Synthetic Weyl semimetal in a one-dimensional system of trilayer photonic grating

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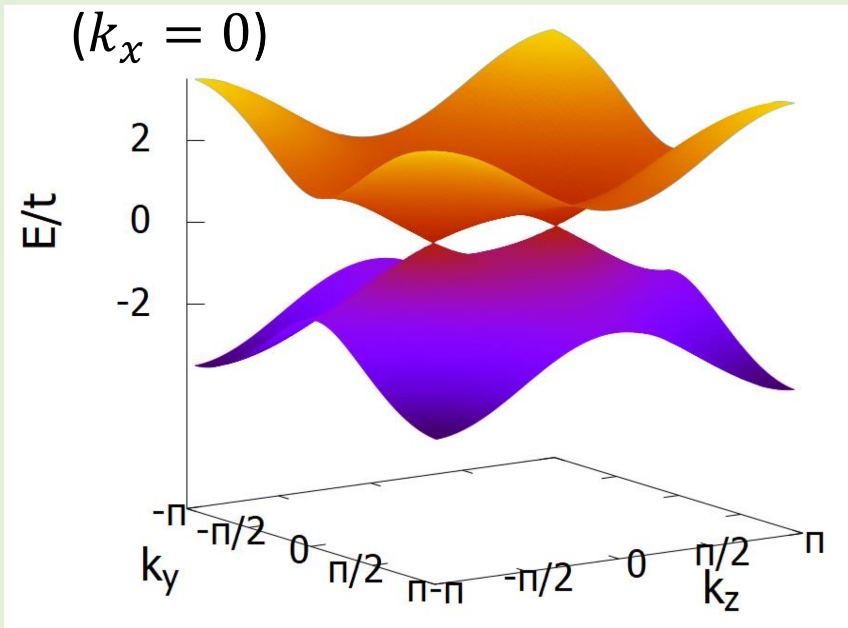
What is Weyl semimetal?

- Weyl semimetal (WSM) is a solid state crystal whose low-energy excitations are Weyl fermion, i.e., massless chiral fermions described by the Weyl equation.
- WSM has non-degenerate conduction and valence bands with linear band touching points near the Fermi energy.
- Typical WSM: TaAs, $Co_3Sn_2S_2$

Spectrum of a minimal model for WSM

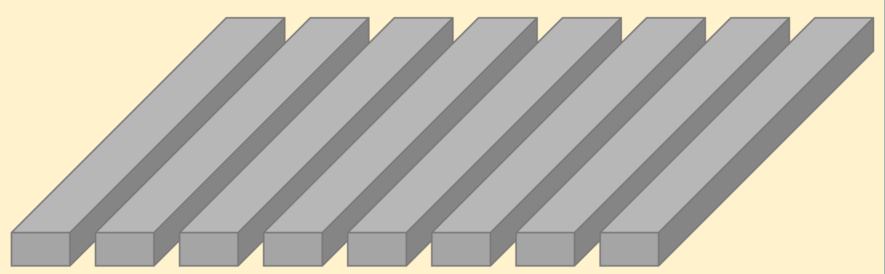


Quick introduction to 1D photonic grating

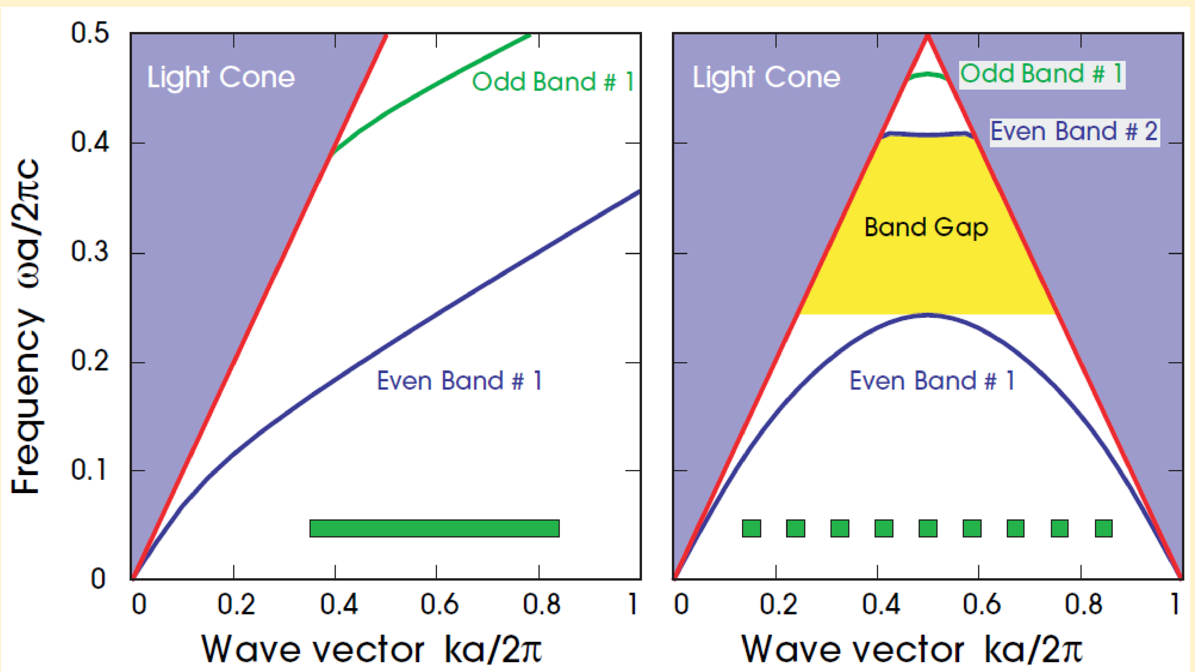
Electromagnetic wave travels along a homogeneous waveguide via total reflection ($\omega = vk$). When the thickness is small, i.e., subwavelength, discrete modes appear in the dispersion

If the waveguide is corrugated:

- band-folding effect → Brillouin zone
- diffractive coupling between left-moving & right-moving modes



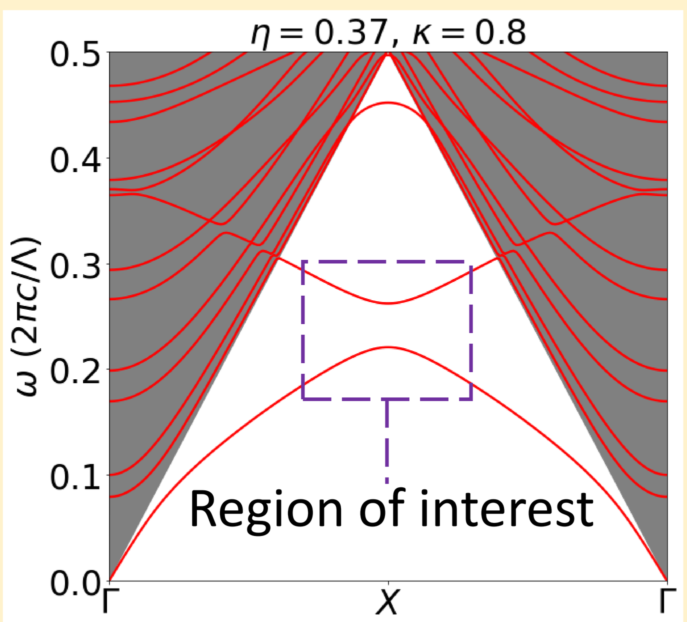
(Photonic crystals: Modeling the flow of light – J. D. Joanopoulos)



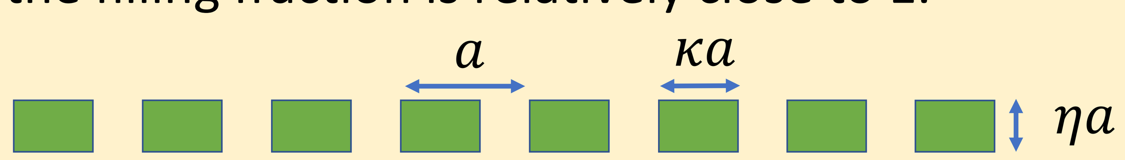
Effective Hamiltonian in the vicinity of X

$$H(k) = \omega_0 + \begin{pmatrix} vk & U \\ U & vk \end{pmatrix}$$

U: refractive coupling constant

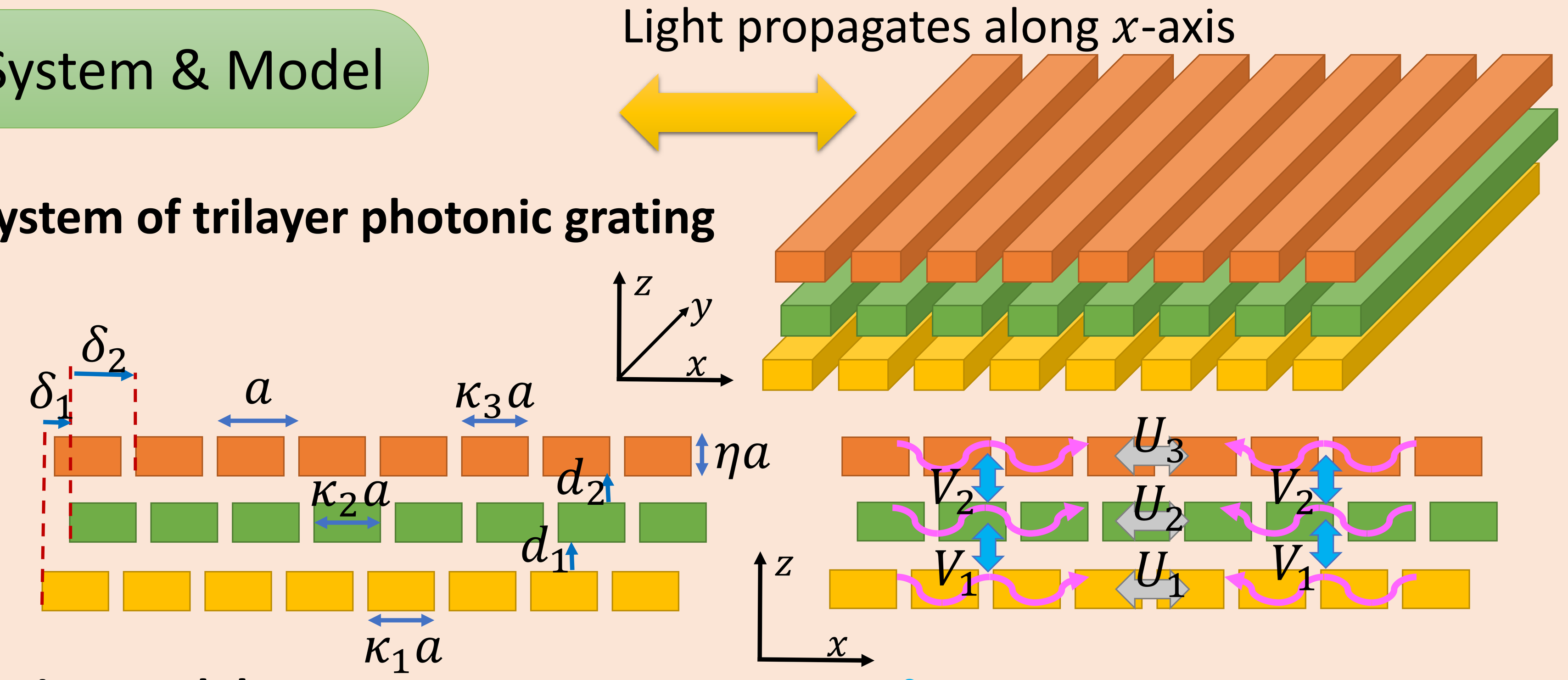


The effective model is valid when the diffractive coupling is not too strong, e.g., the filling fraction is relatively close to 1.



I. System & Model

1D system of trilayer photonic grating



Effective model

$$H(k,\delta_1,\delta_2) = \omega_0 + \begin{pmatrix} vk & U_1 & V_1 e^{-i\pi\frac{\delta_1}{\Lambda}} & 0 & 0 & 0 \\ U_1 & -vk & 0 & V_1 e^{i\pi\frac{\delta_1}{\Lambda}} & 0 & 0 \\ V_1 e^{i\pi\frac{\delta_1}{\Lambda}} & 0 & vk & U_2 & V_2 e^{-i\pi\frac{\delta_2}{\Lambda}} & 0 \\ 0 & V_1 e^{-i\pi\frac{\delta_1}{\Lambda}} & U_2 & -vk & 0 & V_2 e^{i\pi\frac{\delta_2}{\Lambda}} \\ 0 & 0 & V_2 e^{i\pi\frac{\delta_2}{\Lambda}} & 0 & vk & U_3 \\ 0 & 0 & 0 & V_2 e^{-i\pi\frac{\delta_2}{\Lambda}} & U_3 & -vk \end{pmatrix}$$

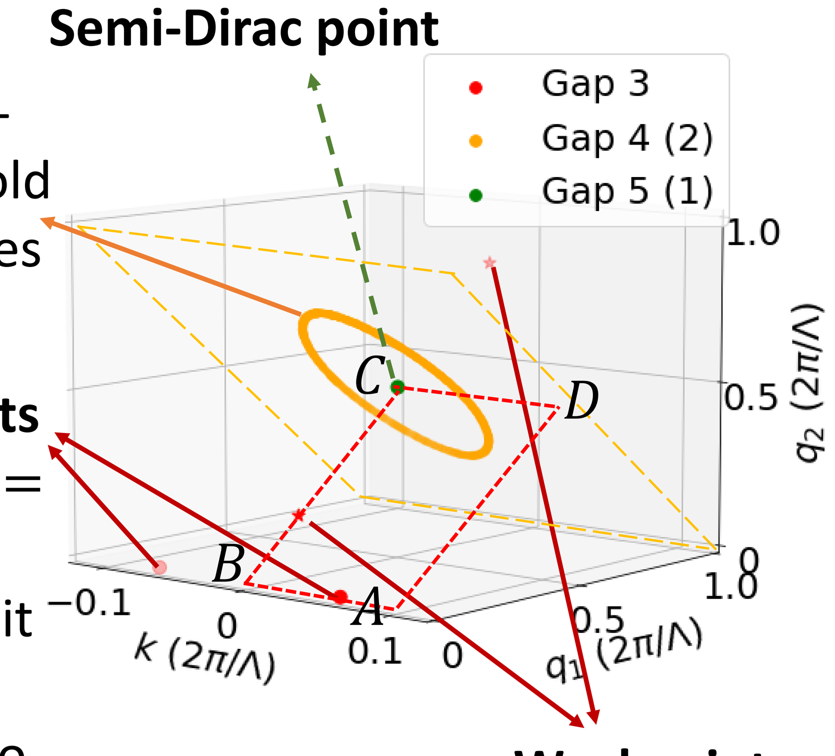
Synthetic momenta $q_i = \frac{2\pi}{\Lambda^2}\delta_i$

II. Results from effective model

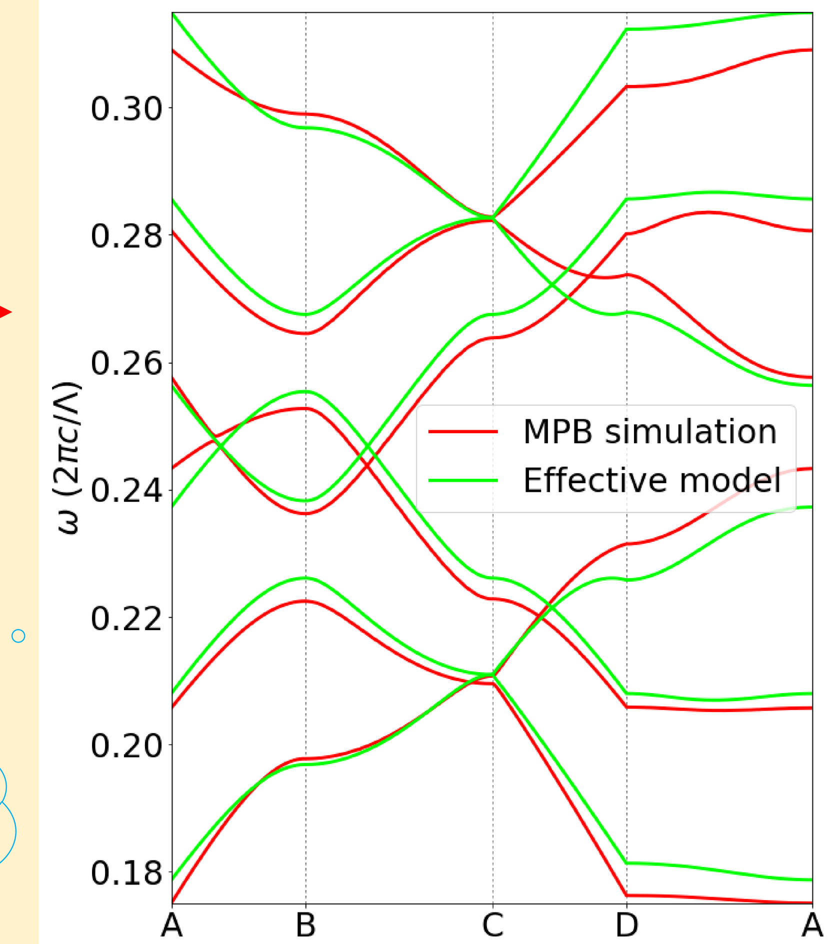
Consider the case where $U_1 = U_2 = U_3 = V_1 = V_2$

Nodal line is in-plane with the gold (thin) dashed lines

Semi-Dirac points at $k \neq 0$ and $q_1 = q_2 = 0$ (each can be split into two Weyl points parallel to those at $k = 0$)



Compare with simulation

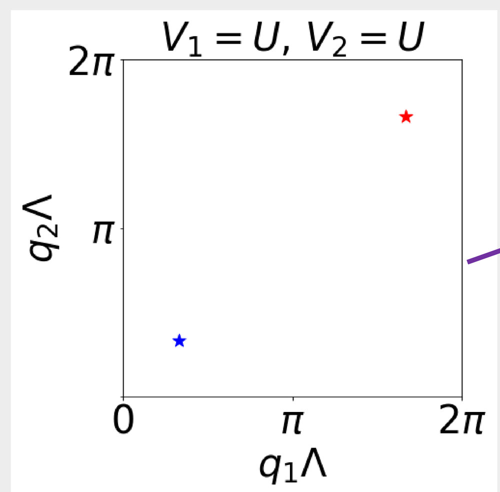


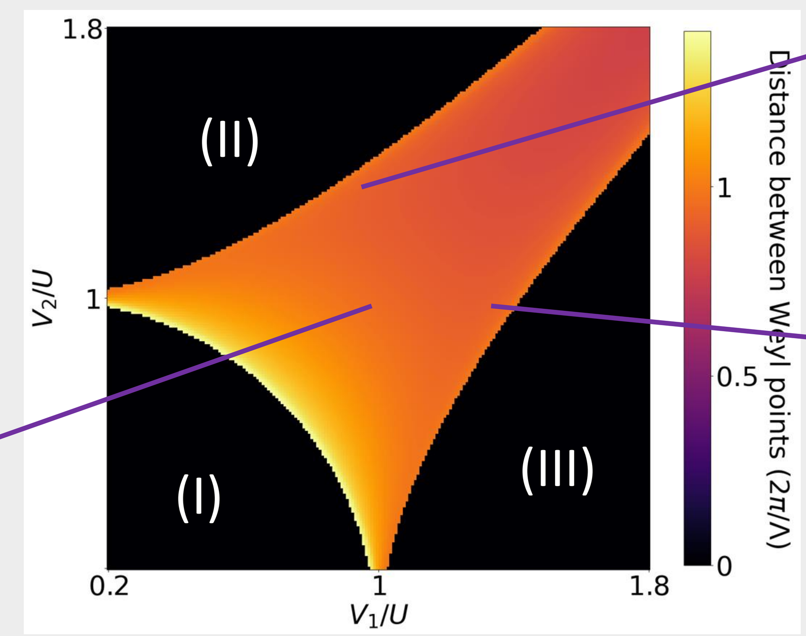
Parameters were obtained from the monolayer & bilayer cases.

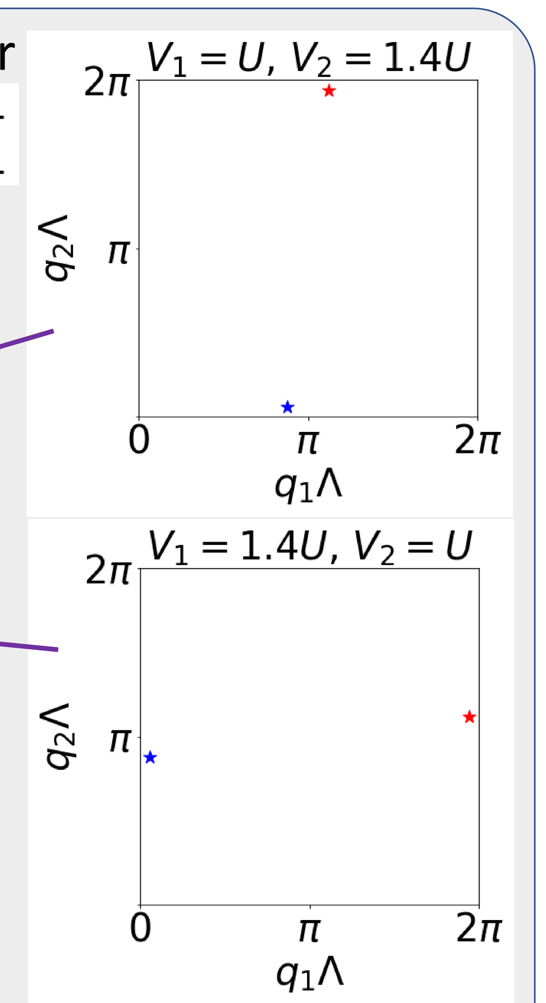
Good agreement

III. Weyl points at $k = 0$

We examine the two Weyl points of gap 3 in the $(k = 0)$-plane with varying V_1 & V_2, i.e., varying d_1 & d_2.







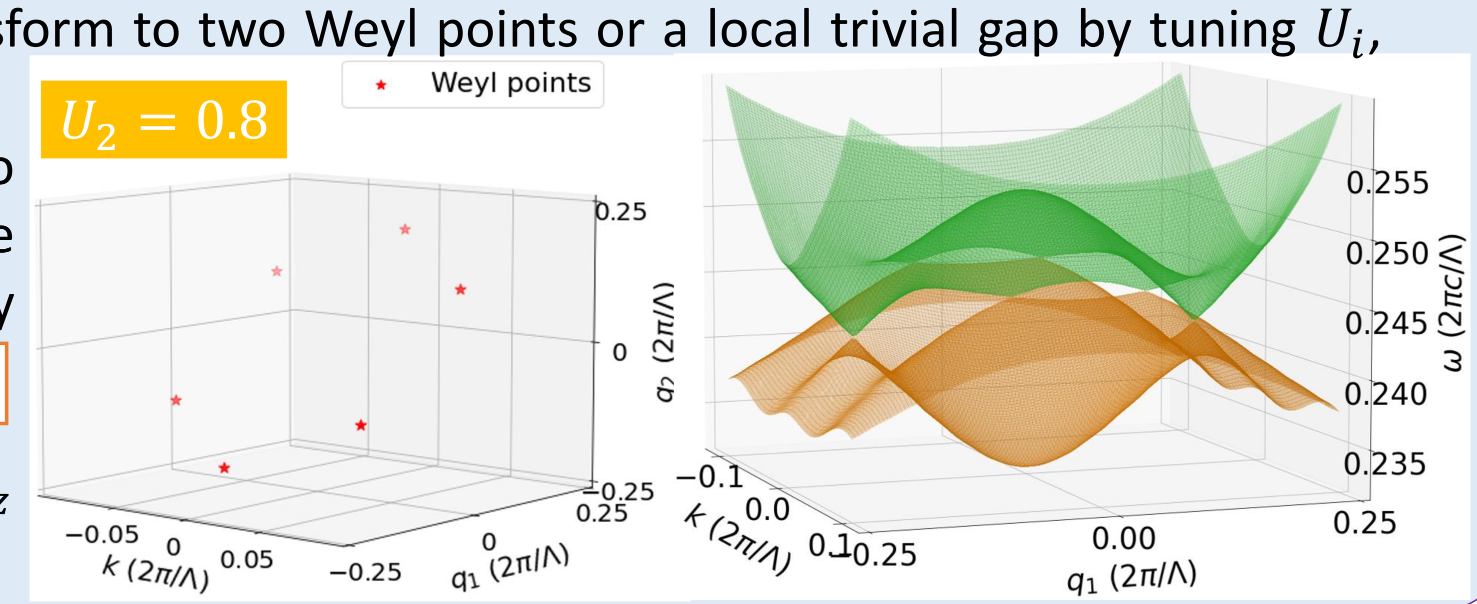
The Weyl points can be moved and rotated by **almost** 90°. They merge with each other at $(q_1, q_2) = (0,0)$, $(\pi, 0)$, and $(0, \pi)$ when the system approaches regions (I), (II), and (III), respectively. In these regions, the Weyl points are gapped out, which gives rise to the quantum anomalous Hall state(*).

IV. Semi-Dirac points

The semi-Dirac points can transform to two Weyl points or a local trivial gap by tuning U_i, i.e., changing κ_i

Example: if we let $U_1 = U_2 = U_3 = V_1 = V_2 = 1$, the two semi-Dirac points of gap 3 are located at $k_s = \pm 1$. When we add a small change in U_2 that $U_2 = 1 - \eta$, the low-energy physics near those points can be described by $k = \pm 1 + q_0$

$$H_\pm(\vec{q}) = \left(\pm 2q_0 - \frac{q_1^2 + q_2^2}{2}\right)\sigma_x - (q_1 - q_2)\sigma_y + 2(q_0 \mp \eta)\sigma_z$$



Discussion

- We theoretically study the spectral properties of a 1D system of trilayer photonic grating. By defining the interlayer displacements as two additional synthetic momenta, we find that the Weyl semimetal, nodal line semimetal, and quantum anomalous Hall phases can be realized in the 3D hybrid momentum space.
- We are in the process of simulating the Fermi arcs of heterostructures based on our system.
- This work is a stepping stone to studying the topology of 4D quantum Hall phase and 5D Weyl semimetal.

(*) visit this link for supplementary materials

References:
K. Y. Lee, et al., PRL 128, 053002 (2022)
D. X. Nguyen, et al., arXiv:2104.12774 (2021)
H. C. Nguyen, et al., arXiv:2111.02843 (2021)