Chiral phononics

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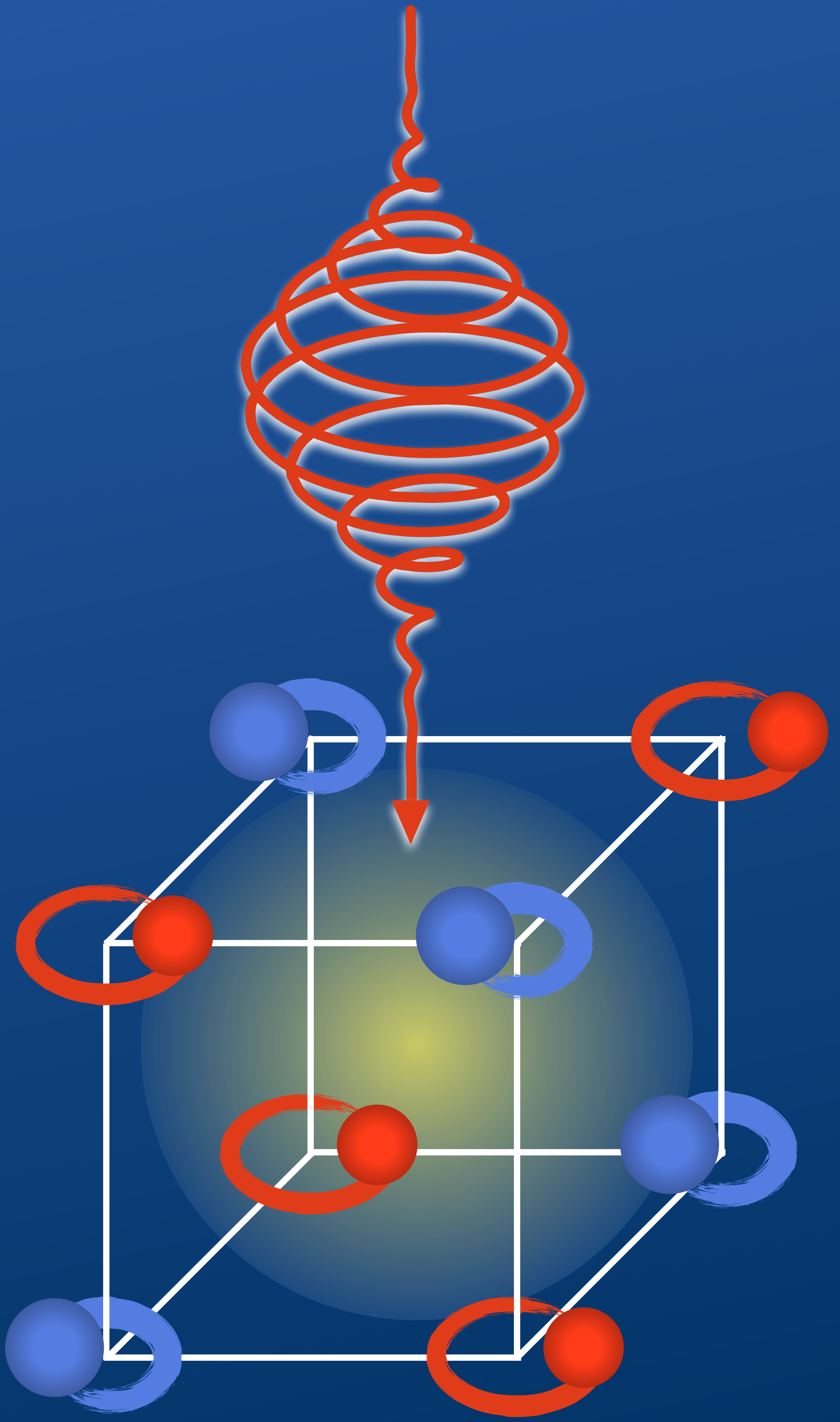
TEL AVIV UNIVERSITY אוניברסיטת תל אביב

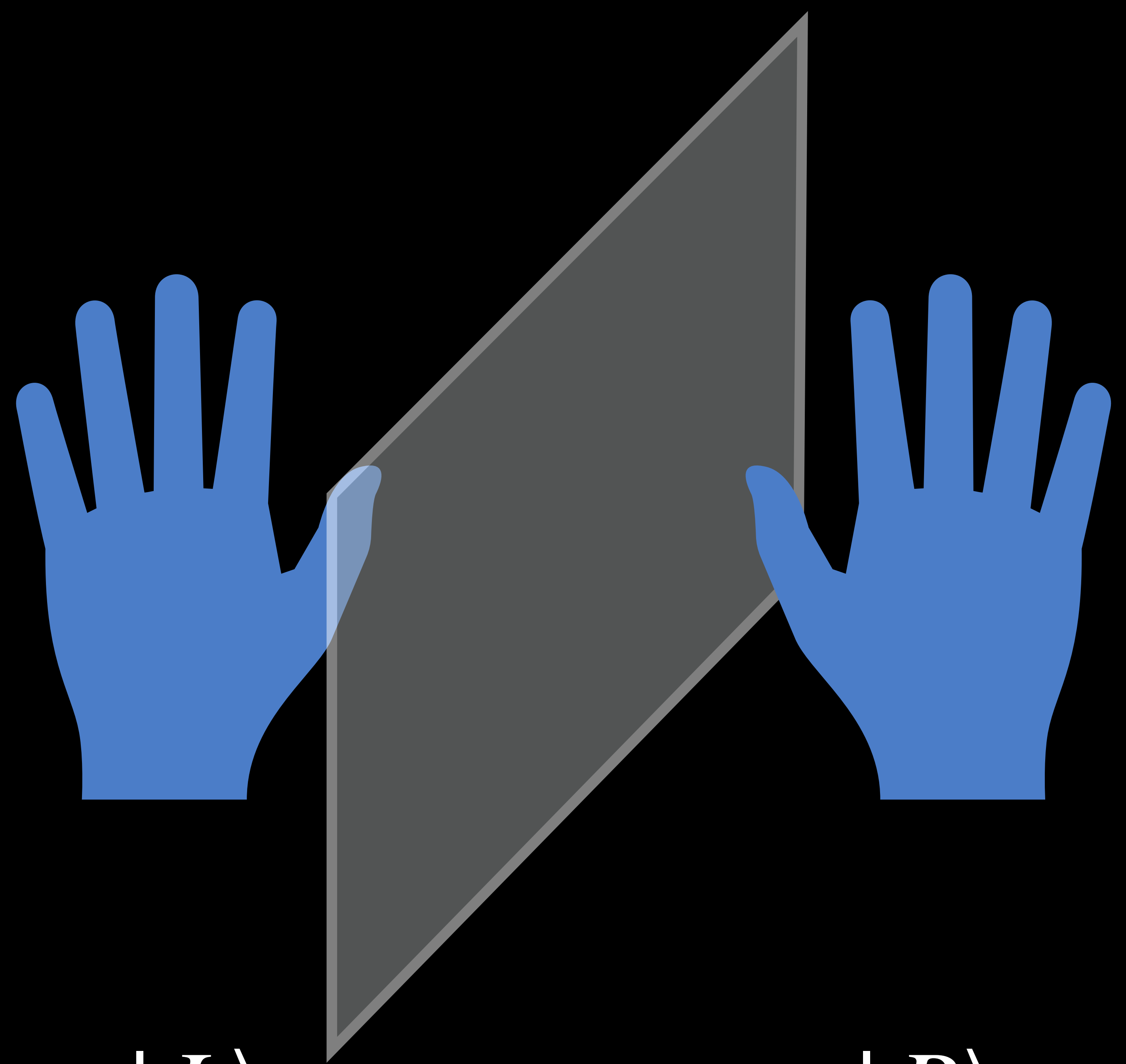
DYNAMICAL



Chirality

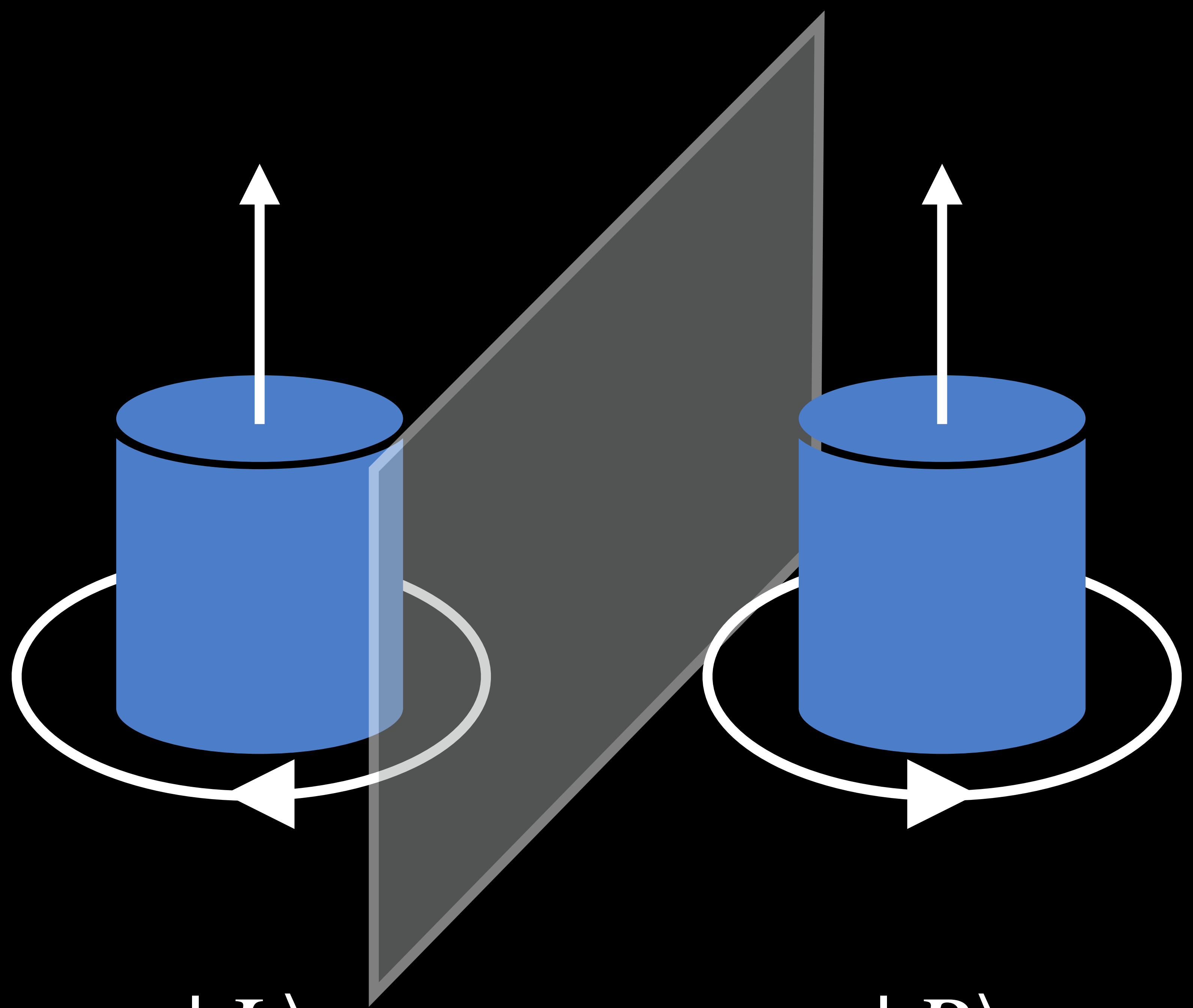
TU/e Chirality means no improper rotation symmetry

Static chirality



$|L\rangle$ $|R\rangle$

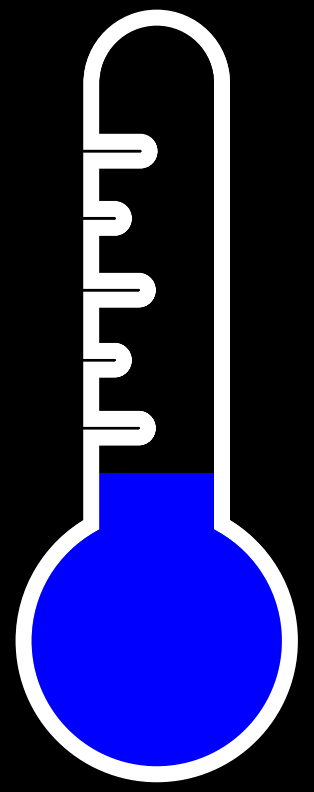
Motion-based chirality

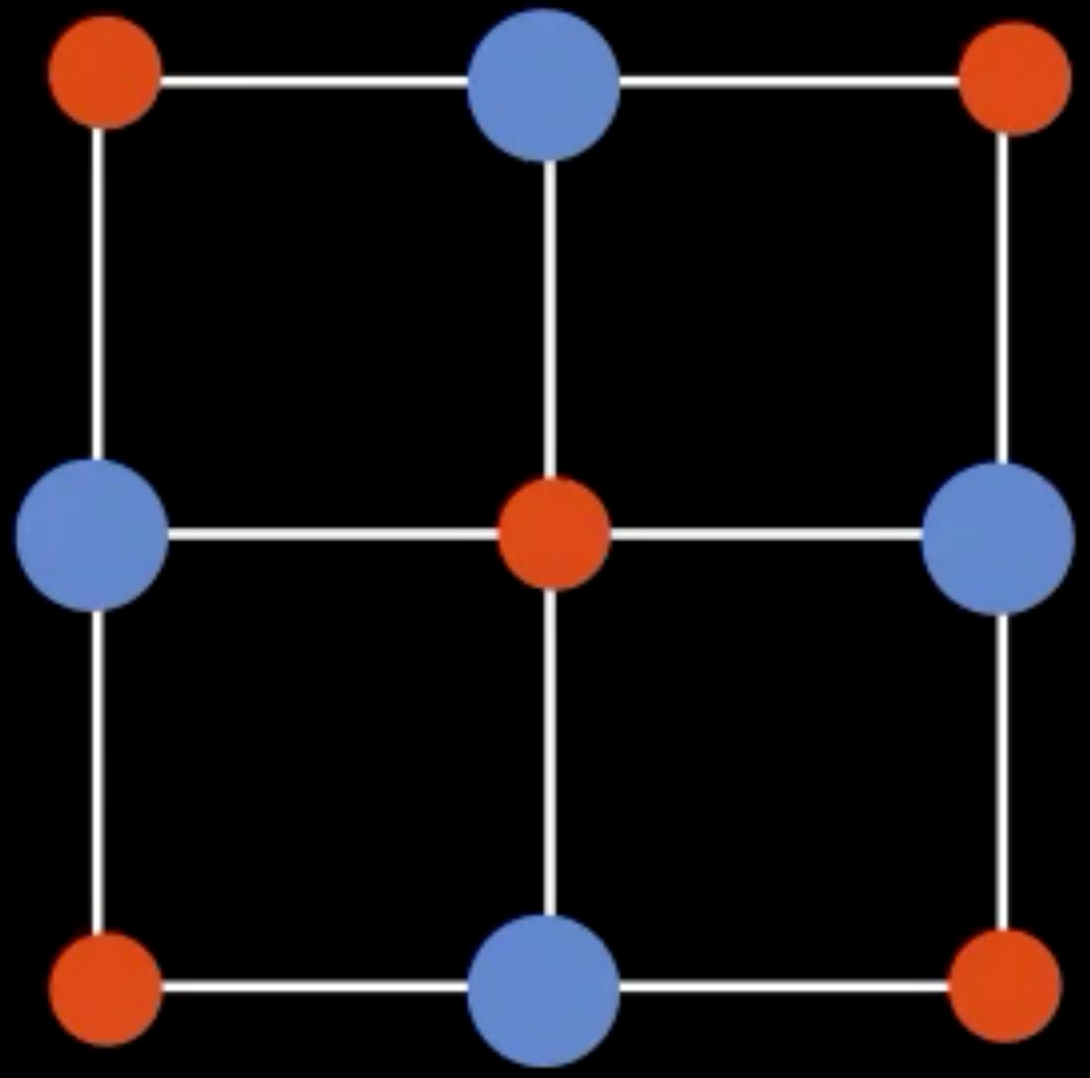


$|L\rangle$ $|R\rangle$

Coherent chiral phonons

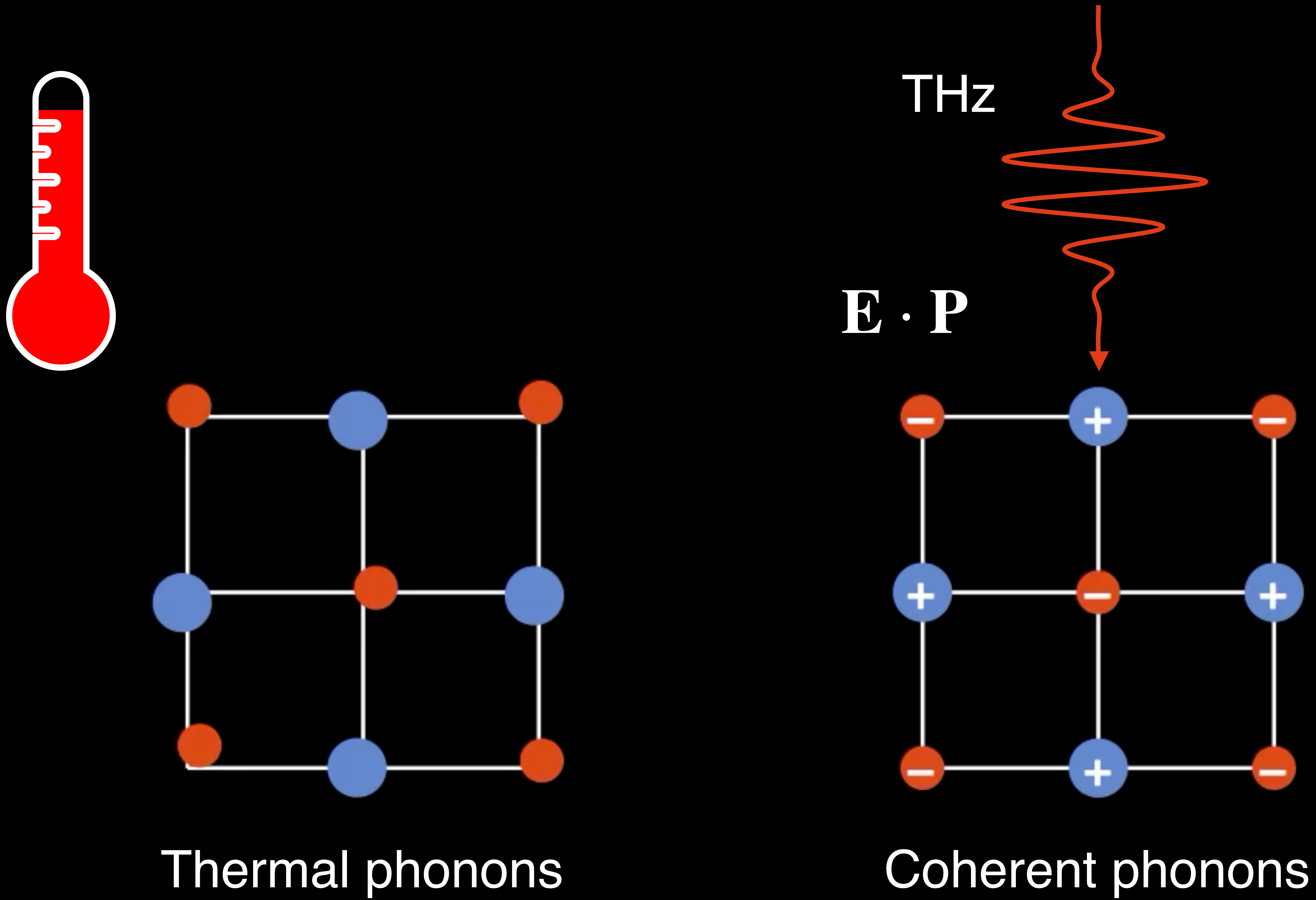
Thermal phonons move atoms randomly



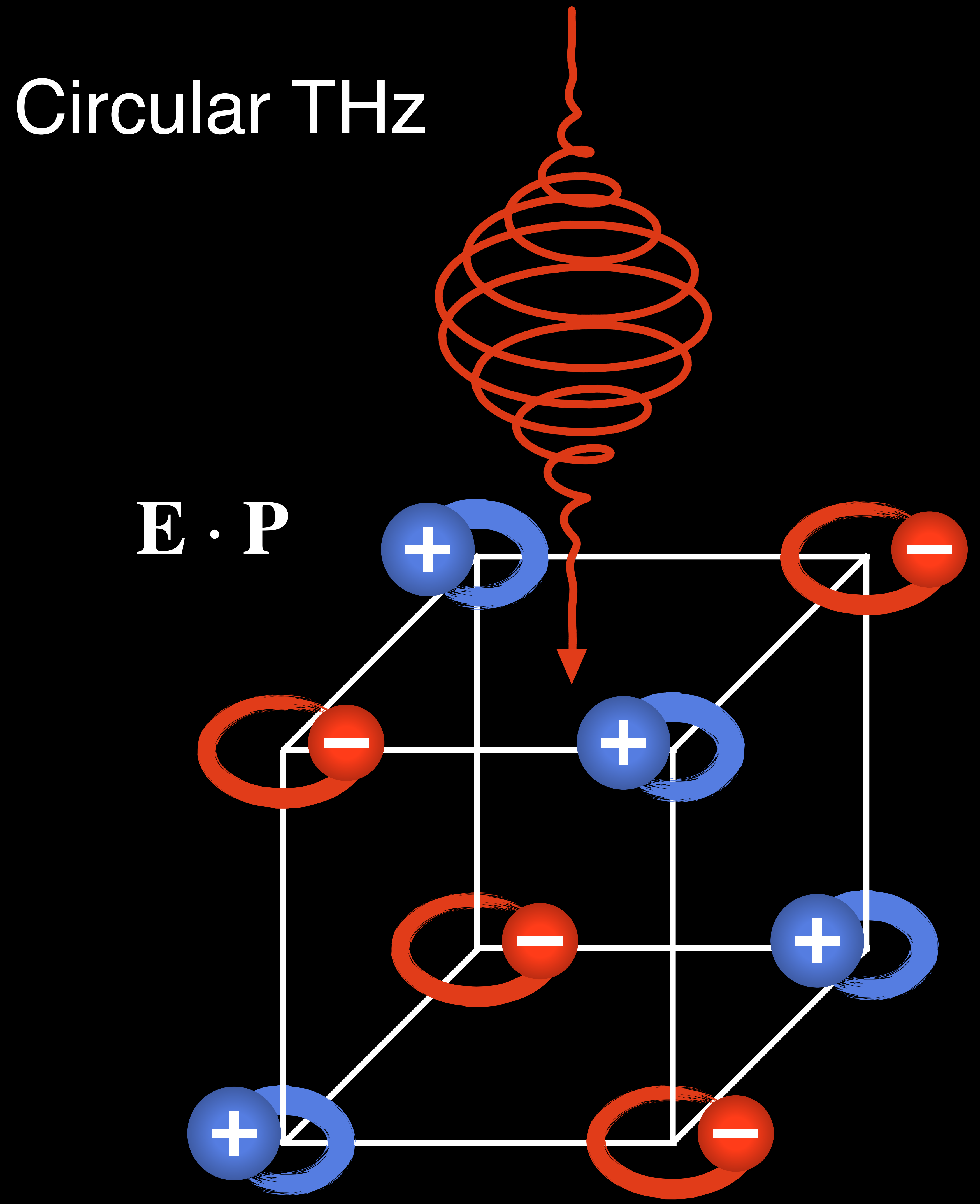


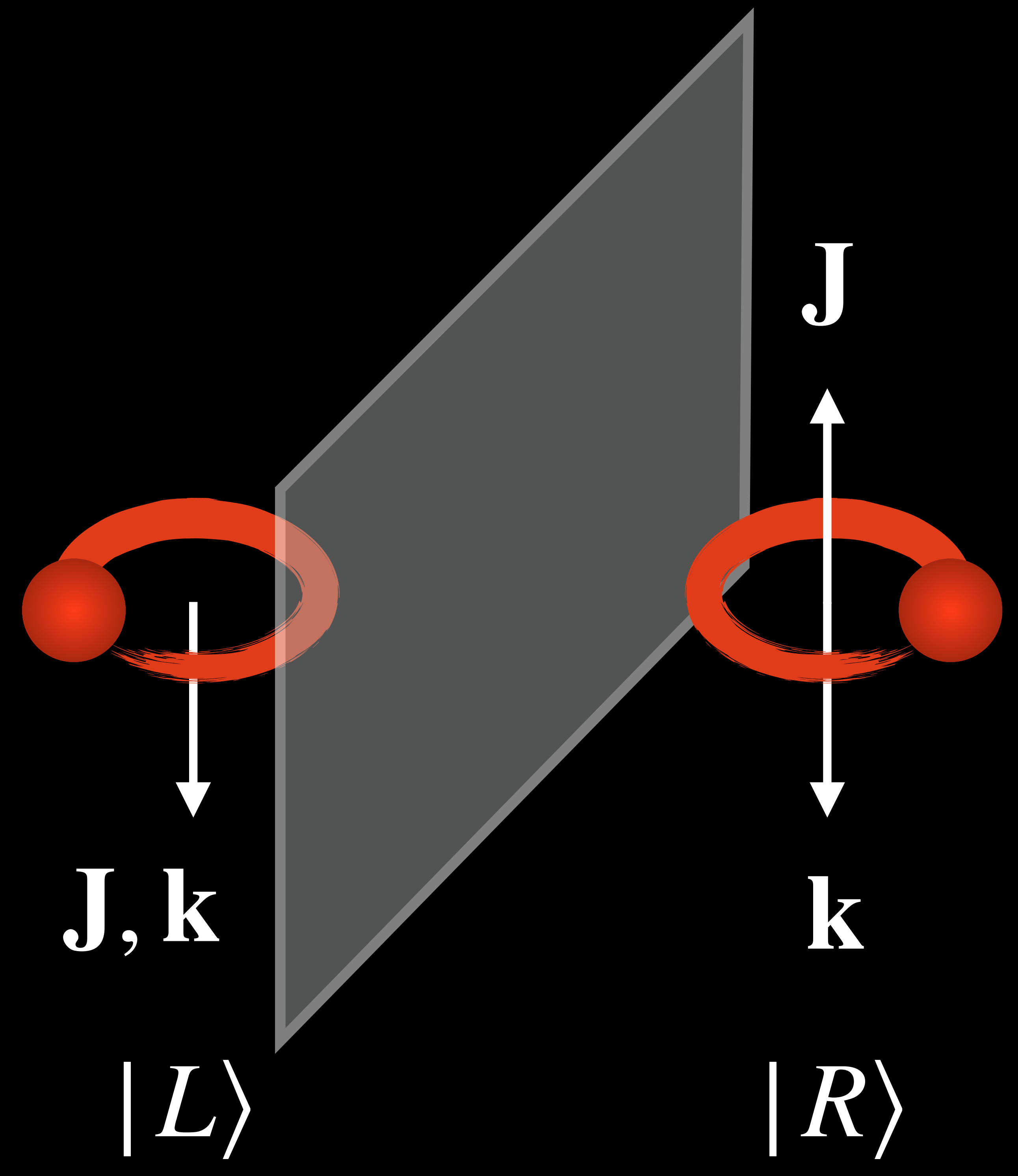
Thermal phonons

Coherent phonons move atoms in unison



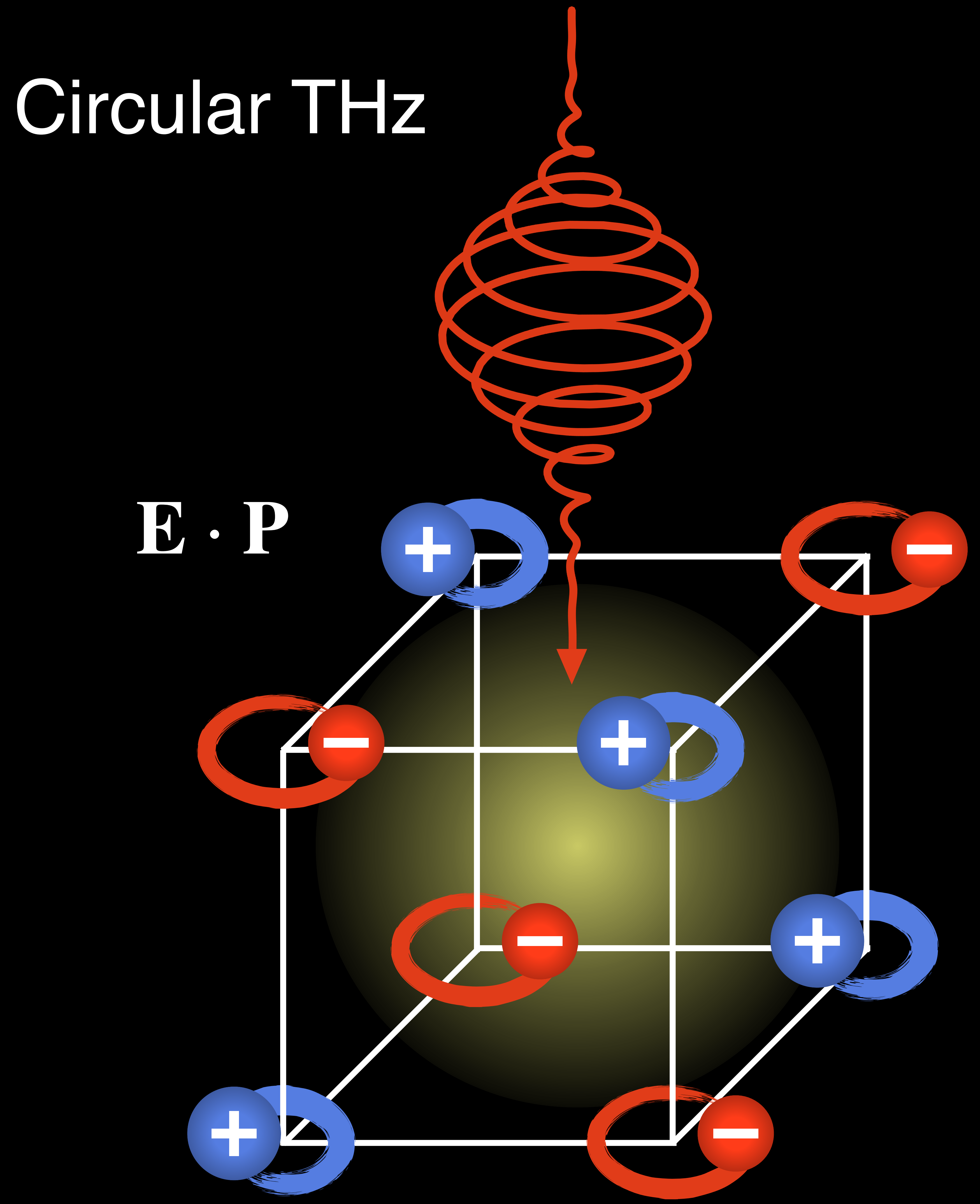
Chiral phonons act as atomic electromagnetic coils





Juraschek et al., Phys. Rev. Materials 1, 014401 (2017)
Juraschek & Spaldin, Phys. Rev. Materials 3, 064405 (2019)

TU/e Chiral phonons act as atomic electromagnetic coils

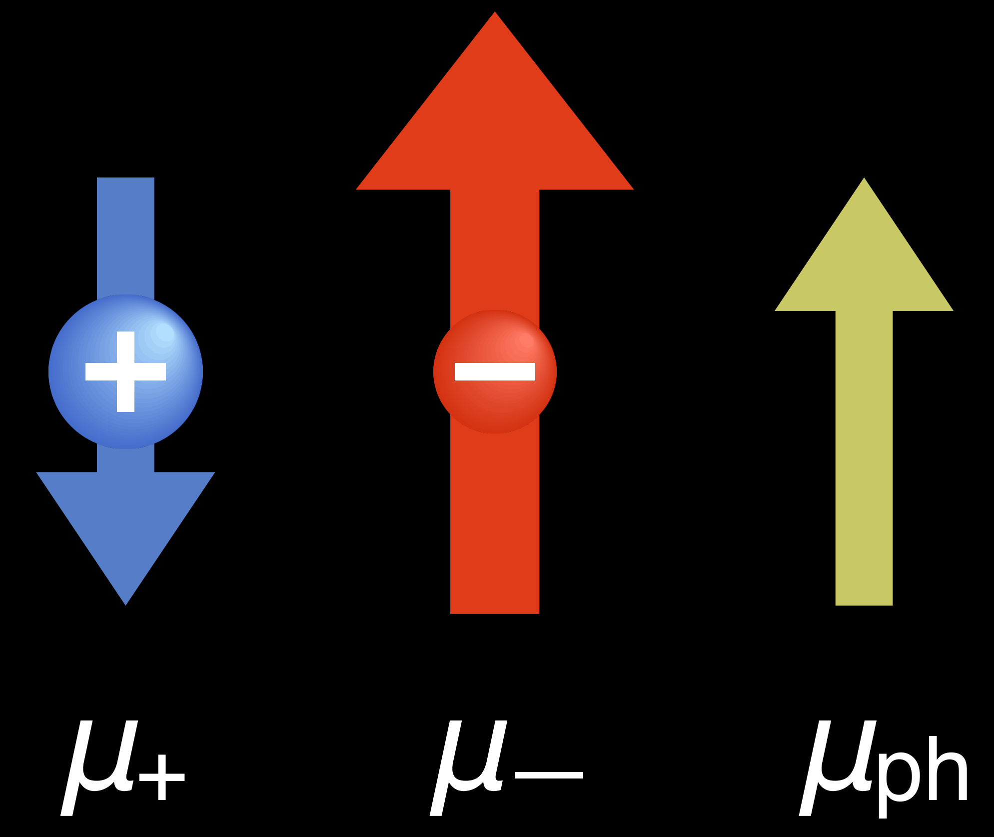


$$\mu_{\mathrm{ph}} = \gamma \mathbf{Q} \times \dot{\mathbf{Q}}$$

$$\gamma \rightarrow \frac{Z}{2M}$$

$\sim \mu_{\mathrm{N}}$

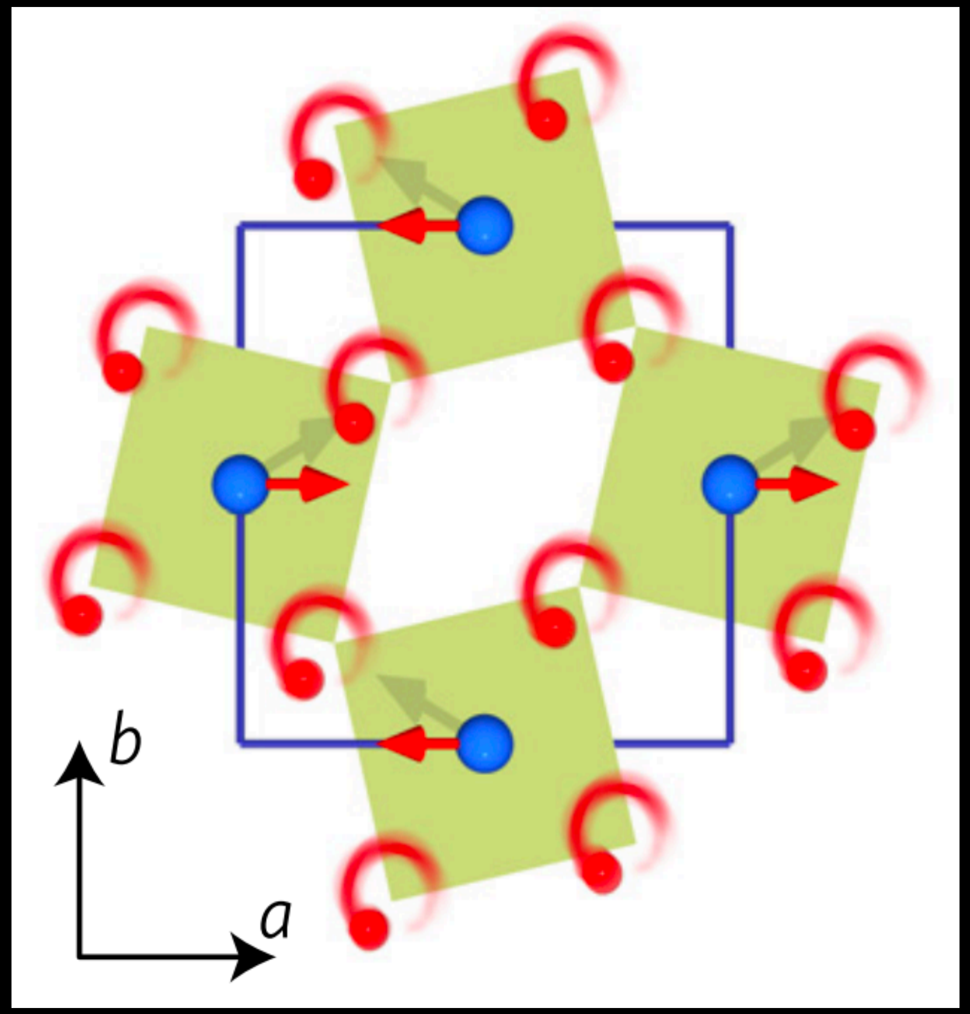
$\sim 1\mu\mathrm{T}$



Juraschek et al., Phys. Rev. Materials 1, 014401 (2017)
Juraschek & Spaldin, Phys. Rev. Materials 3, 064405 (2019)

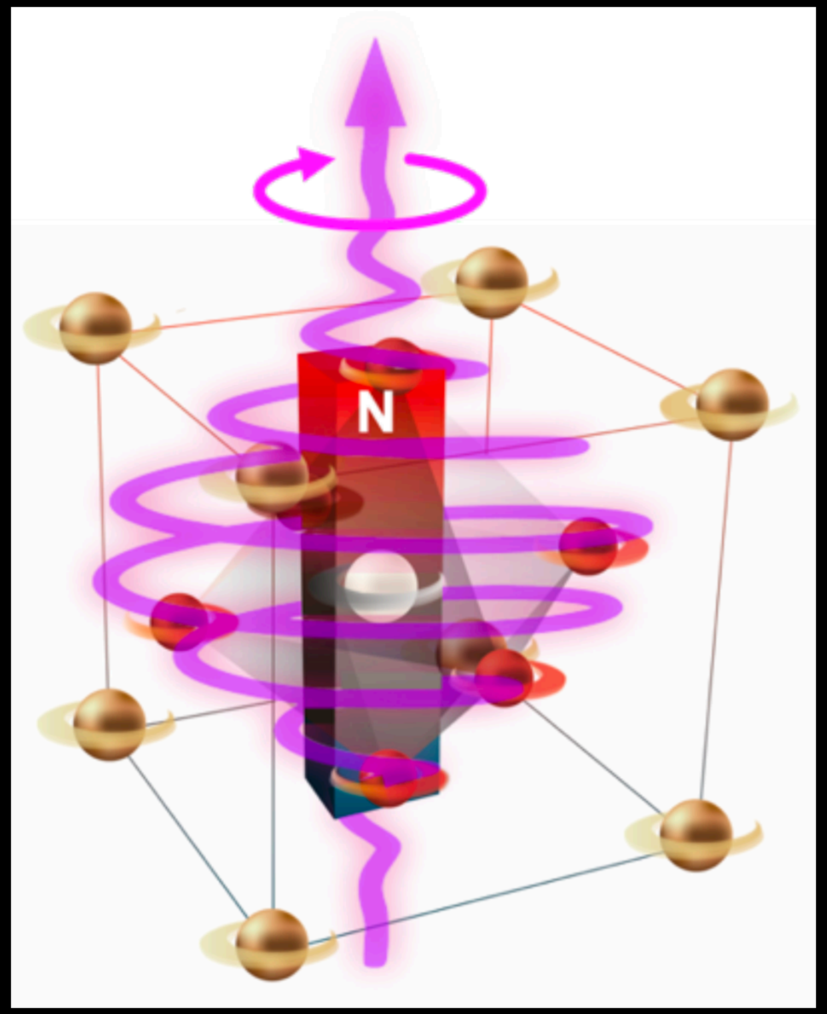
TU/e Different experiments measure phono-magnetic fields

$ErFeO_3$



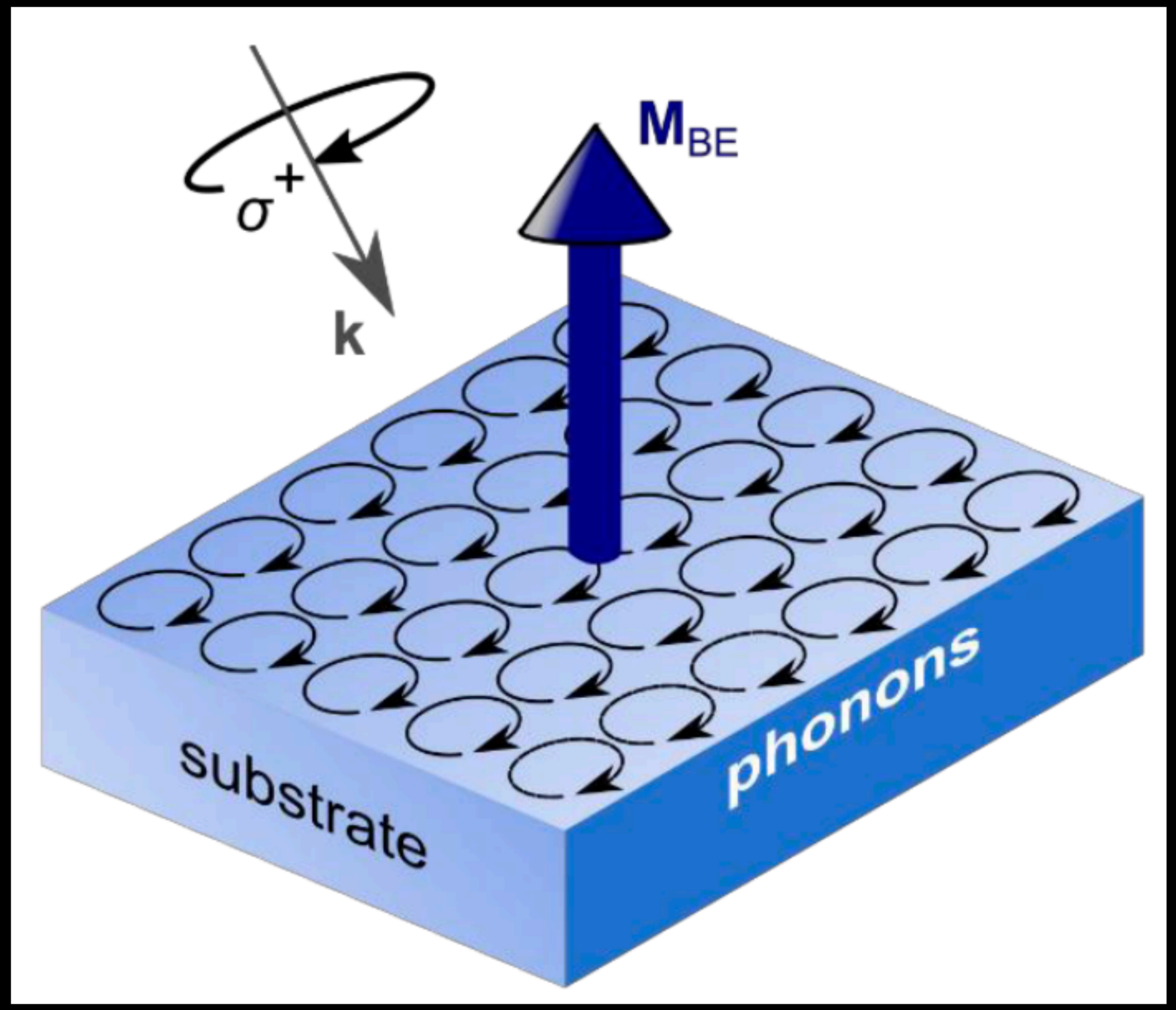
Nova et al., Nat. Phys. 13, 132 (2017)

$SrTiO_3$



Basini et al., Nature 628, 534 (2024)

$GdFeCo/Al_2O_3$



Davies et al., Nature 628, 540 (2024)

$B_{ph} \sim$ 10s mT

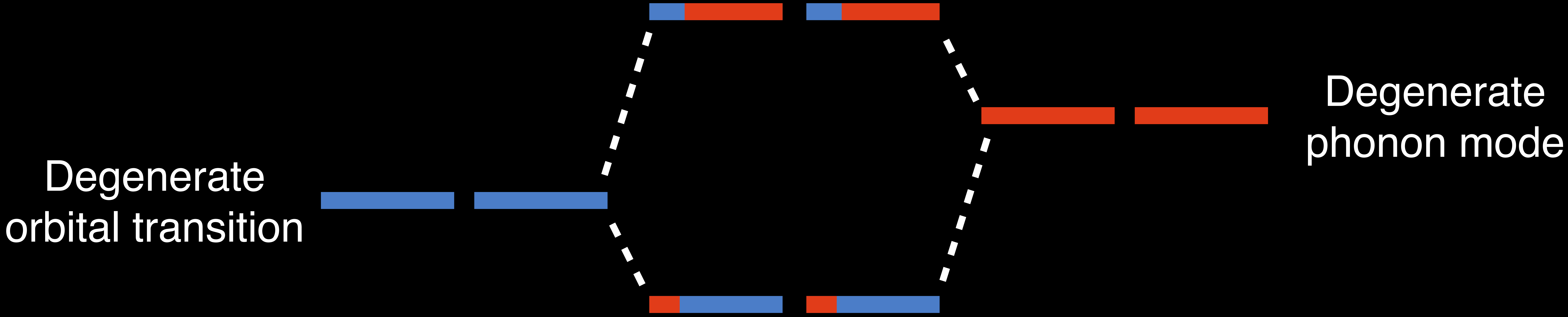
News & Views:
Romao, Juraschek, Nature 628, 505 (2024)

What makes phonon magnetic moments large?

TU/e A general mechanism can be found for magnetic systems

Swati Chaudhary

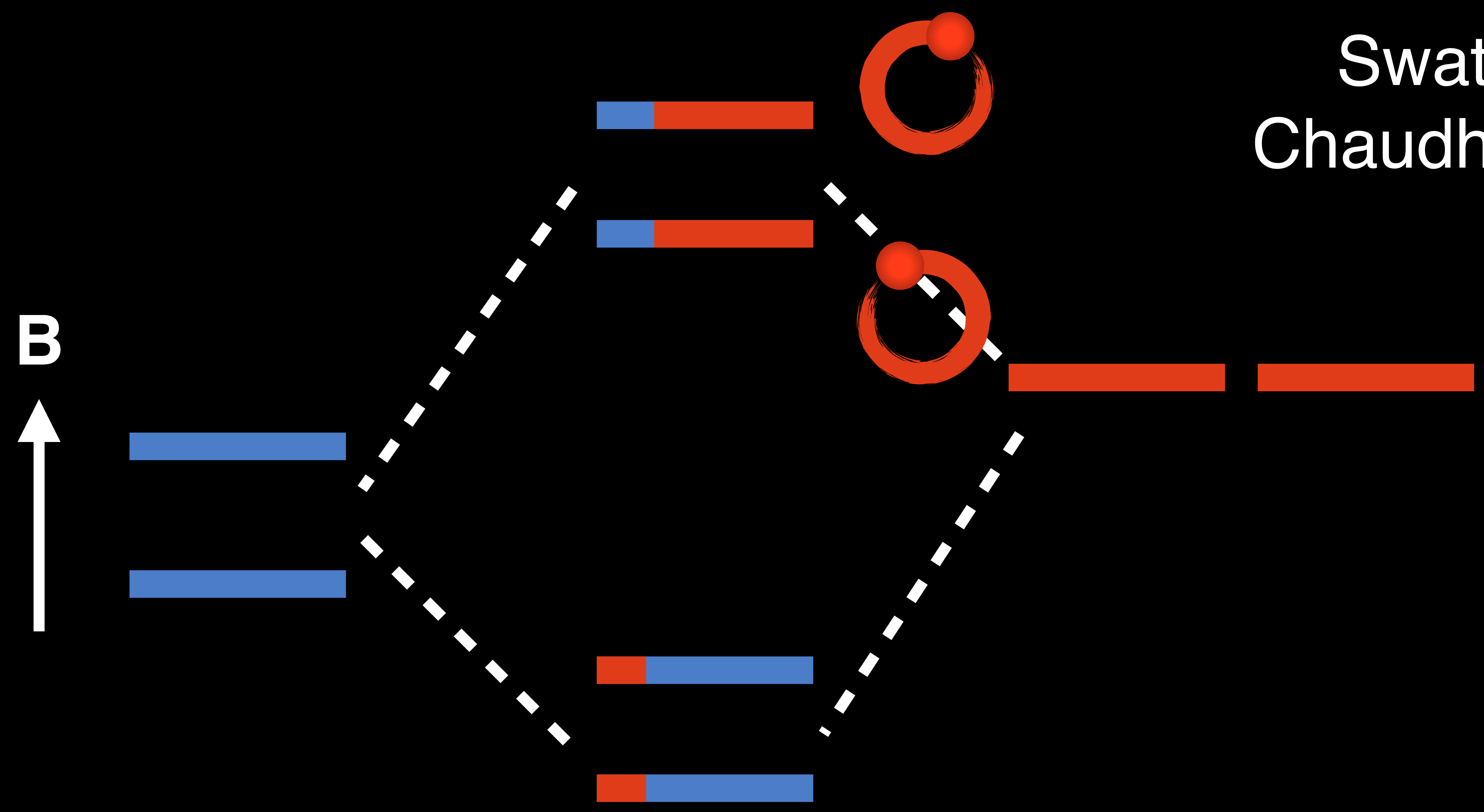
Greg Fiete



Chaudhary, Juraschek, Rodriguez-Vega, Fiete, Phys. Rev. B 110, 094401 (2024)

A general mechanism can be found for magnetic systems

Phonon Zeeman effect!



Degenerate orbital transition

Degenerate phonon mode

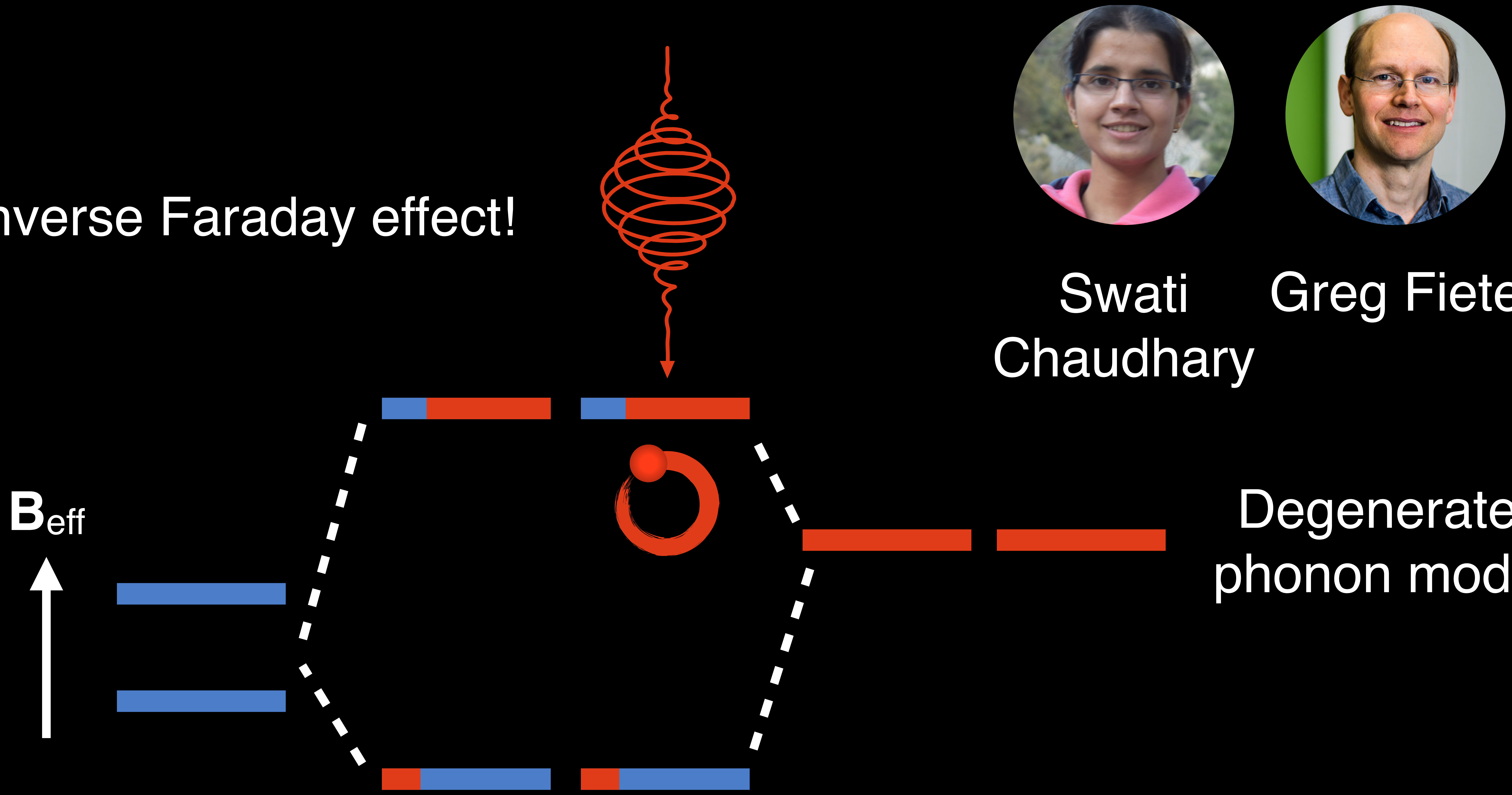
Swati Chaudhary

Greg Fiete

Chaudhary, Juraschek, Rodriguez-Vega, Fiete, Phys. Rev. B 110, 094401 (2024)

A general mechanism can be found for magnetic systems

Phonon inverse Faraday effect!



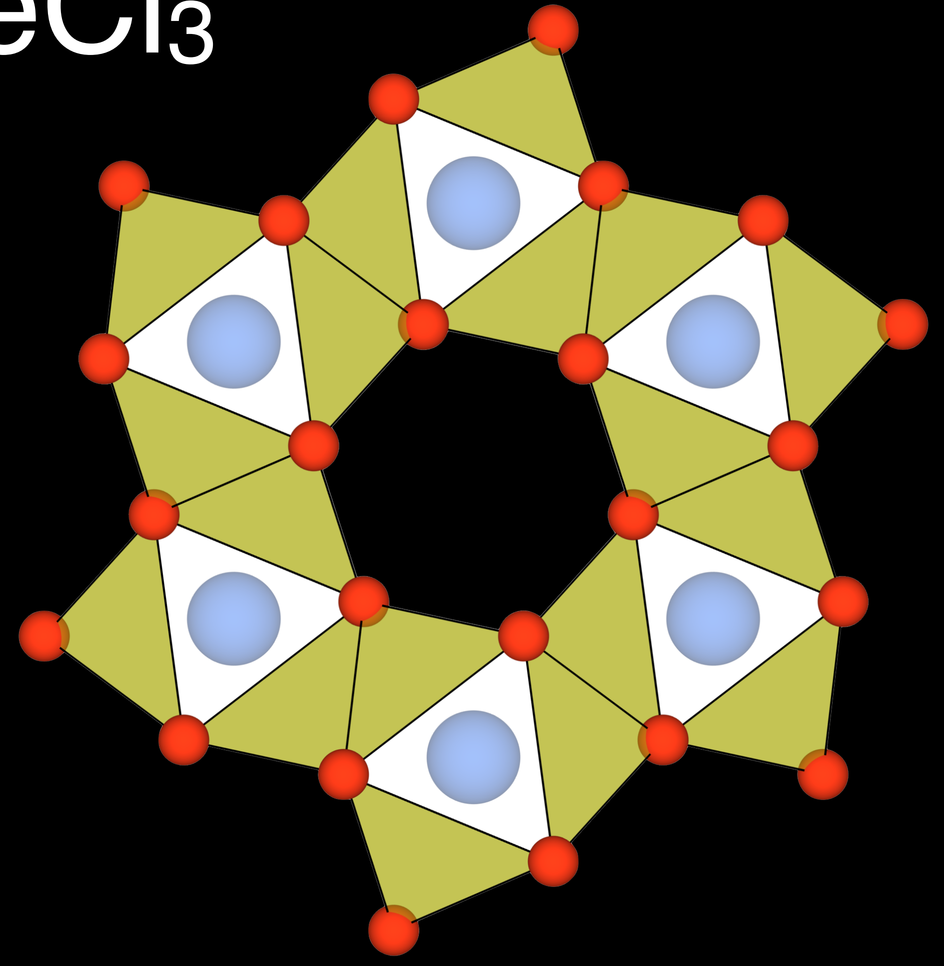
Chaudhary, Juraschek, Rodriguez-Vega, Fiete, Phys. Rev. B 110, 094401 (2024)

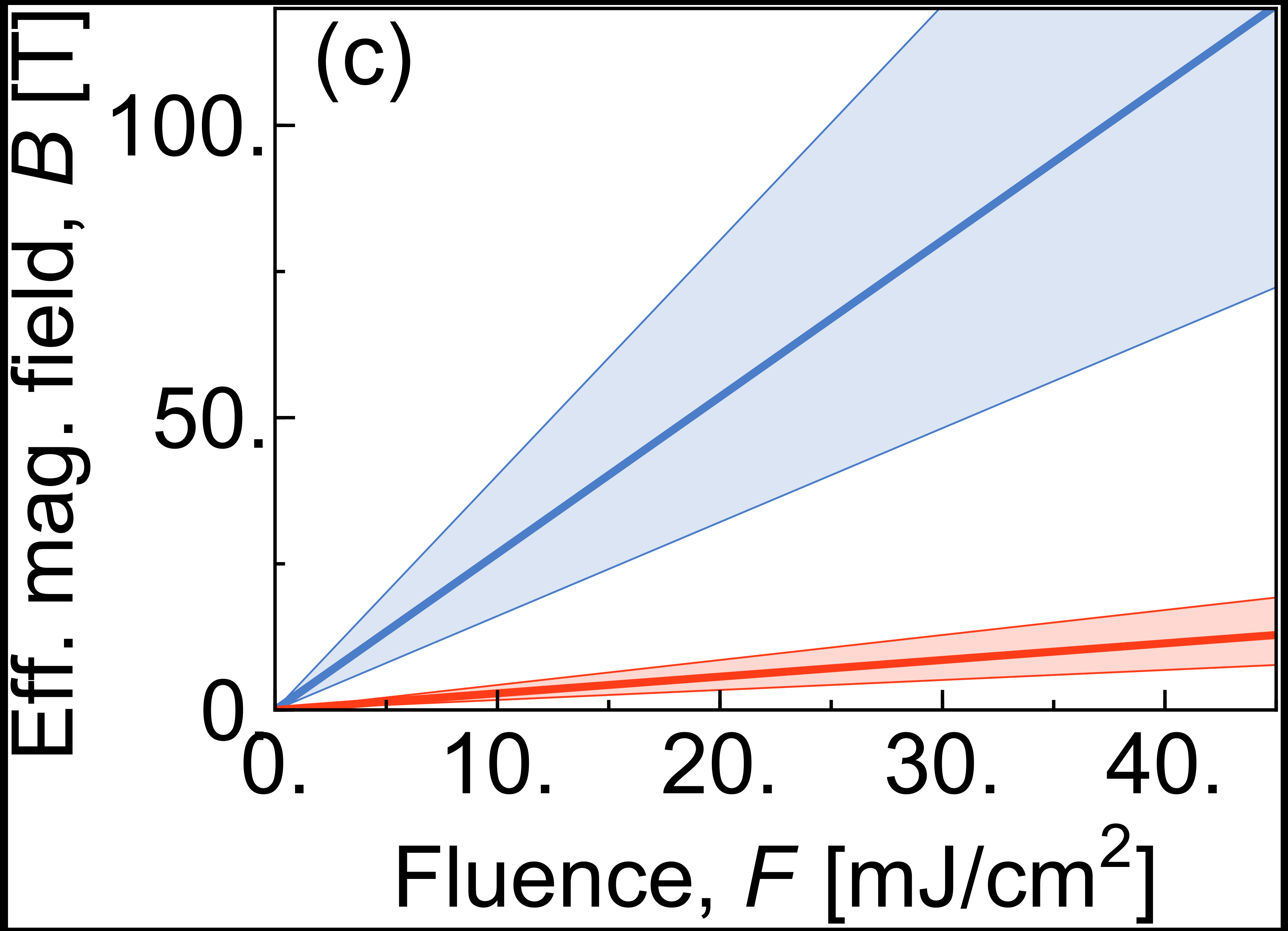
Giant phono-magnetic fields in $CeCl_3$, CeF_3

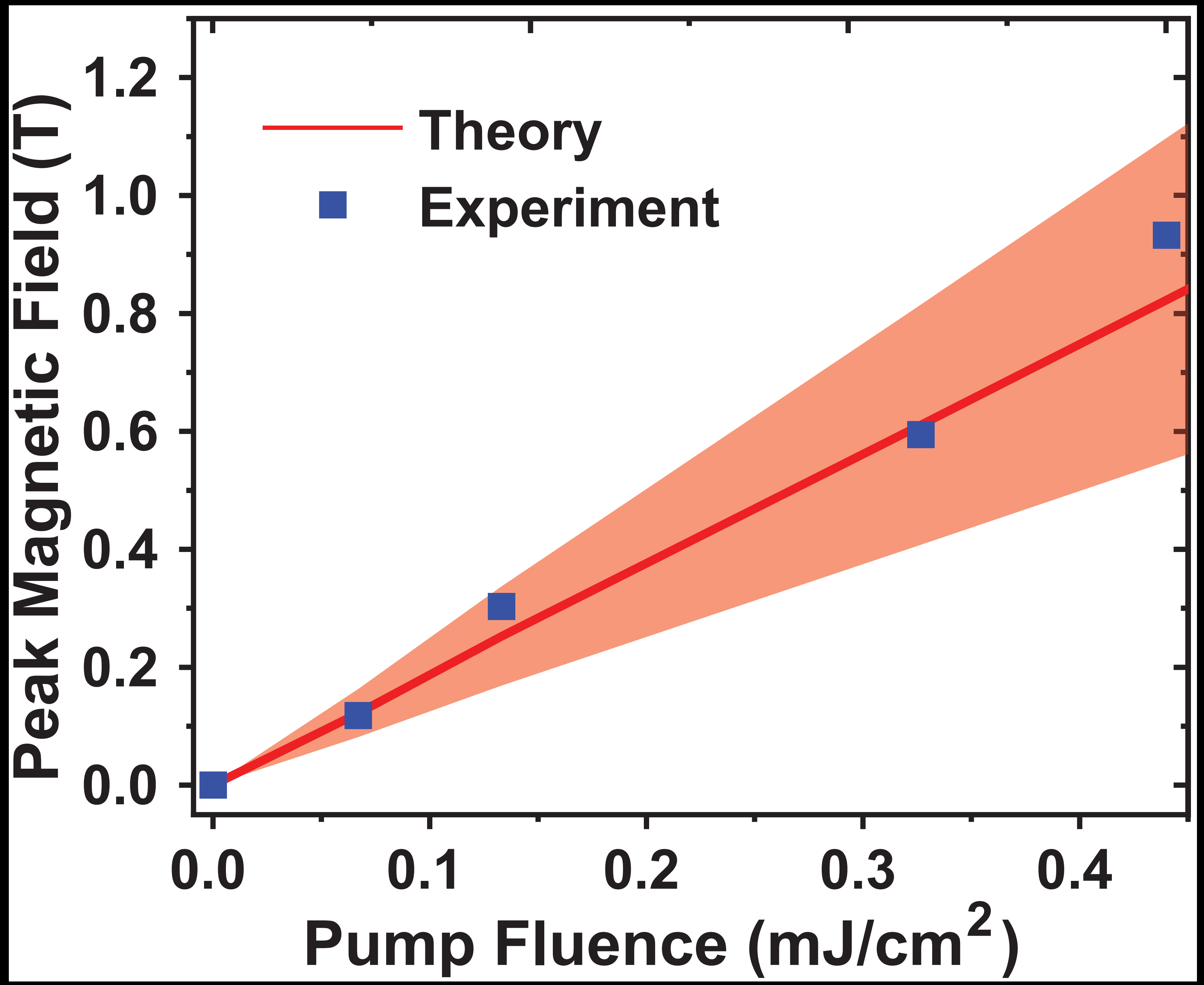
Chiral phonons produce giant effective magnetic fields

$$\mathbf{B}_{\mathrm{ph}} \sim \mu_{\mathrm{ph}} = \gamma\,\mathbf{Q} \times \partial_t \mathbf{Q}$$

CeCl$_3$







10 T for 4 mJ/cm^2

1 T for 0.4 mJ/cm^2

Juraschek et al., Phys. Rev. Research 4, 013129 (2022)

Zhang et al., Science 382, 698 (2023)

Magnetizing antiferromagnets

Phonomagnetic field couples to magnon in AFM

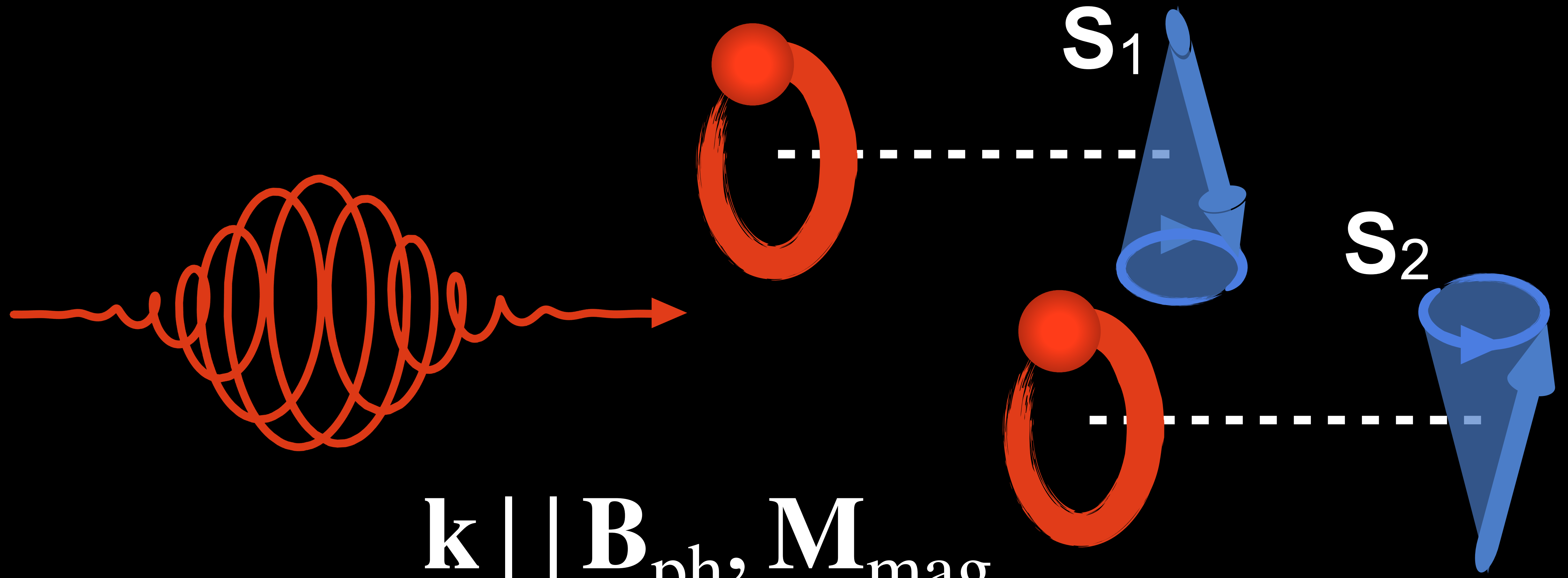
$$V = -\mathbf{M}_{\mathrm{mag}} \cdot \mathbf{B}_{\mathrm{ph}}$$


Tom Kahana


Daniel B.-Lopez

Easy-plane Heisenberg AFM

Chiral phonon   Magnon mode

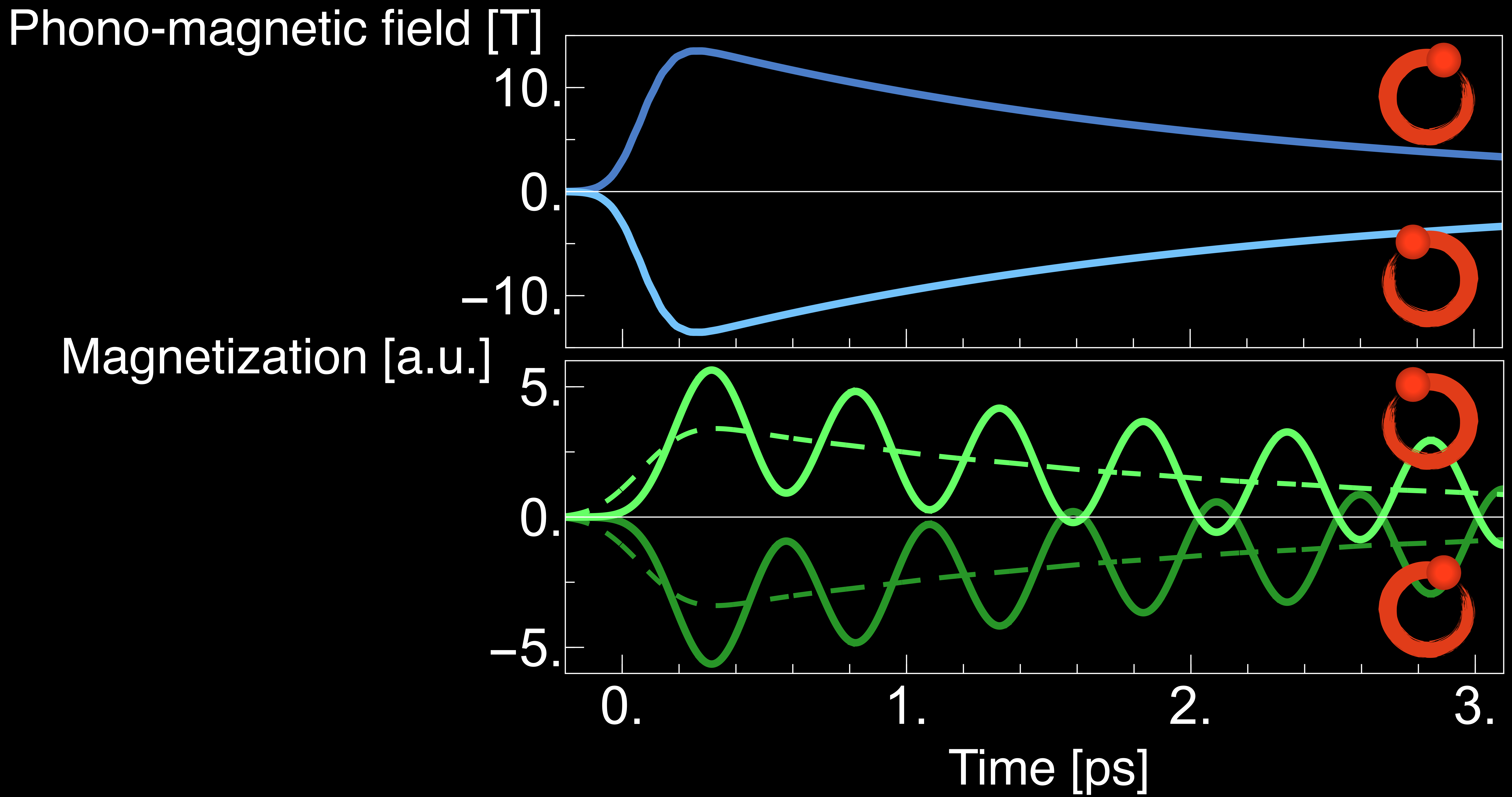


$\mathbf{k} \,||\, \mathbf{B}_{\mathrm{ph}}, \mathbf{M}_{\mathrm{mag}}$

Dynamics: coupled Landau-Lifshitz-Gilbert + oscillator model

Kahana, Bustamante-Lopez, Juraschek, Science Advances, 10, eado0722 (2024)

Magnetization gets rectified by phonomagnetic field



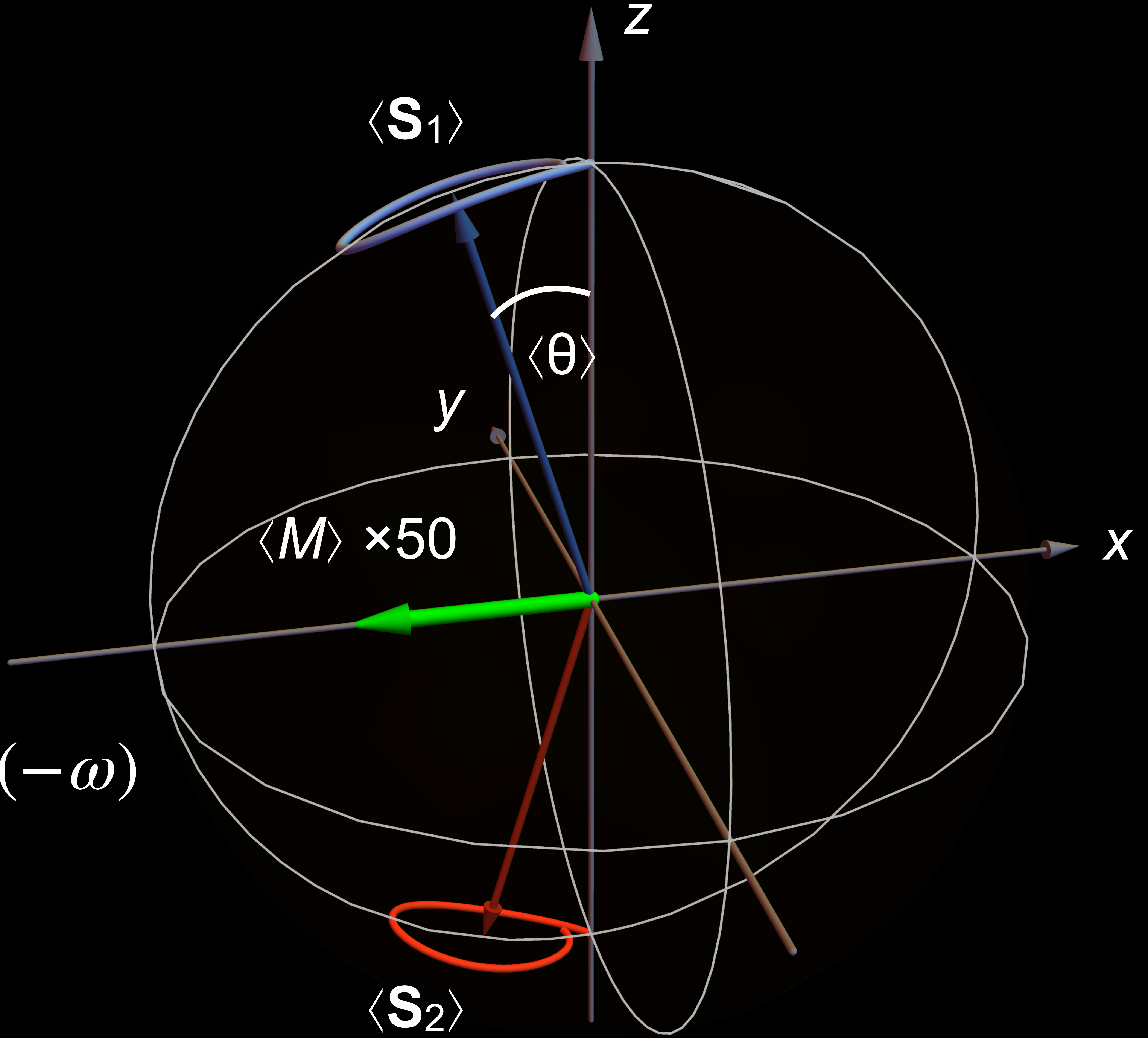
Kahana, Bustamante-Lopez, Juraschek, Science Advances, 10, eado0722 (2024)

TU/e Rectification leads to light-induced weak ferromagnetism

$$\langle \mathbf{M} \rangle \sim \langle \mathbf{Q} \times \partial_t \mathbf{Q} \rangle \neq 0$$

$$\mathbf{Q} \sim \mathbf{E}$$

$$\mathbf{M}(0) = \chi^{(2)}_{\mathrm{mag}}(0; \omega, -\omega)\mathbf{E}(\omega)\mathbf{E}^*(-\omega)$$



Kahana, Bustamante-Lopez, Juraschek, Science Advances, 10, eado0722 (2024)

Beyond circular polarization

TU/e

Multicolor Floquet driving promises advanced control

PHYSICAL REVIEW B **108**, 035151 (2023)

Suppression of heating by multicolor driving protocols in Floquet-engineered strongly correlated systems

Yuta Murakami,[1,*] Michael Schüler,[2,3] Ryotaro Arita,[1,4] and Philipp Werner[3]

PHYSICAL REVIEW RESEARCH **4**, 033213 (2022)

Floquet engineering the band structure of materials with optimal control theory

Alberto Castro,[1,2,*] Umberto De Giovannini,[3,4,†] Shunsuke A. Sato,[5,4,‡] Hannes Hübener,[4,§] and Angel Rubio[4,6,‖]

PHYSICAL REVIEW RESEARCH **4**, 013056 (2022)

Floquet engineering of individual band gaps in an optical lattice using a two-tone drive

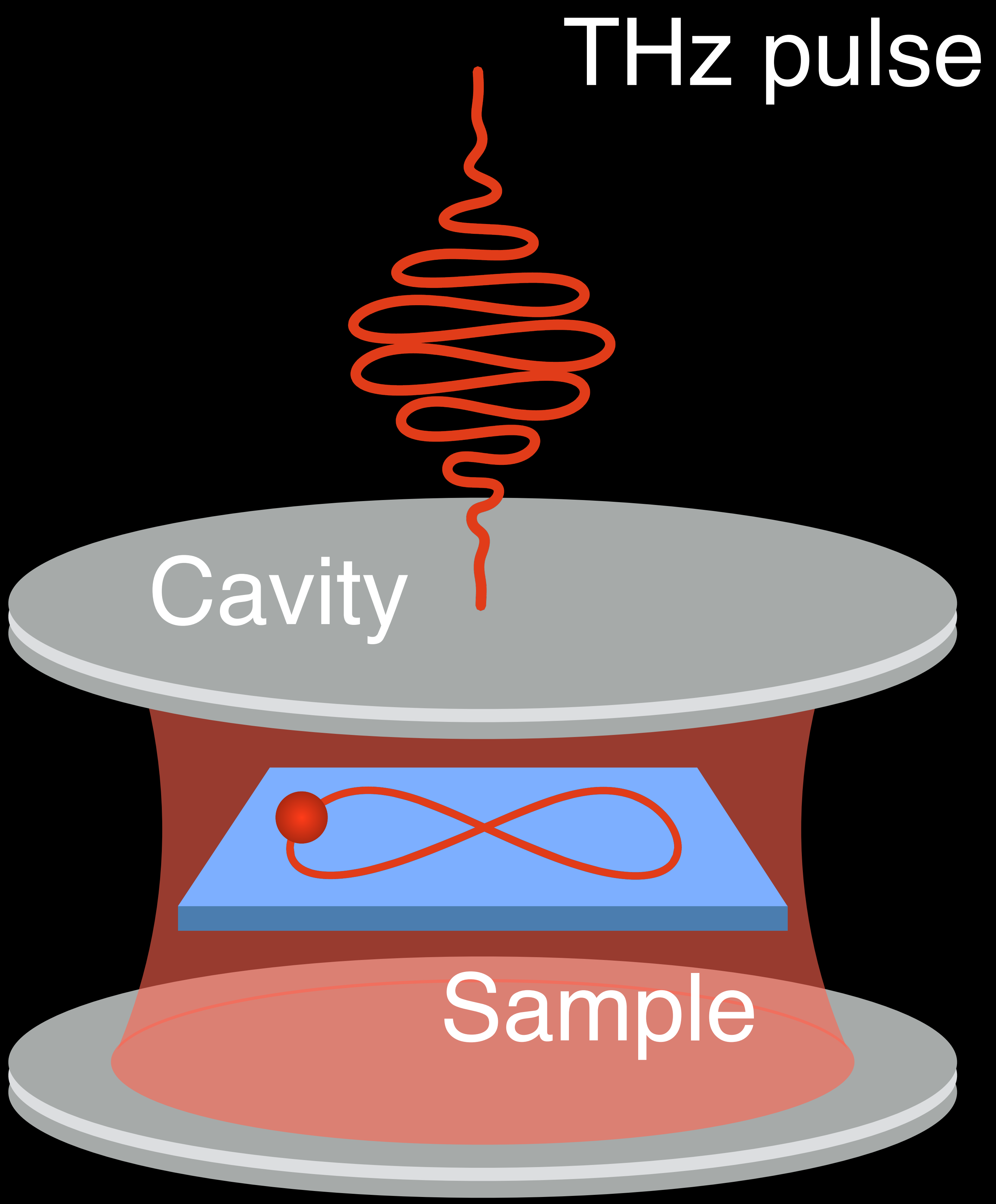
Kilian Sandholzer, Anne-Sophie Walter, Joaquín Minguzzi, Zijie Zhu, Konrad Viebahn, and Tilman Esslinger

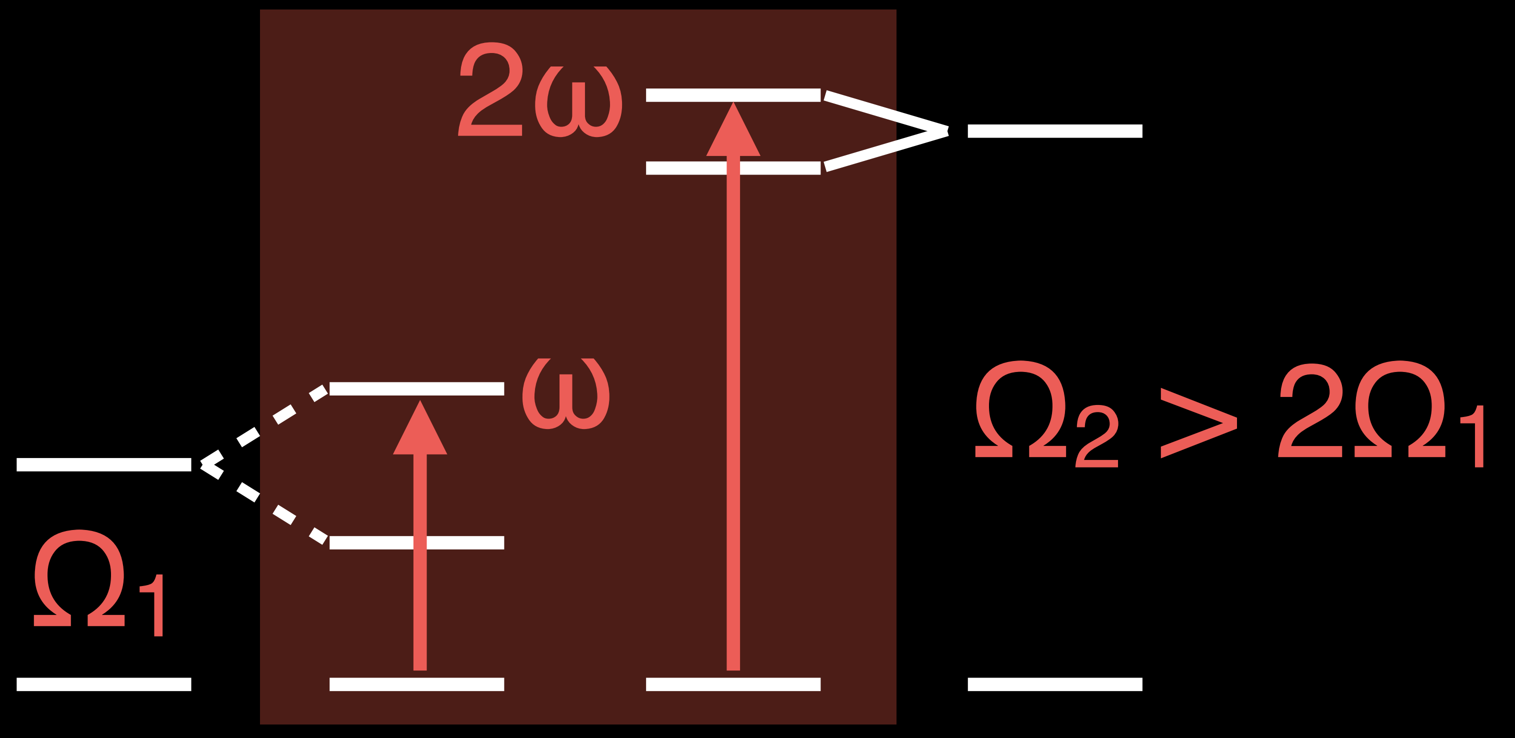
Bosonic Entanglement and Quantum Sensing from Energy Transfer in two-tone Floquet Systems

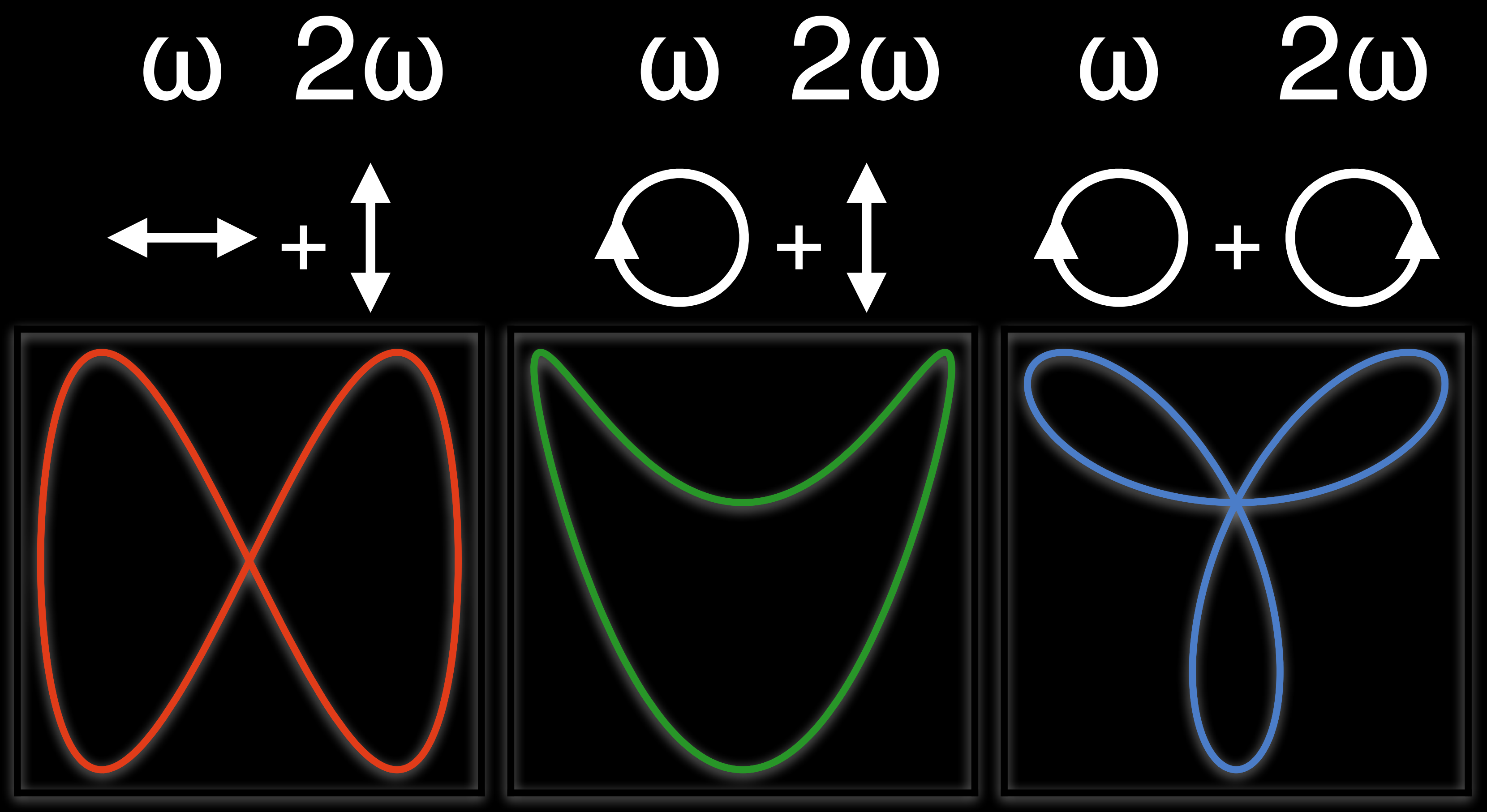
Yinan Chen,[1,2,*] Andreas Elben,[1,3,†] Angel Rubio,[4,5] and Gil Refael[1,2,6,‡]

TU/e

Phononic Lissajous figures require frequency matching







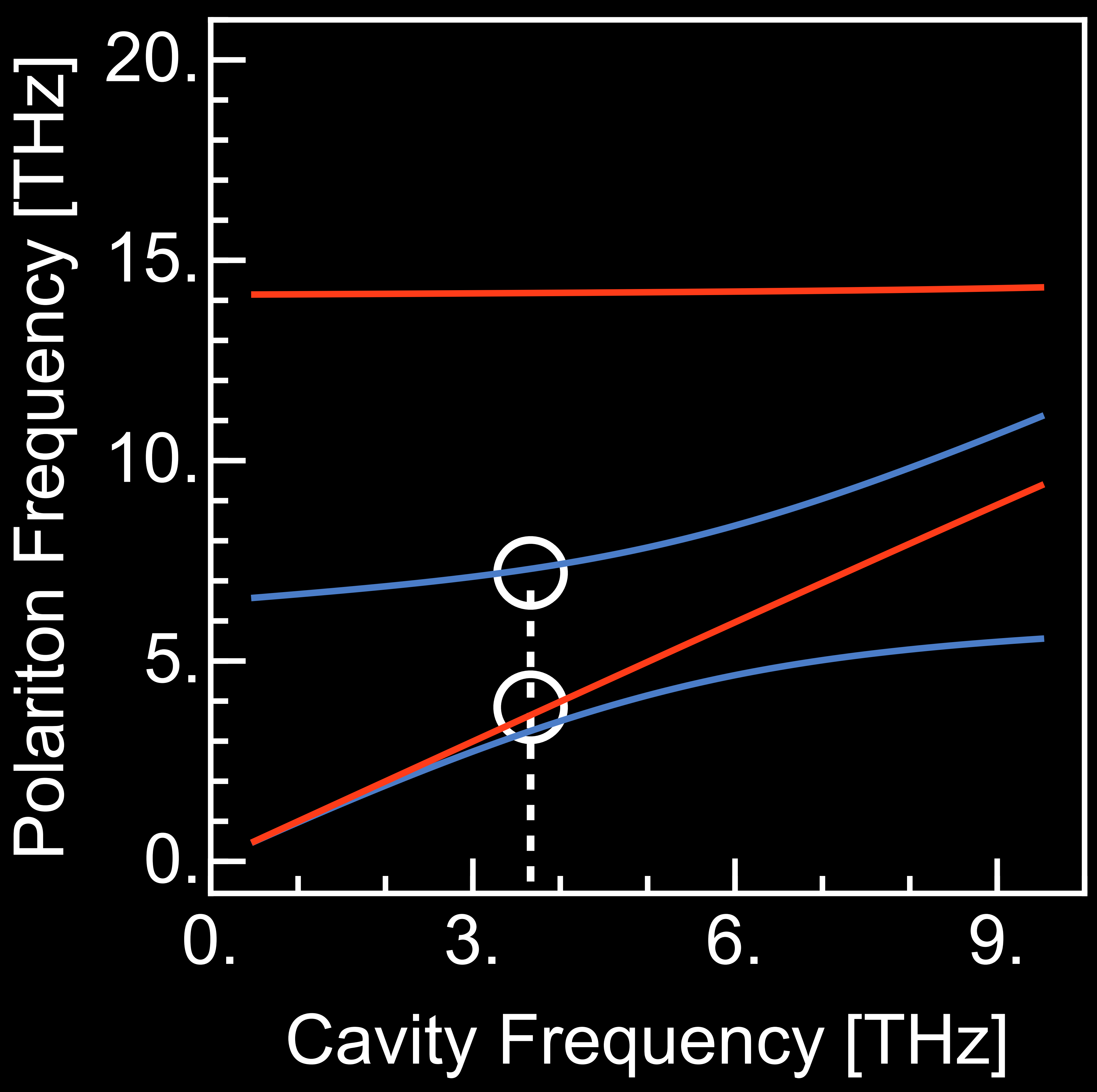
Omer Yaniv

Yaniv, Juraschek, arXiv:2504.03323 (2025)

TU/e Cavity phonon-polariton branches match in $BaTiO_3$

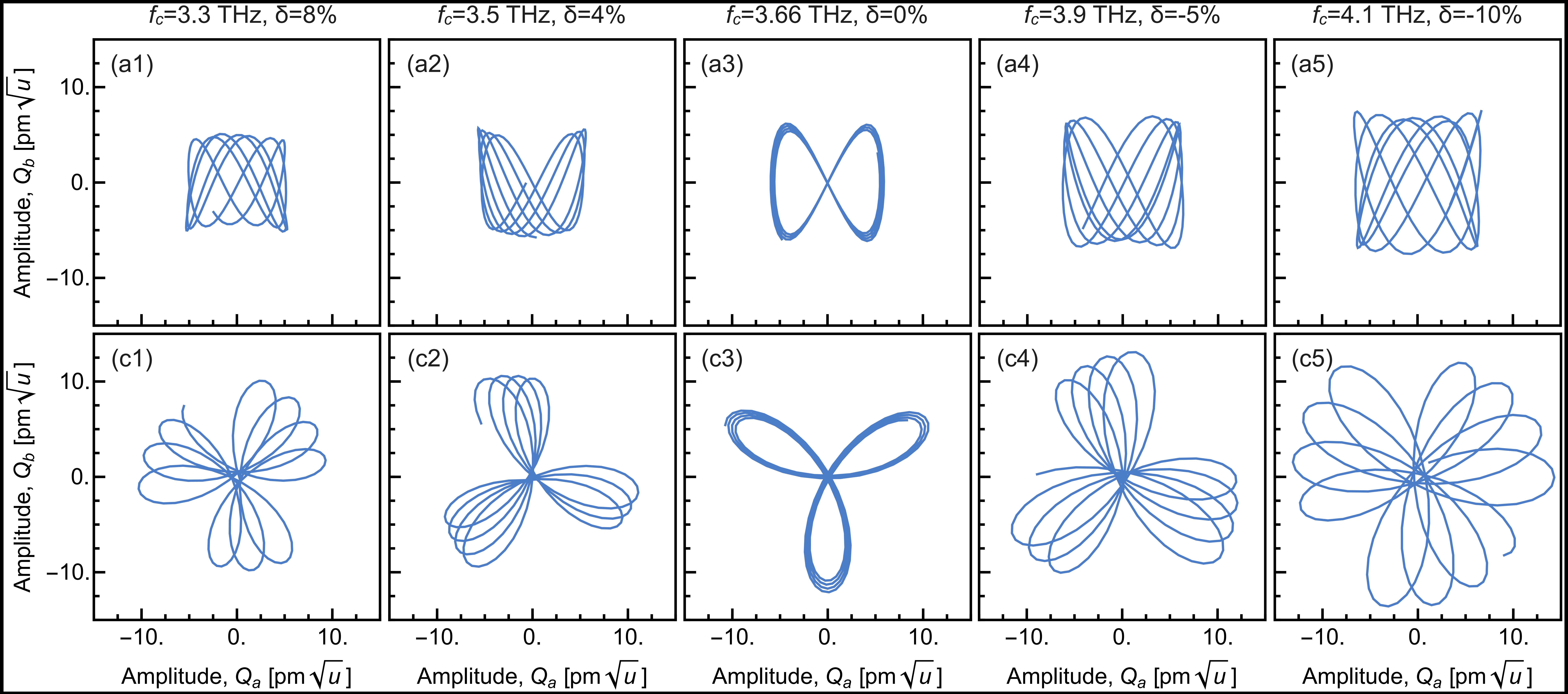
$BaTiO_3$

E_u 6.5 THz
E_u 14.1 THz



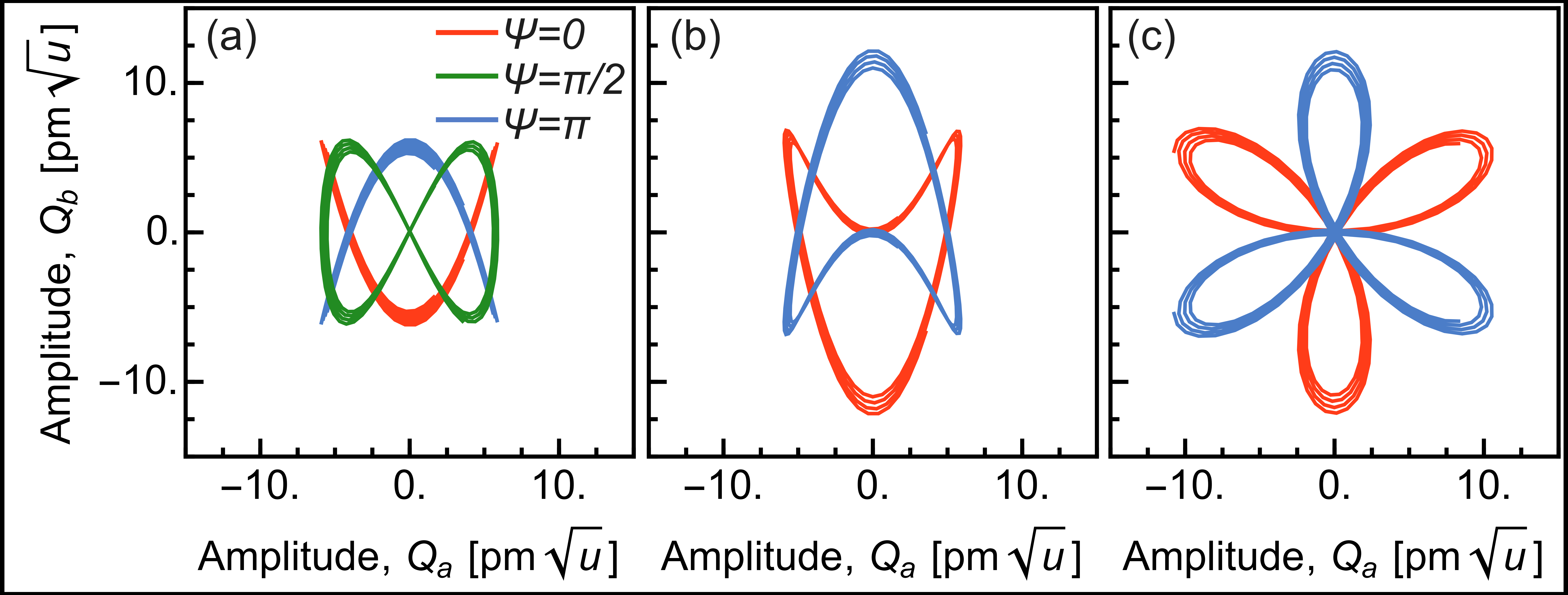
Yaniv, Juraschek, arXiv:2504.03323 (2025)

Cavities can engineer phononic Lissajous figures



Yaniv, Juraschek, arXiv:2504.03323 (2025)

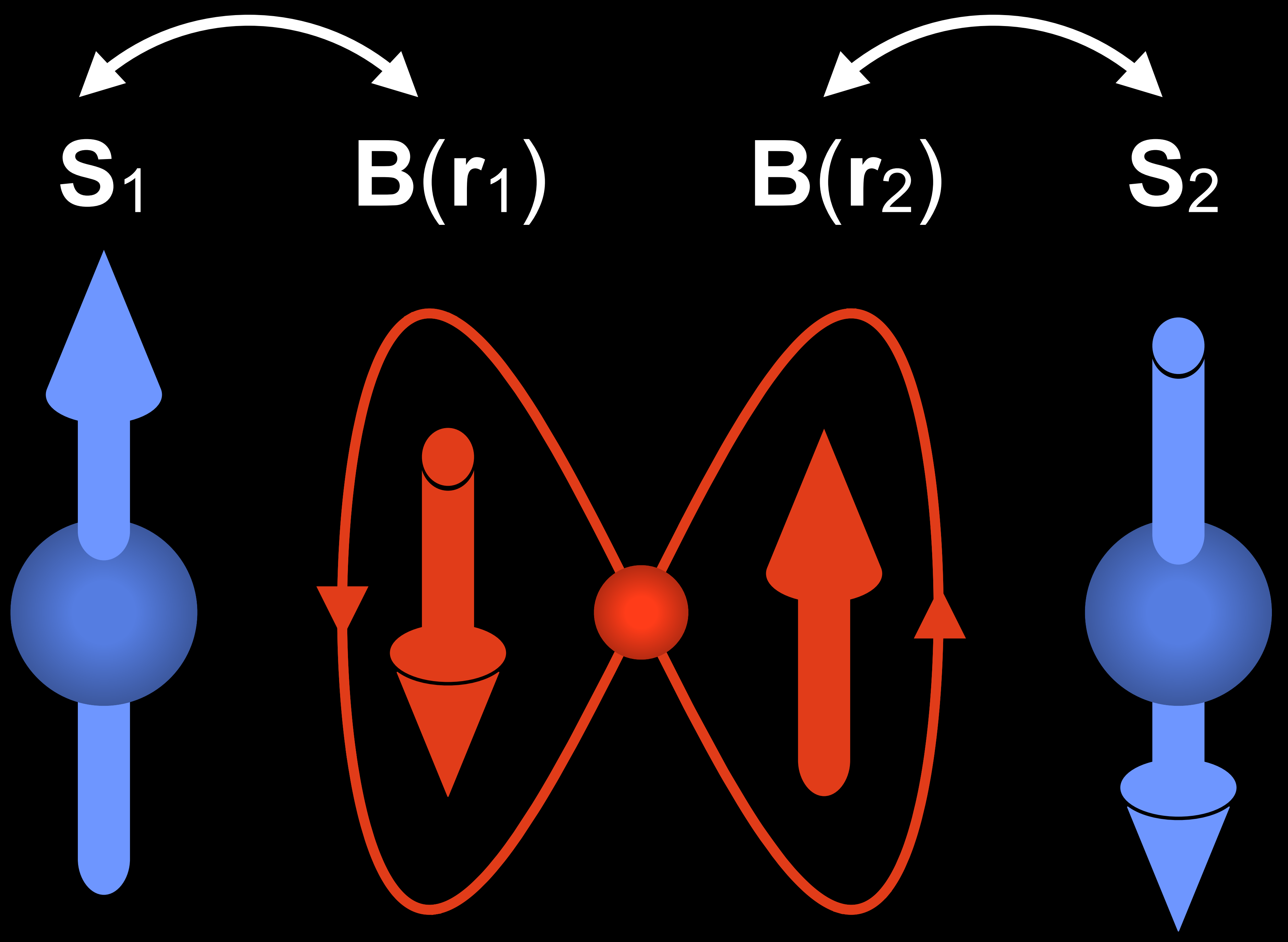
Pulse shaping can control phononic symmetry breaking



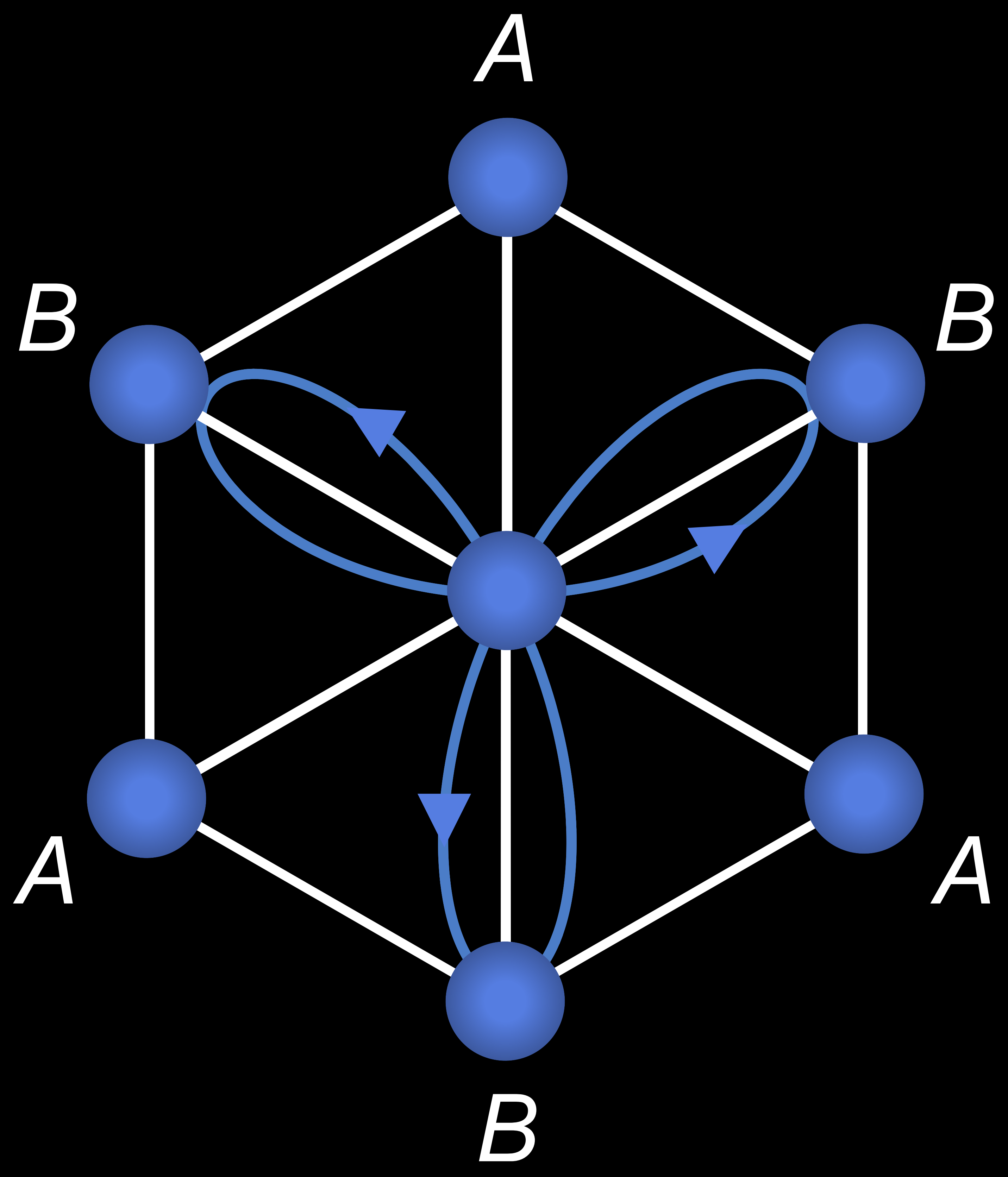
Yaniv, Juraschek, arXiv:2504.03323 (2025)

Possible applications involve Floquet driving

Staggered magnetic fields



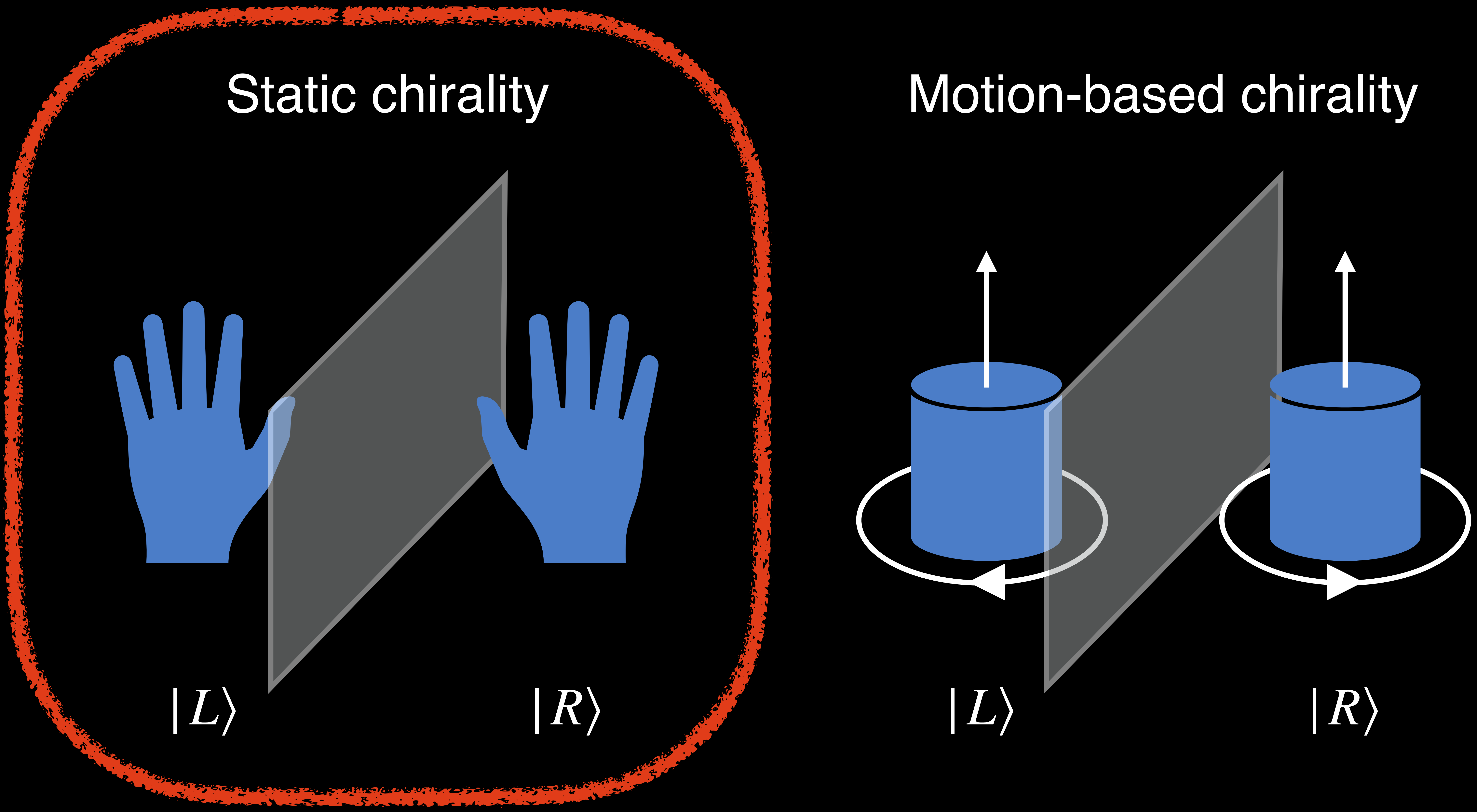
Selective symmetry breaking



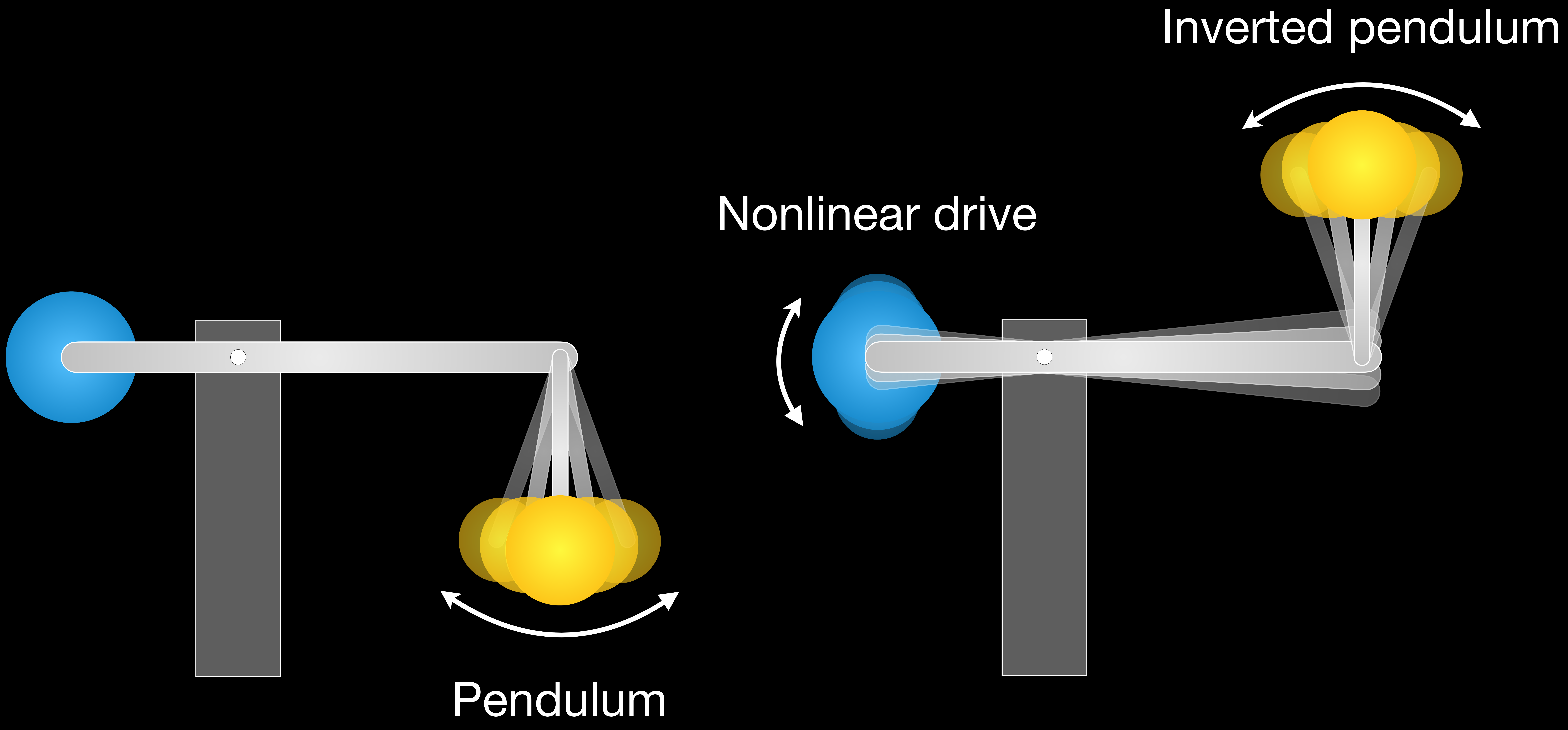
Yaniv, Juraschek, arXiv:2504.03323 (2025)

Can phonons make achiral materials chiral?

Chirality means no improper rotation symmetry



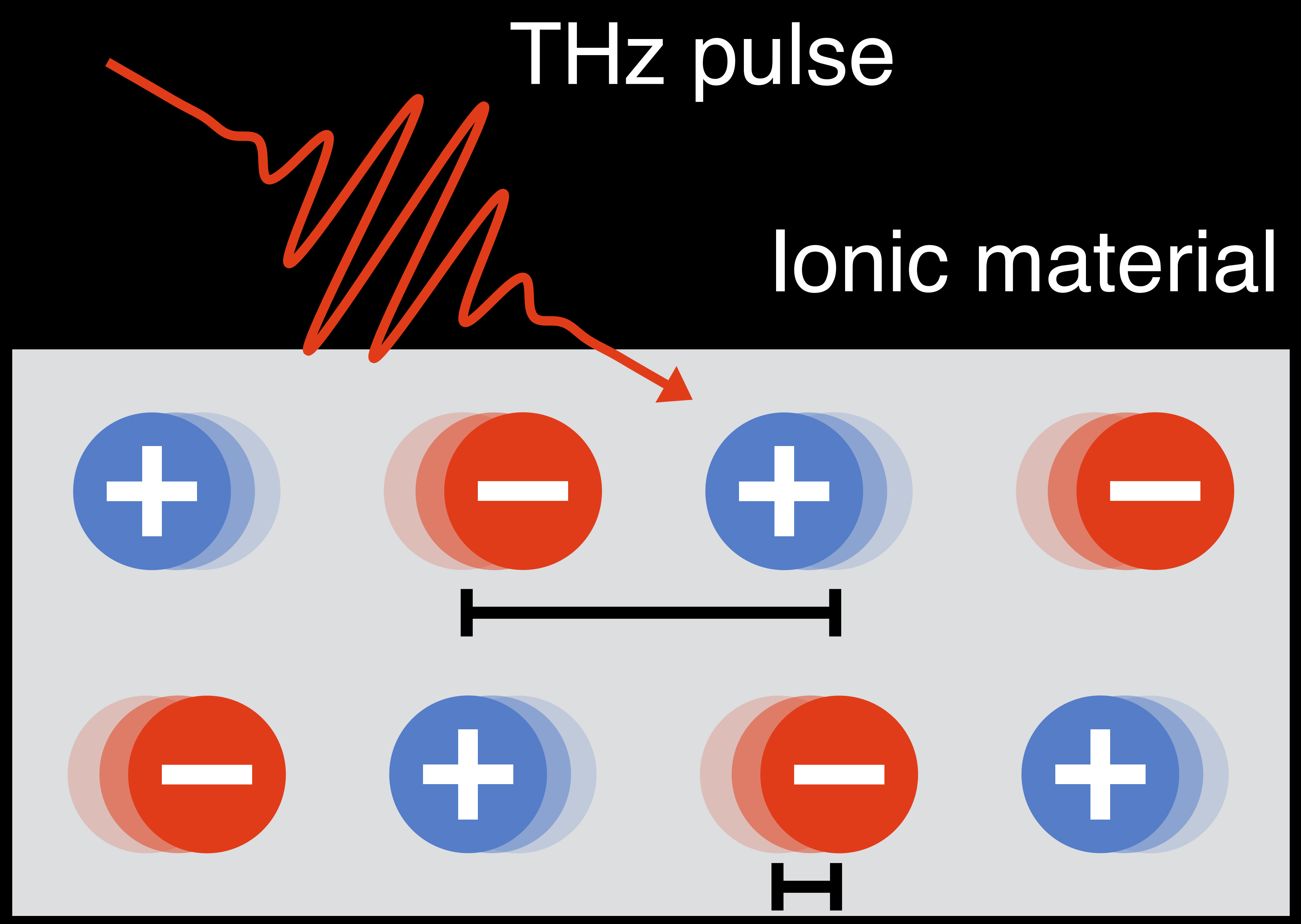
Nonlinear dynamics create metastable oscillator states



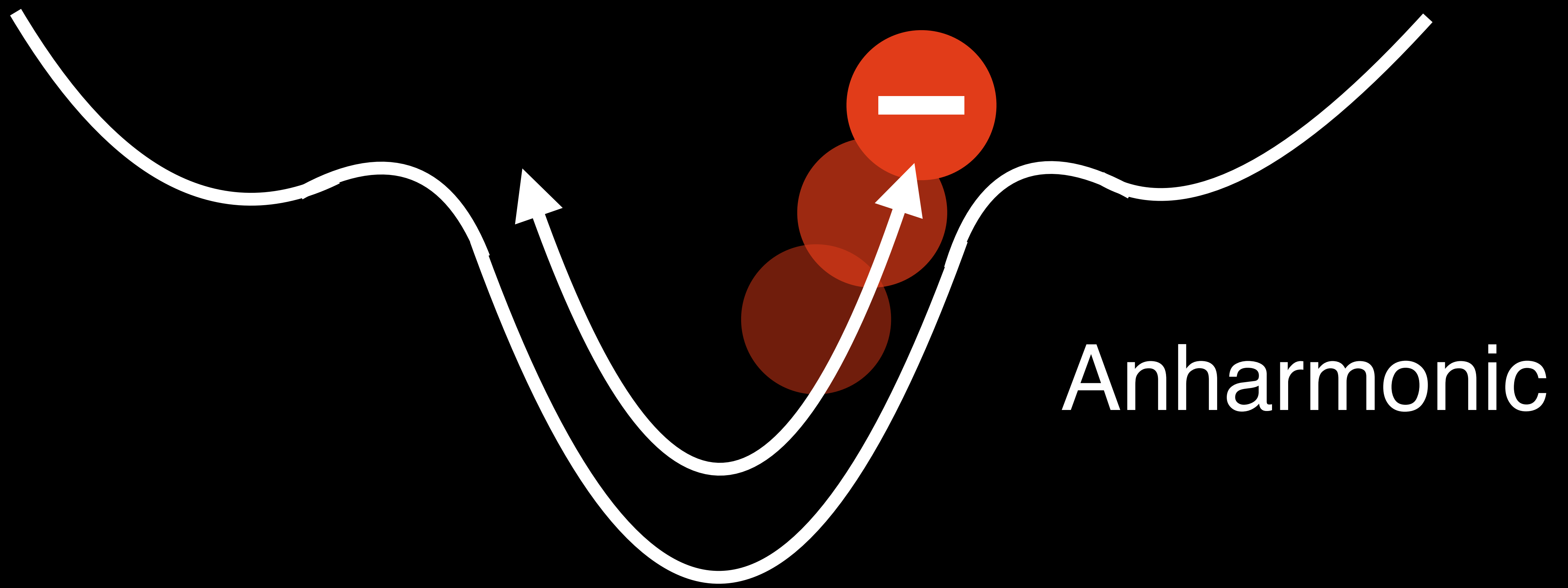
Caruso, …, Juraschek et al., arXiv:2501.06752 (2025)

TU/e

Large amplitude vibrations produce nonlinear phononic effects

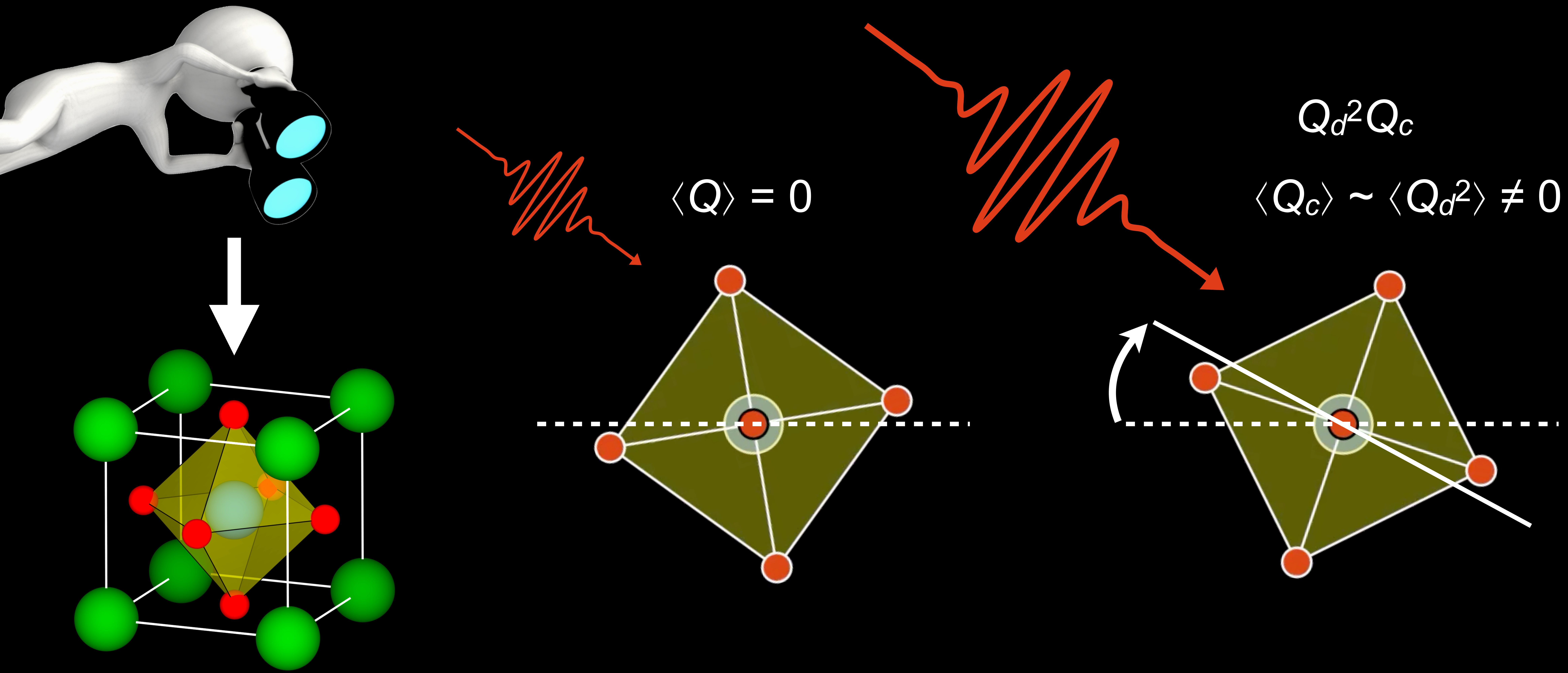


Motion 1-10% of interatomic distance



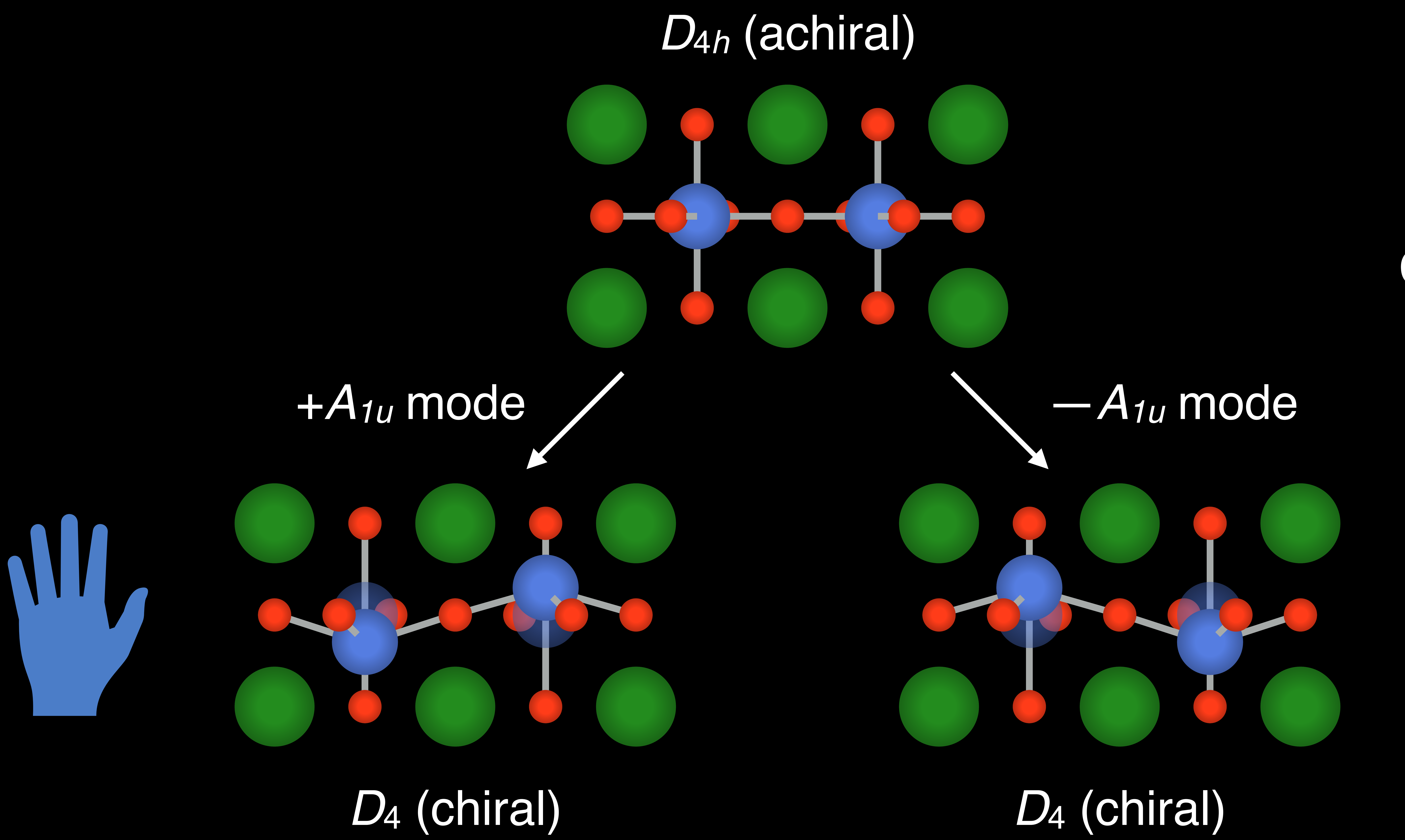
Harmonic

TU/e Phononic rectification induces structural distortions



Först et al., Nat. Phys. 7, 854 (2011)
Subedi et al., Phys. Rev. B 89, 220301(R) (2014)
Juraschek et al., Phys. Rev. Lett. 118, 054101 (2017)

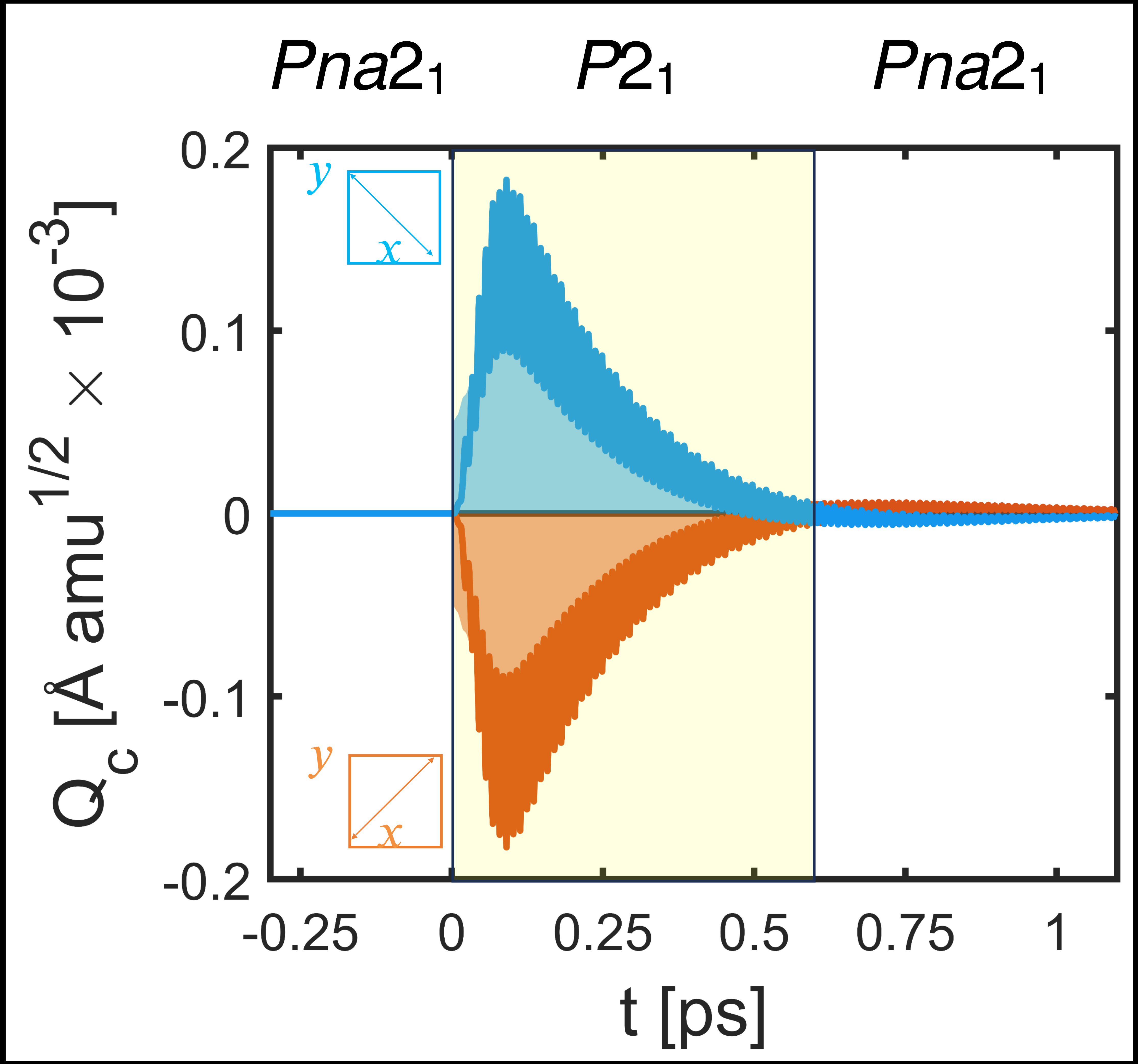
Geometric chiral phonons break all improper rotations



Carl Romao

Romao & Juraschek, ACS Nano 18, 29550 (2024)

TU/e A_2 modes induce chirality in LiB_3O_5

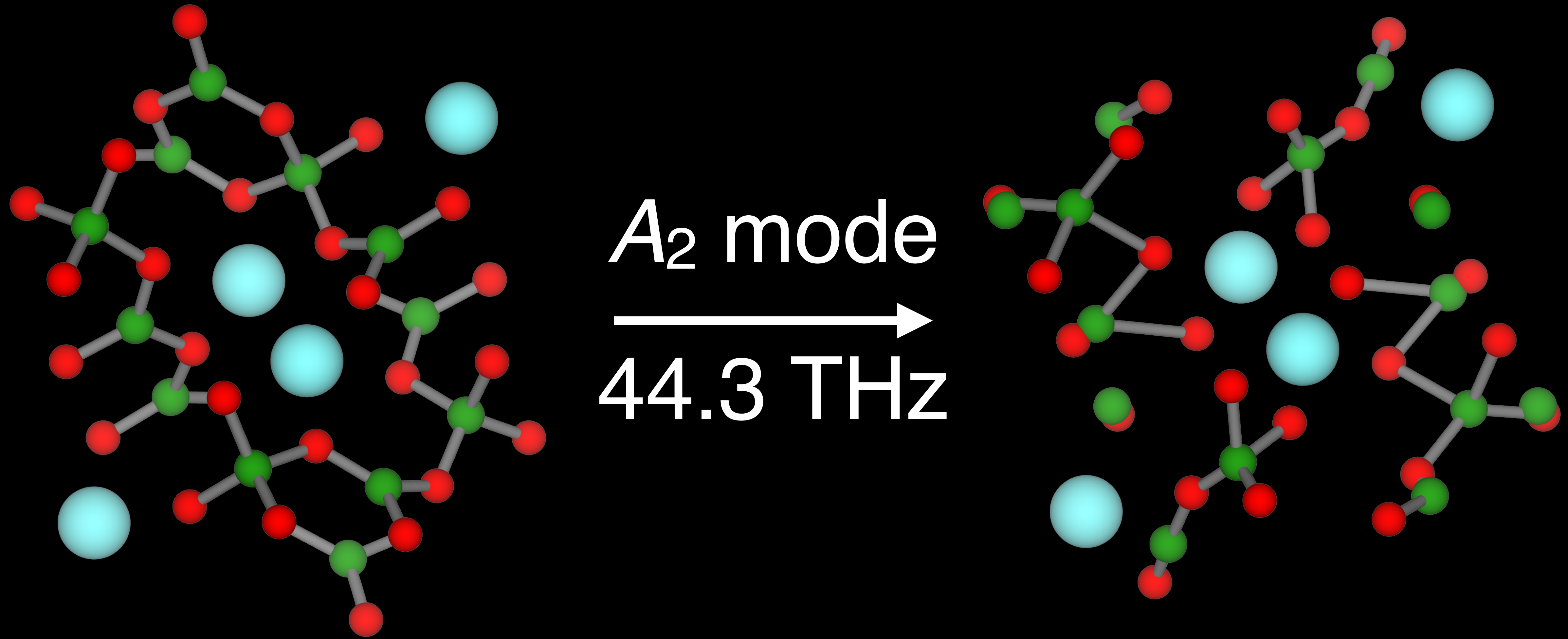


$$V = Q_{B_1} Q_{B_2} Q_{A_2}$$

$$\langle Q_{A_2} \rangle \sim \langle Q_{B_1} Q_{B_2} \rangle \neq 0$$

$$Q_{B_{1/2}} \sim E$$

$$Q_{A_2}(0) = \chi^{(2)}_{\mathrm{ph}}(0; \omega, -\omega)\mathbf{E}(\omega)\mathbf{E}^*(-\omega)$$



Romao & Juraschek, ACS Nano 18, 29550 (2024)

Group theory reveals promising materials

Point group	GCP	Subgroup	IR-active modes	Coupling	Example materials
C_s(m)	A''	$C_1(1)$	$A'(x,y)$, $A''(z)$	$A''A''A'$	KH_2PO_4, $BaGa_4Se_7$
C_{2v}(mm2)	A_2	$C_2(2)$	$B_1(x)$, $B_2(y)$	$A_2B_1B_2$	LiB_3O_5, $CdTiO_3$, $GaFeO_3$
$S_4(\bar{4})$	B	$C_2(2)$	${}^iE(x,y)$	B^iE^iE	BPO_4, Na_2ZnSnS_4
	${}^iE$	$C_1(1)$	${}^iE(x,y)$, $B(z)$	${}^iE^iEB$	
C_{4v}(4mm)	A_2	$C_4(4)$	$E(x,y)$	A_2EE	$SrBaNb_2O_6$
	E	$C_1(1)$, $C_s(\mathrm{m})^*$	$E(x,y)$, $A_1(z)$	EEA_1	
$D_{2d}(\bar{4}2\mathrm{m})$	A_2	$S_4(\bar{4})^*$	$E(x,y)$	A_2EE	$ZnGeP_2$, $AgGaS_2$
	B_1	$D_2(222)$	$E(x,y)$	B_1EE	
	E	$C_1(1)$, $C_2(2)$, $C_s(\mathrm{m})^*$	$E(x,y)$, $B_2(z)$	EEB_2	
C_{3v}(3m)	A_2	$C_3(3)$	$E(x,y)$	A_2EE	$LiNbO_3$, $BiFeO_3$
	E	$C_1(1)$, $C_s(\mathrm{m})^*$	$E(x,y)$, $A_1(z)$	EEA_1, EEE	
$C_{3h}(\bar{6})$	${}^iE''$	$C_1(1)$	${}^iE'(x,y)$, $A''(z)$	${}^iE''{}^jE'A''$	$LiCdBO_3$, $BaZnBO_3F$
C_{6v}(6mm)	A_2	$C_6(6)$	$E_1(x,y)$	$A_2E_1E_1$	$GaBO_3$,
	E_1	$C_1(1)$, $C_s(\mathrm{m})^*$	$E_1(x,y)$, $A_1(z)$	$E_1E_1A_1$	$Ba_3YbB_3O_9$
	E_2	$C_2(2)$, $C_{2v}(\mathrm{mm2})^*$	$E_1(x,y)$	$E_2E_1E_1$	
$D_{3h}(\bar{6}\mathrm{m}2)$	E''	$C_1(1)$, $C_2(2)$, $C_s(\mathrm{m})^*$	$E'(x,y)$, $A_2''(z)$	$E''E'A_2''$	$Na_3La_9B_8O_{27}$
$T_d(\bar{4}3\mathrm{m})$	E	$D_2(222)$, $D_{2d}(\bar{4}2\mathrm{m})^*$	$T_2(x,y,z)$	ET_2T_2	$CsNbMoO_6$,
	T_1	$P_1(1)$, $C_s(\mathrm{m})$,* $S_4(\bar{4})$,* $C_3(3)$	$T_2(x,y,z)$	$T_1T_2T_2$	$Zn_4B_6O_{13}$

*Subgroup is not chiral — $i, j = 1, 2$

Possible experiments involve pump-probe studies

Point group	GCP	Subgroup	IR-active modes	Coupling	Example materials
C_s(m)	A''	$C_1(1)$	$A'(x,y)$, $A''(z)$	$A''A''A'$	KH_2PO_4, $BaGa_4Se_7$
C_{2v}(mm2)	A_2	$C_2(2)$	$B_1(x)$, $B_2(y)$	$A_2B_1B_2$	LiB_3O_5, $CdTiO_3$, $CaFeO_3$
$S_4(\bar{4})$	B	$C_2(2)$	${}^iE(x,y)$	$B\,{}^iE\,{}^iE$	BPO_4, Na_2ZnSnS_4
	${}^iE$	$C_1(1)$	${}^iE(x,y)$, $B(z)$	${}^iE\,{}^iE\,B$	
C_{4v}(4mm)	A_2	$C_4(4)$	$E(x,y)$	A_2EE	$SrBaNb_2O_6$
	E	$C_1(1)$, C_s(m)*	$E(x,y)$, $A_1(z)$	EEA_1	
$D_{2d}(\bar{4}2m)$					$AgGaS_2$
C_{3v}(3m)					…eO_3
$C_{3h}(\bar{6})$					
C_{6v}(6mm					
$D_{3h}(\bar{6}m2)$					…$_8O_{27}$
$T_d(\bar{4}3m)$	E	$D_2(222)$, $D_{2d}(\bar{4}2m)$*	$T_2(x,y,z)$	ET_2T_2	$CsNbMoO_6$,
	T_1	$P_1(1)$, C_s(m),* $S_4(\bar{4})$,* $C_3(3)$	$T_2(x,y,z)$	$T_1T_2T_2$	$Zn_4B_6O_{13}$

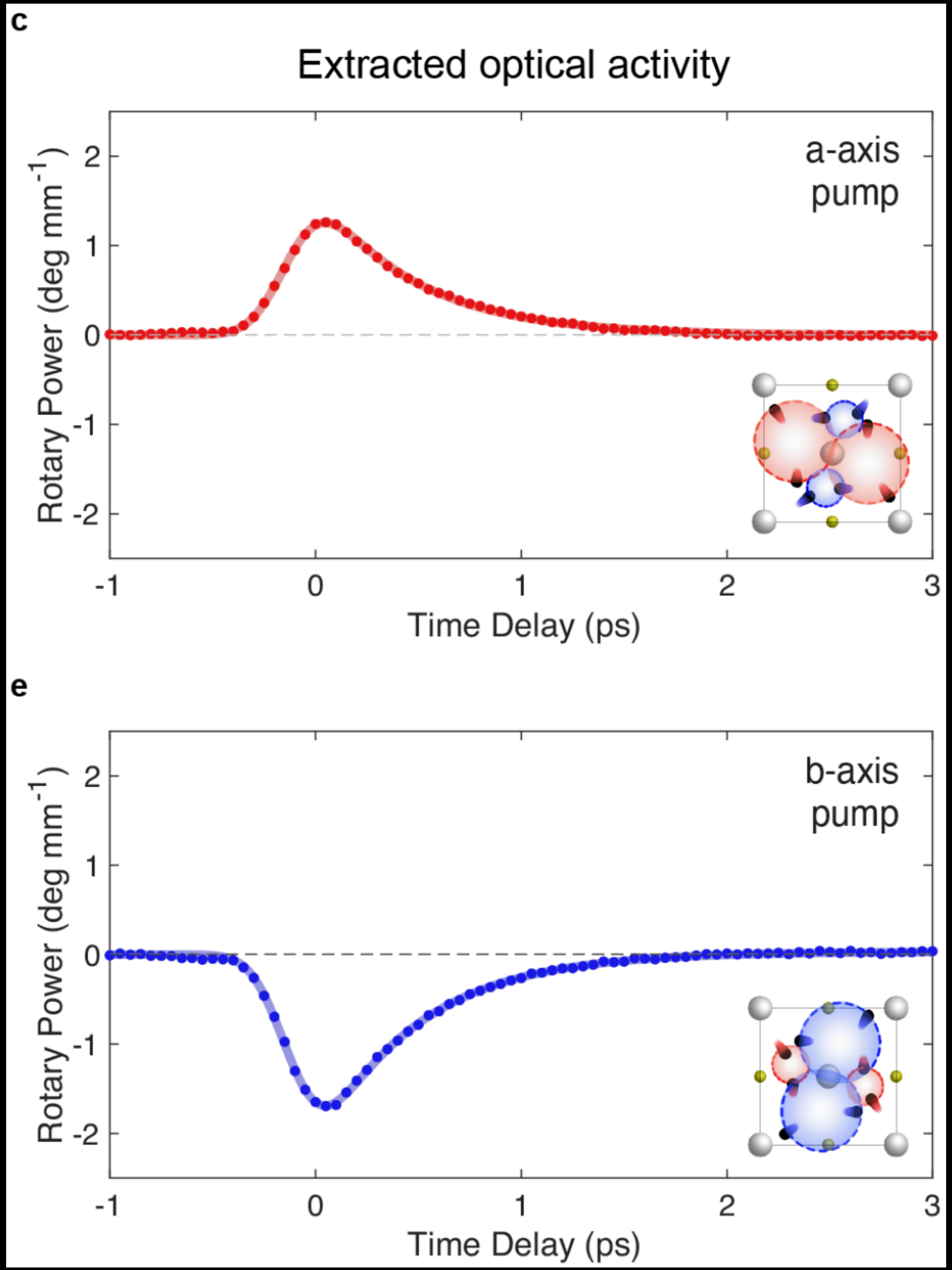
*Subgroup is not chiral — $i, j = 1, 2$

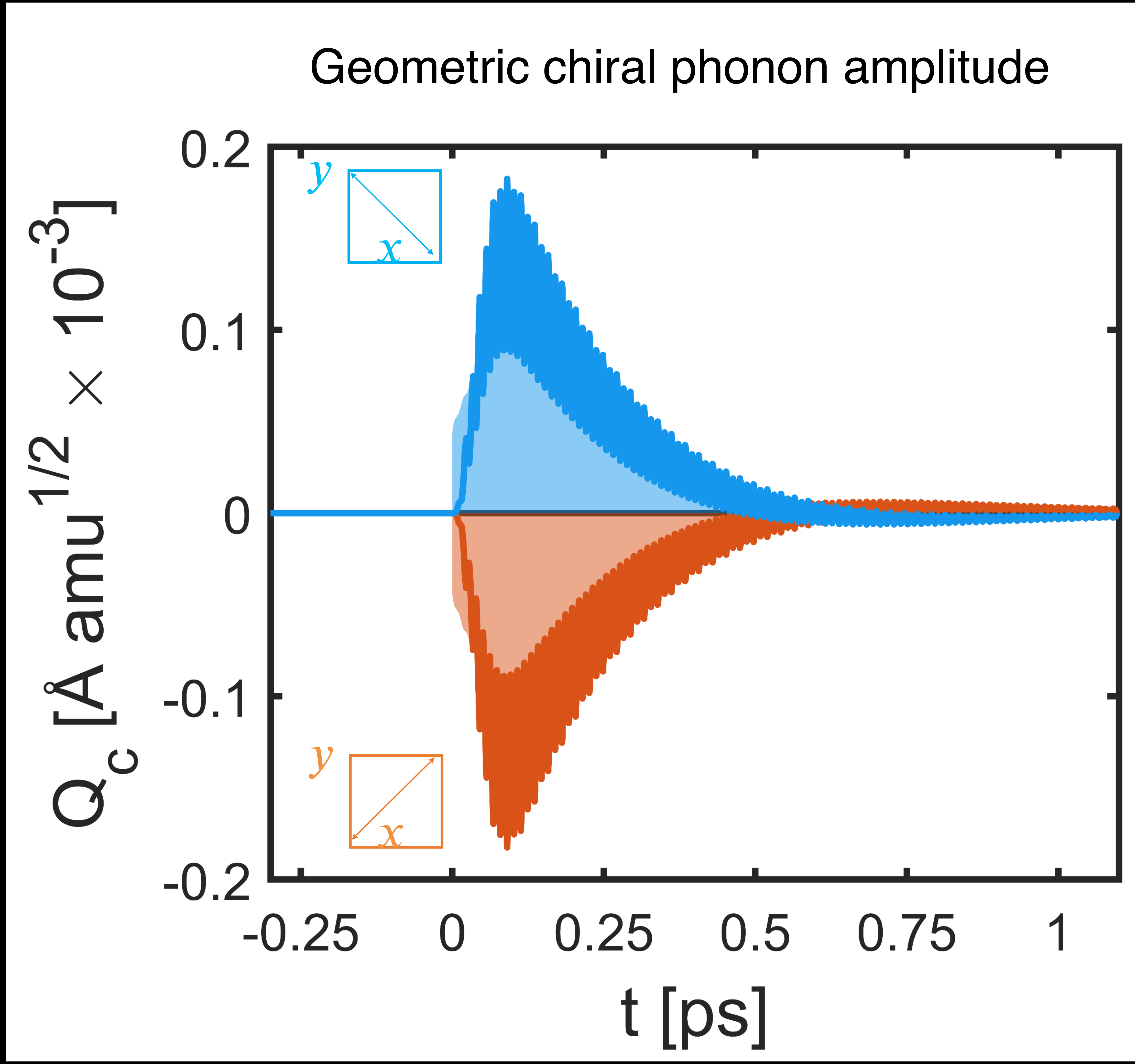
UED: Measure point group

tr-XCD: Distinguish enantiomers

Optical probe: Measure optical activity

First experiment measures optical activity





Zeng et al., Science 387, 431 (2025)
Romao, Juraschek, Science 387, 361 (2025)

Romao & Juraschek, ACS Nano 18, 29550 (2024)

TU/e

Outlook

- Chiral soft modes and displacive phase transitions?
- Order parameter for chirality?
- Modern theory of chiralization?

TU/e Collaborators & Funding

Omer Yaniv
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Czech Technical University

Tom Kahana
U Hamburg

Swati Chaudhary
UTokyo

Daniel B.-Lopez
Boston University

Greg Fiete
Northeastern

Michael Fechner
MPSD

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