Dynamic Quantum Matter

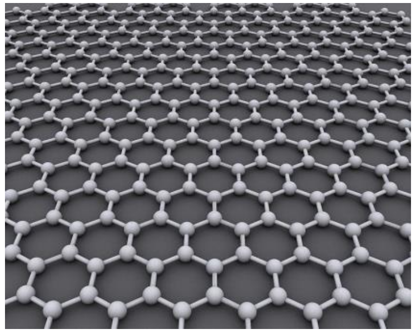
Dynamic 2: Dynamics in Dirac materials

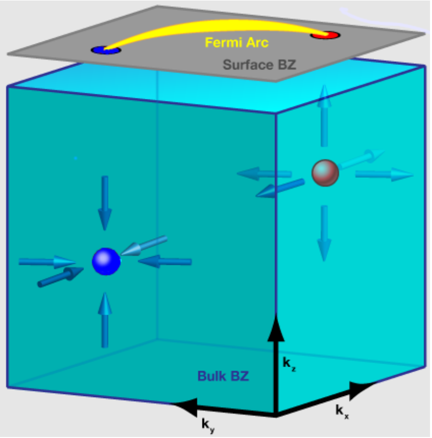
- **Dirac Materials**

- **Dynamics in Dirac Materials 1: Dynamic Exciton instability in DM**

- Dynamics in Dirac materials 2: Axial Magnetoelectric Effect in DM

- Conclusion





bosonic analogues...

- Universal properties
  - Scaling of DoS...
- Nontrivial topology
  - Surface states, anomaly, transport...
- Emergent gauge fields and geometry

Wehling, Black-Schaffer, and Balatsky, Adv. Phys. **63**, 1 (2014)

Dirac equation

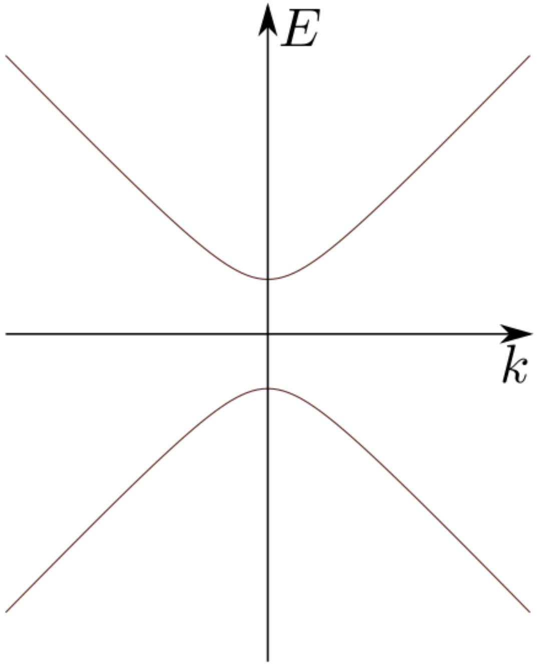
- Dirac equation (1928)

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

$$\gamma^\mu = \left[\begin{array}{cc} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{array} \right], \ \psi = \left[\begin{array}{c} \psi_L \\ \psi_R \end{array} \right]$$

$$\sigma^\mu = (I, \boldsymbol{\sigma}), \ \bar{\sigma}^\mu = (I, -\boldsymbol{\sigma})$$

$$H_{\text{Dirac}} = \left[\begin{array}{cc} \boldsymbol{\sigma} \cdot \mathbf{k} & m \\ m & -\boldsymbol{\sigma} \cdot \mathbf{k} \end{array} \right]$$



What is a Dirac material?

Dirac materials (DMs): low-energy fermionic excitations are described by a Dirac Hamiltonian

Dirac equation: $i\hbar\frac{\partial}{\partial t}\psi = (\underline{c\boldsymbol{\alpha}\cdot\mathbf{p}} + \beta mc^2)\psi$

$\alpha = \begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix} \quad \beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$\Longleftrightarrow$

Dirac Hamiltonian: $H_D = v_F\boldsymbol{\sigma}\cdot\boldsymbol{p}$

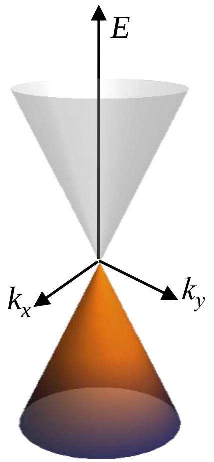
in condensed matter $v_F \approx c/300$

Examples:

→ *d*-wave superconductors, superfluid He-3
→ 2D DM: graphene, TI, TCI
→ 3D DM: Dirac/Weyl semimetals
→ artificial DM
→ bosonic DM

Universal properties:

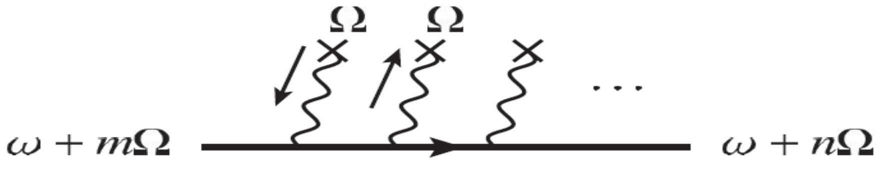
density of states $N(E)\sim E^{d-1}$	Landau levels $E_n \sim \sqrt{n}$
specific heat $C(T) \sim T^d$	impurity resonances $E_{\text{res}} \simeq -1/U$
minimum cond. $\sigma(\omega\to 0) \sim \frac{e^2}{\hbar}4\pi$	e-e interactions $\alpha \equiv \frac{E_C}{E_{kin}} = e^2/\varepsilon\hbar v_F$

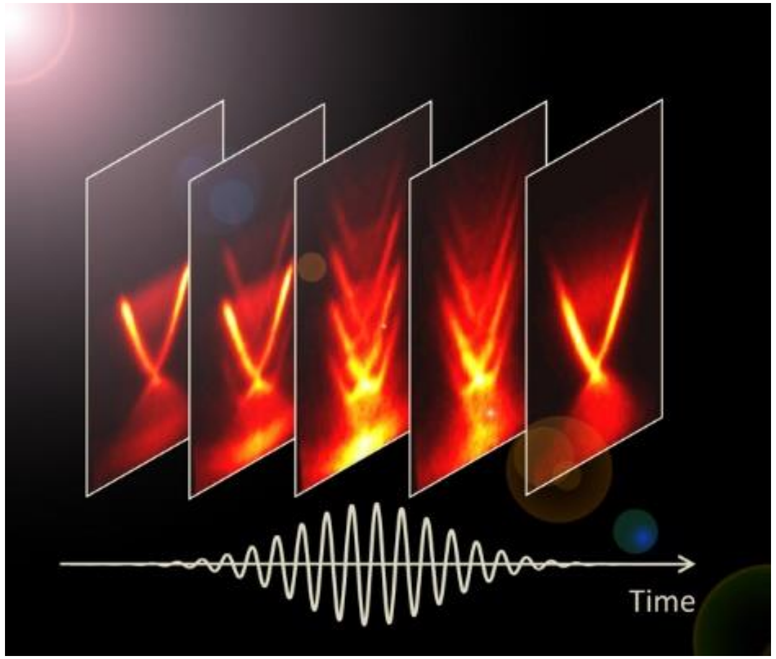


T.O. Wehling, A.M. Black-Schaffer, A.V. Balatsky, Advances in Physics (2014)

Dynamics examples:

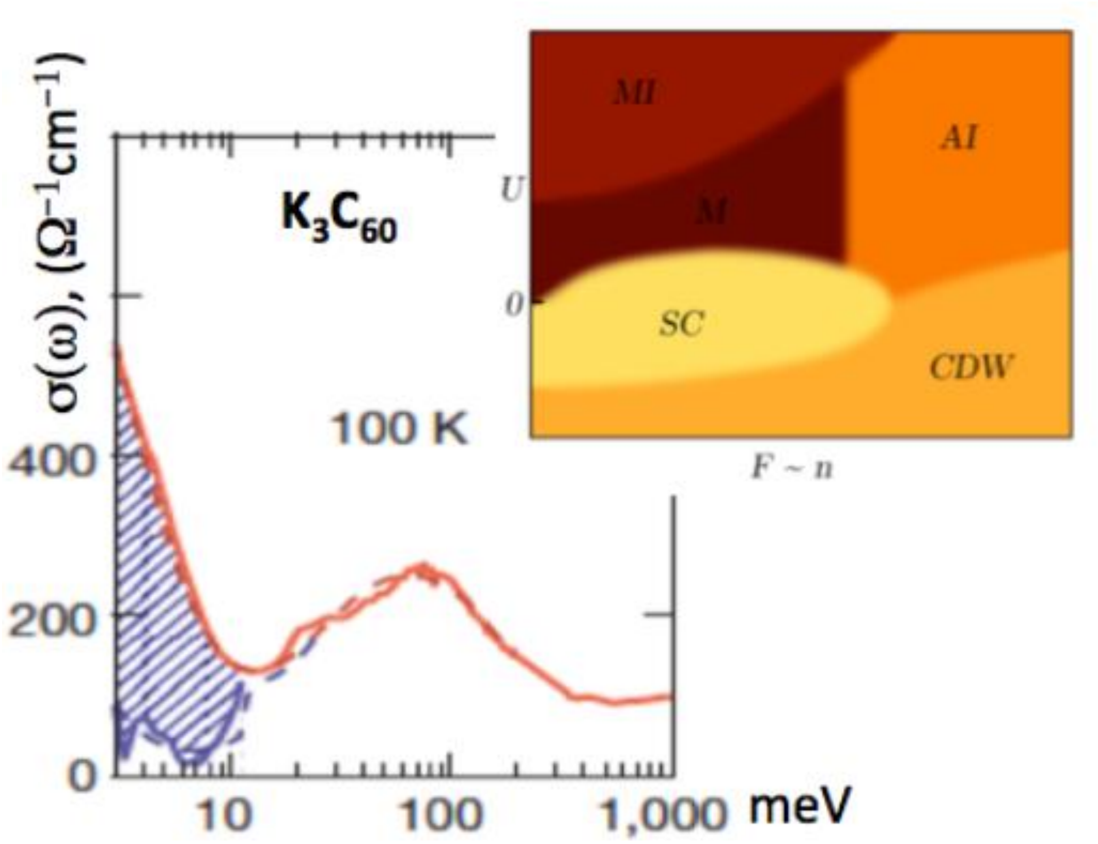
Floquet approach





Gedik grp Nature Physics **volume 12**, pages 306–310 (2016)

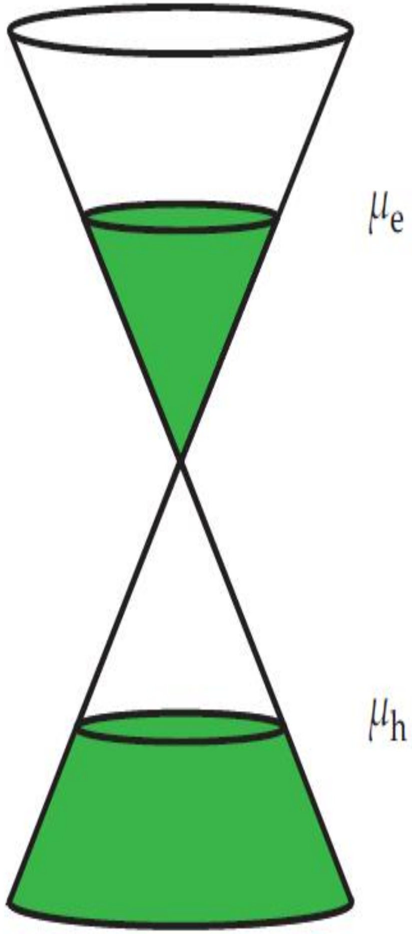
Dynamic induction of superconductivity



Mitrano,M.*etal. Nature* **530,**461(2016).
Kennes,D., et al, Nature Physics **14,**
1 (2017).

Driven Dirac Matter –

a platform for driven excitonic condensate



Collaboration with
A Black-Schaffer, Bardarson,
Bergholz, Bonetti, Tjernberg, Weissenrieder
on dynamics of DM and STO

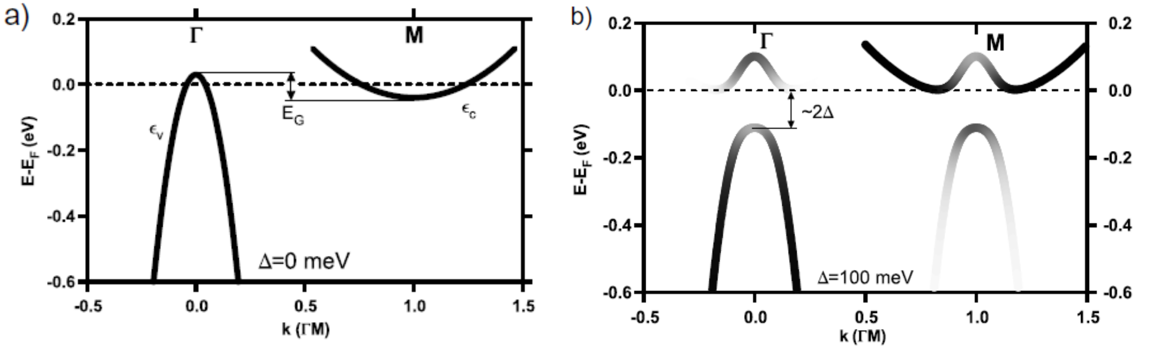
Transient excitonic instability in optically pumped DM

- Exciton: a bound state of electron and hole
- Excitonic instability: exiton binding energy $|E_B|> E_G$ → ground state of an insulator becomes unstable → collective state

Previous search for excitonic condensate:

- Spatially direct excitons (in semicond. or semimetal)
- Spatatially separated e-h systems:
  - semiconductor heterostructures [Lozovik, Yudson Zh. Eksp. Teor. Fiz. (1976)]
  - bilayer graphene [Eisenstein, MacDonald, Nat. Phys. (2004)]

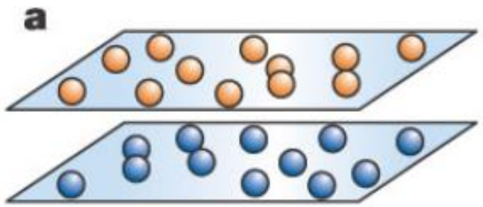
Keldysh and Kopaev Sov. Phys.-Solid State (1965)
Jerome, Rice, Kohn PR (1967); Halperin, Rice RMP(1968)



normal state

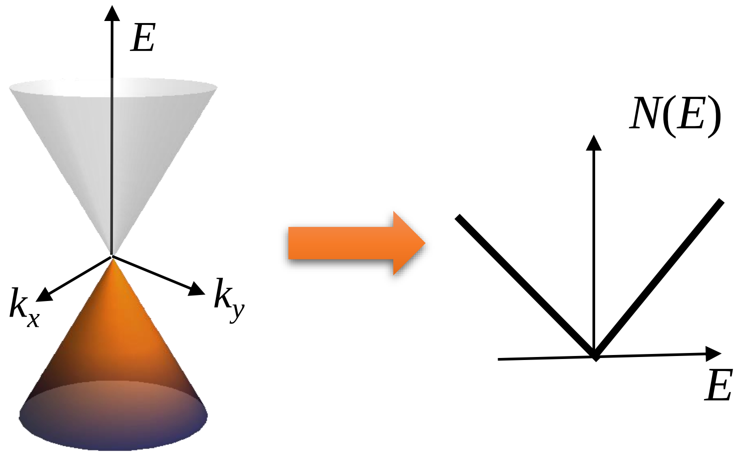
excitonic insulator

Monney et al., NJP (2010) 1T-$TiSe_2$
Cercellier et al., PRL (2015)

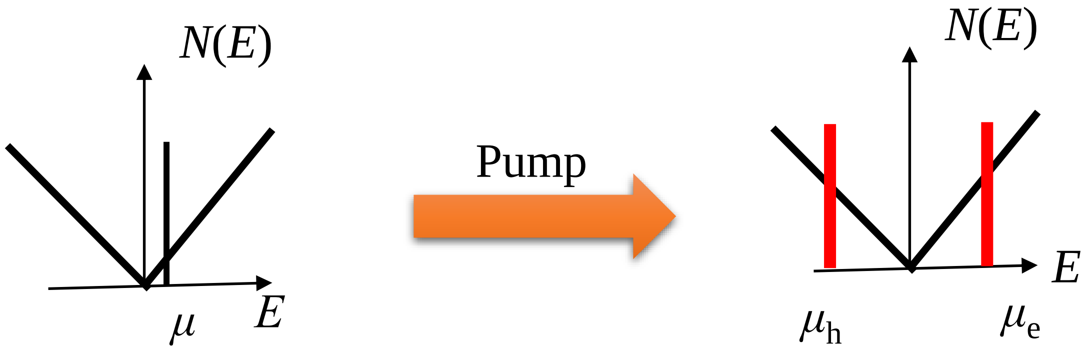


e-h bilayers

Many-body instability in driven DM



- Linear dispersion in DM → vanishing DOS at the node
- Critical coupling for many-body instabilities
- Dirac nodes are stable against interactions
- **Basic idea: move the states away from the node e.g. by pumping**




C. Triola

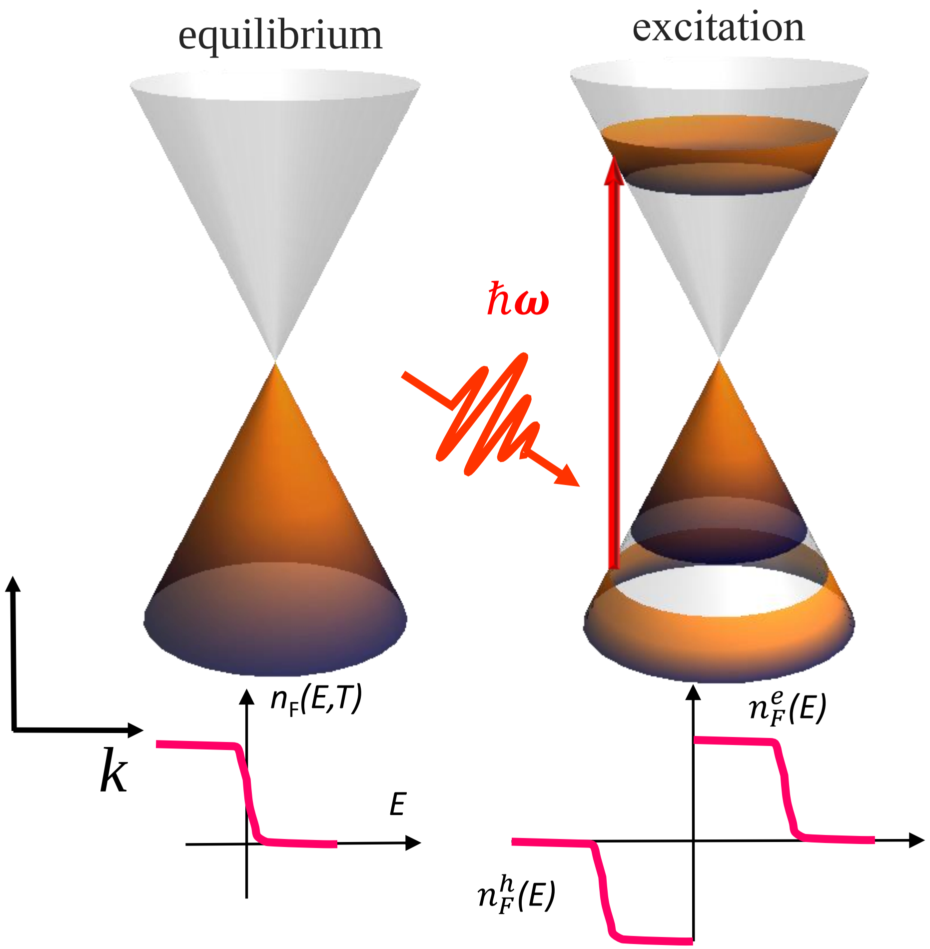

A. Pertsova

C. Triola, A. Pertsova, A.V. Balatsky
Physical Review B 95 (20), 205410 (2017)
K Sumida, et al
Scientific reports 7 (1),14080 (2017)
A Pertsova, AV Balatsky
Physical Review B 97 (7), 075109 (2018)

Tunability of the critical coupling in a driven 2D Dirac material

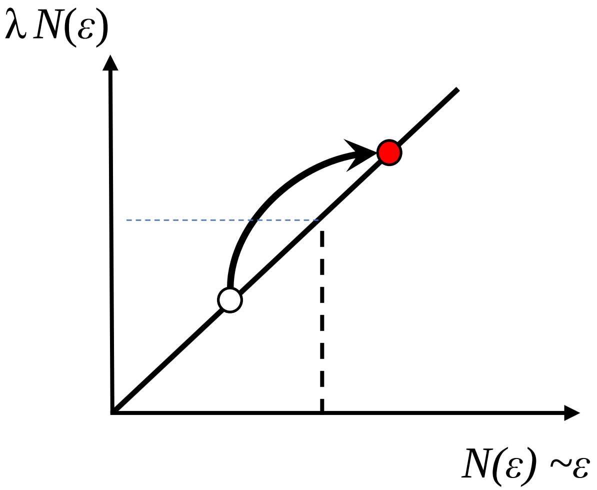
Dimensionless coupling in DM:

$\lambda \equiv \frac{E_C}{E_{kin}} = e^2/\varepsilon\hbar v_F \rightarrow$ critical $\lambda_c; \lambda_c \approx 1$ in graphene



$\lambda\ N(\mu) < crit.$

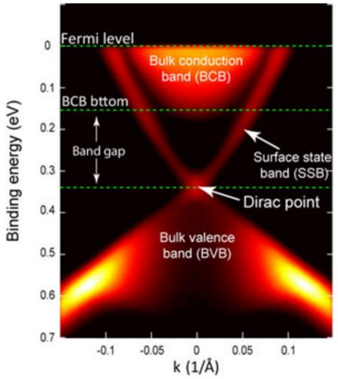
$\lambda\ (N(\mu^e)+N(\mu^h))\ \ > crit.$

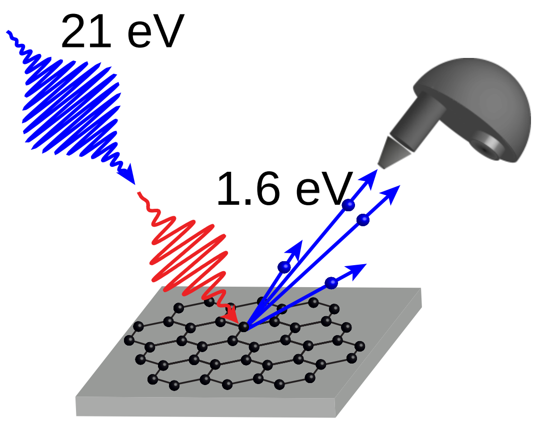


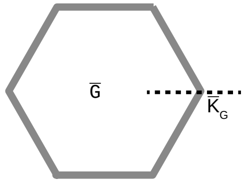
Non-equilibrium drives a many-body instability

Experimental feasibility

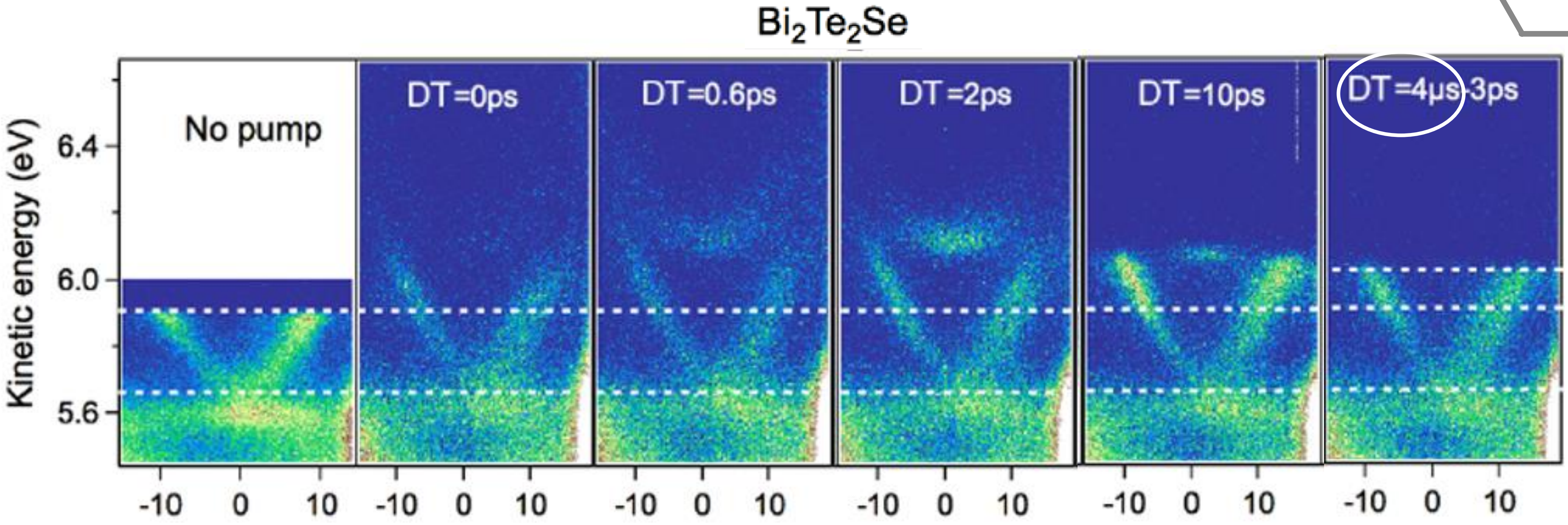
In pumped TIs bulk states are involved.





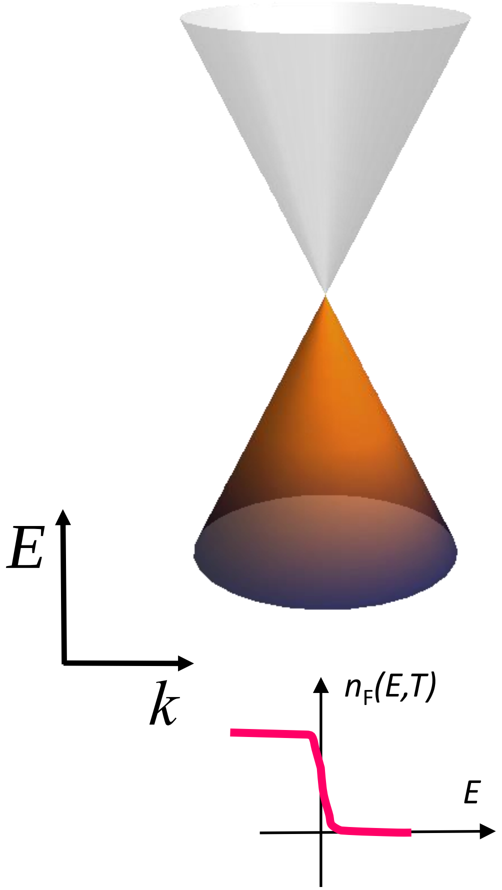


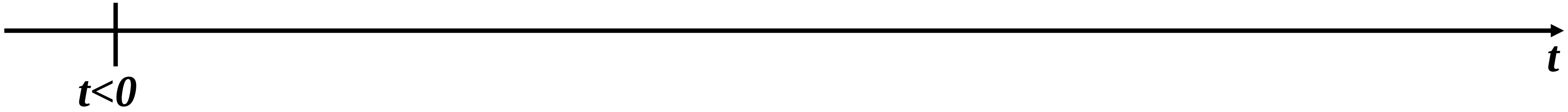
- Gigantic lifetime $\tau \geq \mu s$?

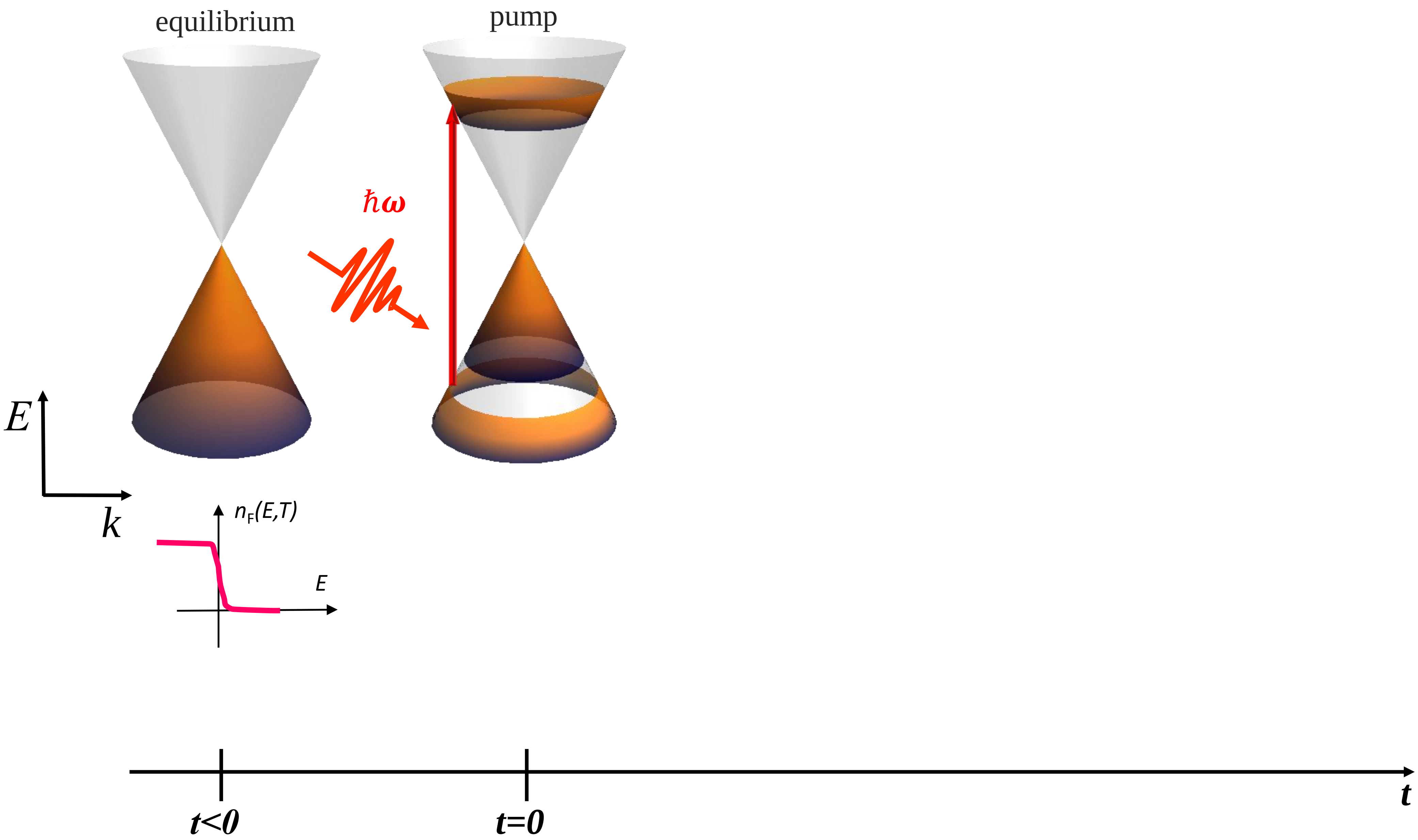


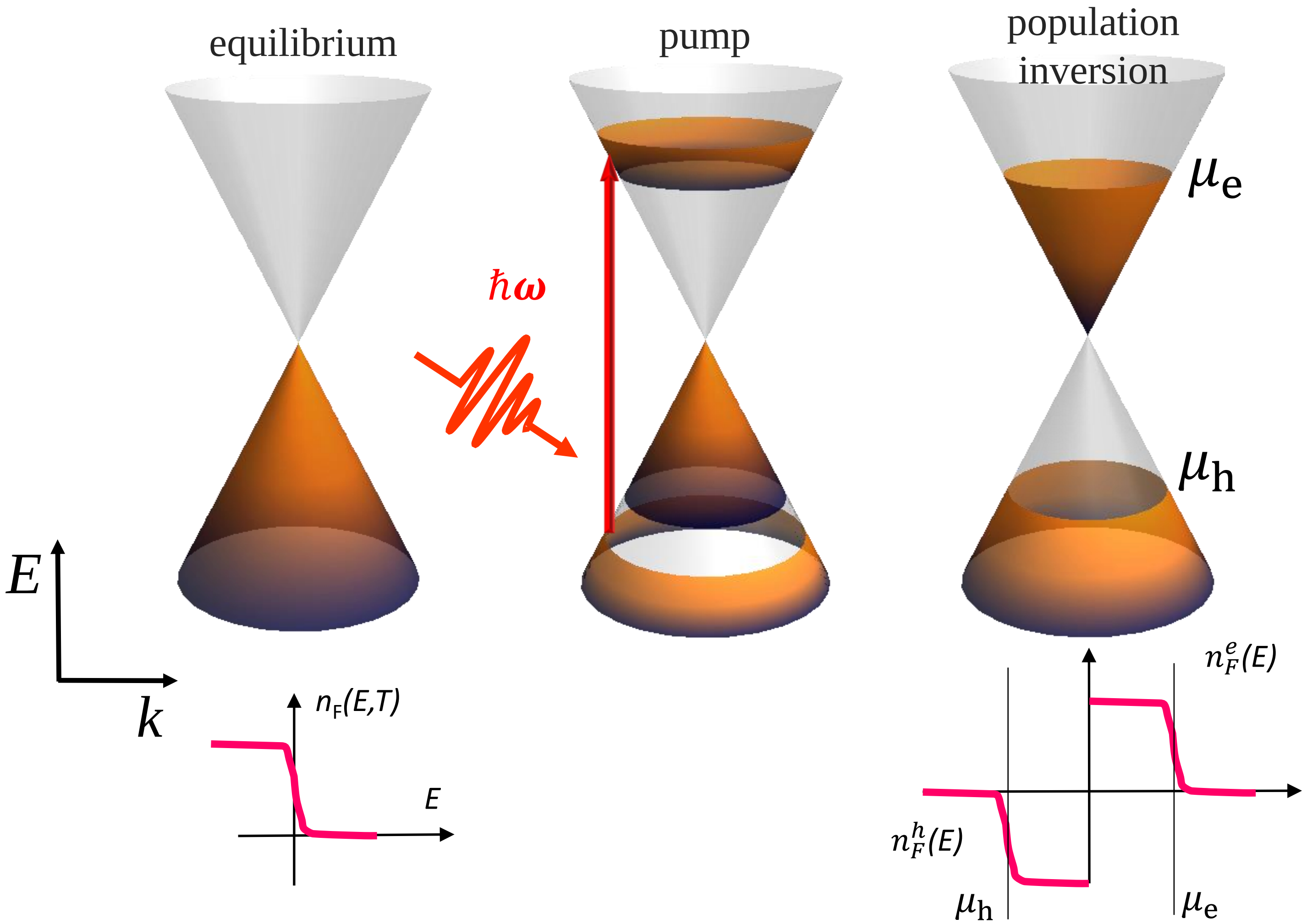
Neupane et al., PRL 115, 116801 (2015);

equilibrium

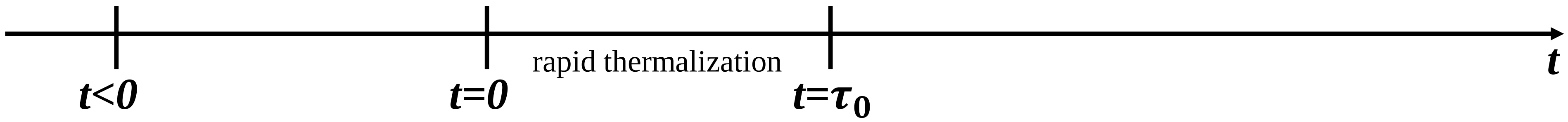


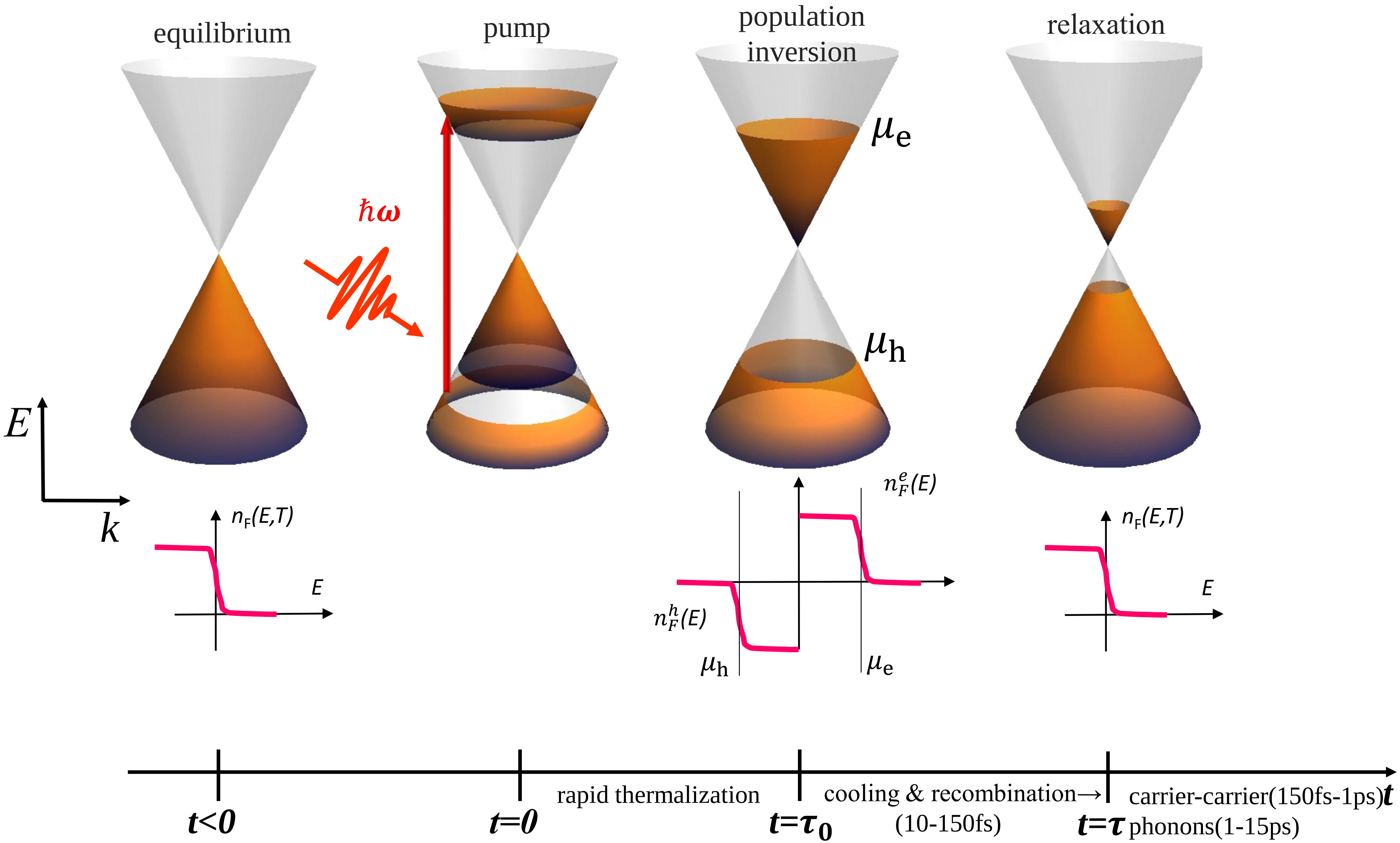


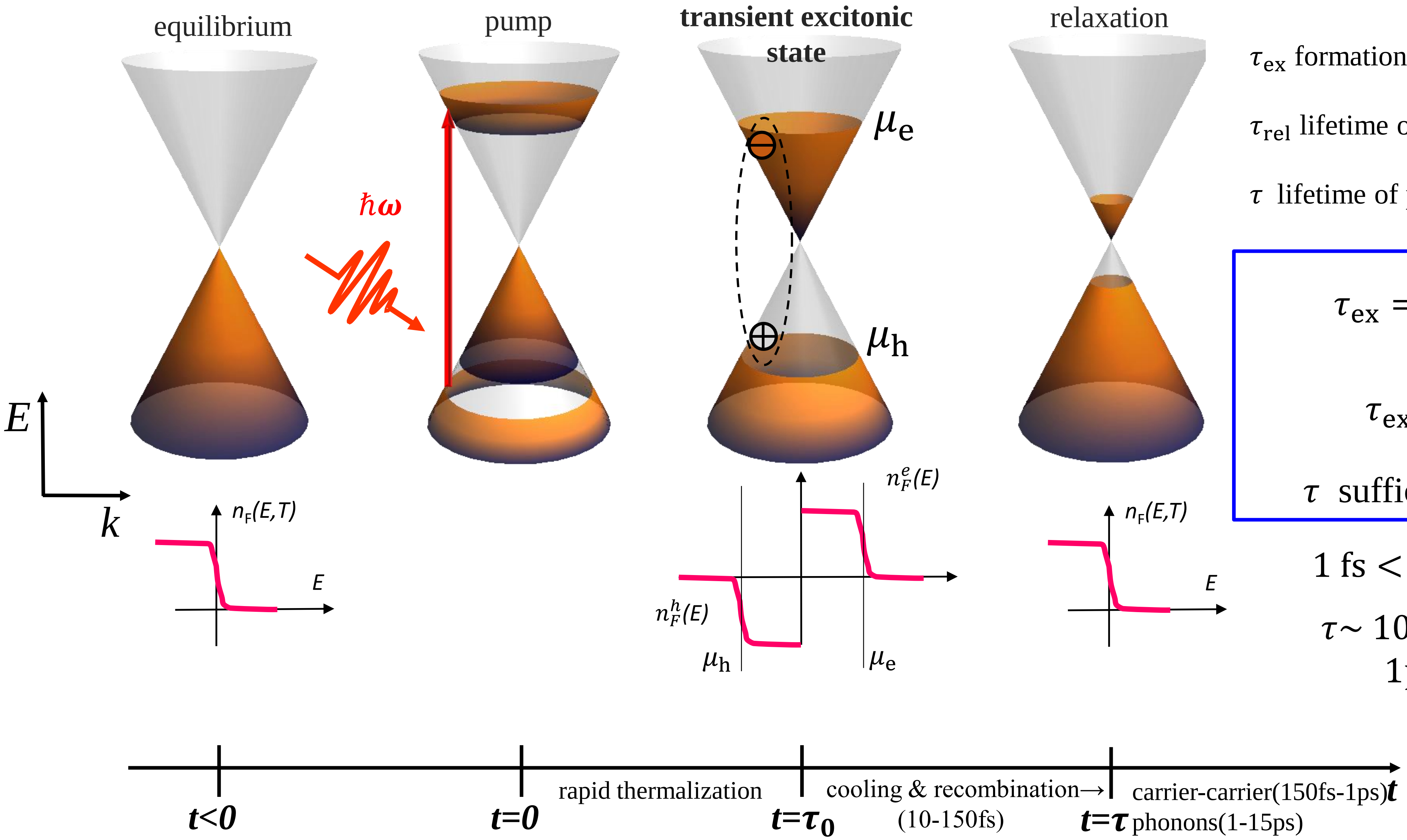

equilibrium
pump
$\hbar\omega$
E
k
$n_F(E,T)$
E
$t<0$
$t=0$
t



Graphene: Gilbertson et al., J.Phys.Chem. Lett. 3, 64 (2011); Griez et al, Nat. Mat. 12, 1119 (2013)
3D TI: Zhu et al., Sci.Rep. 5:13213 (2015); Neupane et al., PRL 115, 116801 (2015);




equilibrium
pump
population inversion
relaxation
$\hbar\omega$
μ_e
μ_h
E
k
$n_F(E,T)$
E
$n_F^e(E)$
$n_F^h(E)$
μ_h
μ_e
$n_F(E,T)$
E
$t<0$
$t=0$
rapid thermalization
$t=\tau_0$
cooling & recombination→
(10-150fs)
$t=\tau$
carrier-carrier(150fs-1ps)
phonons(1-15ps)
t



equilibrium

pump

transient excitonic state

relaxation

t<0

t=0

rapid thermalization

t=τ₀

cooling & recombination→ (10-150fs)

t=τ

carrier-carrier(150fs-1ps)***t***

phonons(1-15ps)

τ_{ex} formation time

τ_{rel} lifetime of the excitonic state

τ lifetime of population inversion

$$\tau_{\text{ex}} = \frac{\hbar}{\Delta_{\text{ex}}} < \tau$$

$$\tau_{\text{ex}} < \tau_{\text{rel}}$$

τ sufficiently long

$$1\text{ fs} < \tau_{\text{ex}} < 30\text{ fs}$$

$\tau \sim$ 100fs graphene

1ps – 1μs(?) TI

Pumped Dirac Materials: Theory

- Excitonic instability can be realized in pumped 2D DM: **excitonic gap ~ 10meV in valley-pumped graphene** [Triola *et al.*, PRB 95, 205410 (2017)]

- **Here we study excitonic instability in pumped 3D DMs (Dirac and Weyl semimetals treated on equal footing)**

Dirac

$$H_{\mathrm{Dirac}} = \sum_{\mathbf{k}} \Psi^\dagger_{\mathbf{k}} \begin{pmatrix} H_+(\mathbf{k}) & 0 \\ 0 & H_-(\mathbf{k}) \end{pmatrix} \Psi_{\mathbf{k}}$$

$$H_\xi(\mathbf{k}) = \xi \hbar v \sigma \cdot \mathbf{k}, \;\; \xi = \pm$$

g=2

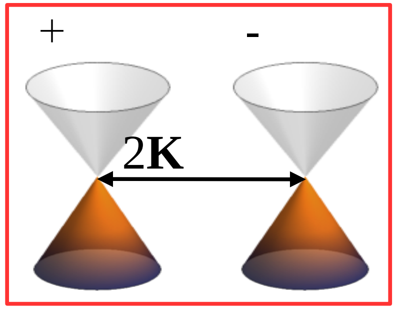
Weyl

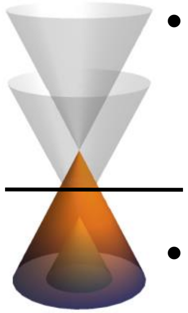
$$H^{\xi}_{\mathrm{Weyl}} = \sum_{\mathbf{k}} \Phi^\dagger_{\mathbf{k}} H_\xi(\mathbf{k}) \Phi_{\mathbf{k}},$$

$$H_\xi(\mathbf{k}) = \boxed{\xi \hbar v_{\mathrm{F}} \sigma \cdot (\mathbf{k} - \xi \mathbf{K})} + I K_0$$

TRS breaking

IS breaking





- EX instability without pumping

- Similar to graphene in $B_{\|}$ (Aleiner PRB 2007)

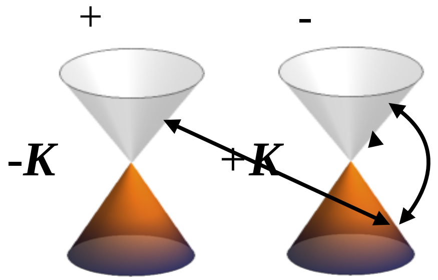
Excitonic phases in pumped 3D DM

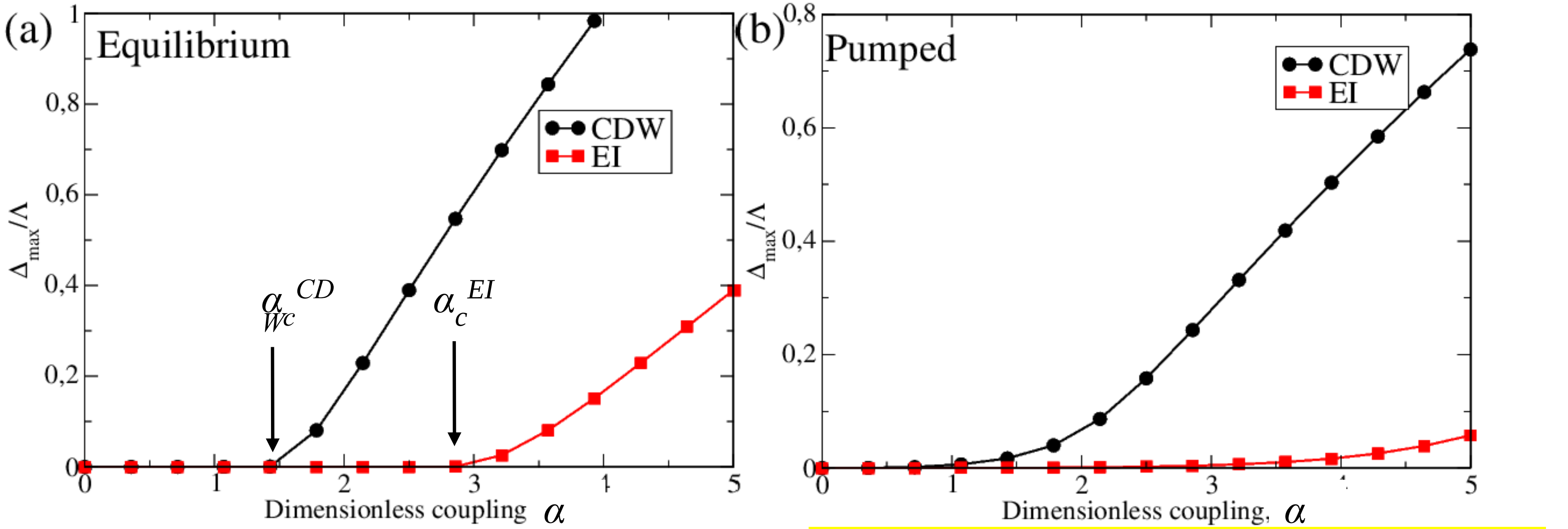
For WSM and DSM (with g>2)

***intra*-nodal and *inter*-nodal interactions**

$q=0$ Excitonic insulator (EI)

Charge density wave (CDW) $q=2K$





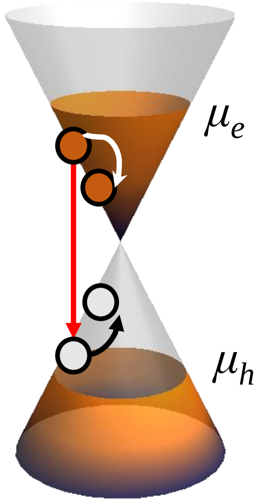
Equilibrium: $\alpha_c^{CDW} < \alpha_c^{EI}$

unscreened Coulomb [Wei *et al.*, PRB 89, 235109 (2014)]

Pumped:
- $\alpha_c^{CDW,EI} \rightarrow 0$
- $\Delta^{CDW} > \Delta^{EI}$ for all α (CDW dominates)

A. Pertsova and A.V. Balatsky, PRB 97, 075109 (2018)

Dynamics of the order parameter



Semiconductor Bloch equations (SBE) for pumped 2D DM

occupations

$$n_k^e = \left\langle a_k^\dagger a_k \right\rangle \qquad n_{-k}^h = \left\langle b_{-k}^\dagger b_{-k} \right\rangle$$

$$f_k = \left\langle a_k^\dagger b_{-k}^\dagger \right\rangle \qquad \Delta_k^* = -\sum_{k'} V_{k-k'} \left\langle a_{k'}^\dagger b_{-k'}^\dagger \right\rangle$$

interband polarization/coherence

$$\boxed{\frac{d\langle O\rangle}{dt} = \mathrm{i}\langle [H, O]\rangle + scat.}$$

$$\begin{cases} \dfrac{dn_k^e}{dt} = i\Delta_k^* f_k^* - i\Delta_k f_k + \dfrac{dn_k^e}{dt}\Big|_{scat}, \\ \dfrac{dn_{-k}^h}{dt} = i\Delta_k^* f_k^* - i\Delta_k f_k + \dfrac{dn_k^h}{dt}\Big|_{scat}, \\ \dfrac{df_k}{dt} = i(\varepsilon_k^e + \varepsilon_k^h) f_k + i\Delta_k^*(1 - n_k^e - n_{-k}^h) + \dfrac{df_k}{dt}\Big|_{scat}. \end{cases}$$

→ dynamics of f_k(t), order parameter Δ(t)

scattering terms:

$$\boxed{\frac{dn_k^e}{dt}\Big|_{scat} = -\frac{n_k^e(t) - n_{\mathrm{F}}(\mu^e(t))}{T_1'} - \frac{n_k^e(t)}{T_1}}$$

intraband relaxation

interband relaxation (recombination)

$$\boxed{\frac{df_k}{dt}\Big|_{scat} = -\frac{f_k(t)}{T_2}}$$

dephasing

$$1/T_2 = 1/T_1 + 1/T_1'$$

$(T\sim\Gamma^{-1})$

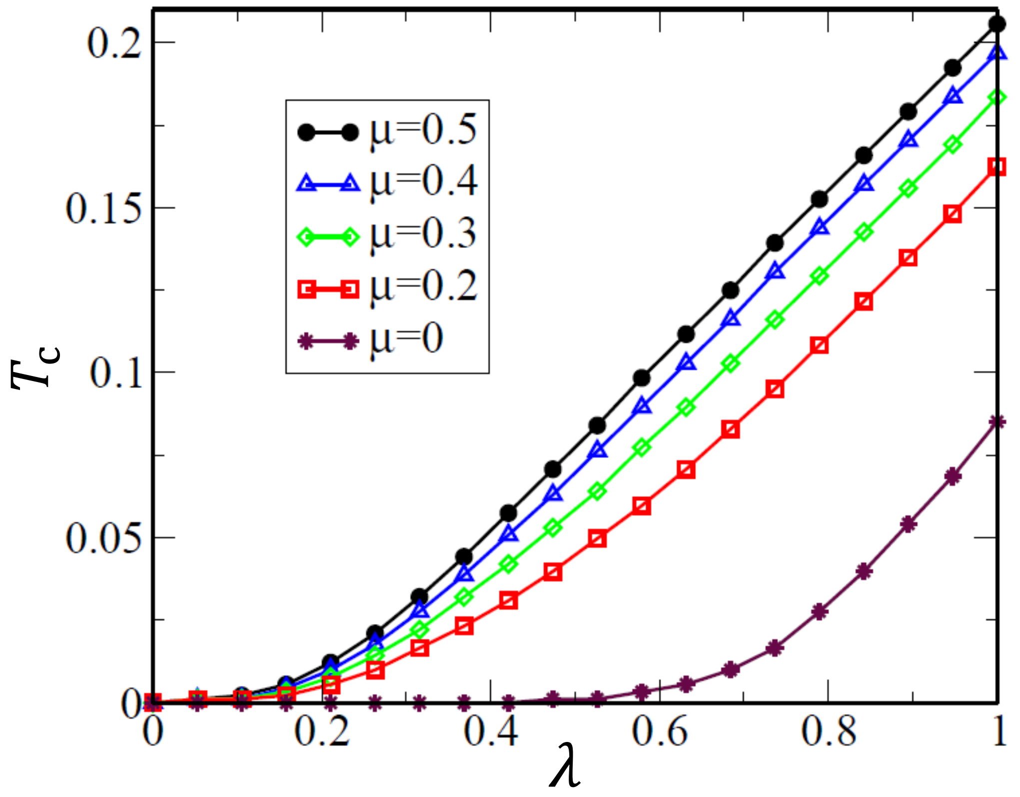
Refs:

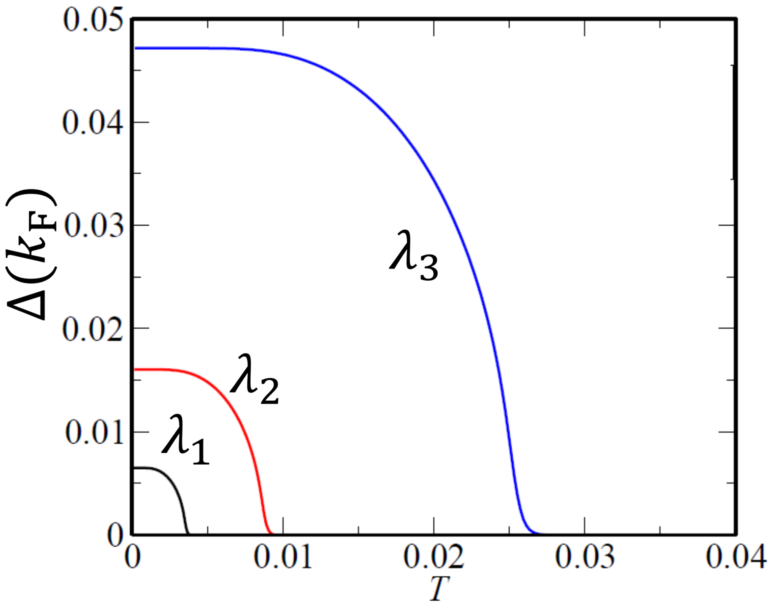
Haug, Kohn, "*Quantum theory of optical and electronic properties of semiconductors*"

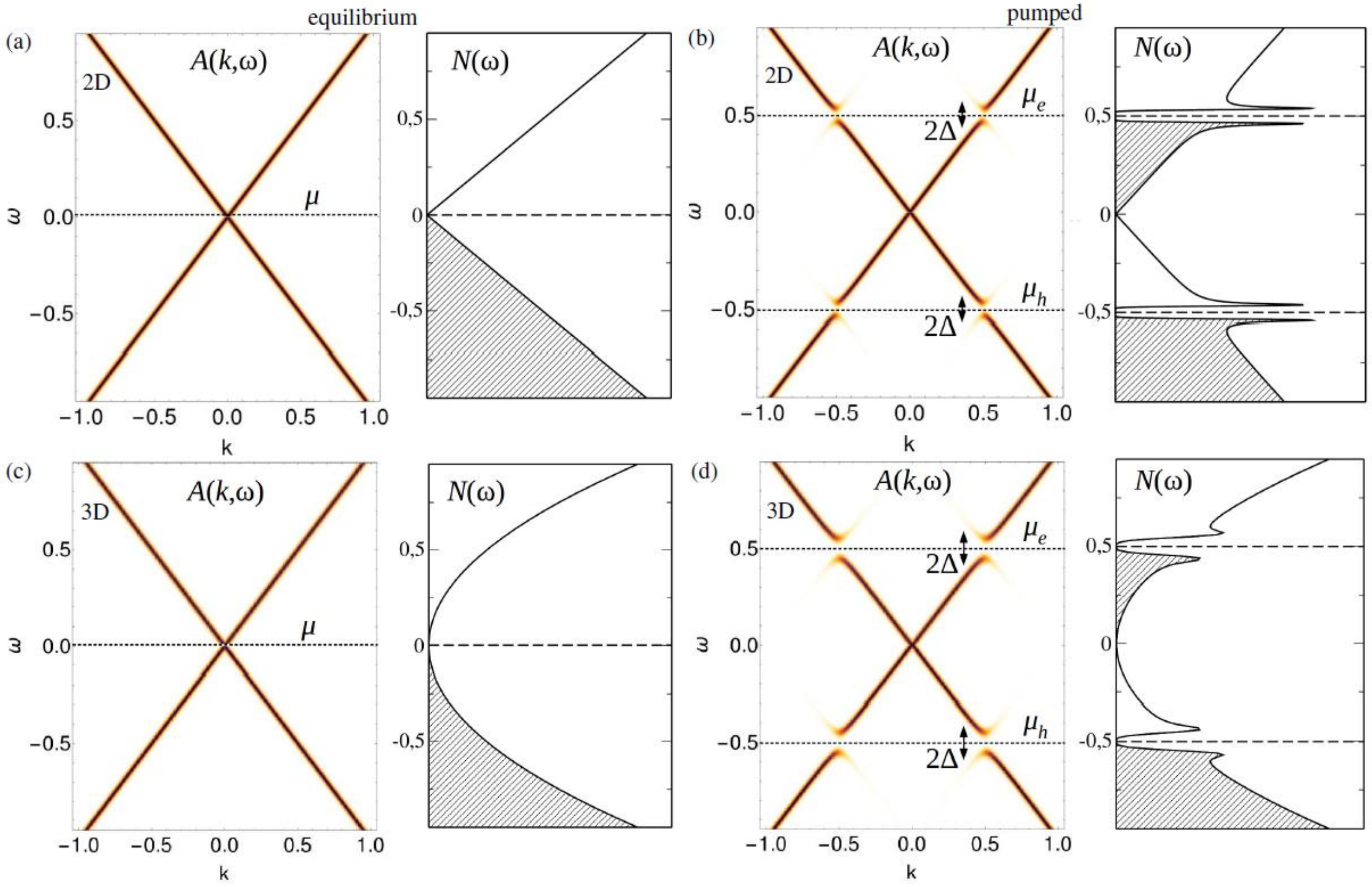
Malic *et al.* PRB 84, 205406 (2011); Goldstein *et al.* PRB 91, 054517 (2015)

$|\mu_e|=|\mu_h|=\mu$

Critical temperature



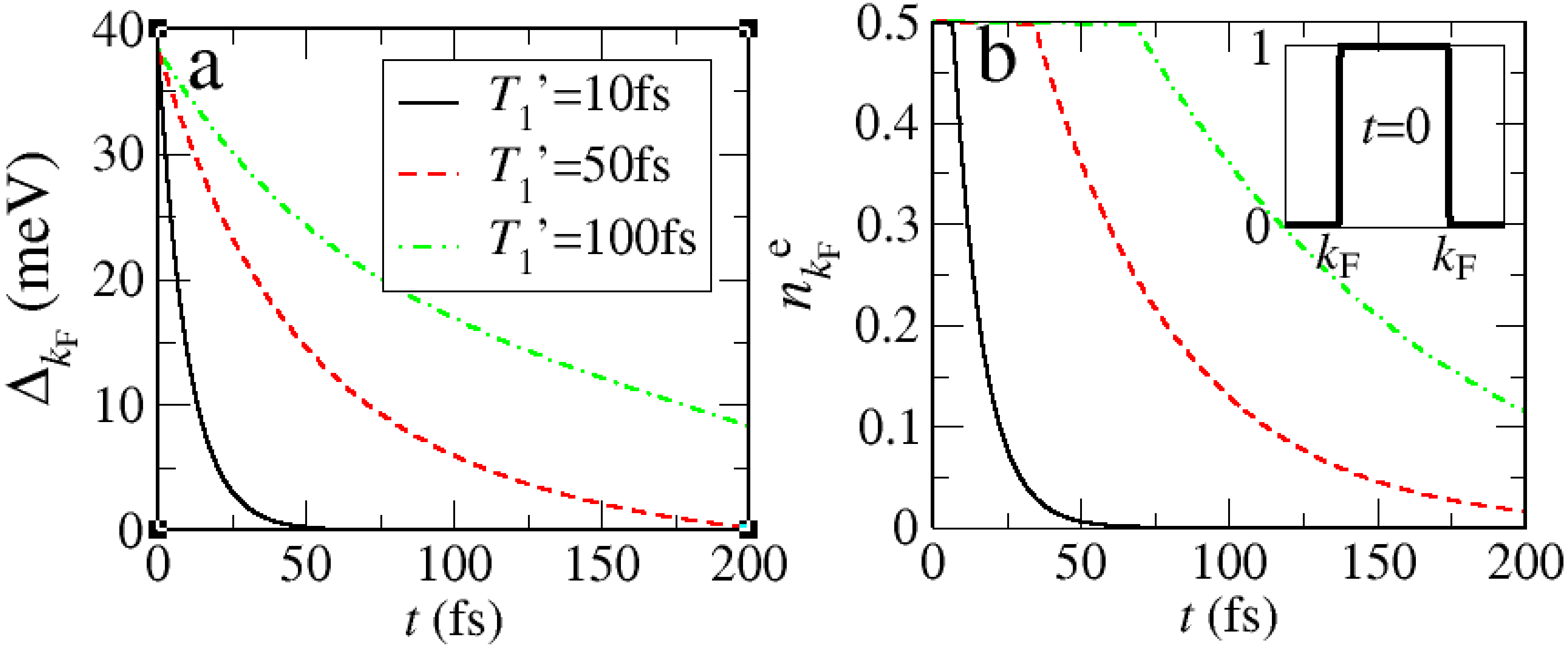



equilibrium
pumped
(a)
2D
$A(k,\omega)$
$N(\omega)$
μ
0.5
0.0
−0.5
0,5
0
-0,5
ω
−1.0 −0.5 0.0 0.5 1.0
k
(b)
2D
$A(k,\omega)$
$N(\omega)$
μ_e
μ_h
2Δ
2Δ
(c)
3D
$A(k,\omega)$
$N(\omega)$
μ
(d)
3D
$A(k,\omega)$
$N(\omega)$
μ_e
μ_h
2Δ
2Δ

Dynamics of the order parameter

Lifetime of the transient excitonic state is controlled by the lifetime of the non-equilibrium e and h distributions.

$T_1 \gg T_1'$ for different T_1'



Time-evolution of the gap Δ_k and electron occupation n_k^e at $k = k_F$.

Parameters for graphene with $\alpha \approx 1$ and $\mu = 200$ meV.

Experimental feasibility 3D DM (Dirac/Weyl)

Size of the gap and T_c is controlled by:

- Coupling α
- Energy scale on which 3D Dirac cones exist (Λ)
- Dirac cone degeneracy

Estimates for a for a hypothetical 3D DM with different g, assuming cut-off energy scale of 1eV and single-valley pumping

System	α	Λ (eV)	T_c (K)	$\Delta_{\max}$ (meV)
Cd_3As_2 DSM	0.1	1	0.1	0.03
TaAs WSM	1	0.2	2	0.3
3D DM $g = 1$	$1-3$	1	$1-20$	$0.3-3$
3D DM $g = 2$	$1-3$	1	$10-60$	$1-10$
3D DM $g = 4$	$1-3$	1	$1-2$	$0.1-0.3$

Large gaps (10meV) and T_c (~100K) could be achieved in new materials.

C. Triola, A. Pertsova, A.V. Balatsky
Physical Review B 95 (20), 205410 (2017)

K Sumida, et al
Scientific reports 7 (1), 14080 (2017)

A Pertsova, AV Balatsky
Physical Review B 97 (7), 075109 (2018)

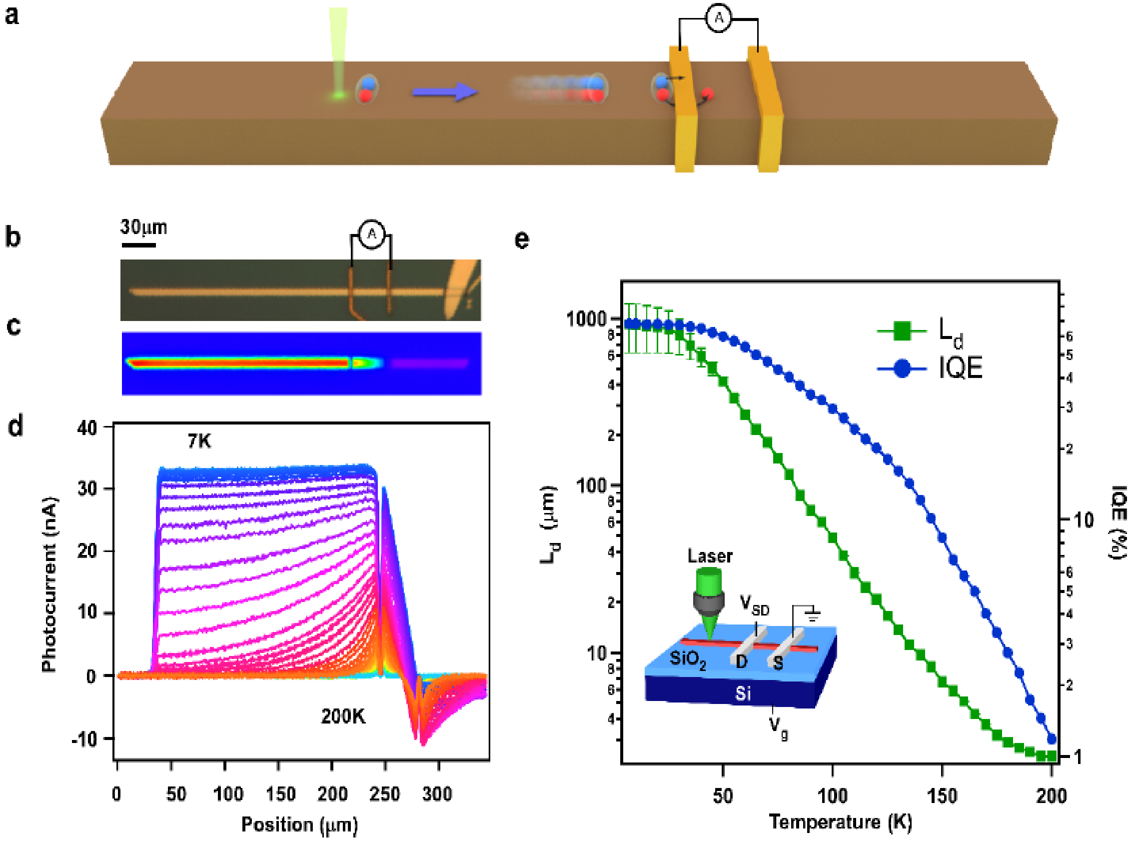
Dynamically Induced Excitonic Instability in Pumped Dirac MaterialsA Pertsova, AV Balatsky
Annalen der Physik 532 (2), 1900549 (2020)

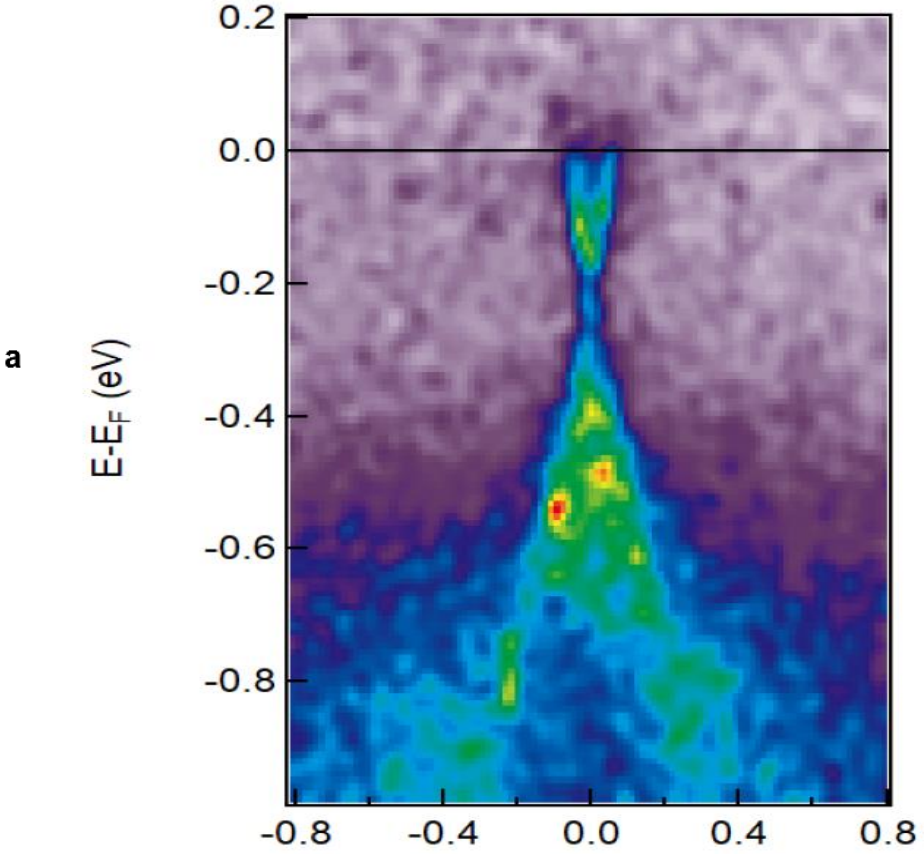
Possible X observation

Y. Hou et al
Nature Communications,
10, 5723 (2019). 10.1038/s41467-019-13711-3

Emergence of excitonic superfluid at topological-insulator surfaces

Yasen Hou[1], Rui Wang[2], Rui Xiao[1], Luke McClintock[1], Henry Clark Travaglini[1], John P. Francia[1], Harry Fetsch[3], Onur Erten[4], Sergey Y. Savrasov[1], Baigeng Wang[5], Antonio Rossi[1] Inna Vishik[1], Eli Rotenberg[6] & Dong Yu[1*]





- **Dirac Materials**

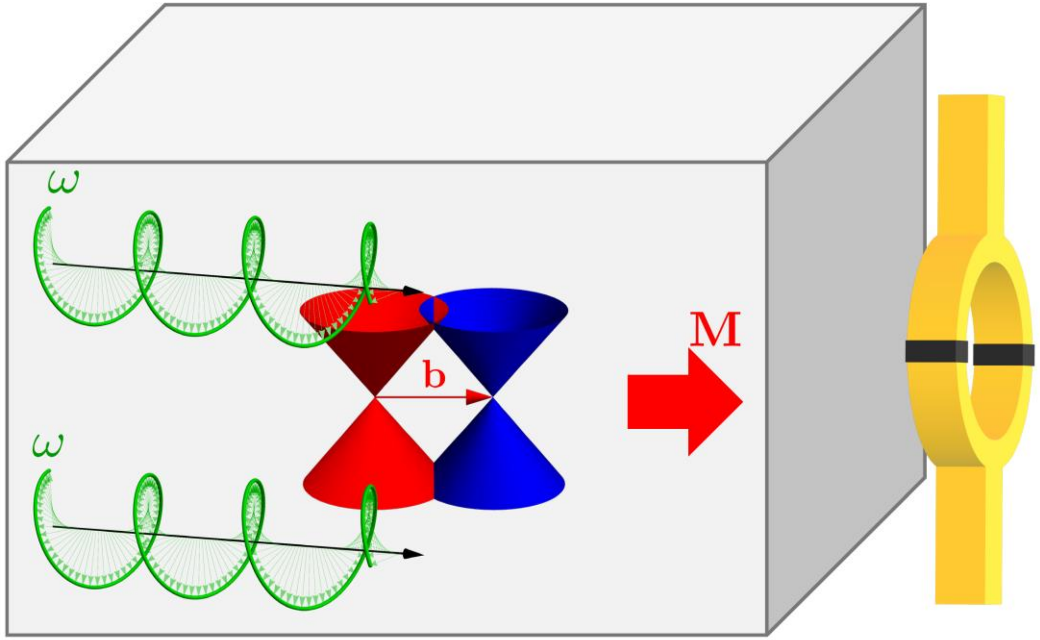
- Dynamics in Dirac Materials 1: Dynamic Exciton instability in DM

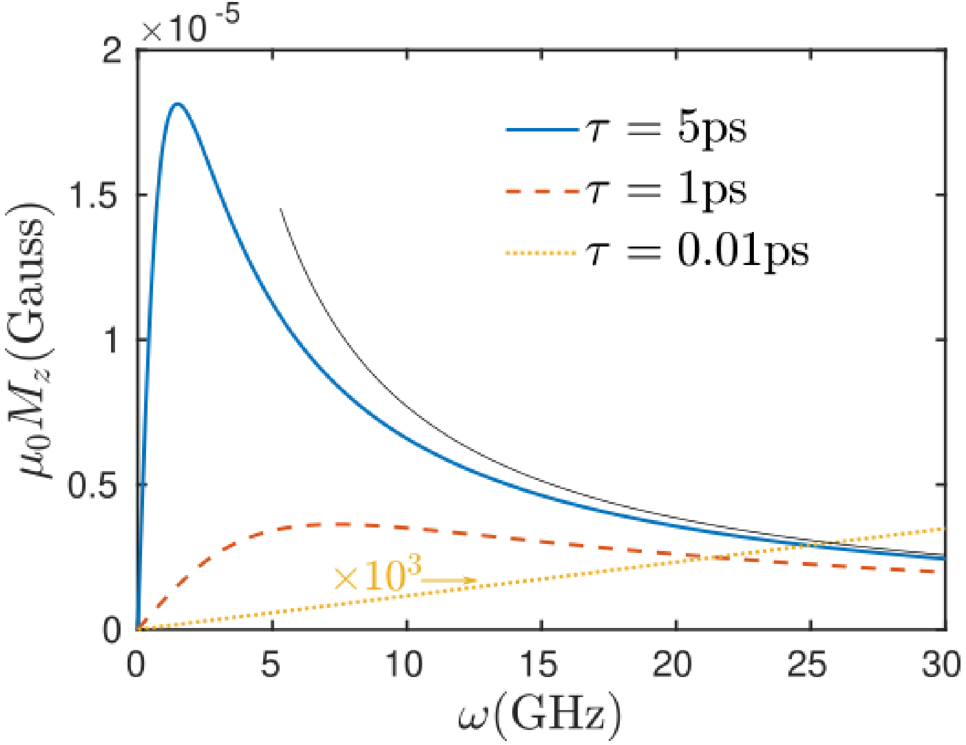
- **Dynamics in Dirac materials 2: Axial Magnetoelectric Effect in DM**

- Conclusion

Dynamic Multiferroic: Axial Magnetoelectric Effect

$$\mathbf{M} \sim \mathbf{E}_5(\omega) \times \mathbf{E}_5^*(\omega)$$





Floating Weyl nodes ~ axial gauge field

Example: Sound generates magnetization in Cd3As2

Long Liang, P. O. Sukhachov, and A. V. Balatsky, arxiv dec 2020, PRL (2021)

Dynamic in DM 2: Axial ME effect in Dirac materials

- Inverse Faraday effect IFE: photon torque -> dc M

$$M \sim E_{\omega} \wedge E_{\omega}^{*}$$

- New Axial gauge fields in DM: $H = \boldsymbol{\sigma}(\boldsymbol{k} - \eta \boldsymbol{A}_{5(r,t)})$ $\mathbf{E}_5 = -\partial_t \boldsymbol{A}^5$

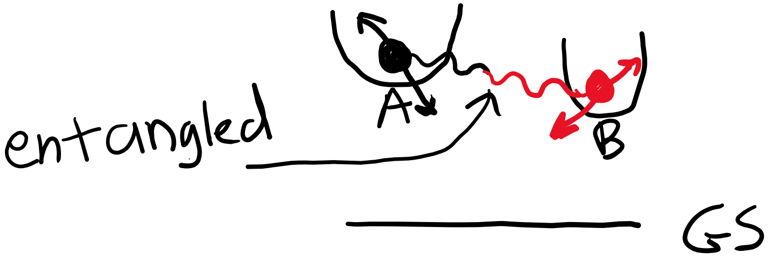
- Axial Magnetoelectric effect: axial gauge field (e.g. phonon) torque -> DC **M**

$$\boldsymbol{M} \sim \boldsymbol{E}_{\boldsymbol{\omega}}^{\mathbf{5}} \wedge \boldsymbol{E}_{\boldsymbol{\omega}}^{*\mathbf{5}}$$

Axial Magnetoelectric Effect in Dirac semimetals L Liang, PO Sukhachov, AV Balatsky, Phys. Rev. Lett. 126, 247202 (2021) arXiv:2012.07888

Time-dependent

<A(t) ⊗ B(t')> ≠ 0 – Dynamic MF -



Dirac equation

- Weyl fermions (1929)

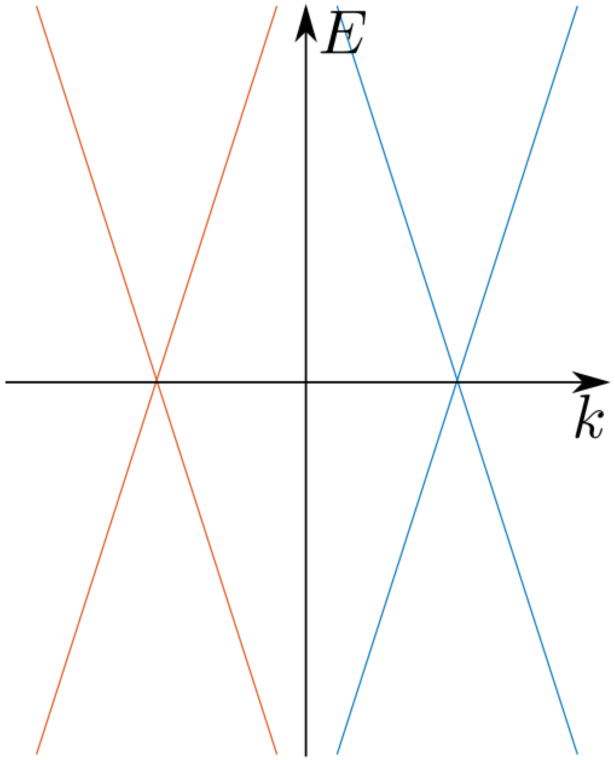
$$H_{\text{Weyl}} = \begin{bmatrix} \boldsymbol{\sigma}\cdot(\mathbf{k}-\mathbf{b})+b_0 & 0 \\ 0 & -\boldsymbol{\sigma}\cdot(\mathbf{k}+\mathbf{b})-b_0 \end{bmatrix}$$

$$(i\gamma^\mu\partial_\mu - b_\mu\gamma^\mu\gamma^5)\psi = 0$$

Positions of the Weyl points in energy-momentum space, axial ‘gauge potential’

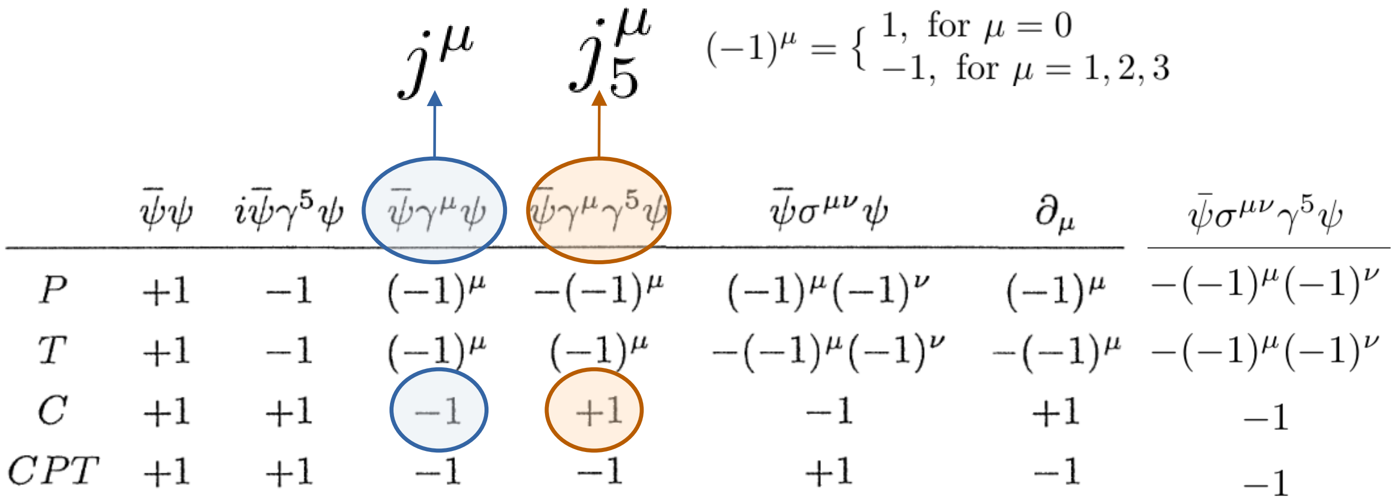
$$\mathbf{E}_5 = \partial_t \mathbf{b} - \nabla b_0$$

$$\mathbf{B}_5 = \nabla \times \mathbf{b}$$



Dirac equation

- The Dirac equation is invariant under time reversal (T), inversion (I or P), and charge conjugation (C) symmetry

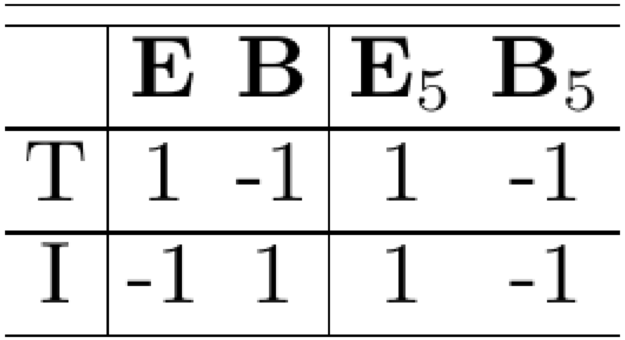


j^μ $\quad$ j_5^μ

$$(-1)^\mu = \begin{cases} 1, & \text{for } \mu = 0 \\ -1, & \text{for } \mu = 1,2,3 \end{cases}$$

	$\bar\psi\psi$	$i\bar\psi\gamma^5\psi$	$\bar\psi\gamma^\mu\psi$	$\bar\psi\gamma^\mu\gamma^5\psi$	$\bar\psi\sigma^{\mu\nu}\psi$	∂_μ	$\bar\psi\sigma^{\mu\nu}\gamma^5\psi$
P	$+1$	-1	$(-1)^\mu$	$-(-1)^\mu$	$(-1)^\mu(-1)^\nu$	$(-1)^\mu$	$-(-1)^\mu(-1)^\nu$
T	$+1$	-1	$(-1)^\mu$	$(-1)^\mu$	$-(-1)^\mu(-1)^\nu$	$-(-1)^\mu$	$-(-1)^\mu(-1)^\nu$
C	$+1$	$+1$	-1	$+1$	-1	$+1$	-1
CPT	$+1$	$+1$	-1	-1	$+1$	-1	-1

Peskin and Schroeder

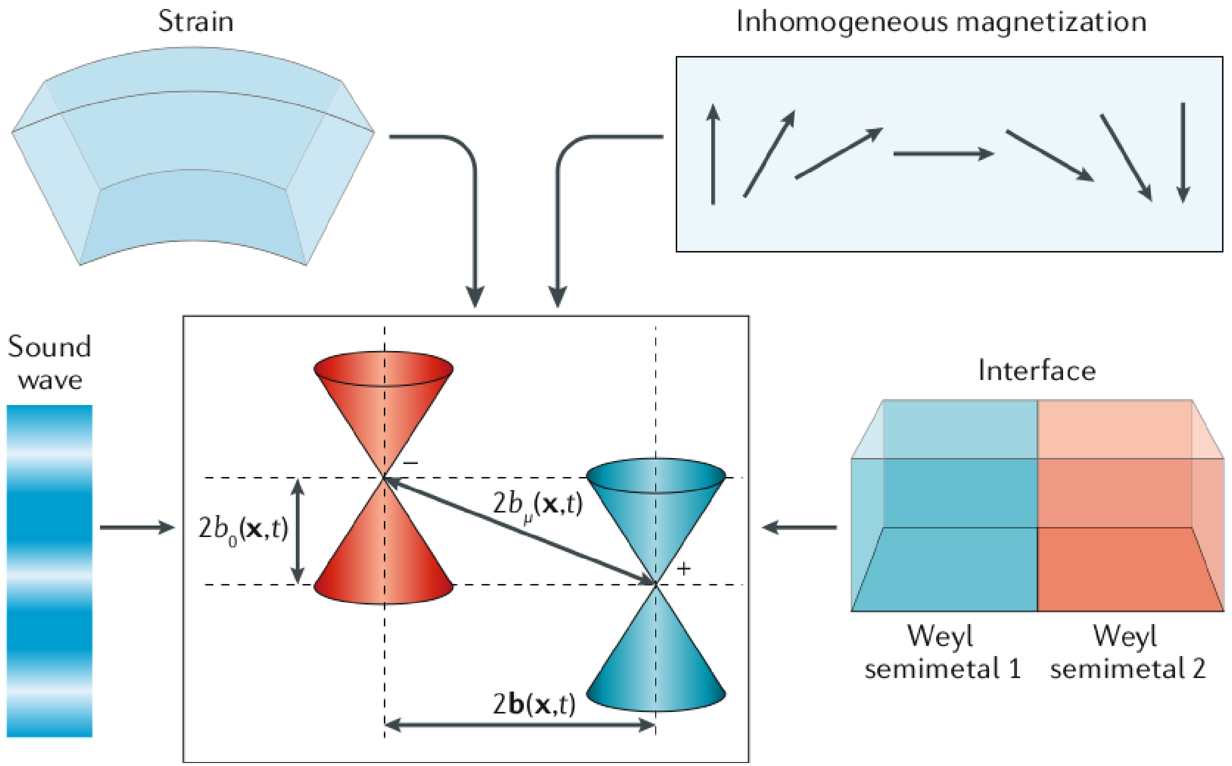


	$\mathbf{E}$	$\mathbf{B}$	$\mathbf{E}_5$	$\mathbf{B}_5$
T	1	-1	1	-1
I	-1	1	1	-1

- Current is odd under C, while axial current is even
- Nonzero chemical potential breaks C

Axial gauge fields in Dirac semimetals

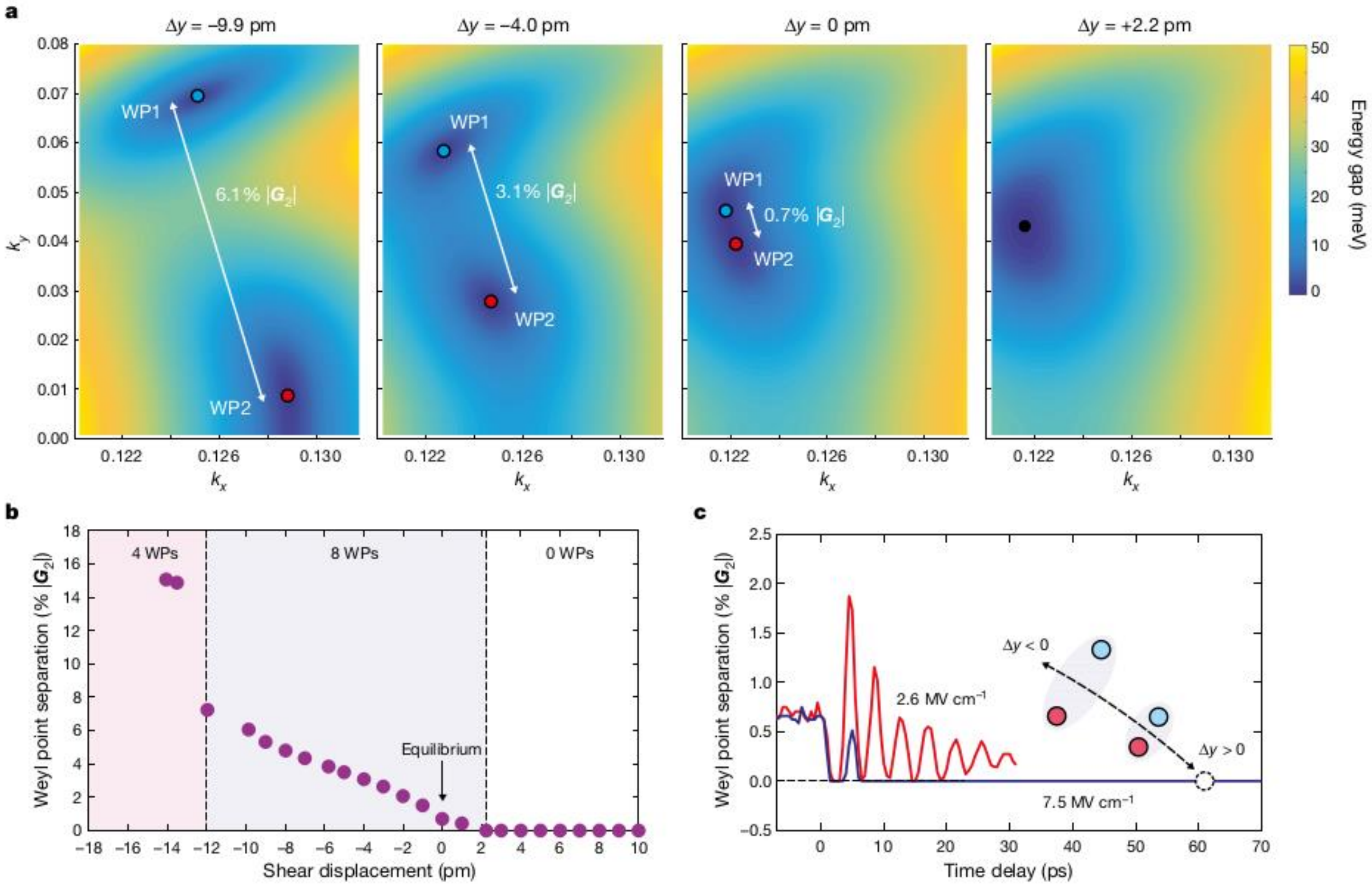
- Space/time dependent Weyl nodes ~ axial gauge fields



Ilan, Grushin and Pikulin, Nat. Rev. Phys. **2**, 29 (2020)

Axial gauge fields in Dirac semimetals

- Manipulating Weyl nodes by light pulses



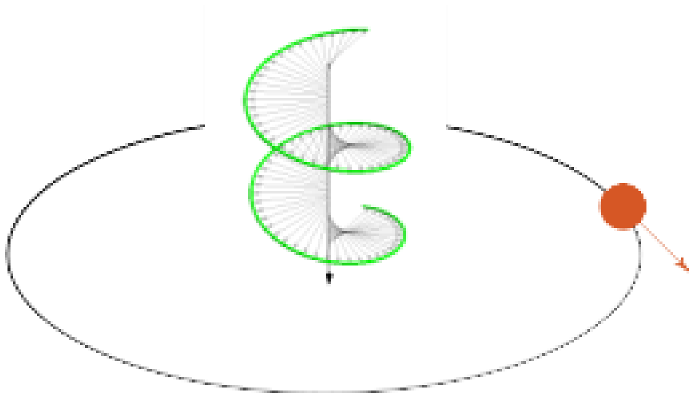
Light pulses induce structural changes in WTe_2

Sie et al., Nature **565**, 61 (2019)

Inverse Faraday effect

- Heuristic explanation

$$m\ddot{\mathbf{r}} = -e\mathbf{E}(t) \qquad \mathbf{E}(t) = E(\cos\omega t, \sin\omega t)$$



Static orbital magnetization

$$\mathbf{M} \propto \mathbf{r} \times \dot{\mathbf{r}} \propto \frac{\mathbf{E}_\omega \times \mathbf{E}^*_\omega}{\omega^3}$$

Dynamical multiferroicity $\mathbf{M} \propto \mathbf{P} \times \partial_t \mathbf{P}$

Juraschek, Fechner, Balatsky, and Spaldin, PRMaterials **1**, 014401 (2017)

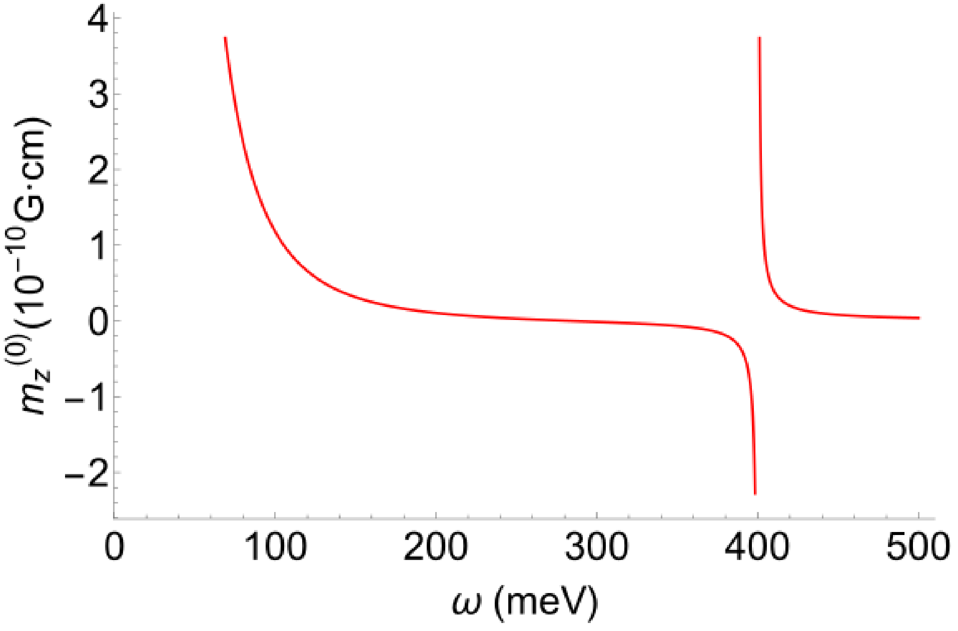
- Semiclassical theory, e.g., Pitaevskii, JETP 1960

Applies only to dissipationless materials

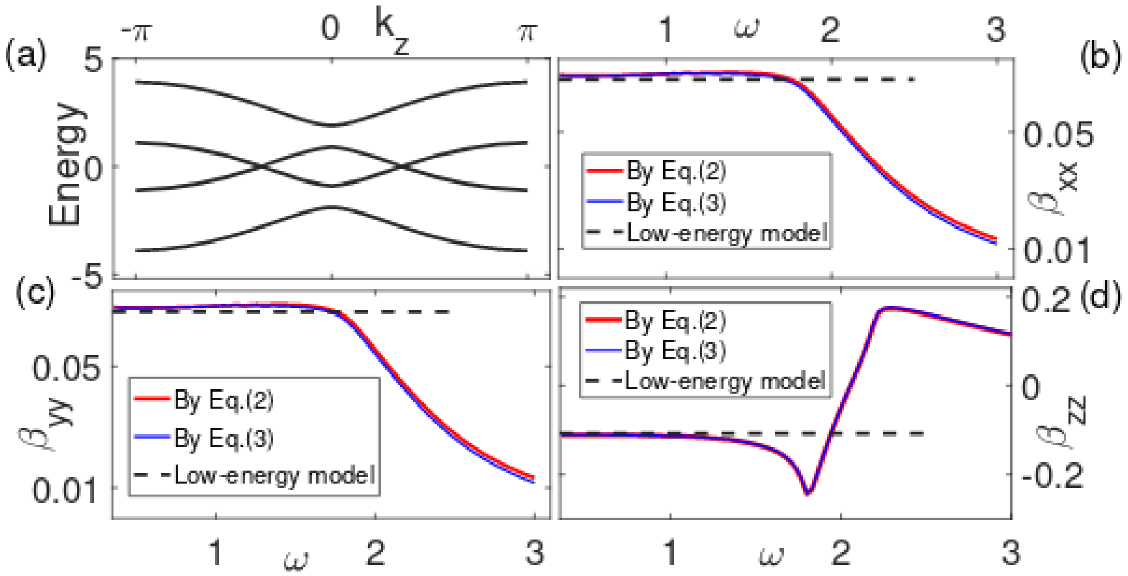
- Quantum theory, e.g., Battiato et al. PRB 2014, PRL 2016

Suitable for ab-initio calcualtions

Inverse Faraday effect in Dirac semimetals

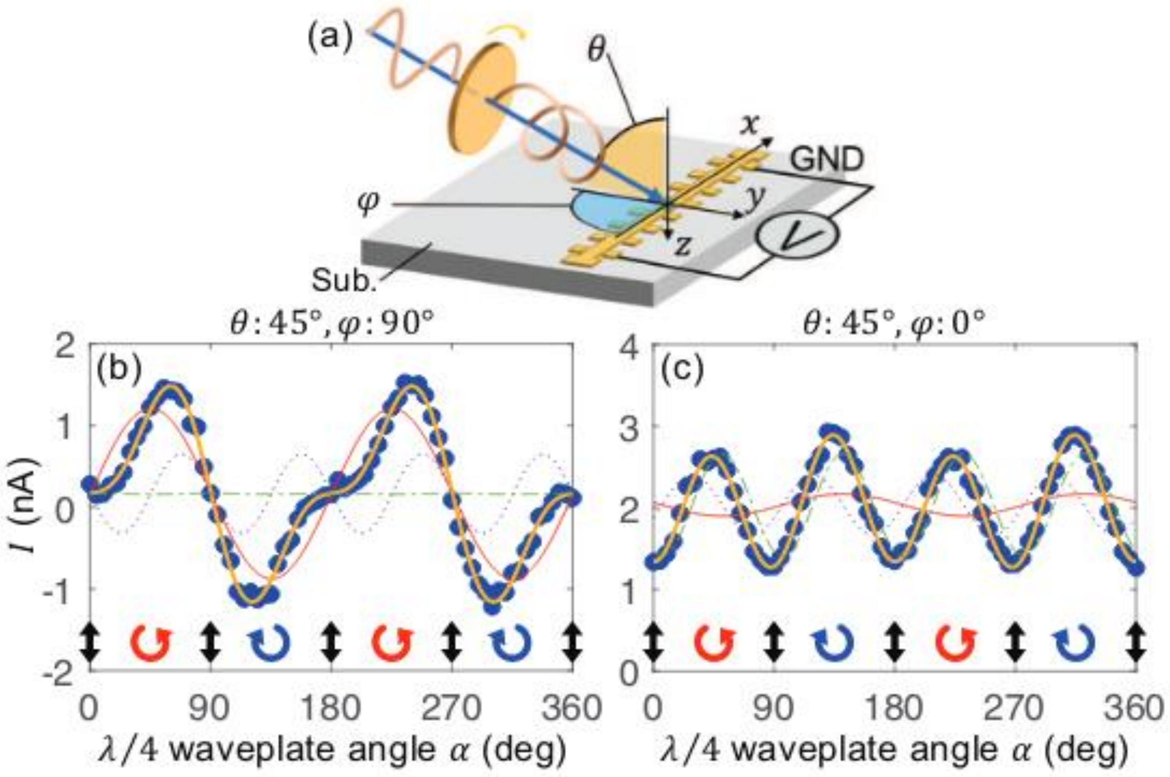


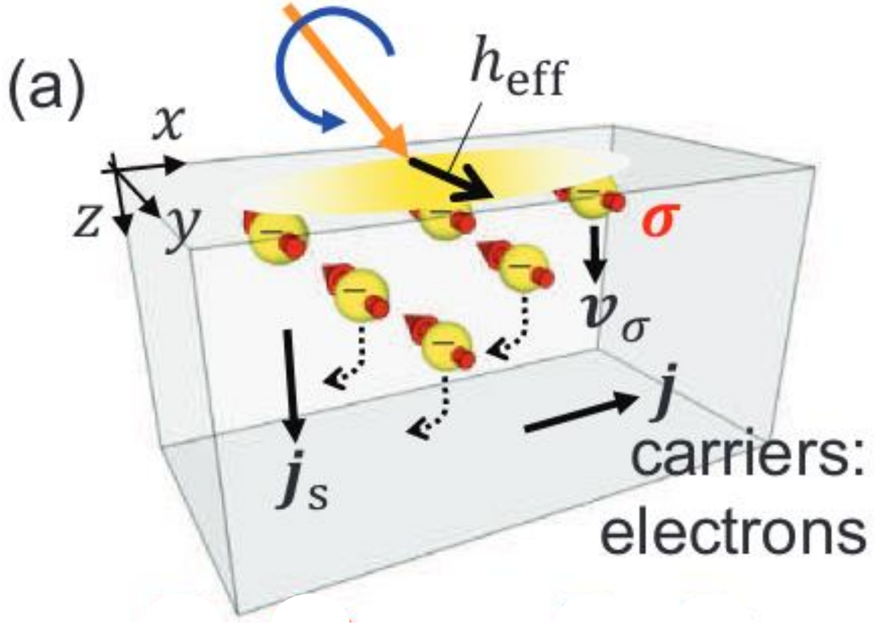
IFE in graphene, chemical is 0.2eV
Tokman et al. PRB **101**, 174429 (2020)



Topological IFE in magnetic Weyl semimetals
Gao, Wang, and Xiao, arXiv: 2009.13392

Inverse Faraday effect in Dirac semimetals





helicity dependent photocurrent in Bi-based Dirac semimetals

Kawaguchi et al. arXiv: 2009.01388

Magnetoelectric effect

- Coupling between electric and magnetic fields in matter

See e.g. Manfred Fiebig, J. Phys. D: Appl. Phys. **38** (2005) R123

$$F(\vec{E},\vec{H}) = F_0 - P_i^S E_i - M_i^S H_i$$
$$-\tfrac{1}{2}\epsilon_0\epsilon_{ij}E_iE_j - \tfrac{1}{2}\mu_0\mu_{ij}H_iH_j - \alpha_{ij}E_iH_j$$
$$-\tfrac{1}{2}\beta_{ijk}E_iH_jH_k - \tfrac{1}{2}\gamma_{ijk}H_iE_jE_k - \cdots$$

	T	I
E	1	-1
H	-1	1

$$M_i(\vec{E},\vec{H}) = M_i^S + \mu_0\mu_{ij}H_j + \alpha_{ij}E_i$$
$$+\beta_{ijk}E_iH_j + \tfrac{1}{2}\gamma_{ijk}E_jE_k - \cdots$$

Linear magnetoelectric effect (ME)
T and I breaking, topological ME in 3D topological insulators, Qi, Hughes, and Zhang, PRB, 2008

I breaking

Inverse Faraday effect, not forbidden by I and T
T breaking by circularly polarized light, $\mathbf{E} \times \mathbf{E}^*$
Proposed by Pitaevskii, JETP **12**, 1008 (1960)

Axial magnetoelectric effect

$$M_i = \alpha_{5,ij} E_{5,j} + \beta_{5,ijk} E_{5,j} B_{5,j} + \boxed{\frac{1}{2}\gamma_{5,ijk} E_{5,j} E_{5,k}}$$

	$\mathbf{E}$	$\mathbf{B}$	$\mathbf{E}_5$	$\mathbf{B}_5$
T	1	-1	1	-1
I	-1	1	1	-1

Axial magnetoelectric effect

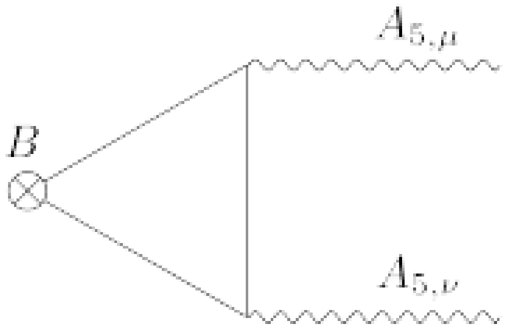
$$\mathbf{M} = -\lim_{B\to 0}\frac{\delta S_{\mathrm{eff}}}{\delta \mathbf{B}}$$

$$e^{iS_{\mathrm{eff}}} = \int \mathrm{D}\bar{\psi}\mathrm{D}\psi e^{i\int \mathrm{d}^4x\,\mathcal{L}},\ \mathcal{L} = \bar{\psi}(i\partial_\mu - A_\mu - A_{5,\mu}\gamma^5)\gamma^\mu\psi$$

$$S_{\mathrm{eff}} \sim \int \langle j^\mu j_5^\nu j_5^\rho\rangle A_\mu A_{5,\nu} A_{5,\rho}$$

$j^\mu = \bar{\psi}\gamma^\mu\psi$ changes sign under C

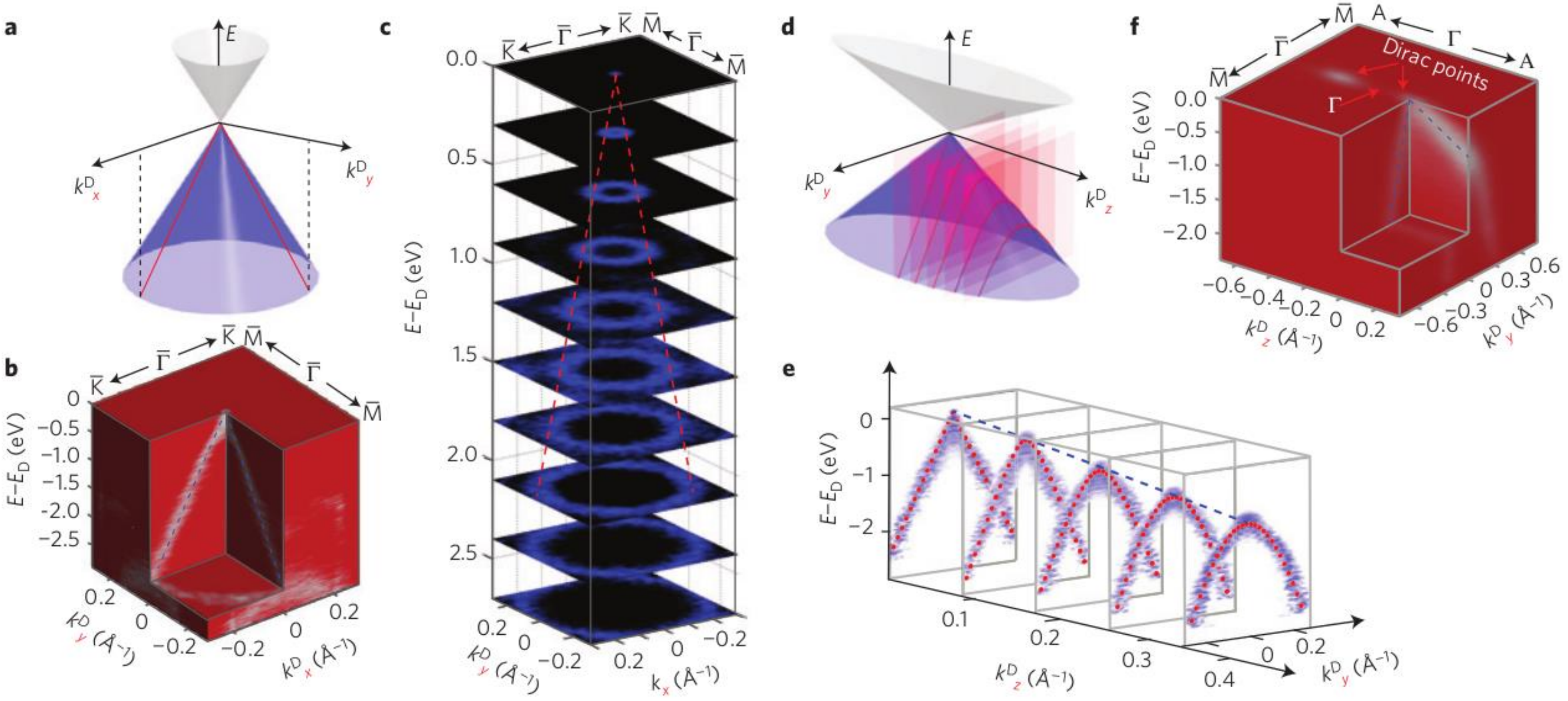
$j_5^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi$ unchanged under C



Triangle diagram, not to be confused with the diagrams giving the chiral anomaly

- Vanishes charge neutral point, Fermi surface effect
- Can be calculated separately for each node (IFE in the **q**=0 limit)
- Other effects such as photo/acoustogalvanic effect, Sukhachov and Rostami, PRL 2020

Dirac semimetal Cd_2As_3



$$v_x = 8.47\mathrm{eV\AA},$$
$$v_y = 8.56\mathrm{eV\AA},$$
$$v_z = 2.16\mathrm{eV\AA},$$
$$b = 0.16\mathrm{\AA}^{-1}.$$

Z. K. Liu et al., Nat. Mater. **13**, 677 (2014)

Large Fermi velocity, high mobility, long life time

Axial magnetoelectric effect in strained Cd_2As_3

- Transverse sound wave propagating in z direction

$$\mathbf{u} = \mathrm{Re}\left[u_0(\mathbf{e}_x - i\mathbf{e}_y)e^{i(q_z z - \omega t)}\right]$$

$$\mathbf{A}_5 = i(\mathbf{e}_x - i\mathbf{e}_y)\frac{b\beta u_0}{4e}q_z e^{i(q_z z - \omega t)} + \mathrm{c.c.},$$

Transverse sound velocity

$$v_s = 1.6 \times 10^3 \mathrm{m/s}$$

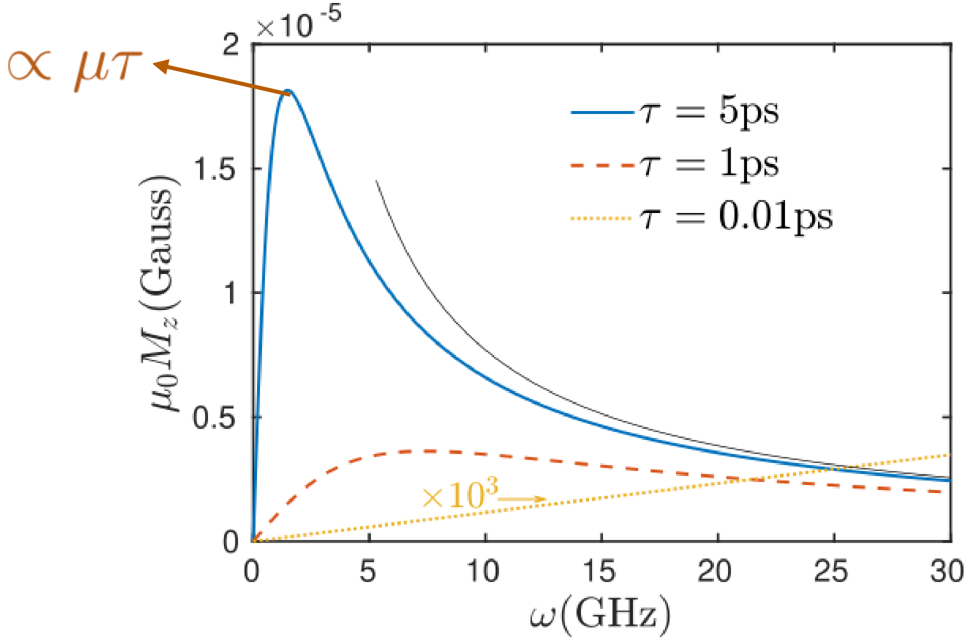
- Key differences between IFE and AME

$$A_5 \propto q_z \propto \omega, E_5 \propto \omega^2$$

$\omega \ll v_F q_z$: momentum dependence can’t be ignored

Axial magnetoelectric effect in strained Cd_2As_3

- Large $\mu\tau$



Maximum at $\omega\tau \propto v_s / v_z$

$q_z v_z \tau \ll 1$ limit

$$M_z \approx M_0 \left[1 - \frac{3}{5}(q_z v_z \tau)^2\right] \mu\omega\tau^2 \propto \omega$$

$q_z v_z \tau \gg 1$ limit

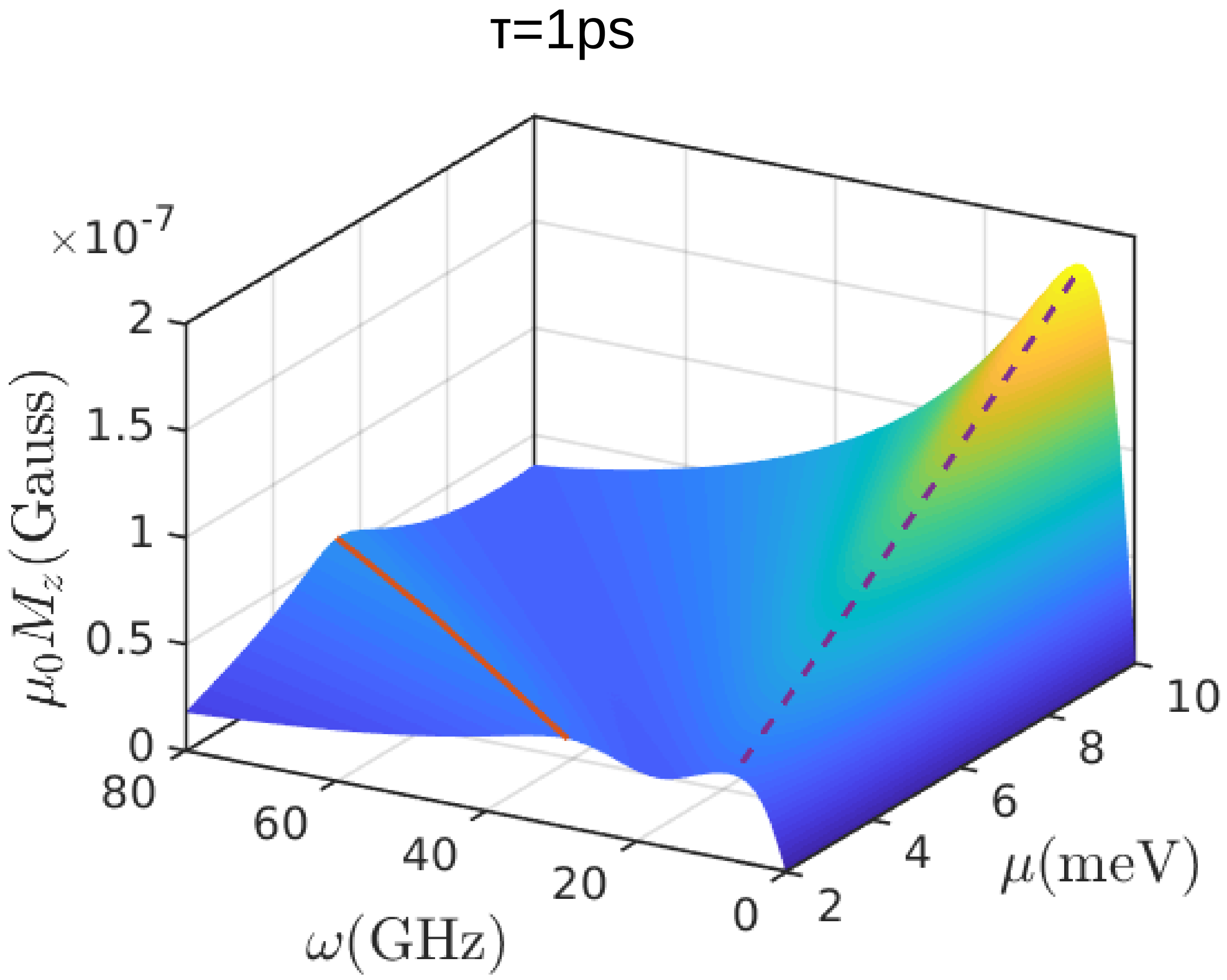
$$M_z \approx 3M_0 \frac{1}{(q_z v_z \tau)^2} \left[1 - \frac{\pi}{2(q_z v_z \tau)}\right] \mu\omega\tau^2 \propto 1/\omega$$

$$M_0 = \frac{e v_x v_y (\beta b u_0 q_z)^2}{48\pi^2 v_z} \propto I$$

I=10W/cm^2 is the sound intensity,
u_0=0.2nm when ω=1GHz

μ is fixed to be 0.2eV (μτ~3 for τ=0.01ps)
For τ=1ps and ω=1GHz, $\mu_0 M_z \approx 1\mu$G

Axial magnetoelectric effect in strained Cd_2As_3



	small ω	large ω
IFE	$\propto 1/\omega$	$\propto 1/\omega^3$
AME	$\propto \omega$	$\propto 1/\omega$

Two peaks at

$$\omega\tau \propto v_x/v_z, \;\; q_z v_z = 2\mu$$

Conclusion Dynamic 2

- Nodal states due to topology- new ground to probe dynamics
- Proposed transient exciton instability in DM
- Axial Magnetoelectric effect – time dependent synthetic gauge fieds in nodal material
- Effect is on the scale of
- Dynamic 3: Dark Matter Dynamics and Quantum Sensors