Magneto-optical conductivity in Weyl Semimetals

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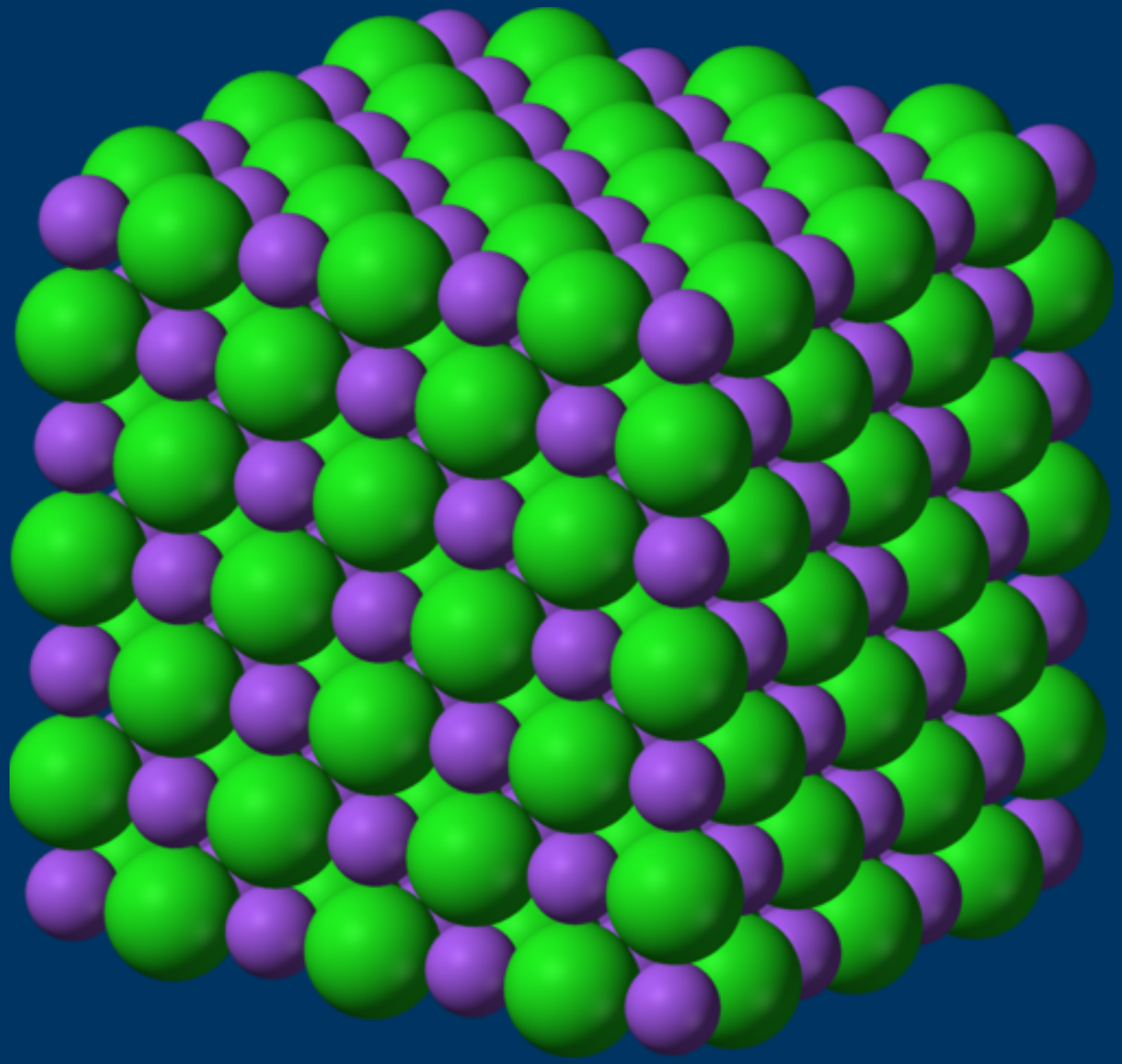
Historical Background and development

- Weyl Fermions were first proposed by Hermann Weyl as the solution to Dirac equation. Later with the advancements this concept has found experimental relevance in condensed matter physics.
- Major breakthroughs came from theoretical studies in 1960s followed by subsequent experimental confirmation in the 21st century.
- Weyl Semimetals have garnered significant interest in recent years due to their unique topological properties and potential applications in various fields.
- Additionally, their unconventional electronic properties hold promise for applications in next-generation electronics, spintronics, and quantum computing.

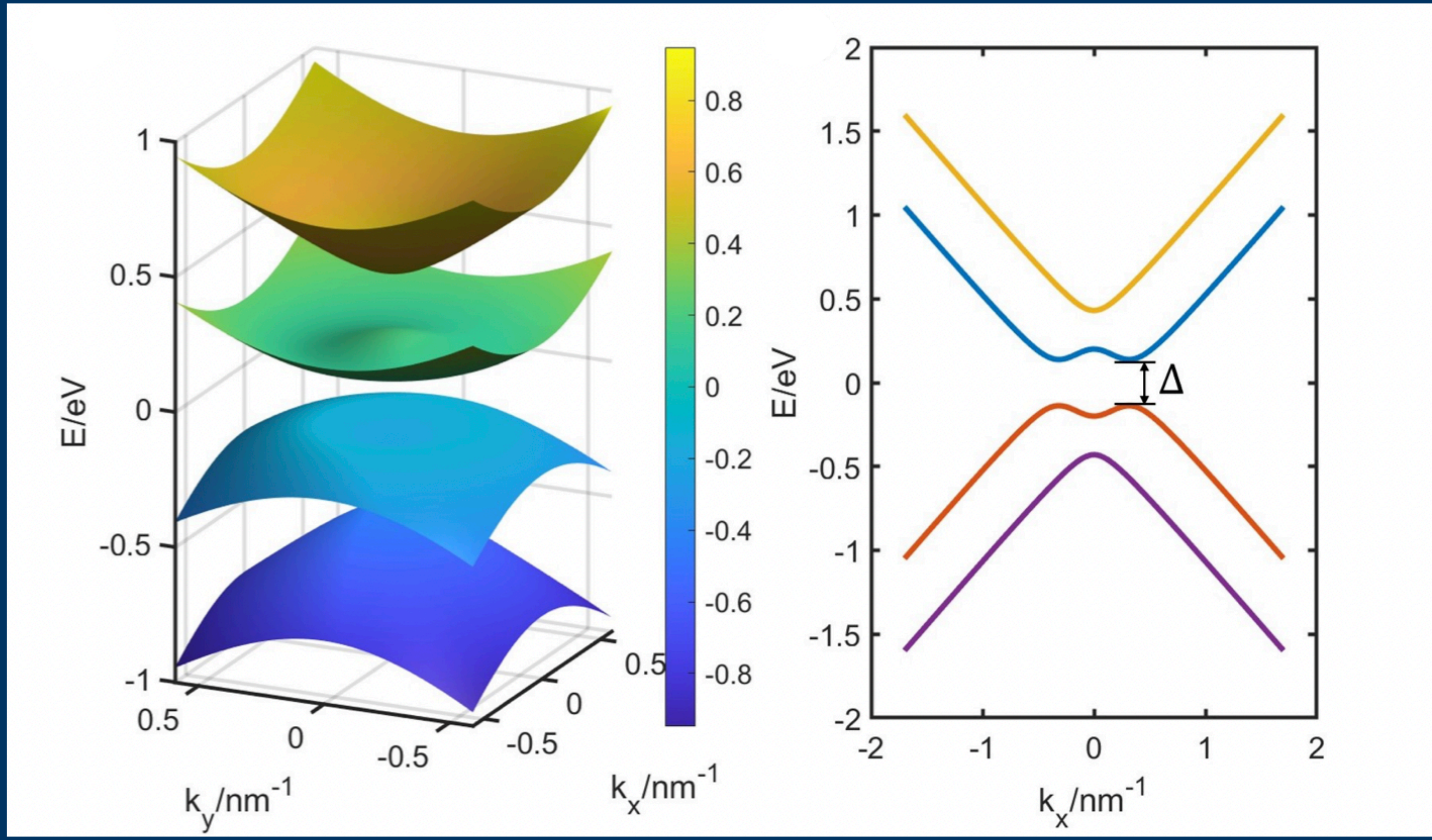
Introduction

- Condensed matter is the study of systems with low energy.
- The energy is low enough for the atoms or the molecules sometimes arrange themselves in crystalline structure.
- To study these crystalline structures we write down something called a Hamiltonian for the system. This Hamiltonian is used to evaluate the energy of the system and other relevant quantities.



Crystal structure of NaCl.

Dispersion plot of materials with a ‘gap’



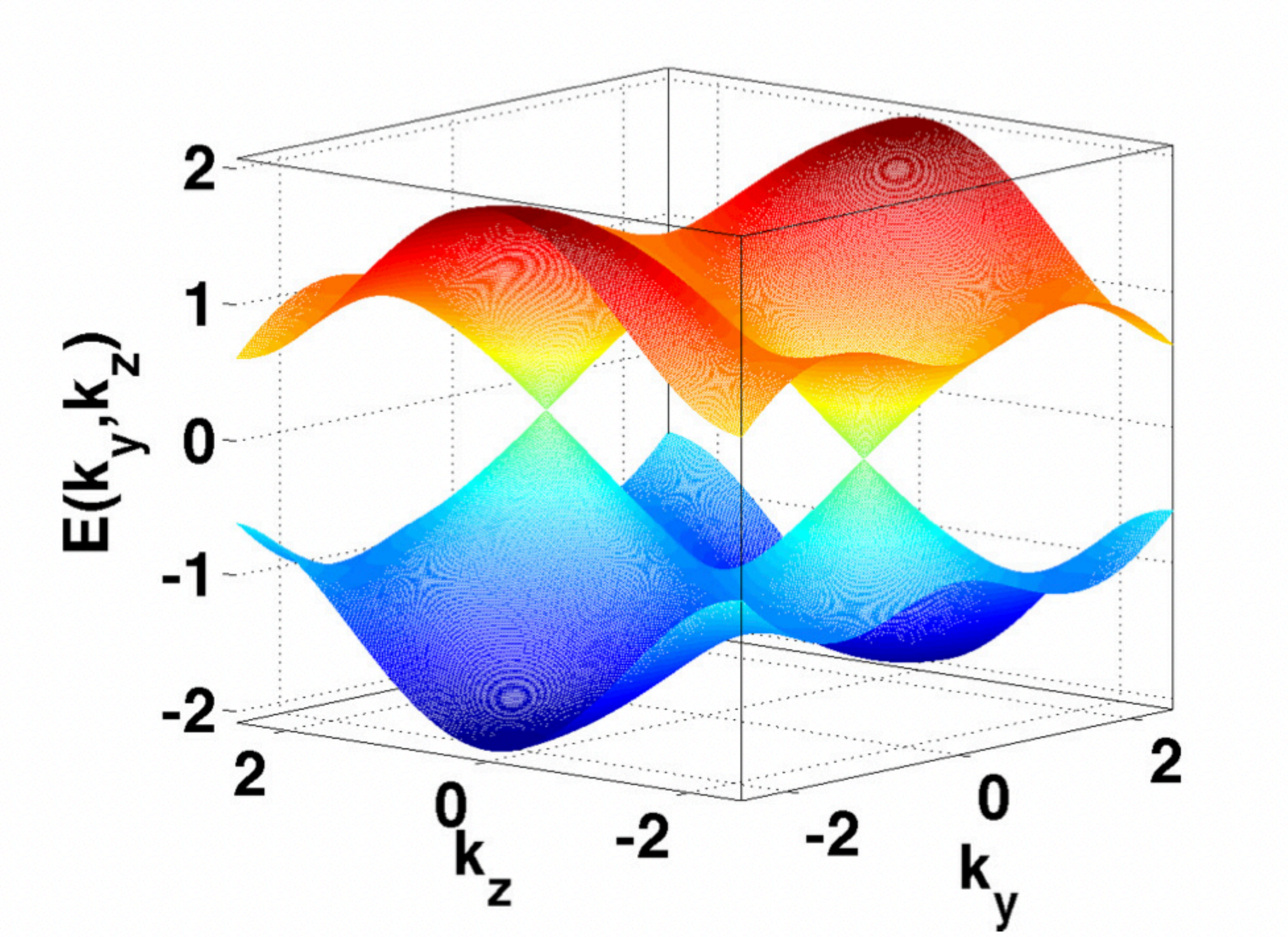
A. Adhikari, B. Guislain, D. Yang, J. Yu and Y. Xiao, A Survey of electronic properties in bilayer graphene.

Dispersion plot for bilayer graphene with interlayer asymmetry. Note that the energy surfaces do not touch each other. There is a ‘gap’ between them. To get an effective electron transport we apply external fields to transfer the electrons from valance band (negative energy) to conduction band (positive energy).

Weyl Semimetals

- These are the materials with gapless dispersion.
- Recently many materials have been found which possess these properties.
- Stacked graphene layers display these gapless modes. TaAs, NbAs and TaP are some of the materials which have been identified as Weyl Semimetals.

This dispersion shows the band touching at $k = (0,0, \pm \pi/2)$. These points are called Wely nodes. The dispersion about the Weyl nodes is linear in nature.



G. Sharma, P. Goswami and S. Tewari, PHYSICAL REVIEW B **93**, 035116 (2016)

Degeneracy and Symmetry

- In quantum mechanics, degeneracy refers to the situation where two or more quantum states have the same energy level.
- A degeneracy can be of two types, exact degeneracy or accidental degeneracy.
- Exact degeneracy implies presence of a symmetry.
- A WSM has exact degeneracies which are called topological degeneracies.
- The symmetry thus gives rise to a conserved quantity. In case of WSM its the Chern number.
- This degeneracy cannot be lifted by a simple local perturbation because its protected by the symmetry of Hamiltonian.

Berry Curvature

- For WSM/mWSM Berry curvature is defined as

$$\Omega_\alpha = \frac{\pm 1}{4|\epsilon|^3}\epsilon_{\alpha\beta\gamma}\,\mathbf{n}_k \cdot \left(\frac{\partial\,\mathbf{n}_k}{\partial k_\beta} \times \frac{\partial\,\mathbf{n}_k}{\partial k_\gamma}\right)$$

- Chern number: $$C = \frac{1}{2\pi}\oint \boldsymbol{\Omega}\cdot d\mathbf{S}$$

- Nielsen–Ninomiya theorem: Total Chern number in the Brillouin zone must vanish.

$$\boldsymbol{\Omega} = \frac{v_0\,\alpha^2}{2|\epsilon|^3}\left(k_x, k_y, k_z\right)$$

- The Hamiltonian in the vicinity of the Weyl node is given by

$$H = \begin{pmatrix} v\,k_z & \alpha\,(k_x - i\,k_y) \\ \alpha\,(k_x - i\,k_y) & -v\,k_z \end{pmatrix}$$

- The energy associated with a Weyl node is given by

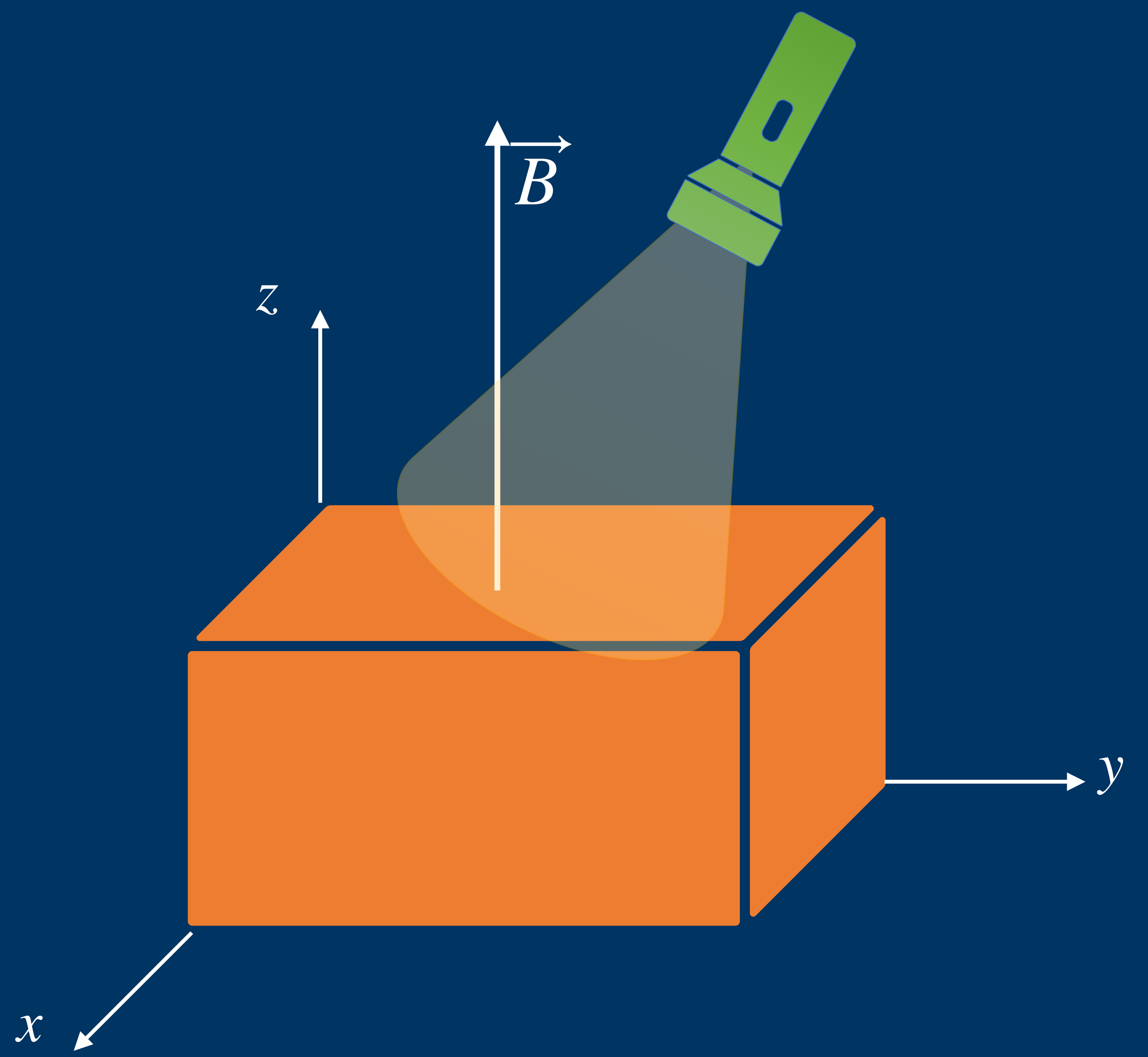
$$E = \pm\sqrt{\alpha^2\,(k_x^2 + k_y^2) + v^2\,k_z^2}$$

- α and v are parameters which depend on the material
- The Hamiltonian is written in the natural units

$$\hbar = 1, \quad c = 1, \quad \text{and} \quad k_\beta = 1$$

Magneto optic conductivity

- We measure the current along different directions in presence of a magnetic field while perturbing the system by shining light on it
- The conductivity of such a setup is given by



$$\sigma_{\mu\nu}(\omega) = \frac{-i\,e\,B}{2\,\pi} \sum_{n,n',s,s'} \int \frac{dk_z}{2\,\pi} \left(\frac{f_{n,s} - f_{n',s'}}{E_{n,s} - E_{n',s'}} \right) \left(\frac{\mathscr{M}_{\mu\,\nu}}{\omega - E_{n,s} + E_{n',s'} + i\,\epsilon} \right)$$

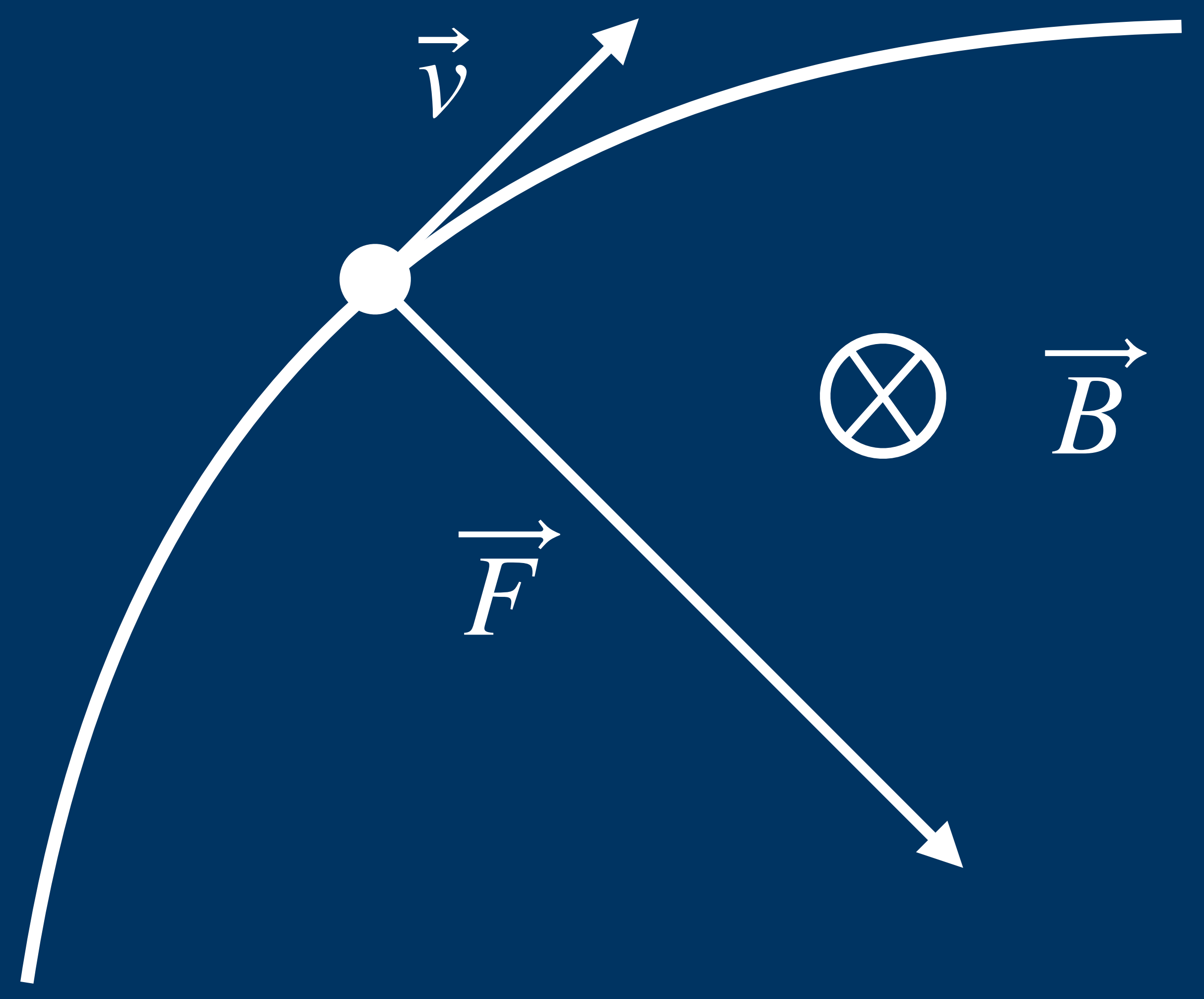
$$f_{n,s} = \frac{1}{1 + e^{\beta(E_{n,s} - \mu)}}$$

Motion of Charged particle in a magnetic field

- Force on a charged particle in a magnetic field is

$$\overrightarrow{F} = q\vec{v} \times \overrightarrow{B}$$

- Quantum mechanically, the energy can only take discrete values
- This enforces a constrain on the value of the energy that electrons can have these are termed as Landau levels



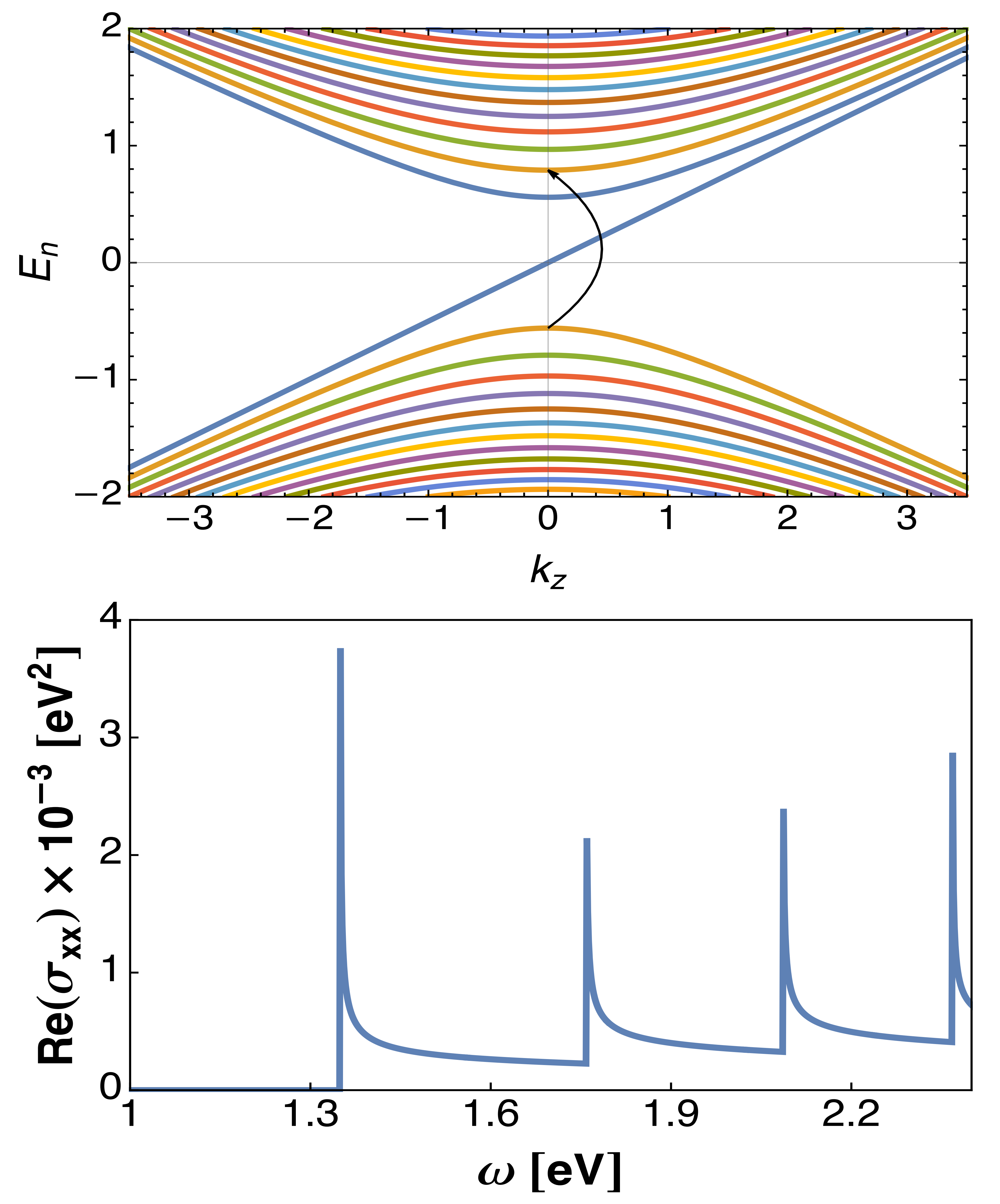
Landau level energies and conductivity

$$E_{n,\pm} = \begin{cases} v\,k_z & n = 0 \\ \pm\sqrt{v^2 k_z^2 + \lambda^2 n} & n \geq 1 \end{cases}$$

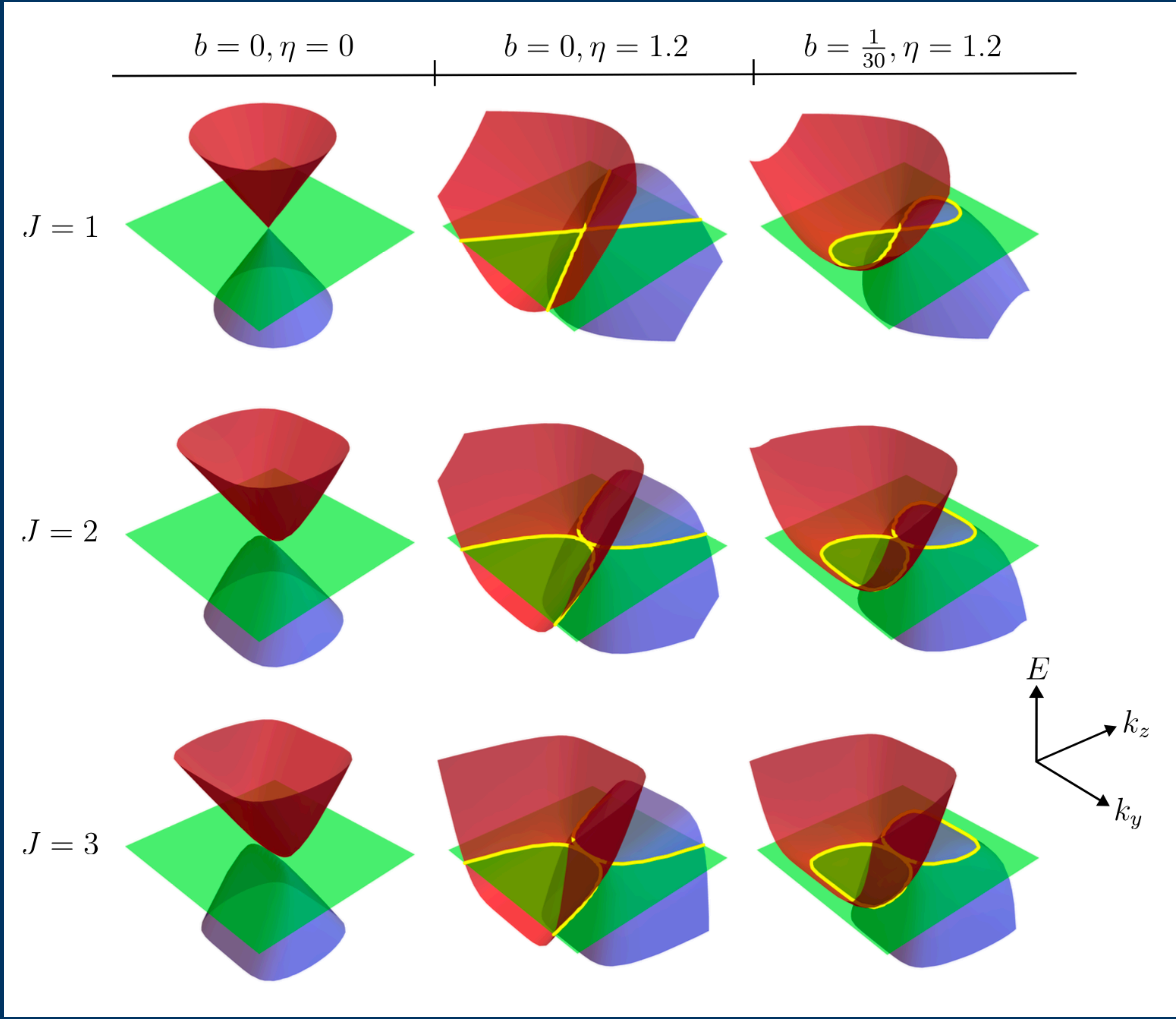
$$\lambda = \sqrt{2\,e\,B}\,\alpha_1$$

$$|\Psi_{n,\pm}\rangle = \begin{cases} \begin{pmatrix} 0 \\ 1 \end{pmatrix} & \text{for } n = 0 \\ \begin{pmatrix} \pm\sqrt{\frac{1}{2}\left(1 + \frac{v\,k_z}{E_{n,\pm}}\right)}\,|n-1\rangle \\ \sqrt{\frac{1}{2}\left(1 - \frac{v\,k_z}{E_{n,\pm}}\right)}\,|n\rangle \end{pmatrix} & \text{for } n \geq 1 \end{cases}$$

Transitions take place : $n \to n + 1$



S Yadav, S Sekh, I Mandal, Magneto-optical conductivity in the type-I and type-II phases of Weyl/multi-Weyl semimetals, Physica B: Condensed Matter, Volume 656, 2023



S Yadav, S Sekh, I Mandal, Magneto-optical conductivity in the type-I and type-II phases of Weyl/multi-Weyl semimetals, Physica B: Condensed Matter, Volume 656, 2023

Thank you