Planar thermal Hall effect from phonons in quantum materials

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Outline

- Introduction
- Planar thermal Hall effect in a Kitaev magnet $Na_2Co_2TeO_6$
- Planar thermal Hall effect in other quantum materials

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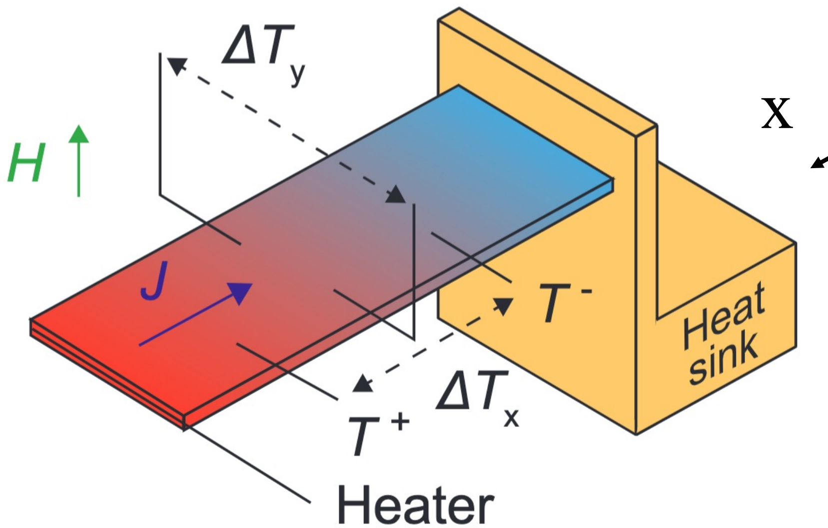
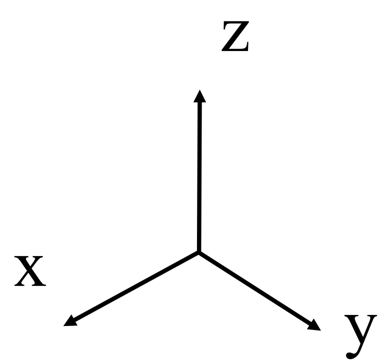
Conventional Thermal Hall Conductivity κ_{xy}

J // a



Thermal transport measurement



$$\kappa_{xx} = \frac{\dot{Q}}{\Delta T_x}\frac{l}{wt}$$

$$\kappa_{xy} = -\kappa_{yy}\frac{\Delta T_y}{\Delta T_x}\frac{l}{w}$$

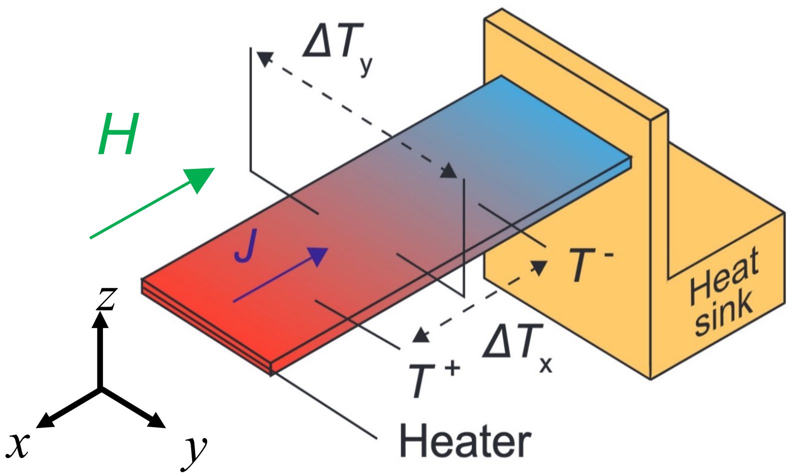
$$\begin{array}{l} \sim mK \longrightarrow \\ \sim K \longrightarrow \end{array} \frac{\Delta T_y}{\Delta T_x} \sim 10^{-3}$$

Source: Electrons, Magnons, Phonons, Majorana fermions

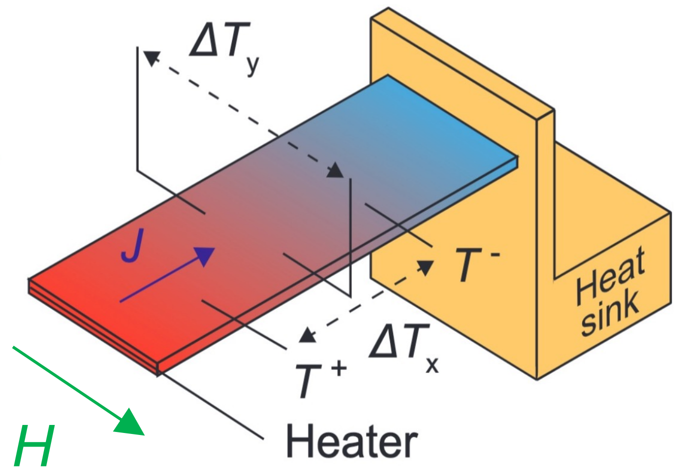
L. Chen*, ME. Boulanger* et al., PNAS 119 (34) e2208016119 (2022)

Planar Thermal Hall Conductivity κ_{xy}

H and *J* in plane



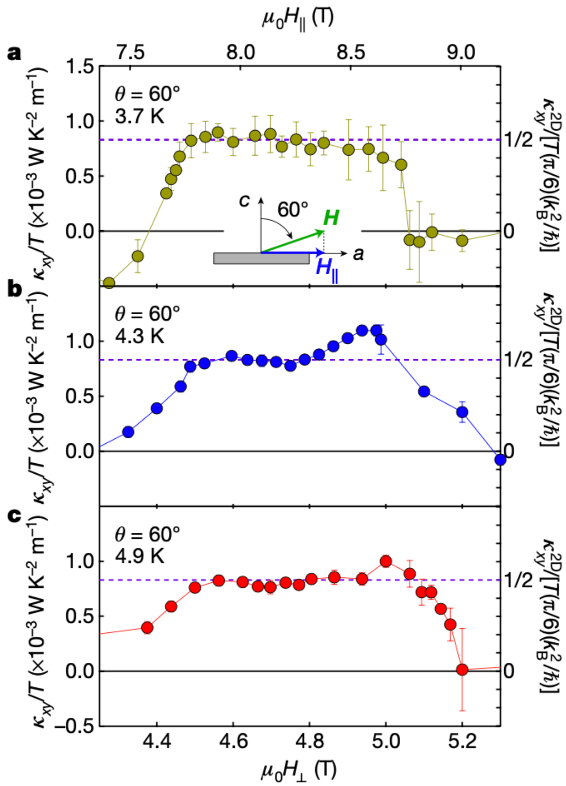
H // J, planar-parallel



$H \perp J$, planar-perpendicular

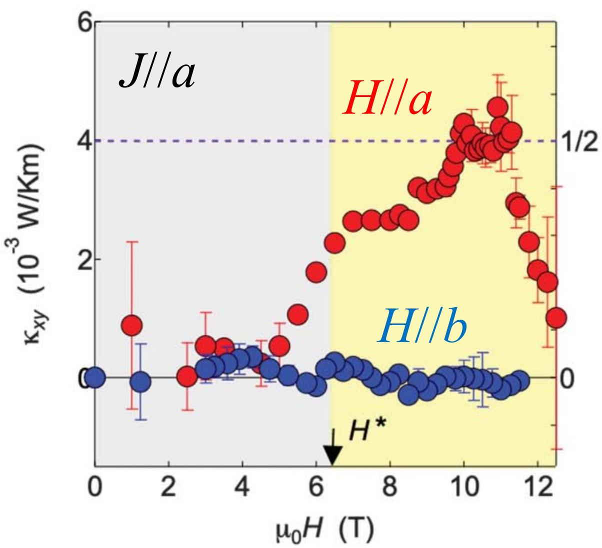
$$\kappa_{xx} = \frac{\dot{Q}}{\Delta T_x}\frac{l}{wt} \qquad \kappa_{xy} = -\kappa_{yy}\frac{\Delta T_y}{\Delta T_x}\frac{l}{w} \qquad \frac{\Delta T_y}{\Delta T_x} \sim 10^{-3}$$

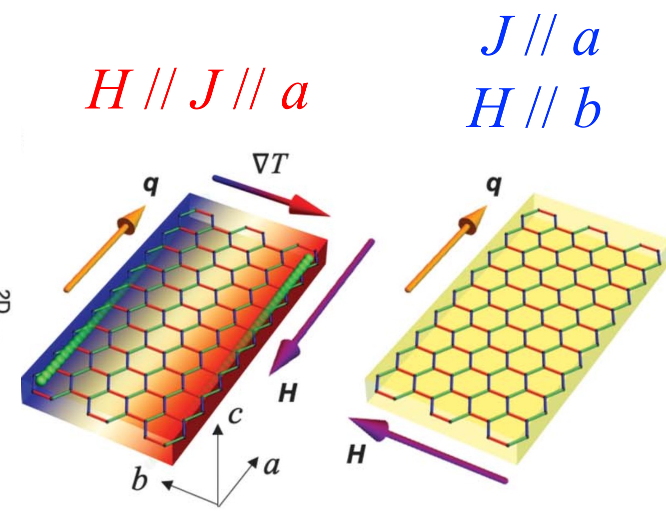
Planar Thermal Hall Conductivity κ_{xy} in α-$RuCl_3$



Half quantized κ_{xy}

Y. Kasahara *et. al.,* Nature 559, 227–231 (2018)

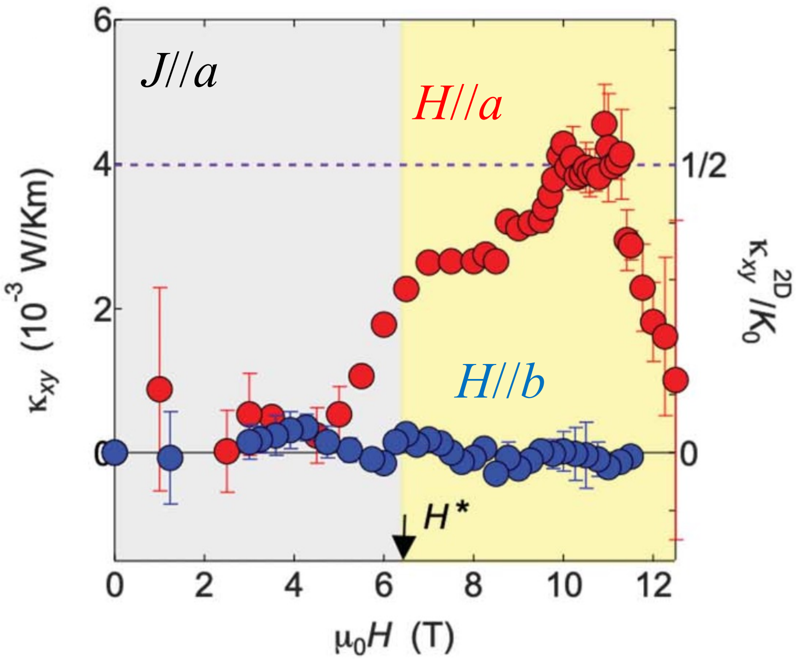




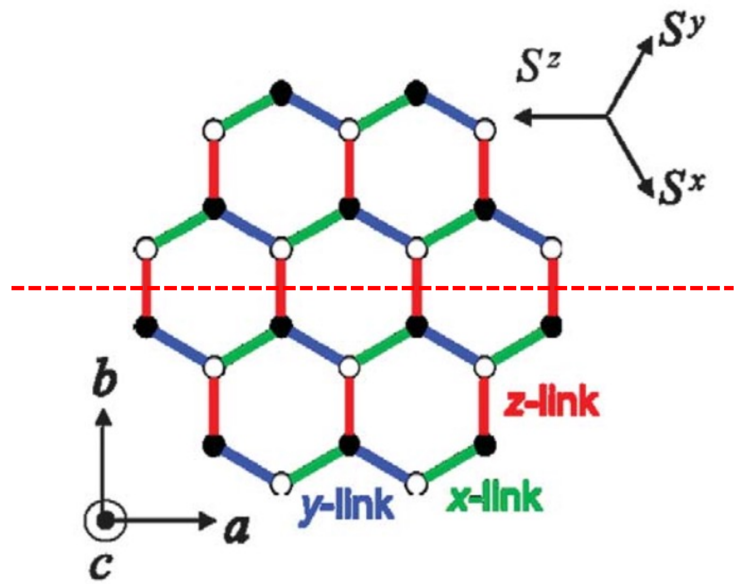
Half quantized planar κ_{xy} is attributed to Majorana fermions

Yokoi *et al*., Science 373, 568-572 (2021)

Planar Thermal Hall Conductivity κ_{xy} in α-$RuCl_3$



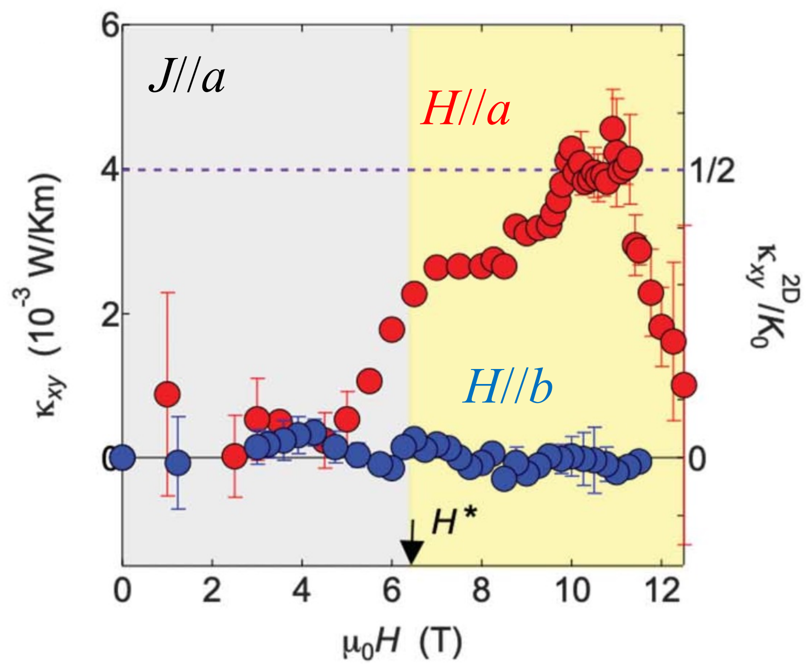
symmetry analysis: C_2/m



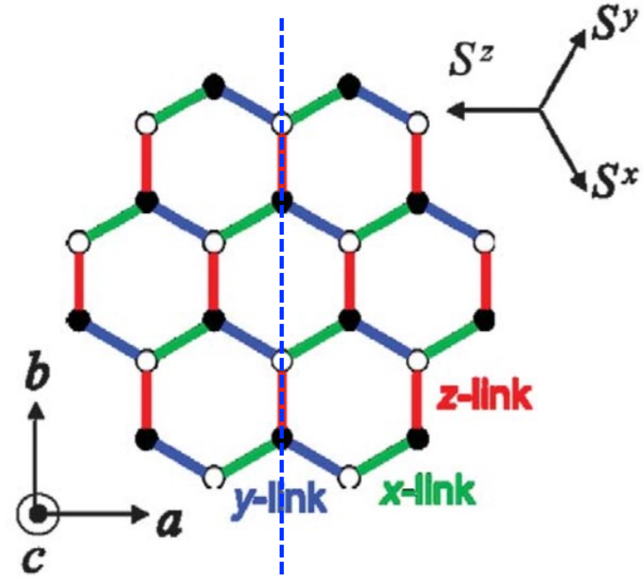
$H//a \rightarrow C_2$ symmetry is broken $\rightarrow \kappa_{xy} \neq 0$

Yokoi *et al.*, Science 373, 568-572 (2021)

Planar Thermal Hall Conductivity κ_{xy} in α-$RuCl_3$



symmetry analysis: C_2/m



$H//a \rightarrow C_2$ symmetry is broken $\rightarrow \kappa_{xy} \neq 0$

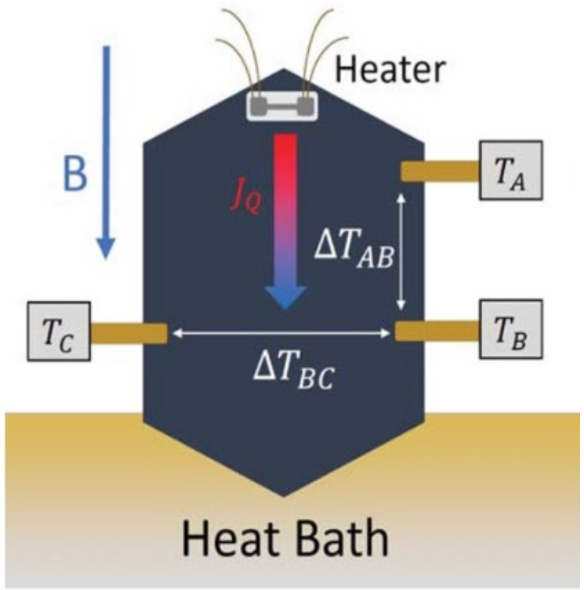
$H//b \rightarrow C_2$ symmetry is preserved $\rightarrow \kappa_{xy} = 0$

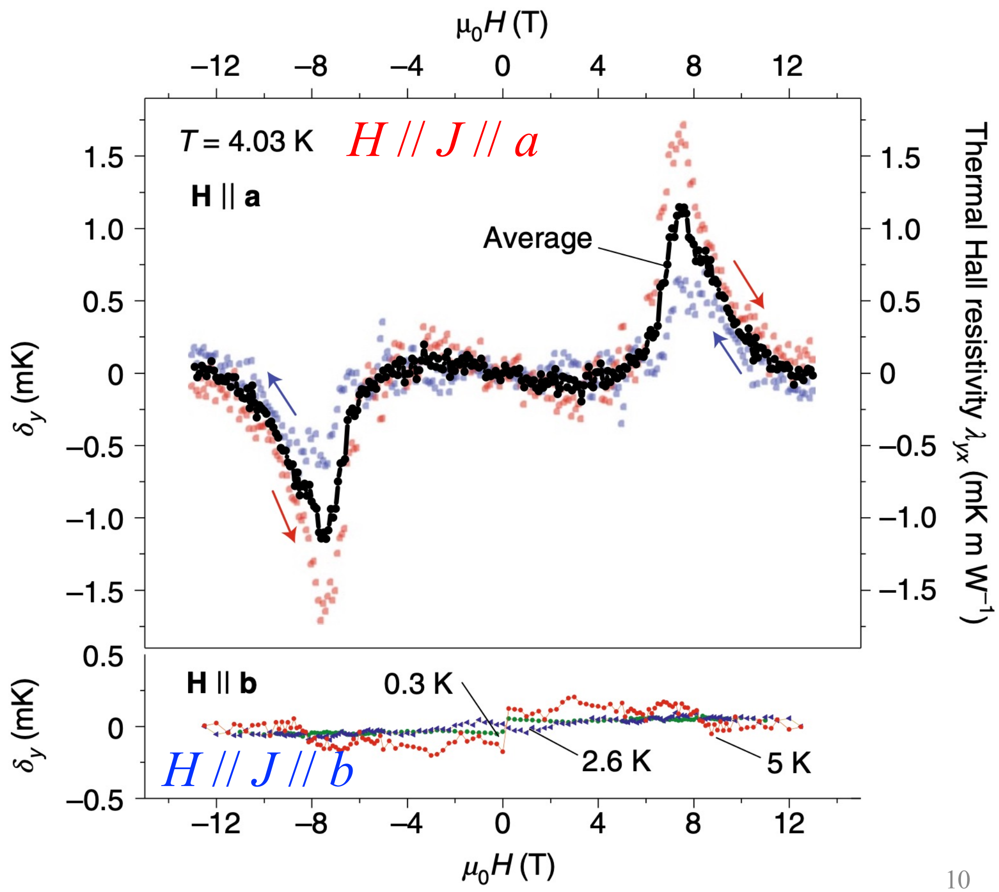
Yokoi *et al.*, Science 373, 568-572 (2021)

Planar Thermal Hall Conductivity κ_{xy} in α-$RuCl_3$

$H \,//\, J \,//\, a$

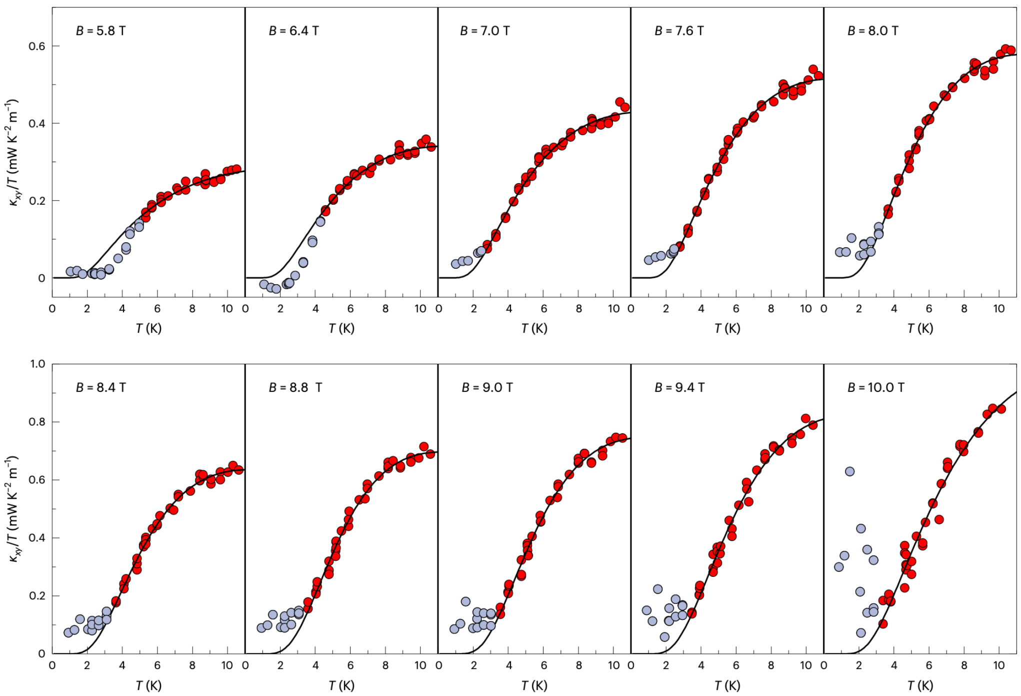
$H \,//\, J \,//\, b$



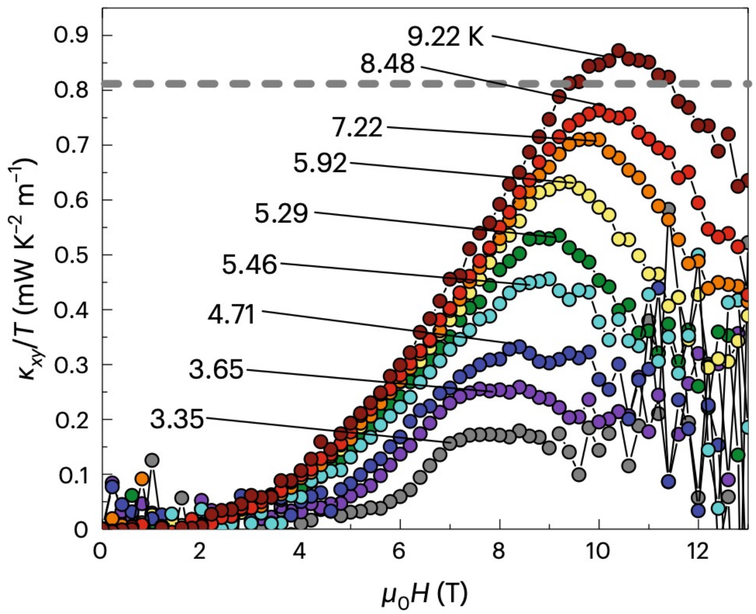


Czajka *et al*., Nat. Phys. 17, 915-919 (2021)

Planar Thermal Hall Conductivity κ_{xy} in α-RuCl$_3$



H // J // a



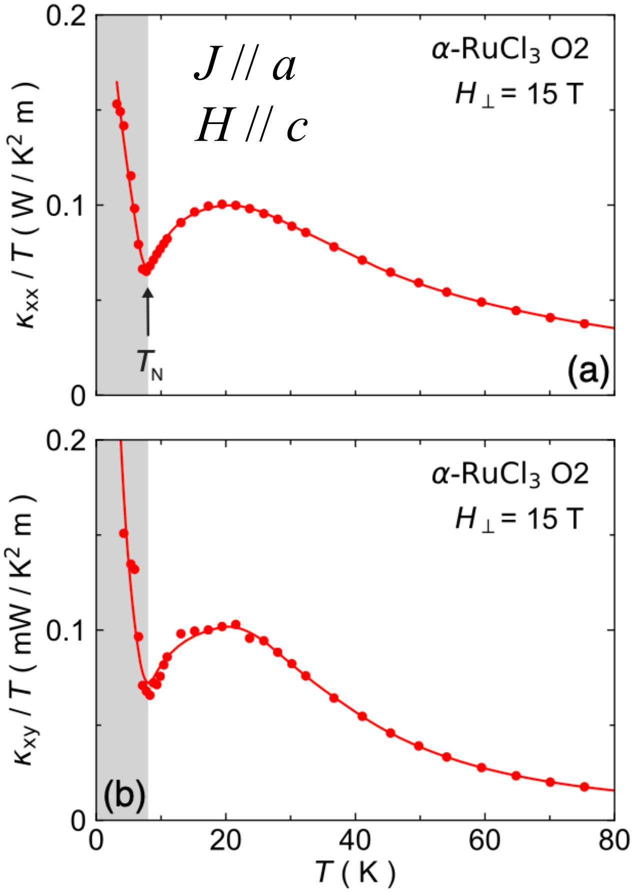
- No half quantization is observed
- *T* dependent κ_{xy} is attributed to topological magnons

Czajka *et al*., Nat. Mater. 22, 36-41 (2023)

Planar Thermal Hall Conductivity κ_{xy} in α-$RuCl_3$

- *Theoretically*, planar κ_{xy} can be generated by Majorana fermions and topological magnons.
- *Experimentally*, conflicting data and interpretations
- Can phonons also generate a planar κ_{xy}?

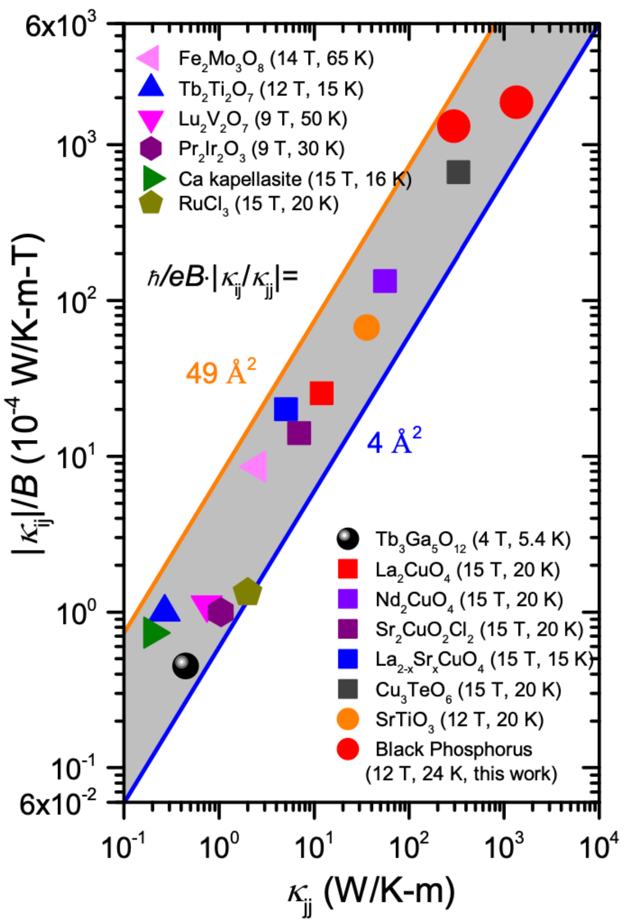
Phononic thermal Hall Conductivity κ_{xy} in α-RuCl$_3$



- Conventional κ_{xy} is measured with J // a & H // c
- κ_{xy} follows the same temperature dependence of κ_{xx}
- Phonon dominated κ_{xy}
- Ratio $\left|\frac{\kappa_{xy}}{\kappa_{xx}}\right| \sim 10^{-3}$ is a typical value for phonon THE in insulators. This explains why the magnitude of κ_{xy} seen in some studies / samples is larger given that κ_{xx} is larger.

É. Lefrançois et al., Phys. Rev. X 12, 021025 (2022)

Phononic thermal Hall Conductivity κ_{xy} in α-$RuCl_3$



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X. Li et al., Nat. Commun. 14, 1027 (2023)

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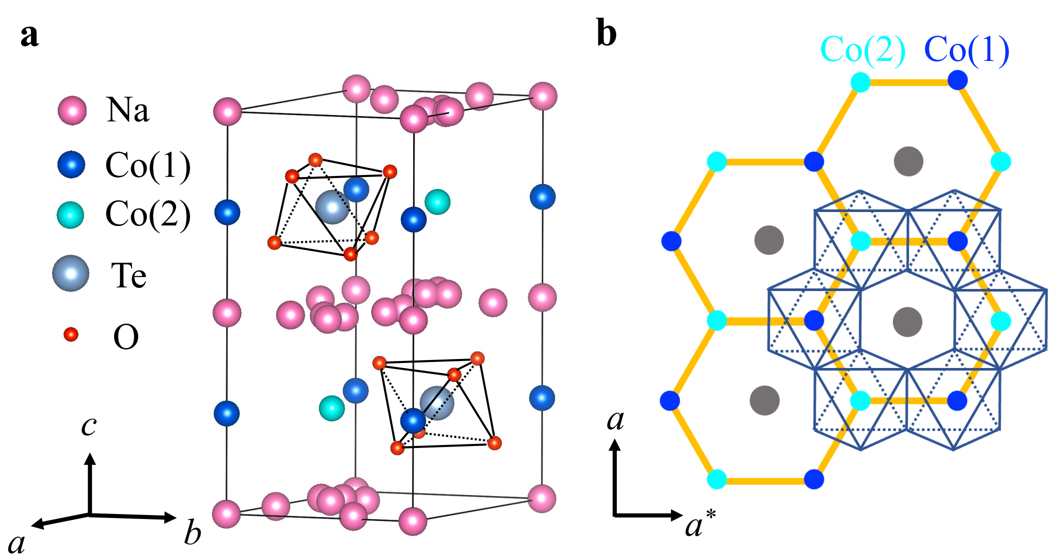
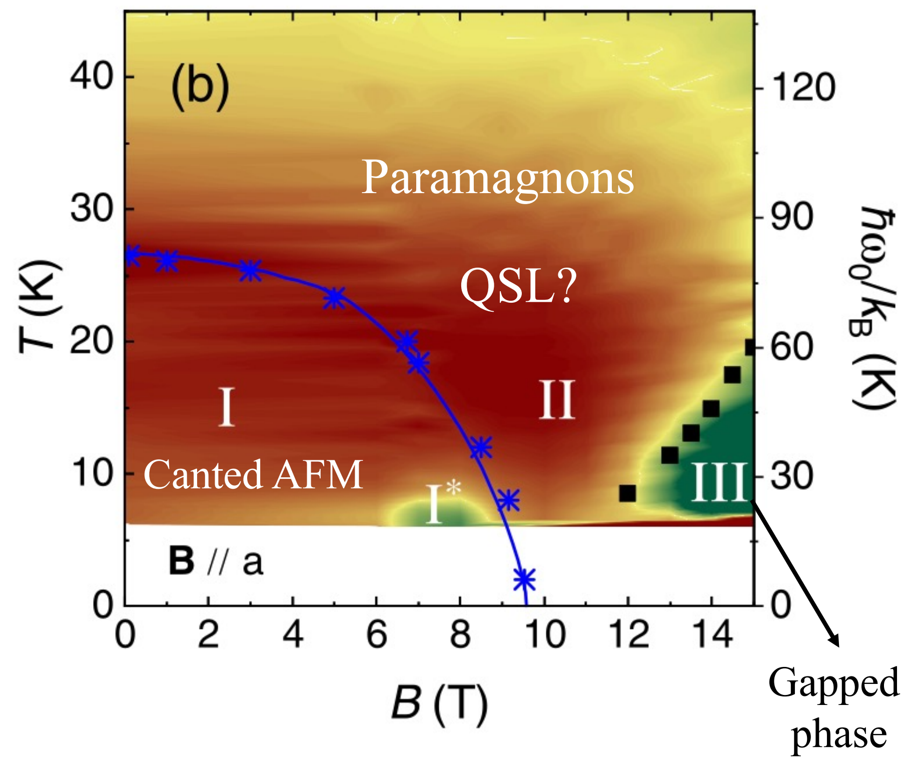
- Planar thermal Hall effect in other quantum materials

Facts about $Na_2Co_2TeO_6$

Hong *et al.*, Phys. Rev. B 104, 144426 (2021)

- Honeycomb lattice, $P6_322$
- Insulator, AFM ordering below $T_N \sim 27$ K
- Phase diagram with in-plane magnetic field





Crystal structure of $Na_2Co_2TeO_6$

Facts about $Na_2Co_2TeO_6$

Hong *et al.*, Phys. Rev. B 104, 144426 (2021)

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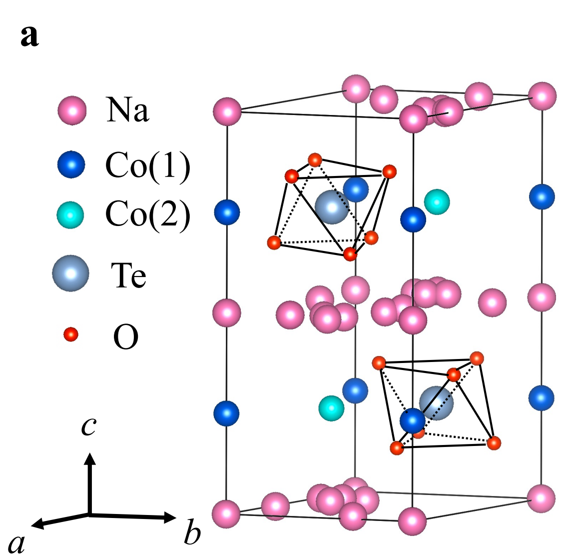
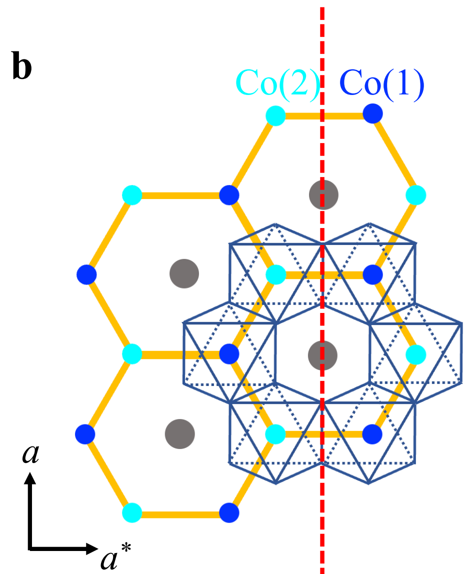
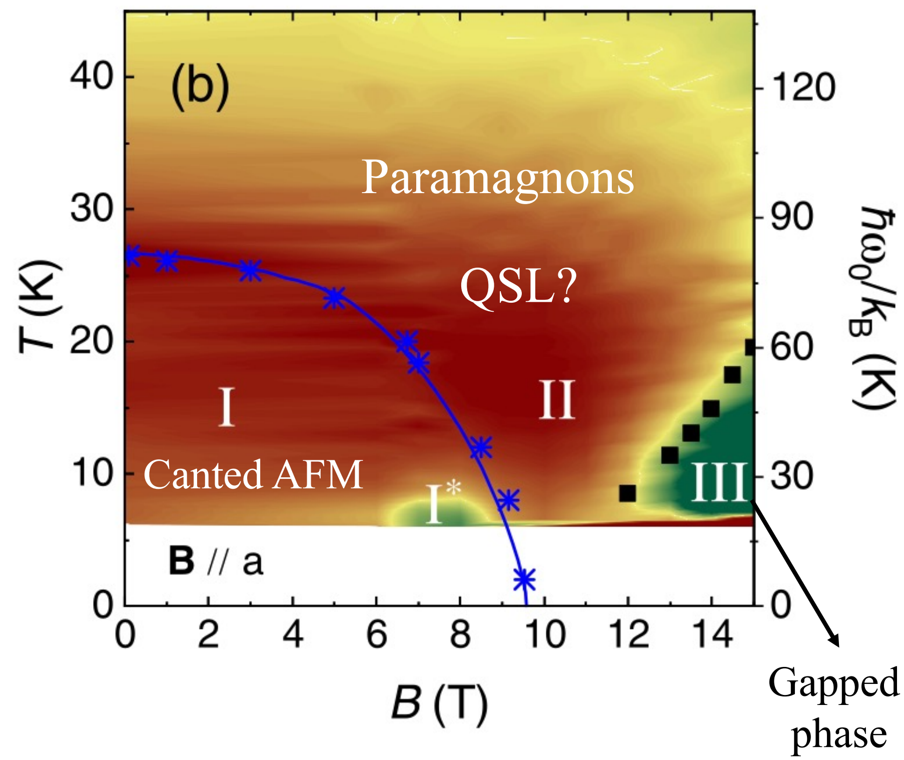


Crystal structure of $Na_2Co_2TeO_6$



$H//a \rightarrow C_2$ symmetry is preserved

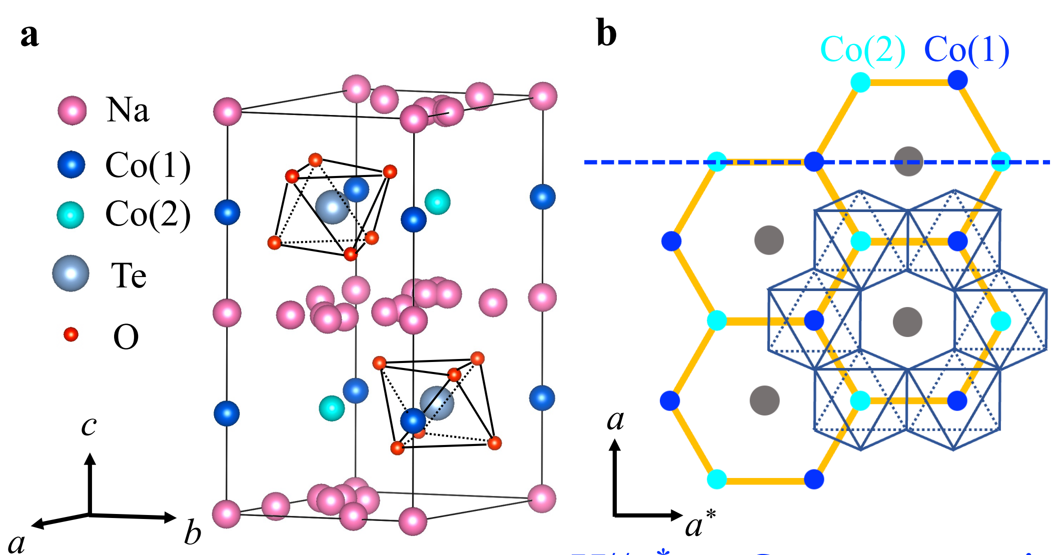
$\rightarrow \kappa_{xy} = 0$



Facts about $Na_2Co_2TeO_6$

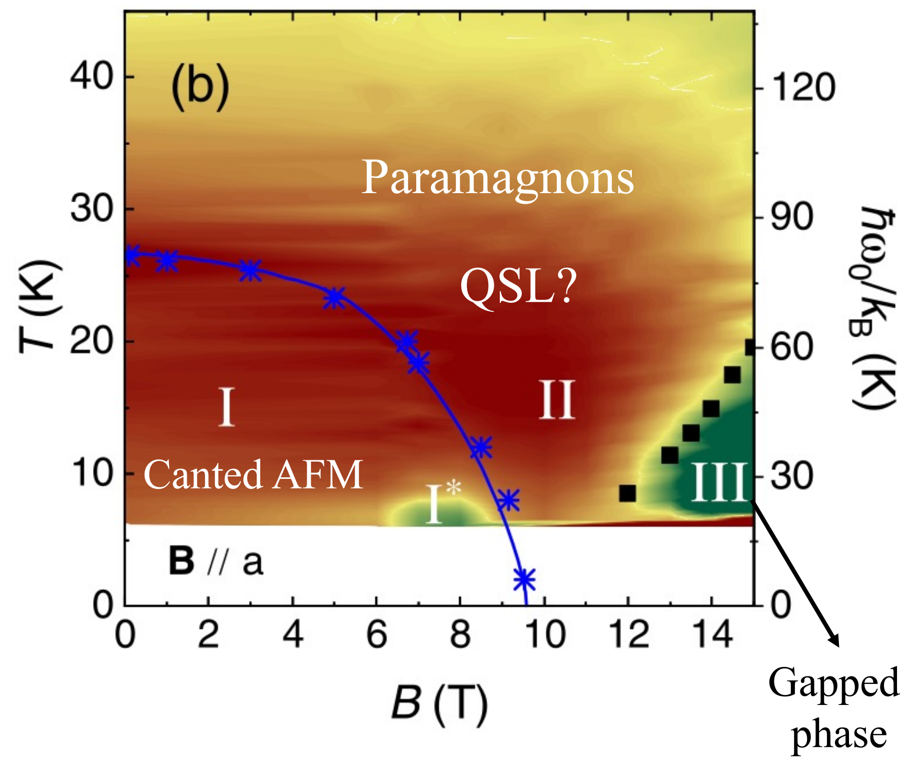
Hong *et al.*, Phys. Rev. B 104, 144426 (2021)

- Honeycomb lattice, *P6₃22*
- Insulator, AFM ordering below $T_N \sim 23$ K
- Phase diagram with in-plane magnetic field

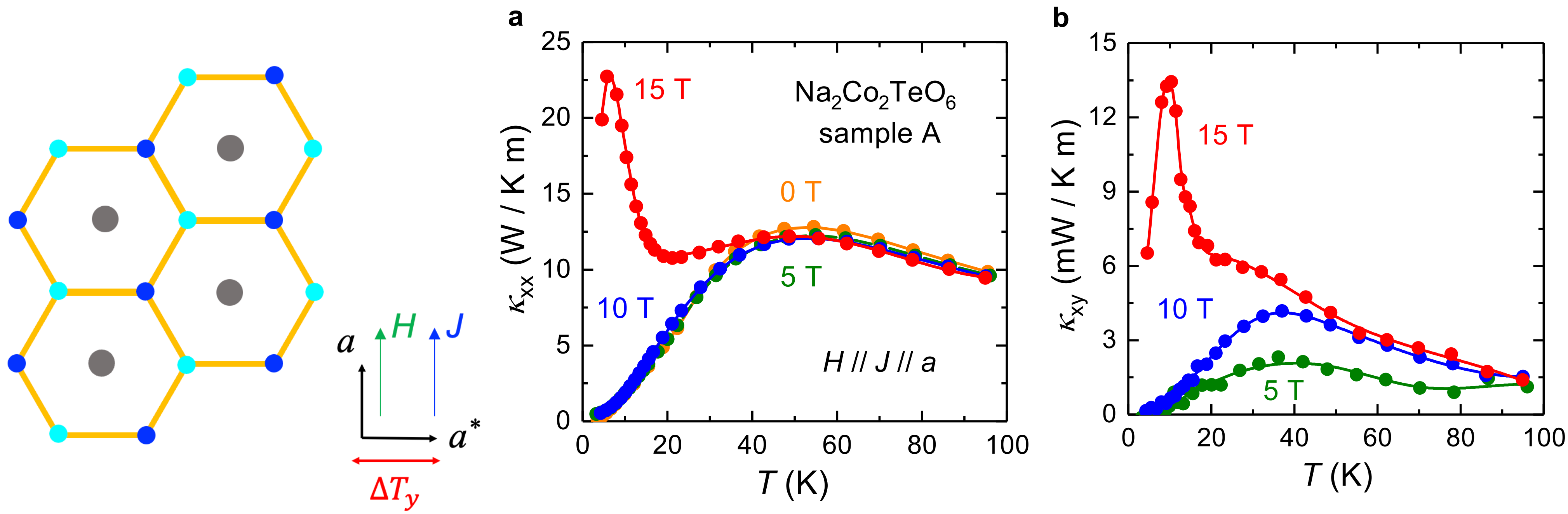


Crystal structure of $Na_2Co_2TeO_6$

$H//a^* \rightarrow C_2$ symmetry is preserved
$\rightarrow \kappa_{xy} = 0$



Thermal transport in $Na_2Co_2TeO_6$ with *H* // *J* // *a*

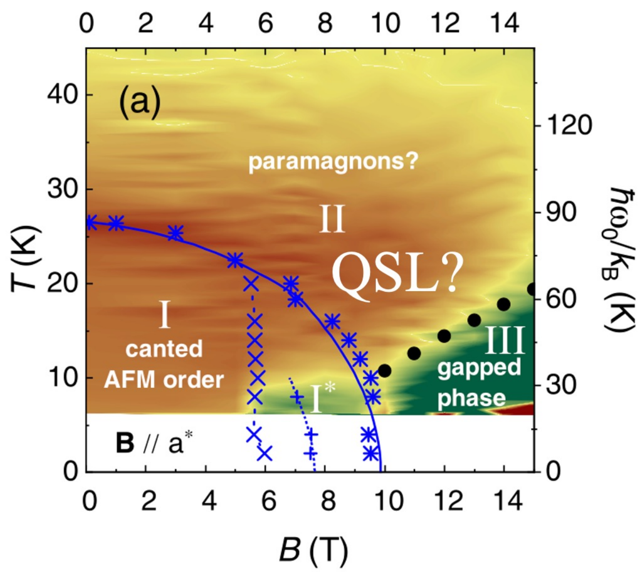


- Phonon dominated κ_{xx}

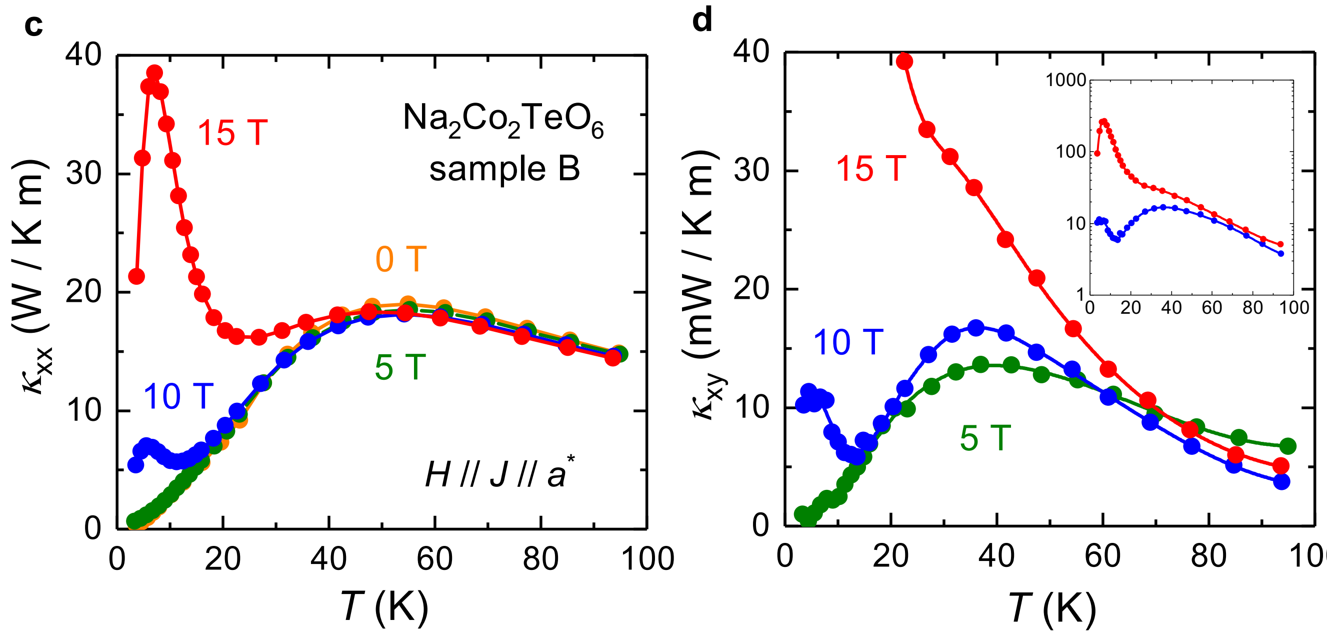
- $\kappa_{xy} \neq 0$ for *H* // *J* // *a*
- Phonon dominated κ_{xy}

Lu Chen et. al., Nat. Commun. 15, 3513(2024)

Thermal transport in $Na_2Co_2TeO_6$ with *H* // *J* // a^*



Hong *et al*., Phys. Rev. B 104, 144426 (2021)

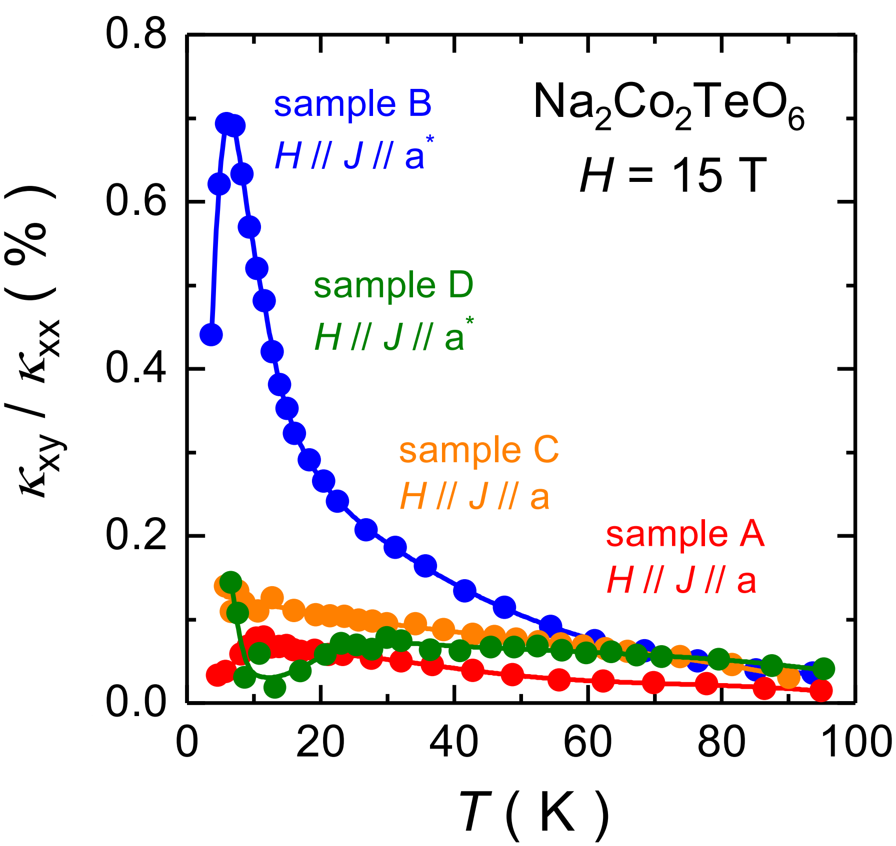


- Phonon dominated κ_{xx}

- $\kappa_{xy} \neq 0$ for *H* // *J* // a^*
- Phonon dominated κ_{xy}

Lu Chen et. al., Nat. Commun. 15, 3513(2024)

Thermal transport data in $Na_2Co_2TeO_6$ with *H* // *J* // *a* and *H* // *J* // *a**



Lu Chen et. al., Nat. Commun. 15, 3513(2024)

- κ_{xy} shows clear sample dependence
- points to some extrinsic mechanism

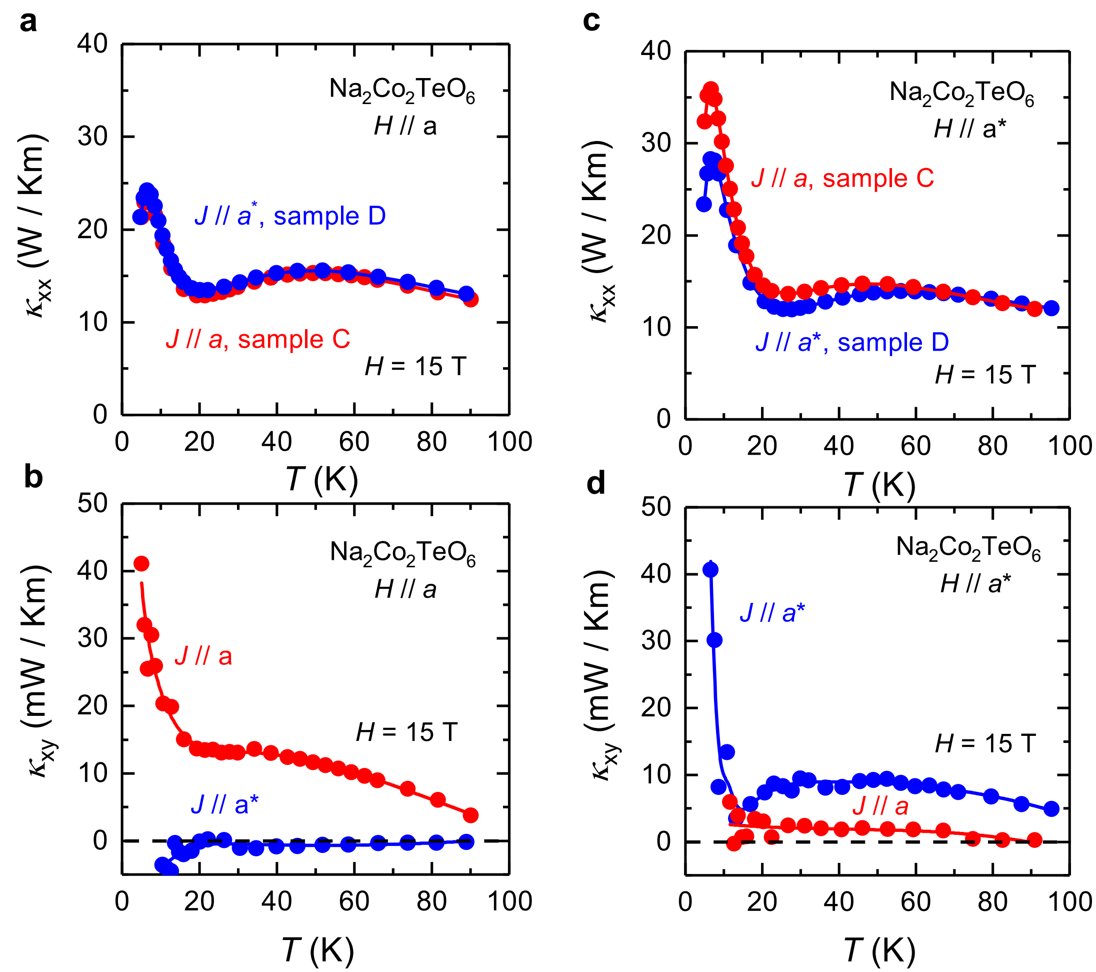
Material	κ_{xy} [mW/Km]	κ_{xx} [W/Km]	κ_{xy}/κ_{xx} [10^{-3}]	T, H [K], [T]
Cu_3TeO_6	- 1000	330	- 3.0	20, 15
$Fe_2Mo_3O_8$ [4]	12	2.5	4.8	65, 14
$Tb_2Ti_2O_7$ [19]	1.2	0.27	4.4	15, 12
$Y_2Ti_2O_7$ [19, 20]	0	18	0	15, 8
La_2CuO_4 [5]	- 38	12	- 3.2	20, 15
$Sr_2CuO_2Cl_2$ [6]	- 21	7	- 3.0	20, 15
Nd_2CuO_4 [6]	- 200	56	- 3.6	20, 15
$SrTiO_3$ [8]	- 80	36	- 2.2	20, 12
$KTaO_3$ [8]	2	32	0.06	30, 12
$RuCl_3$ [21]	2	2	1.0	20, 15

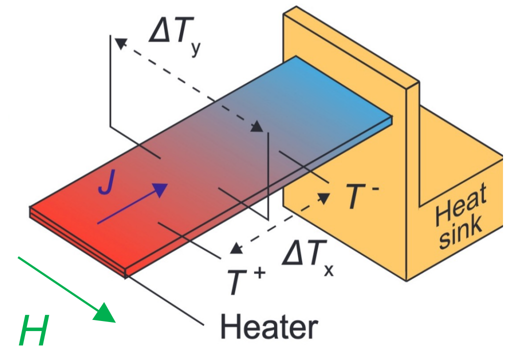
Chen, L. *et al.* PNAS 119 (34) e2208016119 (2022)

Planar Thermal Hall Conductivity κ_{xy} in $Na_2Co_2TeO_6$

- What if we keep the direction of H, but change the direction of J ?

Thermal transport in $Na_2Co_2TeO_6$ with $H \perp J$





- Sample C and sample D are cut from the same mother sample
- $\kappa_{xy} \neq 0$ with H // J, $\kappa_{xy} \approx 0$ with $H \perp J$
- The direction of heat current matters in determining the planar κ_{xy}

Lu Chen et. al., Nat. Commun. 15, 3513(2024)

Summary of findings in $Na_2Co_2TeO_6$

- $\kappa_{xy} \neq 0$ for H // J // a and H // J // a^*, not allowed by crystal symmetry (space group $P6_322$).
- Planar κ_{xy} follows the temperature dependence of κ_{xx} in $Na_2Co_2TeO_6$: points to a phonon dominated planar κ_{xy}.
- Measurements with various H and J configurations reveal that the direction of heat current matters in determining the planar κ_{xy}.
- Ratio of ${}^{\kappa_{xy}}/_{\kappa_{xx}}$ is sample dependent, points to an extrinsic mechanism.
- Impurities or defects, such as Na-layer disorder, could locally break the symmetry and generate this planar κ_{xy} signal?

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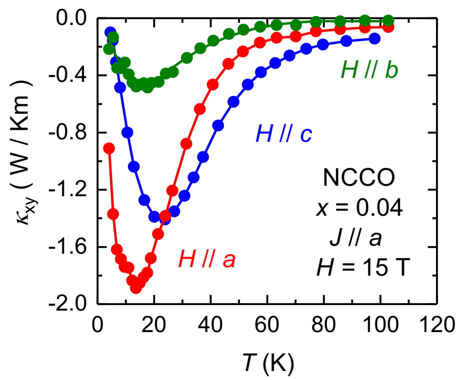
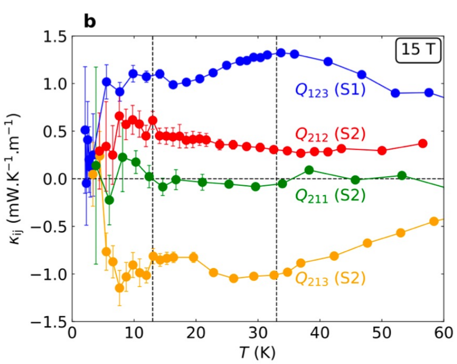
- Planar thermal Hall effect in other quantum materials

Planar κ_{xy} from phonons in other materials



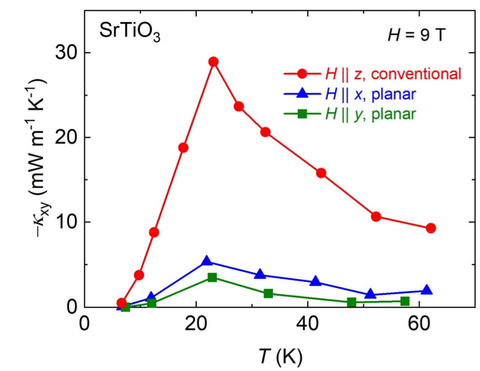
planar κ_{xy} in cuprates (phonons)

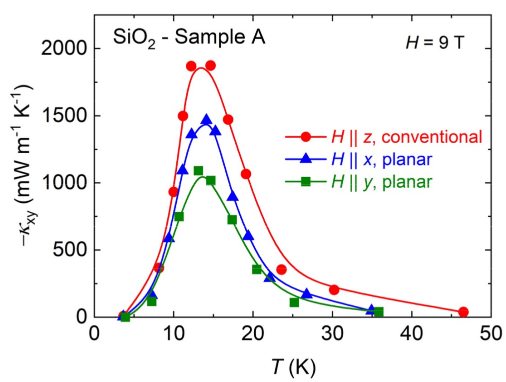
Lu Chen et. al., Phys. Rev. X 14, 041011 (2024)



planar κ_{xy} in Y-kapellasite (phonons)

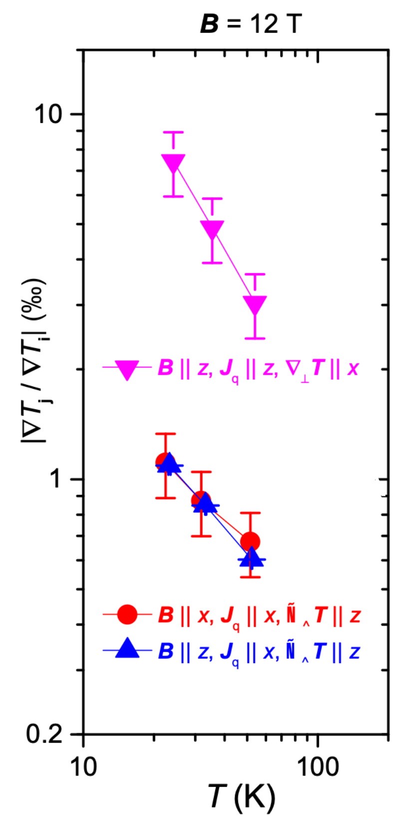
Q. Barthélemy et. al., arXiv:2310.19682





$SrTiO_3$ and SiO_2 (phonons)

Xiaobo Jin et al., arXiv:2404.02863



Black phosphorus (phonons)

Xiaokang Li et al., Sci. Bull. 03, 052 (2025)

Conclusion

- A non-zero planar κ_{xy} contributed by phonons has been observed in both the Kitaev magnet $Na_2Co_2TeO_6$ and other quantum materials like cuprates, Y-kapellasite, $SrTiO_3$, SiO_2, and Black phosphorus.
- In neither case is a planar κ_{xy} allowed by global symmetry.
- Points to an extrinsic mechanism that locally breaks symmetry, perhaps associated with impurities, defects, magnetic texture or domains.

Lu Chen et. al., Nat. Commun. 15, 3513(2024)

Lu Chen et. al., Phys. Rev. X 14, 041011 (2024)

Q. Barthélemy et al., arXiv:2310.19682

Thank you!