SPICE Workshop on Chiral Phonons

Discovery of universal phonon thermal Hall effect in crystals

Shiyan Li

Fudan University

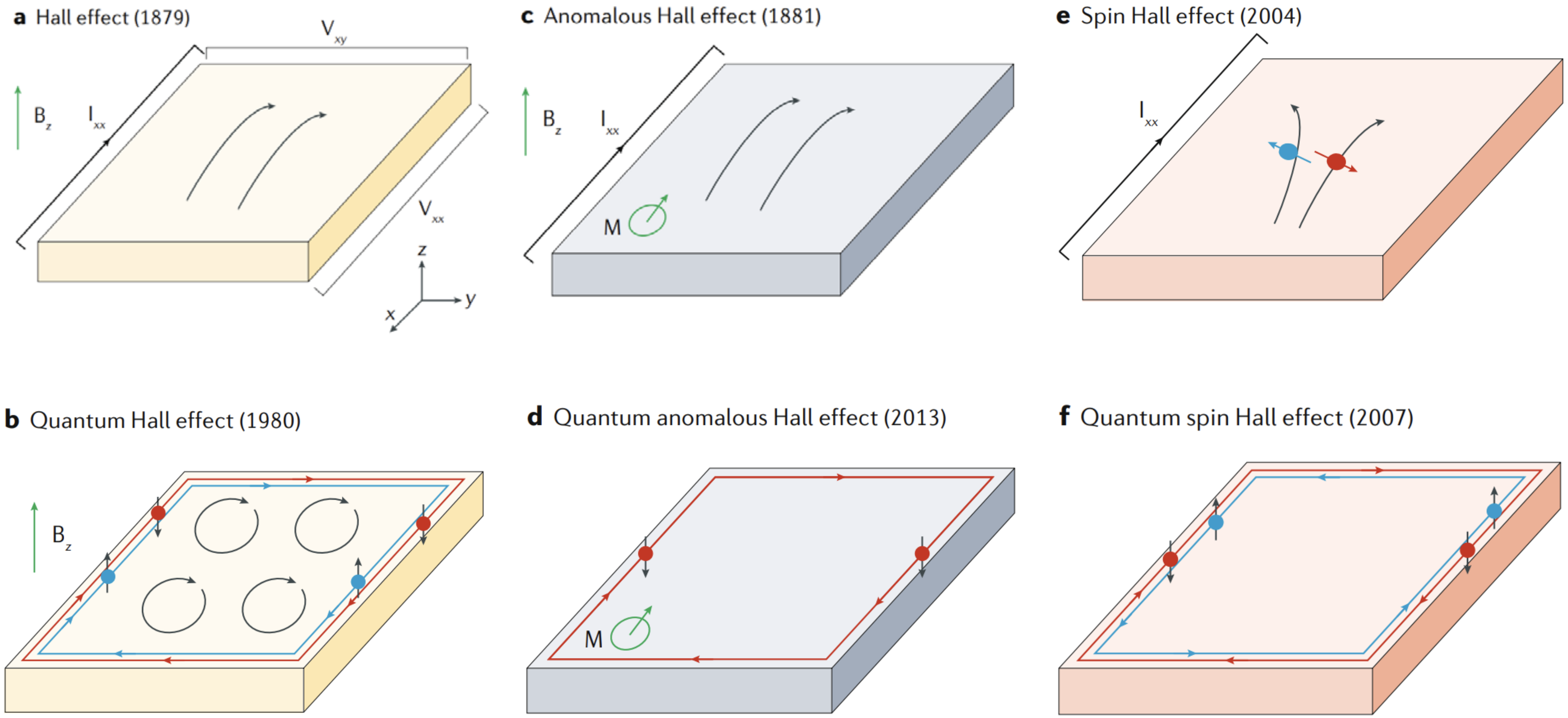
July 29, 2025, Ingelheim, Germany

Collaborators

Xiaobo Jin, Xu Zhang, Wenbo Wan, Hanru Wang,
Yihan Jiao

Fudan University

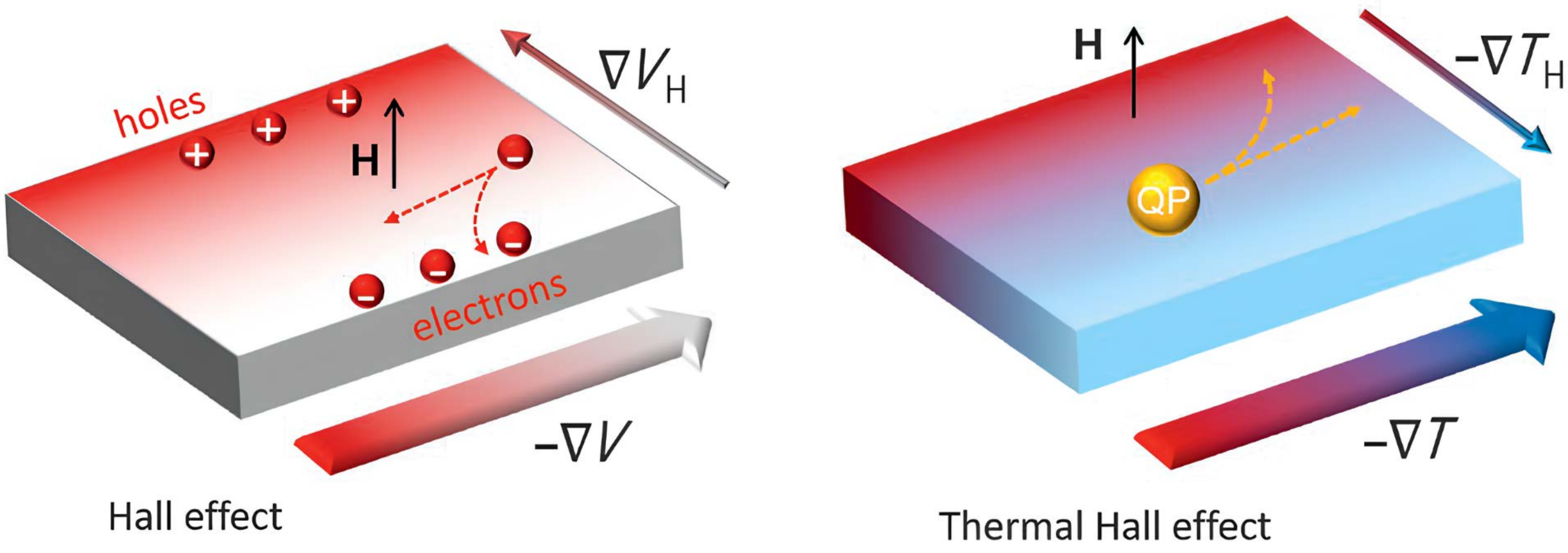
Classical and quantum Hall effects



Electron motion in magnetic field

K. von Klitzing *et al.*, Nat. Rev. Phys. 2, 397 (2020)

Thermal Hall effect

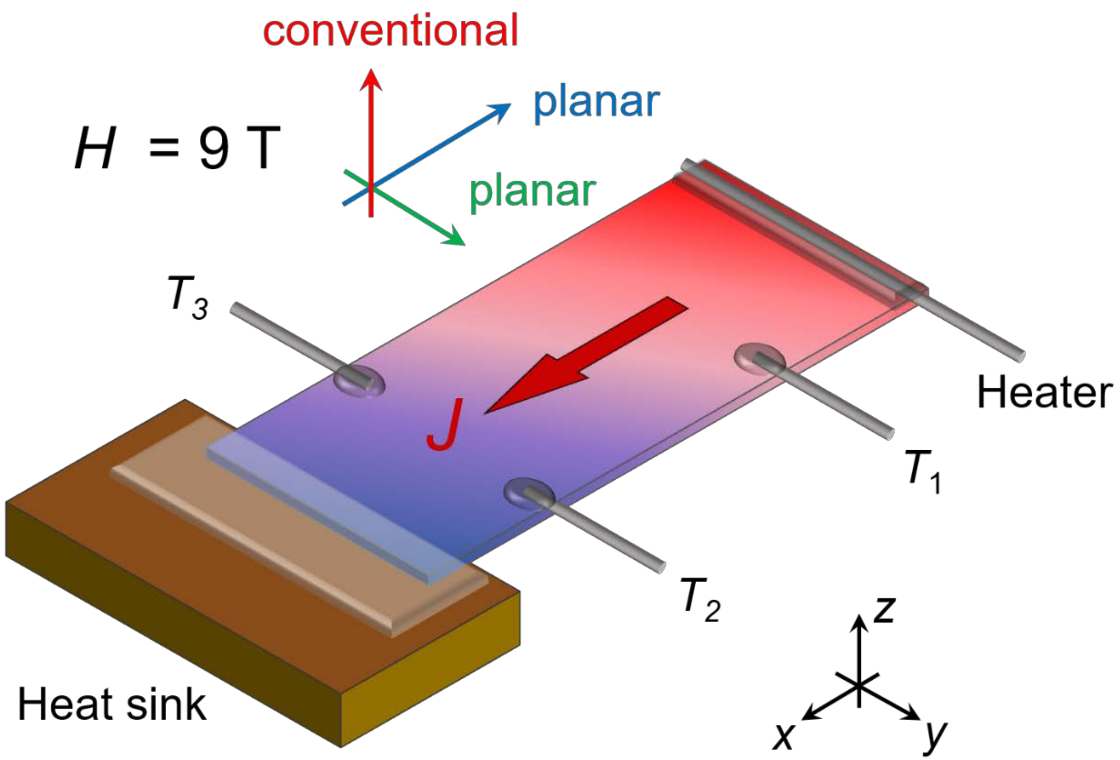


M. Li and G. Chen, MRS Bulletin 45, 348 (2020)

QPs: electron √ (satisfy Wiedemann-Franz law)
magnon ? spinon ? Majorana fermion ?

Can phonon have thermal Hall effect in magnetic field?

Thermal Hall effect：experiment setup



$YBa_2Cu_3O_x$ – electron thermal Hall effect

VOLUME 75, NUMBER 19 PHYSICAL REVIEW LETTERS 6 NOVEMBER 1995

Quasiparticle Mean Free Path in $YBa_2Cu_3O_7$ Measured by the Thermal Hall Conductivity

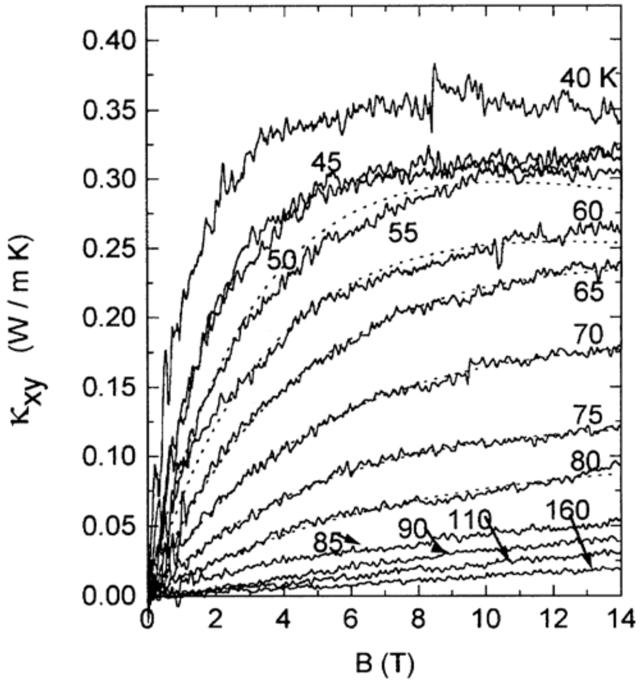
K. Krishana, J. M. Harris, and N. P. Ong

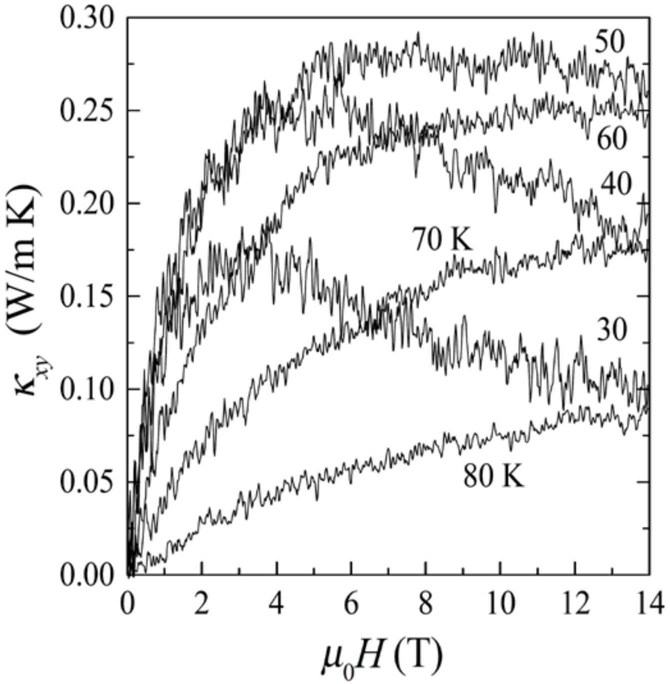
VOLUME 82, NUMBER 25 PHYSICAL REVIEW LETTERS 21 JUNE 1999

Quasiparticle Thermal Hall Angle and Magnetoconductance in $YBa_2Cu_3O_x$

K. Krishana, N. P. Ong, Y. Zhang, and Z. A. Xu*
Joseph Henry Laboratories of Physics, Princeton University, Princeton, New Jersey 08544

R. Gagnon and L. Taillefer†



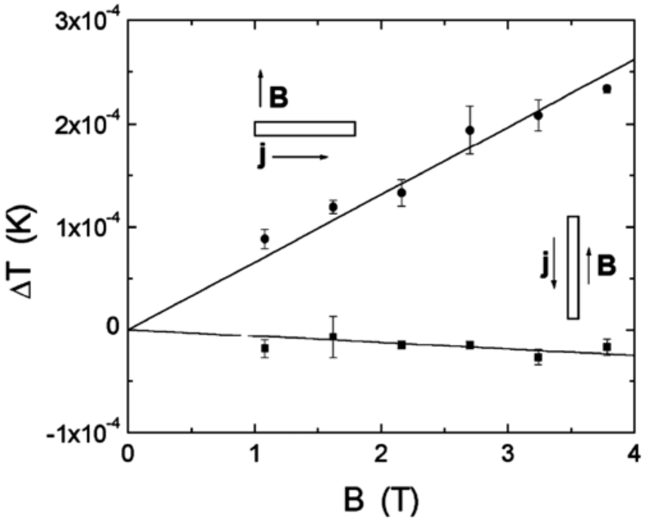


$Tb_3Ga_5O_{12}$

PRL **95,** 155901 (2005) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2005

Phenomenological Evidence for the Phonon Hall Effect

C. Strohm,[1,*] G. L. J. A. Rikken,[1,2] and P. Wyder[1]
[1]*Grenoble High Magnetic Field Laboratory, MPI-FKF/CNRS, BP 169, 38042 Grenoble Cedex 9, France*
[2]*Laboratoire National des Champs Magnétiques Pulsés, CNRS-INSA-UPS, 31432 Toulouse Cedex 4, France*
(Received 5 September 2005; published 4 October 2005)



We have used crystals of paramagnetic terbium gallium garnet, $Tb_3Ga_5O_{12}$ (TGG), to search for the magnetotransverse phonon thermal conductivity. These crystals are dielectric, are cubic, and contain ions that carry both a high charge and a large magnetic moment, both factors that have led us to expect a strong coupling to the magnetic field. We have verified that the zero field magnetic suscep-

- **a paramagnetic insulator**
- **the first observation of phonon thermal Hall effect**
- **skew scattering with magnetic ions?**

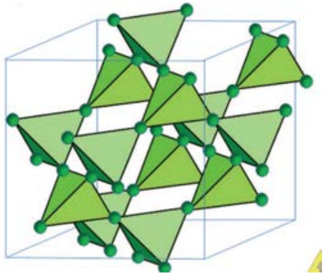
C. Strohm *et al*. Phys. Rev. Lett. 95, 155901 (2005)
M. Mori *et al*. Phys. Rev. Lett. 113, 265901 (2014)

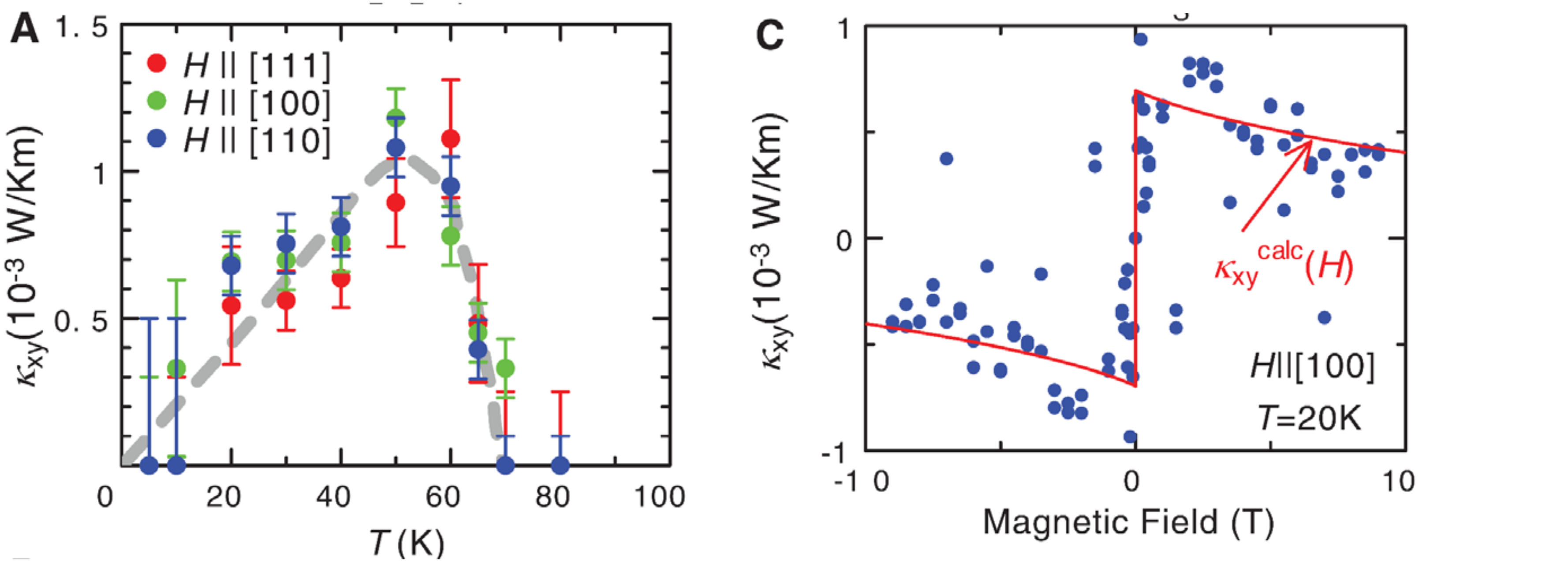
$Lu_2V_2O_7$

Observation of the Magnon Hall Effect

Y. Onose,[1,2]* T. Ideue,[1] H. Katsura,[3] Y. Shiomi,[1,4] N. Nagaosa,[1,4] Y. Tokura[1,2,4]

SCIENCE VOL 329 16 JULY 2010





- an insulating ferromagnet with a pyrochlore lattice
- magnons influenced by DM interaction

Y. Onose *et al*. Science 329, 297 (2010)

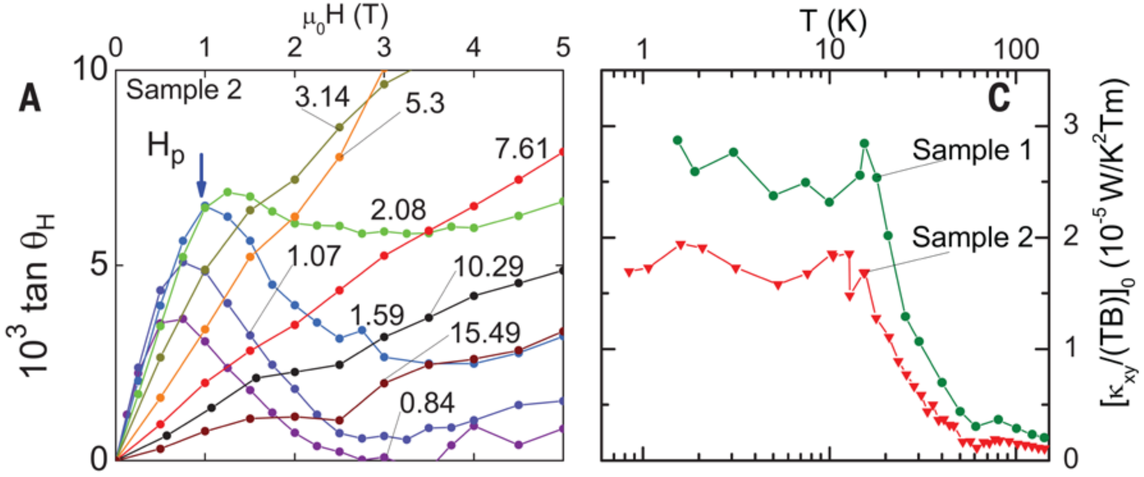
$Tb_2Ti_2O_7$

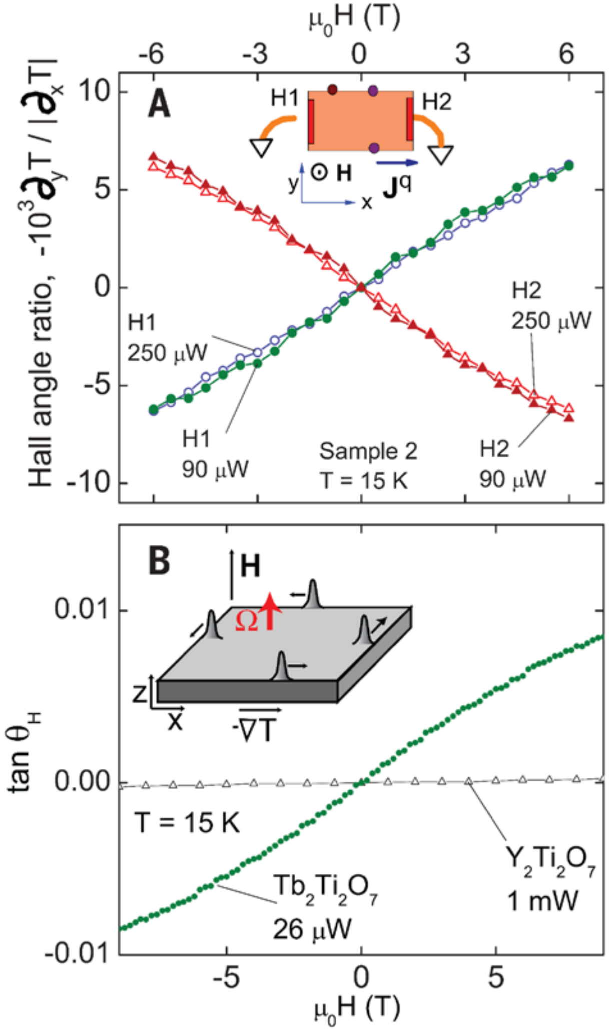
FRUSTRATED MAGNETISM

Large thermal Hall conductivity of neutral spin excitations in a frustrated quantum magnet

Max Hirschberger,[1] Jason W. Krizan,[2] R. J. Cava,[2] N. P. Ong[1]*

3 APRIL 2015 • VOL 348 ISSUE 6230 sciencemag.org SCIENCE





- quantum spin ice with a pyrochlore lattice
- spin excitations distinguished from magnons

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

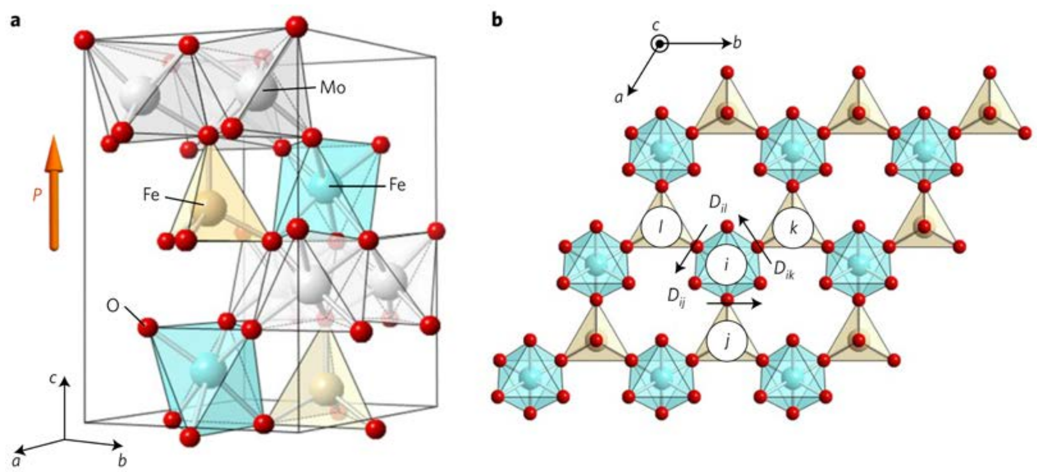
$Fe_2Mo_3O_8$

nature materials
LETTERS
PUBLISHED ONLINE: 15 MAY 2017 | DOI: 10.1038/NMAT4905

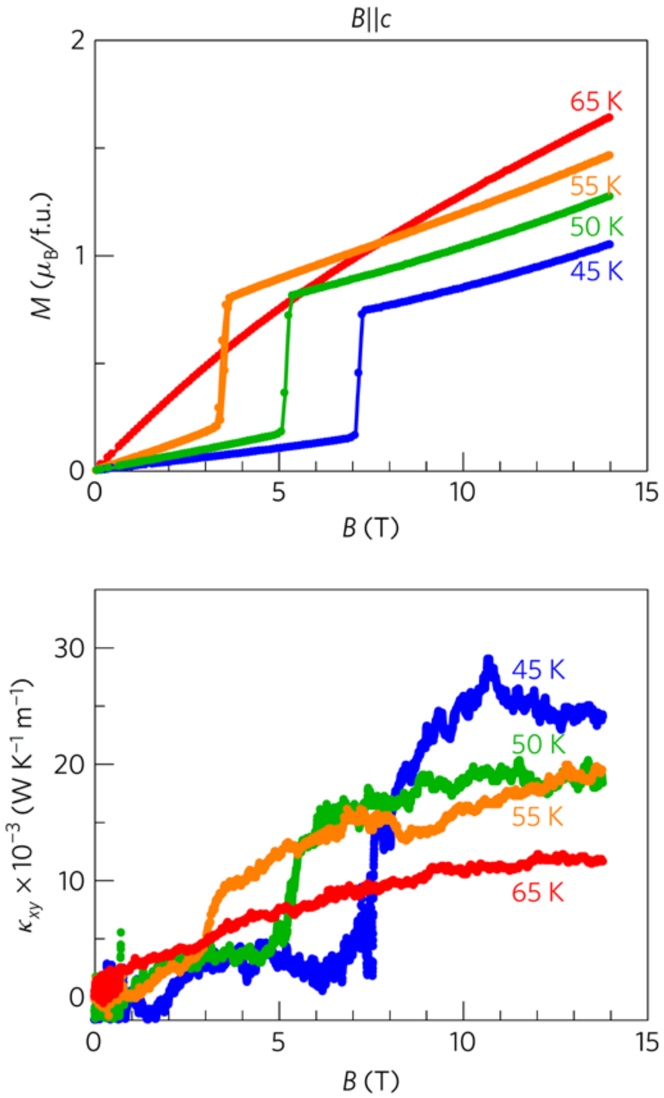
Giant thermal Hall effect in multiferroics

T. Ideue[1]*, T. Kurumaji[2], S. Ishiwata[1,3] and Y. Tokura[1,2]

NATURE MATERIALS | VOL 16 | AUGUST 2017 |



- **Multiferroic material**
- **Phonon thermal Hall effect**
- **Lattice–spin interactions**



T. Ideue *et al*., Nat. Mater. 16, 797 (2017)

α-$RuCl_3$

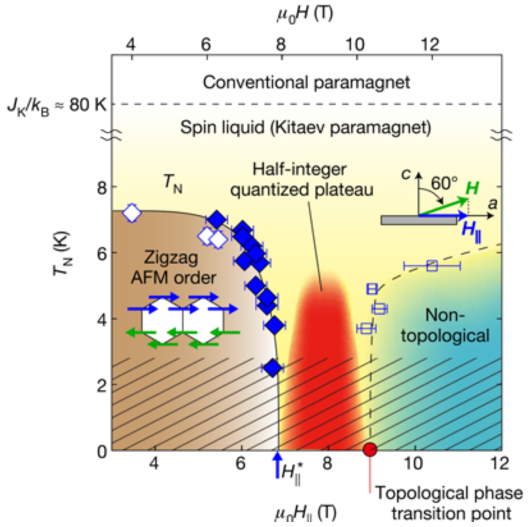
LETTER

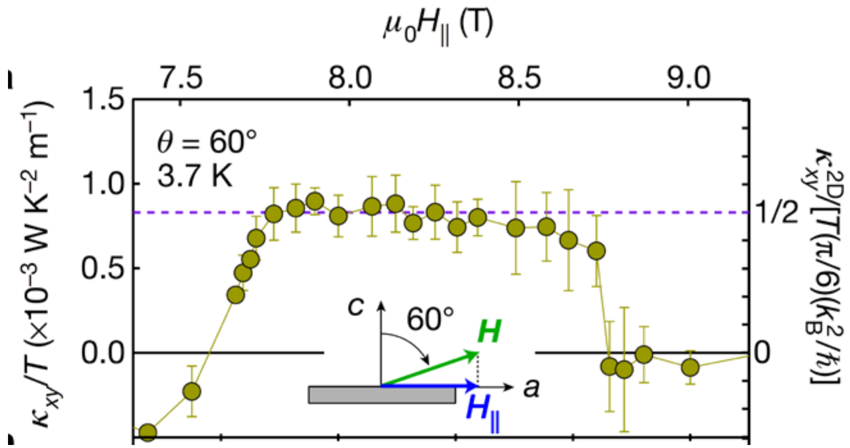
https://doi.org/10.1038/s41586-018-0274-0

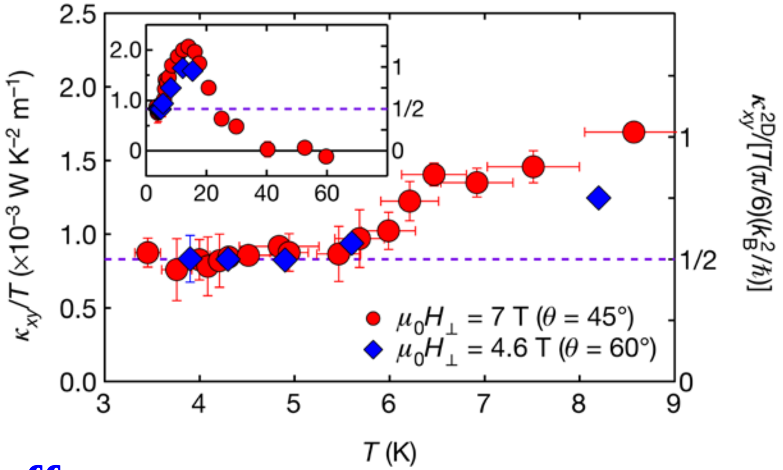
Majorana quantization and half-integer thermal quantum Hall effect in a Kitaev spin liquid

Y. Kasahara[1], T. Ohnishi[1], Y. Mizukami[2], O. Tanaka[2], Sixiao Ma[1], K. Sugii[3], N. Kurita[4], H. Tanaka[4], J. Nasu[4], Y. Motome[5], T. Shibauchi[2] & Y. Matsuda[1]*

12 JULY 2018 | VOL 559 | NATURE |







- **Half-integer thermal quantum Hall effect**
- **Majorana fermions?**

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

cuprates

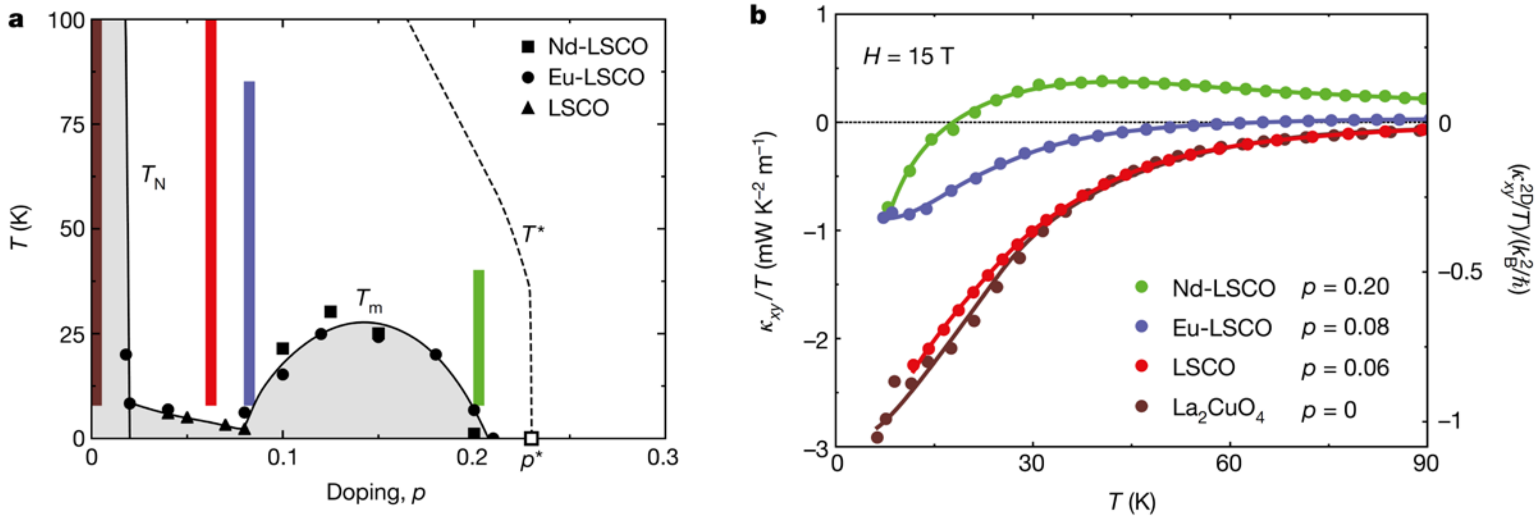
LETTER

https://doi.org/10.1038/s41586-019-1375-0

Giant thermal Hall conductivity in the pseudogap phase of cuprate superconductors

G. Grissonnanche[1]*, A. Legros[1,2], S. Badoux[1], E. Lefrançois[1], V. Zatko[1], M. Lizaire[1], F. Laliberté[1], A. Gourgout[1], J.-S. Zhou[3], S. Pyon[4,5], T. Takayama[4,6], H. Takagi[4,6,7,8], S. Ono[9], N. Doiron-Leyraud[1] & L. Taillefer[1,10]*

NATURE | VOL 571 | 18 JULY 2019



- **Giant thermal Hall conductivity in the pseudogap phase**
- **Neutral excitations with spin chirality?**

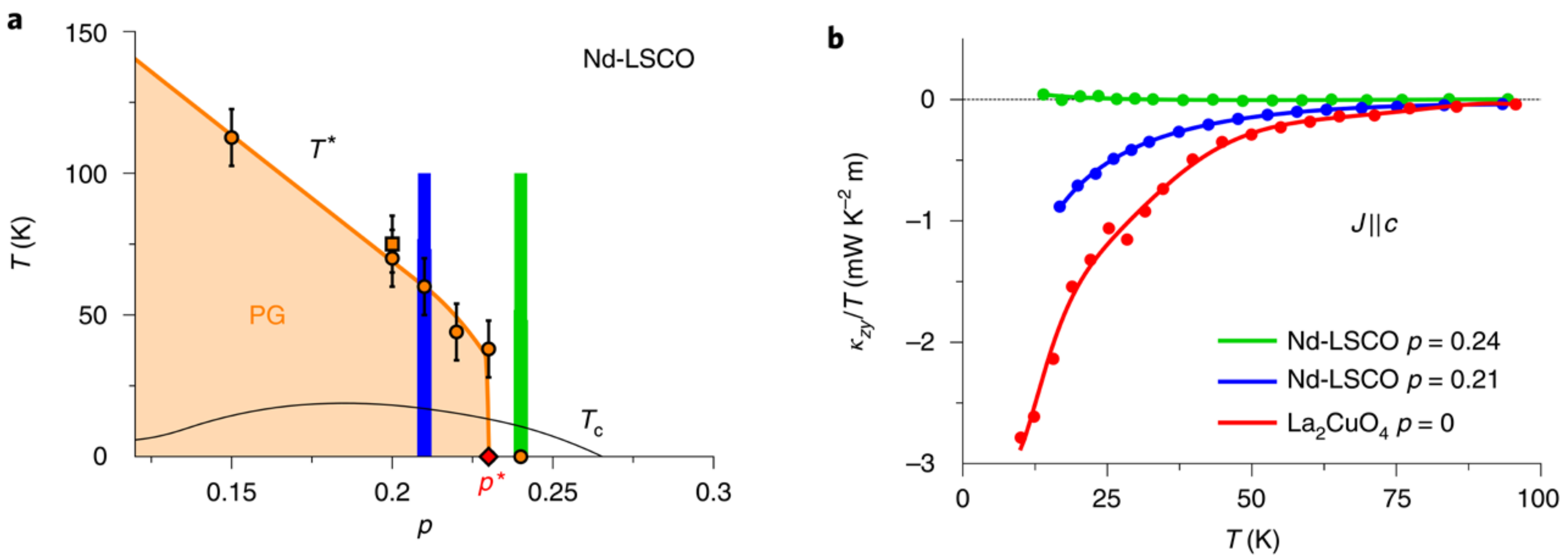
G. Grissonnanche *et al.*, Nature 571, 376 (2019)

cuprates

Chiral phonons in the pseudogap phase of cuprates

G. Grissonnanche[1], S. Thériault[1], A. Gourgout[1], M.-E. Boulanger[1], E. Lefrançois[1], A. Ataei[1], F. Laliberté[1], M. Dion[1], J.-S. Zhou[2], S. Pyon[3,4], T. Takayama[3,5], H. Takagi[3,5,6,7], N. Doiron-Leyraud[1] and L. Taillefer[1,8]

NATURE PHYSICS | VOL 16 | NOVEMBER 2020 | 1108–1111 |



- **Heat current along *c* axis: phonon thermal Hall effect**
- **Inside the psudogap phase: a coupling of phonons to their electronic environment**

G. Grissonnanche *et al*., Nat. Phys. 16, 1108 (2020)

cuprates

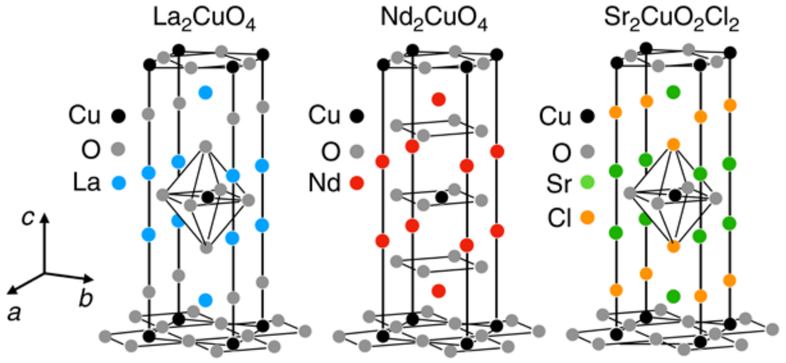
nature COMMUNICATIONS

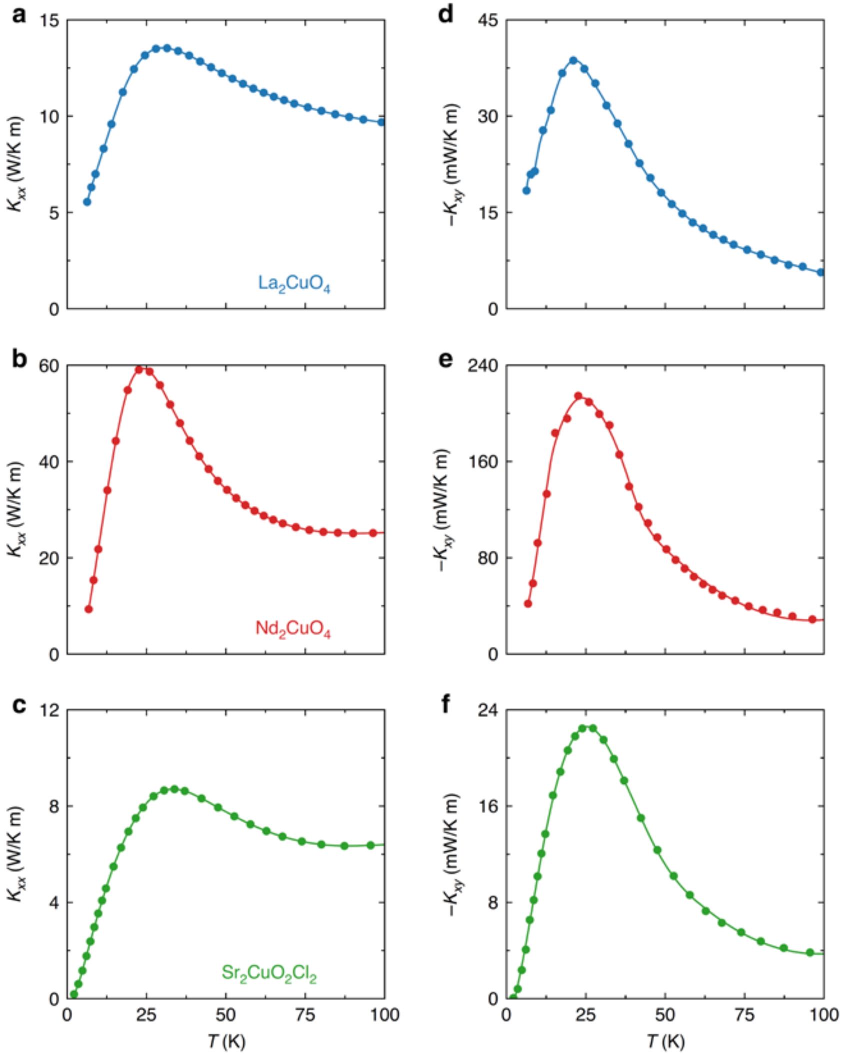
ARTICLE
https://doi.org/10.1038/s41467-020-18881-z OPEN
Check for updates

Thermal Hall conductivity in the cuprate Mott insulators Nd_2CuO_4 and $Sr_2CuO_2Cl_2$

Marie-Eve Boulanger[1,6], Gaël Grissonnanche[1,6], Sven Badoux[1], Andréanne Allaire[1], Étienne Lefrançois[1], Anaëlle Legros[1,2], Adrien Gourgout[1], Maxime Dion[1], C. H. Wang[3], X. H. Chen[3], R. Liang[4], W. N. Hardy[4], D. A. Bonn[4] & Louis Taillefer[1,5✉]

NATURE COMMUNICATIONS | (2020)11:5325 | https://doi.org/10.1038/s41467-020-18881-z |





- **Phonon thermal Hall effect in three cuprate Mott insulators**
- **Coupling of acoustic phonons to the intrinsic excitations of the CuO_2 planes**

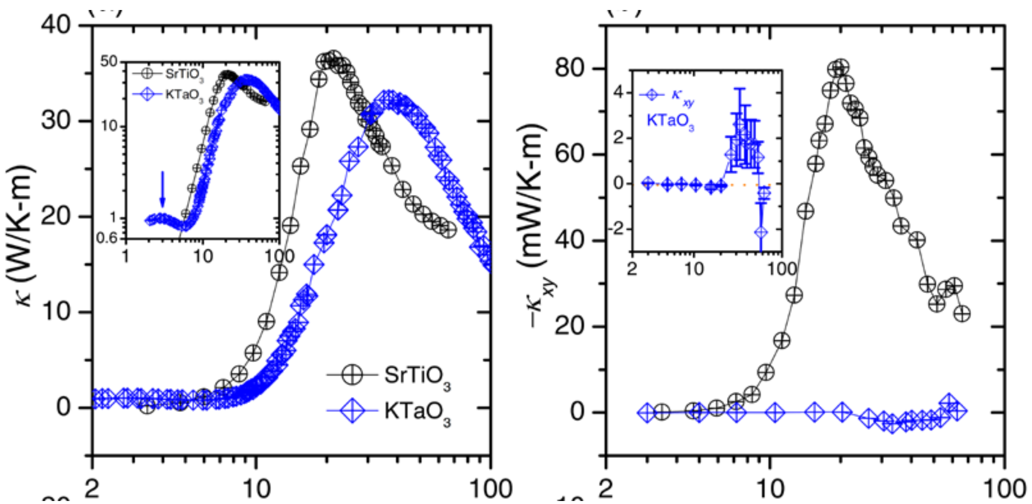
M.-E. Boulanger *et al*., Nat. Commun. 11, 5325 (2020)

$SrTiO_3$

PHYSICAL REVIEW LETTERS **124,** 105901 (2020)

Phonon Thermal Hall Effect in Strontium Titanate

Xiaokang Li,[1,2] Benoît Fauqué,[3] Zengwei Zhu,[2] and Kamran Behnia[1,4]



A crucial role played by antiferrodistortive domains, which may induce hybridization between acoustic phonons with transverse optical phonons

X. Li *et al.*, Phys. Rev. Lett. 124, 105901 (2020)

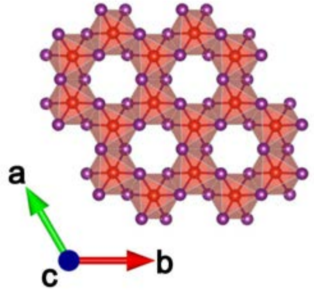
VI_3

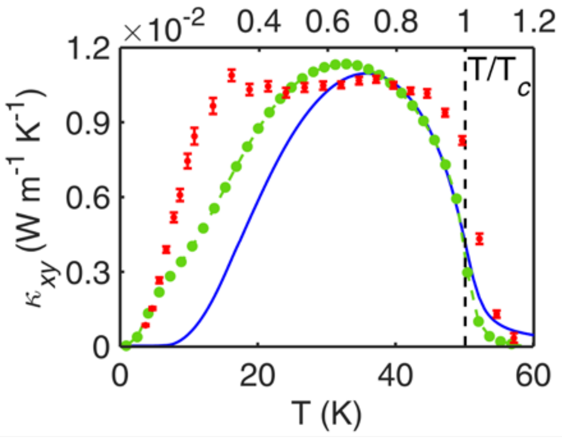
PHYSICAL REVIEW LETTERS **127,** 247202 (2021)

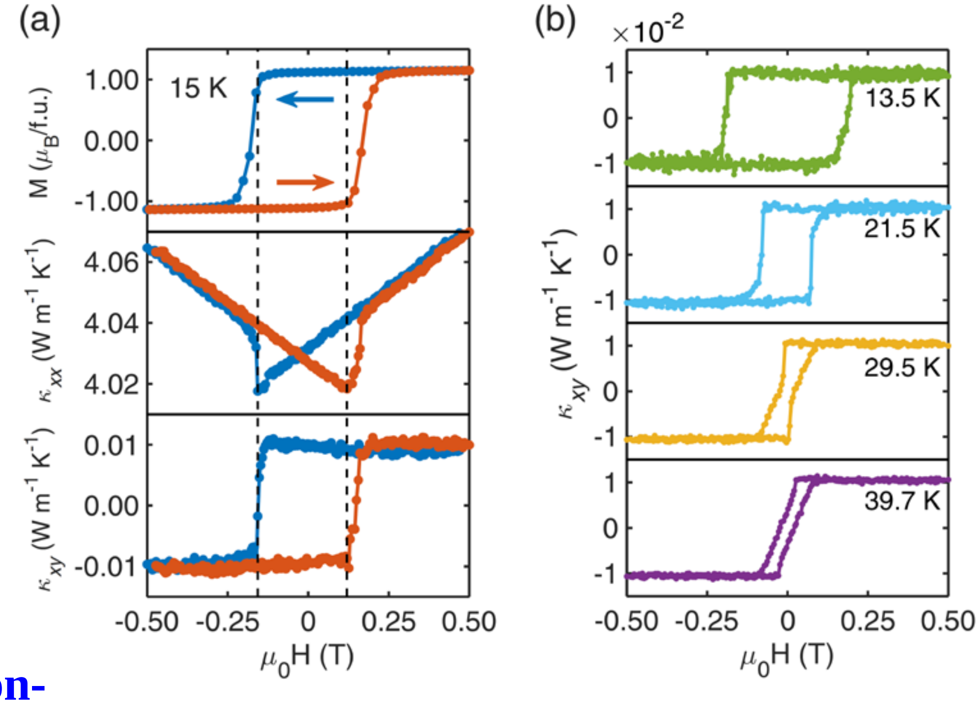
Editors' Suggestion

Anomalous Thermal Hall Effect in an Insulating van der Waals Magnet

Heda Zhang,[1,*] Chunqiang Xu,[1,2,*] Caitlin Carnahan,[3,*] Milos Sretenovic,[1] Nishchay Suri,[3] Di Xiao,[3,4,5] and Xianglin Ke[1]
[1]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-2320, USA







- **Ferromagnet**
- **From topological magnons at higher temperatures**
- **From phonons induced by the magnon-phonon coupling at lower temperatures**

H. Zhang *et al*., Phys. Rev. Lett. 127, 247202 (2021)

α-RuCl$_3$

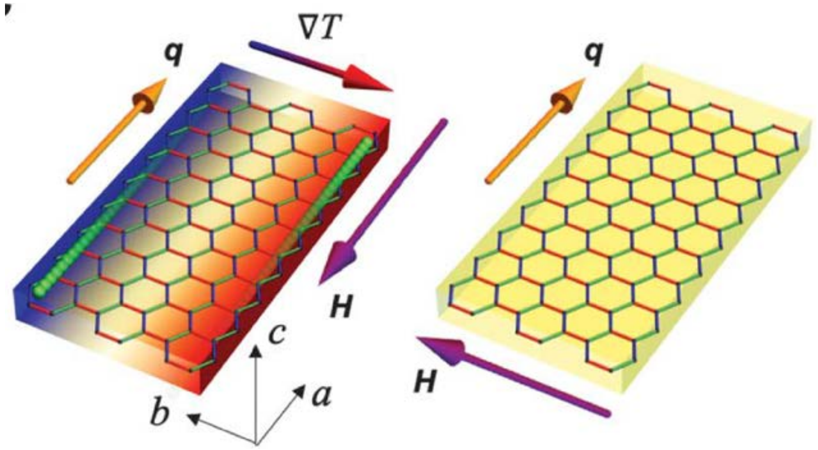
RESEARCH

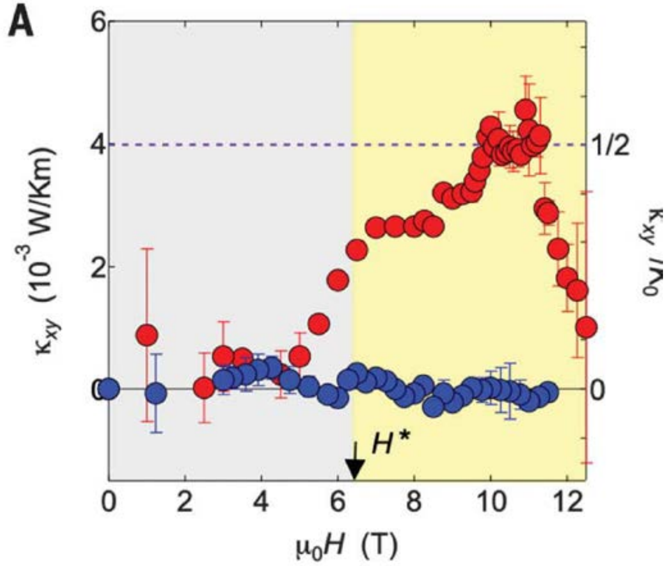
SPIN LIQUIDS

Half-integer quantized anomalous thermal Hall effect in the Kitaev material candidate α-RuCl$_3$

T. Yokoi[1]†, S. Ma[1]†, Y. Kasahara[1]*, S. Kasahara[1], T. Shibauchi[2], N. Kurita[3], H. Tanaka[3], J. Nasu[4], Y. Motome[5], C. Hickey[6], S. Trebst[6], Y. Matsuda[1]*

Yokoi *et al.*, *Science* **373**, 568–572 (2021)   30 July 2021



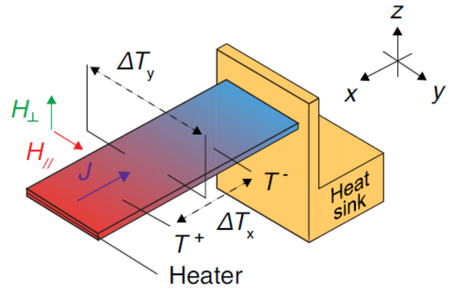


- κ_{xy} with an in-plane H which parallel with the heat current q (planar thermal Hall effect)
- Majorana fermions?

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

α-RuCl$_3$

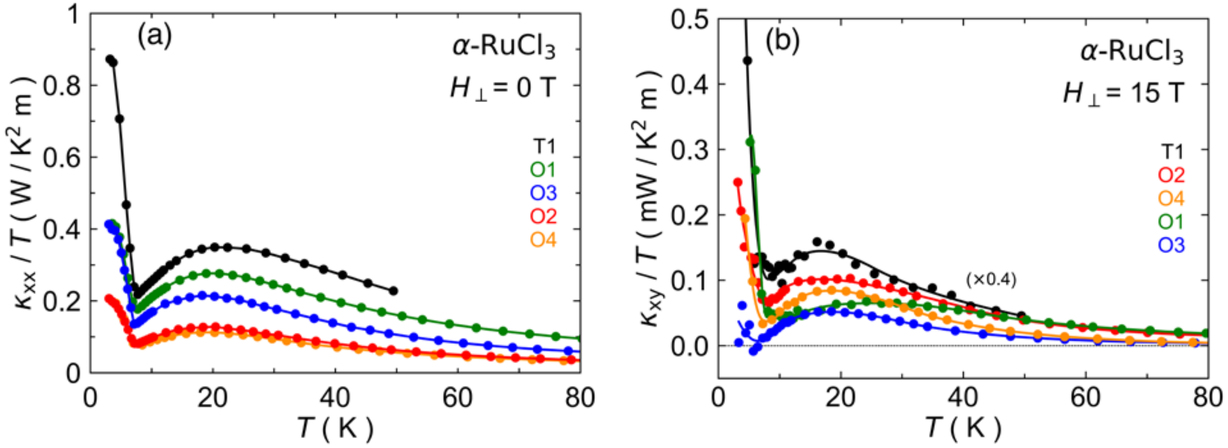
PHYSICAL REVIEW X **12,** 021025 (2022)

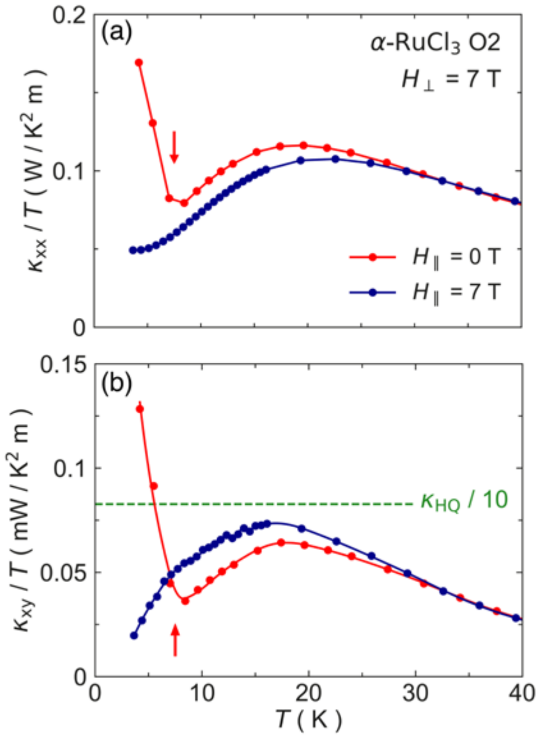


Evidence of a Phonon Hall Effect in the Kitaev Spin Liquid Candidate α-RuCl$_3$

É. Lefrançois,[1,†] G. Grissonnanche,[1] J. Baglo,[1] P. Lampen-Kelley,[2,3] J.-Q. Yan,[2] C. Balz,[4,*] D. Mandrus,[2,3] S. E. Nagler,[4] S. Kim,[5] Young-June Kim,[5] N. Doiron-Leyraud,[1] and Louis Taillefer[1,6,‡]

[1]*Institut Quantique, Département de physique and RQMP, Université de Sherbrooke, Sherbrooke, Québec, Canada*





- **κ_{xy} and κ_{xx} have a similar temperature dependence**
- **κ_{xy} is mostly carried by phonons**

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

α-RuCl$_3$

nature materials

Letter

https://doi.org/10.1038/s41563-022-01397-w

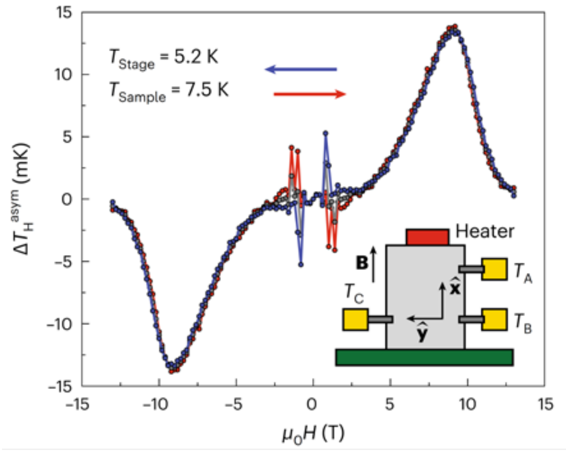
Planar thermal Hall effect of topological bosons in the Kitaev magnet α-RuCl$_3$

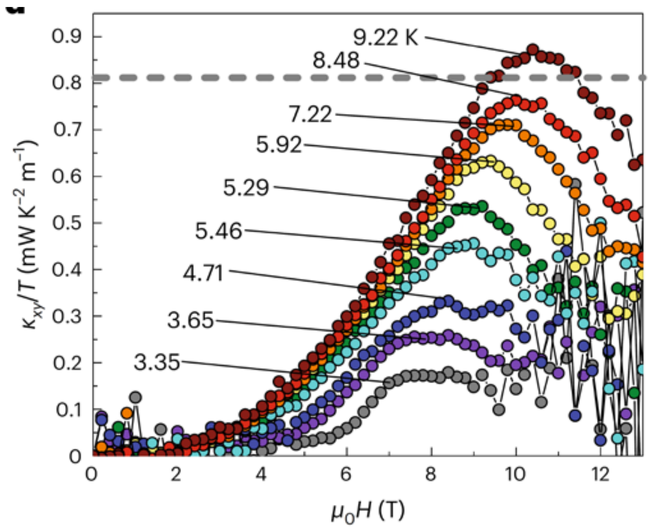
Received: 11 April 2022

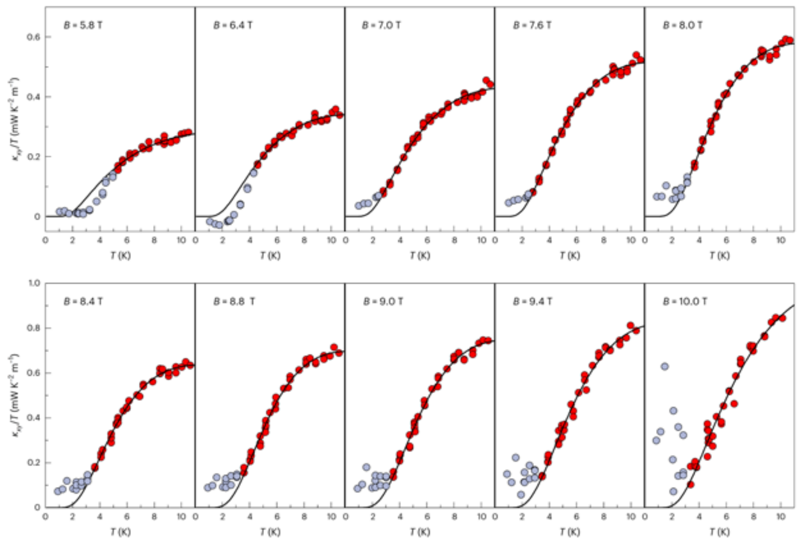
Accepted: 4 October 2022

Peter Czajka[1], Tong Gao[1], Max Hirschberger[2], Paula Lampen-Kelley[3,4], Arnab Banerjee[5], Nicholas Quirk[1], David G. Mandrus[3,4], Stephen E. Nagler[6] & N. P. Ong[1]

Nature Materials | Volume 22 | January 2023 | 36–41







- **Planar κ_{xy} with no half-quantization**
- **κ_{xy}(T) matches topological bosonic modes in a Chern-insulator-like model**

P. Czajka *et al.*, Nat. Mater. 22, 36 (2022)

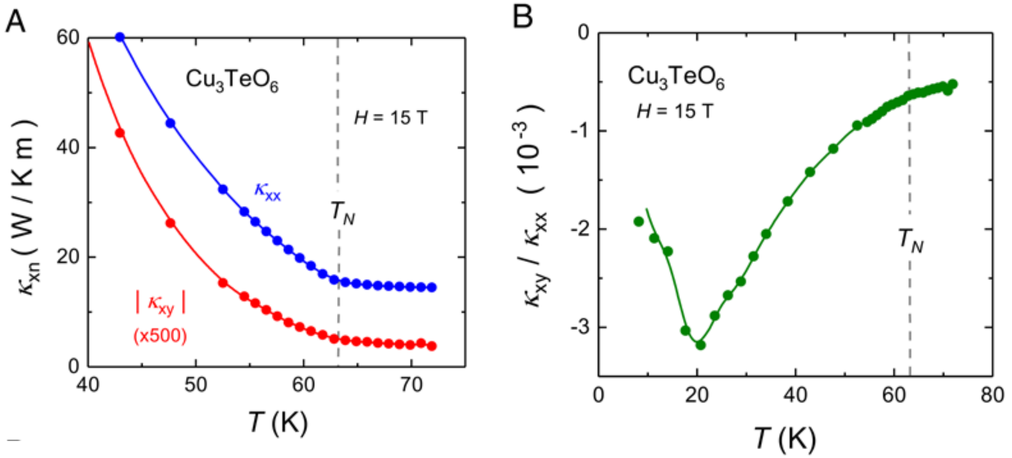
Cu_3TeO_6

PNAS RESEARCH ARTICLE | PHYSICS OPEN ACCESS

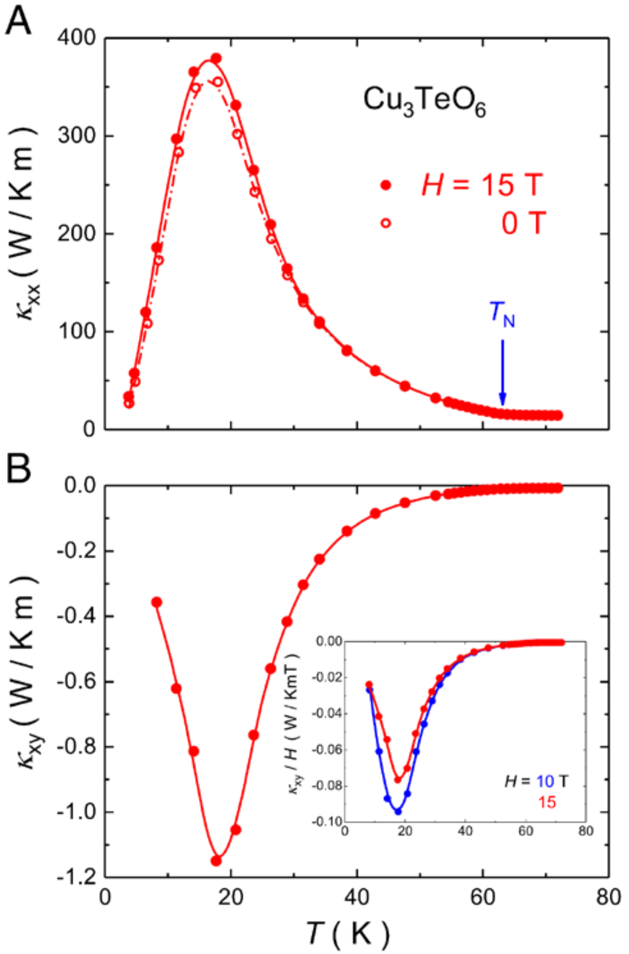
Large phonon thermal Hall conductivity in the antiferromagnetic insulator Cu_3TeO_6

Lu Chen[a,1], Marie-Eve Boulanger[a,1], Zhi-Cheng Wang[b], Fazel Tafti[b], and Louis Taillefer[a,c,2]

PNAS 2022 Vol. 119 No. 34 e2208016119



- **An antiferromagnetic insulator**
- **Phonon thermal Hall effect**
- **Phonon chirality could involve the scattering of phonons by impurities or defects in the magnetic environment**



L. Chen *et al*., Proc. Natl. Acad. Sci. U.S.A. 119, e2208016119 (2022)

$Pr_2Ir_2O_7$

nature communications

Article

https://doi.org/10.1038/s41467-022-32375-0

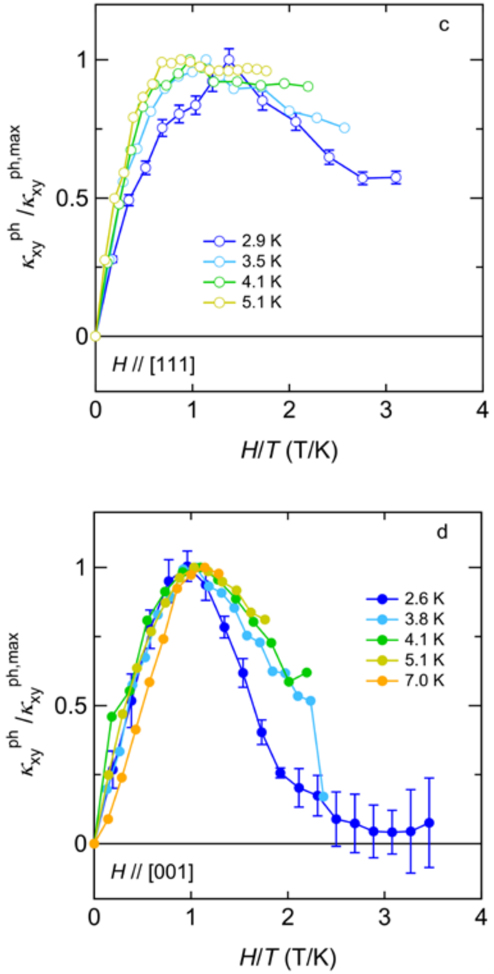
Phonon thermal Hall effect in a metallic spin ice

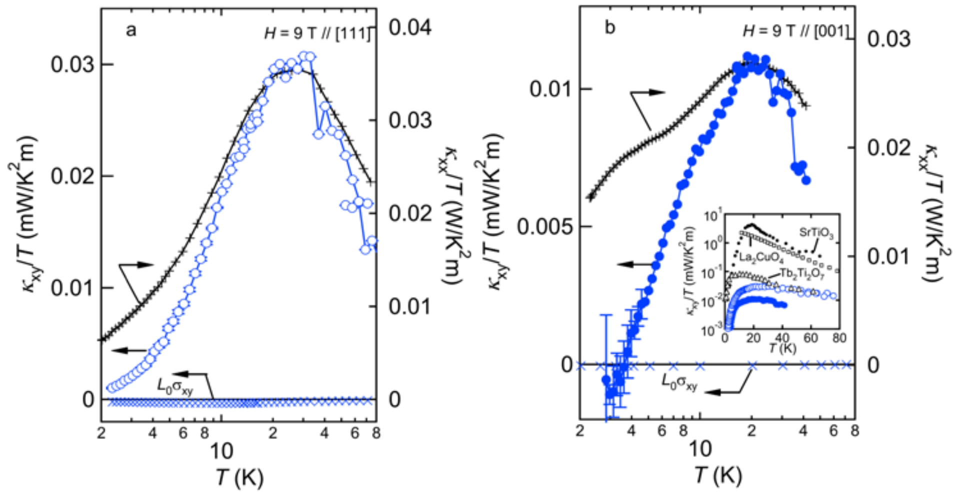
Received: 5 March 2022

Accepted: 26 July 2022

Taiki Uehara[1], Takumi Ohtsuki[2], Masafumi Udagawa[1], Satoru Nakatsuji[2,3,4] & Yo Machida[1]

Nature Communications | (2022)13:4604





- κ_{xy} and κ_{xx} have a very similar temperature dependence → phonons
- T / H scaling → resonant scattering of phonons on paramagnetic spins

T. Uehara *et al*., Nat. Commun. 13, 4604 (2022)

black phosphorus

nature communications

Article

https://doi.org/10.1038/s41467-023-36750-3

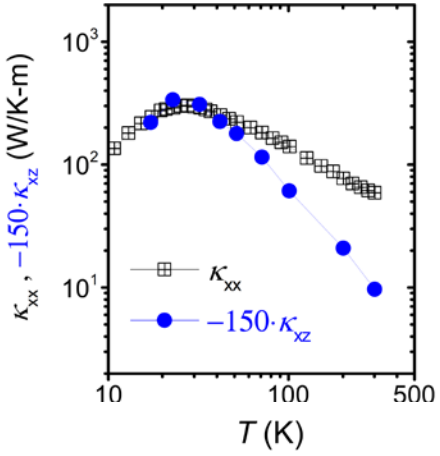
The phonon thermal Hall angle in black phosphorus

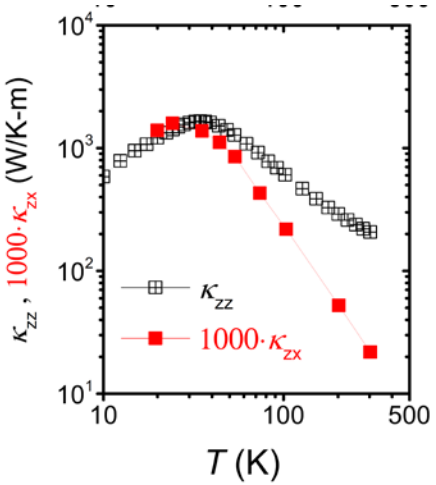
Received: 15 December 2022

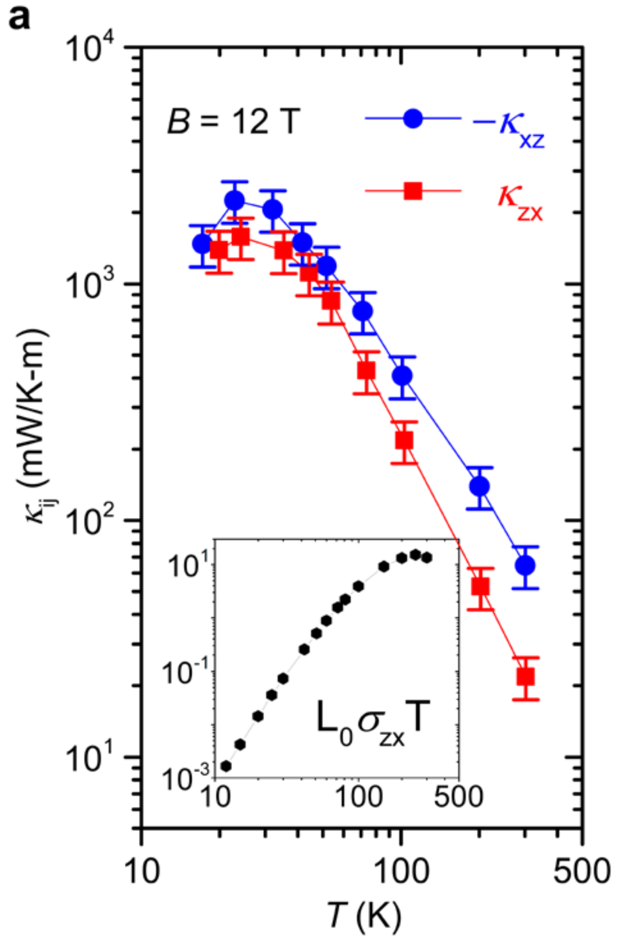
Accepted: 14 February 2023

Xiaokang Li[1], Yo Machida[2], Alaska Subedi[3,4], Zengwei Zhu[1], Liang Li[1] & Kamran Behnia[5]

Nature Communications | (2023)14:1027







- Non-magnetic
- The anisotropic charge distribution surrounding atomic bonds

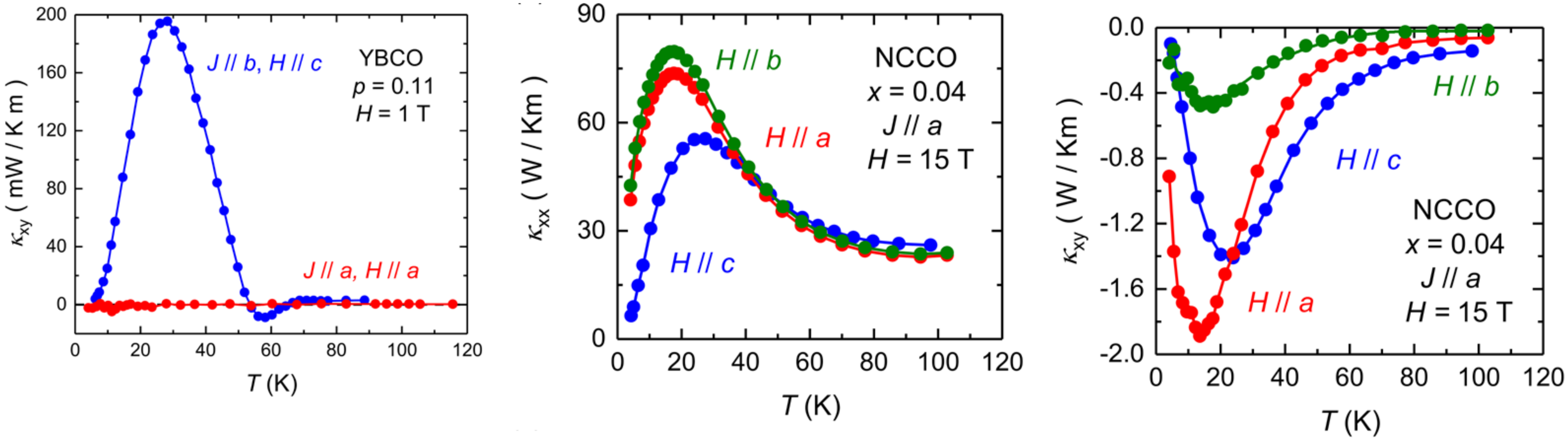
X. Li *et al.*, Nat. Commun. 14, 1027 (2023)

cuprates

PHYSICAL REVIEW X **14**, 041011 (2024)

Planar Thermal Hall Effect from Phonons in Cuprates

Lu Chen,[1,*] Léna Le Roux,[1] Gaël Grissonnanche,[1,2] Marie-Eve Boulanger,[1] Steven Thériault,[1] Ruixing Liang,[3,4] D. A. Bonn,[3,4] W. N. Hardy,[3,4] S. Pyon,[5,6] T. Takayama,[5,7] H. Takagi,[5,7,8,9] Ke-Jun Xu,[10,11,12] Zhi-Xun Shen,[10,11,12] and Louis Taillefer[1,4,†]



- The planar κ_{xy} from electrons in cuprates is zero
- A sizable planar phonon κ_{xy} in electron-doped cuprates

Sr_2IrO_4

nature physics

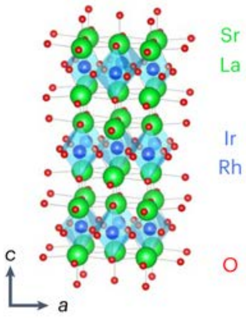
Article https://doi.org/10.1038/s41567-024-02384-5

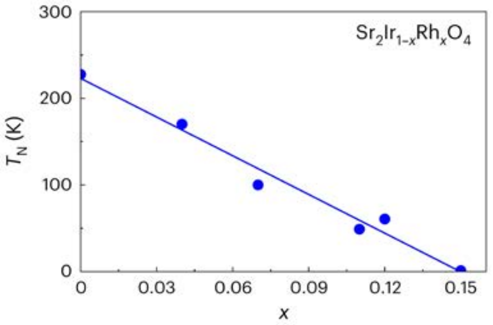
Phonon chirality from impurity scattering in the antiferromagnetic phase of Sr_2IrO_4

Received: 7 February 2023

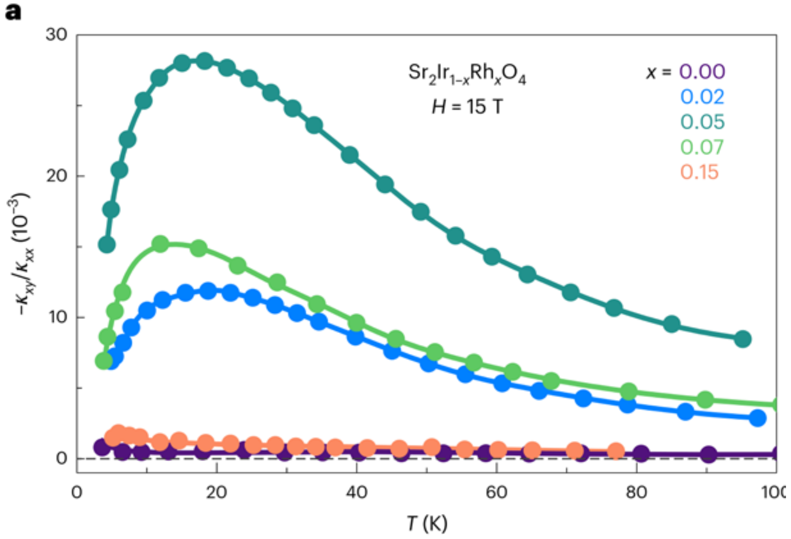
Accepted: 19 December 2023

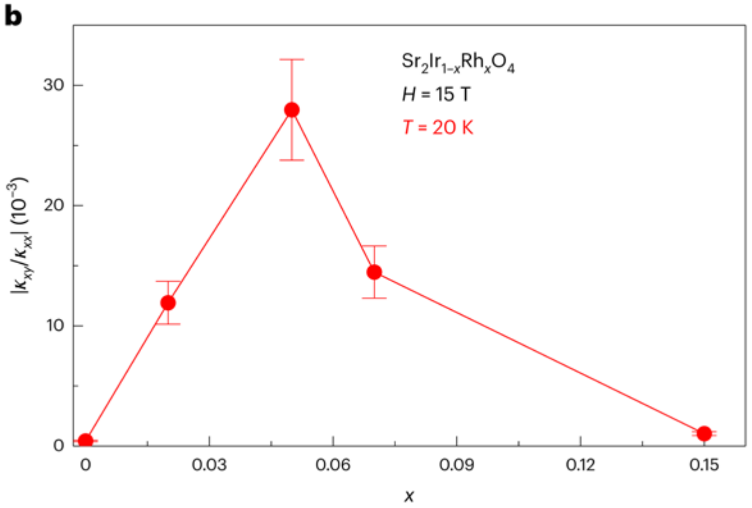
A. Ataei[1], G. Grissonnanche[1,2], M.-E. Boulanger[1], L. Chen[1], É. Lefrançois[1], V. Brouet[3] & L. Taillefer[1,4]





antiferromagnetic





- A finite phonon κ_{xy} is detected in the AF parent compound
- The huge change in κ_{xy} emerging from Rh substitution on the spin-carrying site
- THE is caused by the scattering of phonons by impurities embedded within a magnetic environment

A. Ataei *et al.*, Nat. Phys. 20, 585 (2024)

α-RuCl$_3$

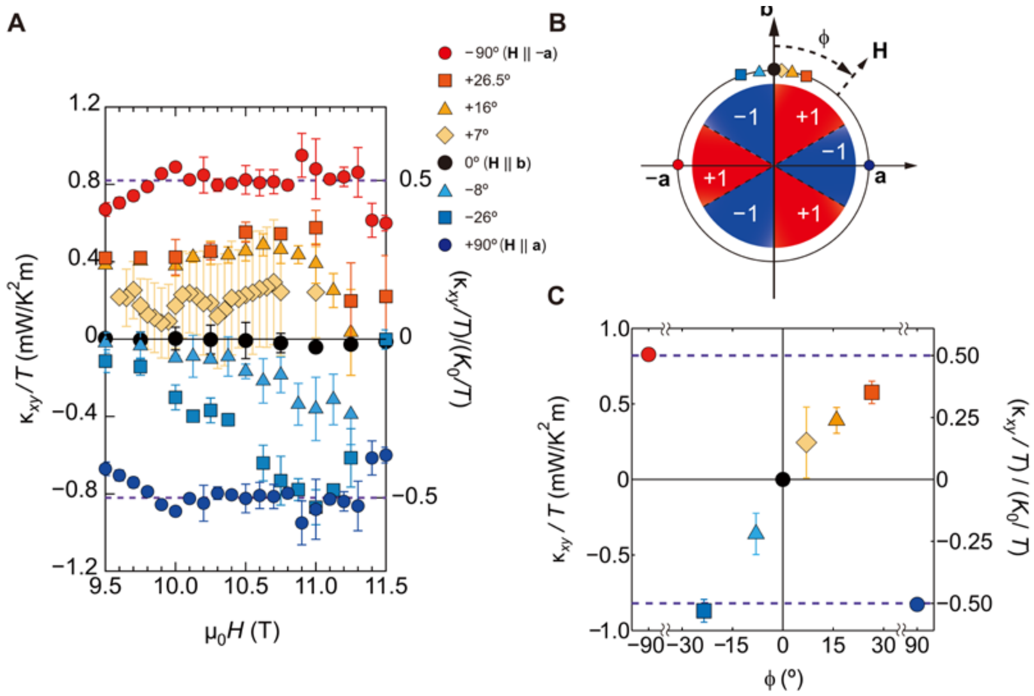
SCIENCE ADVANCES | RESEARCH ARTICLE

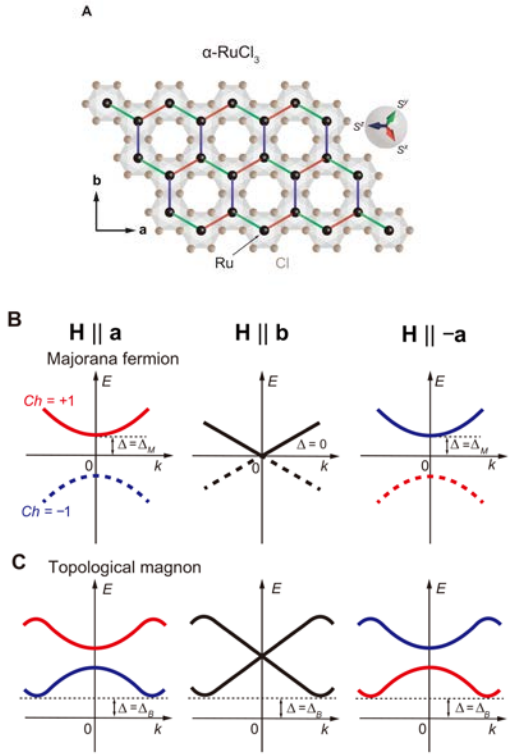
CONDENSED MATTER PHYSICS

Majorana-fermion origin of the planar thermal Hall effect in the Kitaev magnet α-RuCl$_3$

Kumpei Imamura[1]†, Shota Suetsugu[2]†, Yuta Mizukami[1,3], Yusei Yoshida[1], Kenichiro Hashimoto[1], Kenichi Ohtsuka[2], Yuichi Kasahara[2], Nobuyuki Kurita[4], Hidekazu Tanaka[5], Pureum Noh[6], Joji Nasu[3], Eun-Gook Moon[6], Yuji Matsuda[2], Takasada Shibauchi[1]*

Imamura *et al.*, *Sci. Adv.* **10**, eadk3539 (2024)   13 March 2024

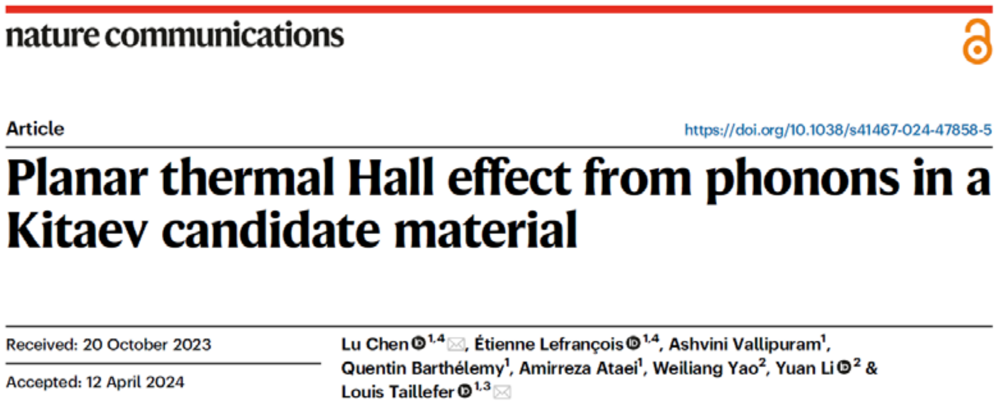




- **Planar thermal Hall effect with sign reversal**
- **The sign reversal corresponds to gap closure and opening of Majorana fermions**
- **Majorana fermions?**

K. Imamura *et al.*, Sci. Adv. 10, eadk3539 (2024)

$Na_2Co_2TeO_6$


nature communications

Article

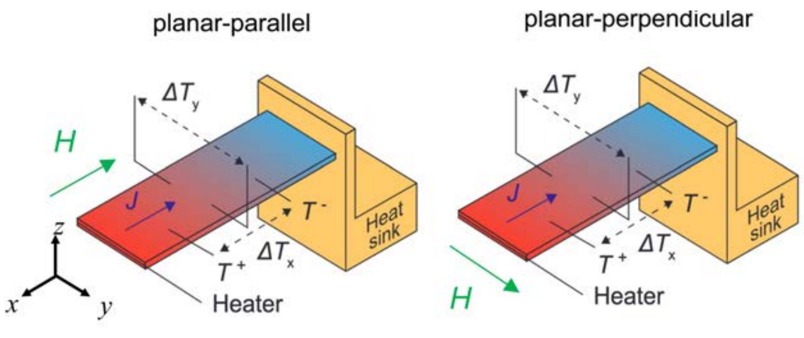
https://doi.org/10.1038/s41467-024-47858-5

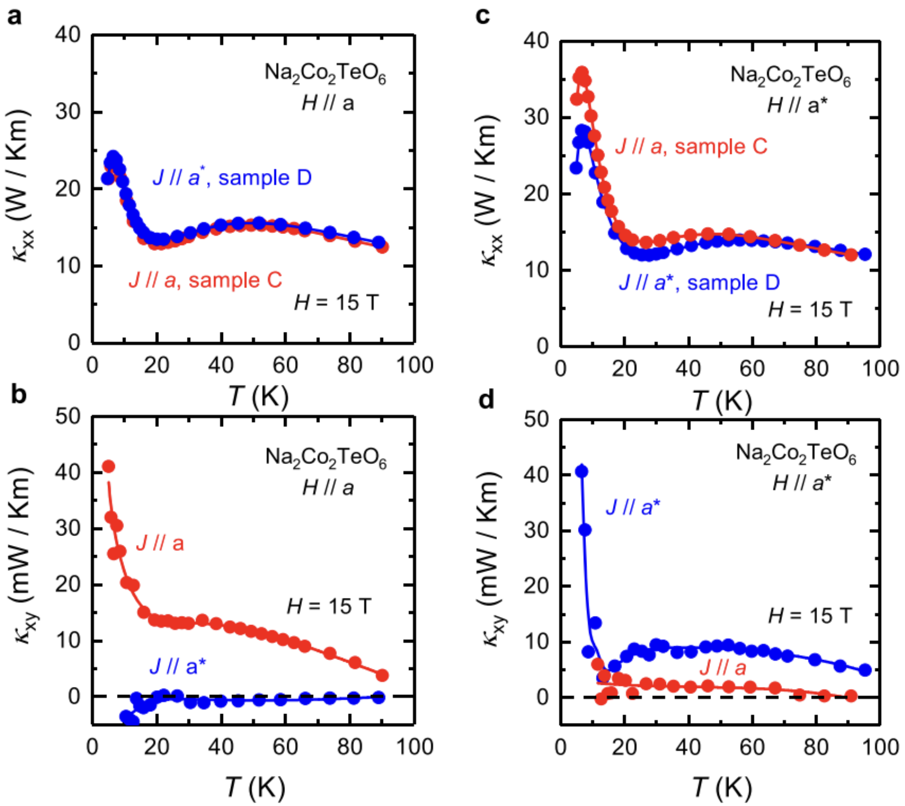
Planar thermal Hall effect from phonons in a Kitaev candidate material

Received: 20 October 2023

Accepted: 12 April 2024

Lu Chen[1,4], Étienne Lefrançois[1,4], Ashvini Vallipuram[1], Quentin Barthélemy[1], Amirreza Ataei[1], Weiliang Yao[2], Yuan Li[2] & Louis Taillefer[1,3]





- **Another Kitaev candidate material**
- **Planar THE from phonons**
- **A non-zero κ_{xy} signal in two field directions H // J // a and H // J // a***
- **Re-evaluation of the planar κ_{xy} origin in α-$RuCl_3$**

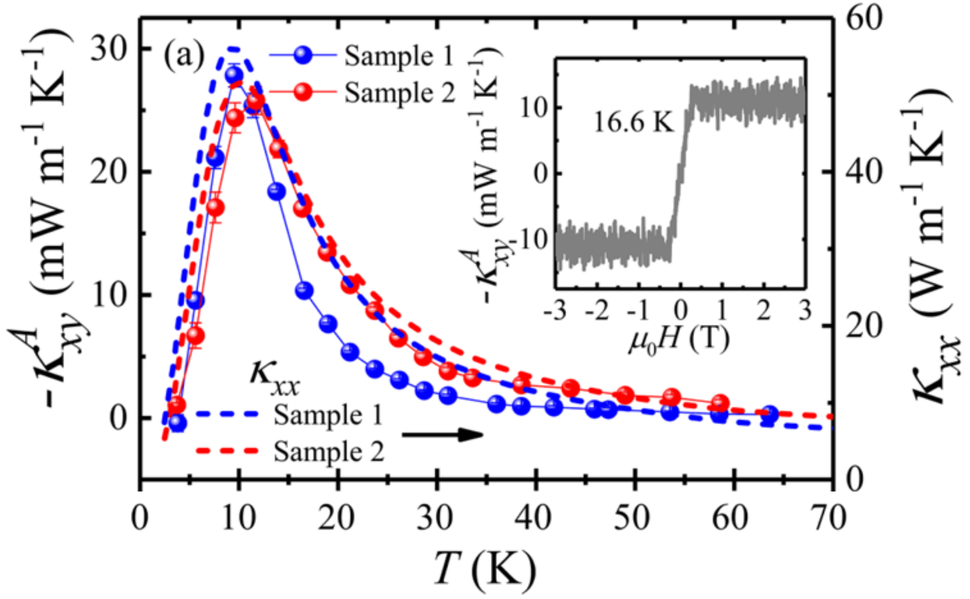
L. Chen *et al.*, Nat. Commun. 15, 3513 (2024)

CrI_3

PHYSICAL REVIEW B **109**, 094415 (2024)

Thermal Hall effect in the van der Waals ferromagnet CrI_3

Chunqiang Xu,[1,2,*] Heda Zhang,[1,*] Caitlin Carnahan,[3] Pengpeng Zhang,[1] Di Xiao,[4,5] and Xianglin Ke[1]
[1]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-2320, USA*



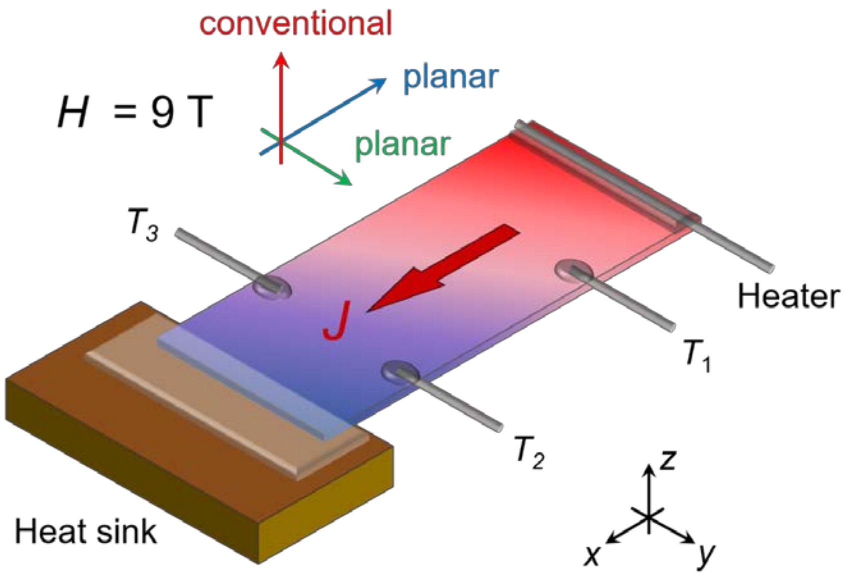
- **A prototypical van der Waals ferromagnet similar with VI_3**
- **Magnon-phonon hybridization or magnon-phonon scattering?**

C. Xu *et al.*, Phys. Rev. B 109, 094415 (2024)

Previous interpretations of THE in insulators

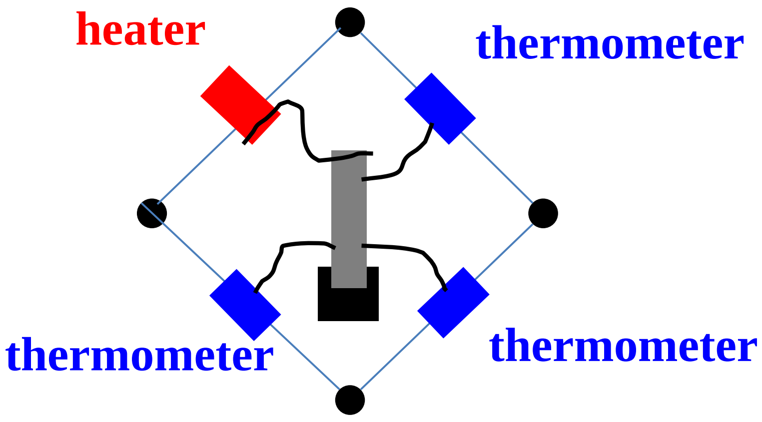
Title	Group	Arising from	Cite
Observation of the Magnon Hall Effect	Y. Tokura	the propagation of the spin waves influenced by the Dzyaloshinskii-Moriya spin-orbit interaction.	Science 329, 297 (2010)
Large thermal Hall conductivity of neutral spin excitations in a frustrated quantum magnet	N. P. Ong	the spin excitations with specific characteristics that distinguish them from magnons.	Science 348, 106 (2015)
Emergence of nontrivial magnetic excitations in a spin-liquid state of kagomé volborthite	M. Yamashita	the nontrivial elementary excitations in the gapless spin liquid state.	Proc. Natl. Acad. Sci. U.S.A. 113, 8653 (2016)
Giant thermal Hall effect in multiferroics	Y. Tokura	a coupling between magnetism and phonons.	Nat. Mater. 16, 797 (2017)
Majorana quantization and half-integer thermal quantum Hall effect in a Kitaev spin liquid	Y. Matsuda	the topologically protected chiral edge currents of charge-neutral Majorana fermions.	Nature 559, 227 (2018)
Giant thermal Hall conductivity in the pseudogap phase of cuprate superconductors	L. Taillefer	the neutral excitations with spin chirality in the pseudo-gap phase.	Nature 571, 376 (2019)
Chiral phonons in the pseudogap phase of cuprates	L. Taillefer	a coupling of phonons to their electronic environment.	Nat. Phys. 16, 1108 (2020)
Thermal Hall conductivity in the cuprate Mott insulators Nd_2CuO_4 and $Sr_2CuO_2Cl_2$	L. Taillefer	a coupling of acoustic phonons to the intrinsic excitations of the CuO_2 planes.	Nat. Commun. 11, 5325 (2020)
Half-integer quantized anomalous thermal Hall effect in the Kitaev material candidate a-$RuCl_3$	Y. Matsuda	the neutral Majorana fermions.	Science 373, 568 (2021)
Large phonon thermal Hall conductivity in the antiferromagnetic insulator Cu_3TeO_6	L. Taillefer	a likely possibility is scattering from local spin texture created by an impurity or defect embedded in a magnetic environment.	Proc. Natl. Acad. Sci. U.S.A. 119, e2208016119 (2022)
Planar thermal Hall effect of topological bosons in the Kitaev magnet α-$RuCl_3$	N. P. Ong	the spin excitations evolve into magnon-like modes with a Chern number of 1.	Nat. Mater. 22, 36 (2023)
The phonon thermal Hall angle in black phosphorus	K. Behnia	the anisotropic charge distribution surrounding atomic bonds.	Nat. Commun. 14, 1027 (2023)
Majorana-fermion origin of the planar thermal Hall effect in the Kitaev magnet α-$RuCl_3$	Y. Matsuda	the neutral Majorana fermions.	Sci. Adv. 10, eadk3539 (2024)
Phonon chirality from impurity scattering in the antiferromagnetic phase of Sr_2IrO_4	L. Taillefer	the scattering of phonons by impurities embedded within a magnetic environment.	Nat. Phys. 20, 585 (2024)

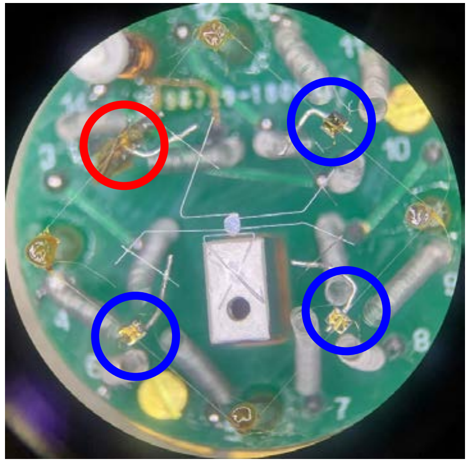
Experiment setup



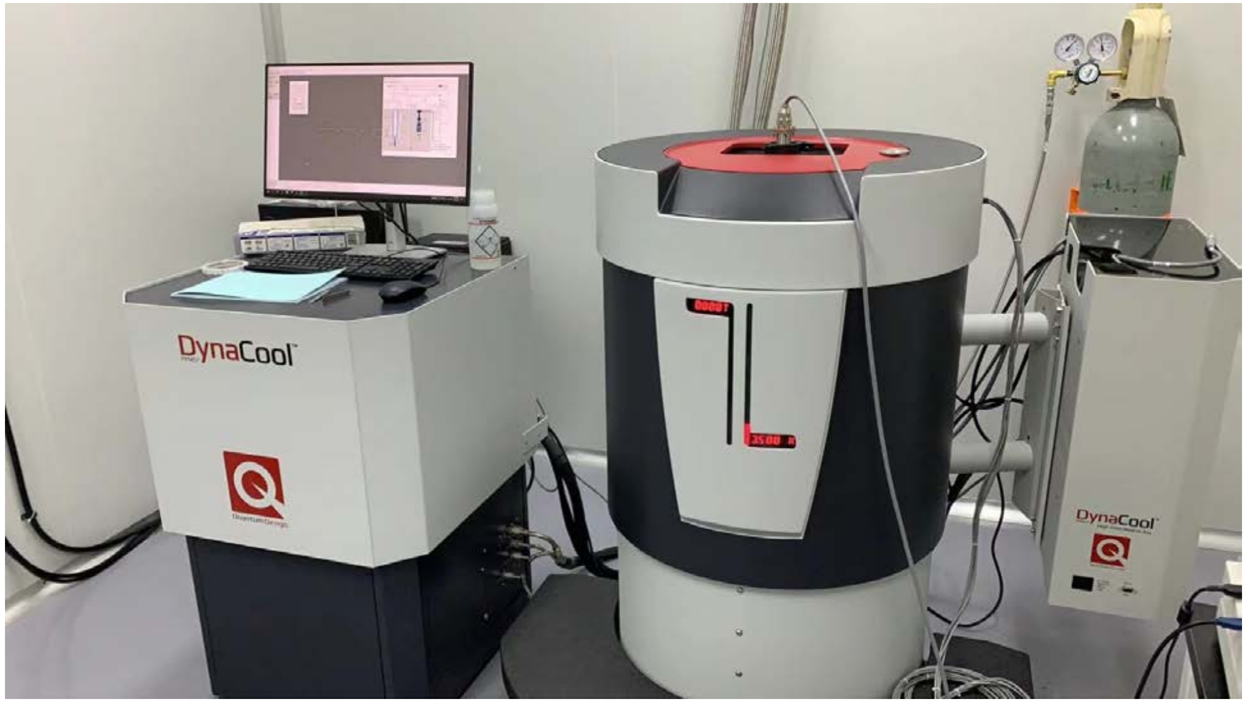
$$\kappa_{xx} = \frac{Q}{\Delta T_x} \frac{l}{w\,t}$$

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



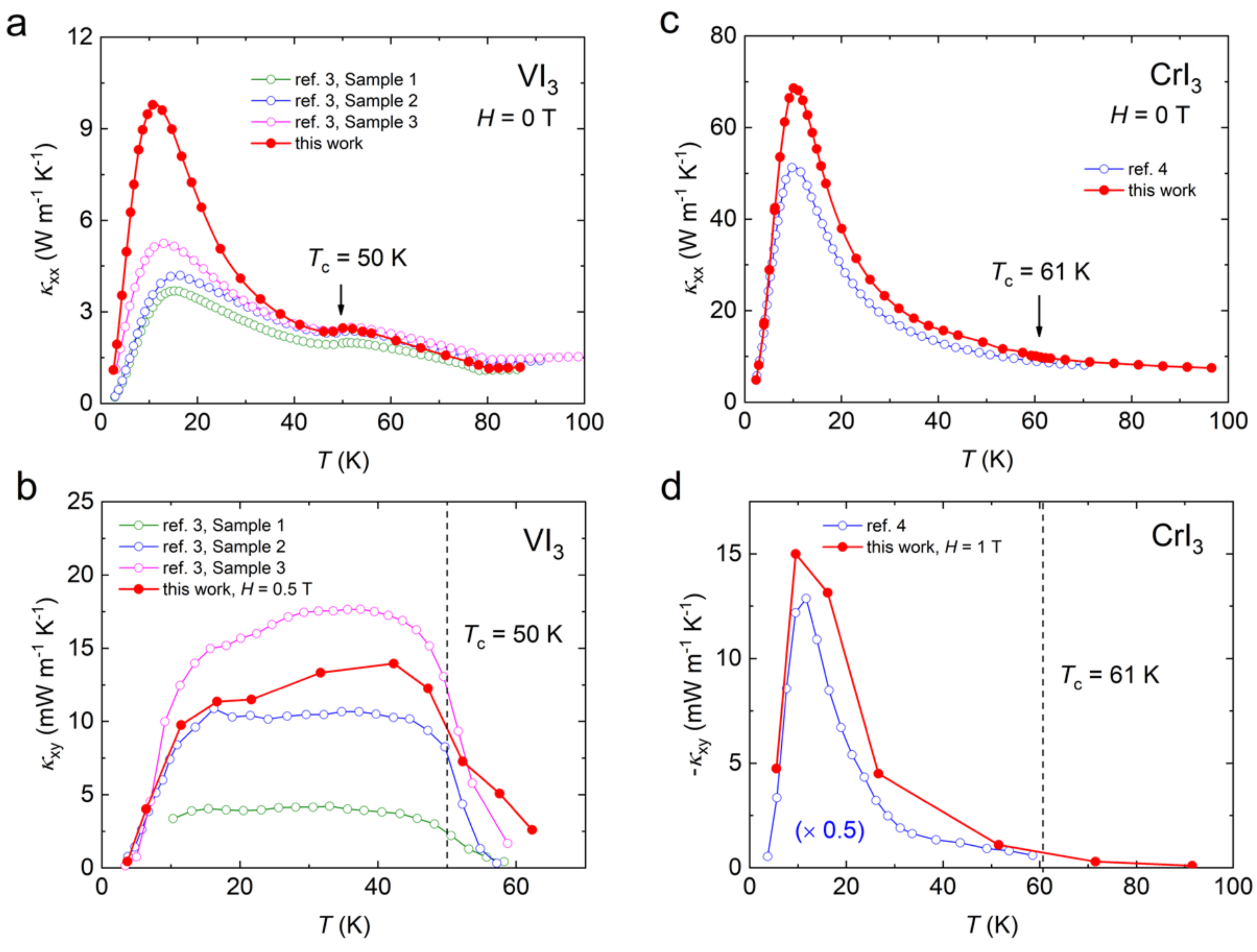


PPMS



1.8 K, 12 T

CrI_3、$CrBr_3$、$CrCl_3$



Chiral phonons in SiO_2

Hiroki Ueda (*Paul Scherrer Institute*)

Chiral phonons probed by X rays

Article

Chiral phonons in quartz probed by X-rays

https://doi.org/10.1038/s41586-023-06016-5
Received: 20 January 2023
Accepted: 27 March 2023
Published online: 7 June 2023

Hiroki Ueda[1,2✉], Mirian García-Fernández[3], Stefano Agrestini[3], Carl P. Romao[4], Jeroen van den Brink[5,6], Nicola A. Spaldin[4], Ke-Jin Zhou[3] & Urs Staub[1✉]

The concept of chirality is of great relevance in nature, from chiral molecules such as sugar to parity transformations in particle physics. In condensed matter physics,

Chiral phonons in SiO_2

Article

Chiral phonons in quartz probed by X-rays

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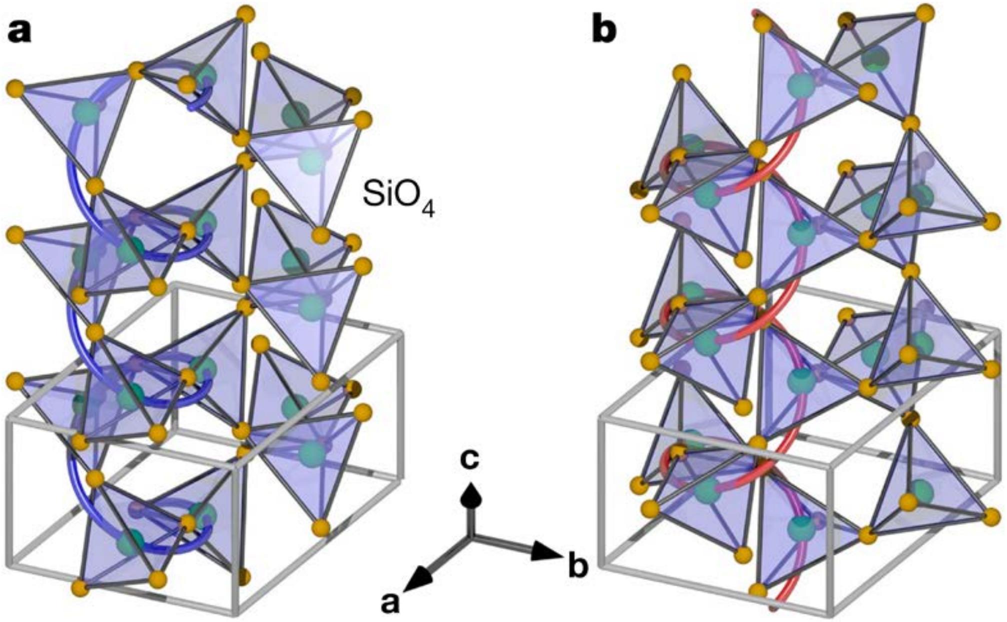
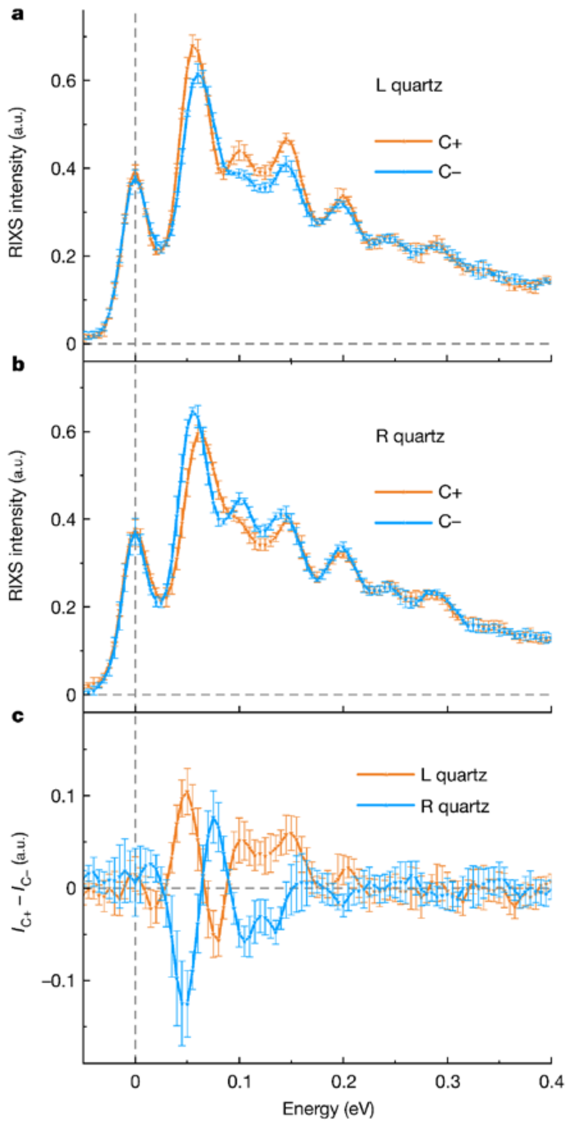
Hiroki Ueda[1,2] ✉, Mirian García-Fernández[3], Stefano Agrestini[3], Carl P. Romao[4], Jeroen van den Brink[5,6], Nicola A. Spaldin[4], Ke-Jin Zhou[3] & Urs Staub[1] ✉

The concept of chirality is of great relevance in nature, from chiral molecules such as sugar to parity transformations in particle physics. In condensed matter physics,

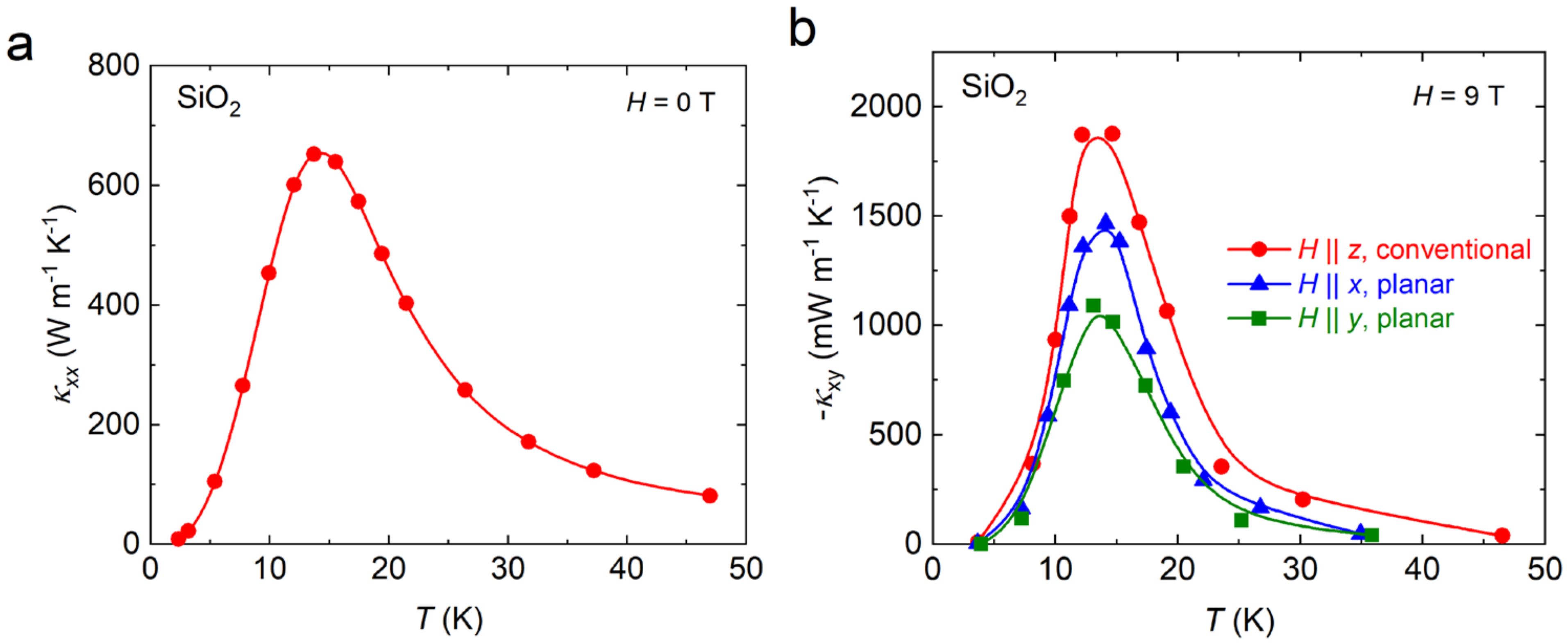




Chiral structure in SiO_2

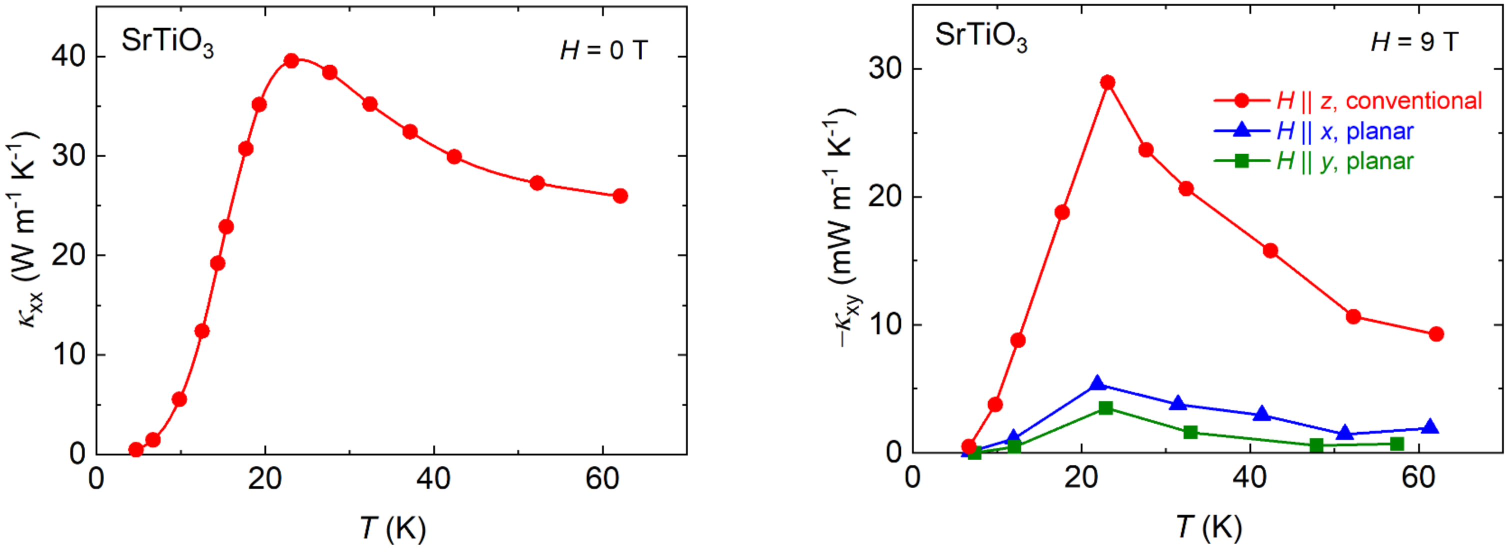
H. Ueda *et al.*, Nature 618, 946-950 (2023)

Phonon thermal Hall effect in SiO_2



Chiral phonons?

Phonon thermal Hall effect in $SrTiO_3$



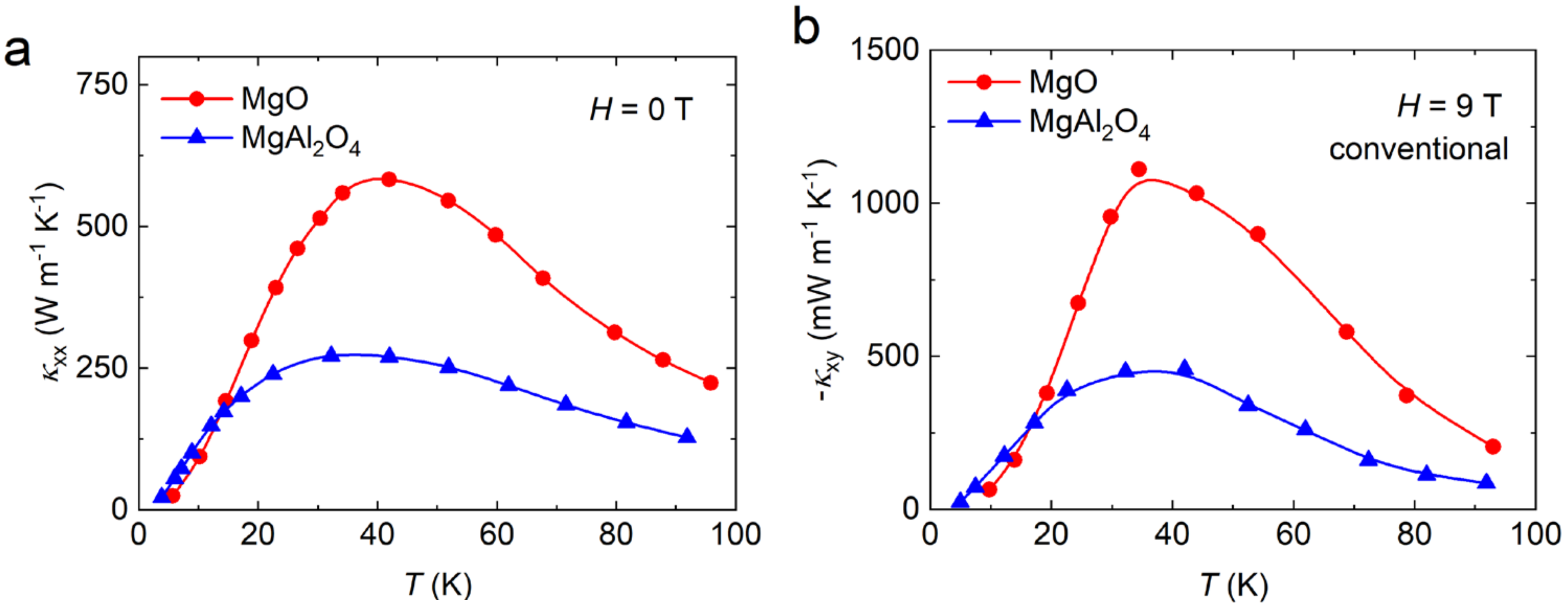
Non-magnetic material

phonon is the only well-defined quasiparticle, leaving no doubt that THE comes from phonons

Our results show that planar phonon THE also exists in non-magnetic material without the need to interact with a magnetic environment.

Structure domains?

First surprise: phonon thermal Hall effect in MgO



Why does trivial insulator MgO have phonon THE ?

Hall viscosity induced by magnetic field in ionic crystals

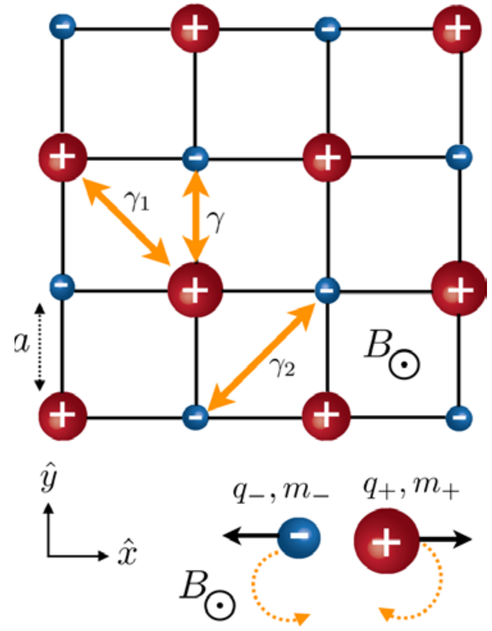
PHYSICAL REVIEW LETTERS **131,** 236301 (2023)

Phonon Hall Viscosity of Ionic Crystals

B. Flebus[1] and A. H. MacDonald[2]

$$\omega^2 \begin{pmatrix} \mathbf{u}_+ \\ \mathbf{u}_- \end{pmatrix} = \mathcal{A}(\mathbf{k},\omega) \begin{pmatrix} \mathbf{u}_+ \\ \mathbf{u}_- \end{pmatrix}$$

- Action of Lorentz forces on dipoles
- Coupling between acoustic and optical phonon in magnetic fields



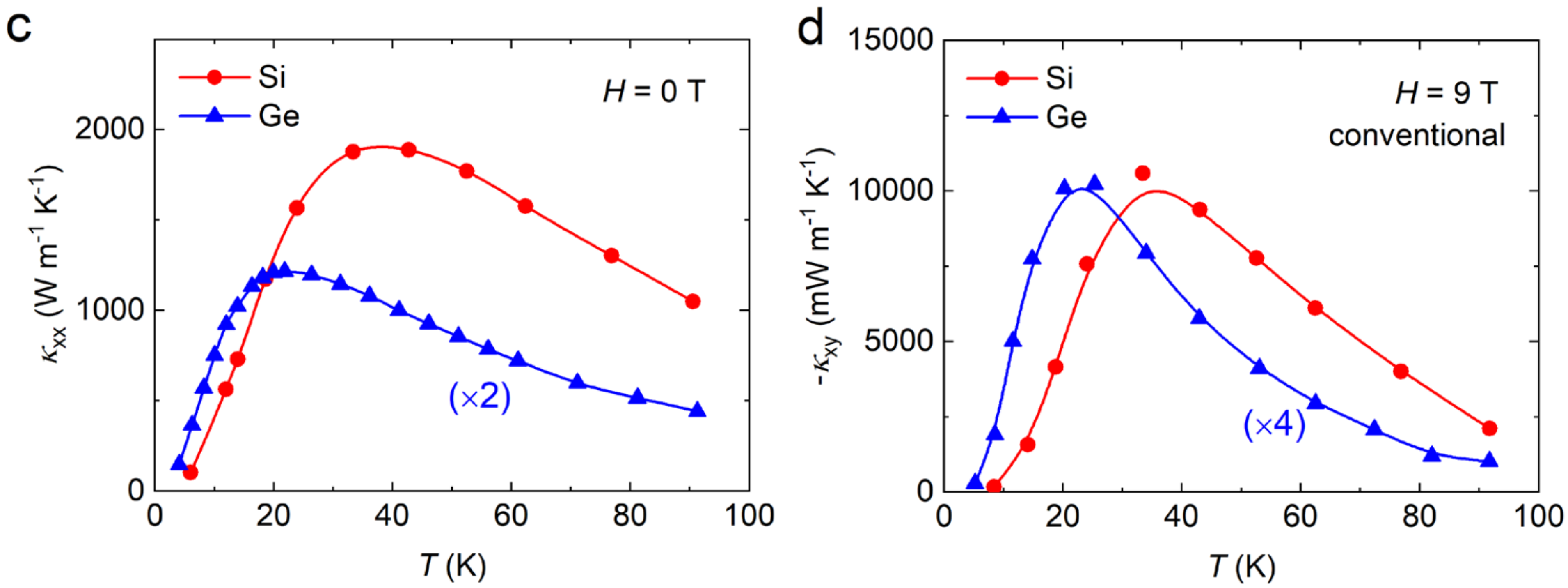
$$\mathcal{A}(k_x,\omega) = \begin{bmatrix} \frac{(2\gamma+\gamma_1+\gamma_2)(k_x a)^2}{m_+ + m_-} & 0 & \frac{[m_+(\gamma+\gamma_2)-m_-(\gamma+\gamma_1)](k_x a)^2}{\sqrt{m_+ m_-}(m_+ + m_-)} & -\frac{iZeB\omega}{\sqrt{m_+ m_-}} \\ 0 & \frac{(\gamma_1+\gamma_2)(k_x a)^2}{m_+ + m_-} & \frac{iZeB\omega}{\sqrt{m_+ m_-}} & \frac{(m_+\gamma_2 - m_-\gamma_1)(k_x a)^2}{\sqrt{m_+ m_-}(m_+ + m_-)} \\ \frac{[m_+(\gamma+\gamma_2)-m_-(\gamma+\gamma_1)](k_x a)^2}{\sqrt{m_+ m_-}(m_+ + m_-)} & -\frac{iZeB\omega}{\sqrt{m_+ m_-}} & \frac{2\gamma(m_+ + m_-)^2 + (\gamma_2 m_+^2 + \gamma_1 m_1^2 - 2\gamma m_+ m_-)(k_x a)^2}{m_+ m_-(m_+ + m_-)} & -\frac{iZeB(m_+ - m_-)\omega}{m_+ m_-} \\ \frac{iZeB\omega}{\sqrt{m_+ m_-}} & \frac{(m_+\gamma_2 - m_-\gamma_1)(k_x a)^2}{\sqrt{m_+ m_-}(m_+ + m_-)} & \frac{iZeB(m_+ - m_-)\omega}{m_+ m_-} & \frac{2\gamma(m_+ + m_-)^2 + (m_+^2\gamma_2 + m_-^2\gamma_1)(k_x a)^2}{m_+ m_-(m_+ + m_-)} \end{bmatrix}$$

$$\eta_H = \frac{m_+(\gamma + 2\gamma_2) - m_-(\gamma + 2\gamma_1)}{2\gamma(m_+ + m_-)} Z^* eB.$$

the Lorentz forces on cations and anions moving in opposite directions do not cancel

B. Flebus and A. H. MacDonald, Phys. Rev. Lett. 131, 236301 (2023)

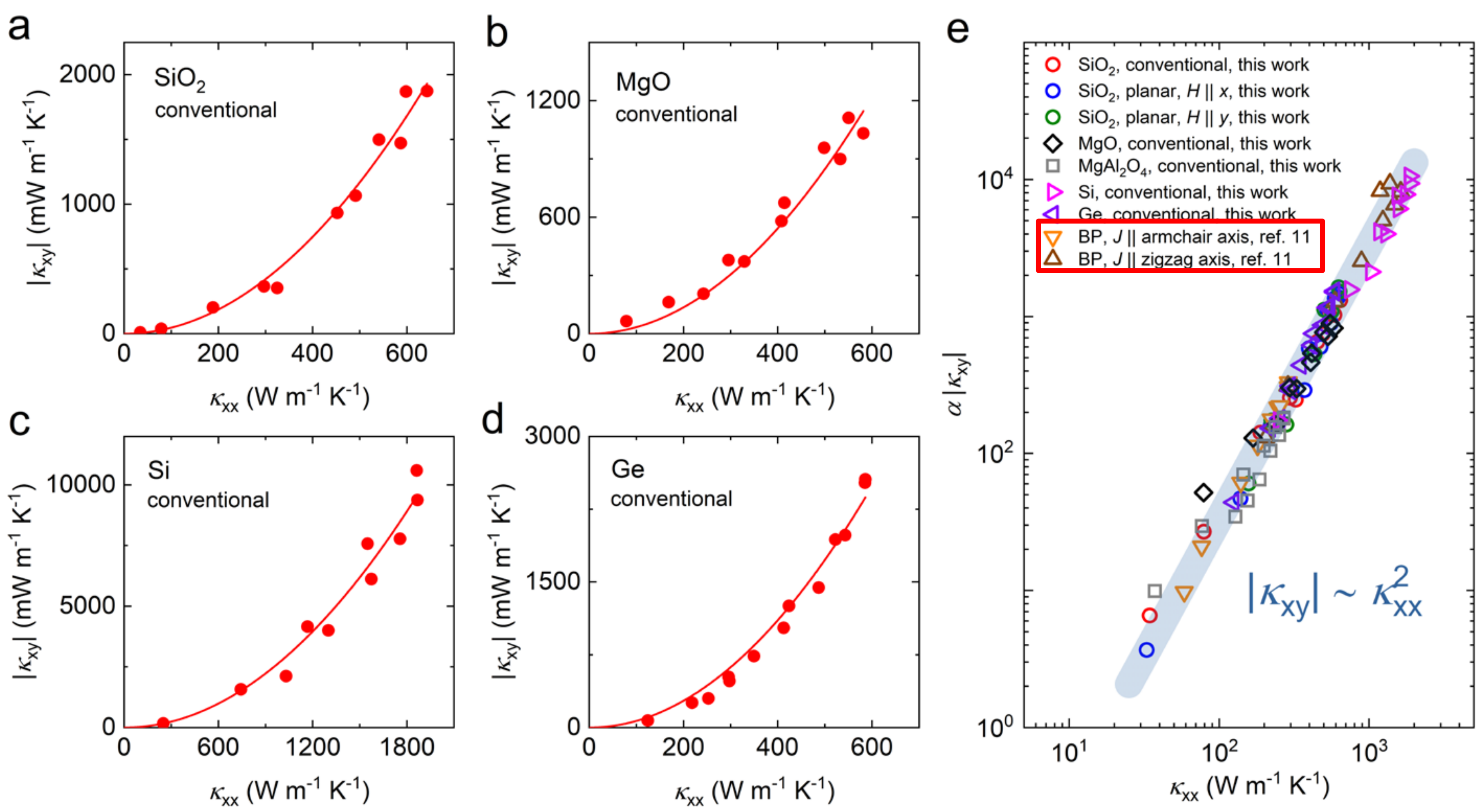
Second surprise: phonon thermal Hall effect in Si



We finally realize that phonon thermal Hall effect is a universal property of all crystals!

The peak magnitude of κ_{xy} in Si is about 10 W m^{-1} K^{-1}, which is the largest in all reported crystals so far.

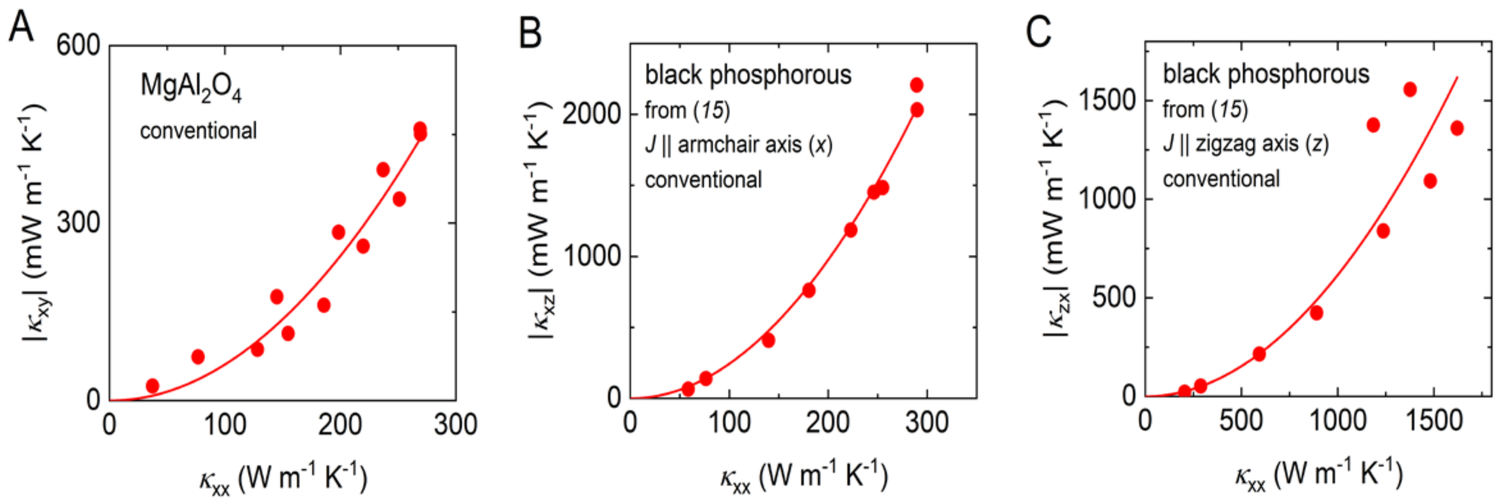
Universal scaling law of $|\kappa_{xy}| \sim \kappa_{xx}^2$



Universal phonon thermal Hall effect!

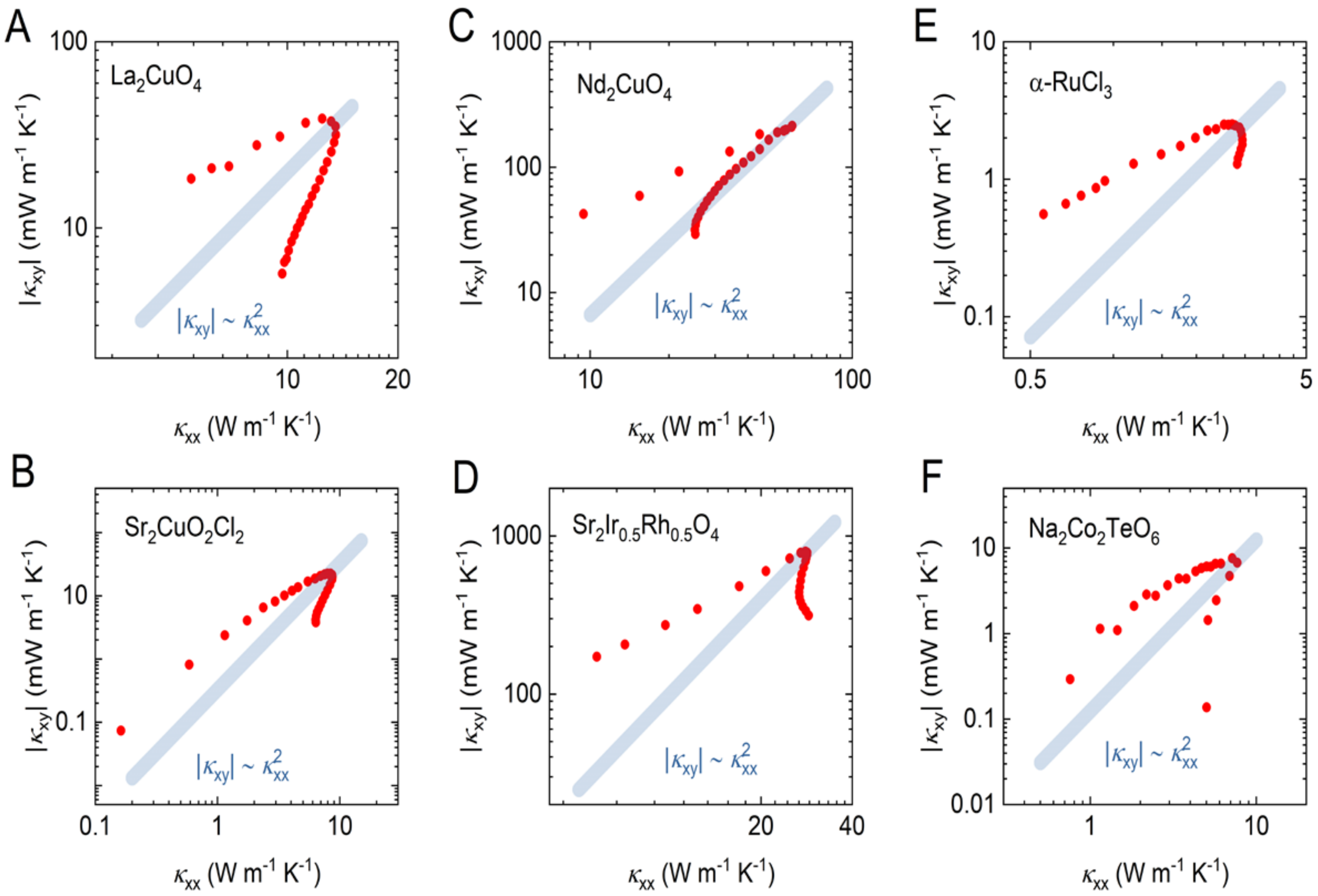
Universal scaling law of $|\kappa_{xy}| \sim \kappa_{xx}^2$

BP data from Li, X. *et al*. Nat. Commun. 14, 1027 (2023)



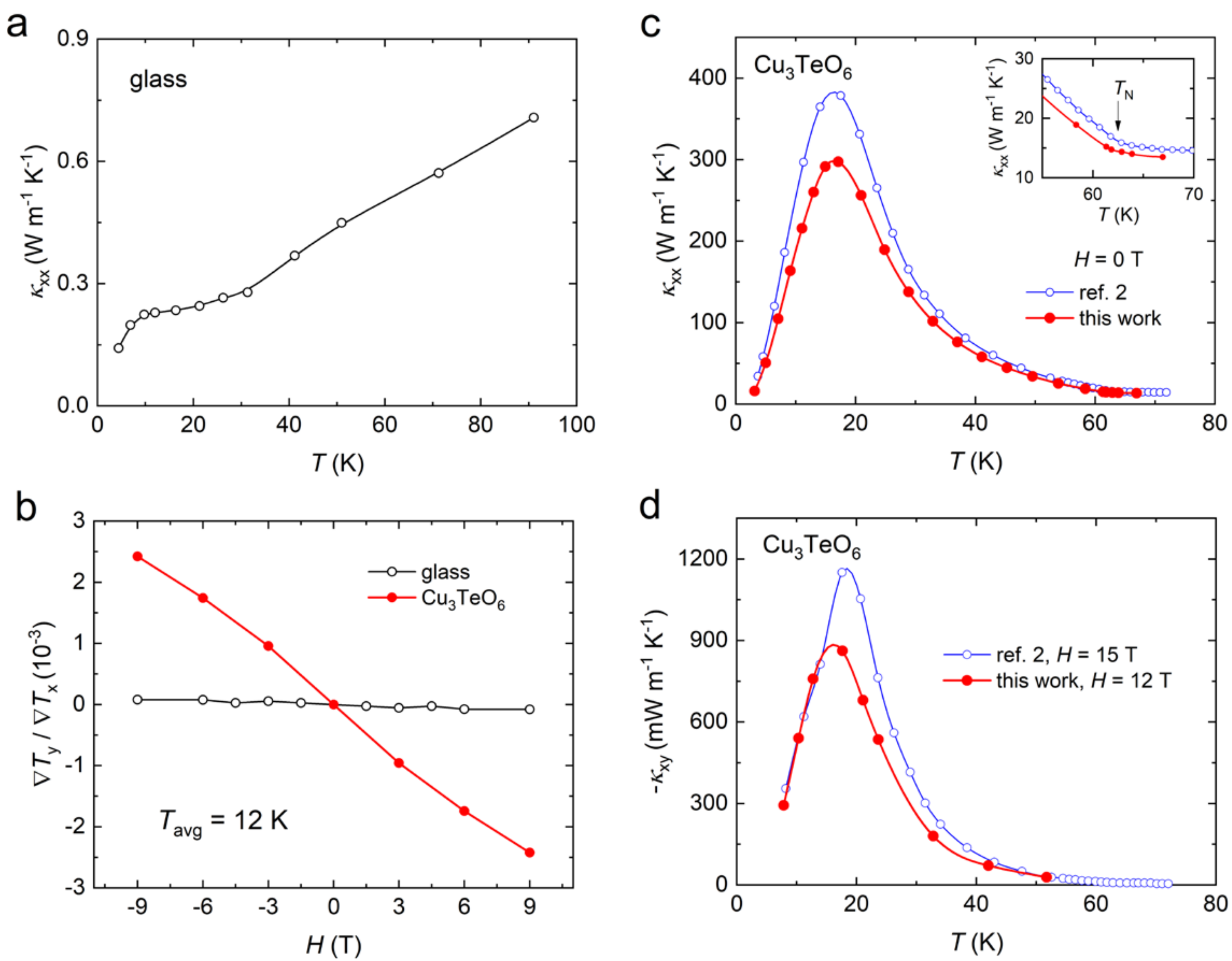
Universal phonon thermal Hall effect!

Deviation from universal scaling law in magnetic insulators



X. B. Jin *et al.*, arXiv:2404.02863

Examinations on the experiment setup



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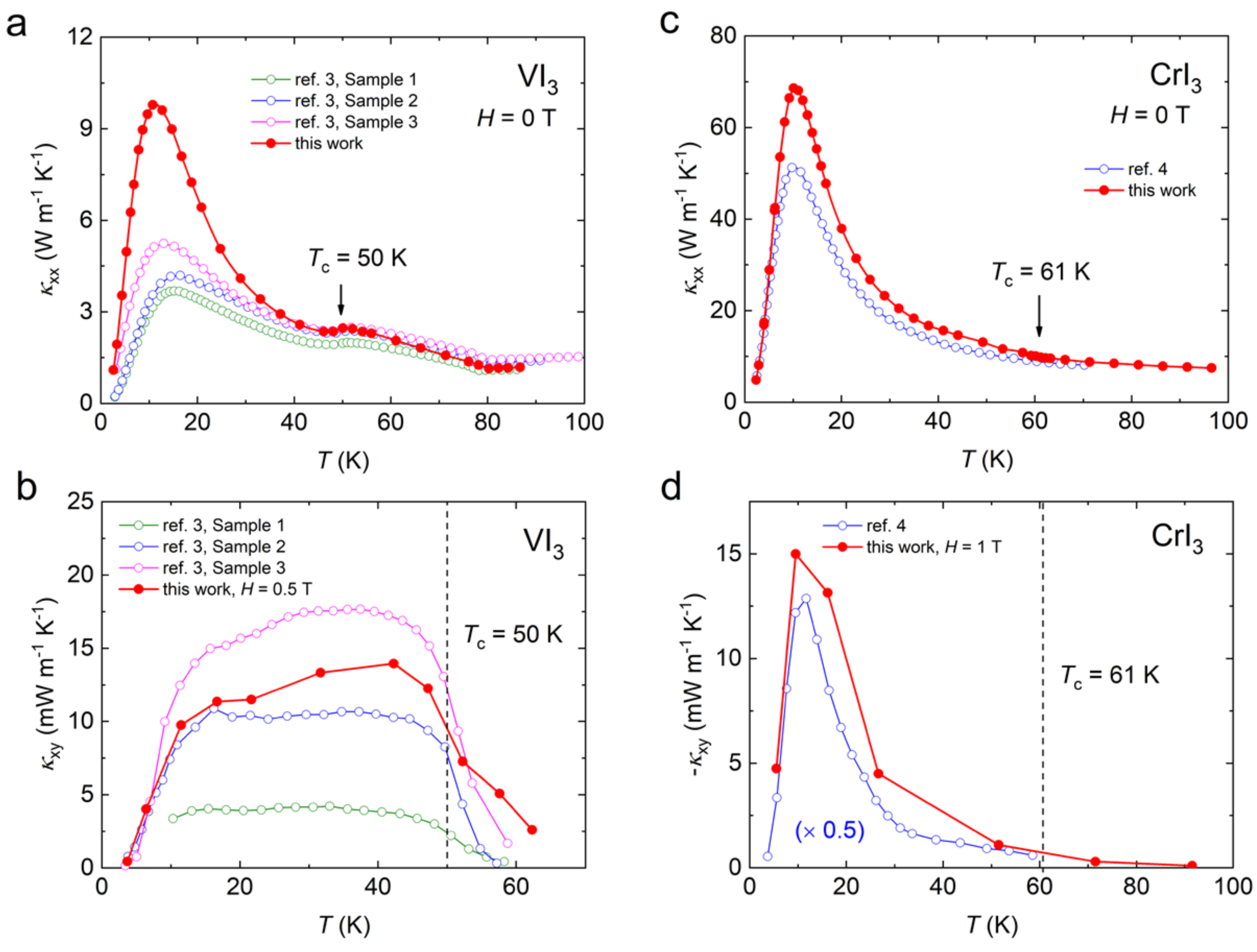
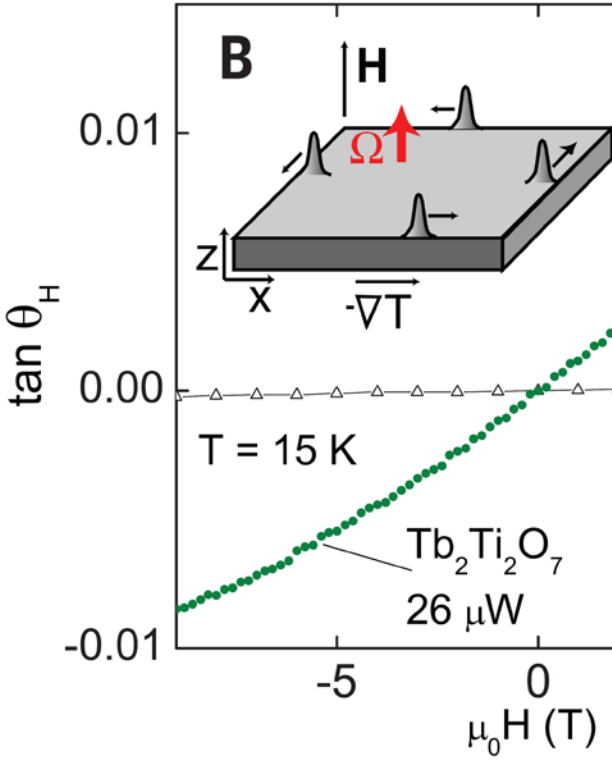
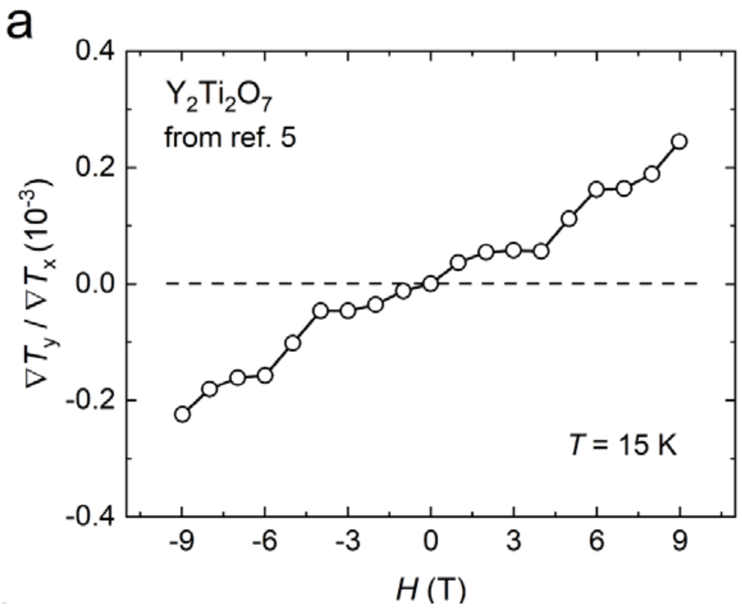


The effect of copper block heat sink





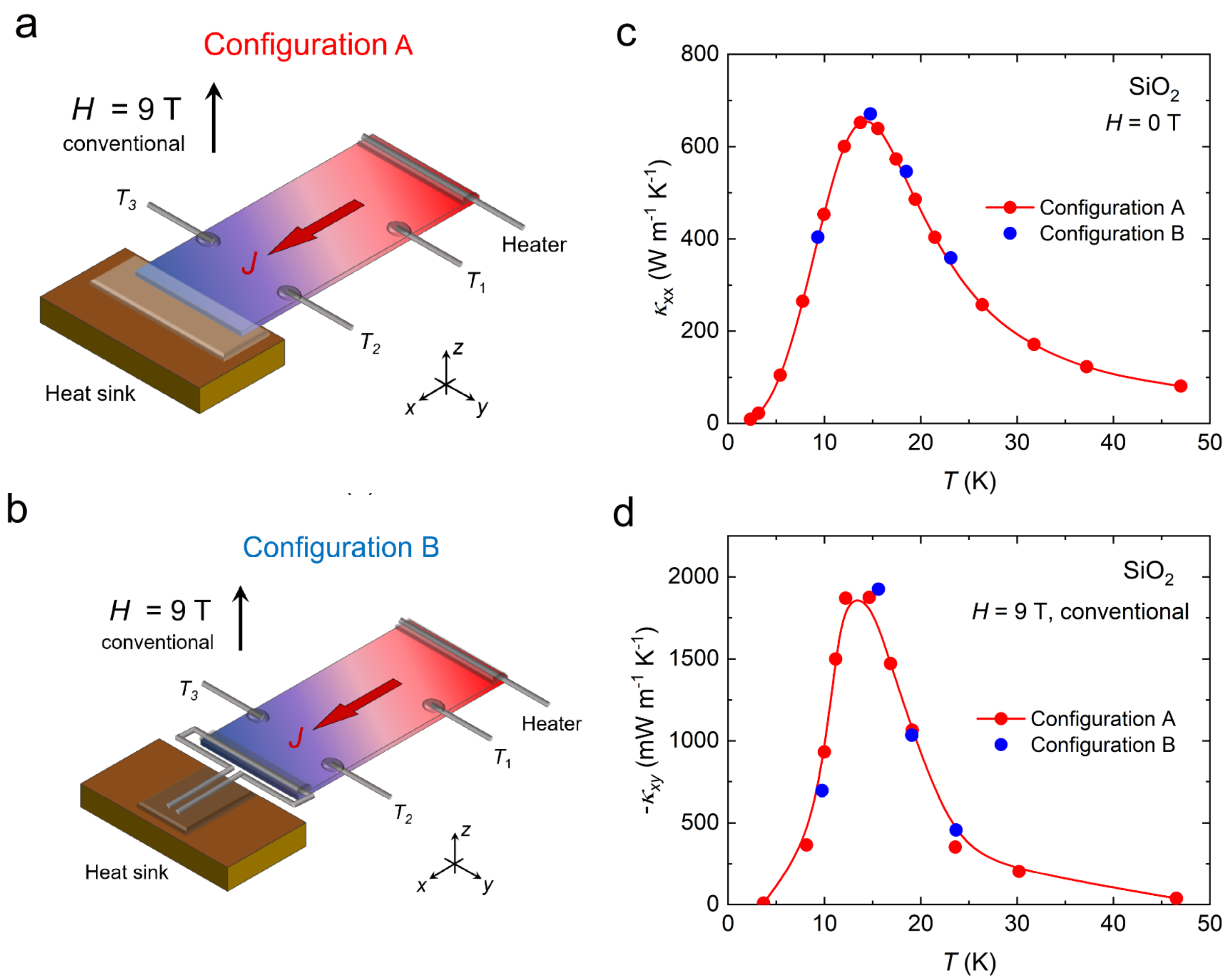
Thermal Hall angle： ~ 0.25%

$Y_2Ti_2O_7$ ~ $SrTiO_3$

pound. We attribute the remaining, non-vanishing Hall signal in $Y_2Ti_2O_7$ to temperature gradients on the brass block (heat bath) our sample is mounted on. This type

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

The effect of copper block heat sink



Thermal Hall effect in $Y_2Ti_2O_7$

PHYSICAL REVIEW B
covering condensed matter and materials physics

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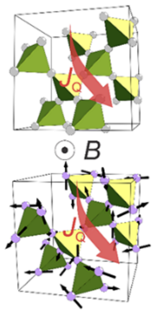
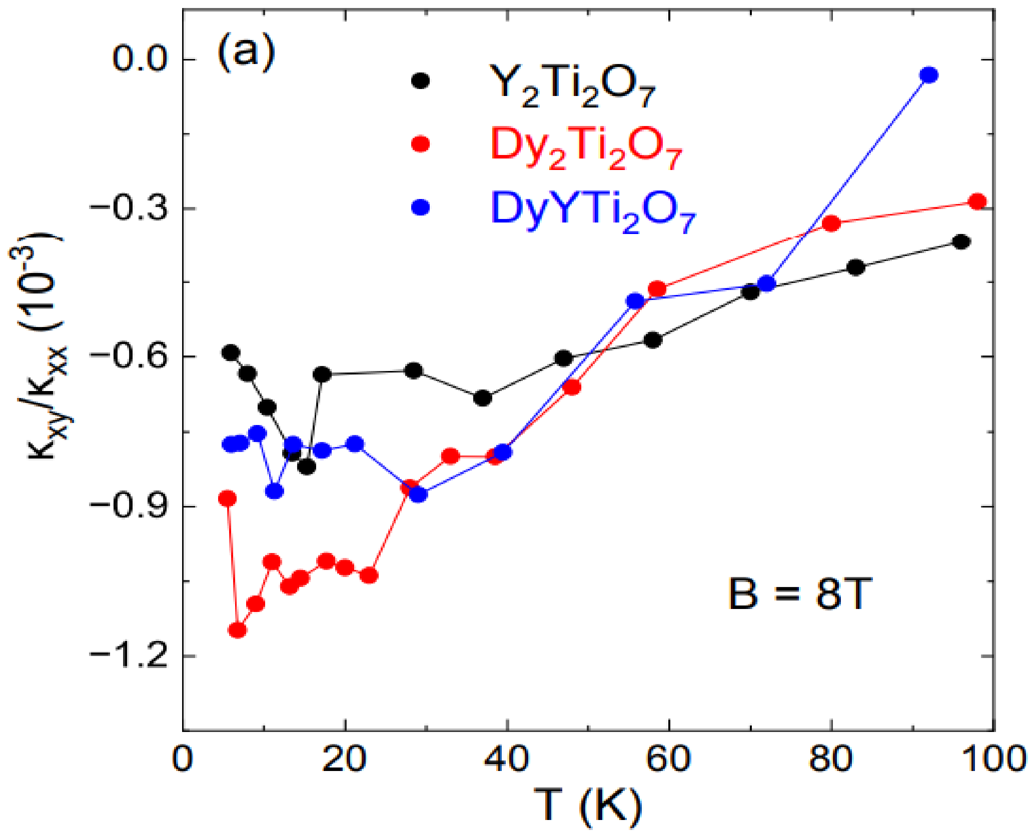


EDITORS' SUGGESTION

Phonon thermal Hall effect in nonmagnetic $Y_2Ti_2O_7$

The authors report a field-linear thermal Hall effect in single-crystal samples of $Y_2Ti_2O_7$, $Dy_2Ti_2O_7$, and $DyYTi_2O_7$. The slopes κ_{xy}/B show temperature-dependent peaks that align with corresponding peaks in the respective longitudinal thermal conductivities $\kappa_{xx}(T)$. This is consistent with a phononic thermal Hall effect, observed in a growing number of insulating materials. While the presence of magnetic Dy^{3+} ions significantly influences the longitudinal thermal conductivities, the thermal Hall ratios vary rather weakly between magnetic and nonmagnetic materials, suggesting a primarily nonmagnetic origin of the thermal Hall effect.

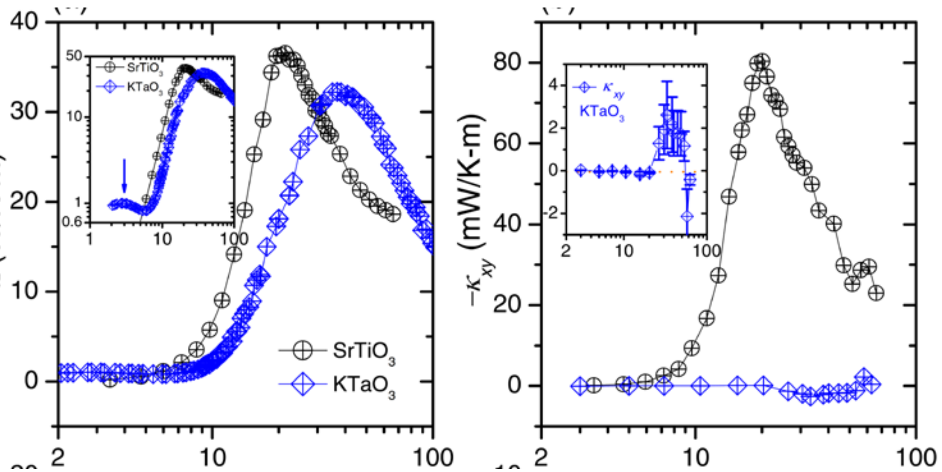
Rohit Sharma, Martin Valldor, and Thomas Lorenz
Phys. Rev. B **110**, L100301 (2024)



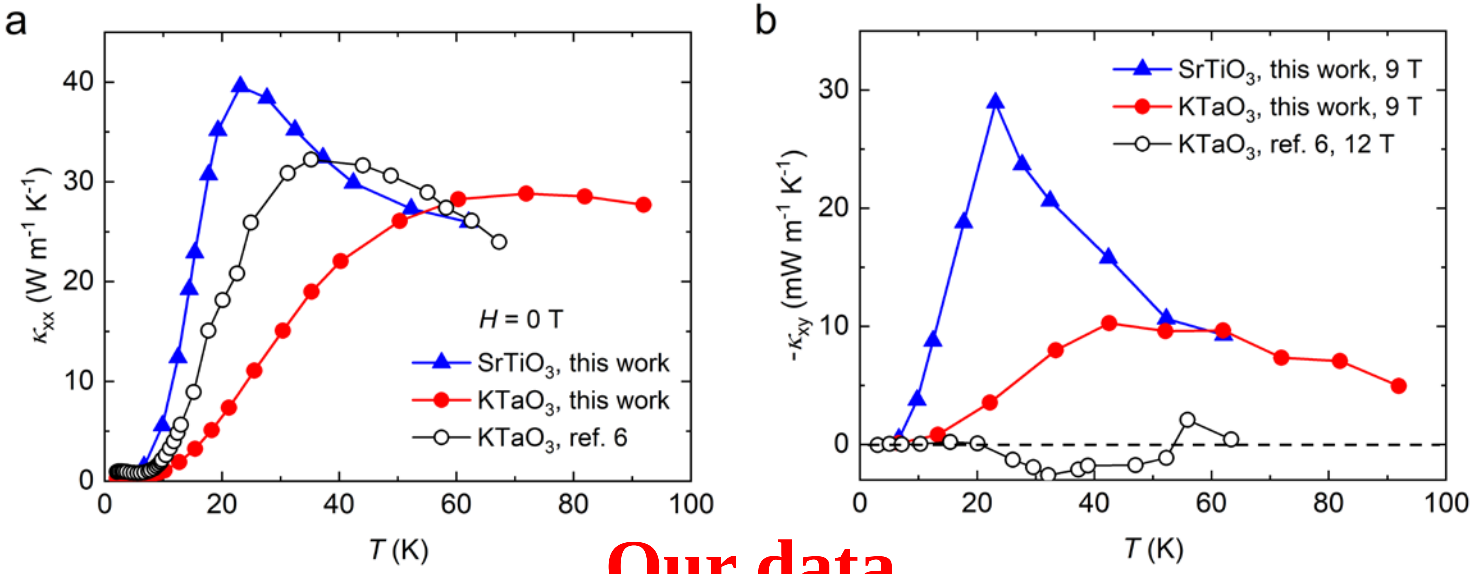
Prof. Thomas Lorenz's group

R. Shama *et al*. Phys. Rev. B 110, L100301 (2024)

Thermal Hall effect in $KTaO_3$



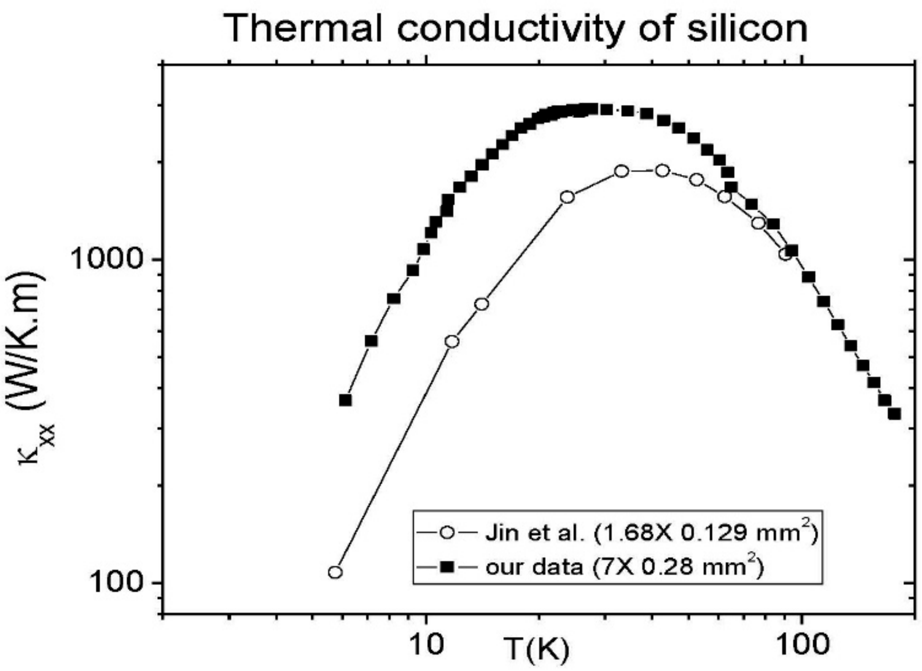
Li, X. *et al*. Phys. Rev. Lett. 124, 105901 (2020)

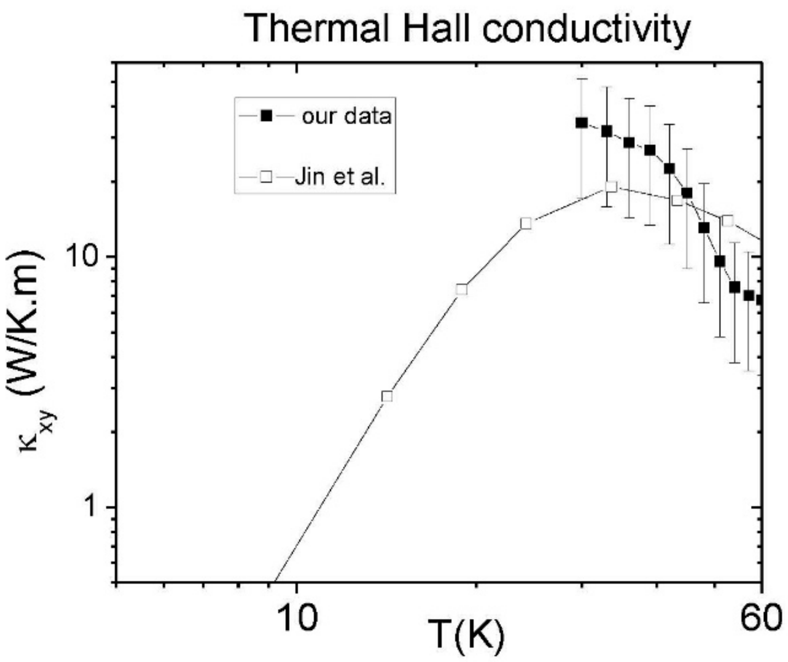


Our data

Reproducibility of our results

Longitudinal and Hall thermal conductivity in silicon





Thomas Bouteiller et al. (Behnia group) , to be published.

Prof. Kamran Behnia's group reproduced our Si results

Looking back …

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Observation of the Magnon Hall Effect	Y. Tokura	the propagation of the spin waves influenced by the Dzyaloshinskii-Moriya spin-orbit interaction.	Science 329, 297 (2010)
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Majorana-fermion origin of the planar thermal Hall effect in the Kitaev magnet α-$RuCl_3$	Y. Matsuda	the neutral Majorana fermions.	Sci. Adv. 10, eadk3539 (2024)
Phonon chirality from impurity scattering in the antiferromagnetic phase of Sr_2IrO_4	L. Taillefer	the scattering of phonons by impurities embedded within a magnetic environment.	Nat. Phys. 20, 585 (2024)

All previous THE can be understood, starting from an intrinsic phonon THE. No need for monopoles, Majorana fermions …

The planar THE: phonons couple to the field in any direction.

The origin of universal phonon thermal Hall effect?

- Extrinsic: coupling to the magnetic environment, impurity scattering, AFD domains…
- **Intrinsic:**

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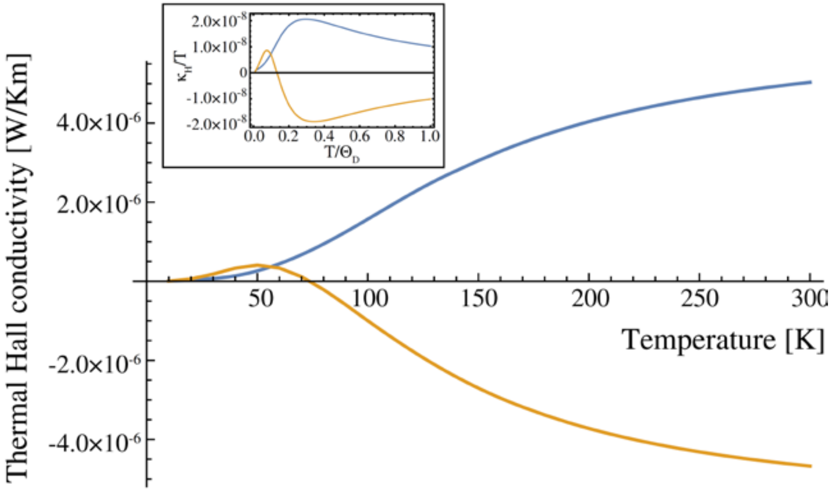
Berry Phase of Phonons and Thermal Hall Effect in Nonmagnetic Insulators

Takuma Saito,[1] Kou Misaki,[1] Hiroaki Ishizuka,[1] and Naoto Nagaosa[1,2]
[1]*Department of Applied Physics, The University of Tokyo, Bunkyo-ku, Tokyo, 113-8656, Japan*
[2]*RIKEN Center for Emergent Matter Science (CEMS), Wako, Saitama, 351-0198, Japan*



Si

Calculation: $\kappa_{xy} \sim 10^{-6}$ **W m^{-1} K^{-1}**

Our result: $\kappa_{xy} \sim 10$ **W m^{-1} K^{-1}**

Summary

1、By measuring a series of trivial non-magnetic insulators and intrinsic semiconductors, including $SrTiO_3$, SiO_2, MgO, $MgAl_2O_4$, Si and Ge, we have experimentally discovered a universal phonon THE in crystals, characterized by a scaling law of $|\kappa_{xy}| \sim \kappa_{xx}^2$.

2、All previous THE can be understood, starting from this universal phonon THE. No need for exotic excitations.

3、Theory for the fundamental physics of this universal phonons THE is highly desired, which should relate to the direct coupling of atom vibrations to the magnetic field.

However, when we broaden our knowledge, we may encounter new phenomena which cannot be explained by old theory. Then we have to re-examine the basis of our old system and suggest new method.

—— T. D. Lee, Nobel Prize Award Ceremony, 1957

X. B. Jin *et al.*, arXiv:2404.02863

Thank you for your attention !