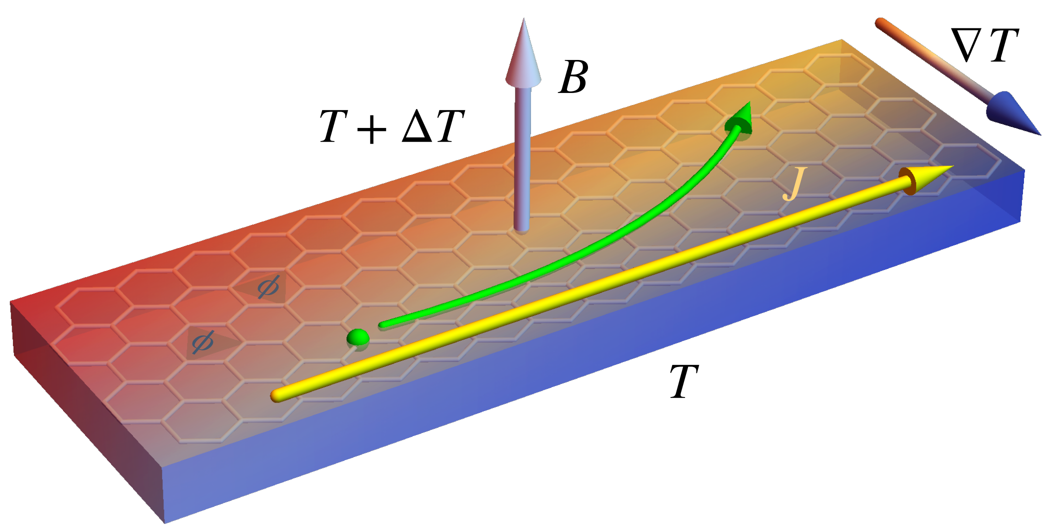
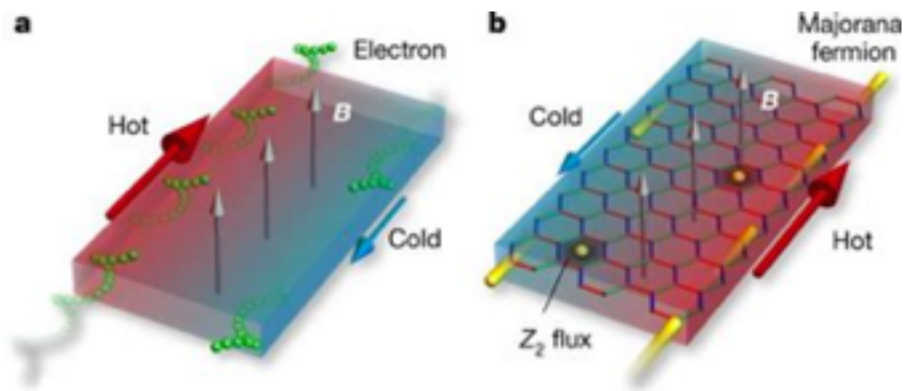
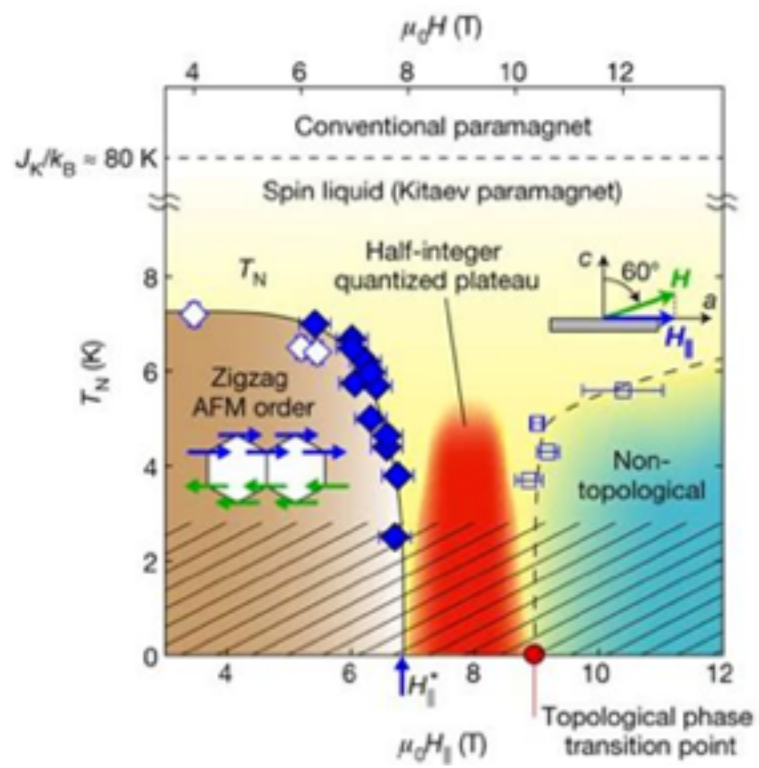
Non-quantized and topological thermal Hall effect in spin liquids

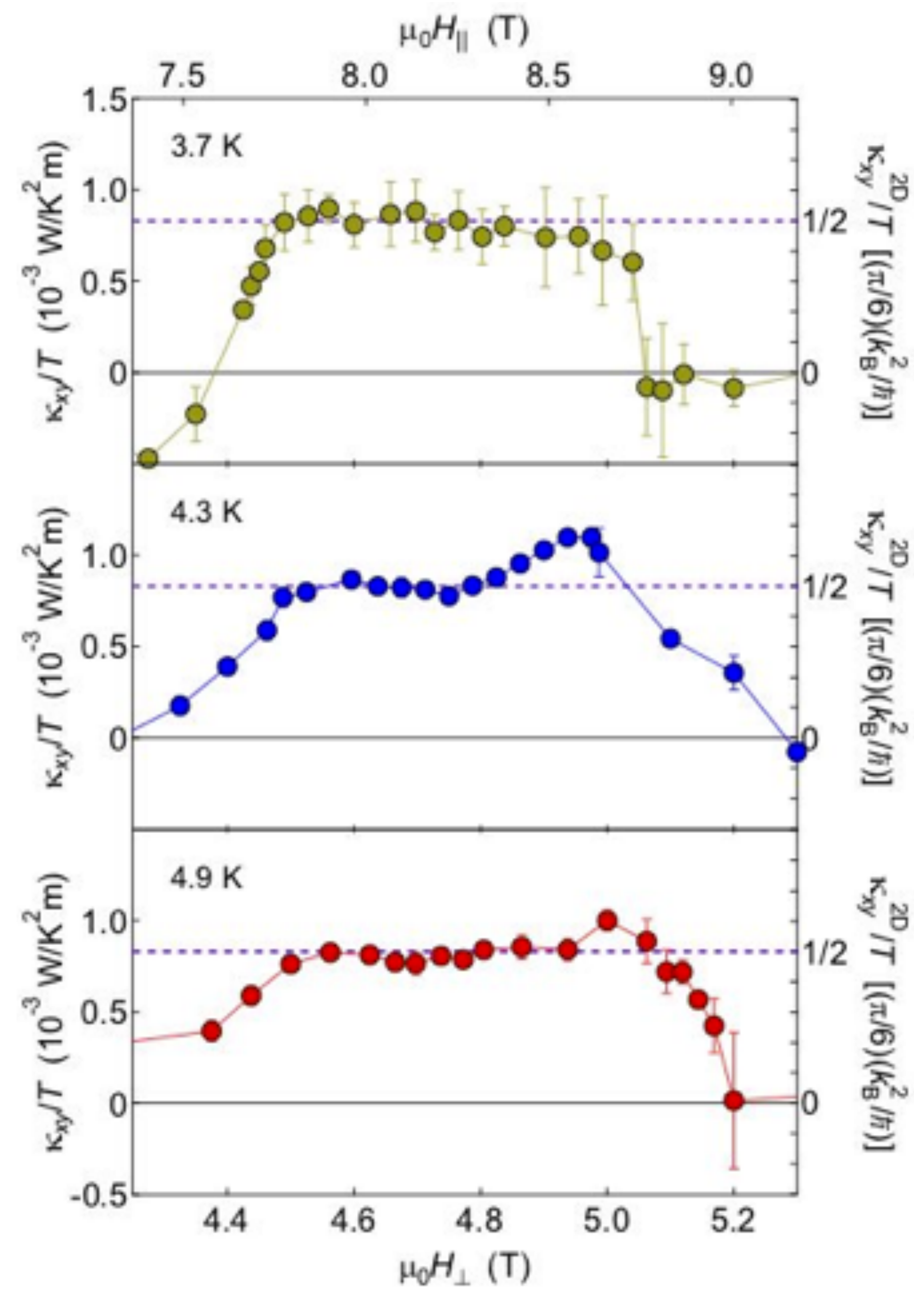


Gang Chen

Quantized thermal Hall effect in $RuCl_3$?

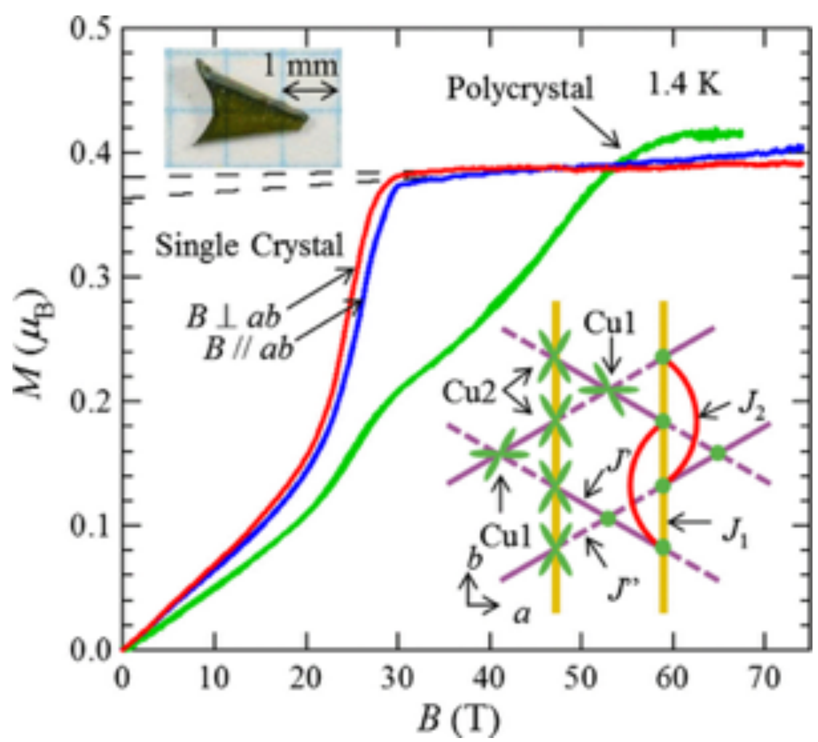




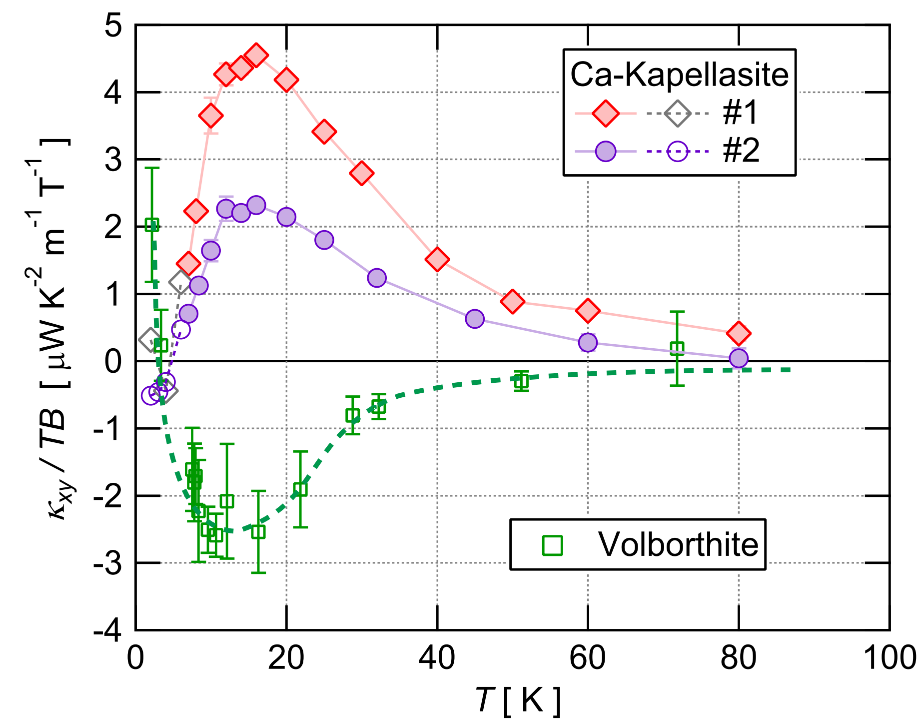


Yuji Matsuda's group

Remark: Expts provide a lot of random information. More generic and robust phenomenon is non-quantized thermal Hall conductivity for RuCl3 in fields. This is also quite unusual.



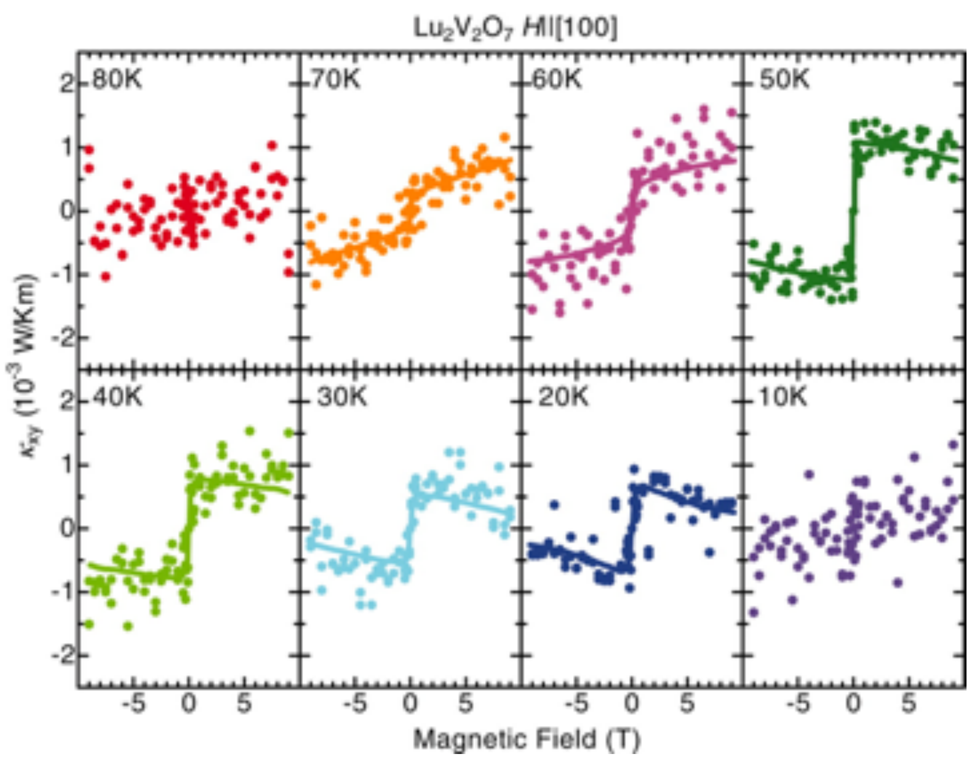
Z Hiroi's group

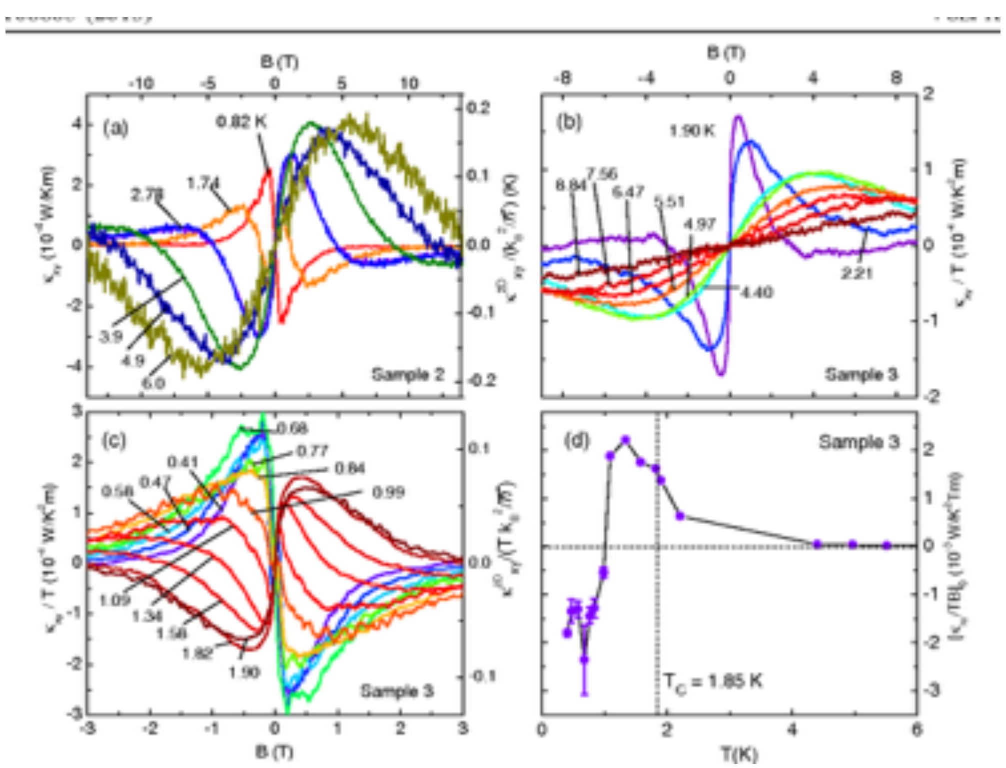


Minoru Yamashita's group

We are not quite interested in spin wave / magnons in ordered systems, where everything is more or less understood. Orders are relatively easy to detect.

Magnon thermal Hall effect





Lu2V2O7: pyrochlore ferromagnet

Cu(1-3, bdc): kagome ferromagnet

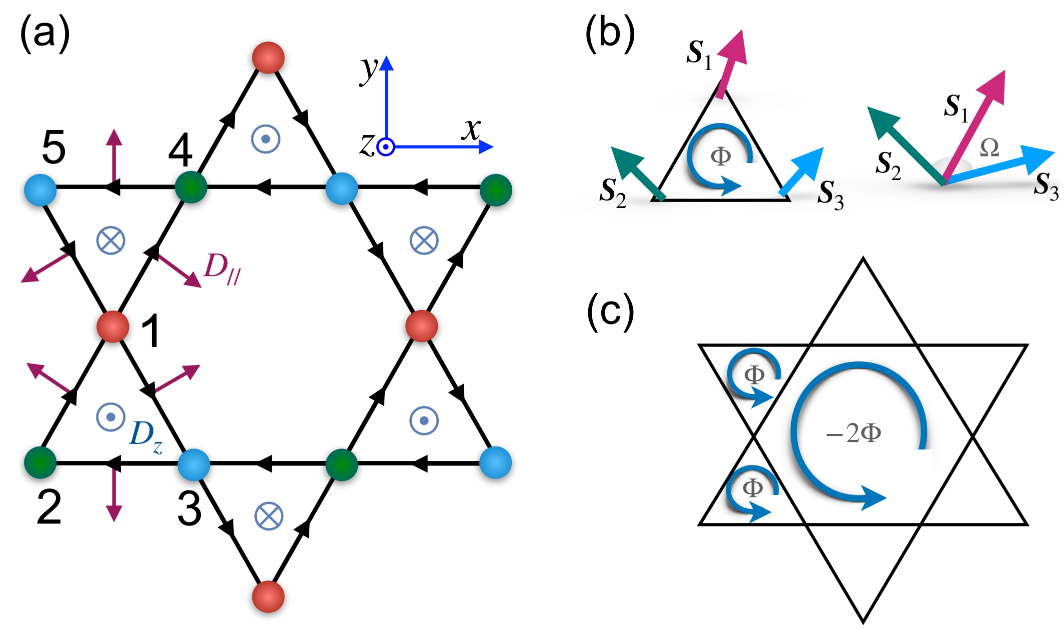
Nagaosa, Takura, et al

Young Lee, P Ong, et al

Our observation: induced internal U(1) gauge flux and emergent Lorentz force for spinons

Yong Hao Gao

Yong Hao Gao, GC, arXiv 1901.01522



$$H = \sum_{i,j} J_{ij} \boldsymbol{S_i} \cdot \boldsymbol{S_j} + \sum_{i,j} \boldsymbol{D}_{ij} \cdot \boldsymbol{S_i} \times \boldsymbol{S_j} - \sum_i B S_i^z,$$

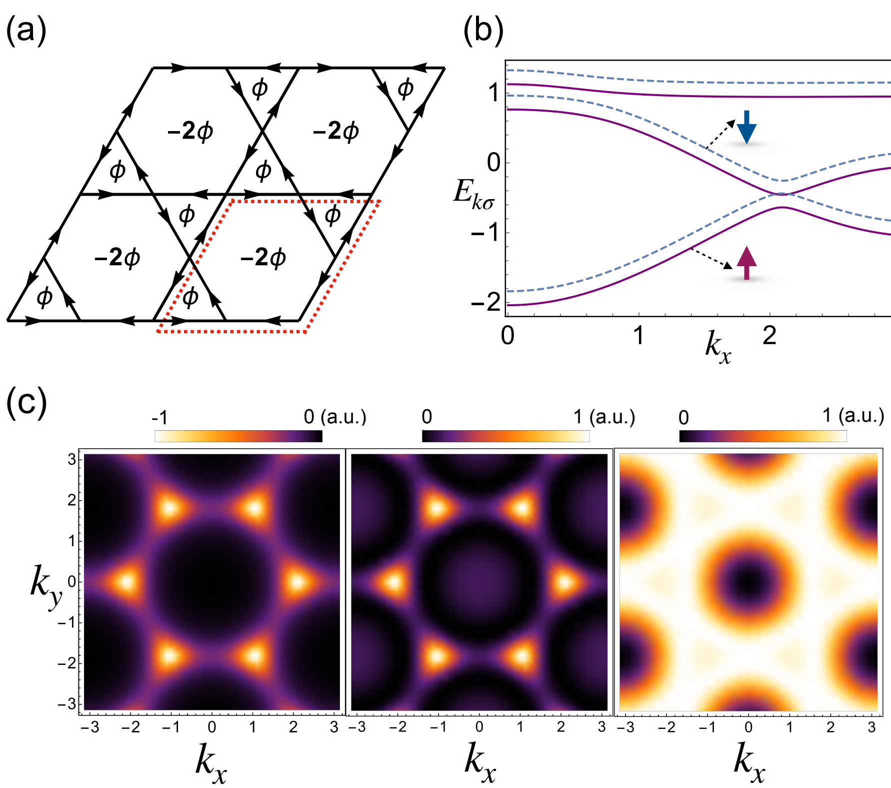
$$\langle \boldsymbol{S}_i \times \boldsymbol{S}_j \cdot \boldsymbol{S}_k \rangle \sim \langle \boldsymbol{S}_i \times \boldsymbol{S}_j \rangle \cdot \langle \boldsymbol{S}_k \rangle \neq 0$$

$\sin \Phi = \frac{1}{2} \mathbf{S_1} \cdot (\boldsymbol{S_2} \times \boldsymbol{S_3})$ XG Wen, F Wilczek, A Zee, PRB, 1989

The combination of Zeeman coupling and DMI generates an internal U(1) gauge flux distribution.

This provides a way to **control** emergent D.O.F. with external probes.

Topological thermal Hall effect



Spinon bands and
Berry curvatures

$$H_{\mathrm{MF}}[\phi] = -t\sum_{\langle ij\rangle}[e^{-i\phi/3}f^\dagger_{i\sigma}f_{j\sigma} + h.c.] - \mu\sum_i f^\dagger_{i\sigma}f_{i\sigma}$$

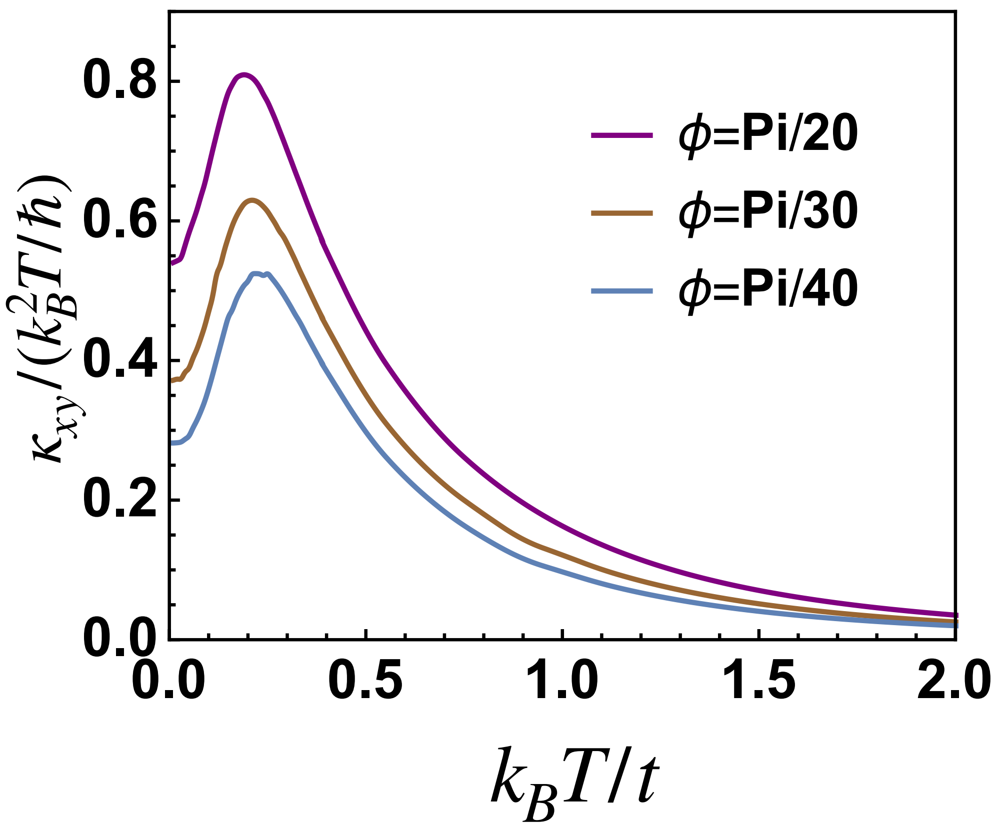
$$-B\sum_{i,\alpha\beta} f^\dagger_{i\alpha}\frac{\sigma^z_{\alpha\beta}}{2}f_{i\beta},$$

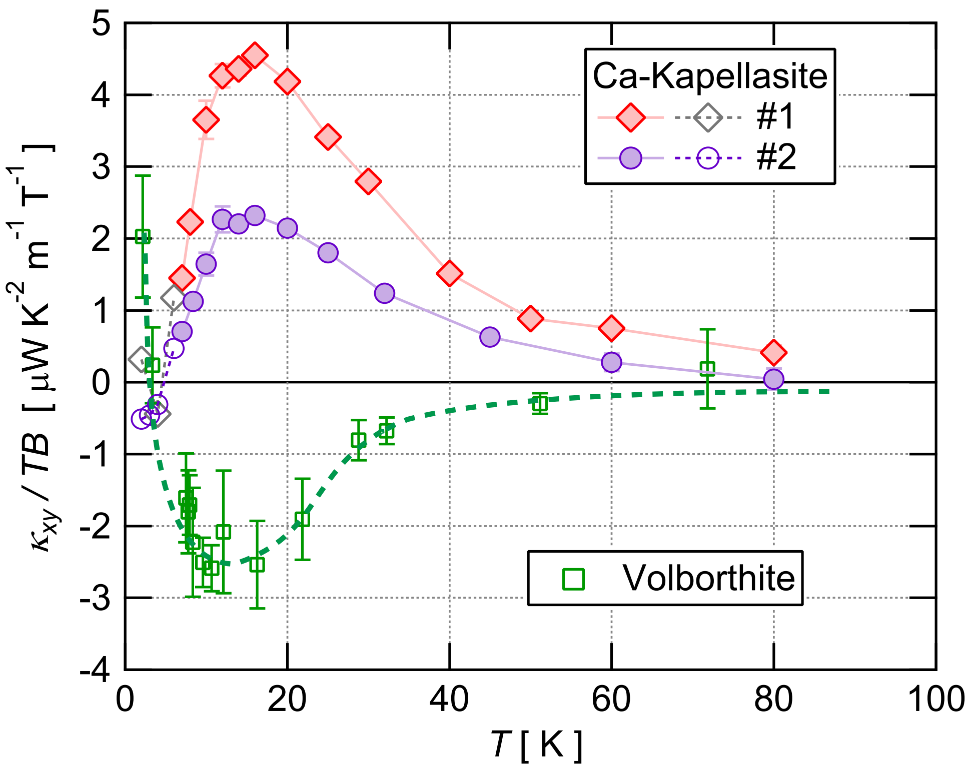
$$\kappa_{xy} = -\frac{1}{T}\int d\epsilon(\epsilon-\mu)^2\frac{\partial f(\epsilon,\mu,T)}{\partial\epsilon}\sigma_{xy}(\epsilon).$$

$$\sigma_{xy}(\epsilon) = -\sum\nolimits_{\boldsymbol{k},\sigma,\xi_{n,\boldsymbol{k}}<\epsilon}\Omega_{n,\boldsymbol{k},\sigma}$$

Yong Hao Gao

Topological thermal Hall effect



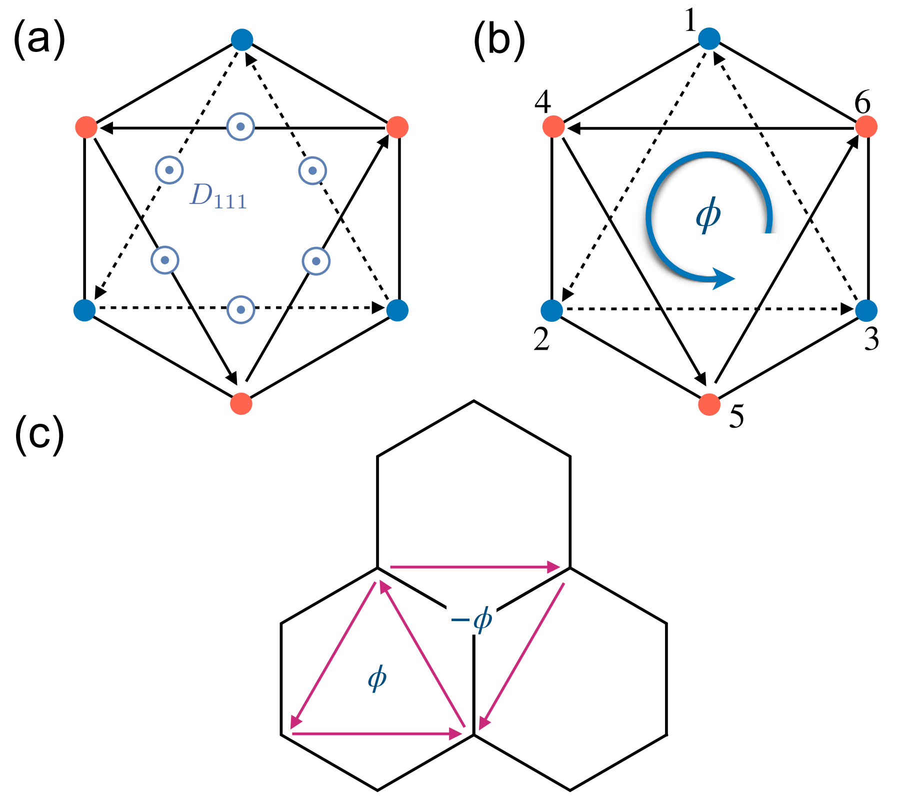


Minoru Yamashita's group

1. Why it is finite? All neutral excitations.
2. Non-monotonic.
3. Opposite signs in two materials.

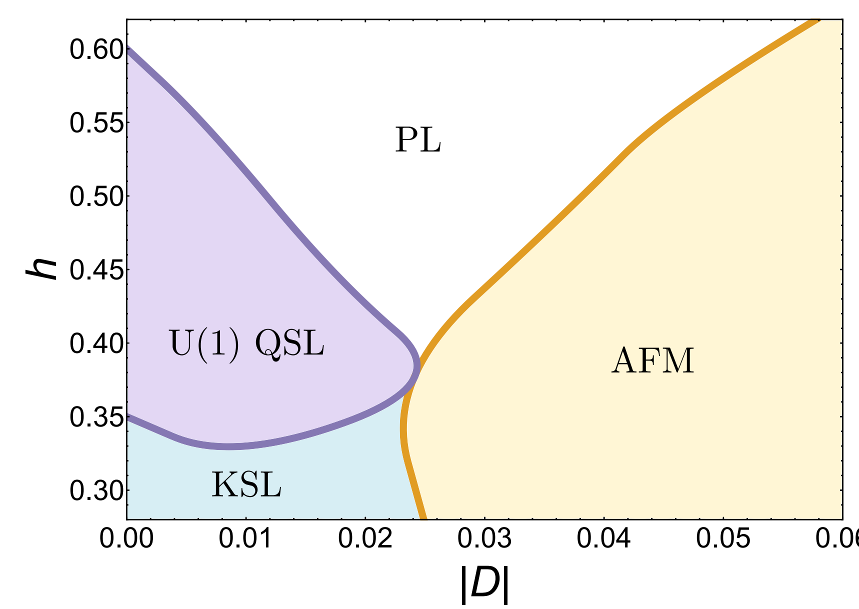
Thermal Hall signatures of non-Kitaev spin liquids in honeycomb Kitaev materials

Yong Hao Gao[1], Ciarán Hickey[2], Tao Xiang[3,4], Simon Trebst[2], and Gang Chen[5]



$$H = \sum_{\langle ij\rangle\in\gamma} K S_i^\gamma S_j^\gamma + \sum_{\langle\langle i,j\rangle\rangle} \boldsymbol{D}_{ij}\cdot\boldsymbol{S_i}\times\boldsymbol{S_j} - \sum_i \boldsymbol{h}_i\cdot\boldsymbol{S}_i. \quad (18)$$

In Fig. 6 we show the resulting phase diagram, with the U(1) spin liquid region stable up to a maximal Dzyaloshinskii-Moriya interaction of about $|\boldsymbol{D}| \sim 0.025K$. We should



Summary

1. We point out the physical origin of emergent Lorentz force on spinons and obtain the resulting topological thermal Hall effects.

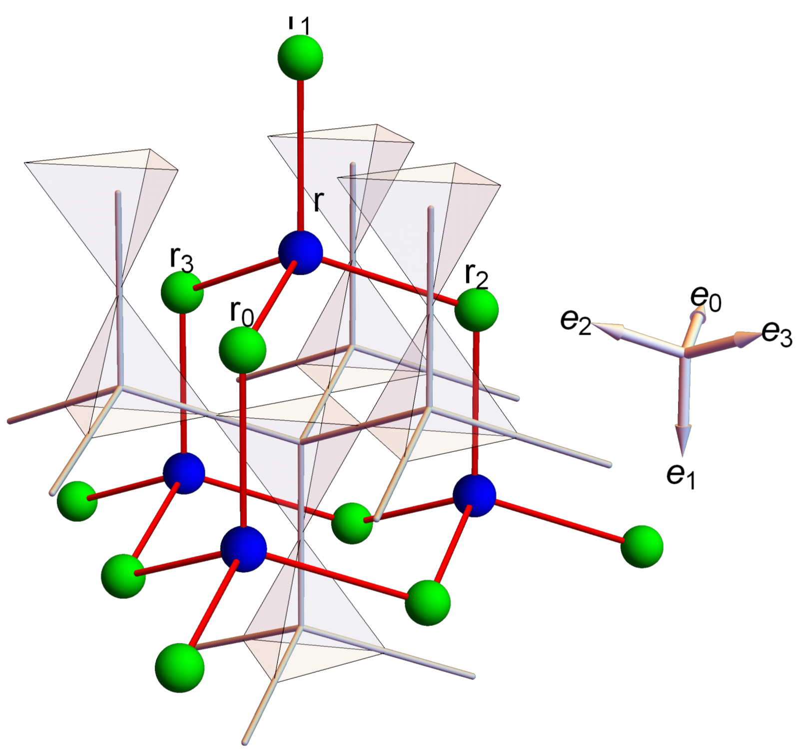
2. We establish the connection between microscopic interactions and emergent D.O.F. and thus provide a scheme to control the emergent D.O.F.

3. Our results can be extended to other non-centrosymmetric QSLs with with Dzyaloshinskii-Moriya interaction.

4. **Thermal transports in Mott insulators are not well understood.**

Topological thermal Hall effect of "magnetic monopoles" in pyrochlore U(1) spin liquid

Xiao-Tian Zhang[1,4], Yong Hao Gao[2,4], Chunxiao Liu[3], and Gang Chen[4*]
International Center for Quantum Materials, Peking University, Beijing, 100871, China



netic monopoles" and creates a TTHE in the system. The dual Hamiltonian for the "magnetic monopoles", that captures this effect, is given as

$$\mathcal{H}_{\text{dual}} = -t \sum_{\mathsf{rr'}} \Phi_{\mathsf{r}}^{\dagger} \Phi_{\mathsf{r'}} e^{-i2\pi a_{\mathsf{rr'}}} - \mu \sum_{\mathsf{r}} \Phi_{\mathsf{r}}^{\dagger} \Phi_{\mathsf{r}} + \sum_{rr'} \frac{U}{2} (\text{curl } a - \bar{E}_{rr'})^2 - K \sum_{\mathsf{rr'}} \cos B_{\mathsf{rr'}} \quad (1)$$

$$\mathcal{H}_{\text{Zeeman}} = -g\mu_B H_0 \sum_i (\hat{n} \cdot \hat{z}_i) \tau_i^z \simeq -g\mu_B H_0 \sum_i (\hat{n} \cdot \hat{z}_i)(\text{curl } a_{rr'} - \bar{E}_{rr'}),$$

Experiments by P Ong's group.

Three cases of thermal Hall effects

1. Chiral spin liquids: quantized w/o field
2. Magnetic field changes the spinon band topology and creates chiral edge states: e.g. Kitaev spin liquid, (not much different from case 1), apply to QSL w/ gapped gauge.
3. External field comes to modify the internal continuous gauge field and thereby indirectly twists the motion of matter fields, and generate thermal Hall effects.