Berry opto-electronics: new tools for engineering light-matter interaction

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Graphene 2017, Barcelona

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Funding:

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Plan

Part I.

Giant Hall photoconductivity

gapped Dirac materials with a narrow gap yield Hall photoconductivity
order ~ e^2/h; access to new "Berry" transport regime

JS, Kats, Nano Letters (2016)

if we have time:

Part II.

Anomalous plasmons

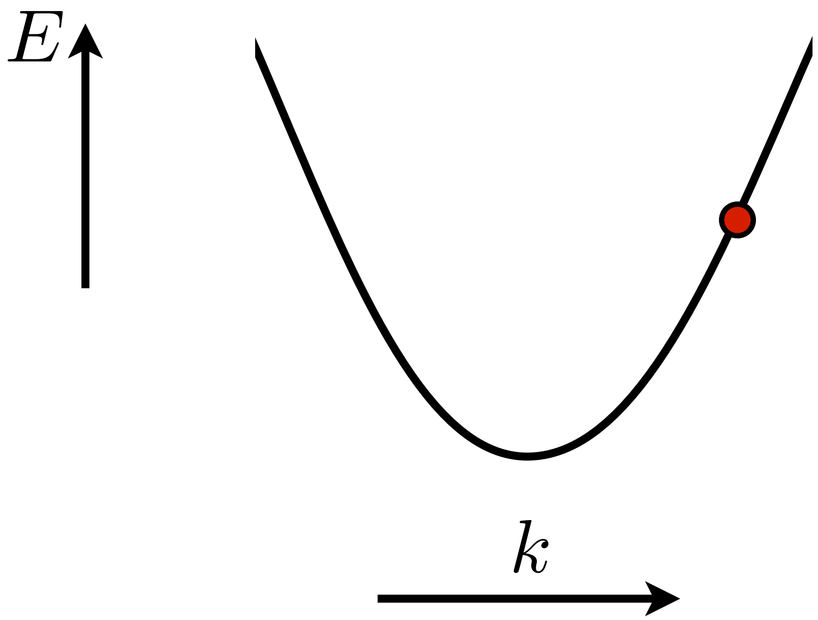
(i) electron interactions + Berry curvature = new collective modes ("Berry Plasmons")

(ii) unusual Fermi-arc plasmons in Weyl semimetals

JS, Rudner, PNAS (2016)

JS, Rudner, arXiv (2017)

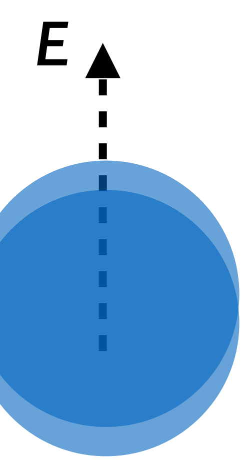
Solid state 101: “*Vanilla*” electrons



free-electron eq. of motion:

$$\dot{\mathbf{p}} = e\mathbf{v} \times \mathbf{B} + e\mathbf{E}$$

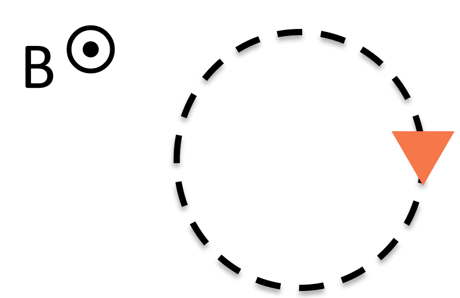
E pushes Fermi surface out of equilibrium



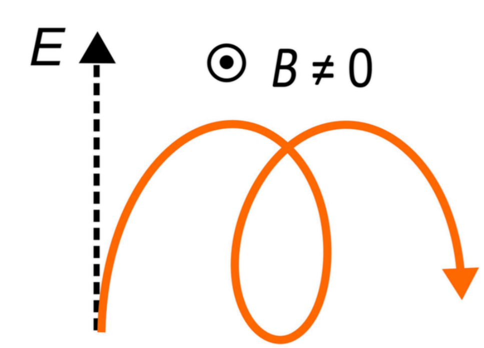
Litany of free electron properties:

- Fermi-surface + thermody. properties,
- Drude-type transport [e.g., electrical conductivity], and dynamical response
- Hall resistance, ….

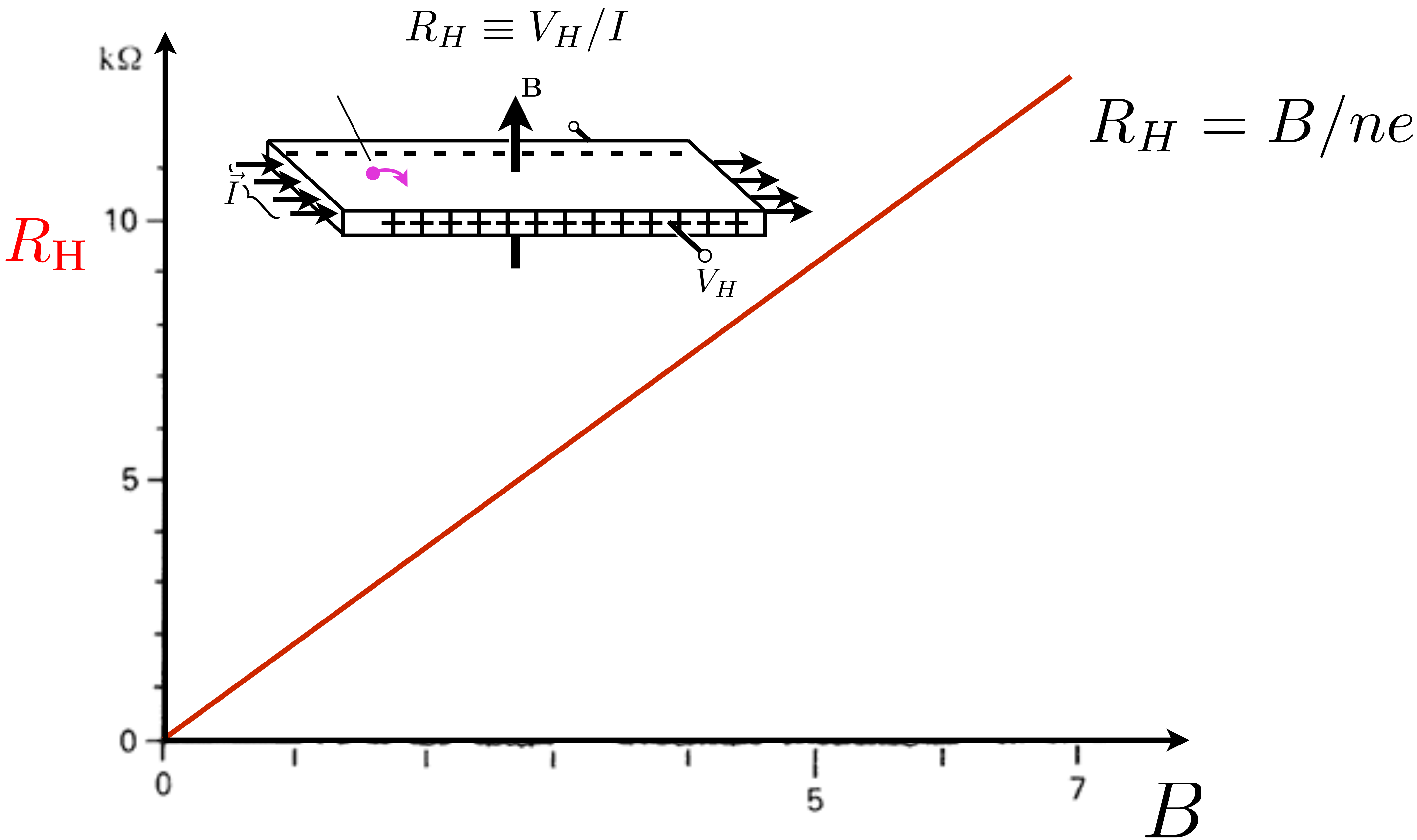
cyclotron motion



drifting cyclotron orbits



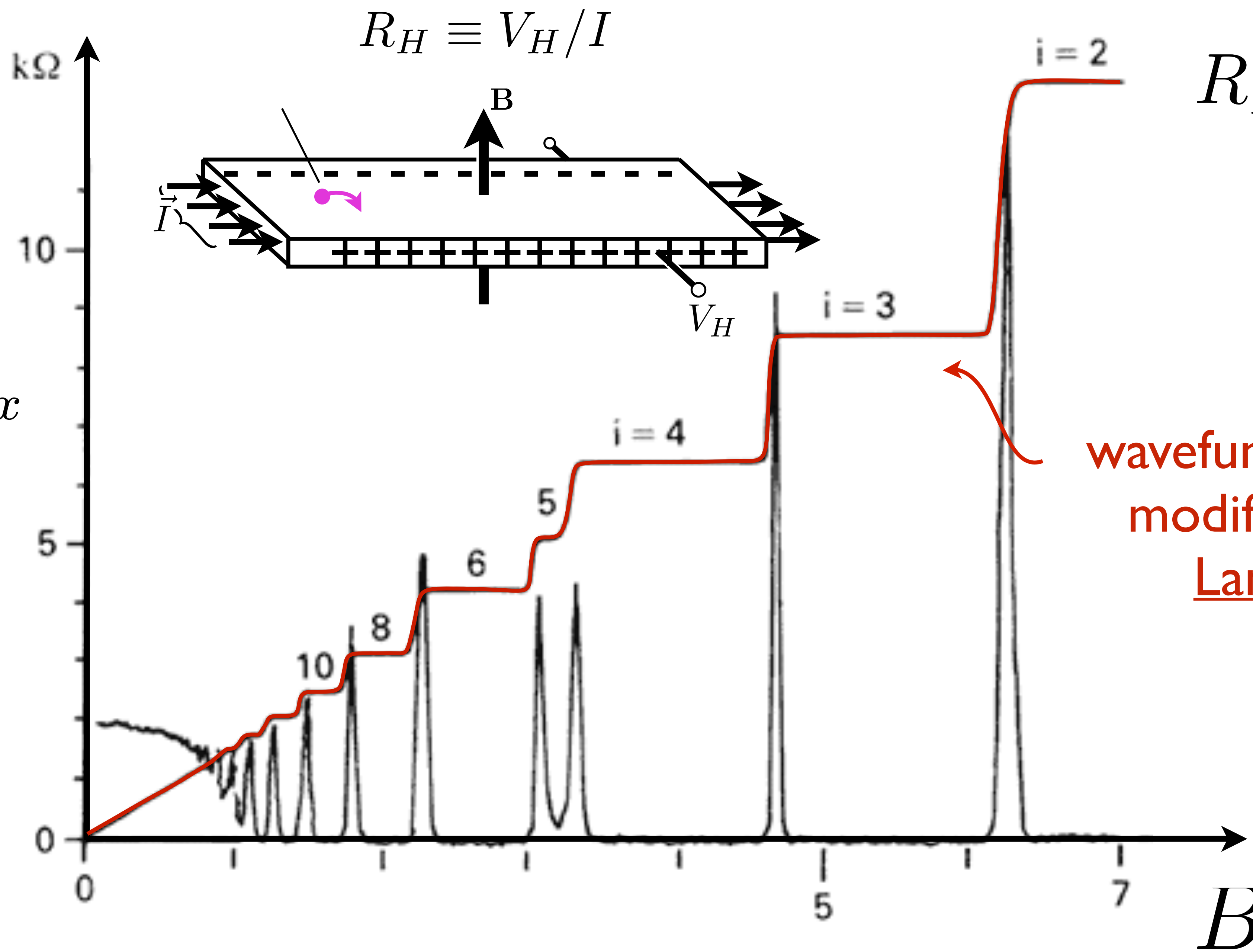
Solid state 101: Hall effect



Quantum coloring: Quantum Hall effect

R_H

R_{xx}



$$R_H = h/\nu e^2$$

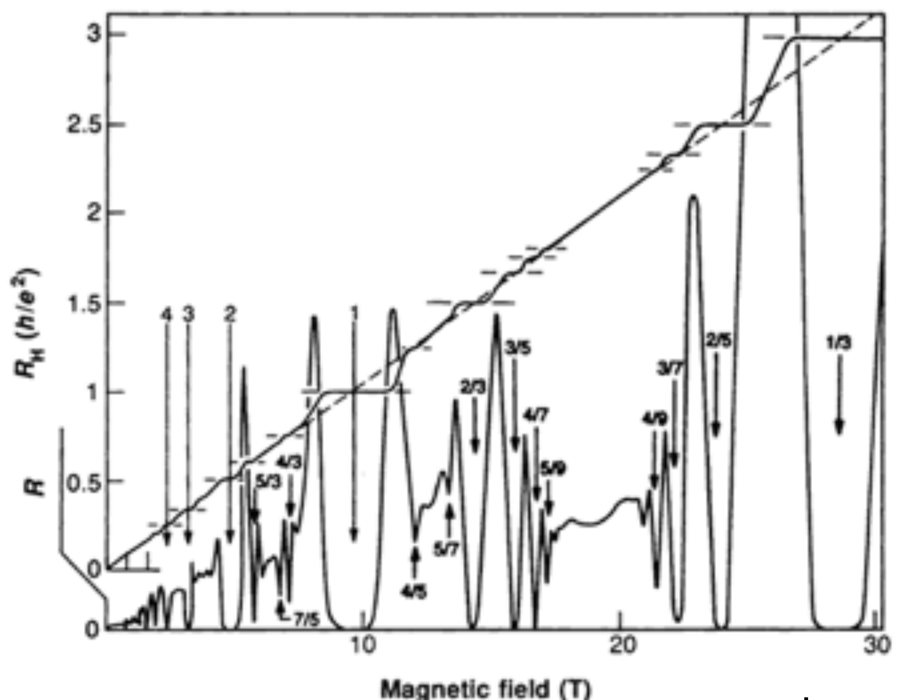
wavefunctions strongly modified by B field: Landau levels

wavefunction matters: QH wavefunction gives *qualitatively* different behavior

Figure adapted from nobelprize.org

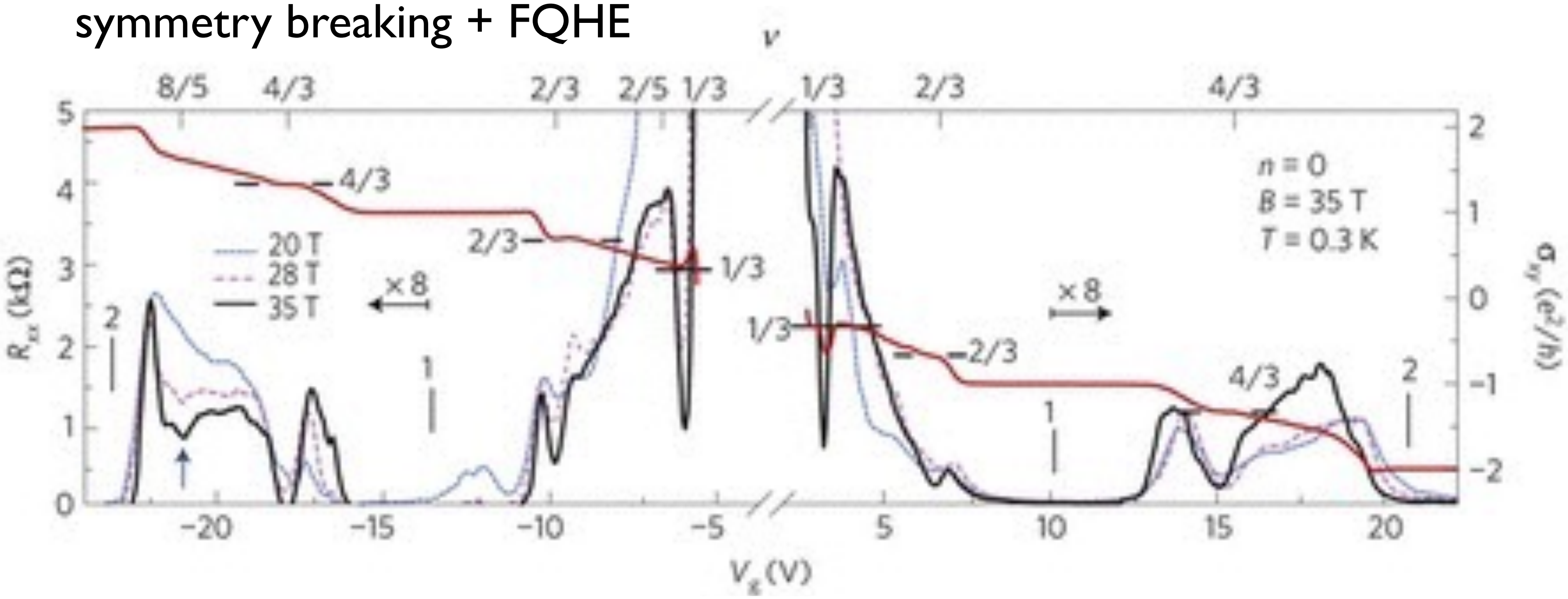
Quantum Hall systems possess rich phenomenology

fractional QHE



adapted from nobelprize.org

symmetry breaking + FQHE

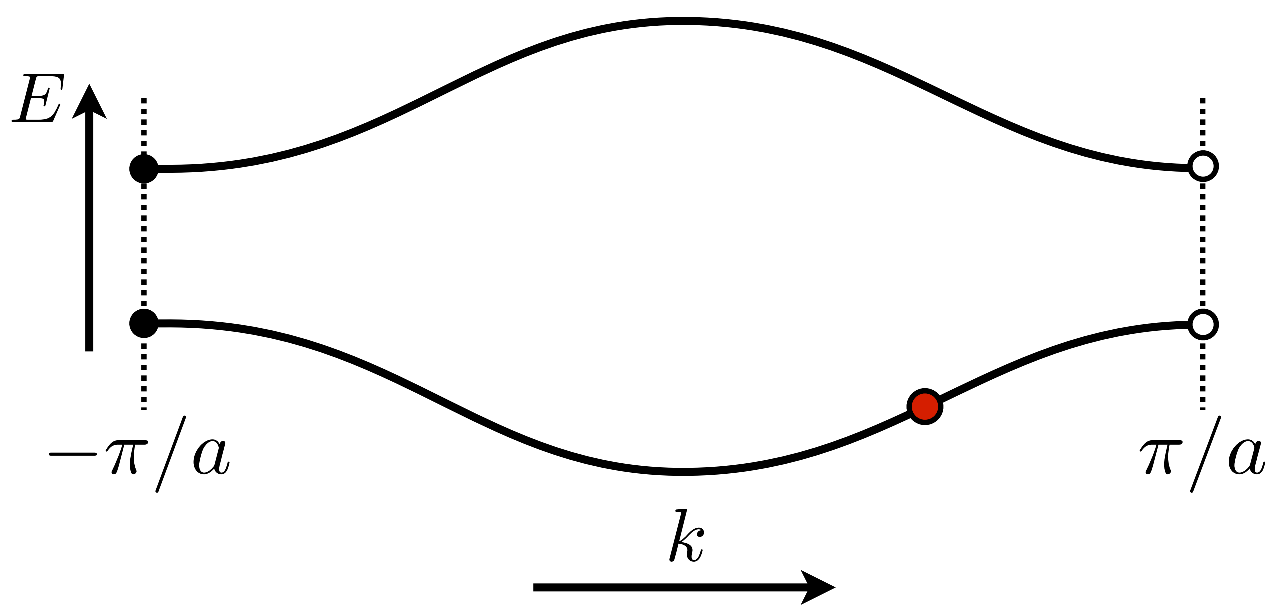


Kim and Shepard Groups, Nature Physics (2011), lots of others as well

Can we use crystal fields instead?

Quasiparticles in a crystal

Energy bands in a crystal; depends on *k*



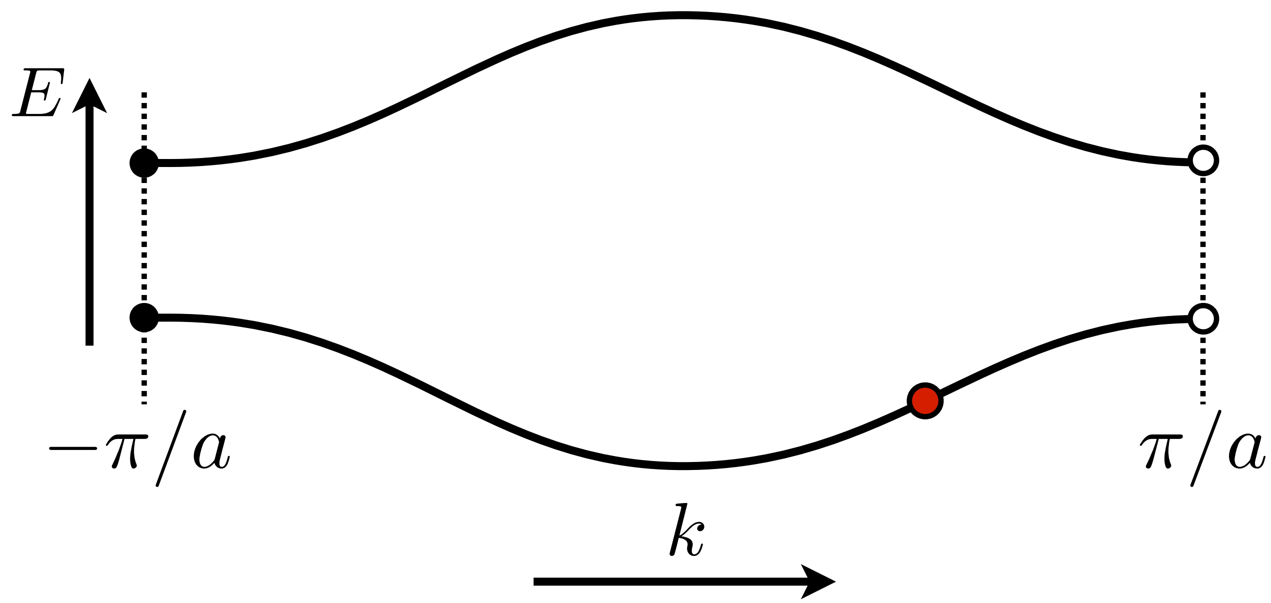
Energy → Energy bands

Momentum → Quasi-momentum

Mass → Effective mass

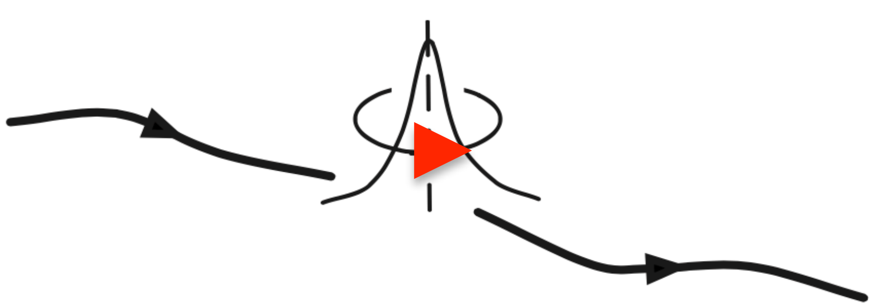
Wavefunction matters: Berry curvature

Energy bands in a crystal; depends on *k*



Energy	→	Energy bands
Momentum	→	Quasi-momentum
Mass	→	Effective mass

Emergent quantum mechanical property:

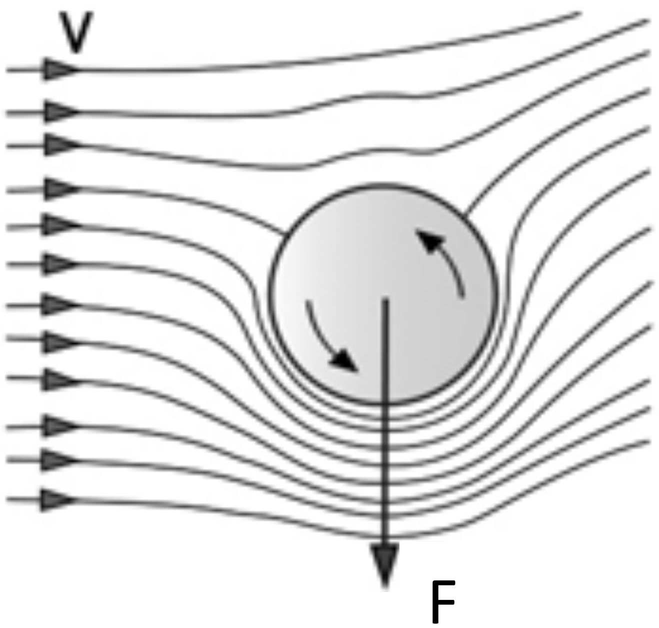


Berry curvature
(self-rotation of wavepackets)

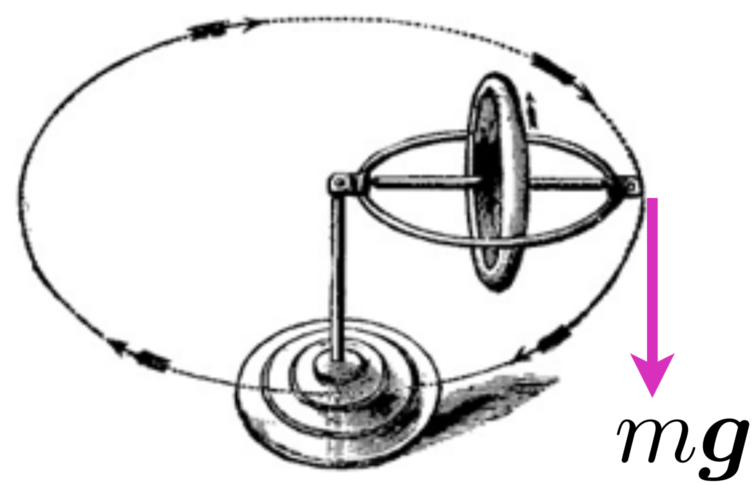
Electron wavepacket traveling through certain *special* crystals

(Self-) Rotation enables transverse motion

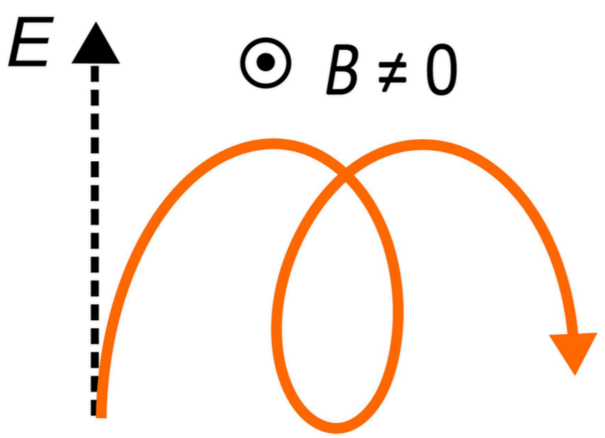
Magnus effect:



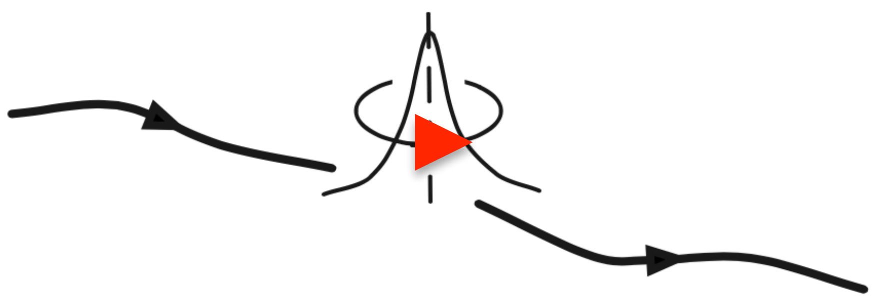
Gyroscopes:



Drifting cyclotron motion:



Anomalous velocity and *Berry curvature* $\Omega(\mathbf{p})$



Electron wavepacket traveling through certain *special* crystals

Semiclassical equations of motion

Group velocity

"Anomalous velocity"

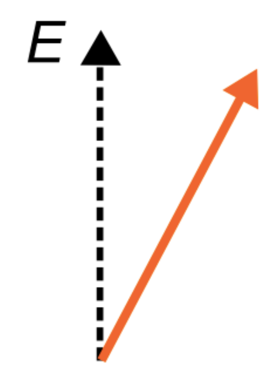
$$\dot{\boldsymbol{x}} = \frac{d\varepsilon}{d\boldsymbol{p}} + \dot{\boldsymbol{p}} \times \Omega$$

$$\dot{\boldsymbol{p}} = -\frac{dV}{d\boldsymbol{x}} + \dot{\boldsymbol{x}} \times \boldsymbol{B}$$

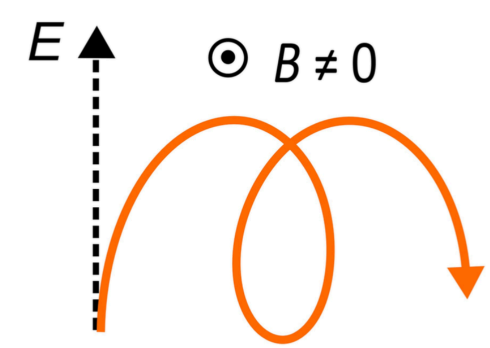
Lorentz force

Contrasting trajectories

Anomalous velocity:
Skewed trajectory:



Lorentz force:
Drifting cyclotron:



for extended discussion see Xiao, Chang, Niu RMP (2010)

Zero-field quantum Hall effect

VOLUME 61, NUMBER 18 PHYSICAL REVIEW LETTERS 31 OCTOBER 1988

Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the "Parity Anomaly"

F. D. M. Haldane

Department of Physics, University of California, San Diego, La Jolla, California 92093

(Received 16 September 1987)

A two-dimensional condensed-matter lattice model is presented which exhibits a nonzero quantization of the Hall conductance σ^{xy} in the *absence* of an external magnetic field. Massless fermions *without spectral doubling* occur at critical values of the model parameters, and exhibit the so-called "parity anomaly" of (2+1)-dimensional field theories.

tight-binding "graphene" type model with complex second neighbor hopping

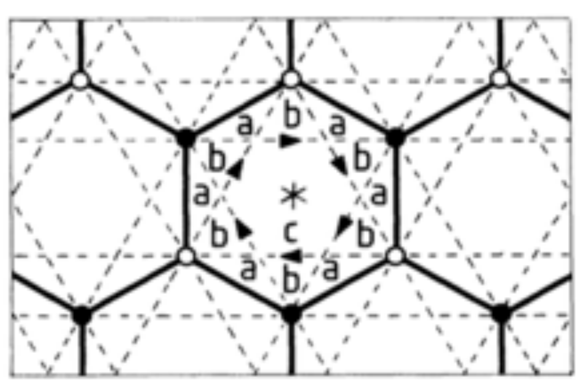


FIG. 1. The honeycomb-net model ("2D graphite") showing nearest-neighbor bonds (solid lines) and second-neighbor bonds (dashed lines). Open and solid points, respectively, mark the *A* and *B* sublattice sites. The Wigner-Seitz unit cell is conveniently centered on the point of sixfold rotation symmetry (marked "*") and is then bounded by the hexagon of nearest-neighbor bonds. Arrows on second-neighbor bonds mark the directions of positive phase hopping in the state with broken time-reversal invariance.

summing up Berry curvature over BZ = topology

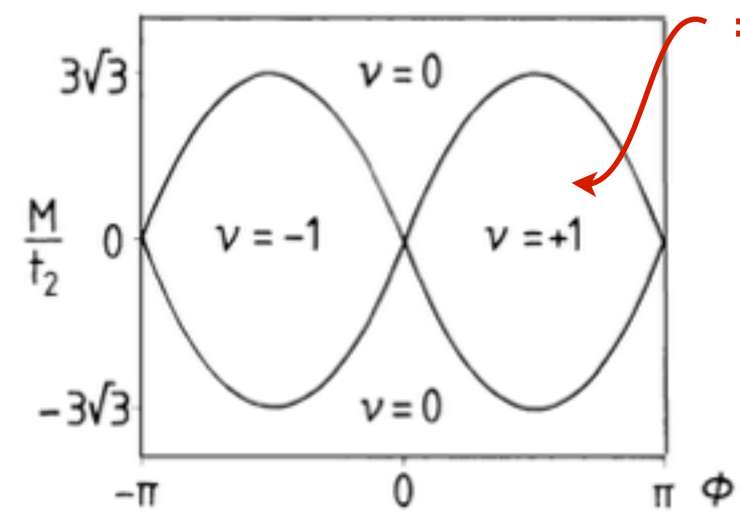
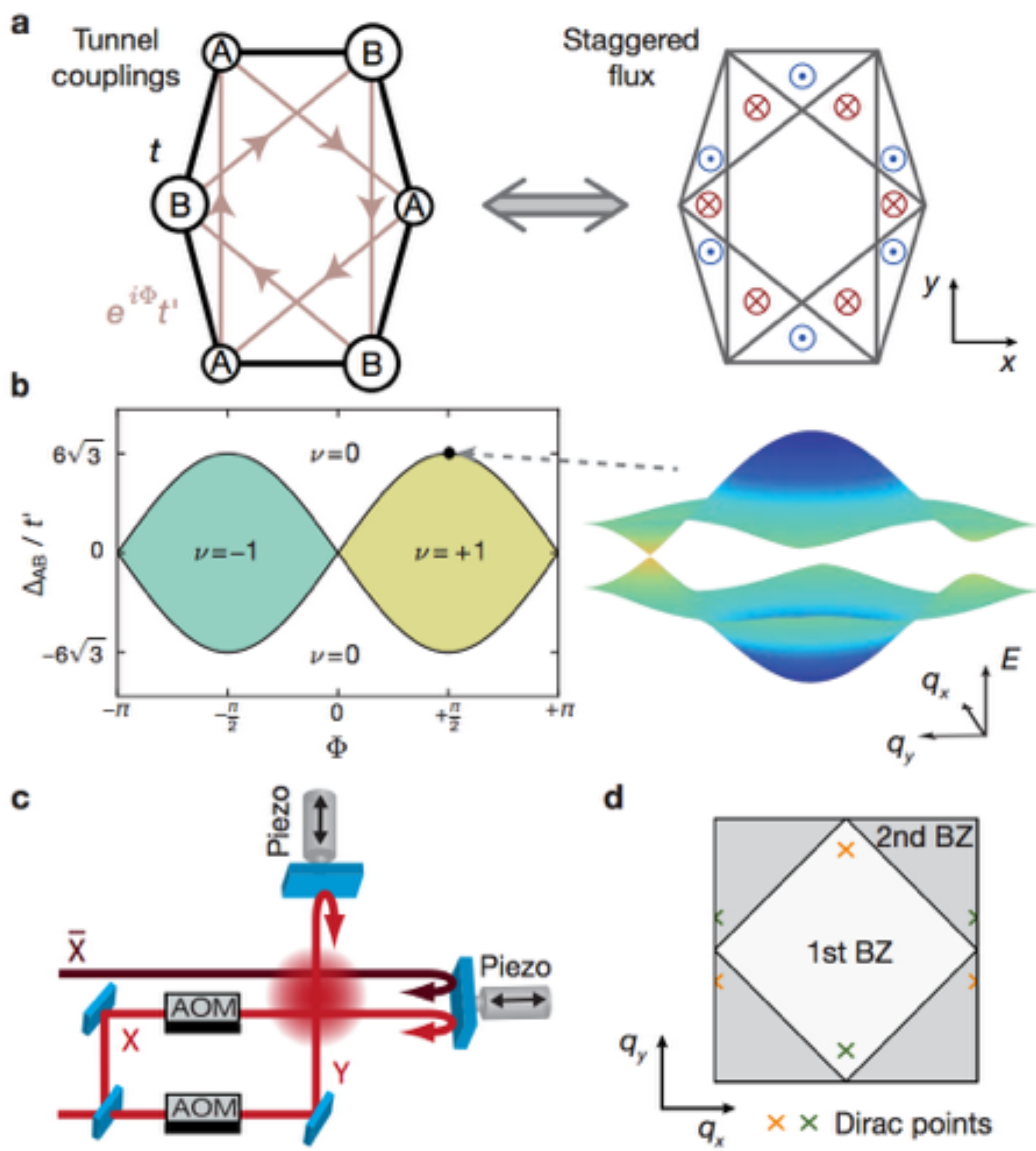
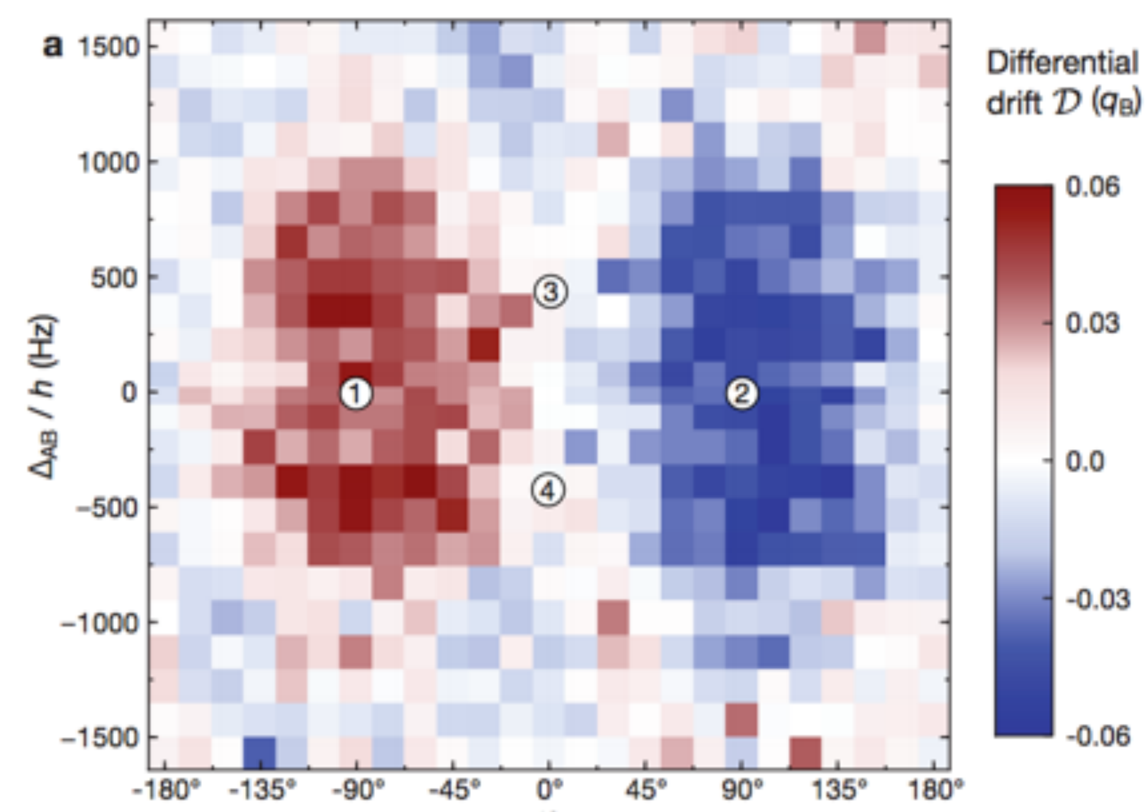


FIG. 2. Phase diagram of the spinless electron model with $|t_2/t_1| < \frac{1}{3}$. Zero-field quantum Hall effect phases ($\nu = \pm 1$, where $\sigma^{xy} = \nu e^2/h$) occur if $|M/t_2| < 3\sqrt{3}|\sin\phi|$. This figure assumes that t_2 is positive; if it is negative, ν changes sign. At the phase boundaries separating the anomalous and normal ($\nu = 0$) semiconductor phases, the low-energy excitations of the model simulate undoubled massless chiral relativistic fermions.

Realizing Haldane model and imaging Berry curvature



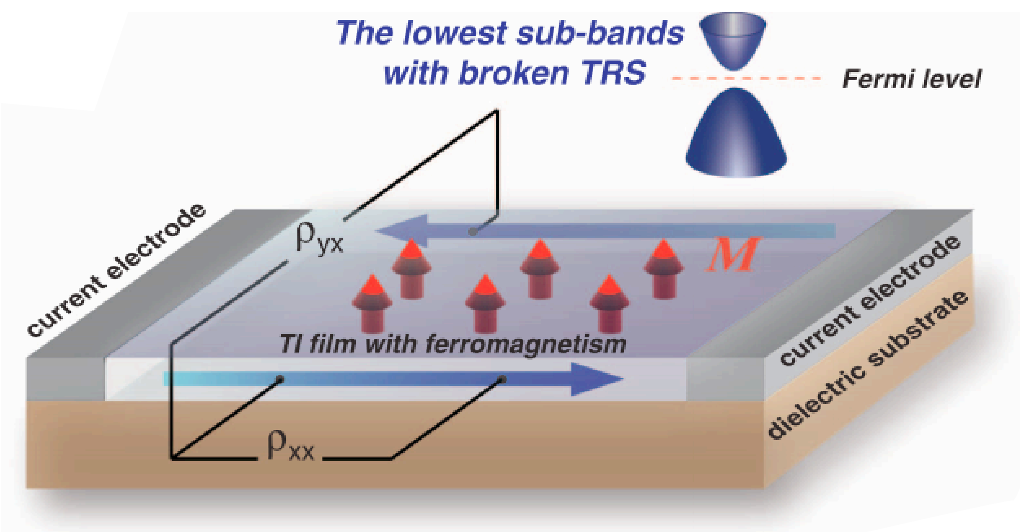


Jotzu, …, Esslinger, Nature (2014)

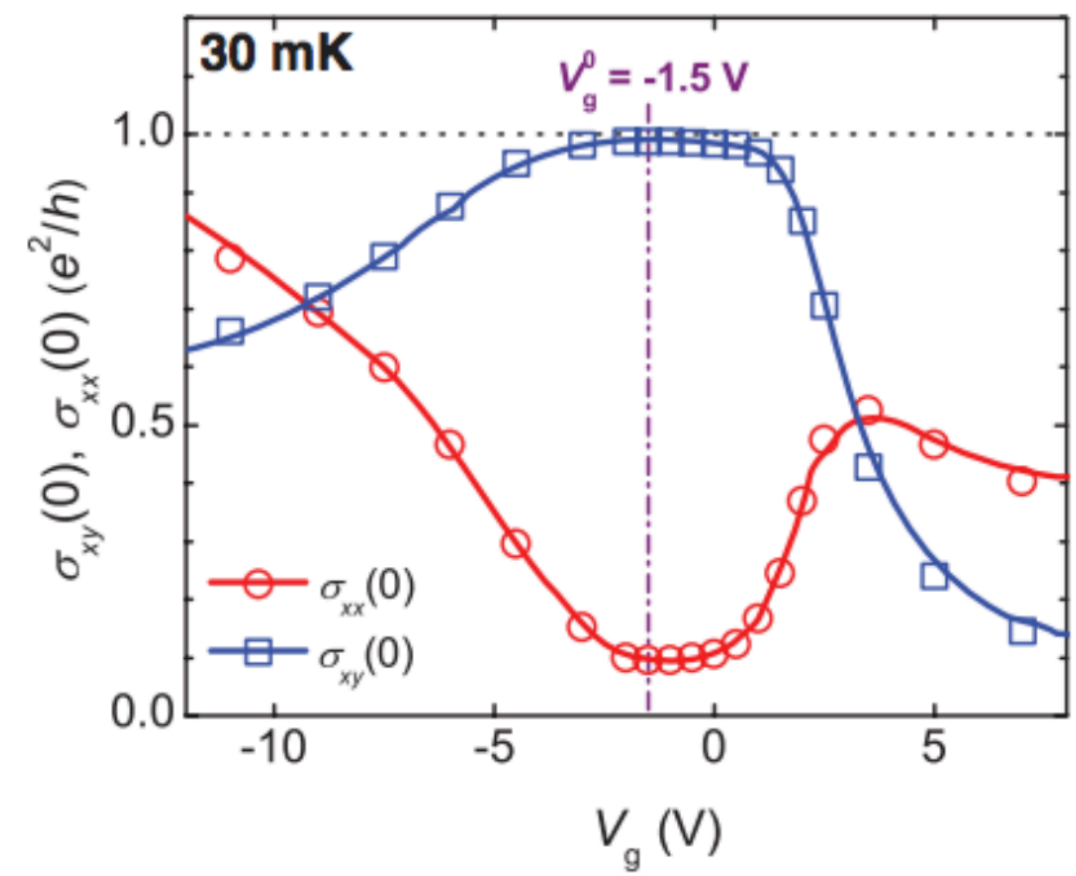
Electronic chirality without magnetic field

(Quantum) Anomalous Hall effect:

$$\mathbf{B} = 0$$



$Cr_{0.15}(Bi_{0.1}Sb_{0.9})_{1.85}Te_3$

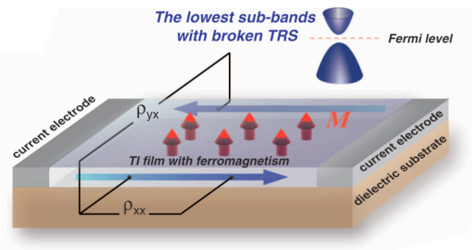


Zhang, et al, Science (2013)

Topological materials: novel electronic + opto-electronics

(Quantum) Anomalous Hall effect:

$\mathbf{B} = 0$



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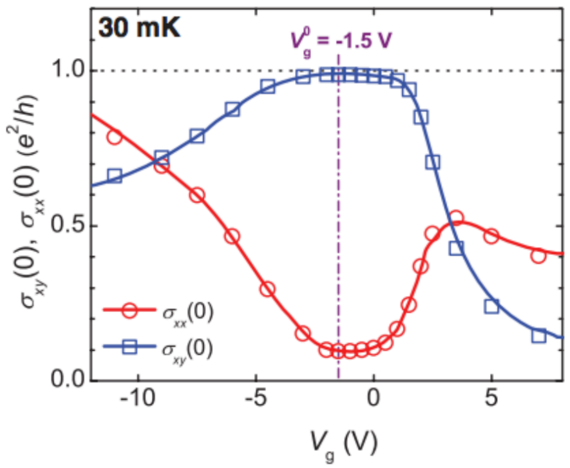
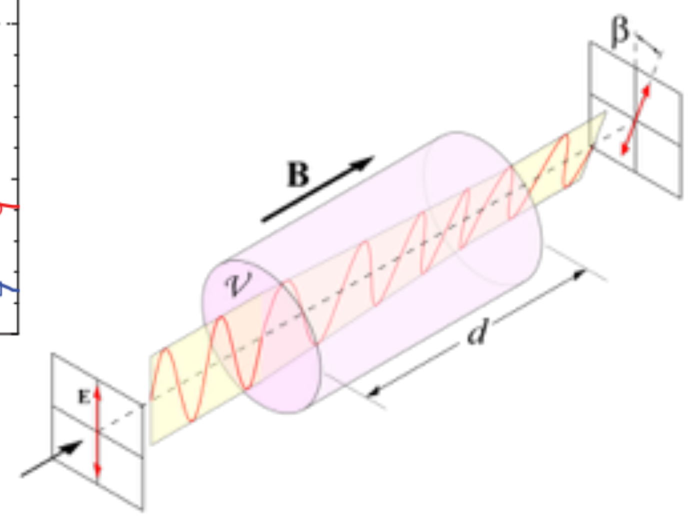
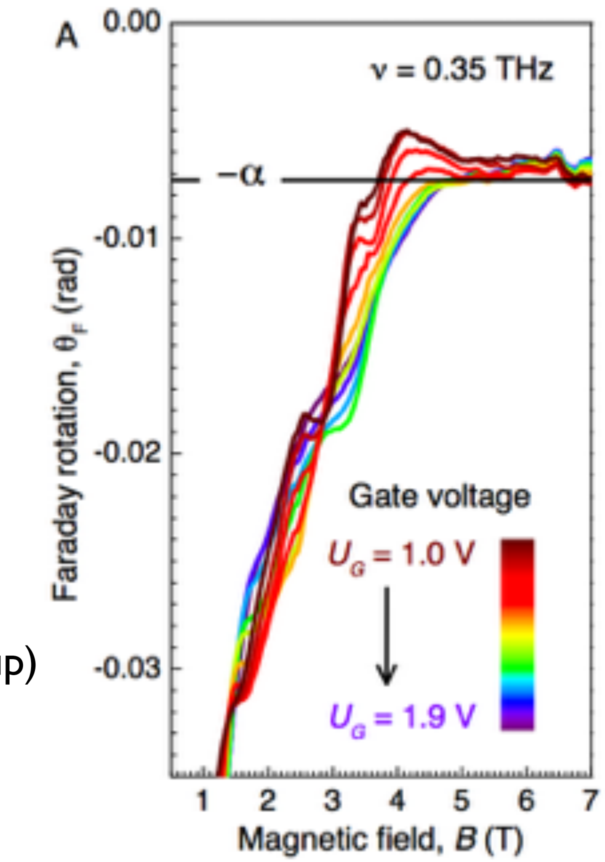


Zhang, et al, Science (2013)

"Topological Magneto-electric effect" and

Quantized Faraday (and Kerr) rotations in 3D TIs

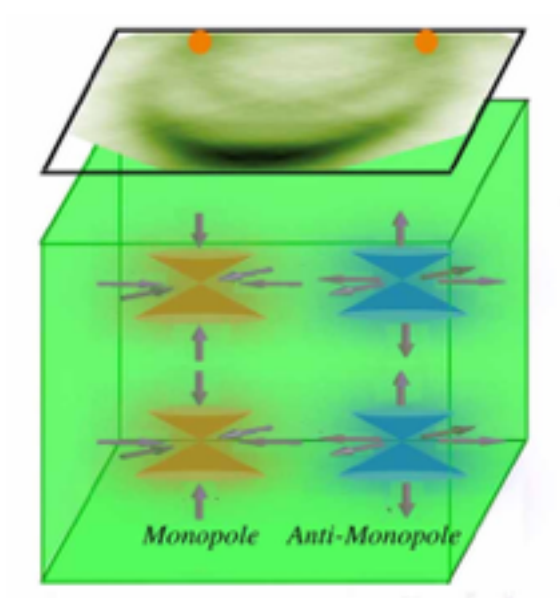




Strained HgTe 3D TI (Molenkamp group)
Dziom, et al, arXiv (2016)

see also
Bi2Se3 films, Wu et al (Armitage group), Science (2016)
& magnetic TI Okada, et al (Tokura group), Nat. Comm. (2016)

3D Weyl/Dirac semimetals & Fermi arcs



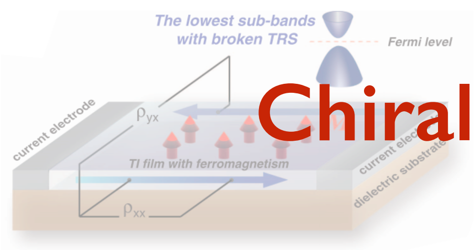
Weyl: TaAs,
Dirac: Cd3As2, Na3Bi, …

Xu et al, Science (2015), [Hasan group, and many others]

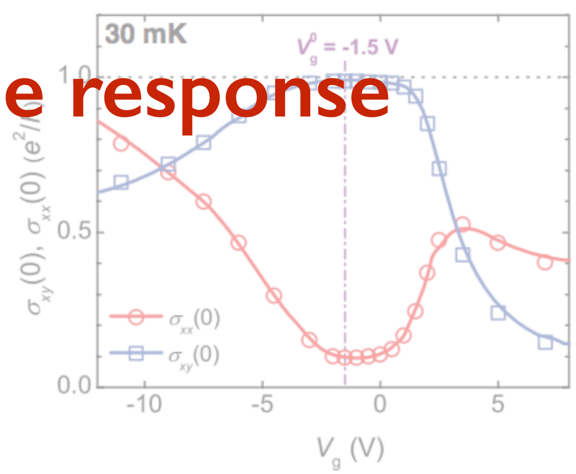
Topological materials: novel electronic + opto-electronics

(Quantum) Anomalous Hall effect

$\mathbf{B} = 0$



Chiral type response



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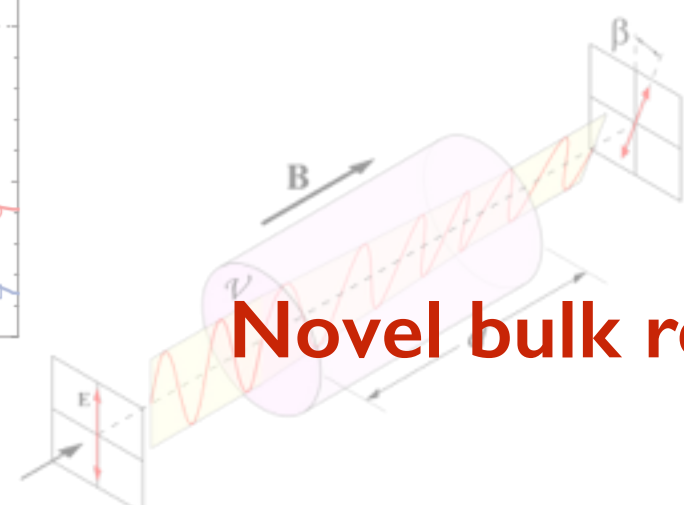
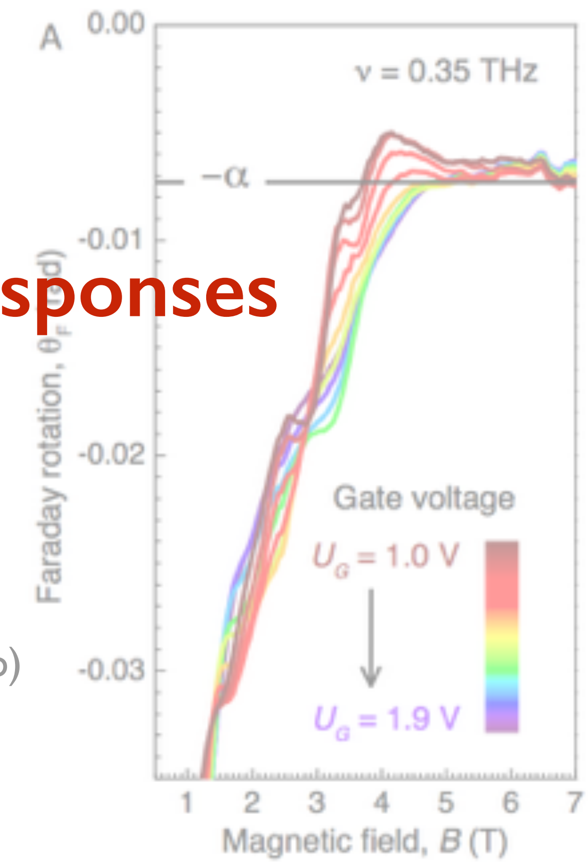


Novel bulk responses



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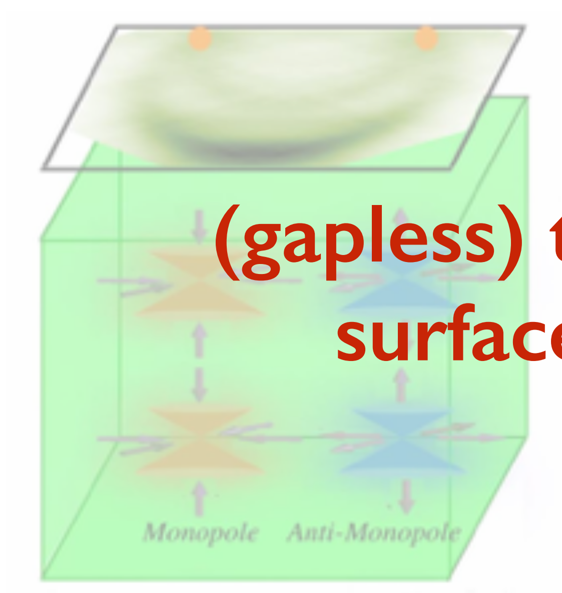


(gapless) topological surface states

Weyl: TaAs,
Dirac: Cd3As2, Na3Bi, …

Xu et al, Science (2015), [Hasan group, and many others]

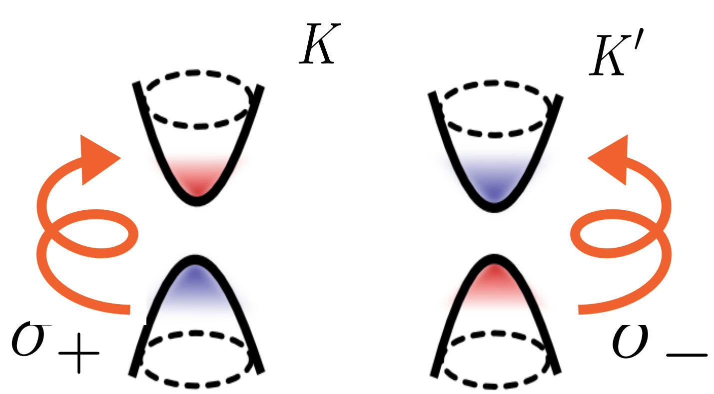
Hall regime: Transverse motion dominates response

$$\sigma_{xy} \gg \sigma_{xx}$$

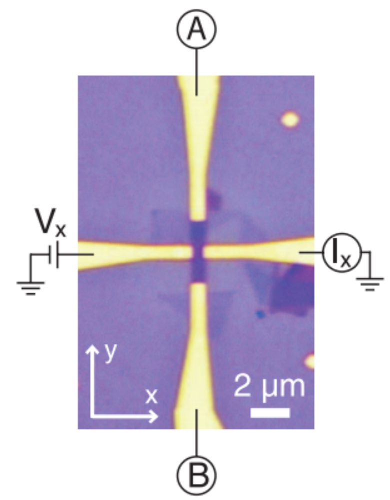
Search for new "topological" flavored responses in more readily available materials?

Hall photoconductivity in gapped Dirac materials

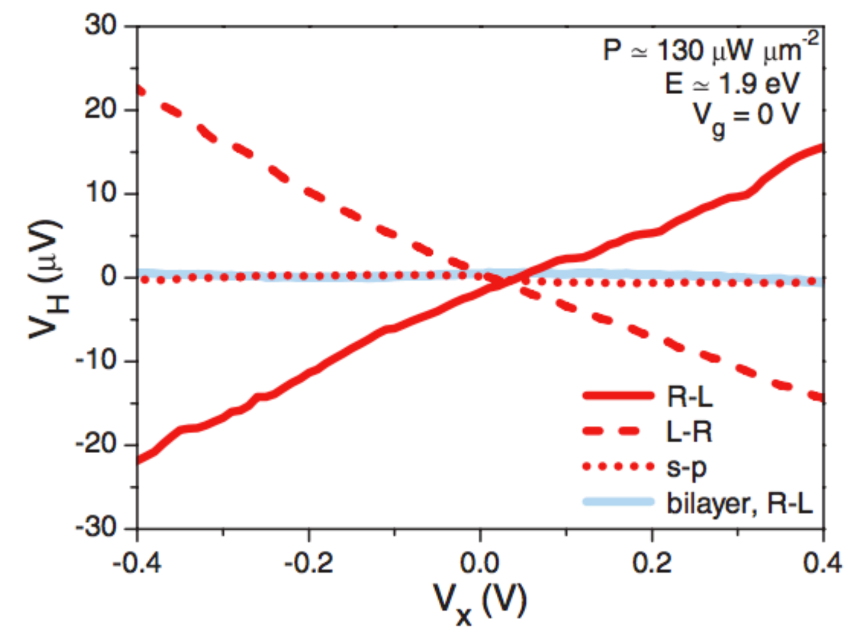
Circularly polarized light absorption in MoS_2



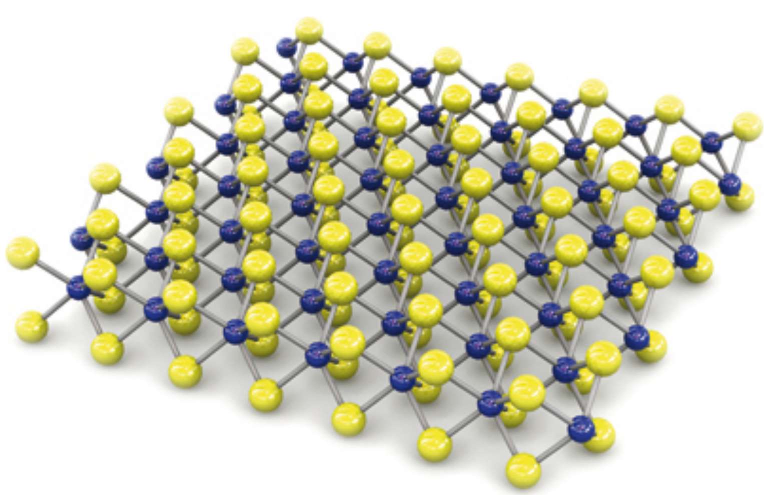
Left Handed Right Handed



Hall effect at zero magnetic field



KF Mak, K McGill, JW Park, PL McEuen, Science (2014)



Hall photoconductivity in gapped Dirac materials

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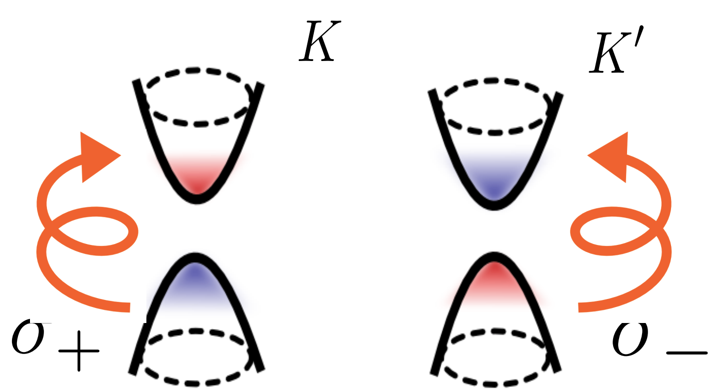

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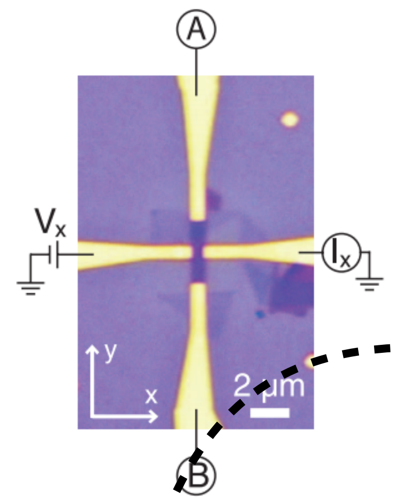
Right Handed



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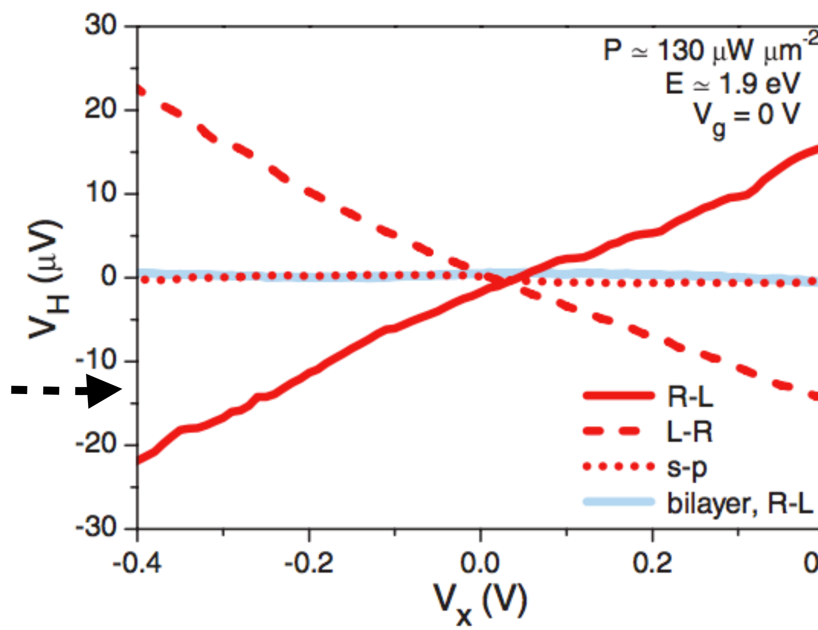


KF Mak, K McGill, JW Park, PL McEuen, Science (2014)

Effect is ***tiny***

Hall photoconductivity:

$$\sigma_{xy} \sim 1\,\mathrm{nS}$$
$$= 2.5 \times 10^{-5} [e^2/h]$$

$$\sigma_{xx} \gg \sigma_{xy}$$

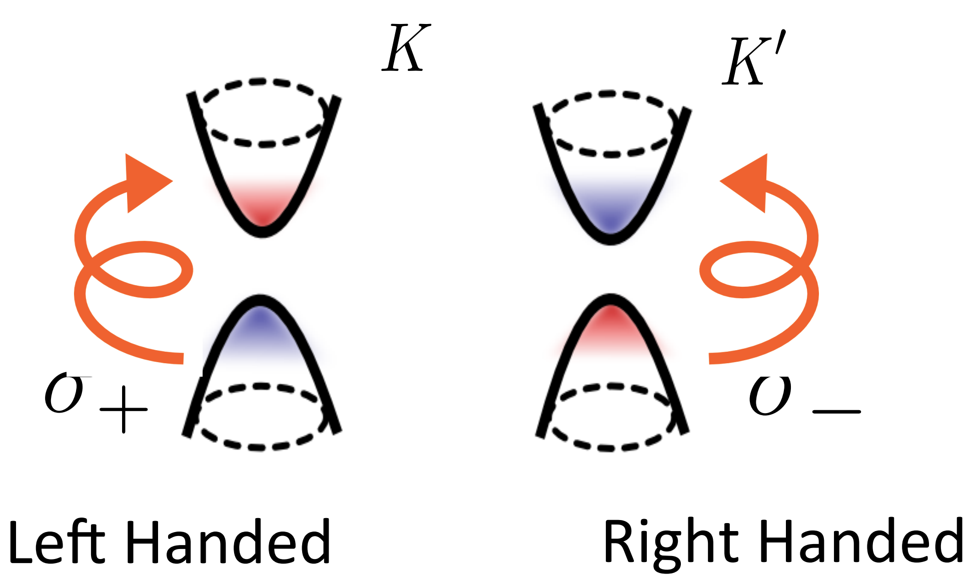
Can we achieve Hall regime in gapped Dirac materials?

Plan

Part I.

Giant Hall photoconductivity

gapped Dirac materials with a narrow gap yield Hall photoconductivity order ~ e^2/h; access to "Berry" transport regime



JS, Kats, Nano Letters (2016)

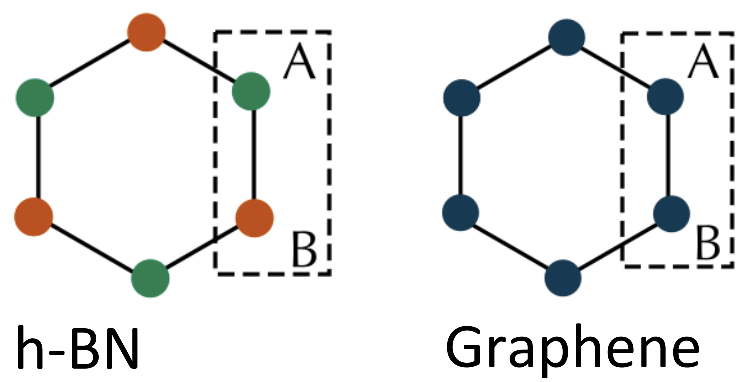
In collaboration with:

Mikhail Kats

(Wisconsin)

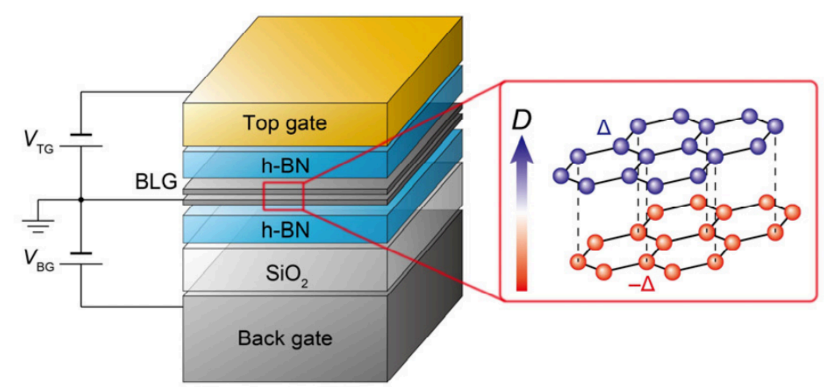
Narrow gapped Dirac materials (GDM)

G/h-BN heterostructures

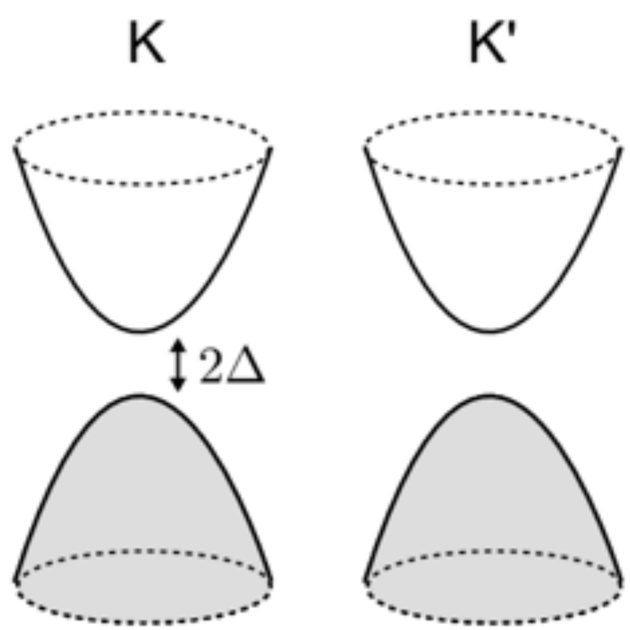


narrow gaps: $\Delta \approx 5 - 30\,\mathrm{meV}$

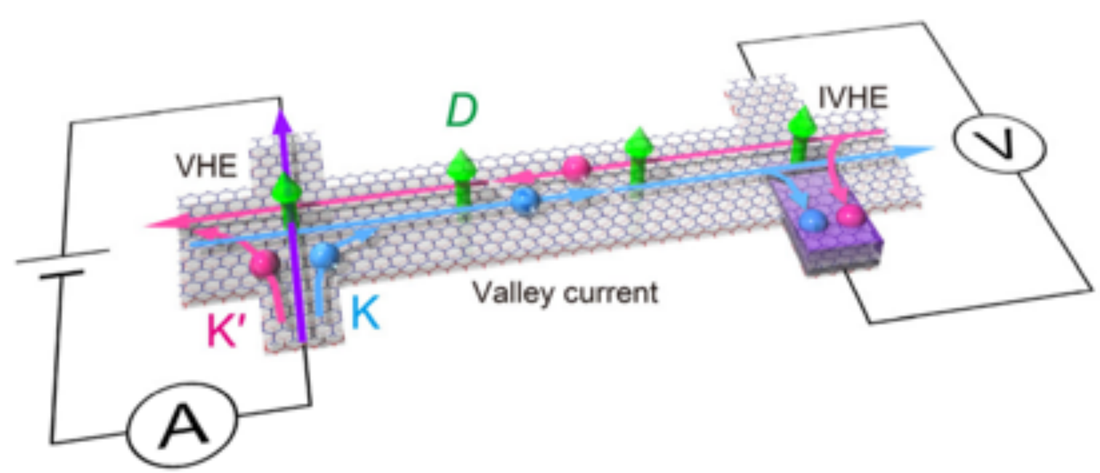
Dual-gated Bilayer graphene



Tunable gaps from 0 up to100-200 meV



Berry curvature and Valley Hall effect observed

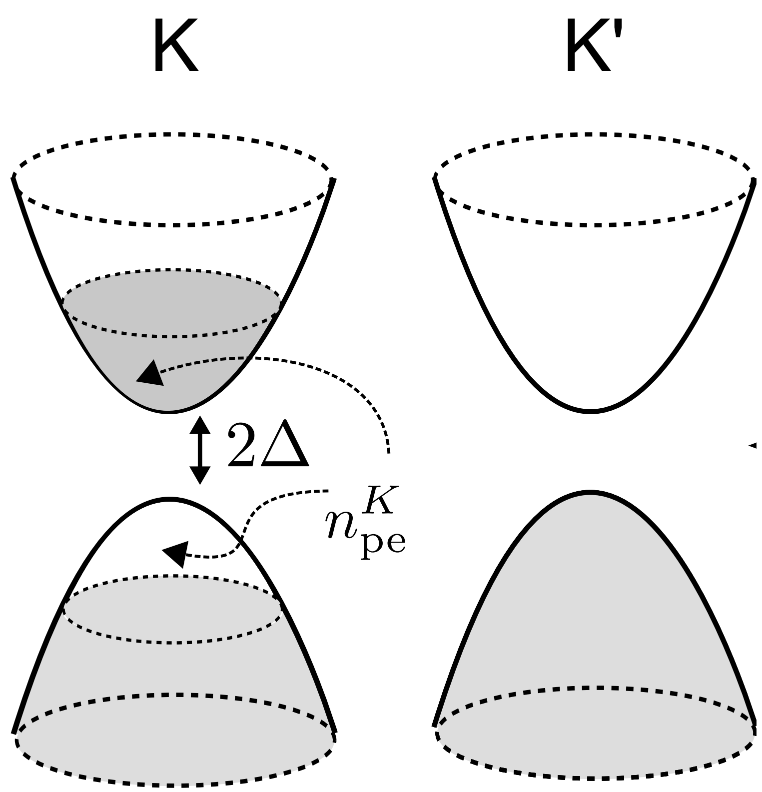


G/hBN: Gorbachev, JS, et al, Science (2014),
Dual-gated bilayer graphene: Shimazaki, et al Nature Physics (2015), Sui, et al Nature Physics (2015)

Giant Hall photoconductivity in narrow gap GDMs

Intrinsic Hall photoconductivity:

$$\sigma_{xy} = \frac{Ne^2}{\hbar}[\sum_{\mathbf{p},\pm} f_\pm^K(\mathbf{p})\Omega_\pm^K(\mathbf{p}) + \sum_{\mathbf{p},\pm} f_\pm^{K'}(\mathbf{p})\Omega_\pm^{K'}(\mathbf{p})]$$



photoexcited carrier density

For gapped Dirac materials (GDMs):

$$\sigma_{xy}^{\rm pe} = \frac{Ne^2}{h}\left[\mathcal{F}_K(n_{\rm pe}^K/2) + \mathcal{F}_{K'}(n_{\rm pe}^{K'}/2)\right],$$

$$\mathcal{F}_\zeta(x) = \frac{\zeta}{2}\Big(1 - \big[\frac{\tilde{n}^{1/2}}{\sqrt{\tilde{n}+n_0+x}} + \frac{\tilde{n}^{1/2}}{\sqrt{\tilde{n}+x}}\big]\Big),$$

+1(-1) for K (K')

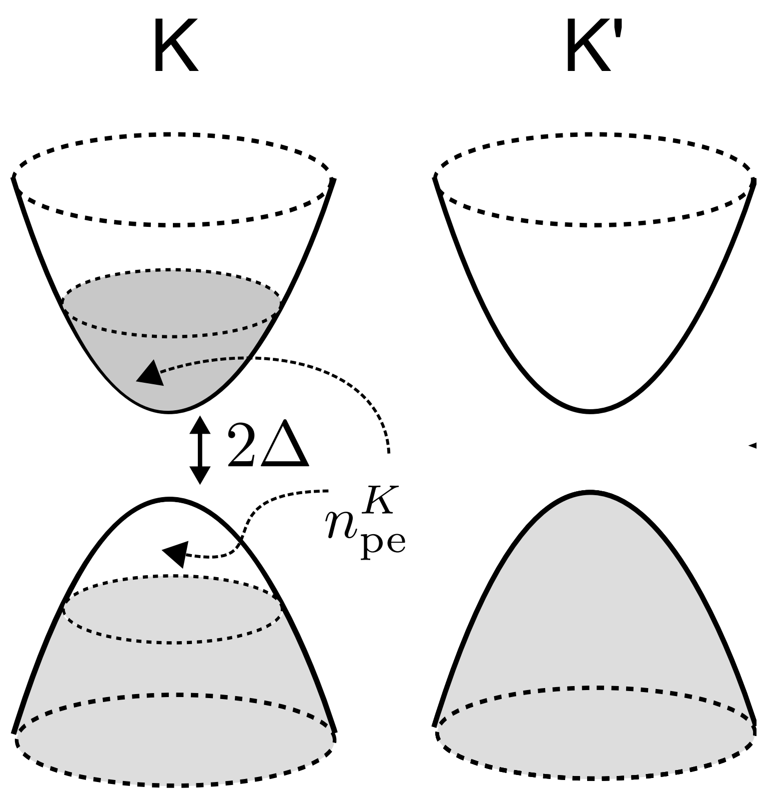
dependent on gap size

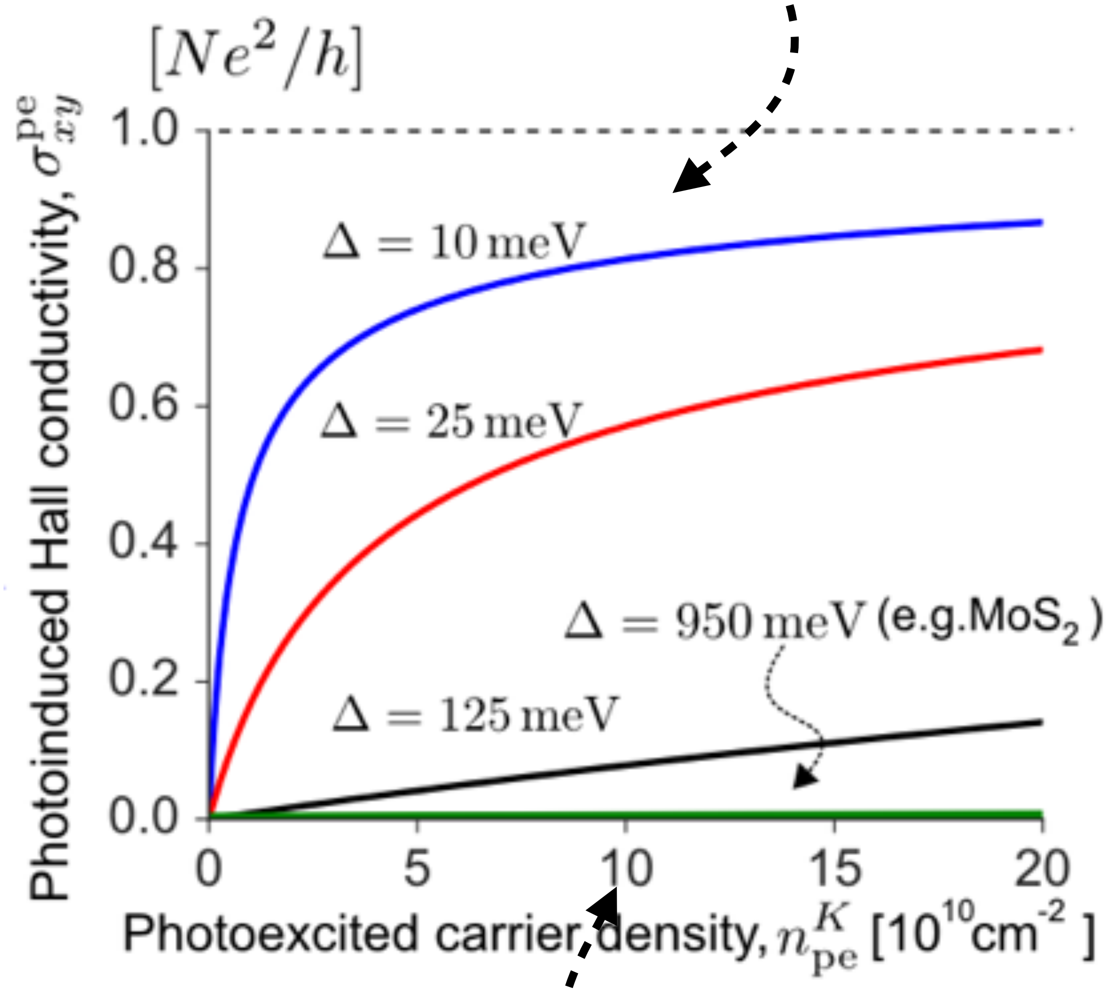
$$\tilde{n} = \Delta^2/4\pi v^2\hbar^2$$

JS, Kats, Nano Letters (2016)

Giant Hall photoconductivity in narrow gap GDMs

(i) narrow gaps yield giant $\sigma_{xy} \sim e^2/h$





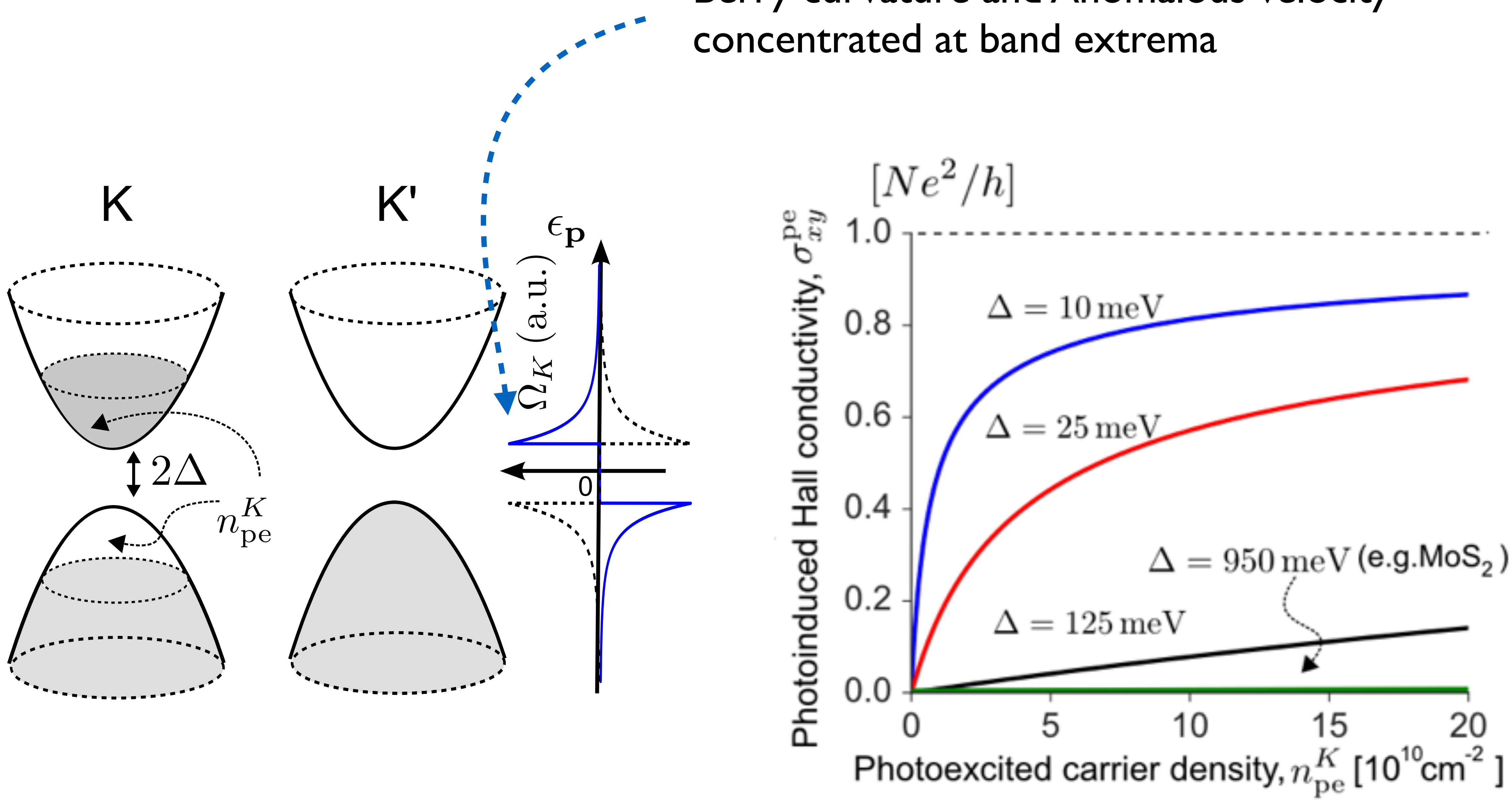
(iii) giant change, several orders of magnitude

(ii) achievable even for small $n_{\rm pe}^K \sim 10^{10}{\rm cm}^{-2}$

JS, Kats, Nano Letters (2016)

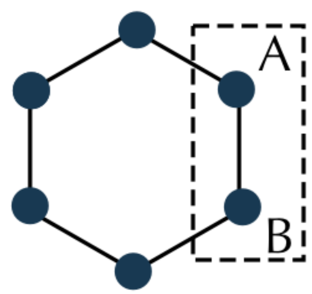
Giant Hall photoconductivity in narrow gap GDMs

Berry curvature and Anomalous velocity concentrated at band extrema



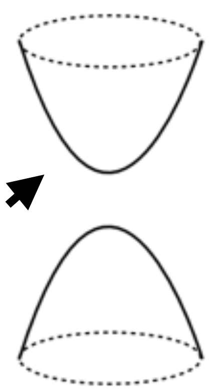
JS, Kats, Nano Letters (2016)

Intuitive explanation: pseudo-spin and velocity



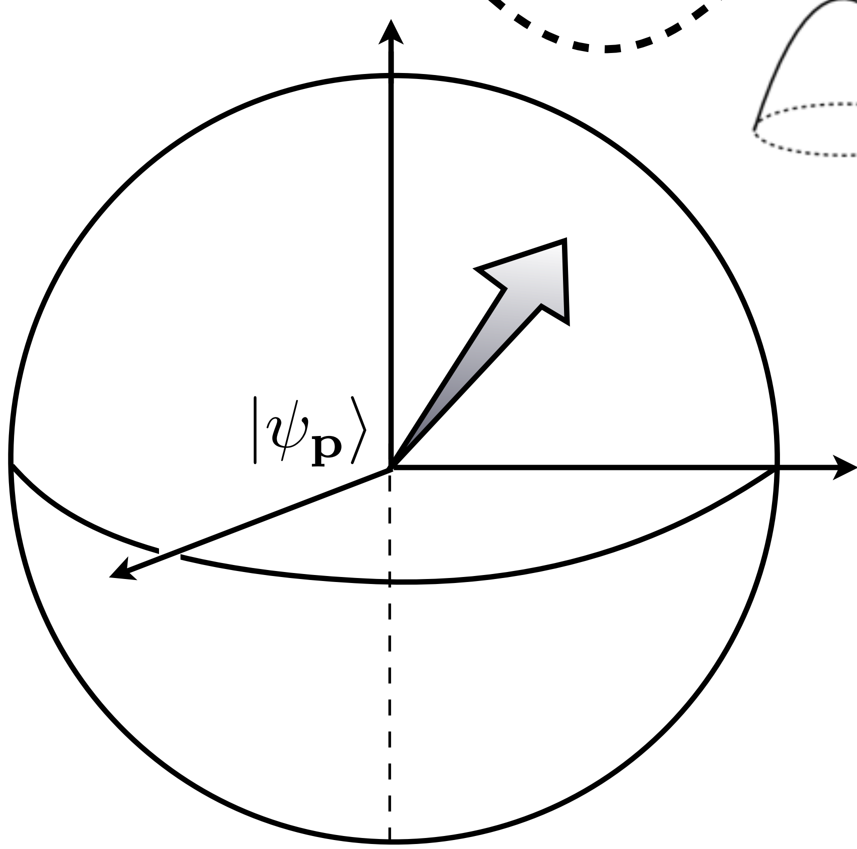
velocity depends on amplitude + phase on A/B sub lattice

e.g. at band extrema, velocity vanishes (all on A site)



$$\mathbf{v_p} = \langle \psi(\mathbf{p}) | \boldsymbol{\sigma} | \psi(\mathbf{p}) \rangle$$

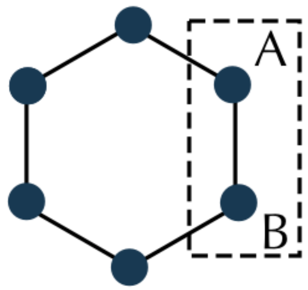
all on A site



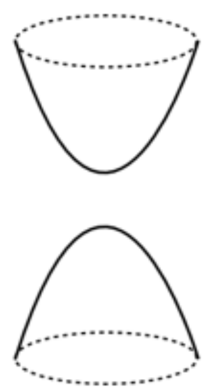
all on B site

JS, Kats, Nano Letters (2016)

Intuitive explanation: pseudo-spin and velocity

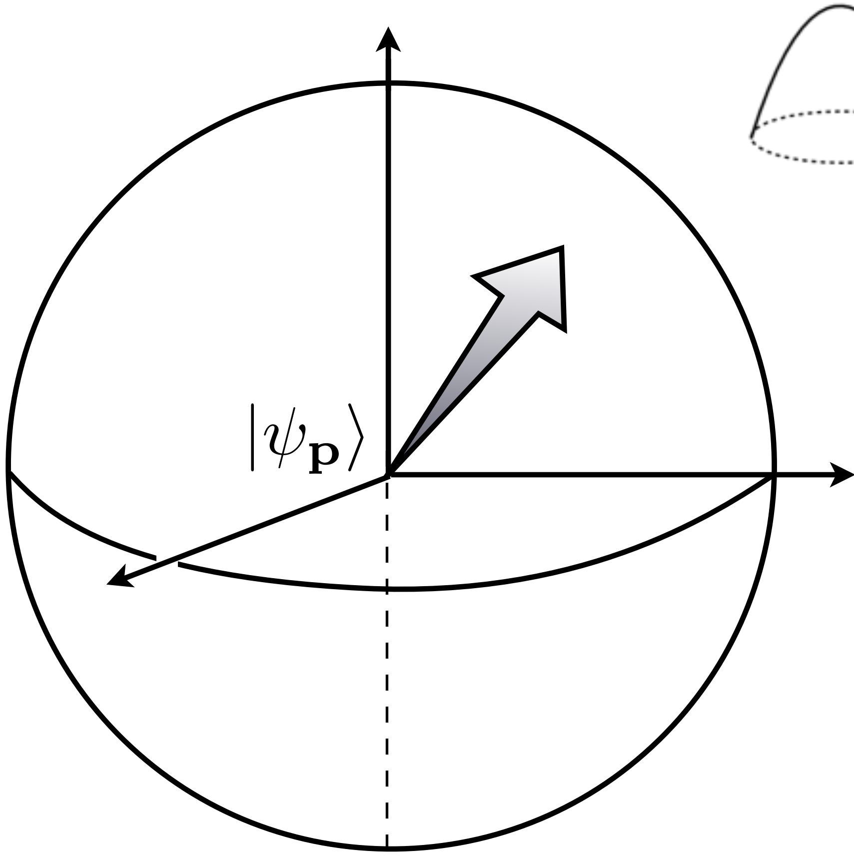


velocity depends on amplitude + phase on A/B sub lattice



$$\mathbf{v}_{\mathbf{p}} = \langle \psi(\mathbf{p}) | \boldsymbol{\sigma} | \psi(\mathbf{p}) \rangle$$

all on A site



all on B site

Apply electric field, wave function is perturbed

perturbation

$$|\psi_-(\mathbf{p})\rangle = \psi_-^{(0)}(\mathbf{p}) + \frac{\langle \psi_+^{(0)} | H' | \psi_-^{(0)} \rangle}{\epsilon_-(\mathbf{p}) - \epsilon_+(\mathbf{p})} |\psi_+^{(0)}\rangle$$

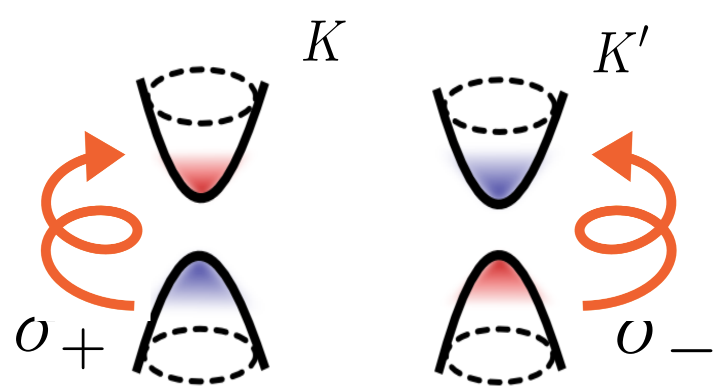
1st order perturbation theory

anomalous equation of motion

$$\dot{\boldsymbol{x}} \;=\; \frac{d\varepsilon}{d\boldsymbol{p}} + \dot{\boldsymbol{p}} \times \Omega$$

JS, Kats, Nano Letters (2016)

Enhancement of valley imbalance rate



Left Handed   Right Handed

Fermi's golden rule (valley selective absorption rate)

$$W_{K(K')} = \frac{2\pi}{\hbar} \sum_{\mathbf{k}} |M_{\mathbf{k}}^{K(K')}|^2 \delta(\varepsilon_{\mathbf{k}} - \hbar\omega/2)$$

Valley population imbalance rate:

maximized when $\hbar\omega = 2\Delta$

$$\frac{d\delta n}{dt} = 2(W_K^d - W_{K'}^d) = d\frac{e^2|\mathbf{E}|^2}{\hbar^2\omega}\frac{\Delta}{\hbar\omega}$$

Hall photoconductivity per fluence:

characteristic conductivity per fluence scales as $\propto \Delta^{-3}$ on resonance

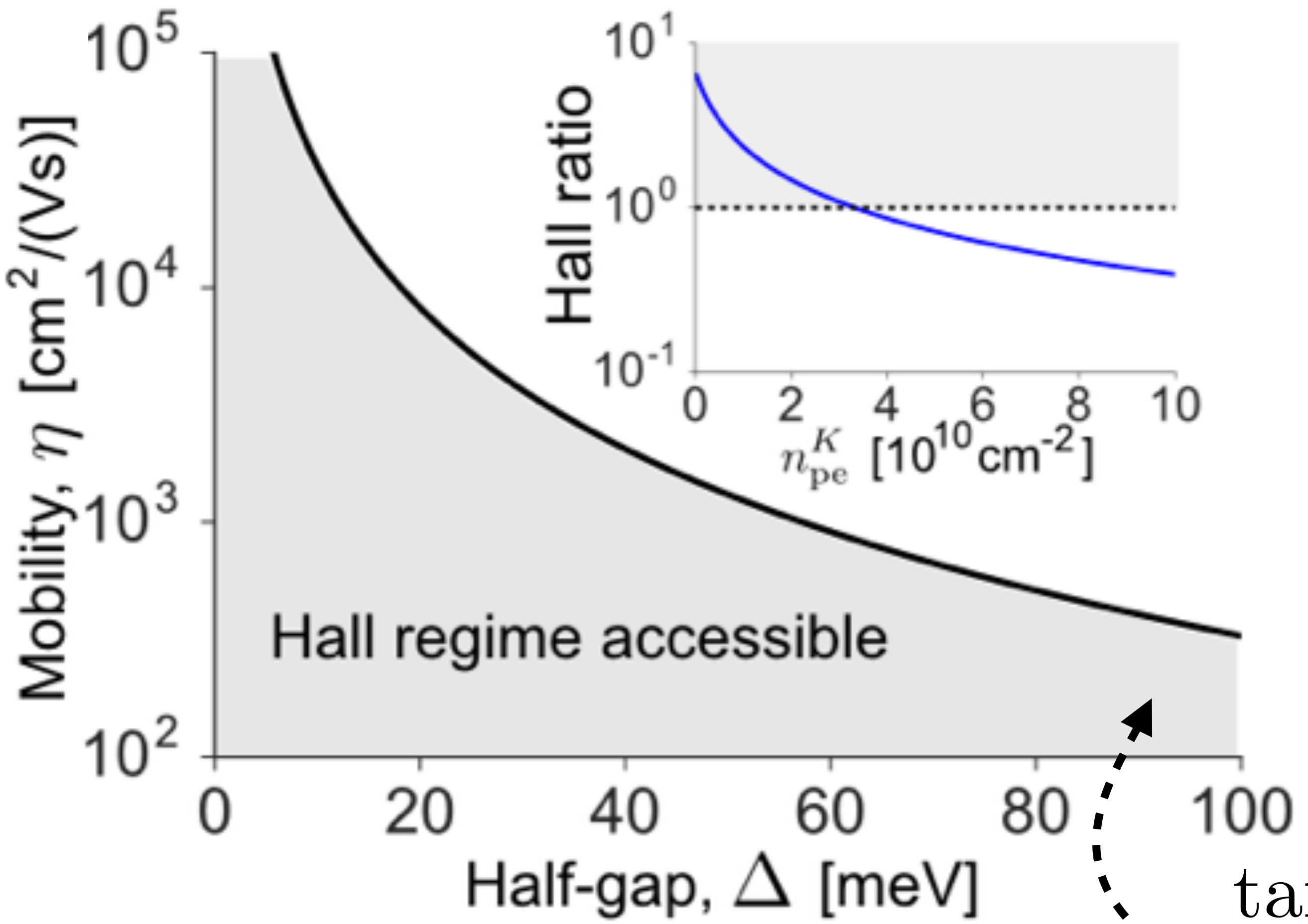
$$\frac{\tilde{\sigma}_{xy}^{\mathrm{pe}}}{\mathcal{P}_{\mathrm{in}}} = d\frac{S_0}{(\hbar\omega)^2\Delta},$$

six orders of magnitude enhancement for $\Delta = 1\,\mathrm{eV} \rightarrow 10\,\mathrm{meV}$

JS, Kats, Nano Letters (2016)

How large? Accessing Hall regime $\sigma_{xy} \gg \sigma_{xx}$

$$\tan\theta_{\mathrm{H}} = \sigma_{xy}^{\mathrm{pe}}/\sigma_{xx}^{\mathrm{pe}}$$



longitudinal motion:

$$\sigma_{xx}^{\mathrm{pe}} = eN\eta n_{\mathrm{pe}}$$

mobility

transverse motion:

$$\sigma_{xy}^{\mathrm{pe}} = \frac{Ne^2}{h}\Big[\mathcal{F}_K(n_{\mathrm{pe}}^K/2) + \mathcal{F}_{K'}(n_{\mathrm{pe}}^{K'}/2)\Big],$$

$$\mathcal{F}_\zeta(x) = \frac{\zeta}{2}\Big(1 - \Big[\frac{\tilde{n}^{1/2}}{\sqrt{\tilde{n}+n_0+x}} + \frac{\tilde{n}^{1/2}}{\sqrt{\tilde{n}+x}}\Big]\Big),$$

dependent on gap size

$$\tan\theta_H > 1$$

Hall (transverse) motion
overwhelms **longitudinal motion**

JS, Kats, Nano Letters (2016)

Signatures of the Hall regime: $\sigma_{xy} \gg \sigma_{xx}$

Magneto-transport: Lorentz force
impedes longitudinal motion

$$\dot{\boldsymbol{x}} = \frac{d\varepsilon}{d\boldsymbol{p}}$$

$$\dot{\boldsymbol{p}} = -\frac{dV}{d\boldsymbol{x}} + \dot{\boldsymbol{x}} \times \boldsymbol{B}$$

Signatures of the "Berry" Hall regime: $\sigma_{xy} \gg \sigma_{xx}$

Magneto-transport: Lorentz force **impedes** longitudinal motion

$$\dot{\boldsymbol{x}} = \frac{d\varepsilon}{d\boldsymbol{p}}$$

$$\dot{\boldsymbol{p}} = -\frac{dV}{d\boldsymbol{x}} + \dot{\boldsymbol{x}} \times \boldsymbol{B}$$

"Berry transport": Berry curvature **boosts** longitudinal motion

$$\dot{\boldsymbol{x}} = \frac{d\varepsilon}{d\boldsymbol{p}} + \dot{\boldsymbol{p}} \times \Omega$$

$$\dot{\boldsymbol{p}} = -\frac{dV}{d\boldsymbol{x}}$$

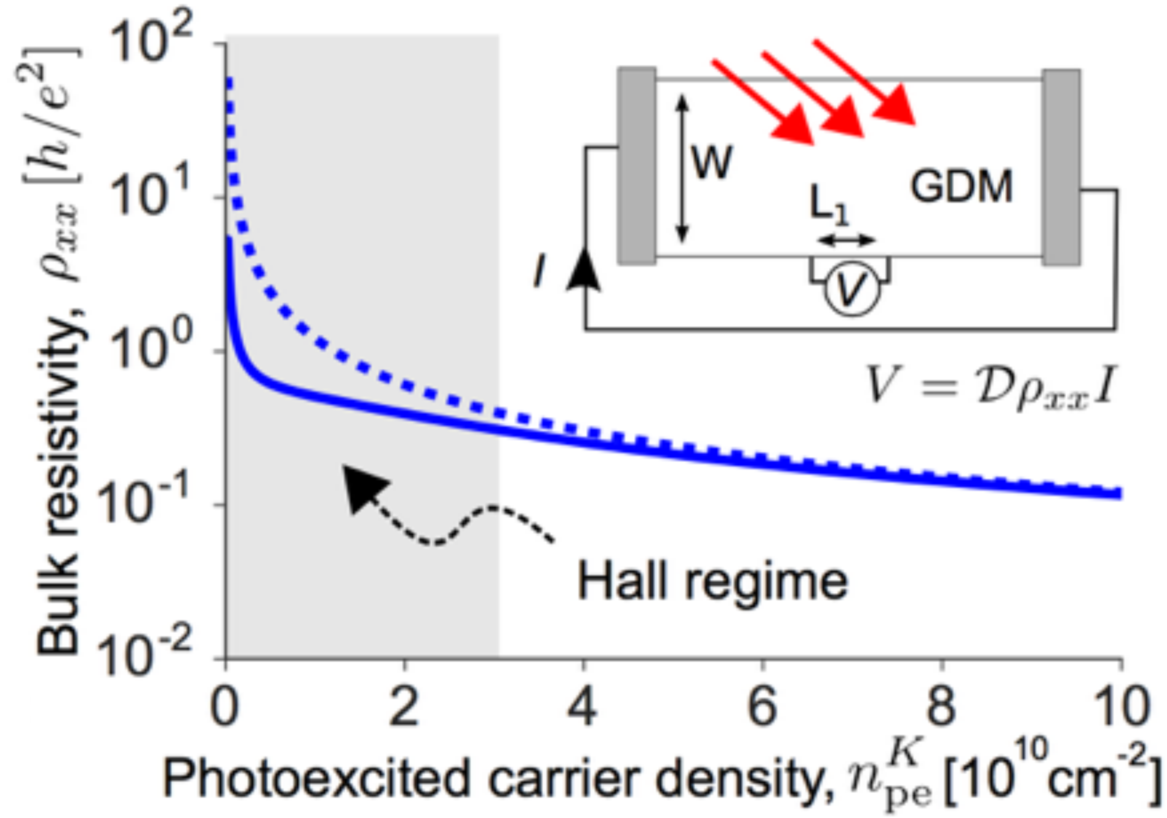
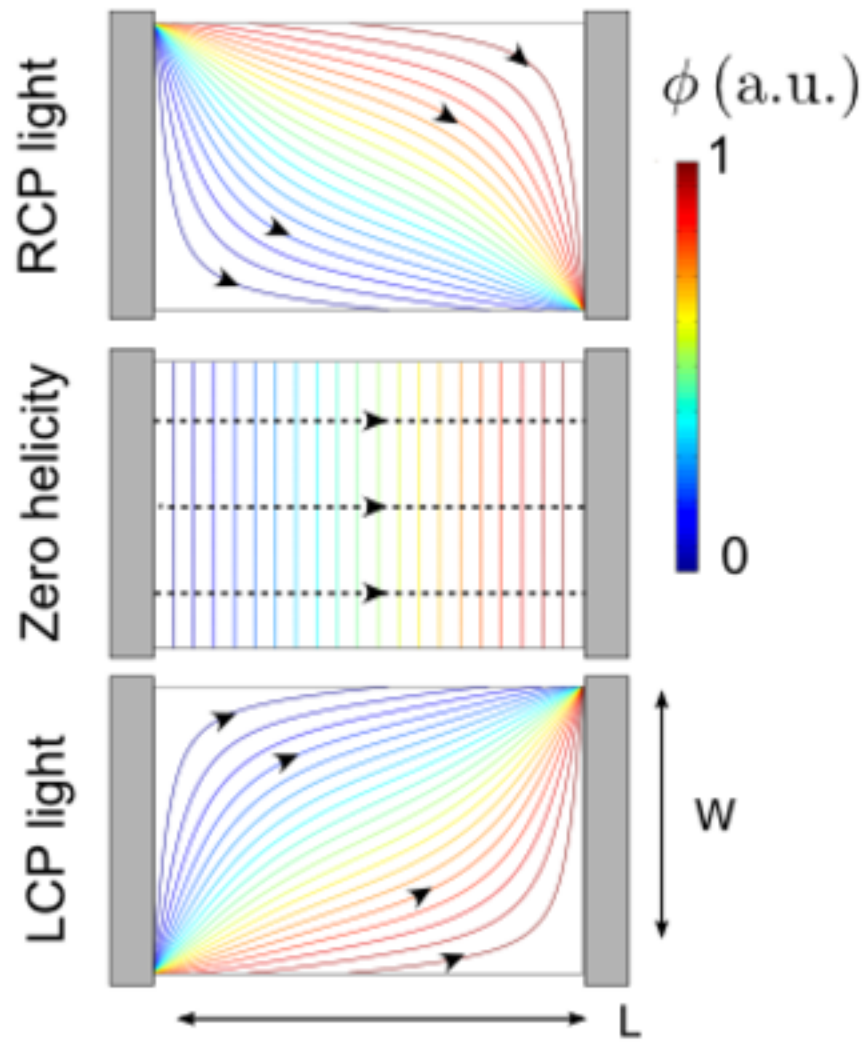


photo-resistivity is *suppressed* in "Berry" Hall regime

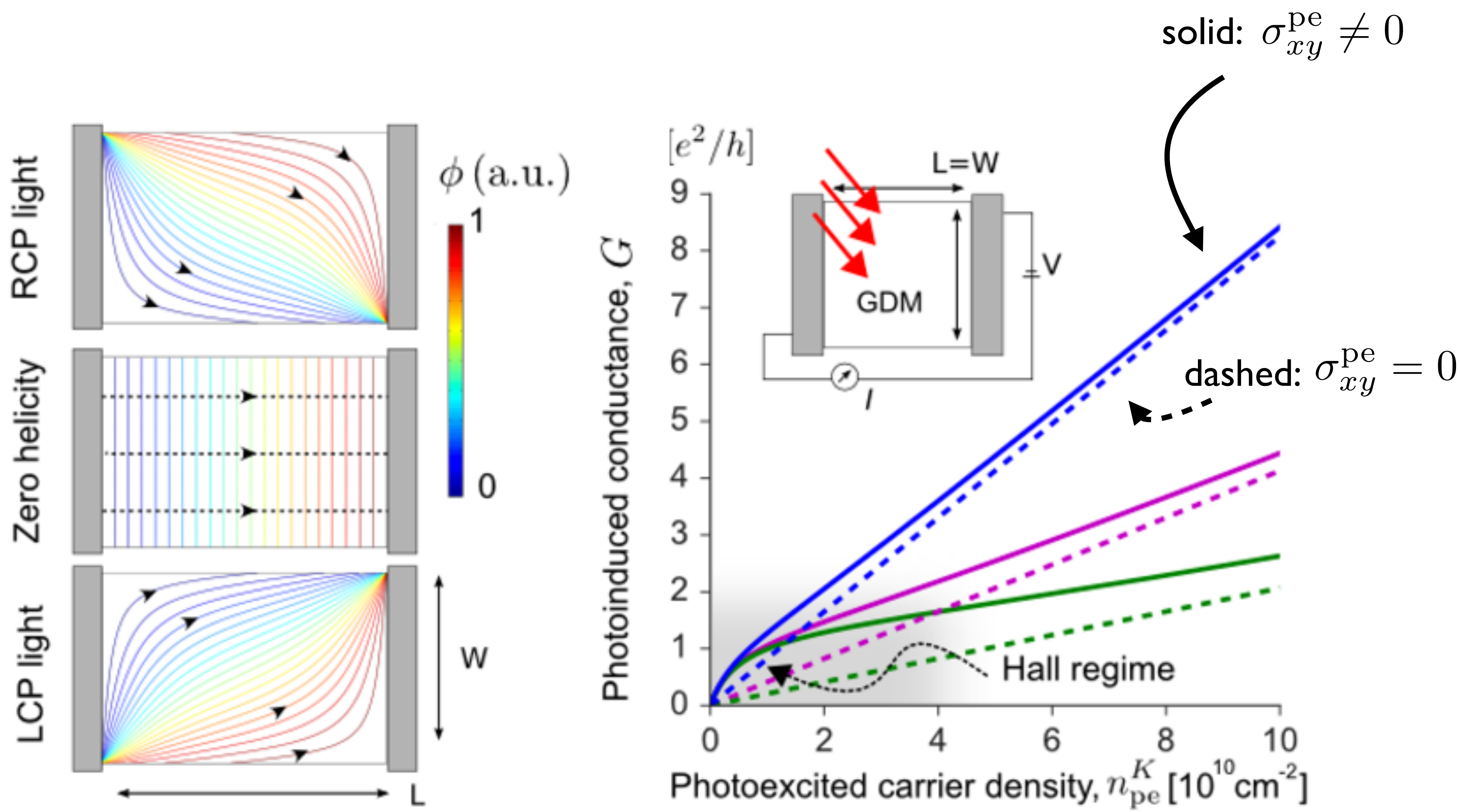
JS, Kats, Nano Letters (2016)

Anomalous two-terminal conductance



JS, Kats, Nano Letters (2016)

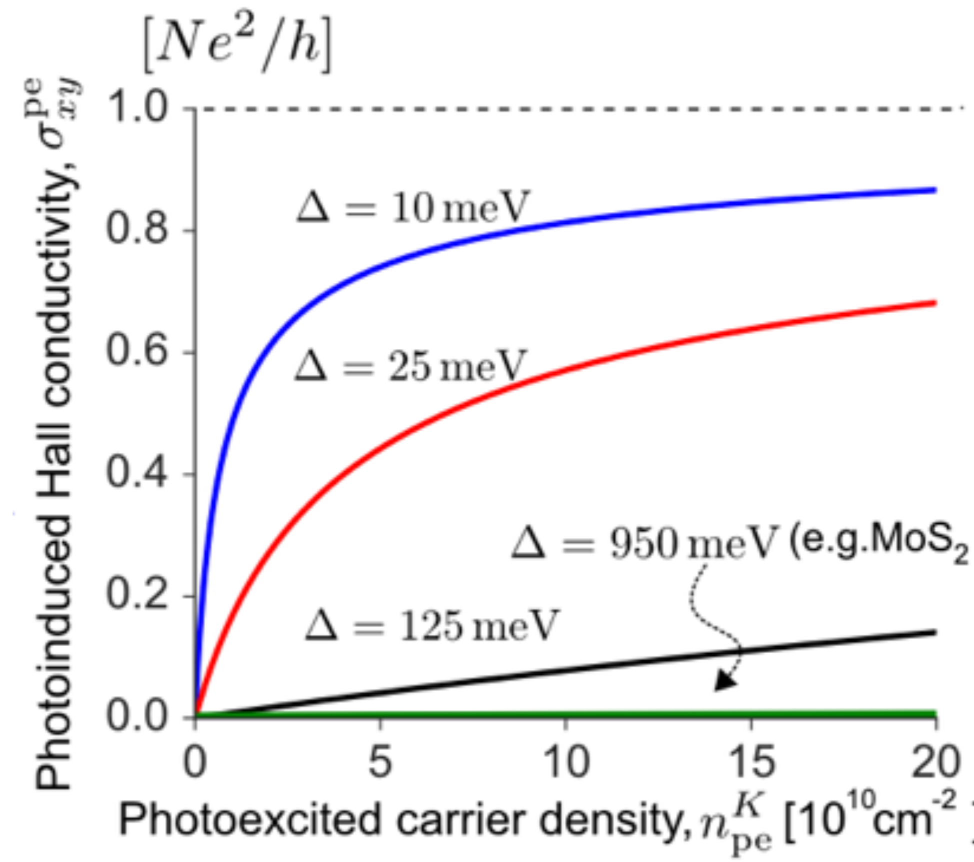
Anomalous two-terminal conductance *boost*



JS, Kats, Nano Letters (2016)

“Berry transport” in narrow GDMs

Narrow gapped Dirac materials enable
⟶ *giant* Hall photoconductivity



Far larger than wide gap Dirac materials.
new characteristics; readily accessible

Hall photoconductivity can overwhelm longitudinal conductivity: **Hall regime**.

Narrow gapped Dirac materials:
platform for novel “Berry” opto-electronics

In collaboration with:

Mikhail Kats
(Wisconsin)

Funding:
NATIONAL RESEARCH FOUNDATION
(Singapore)

Plan

Part I.

Giant Hall photoconductivity

gapped Dirac materials with a narrow gap yield giant Hall photoconductivity order ~ e^2/h = access to "Berry" transport regime [Hall regime]

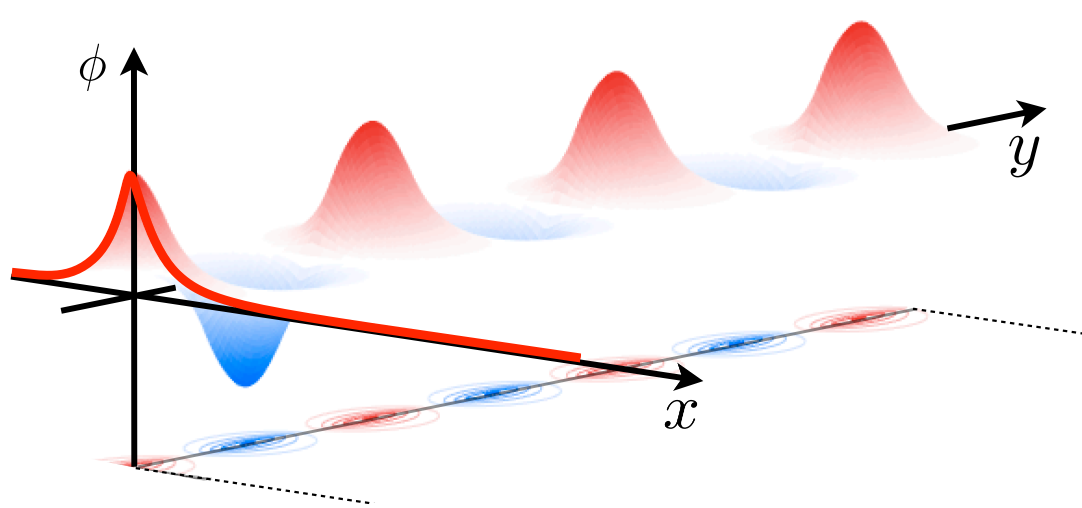
Part II.

Anomalous Plasmons

electron interactions + Berry curvature = new collective modes ("Berry Plasmons")

Berry plasmons: **JS**, Rudner, PNAS (2016)

Weyl semimetals: **JS**, Rudner, arXiv (2017)



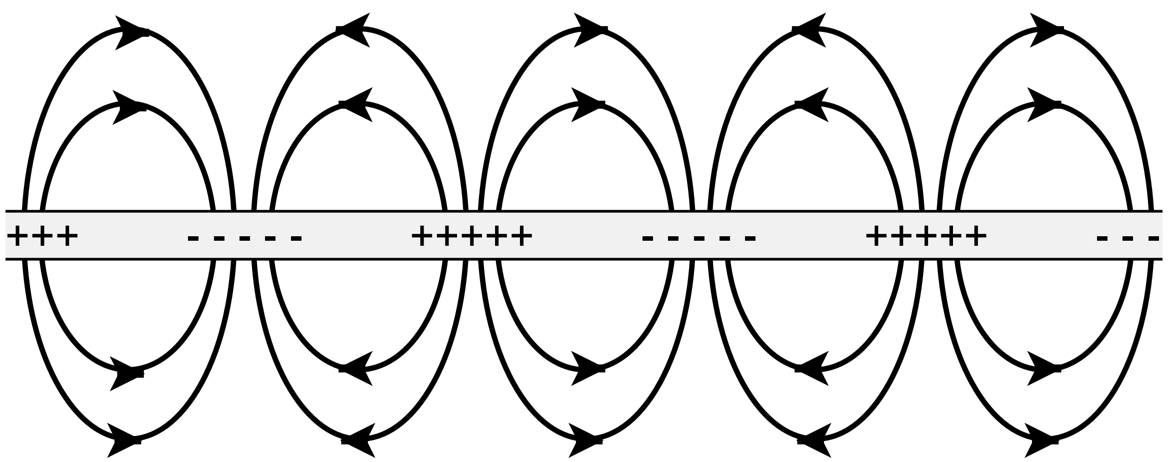
In collaboration with:

Mark Rudner

(Copenhagen)

Interactions and Collective modes

Plasmons



Spin waves/magnons

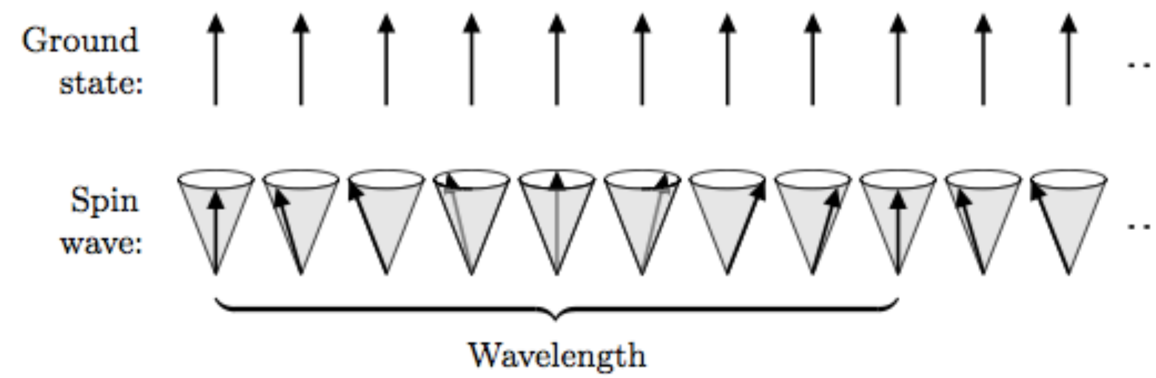
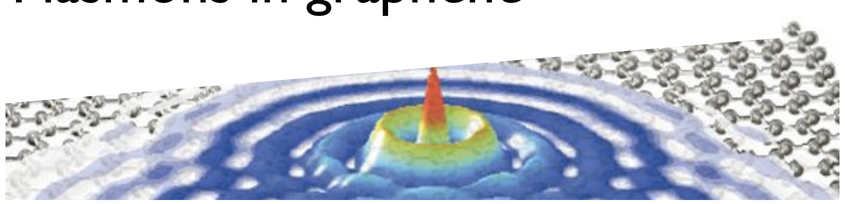


Image from http://wikipedia.org

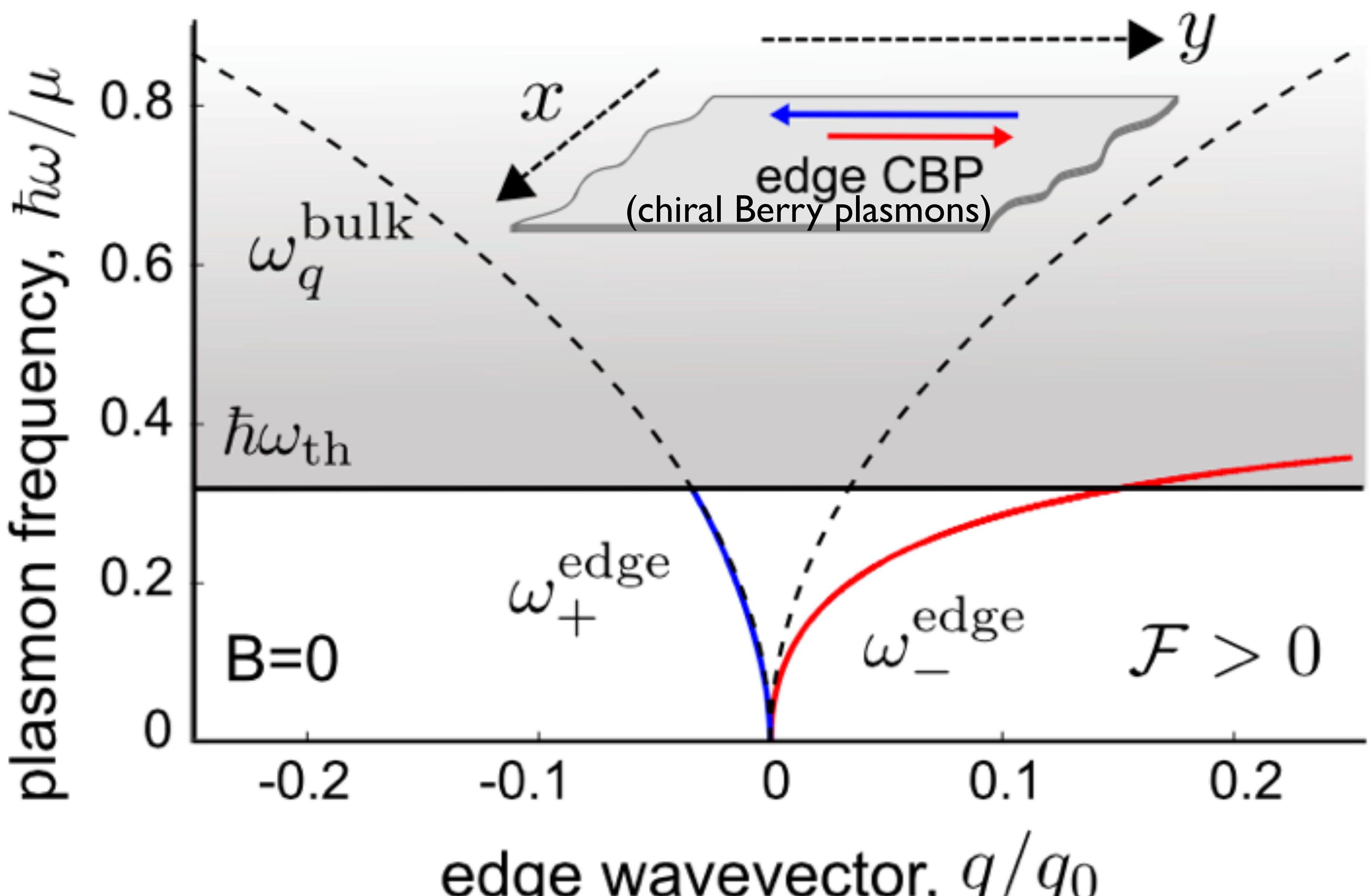
e.g. Plasmons in graphene



Koppens group, Nature (2013) Basov group Nature (2013)

Interactions + Berry curvature = Berry plasmons?

Chiral edge plasmons induced by Berry curvature

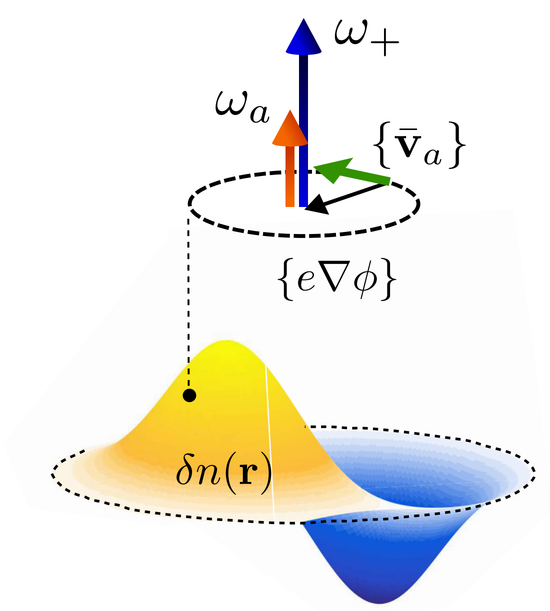


characteristic wavevector

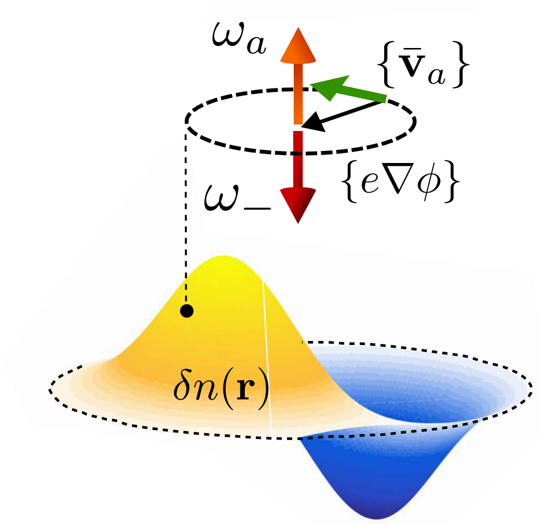
$$q_0 = \kappa\mu/e^2$$

Berry plasmons in a disk

Counter-clockwise (fast) mode



Clockwise (slow) mode



Linearized equation of motion:

$$\begin{pmatrix} \frac{d^2}{dt^2} + \omega_0^2 & -\omega_a \frac{d}{dt} \\ \omega_a \frac{d}{dt} & \frac{d^2}{dt^2} + \omega_0^2 \end{pmatrix} \begin{pmatrix} \{x(t)\} \\ \{y(t)\} \end{pmatrix} = 0 \qquad \omega_a = \frac{\mathcal{F}\omega_0^2 m}{n_0 \hbar}$$

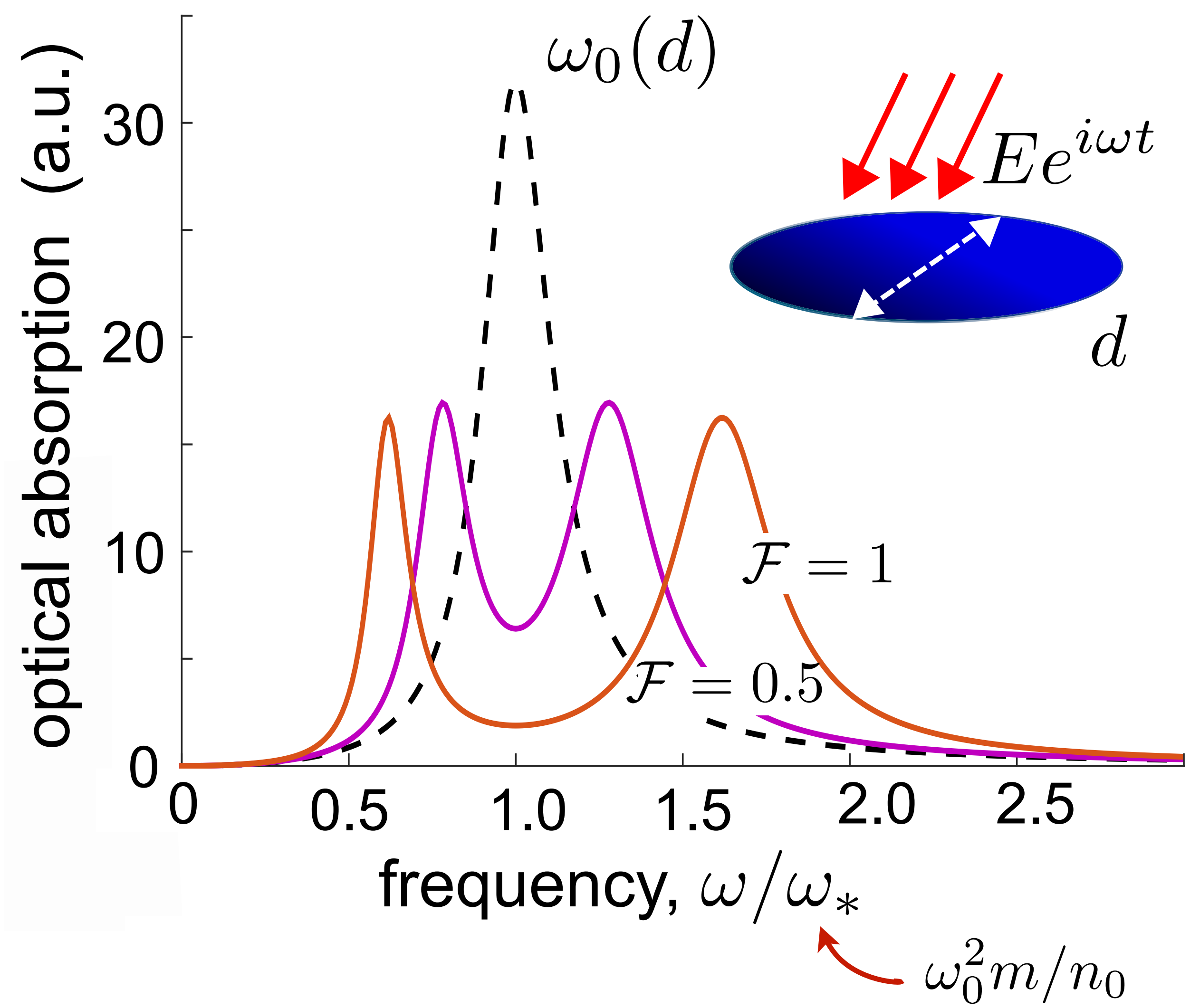
Obtain two chiral modes:

$$\{\mathbf{x}(t)\}_\pm = \frac{|\mathbf{x}_0|}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm i \end{pmatrix} e^{i\omega_\pm t}, \quad \omega_\pm = \sqrt{\omega_0^2 + \frac{\omega_a^2}{4}} \pm \frac{\omega_a}{2}$$

using $\omega_0 \sim \omega_{2D}(q = 1/d)$, find

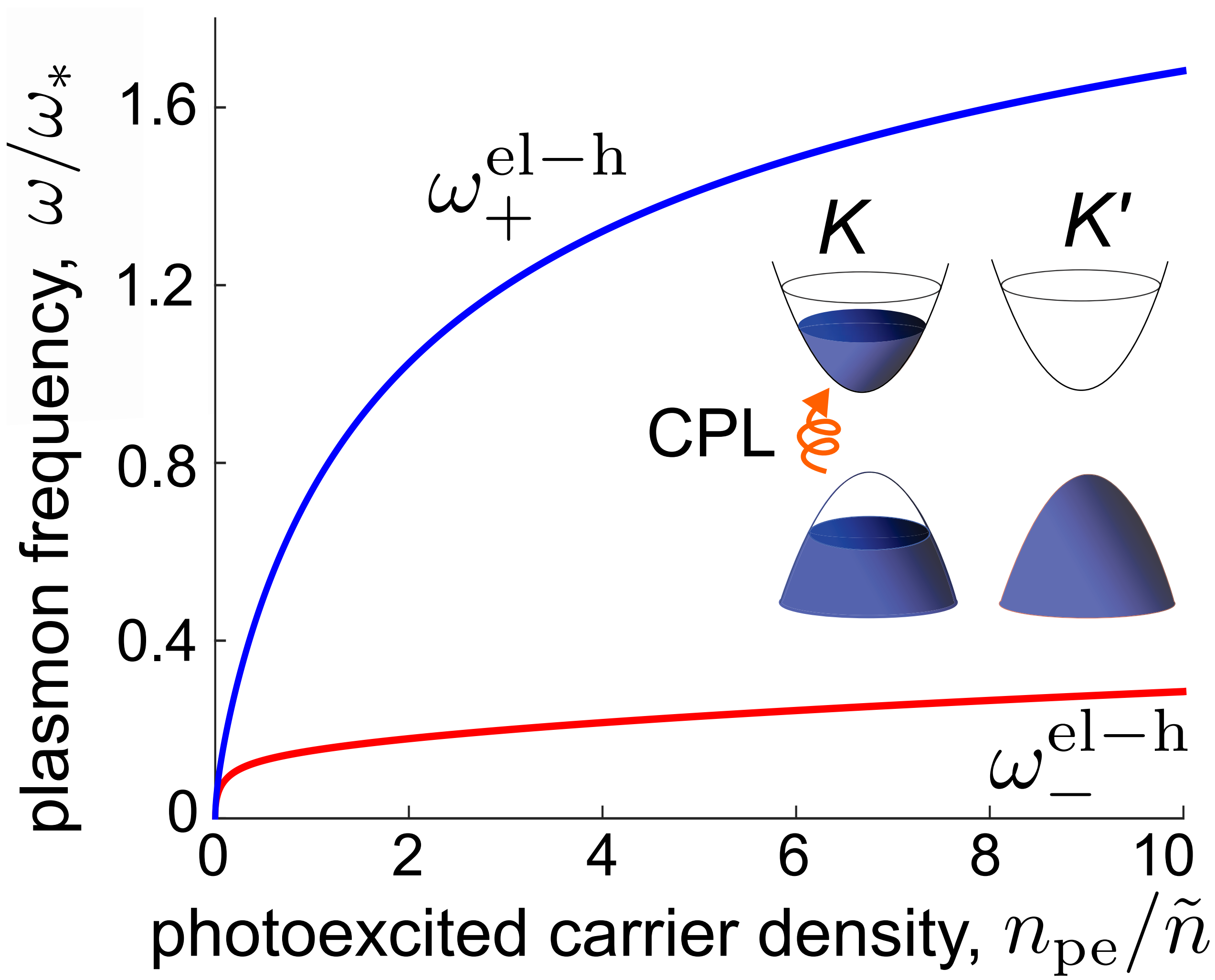
$$\delta\omega \approx \frac{9\mathcal{F}}{d[\mu\mathrm{m}]}\,\mathrm{meV}$$

Experimental signatures: optical absorption



JS, Rudner, PNAS (2016)

Optical valley polarization enables CBPs "on demand" in *non-magnetic* materials (e.g., Gapped Dirac Materials)



controls $\mathcal{F} \sim n_K - n_{K'}$

JS, Rudner, PNAS (2016)

Topological materials

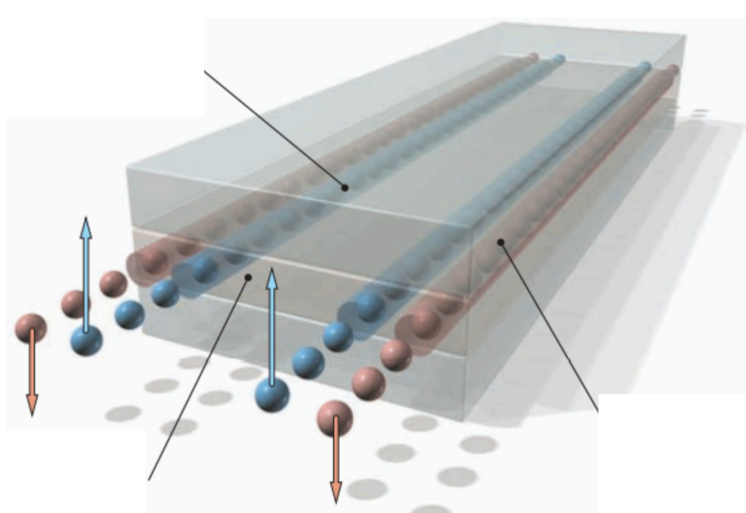
Topological Insulators

Surfaces of 3D TIs:
Bi_2Se_3, Bi_2Te_3 Bi_xSb_{1-x} ,…

Topological Crystalline Insulators:
Sn Te, …

Magnetic Topological Insulators:
Cr-doped BiSbTe

$Hg_xCd_{1-x}Te$ Quantum Wells,
InAs/GaSb QWs



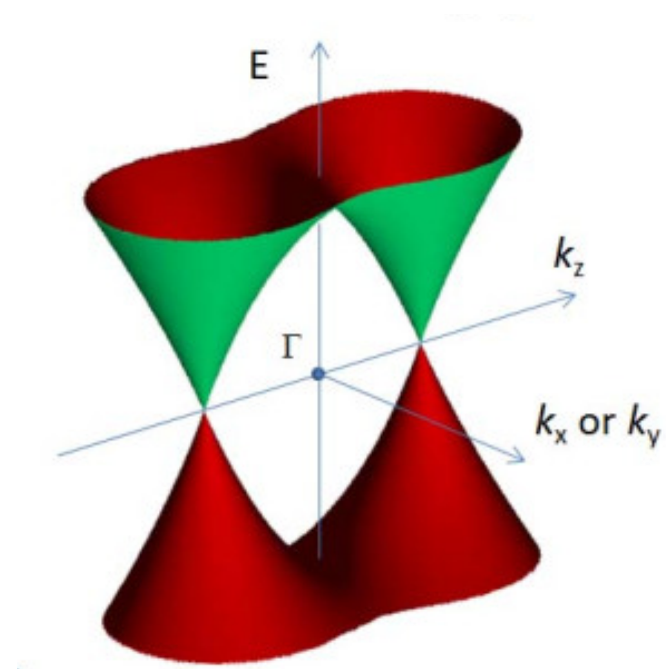
3D Dirac/Weyl

Experimentally Observed:
Cd_3As_2, Na_3Bi, TiBiSe
$TaAs_2$, …

Type II Weyl semimetals
(candidates): WTe2, MoTe2

Proposed in TI stacks;
HgCdTe Stacks

Nodal-line semimetals



2D Dirac Materials

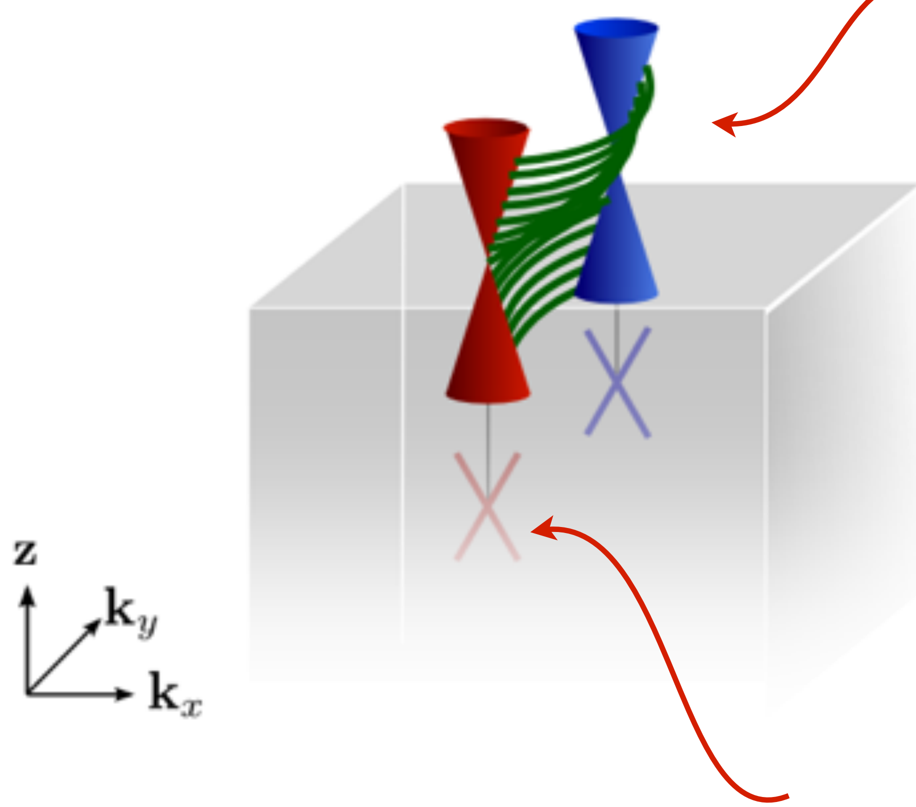
(materials that host Berry curvature)

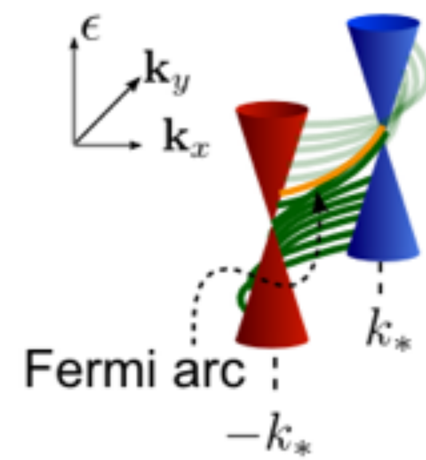
Graphene heterostructures:
G/hBN,
dual-gated Bilayer graphene, …

Transition metal dichalcogenides:
MoS_2, WS_2, WSe_2, $MoSe_2$,
$MoTe_2$, ….

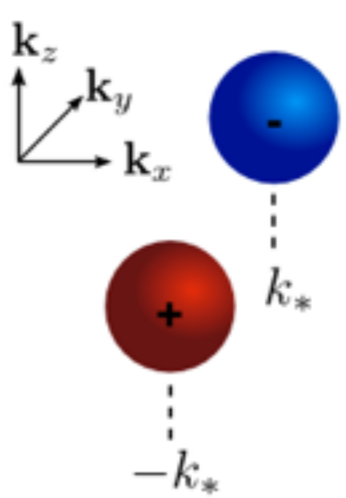
Weyl semimetals and Fermi arc surface states

topological surface states and (**<u>open</u>**) Fermi arcs





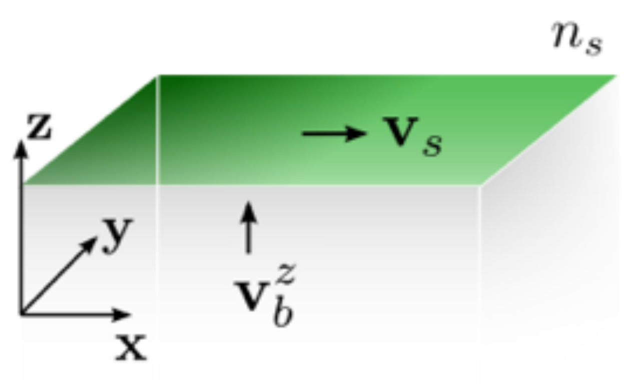
bulk Weyl nodes and bulk (**<u>closed</u>**) Fermi surface

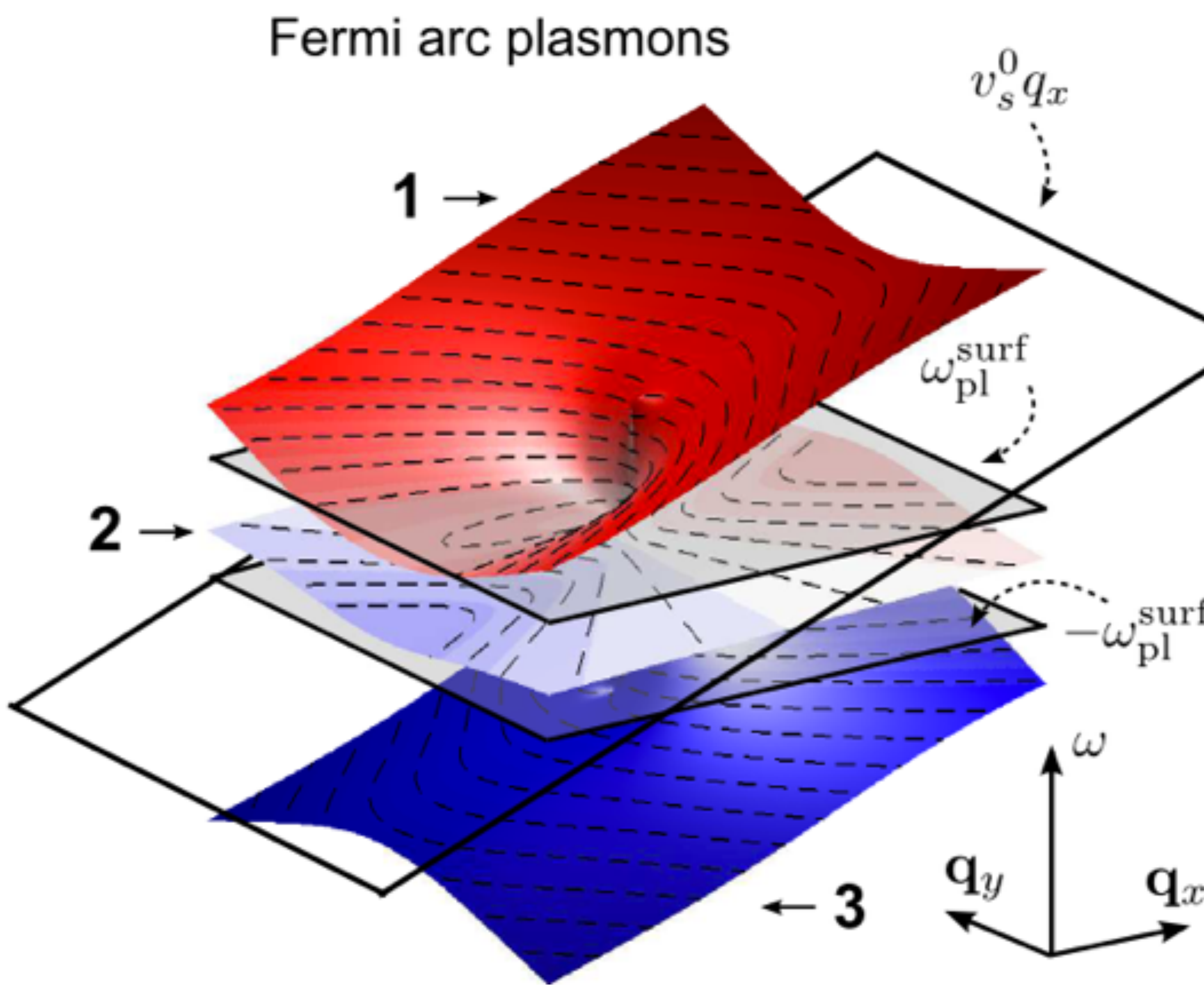


Fermi arc plasmons in Weyl semimetals

with broken TRS

inter bulk/surface[fermi-arc] dynamics

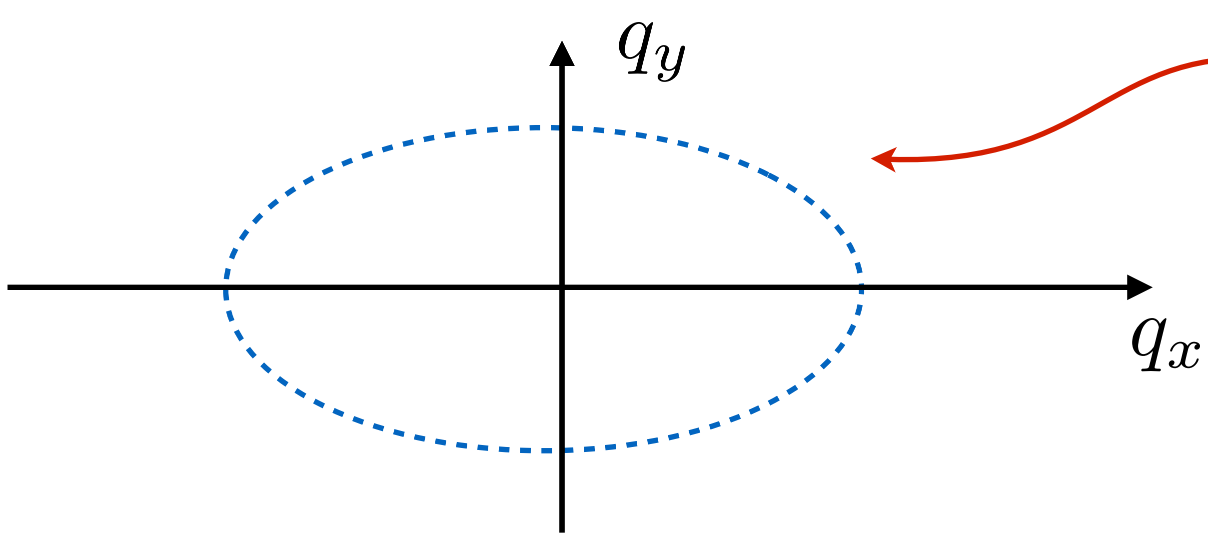




JS, Rudner, arxiv (2017)

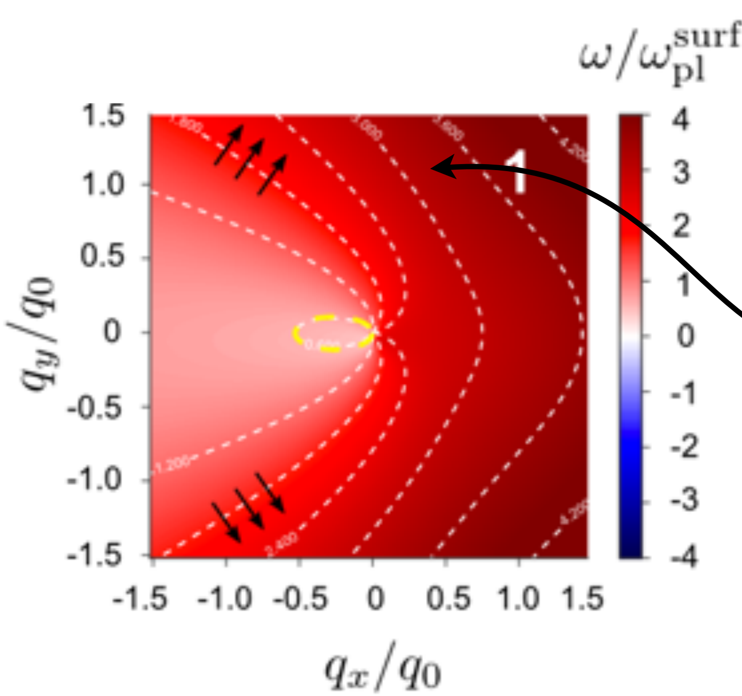
Hyperbolic plasmons

conventionally, plasmons have ***elliptical*** dispersions (closed) = **finite** wave vector magnitude



"conventional" plasmonic constant energy contour

Hyperbolic dispersion does not close on itself (open) = sustain **large** wavevectors for fixed energy

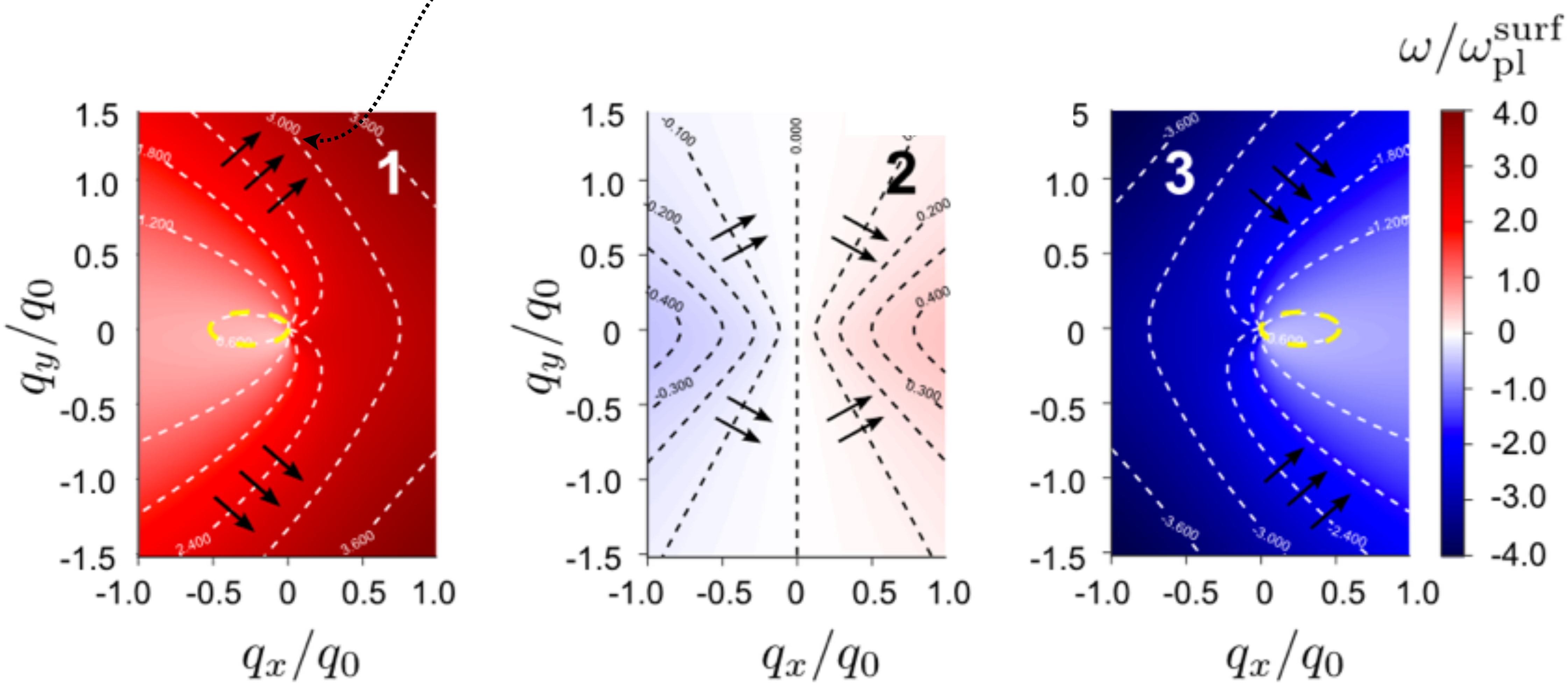


"hyperbolic" plasmonic constant energy contour

JS, Rudner, arxiv (2017)

Fermi arc plasmons in Weyl semimetals

collimated plasmonic beams; FAPs intrinsically *hyperbolic*



JS, Rudner, arxiv (2017)

Fermi arc plasmons

characteristic of bulk "topological" Weyl carrier dynamics

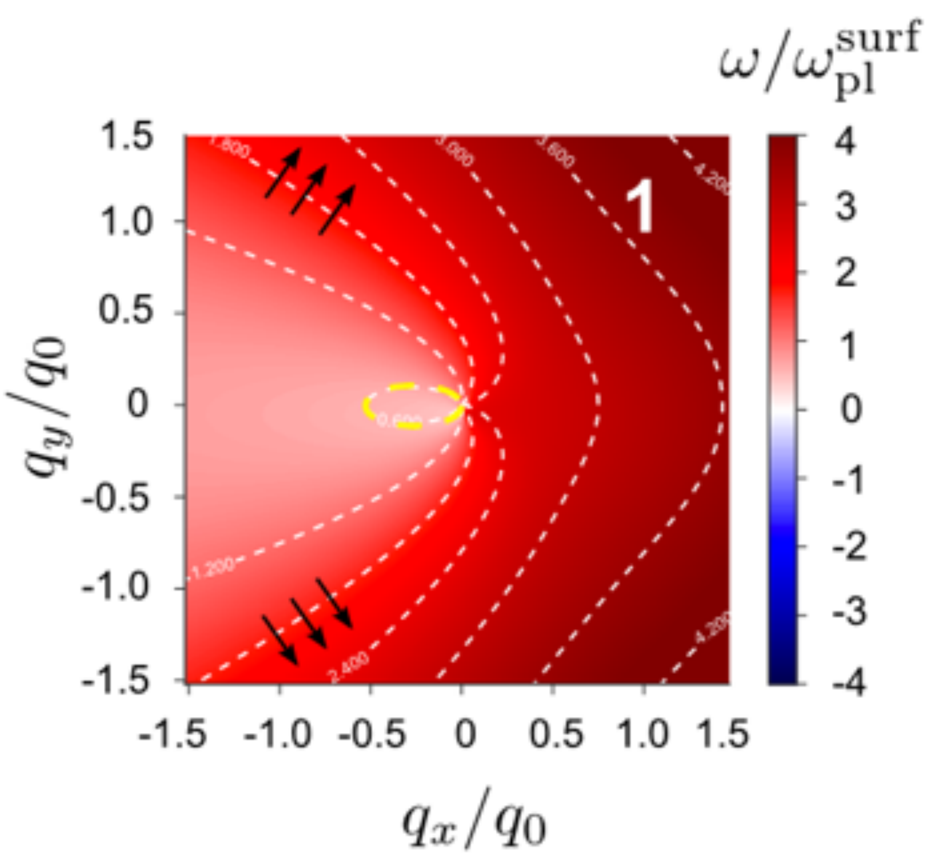
collimated beam pitch controlled by frequency:

$$\frac{\sin^2\theta_\infty}{\cos\theta_\infty} = -\frac{\tilde{\omega}}{\tilde{\mathcal{D}}}\left(1 - \frac{1}{\tilde{\omega}^2}\right),$$

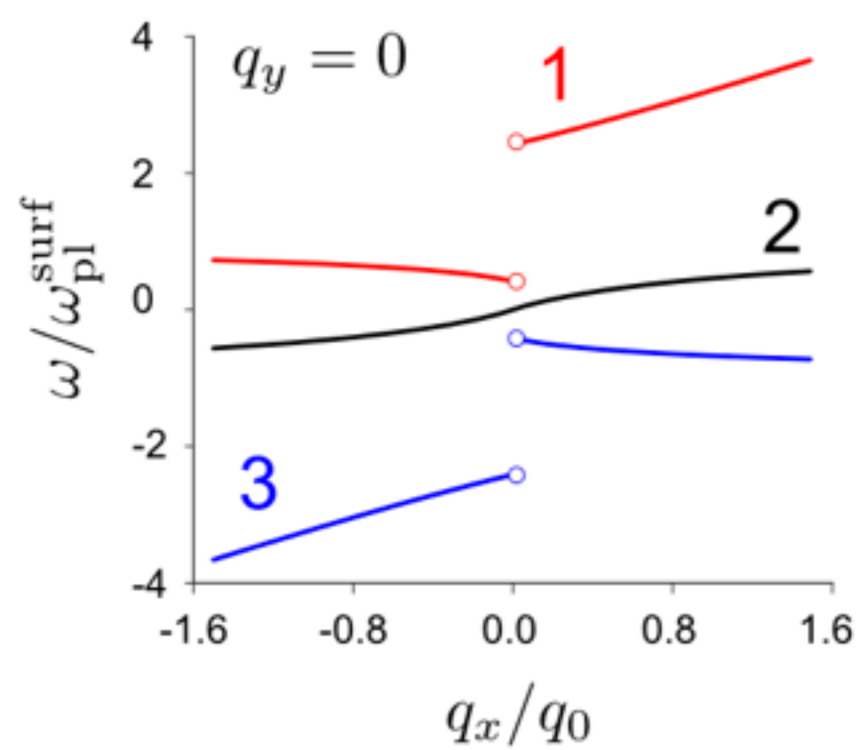
plasmon dispersion can be dominated by σ_H

$$\omega_{\pm}^{(1)} = \sqrt{\left[2\pi\sigma_H/(\kappa+1)\right]^2 + [\omega_{\rm pl}^{\rm surf}]^2} \pm \frac{2\pi\sigma_H}{(\kappa+1)},$$

large q limit: hyperbolic plasmons



small q limit: non-reciprocal discontinuity



JS, Rudner, arxiv (2017)

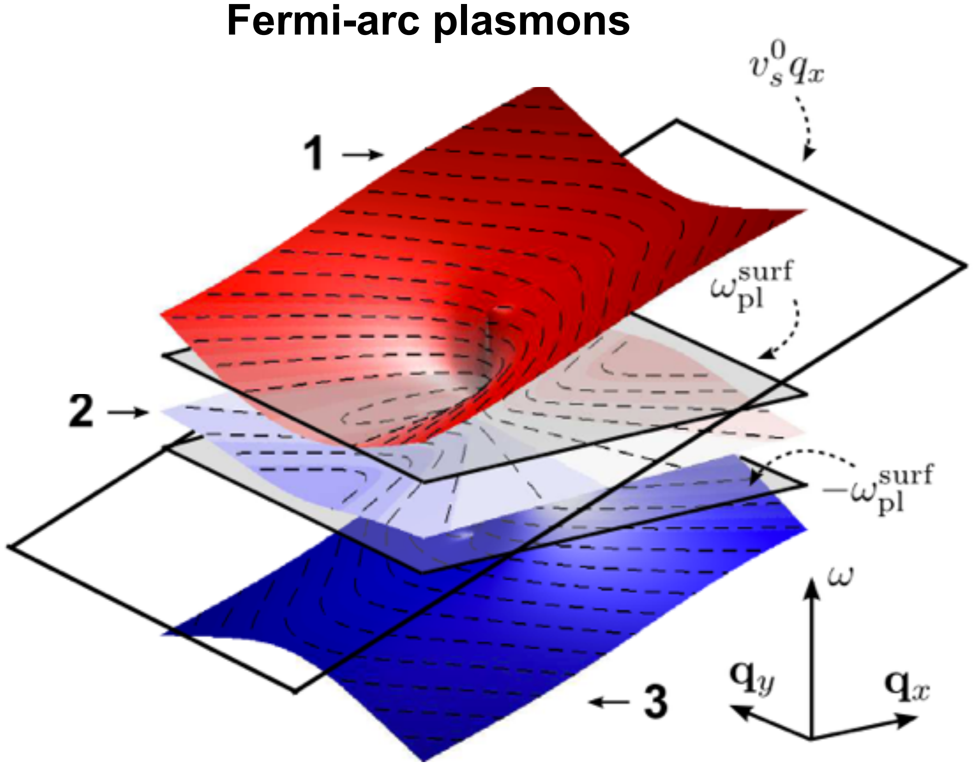
new opto-electronics in topological materials

quantum coloring: new tools, lots to be done

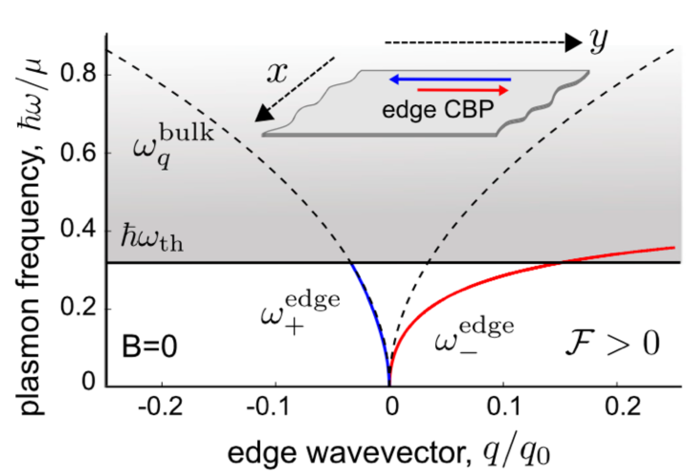
unusual properties of the crystal wave function (e.g., encoded in Berry curvature, chiral edge states) yield unconventional single-particle as well as interacting behavior

new opto-electronics couplings, and tools to be found in “topological” materials

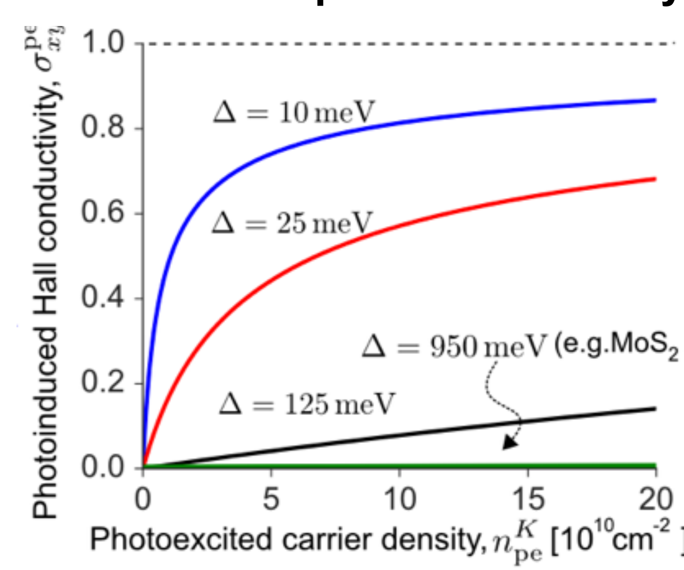
Fermi-arc plasmons



chiral edge Berry plasmons



anomalous photoconductivity



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NATIONAL RESEARCH FOUNDATION