Photoinduced Anomalous Hall Effect in Weyl Semimetal

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* Intense circularly polarized light will modify the band structure of WSM, its Berry curvature distribution, and leads to nonzero AHE

Weyl Electrons Meet Chiral Photons

When Chiral Photons Meet Chiral Fermions: Photoinduced Anomalous Hall Effects in Weyl Semimetals

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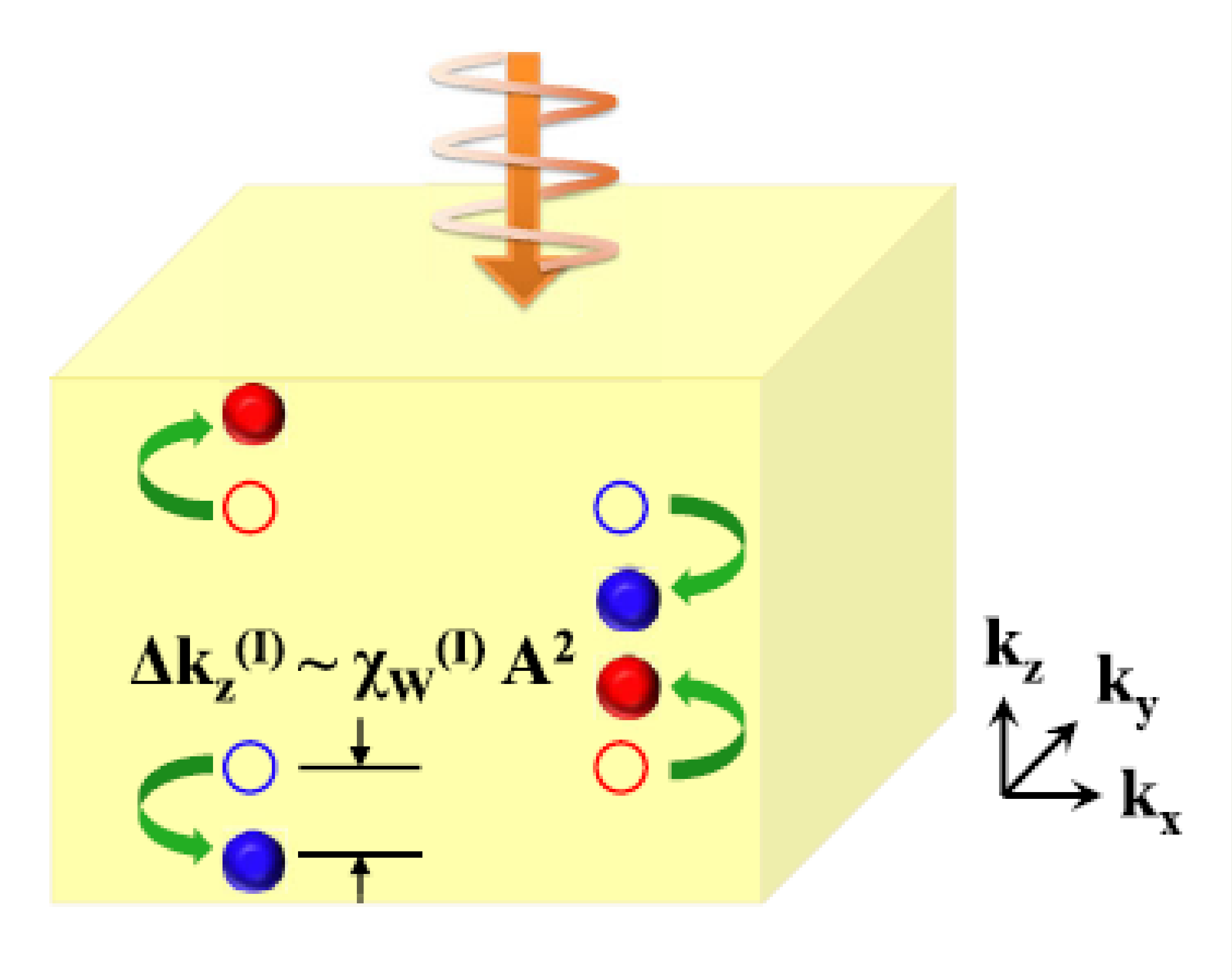
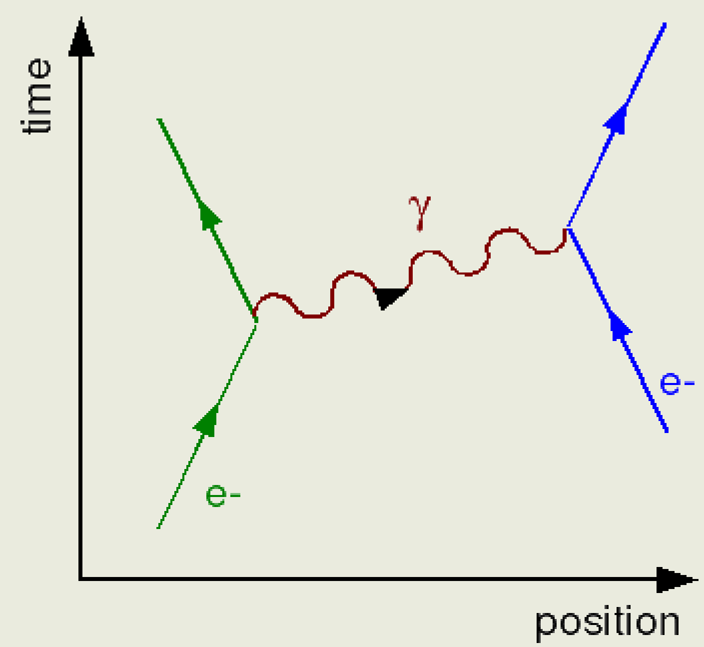


Schematics of the proposed setup

Electron – Photon Interaction in Condensed Matter

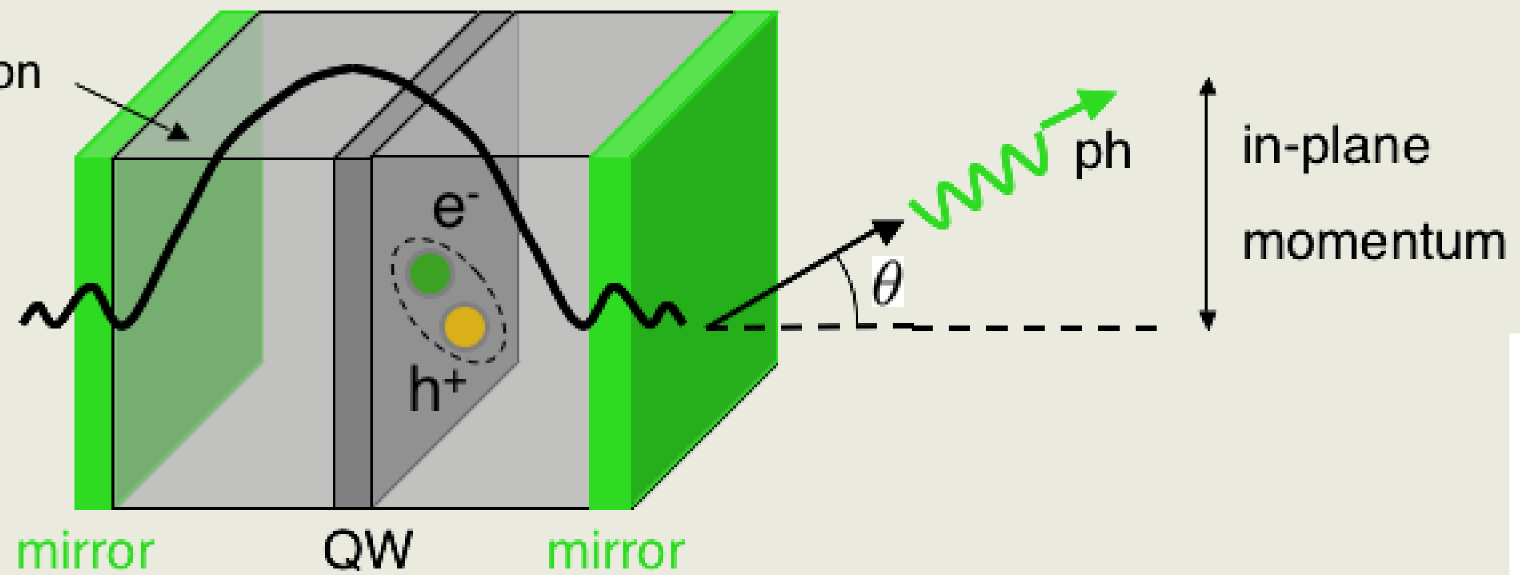
- e-photon interaction (in vacuum) is earliest form of many-body theory -> Quantum Electrodynamics



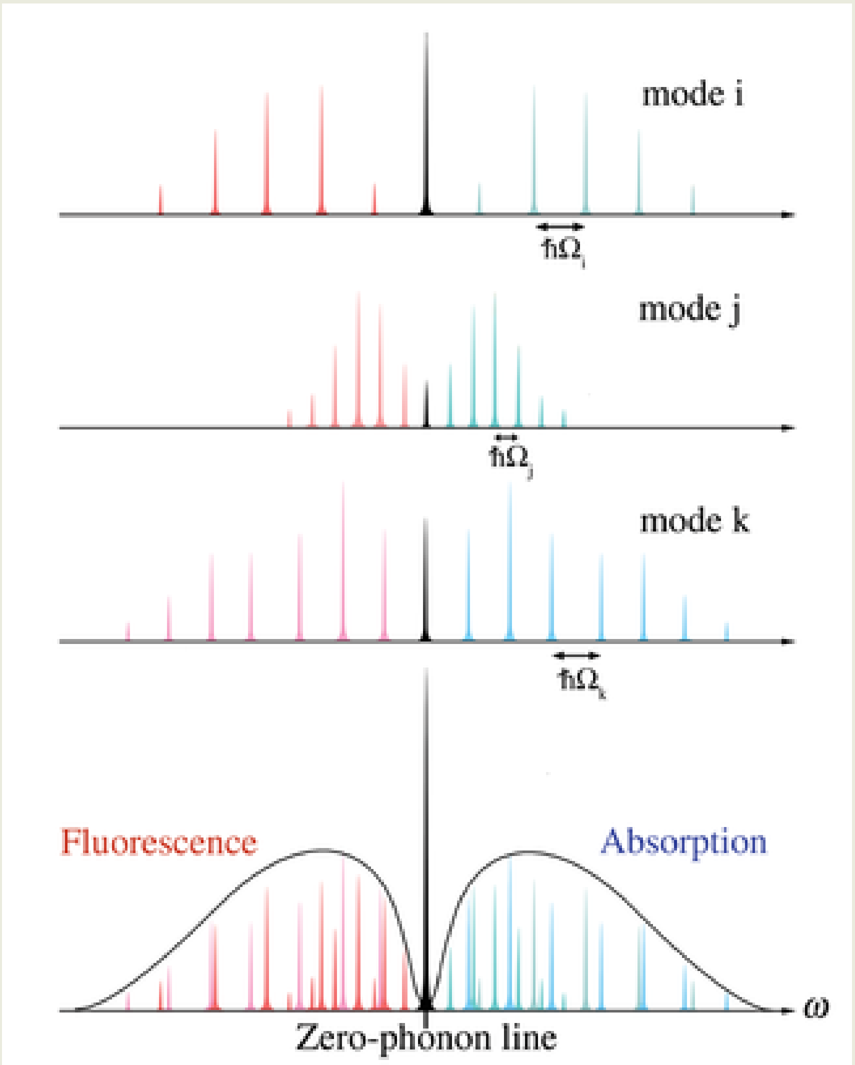
- e-photon interaction inside bulk matter received less attention than e-phonon interaction which has more direct structural, transport implications

Notion of Dressed (Renormalized) Electrons

- Polariton: photon creates e-h pair and forms a e-h-ph composite which travels through the matter



- e-phonon interaction leads to phonon sideband formation



Recent Trends

- These days we are interested in relativistic condensed matter: graphene, topological insulator, Weyl semimetal, etc.

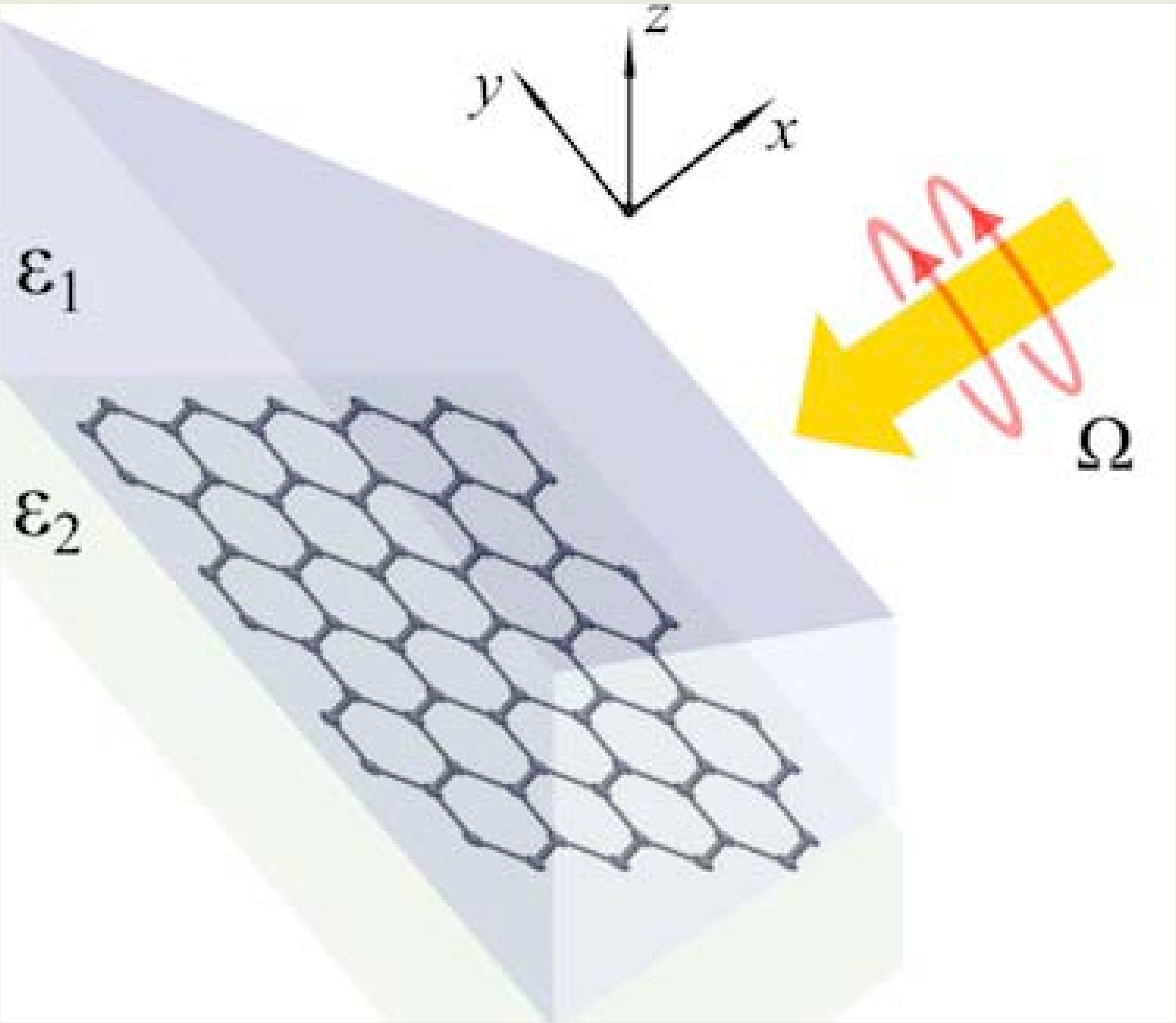
- Hamiltonian contains Pauli matrices; $H(k) = k*\sigma$; naturally contains notion of chirality

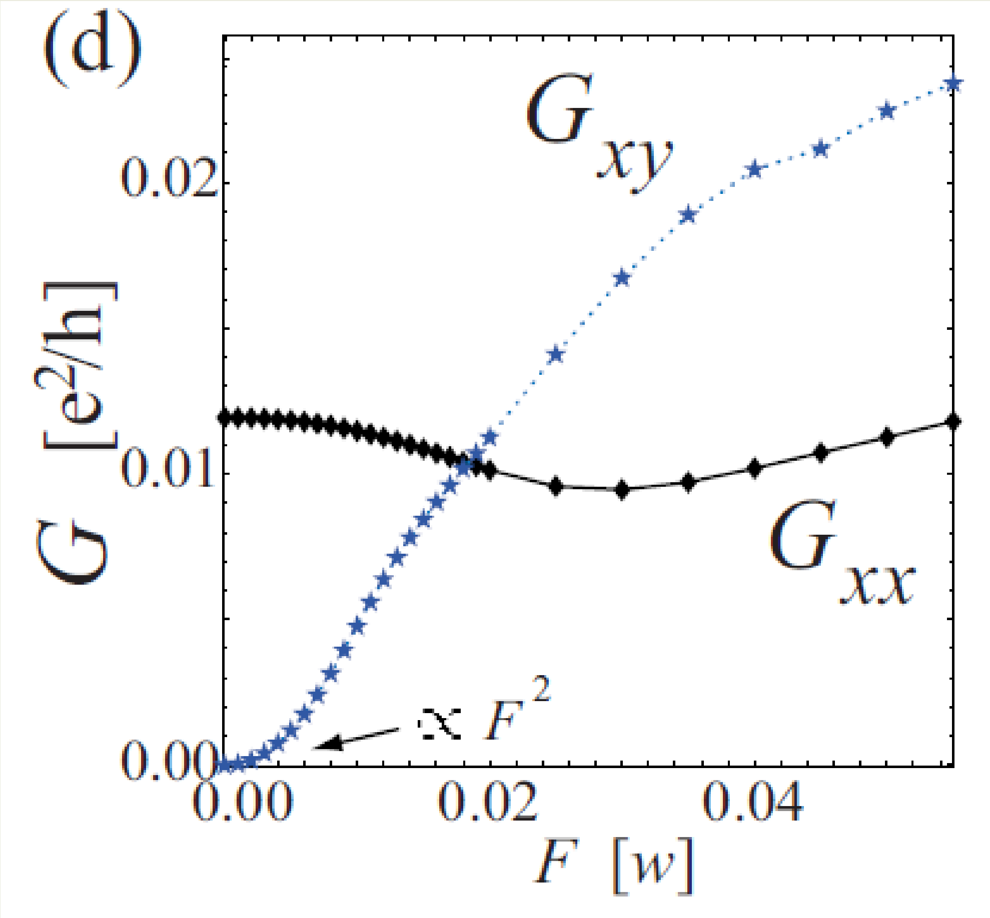
- Development of powerful pulse laser; refinement of pump-probe techniques over short time scales (< electron relaxation time)

chiral electrons + coherent photons

Graphene + Chiral Photons

- Oka+Aoki proposal to shine CP laser on graphene (2009); predicted gap opening at Dirac crossing





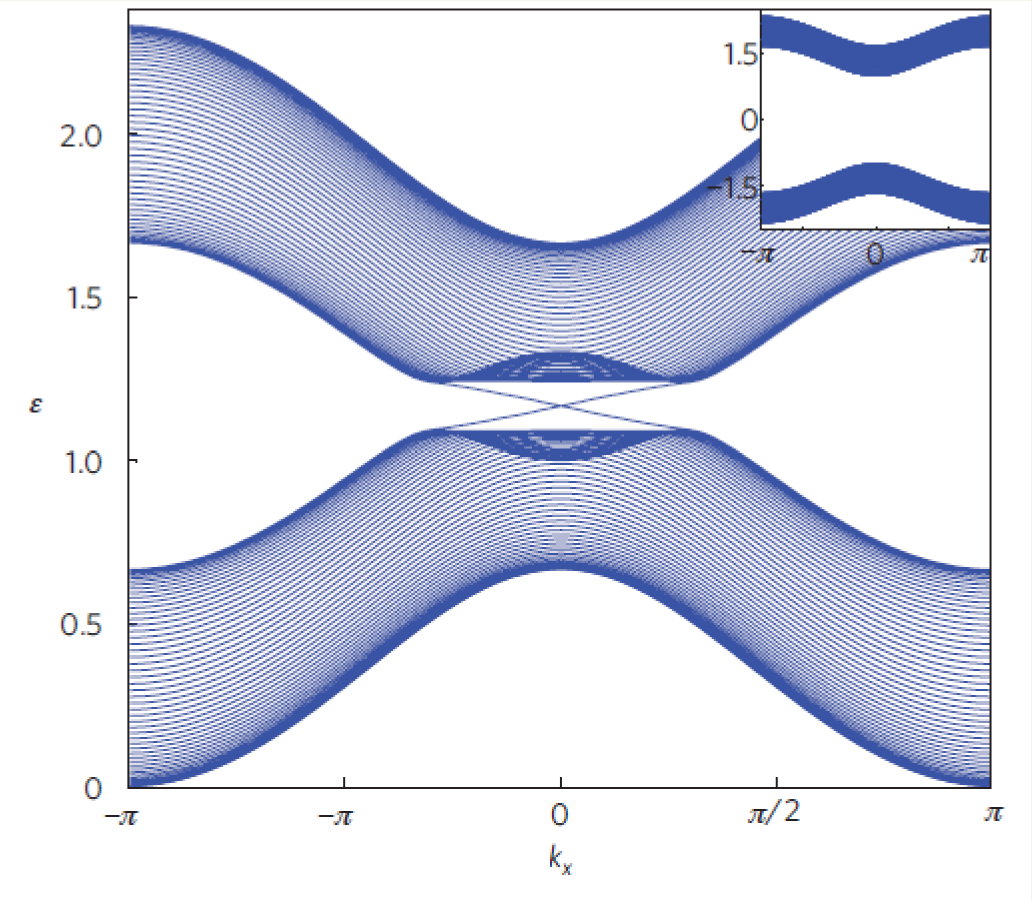
- (2+1)D Dirac gap opening implies parity anomaly -> Hall effect

2D Topological Insulator + (Chiral) Photons

- Inoue, Tanaka proposal to alter Chern number of 2D Haldane model by chiral photons (2010)

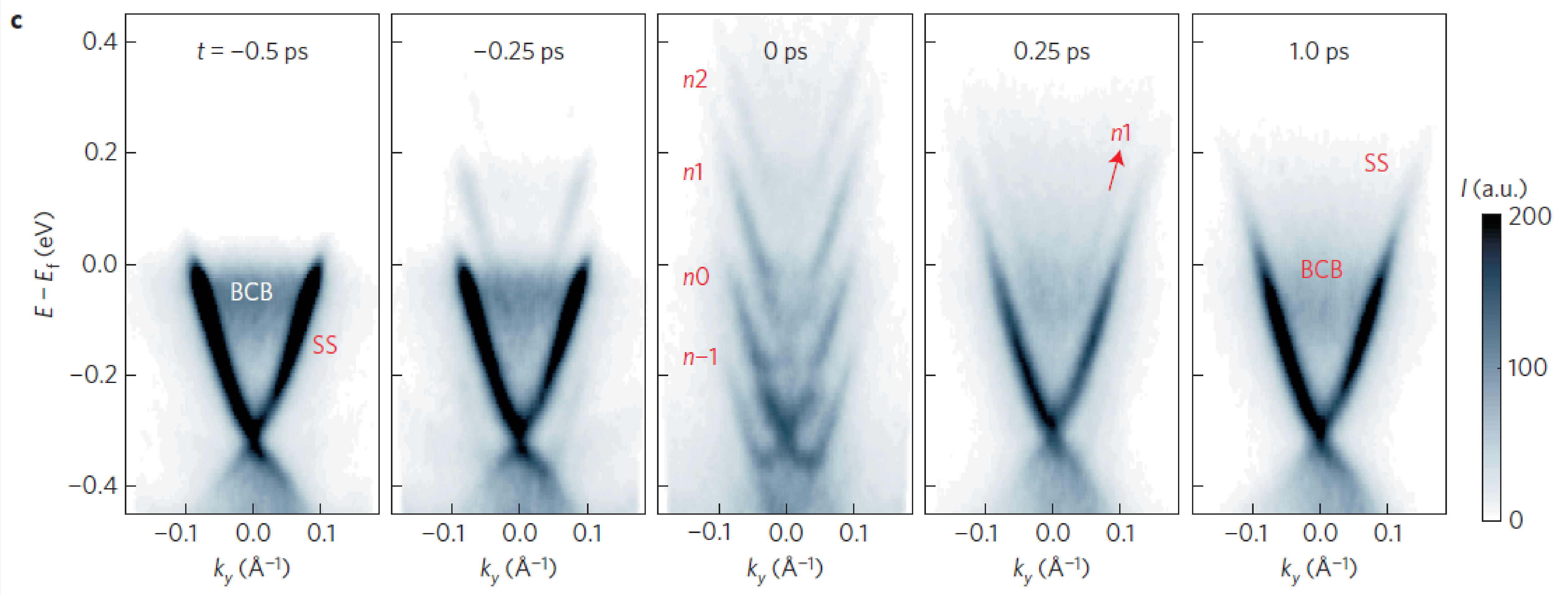
- Lindner, Refael, Galitski proposal to change Chern number of 2D HgTe/CdTe bands by e-photon coupling (2011)

Berry curvature distribution altered by electron-photon coupling



2D Surface of 3D Topological Insulator + (Chiral) Photons

- Same ideas works for 2D Dirac surface of TI -> gap opening at the Dirac point (Kitazawa et al. 2011; Fregoso et al. 2013)
- State-of-the-art pump probe ARPES (trARPES) on Bi2Se3 surface by Gedik group (2013, 2016)



Personal

- This is real science. Pump-probe ARPES is here to stay and will continue to surprise us.

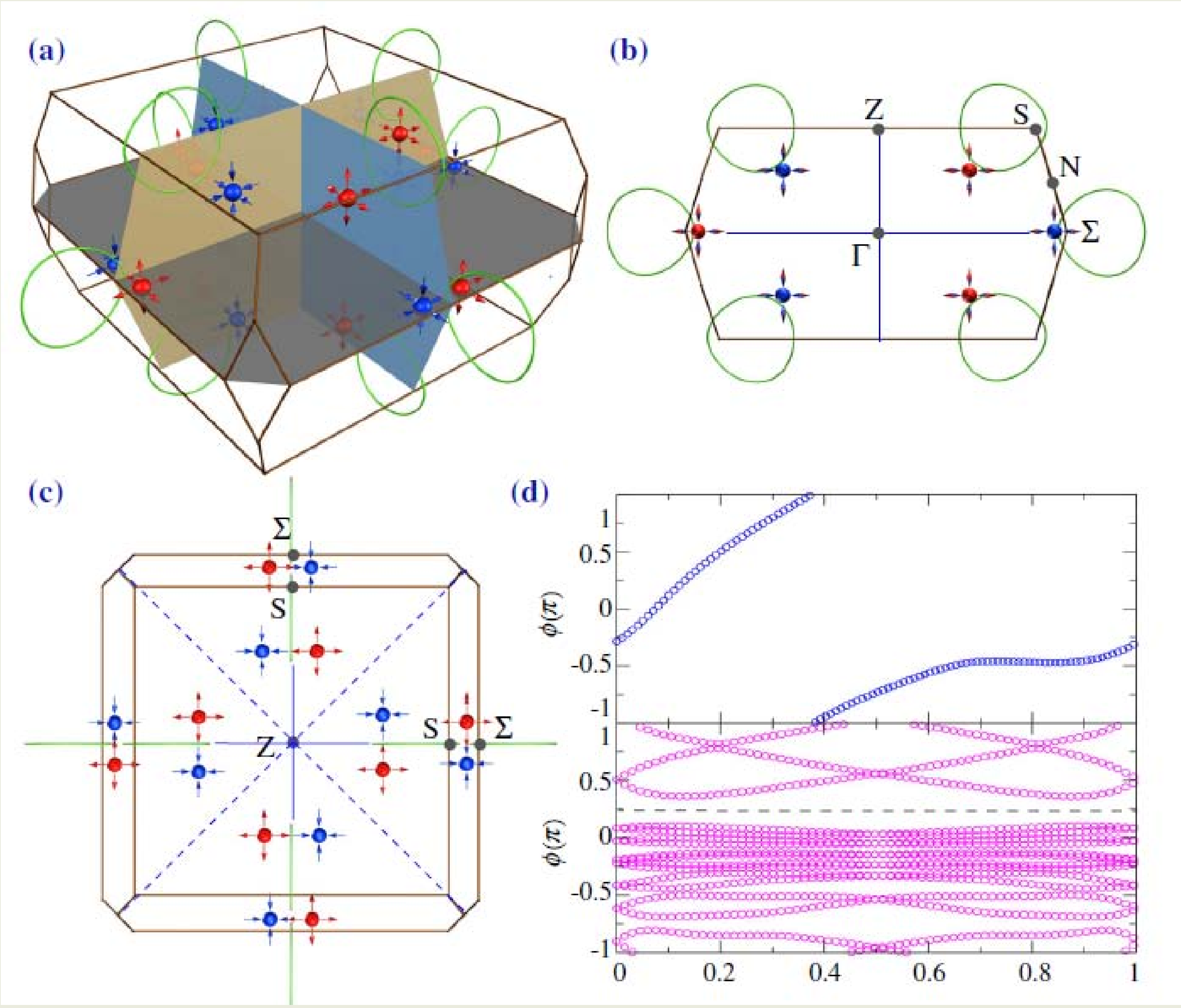
- How do the side bands form (when pump laser is on) and how do they die (when pump laser is off)? Transient dynamics. Time-dependent Green's function stuff.

- Quantizing the photons? Hard to do.

- Application to other Dirac matter? In 3D? That's Weyl.

WSM Review

- Semimetallic material with 2N point nodes at the Fermi level – N Weyl and N anti-Weyl pts.

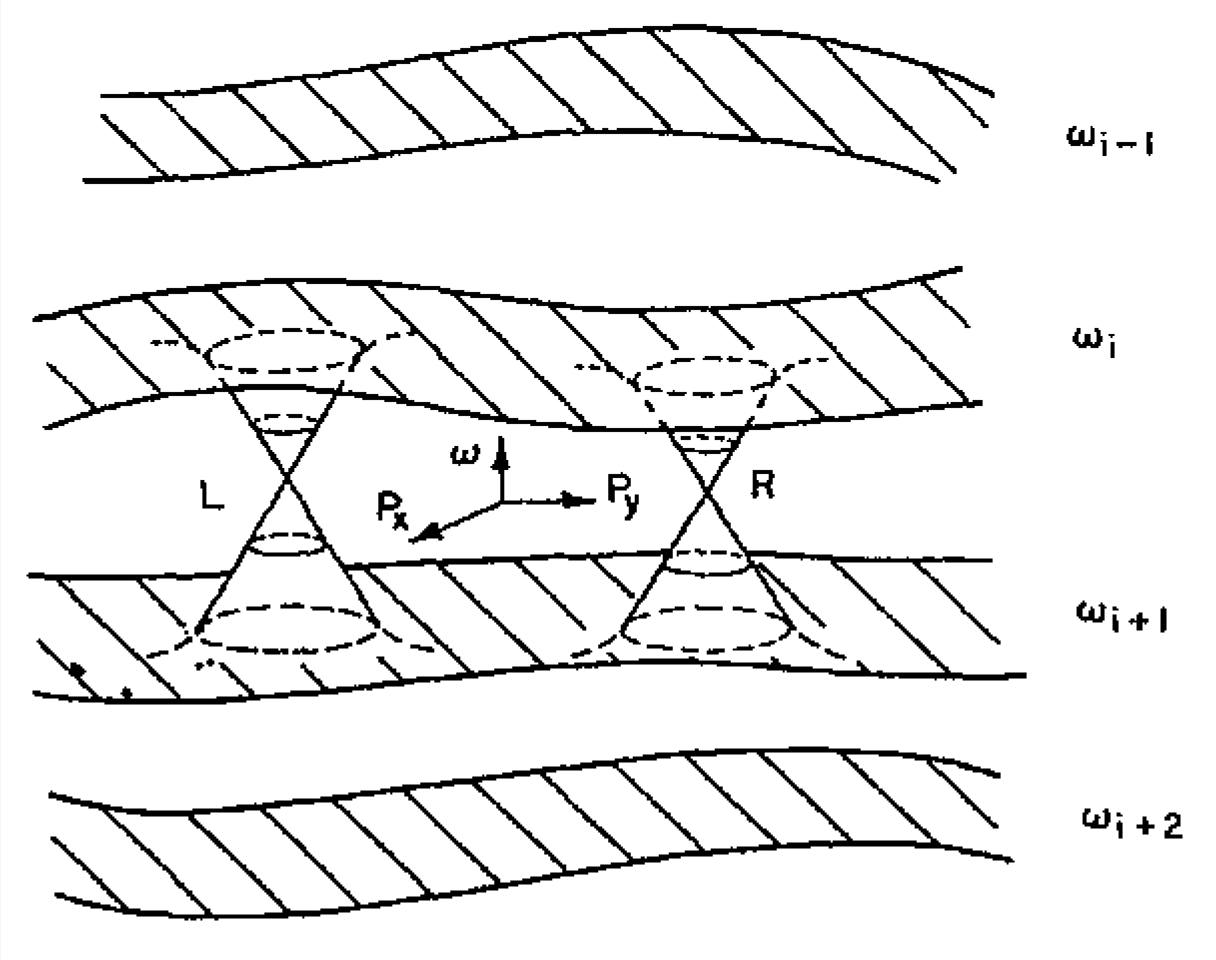


TaAs

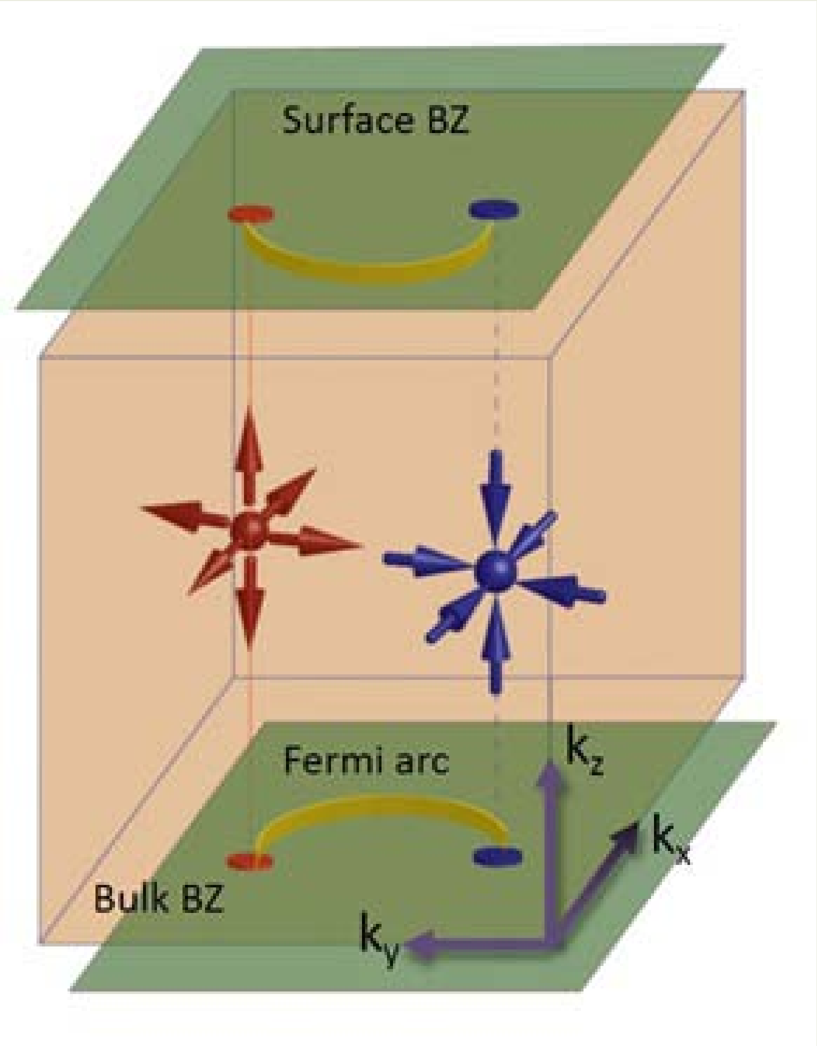
(PRX, 2015)

WSM Review

- Nielsen-Ninomiya (1983)



- WSM (2011-)



NN did not foresee surface Fermi arc states;

NN did not see close connection of their model to QHE

AHE in WSM

- General formula for Berry-curvature-induced AHE for 3D metal reduces to remarkably simple form for WSM (Ran, 2011)

$$\vec{\nu}_{\text{node}} = \sum_i (-)^{\xi_i} \vec{\mathbf{P}}_i$$

- A "dipole moment" formula for Chern vector: charge=+1,-1 for Weyl and anti-Weyl points, P is the momentum position of each Weyl point

- Generic ground state has (Chern vector) = 0; some symmetry-breaking required to give AHE

Symmetry breaking due to coupling to chiral photons leads to AHE in WSM

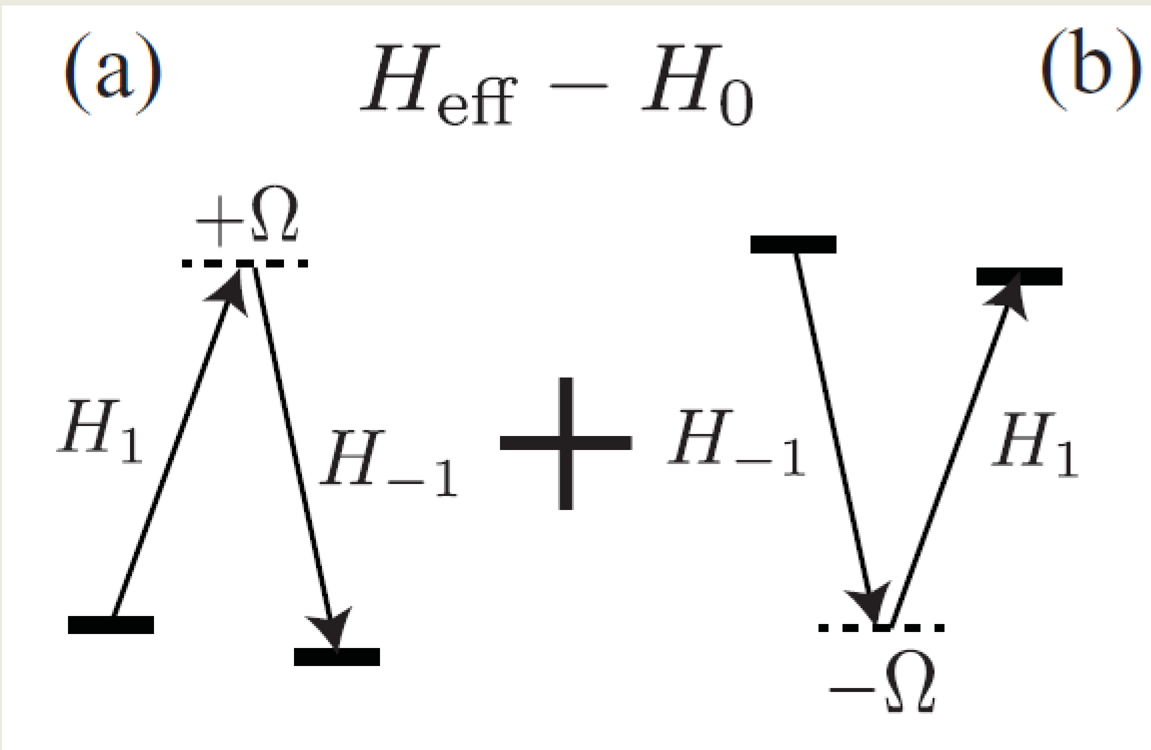
- Shift of the Chern vector can arise from shift of Weyl nodal position

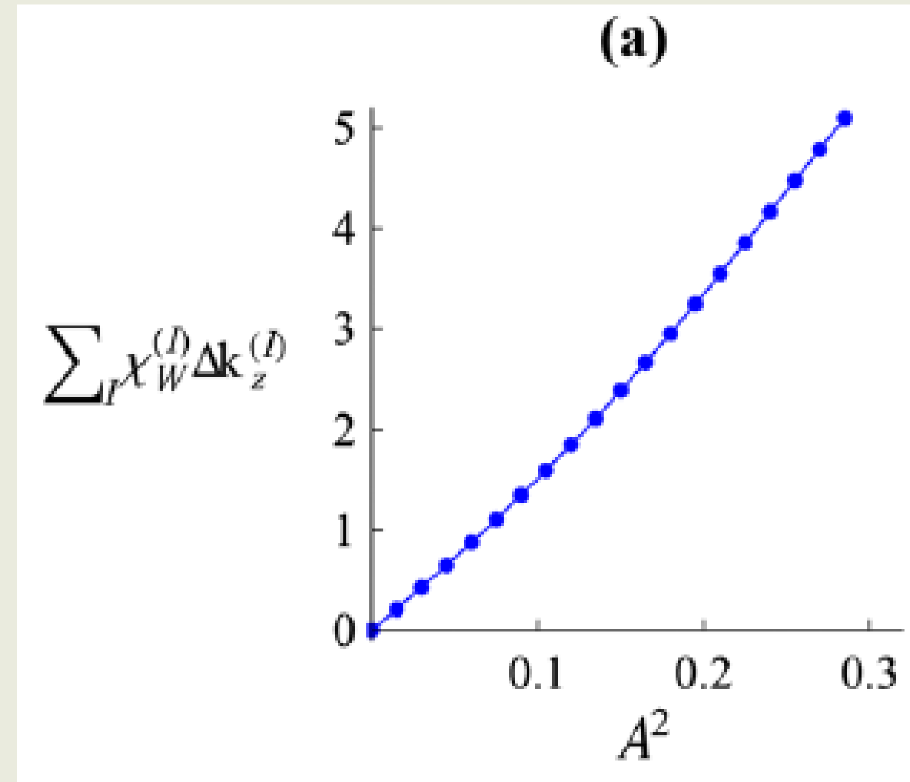
$$\delta\sigma_{ij} = \frac{e^2}{2\pi h}\epsilon_{ijk}\delta\nu_k, \quad \text{where } \delta\nu_k = \sum_I \chi_W^{(I)} \cdot \delta q_k^{(I)}$$

- Coupling light (vector potential) is same as shifting the momentum: $H(k+A) = \sigma^*(k+A)$

- A for external EM averages out to zero: $\langle A \rangle = 0$

- A net effect from second-order processes (virtual emission and re-absorption of photons or vice versa)

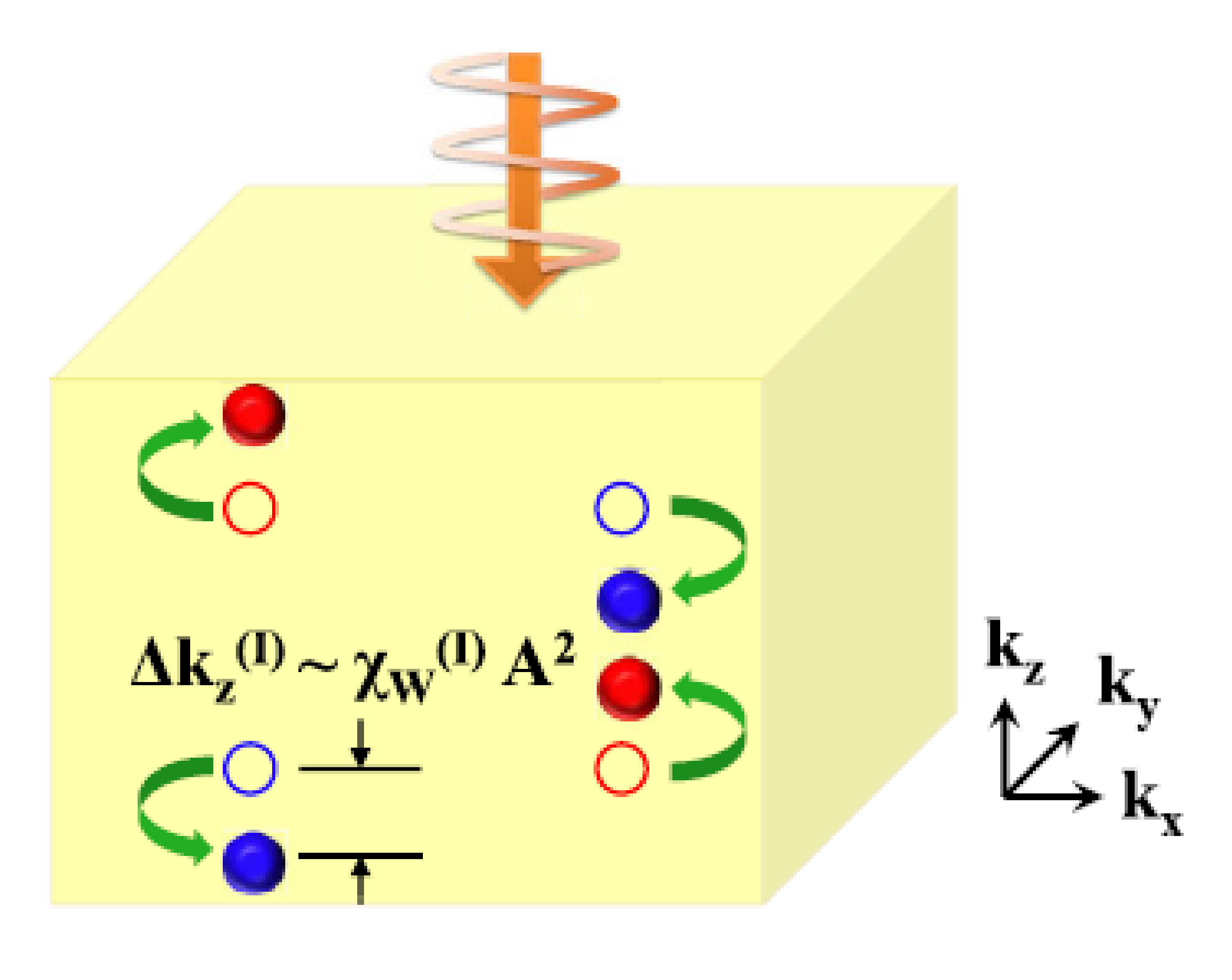




$$\delta\sigma_{ij} = \frac{e^2}{2\pi h}\epsilon_{ijk}\delta\nu_k, \quad \text{where } \delta\nu_k = \sum_I \chi_W^{(I)} \cdot \delta q_k^{(I)}$$

- When we do the math, we find net shift of Chern vector proportional to laser intensity

Chirality-selective Shift



- Positive charge moves one way, negative charge moves the other way; additive contribution to Chern vector

$$\sigma_{xy} = \frac{e^2}{2\pi h}(8 \times \delta q^P + 16 \times \delta q^Q)$$

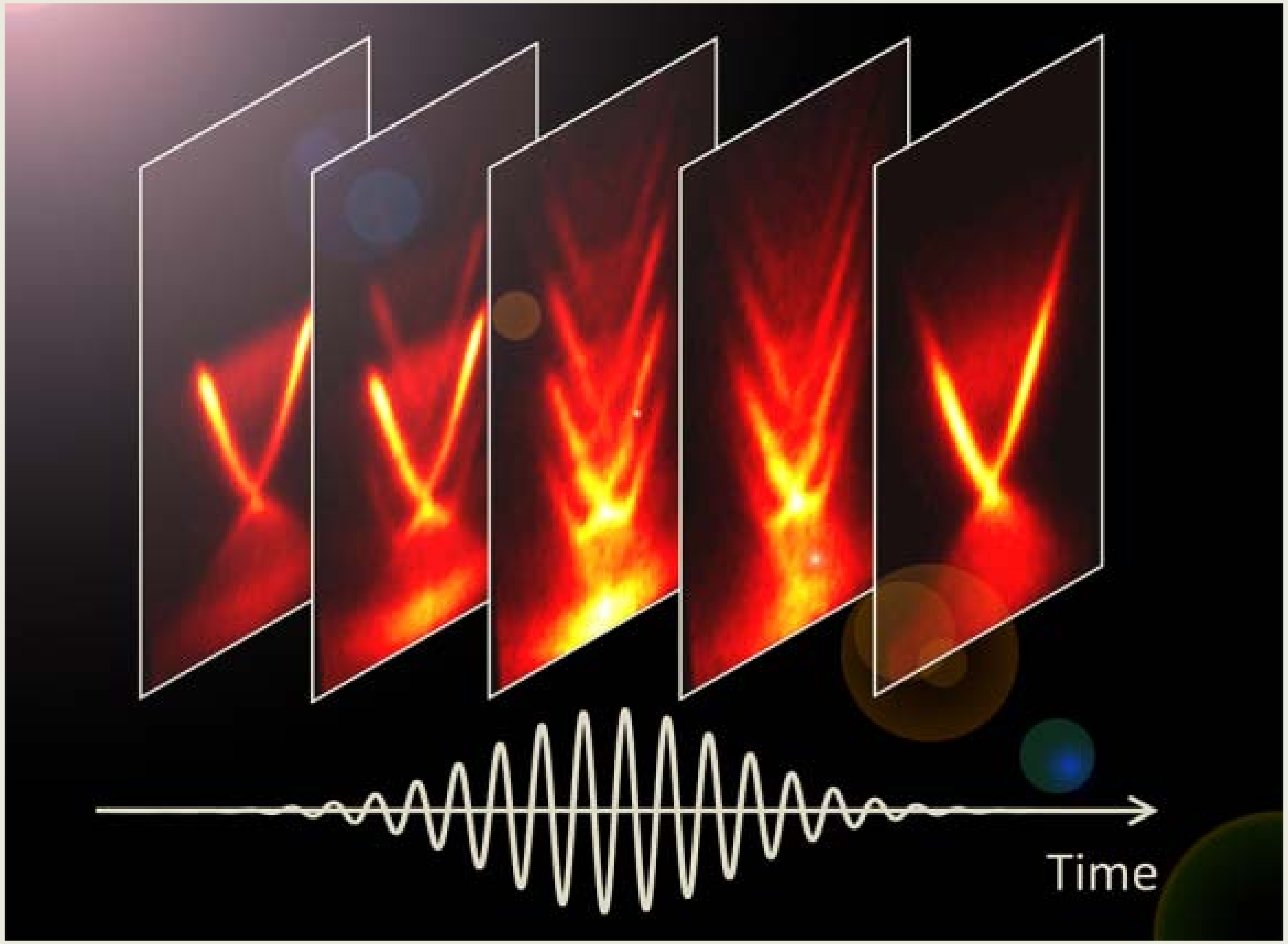
- Having many Weyl modes is good for observation of AHE

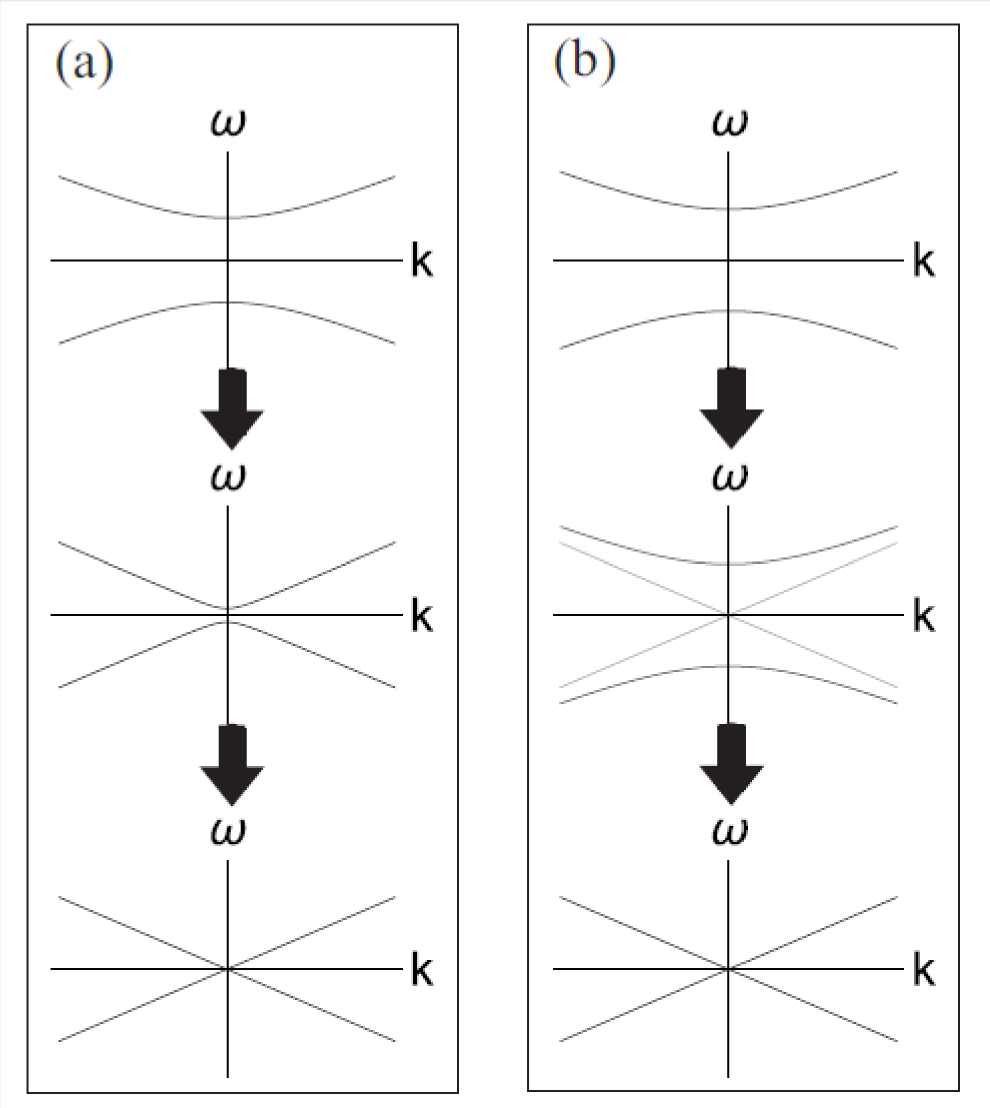
Summary: Part I

- Take a slab of WSM, shine intense laser on it; measure Hall current in the plane of the slab (order-of-magnitude estimate checks out)

- We do not know the impact on Fermi arc states yet; inconsequential? Geometry-dependent? (very little discussion on arc vs. bulk transport contributions)

Two Cartoon Scenarios





- Preprint by Oh,Higashi,Chan,Han (16): Dirac bands must close as pump laser dies; Two possible paths back to the ground state. Which path is physically realized?

We need some tools…

- Even the sideband spectral function is difficult to reproduce from calculation; let alone its transients

- Only known case with exactly solved sidebands is Lang-Firsov model (1962)

- We tried to see if time-dependent LF can be solved exactly

Time-dependent Lang-Firsov and its Green function

- Time-independent LF (1962):

$$H = \varepsilon c^\dagger c + \omega_0 a^\dagger a + \omega_0 c^\dagger c \left(g^* a + g a^\dagger\right)$$

- Time-dependent LF (2016):

$$H(t) = \varepsilon c^\dagger c + \omega_0 a^\dagger a + c^\dagger c \omega_0 \left(g^*(t) a + g(t) a^\dagger\right)$$

- LF model = Single fermion level coupled to a single harmonic oscillator

Adiabatic Two-time Green function

- Time-dependent LF:

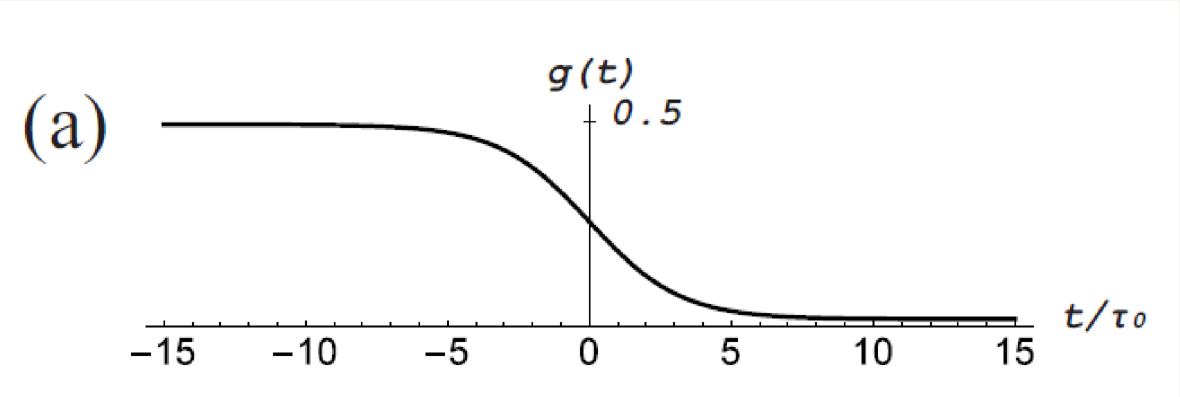
$$H(t) = \varepsilon c^\dagger c + \omega_0 a^\dagger a + c^\dagger c \omega_0 \left(g^*(t) a + g(t) a^\dagger\right)$$

- Adiabatic Green function (arXiv:1601.04872)

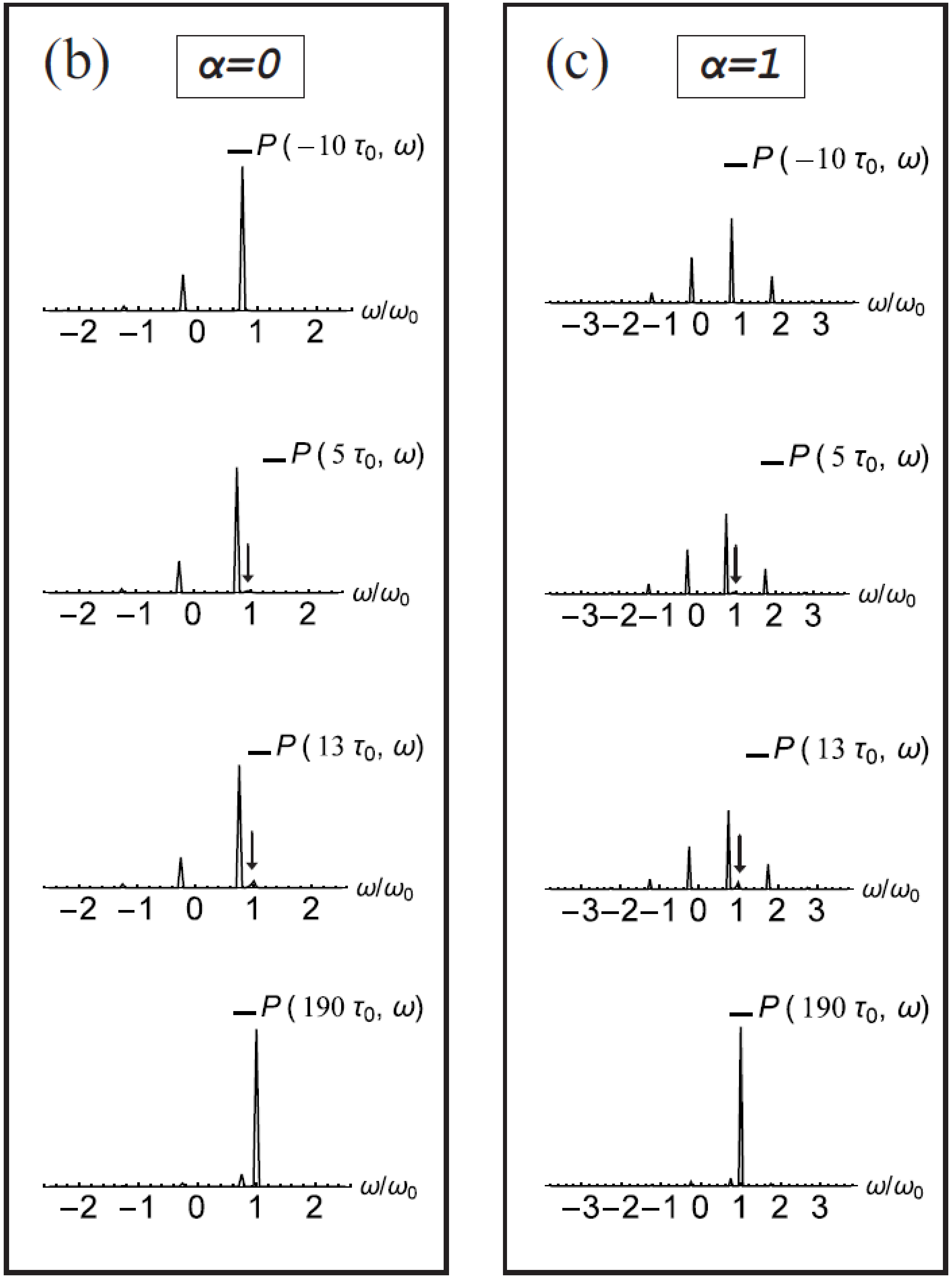
$$\begin{aligned}
&G^{(0)}(t,t') \\
&= -i e^{-i\int_{t'}^{t} dt_1 [\bar{\varepsilon}(t_1) - |g'(t_1)|^2/\omega_0]} \langle \alpha | X(t) c c^\dagger X^\dagger(t') | \alpha \rangle, \\
&\langle \alpha | X(t) c c^\dagger X^\dagger(t') | \alpha \rangle = \\
&\exp\left[[g(t)]^* g(t') e^{-i\omega_0 (t-t')} - \frac{1}{2}\left(|g(t)|^2 + |g(t')|^2 \right) \right] \\
&\times \exp\left[\alpha e^{i\omega_0 t_0} \left([g(t)]^* e^{-i\omega_0 t} - [g(t')]^* e^{-i\omega_0 t'} \right) \right] \\
&\times \exp\left[-\alpha^* e^{-i\omega_0 t_0} \left(g(t') e^{i\omega_0 t'} - g(t') e^{i\omega_0 t'} \right) \right]. \qquad (3.22)
\end{aligned}$$

Adiabatic evolution of spectral weights

- Gradually turn off g(t):



- Watch how the spectral weight evolves over time



Ideas behind Adiabatic Green function

- Recall Berry's solution of adiabatic problem:
- Berry was looking for solution to adiabatic time-dependent Schrodinger equation

$$i\partial_t |\psi(t)\rangle = H[\mathbf{R}(t)]|\psi(t)\rangle$$

- What if at each instant in time, H(t) is exactly solvable?

$$H[\mathbf{R}(t)]|n[\mathbf{R}(t)]\rangle = E_n[\mathbf{R}(t)]|n[\mathbf{R}(t)]\rangle$$

- Neither energy, nor eigenstates, these are contraptions to allow an exact adiabatic solution.

- Exact, adiabatic solution:

$$|\psi(t)\rangle = e^{-i\int_0^t dt' E_n[\mathbf{R}(t')]} e^{i\gamma_n(t)} |n[\mathbf{R}(t)]\rangle$$

$$\frac{d\gamma_n(t)}{dt} = i\langle n[\mathbf{R}(t)]| \frac{\partial}{\partial \mathbf{R}(t)} |n[\mathbf{R}(t)]\rangle \cdot \frac{d\mathbf{R}(t)}{dt}$$

- Apply the same idea, to time-dependent many-body H(t), exactly solvable at each instant of time t:

$$H(t) = \varepsilon c^\dagger c + \omega_0 a^\dagger a + c^\dagger c \omega_0 \left(g^*(t) a + g(t) a^\dagger\right)$$

- We can work out the propagator U(t,t') exactly in the adiabatic limit

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Summary: Part II

- As studies of ultrafast dynamics and time-dependent ARPES becomes commonplace, there is growing need to develop tools to compute Green function of time-dependent manybody system
- Keldysh (to take care of time dependence) + DMFT (to take care of strong correlation) method pioneered by Devereaux, Freericks
- Hopefully our method (=adiabatic Green's function) finds some use for topological bands under irradiation