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YITP, Kyoto University

Half-integer thermal Hall conductance in a Kitaev spin liquid

– Evidence for chiral Majorana edge current –

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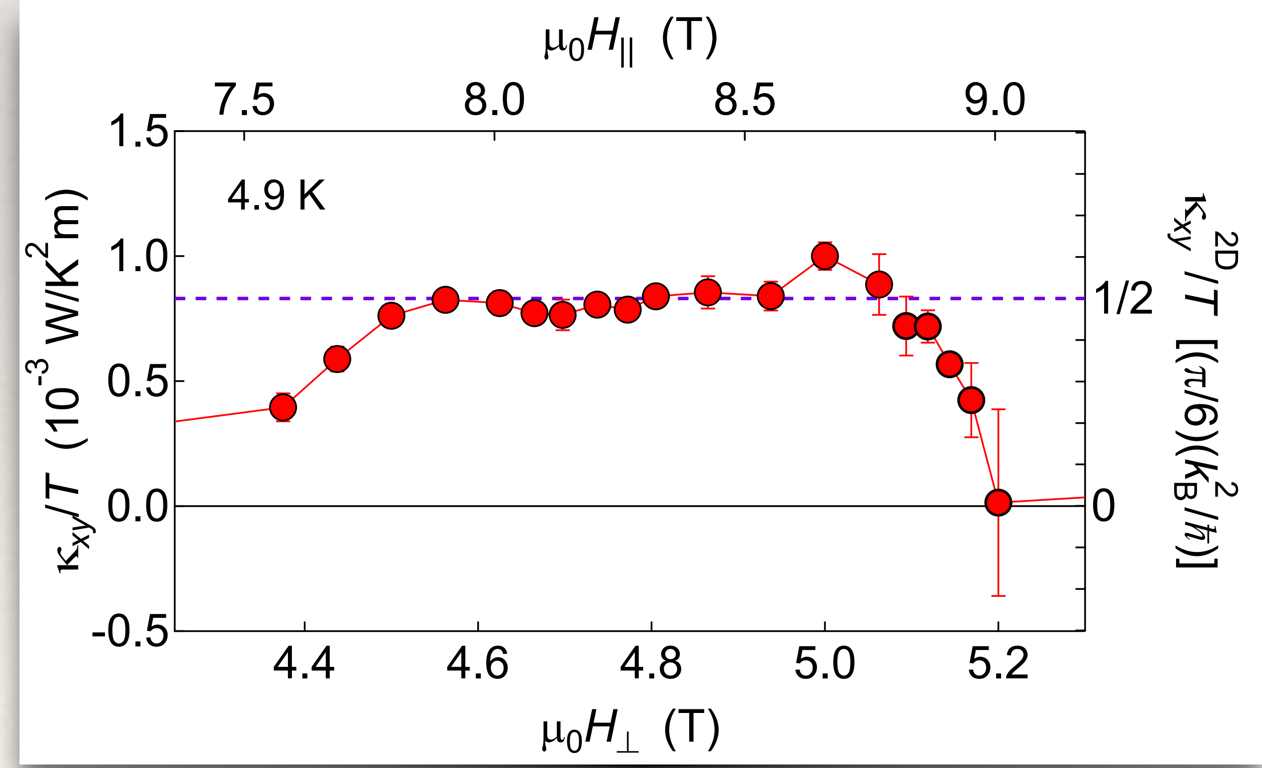
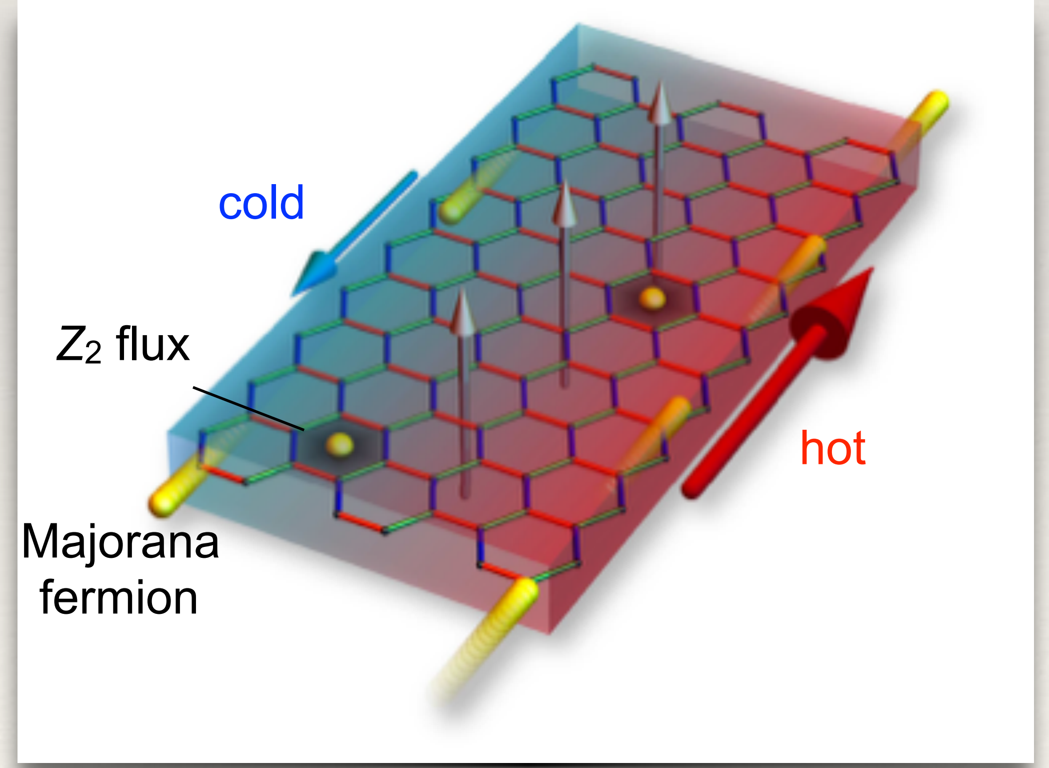


Half-integer thermal Hall conductance



Chiral Majorana edge current

Collaborators

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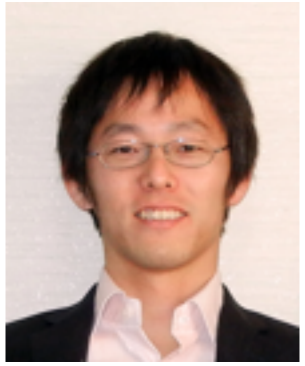
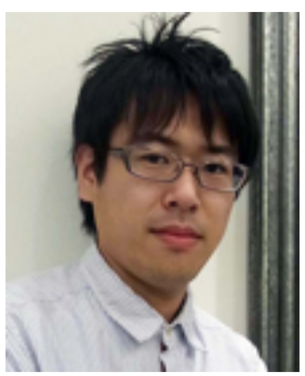


Yamashita

Sugii



Shimozawa

Motome

Outline

1. Introduction: Kitaev quantum spin liquid
2. A candidate of Kitaev magnet α-$RuCl_3$
3. Thermal Hall effect in perpendicular fields
4. Thermal Hall effect in tilted fields
   Observation of half-integer thermal Hall conductance
5. Summary

Y. Kasahara *et al*., arXiv:1709.10286 (2017).

Introduction

Quantum spin liquid (QSL)

Quantum fluctuations melt the long-range magnetic order even at $T = 0$.
The ground state with massive entanglement of local spins.

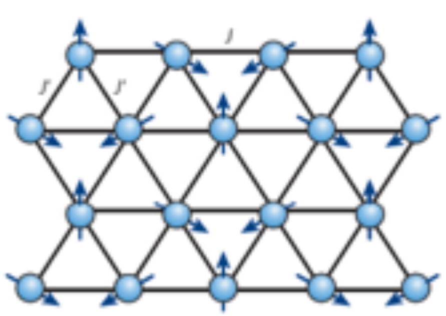
Spin liquid are states which do not break any simple symmetry:
Neither spin-rotational symmetry nor lattice translational symmetry.

Platforms of QSL

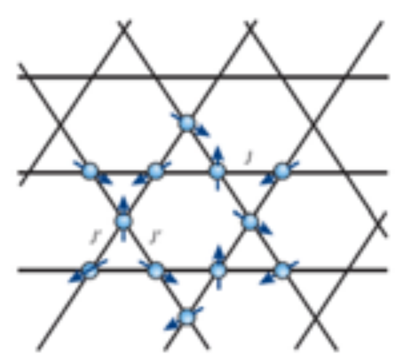
1D: S = 1/2 XXZ chain

2D & 3D: Geometrically frustrated magnets

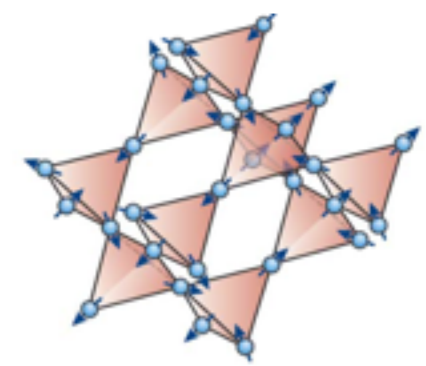
2D trianglar



2D kagome

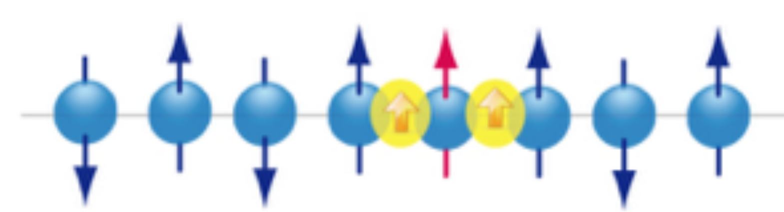


3D pyrochlore



Exotic physical properties in QSLs

Topological phases
Gauge fluctuations
Fractionalized excitations

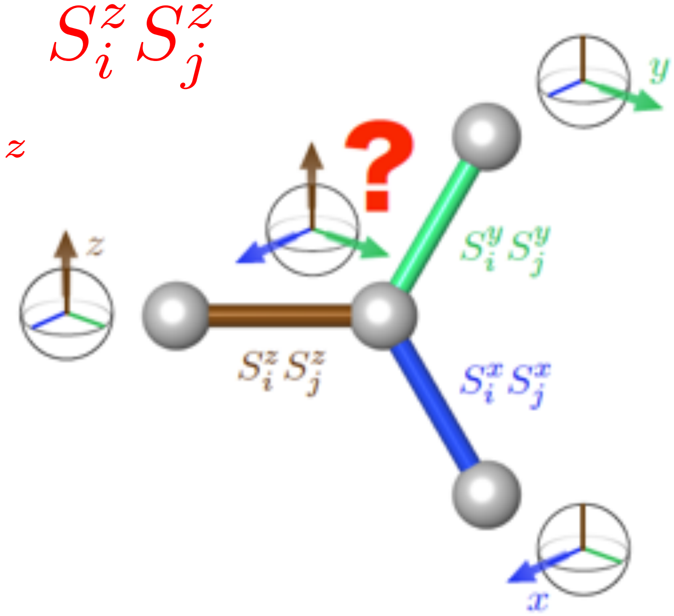


Spinon excitation (S=1/2, e=0)

Kitaev model

S = 1/2 spins on tri-coordinate lattices A. Kitaev, Ann. Phys. **321**, 2 (2006).

$$\mathcal{H} = -J_x \sum_{<ij>_x} S_i^x S_j^x - J_y \sum_{<ij>_y} S_i^y S_j^y - J_z \sum_{<ij>_z} S_i^z S_j^z$$



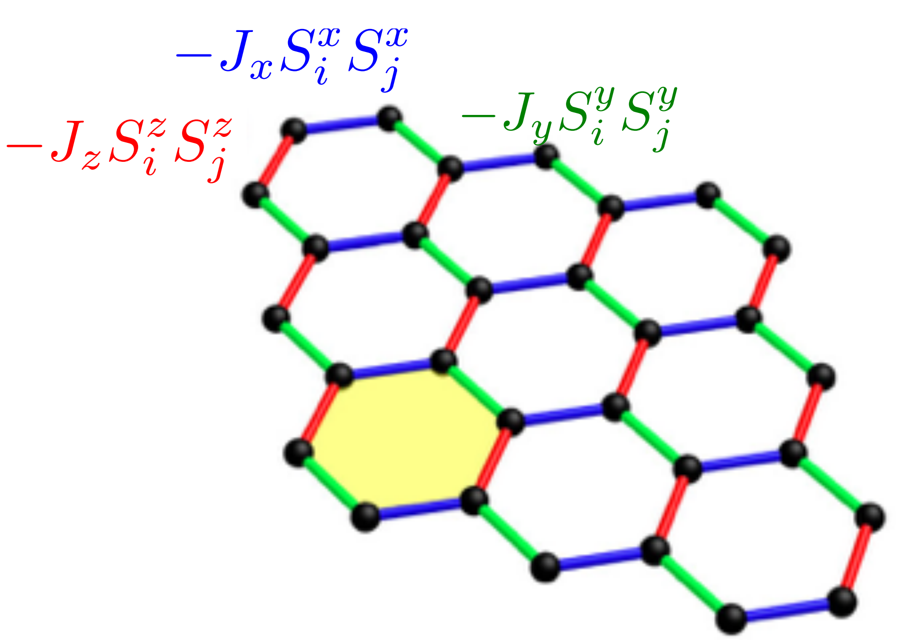
Kitaev Interaction

Bond-dependent Ising-like interaction

→ **Exchange frustration**

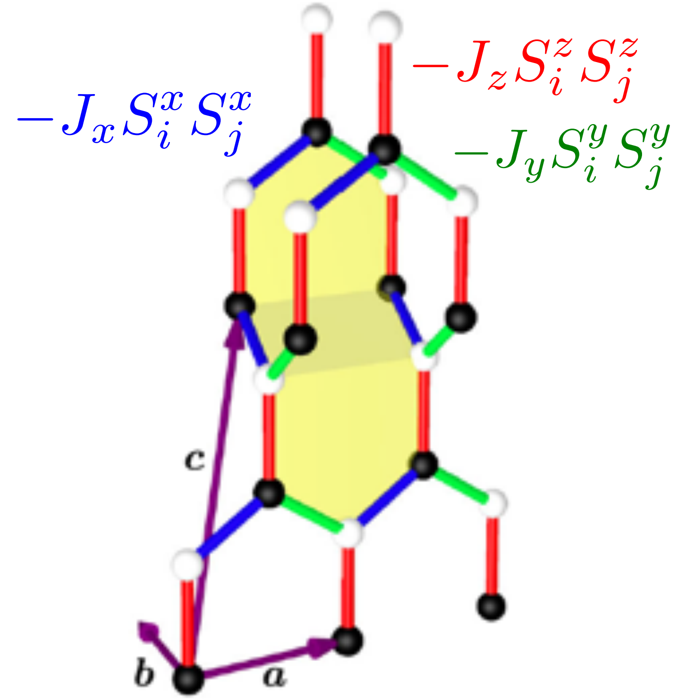
Honeycomb lattice (2D)

A. Kitaev, Ann. Phys. **321**, 2 (2006).



Hyper-honeycomb lattice (3D)

S. Mandal & N. Surendran, PRB **79**, 024426 (2009).



Kitaev model

$$\mathcal{H}_{\rm K} = -J_x \sum_{<ij>_x} S_i^x S_j^x - J_y \sum_{<ij>_y} S_i^y S_j^y - J_z \sum_{<ij>_z} S_i^z S_j^z$$

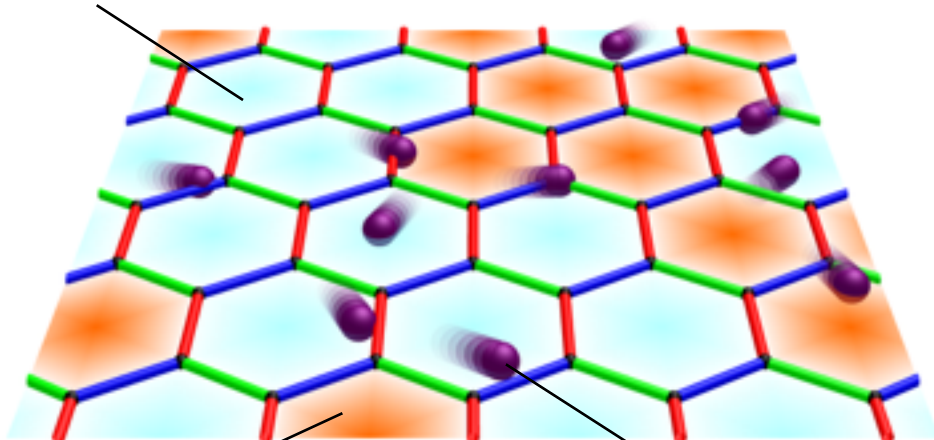
Jordan-Wigner transformation

Majorana representation

$$\mathcal{H}_{\rm K} = \frac{iJ_x}{4} \sum_{<ij>_x} c_i c_j - \frac{iJ_y}{4} \sum_{<ij>_y} c_i c_j - \frac{iJ_z}{4} \sum_{<ij>_z} \eta_r c_i c_j \qquad \eta_r = i\bar{c}_i \bar{c}_j$$

Free Majorana fermions on a honeycomb lattice

A. Kitaev, Ann. Phys. **321**, 2 (2006).

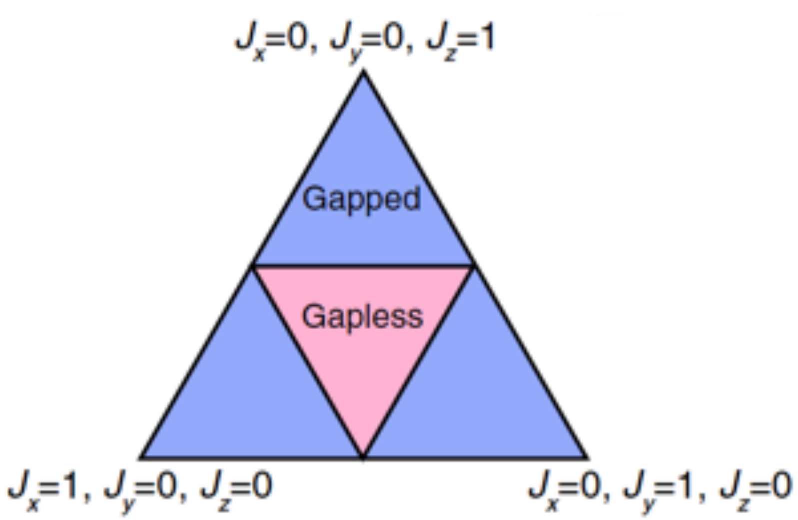


Fractionalization of quantum spins

Spin 1/2 S_i

- **Itinerant** Majorana fermion c_i with Dirac cone dispersion
- **Localized** Majorana fermion $\bar{c}_i$ → Z_2 fluxes $W_p = \eta_r \eta_{r'}$

Spin fractionalization occurs below ~J_K/k_B.
(proximate spin liquid state)



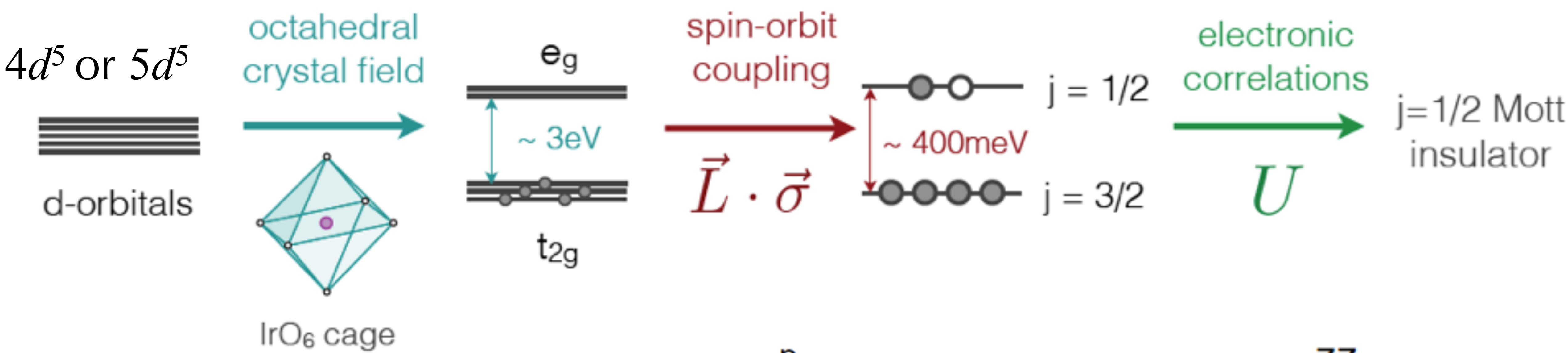
Two types of QSLs

Gapped QSL: Toric code

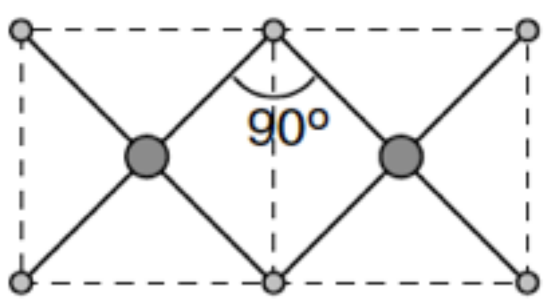
Gapless QSL: Majorana metal

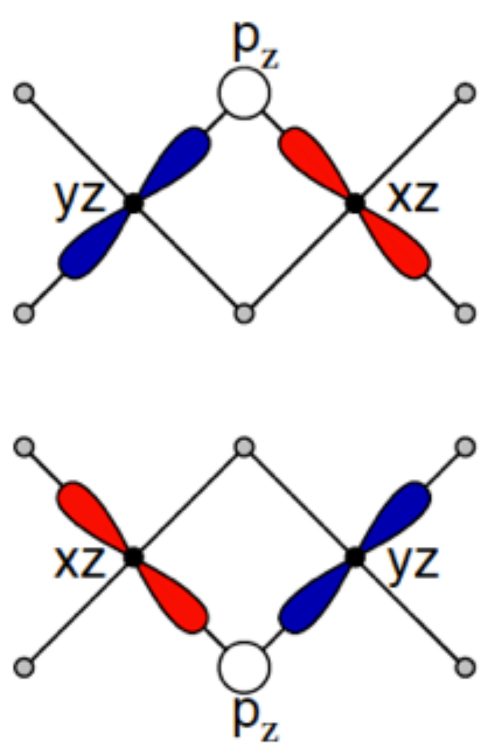
Candidate materials

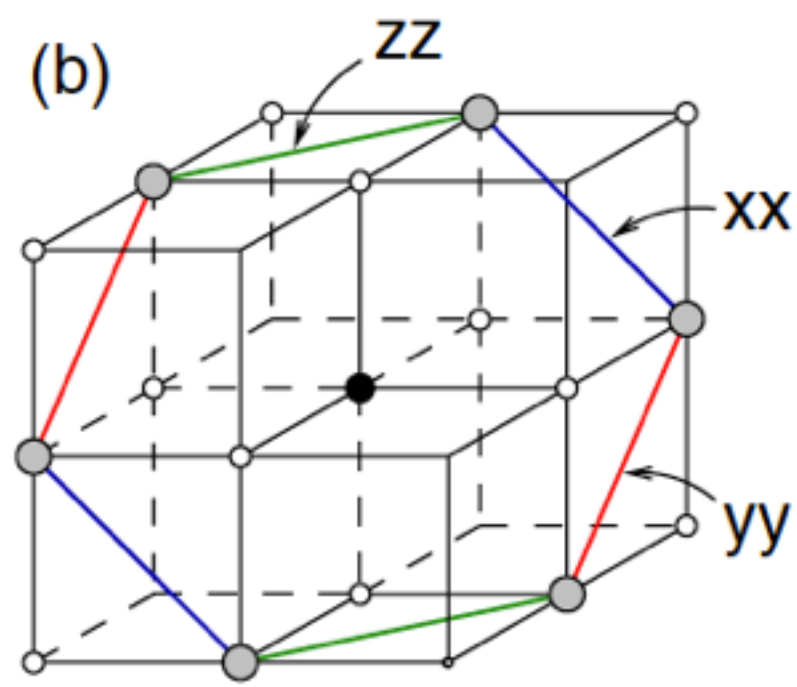
Spin-orbit assisted Mott insulator with *j* = 1/2



90° bond formed by
edge-shared octahedra





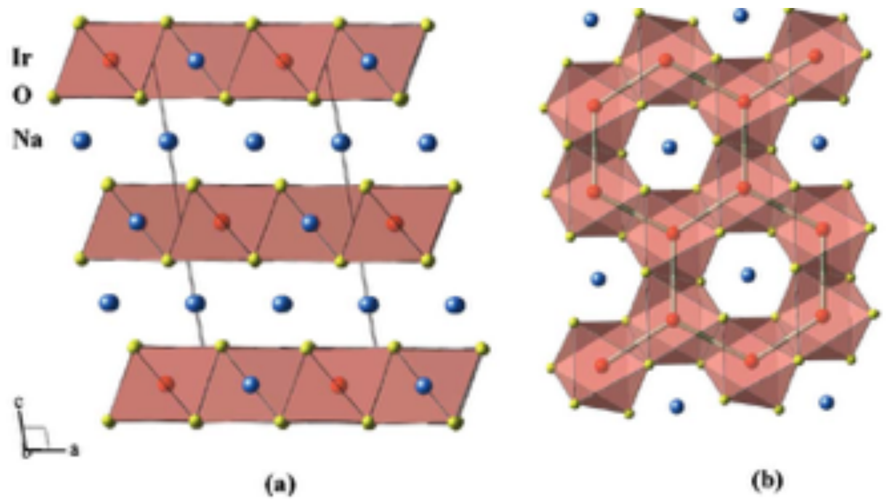


G. Jackeli & G. Khaliullin, PRL **102**, 017205 (2006).

Candidate materials

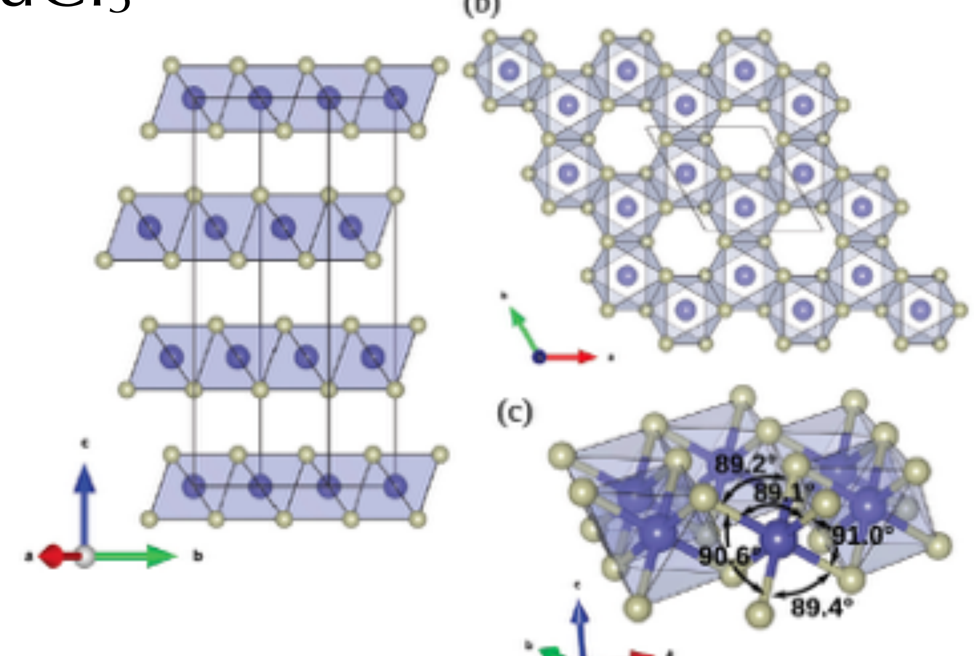
2D honeycomb lattice

Na_2IrO_3



Y. Singh & P. Gegenwart, PRB **82**, 064412 (2010).

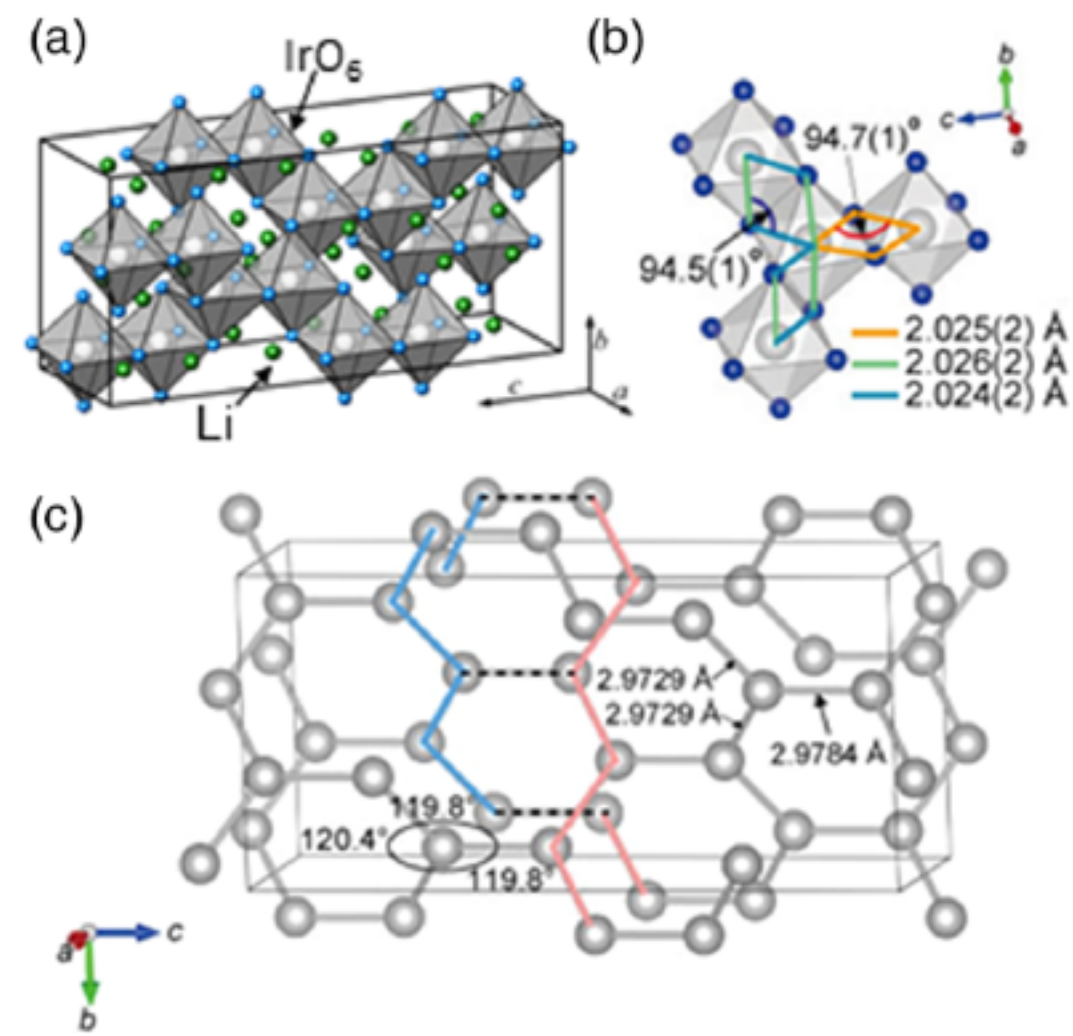
α-$RuCl_3$



K. W. Plumb *et al.*, PRB **90**, 041112 (2014).

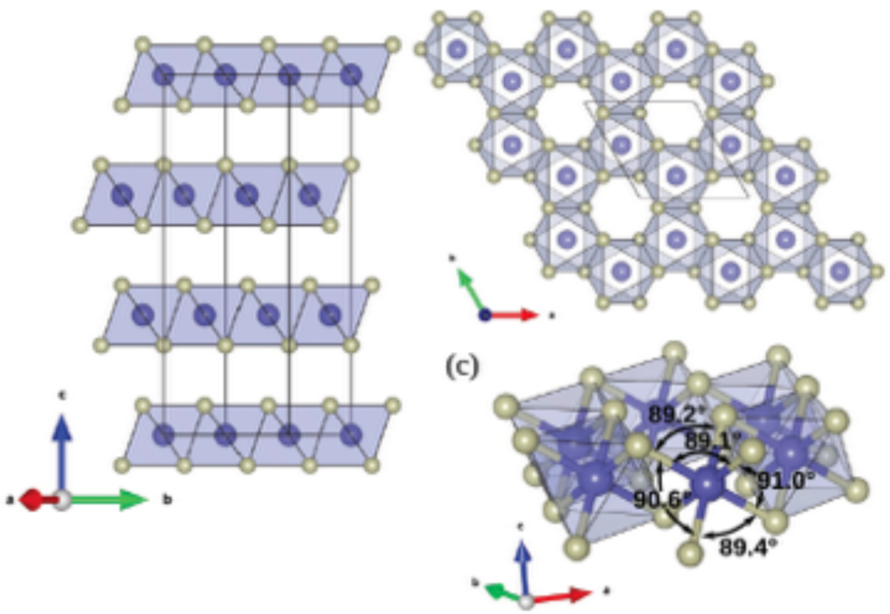
3D hyper-honeycomb lattice

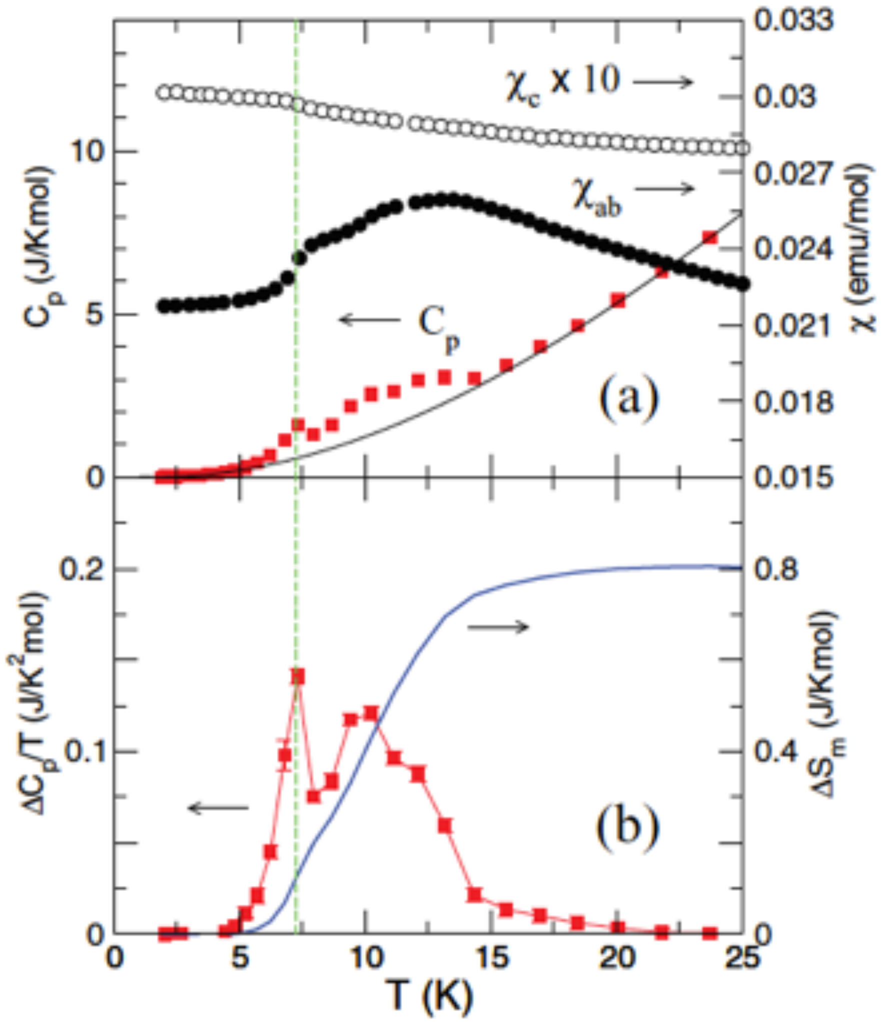
β-Li_2IrO_3



T. Takayama *et al.*, PRL **114**, 077202 (2015).

Layered honeycomb magnet α-$RuCl_3$





J. A. Sears *et al.*, PRB **91**, 144420 (2015).

$$\mathcal{H} = \sum_{<ij>} [\underbrace{J\vec{S}_i \cdot \vec{S}_j}_{\text{Heisenberg}} + \underbrace{J_K S_i^\gamma S_j^\gamma}_{\text{Kitaev}} + \underbrace{\Gamma(S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha)}_{\text{off-diagonal exchange}}]$$

Heisenberg **Kitaev** **off-diagonal exchange**

$$\begin{aligned} J &= -1.7\,\text{meV} \\ K &= -6.7\,\text{meV} \\ \Gamma &= +6.6\,\text{meV} \end{aligned}$$

Dominant Kitaev term $J_K/k_B \sim 100$ K

$K_x = -6.7$ meV, $K_y = -6.7$ meV, $K_z = -5.0$ meV

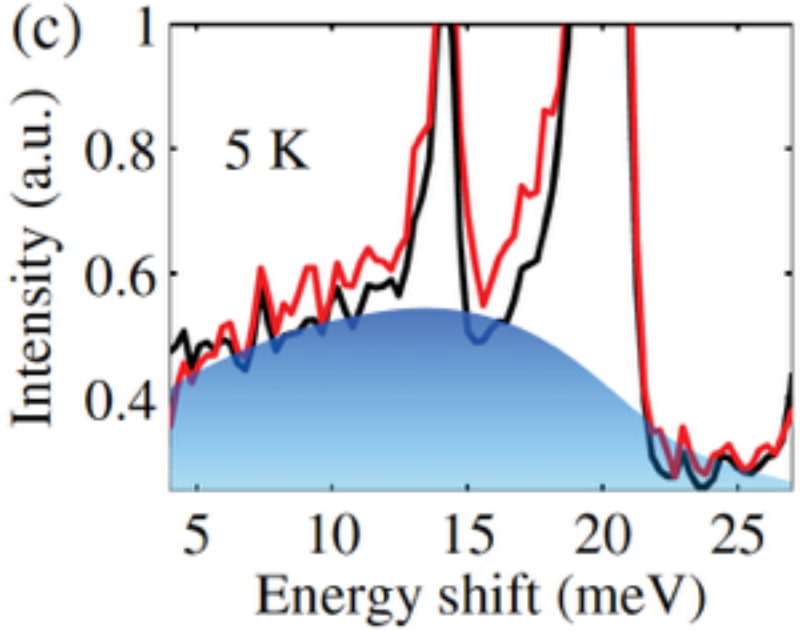
S. M. Winter *et al.*, PRB **93**, 214431 (2016).

Presence of non-Kitaev interaction

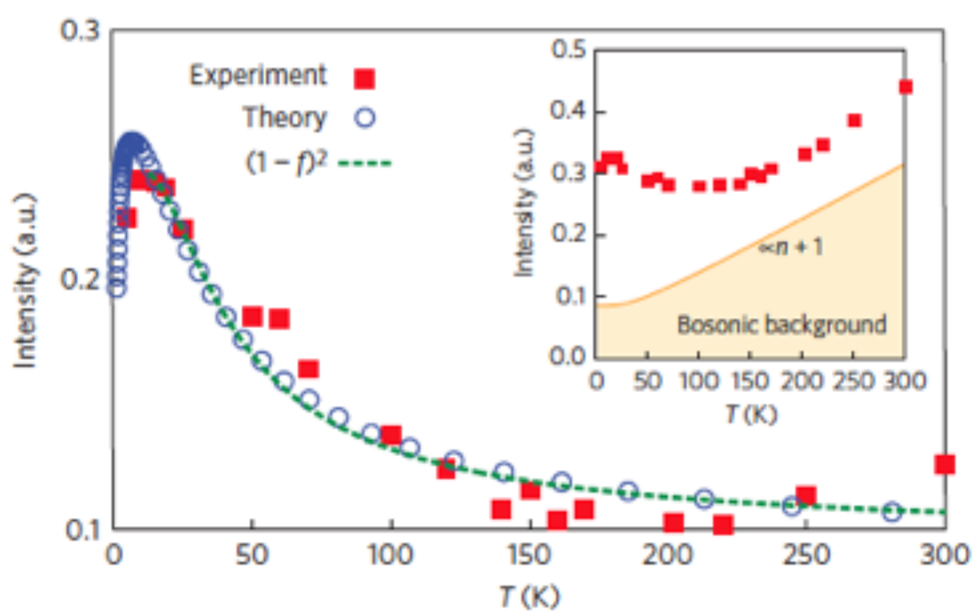
- AFM order with zigzag spin structure at $T_N \sim 7.5$ K
- Transition at 14 K appears due to stacking faults.

Possible signatures of Kitaev QSL in α-$RuCl_3$

Raman scattering



L. J. Sandilands *et al.*, PRL **114**, 147201 (2015).



J. Nasu *et al.*, Nat. Phys. **12**, 912 (2016).

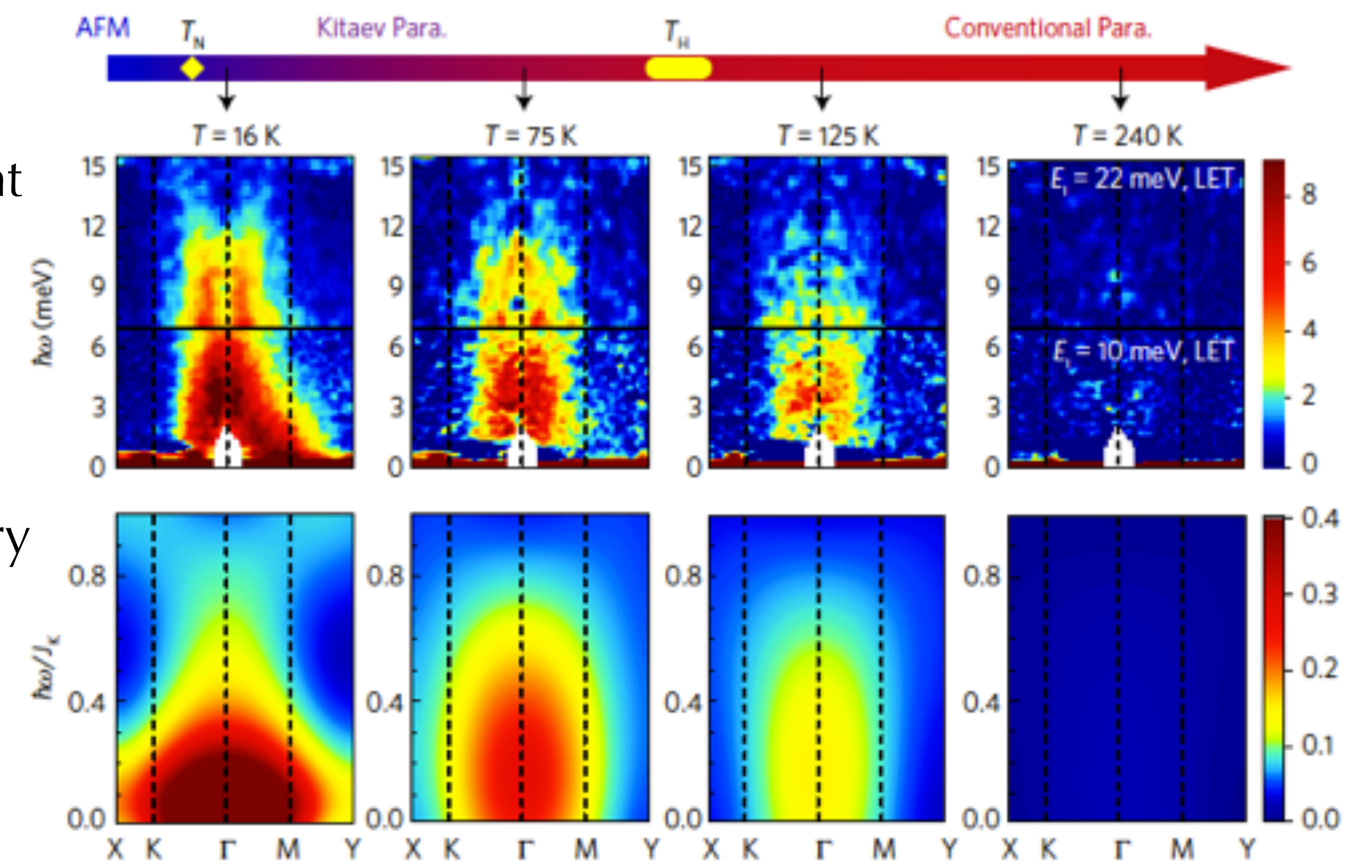
Broad magnetic continuum at high energy

Fermionic excitations

Inelastic neutron scattering

Experiment

Theory



S.-H. Do *et al.*, Nat. Phys. http://doi.org/10.1038/nphys4298.
A. Banerjee *et al.*, Nat. Mater. **15**, 733 (2016).
A. Banerjee *et al.*, Science **356**, 1055 (2017).

Broad magnetic continuum appears below ~ J_K/k_B

Possible signature of spin fractionalization

More direct measurements are required.

What gives direct signature of Majorana fermions?

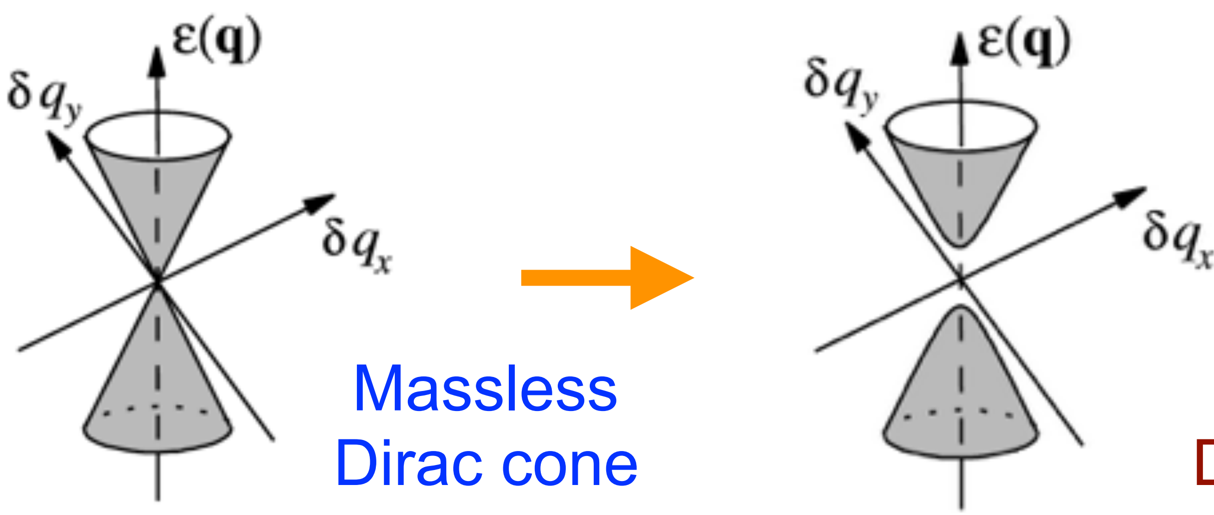
Effect of magnetic field (h || [111]) A. Kitaev, Ann. Phys. **321**, 2 (2006).

$$\mathcal{H} = \mathcal{H}_{\mathrm{K}} + \mathcal{H}_h^{\mathrm{eff}}$$

$$\mathcal{H}_{\mathrm{K}} = -J_x \sum_{<ij>_x} S_i^x S_j^x - J_y \sum_{<ij>_y} S_i^y S_j^y - J_z \sum_{<ij>_z} S_i^z S_j^z$$

$$\mathcal{H}_h^{\mathrm{eff}} = -\tilde{h} \sum_{(ijk)} S_i^x S_j^y S_k^z \qquad \tilde{h} = \lambda h^3 \sim \frac{h^3}{\Delta_f^2}$$

Flux gap $\Delta_f \sim 0.06 J_{\mathrm{K}}$



Massless Dirac cone

$H = 0$

$H \neq 0$

Massive Dirac cone

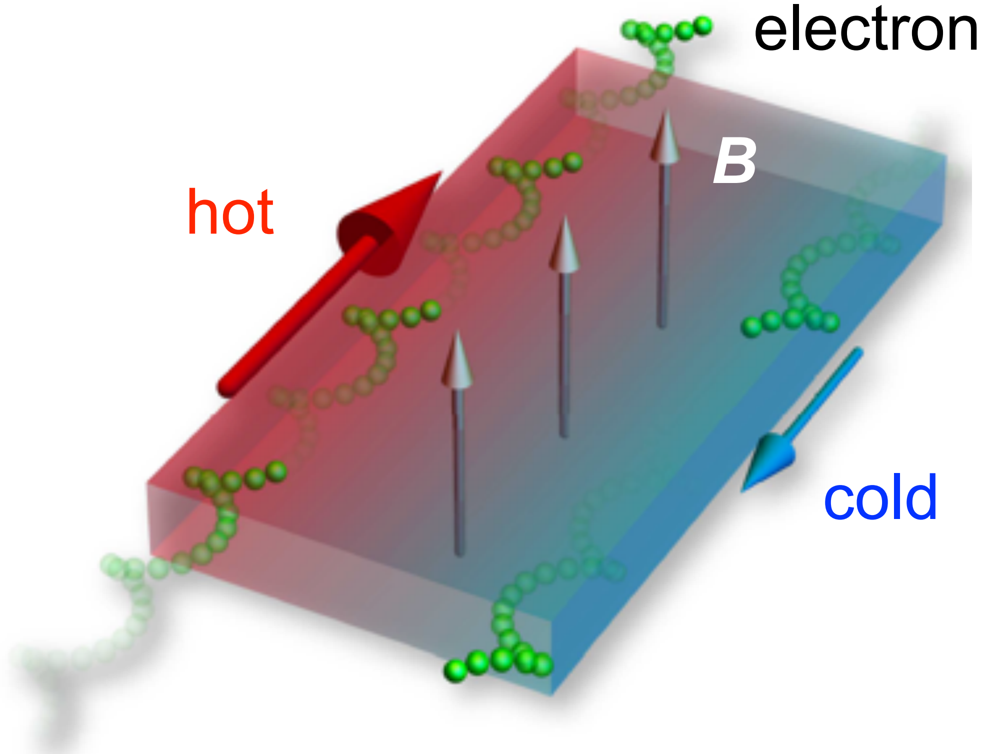
Non Abelian phase

Topological system characterized by Chern insulator under H

→ **Chiral edge current of Majorana fermions**

What gives direct signature of Majorana fermions?

Integer QHE



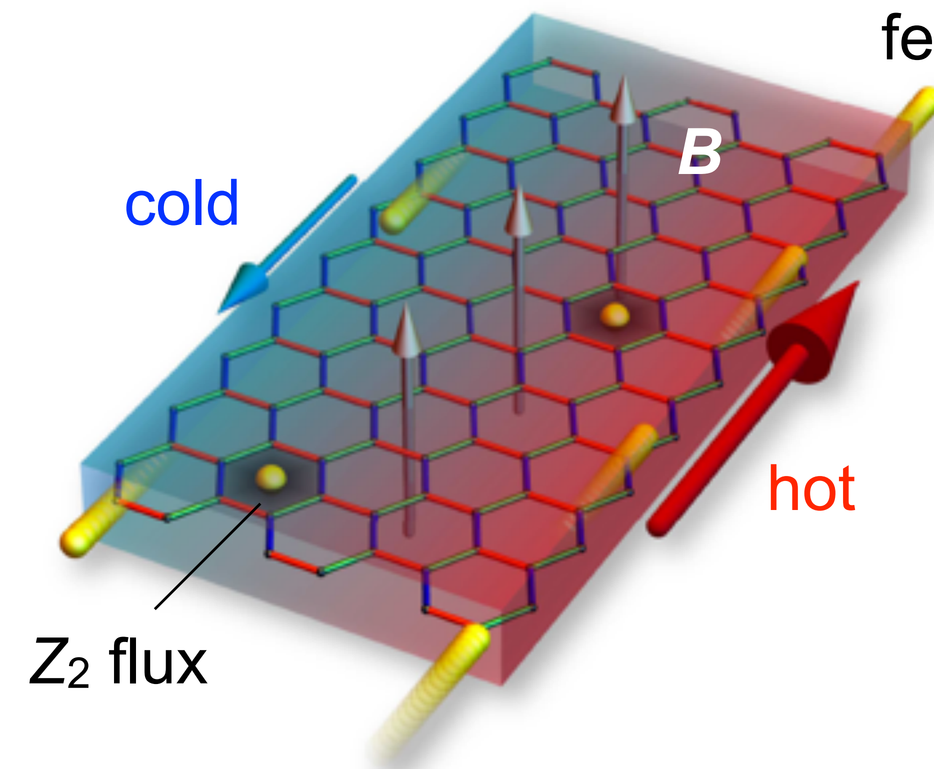
Chiral edge current of electrons

$$\sigma_{xy}^{2D} = \nu \frac{e^2}{h}$$

ν : Chern number
= # of chiral edge modes

$$\frac{\kappa_{xy}^{2D}}{T} = \nu \frac{\pi}{6} \frac{k_B^2}{\hbar}$$

Kitaev QSL



Chiral edge current of **charge neutral** ***Majorana fermions***

$$\frac{\kappa_{xy}^{2D}}{T} = q \frac{\pi}{6} \frac{k_B^2}{\hbar}$$

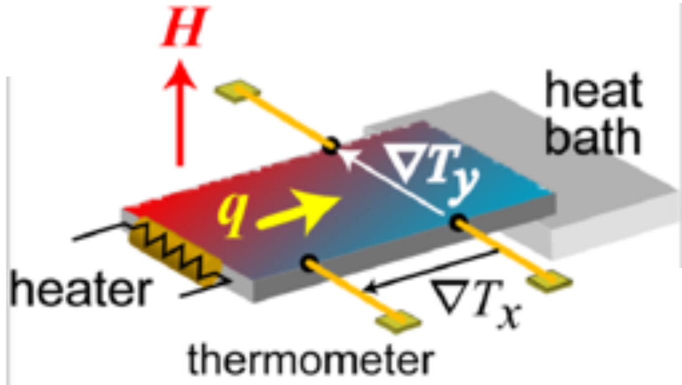
q : **Central charge**

$q = \nu$ in IQHE

$$q = \frac{\nu}{2} \rightarrow \frac{\kappa_{xy}^{2D}}{T} = \frac{1}{2} \left(\frac{\pi}{6} \frac{k_B^2}{\hbar} \right)$$

Half-integer thermal Hall conductance in a Kitaev QSL

Thermal Hall effect in insulating magnets

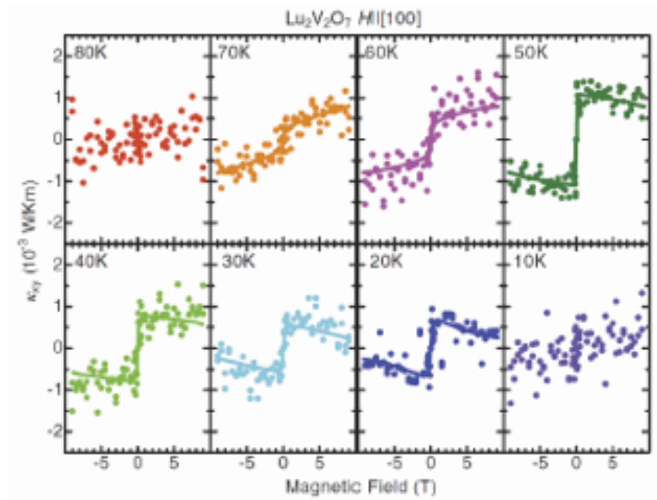


$$\begin{pmatrix} q \\ 0 \end{pmatrix} = \begin{pmatrix} \kappa_{xx} & \kappa_{xy} \\ -\kappa_{xy} & \kappa_{xy} \end{pmatrix} \begin{pmatrix} -\nabla T_x \\ -\nabla T_y \end{pmatrix}$$

Ferromagnetically ordered state

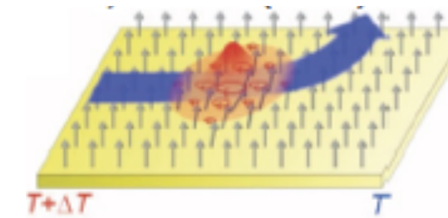
$Lu_2V_2O_7$
$Ho_2V_2O_7$, $In_2Mn_2O_7$, $BiMnO_3$
Cu(1-3,bdc)

Y. Onose *et al*, Science **329**, 297 (2010).
Ideue *et al*., PRB **85**, 134411 (2012).
M. Hirschberger *et al*., PRL **115**, 106603 (2015).



$Lu_2V_2O_7$

Magnon Hall effect arising from Berry phase



$$\kappa_{xy} = -\frac{k_B^2 T}{\hbar V} \sum_k \sum_{n=1}^{N} \left\{ c_2[g(\varepsilon_{nk})] - \frac{\pi^2}{3} \right\} \Omega_{nk}.$$

R. Matsumoto *et al*.,
PRB **89**, 054420 (2014).

Paramagnetic state

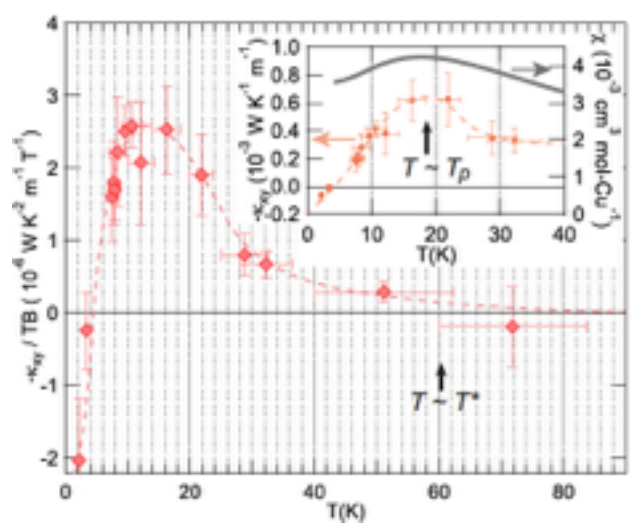
$Tb_2Ti_2O_7$

M. Hirschberger *et al*., Science **348**, 106 (2015).

Spin liquid state

$Cu_3V_2O_7(OH)_2 \cdot 2H_2O$

D. Watanabe, PNAS **113**, 8653 (2016).



Spinon Hall effect in QSL state with spinon Fermi surface

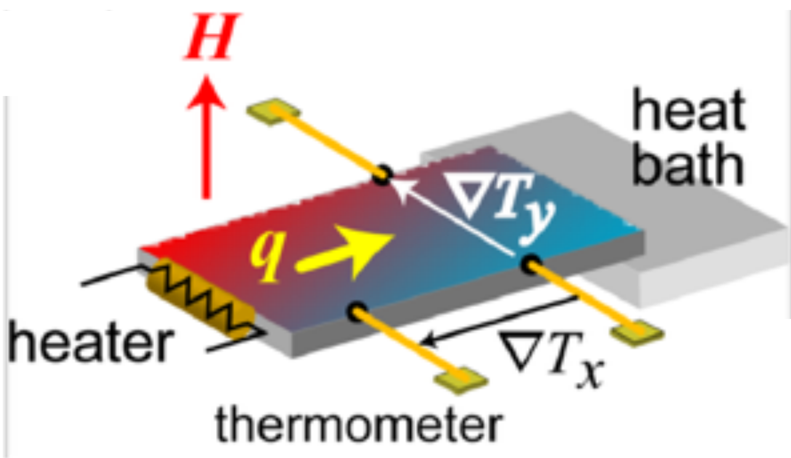
$$\kappa_{xx}^{\text{spinon}} = 2\frac{\pi^2}{3}\left(\frac{\varepsilon_F}{\hbar}\tau\right)\frac{k_B^2 T}{h}\frac{1}{d}$$

$$\kappa_{xy}^{\text{spinon}} = \kappa_{xx}^{\text{spinon}}(\omega_c \tau)$$

H. Katsura *et al*., PRL **104**, 066403 (2010).

Thermal transport measurements in α-$RuCl_3$

Thermal Hall effect



$$\begin{pmatrix} q \\ 0 \end{pmatrix} = \begin{pmatrix} \kappa_{xx} & \kappa_{xy} \\ -\kappa_{xy} & \kappa_{xy} \end{pmatrix} \begin{pmatrix} -\nabla T_x \\ -\nabla T_y \end{pmatrix}$$

ex.) Spin liquid state:

Kagome volborthite $Cu_3V_2O_7(OH)_2 \cdot 2H_2O$

$\kappa_{xy}/T \sim 10^{-5}$ W/K^{2}m spinon

Magnetically ordered state:

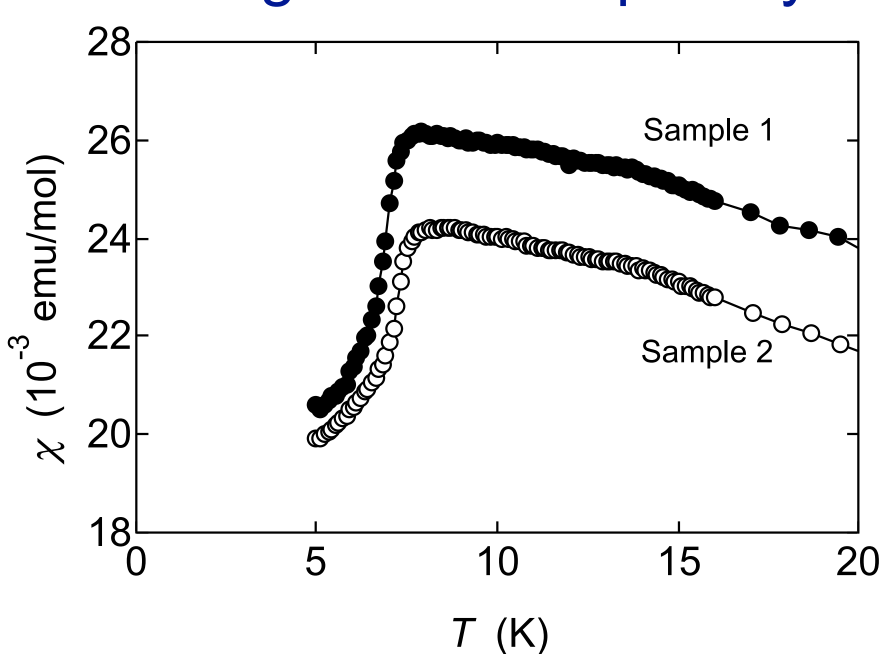
Kagome Cu-(1-3,bdc) $\kappa_{xy}/T \sim 10^{-5}$ - 10^{-4} W/K^{2}m

Pyrochlore $Lu_2V_2O_7$ magnon

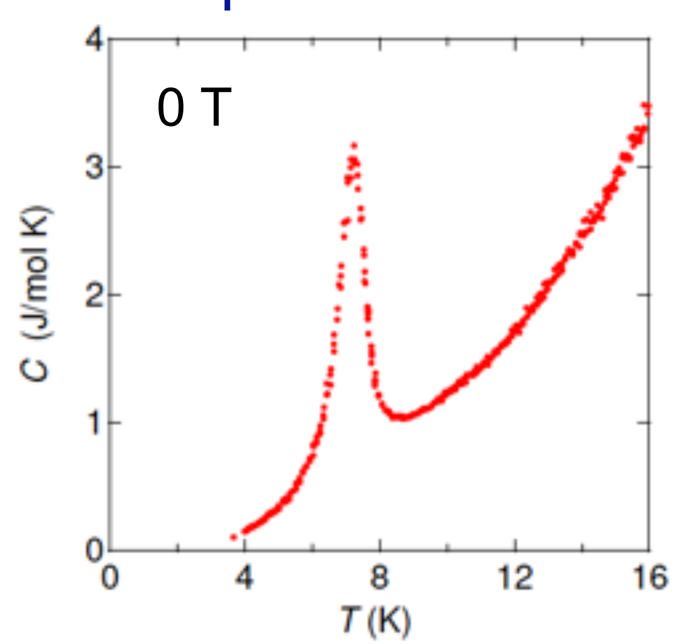
cf.) Phonon thermal Hall effect $\kappa_{xy}/T \sim 10^{-6}$ W/K^{2}m

α-$RuCl_3$ single crystals

Magnetic susceptibility



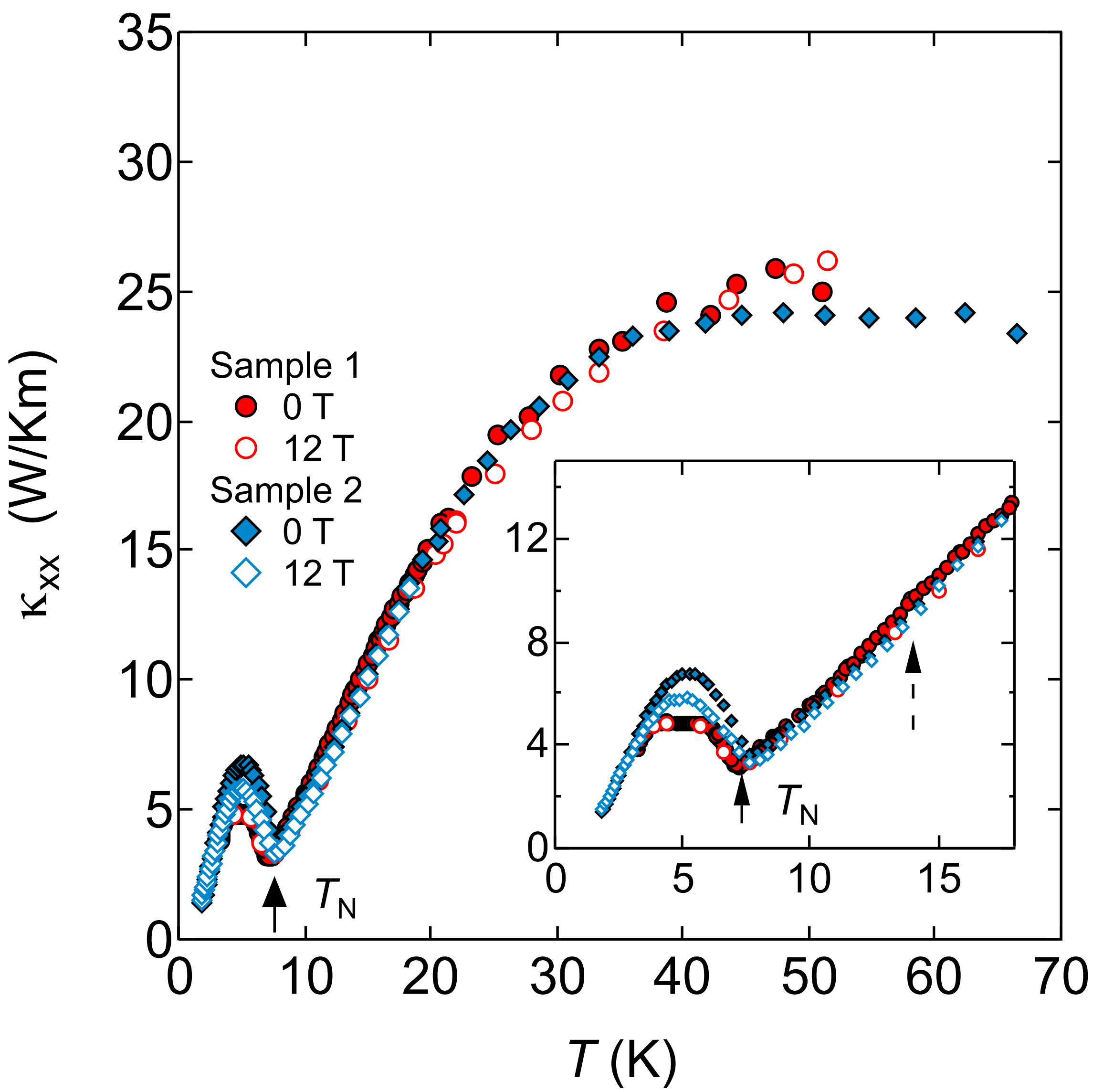
Specific heat

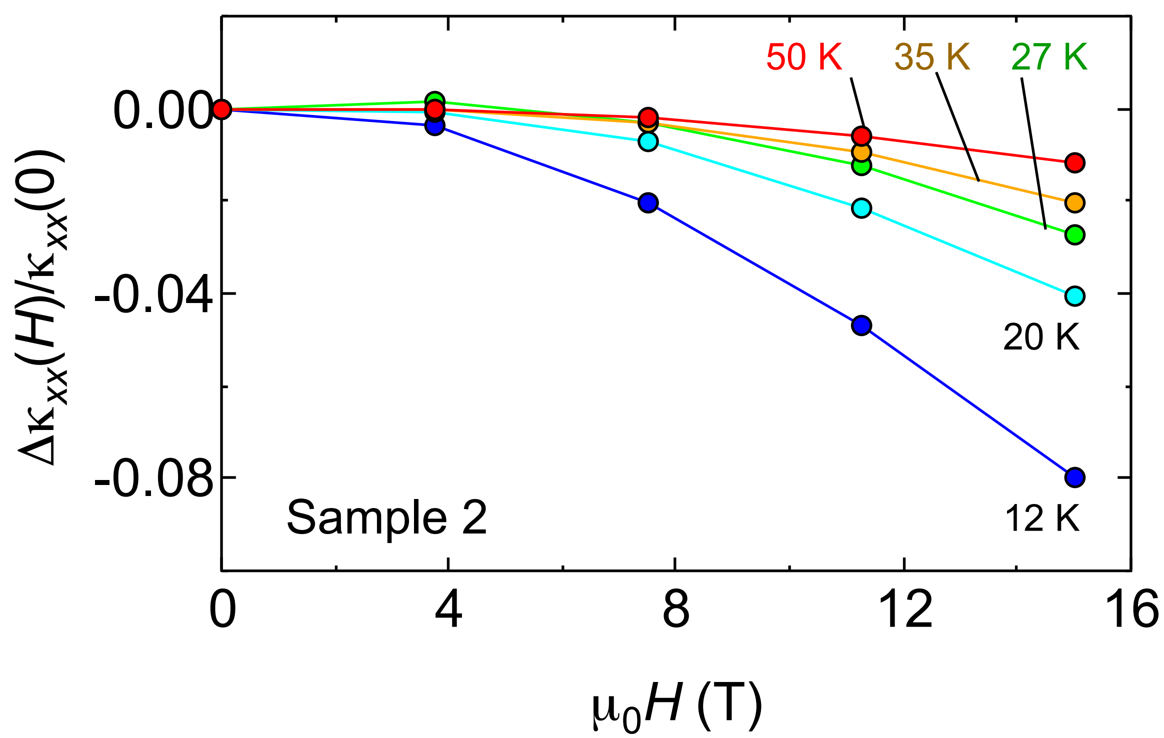


- Clear anomaly at $T_N \sim 7.5$ K
- No discernible anomaly at ~ 14 K due to stacking faults

High quality single crystal

Longitudinal thermal conductivity κ_{xx}





$$\kappa_{xx} = \underbrace{\kappa_{xx}^{\mathrm{sp}}}_{\text{spin}} + \underbrace{\kappa_{xx}^{\mathrm{ph}}}_{\text{phonon}}$$

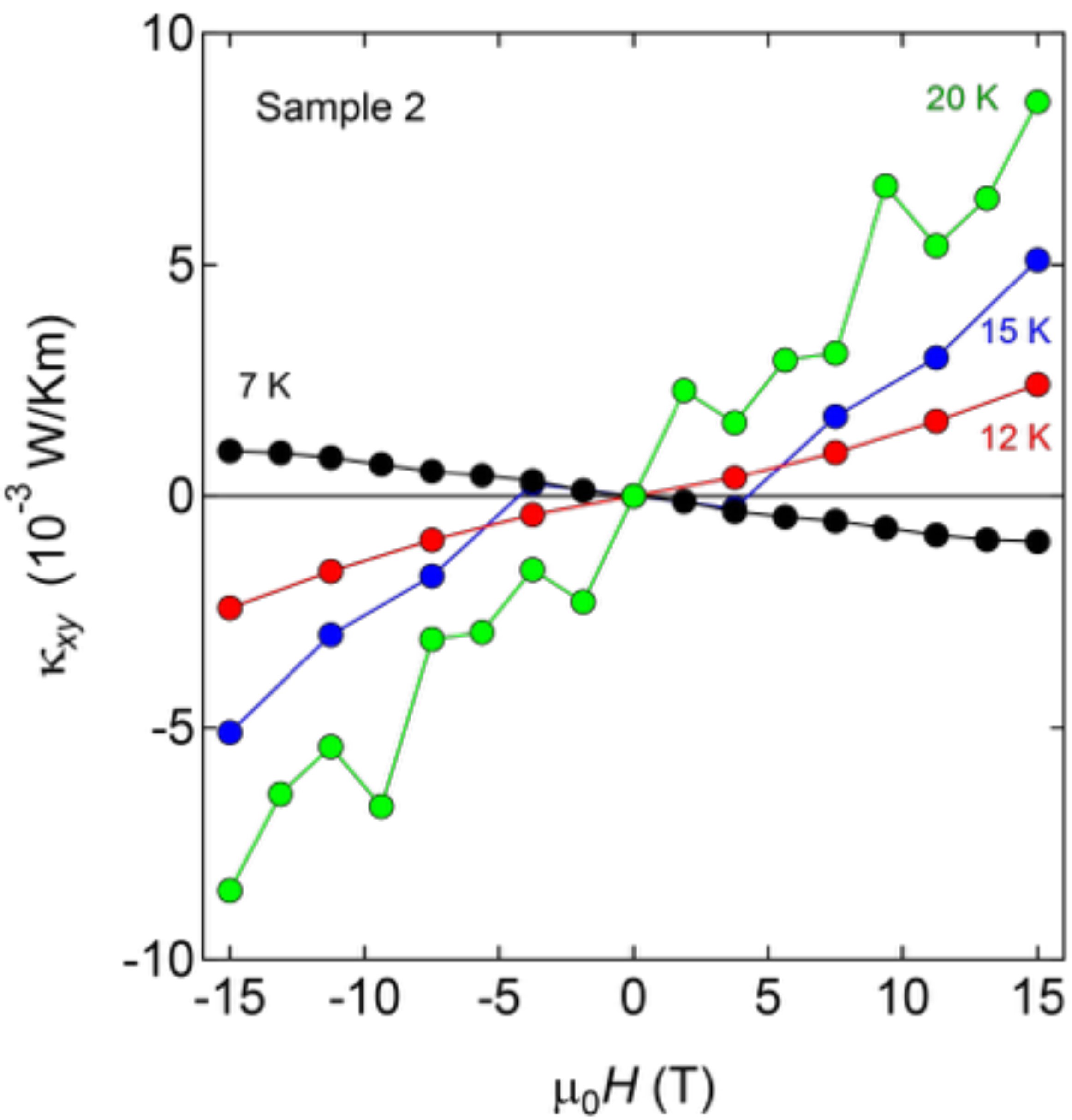
- Clear anomaly in κ_{xx} at T_N
- Suppression of κ_{xx} by magnetic field ↔ κ_{xx}^{ph} is usually enhanced due to suppression of spin-phonon scattering by spin polarization.

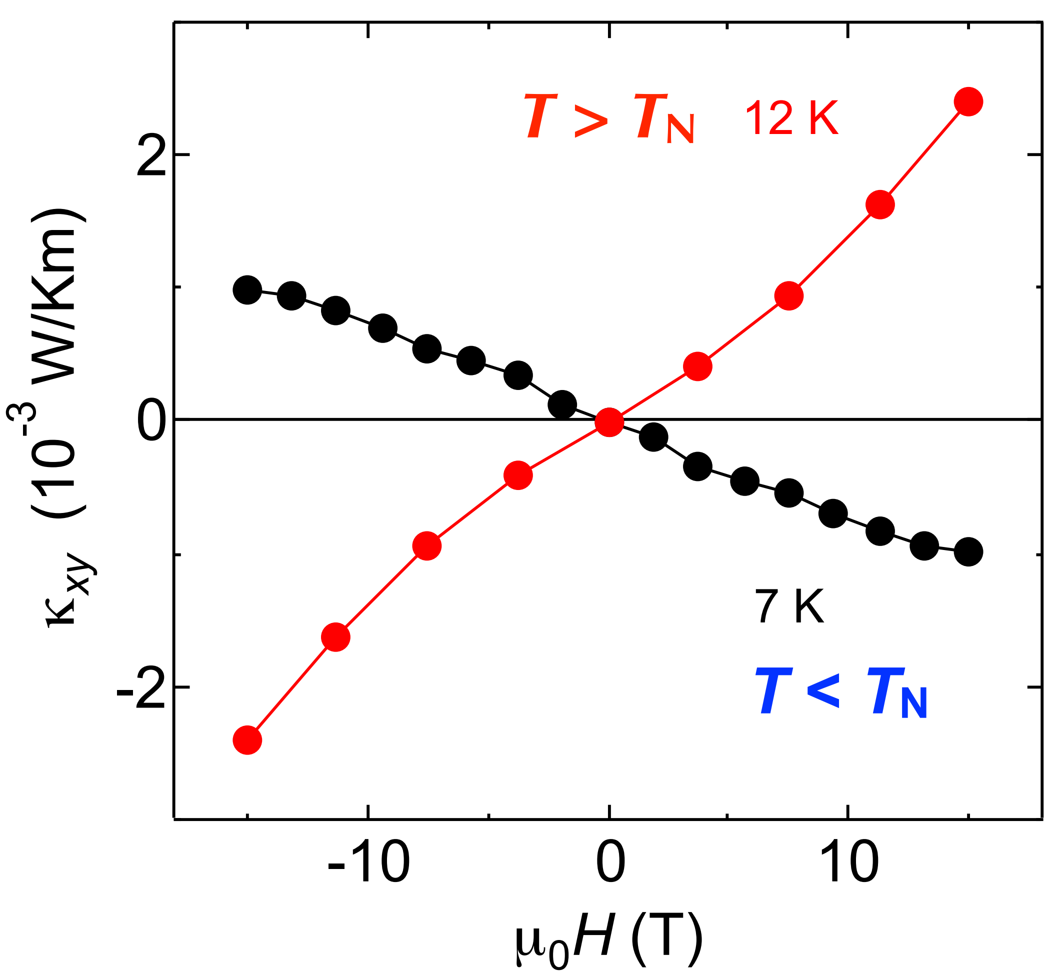
Thermal transport is governed by *spin excitations*.

However, it is difficult to separate spin & phonon contributions.

Thermal Hall effect

Thermal Hall conductivity κ_{xy}





Distinct H-dependence below and above T_N

- Sign change below T_N
- Upward curvature above T_N but downward below T_N

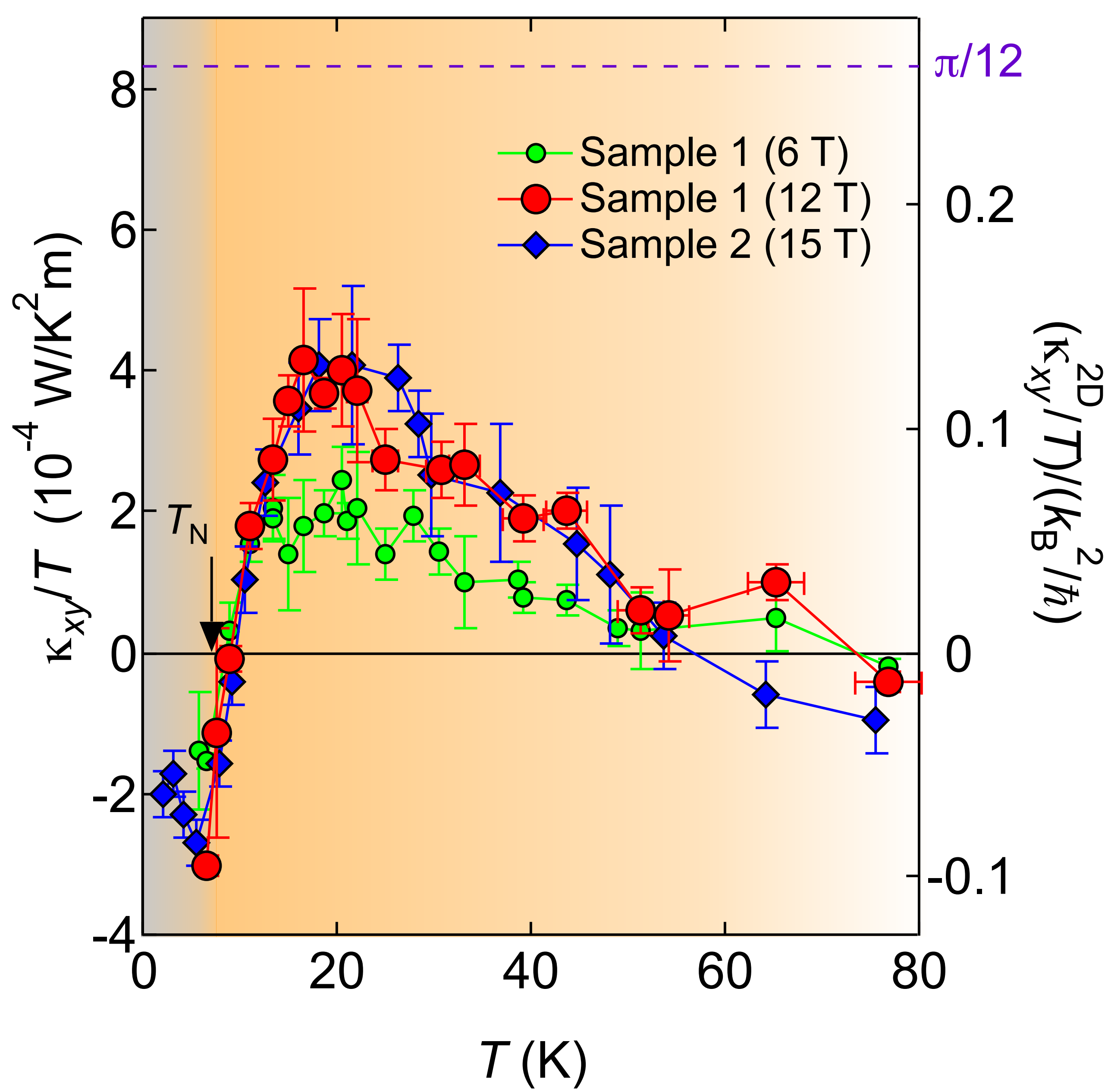
Finite $\kappa_{xy} \sim 10^{-2}$ W/Km at $T < J_K/k_B$

e.g.) $\kappa_{xy} < 10^{-3}$ W/Km

in volborthite (spin liquid)
$Tb_2Ti_2O_7$ (paramagnet)

Thermal Hall effect below and above T_N is different in origin.

Thermal Hall conductivity κ_{xy}



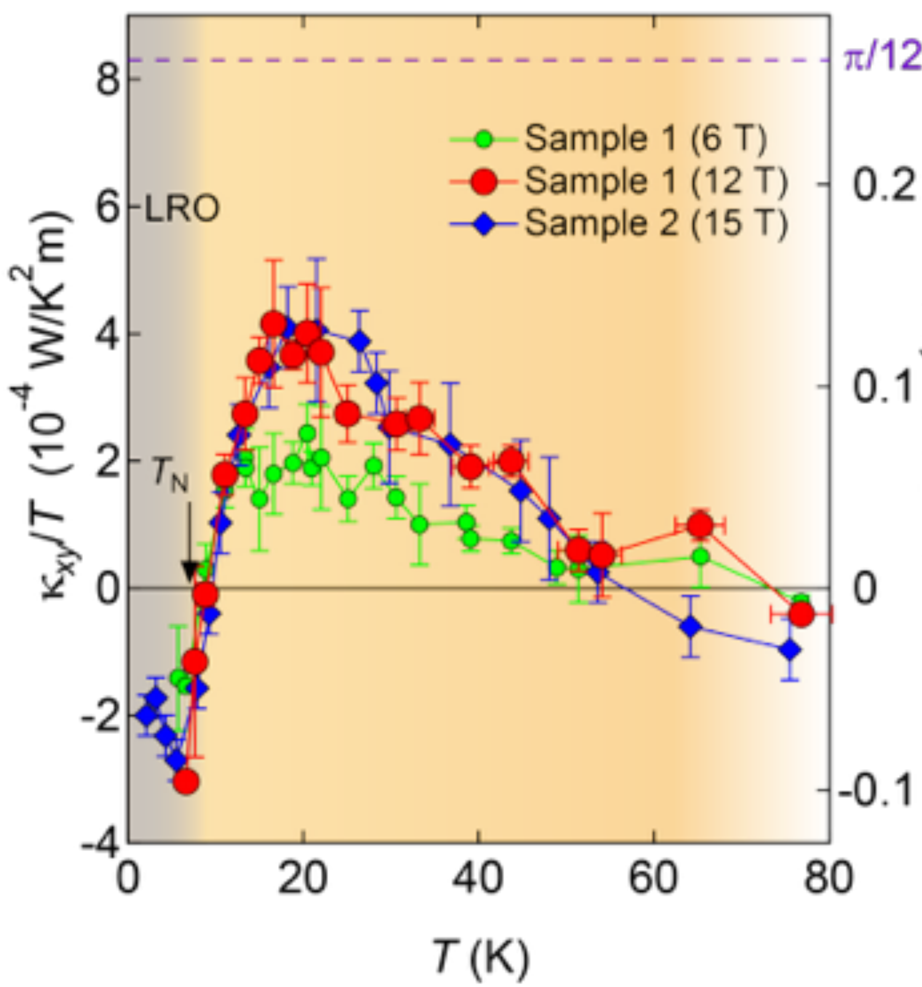
- Enhancement of κ_{xy} with *positive sign* below J_K/k_B ~ 80 K
- Broad peak at ~ 20 K

- **Phonons** $\kappa_{xy}/T \sim 10^{-6}$ W/K^{2}m
  Different T-dependence
  A. V. Inyushkin & . N. Taldenkov, JETP Lett. **86**, 379 (2007).
- **Magnons** Finite κ_{xy}/T usually appears in the ordered state.
  Small DM interaction
  D/k_B ~ 5 K << J/k_B ~ 80 K
  S. M. Winter *et al.*, PRB **93**, 214431 (2016).
- **Spin liquid with spinon Fermi surface**
  In volborthite,
  Hall signal is negative.
  $\kappa_{xy}/T \sim 10^{-5}$ W/K^{2}m
  D. Watanabe, PNAS **113**, 8653 (2006).

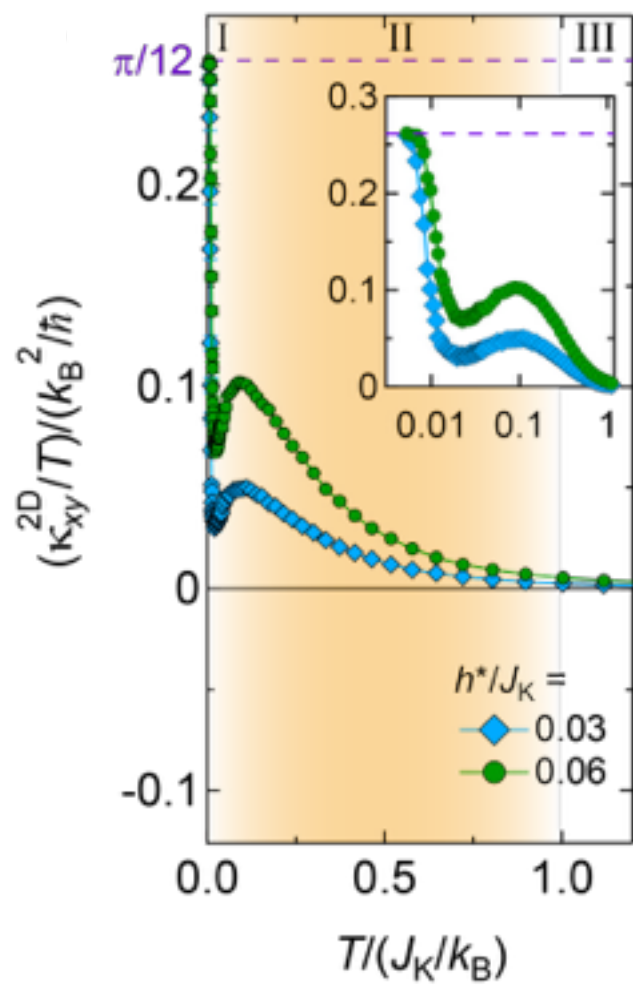
- Exotic quasiparticle excitations inherent to the spin-liquid state of α-$RuCl_3$.

Comparison with numerical calculations

Experiments



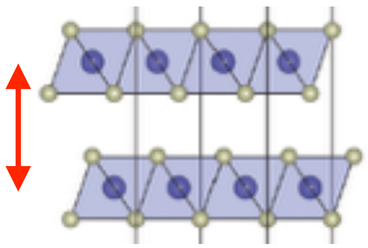
Calculations



thermal Hall conductance per 2D honeycomb layer

$$\kappa_{xy}^{2D} = \kappa_{xy} d$$

interlayer distance
d = 5.72 Å



J. Nasu, J. Yoshitake & Y. Motome, PRL **119**, 127204 (2017).

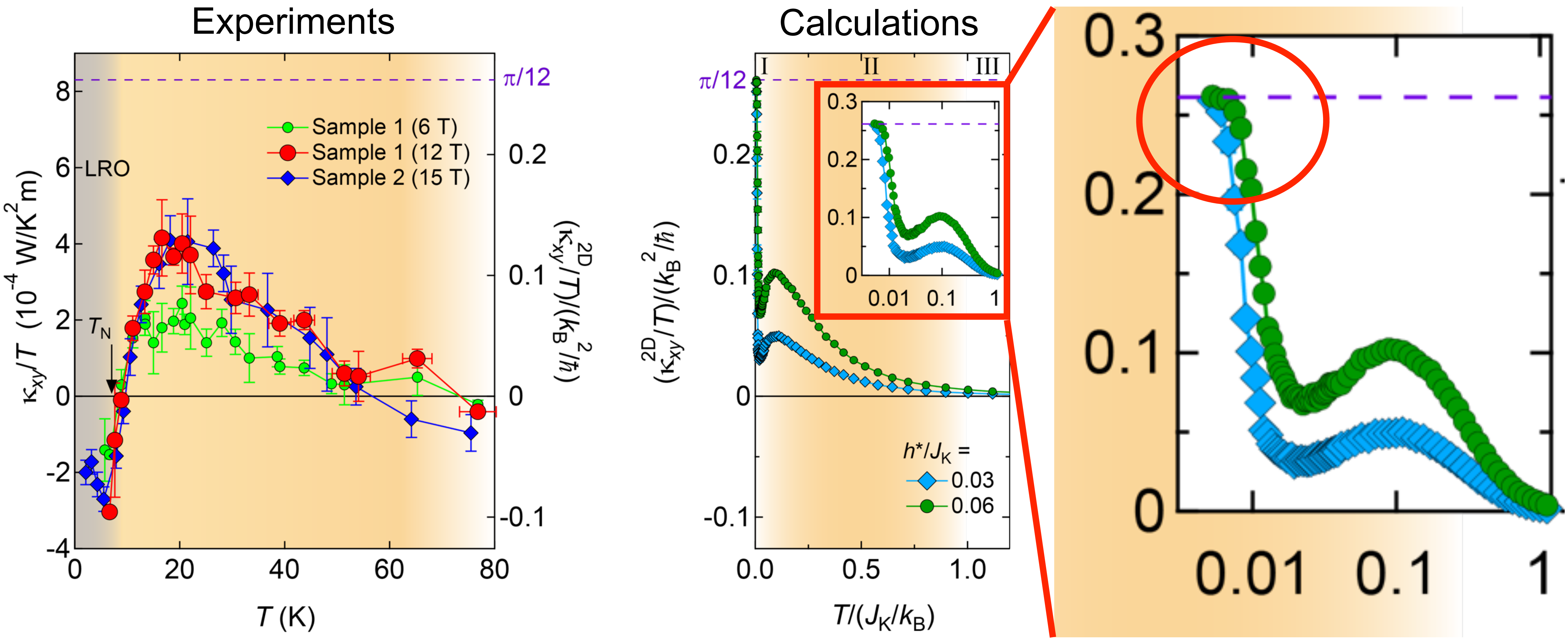
T-dependence is consistent with numerical calculations for the 2D pure Kitaev model.

- Enhancement of κ_{xy} with *positive sign* below $T < J_K/k_B$
- Broad peak at $T \sim 0.1 J_K/k_B$
- κ_{xy}/T reaches close to *half of the quantization value*.

Possible signature of Majorana fermion excitations

Y. Kasahara *et al.*, arXiv:1709.10286 (2017).

Comparison with numerical calculations



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Possible signature of Majorana fermion excitations

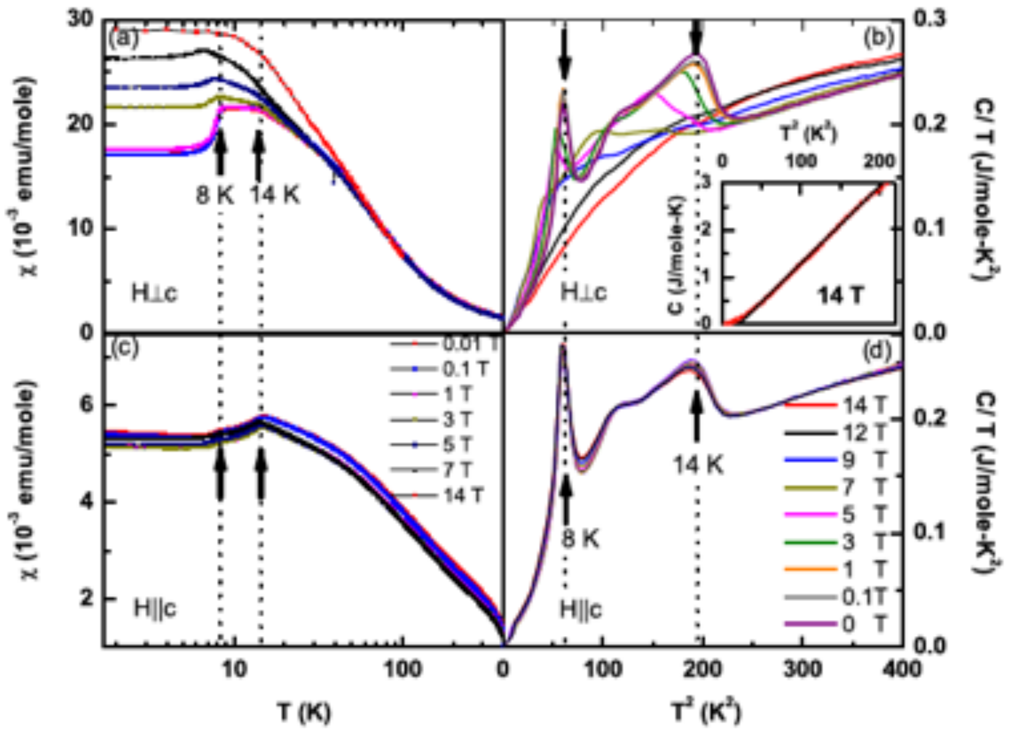
However, quantization of κ_{xy}^{2D}/T is not attained due to the magnetic order.

Y. Kasahara *et al.*, arXiv:1709.10286 (2017).

Suppression of AFM order by in-plane fields

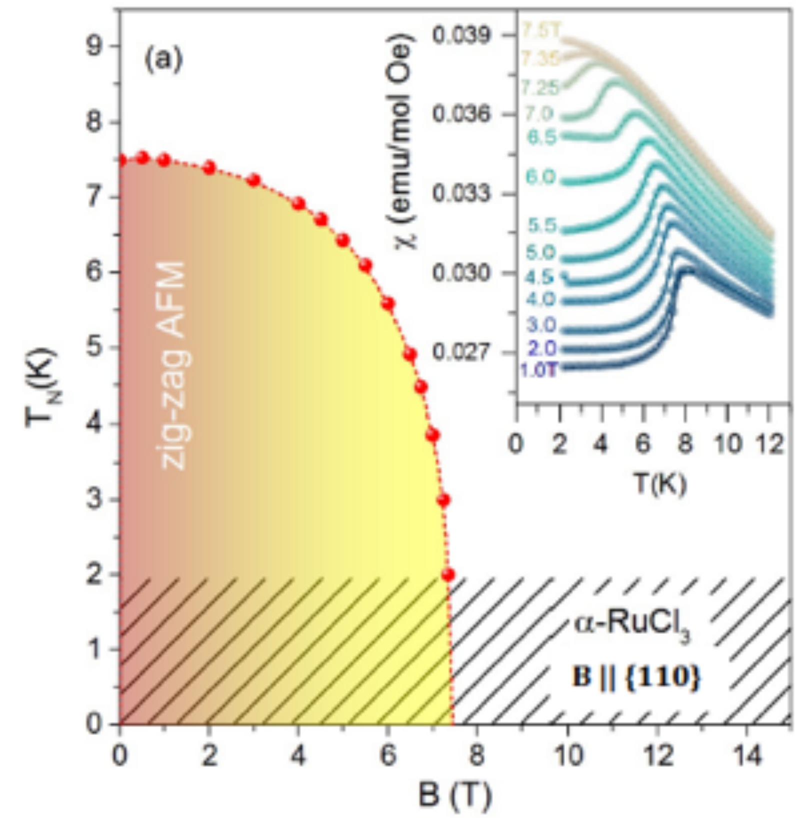
Low-temperature properties are masked by the magnetic order.

Key questions: Is the magnetic order suppressed by tuning parameters?
Whether Kitaev QSL survives when suppressing the order?



AFM order is little influenced by out-of-plane fields,
but it is easily suppressed by in-plane fields.

M. Majumder *et al.*, PRB **91**, 180401(R) (2015).



$H_{c\parallel} \sim$ 7-8 T

A. Banerjee *et al.*, arXiv:1706.0703 (2017).

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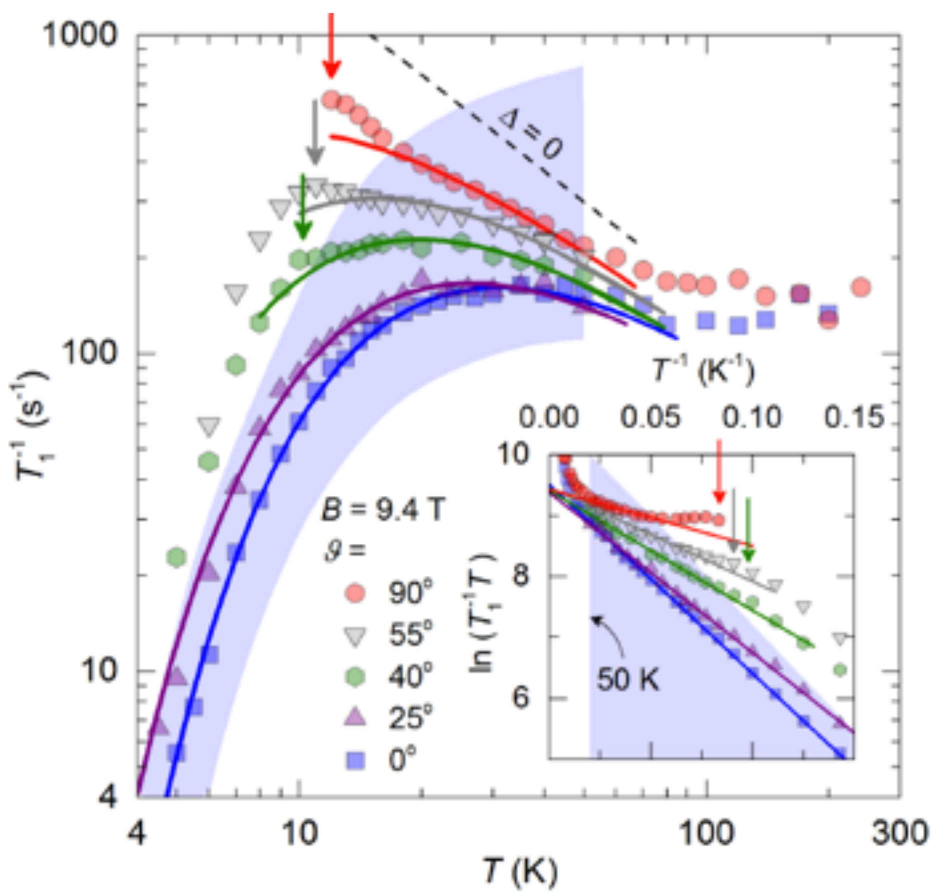
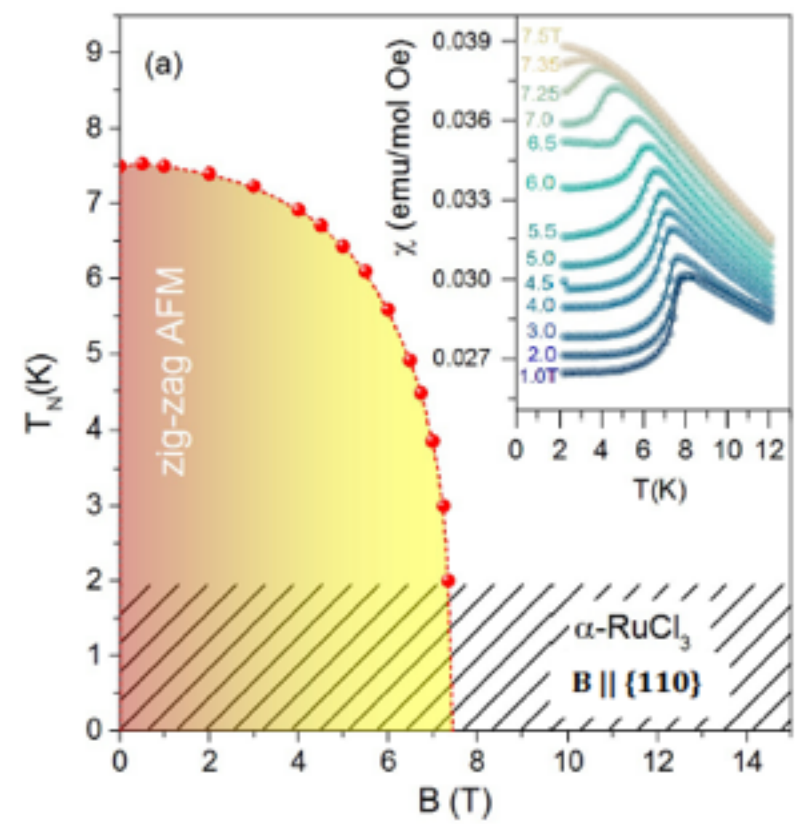
NMR





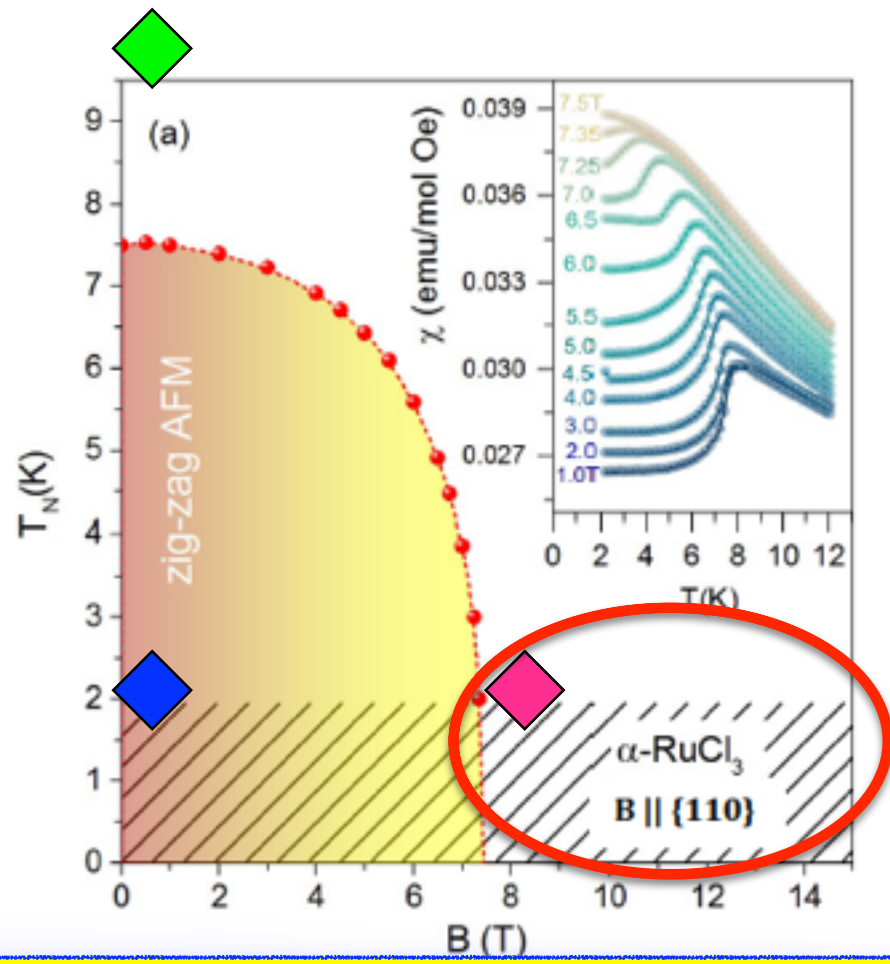
$H_{c\parallel} \sim$ 7-8 T

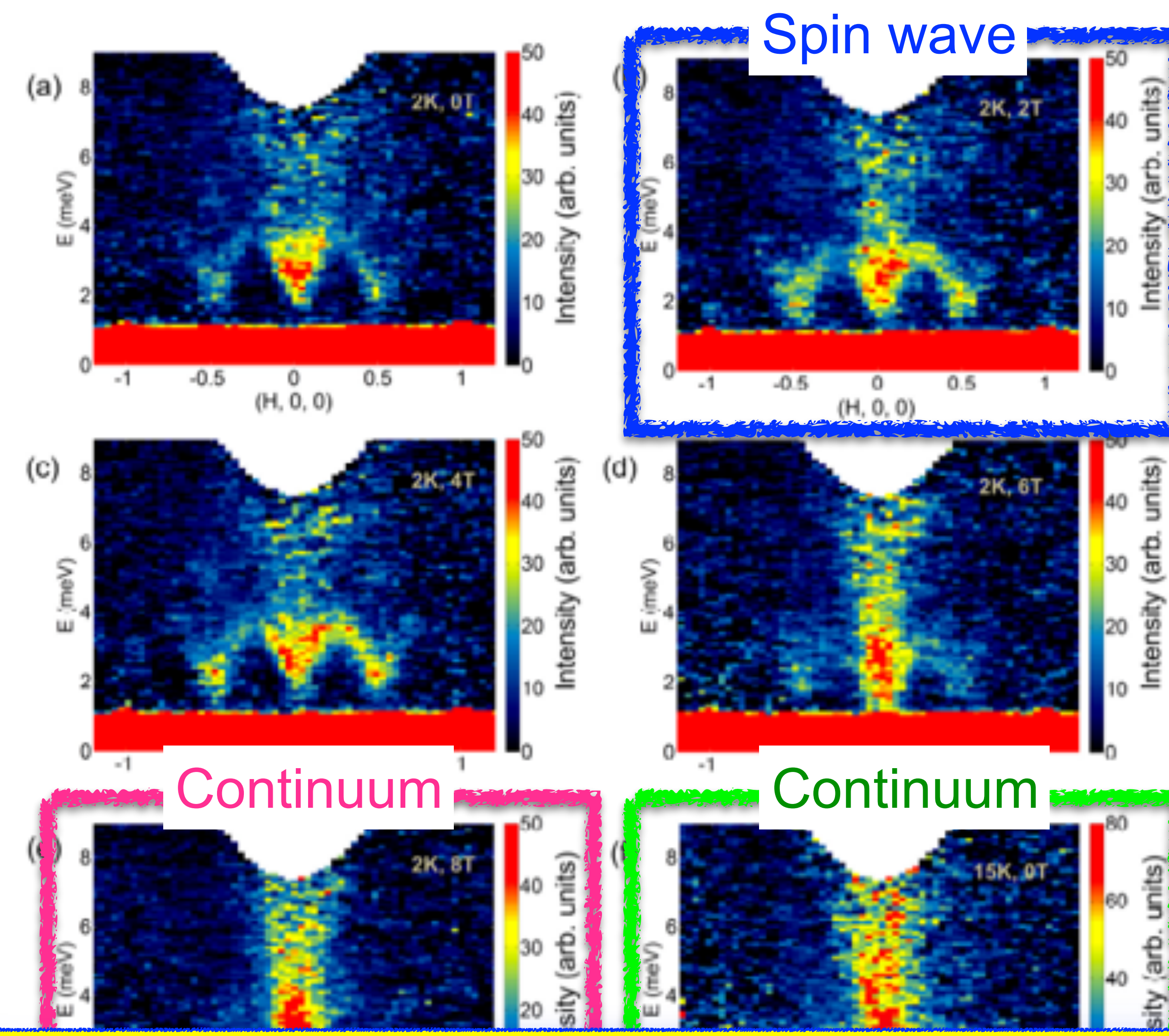
N. Jansa *et al.*, arXiv:1706.08455 (2017).   A. Banerjee *et al.*, arXiv:1706.0703 (2017).

NMR: Unusual spin gap $T_1^{-1} \propto \frac{1}{T} \exp\left(-\frac{n\Delta}{T}\right)$

Suppression of AFM order by in-plane fields

Inelastic neutron scattering





Low-temperature properties are masked by the magnetic order.

Key question: Kitaev QSL survives when suppressing the magnetic order?

Kitaev QSL emerges under in-plane magnetic fields.

Neutron scattering: Magnetic continuum at high energy above $H_{c||}$

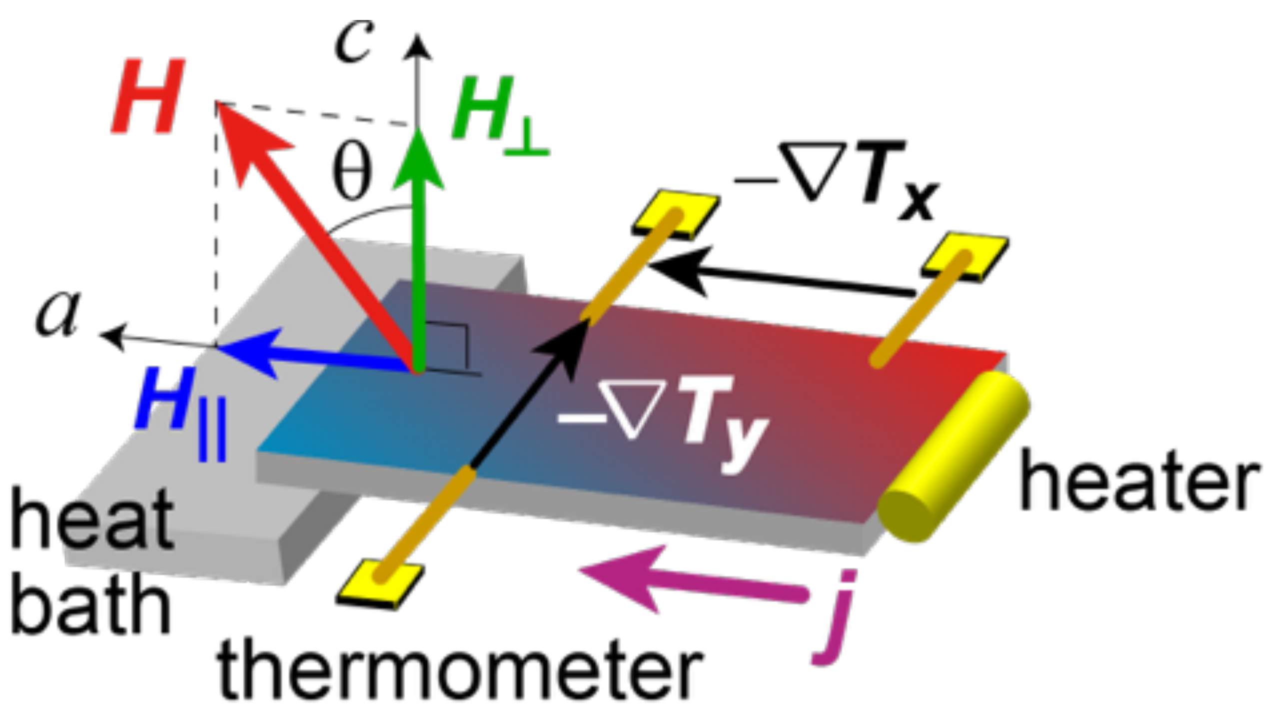
What gives direct signature of Majorana fermions?

Low-temperature properties are masked by the magnetic order.

Key questions: The magnetic order can be suppressed by tuning parameters?
Kitaev QSL survives when suppressing the magnetic order?

Thermal Hall effect in a Kitaev QSL state

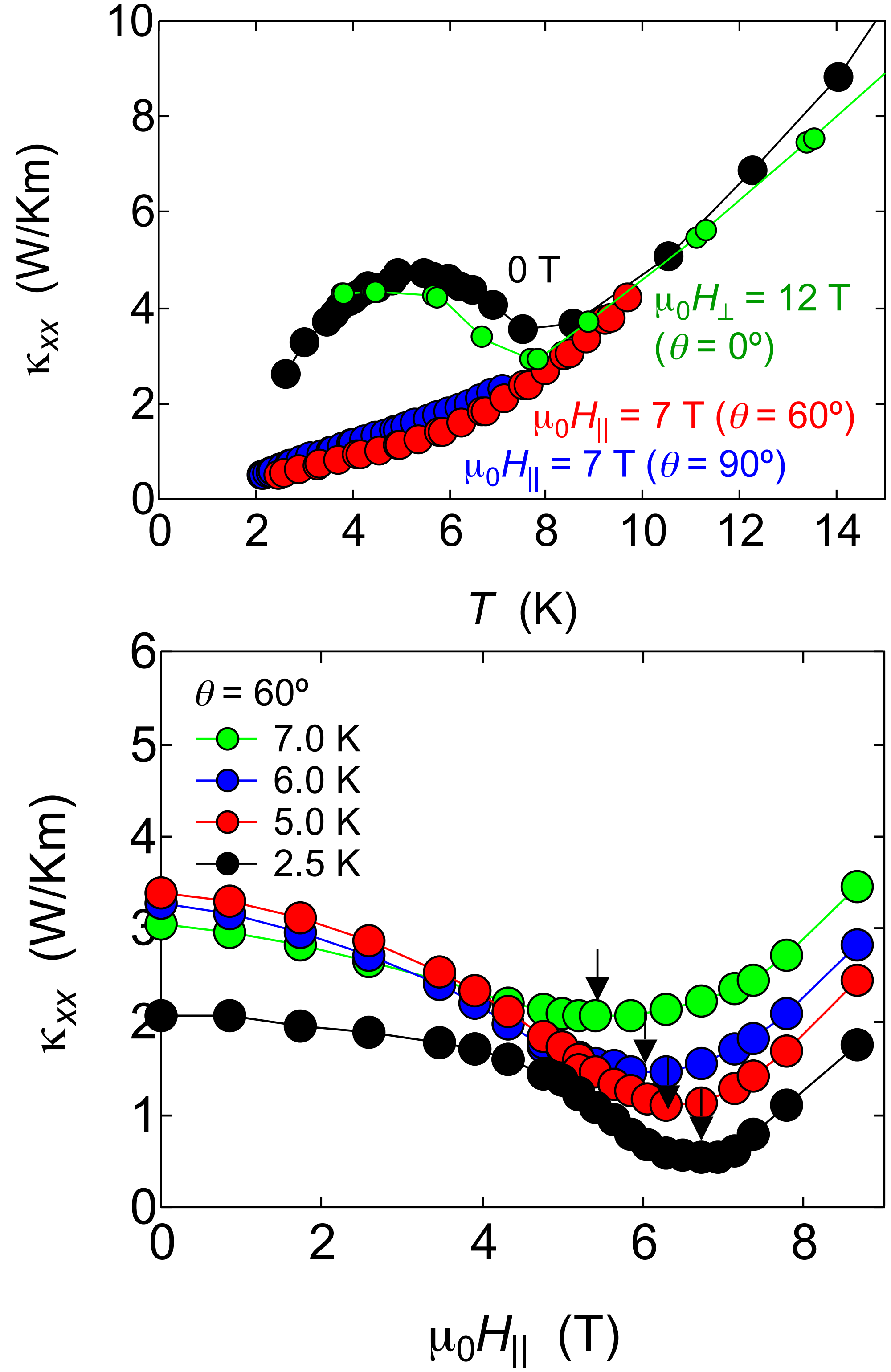
Measurements of thermal Hall effect in tilted fields

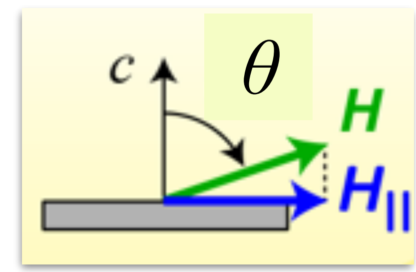


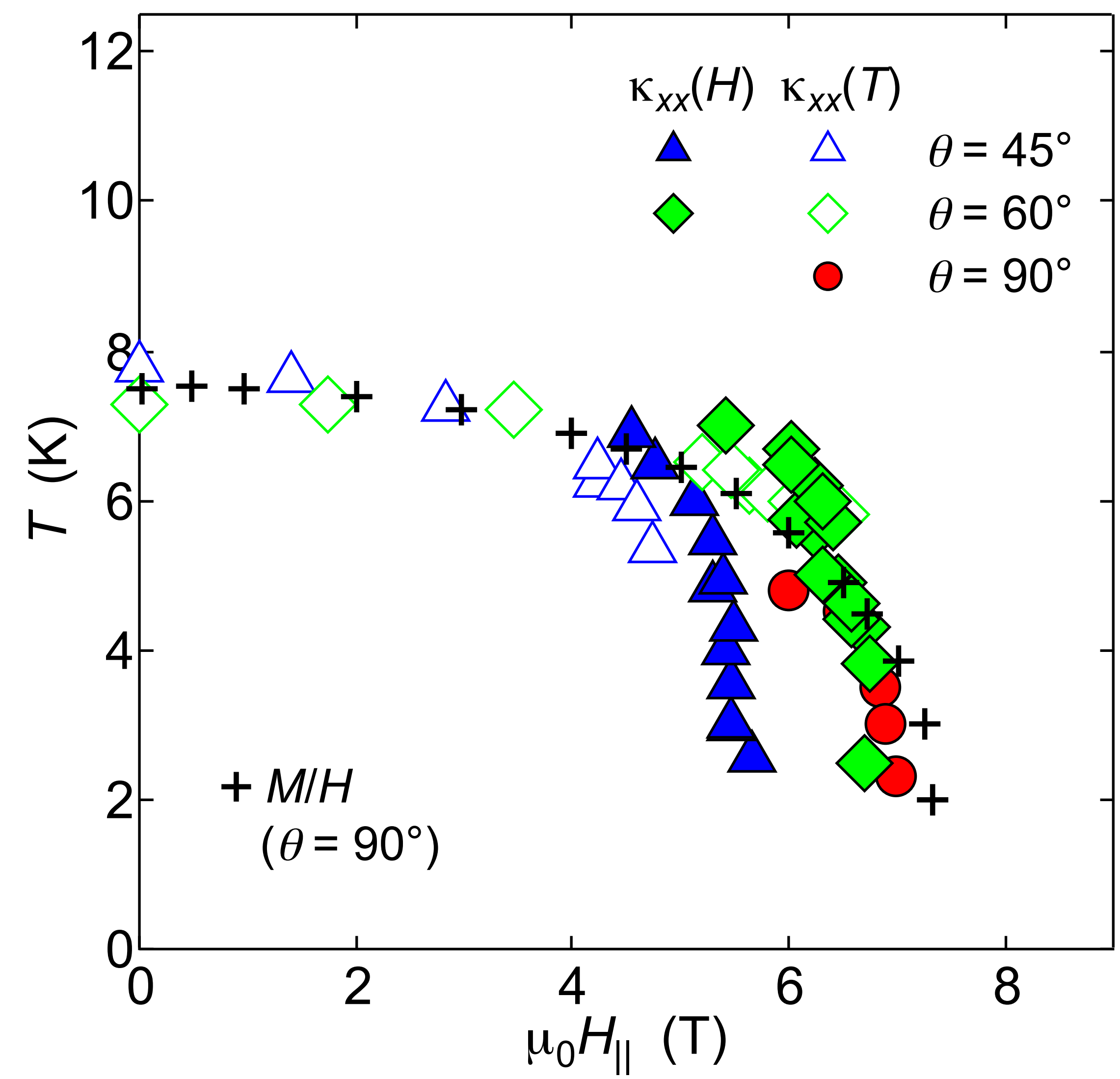
Phase transition is tuned by $H_{||} = H\sin\theta$.

Thermal Hall response is determined by $H_\perp = H\cos\theta$.

Longitudinal thermal conductivity κ_{xx}







Strongly anisotropic response: Quasi 2D nature of magnetic properties.

Suppression of the AFM order by in-plane field component.

Summary

Measurements of thermal Hall effect in a Kitaev magnet candidate α-$RuCl_3$

Perpendicular fields

Striking enhancement of κ_{xy}/T with positive sign below $T \sim J_K/k_B$

A broad peak at $T \sim 0.1 J_K/k_B$

Signature of Majorana fermion excitations

Y. Kasahara *et al*., arXiv:1709.10286 (2017).

Tilted fields

Observation of half-integer thermal Hall conductance for the first time.

Evidence for chiral Majorana edge current

Sudden disappearance of the quantum Hall plateau at high field

Topological phase transition