- Profound impact on: ***energetics, transport, dynamics***
- Platform for "advanced" and/or topological concepts

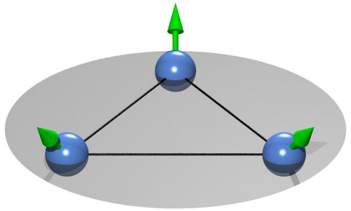


Teleportation & Entanglement

Spin superfluidity

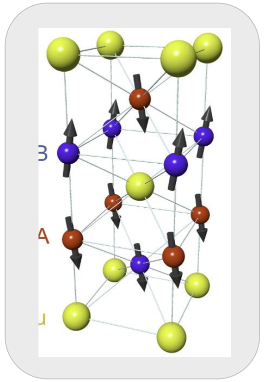
Superconductivity

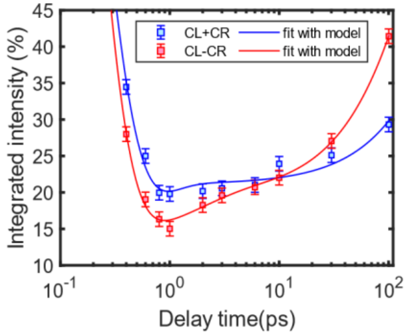
Skyrmions



(Ultrafast) topological robustness

Kerber *et al.*,
Nat. Comm. **11**, 6304 (2020)





Exotic States of Matter: chiral spin liquids

Novel Topological States

Concept of chiral currents

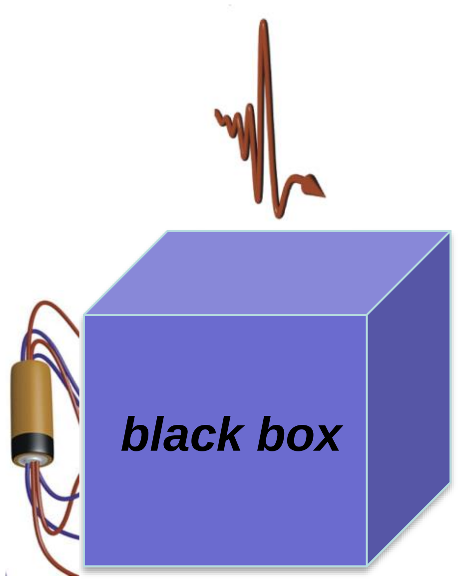
Chiral Hall effect in canted systems

Chiral Hall effect in textures

Chiral spin currents

Chirality, Berry phase & spin torque

How to read out chirality and chiral states?



Chirality?

Magnetization

magnetic sample

How to switch chirality?

Chiral currents

for chirality switching

Driving chirality by laser excitations

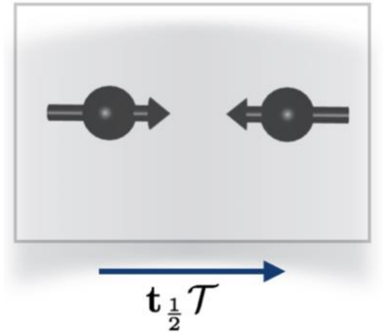
Chirality by fluctuations

Magnon drag of chirality

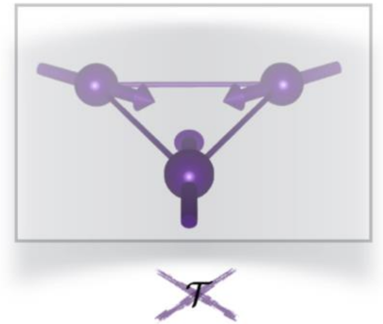
Chirality and g-factor

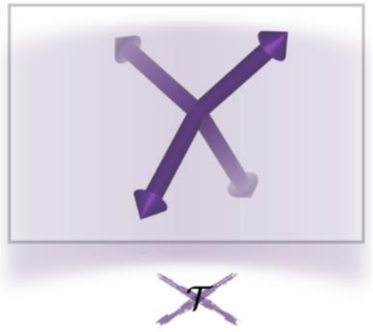
“Hidden” and “driven” chirality out of equilibrium

Read-Out: Anomalous Hall Effect



(images from) Smejkal *et al.* Sci. Adv. **6**, eaaz8809 (2020)





- AHE **vanishes** in collinear AFMs
- Non-collinear AFMs offer a rich platform

Taguchi *et al.*, Science **291**, 2573 (2001) (exp. $Nd_2Mo_2O_7$)
Shindou, Nagaosa, PRL **87**, 116801 (2001) (fcc 3Q)
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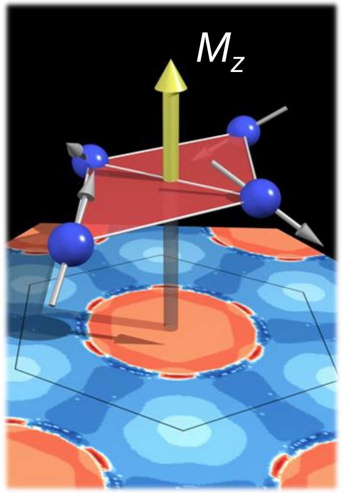
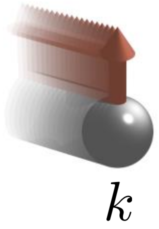
Nayak *et al.*, Sci. Adv. **2**, e1501870 (2016) (exp. Mn_3Ge)
Sürgers *et al.*, Nat. Comm. **5**, 3400 (2014) (exp. Mn_5Si_3)
Zhou, Hanke, Feng, et al. PRB 2019, PRM 2020 (Mn_3XN)
... goes on ...

- Coplanar AFMs + Spin-Orbit Interaction (SOI)
- Non-coplanar AFMs: SOI not needed

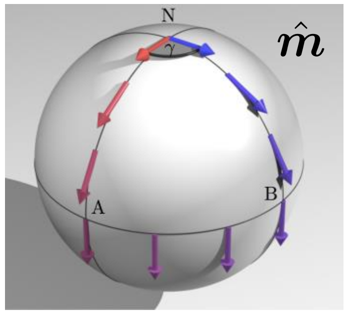
Ferromagnets

$$\mathrm{AHE} = \alpha\, M_z$$





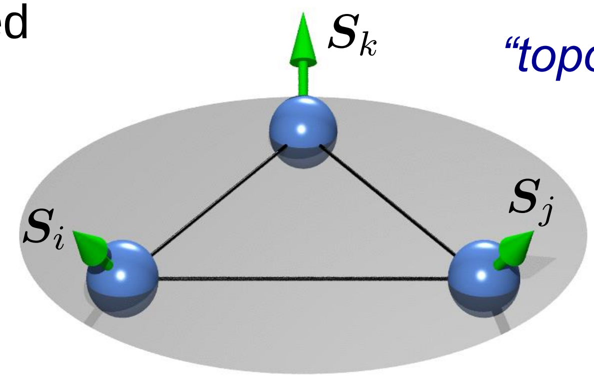
$\Omega_{xy}^{\boldsymbol{kk}}$



scalar spin chirality

$$\chi_{ijk} = \mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k)$$

Smejkal, YM, Yan, MacDonald, Nat. Phys. **14**, 242 ‘18



“topological” Hall effect
prominent e.g. in skyrmions

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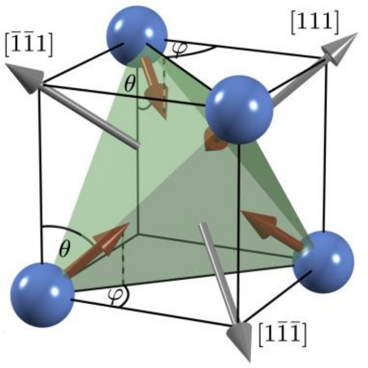
Probing Scalar Chirality by Magneto-Optics

Feng, Hanke, YM *et al.* Nature Comm. **11**, 118 (2020)

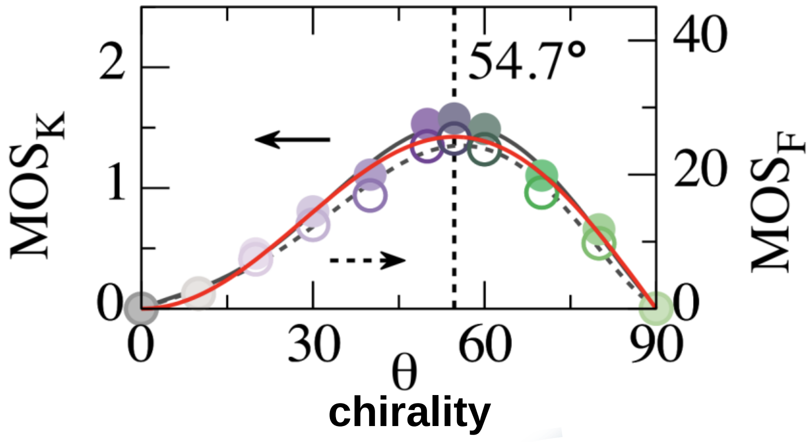


γ-Fe_xMn_{1-x}

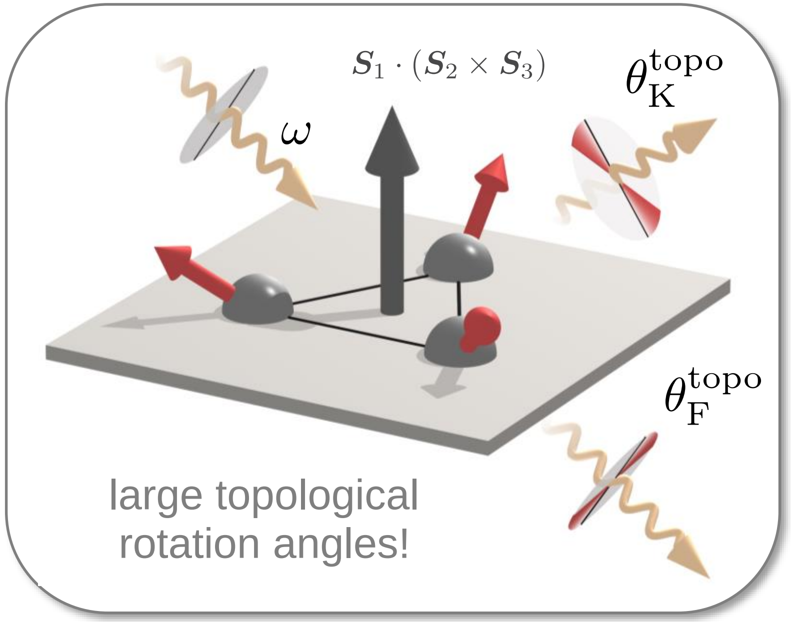
Scalar spin chirality mediates **topological** magneto-optical phenomena

- Kerr and Faraday effects

$$\mathrm{MOS}_{\mathrm{K,F}} = \int_0^{+\infty} \hbar |\theta_{\mathrm{K,F}}(\omega)| \mathrm{d}\omega$$



No spin-orbit!
No net magnetization!



Strong MO response as scalar chirality marker!

- Optical / electrical probe for spin structures (?)

frustrated systems, helimagnets, skyrmions…

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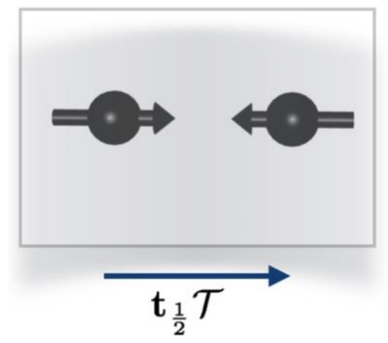
Read-Out: Anomalous Hall Effect



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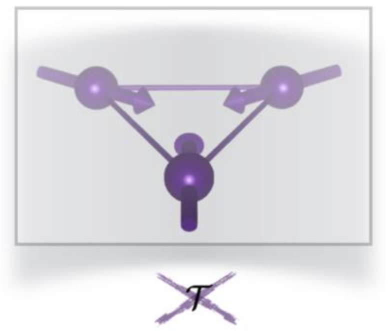

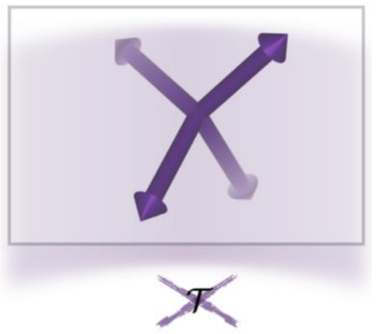

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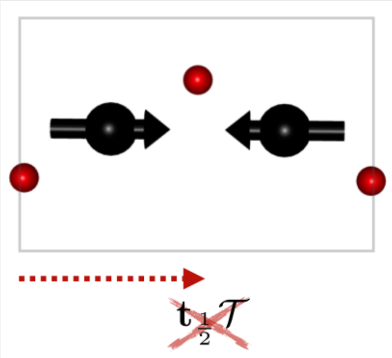
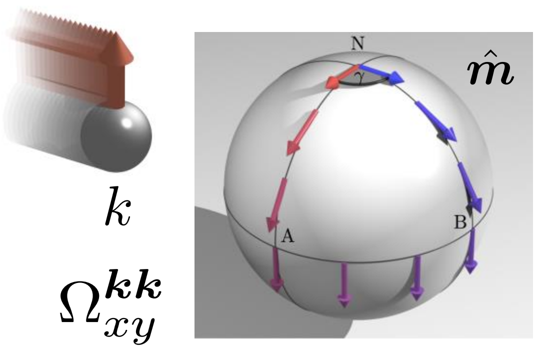
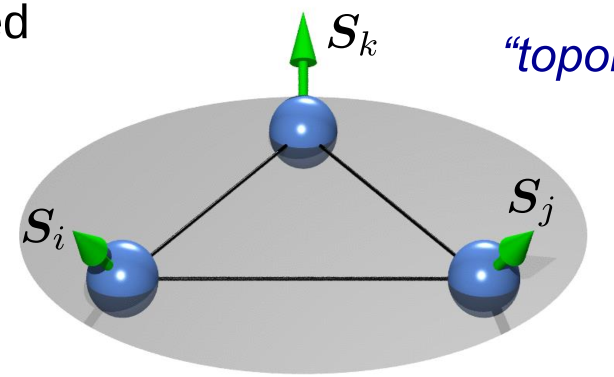
Smejkal, YM, Yan, MacDonald, Nat. Phys. **14**, 242 '18

Crystal Hall Effect

when there is SOI and crystal symmetry is low...







"topological" Hall effect…

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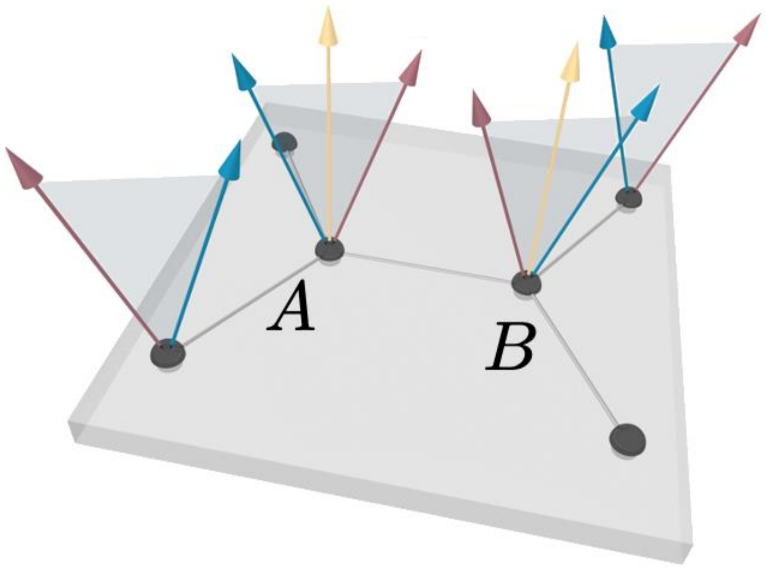
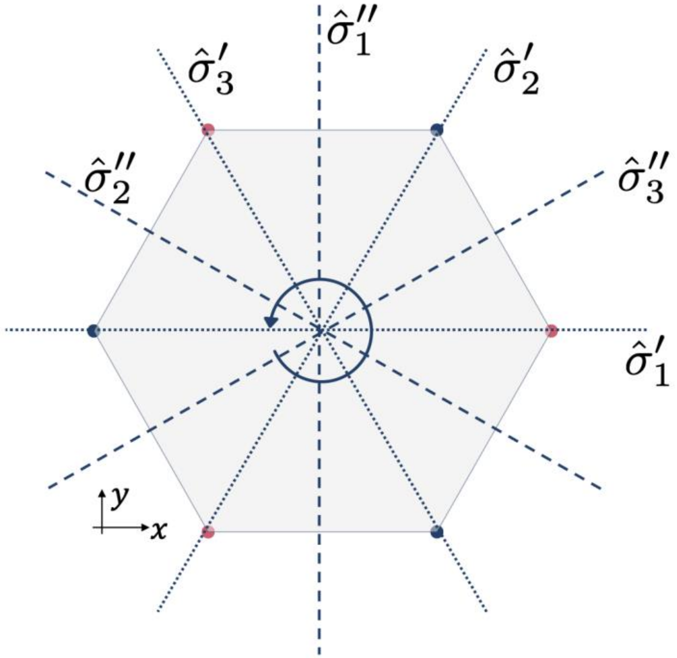
Toy Model : 2 atoms per cell

Point group symmetry C_{6v}





hopping **Rashba spin-orbit** **exchange**

$$H = -t \sum_{\langle ij \rangle \alpha} c^\dagger_{i\alpha} c_{j\alpha} + i\alpha_{\mathrm{R}} \sum_{\langle ij \rangle \alpha\beta} \hat{\mathbf{e}}_z \cdot (\boldsymbol{\sigma} \times \mathbf{d}_{ij})_{\alpha\beta}\, c^\dagger_{i\alpha} c_{j\beta} + \lambda_{\mathrm{ex}} \sum_{i\alpha\beta} (\hat{\mathbf{s}}_i \cdot \boldsymbol{\sigma})_{\alpha\beta}\, c^\dagger_{i\alpha} c_{i\beta}$$

And let's assume that everything is possible…

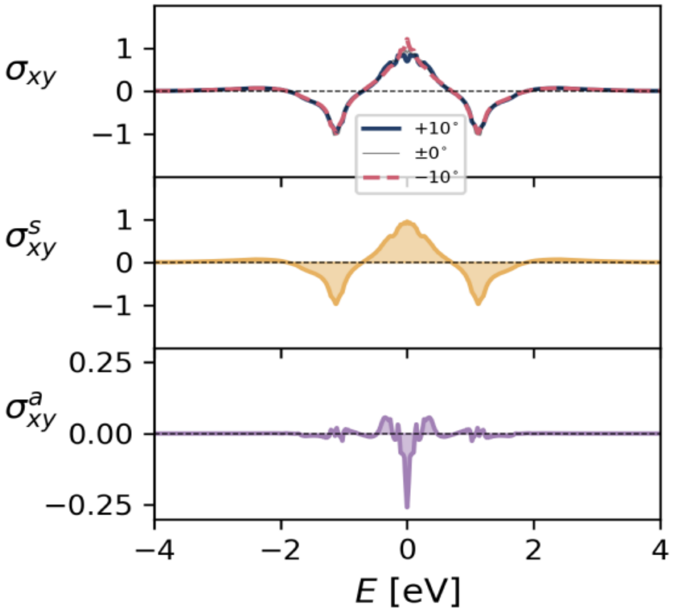
Hall effect : Effect of canting

Kipp, Samanta, Lux, Go, Merte, YM *et al.* Comm. Physics **4**, 99 (2021)

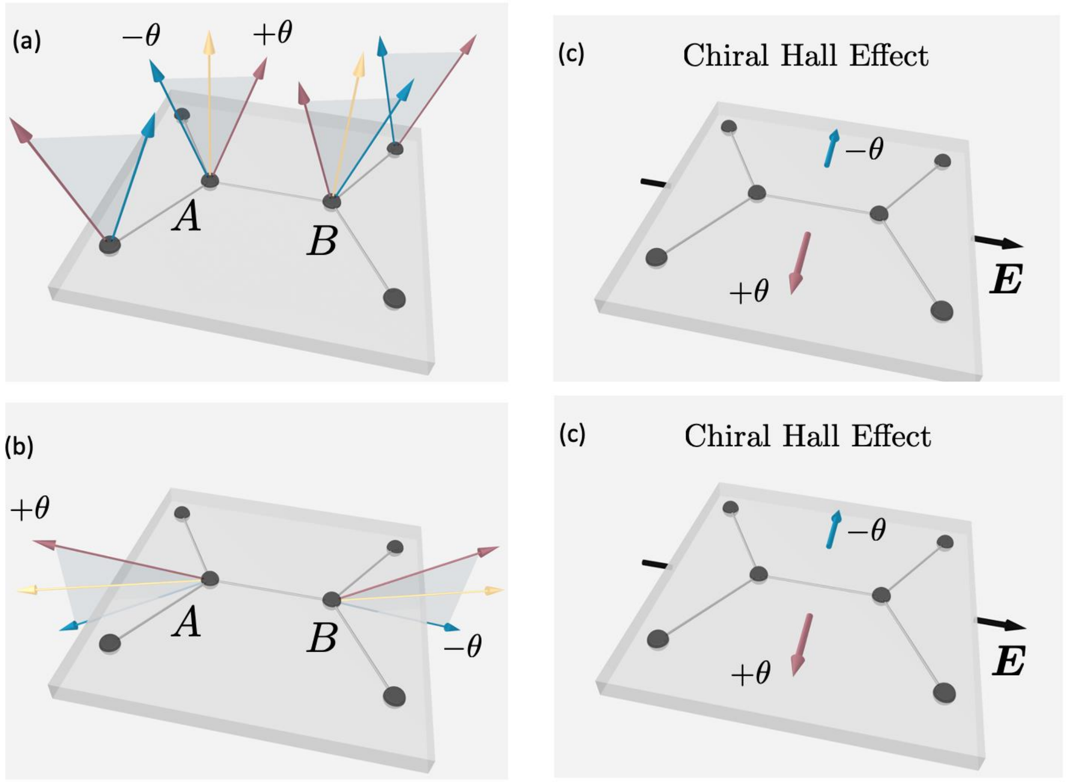
$$\boldsymbol{\chi} = \mathbf{S}_{\rm A} \times \mathbf{S}_{\rm B} \sim \theta$$

Chiral Hall Effect of FMs

honeycomb Rashba ferromagnet



No change in magnetization with sense of chirality!



$$\sigma_{xy}^{s(a)}(\theta) = \frac{\sigma_{xy}(\theta) \pm \sigma_{xy}(-\theta)}{2} = \int_{\rm BZ} \Omega_{xy}^{s(a)}(\theta, \mathbf{k})\, d\mathbf{k}$$

Chiral Hall Effect

Smejkal et al. Sci. Adv. ***6****, eaaz8809*

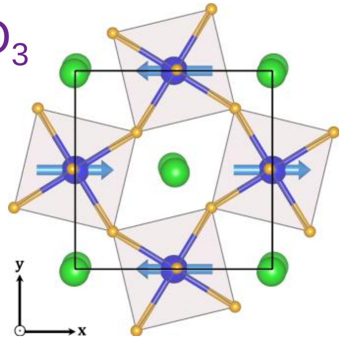
Crystal Hall Effect

Chiral Hall Effect in AFMs

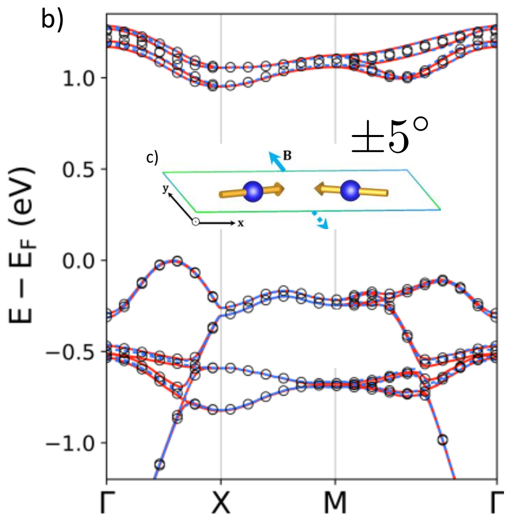
Kipp, Samanta, Lux, Go, Merte, YM *et al.* Comm. Physics **4**, 99 (2021)

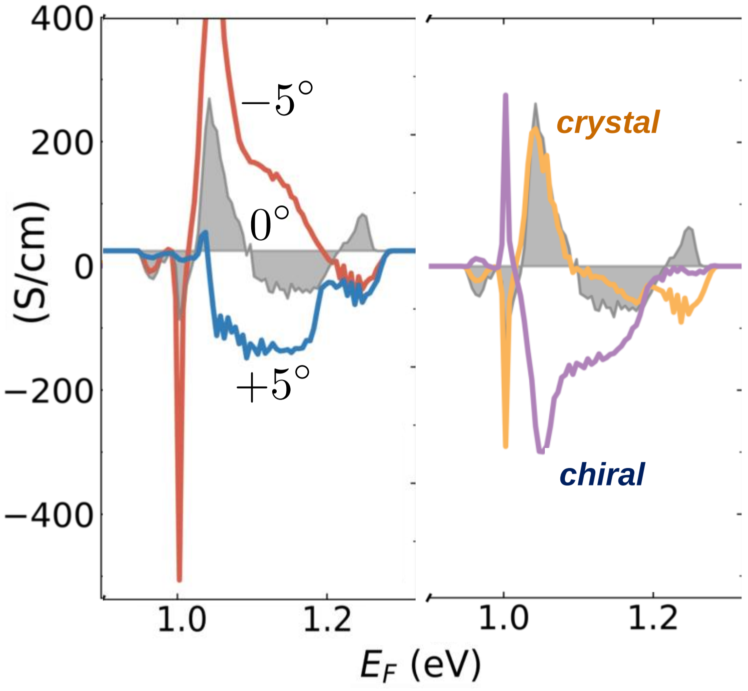
...

SrRuO$_3$

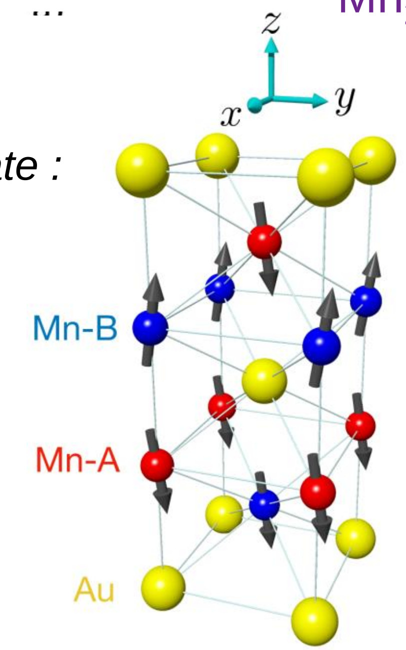


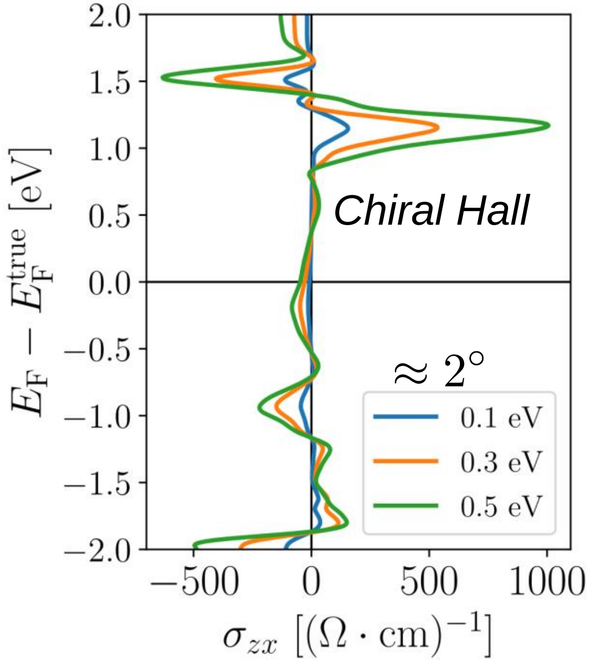
No crystal Hall effect in collinear state :





Mn$_2$Au





Colossal Chiral Hall Effect

DyPtBi: Zhang, **GdPtBi**: Suzuki, **EuTiO$_3$**: Takahashi
CaNaMnBi$_2$: Yang et al. PRL **124**, 137201 (2020)

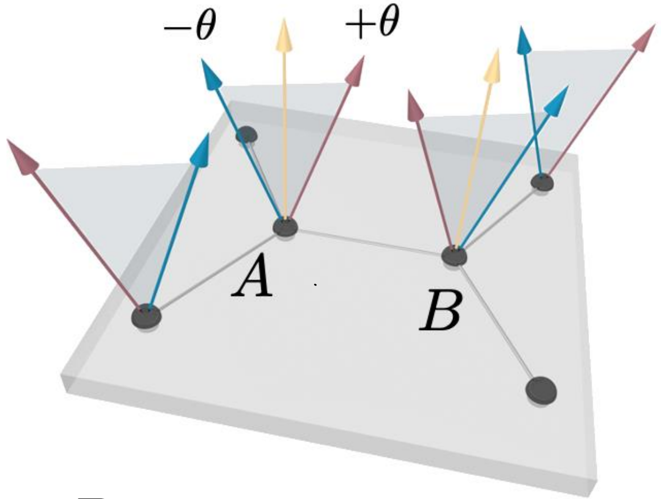
Samanta, Ležaić, YM, *et al.* JAP **127**, 213904 (2020)

Zelezny *et al.* PRL **113**, 157201 (2014)
Bodnar *et al.* Nat. Comm. **9**, 348 (2018)

***Chiral** and **Crystal Hall :** can be also distinguished by optical means*

Chiral Currents : Symmetry

Kipp, Samanta, Lux, Merte, Lezaic, YM *et al.* Comm. Physics **4**, 99 (2021)



$$P\ \mathbf{n}_\pm = \pm\mathbf{n}_\pm$$

staggered / ferromagnetic:

$$\mathbf{n}_\pm = \mathbf{s}_\mathrm{A} \pm \mathbf{s}_\mathrm{B}$$

AHE is *odd* under time-reversal $\sigma_{[xy]} = \frac{1}{2}(\sigma_{xy} - \sigma_{yx})$

This suggests the following expansion :

$$\sigma_{xy}^{\text{odd}} = \sum_{k,l=0}^{\infty} (c_{xy}^{\text{odd}})^i : (\mathbf{n}_-^{\otimes 2k+1} \otimes \mathbf{n}_+^{\otimes 2l})_i \qquad \text{odd in } A \leftrightarrow B$$

$$\sigma_{xy}^{\text{even}} = \sum_{k,l=0}^{\infty} (c_{xy}^{\text{even}})^i : (\mathbf{n}_-^{\otimes 2k} \otimes \mathbf{n}_+^{\otimes 2l+1})_i \qquad \text{even in } A \leftrightarrow B$$

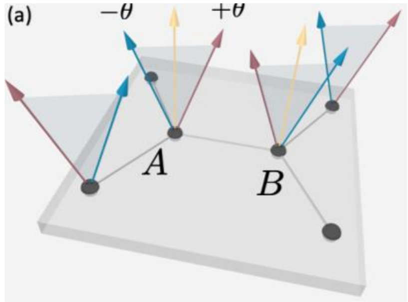
After including the *staggered* nature of tensors into account:

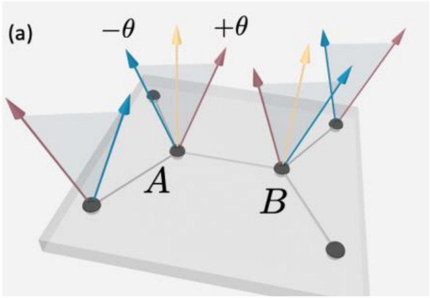
$$\frac{\sigma_{xy}^{\text{odd}} - \sigma_{yx}^{\text{odd}}}{2} \in \text{span}\{n_-^y n_+^y n_+^x + n_-^y n_+^x n_+^y + n_-^x n_+^y n_+^y - n_-^x n_+^x n_+^x\} + \mathcal{O}(n^5)$$

$$\frac{\sigma_{xy}^{\text{even}} - \sigma_{yx}^{\text{even}}}{2} = \in \text{span}\{n_+^z, n_-^z n_-^x n_+^x + n_-^z n_-^y n_+^y,\ n_-^x n_-^z n_+^x + n_-^y n_-^z n_+^y,\ n_-^x n_-^x n_+^z + n_-^y n_-^y n_+^z\} + \mathcal{O}(n^5)$$

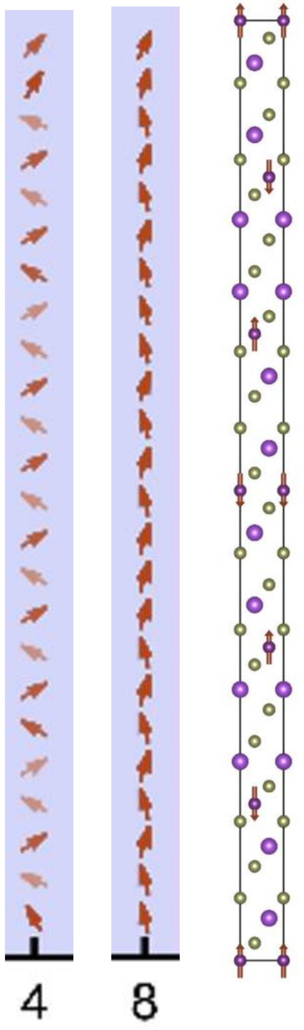
Chiral Hall Effect: Impact

Kipp, Samanta, Lux, Merte, YM *et al.* Comm. Physics **4**, 99 (2021)
Bac, Koller, Lux, Assaf *et al.* arXiv:2103.15801 (2021)





$MnBi_2Te_4$



Tesla

- Prediction of symmetry analysis:

$$\delta\sigma_{xy} \sim \mathbf{n}_+ \cdot \mathbf{n}_-^2$$

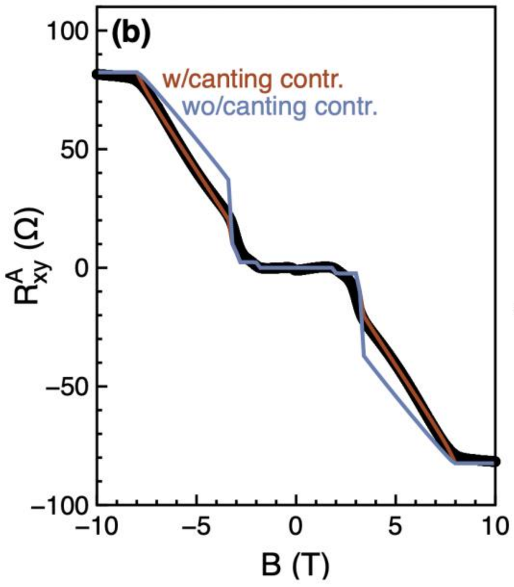
AFM chirality

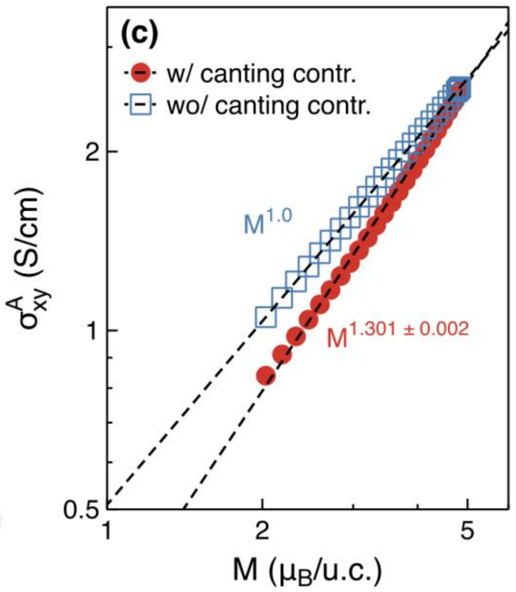
$(\text{FM chirality})^2$

"features" in B-field behavior

scaling law with magnetization

Will help you read out chirality





even	Crystal Hall Effect	Chiral Hall Effect
	$\hat{\mathbf{n}}_+ + \beta_{ij}^{\mathrm{FM}}(\hat{\mathbf{n}}_+)\chi_i\chi_j$	$\beta_i^{\mathrm{AFM}}(\hat{\mathbf{n}}_-)\chi_i$
	inversion symmetry	

8 Tesla ← *4 Tesla*

$$n_\pm = S_A \pm S_B$$

$$\chi = S_A \times S_B = \frac{1}{2}(n_- \times n_+)$$

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Chiral Hall Effect: Origins

Kipp, Samanta, Lux, Go, Lezaic, YM *et al.* Comm. Physics **4**, 99 (2021)

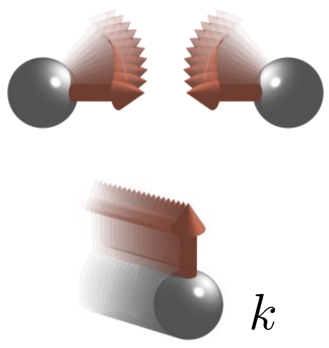
➢ Reference state + small admixture of needed chirality
apply perturbation theory → **obtain expressions**

2-spin chiral Hall effect:

$$\Omega^a_{xy} \approx |\theta| \cdot \delta\Omega_{xy}$$

λ

Staggered tilt

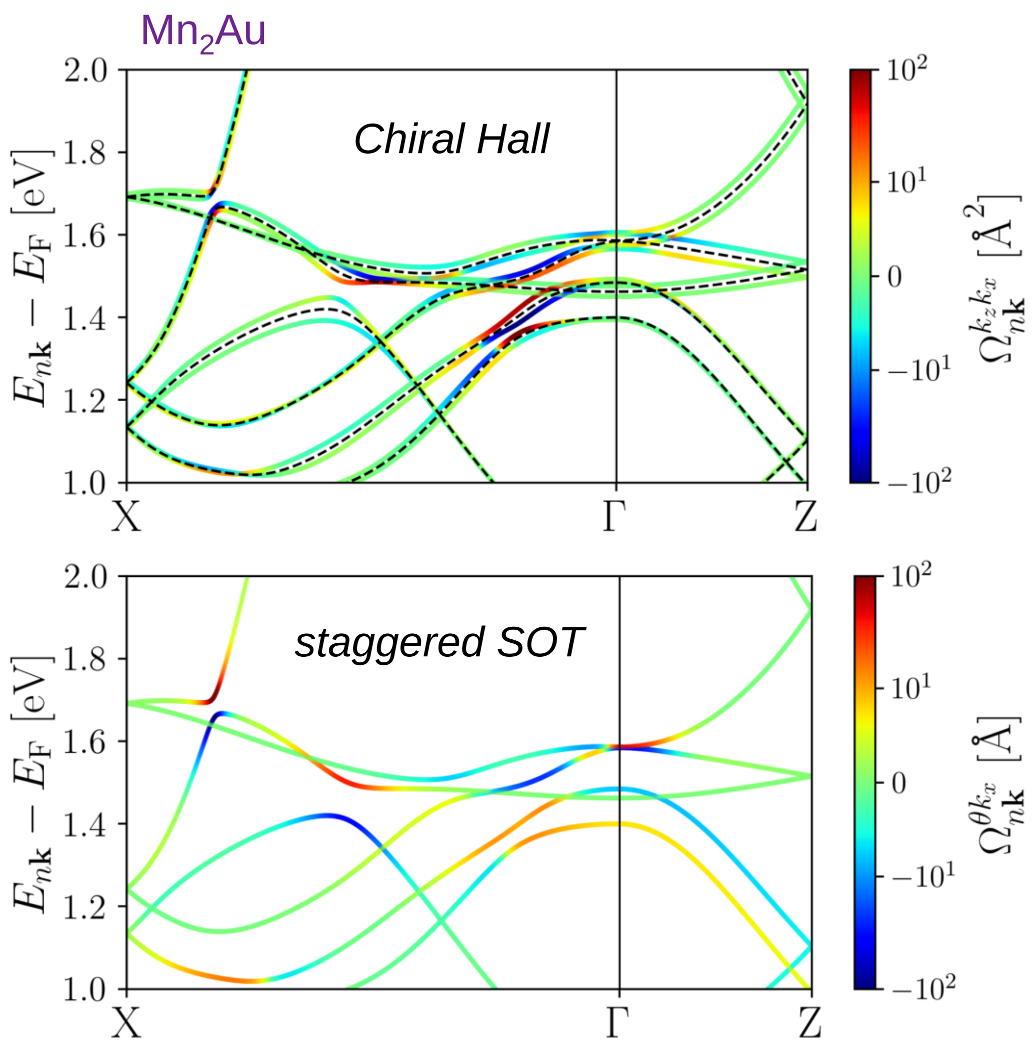


k

Non-linear in *E* contributions to the Hall effect

"staggered" mixed Berry curvature

"staggered" ***spin-orbit torques*** → $\Omega_{x\lambda}$



Complex geometric nature:

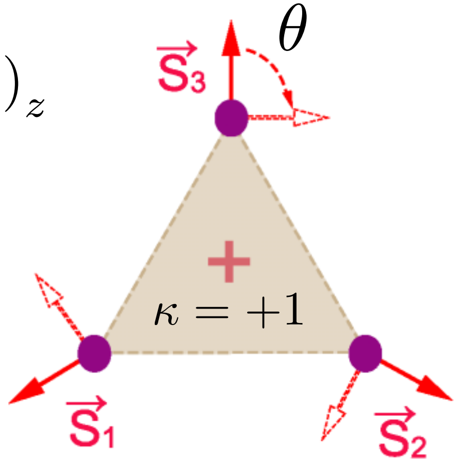
k-curvature tensor *quantum metric tensor* *mixed curvature tensor*

$$\delta\Omega_{xy} = \mathrm{tr}_{\mathrm{occ}}\Im\left([\Omega_{xy}, \mathcal{A}_\lambda] + [\mathcal{Q}_{\lambda y}, \mathcal{A}_x] + [\Omega_{x\lambda}, \mathcal{A}_y]\right)$$

Chiral Currents : Mn_3X

Zhou, Hanke, Feng, Blügel, Yao, Y.M. + Lux (2019, 2022)

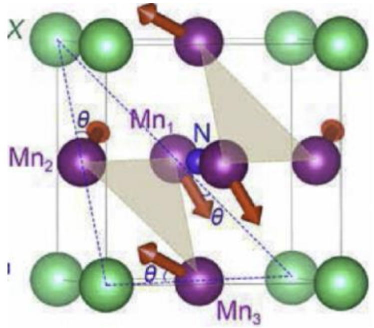
vector chirality $\kappa \sim \sum_{<i,j>} (\mathbf{S}_i \times \mathbf{S}_j)_z$



"octupolar" chirality $\mathcal{O} \sim \mathbf{S}_1 + R_{\frac{2\pi}{3}} \mathbf{S}_2 + R^2_{\frac{2\pi}{3}} \mathbf{S}_3 \sim \mathbf{S}_1 \times (\mathbf{S}_2 \times \mathbf{S}_3)$

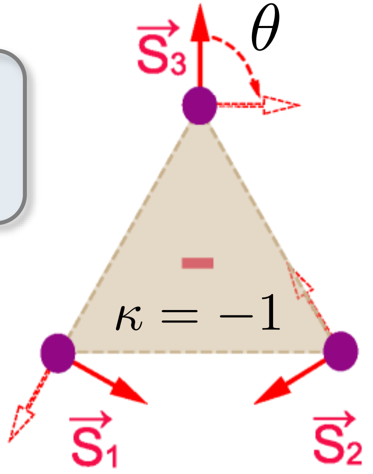
Magnetic state: $\Gamma_{\mathrm{mag}} = \Gamma_{\mathbf{s}} \otimes \Gamma_{3c}$

$(\sigma_{[yz]}, \sigma_{[zx]}, \sigma_{[xy]}) = T_{1g}$

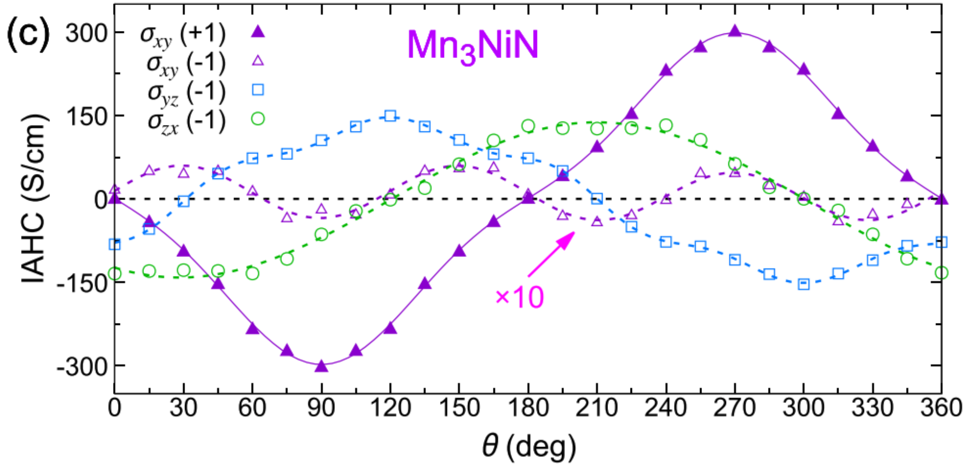


Projector onto relevant subspace: $P^{\nu}_{T_{1g}} = \frac{3}{48} \sum_{\sigma \in m\bar{3}m} (T_{1g}(\sigma))_{\nu\nu}\, \Gamma_{\mathrm{mag}}(\sigma)$

$$(\sigma_{[yz]}, \sigma_{[zx]}, \sigma_{[xy]}) = \gamma_{\mathrm{AHE}}\,(S_1^x + S_2^x + S_3^x, S_1^y + S_2^y + S_3^y, S_1^z + S_2^z + S_3^z) + \gamma_{\mathrm{CHE}}\,(-S_1^x + S_2^x + S_3^x, S_1^y - S_2^y + S_3^y, S_1^z + S_2^z - S_3^z)$$



enables read-out via AHE



$$\sigma_{[xy]} \sim \begin{cases} \gamma_{\mathrm{CHE}}\, \mathcal{O}_x, & \kappa = +1 \\ 0, & \kappa = -1 \end{cases}$$

Good fit to ab-initio data:

$\gamma_{\mathrm{CHE}} \approx 90\,\mathrm{S/cm}$

Suzuki et al. PRB **95**, 094406 (2017)

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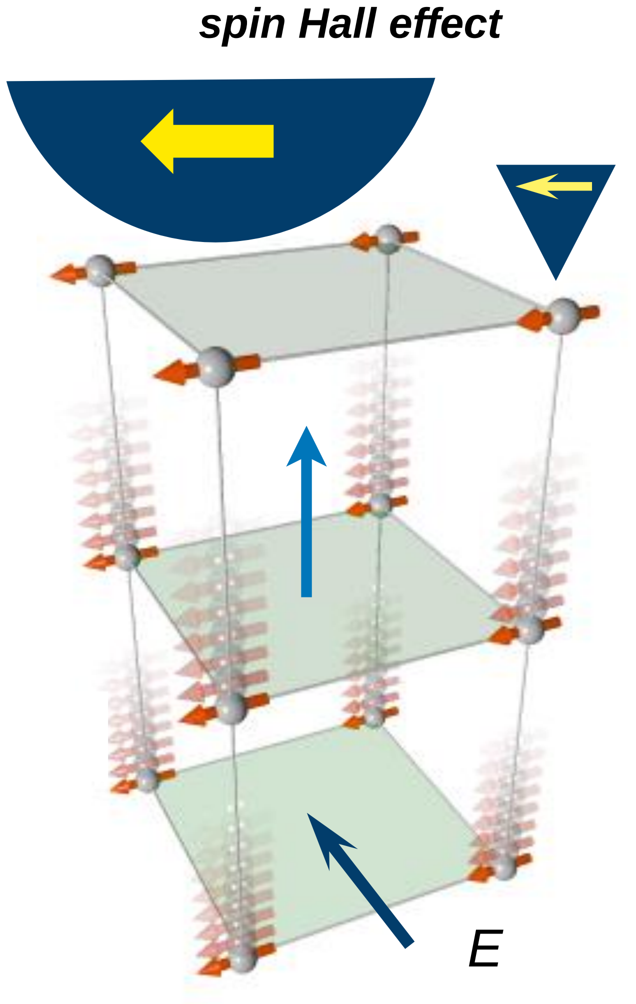
Chiral Spin Currents

Go, Sallermann, Lux, Blügel, Gomonay, Y.M., arXiv:2201.11476 (2022)

Freimuth, Blügel, Y.M. PRL **105**, 246602 ’10
Rauch, Töpler, Mertig PRB **101**, 064206 ‘20



non-magnetic crystal

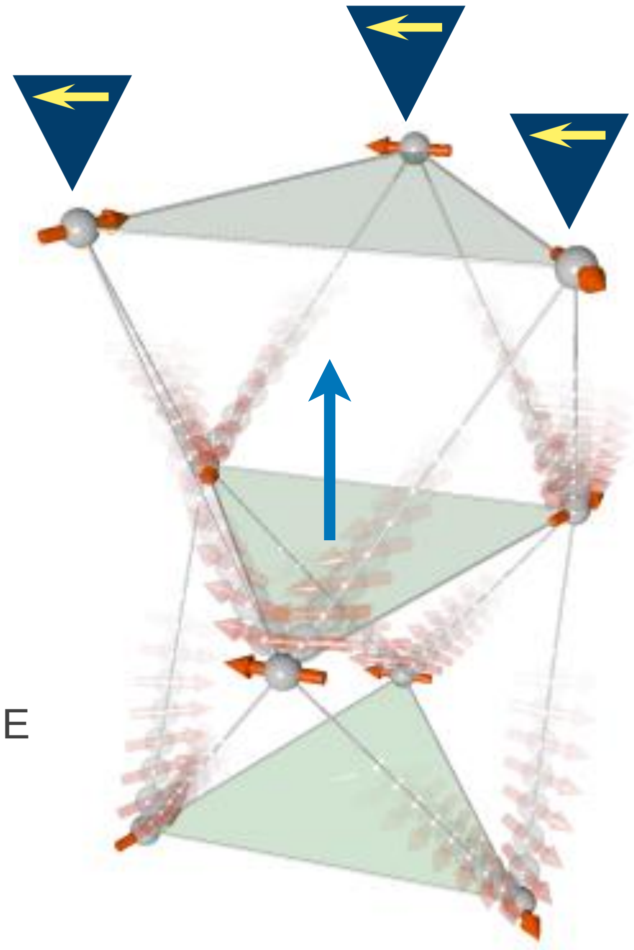
Allow for “hidden” structure of spin currents :

“normal” spin current

$$\mathbf{Q} = \sum_{ijs} \sigma^{s}_{ij} \; \hat{\mathbf{e}}_i \otimes \hat{\mathbf{s}}_s \qquad E_j$$

spin current density — *current* — *spin polarization*

in spirit: spin-decomposition of AHE

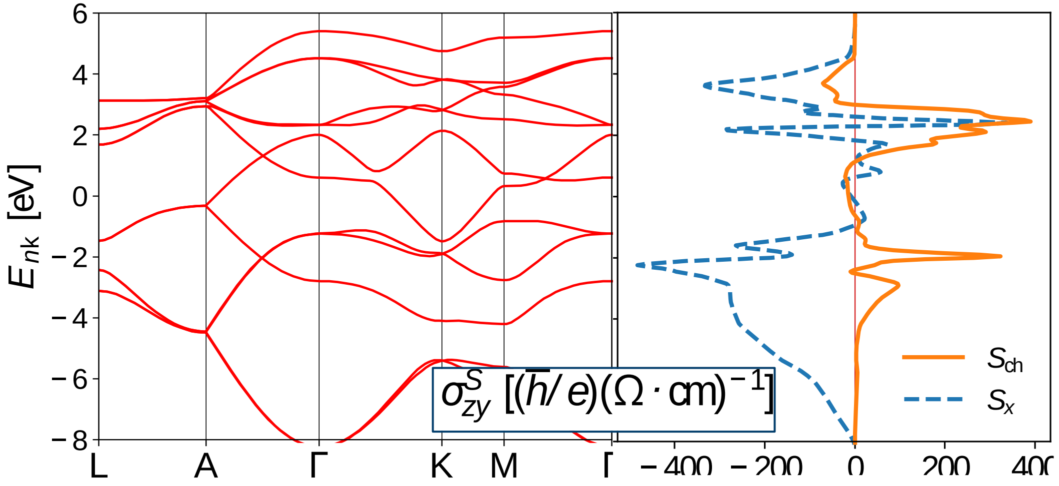


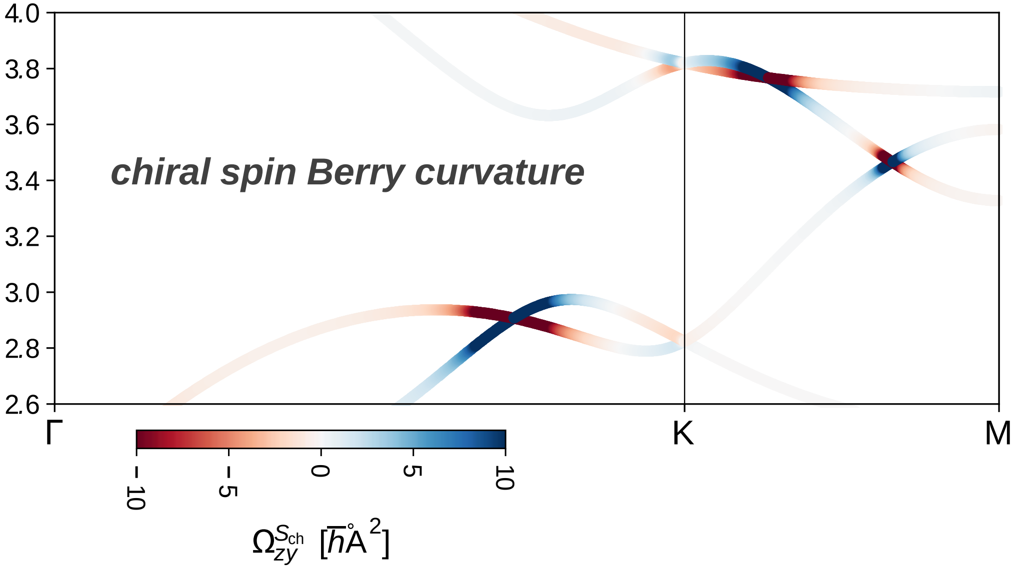
Symmetry allows for ***site-dependent***
spin current polarization!

Chiral Spin Hall Effect : Mn_3X

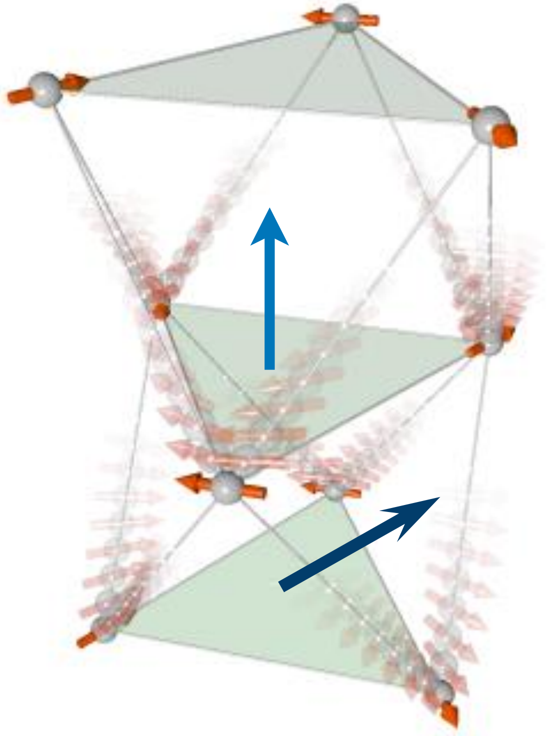
Go, Sallermann, Lux, Blügel, Gomonay, Y.M., arXiv:2201.11476 (2022)

tight-binding model for Mn_3X structure





chiral spin Hall effect



Non-magnetic Mn3X lattice:

electric field along y

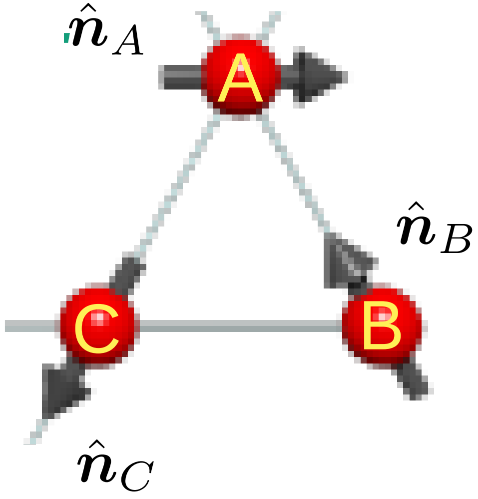
spin current along z

Chiral current operator:

$$j_z^{\mathrm{chi}} = 1/2\,(S_{\mathrm{chi}} v_z + v_z S_{\mathrm{chi}})$$

Chiral spin operator

$$S_{\mathrm{chi}} = \boldsymbol{S}_A \cdot \hat{\boldsymbol{n}}_A + \boldsymbol{S}_B \cdot \hat{\boldsymbol{n}}_B + \boldsymbol{S}_C \cdot \hat{\boldsymbol{n}}_C$$

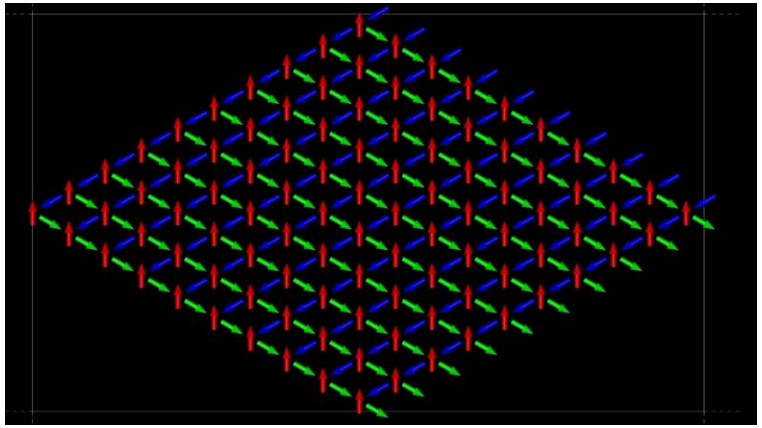


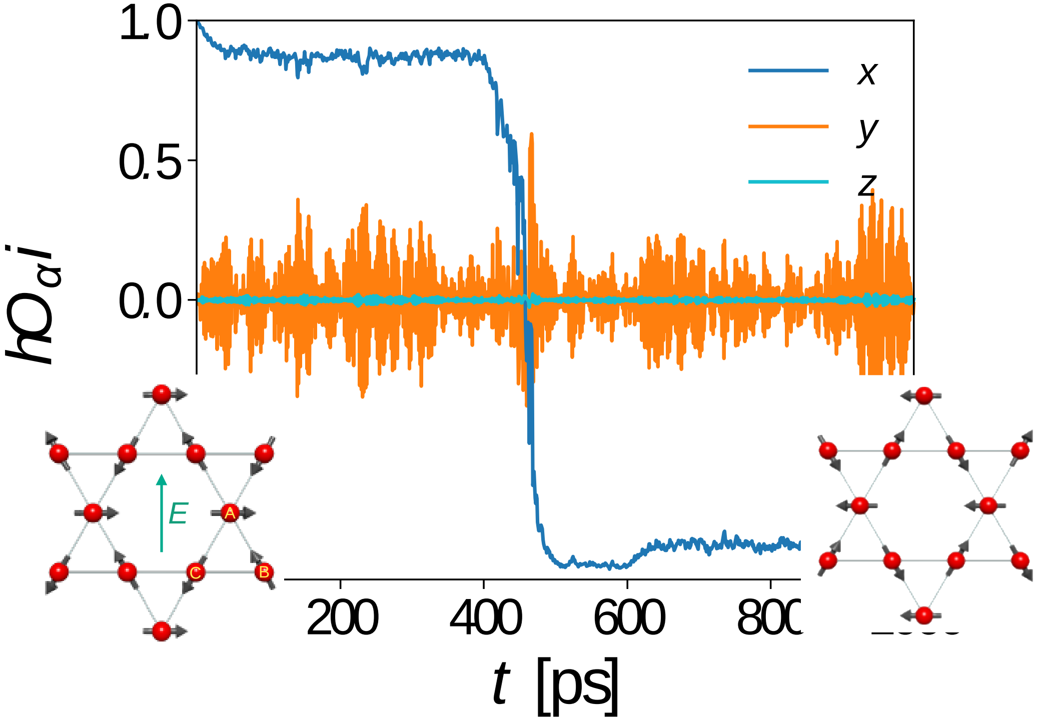
Kubo formalism for response

Can couple to the spin texture!

Chiral Spin Currents for Chirality Switching

Go, Sallermann, Lux, Blügel, Gomonay, Y.M., arXiv:2201.11476 (2022)





Chiral spin currents : accumulate at the surface

$$\boldsymbol{\tau}_i^{\text{chiral}} \sim \hat{\mathbf{m}}_i \times (\hat{\mathbf{m}}_i \times \hat{\boldsymbol{n}}_i)$$

anomalous torque

LLG dynamics:

$$\frac{d\hat{m}_i}{dt} = -|\gamma|\hat{m}_i \times (B_i^{\text{eff}} + B_i^{\text{fl}}) + \alpha \hat{m}_i \times \frac{d\hat{m}_i}{dt} + \tau_i^{\text{chiral}}$$

Predicts switching of octupolar chirality on 100 ps **scale**

Different from:

Tsai et al., Nature **580**, 608 (2020)
Takeuchi et al., Nature Mat. **20**, 1364 (2021)

Spin-dependent contributions: higher-order

complex anatomy of spin currents possible!

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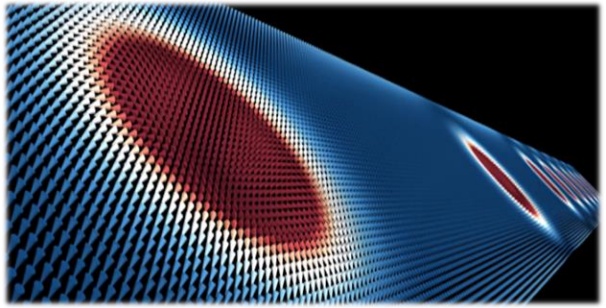
Gradient expansion : (very) smooth textures

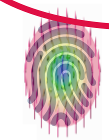
Kipp, Lux, YM, Phys. Rev. Research **3**, 043155 (2021)



- Given a texture, the spirit of gradient expansion dictates:

$$\sigma_{\alpha\beta}[\hat{\boldsymbol{n}}] = \langle \sigma^{col}_{\alpha\beta}(\hat{\boldsymbol{n}}) + \sigma^{\chi}_{\alpha\beta\gamma\delta}(\hat{\boldsymbol{n}})\partial_\gamma n_\delta + \mathcal{O}(\partial^2)\rangle$$

Collinear terms



Chiral terms

Onsager relations

$$\sigma_{[\alpha\beta]}[\hat{\boldsymbol{n}}] = -\sigma_{[\alpha\beta]}[-\hat{\boldsymbol{n}}]$$

$$\sigma_{(\alpha\beta)}[\hat{\boldsymbol{n}}] = \sigma_{(\alpha\beta)}[-\hat{\boldsymbol{n}}]$$

Point group symmetry C_{6v}

- Conductivity in terms of irreducible representations of the symmetry group: $\sigma = A_1 + A_2 + E_2$

magnetoconductivity

$$\sigma_{A_1}[\hat{\mathbf{n}}] = (\gamma_{\mathrm{LC}} + \gamma_{\mathrm{MC}}) + \gamma_{\mathrm{AMC}} \langle n_\perp^2 - n_\parallel^2\rangle + \gamma_{\mathrm{CMC}} \langle(\nabla\cdot\hat{\mathbf{n}} - \hat{\mathbf{n}}\cdot\nabla)n_z$$

planar Hall effect

$$\sigma_{E_2}[\hat{\mathbf{n}}] = \gamma_{\mathrm{PHE}} \langle[(n_x^2 - n_y^2)/2, n_x n_y]\rangle + \gamma_{\mathrm{CPHE}} \langle n_z(\partial_x n_x - \partial_y n_y, \partial_x n_y + \partial_y n_x)\rangle$$

anomalous Hall effect

$$\sigma_{A_2}[\hat{\mathbf{n}}] = \gamma_{\mathrm{AHE}} \langle n_z\rangle + \gamma_{\mathrm{CHE}} \langle(\nabla\cdot\hat{\mathbf{n}})(n_\perp^2 - n_\parallel^2)\rangle$$

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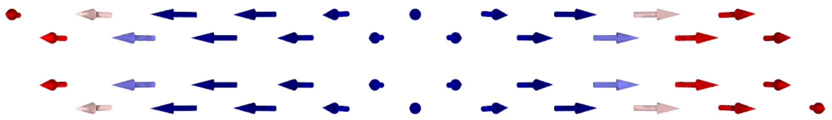
Gradient expansion : Predictions

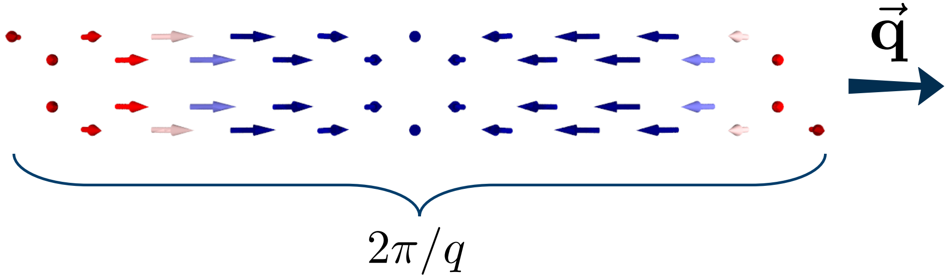
Kipp, Lux, YM, Phys. Rev. Research **3**, 043155 (2021)

Irrep	Channel	Name	Collinear effects $\mathcal{O}(\partial^0)$	Chiral effects $\mathcal{O}(\partial^1)$
A_1	$(\sigma_{(xx)} + \sigma_{(yy)})/2$	isotropic longitudinal	longitudinal conductivity (LC), magnetoconductivity (MC), anisotropic magnetoconductivity (AMC)	chiral magnetoconductivity (CMC)
A_2	$\sigma_{[xy]}$	antisymmetric transverse	anomalous Hall effect (AHE)	chiral Hall effect (CHE)
$(E_2)_1$	$(\sigma_{(xx)} - \sigma_{(yy)})/2$	anisotropic longitudinal	longitudinal planar Hall effect (LPHE)	chiral longitudinal planar Hall effect (CLPHE)
$(E_2)_2$	$\sigma_{(xy)}$	symmetric transverse	planar Hall effect (PHE)	chiral planar Hall effect (CPHE)

Type		AHE	CHE	MC	CMC	PHE	CPHE
Néel	[100]			✓	✓		
	[0$\bar{1}$1]			✓	✓		
	[110]			✓	✓	✓	✓
Bloch	[100]			✓			✓
	[0$\bar{1}$1]			✓			✓
	[110]			✓	✓	✓	✓
Cone	[100]	✓	✓	✓	✓		
	[0$\bar{1}$1]	✓	✓	✓	✓		
	[110]	✓	✓	✓	✓	✓	✓



$$\sigma^{c(nc)}_{\alpha\beta} = \frac{\sigma_{\alpha\beta}(q) \mp \sigma_{\alpha\beta}(-q)}{2}$$



- *Kubo formalism*
- *Up to 2000 atoms*
- *Variable disorder*

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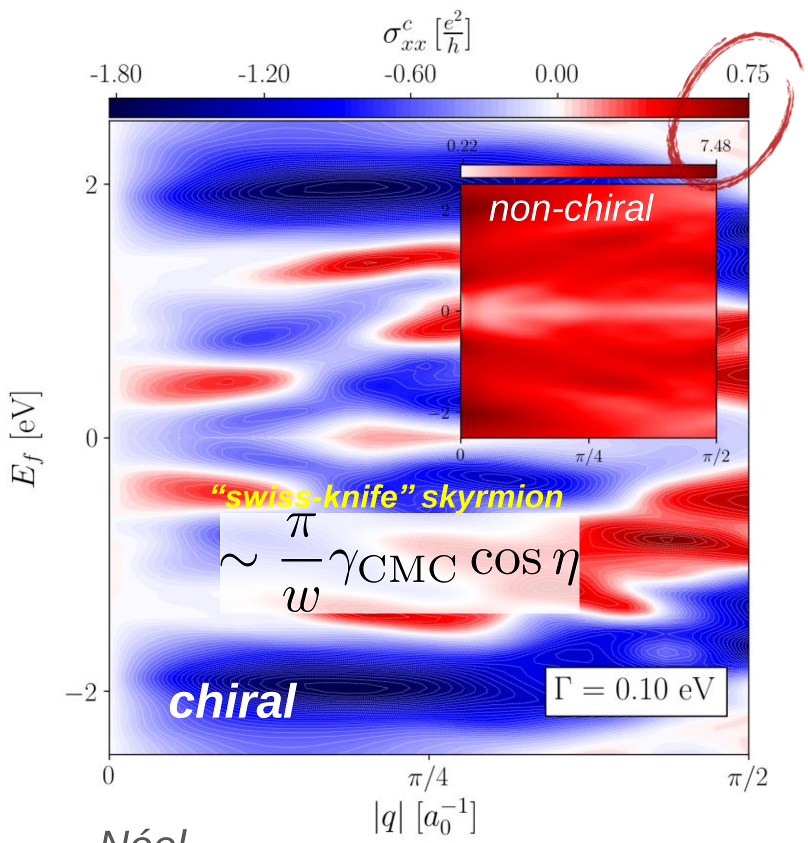
Redies, Lux, YM, *et al*. PRB **102**, 184407

Chiral Transport of Spirals

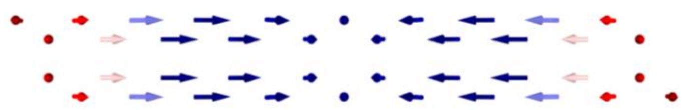
Kipp, Lux, YM, Phys. Rev. Research **3**, 043155 (2021)

prominent Berry phase signal

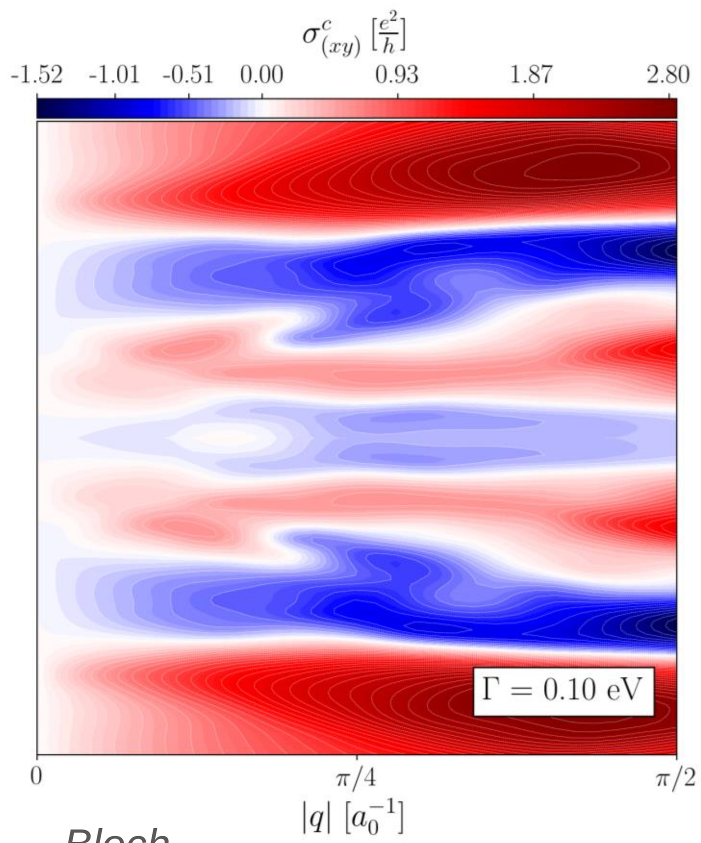
chiral magnetoconductivity



Néel

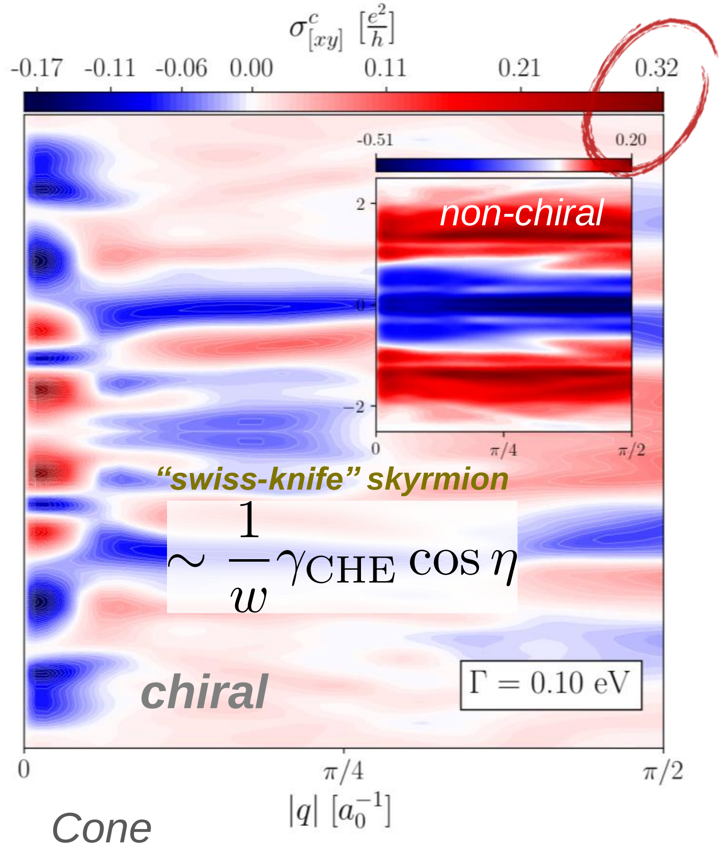


chiral planar Hall effect



Bloch

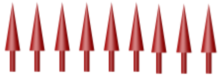
chiral Hall effect

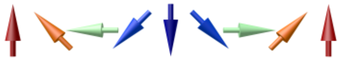


Cone

Chiral Hall Effect of Textures

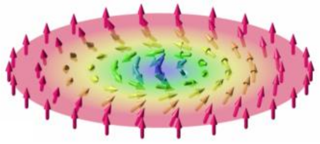
Lux, Freimuth, Praß, Blügel, Y.M., arXiv:2005.12629; PRL **124**, 096602 (2020)

Anomalous Hall effect 

 ***Chiral Hall Effect***

$$G^< = G_0^< + \hbar[G_E^<] : \mathbf{E} + \hbar^2[G_{E\partial n}^<] : \mathbf{E}\ \boldsymbol{\partial}\hat{\mathbf{n}} + \hbar^3[G_{E\partial n\partial n}^<] : \mathbf{E}\ \boldsymbol{\partial}\hat{\mathbf{n}}\ \boldsymbol{\partial}\hat{\mathbf{n}}$$

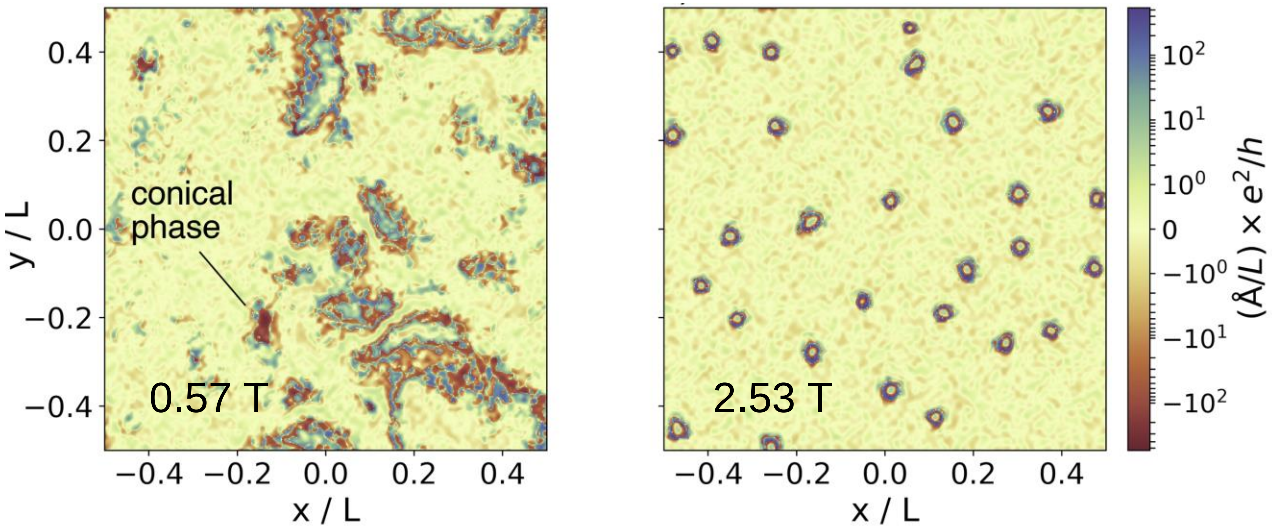
Gradient expansion technique



topological Hall effect

also beyond emergent field…

$$J = 1\,\mathrm{meV} \quad D = 0.5\,\mathrm{meV}$$



Emerges in complex textures,
e.g. skyrmions, vortices, bobbers…

➢ **Possibly observed in many systems:**

can tell you more than you'd think!

Redies, Lux, YM, *et al*. PRB **102**, 184407
Meynell, Monchesky *et al.* PRB **90**, 224419
Bouaziz, Blügel *et al.* PRL **126**, 147203 (2021)

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Non-commutative phase-space picture

$$\sigma_{xy}^{\mathrm{sea}} = \hbar e^2 \Re\, \mathfrak{Tr}_{\mathrm{sea}} \left\langle G^{\mathrm{R}} \star v_x \star G^{\mathrm{R}} \star v_y \star G^{\mathrm{R}} - (x \leftrightarrow y)\right\rangle$$

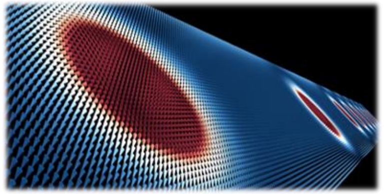
noncommutative geometry

Non-commutative Berry phase

$$\sigma_{xy}^{\mathrm{Berry}} \propto \int \mathrm{d}\mathbf{x} \int \mathrm{d}\mathbf{p}\; \rho(\mathbf{x},\mathbf{p}) \sum_i \Omega_{p_x p_y} \Omega_{x_i p_i}$$

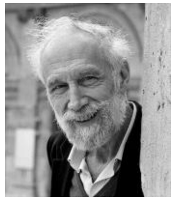
gauge theory of skyrmions
~ string theory!

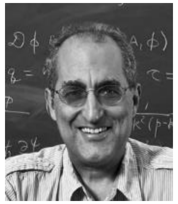
nuclear physics string theory



$$\star \;\equiv\; \exp\left\{\frac{i\hbar}{2}\left(\overleftarrow{\partial}_x \overrightarrow{\partial}_p - \overleftarrow{\partial}_p \overrightarrow{\partial}_x\right)\right\}$$

integer & fractional quantum Hall effect



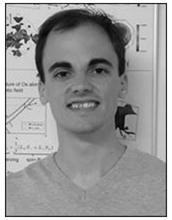


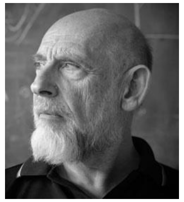
A. Connes **N. Seiberg** **E. Witten**

J. High Energy Phys. 1998, 003 (1998).

J. High Energy Phys. 1999, 032 (1999)

noncommutative gauge theory





L. Susskind *arXiv* (2001)

J. Bellissard *J. Math. Phys.* '94

Fabian Lux, Freimuth, Praß, Blügel, Y.M.,
arXiv:2005.12629
PRL **124**, 096602 (2020)
arXiv:2103.01047

Chirality and Magnons

Zhang, Lux, Go, Y.M. *et al.* Comm. Phys. **3**, 227 (2020)

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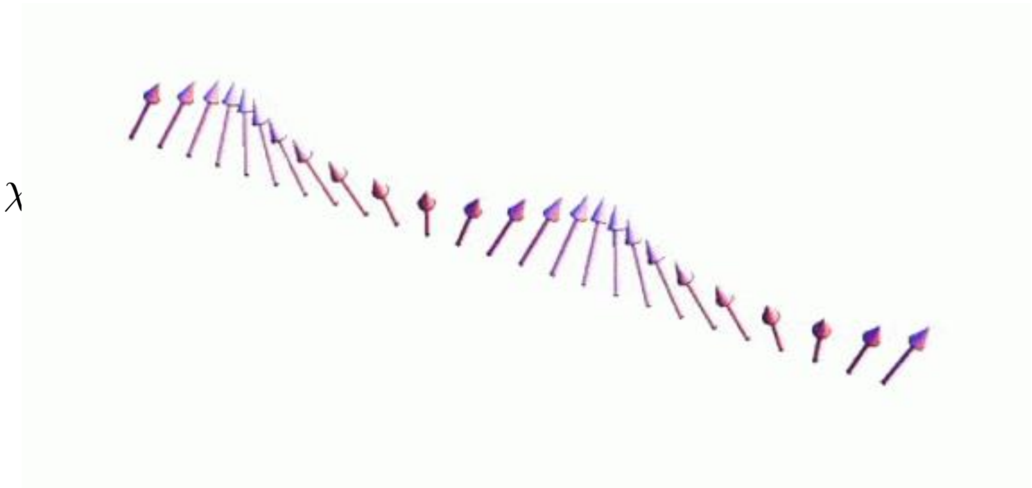
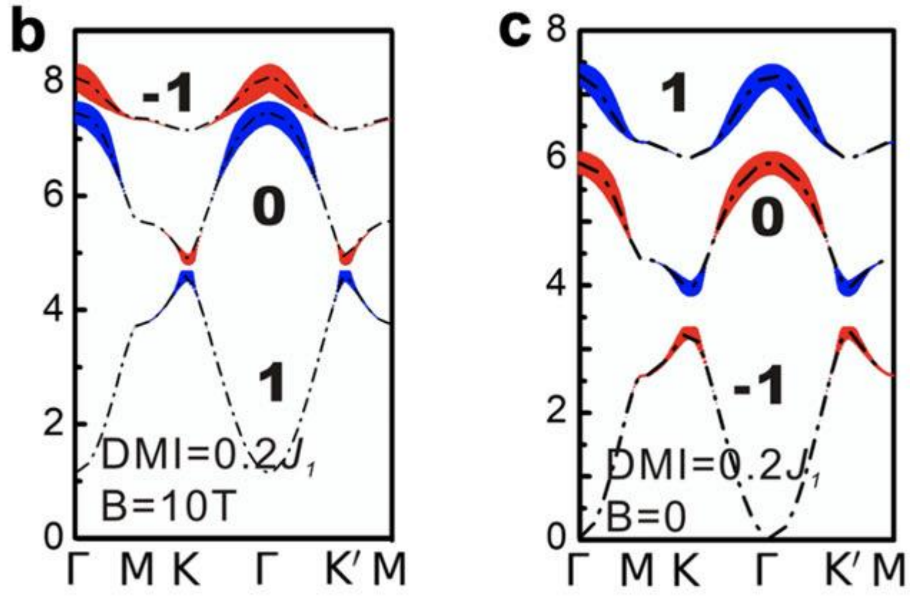
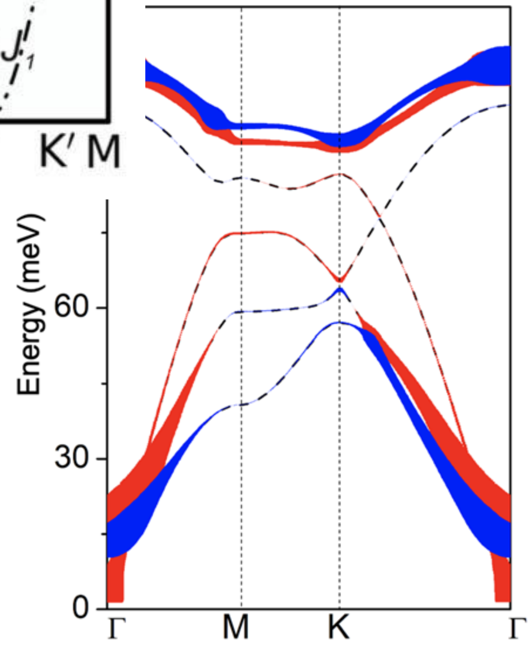
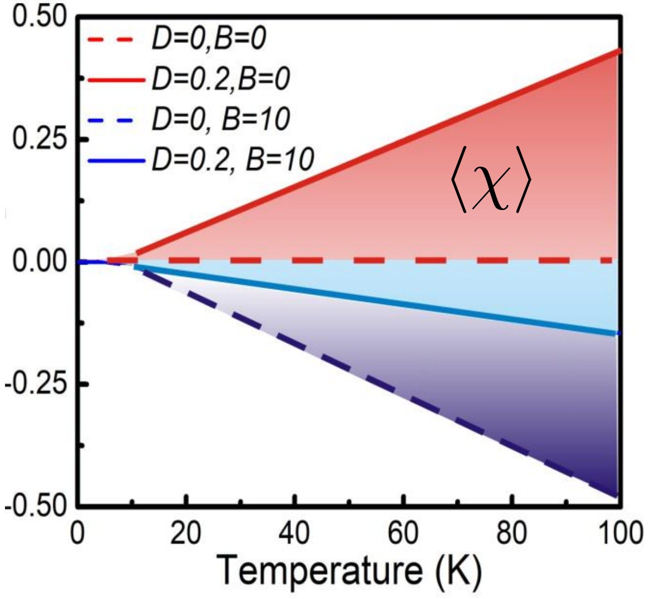




→ *ferromagnetic kagome lattice*

→ ***Mn_3Ge*** *non-collinear coplanar*





"Topological / Chiral" electronic effects

in fluctuating "non-chiral" magnets

Makes chirality relevant even if you don't know it

$$H = -\frac{1}{2}\sum_{ij} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j - \frac{1}{2}\sum_{ij} \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

$$- \mathbf{B} \cdot \kappa^{\mathrm{TO}} \sum_{ijk} \hat{\mathbf{e}}_{ijk}[\mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k)] - \mathbf{B} \cdot \sum_i \mathbf{S}_i \,,$$

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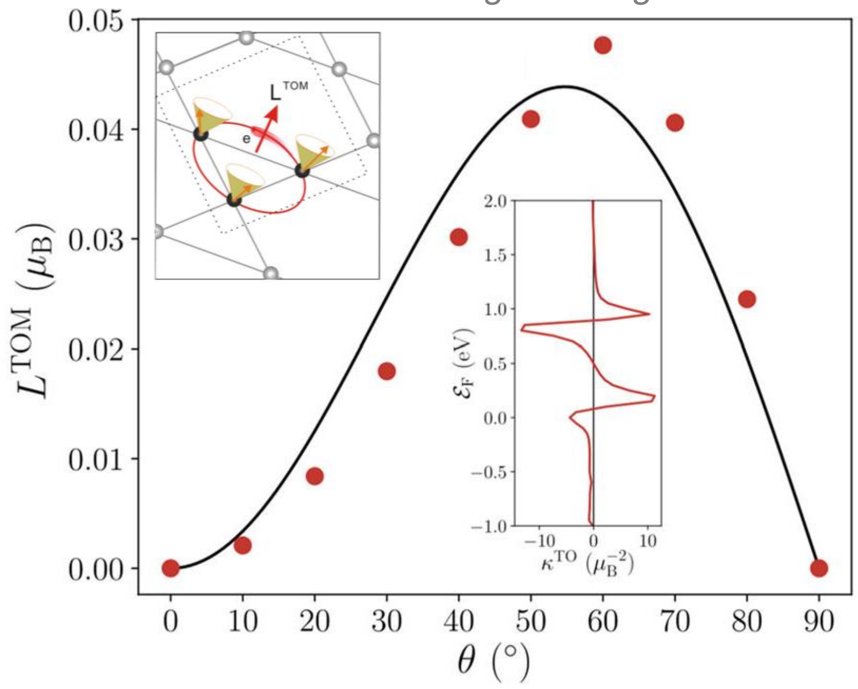
Orbital magnetism of magnons

Zhang, Lux, Go, Y.M. *et al.* Comm. Phys. **3**, 227 (2020)

ferromagnetic kagome lattice



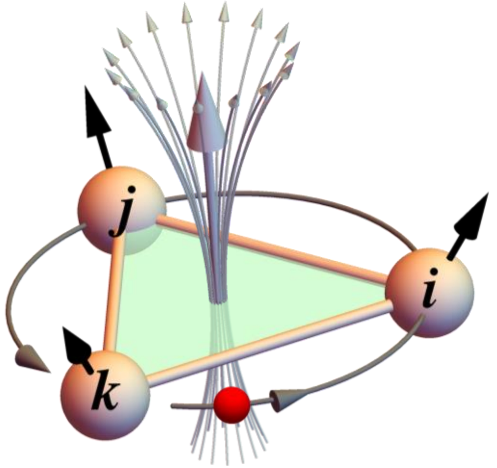
Magnon-driven orbital moment:

$$L^{\mathrm{TOM}}_{n\mathbf{k}} = \kappa^{\mathrm{TO}} \langle \Psi_{n\mathbf{k}} | \chi(\mathbf{k}) | \Psi_{n\mathbf{k}} \rangle$$

Topological Orbital Magnetism

giant effective fields

$$\boldsymbol{L}^{\mathrm{TO}}_{ijk} = \varkappa^{\mathrm{TO}}_{ijk} \left[\boldsymbol{S}_i \cdot (\boldsymbol{S}_j \times \boldsymbol{S}_k)\right] \boldsymbol{\tau}_{ijk}$$



Hanke, YM *et al.* Sci. Rep. **7**, 41078; Dias *et al.* Nat. Commun. **7**, 13613
Lux, Freimuth, Blügel, YM *et al.* Commun. Phys. **1**, 60 (2018)
Redies, Lux, Hanke, YM *et al.* PRB **99**, 140407(R) (2020)

Taguchi *et al.* Science **291**, 2573 (2001)
Shindou, Nagaosa, PRL **87**, 116801 (2001)

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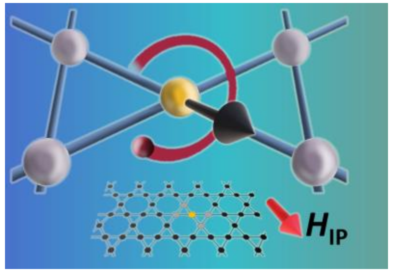
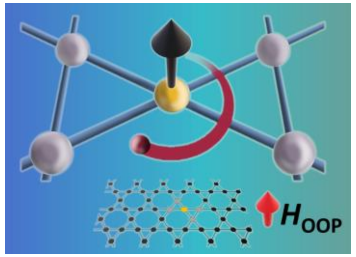
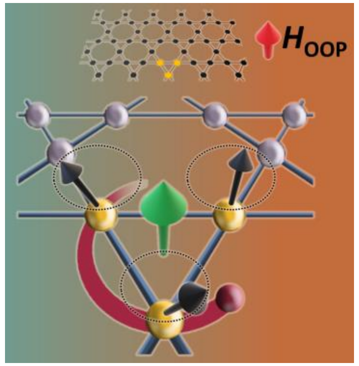
Chirality and g-factor

Alahmed, Wen, Zhang, Lux, Y.M., Zhang, Lee, Li et al. (2021)







Orbital moment is correlated with the (spectroscopic) ***g*-factor** as:

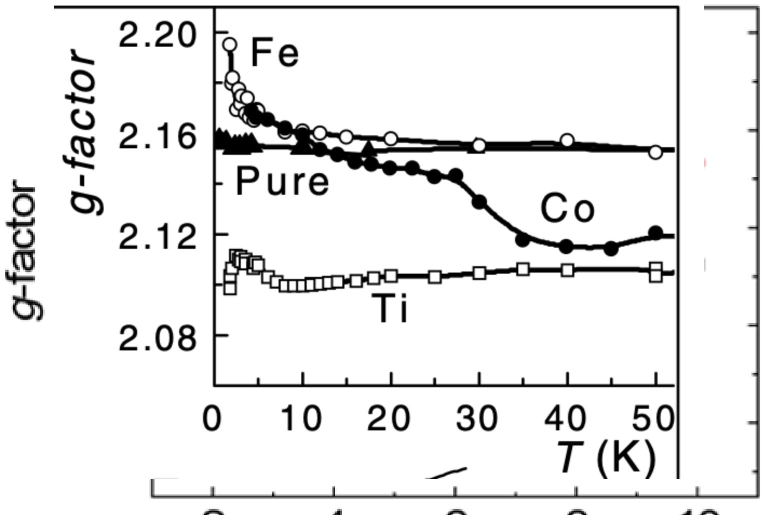
$$g = 2\left(1 + \frac{M_L}{M_S}\right)$$

Expectation:

- **OOP *g*-factor increases with *T***
- **IP *g*-factor decreases with T**

Magnons mediate OOP orbital moment with increasing T

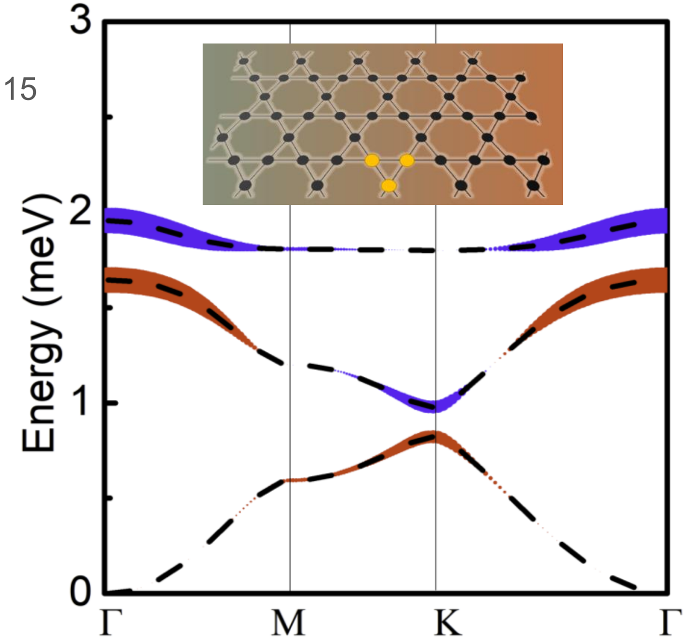
Kittel Phys. Rev. **76**, 743 (1949)
Kläui, Weiler, Mokrousov, *Physik Journal* Feb 2022



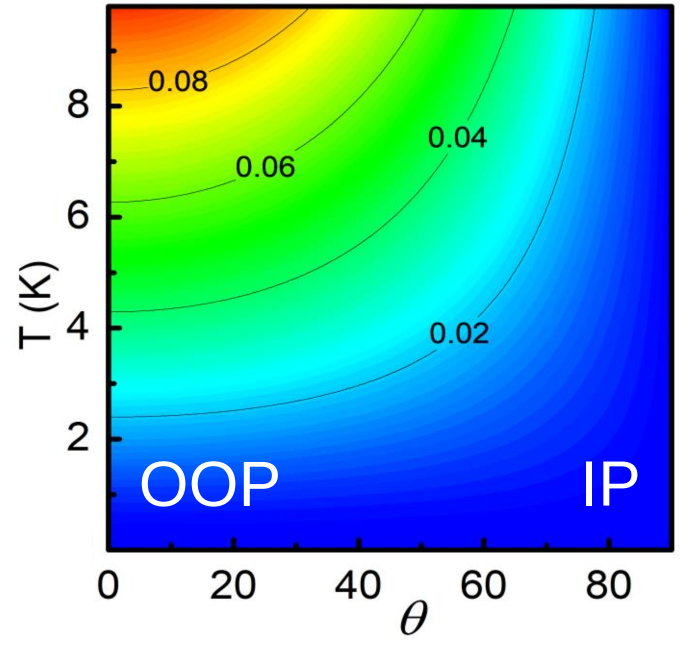
Demishev et al. EPL 63, 446 (2003), $CuGeO_3$
Farle, Rep. Prog. Phys. 1998

Chisnell et al.
PRL **115**, 147201 '15

Cu(1,3-bdc)



Orbital magnetization (m_B)



Transport of chirality by magnons

Zhang, Lux, Go, Y.M. *et al.* Comm. Phys. **3**, 227 (2020)

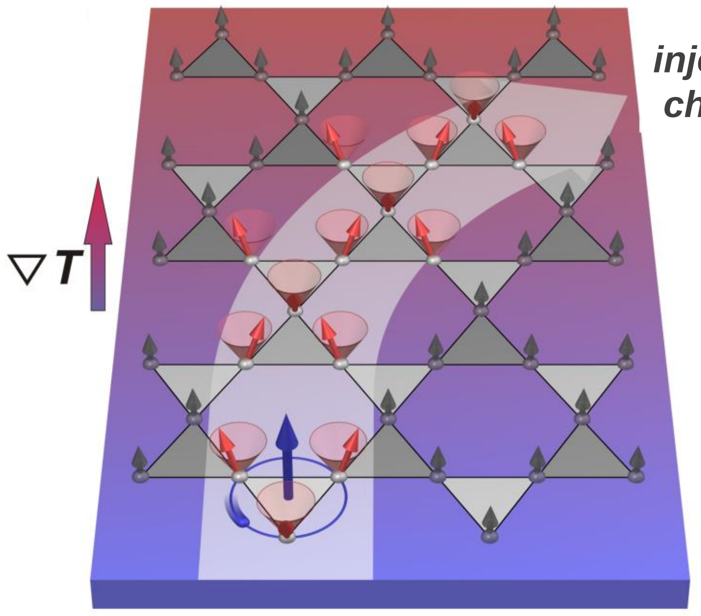
Orbital Nernst Effect:

$$\kappa_{\mathrm{ONE}}^{xy} = -\frac{k_{\mathrm{B}}}{4\pi^2\mu_{\mathrm{B}}}\sum_n \int_{\mathrm{BZ}} c_1(n_{\mathrm{B}}(\epsilon_{n\mathbf{k}}))\;\Omega_{n\mathbf{k}}^{xy} L_{n\mathbf{k}}^{\mathrm{TOM}}\;\mathbf{dk}$$

$$L_{n\mathbf{k}}^{\mathrm{TOM}} = \kappa^{\mathrm{TO}}\langle\Psi_{n\mathbf{k}}|\chi(\mathbf{k})|\Psi_{n\mathbf{k}}\rangle$$

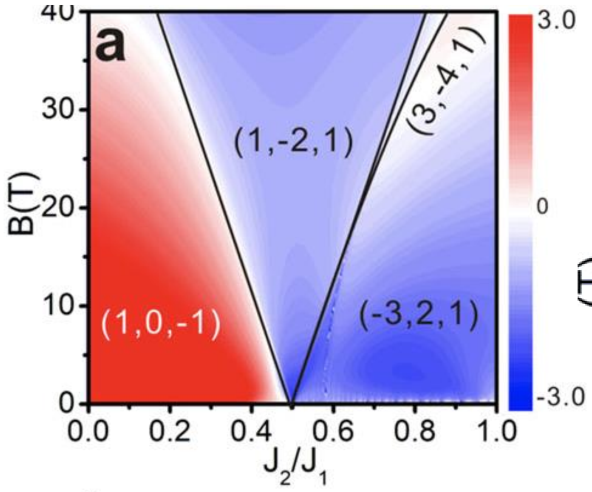
Magnonic transport of orbital angular momentum

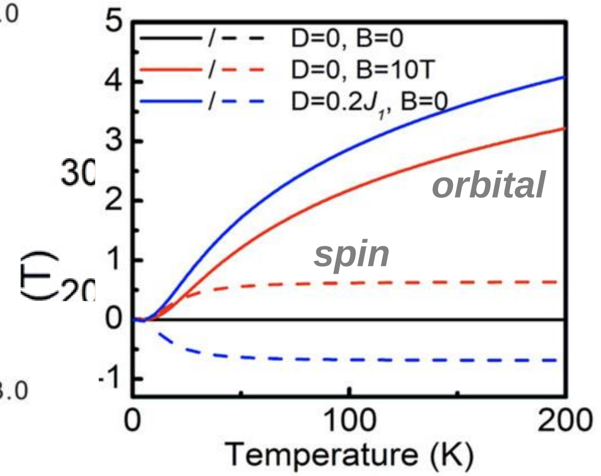
Go, Jo, Lee, Kläui, Y.M. *EPL* **135** (2021)



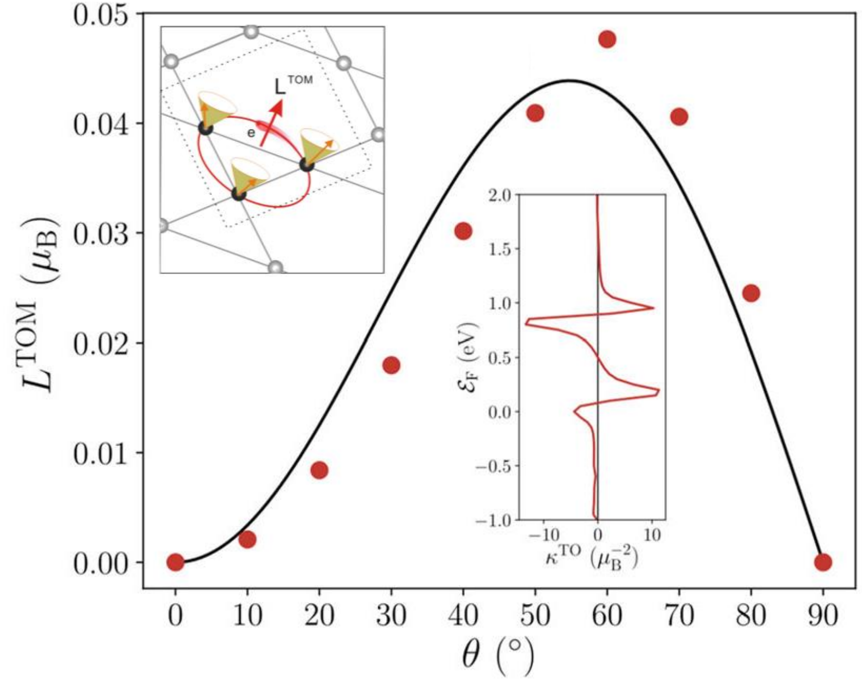
Drag of electronic orbital momentum by magnons

sensitive to topology





ferromagnetic kagome lattice



➢ *Competitor to magnon Nernst effect*

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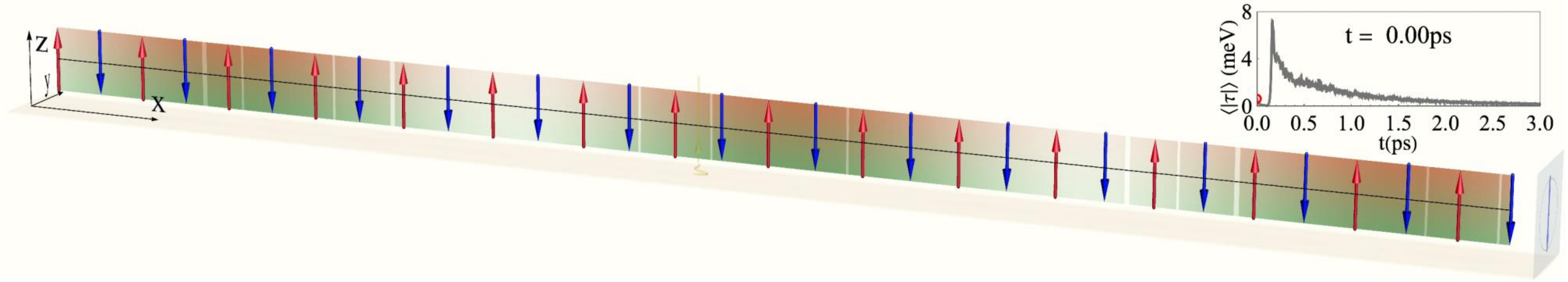
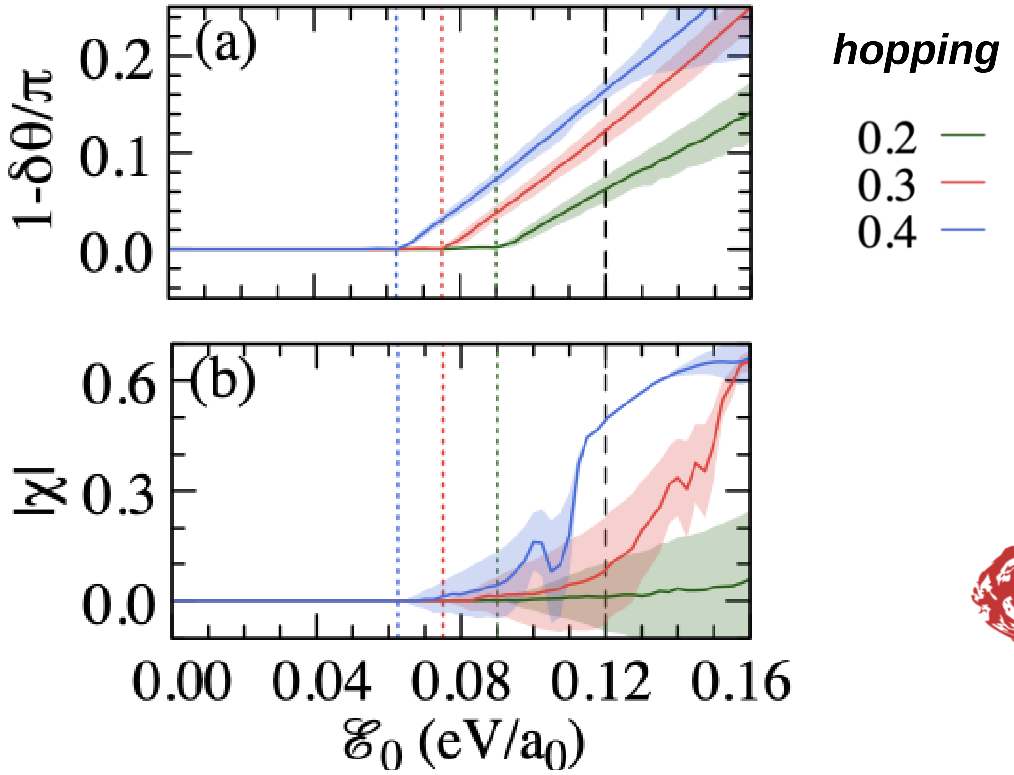
Optical chirality engineering

Ghosh, Freimuth, Gomonay, Blügel, YM, in press (arXiv:2011.01670)

Not an effect of thermal repopulation





„Chiral“ coherent electronic excitations

chiral interactions out of equilibrium

Karnad, Freimuth, Y.M., Kläui, et al. PRL **121**, 147203 ’18
Freimuth, Blügel, Y.M., Phys. Rev. B 102, 245411 (2020)

Engineer chirality at will!

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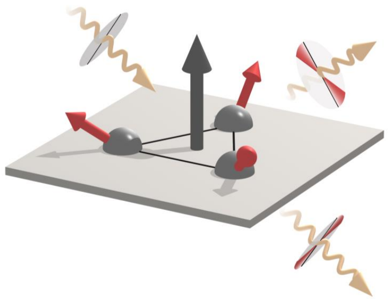
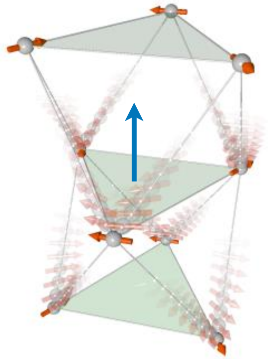
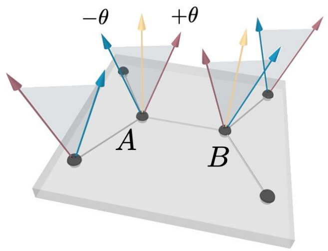
TRANSPORT

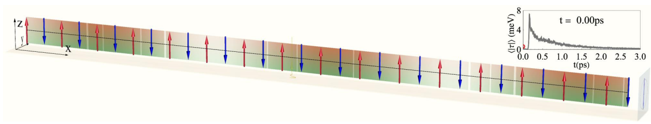
Chiral currents

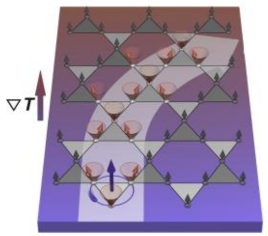


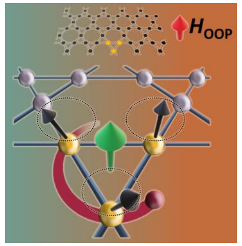




Chirality by Excitations

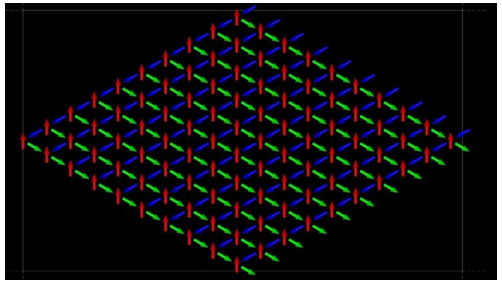






CHIRALITY

DYNAMICS



EXCITATIONS

Chirality Switching

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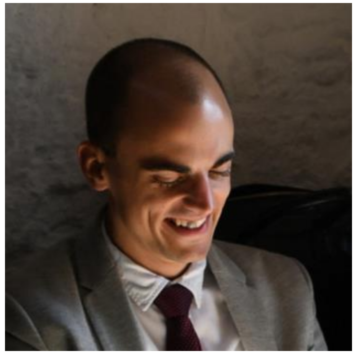
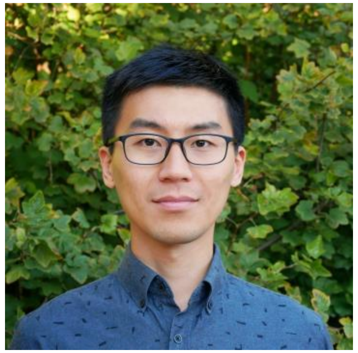
People



Fabian Lux



Dongwook Go

Sumit Ghosh

Helen Gomonay

Jonathan Kipp

Li-Chuan Zhang

Frank Freimuth (JGU)
Sergii Grytsiuk
Jan-Philipp Hanke
Kartik Samanta
Matthias Redies
Pascal Praß (JGU)
Max Merte
Markus Sallermann
Marjana Ležaić
Mathias Kläui (JGU)
Stefan Blügel

Wanxiang Feng *@ Beijing*
Yugui Yao & Co. *@ Beijing*
Badih Assaf & Co. *@ Notre Dame*
Laith Alahmed, Peng Li & Co. *@ Auburn*
Wei Zhang & Co. *@ Oakland*

Thank you

Elasto-Q-Mat

SPP2137 Skyrmionics
MO 1731/7-1 “Magneto-chiral transport effects in skyrmions” (CHITOS)

TopDyn

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