Majorana-fermion origin for the thermal Hall effect of Kitaev candidate α-$RuCl_3$

Yuji Matsuda

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Y. Kasahara, S. Suetsugu, T. Asaba, Y. Xing,
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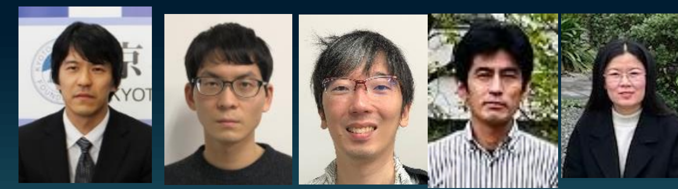
Department of Physics, Kyoto Univ., Japan



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Department of Physics, Univ. of Cologne, Germany

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1. Half integer quantized thermal Hall effect in α-$RuCl_3$

2. Is α-$RuCl_3$ really Kitaev material?

   Topology: Topological invariant

   Thermodynamics: Dirac cone and Majorana gap

   Thermal transport properties of very clean crystals

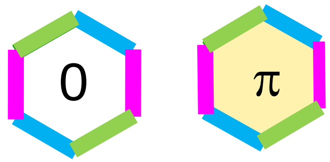
3. STM studies on monolayer α-$RuCl_3$

   Local density of states around defects

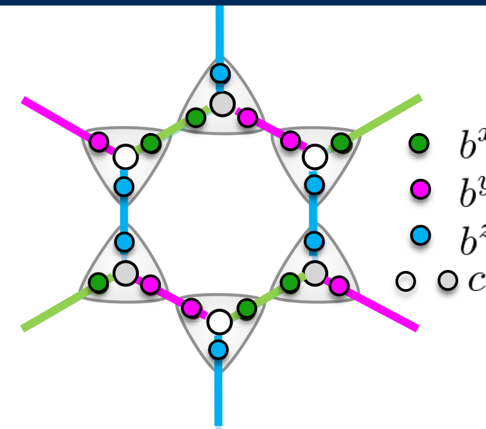
Kitaev quantum spin liquid

Spin 1/2 → Itinerant Majorana c

Spin 1/2 → Localized Majorana b^x, b^y, b^z



Z2 gauge flux (Vison)

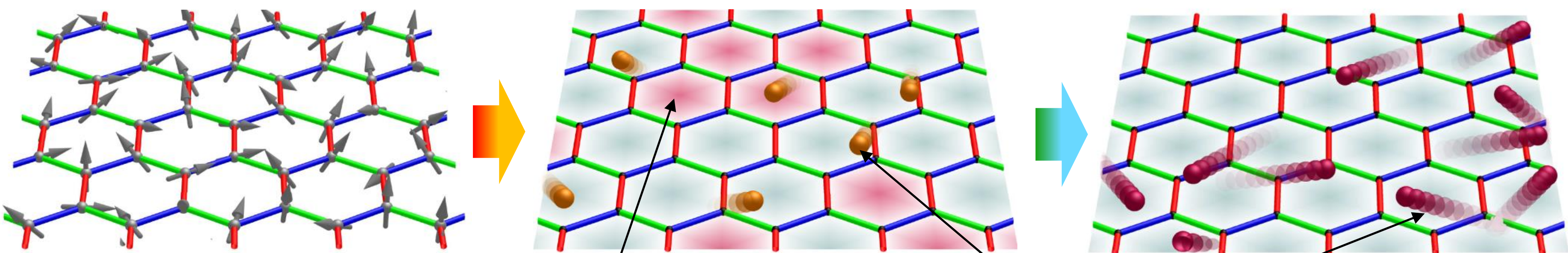


Energy gap: $\Delta_F \sim 0.1 J_K$

$T > J_K$ Paramagnetic

$T < J_K$ Spin fractionalization

$T \ll J_K$ Quantum spin liquid



Z2 flux

Itinerant Majorana fermions

J. Nasu and Y. Motome

Strongly spin-orbit coupled j=1/2 Mott insulator α-$RuCl_3$

A prime candidate for hosting an approximate Kitaev QSL

$$\mathcal{H}_{ij}^{(z)} = K S_i^z S_j^z + J \boldsymbol{S}_i \cdot \boldsymbol{S}_j + \Gamma(S_i^x S_j^y + S_i^y S_j^x) + \Gamma'(S_i^x S_j^z + S_i^z S_j^x + S_i^y S_j^z + S_i^z S_j^y)$$

Kitaev | Heisenberg | off-diagonal | off-diagonal (distortion)

Significant Kitaev term

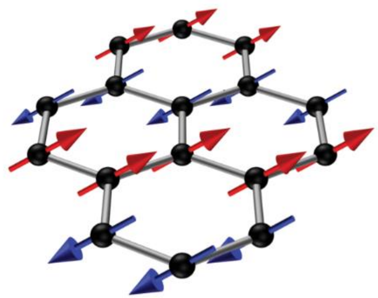
RIXS $K = -5\,\mathrm{meV}$ Ferromagnetic

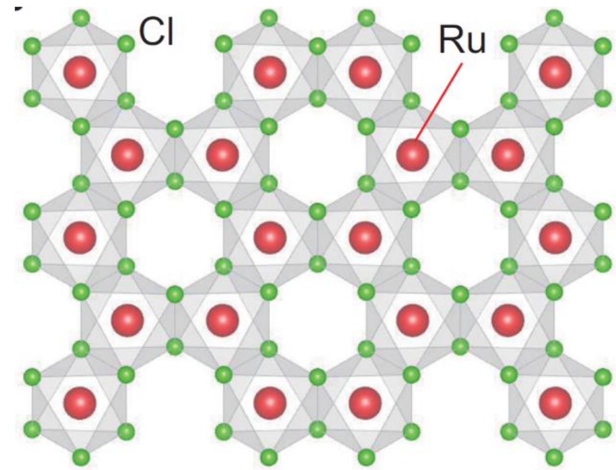
$J = -3\,\mathrm{meV}$ $\Gamma = 2.5\,\mathrm{meV}$ $\Gamma' \approx 0.1\,\mathrm{meV}$

H. Suzuki et al. Nature Commun. **12**, 4512 (2021).

Non-Kitaev interaction

AFM order at T_N=7.5 K





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

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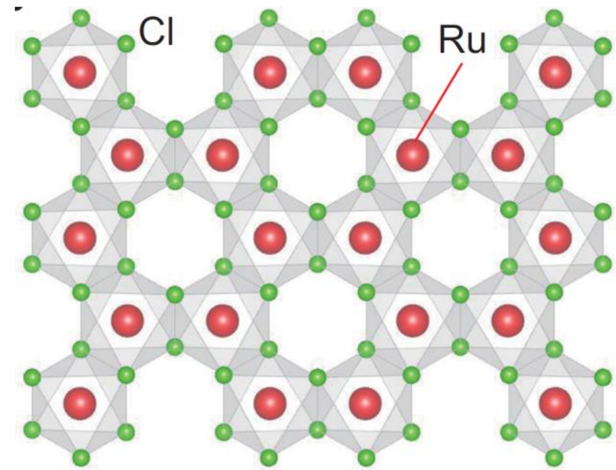

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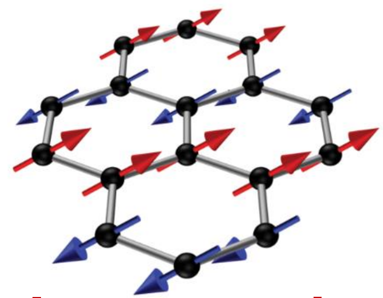


Signatures of fractionalization of electron spin

Specific heat — Entropy release due to itinerant Majorana fermions

S-H.Do *et al*. Nature Phys. **13**, 1079 (2017).

S. Widmann *et al.* PRB **99**, 094415 (2019).

Raman — Fermionic excitations inconsistent with bosonic magnons

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

Neutron — Broad magnetic continuum in good agreement with Kitaev QSL

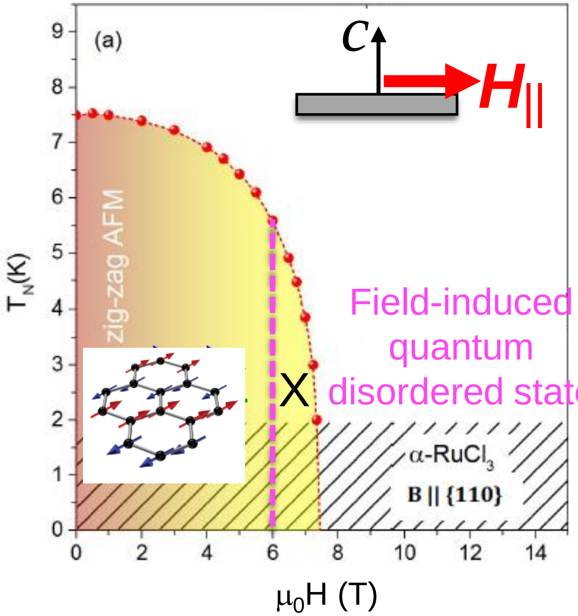
A. Banerjee *et al*., Nature Mater. **15**, 733 (2016).

A. Banerjee *et al.*, Science **356**, 1055 (2017).

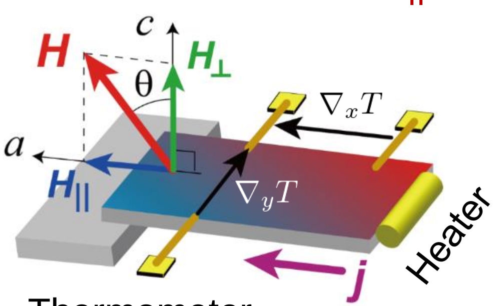
Half-integer quantized thermal Hall conductance plateau

A. Banerjee *et al*., npj Quantum Mat. **3**, 8 (18).

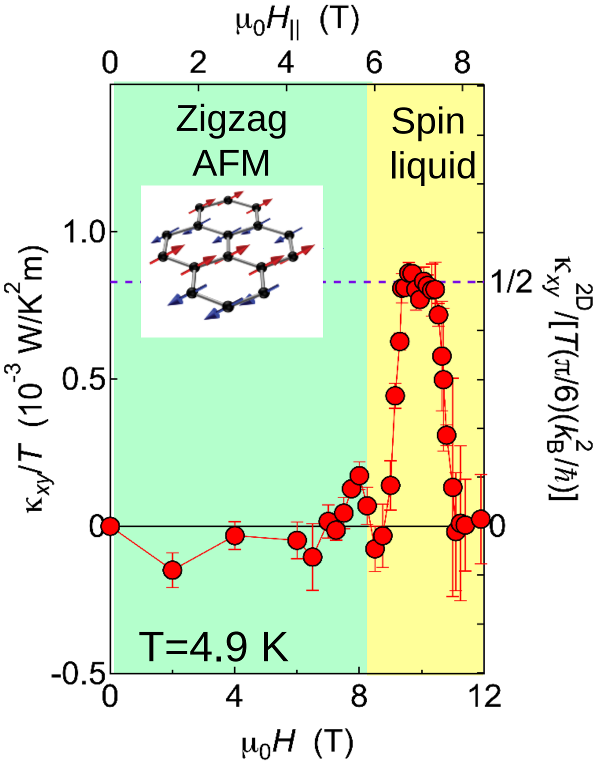
Y. Kasahara, YM, *et al.* Nature **559**, 227 (2018).



Zigzag AFM order is suppressed by $H_{||}$



Thermal Hall effect in tilted fields

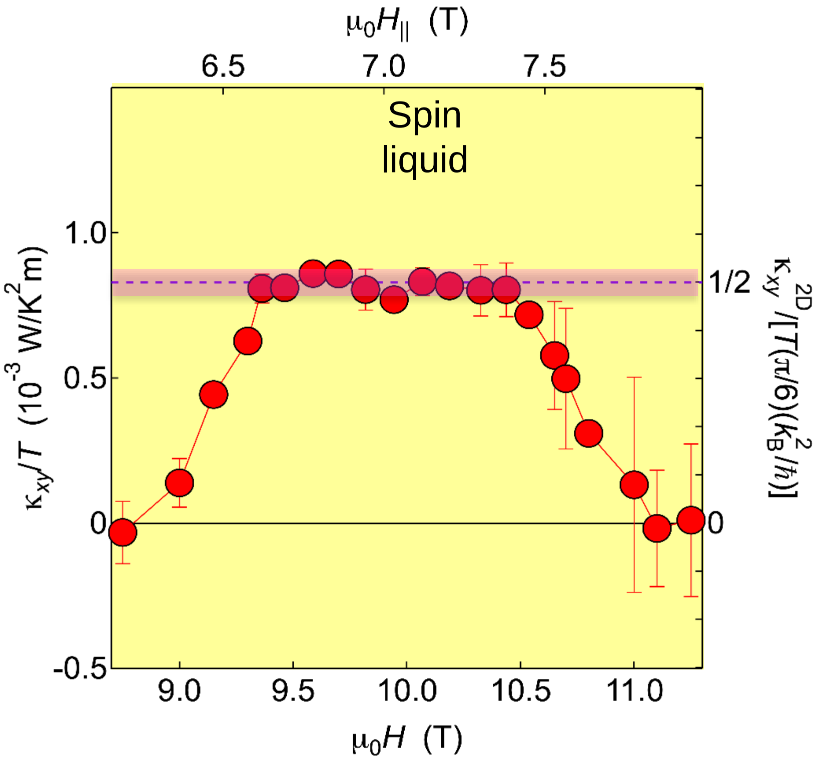


$$\kappa_{xy}^{2D} = \frac{1}{2} K_0$$

$$K_0 = \frac{\pi^2 k_B^2}{3h} T$$

Quantum Thermal Conductance

$$\theta = -45^\circ$$



Thermal Hall plateau

Majorana edge current

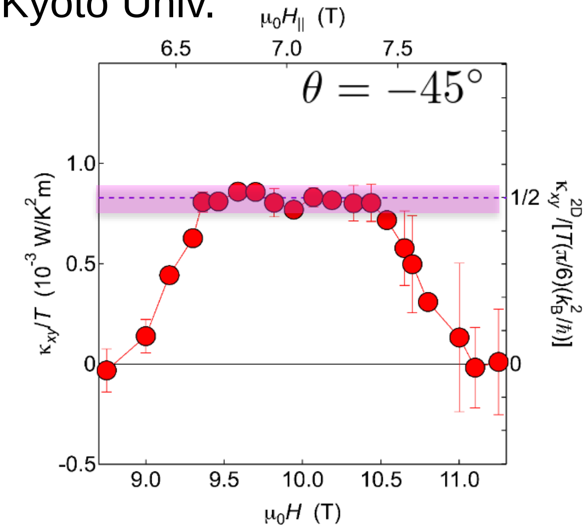
Non-abelian anyon

Reproducibility of thermal Hall effect

Crystals grown by Bridgman method

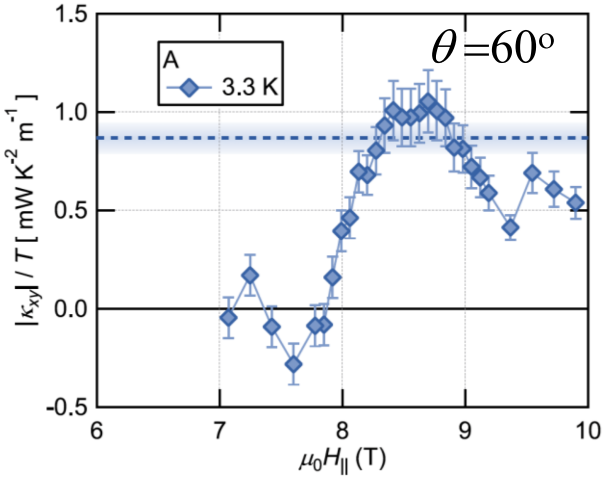
1. Quantized plateau

Kyoto Univ.



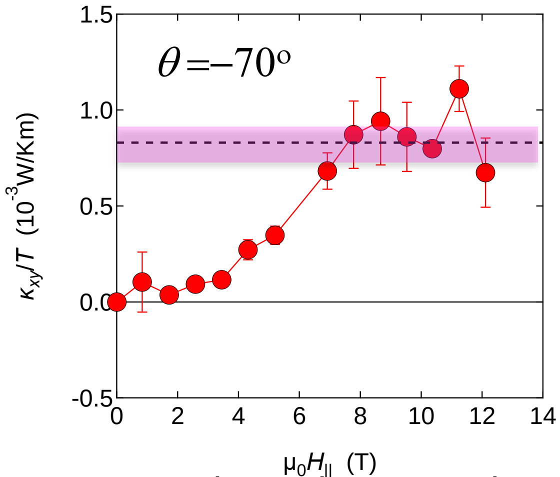
Y. Kasahara *et al*. Nature (2018).

Univ. of Tokyo



M. Yamashita *et al*. PRB (2020).

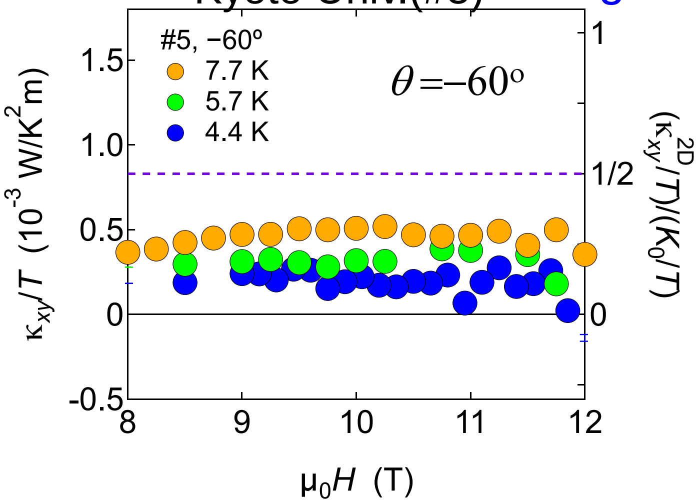
MPI Stuttgart



J.A.N. Bruin *et al*. Nature Phys. (2022).

2. Plateau but no quantization

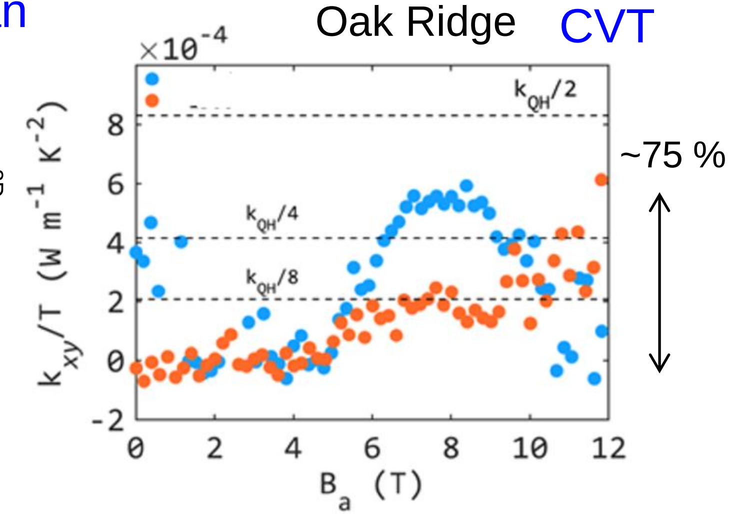
Kyoto Univ.(#5) Bridgman



Y. Kasahara *et al.* PRB (2022).

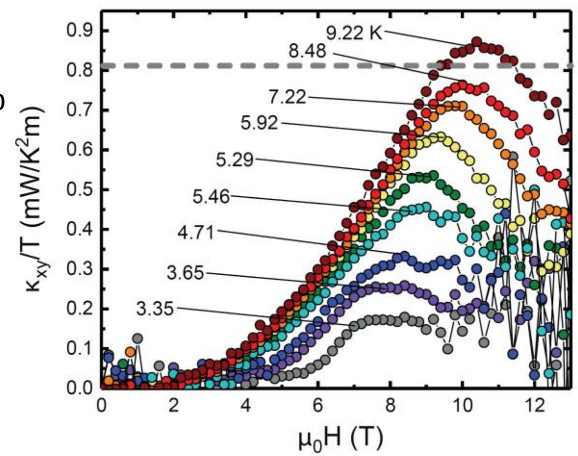
3. No plateau and no quantization

Oak Ridge CVT



H. Zhang *et al*.arXiv:2303.03682

Princeton Univ. CVT



P. Czajka *et al*., Nature Mater. (2022)

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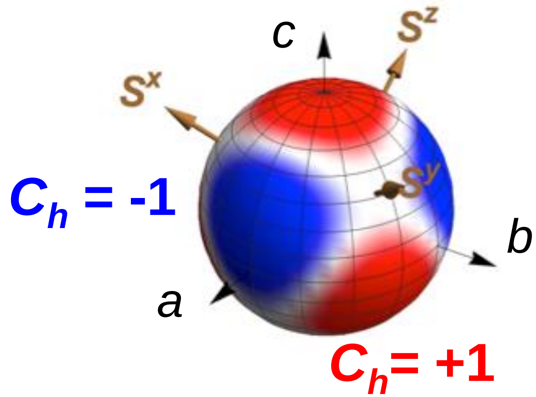
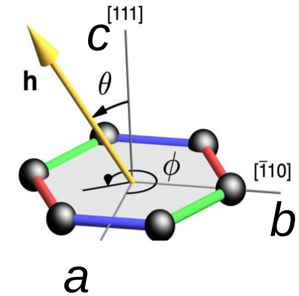
$$\kappa_{xy}^{2D} = C_h \frac{1}{2} K_0 \qquad C_h = \mathrm{sgn}(h_x h_y h_z) = \pm 1$$

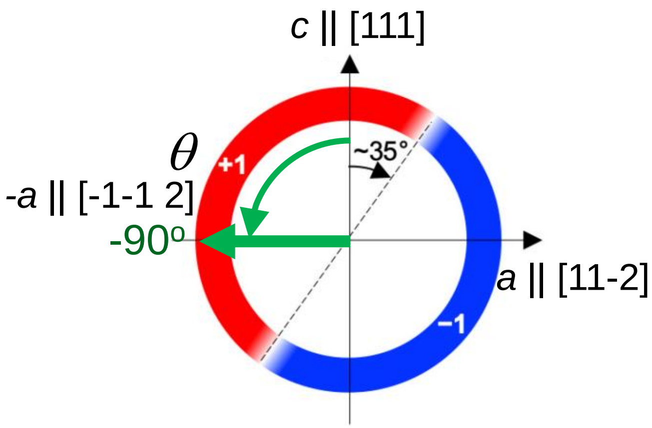
***H*-component with respect to the spin axis**

Spin axis is different from crystal axis





ac-plane



Finite Chern number in parallel field (***H* ||**-a, C_h=+1)

Emergence of **planar thermal Hall effect** in paramagnetic state

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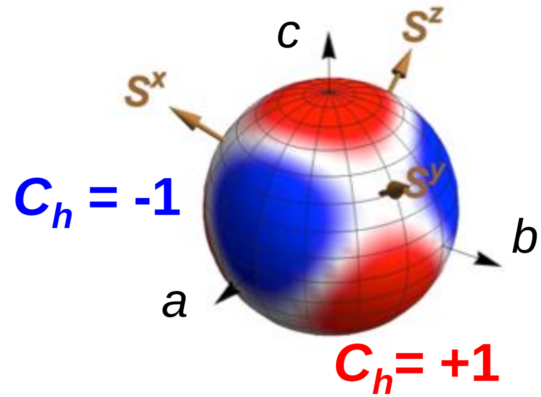

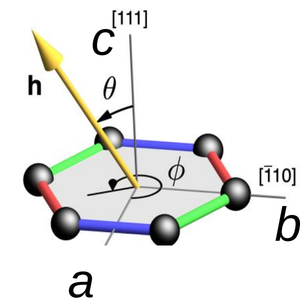

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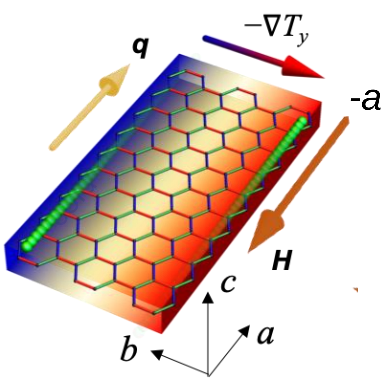
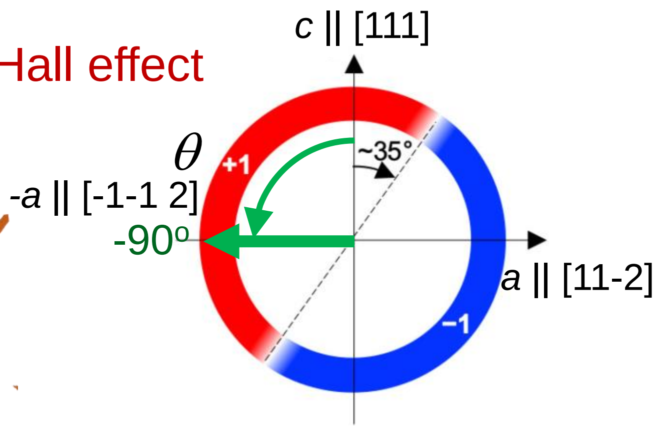
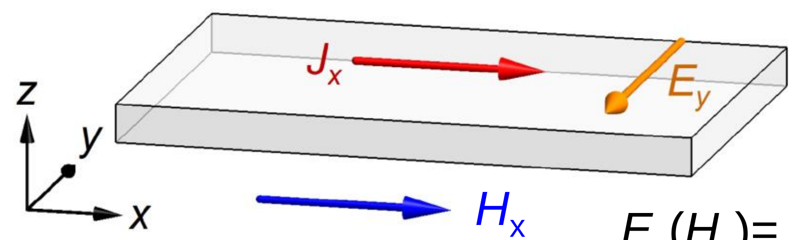
Planar thermal Hall effect



$$\nabla T_y(H_x) = -\nabla T_y(-H_x)$$



Planar Hall effect



$E_y(H_x) = -E_y(-H_x)$

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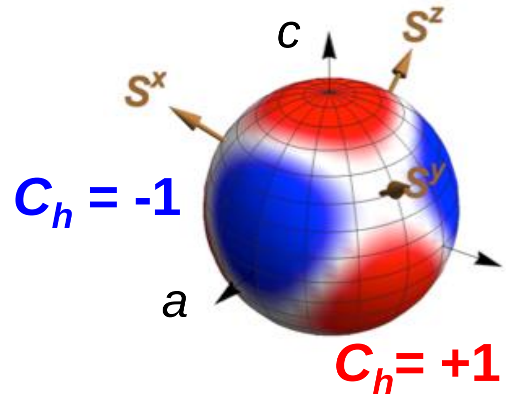
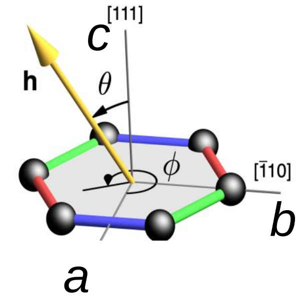
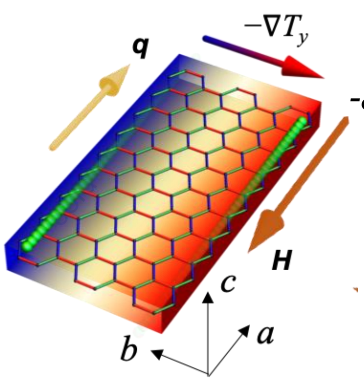




ac-plane

Planar thermal Hall effect



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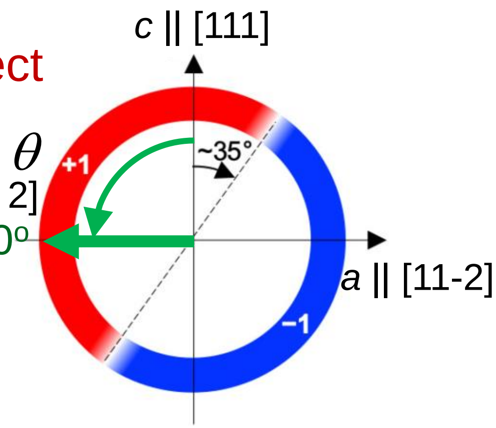

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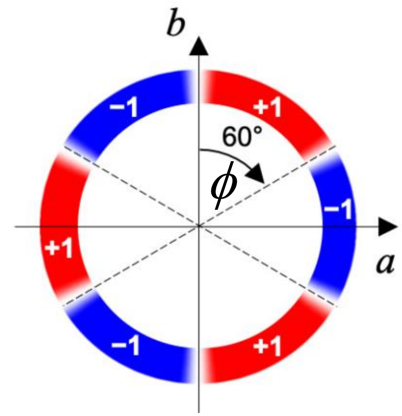

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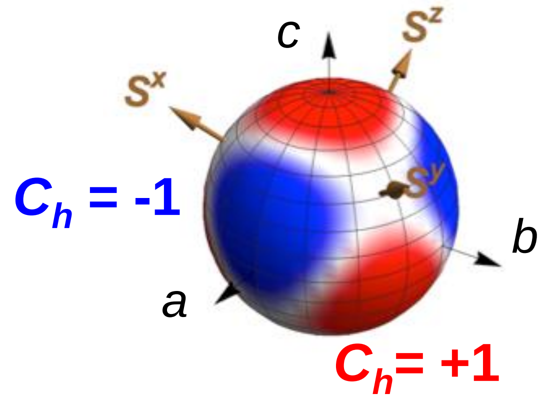
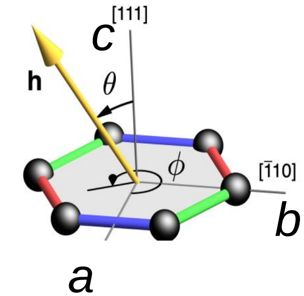
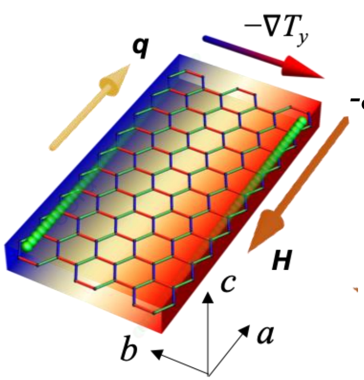




ac-plane

Planar thermal Hall effect



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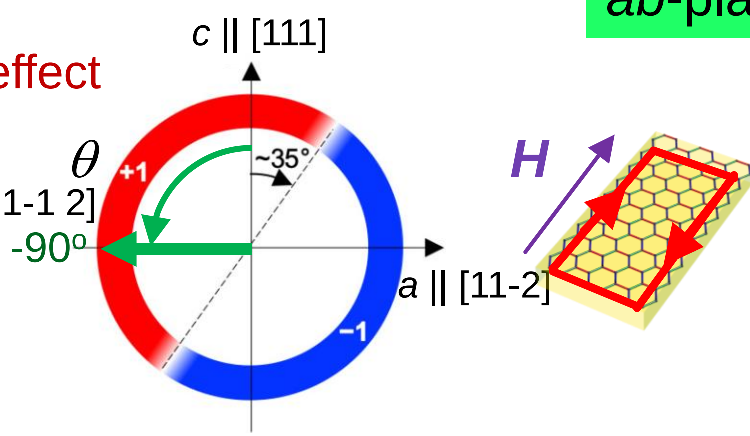

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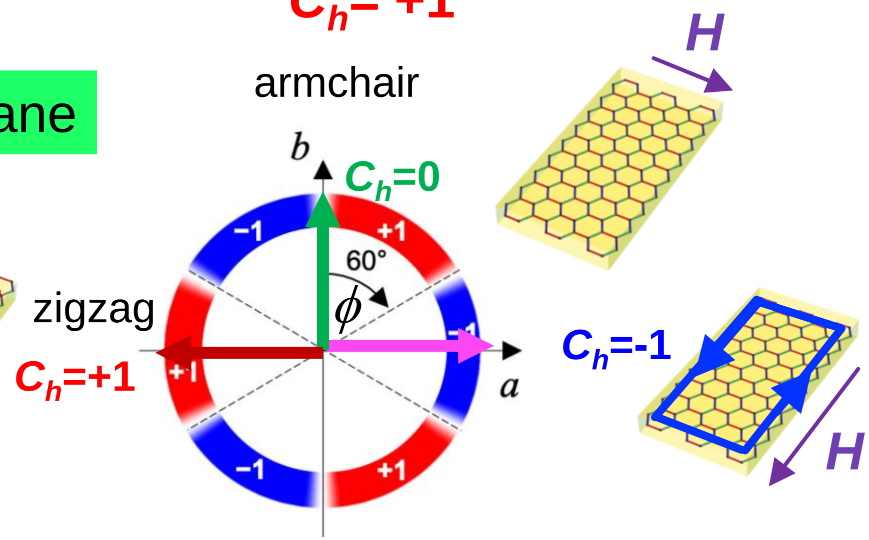

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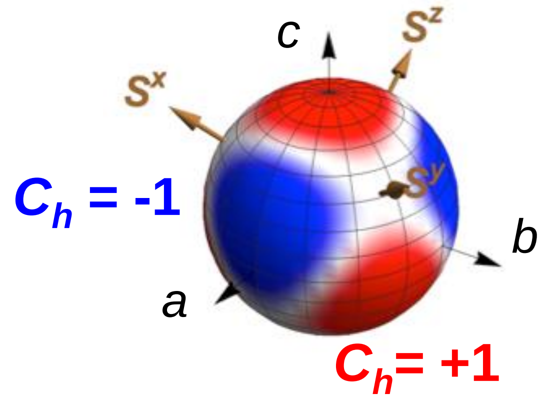

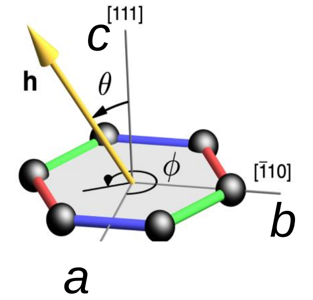

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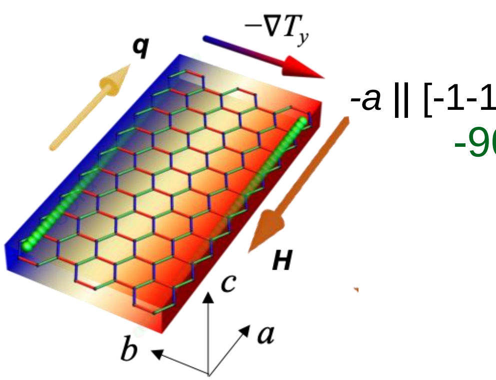
Planar thermal Hall effect



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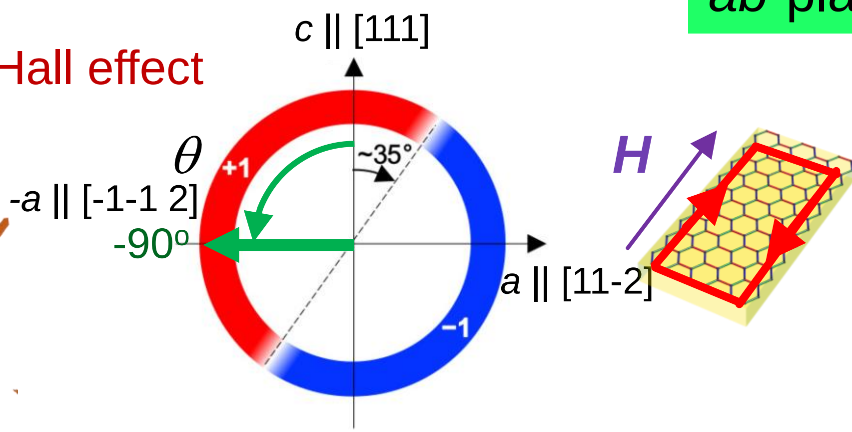

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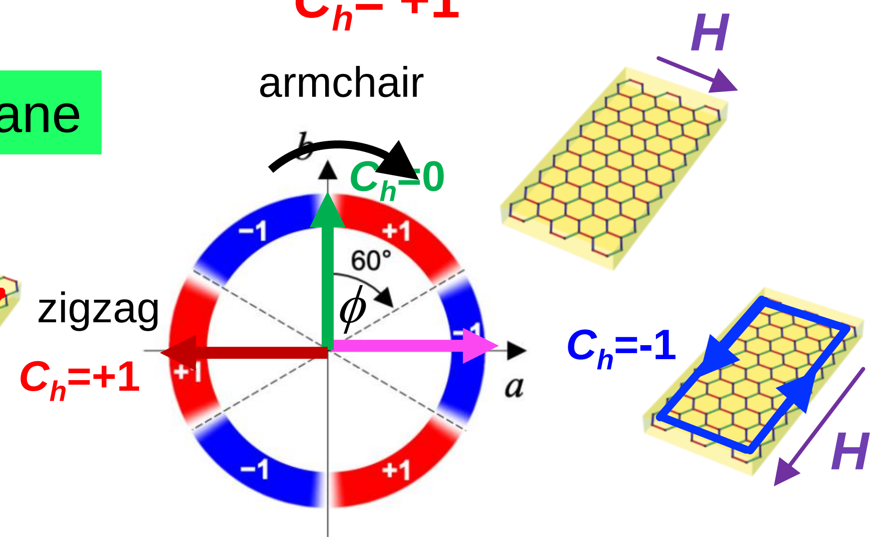

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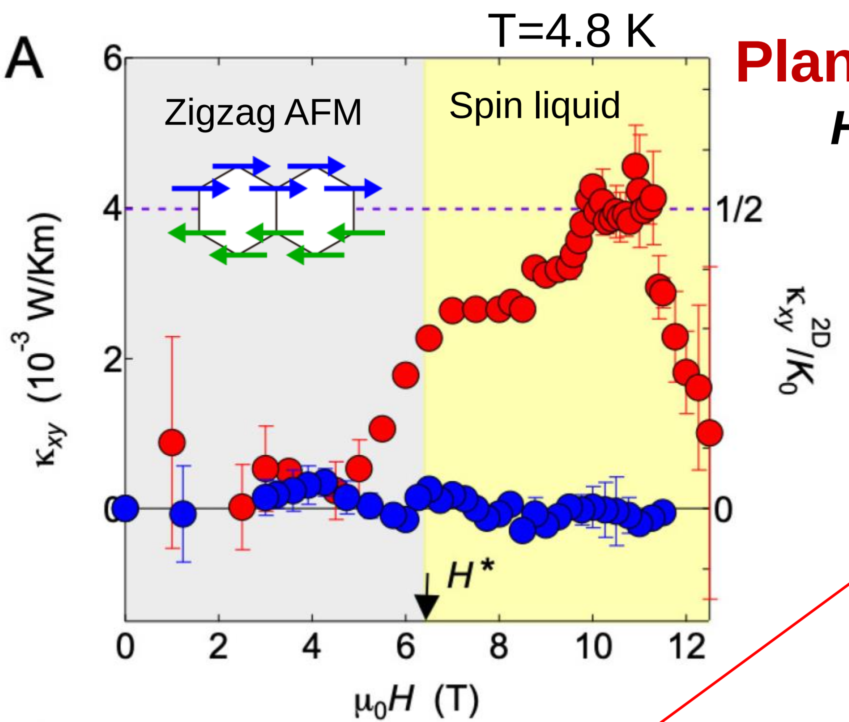
Emergence of **planar thermal Hall effect** in paramagnetic state

Angle-rotation induced topological transition

Rotating ***H*** clockwise changes the thermal Hall sign from negative to positive when ***H*** crosses the *b* axis.

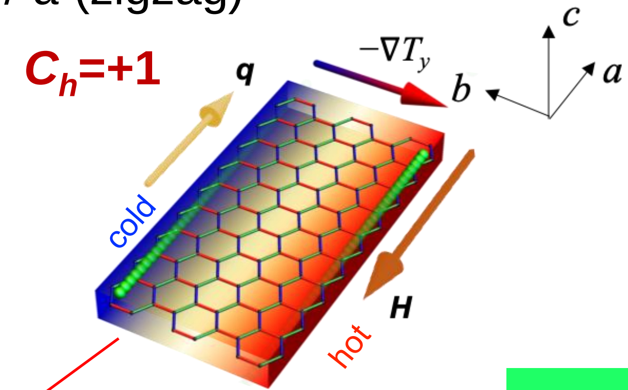
Half-integer thermal QHE in in-plane magnetic field

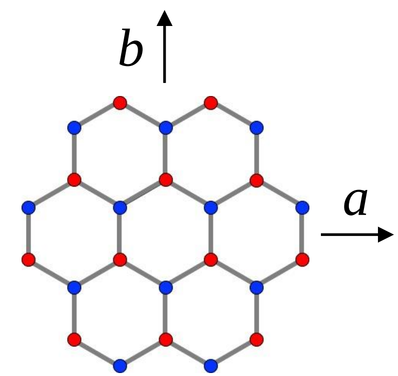
T. Yokoi, YM *et al*. Science **373**, 568 (2021).



Planar thermal Hall effect

H//-*a* (zigzag)





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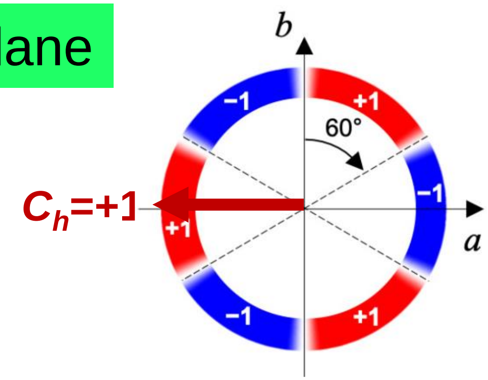

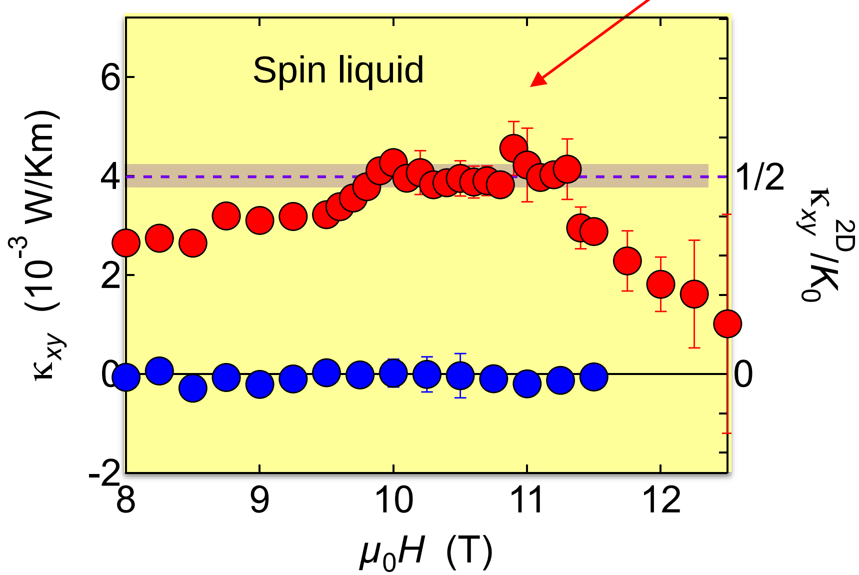

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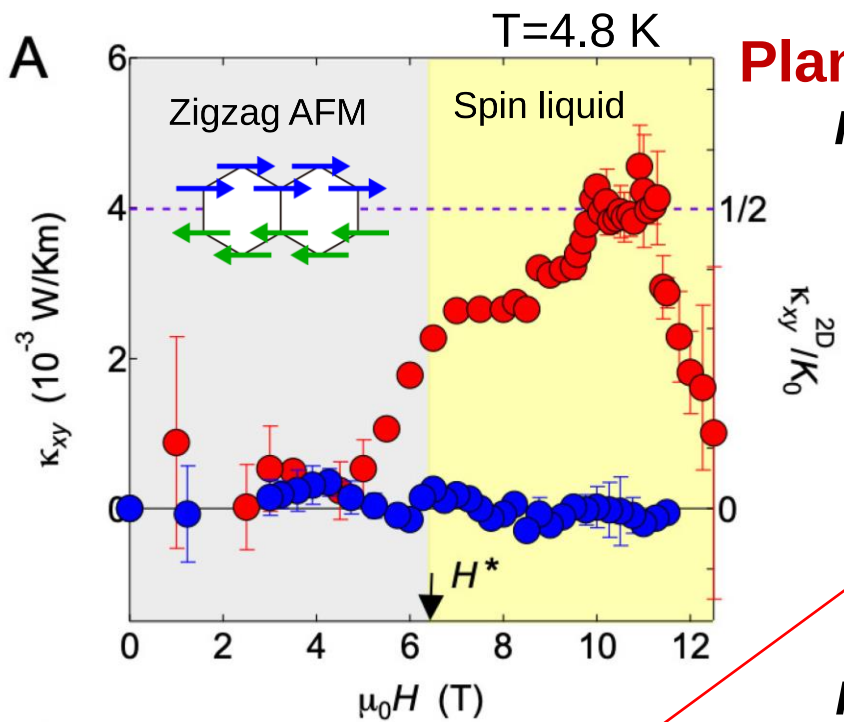

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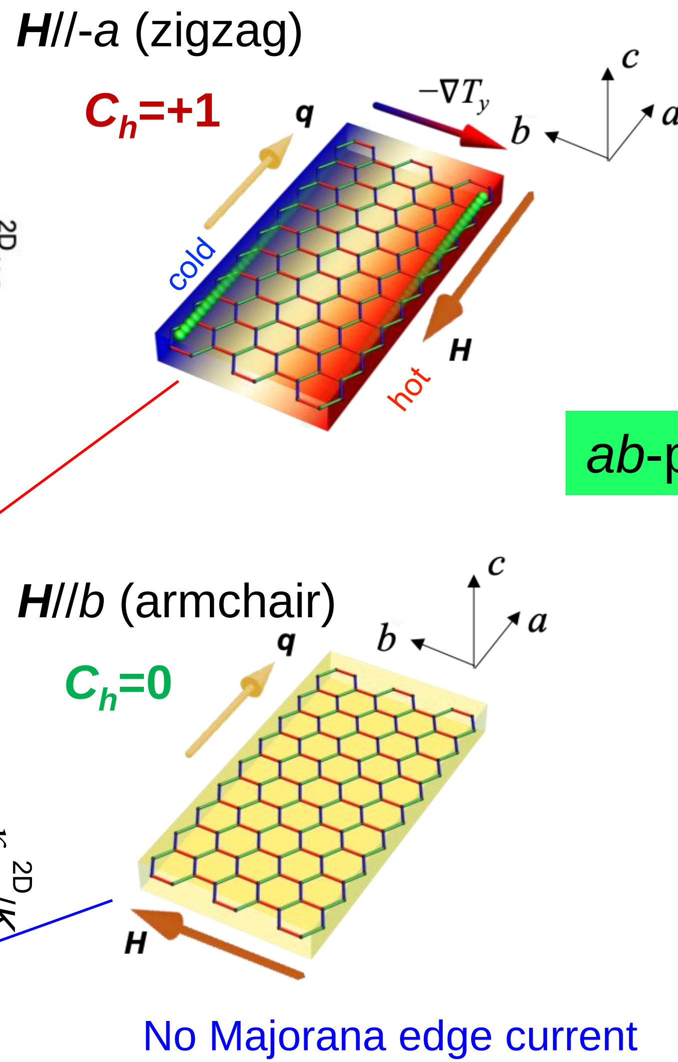
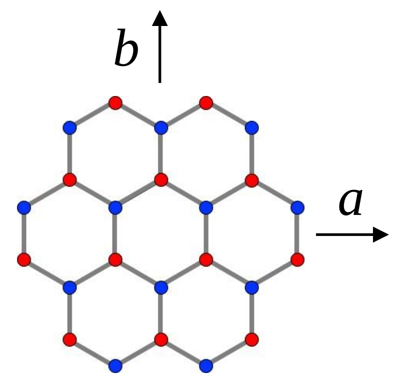
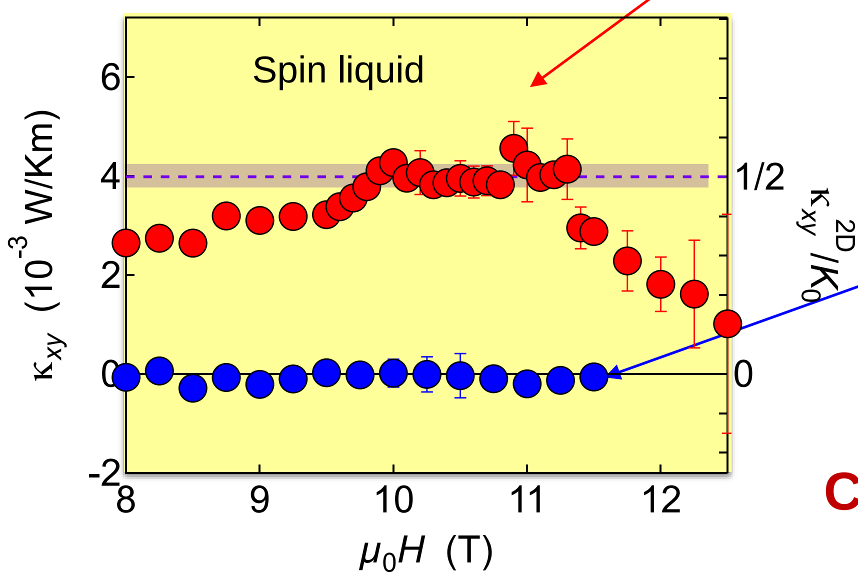
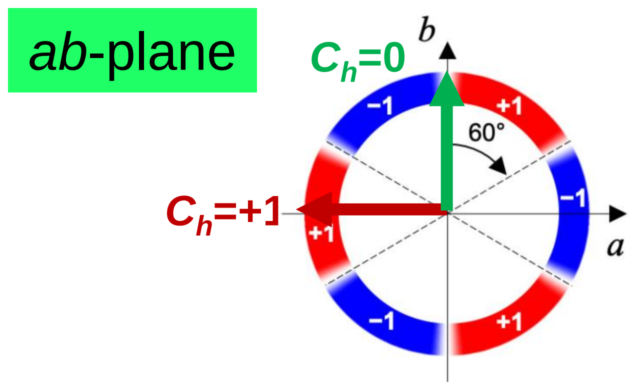




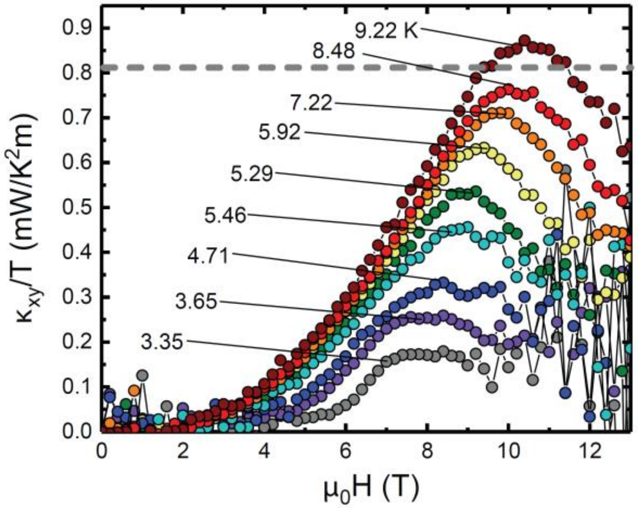




Consistent with Majorana band of Kitaev QSL

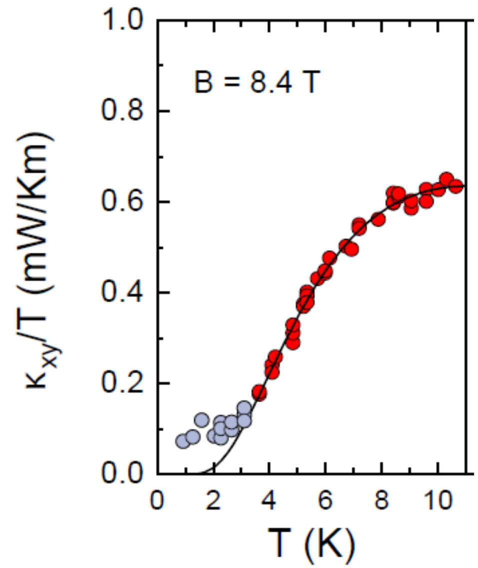
Origin of planar thermal Hall: Majorana or magnon ?

Bosonic scenario



H||***q***||a

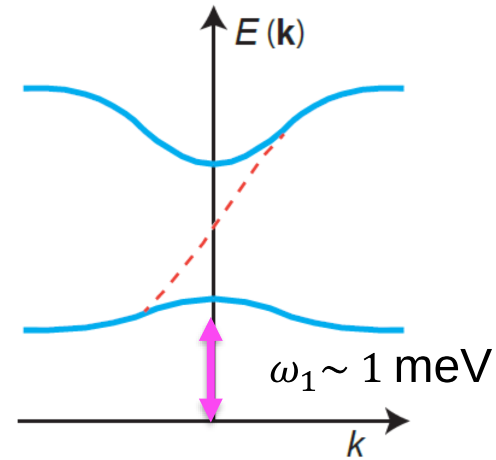
No quantization



κ_{xy}/T decreses with T

P. Czajka *et al*. Nature Phys. **17**, 915 (2021).

P. Czajka *et al*., Nature Mater. (2022)



bosonic edge excitations (topological magnons)

Magnon Chern number $\upsilon \sim 1$

Topological magnons

Sign of κ_{xy} can be explained by topological magnon thermal Hall effect in specific parameter range

E. Z. Zhang *et al.*, Phys Rev B **103**, 174402 (2021).
L. Chern *et al.*, Phys. Rev. Lett. **126**, 147201 (2021).

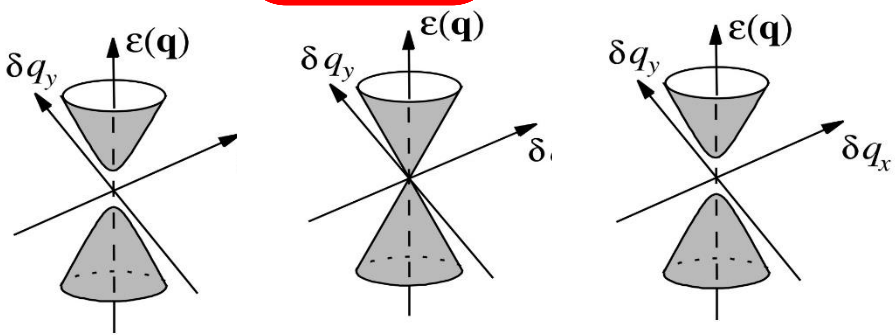
How to distinguish Majorana and magnon ?

Majorana fermions | **Topological magnons (boson)**

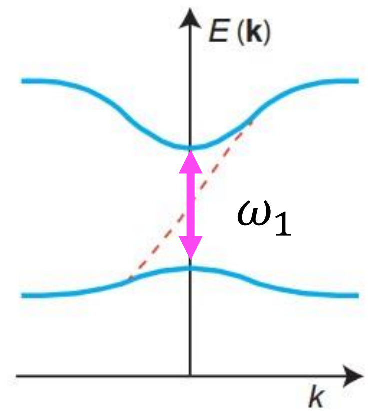
H* || -*a	***H* || *b***	***H* || *a***		***H* || -*a***	***H* || *b***	***H* || *a***
$+1$	0	-1	Chern number	± 1	0	∓ 1
gapped	**gapless**	gapped	gap	gapped	**gapped**	gapped

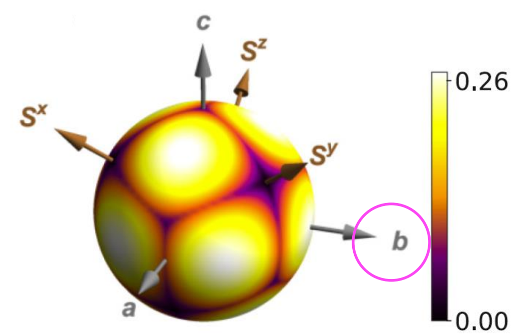
How to distinguish Majorana and magnon ?

Majorana fermions				Topological magnons (boson)		
H* || -*a	***H* || *b***	***H* || *a***		***H* || -*a***	***H* || *b***	***H* || *a***
+1	0	−1	Chern number	±1	0	∓1
gapped	**gapless**	gapped	gap	gapped	**gapped**	gapped



Dirac cone





For Majorana, gap closes at *H*//*b* ⟷ For magnon, gap (~1meV) opens at *H*//*b* in polarized state

S. Koyama and J. Nasu, Phys. Rev. B **104**, 075121 (2021).

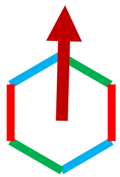
K. Hwang, E-G. Moon *et al*. Nature Commun. **13**, 1 (2021).

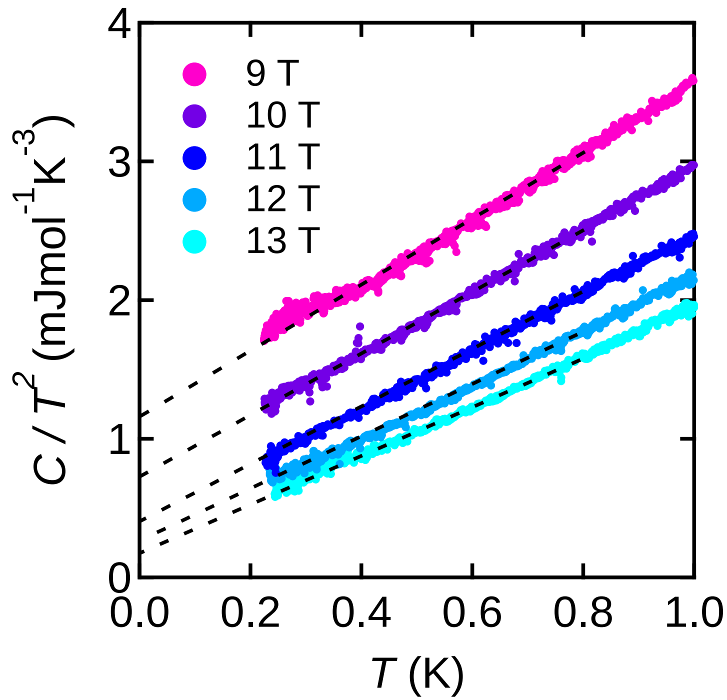
Rigorous testing of the Kitaev QSL: Dirac cone for *H*||b

Dirac cone for ***H***||*b*: specific heat in FIQD state

H* || *b

armchair

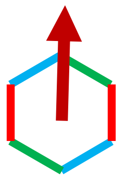




Dirac cone for ***H*//*b***: specific heat in FIQD state

H* || *b

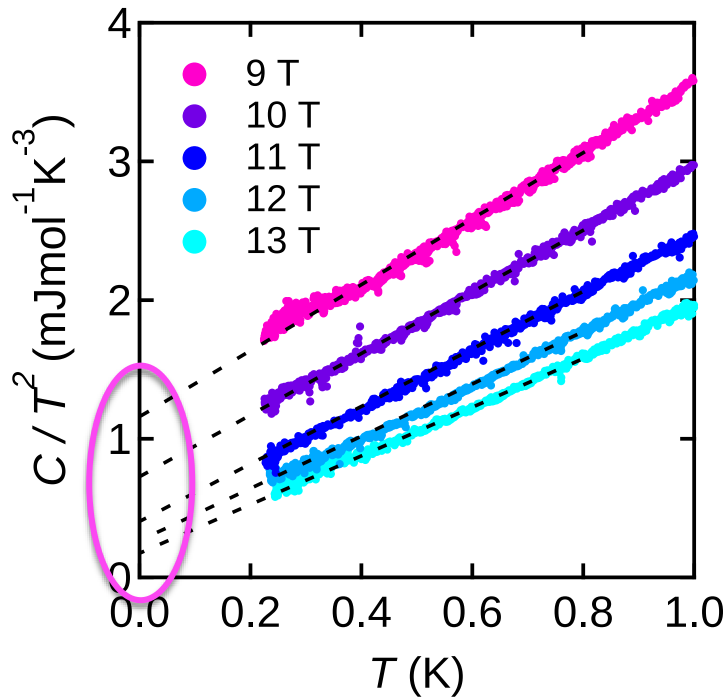
armchair



Finite intercepts at $T \rightarrow 0$

$$C \propto T^2$$

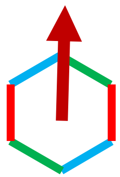
over a wide *H* range above H_{AF}~7T

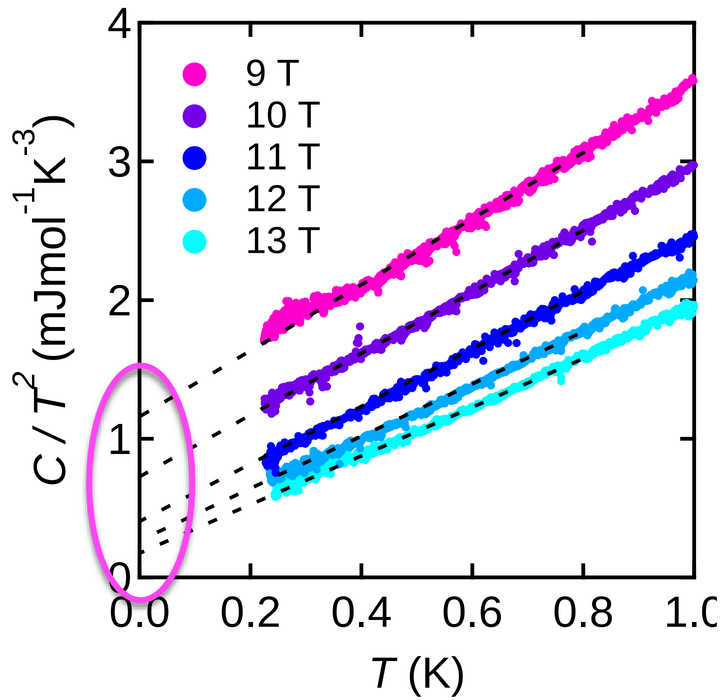


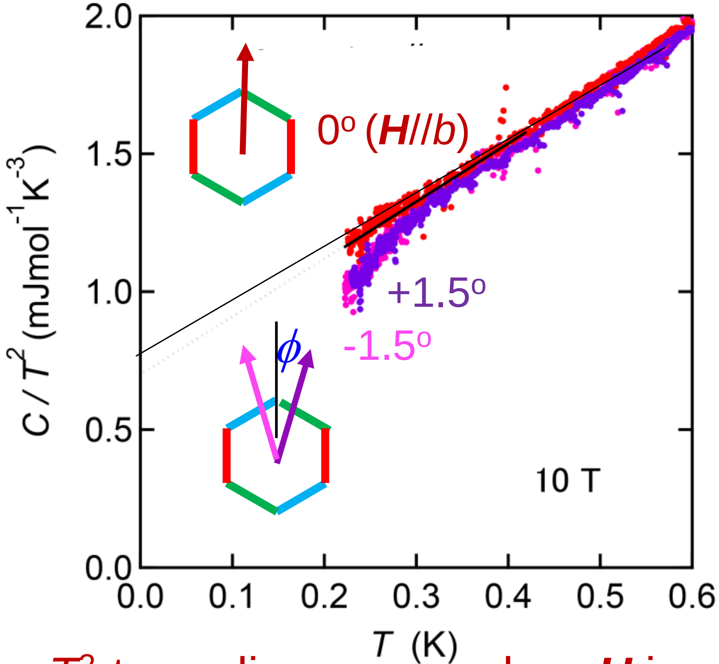
Dirac cone for *H*//*b*: specific heat in FIQD state

H* || *b

armchair





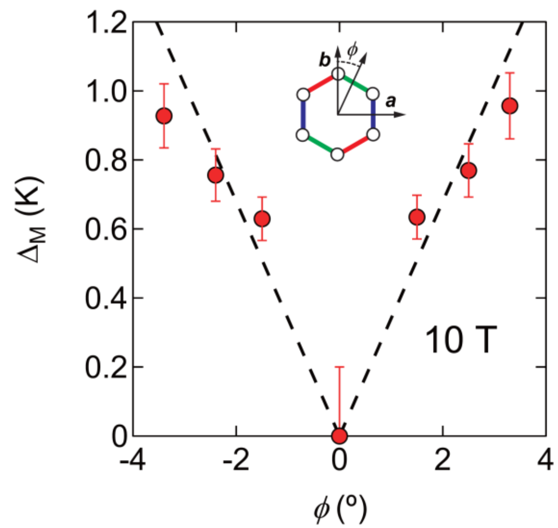


Finite intercepts at $T \rightarrow 0$

$$C \propto T^2$$

over a wide *H* range
above H_{AF}~7T

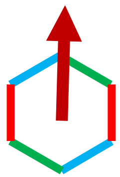
T^2-term disappears when ***H*** is slightly away from *b*-axis

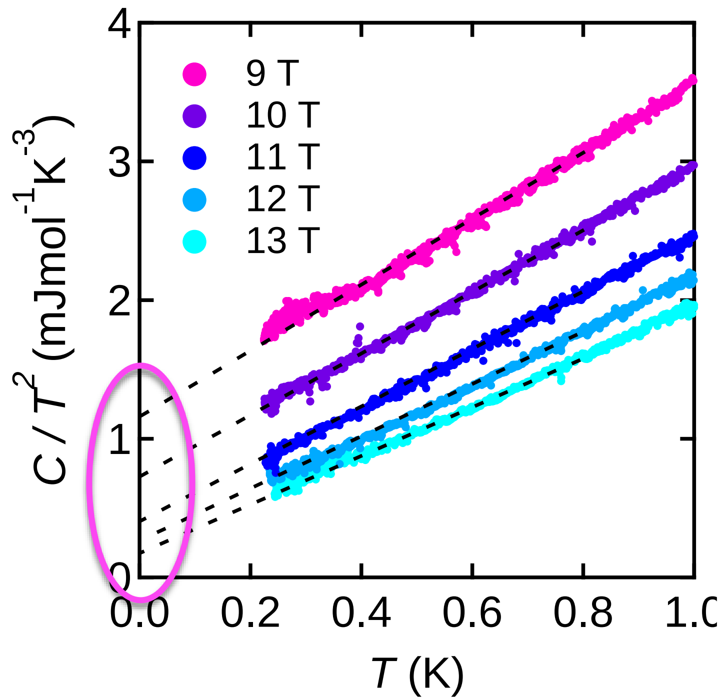


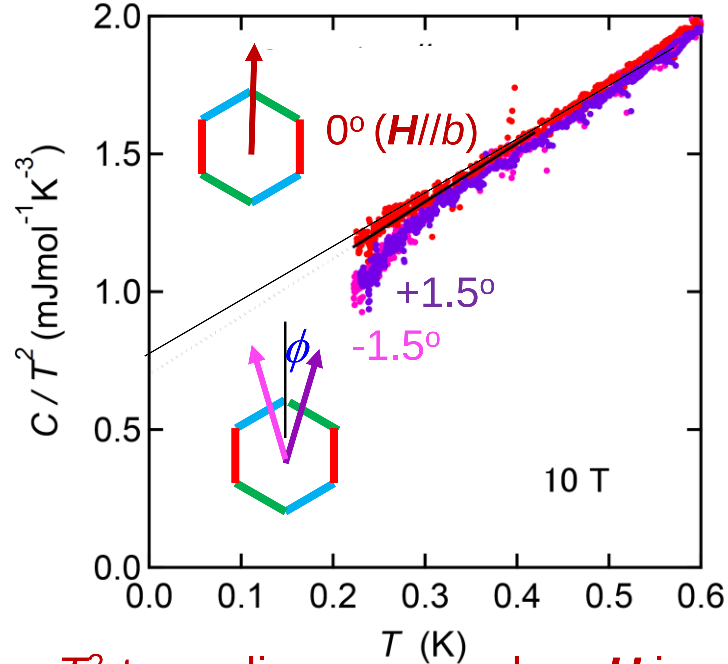
Dirac cone for *H*//*b*: specific heat in FIQD state

H* || *b

armchair







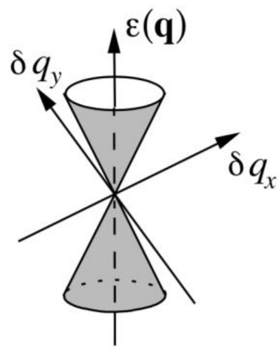
Finite intercepts at $T \rightarrow 0$

$$C \propto T^2$$

over a wide *H* range above H_{AF}~7T

T^2-term disappears when ***H*** is slightly away from *b*-axis

Incompatible with 2D magnon and phonon

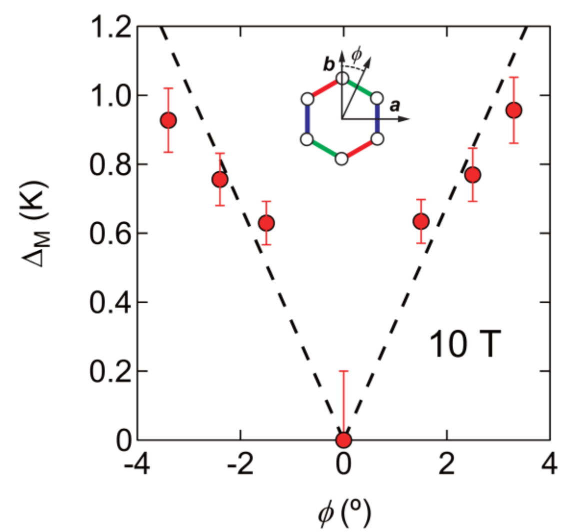


$$C_{\mathrm{mag}}/T \propto T$$

Linear dispersion

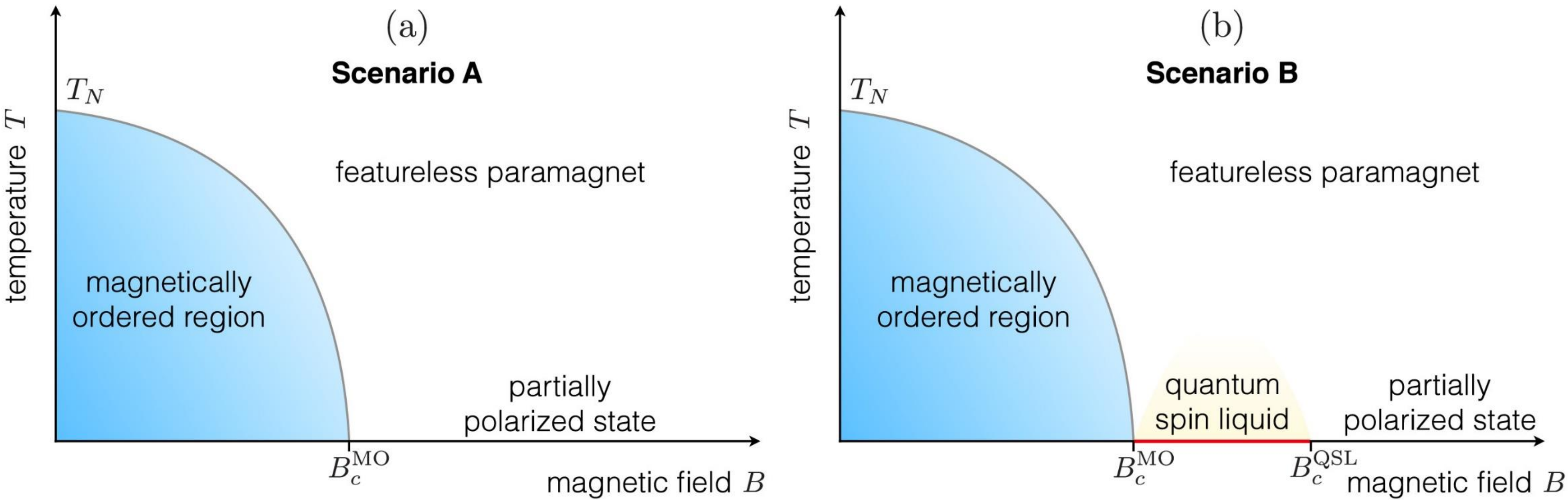
Dirac cone

Consistent with the Kitaev QSL



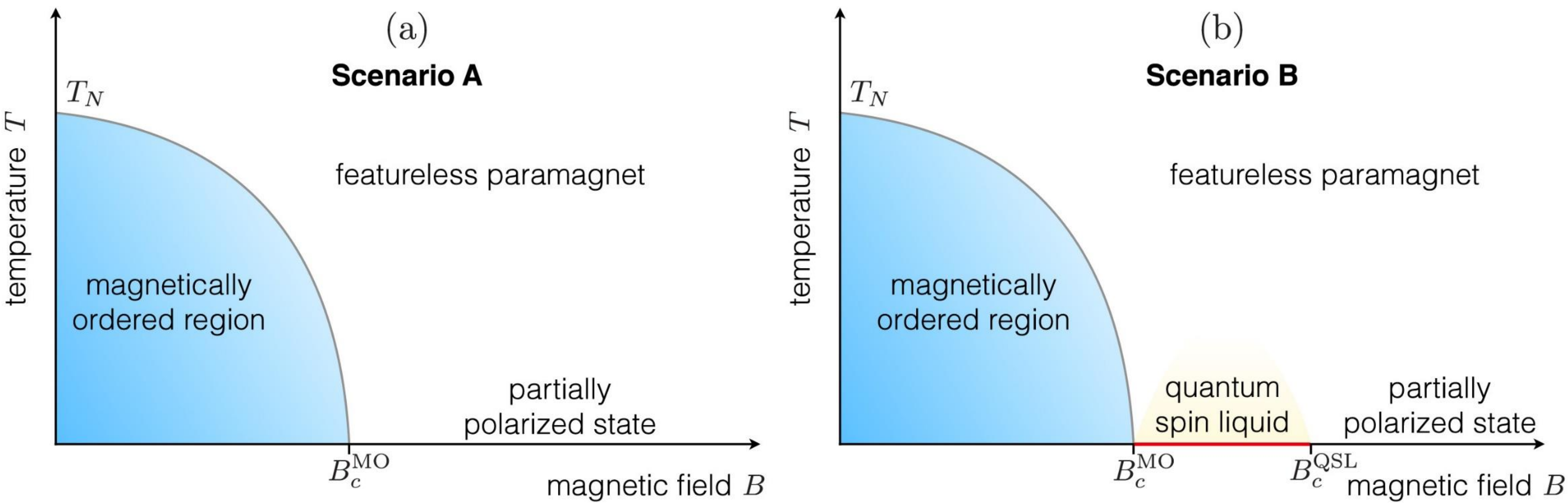
K. Imamura, S. Suetsugu , YM, T. Shibauchi *et al*. arXiv:2305.10619

Phase diagram



S. Trebst and C. Hickey, Phys. Reports **950**, 1-37 (2022)

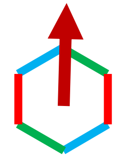
Phase diagram

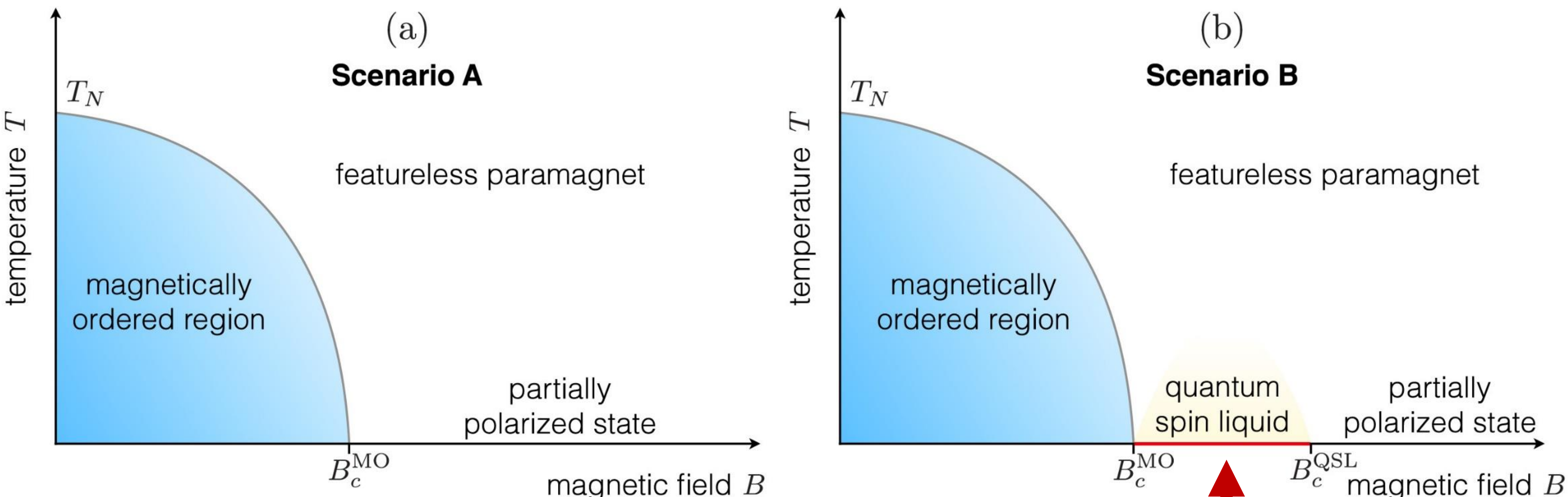


Gapped Gapped Gapped Gapped

S. Trebst and C. Hickey, Phys. Reports **950**, 1-37 (2022)

Phase diagram

H||b  armchair



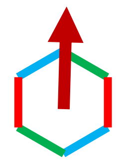
Gapped Gapped Gapped Gapped

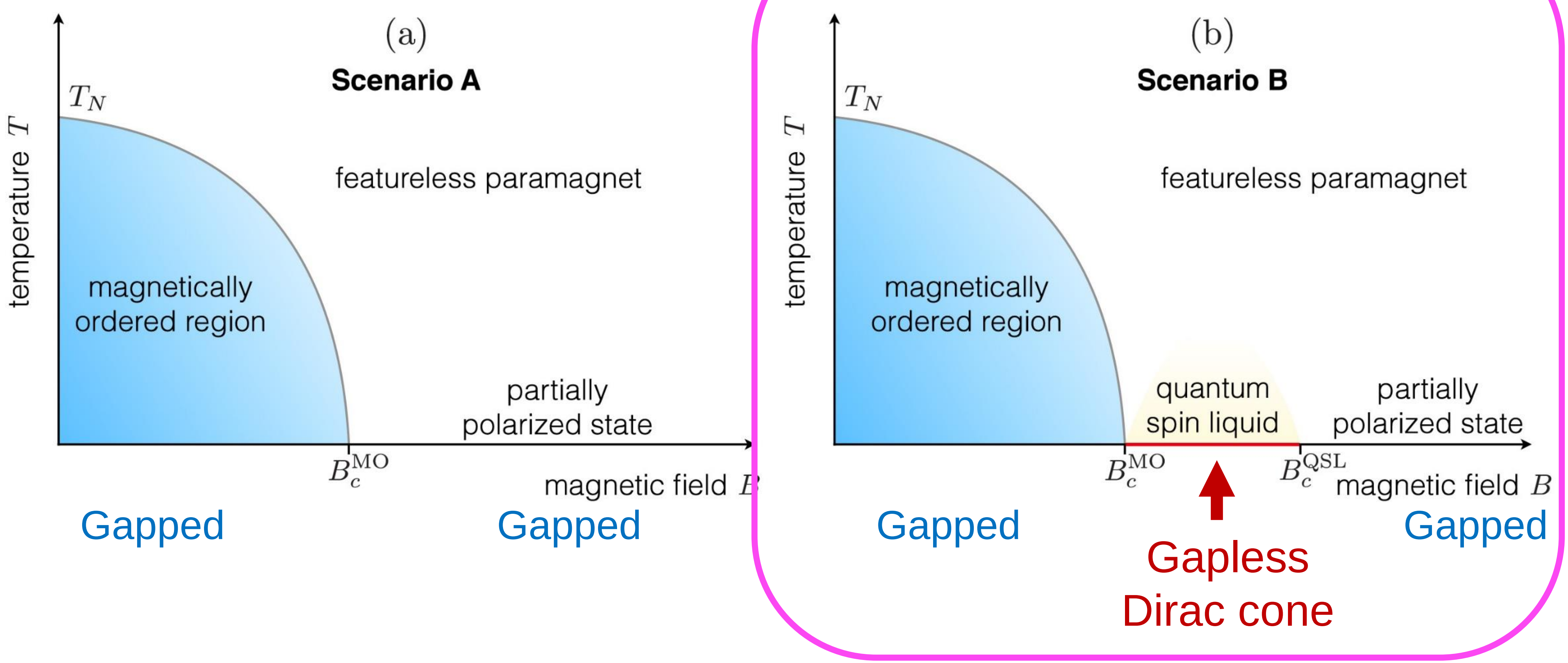
Gapless
Dirac cone

S. Trebst and C. Hickey, Phys. Reports **950**, 1-37 (2022)

Phase diagram

H||b

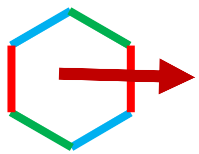


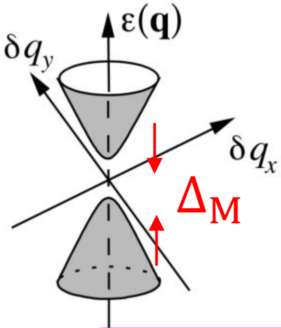


S. Trebst and C. Hickey, Phys. Reports **950**, 1-37 (2022)

Majorana gap and Dirac cone in FIQD state

H* || *a



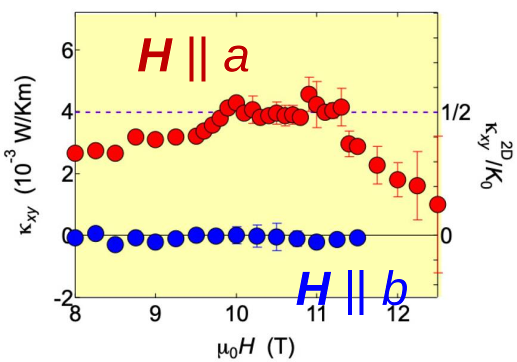


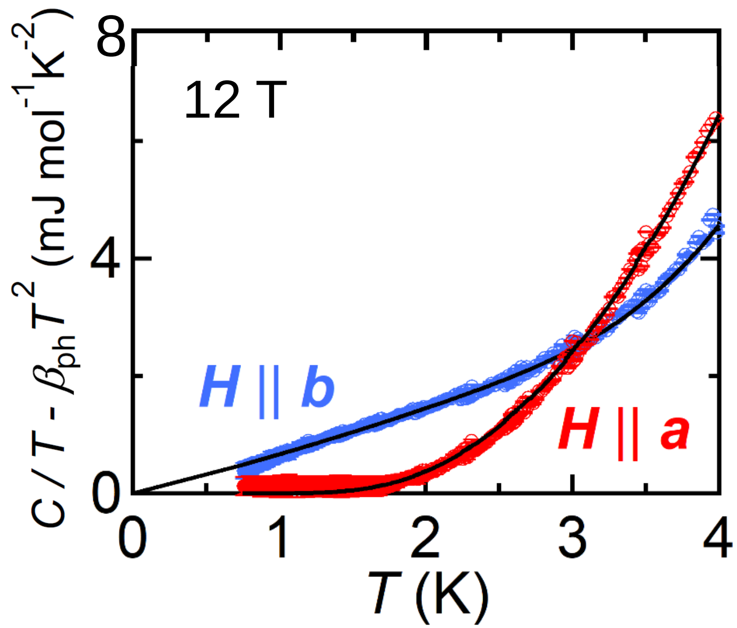
Bulk gap

$$C_{\mathrm{mag}}/T \propto e^{-\frac{\Delta_M}{T}}$$

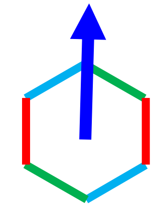
$$\Delta_M \propto \frac{H^3}{\Delta_{\mathrm{flux}}^2}$$

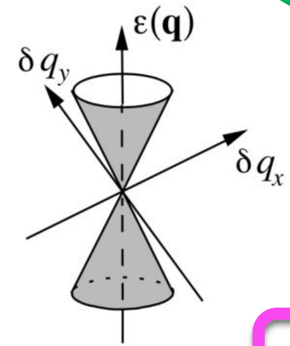
Majorana gap





H* || *b



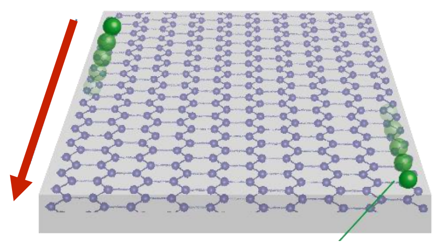


Linear dispersion

$$C_{\mathrm{mag}}/T \propto T$$

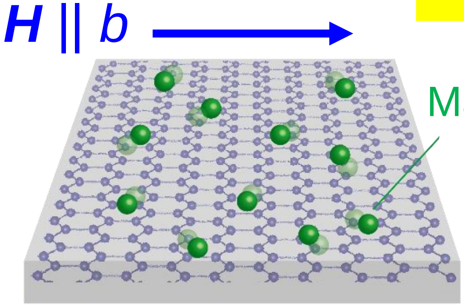
Dirac cone

H* || *a



Majorana fermions (edge)

H* || *b



Majorana fermions (bulk)

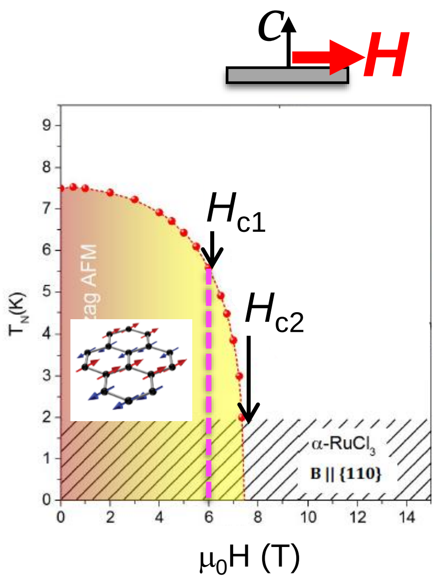
Bulk-edge correspondence

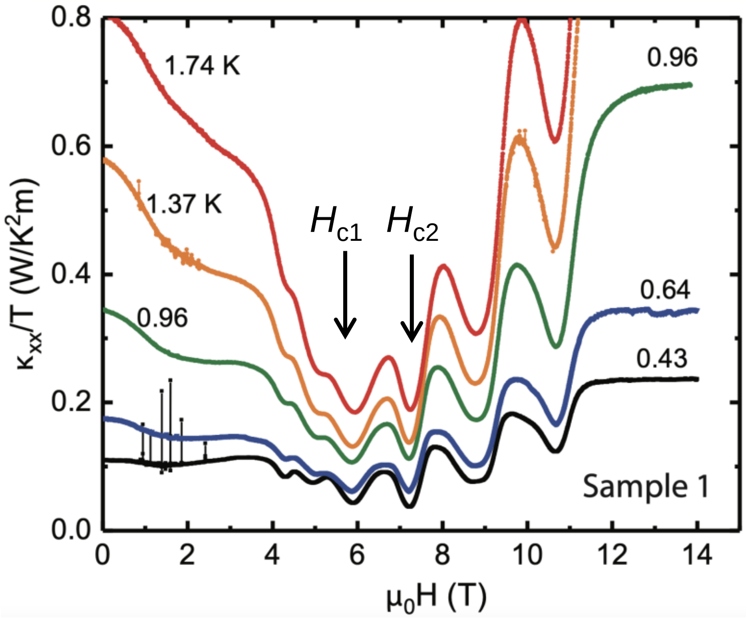
O. Tanaka, YM, T. Shibauchi *et al.* Nature Phys. **18**, 429 (2022).

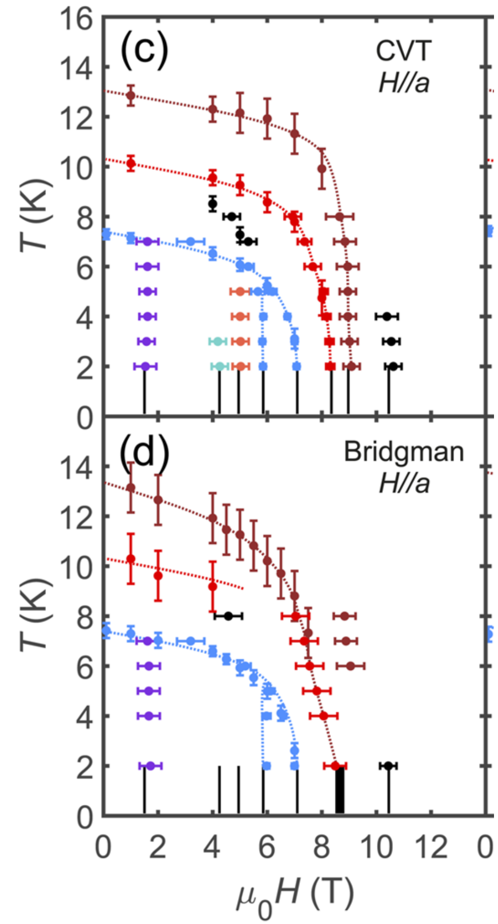
A.U.B. Wolter and C. Hess, Nature Phys. **18**, 378 (2022).

Oscillating thermal conductivity

CVT







Quantum oscillations of fermionic quasiparticles

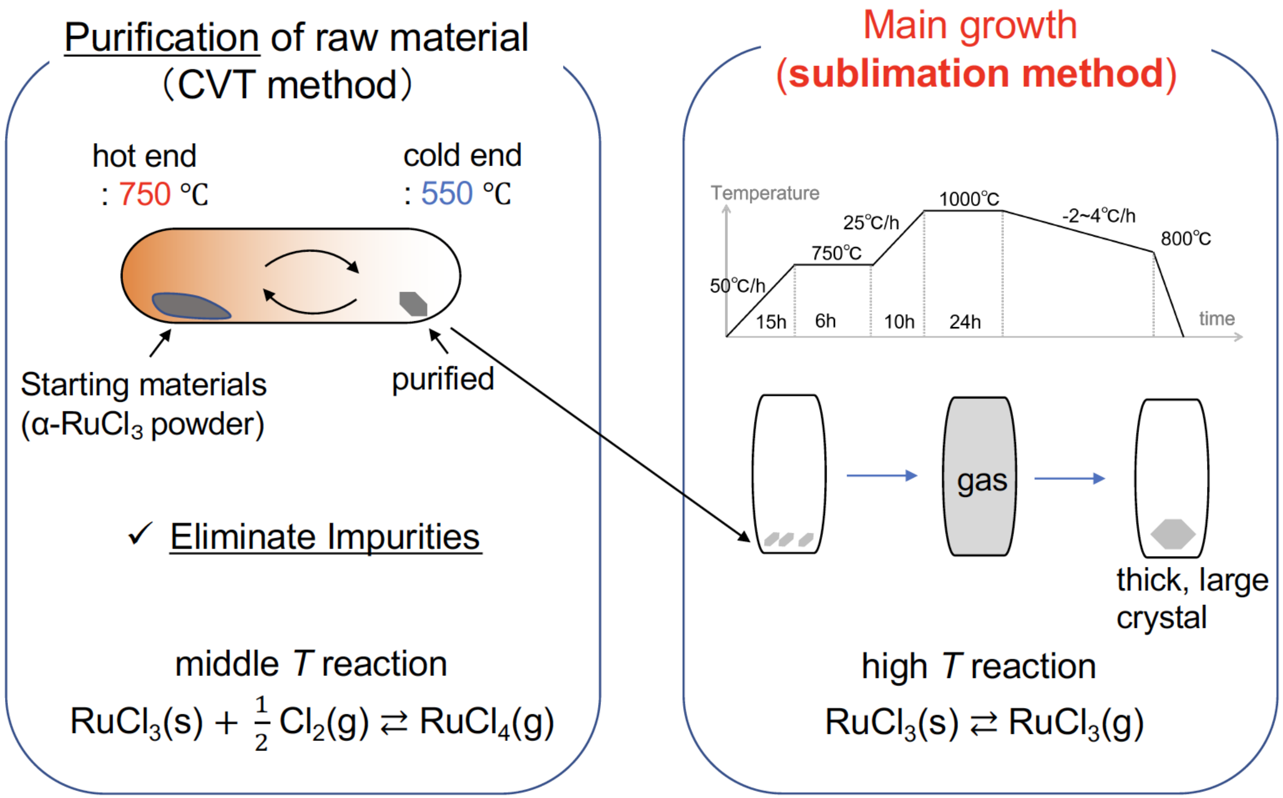
P. Czajka *et al.* Nature Phys. **17**, 915 (2021).

Magnetic transitions due to stacking faults

J.A.N. Bruin *et al*. APL Mater. **10**, 090703 (2022).

E. Lefrancois *et al*. PRB **107**, 064408 (2023).

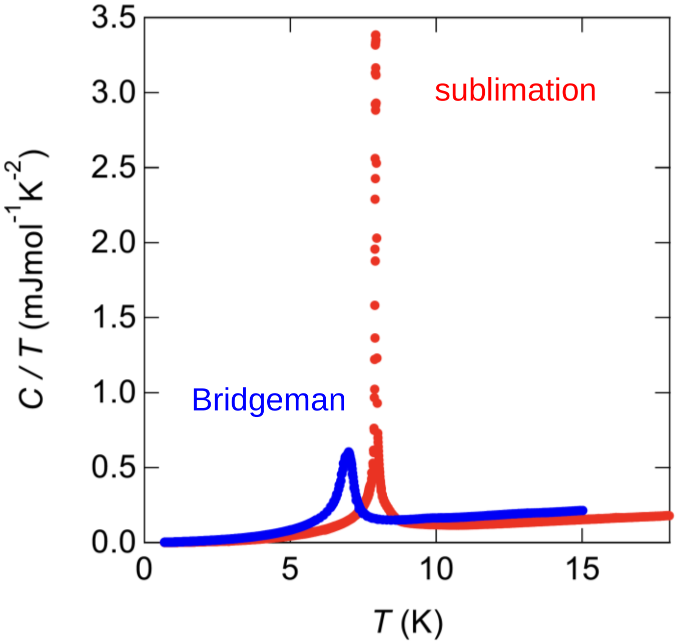
Very clean α-$RuCl_3$ single crystals

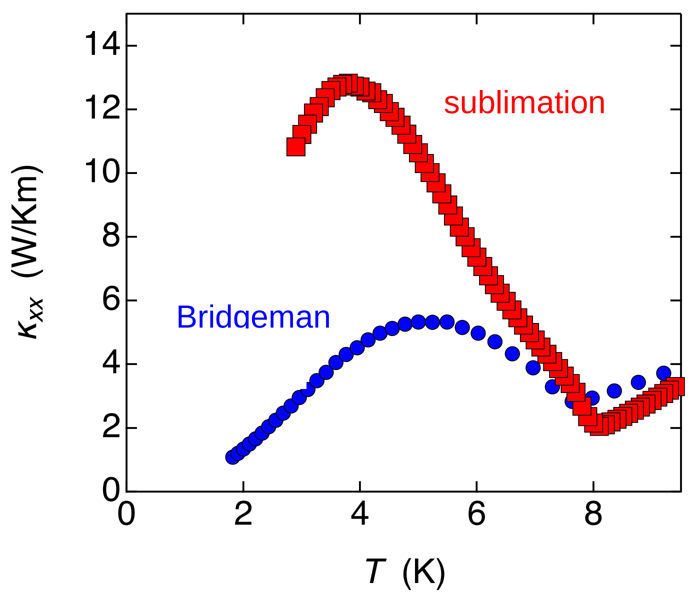


Disorders and defects can
be removed by slow growth

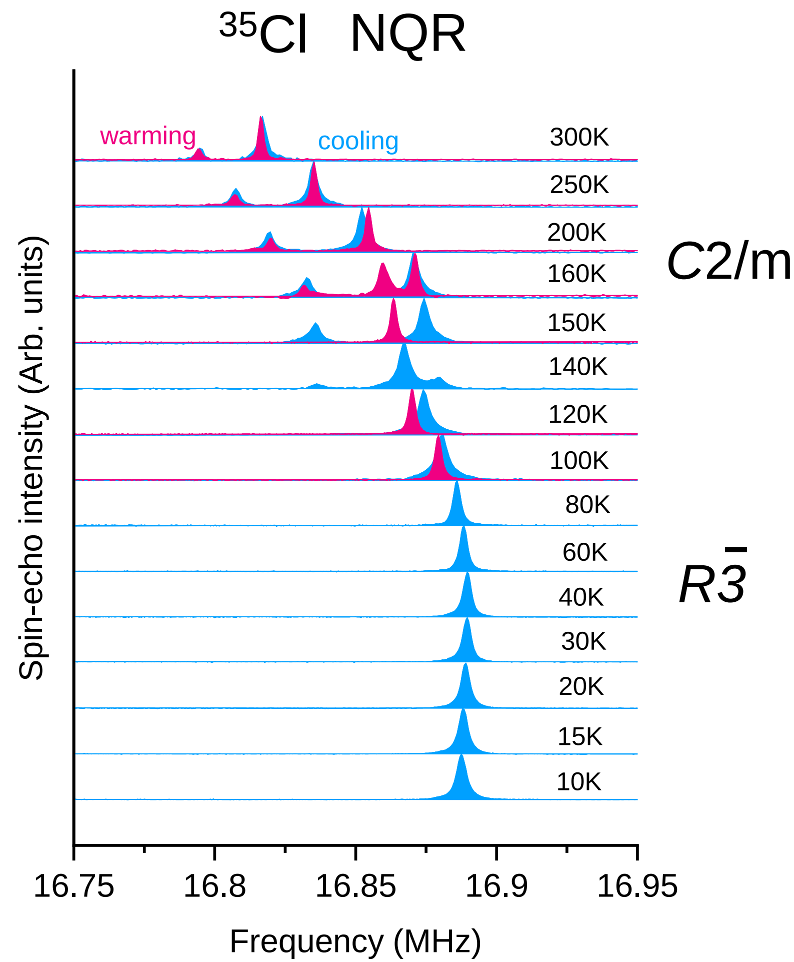
R. Namba、YM, T. Shibauchi *et al*. in preparation.

Very clean α-RuCl$_3$ single crystals



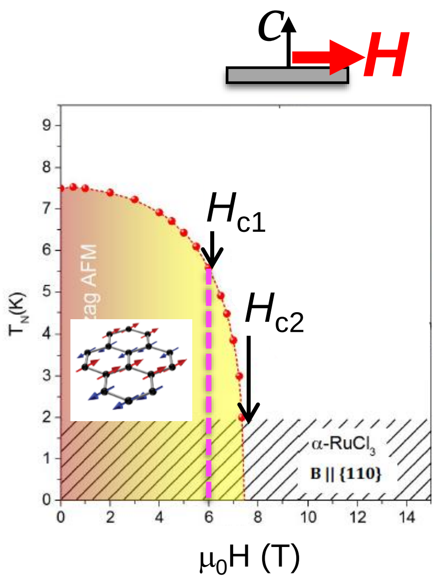


R. Namba、YM, T. Shibauchi *et al.* in preparation.

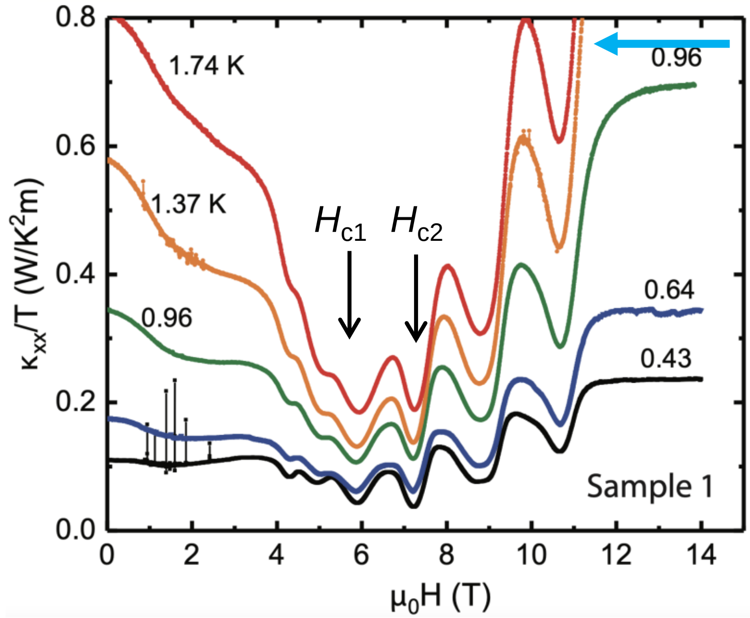


Y. Shimizu *et al*. unpublished

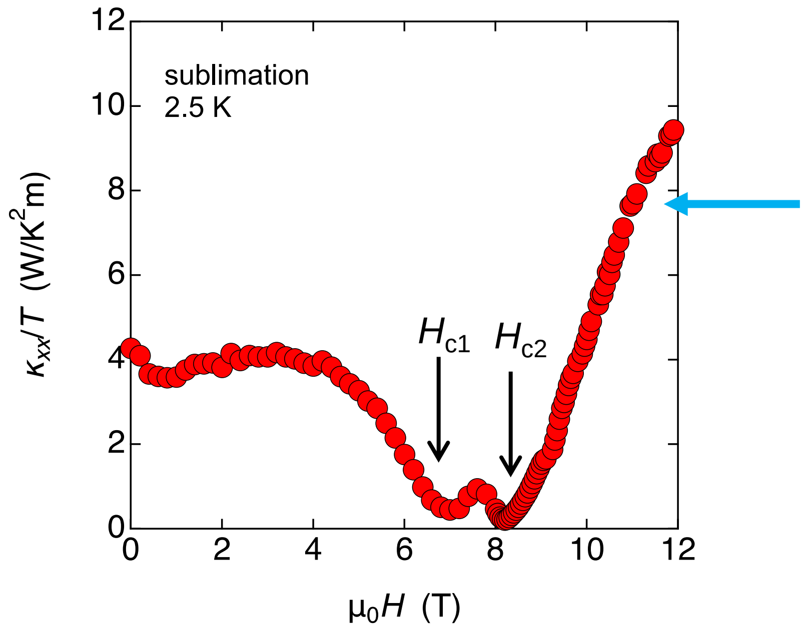
Oscillating thermal conductivity



CVT



Sublimation



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P. Czajka *et al*. Nature Phys. **17**, 915 (2021).

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J.A.N. Bruin *et al.* APL Mater. **10**, 090703 (2022).

E. Lefrancois *et al*. PRB **107**, 064408 (2023).

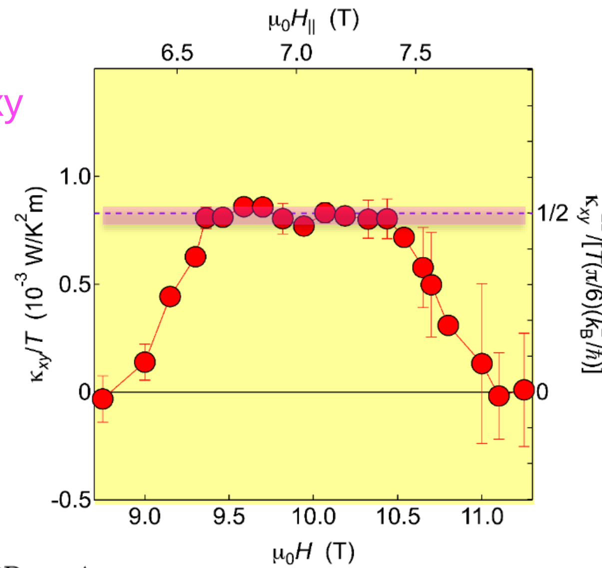
No oscillations in very clean crystals

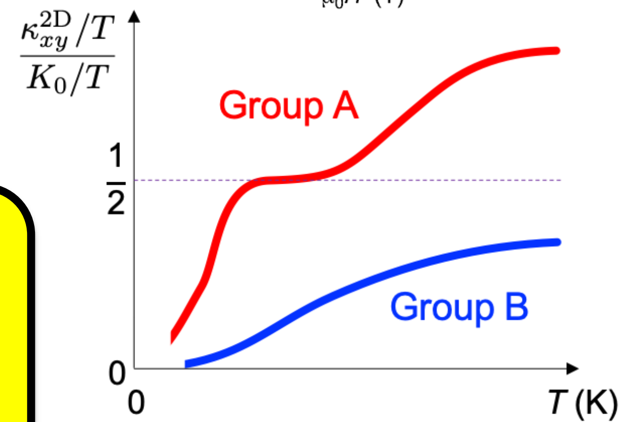
Y. Xing, YM *et al*. in preparation.

Origin of the thermal Hall effect

Some people are not still convinced by the quantized κ_{xy}

1. We cannot determine κ_{xy} accurately
2. The deviation from the quantized value at low temperatures
3. We cannot fully explain the sample dependent quantization.





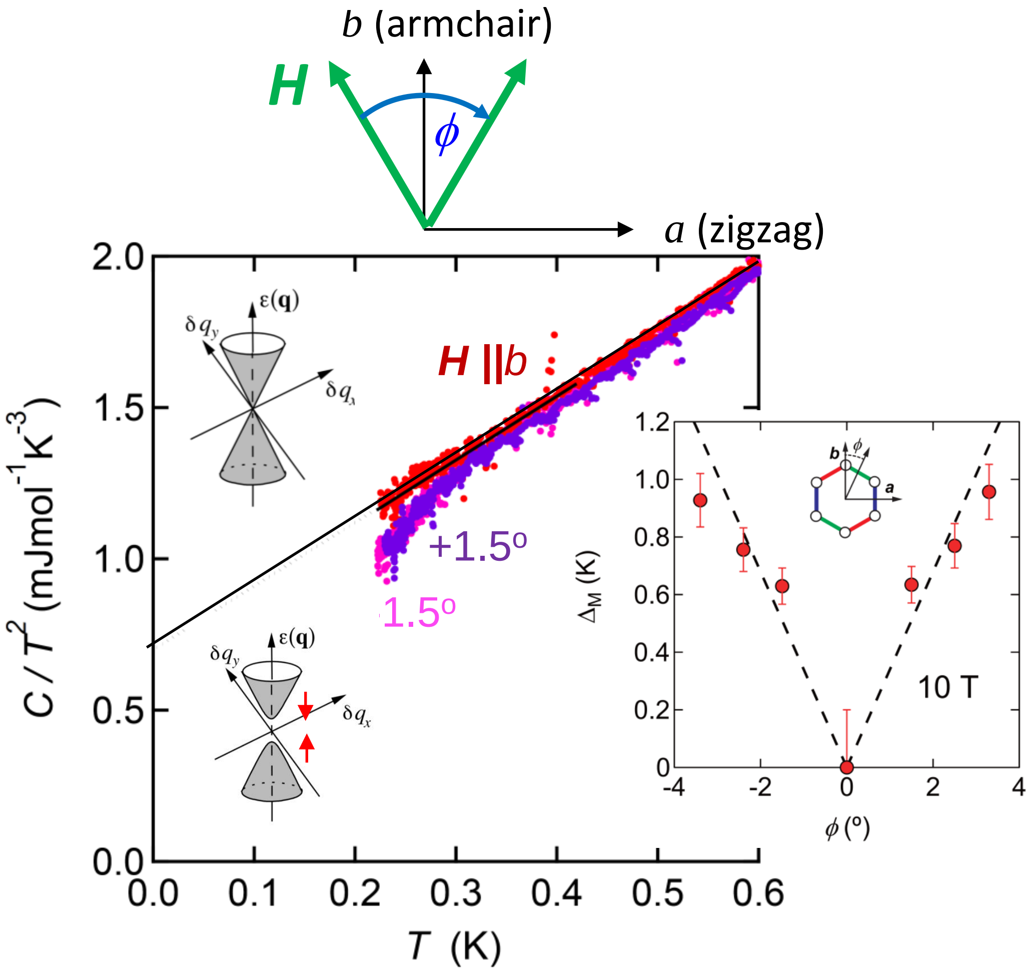
We need a new approach to tackle the quantized thermal Hall issue **without relying on the MAGNITUDE of κ_{xy}.**

Origin of planar thermal Hall: bosonic or fermionic ?

In-plane ***H*** rotation across *b*-axis

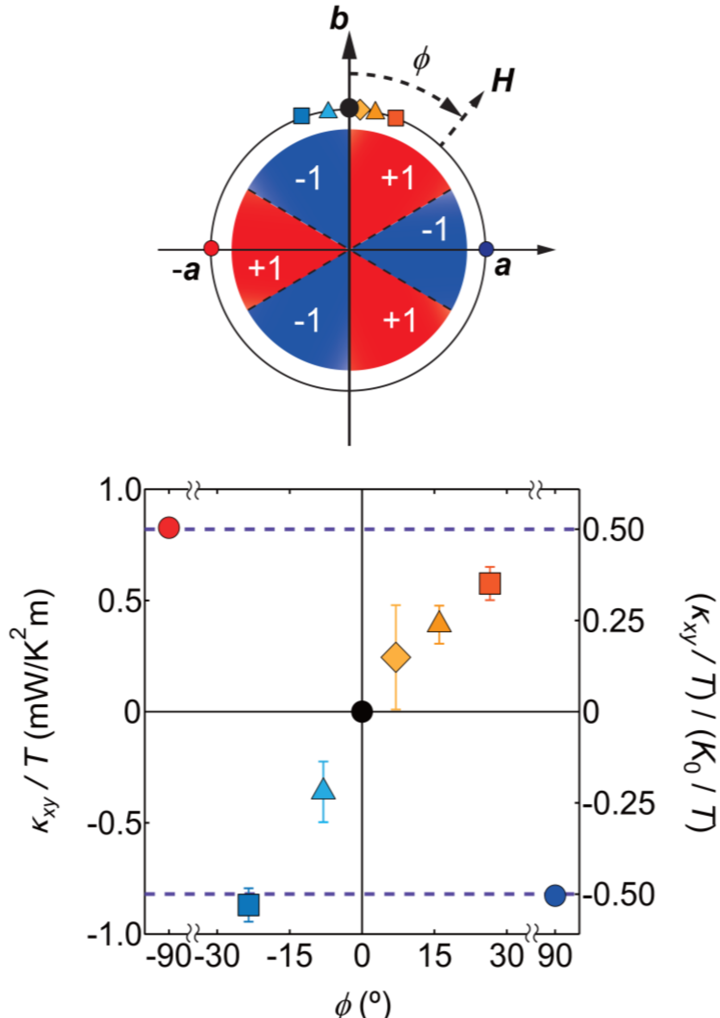
K. Imamura, S. Suetsugu *et al*. arXiv:2305.10619.

① Specific heat



Gap closing at ***H*** || *b*

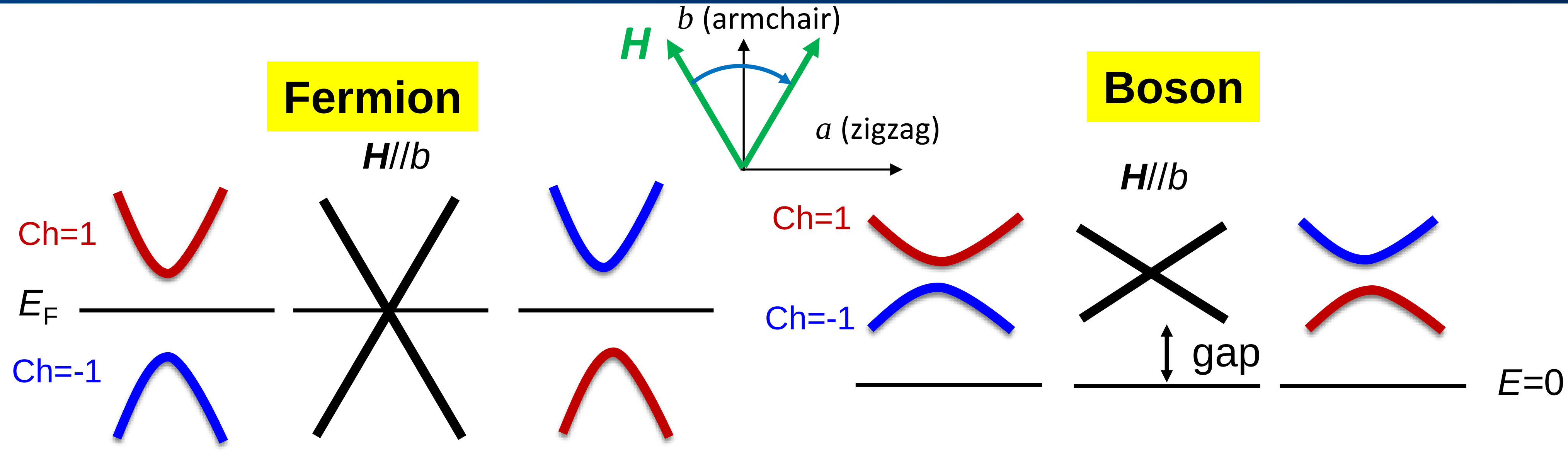
② Planar thermal Hall effect



Hall sign change at ***H*** || *b*

Two distinct features are observed concurrently at ***H* ||** *b*

Origin of planar thermal Hall: bosonic or fermionic ?



Sign change of κ_{xy} is always accompanied by gap closing

Gap is always finite.
Sign change is not related to the gap closing.

In α-$RuCl_3$

Gap closing
Sign change of the planar thermal Hall effect

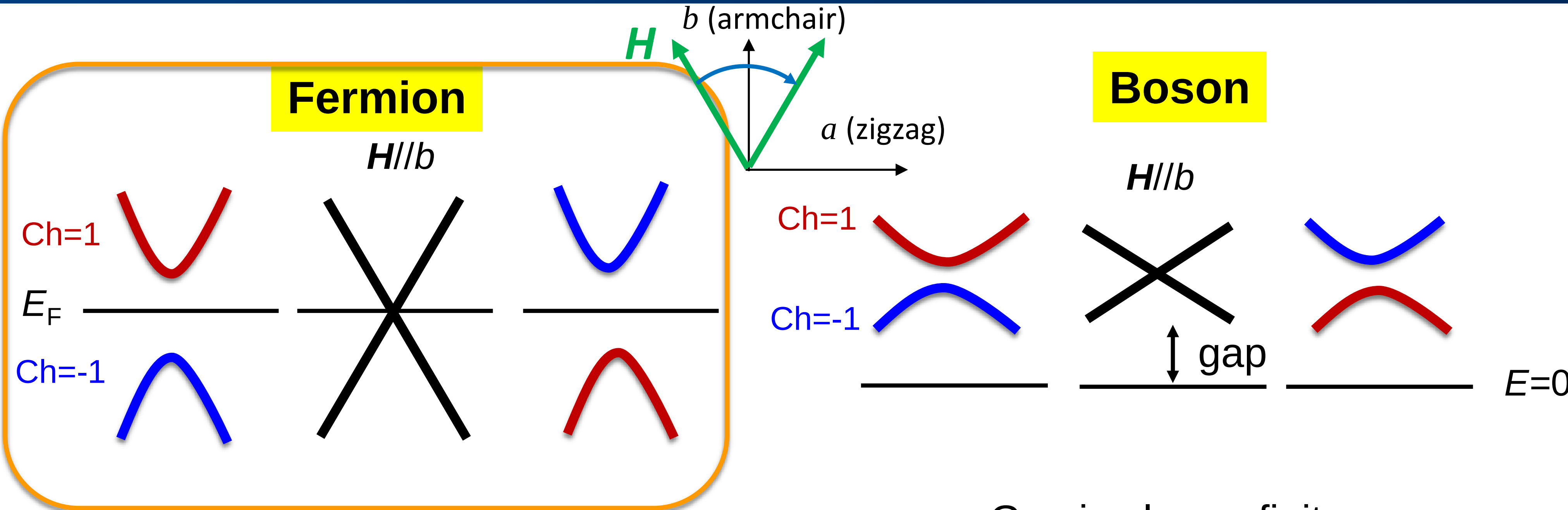
Concurrently occur at ***H*** || *b*

Evidence for **fermionic origin** of the thermal Hall effect

In this case, **thermal Hall conductance is quantized.**

K. Imamura, S. Suetsugu, YM *et al.* arXiv:2305.10619..

Origin of planar thermal Hall: bosonic or fermionic ?



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In α-$RuCl_3$

Gap closing
Sign change of the planar thermal Hall effect

] Concurrently occur at ***H*** || *b*

Evidence for **fermionic origin** of the thermal Hall effect

In this case, **thermal Hall conductance is quantized.**

K. Imamura, S. Suetsugu, YM *et al.* arXiv:2305.10619..

1. Half integer quantized thermal Hall effect in α-$RuCl_3$

2. Is α-$RuCl_3$ really Kitaev material?

Topology: Topological invariant

Thermodynamics: Dirac cone and Majorana gap

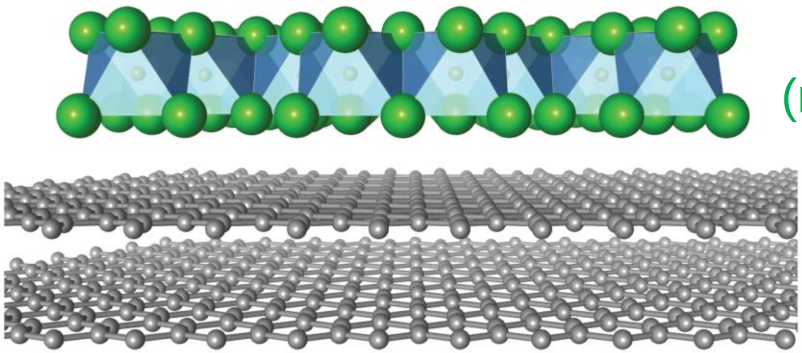
Thermal transport properties of very clean crystals

3. STM studies on monolayer α-$RuCl_3$

Local density of states around defects

STM image of monolayer α-$RuCl_3$ on HOPG

Y. Kohsaka, YM, *et al*. a preprint

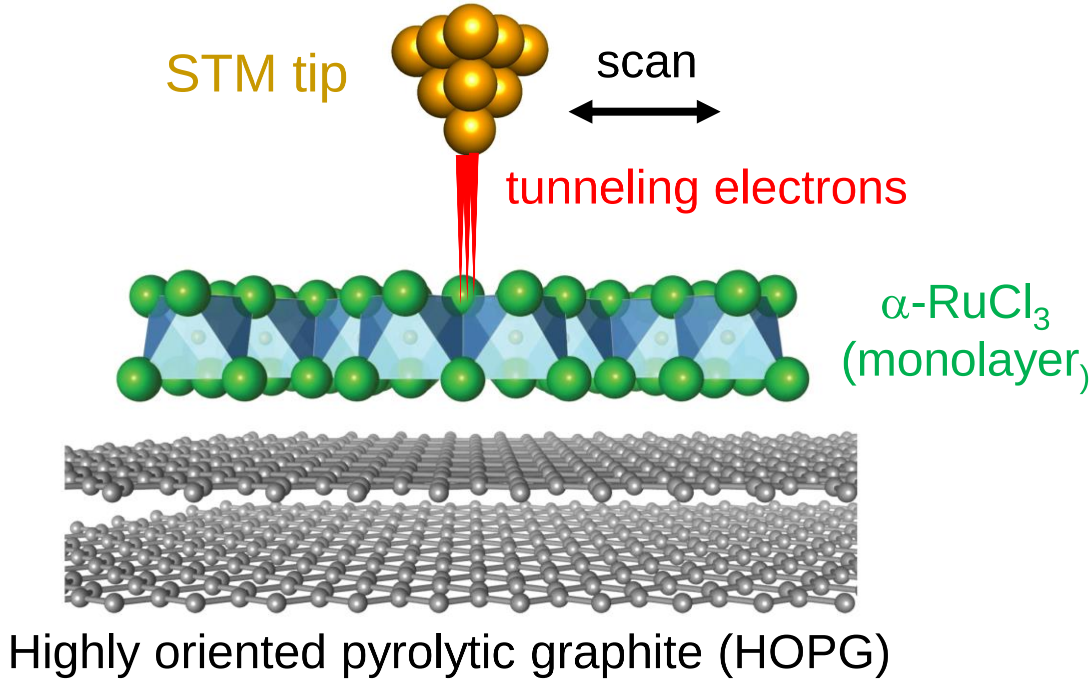


Highly oriented pyrolytic graphite (HOPG)

Ru

STM image of monolayer α-$RuCl_3$ on HOPG

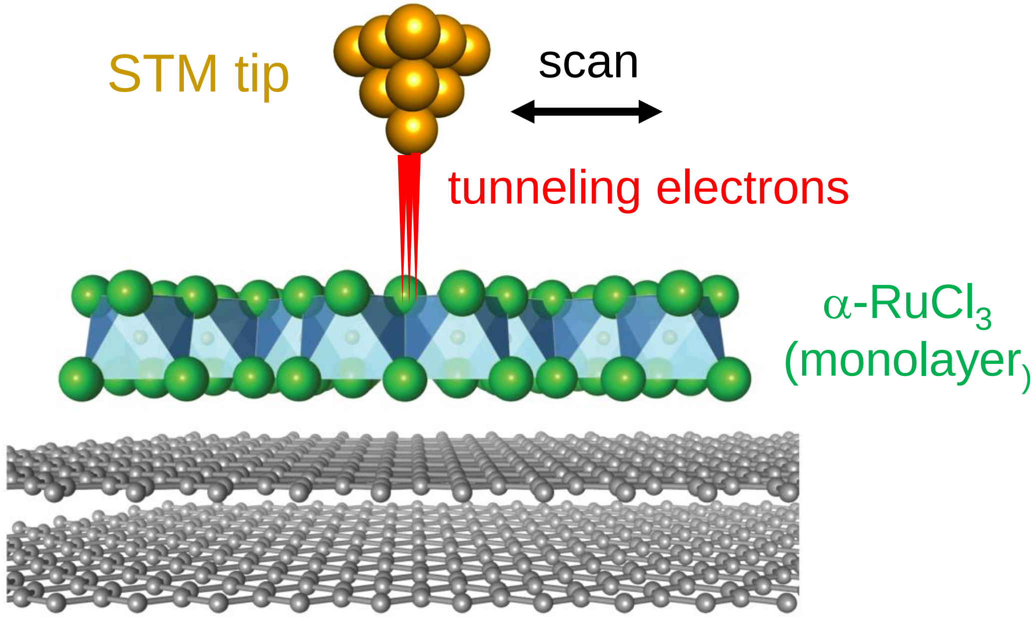
Y. Kohsaka, YM, *et al*. a preprint



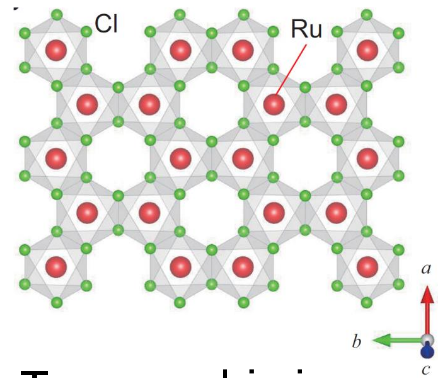
Ru

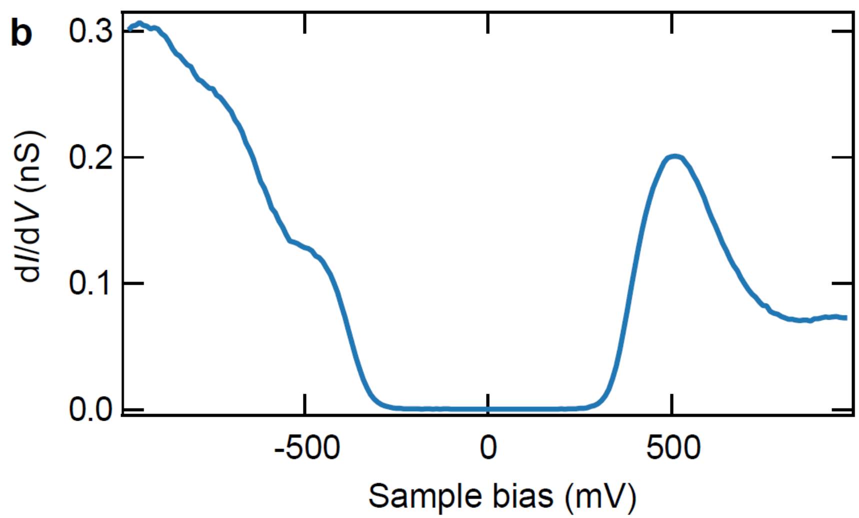
STM image of monolayer α-$RuCl_3$ on HOPG

Y. Kohsaka, YM, *et al*. a preprint

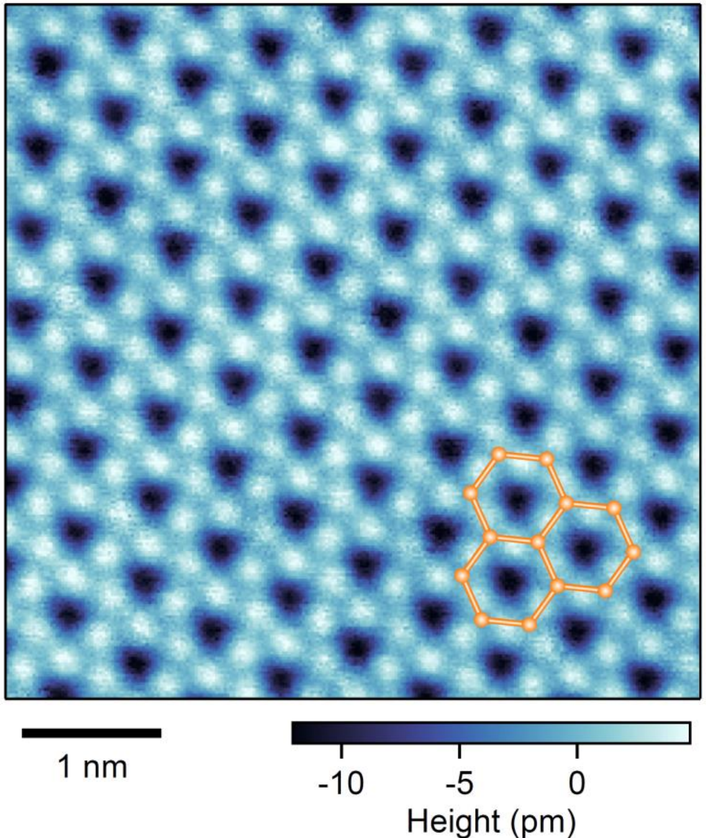


Highly oriented pyrolytic graphite (HOPG)



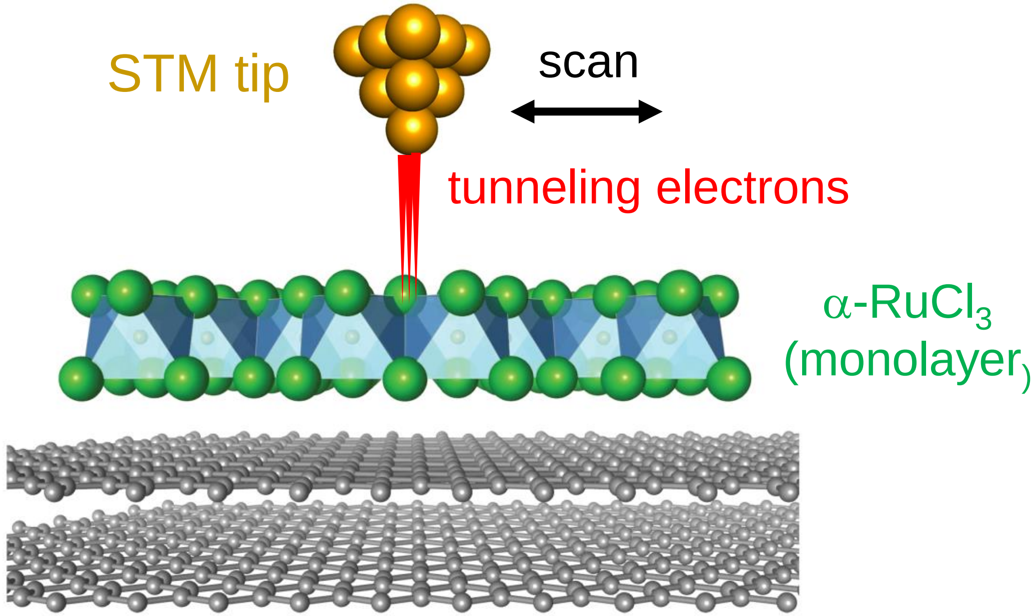


Topographic image (5 K)

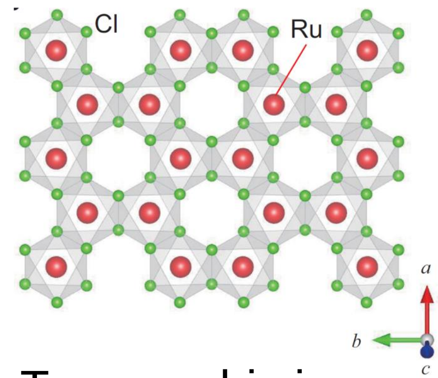


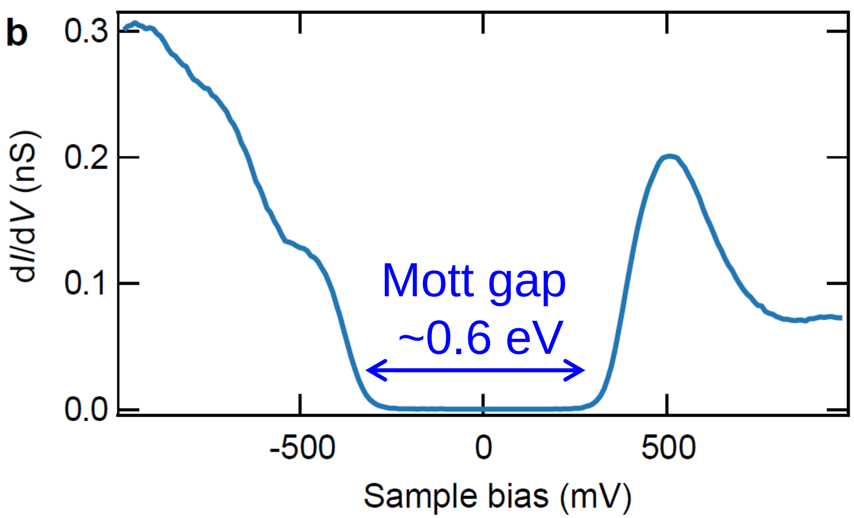
STM image of monolayer α-$RuCl_3$ on HOPG

Y. Kohsaka, YM, *et al*. a preprint

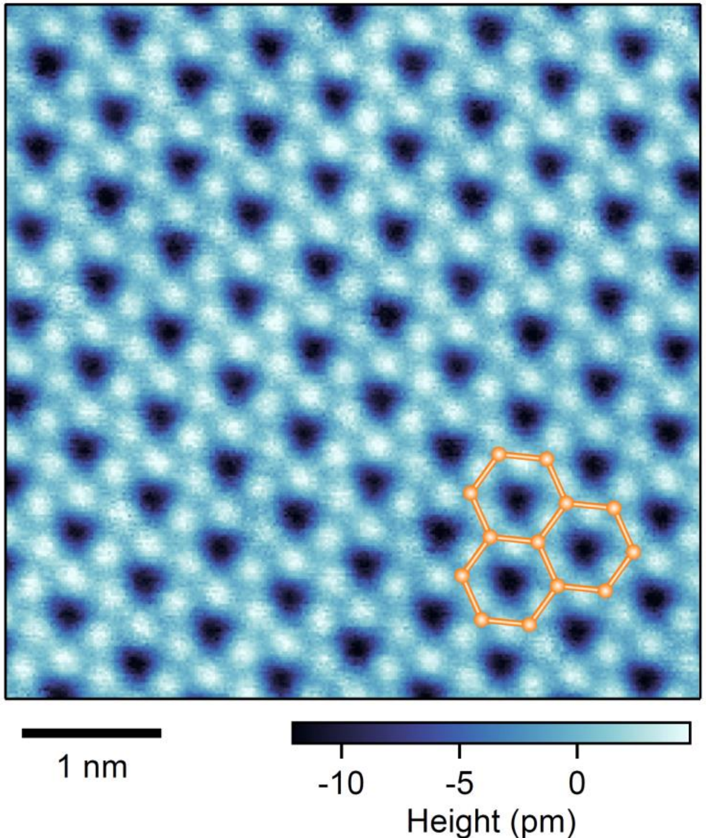


Highly oriented pyrolytic graphite (HOPG)

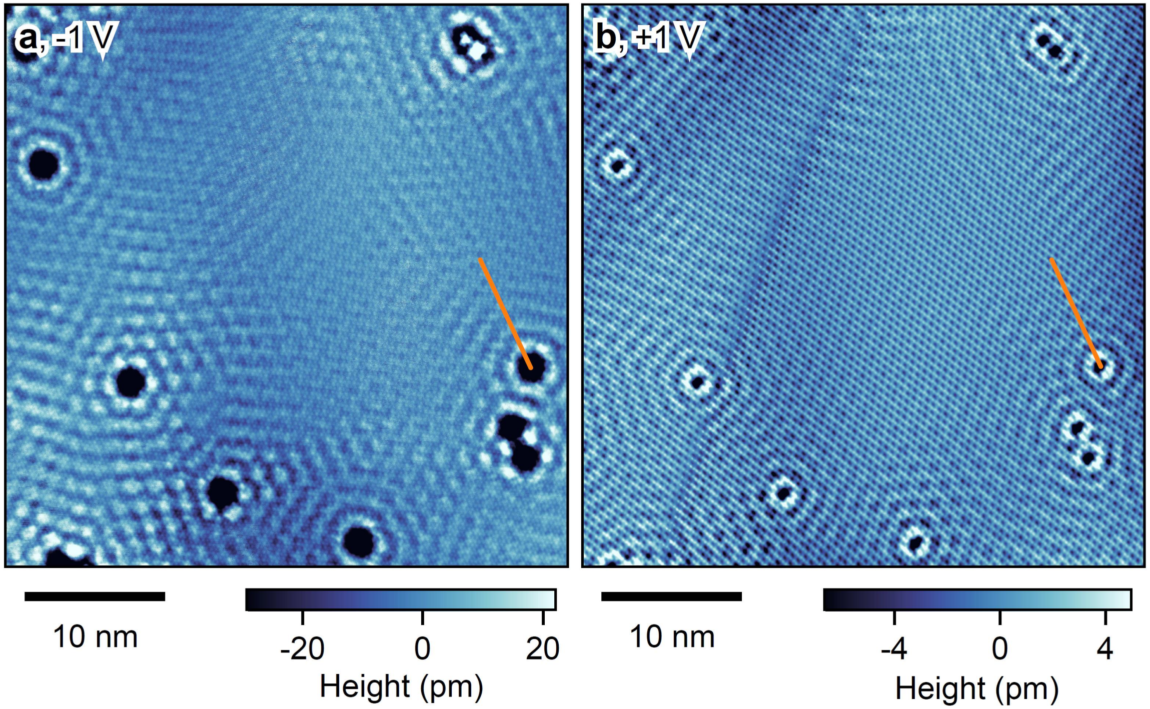




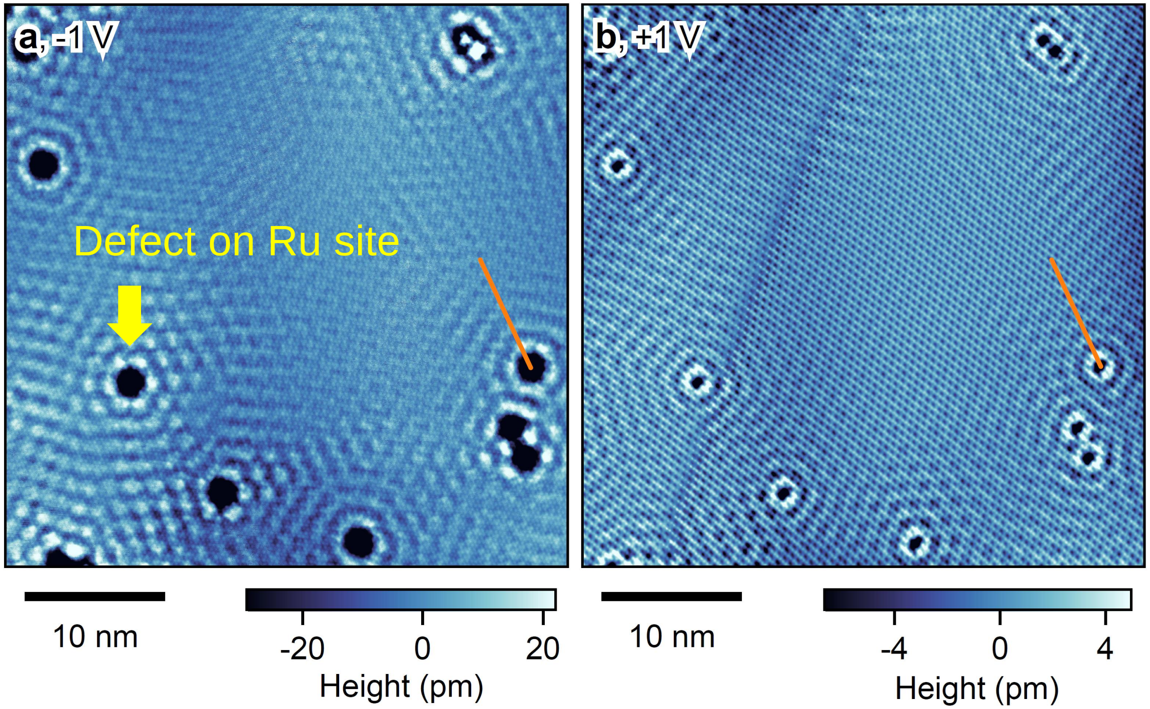
Topographic image (5 K)

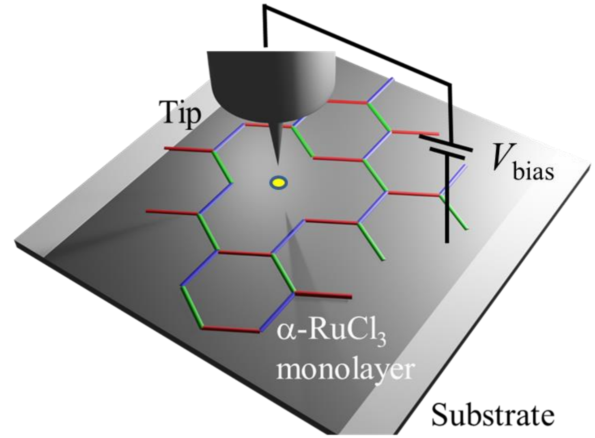


Anomalous spatial oscillations in Kitaev QSL

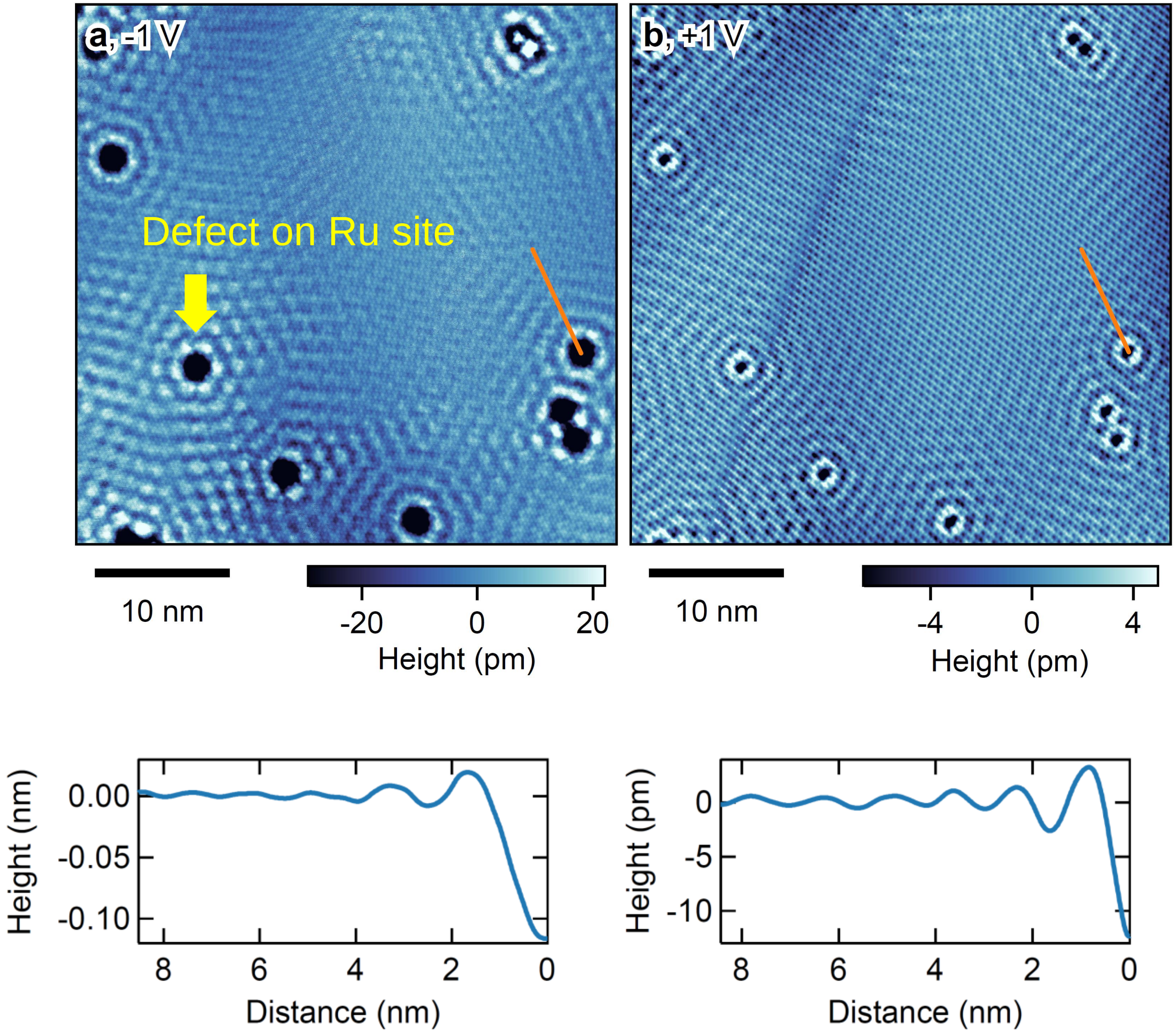


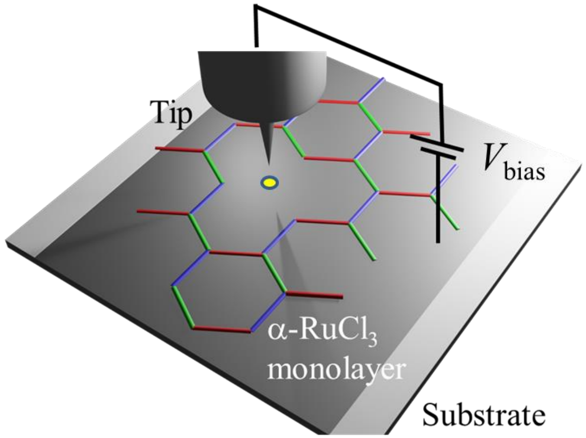
Anomalous spatial oscillations in Kitaev QSL



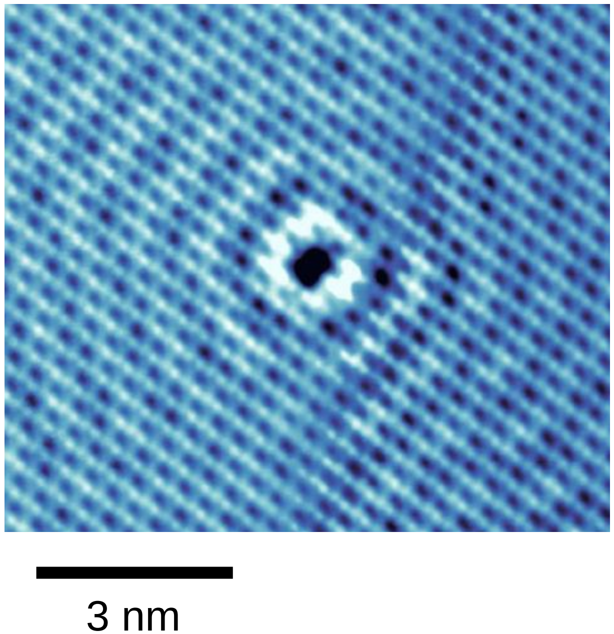


Anomalous spatial oscillations in Kitaev QSL





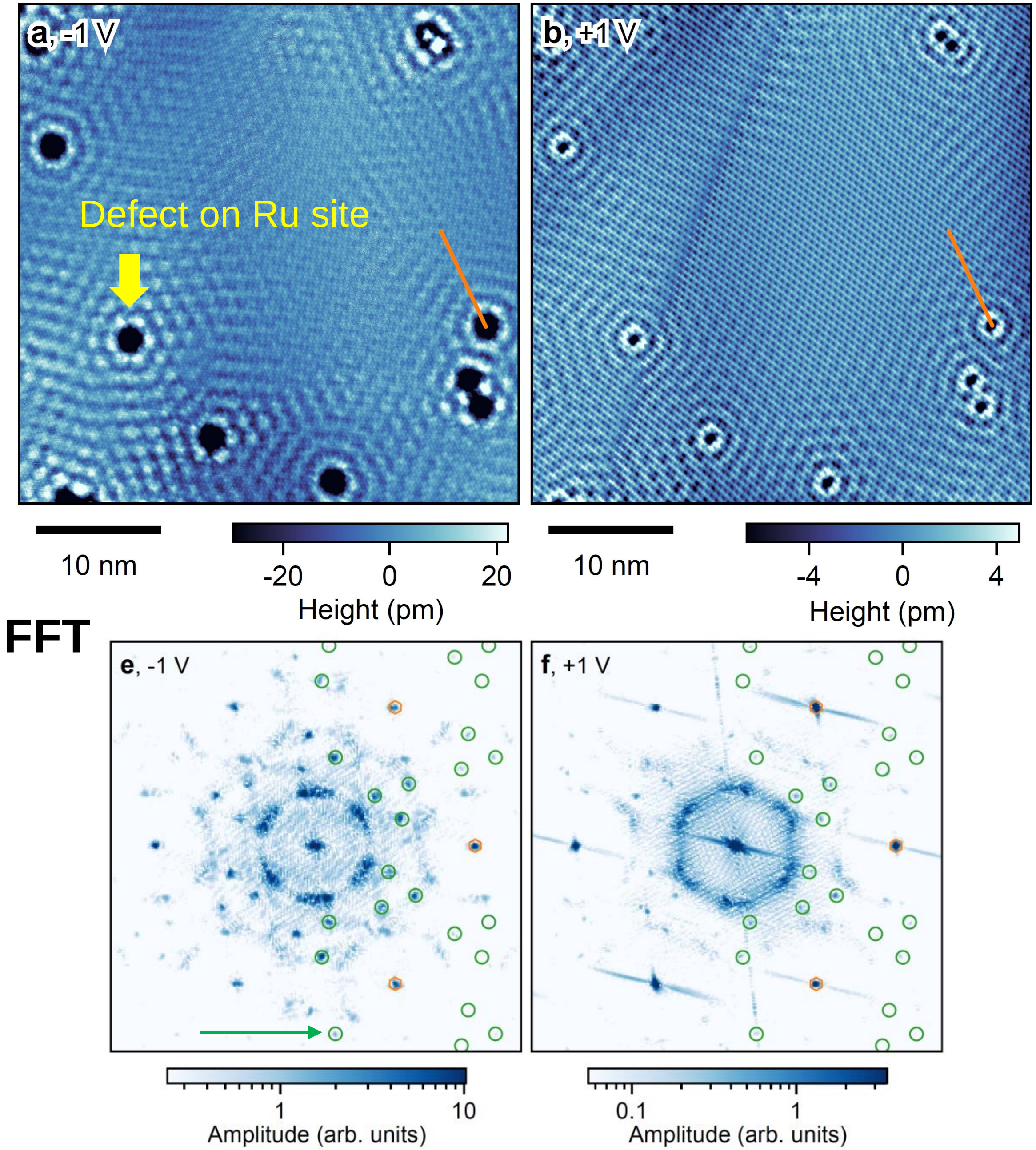
Ripples around defects



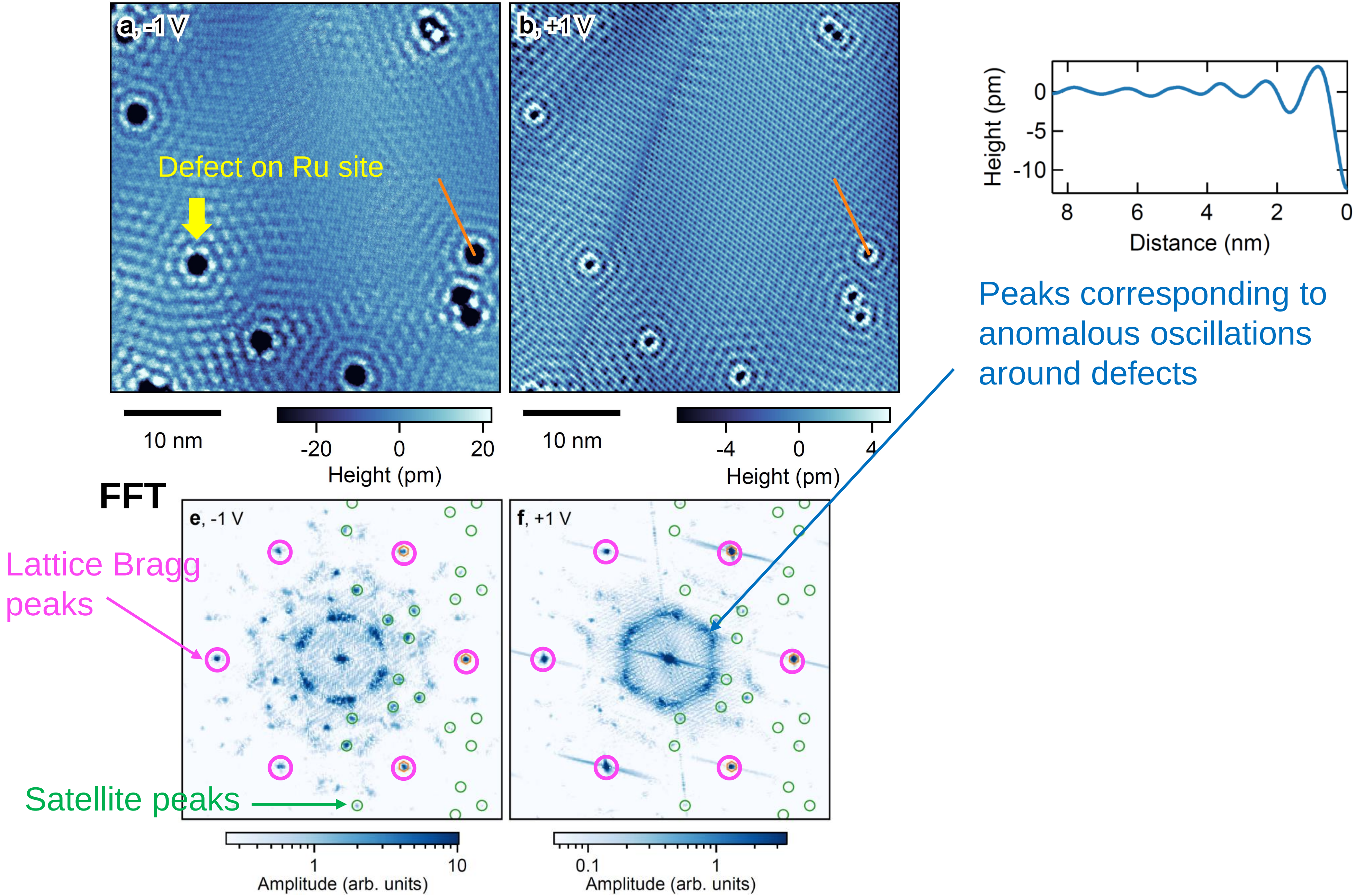
Long-wavelength oscillations around defects

Incommensurate to the lattice spacing

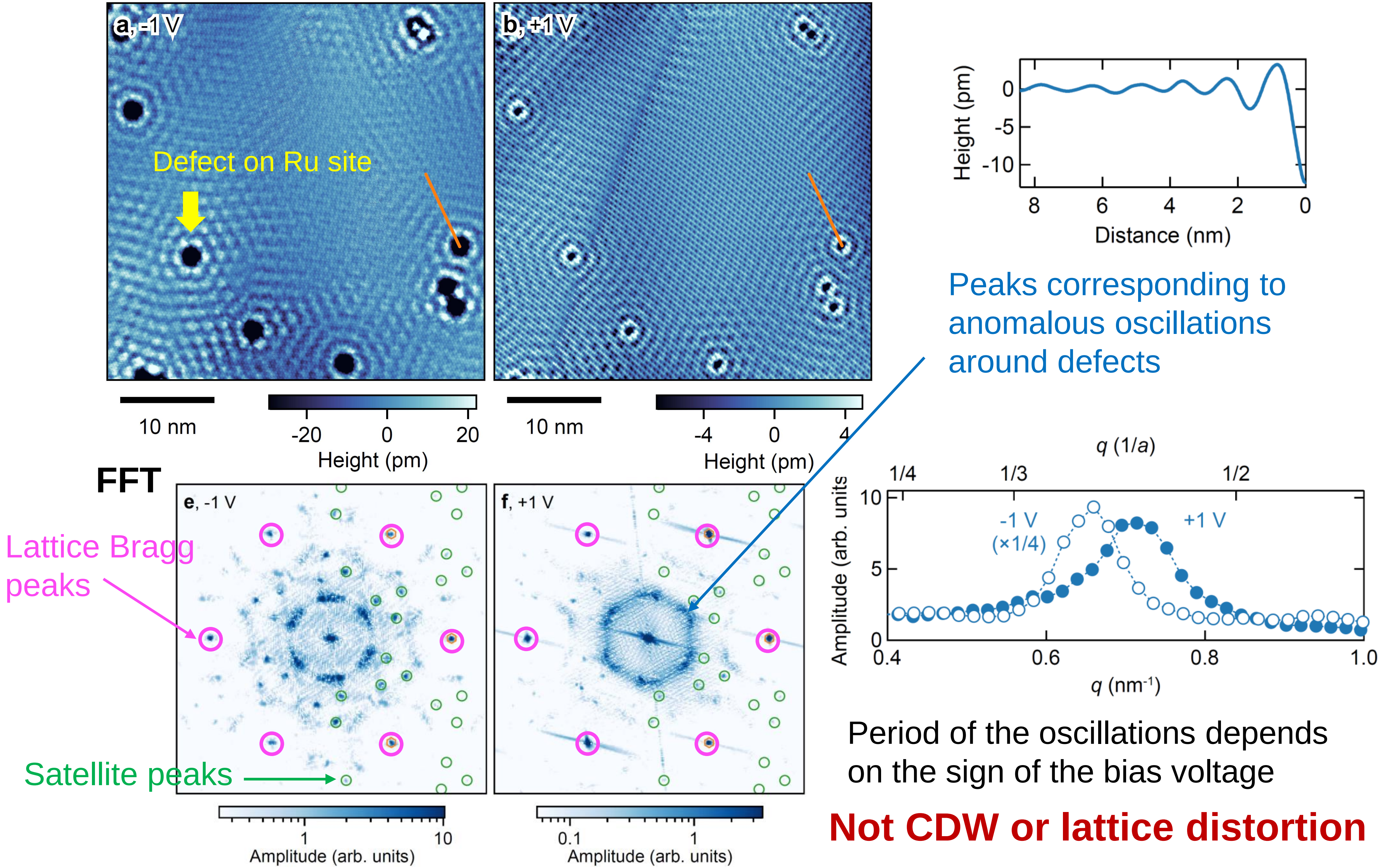
Anomalous spatial oscillations in Kitaev QSL



Anomalous spatial oscillations in Kitaev QSL



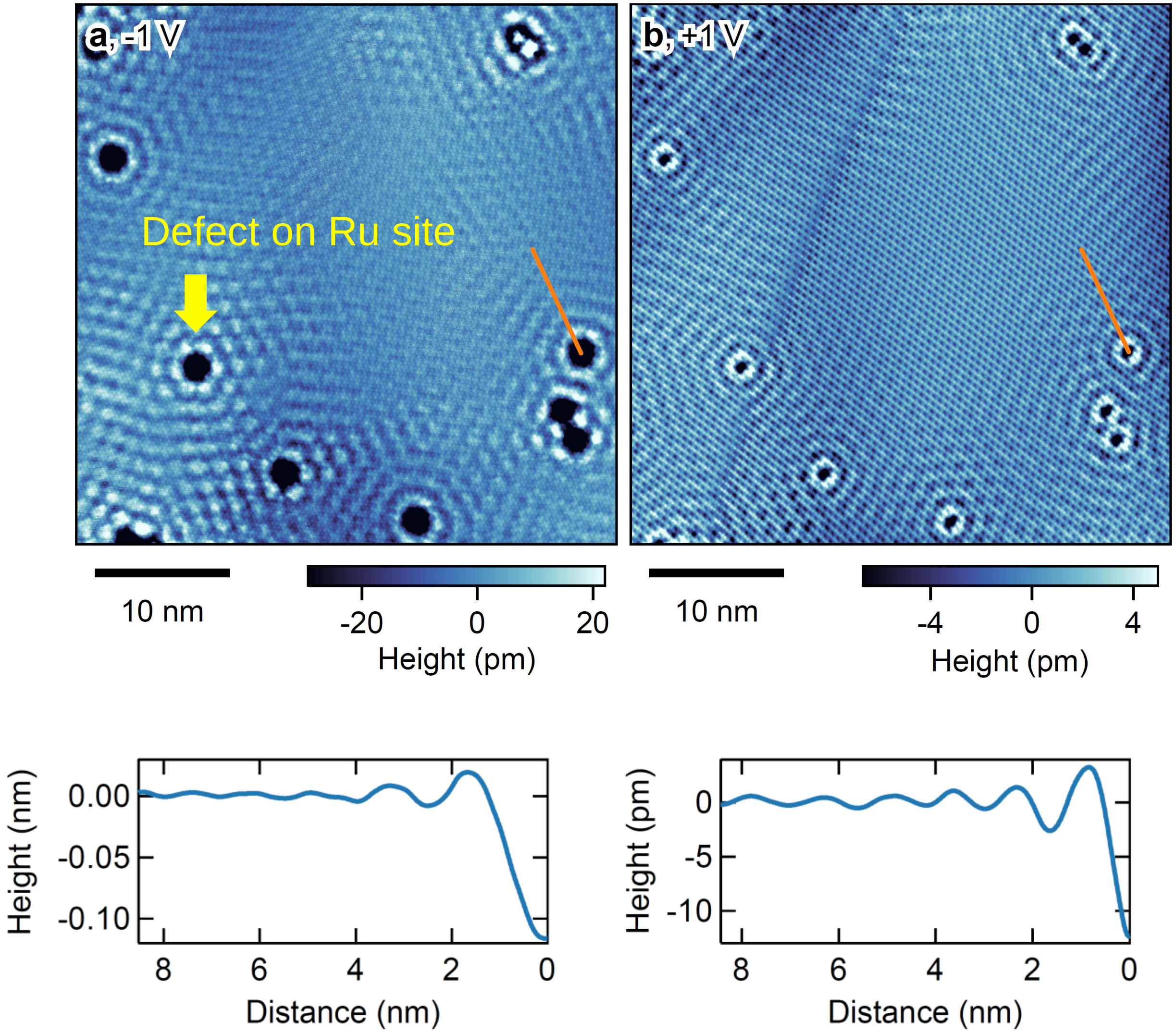
Anomalous spatial oscillations in Kitaev QSL



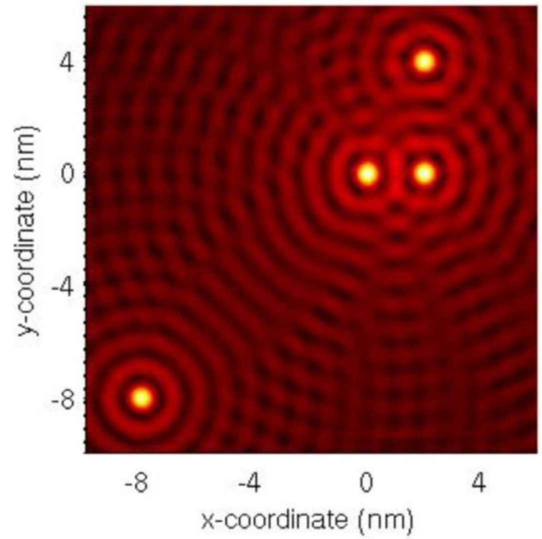
Period of the oscillations depends on the sign of the bias voltage

Not CDW or lattice distortion

Anomalous spatial oscillations in Kitaev QSL

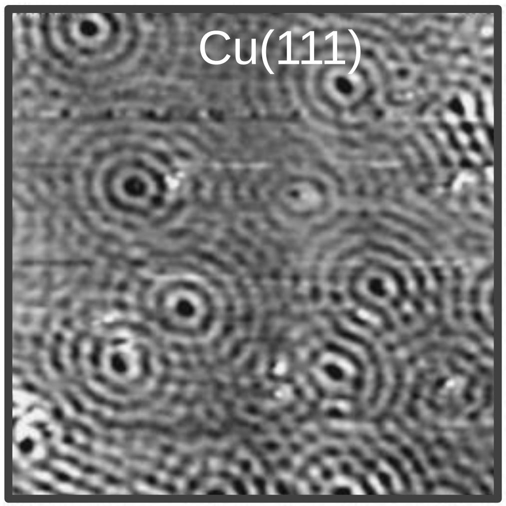


Friedel oscillations (metal)



J. Fransson and A. V. Balatsky PRB (2007)

Quasiparticle interference (QPI)

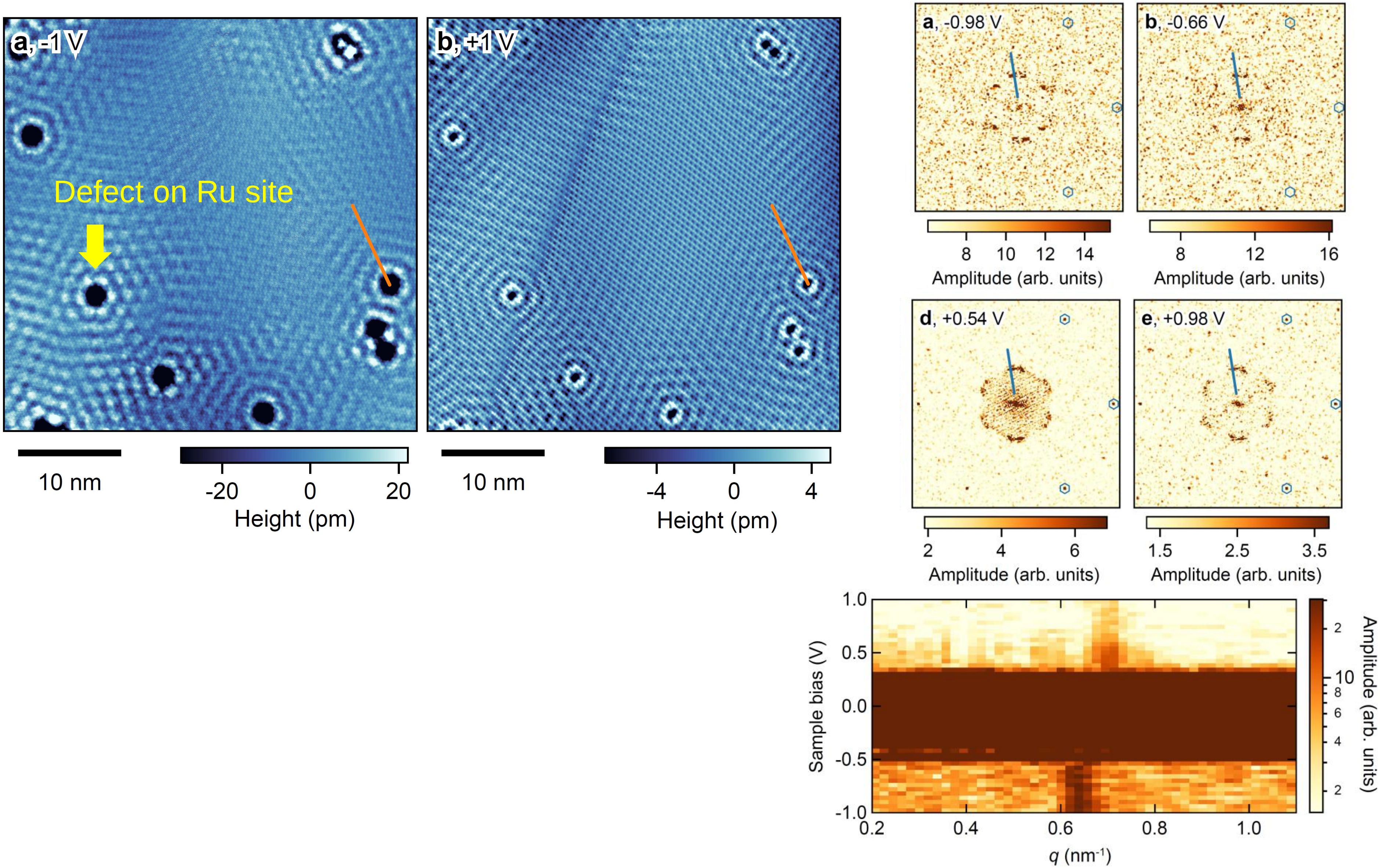


L. Petersen *et al.*, PRB (1998).

Long-wavelength oscillation around Ru defects

Incommensurate to the lattice spacing

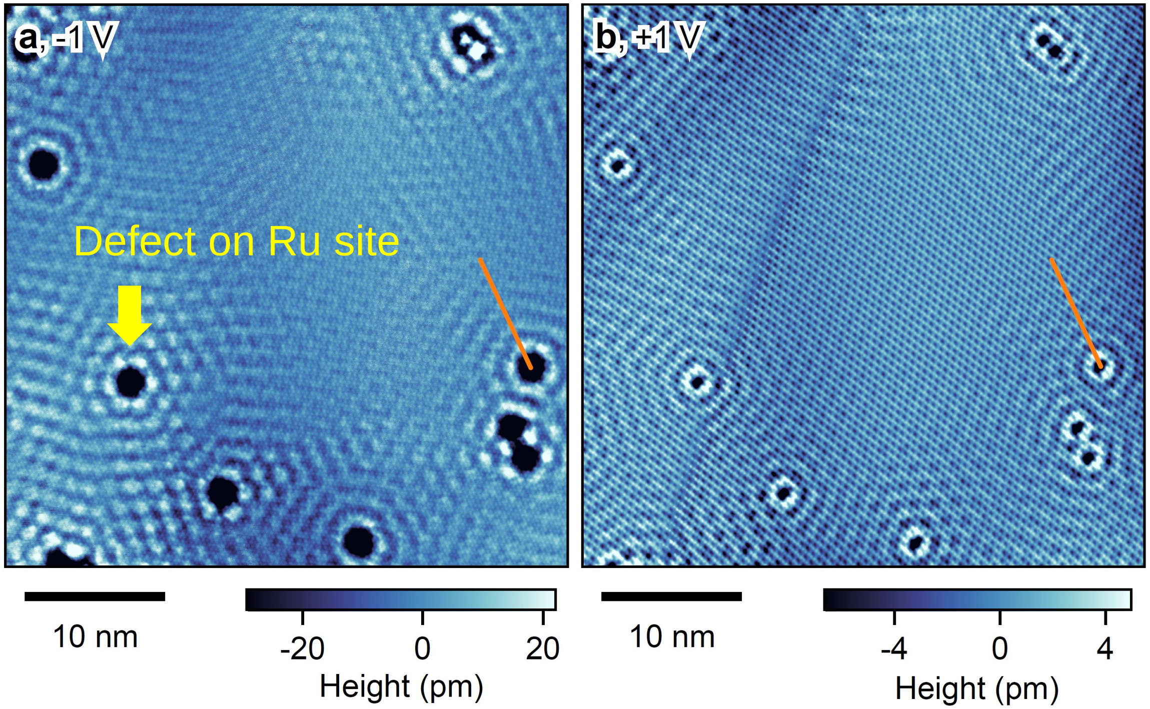
Anomalous spatial oscillations in Kitaev QSL

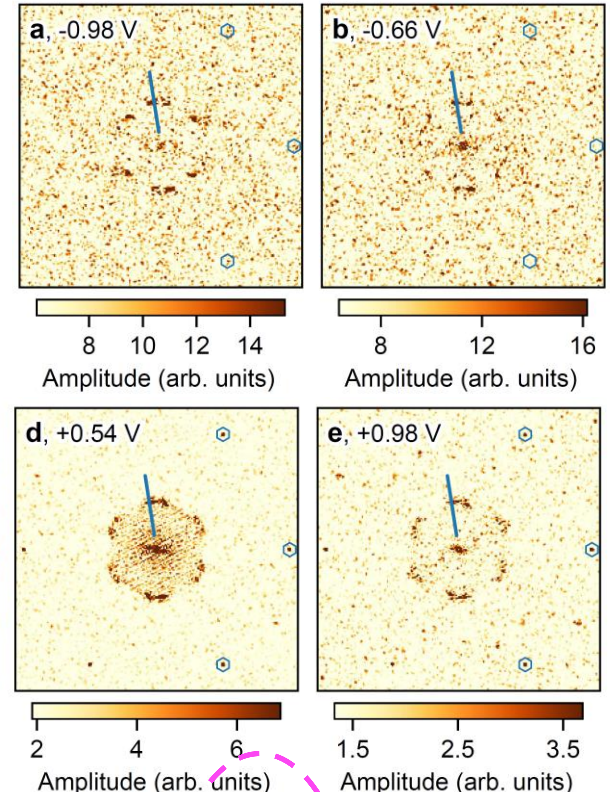


Negligibly small ***q***-dependence

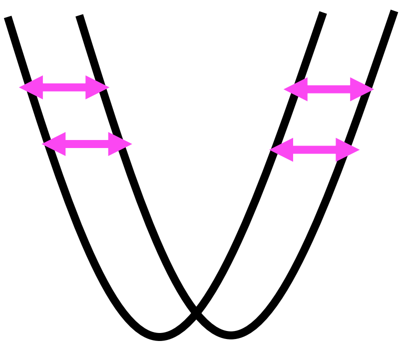
Not QPI

Anomalous spatial oscillations in Kitaev QSL

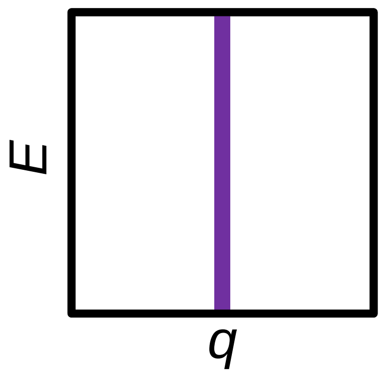


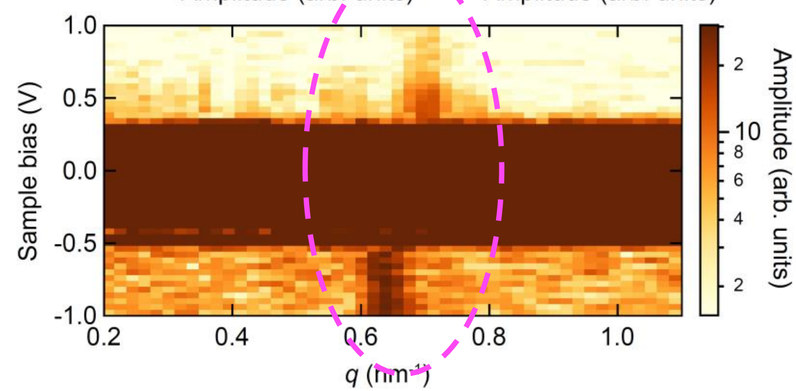


Destructive interference



Vertical dispersion does not appear in QPI spectra

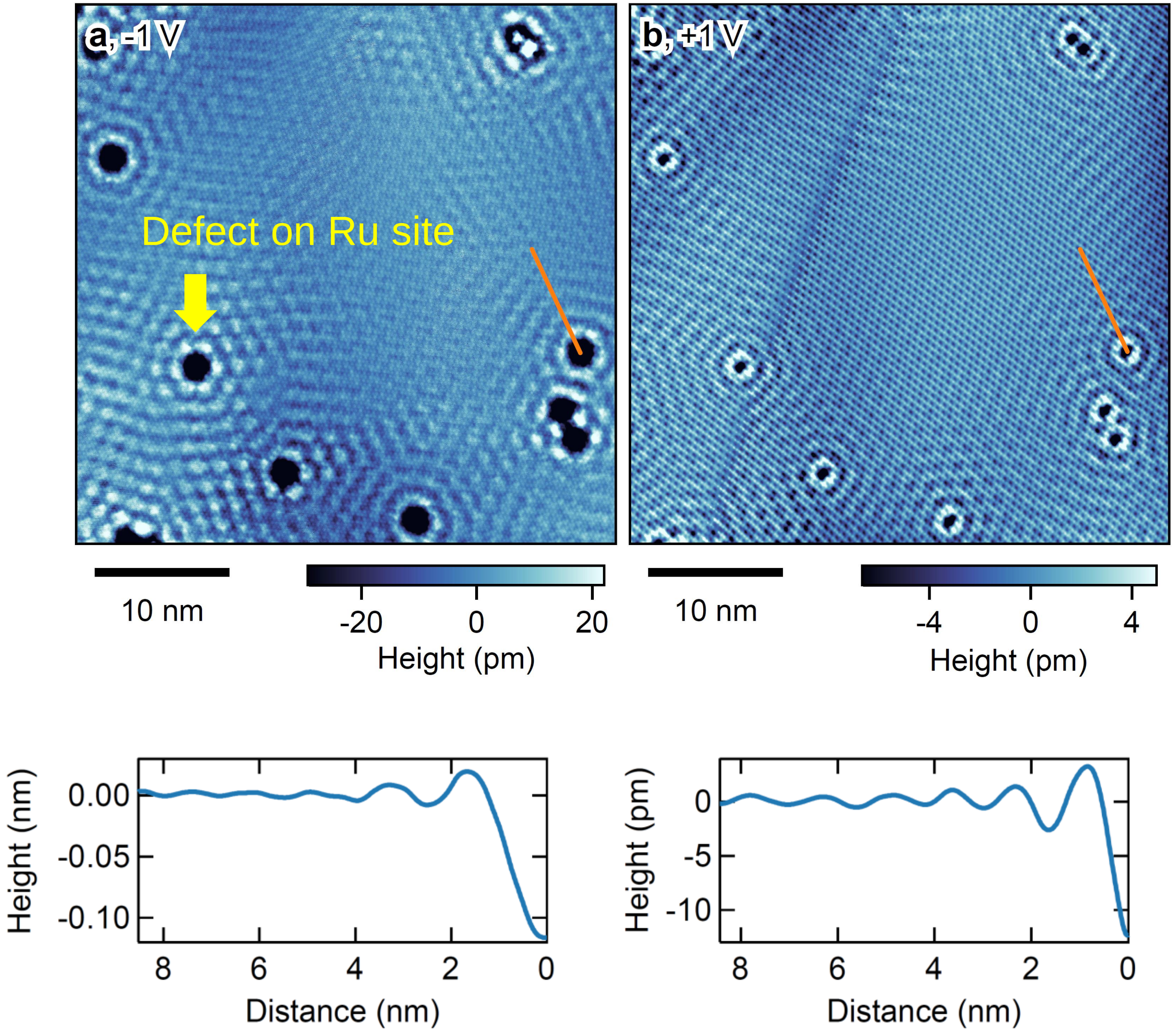




Negligibly small ***q***-dependence

Not QPI

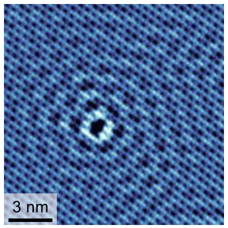
Enigmatic spatial oscillations in Kitaev QSL



Lattice distortion
Moiré
Charge density wave
Friedel oscillations
Quasiparticle Interference

are NOT the origin of the observed spatial oscillations

Interference phenomena related to Majorana excitations?



Long-wavelength oscillation around Ru defects
Incommensurate to the lattice spacing

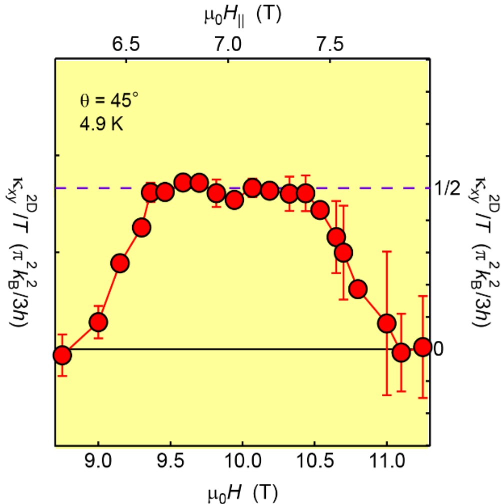
Something is oscillating

Summary

Topology and thermodynamics in α-$RuCl_3$

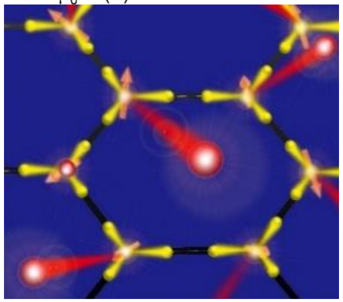
- Half-integer quantized thermal Hall effect in α-$RuCl_3$

Y. Kasahara *et al*. Phys. Rev. Lett. **120**, 217205 (2018).
Y. Kasahara *et al*. Nature **559**, 227 (2018).
Y. Kasahara *et al*. Phys. Rev. B **106**, L060410 (2022).



- Hall sign consistent with topological invariant of KQSL
- Dirac cone for ***H*** || *b* and gap Δ_M for ***H*** || *a* ($\Delta_M \propto H^3$)

T. Yokoi *et al*. Science **373**, 568 (2021).
O. Tanaka *et al*. Nature Phys. **18**, 429 (2022).



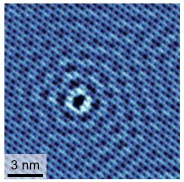
- Sign change of the planar thermal Hall effect and gap closing occur simultaneously at ***H***||*b*

K. Imamura, S. Suetsugu *et al.* arXiv:2305.10619.

Fermion, not boson

No κ_{xx} oscillations in very clean crystals

Majorana fermion is the origin of thermal Hall effect



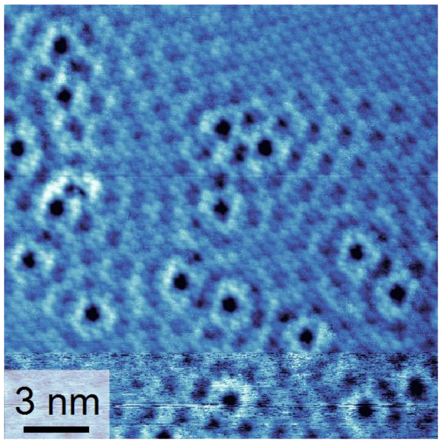
STM studies on α-$RuCl_3$ monolayer

Enigmatic spatial oscillations around defects

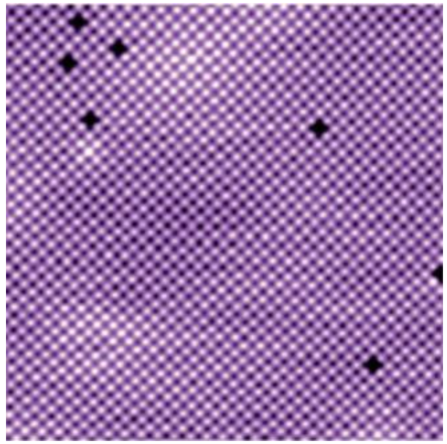
Y. Kohsaka *et al*. a preprint.

Periodic long-wavelength structure

α-$RuCl_3$

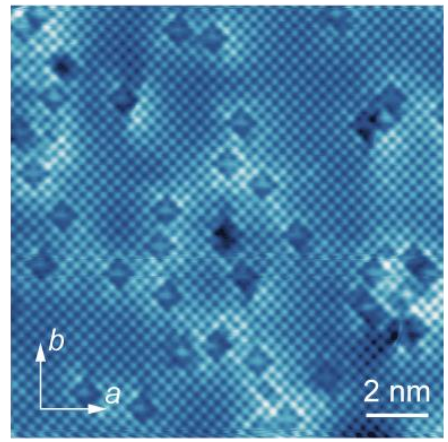


$Ca_2CuO_2Cl_2$



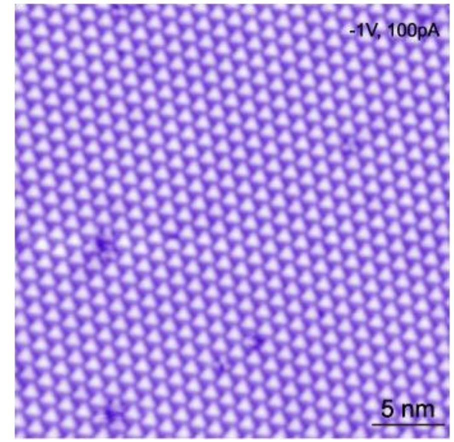
C. Ye *et al.*, *Nat. Commun.* **4**, 1365 (2013).

Sr_2IrO_4



Z. Sun *et al.*, *Phys. Rev. Res.* **3**, 023075 (2021).

1T-TaS_2



Z. Wu *et al.*, *Phys. Rev. B* **105**, 035109 (2022).

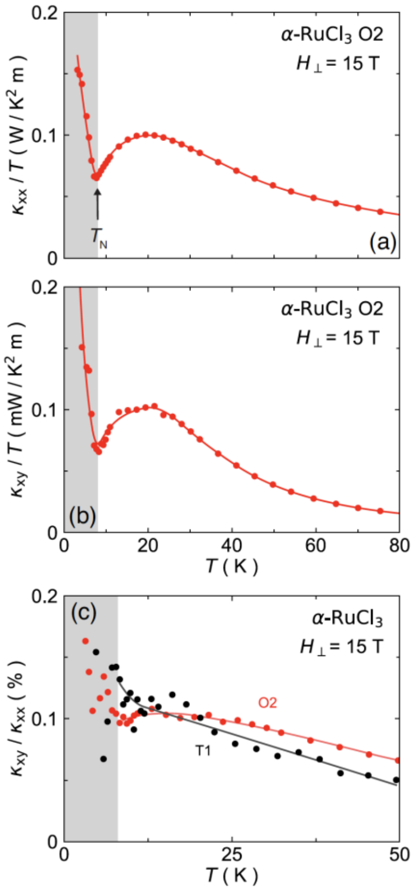
No long-wavelength oscillations have been reported in other Mott insulators

Evidence against phonon thermal Hall effect

Sherbrooke

$\boldsymbol{q} \parallel a$

$\boldsymbol{H} \parallel c$



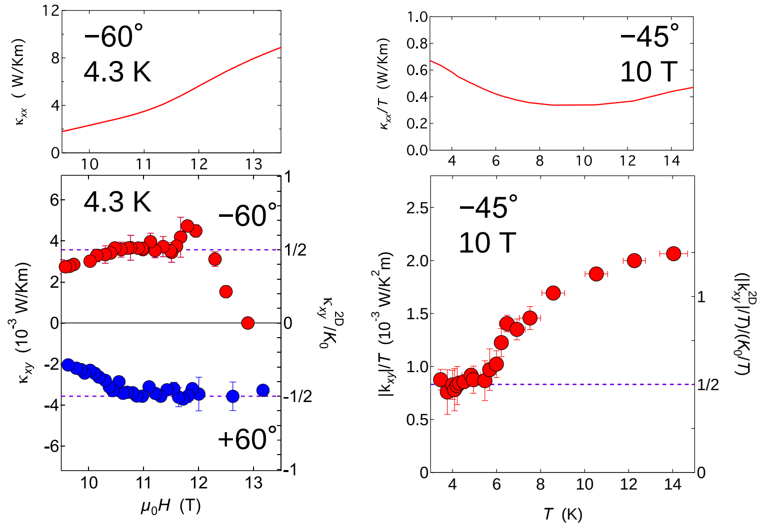
Scaling between κ_{xx} and κ_{xy}

Phonon origin of κ_{xy}?

É. Lefrançois *et al*., PRX **12**, 021025 (2022).

Kyoto

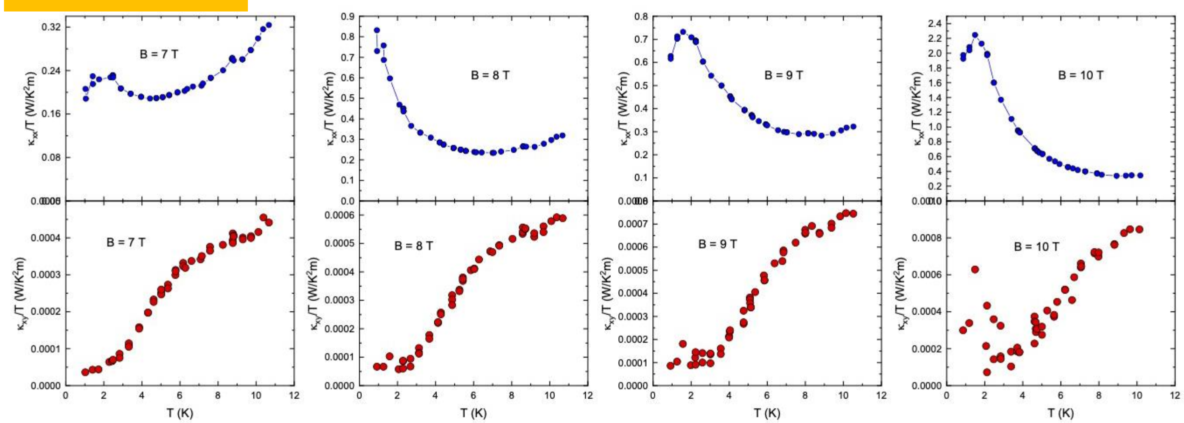
$\boldsymbol{q} \parallel a$



T. Yokoi *et al*., Science **373**, 568 (2021).

Princeton

$\boldsymbol{q} \parallel \boldsymbol{H} \parallel a$

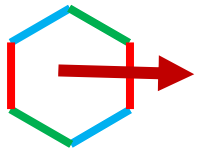


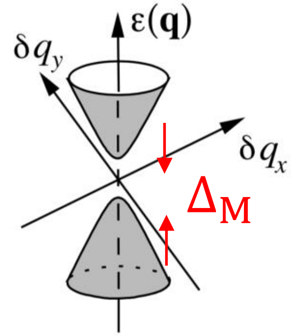
P. Czajka *et al*., Nat. Mater. **22**, 36 (2023).

κ_{xx} and κ_{xy} show essentially different T- & H-dependencies.

Majorana gap for ***H*//*a*** : specific heat in FIQD state

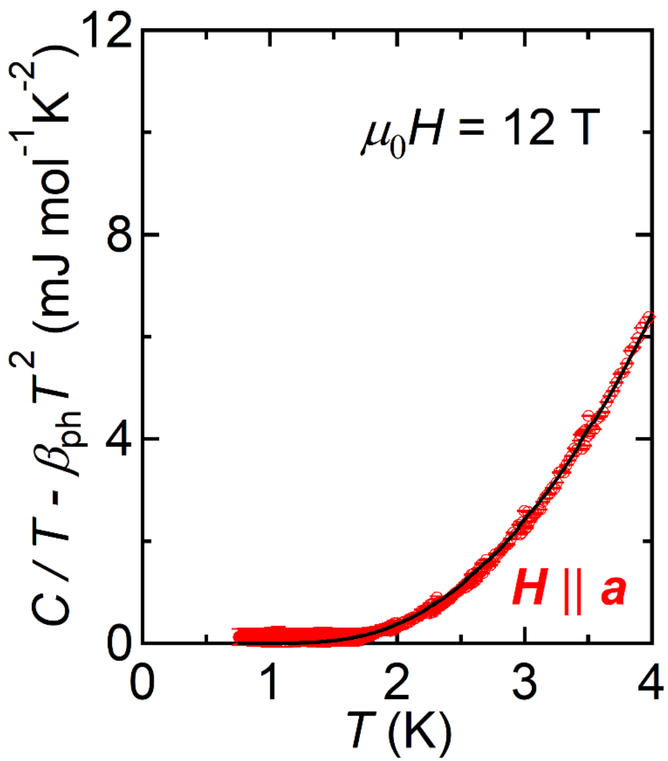
H* || *a
zigzag

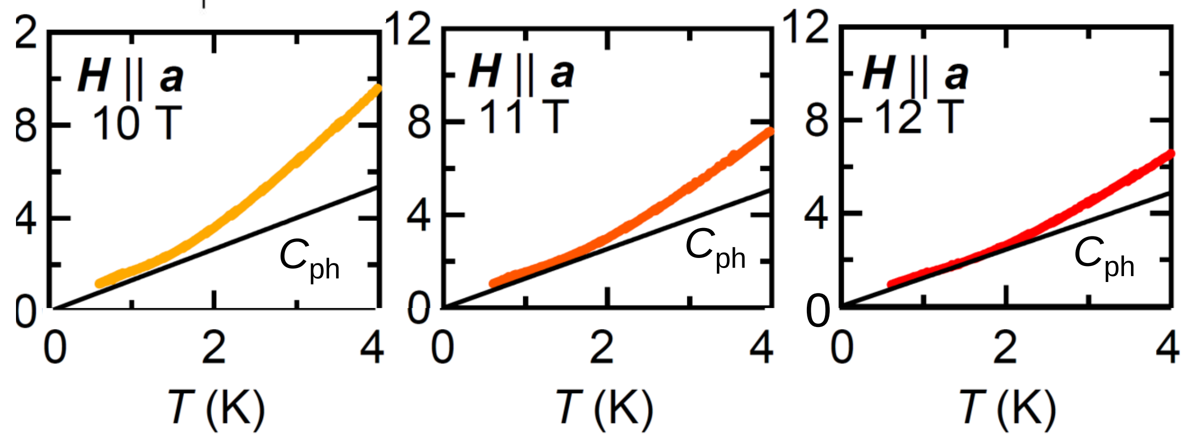


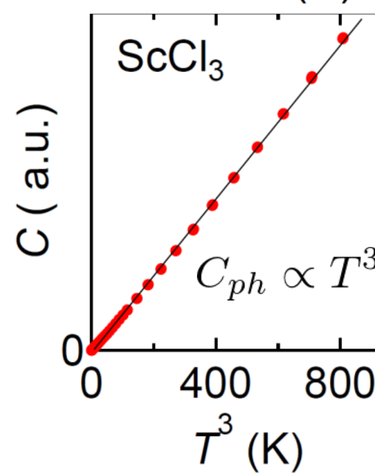


$$C_{\mathrm{mag}}/T \propto e^{-\frac{\Delta_{\mathrm{M}}}{T}}$$

Bulk gap



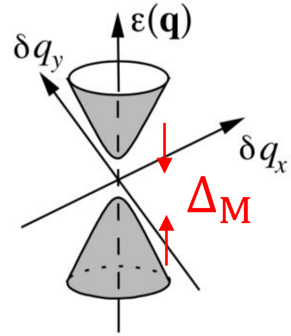




Nonmagnetic reference

O. Tanaka *et al.* Nature Phys. **18**, 429 (2022).

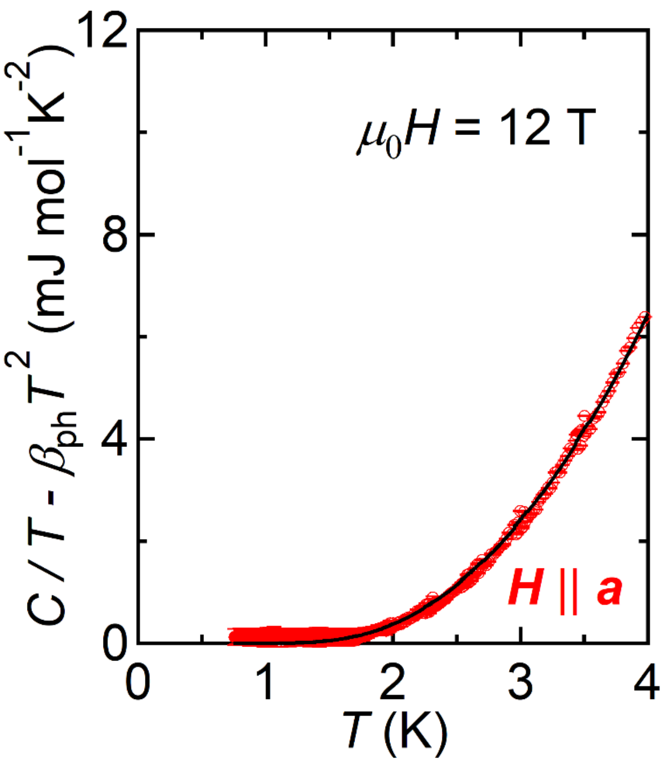
Majorana gap for *H*//*a* : specific heat in FIQD state



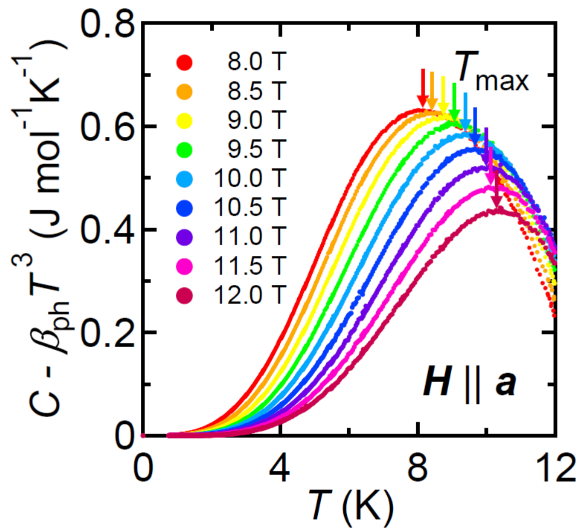
$C_{\mathrm{mag}}/T \propto e^{-\frac{\Delta_M}{T}}$

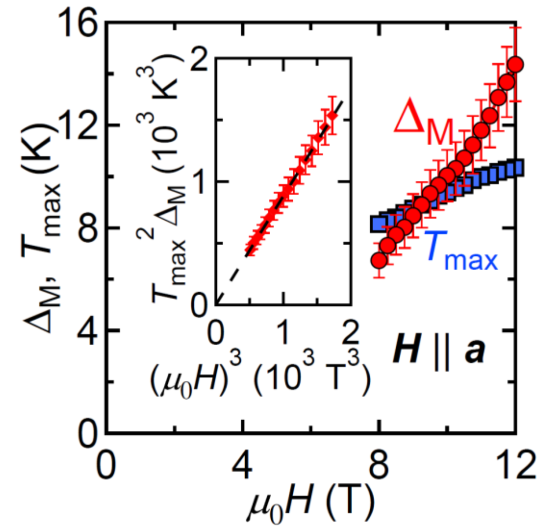
Bulk gap

Δ_M: Majorana gap



O. Tanaka *et al.* Nature Phys. **18**, 429 (2022).





$T_{\mathrm{max}} \propto \Delta_{\mathrm{flux}}$

Flux (vison) gap

$\Delta_M T_{\mathrm{max}}^2 \propto H^3$

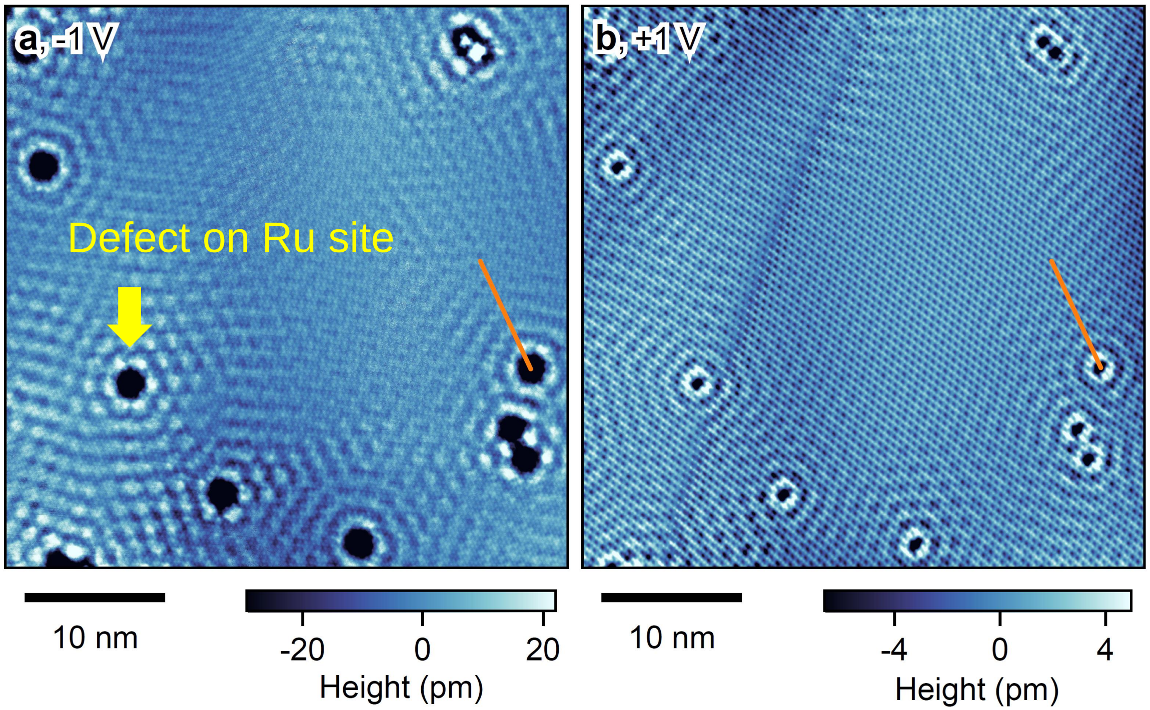
Y. Motome and J. Nasu, JPSJ (2020).

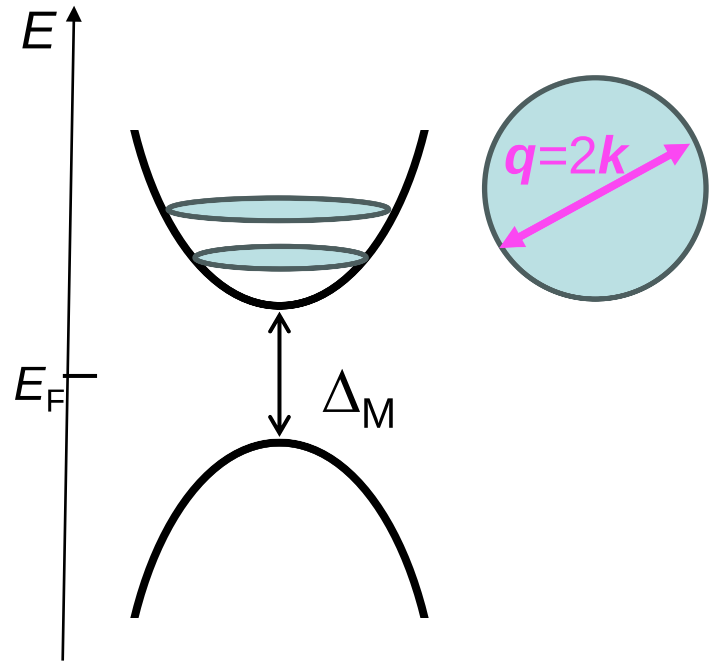
$$\Delta_M \approx \frac{|h_x h_y h_z|}{\Delta_{\mathrm{flux}}^2}$$

Majorana gap

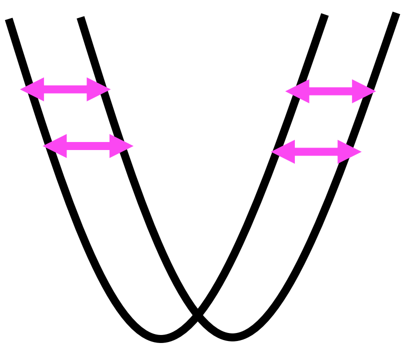
3rd order perturbation opens Majorana gap

Anomalous spatial oscillations in Kitaev QSL

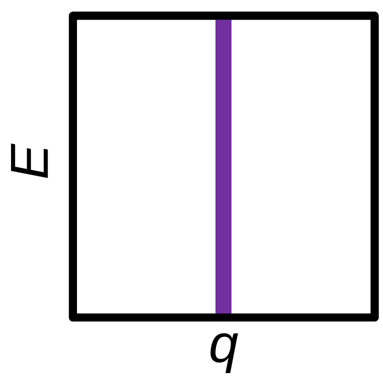




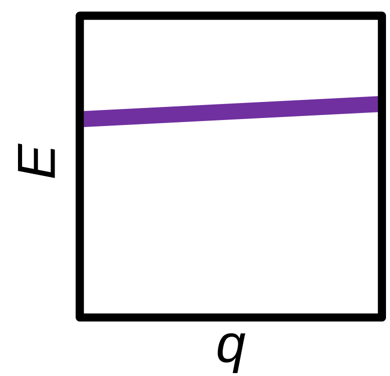
Destructive interference



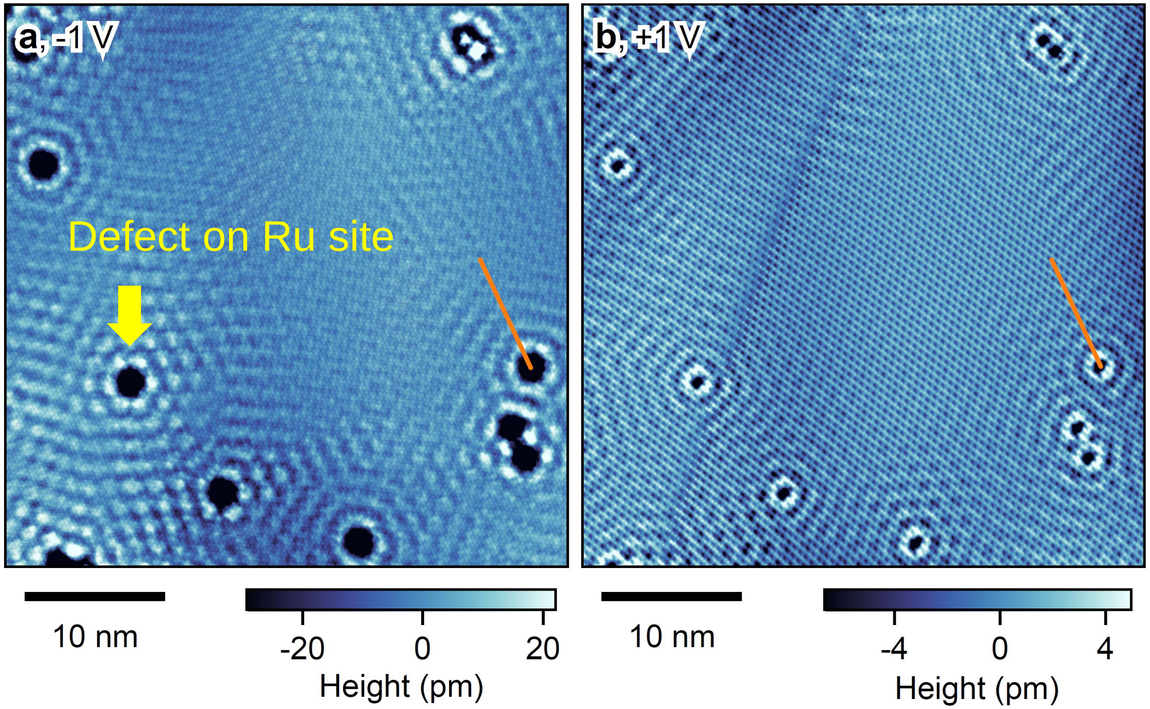
Vertical dispersion does not appear in QPI spectra

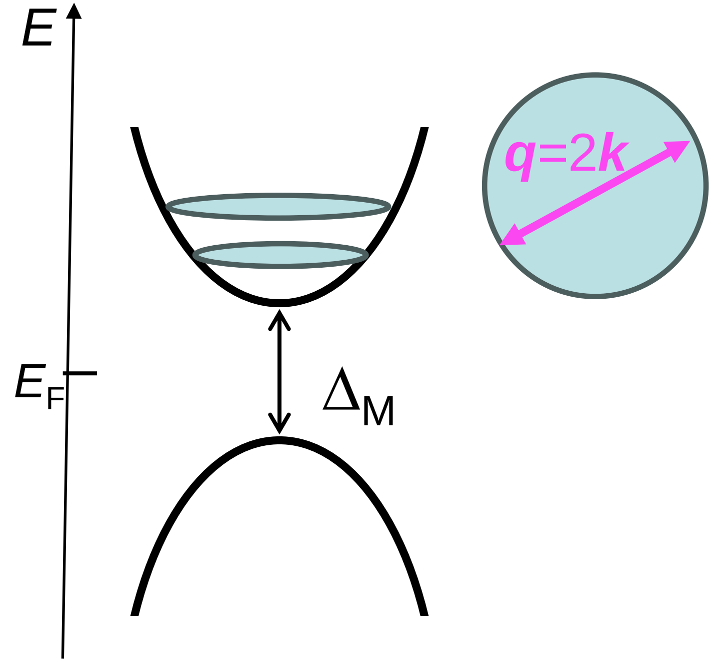


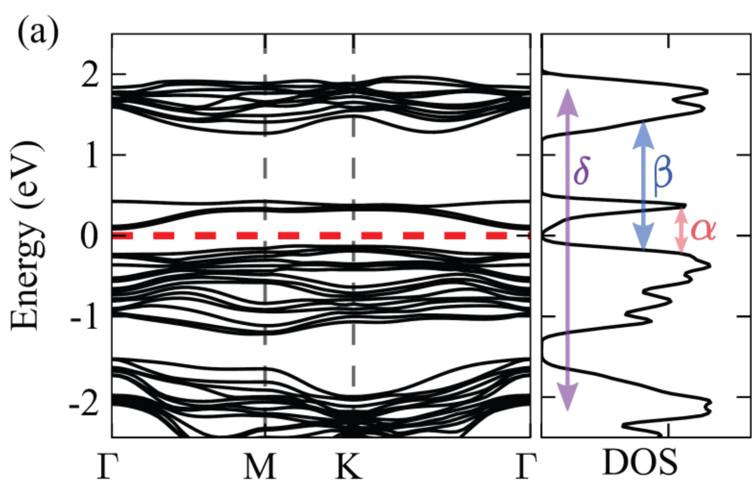
Expected QPI spectra



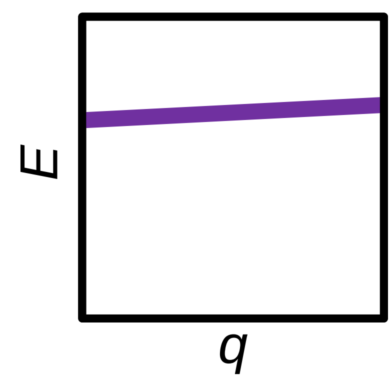
Anomalous spatial oscillations in Kitaev QSL







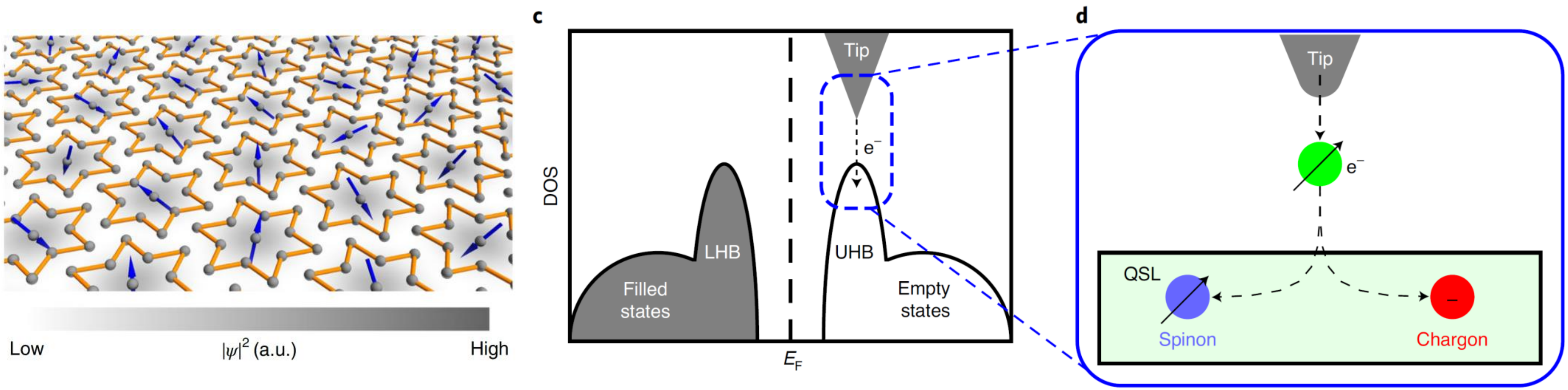
Expected QPI spectra



ARTICLES
https://doi.org/10.1038/s41567-021-01321-0
nature physics

Evidence for quantum spin liquid behaviour in single-layer 1T-$TaSe_2$ from scanning tunnelling microscopy

Wei Ruan[1,2,3,16], Yi Chen[1,2,16], Shujie Tang[4,5,6,7,8], Jinwoong Hwang[4,6,9], Hsin-Zon Tsai[1,10], Ryan L. Lee[2], Meng Wu[1,2], Hyejin Ryu[6,11], Salman Kahn[2], Franklin Liou[2], Caihong Jia[1,2,12], Andrew Aikawa[2], Choongyu Hwang[9], Feng Wang[1,2,13], Yongseong Choi[14], Steven G. Louie[1,2], Patrick A. Lee[15], Zhi-Xun Shen[4,5], Sung-Kwan Mo[6] and Michael F. Crommie[1,2,13] ✉

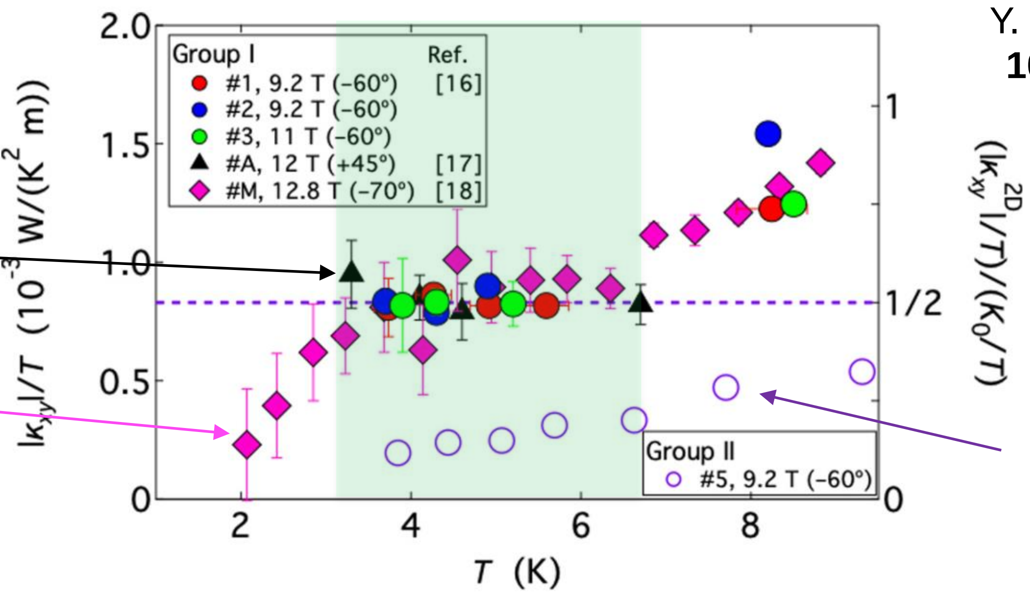


Quantized and unquantized thermal Hall effect

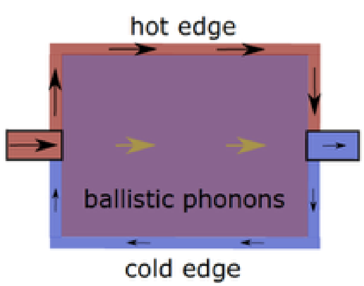
Y. Kasahara, *et al.* PRB **106**, L060410 (2022).

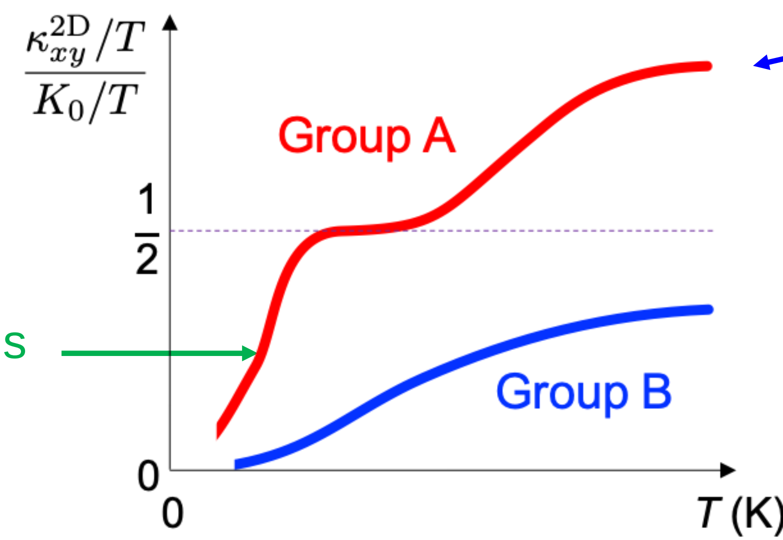
M. Yamashita *et al*. PRB **102**, 220404(R) (2020).

J.A.N. Bruin *et al.* Nature Phys. **18**, 401 (2022).



#5





Majorana+Vison

A.P. Joy and A. Rosch, arXiv:2109.00250

Different types of Majorana excitations

A. Go.J. Jung and E-G. Moon, PRL **122**, 147203 (2019).

Decoupling of phonons and edge currents

(sample size ~ ℓ_{ph})

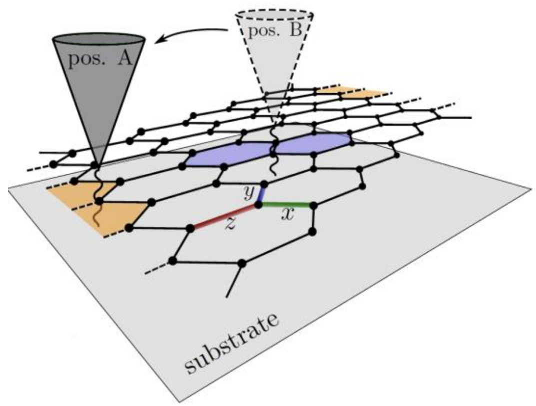
Y. Vinkler-Aviv and A. Rosch, PRX **8**, 021032 (2018).

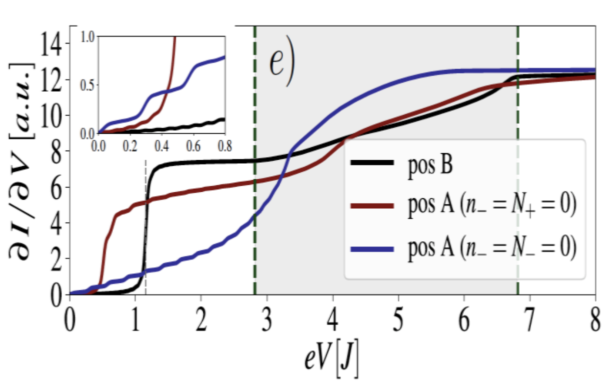
M.Ye, *et al.*, PRL **121**, 147201 (2018).

Tunneling spectroscopy of Kitaev QSL using monolayer films

Detections of

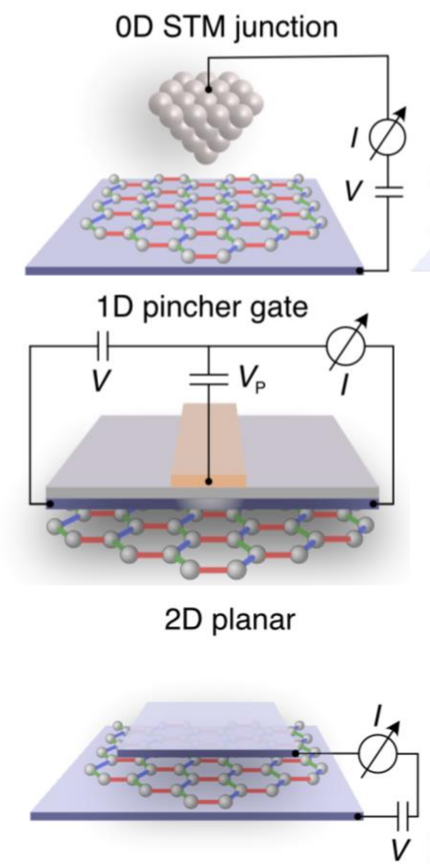
Charge-neutral edge state





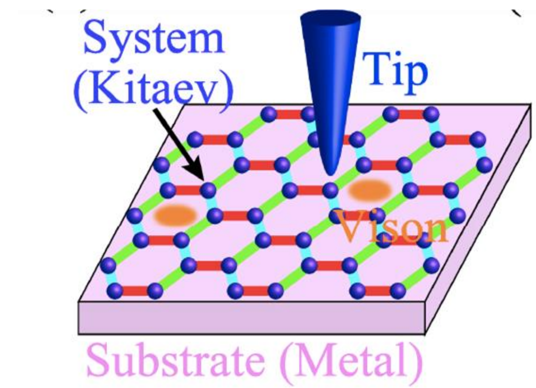
J. Feldmeier, *et al.*,
Phys. Rev. B **102**, 134426 (2020).

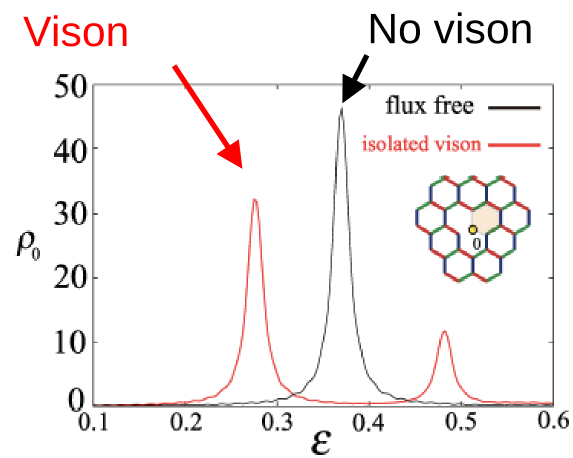
Spin gap



E. J. König *et al.*,
Phys Rev. Lett. **125**, 267206 (2020).

Non-abelian anyon

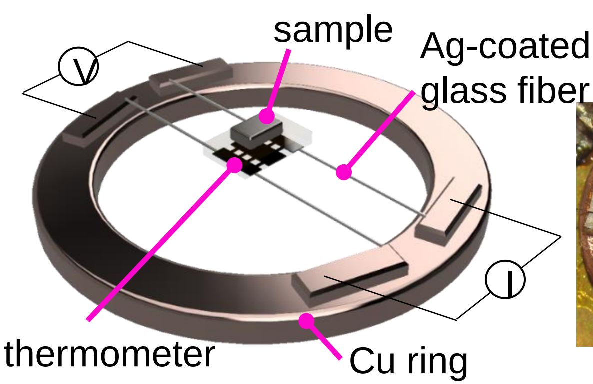


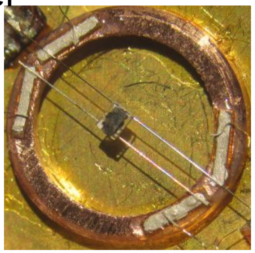


M. Udagawa, *et al.*,
Phys. Rev. Lett. **126**, 127201 (2021).

High-resolution specific heat measurements

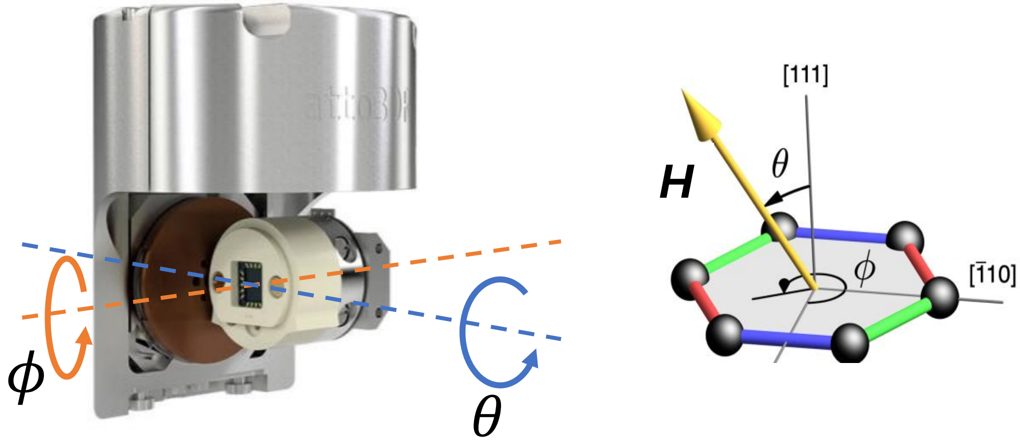
Long-relaxation calorimetry



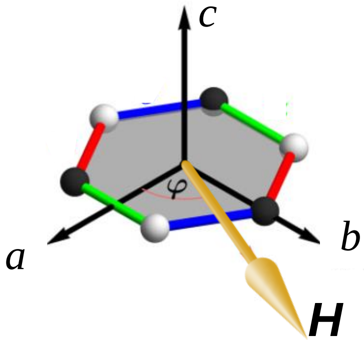


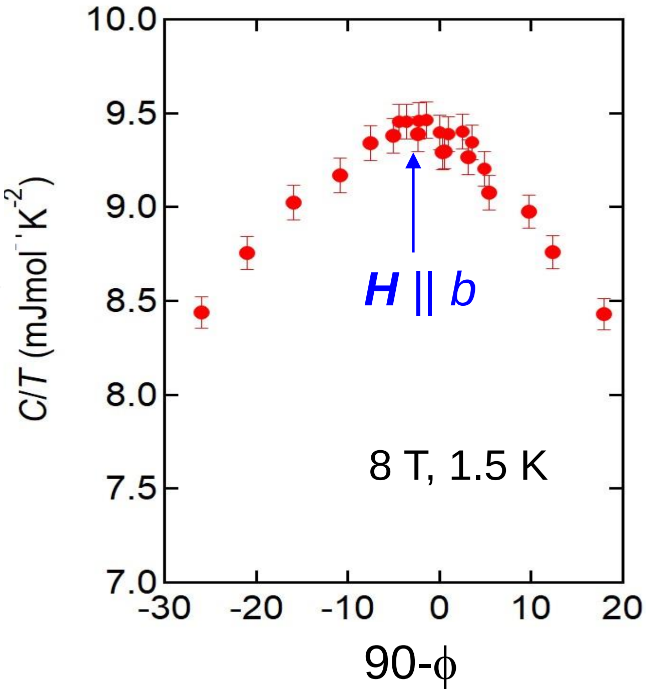
Our addenda ~ 100 pJ/K
Typical PPMS > 100000 pJ/K

Two-axis rotator



In-plane field rotation (θ=90º)





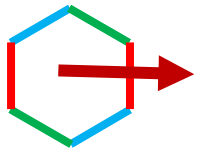
Precise determination of C for small single crystals (10- 100 μg) down to 250 mK.

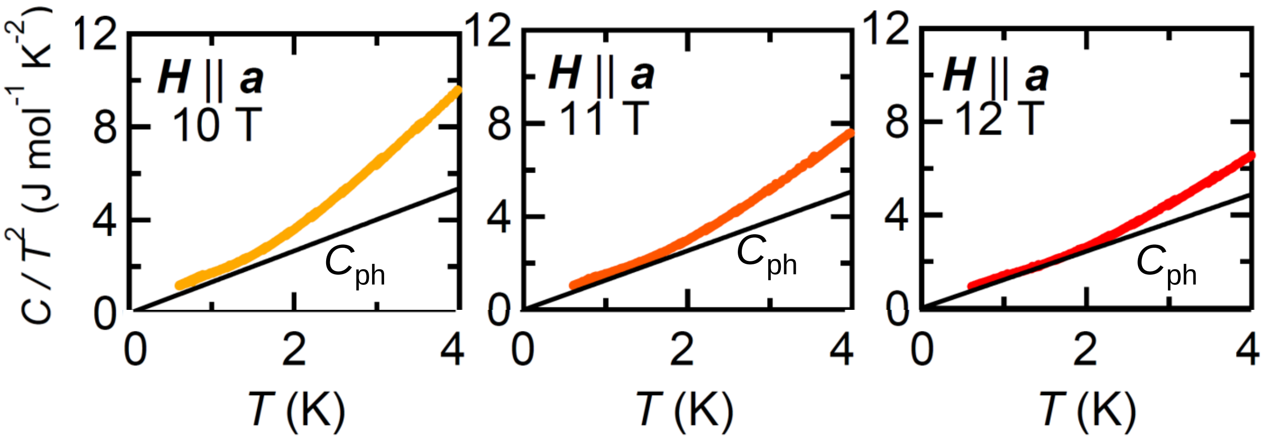
Magnetic field direction can be controlled very precisely with respect to the crystal axis.

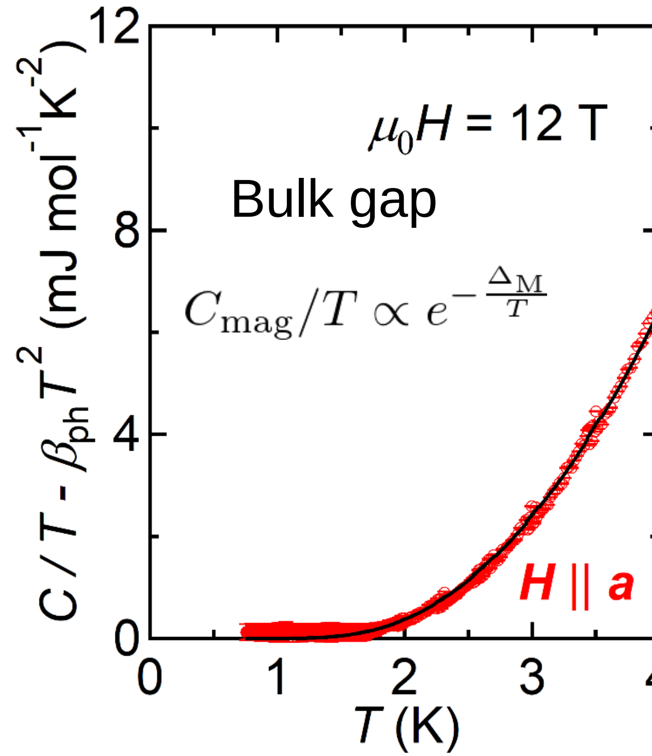
Majorana gap for *H*//*a* : specific heat in FIQD state

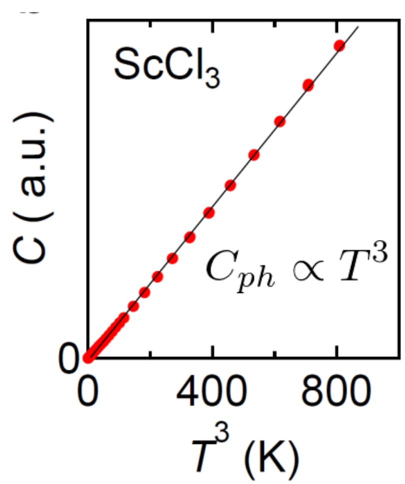
O. Tanaka *et al.* Nature Phys. **18**, 429 (2022).

H* || *a
zigzag

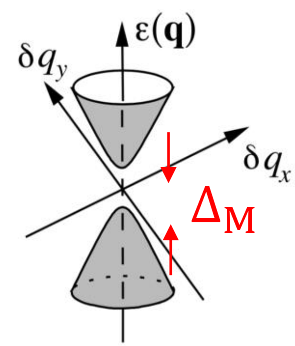








Nonmagnetic reference



$\Delta_M \sim H^3$

Consistent with Majorana gap

Reproducibility of thermal Hall effect

	sample	κ_{xy} plateau	$\kappa_{xy}^{2D} = K_0/2$	sign of κ_{xy}	Planar thermal Hall
Kyoto[1,2]	Bridgman *Tokyo Institute of Technology*	Yes	Yes	+60°+45° κ_{xy}< 0 −60°-45° κ_{xy} >0 ***H*** || ***-a*** : κ_{xy}>0	Yes
ISSP Tokyo[3]	Bridgman *Tokyo Institute of Technology*	Yes	Yes	+60°κ_{xy} < 0	
MPI Stuttgart[4]	Bridgman *Tokyo Institute of Technology*	Yes	Yes	−70°κ_{xy} >0	
Princeton[5]	CVT *Oak Ridge*	No	No		Yes
Oak Ridge[6]	CVT *Oak Ridge*	Yes	~75% of $K_0/2$	***H*** || ***-a*** : κ_{xy}>0	Yes

Inconsistent with Kitaev QSL

Consistent with Kitaev QSL

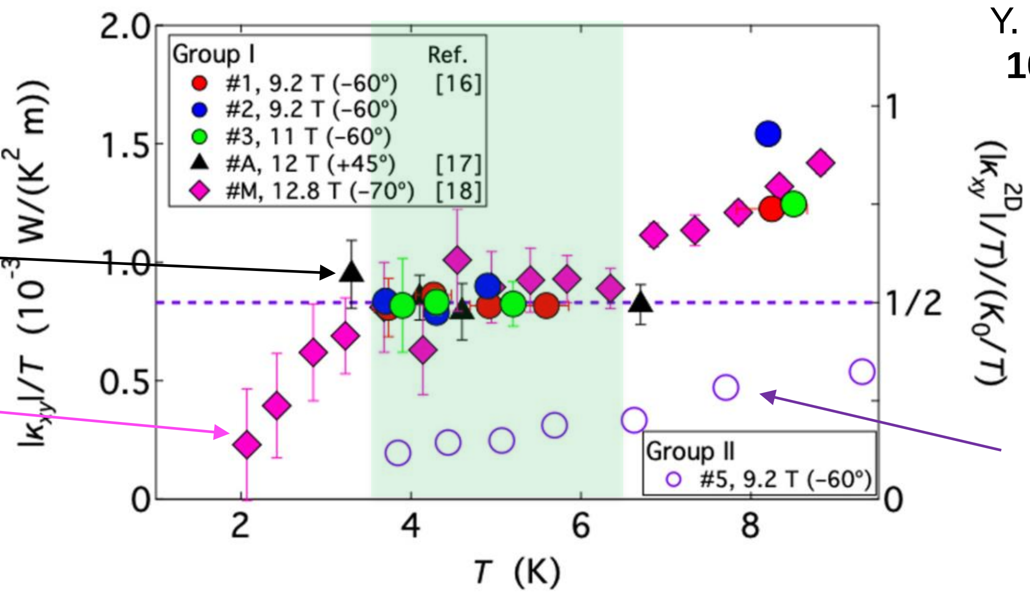
1) Y. Kasahara, YM *et al*. Nature **559**, 227 (2018).
2) T. Yokoi, YM *et al*. Science **373**, 568 (2021).
3) M. Yamashita *et al*. PRB **102**, 220404(R) (2020).
4) J.A.N. Bruin *et al.* Nature Phys. **18**, 401 (2022).
5) P. Czajka *et al*. Nature Phys. **17**, 915 (2021).
6) H. Zhang *et al*.arXiv:2303.03682.

Quantized and unquantized thermal Hall effect

Y. Kasahara, *et al.* PRB **106**, L060410 (2022).

M. Yamashita *et al*. PRB **102**, 220404(R) (2020).

J.A.N. Bruin *et al.* Nature Phys. **18**, 401 (2022).



#5

For further confirmation of Majorana fermion, we need to clarify

1. Topology

   Chern number, Dirac cone, Majorana gap etc.

2. Reproducibility

(sample size ~ ℓ_{ph})

on,

PRL **122**, 147203 (2019).

Y. Vinkler-Aviv and A. Rosch, PRX **8**, 021032 (2018).
M.Ye, *et al.*, PRL **121**, 147201 (2018).

Kitaev quantum spin liquid

Spin-1/2 on 2D honeycomb lattice with three inequivalent bonds

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

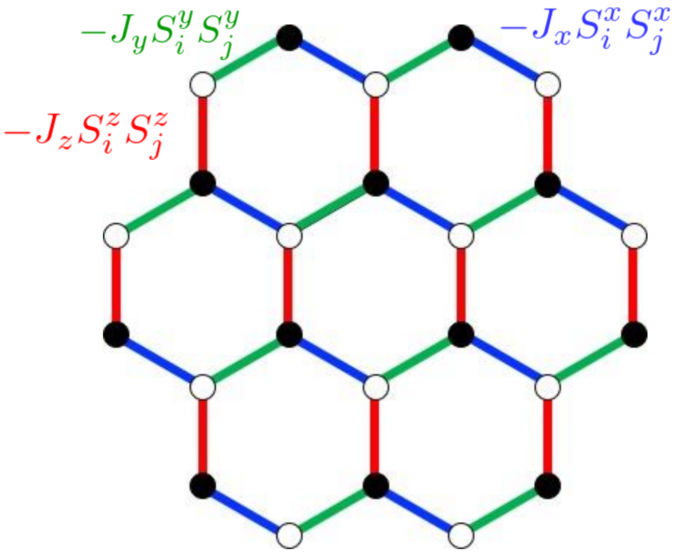
$$\mathcal{H} = -J_x \sum_{<ij>_x} S_i^x S_j^x - J_y \sum_{<ij>_y} S_i^y S_j^y - J_z \sum_{<ij>_z} S_i^z S_j^z$$

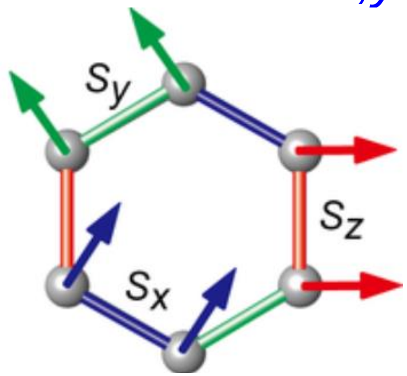
Kitaev interaction

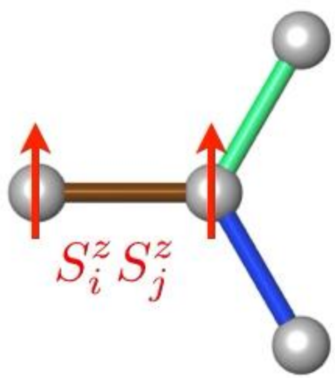
Bond-dependent Ising-like

Each bond favors different directions of *x*,*y* and *z*. → **Exchange frustration**

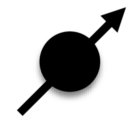
2D Honeycomb





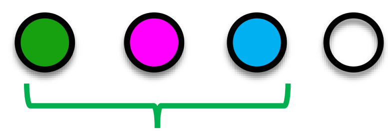


Spin-1/2

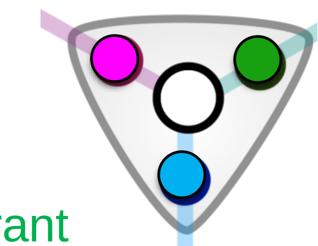


Majorana fermions

b^x b^y b^z c



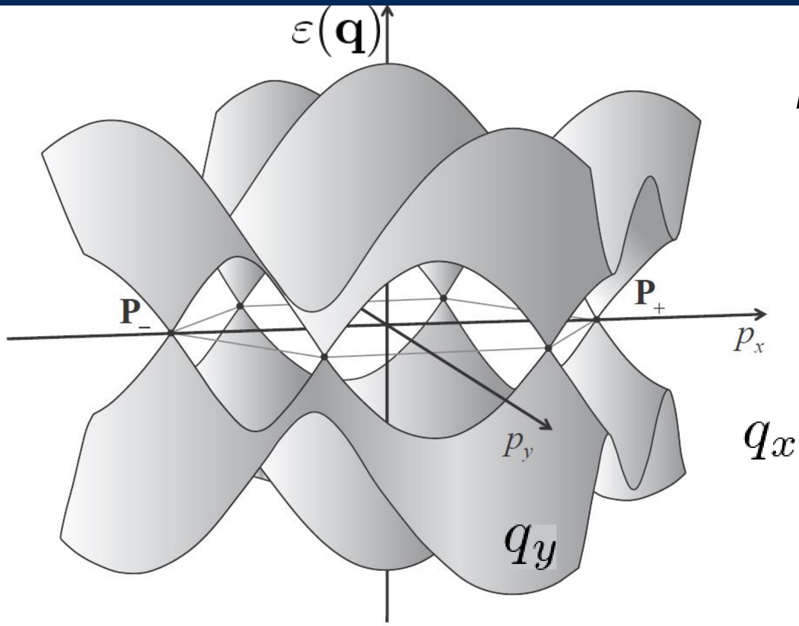
Localized Itinerant



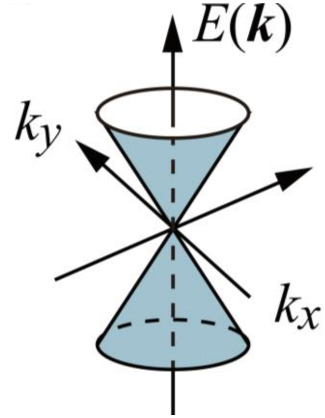
$$b^{\alpha\dagger} = b^\alpha \quad c^\dagger = c$$

Review: Y. Motome & J. Nasu, JPSJ **89**, 012002 (2020).

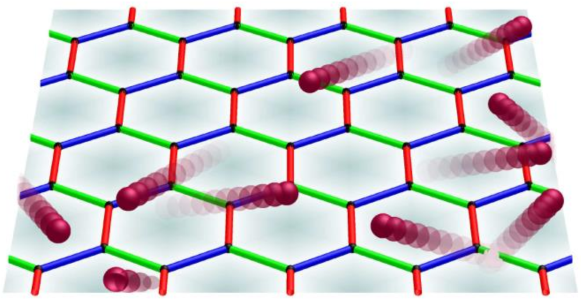
Energy dispersion of itinerant Majorana



$H = 0$

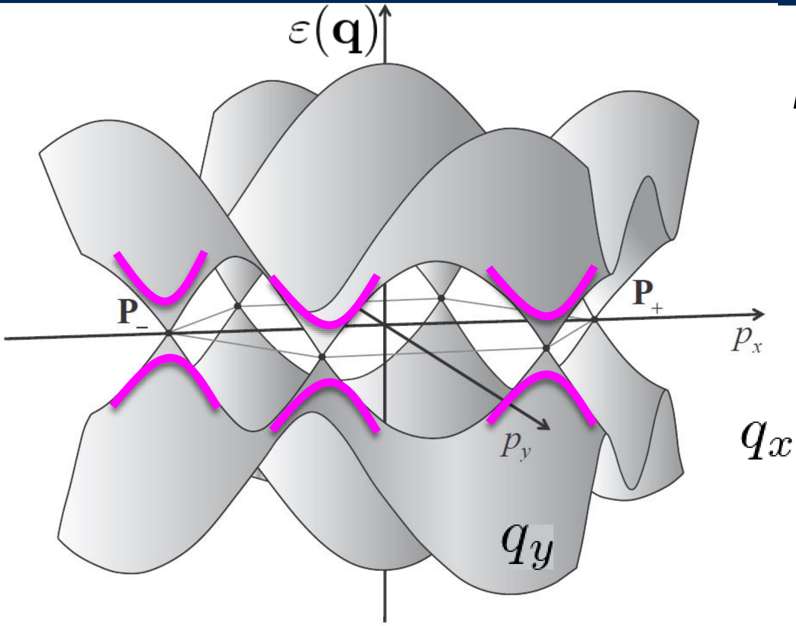


Itinerant Majorana

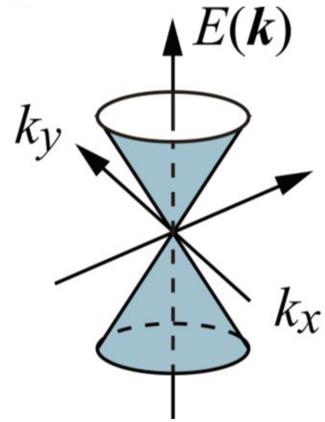


Majorana semimetal

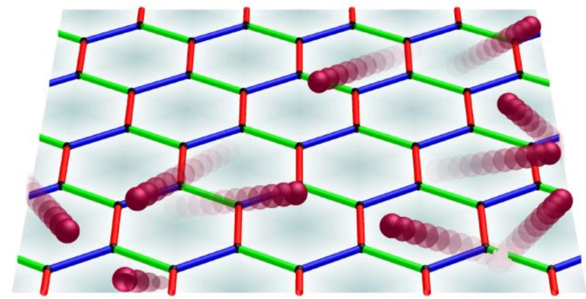
Energy dispersion of itinerant Majorana



$H = 0$

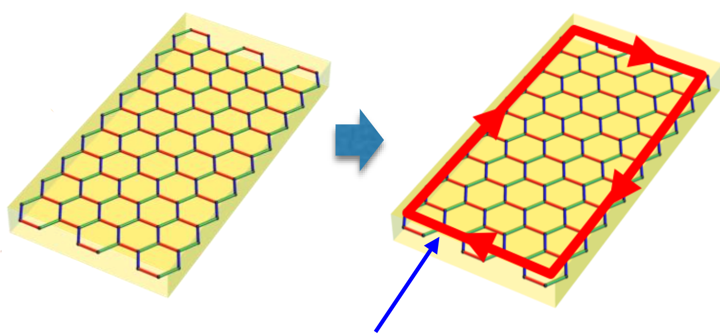


Itinerant Majorana



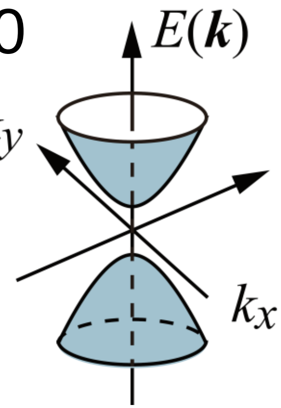
Majorana semimetal

$H = 0$ $H \neq 0$



Chiral Majorana edge current

$H \neq 0$



Majorana Chern insulator

Chern number $C_h = \frac{\Delta}{|\Delta|} = \pm 1$

$$\kappa_{xy}^{2D} = \frac{1}{2} K_0 \qquad K_0 = \frac{\pi^2 k_B^2}{3h} T$$

Quantum Thermal Conductance

Half integer thermal QHE

One Majorana = "*half*" of a fermion $\ominus = \frac{1}{2}(\bullet + \circ)$