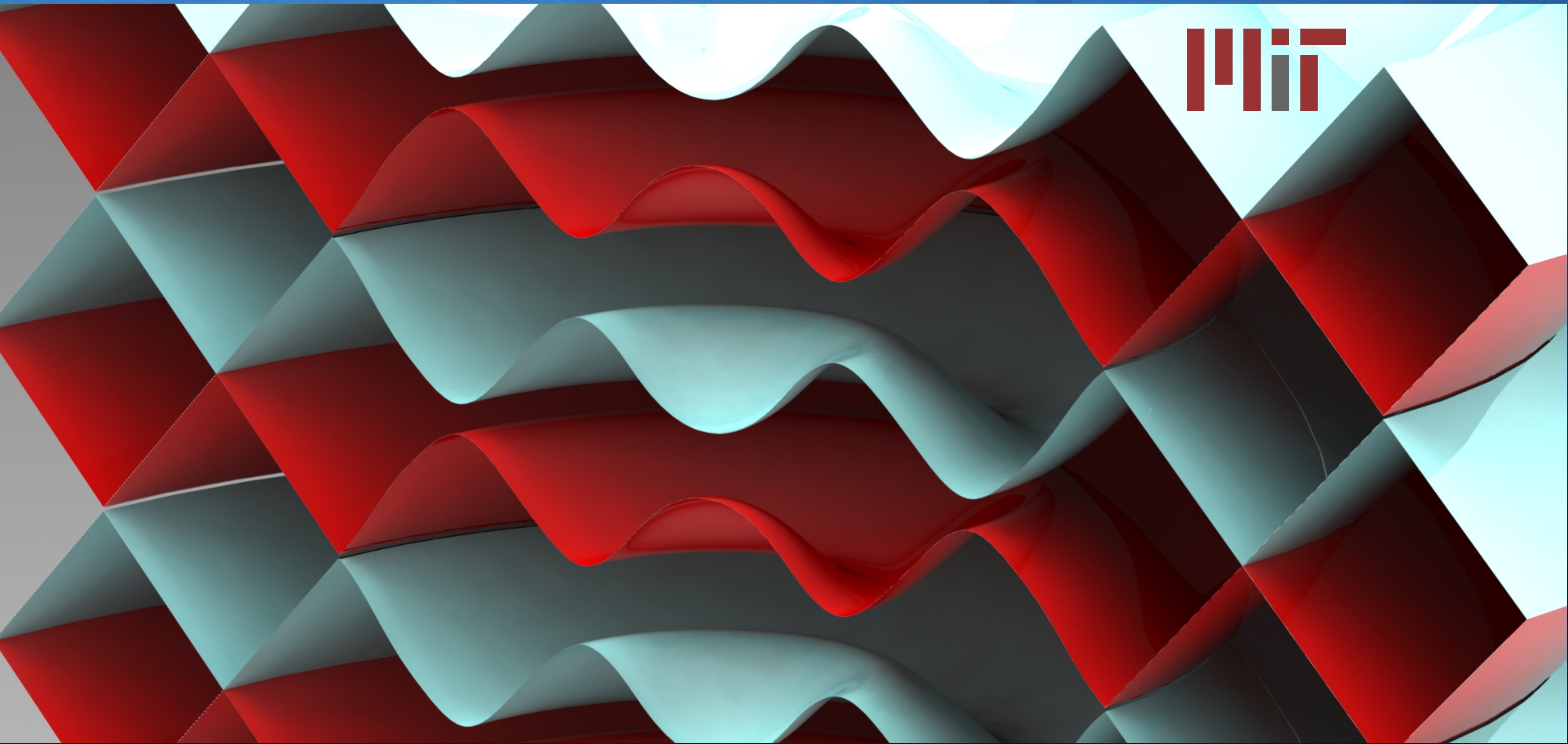
Observation of Floquet-Bloch States in Topological Insulators

Nuh Gedik



Acknowledgements

Experiment:

Yihua Wang

Materials growth:

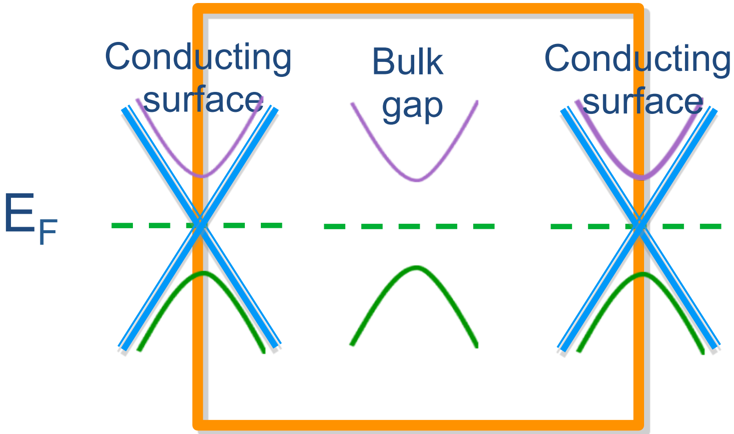
Hadar Steinberg Pablo Jarillo-Herrero

Funding

Stimulating discussions with:
Liang Fu, Takuya Kitagawa, Takashi Oka, Benjamin Fregoso and Victor Galitski

“Observation of Floquet-Bloch states on the surface of a topological insulator”
Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 342,** 453 (2013)

3D Topological Insulator

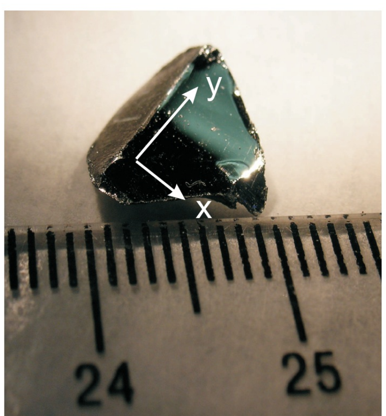


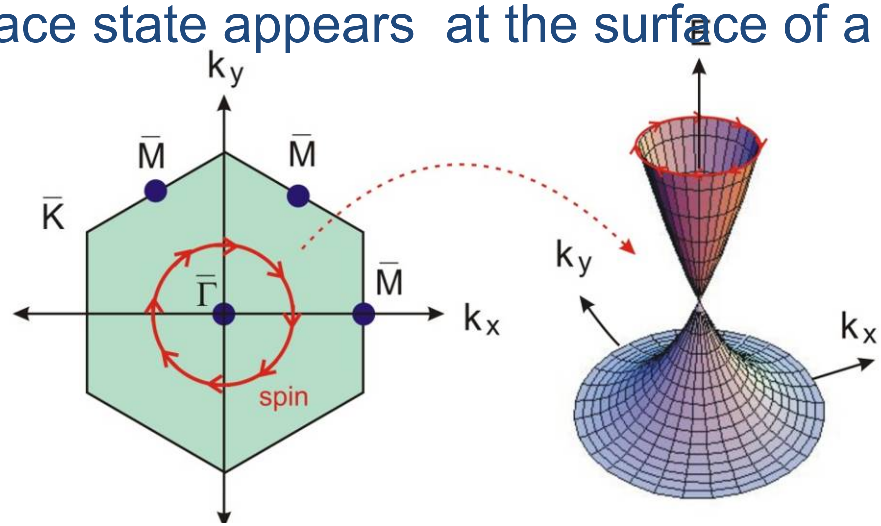
Some known TI materials:

- **Bi_2Se_3**, Bi_2Te_3
- Sb_2Te_3
- $Bi_{1-x}Sb_x$

Hundreds other materials recently proposed

A gapless metallic surface state appears at the surface of a TI!



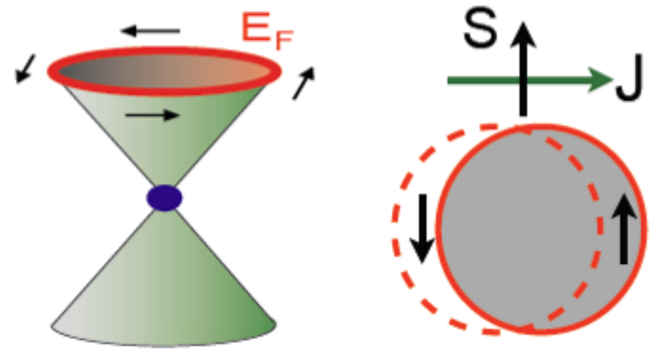


Properties of 2D helical Dirac fermions

Charge current ∝ Magnetization

$\vec{j} = v_F \vec{S} \times \hat{z}$ (*Raghu et al, 2009*)

Potential new functionalities for spintronic and opto-electronic devices

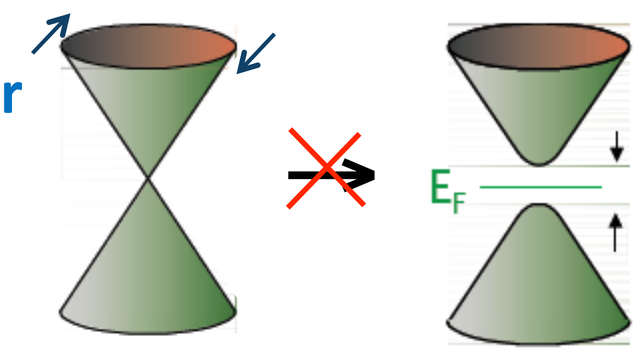


Absence of backscattering

High mobility ~ 10,000 cm^2/V·s (*Qu et al, 2010*)
Potential for robust and low power electronics

Immunity against non-magnetic disorder

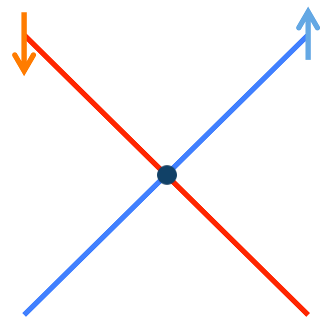
Surface states are protected by time reversal symmetry and protected against non-magnetic disorder



Hasan and Kane Rev.Mod.Phys.82:3045,2010

Topological insulator phase is protected by time reversal symmetry (TRS)

Kramers' Theorem: for spin 1⁄2 all eigenstates are at least 2 fold degenerate



$$|\chi\rangle \text{ and } \Theta\,|\chi\rangle \text{ must have the same energy } E!$$

Consequences for edge states :

- States at "time reversal invariant momenta" k*=0 and k*=π/a (=-π/a) are degenerate.
- The crossing of the edge states is protected
- Absence of backscattering, even for strong non-magnetic disorder

Breaking of TRS in TIs leads to fascinating effects

Breaking of TRS -> Massive Dirac Fermions

- Quantum anomalous Hall effect
- Magnetic monopole imaging
- Topological contribution to the Faraday and Kerr effects
- ...

How can we break TRS in TIs?

- We need a T breaking perturbation
  - Put TI in external magnetic field
  - Coat the surface of the TI with a ferromagnetic material
  - Magnetically dope the TI, magnetic impurities can order by interacting through Dirac Fermions
  - Or…

Can we break TRS with light?

- Circularly polarized light naturally breaks TRS
- Could we then use coherent interaction with light?
- This is done regularly in atoms and molecules
- The problem in solids is direct absorption and real transitions messes up the coherence
- We can choose off-resonant energy (i.e. below the band gap) to avoid direct transitions

Outline

- Coherent interaction of light with solids
- Time resolved ARPES
- Observation of Floquet-Bloch States
- Breaking of TRS by light in TIs
- Summary and Outlook

Coherent interaction of light with solids

- What if you shine non-resonant light into a solid?
- Light would provide perturbation that is periodic in time.
- Hamiltonian for solids is periodic in space

$$H(r+R) = H(r)$$

- We get Bloch states as solutions

$$\Psi_{nk}(r) = e^{ik\cdot r}u_{nk}(r)$$

$$u_{nk}(r+R) = u_{nk}(r)$$

Coherent interaction of light with solids

- Spatially periodic:

$$H(r+R) = H(r)$$

$$\Psi_{nk}(r) = e^{ik\cdot r} u_{nk}(r)$$

$$u_{nk}(r+R) = u_{nk}(r)$$

$$k \text{ and } k + nG$$
$$(G = 2\pi/R)$$

- Temporally periodic

$$H(t+T) = H(t)$$

$$\Psi_{\alpha}(t) = e^{-\frac{i}{\hbar}\epsilon_{\alpha}(t-t_0)} \phi_{\alpha}(t)$$

$$\phi_{\alpha}(t) = \phi_{\alpha}(t+T)$$

$$\epsilon_{\alpha} \text{ and } \epsilon_{\alpha} + n\hbar\omega$$
$$(\omega = 2\pi/T)$$

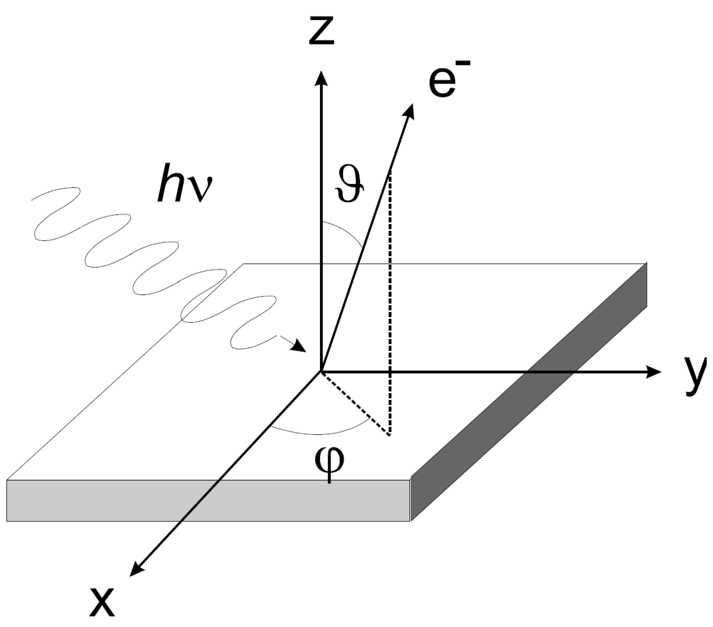
If you have both spatially and temporally periodic Hamiltonian, Eigenvalues are periodic both in k and E! -> Floquet-Bloch states!

Need to measure band structure under light excitation!

Outline

- Coherent interaction of light with solids
- Time resolved ARPES
- Observation of Floquet-Bloch States
- Breaking of TRS by light in TIs
- Summary and Outlook

Kinematics of the photoemission process



$$K_x = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\cos\varphi$$

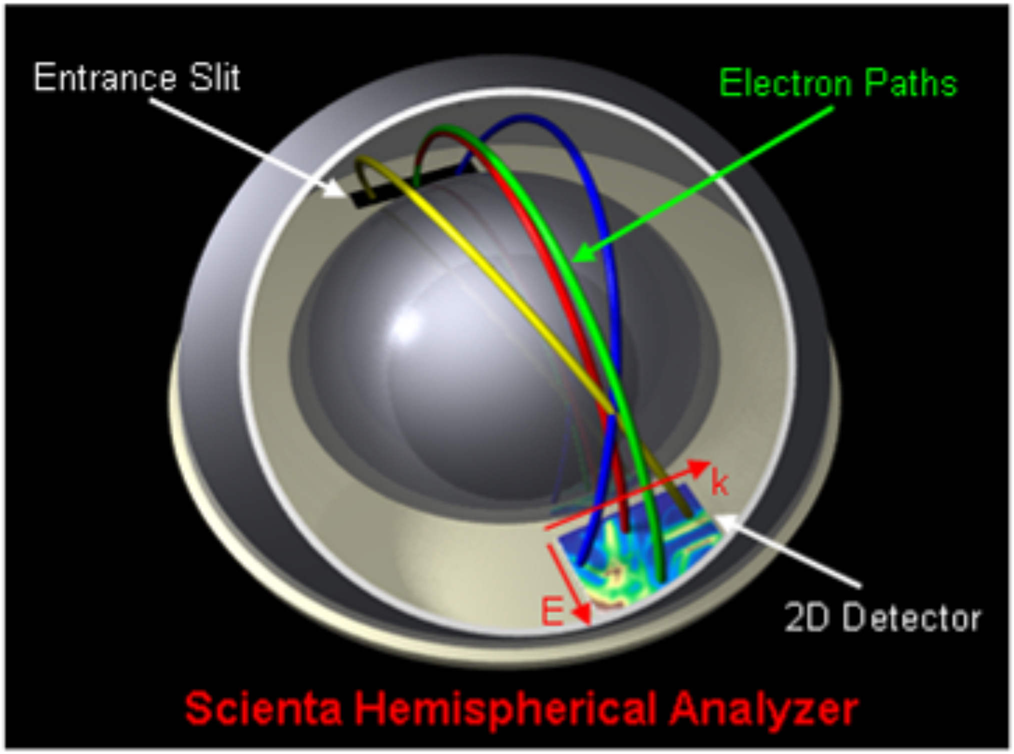
$$K_y = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\sin\varphi$$

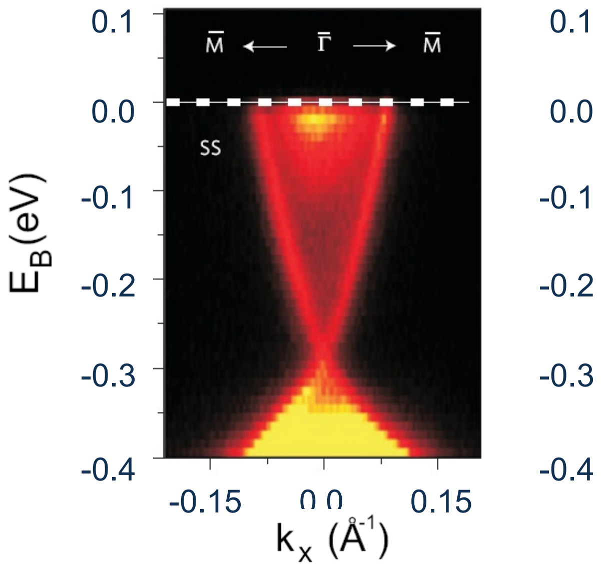
$$K_z = \frac{1}{\hbar}\sqrt{2mE_{kin}}\cos\vartheta$$

By measuring electron intensity as a function of E_{kin}, ϑ and φ, the band dispersion can be constructed.

Conventional photoemission technique

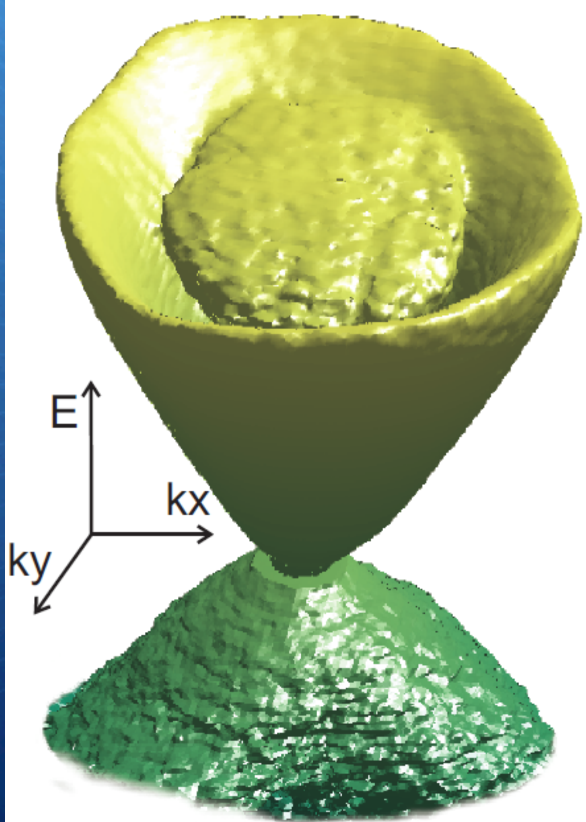
Resolve *ENERGY* vs. *1 momentum component*

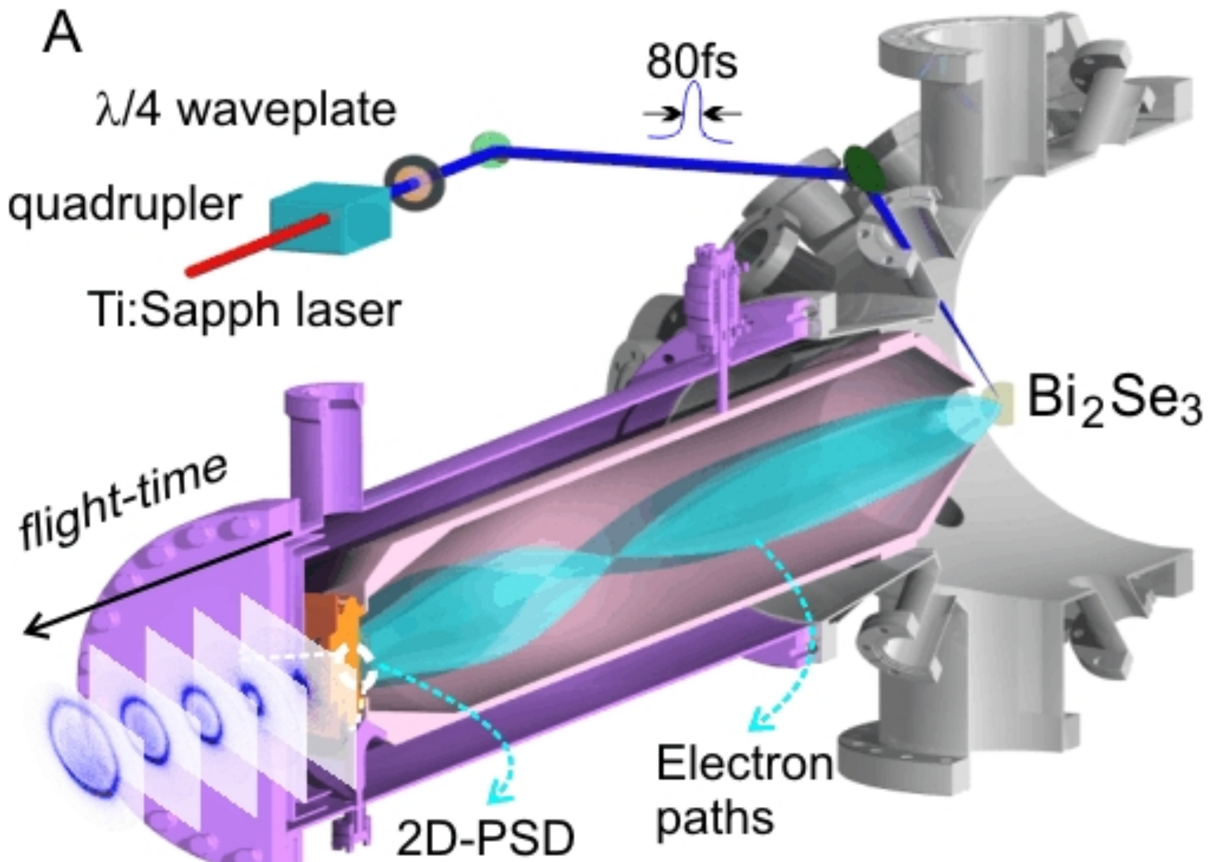




Sample data from Hsieh et. al.
(Hasan Group, Princeton)

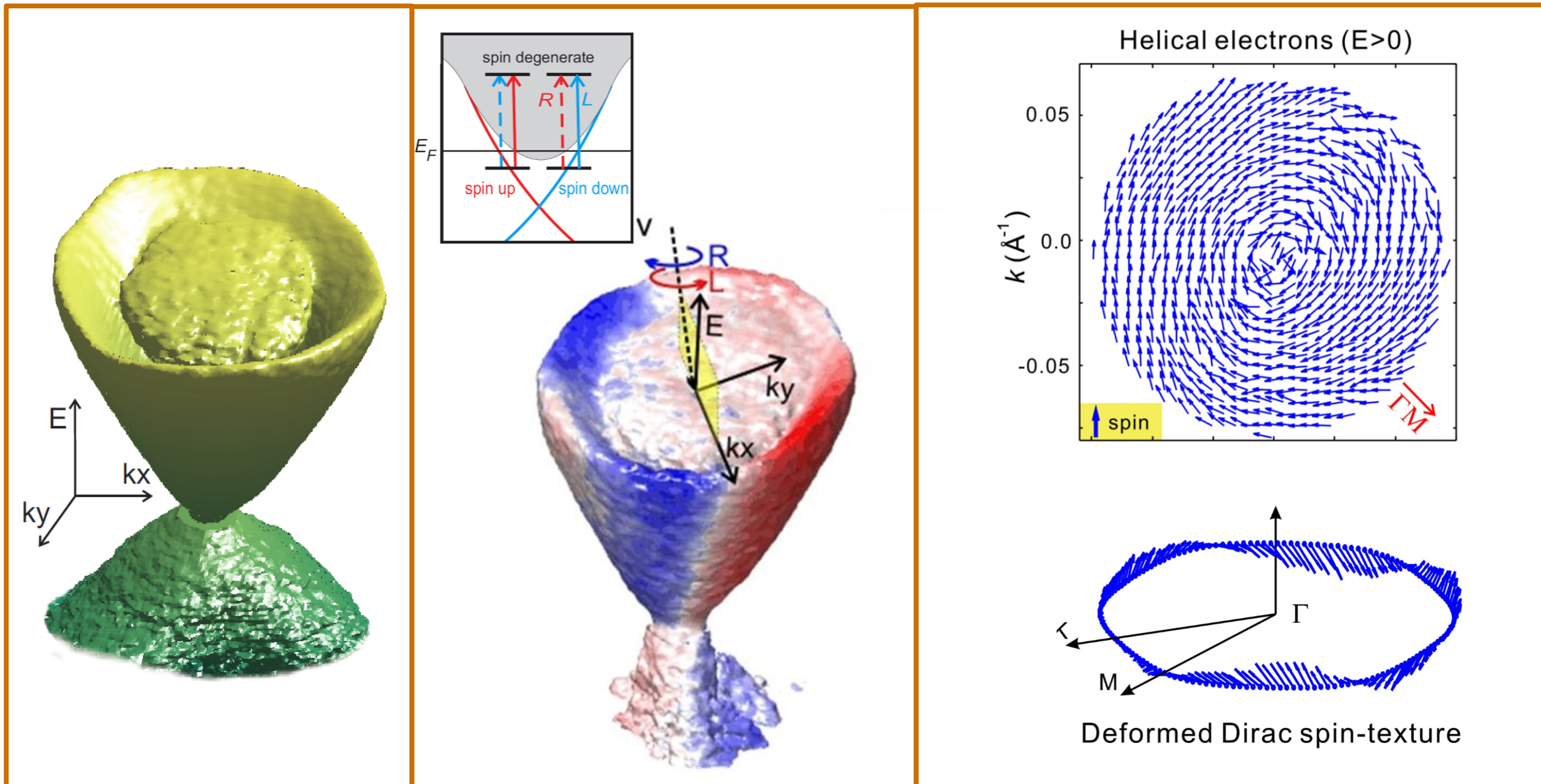
Novel Time-of-flight ARPES





Position sensitive detector

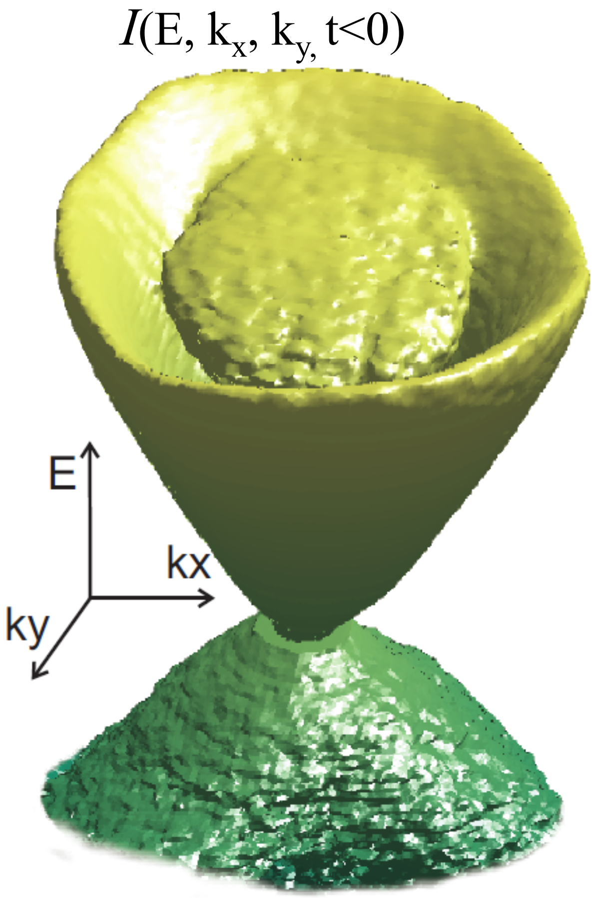
3D Band and Spin Mapping with Novel Time-of-flight ARPES

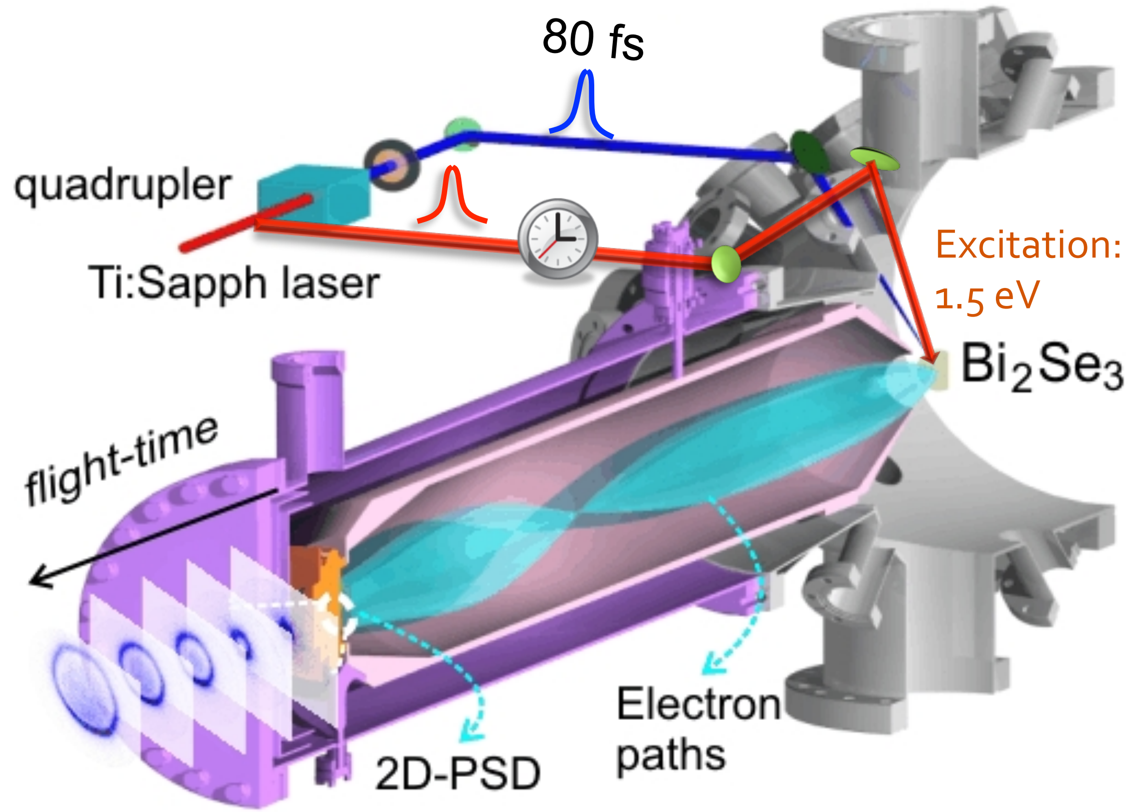


Y. Wang ...N. Gedik ***Phys. Rev. Lett. 107****,* 207602 (2011)

Wang ... Gedik ***Phys. Rev. Lett. 107****,* 207602 (2011)

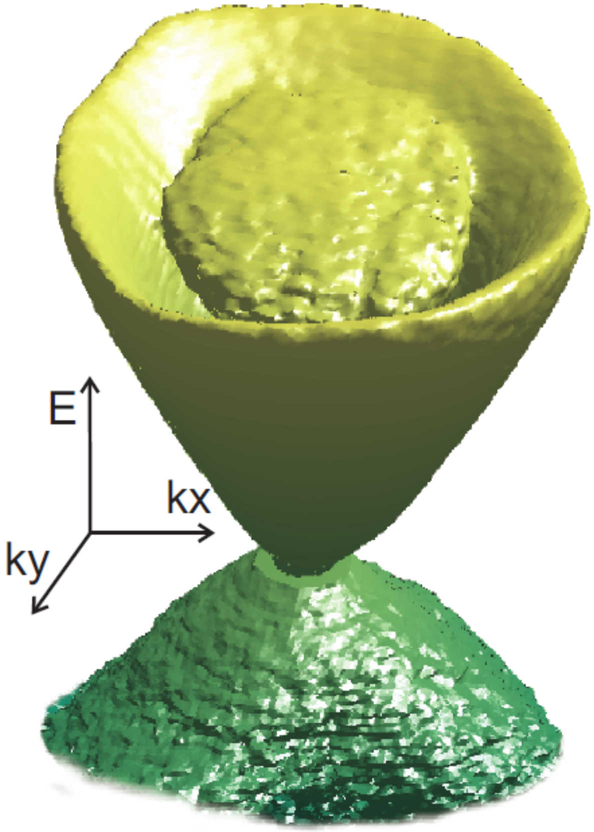
Time resolved ARPES



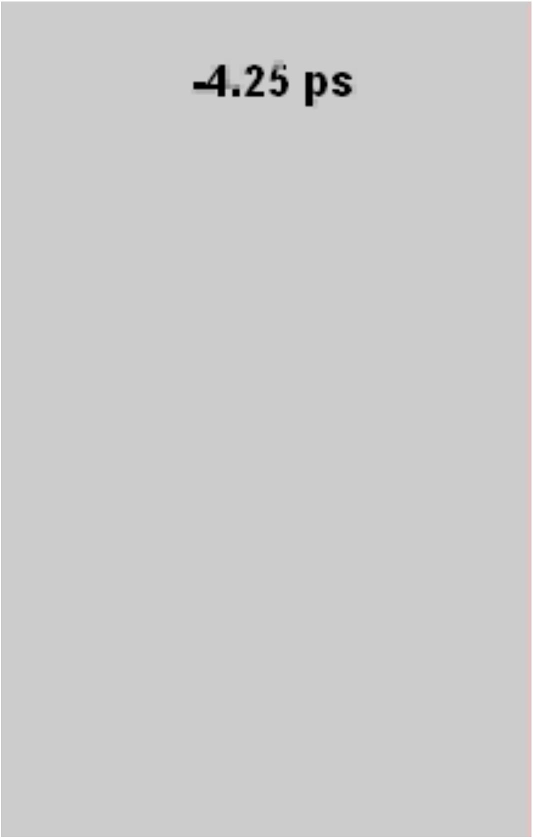


Movie of the 3D electronic band structure

$I(E, k_x, k_y, t<0)$



$I(E, k_x, k_y, t>0) - I(E, k_x, k_y, t<0)$

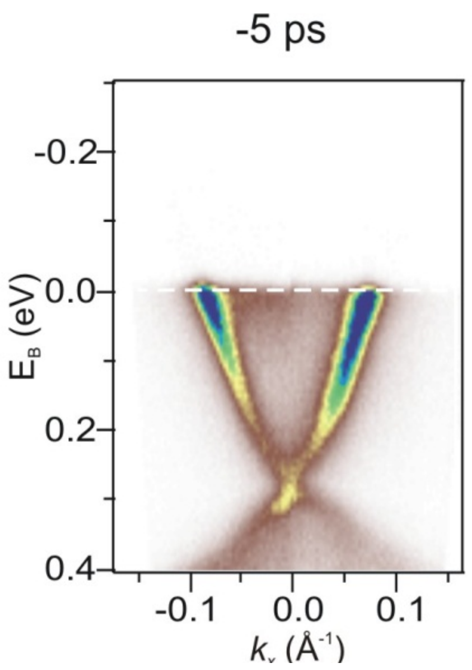


Difference Movie

Wang et al. … N. Gedik ***Phys. Rev. Lett.* 109**, 127401 (2012)

Photoexcitation of TI with light $E>E_g$

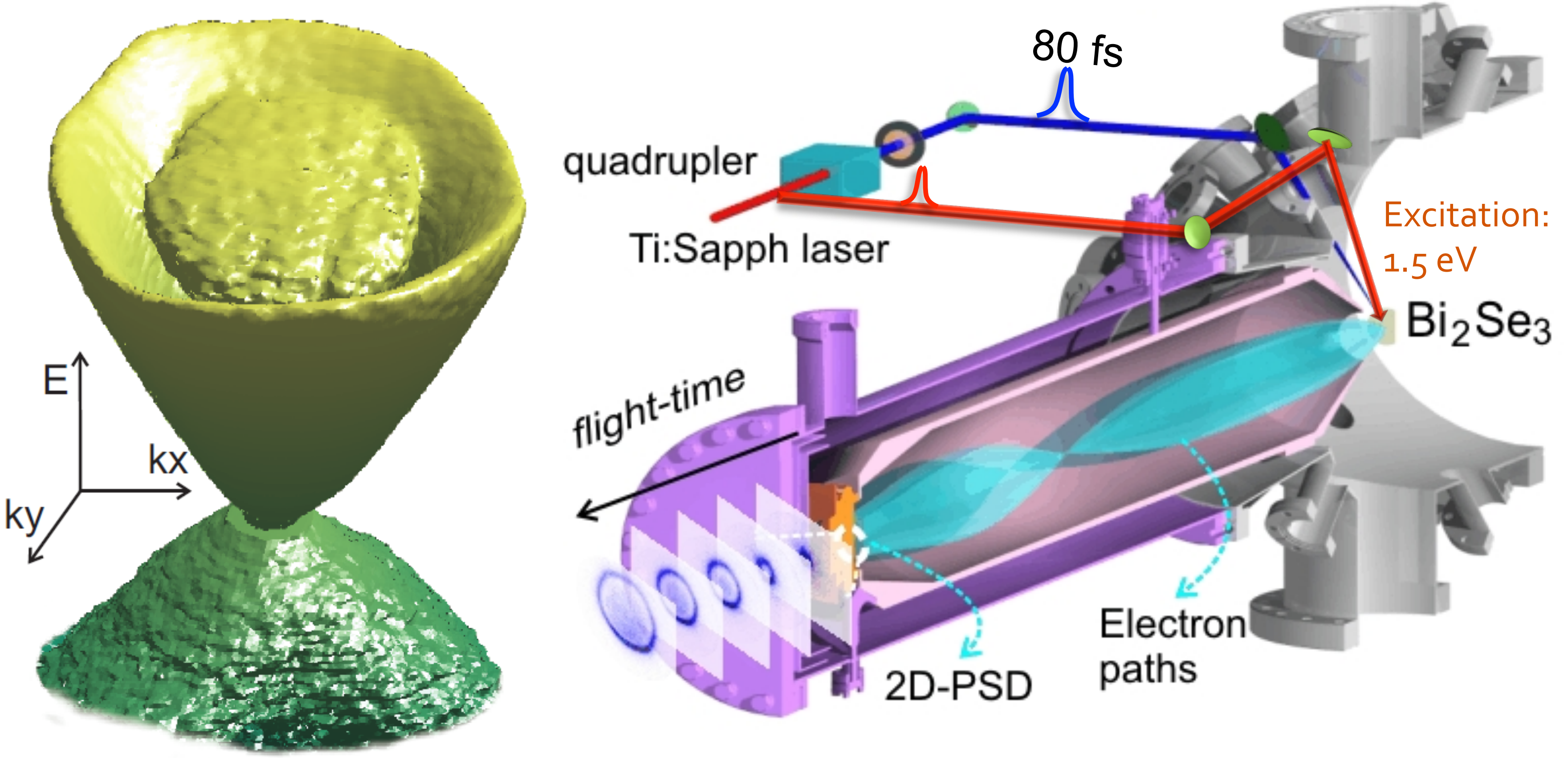
- Light energy is **bigger** than the bulk band gap:



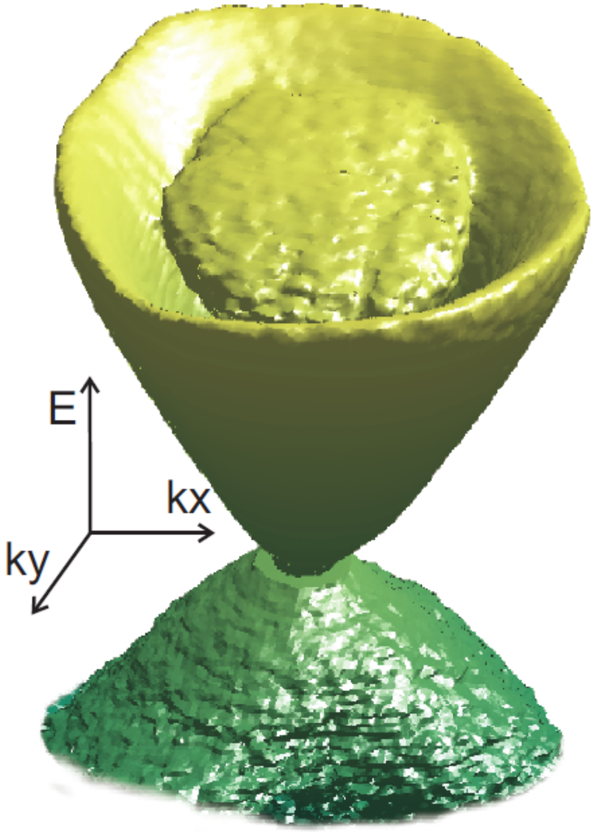
Excitation Energy = 1.5 eV

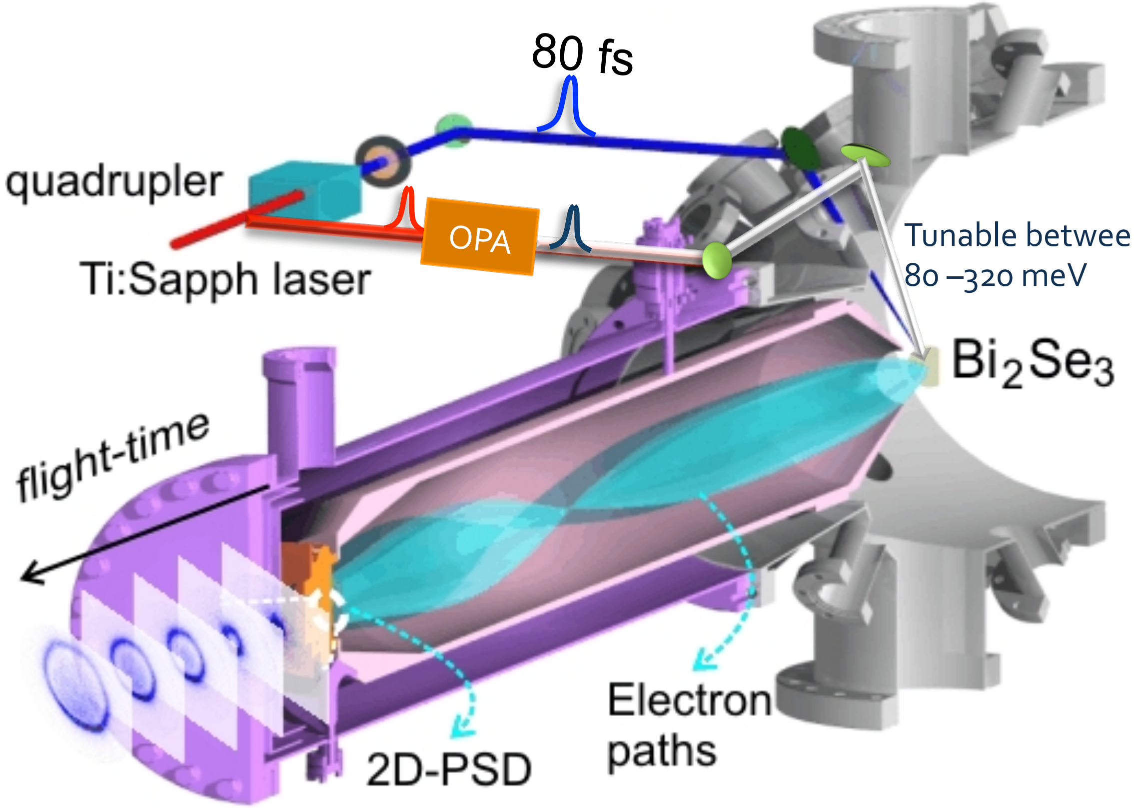
Wang *et al… N. Gedik Phys. Rev. Lett.* 109, 127401 (2012)

Time resolved ARPES



Time resolved ARPES





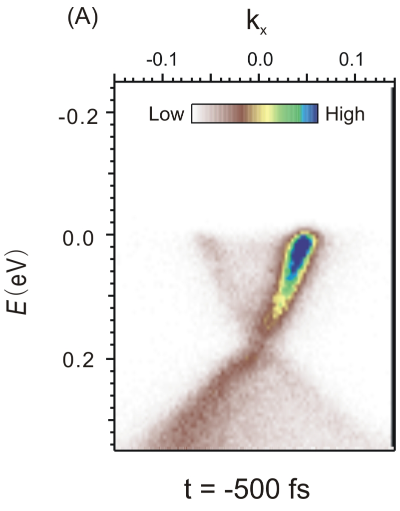
Outline

- Coherent interaction of light with solids
- Time resolved ARPES
- Observation of Floquet-Bloch States
- Breaking of TRS by light in TIs
- Summary and Outlook

Photoexcitation of TI with light E<E_g

- If the light energy is **smaller** than the bulk band gap:

Bulk band gap= 300 meV



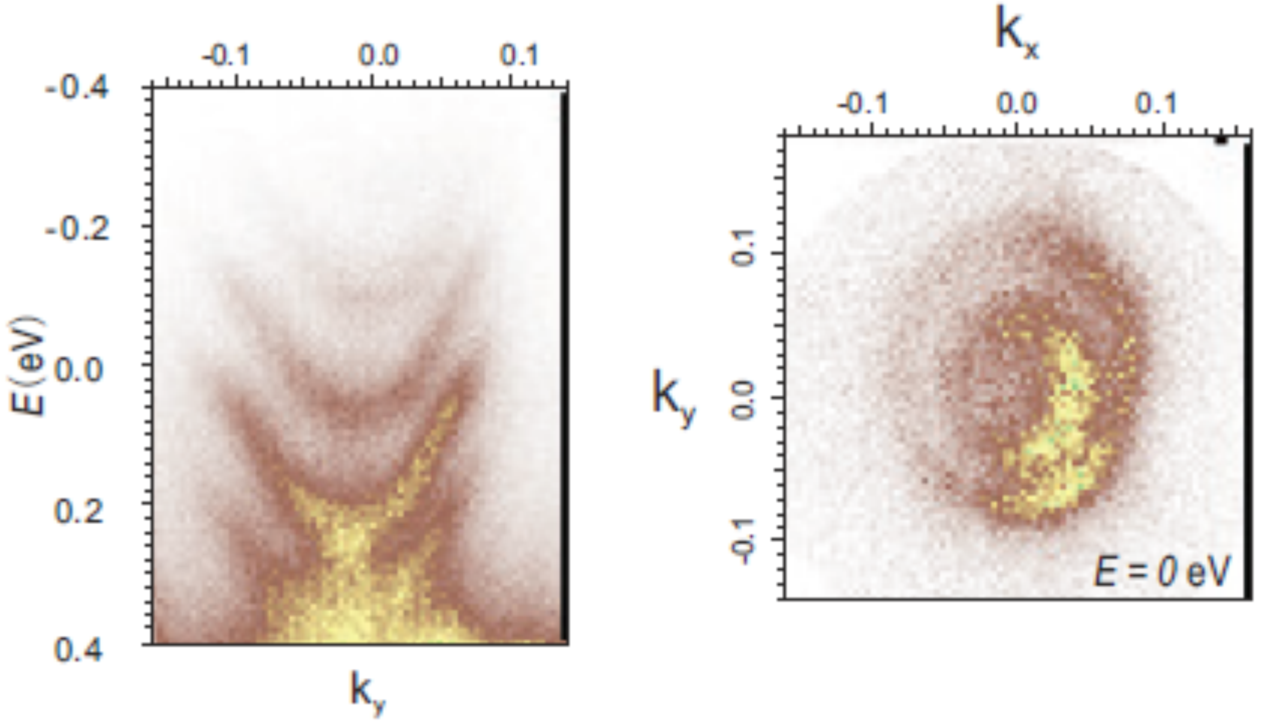
Excitation Energy = 120 meV

Photon dressed states!

Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 342, 453 (2013)**

Coherent interaction of light with TI

- Another doping



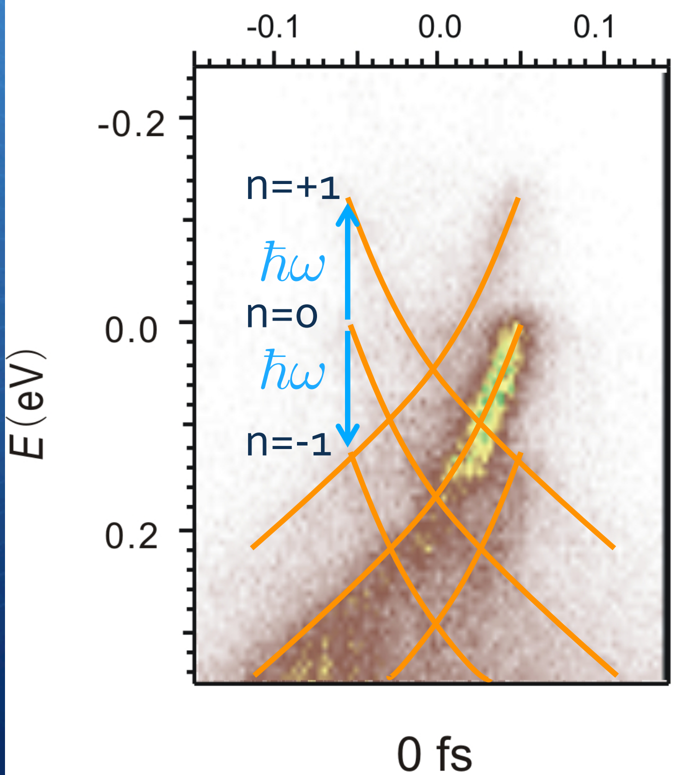
t = 0 fs

Photon dressed states!

Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 342, 453 (2013)**

Are these the Floquet-Bloch states?

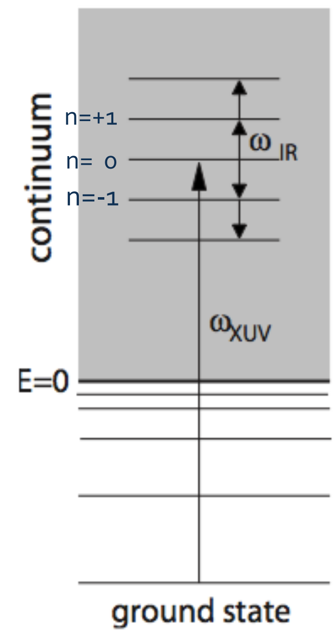
- Photon Dressed States



- Are we dressing the initial or the final state?

Floquet

LAPE



$$A_n = J_n^2\left(\frac{\vec{p}\cdot\vec{E}}{\omega^2}\right)$$

$$\approx \left(\frac{\vec{p}\cdot\vec{E}}{\omega^2}\right)^2$$

Laser Assisted Photoemission (LAPE)

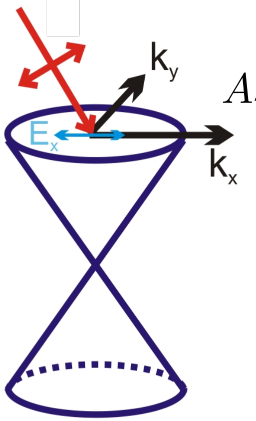
Saathoff et. al **PRA 77**, 022903, 2008

Are these the Floquet-Bloch states?

Floquet

- Are we dressing the initial or the final state?

LAPE



$$A_n = J_n^2\left(\frac{\vec{p}\cdot\vec{E}}{\omega^2}\right) \approx \left(\frac{\vec{p}\cdot\vec{E}}{\omega^2}\right)^2$$

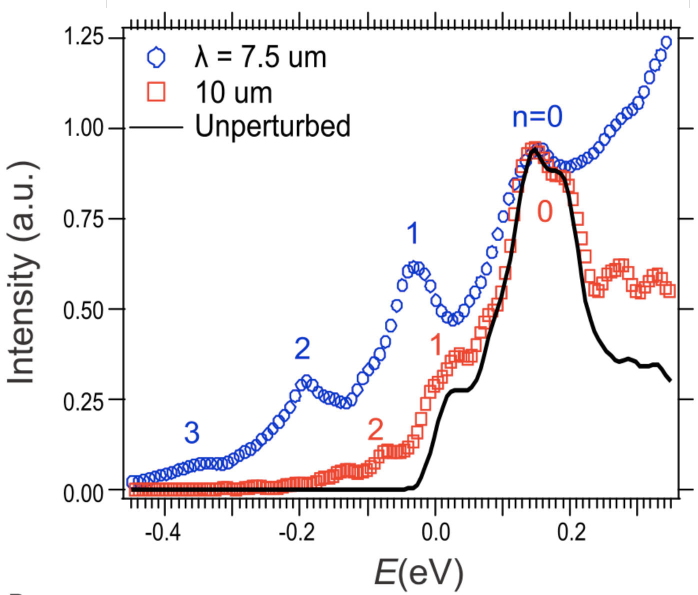
Saathoff et. al **PRA 77**, 022903, 2008

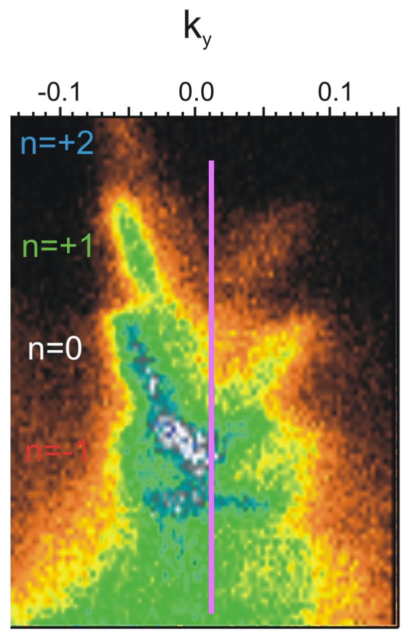
Are these the Floquet-Bloch states?

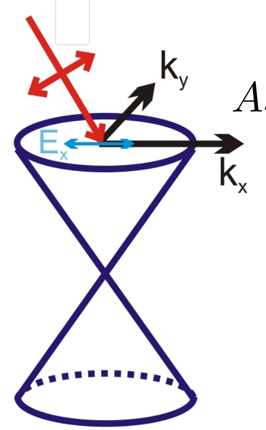
Floquet

- Are we dressing the initial or the final state?

LAPE





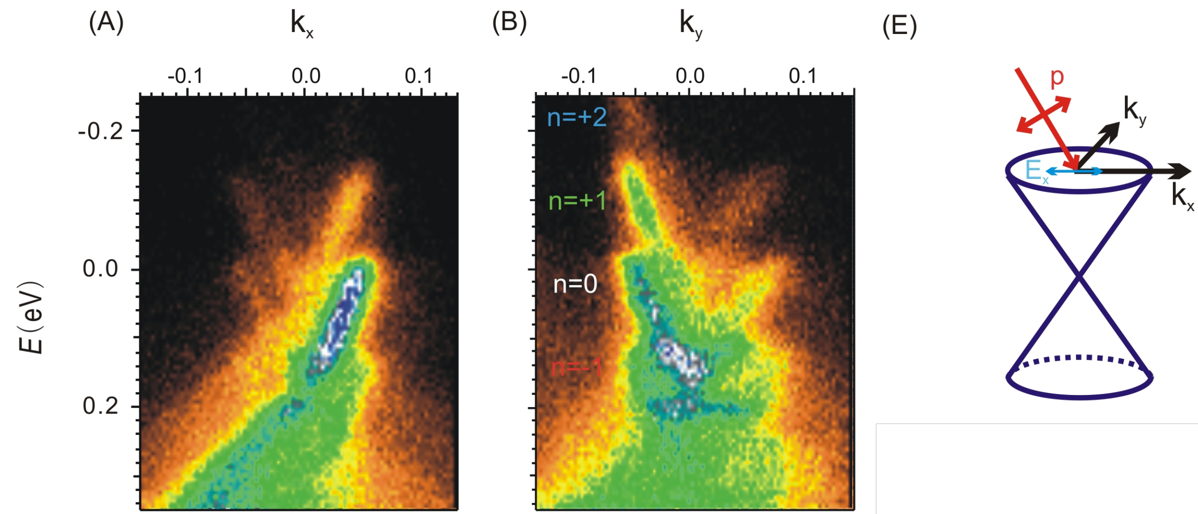


$$A_n = J_n^2\left(\frac{\vec{p}\cdot\vec{E}}{\omega^2}\right)$$

$$\approx \left(\frac{\vec{p}\cdot\vec{E}}{\omega^2}\right)^2$$

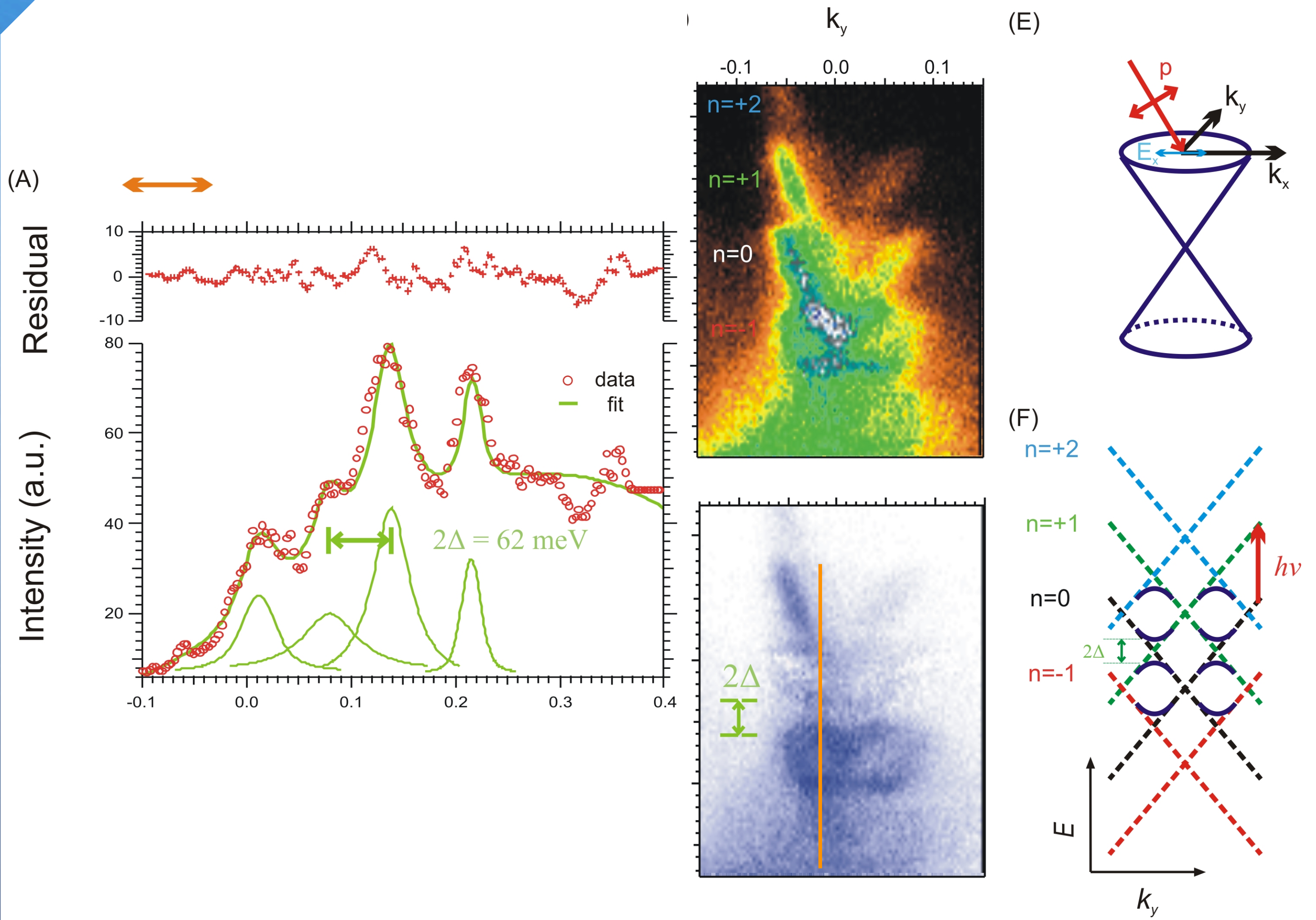
Saathoff et. al **PRA 77**, 022903, 2008

Dependence on momentum direction



Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 342, 453 (2013)**

Photoinduced Gap at the Crossing Points



Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 342, 453 (2013)**

Theory of Floquet-Bloch states in Dirac Systems

- Y. Zhou and M. W. Wu, "*Optical response of graphene under intense terahertz fields*," *Phys. Rev. B.*, **83**, 245436, (2011).
- T. Kitagawa, T. Oka, A. Brataas, L. Fu, and E. Demler, "*Transport properties of nonequilibrium systems under the application of light: Photoinduced quantum Hall insulators without Landau levels*," *Phys. Rev. B*, **84**, 235108, (2011).
- T. Oka and H. Aoki, "*Photovoltaic Hall effect in graphene*," *Phys. Rev. B*, **79**, 081406, (2009).
- S. V. Syzranov, M. V. Fistul, and K. B. Efetov, "*Effect of radiation on transport in graphene*," *Phys. Rev. B.*, **78**, 045407, (2008).
- B. Fregoso, Y. H. Wang, N. Gedik and V. Galitski, "*Driven Electronic States at the Surface of a Topological Insulator," Phys. Rev. B 88, 155129 (2013).*


Theory of coherent light interaction with TI

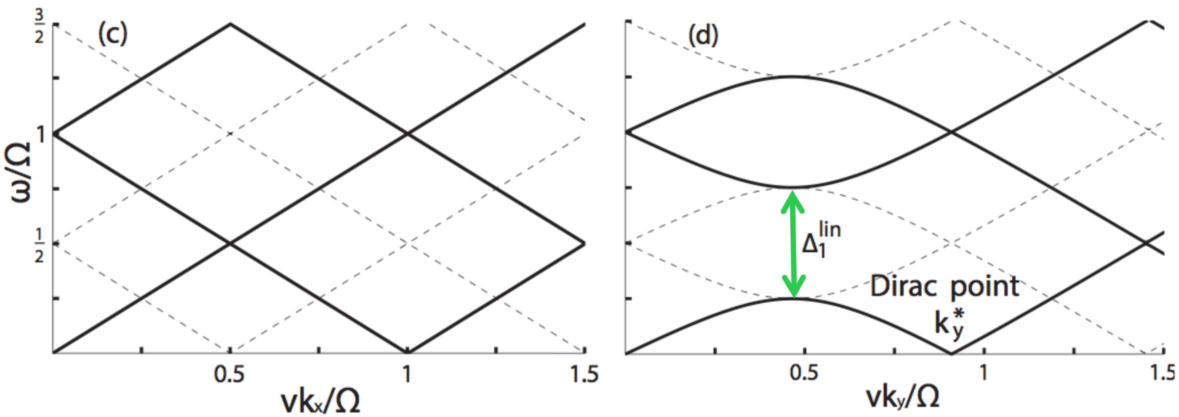
$$H_0(\mathbf{k}) = v(k_x\sigma_y - k_y\sigma_x)$$

$$H(\mathbf{k},t) = H_0(\mathbf{k}) + H_{ext}(t)$$

$$k \rightarrow k + eA(t)$$
$$V = evE_0/\omega$$

$$H_{ext}(t) = V\Theta(t-t_0)(\mathrm{a}_x(t)\sigma_y - \mathrm{a}_y(t)\sigma_x)$$

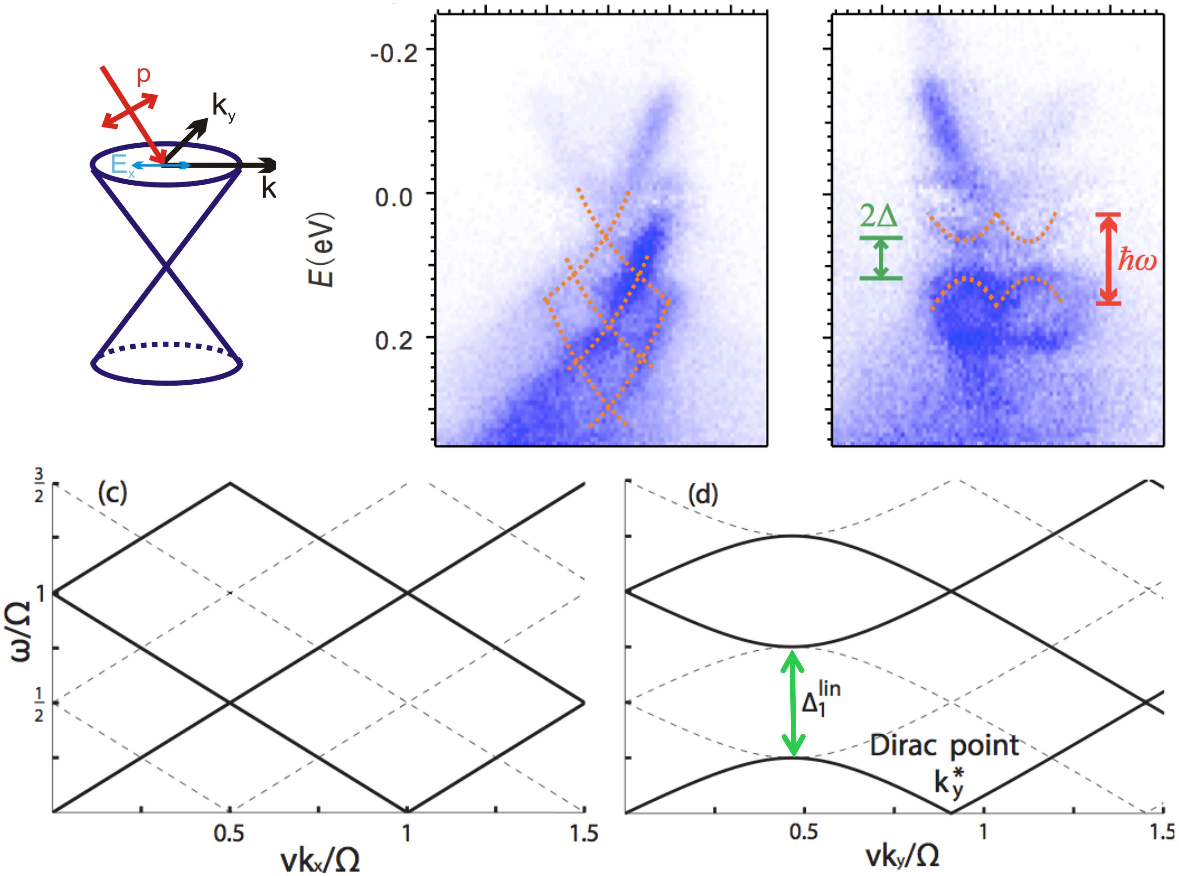
$$\text{Linear } a(t) = (cos\omega t, 0)$$



$$2\Delta = V = \frac{evE_0}{\omega}$$

"Driven Electronic States at the Surface of a Topological Insulator"
Phys. Rev. B 88, 155129 (2013) and other works

Theory: Linear polarization



$$V = evE_0/\omega$$

$$\text{Exp.: } 2\Delta = 62 \text{ meV}$$
$$\text{Theory: } 2\Delta = 63 \text{ meV}$$

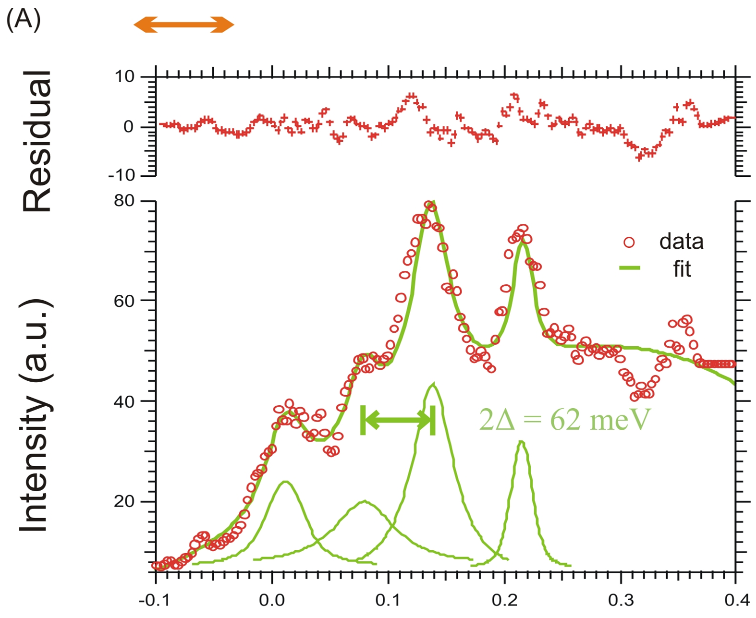
$$2\Delta = V = \frac{evE_0}{\omega}$$

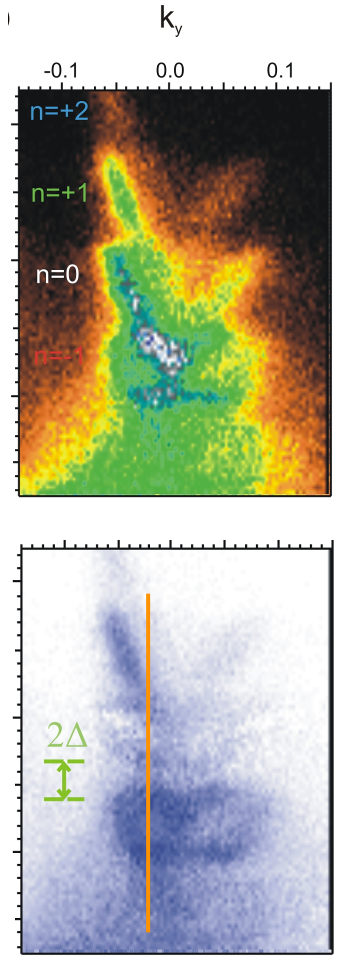
“Driven Electronic States at the Surface of a Topological Insulator”
Phys. Rev. B 88, 155129 (2013) and other works

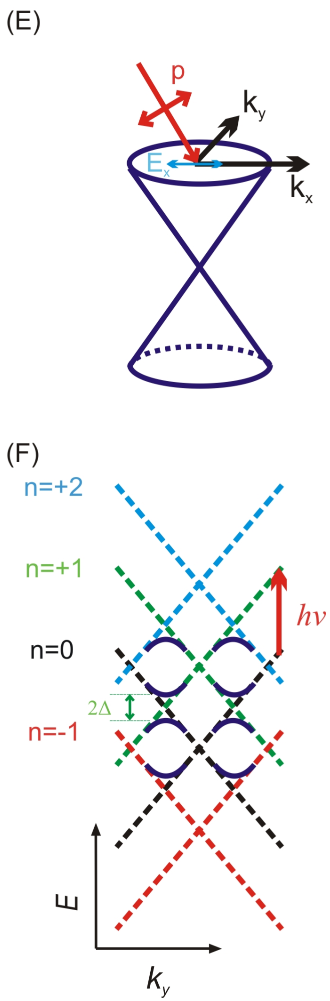
Outline

- Coherent interaction of light with solids
- Time resolved ARPES
- Observation of Floquet-Bloch States
- Breaking of TRS by light in TIs
- Summary and Outlook

Linear Polarization: Photoinduced Gap at the Crossing Points

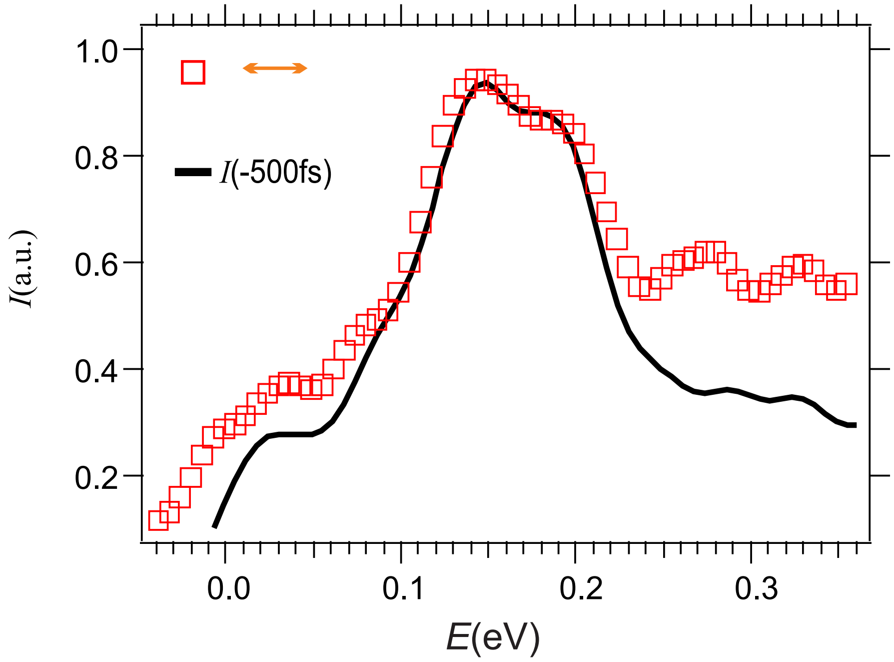


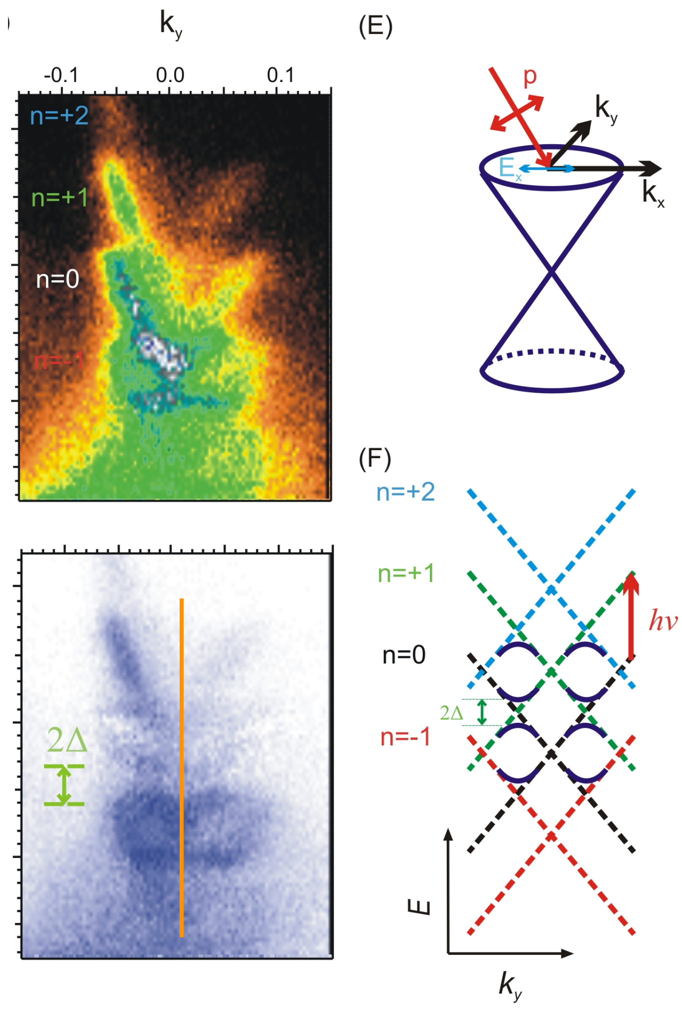




Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 342, 453 (2013)**

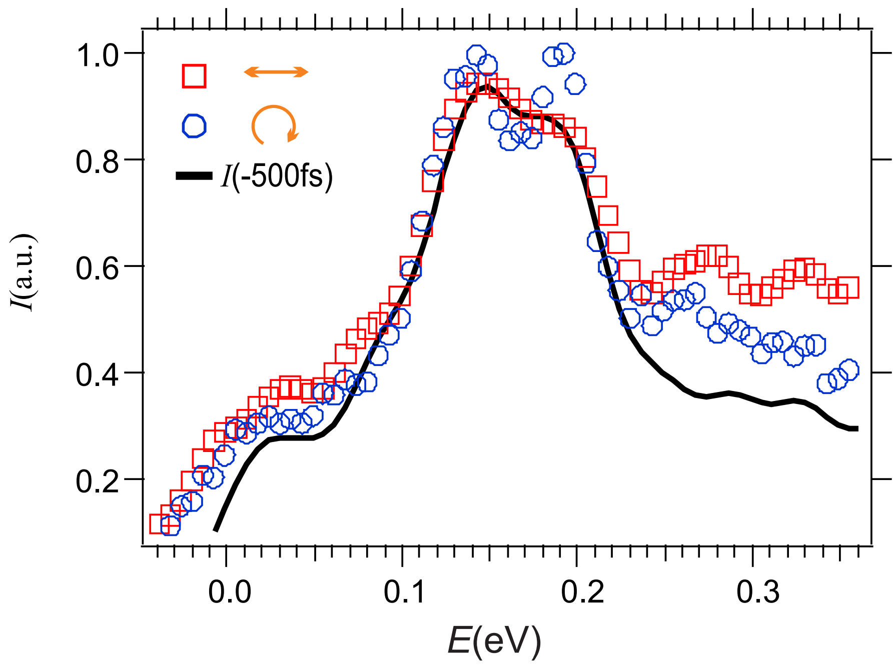
Linear Polarization:
No Gap at the Dirac Point!

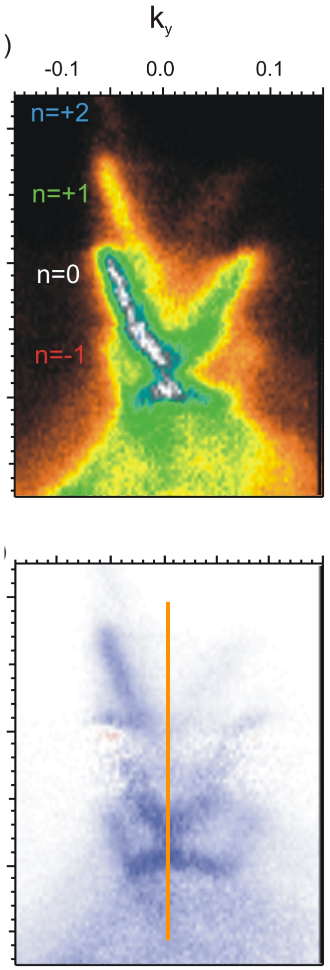


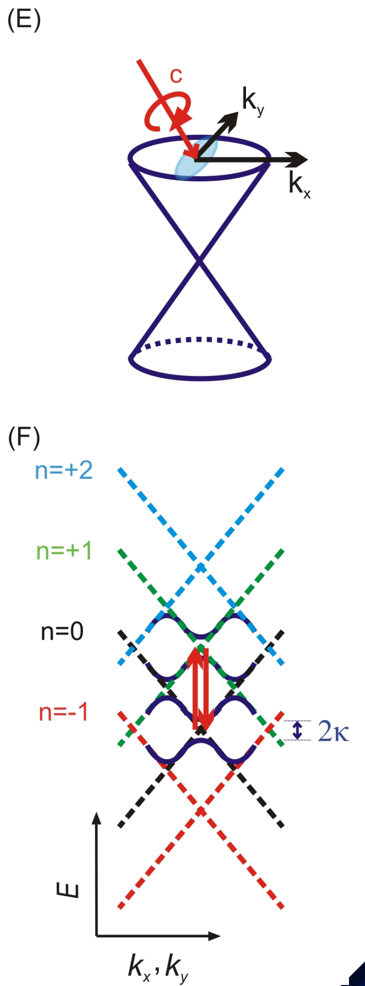


Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 342, 453 (2013)**

Circular Polarization:
Photoinduced Gap at the Dirac Point!

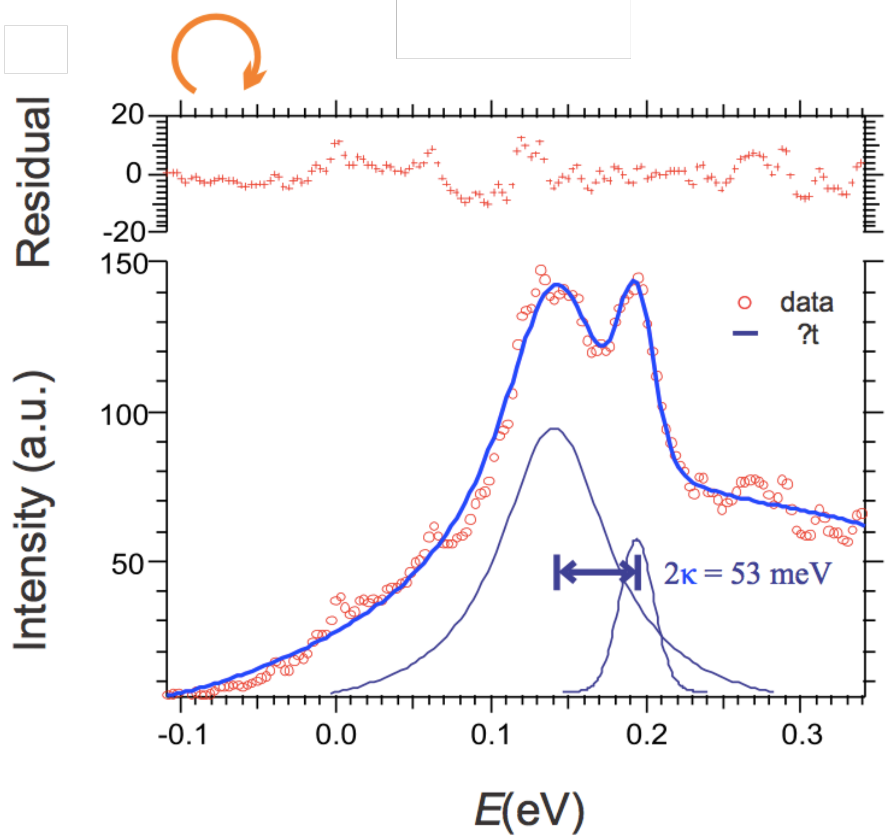


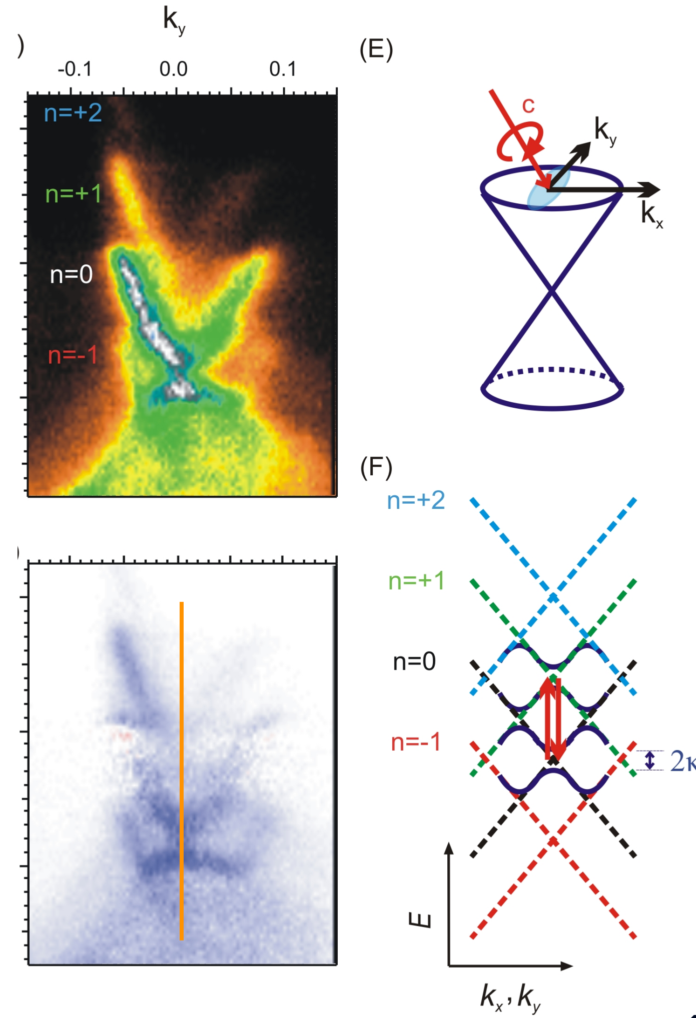




Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 342, 453 (2013)**

Circular Polarization:
Photoinduced Gap at the Dirac Point!





Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 342, 453 (2013)**

Theory of coherent light interaction with TI

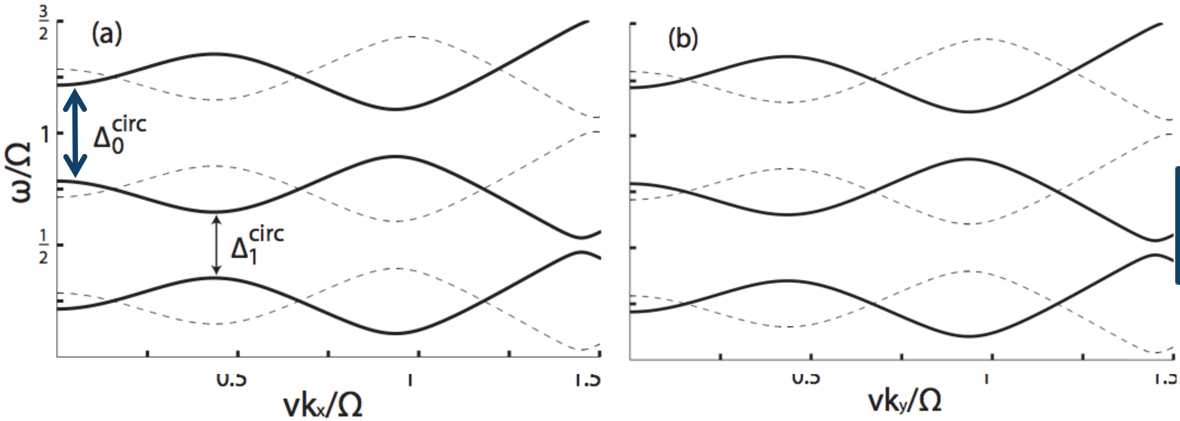
$$H_0(\mathbf{k}) = v(k_x\sigma_y - k_y\sigma_x)$$

$$H(\mathbf{k},t) = H_0(\mathbf{k}) + H_{ext}(t)$$

$$k \to k + eA(t)$$
$$V = evE_0/\omega$$

$$H_{ext}(t) = V\Theta(t-t_0)(\mathrm{a}_x(t)\sigma_y - \mathrm{a}_y(t)\sigma_x)$$

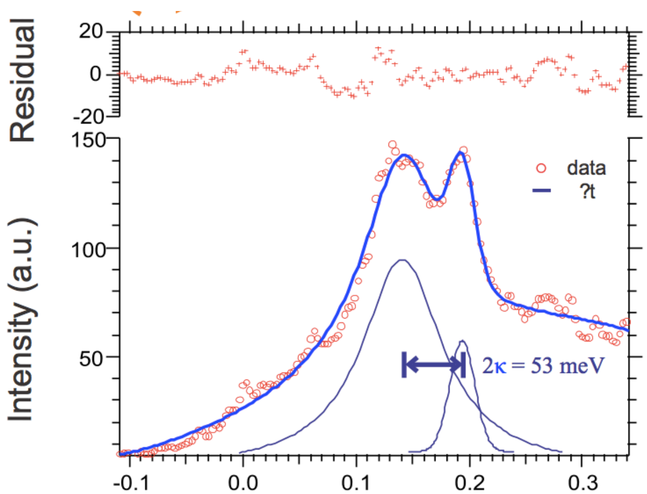
Linear: $a(t) = (\cos\omega t, 0)$ Circular: $a(t) = (\pm\cos\omega t, \sin\omega t)$

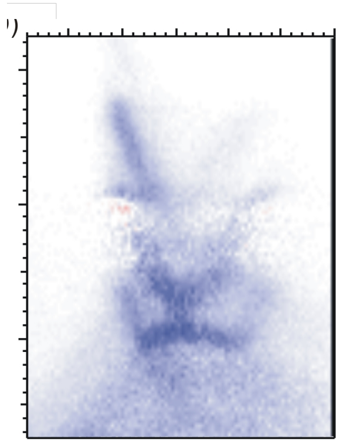


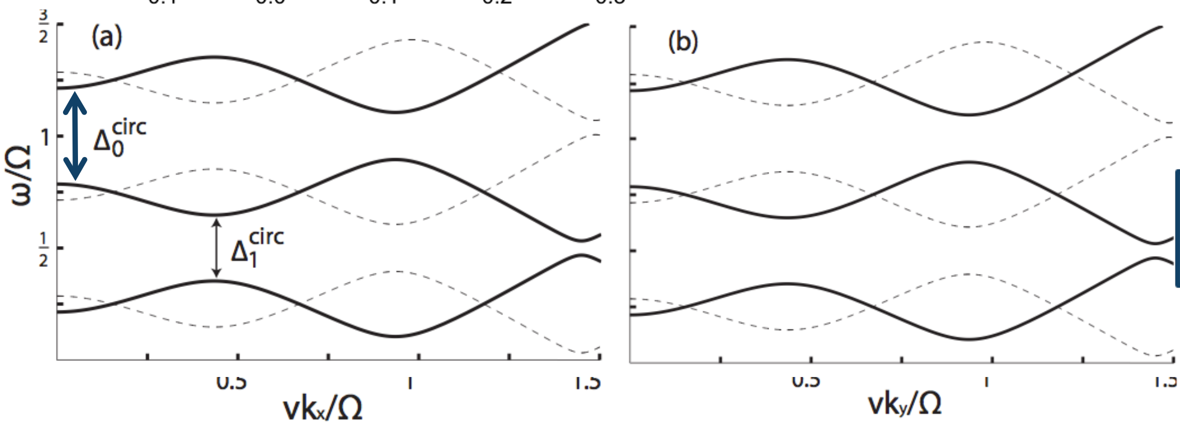
$$2\kappa = \sqrt{4V^2 + (\hbar\omega)^2} - \hbar\omega$$

"Driven Electronic States at the Surface of a Topological Insulator"
Phys. Rev. B 88, 155129 (2013) and other works

Theory: Circular polarization







$$V = evE_0/\omega$$

Exp.: $2\kappa = 53$ meV

Theory: $2\kappa = 54$ meV

$$2\kappa = \sqrt{4V^2 + (\hbar\omega)^2} - \hbar\omega$$

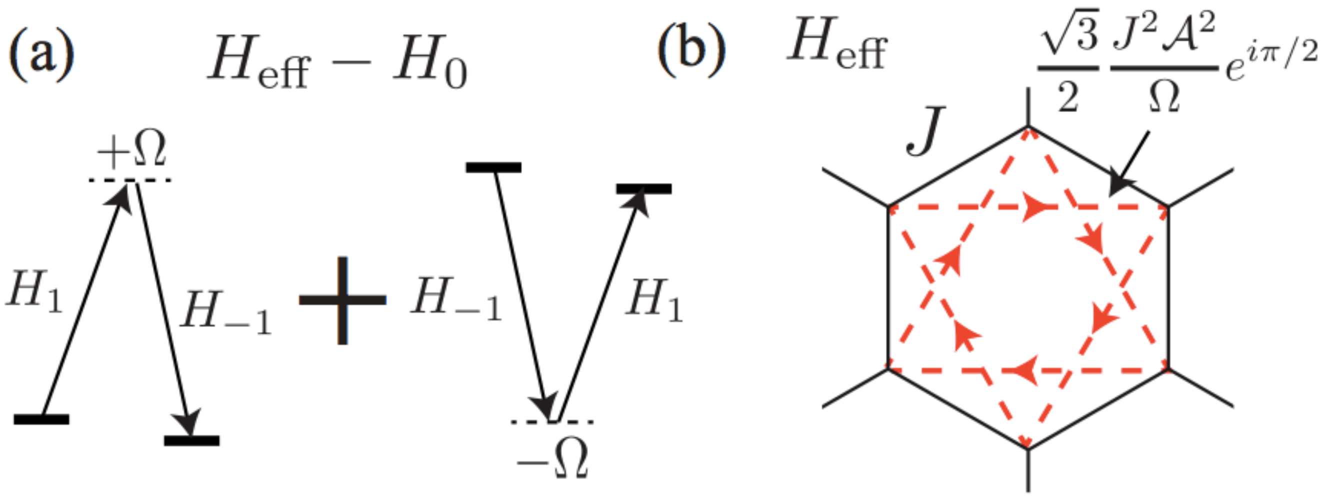
Small Coupling $V \ll \hbar\omega$

$$2\kappa \approx \frac{2V^2}{\hbar\omega}$$

"Driven Electronic States at the Surface of a Topological Insulator"
Phys. Rev. B 88, 155129 (2013) and other works

Photoinduced gapped state

Kitagawa et. al., PHYSICAL REVIEW B **84**, 235108 (2011)



The Hamiltonian is identical to the Chern insulator as originally proposed by Haldane!

Realization of Quantum Hall Insulator without Landau Levels!!!

$$2\kappa \approx \frac{2V^2}{\hbar\omega}$$

Summary

- Observation of Floquet-Bloch states in solids!
- Breaking of TRS with light in a TI!
- Floquet-Bloch bands agrees well with theory.
- Realization of quantum hall insulator without Landau levels

Y. H. Wang, H. Steinberg, P. Jarillo-Herrero & N. Gedik, **Science 2013 (in press)**

Gedik Group at MIT