TU Delft
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Topological valley transport of magnons in 2D vdW magnets

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- Spin waves
- Magnons in 2D magnets
- Magnon spectra and Berry curvature
- Valley Hall thermal conductivity

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Gerrit Bauer (Tohoku University)
Xuechao Zhai (Nanjing University of Posts and Telecommunications)

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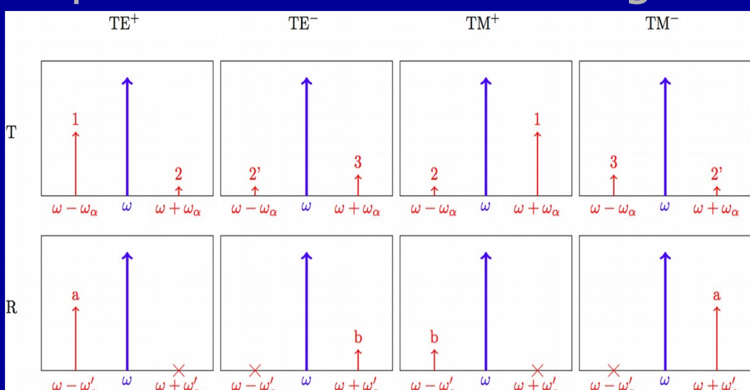
My recent research

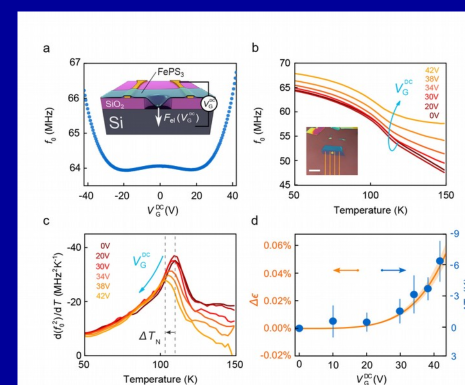
(Nano- and optomechanics)

Interaction of magnons with Optical and microwave light



Sideband asymmetry in Brillouin light scattering on magnons
S. Sharma, YMB, and G. E. W. Bauer, Phys. Rev. B **96**, 094412 (2017)

Nanomechanics with magnetic materials



Mechanical detection of magnetic transition in $FePS_3$
M. Šiškins, M. Lee, S. Mañas-Valero, E. Coronado, YMB, H. S. J. van der Zant, and P. G. Steeneken, Nature Communications **11**, 2698 (2020)

Spin waves

Magnons are elementary excitations of magnetic structure

Classical limit (large occupation numbers): spin waves

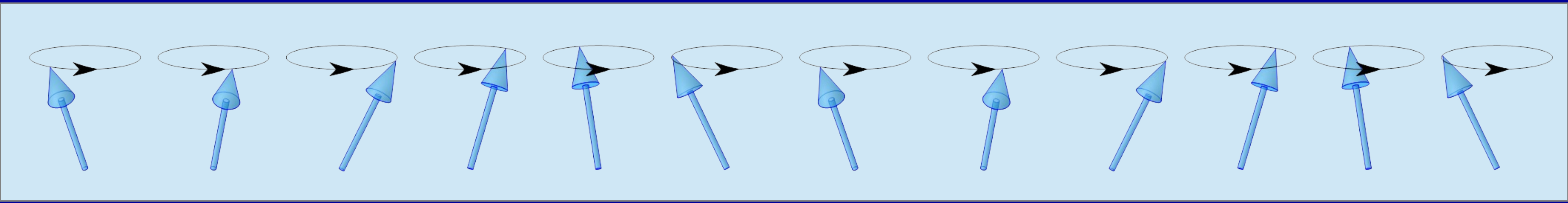


Image credit: Jens Böning, Wikimedia Commons

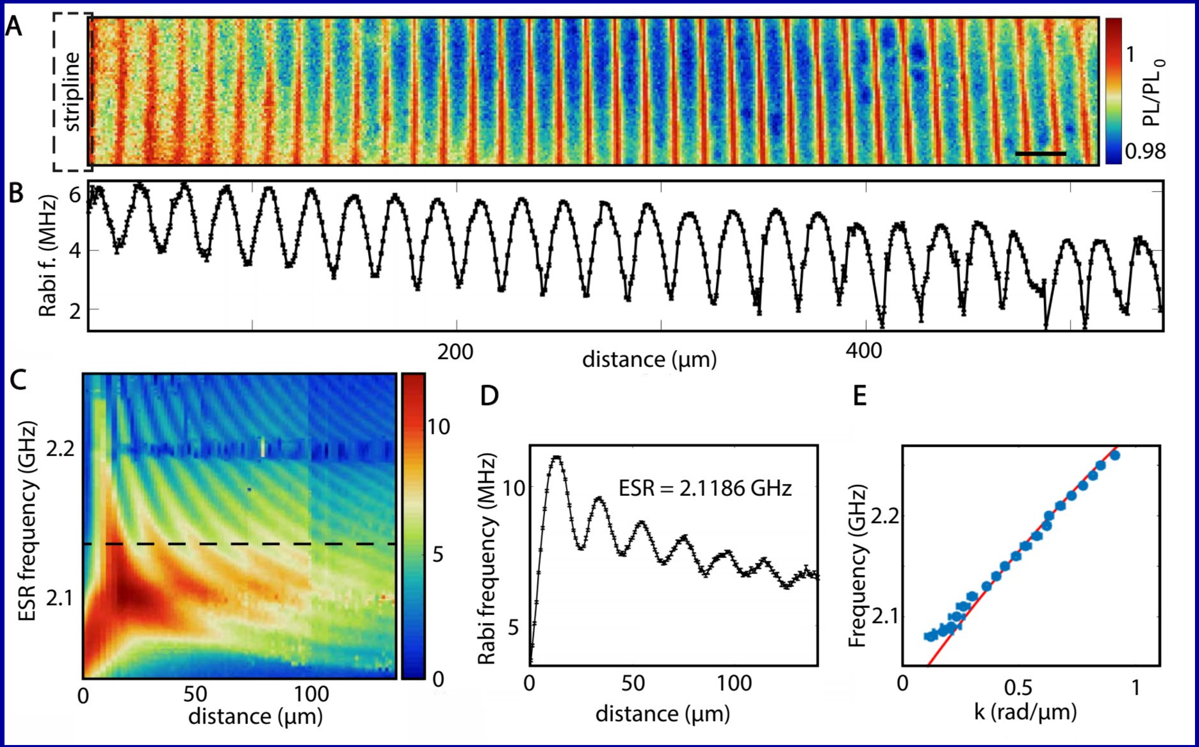
1D ferromagnetic chain: $\hat{H} = -\frac{2J}{\hbar^2} \sum_{<ij>} \vec{S}_i \vec{S}_j$

Spectrum: $\omega(k) = \frac{2J}{\hbar}\left(1 - \cos ka\right)$

- Parabolic gapless spectrum at k=0
- Anisotropy would open a gap

Imaging of spin waves

Spin waves in YIG films imaged by NV center magnetometry



I. Bertelli, J. J. Carmiggelt, T. Yu, B. G. Simon, C. C. Pothoven, G. E. W. Bauer, YMB, J. Aarts, and T. van der Sar, Arxiv:2004.07746, accepted to Science Adv.

Quantizing spin waves

Holstein-Primakoff transformation

$$S_i^+ = S_j^x + iS_j^y = \hbar\sqrt{2s}\sqrt{1-a_j^\dagger a_j/(2s)}\,a_j$$

$$S_i^- = S_j^x - iS_j^y = \hbar\sqrt{2s}\,a_j^\dagger\sqrt{1-a_j^\dagger a_j/(2s)}$$

$$S_j^z = \hbar\left(s - a_j^\dagger a_j\right)$$

→ Non-linear terms responsible for magnon-magnon interaction

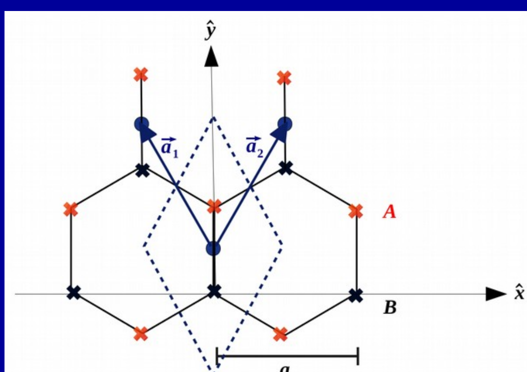
Linearizing and taking the Fourier transform: a set of linear oscillators

$$\hat{H} = \sum_k \hbar\omega(k) a_k^\dagger a_k$$

Magnons in a FM monolayer

FM monolayer, no anisotropy – spectrum with two Dirac points (same as electrons in graphene)

But the bottom of the band is at zero frequency!



S. S. Pershoguba *et al*, PRX **8**, 011010 (2018)

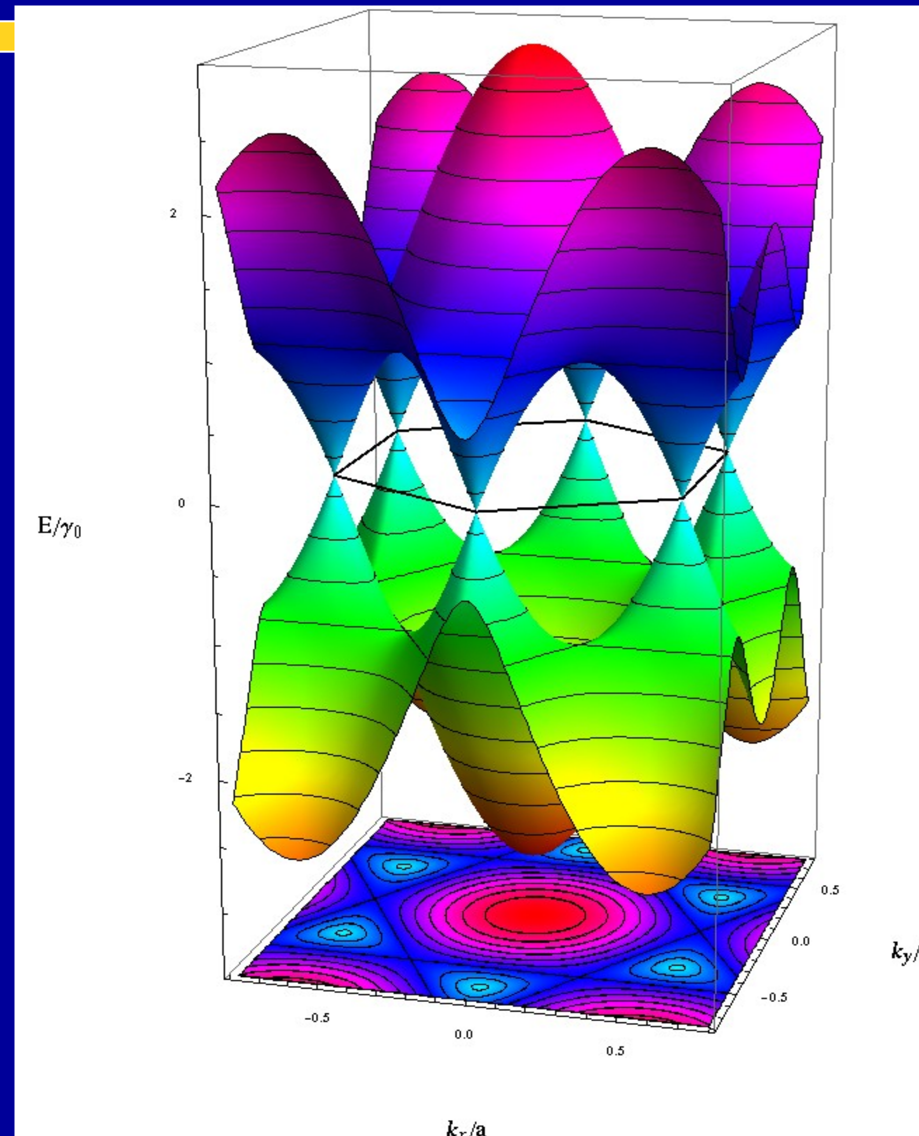


Image: Paul Wenk, Wikimedia Commons

Magnons in a FM monolayer

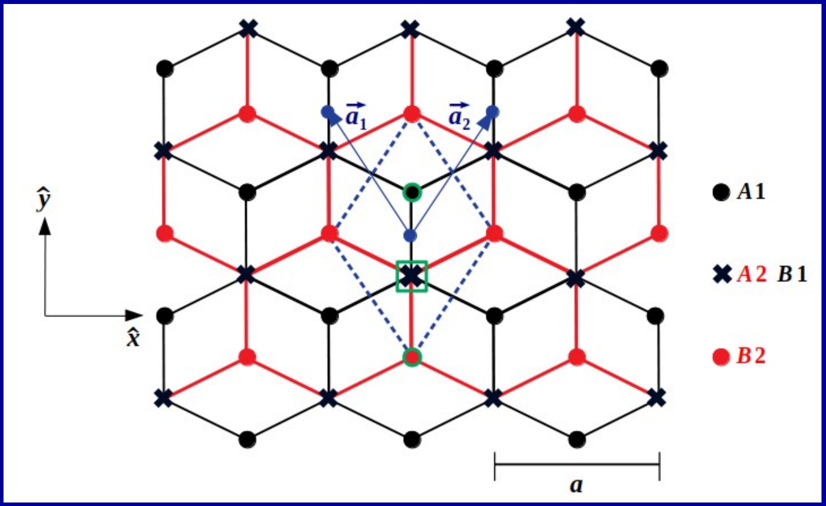
Magnetic anisotropy: The whole spectrum is shifted up opening a gap at *k=0*

$$\hat{H} = -\frac{2}{\hbar^2}\left(J\sum_{<ij>} \vec{S}_i \vec{S}_j + \Lambda \sum_{<ij>} S_i^z S_j^z \right)$$

Magnons in 2D van der Waals magnets

FM bilayer, no anisotropy:
- Four magnon bands
- Structure similar to a monolayer
- At k=0: Only one frequency is zero
- At the Dirac point: three-fold degeneracy

With anisotropy:
- Spectrum is shifted at k=0, no zero frequency
- At the Dirac point: two-fold degeneracy (anisotropy b/w layers)



$$\hat{H} = -\frac{2}{\hbar^2}\left(J\sum_{<ij>} \vec{S}_i \vec{S}_j + \Lambda \sum_{<ij>} S_i^z S_j^z \right)$$

$$E_{1,2} = 6J_{\parallel}s \pm 2J_{\parallel}s\left|c\right|$$

$$E_{3,4} = 6J_{\parallel}s + 2J_{\perp}s \pm 2s\sqrt{J_{\perp}^2 + J_{\parallel}^2\left|c\right|^2}$$

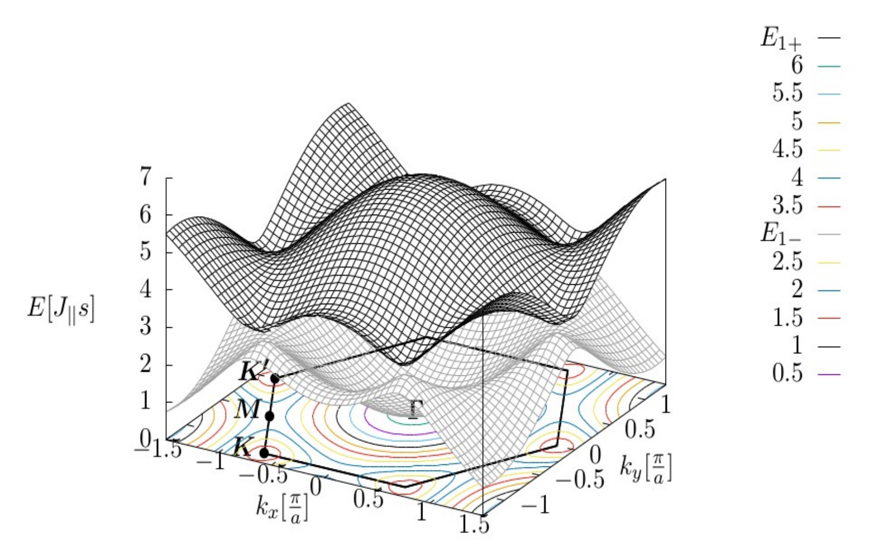
$$c = 1 + e^{-i\vec{k}\vec{a}_1} + e^{-i\vec{k}\vec{a}_2}$$

S. Owerre, Phys. Rev. B **94**, 094405 (2016)
L. C. Ortmanns, G. E. W. Bauer, YMB, arXiv:2008.06875

Magnons in 2D van der Waals magnets

CrI_3 bilayer: FM coupling in a layer
AFM between the layers

No anisotropy:
- Quadratic dispersion near k=0
- Two doubly-degenerate bands with a gap at Dirac points



$$\hat{H} = -\frac{2J_{\|}}{\hbar^2}\sum_{\langle ij\rangle\in\mathrm{intra}}\vec{S}_i\vec{S}_j + \frac{2J_{\perp}}{\hbar^2}\sum_{\langle ij\rangle\in\mathrm{inter}}\vec{S}_i\vec{S}_j$$

Bogoliubov paraunitary transformation to diagonalize the Hamiltonian due to the presence of terms of the type

$$\hat{a}\hat{a}, \hat{a}^\dagger\hat{a}^\dagger$$

S. Owerre, Phys. Rev. B **94**, 094405 (2016)
L. C. Ortmanns, G. E. W. Bauer, YMB, arXiv:2008.06875

Magnons in 2D van der Waals magnets

CrI_3 bilayer: FM coupling in a layer, AFM between the layers

Anisotropy (out-of-plane):

$$\hat{H} = -\frac{2J_{\parallel}}{\hbar^2}\sum_{\langle ij\rangle \in \mathrm{intra}}\left(S_i^x S_j^x + S_i^y S_j^y\right) - \frac{2J_{\parallel}^{zz}}{\hbar^2}\sum_{\langle ij\rangle \in \mathrm{intra}} S_i^z S_j^z \qquad J_{\parallel}^{zz} > J_{\parallel},\ J_{\perp}^{zz} > J_{\perp}$$

$$+\frac{2J_{\perp}}{\hbar^2}\sum_{\langle ij\rangle \in \mathrm{inter}}\left(S_i^x S_j^x + S_i^y S_j^y\right) + \frac{2J_{\perp}^{zz}}{\hbar^2}\sum_{\langle ij\rangle \in \mathrm{inter}} S_i^z S_j^z$$

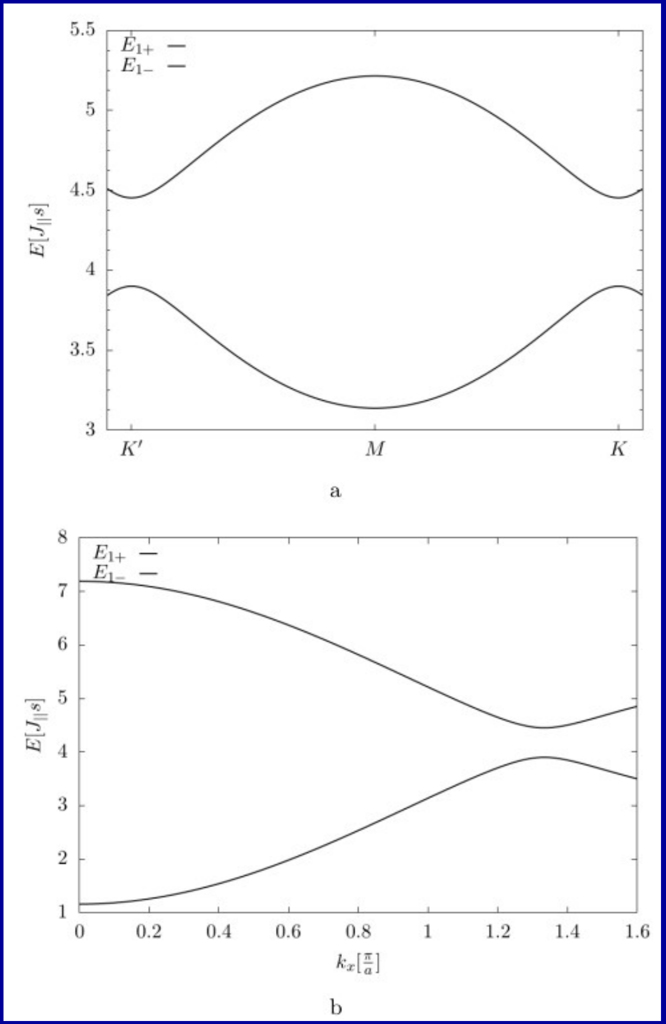
$$2E^2/s^2 = 18J_{\parallel}^{zz\,2} + 6J_{\parallel}^{zz}J_{\perp}^{zz} + J_{\perp}^{zz\,2} - J_{\perp}^2 + 2J_{\parallel}^2\left|c\right|^2$$
$$\pm\sqrt{\left(6J_{\parallel}^{zz}J_{\perp}^{zz} + J_{\perp}^{zz\,2} - J_{\perp}^2\right)^2 + \left[\left(12J_{\parallel}^{zz} + 2J_{\perp}^{zz}\right)^2 - 4J_{\perp}^2\right]J_{\parallel}^2\left|c\right|^2}$$

S. Owerre, Phys. Rev. B **94**, 094405 (2016)
L. C. Ortmanns, G. E. W. Bauer, YMB, arXiv:2008.06875

Magnons in 2D van der Waals magnets

CrI_3 bilayer: FM coupling in a layer
AFM between the layers

Anisotropy:
– Qualitatively the same for out-of-plane anisotropy, quantitatively different

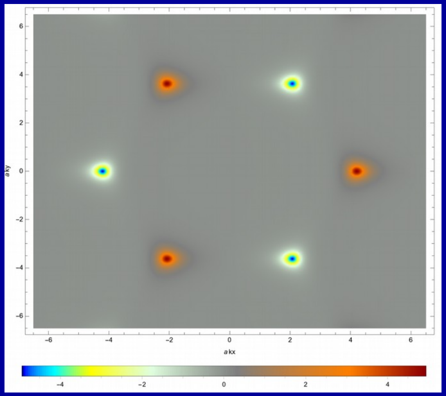


S. Owerre, Phys. Rev. B **94**, 094405 (2016)
L. C. Ortmanns, G. E. W. Bauer, YMB, arXiv:2008.06875

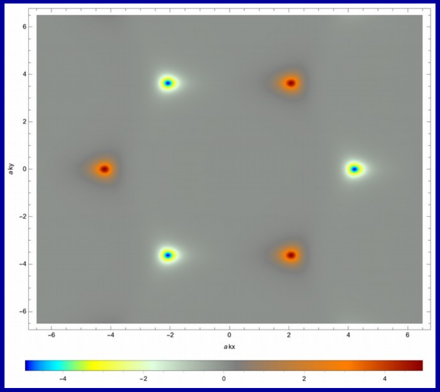
How do we probe Dirac points in magnon spectra?

- Can we single out properties of magnons at the Dirac points?
- Can we discriminate between the Dirac points?

Berry curvature: $$\Omega_{nk} = \nabla_k \times \langle u_{nk} | \nabla_k | u_{nk} \rangle$$



Ω_+



Ω_-

Only non-zero around the K-points

Trivial topology: the gap protected by the inversion symmetry

L. C. Ortmanns, G. E. W. Bauer, YMB, arXiv:2008.06875

Dzyaloshinskii-Moriya interactions (DMI): $\propto \vec{S}_i \times \vec{S}_j$

Bilayer FM with broken inversion symmetry

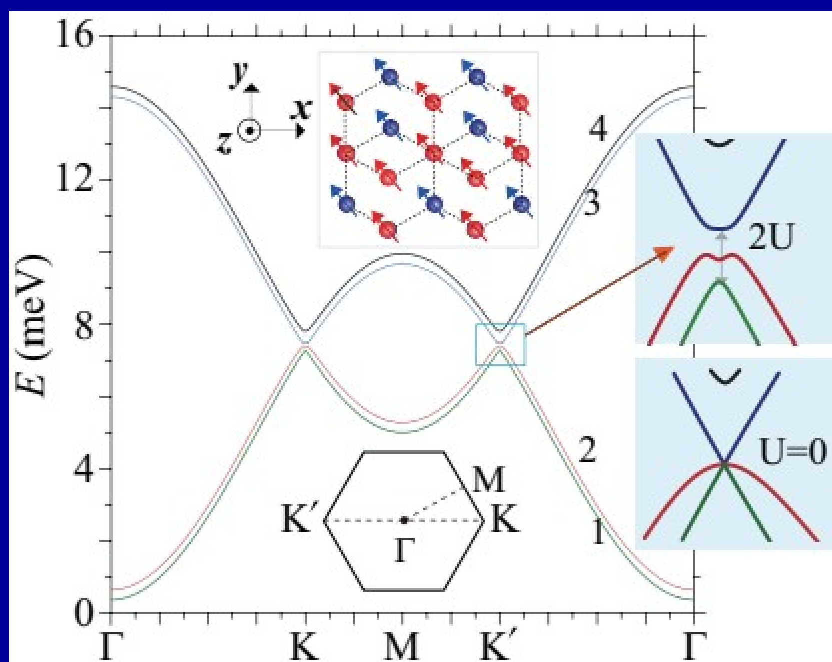
$CrBr_3$ bilayers

layers

Breaks inversion symmetry

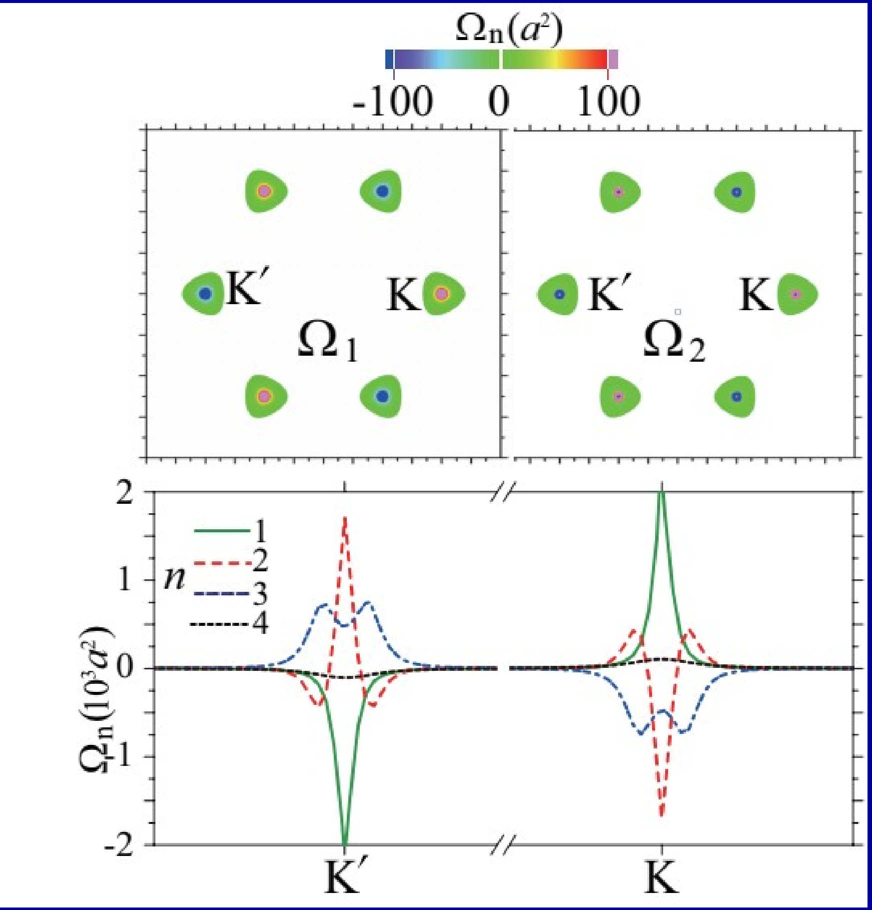
$$\hat{H} = -\sum_{\langle ij \rangle} J_{ij} \vec{S}_i \vec{S}_j - \Lambda \sum_{\langle ij \rangle} S_i^z S_j^z \pm U \sum_i S_i^z$$

$$J_{ij}, \Lambda > 0$$



X. Zhai and YMB, Phys. Rev. B **102**, 075407 (2020)

Berry curvature



X. Zhai and YMB, Phys. Rev. B **102**, 075407 (2020)

Probing Dirac points

Energy current:

$$J_E = -\frac{1}{V}\sum_{mnk} u^{\dagger}_{mk}\left(\frac{\partial H}{\partial k}\right)_{mn} u_{nk}$$

Thermal Hall conductivity of magnons:

$$\kappa_{xy} = -\frac{k_B^2 T}{\hbar V}\sum_{nk} C(\omega_{nk})\Omega_{nk}$$

$$C(E) = (1+f_B)\left[\ln(1+1/f_B)\right]^2 - (\ln f_B)^2 - 2Li_2(-f_B)$$

Determined by the Dirac points

X. Zhai and YMB, Phys. Rev. B **102**, 075407 (2020)

Magnon transport

Thermal Hall conductivity of magnons:

$$\kappa_{xy} = -\frac{k_B^2 T}{\hbar V} \sum_{nk} C(\omega_{nk}) \Omega_{nk}$$

Contributions of K and K' cancel each other: $\kappa_{xy} = \kappa_{xy}^{K} + \kappa_{xy}^{K'} = 0$

Valley Hall conductivity: $\kappa_{xy}^{v} = \kappa_{xy}^{K} - \kappa_{xy}^{K'} \neq 0$

But how can we measure it?

X. Zhai and YMB, Phys. Rev. B **102**, 075407 (2020)

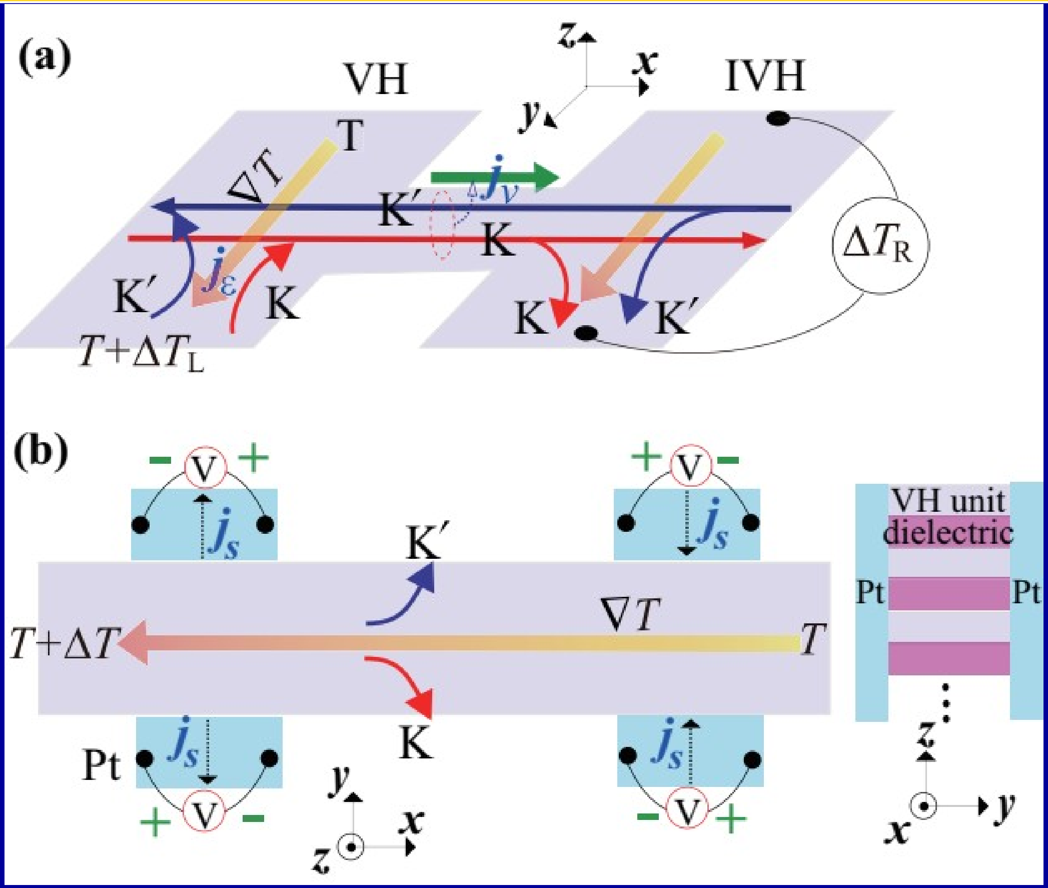
How to measure thermal Hall conductivity?

1) Thermal flux density:

$$R_{NL} = \Delta T / j_E \propto \left(\kappa_{xy}^{v}\right)^2$$

(no electron or phonon contribution)

2) Valley Seebeck effect: convert magnons to charge with ISHE



X. Zhai and YMB, Phys. Rev. B **102**, 075407 (2020)

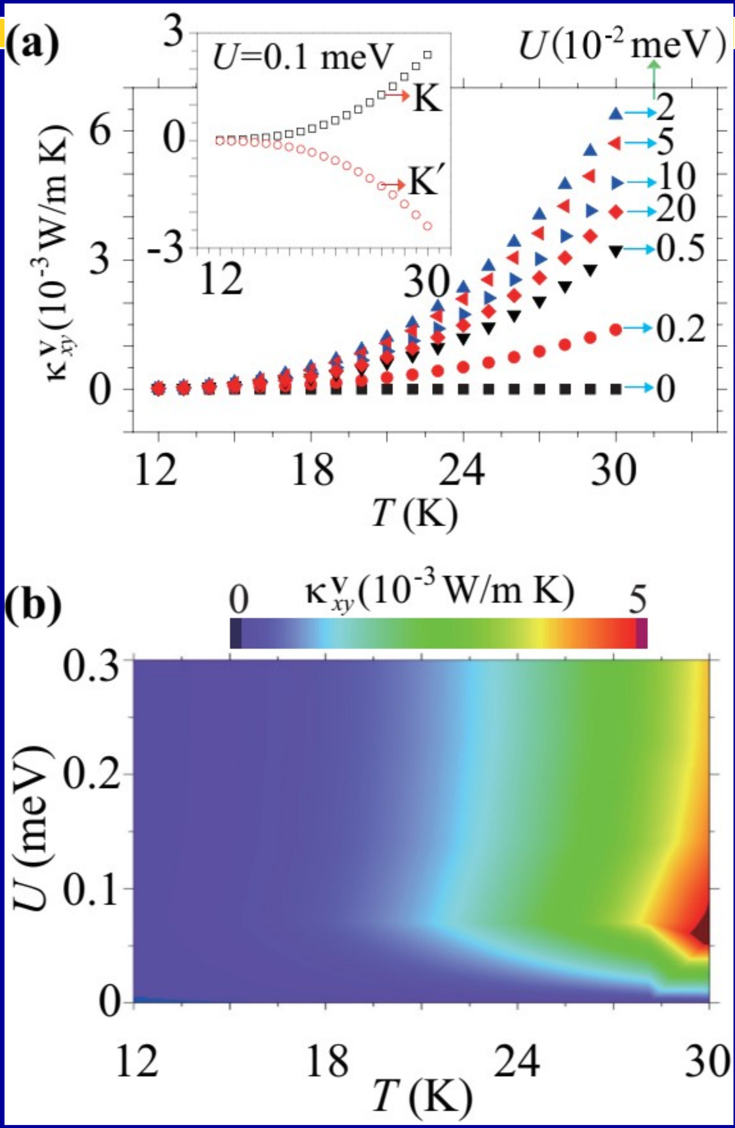
Realization in $CrBr_3$

U – by electron/hole doping

Significant effect – above 15K
Curie temperature: 34K

DMI – suppresses the effect
(but strong DMI would induce
States in the gap)

Magnon damping - ???



X. Zhai and YMB, Phys. Rev. B **102**, 075407 (2020)

Conclusions

- Magnons: Dirac-like spectra; Dirac points can be probed by the Berry curvature
- Thermal Hall conductivity as a means to separate valleys

L. C. Ortmanns, G. E. W. Bauer, and YMB, arXiv:2008.06875

X. Zhai and YMB, Phys. Rev. B **102**, 075407 (2020)