Topology and geometry under nonlinear electromagnetic spotlight: An experimental perspective

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Nonreciprocal responses from non-centrosymmetric quantum materials

Yoshinori Tokura & Naoto Nagaosa

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Topology and Symmetry of Quantum Materials via Nonlinear Optical Responses

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nature materials
REVIEW ARTICLE
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Topology and geometry under the nonlinear electromagnetic spotlight

Qiong Ma[1,2], Adolfo G. Grushin[3] and Kenneth S. Burch[2]

For many materials, a precise knowledge of their dispersion spectra is insufficient to predict their ordered phases and physical responses. Instead, these materials are classified by the geometrical and topological properties of their wavefunctions. A key challenge is to identify and implement experiments that probe or control these quantum properties. In this Review, we describe recent progress in this direction, focusing on nonlinear electromagnetic responses that arise directly from quantum geometry and topology. We give an overview of the field by discussing theoretical ideas, experiments and the materials that drive them. We conclude by discussing how these techniques can be combined with device architectures to uncover, probe and ultimately control quantum phases with emergent topological and correlated properties.

Symmetry Breaking and Nonlinear Electric Transport in van der Waals Nanostructures

Annual Review of Condensed Matter Physics
Vol. 12:201-223 (Volume publication date March 2021)
https://doi.org/10.1146/annurev-conmatphys-060220-100347

Toshiya Ideue[1] and Yoshihiro Iwasa[1,2]
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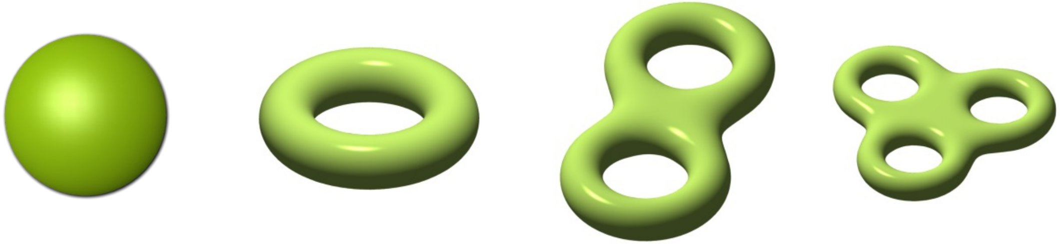
Topology and Geometry

Geometry and Topology in real space



$\boldsymbol{g}=0$ $\boldsymbol{g}=1$ $\boldsymbol{g}=2$ $\boldsymbol{g}=3$

Gauss-Bonnet Theorem:

$$\int_S K_{Gauss}\, ds = 2(1-\boldsymbol{g})$$

K_{Gauss} → Gauss curvature

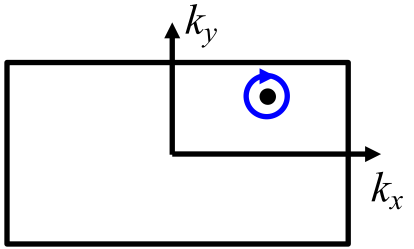
$\boldsymbol{g}$ → # of holes

Geometry and Topology in the electronic wave functions $\left|\psi(\vec{k})\right\rangle$

$$\int_{BZ} d^2k\, \nabla_{\vec{k}} \times i\left\langle \psi(\vec{k}) \middle| \nabla_{\vec{k}} \middle| \psi(\vec{k}) \right\rangle = C$$

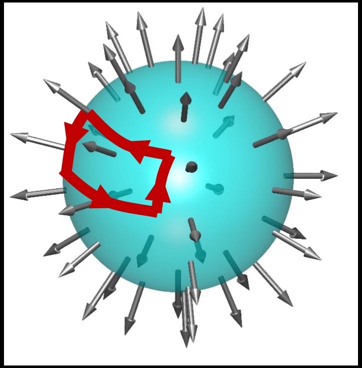
$\nabla_{\vec{k}} \times i\left\langle \psi(\vec{k}) \middle| \nabla_{\vec{k}} \middle| \psi(\vec{k}) \right\rangle$ → Berry curvature

C → Chern number

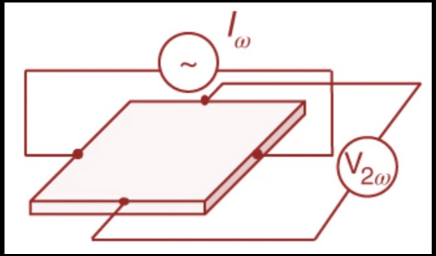


$$\gamma = i\oint_c d\vec{k} \left\langle \psi(\vec{k}) \middle| \nabla_{\vec{k}} \middle| \psi(\vec{k}) \right\rangle = \int_S d\vec{S} \cdot \vec{\Omega}(\vec{k})$$

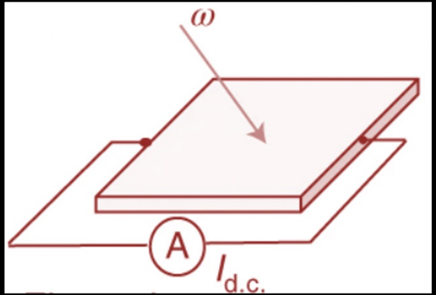
Outline



- Using graphene to visualize Geometry and Topology



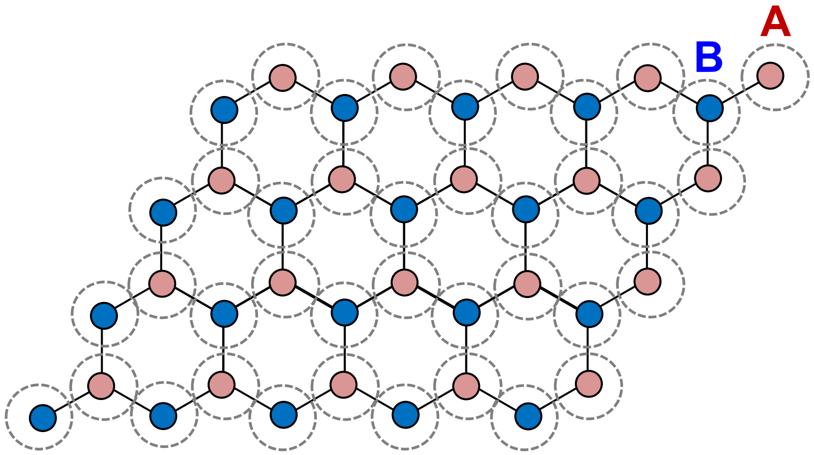
- Nonlinear responses – symmetry-sensitive tools
- I. Nonlinear Transport Phenomena (This lecture)

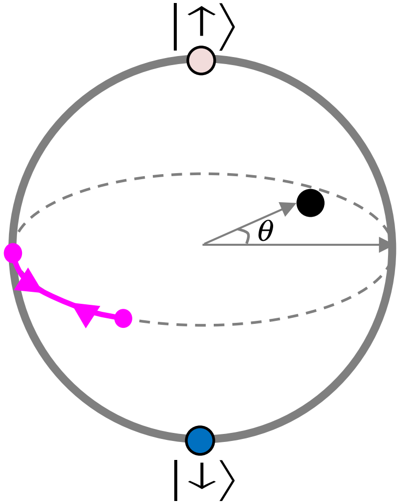


- II. Nonlinear Photocurrents (Next lecture)
- Outlook

Visualizing geometry and topology in momentum space

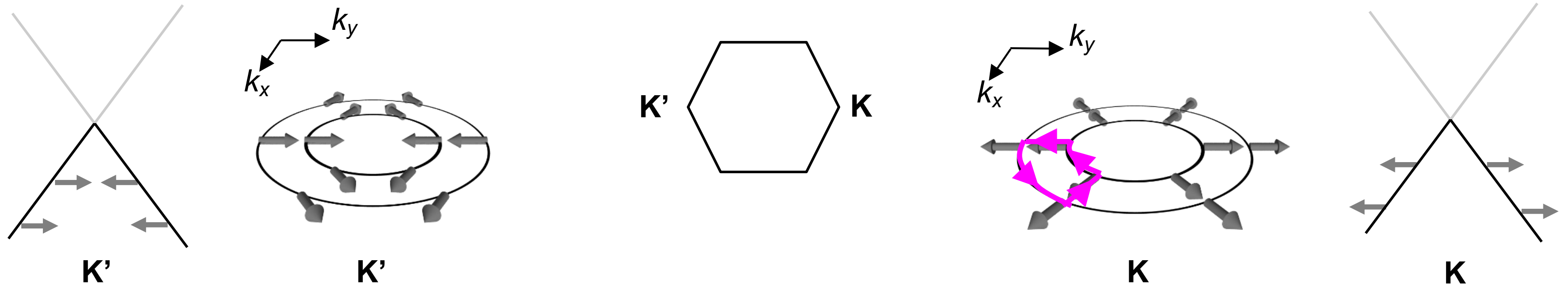
Pristine Graphene





Equator:

$\bullet = |\uparrow\rangle + e^{i\theta}|\downarrow\rangle$

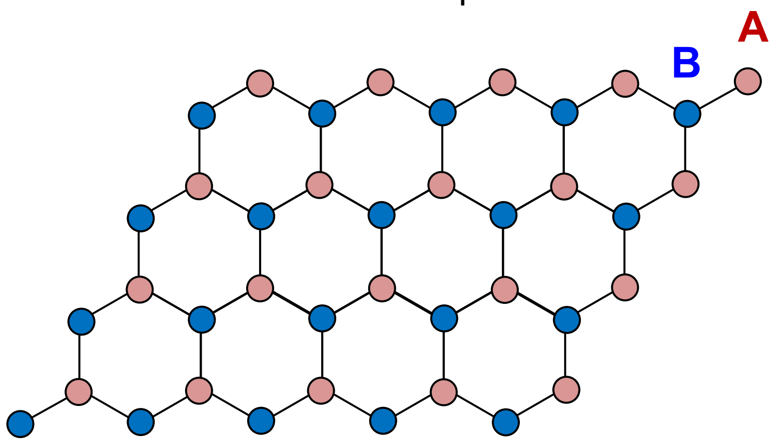


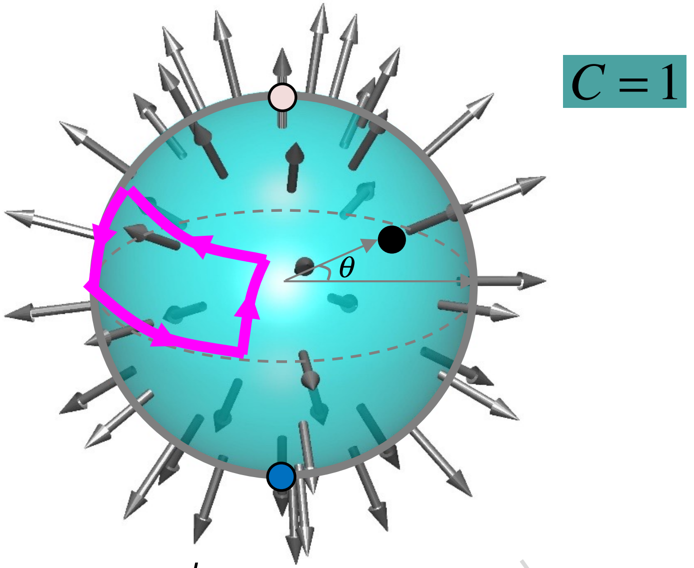
Pristine graphene has both T and I, so Berry curvature = 0

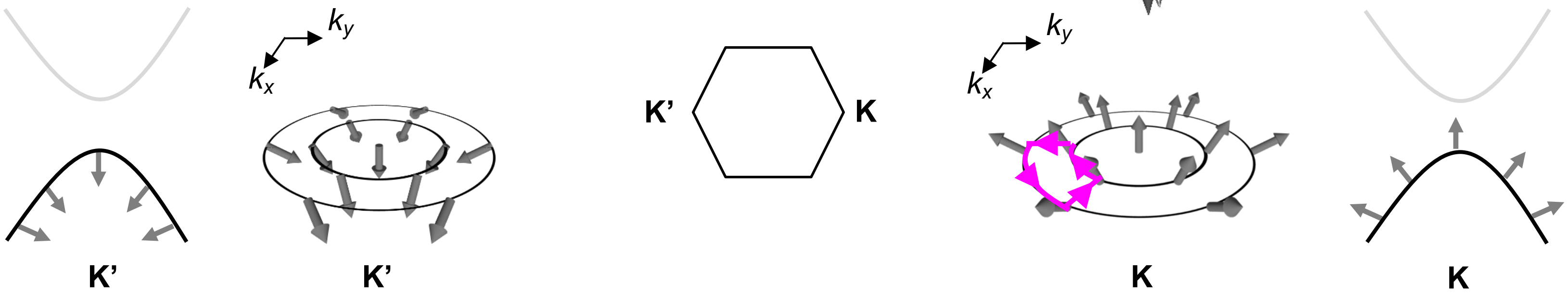
T: time reversal symmetry; I: inversion symmetry

Visualizing geometry and topology in momentum space

Pristine Graphene

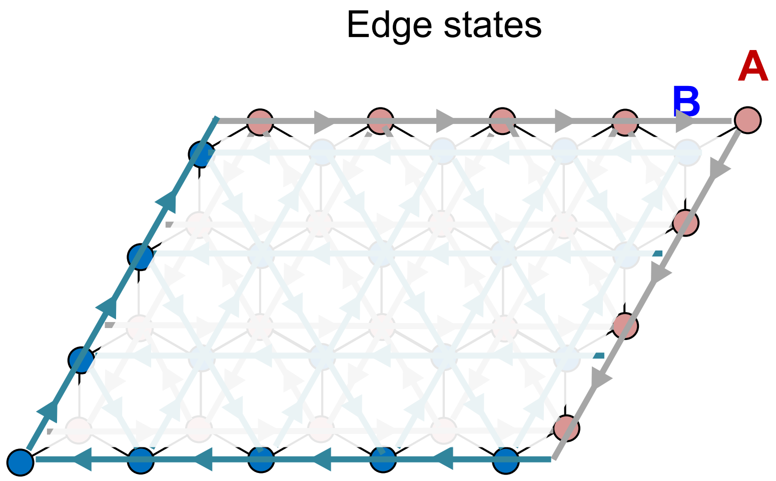


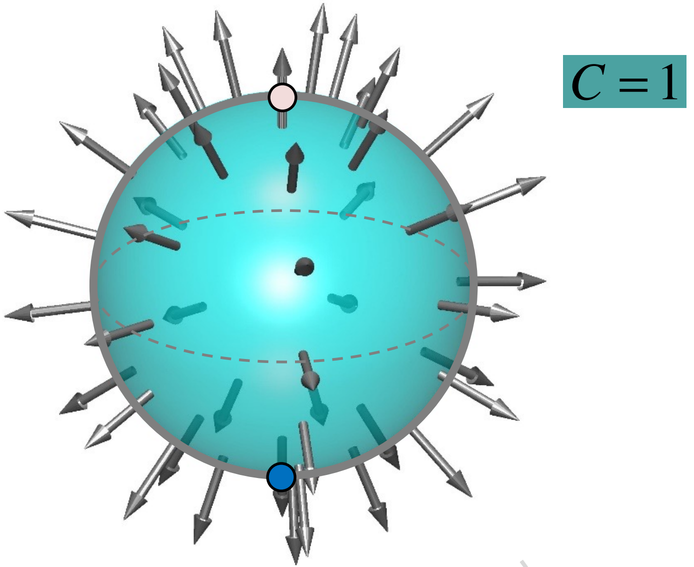


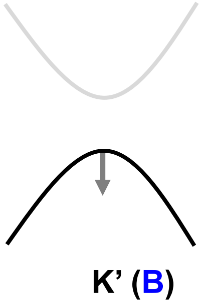


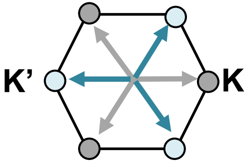
T breaking, Berry curvature ≠ 0
Haldane PRL **61**, 2015 (1988)

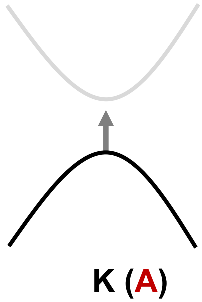
Visualizing geometry and topology in momentum space











T breaking, Berry curvature $\neq 0$

Haldane PRL **61**, 2015 (1988)

A few points to make about quantum geometry

- **Beyond topology:**
  Even in a non-topological context, quantum geometry could lead to interesting phenomena.

- **Beyond the total Berry curvature:**
  Even when total Berry curvature is zero, the distribution of Berry curvature could lead to interesting phenomena.

- **Beyond Berry curvature:**
  Even when Berry curvature is zero, other geometric properties could exist and lead to interesting phenomena.

- **Symmetry is important:**
  Space group or magnetic space group determines whether we have nontrivial quantum geometry and how the quantum geometry depends on ***k***.

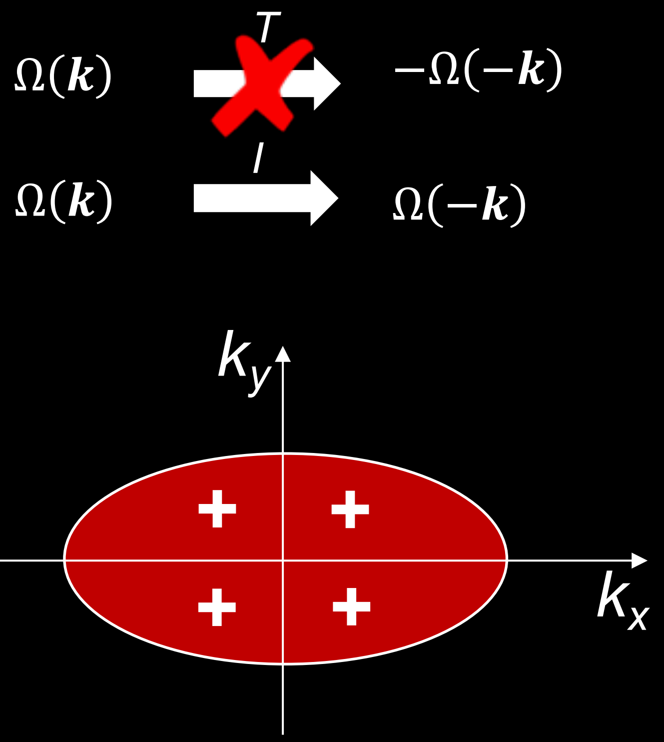
Quantum geometric (Berry curvature) effect is beyond topological effect

Anomalous Hall conductivity

$$\sigma_{\mathrm{AHE}} = \int d^2k\, f(k)\Omega(k)$$

Quantum anomalous Hall conductivity

$$\sigma_{\mathrm{QAHE}} = \int d^2k\, f(k)\Omega(k) = C\,\frac{\mathrm{e}^2}{\mathrm{h}}$$



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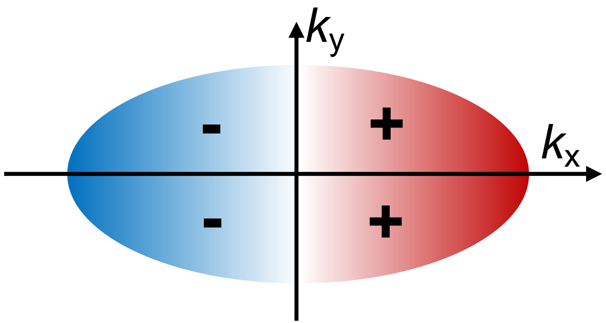
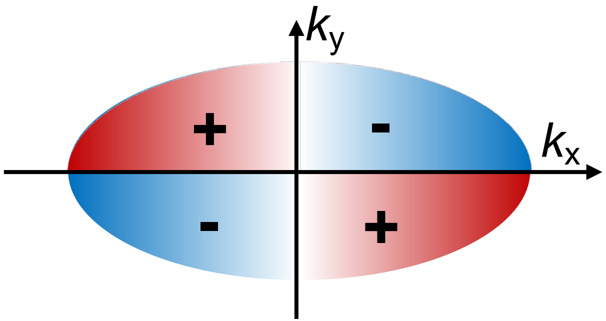
Beyond the total Berry curvature effect

A dipolar distribution of Berry curvature



A quadruple distribution of Berry curvature



A few points to make about geometry

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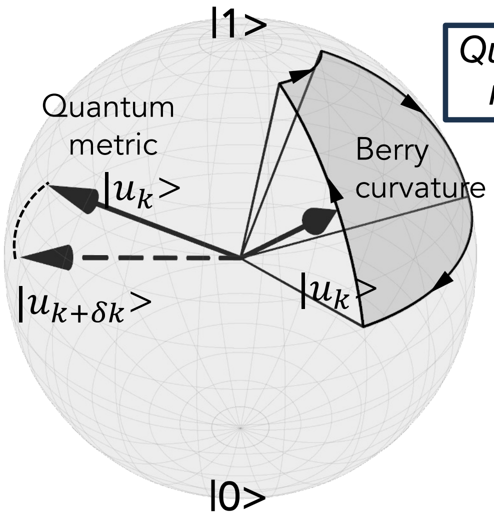
Beyond Berry curvature effect

Quantum geometric tensor $T = g + i\Omega$

Quantum metric — *Berry curvature*



A few points to make about geometry

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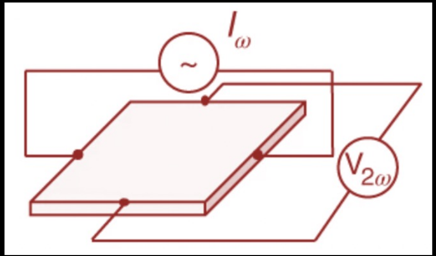
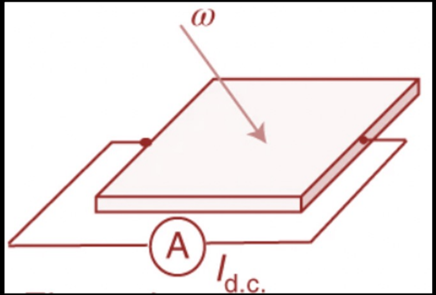
Outline

- Using graphene to visualize Geometry and Topology
- Second-order responses – symmetry-sensitive tools
- I. Nonlinear Transport Phenomena (This lecture)
- II. Nonlinear Photocurrents (Next lecture)
- Outlook





Symmetry-sensitive probe

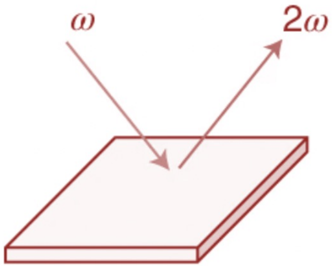
$$A_i = A_0 + \underbrace{\alpha_{ij}E_j}_{\text{Linear response}} + \underbrace{\chi^{(2)}_{ijk}E_iE_j}_{\text{Second-order response}} + \cdots$$

Linear response   Second-order response

Second-harmonic generation (SHG)

$\omega \Rightarrow \omega + \omega$

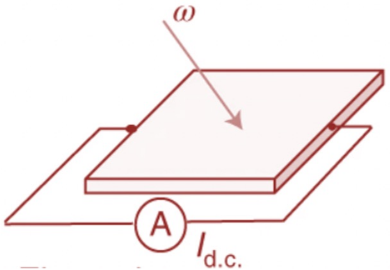
$$P_i^{2\omega} = \chi^{(2)}_{ijk}E_j^{\omega}E_k^{\omega}$$



Photocurrent generation (PC)

$\omega \Rightarrow \omega - \omega$

$$I_i^{0\omega} = \chi^{(2)}_{ijk}E_j^{\omega}E_k^{\omega}$$



$$P_i^{2\omega} = \chi^{(2)}_{ijk}E_j^{\omega}E_k^{\omega}$$

$$i, j, k \rightarrow -i, -j, -k$$

$$P_{-i} \rightarrow -P_i$$

$$E_{-j} \rightarrow -E_j$$

$$E_{-k} \rightarrow -E_k$$

$$\chi^{(2)}_{-i,-j,-k} = \chi^{(2)}_{ijk}$$

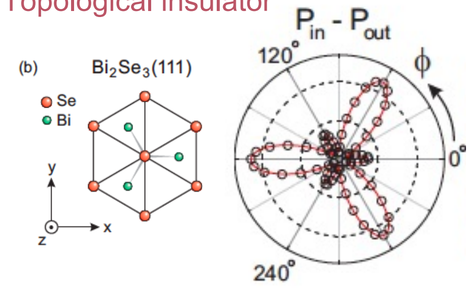
Under inversion symmetry

$$P_i^{2\omega} = -\chi^{(2)}_{ijk}E_j^{\omega}E_k^{\omega}$$

$$\boxed{\chi^{(2)}_{ijk} = 0}$$

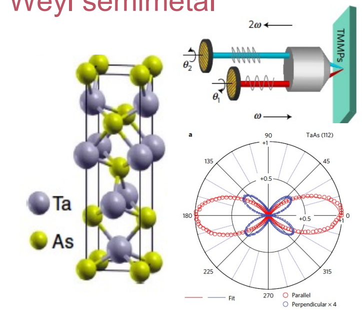
Optical second-harmonic generation (SHG)

Topological insulator



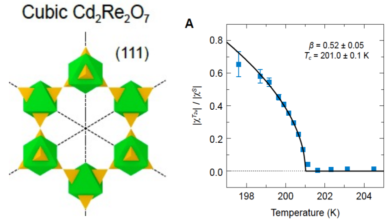
Hsieh et al, PRL (2011)

Weyl semimetal



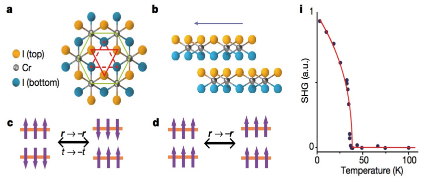
Wu et al, Nature Physics (2017)

Correlated materials



Zhao et al, Nature Physics (2016)
Harter et al, Science (2017)

2D magnet



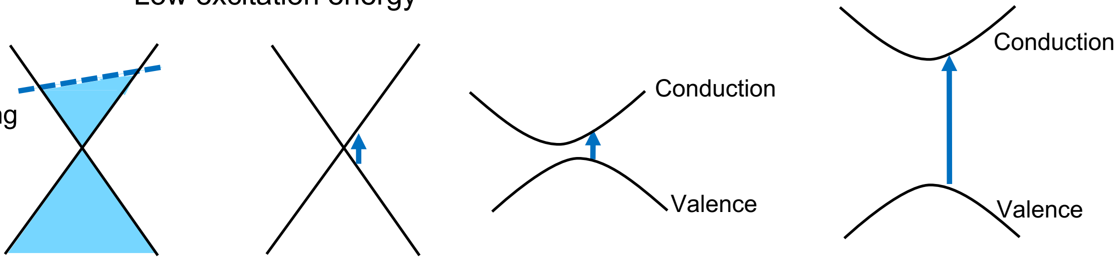
Sun et al, Science (2019)

Excitation frequency

DC/kHz | Microwave | THz | Infrared | Visible | UV

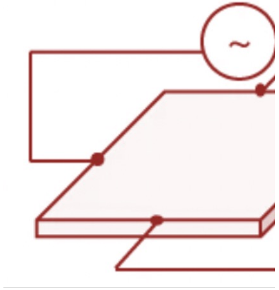
$\hbar\omega \rightarrow 0$

Low excitation energy



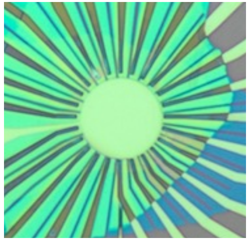
Second-order responses: different experimental setups

Devices/Electro
DC/RF sources
Frequency lock-



DC/kHz

Device structures



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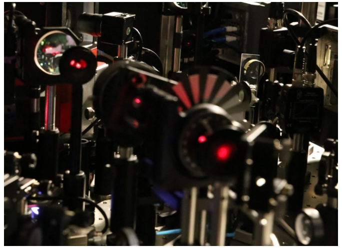
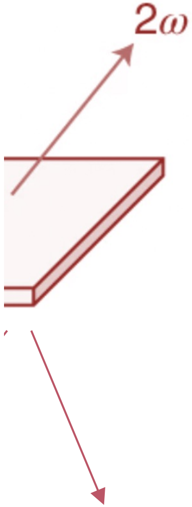
Electronics

+

Lasers, Optics



sources
sensitive optics

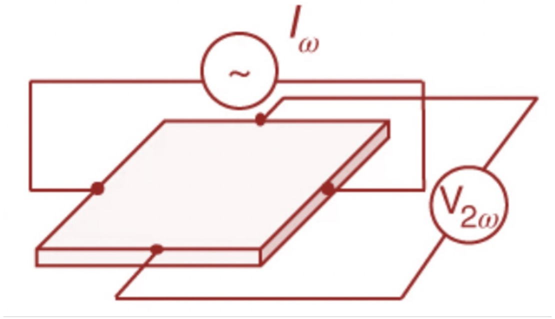


UV

Ma, et al., Nature

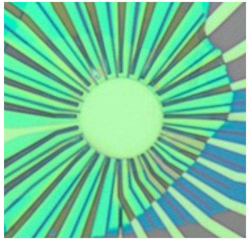
Second-order electrical responses

Devices/Electrodes
DC/RF sources
Frequency lock-in technique



DC/kHz | Microwave

Device structures



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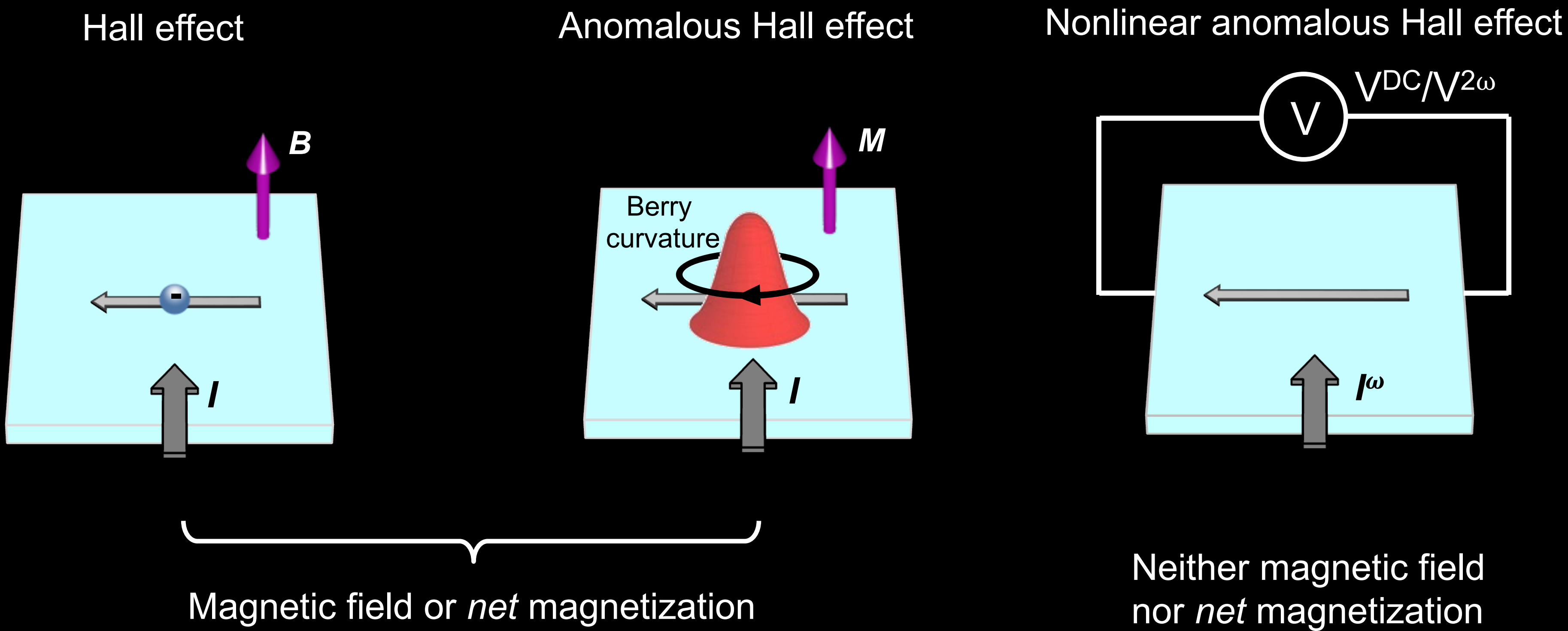
Electronics

Ma, et al., Nature Materials 20, 1601 (2

Topology and geometry under nonlinear electromagnetic spotlight: An experimental perspective

I. Second-order anomalous Hall responses



Anomalous Hall effect (AHE)

Anomalous Hall conductivity

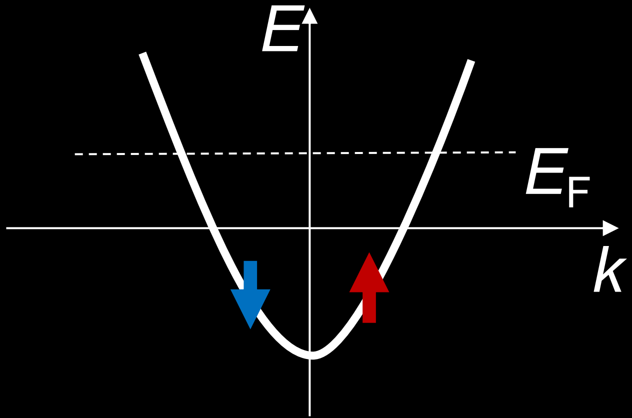
$$\sigma_{\mathrm{AHE}} = \int d^2k \, f(k)\Omega(k)$$

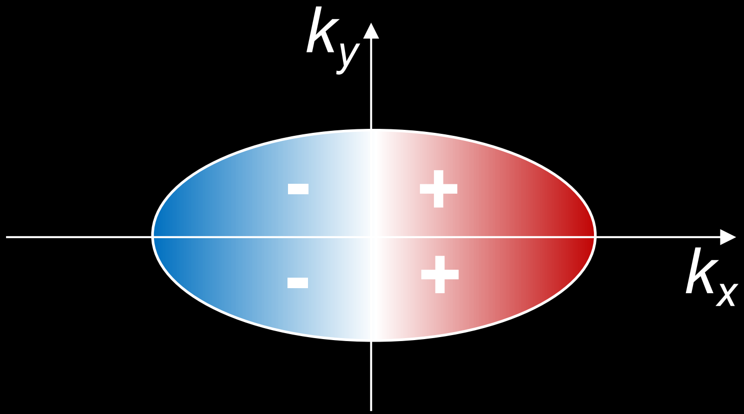
0

T : Time reversal symmetry operation
I : Inversion symmetry operation

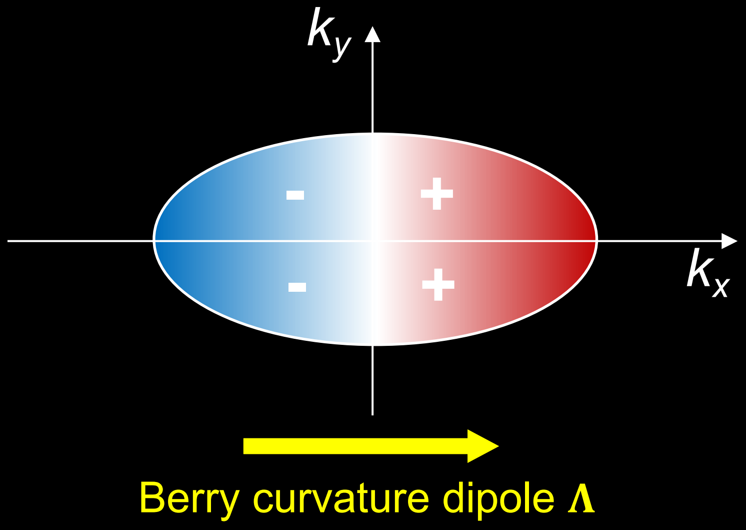
$$\Omega(\boldsymbol{k}) \xrightarrow{T} -\Omega(-\boldsymbol{k})$$

$$\Omega(\boldsymbol{k}) \xrightarrow{I} \Omega(-\boldsymbol{k})$$



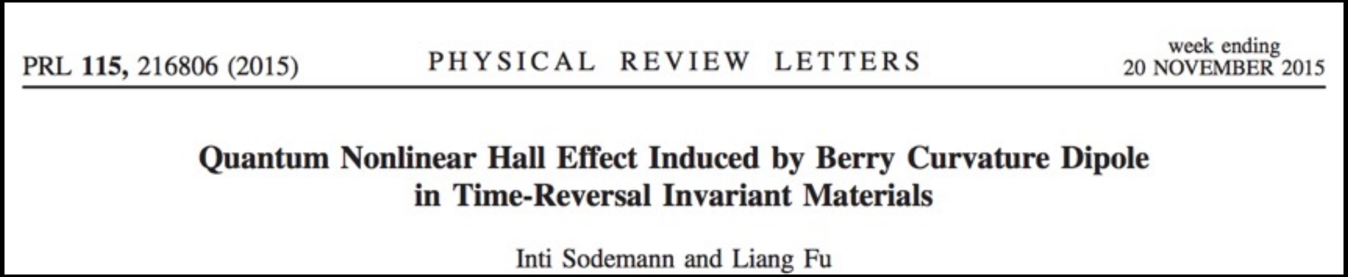


Berry curvature dipole and nonlinear Hall response



$$\boldsymbol{j}^{\text{NLHE}} = \frac{e^3\tau}{2(1+i\omega\tau)}\hat{\boldsymbol{z}}\times\boldsymbol{E}(\boldsymbol{\Lambda}\cdot\boldsymbol{E})$$

$$\boldsymbol{\Lambda} = \int d^2k\, f(\boldsymbol{k})\nabla_{\boldsymbol{k}}\Omega_z(\boldsymbol{k})$$



PRL **115**, 216806 (2015) PHYSICAL REVIEW LETTERS week ending 20 NOVEMBER 2015

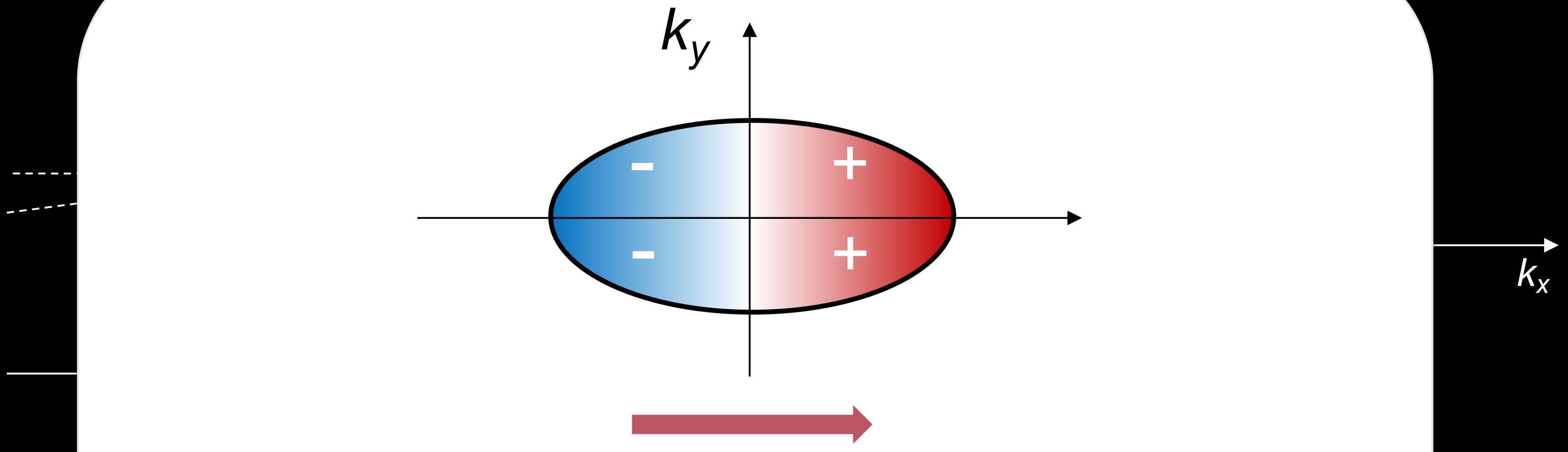
Quantum Nonlinear Hall Effect Induced by Berry Curvature Dipole in Time-Reversal Invariant Materials

Inti Sodemann and Liang Fu

Deyo and Spivak, et al, (2009) arxiv:0904.1917
Moore and Orenstein, PRL 105, 026805 (2010)

Berry curvature dipole and nonlinear Hall response

Net Berry curvature in current carrying state

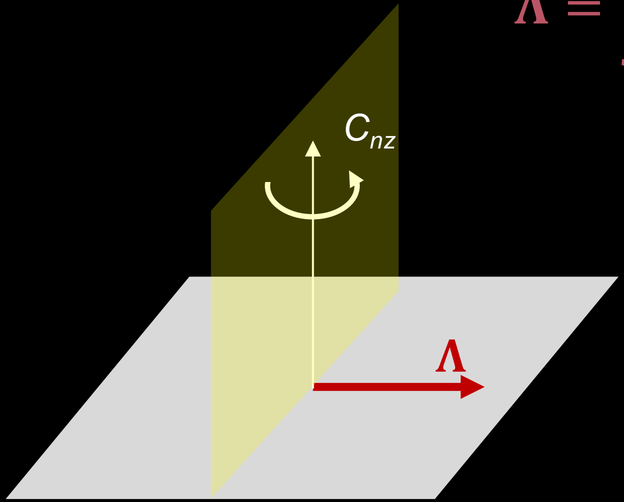


Berry curvature dipole $\boldsymbol{\Lambda}$

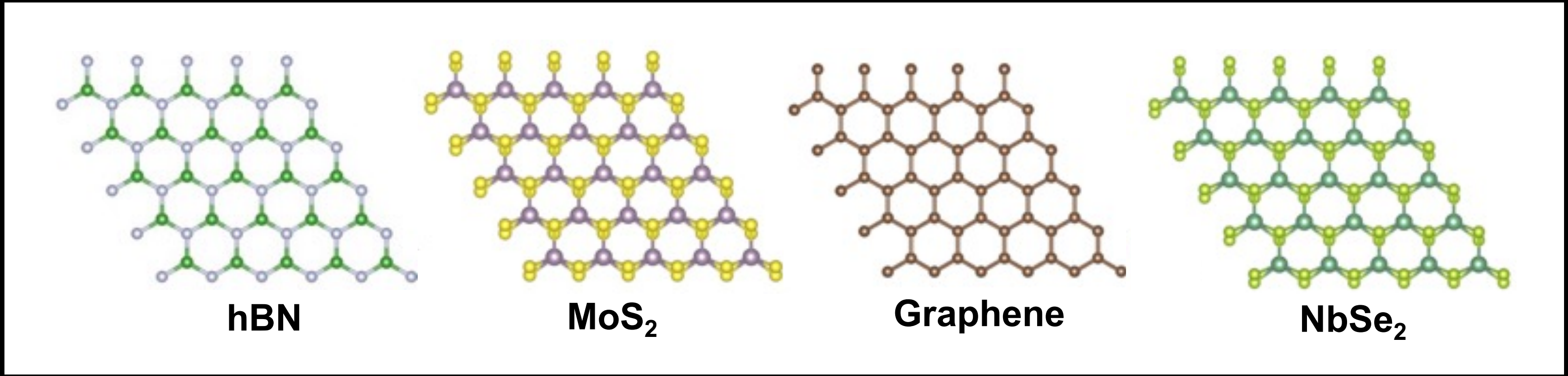
Material system ?

Symmetry constraint of the dipole

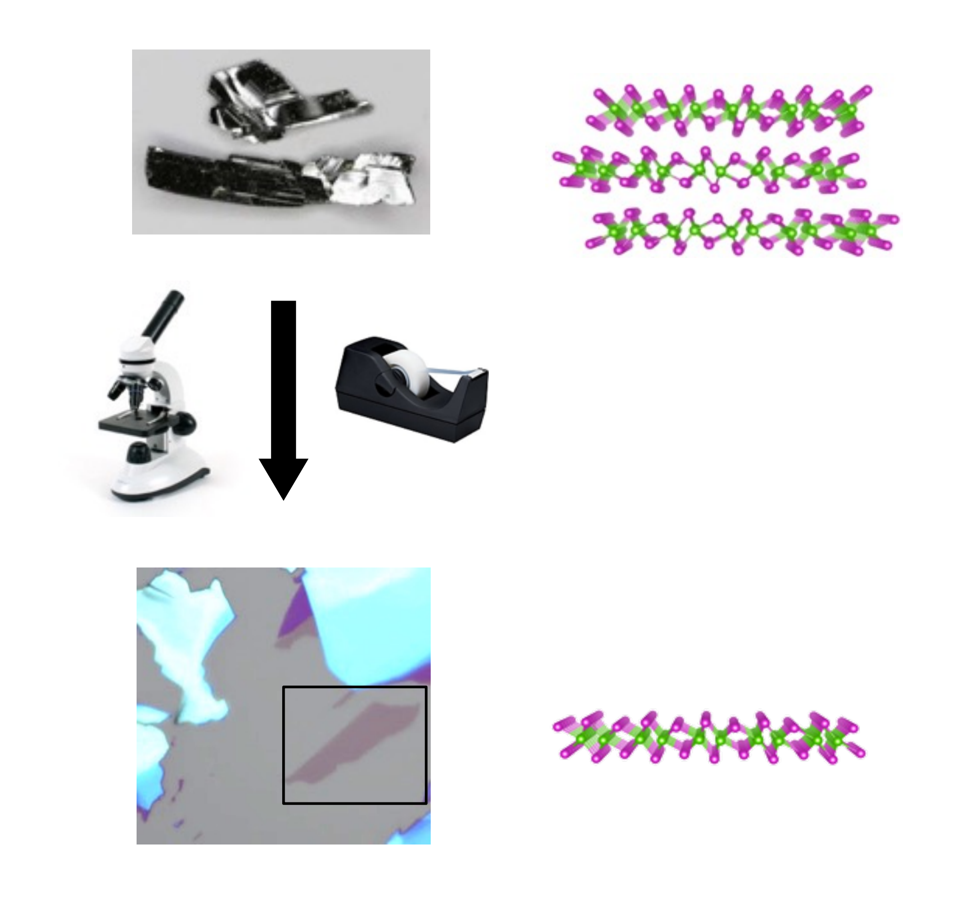
$$\Lambda = \int d^2k\, f(\boldsymbol{k}) \nabla_{\boldsymbol{k}} \Omega_z(\boldsymbol{k})$$



- No inversion center
- No out-of-plane rotation C_{nz}
- No simultaneous mirrors M_x and M_y



Layered transition metal dichalcogenide T_d-WTe_2



Bulk:
- Magnetoresistance
- Weyl semimetal
- Hydrodynamic

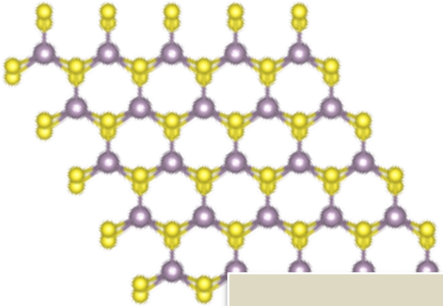
Ong group, Nature 14’
Bernevig group, Nature 15’
Yacoby&Narang, Nature Physics 21’

Monolayer:
- Quantum spin Hall insulator
- Superconductivity
- Excitonic insulator

Cobden group, Nature Physics 17’ Science 18’
Shen group, Nature Physics 17’
PJH group, Science 18’ Science 18’’
Wu group, Nature 21’

Low crystal symmetry of WTe_2

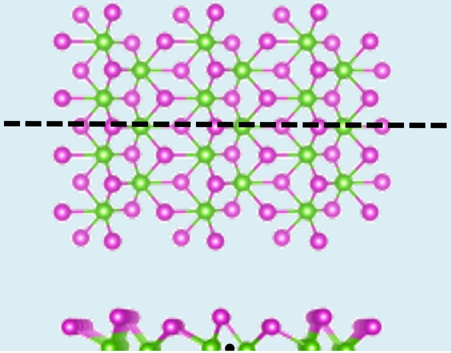
Monolayer H-TMDs (MoS_2, $NbSe_2$, etc.)



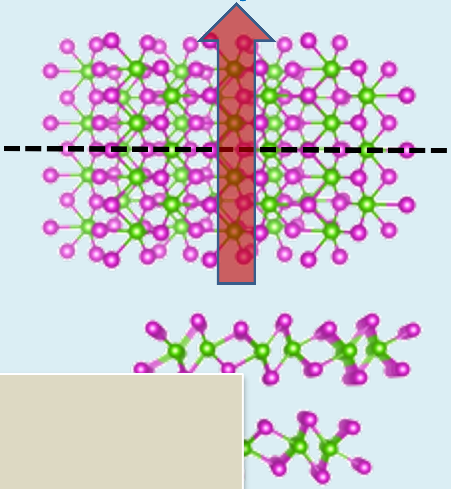
- C_3 rotation
- > 1 mirror plai
- No inversion

T_d-TMD WTe_2

Monolayer



Bilayer

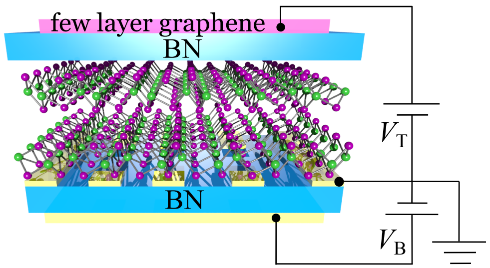


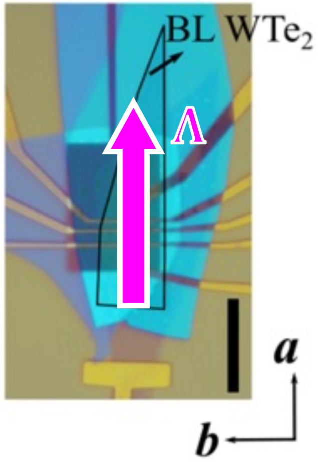
lane rotation
r plane
symmetry

Bilayer WTe_2 is an ideal candidate:

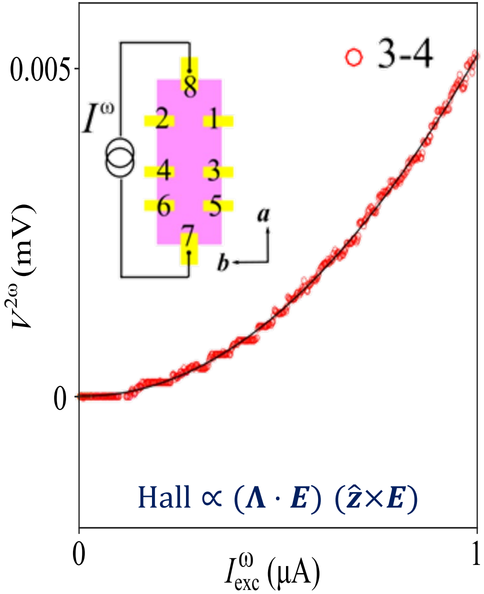
- ➢ Correct symmetry
- ➢ Massive Dirac Fermion, large Berry curvature
- ➢ 2D system, gate-tunable

Nonlinear anomalous Hall in bilayer WTe_2

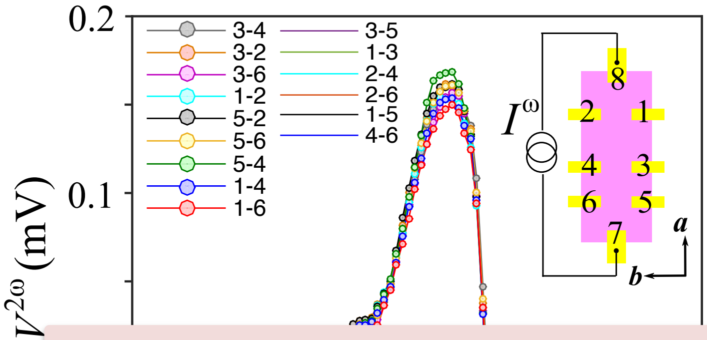




Electrical (Fermi surface) + SHG (Symmetry)



ω : 1 Hz to 1000 Hz

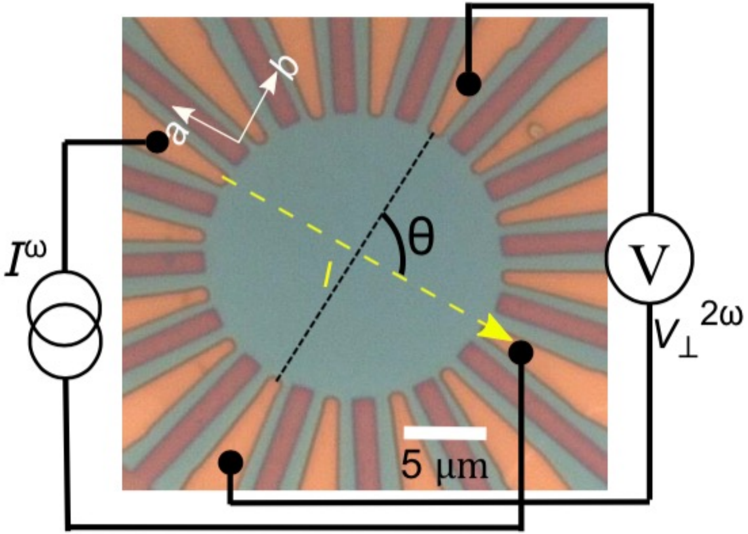


Hall response!

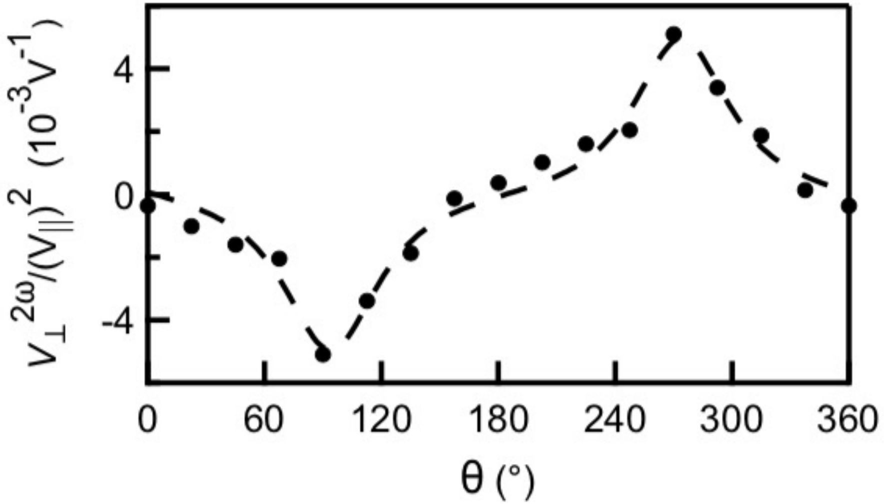
Ma, et al., Nature **565**, 337–342 (2019)

Nonlinear anomalous Hall in WTe_2

$$\text{Hall} \propto \boxed{(\boldsymbol{\Lambda} \cdot \boldsymbol{E})}\,(\hat{\boldsymbol{z}} \times \boldsymbol{E})$$

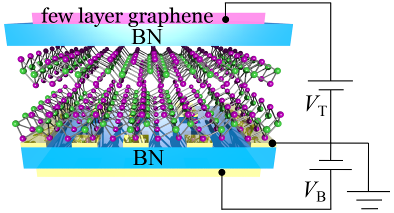


Few-layer WTe_2

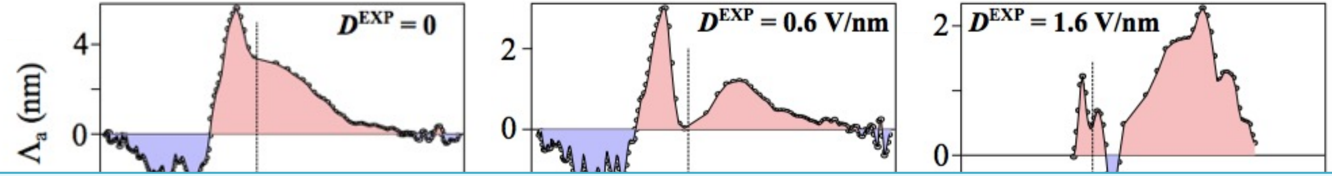


KK, JS & KFM, Nature Mat. **18**, 324–328 (2019)

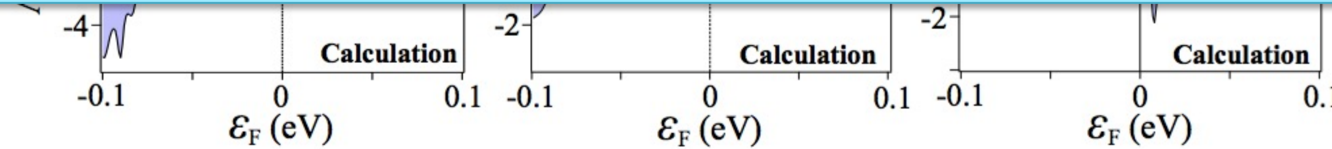
Nonlinear anomalous Hall in bilayer WTe_2



$$j^{\mathrm{NLHE}} = \frac{e^3\tau}{2(1+i\omega\tau)}\hat{\boldsymbol{z}}\times\boldsymbol{E}(\boldsymbol{\Lambda}\cdot\boldsymbol{E})$$



The nonlinear Hall signal directly measures the Berry dipole in the nonmagnetic WTe_2 in an energy-resolved way.



Hsin Lin

Efthimios Kaxiras

A probe of Berry curvature of non-magnetic quantum materials

TABLE I. **Experiments on the nonlinear Hall effect.**

Materials	Dimension	Temperature (K)	Input current frequency (Hz)	Input current maximum (μA)	Output voltage maximum (μV)	Carrier density (cm^{-2}) in 2D (cm^{-3}) in 3D
Bilayer WTe_2 [24]	2	10-100	10-1000	1	200	$\sim 10^{12}$
Few-layer WTe_2 [25]	2	1.8-100	17-137	600	30	$\sim 10^{13}$
Strained monolayer WSe_2 [40]	2	50-140	17.777	5	20	$\sim 10^{13}$
Twisted bilayer WSe_2 [42]	2	1.5-30	4.579	0.04	20000	$\sim 10^{12}$
Corrugated bilayer graphene [41]	2	1.5-15	77	0.1	2	$\sim 10^{12}$
Bi_2Se_3 surface [45]	2	2-200	9-263	1500	20	$\sim 10^{13}$
Bulk WTe_2 [38]	3	1.4-4.2	110	4000	2	-
Cd_3As_2 [38]	3	1.4-4.2	110	4000	1	$\sim 10^{18}$
$Ce_3Bi_4Pd_3$ [39]	3	0.4-4	dc	100	-	-
$TaIrTe_4$ [46]	3	2-300	13.7-213.7	600	120	$\sim 10^{19\text{-}20}$
T_d-$MoTe_2$ [43]	3	2-40	17-277	5000	0.4	$\sim 10^{19\text{-}20}$
α-$(BEDT\text{-}TTF)_2I_3$ [44]	3	4.2-40	dc	2000	40	$\sim 10^{17}$

Different regimes for nonlinear responses

Diffusive, ballistic, hydrodynamic, scattering, interaction…

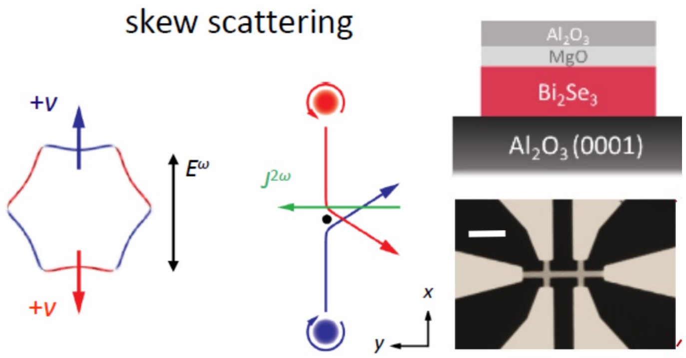
Magnus Hall effect
Phys. Rev. Lett. 123, 216802 (2019)

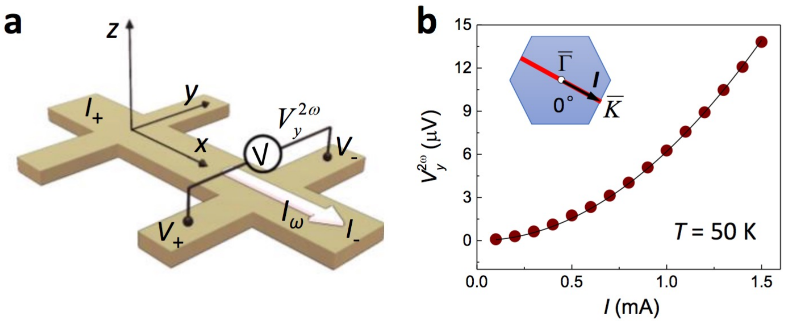
Disorder-induced nonlinear Hall effect with time-reversal symmetry
Nature Comm. 10, 3047 (2019)

Symmetry and Quantum Kinetics of the Non-linear Hall Effect
Phys. Rev. B 100, 195117 (2019)

Gyrotropic Hall effect in Berry-curved materials
Phys. Rev. B **99**, 155404 (2019)

High-frequency rectification via chiral Bloch electrons
Science Adv. 6, eaay2497 (2020)
…

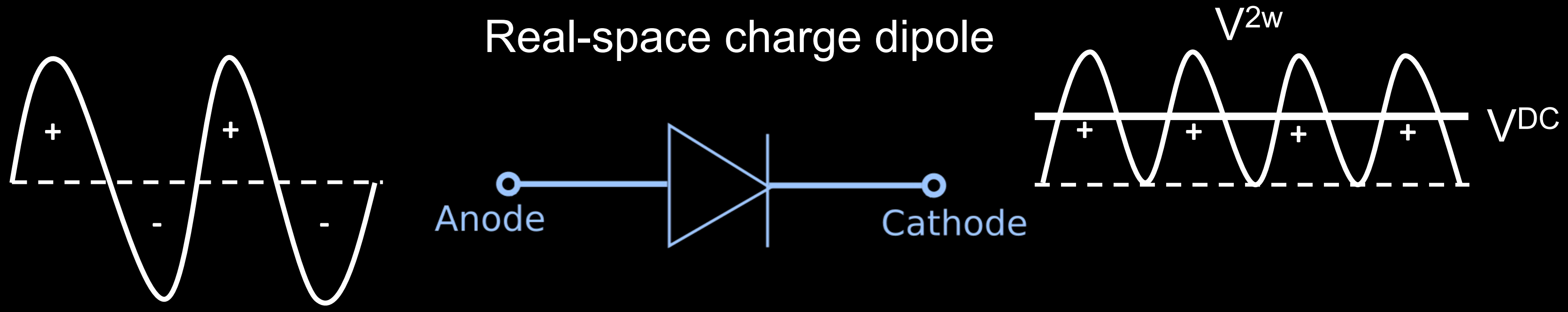




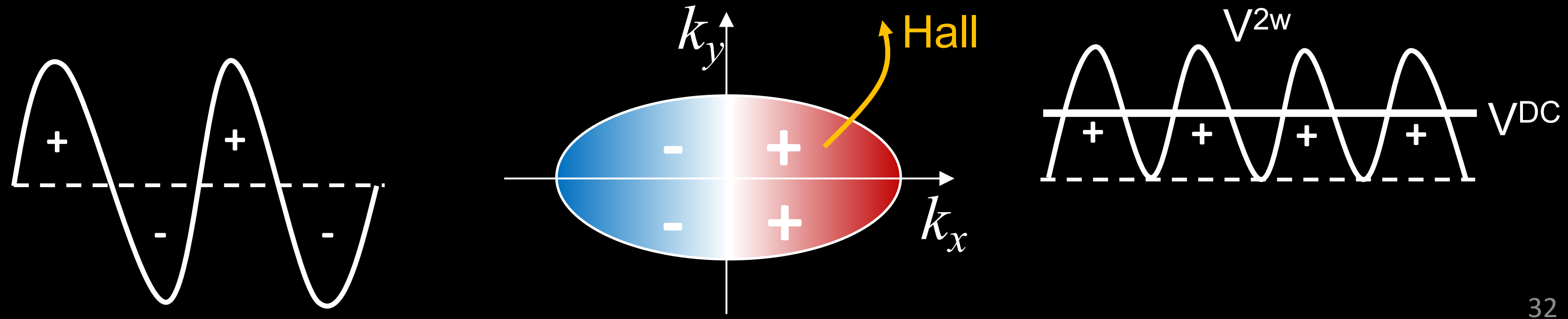
Nature Communications **12**, 698 (2021)

Electrical rectification and energy harvesting

Real-space charge dipole

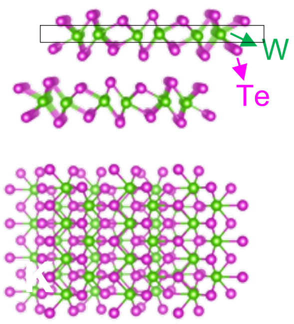


Momentum-space dipole

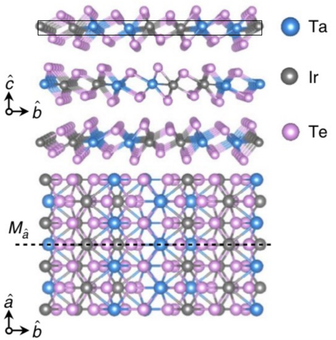


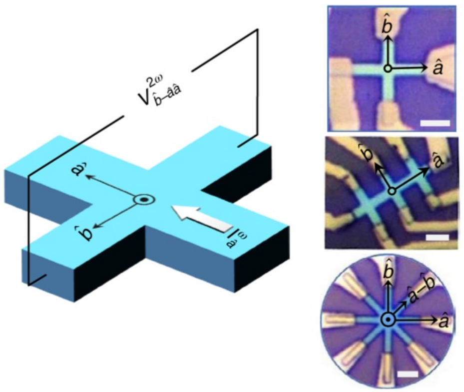
Room-temperature RF nonlinear Hall in $TaIrTe_4$

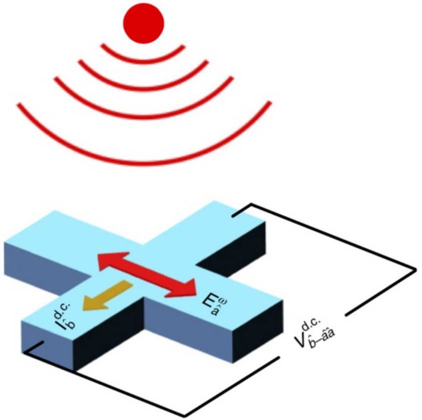
WTe_2

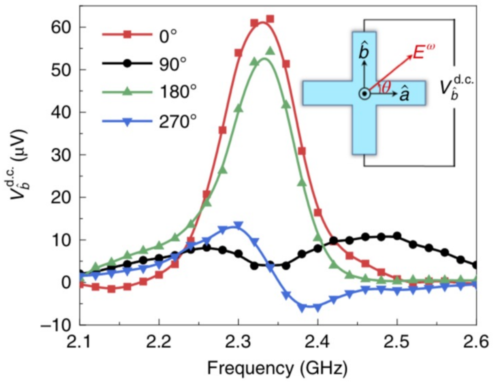


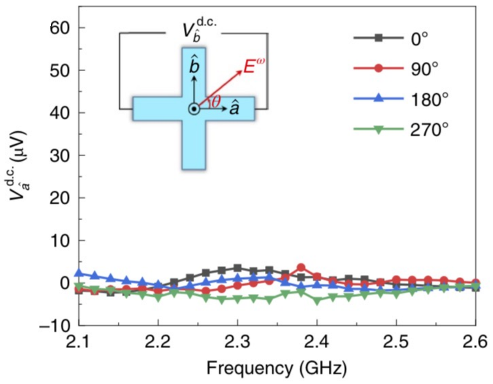
$TaIrTe_4$



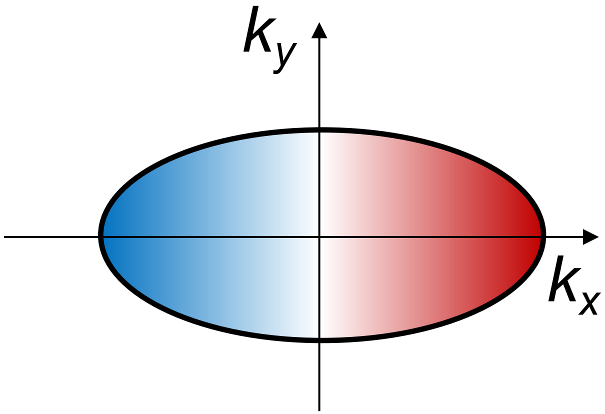








Kumar, et al., Nature Nano. **16**, 421–425 (2021)



Berry curvature dipole nonlinear Hall

Quantum metric dipole nonlinear Hall

g_{ij}

Geometrical properties of electron quantum wavefunctions

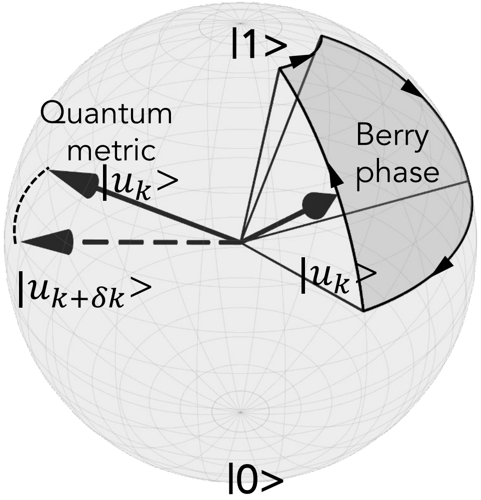
Quantum geometric tensor $T = g + i\Omega$

Quantum metric

$$ds^2 = g_{uv} dk^u dk^v$$

Quantum metric describes how different two states near k are in the Hilbert space (how different the two states are).

Electron correlations
Conductivity of flat bands
Superfluid weight
Quantum metric hall
…



Berry curvature

$$\gamma = i\oint_c d\vec{k} \langle \psi(\vec{k}) | \nabla_{\vec{k}} | \psi(\vec{k}) \rangle = \int_S d\vec{S} \cdot \vec{\Omega}(\vec{k})$$

Berry curvature describes the additional quantum phase picked up around a ***k*** point.

Anomalous Hall conductivity
Nonlinear Hall
Valley Hall
Orbital magnetism
Chern insulator
Circular dichroism in TMD
…

Significance of quantum metric

PRL 107, 116801 (2011) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2011

Geometrical Description of the Fractional Quantum Hall Effect

F. D. M. Haldane

PHYSICAL REVIEW B 105, L140506 (2022)

Letter

Quantum-metric-enabled exciton condensate in double twisted bilayer graphene

Xiang Hu,[1,*] Timo Hyart,[2,3] Dmitry I. Pikulin,[4,5] and Enrico Rossi[1]
[1]Department of Physics, William & Mary, Williamsburg, Virginia 23187, USA
[2]International Research Centre MagTop, Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL-02668 Warsaw, Poland
[3]Department of Applied Physics, Aalto University, 00076 Aalto, Espoo, Finland
[4]Microsoft Quantum, Redmond, Washington 98052, USA
[5]Microsoft Quantum, Station Q, Santa Barbara, California 93106-6105, USA

Quantum metric dipole and non-reciprocal bulk plasmons in parity-violating magnets

Arpit Arora[1], Mark S. Rudner[2], and Justin C. W. Song[1*]
[1]Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371 and
[2]Department of Physics, University of Washington, Seattle WA 98195, USA

PHYSICAL REVIEW LETTERS 122, 227402 (2019)

Nonreciprocal Directional Dichroism Induced by the Quantum Metric Dipole

Yang Gao and Di Xiao
Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

PHYSICAL REVIEW LETTERS 123, 237002 (2019)

Featured in Physics

Geometric and Conventional Contribution to the Superfluid Weight in Twisted Bilayer Graphene

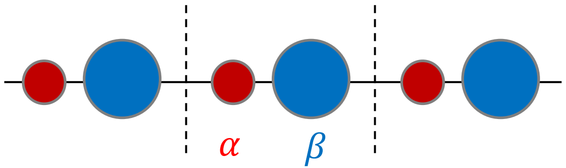
Xiang Hu,[1,*] Timo Hyart,[2] Dmitry I. Pikulin,[3] and Enrico Rossi[1]
[1]Department of Physics, William & Mary, Williamsburg, Virginia 23187, USA
[2]International Research Centre MagTop, Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL-02668 Warsaw, Poland
[3]Microsoft Quantum, Microsoft Station Q, University of California, Santa Barbara, California 93106-6105, USA

Quantum Metric and Correlated States in Two-dimensional Systems

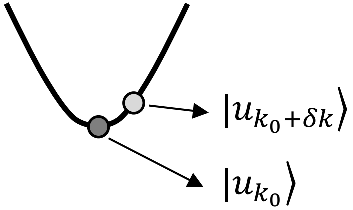
Enrico Rossi[1,*]
[1]Department of Physics, William & Mary, Williamsburg, Virginia (23187), USA

How to visualize quantum metric?

Real space: two distinct orbitals

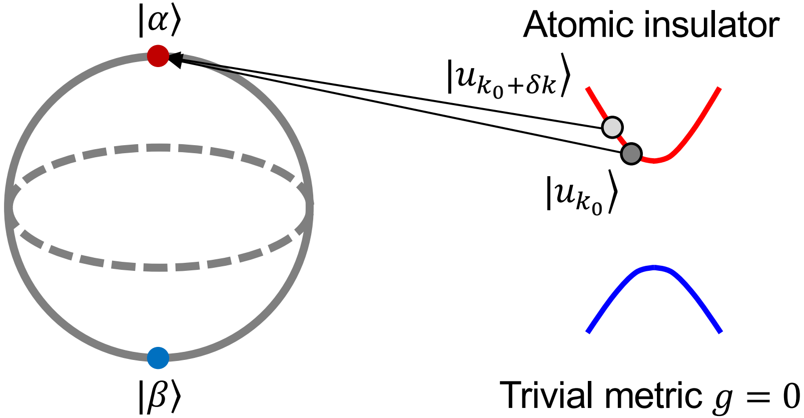


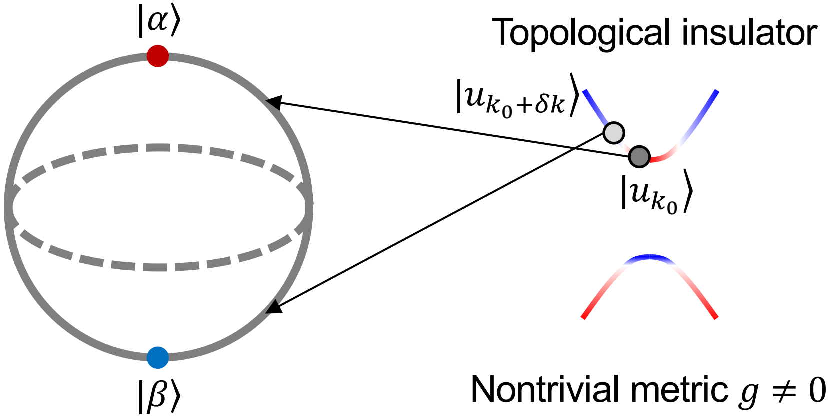
k-space: nearby quantum states



$g_{ij}(k_0)$ (quantum metric) is the distance between $|u_{k_0}\rangle$ and $|u_{k_0+\delta k}\rangle$

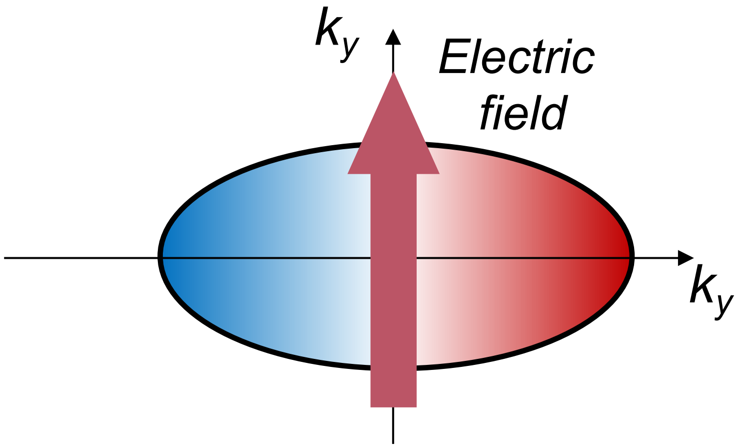
$$ds^2 = 1 - |\langle u_{k_0}|u_{k_0+\delta k}\rangle| = g_{ij}(k_0)\, dk_i\, dk_j$$





How to visualize quantum metric?

Quantum metric dipole

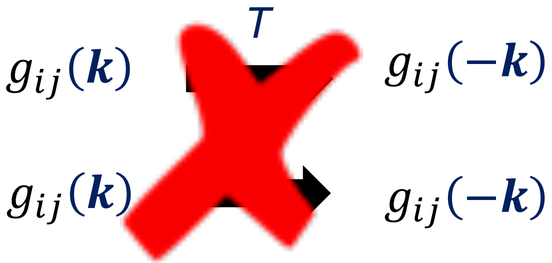


If quantum metric $g \neq 0$

Applying electric field will drive a correction to Berry curvature according to quantum metric.

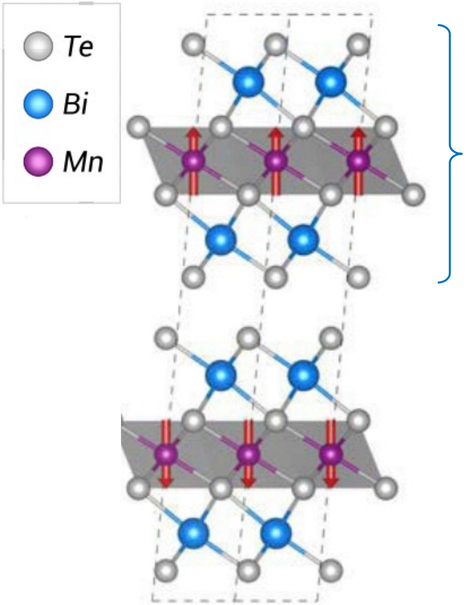
$$\mathbf{\Omega} = [\nabla_{\boldsymbol{k}} \times (g_{ij}\mathbf{E})] = [\nabla_{\boldsymbol{k}} g_{ij}] \times \mathbf{E}$$

$$V_{\mathrm{NHE}} \propto \int \mathbf{E} \times [(\nabla_{\boldsymbol{k}} g_{ij}) \times \mathbf{E}]$$



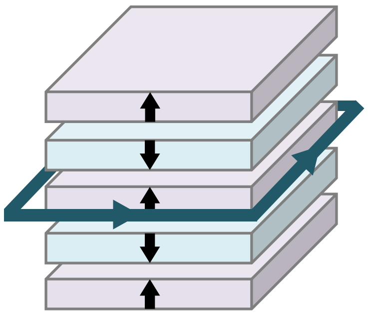
Y. Gao, Q. Niu, et al. PRL 112, 166601 (2014)
Di Xiao et al. PRL 127, 277201 (2021)
S-Y. Yang et al. PRL 127, 277201 (2021)
A. Srivastava et al. PRR 4, 013217 (2022)

$MnBi_2Te_4$ – A topological antiferromagnet

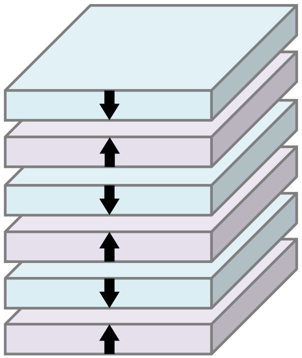


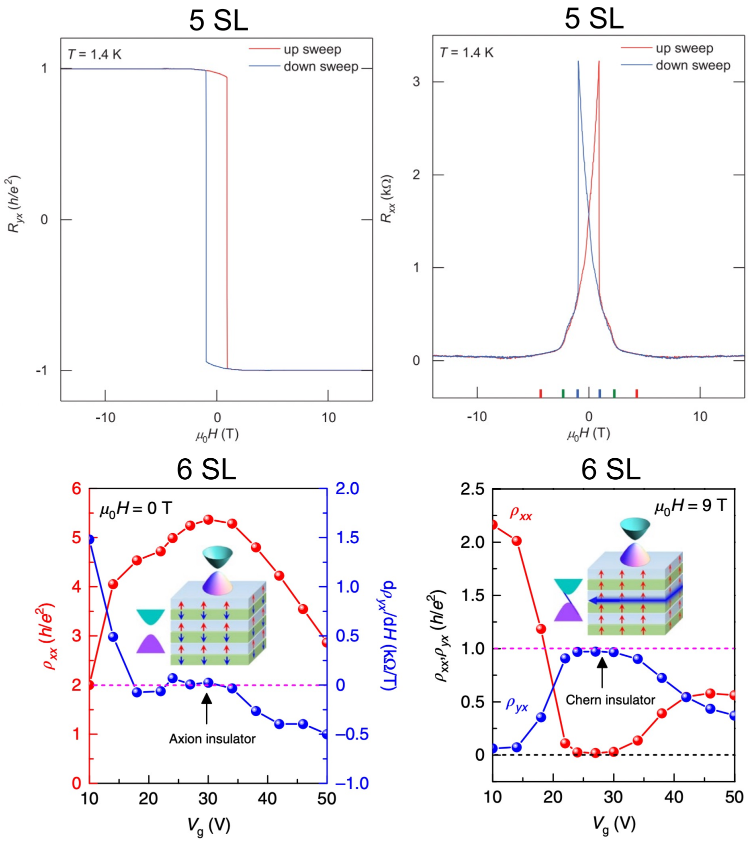
One septuple layer (SL)

5 SL – Chern insulator



6 SL – Axion insulator

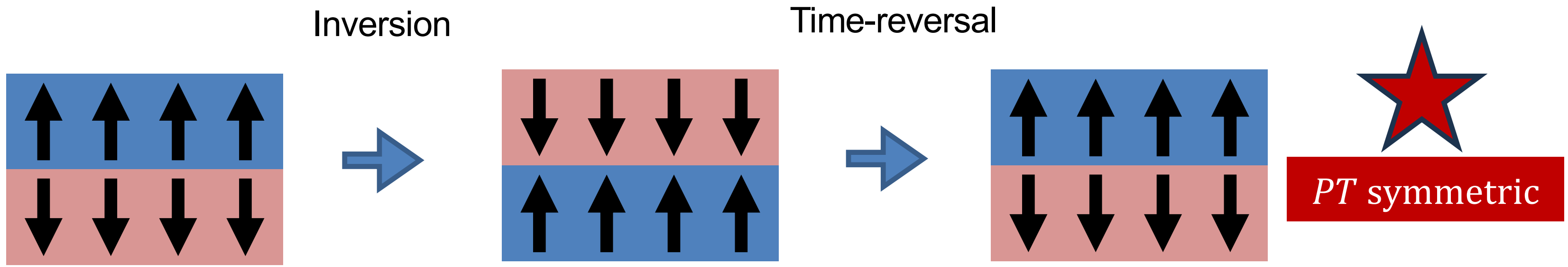




K He, npj Quantum Materials 5, 90 (2020)
P Wang, et al., The Innovation 2, 100098 (2021)
S Li, et al., National Science Review, nwac296 (2023)

Y Deng, YB Zhang, et al., Science 367, 895–900 (2020)
C Liu, YY Wang, et al., Nature Materials, **19**, 522–527 (2020)

Exploring quantum metric physics in $MnBi_2Te_4$



Berry curvature

$$\Omega\,(\boldsymbol{k}) \xrightarrow{P} \Omega(-\boldsymbol{k}) \xrightarrow{T} -\Omega(\boldsymbol{k})$$

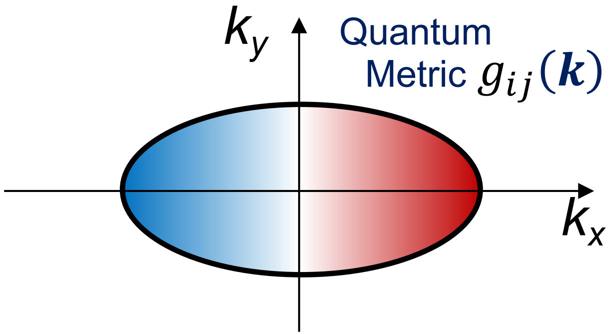
$$\Omega(\boldsymbol{k}) = 0$$

Quantum metric

$$g_{ij}(\boldsymbol{k}) \xrightarrow{P} g_{ij}(-\boldsymbol{k}) \xrightarrow{T} g_{ij}(\boldsymbol{k})$$

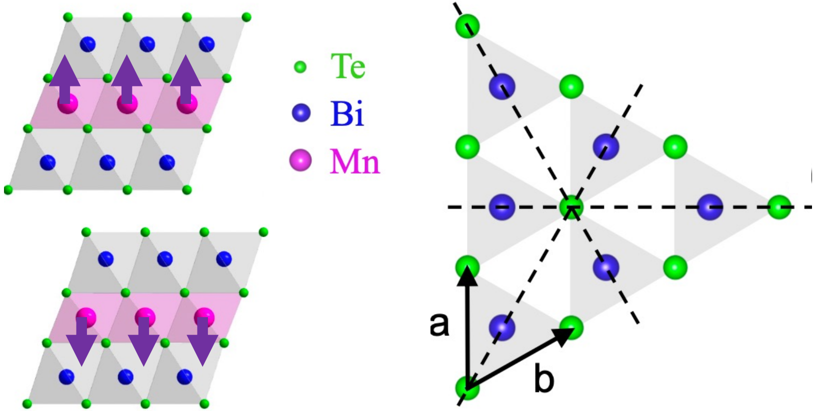
$$g_{ij}(\boldsymbol{k}) \neq 0$$

Break three-fold rotational symmetry

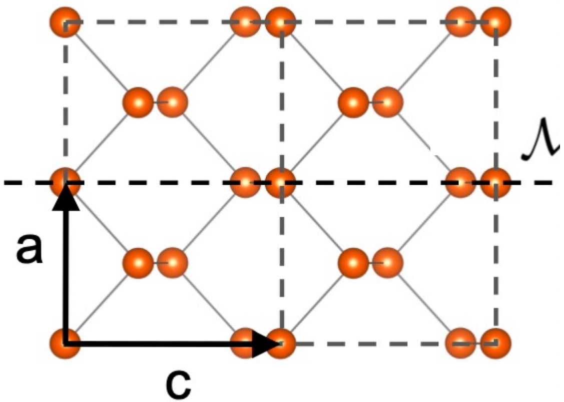


Need to break three-fold rotational symmetry to get a dipole moment.

$MnBi_2Te_4$ (MBT)

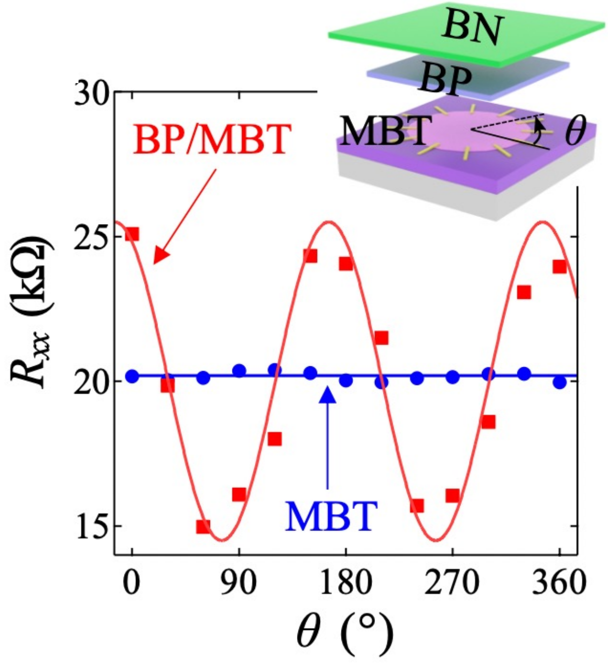


Black phosphorus (BP)

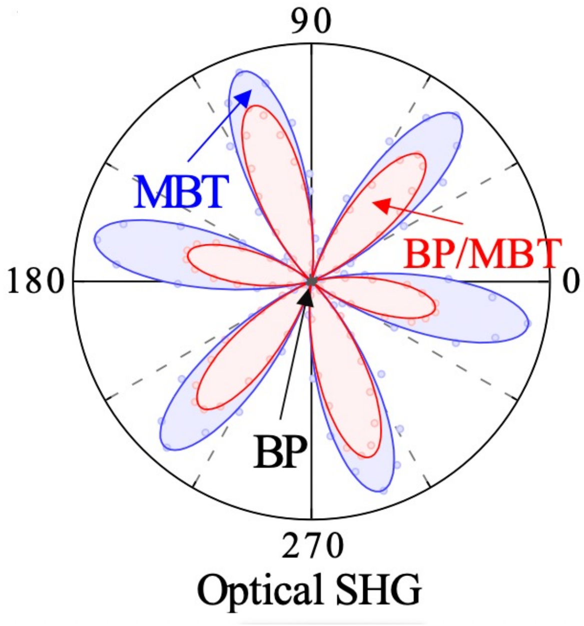


Three-fold rotational symmetry breaking

Angle-resolved transport

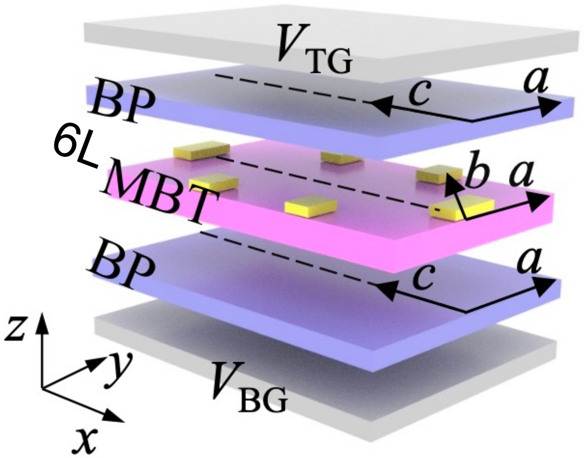


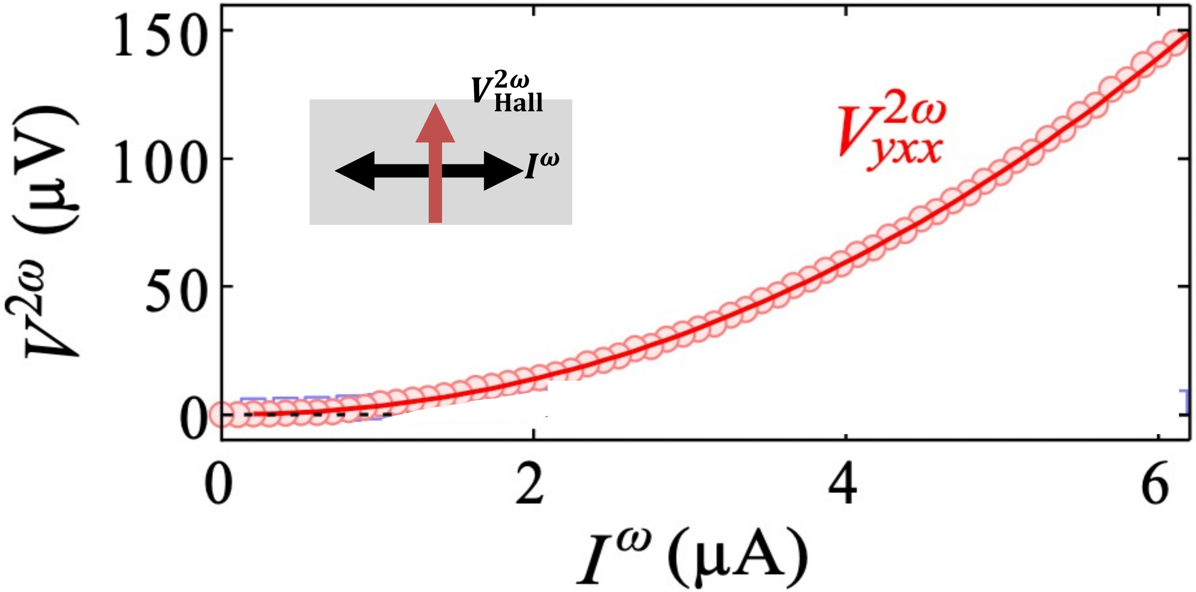
Optical SHG



BP/6L $MnBi_2Te_4$/BP

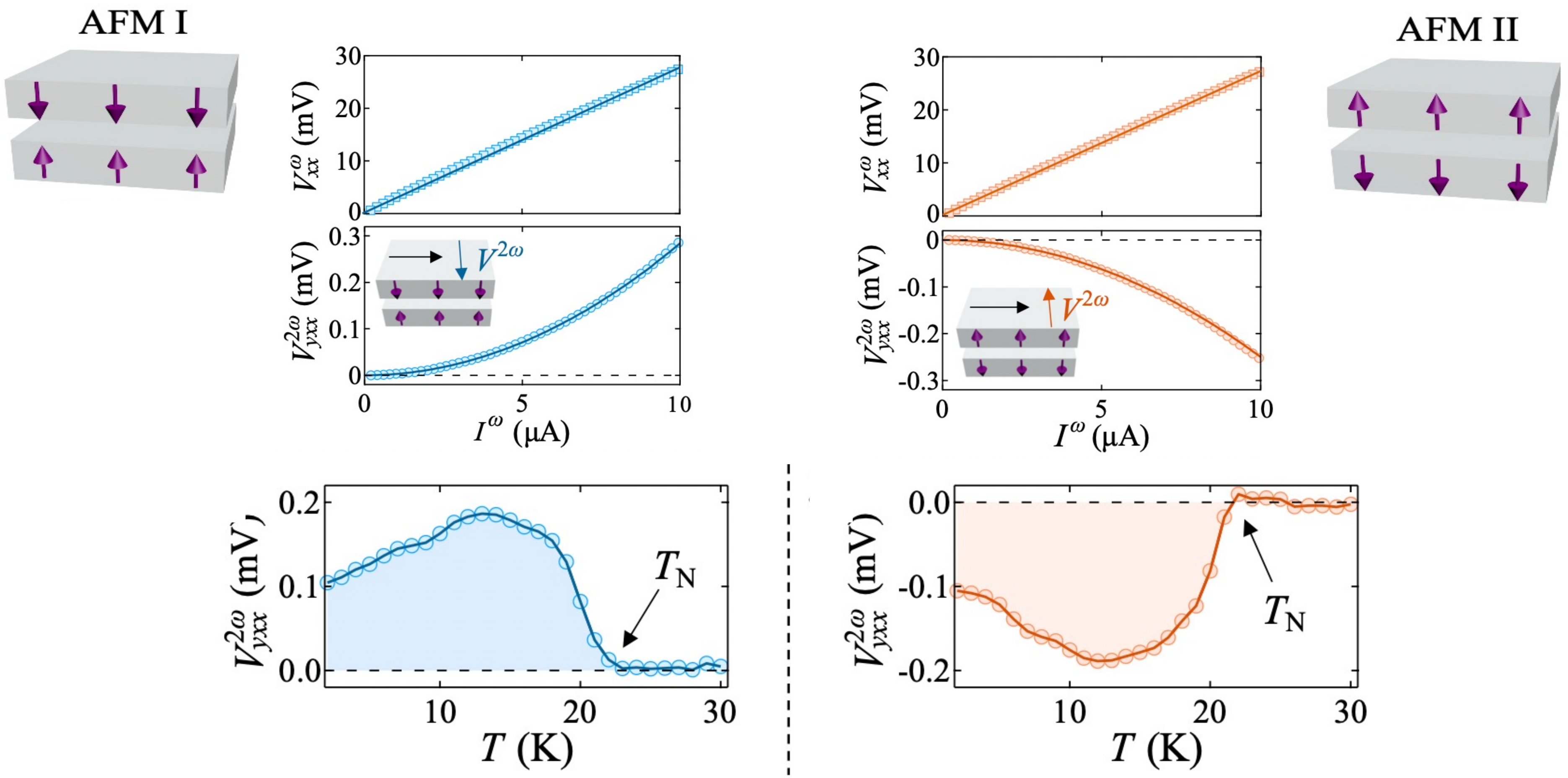
Experimental demonstration of nonlinear Hall



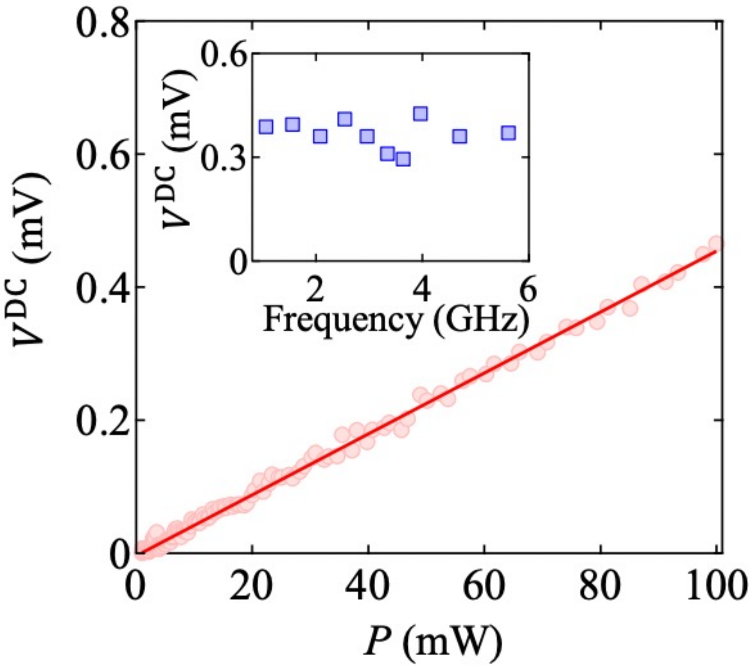


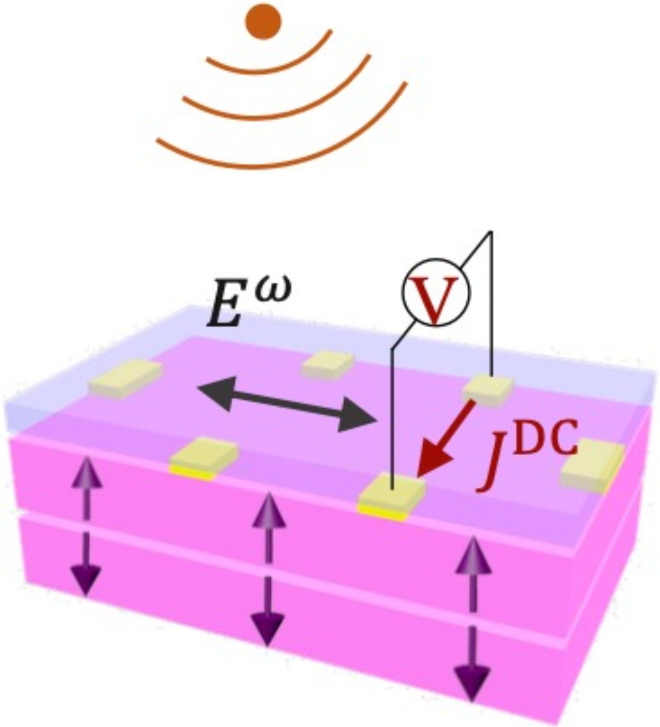
Science 381, 181-186 (2023)

Hall direction vs. AFM order



Wireless energy harvesting





Science 381, 181-186 (2023)

HOME > SCIENCE > VOL. 381, NO. 6654 > QUANTUM METRIC NONLINEAR HALL EFFECT IN A TOPOLOGICAL ANTIFERROMAGNETIC HETEROSTRUCTURE

RESEARCH ARTICLE | TOPOLOGICAL MATTER

Quantum metric nonlinear Hall effect in a topological antiferromagnetic heterostructure

ANYUAN GAO, YU-FEI LIU, JIAN-XIANG QIU, BARUN GHOSH, THAÍS V. TREVISAN, YUGO ONISHI, CHAOWEI HU, TIEMA QIAN, HUNG-JU TIEN, [...], AND SU-YANG XU +21 authors Authors Info & Affiliations

SCIENCE • 15 Jun 2023 • Vol 381, Issue 6654 • pp. 181-186 • DOI: 10.1126/science.adf1506

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Article | Published: 29 June 2023

Quantum metric-induced nonlinear transport in a topological antiferromagnet

Naizhou Wang, Daniel Kaplan, Zhaowei Zhang, Tobias Holder, Ning Cao, Aifeng Wang, Xiaoyuan Zhou, Feifei Zhou, Zhengzhi Jiang, Chusheng Zhang, Shihao Ru, Hongbing Cai, Kenji Watanabe, Takashi Taniguchi, Binghai Yan & Weibo Gao

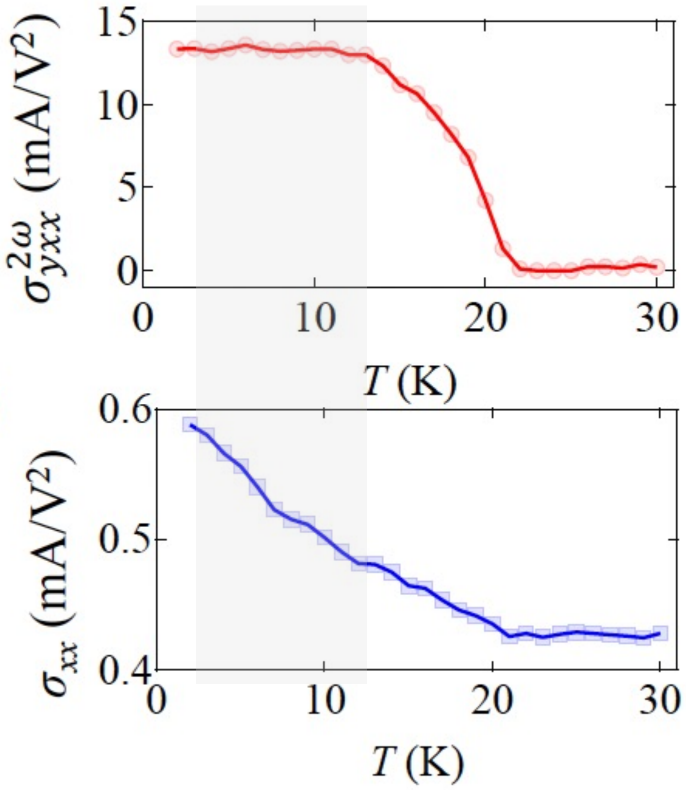
Nature (2023) | Cite this article

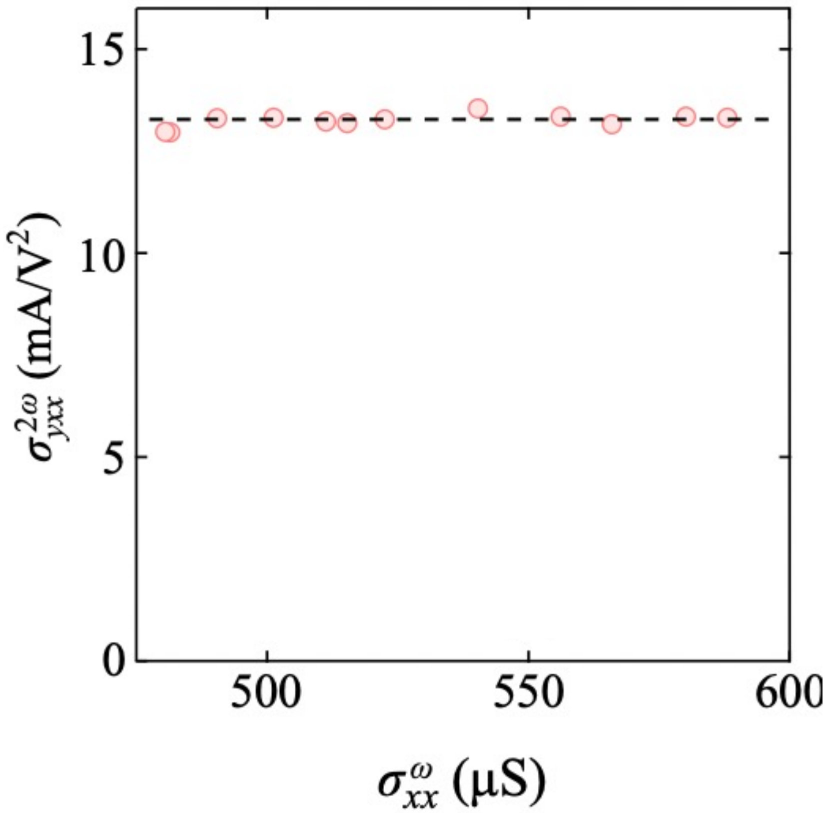
Take-home messages

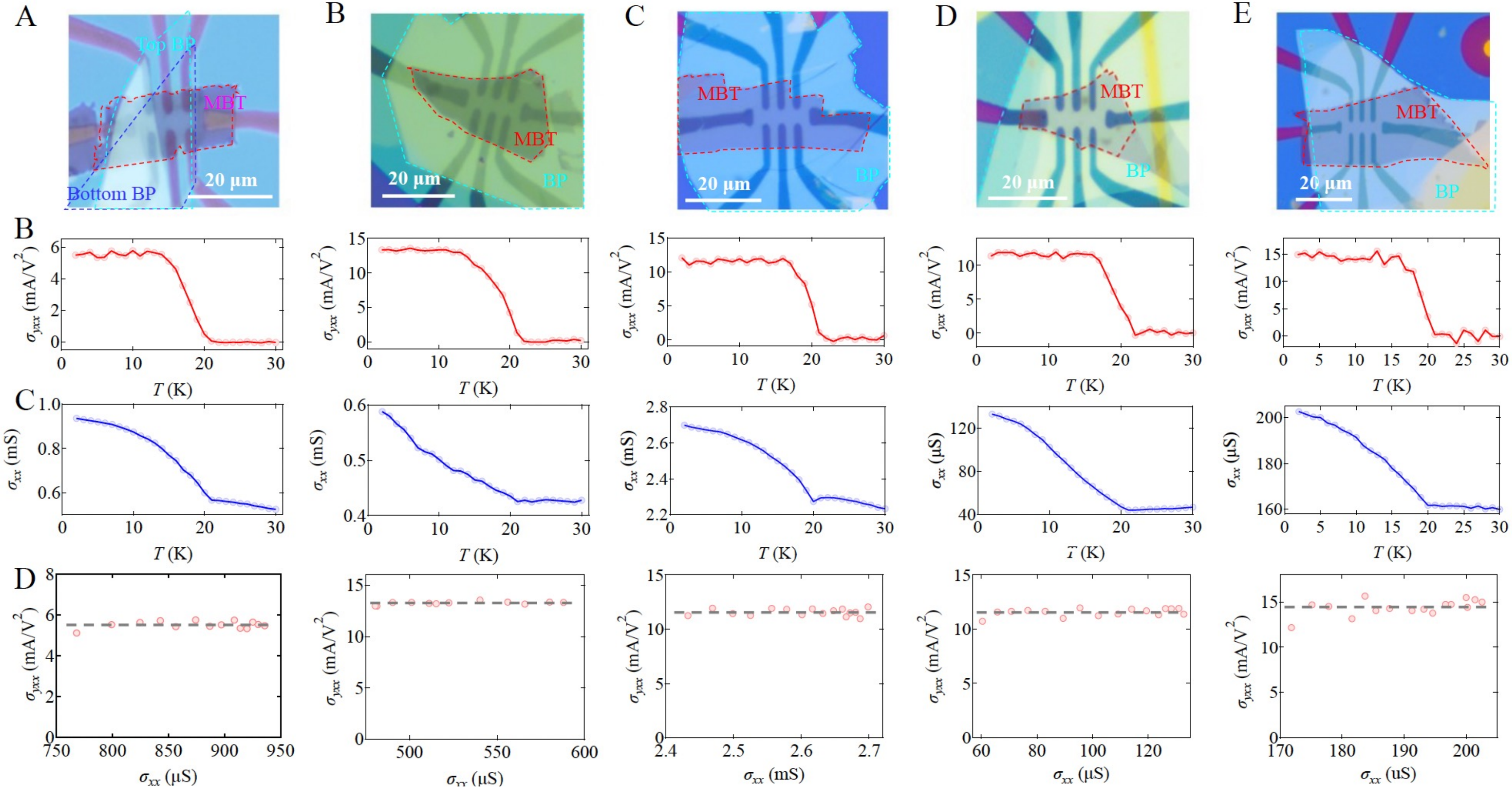
- New physical phenomena - second-order Hall effect.
    - No requirement of magnetic field
    - No requirement of total magnetization
    - Arise from Berry curvature and quantum metric dipoles.
    - Diffusive, ballistic, hydrodynamic, scattering, interaction…

- New technology for energy harvesting – early stage.

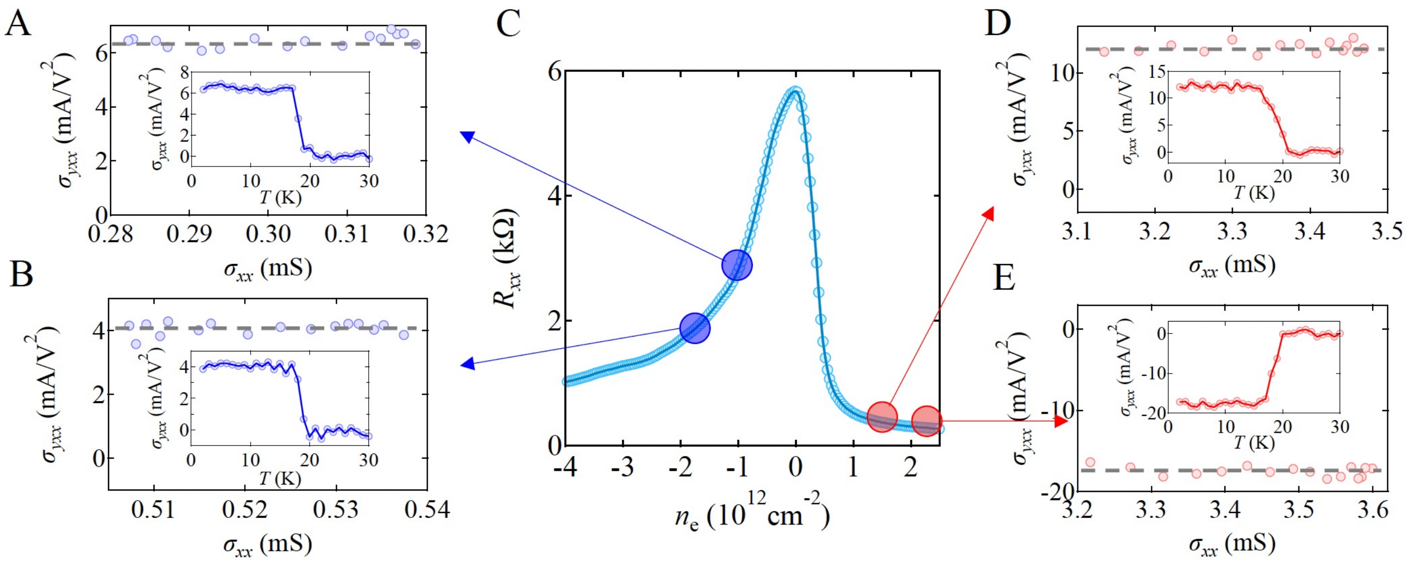
Dependence on the scattering time

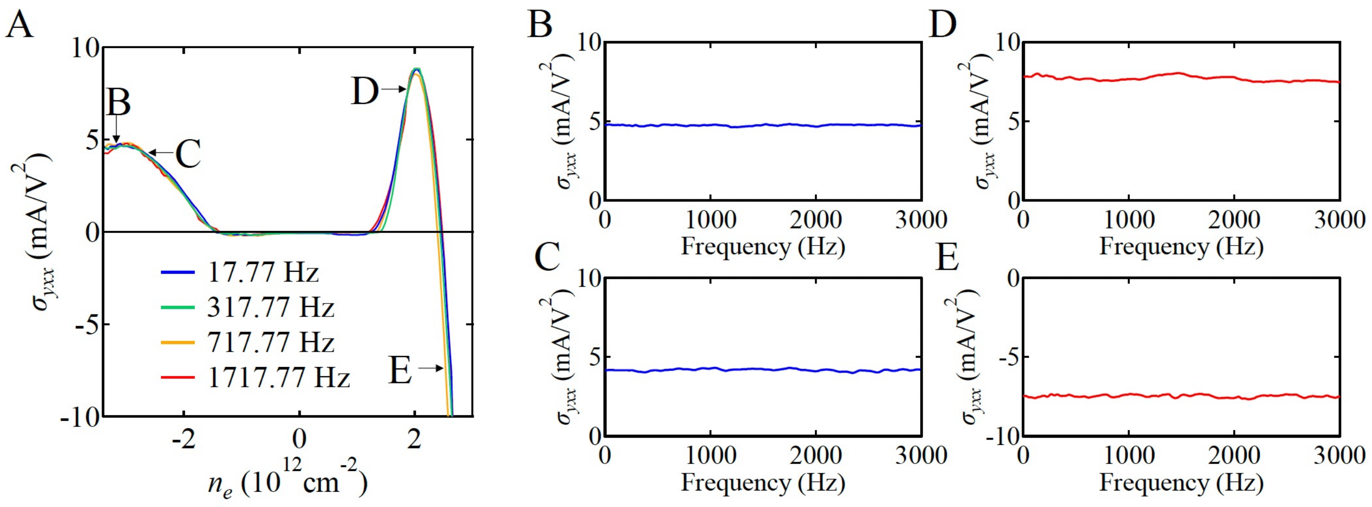






A
B
C
D
E
Top BP
Bottom BP
MBT
BP
20 µm
σ_{yxx} (mA/V^2)
σ_{xx} (mS)
σ_{xx} (µS)
T (K)
σ_{xx} (µS)
σ_{xx} (mS)


A
B
C
D
E
σ_{yxx} (mA/V^2)
σ_{xx} (mS)
T (K)
R_{xx} (kΩ)
n_e (10^{12}cm^{-2})


A
B
C
D
E
σyxx (mA/V2)
ne (10^12 cm^-2)
17.77 Hz
317.77 Hz
717.77 Hz
1717.77 Hz
Frequency (Hz)
10
5
0
-5
-10
-2
0
2
1000
2000
3000

Compare with calculations