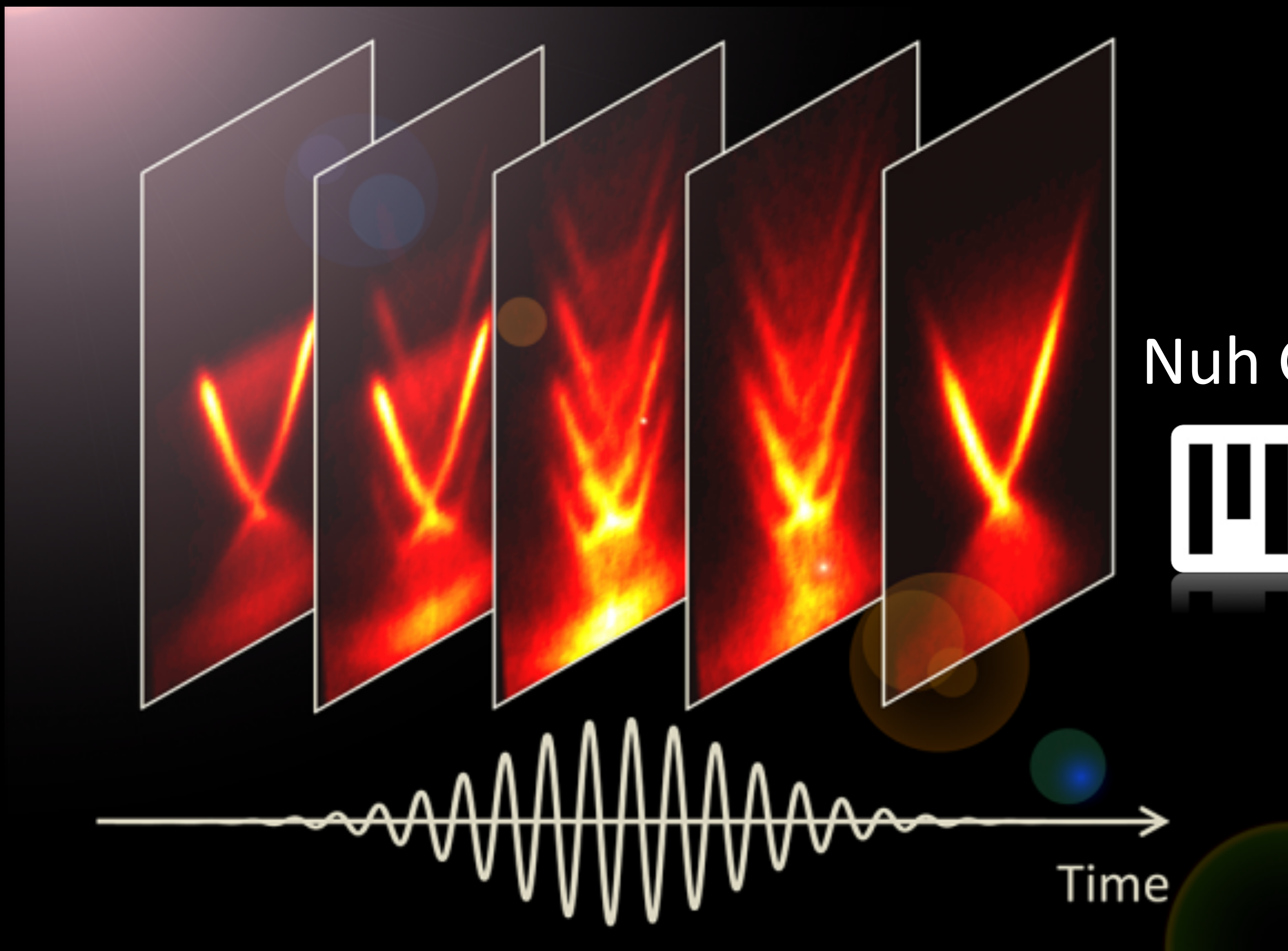
Optical manipulation of electronic bands using Floquet-Bloch States

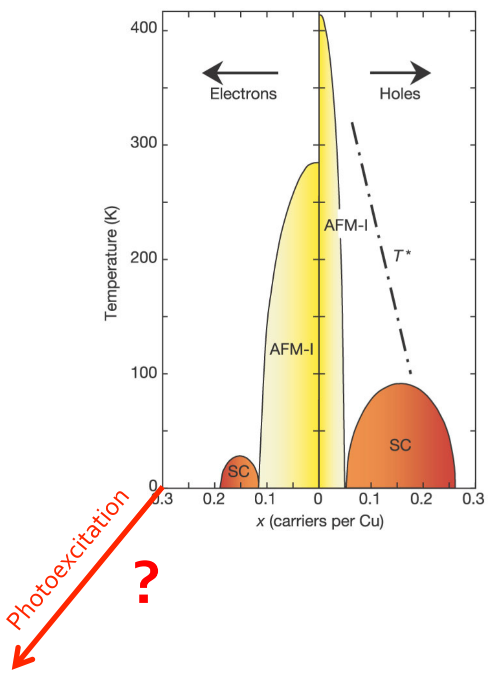


Nuh Gedik

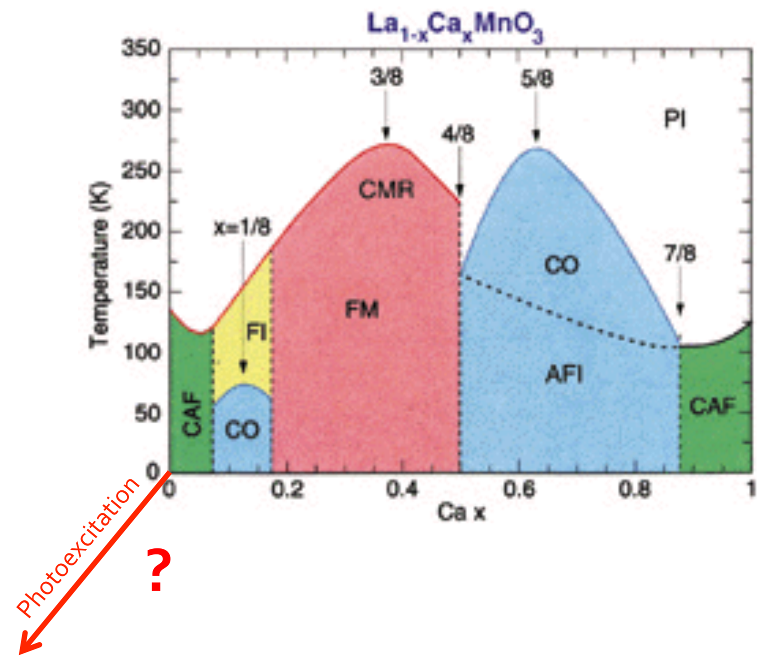
Motivation

Can we use light excitation to create and manipulate new phases of quantum materials?

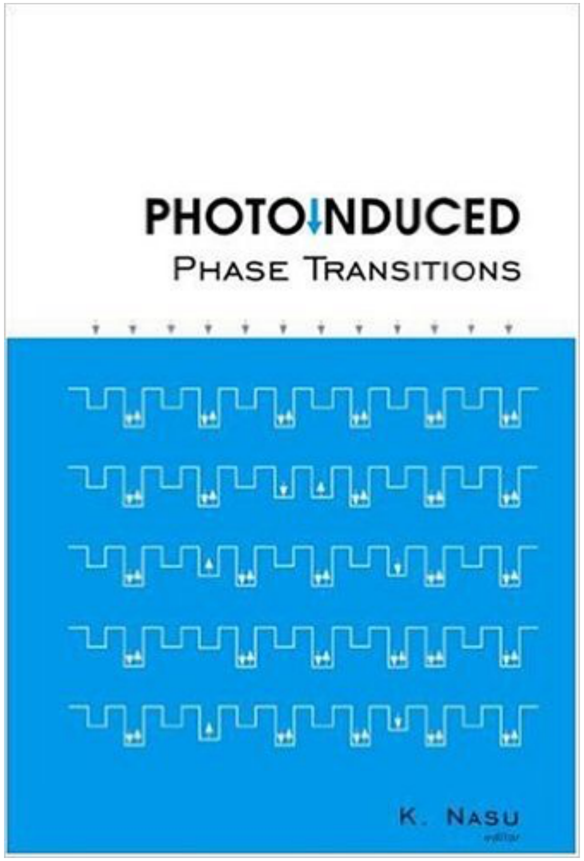
Cuprates



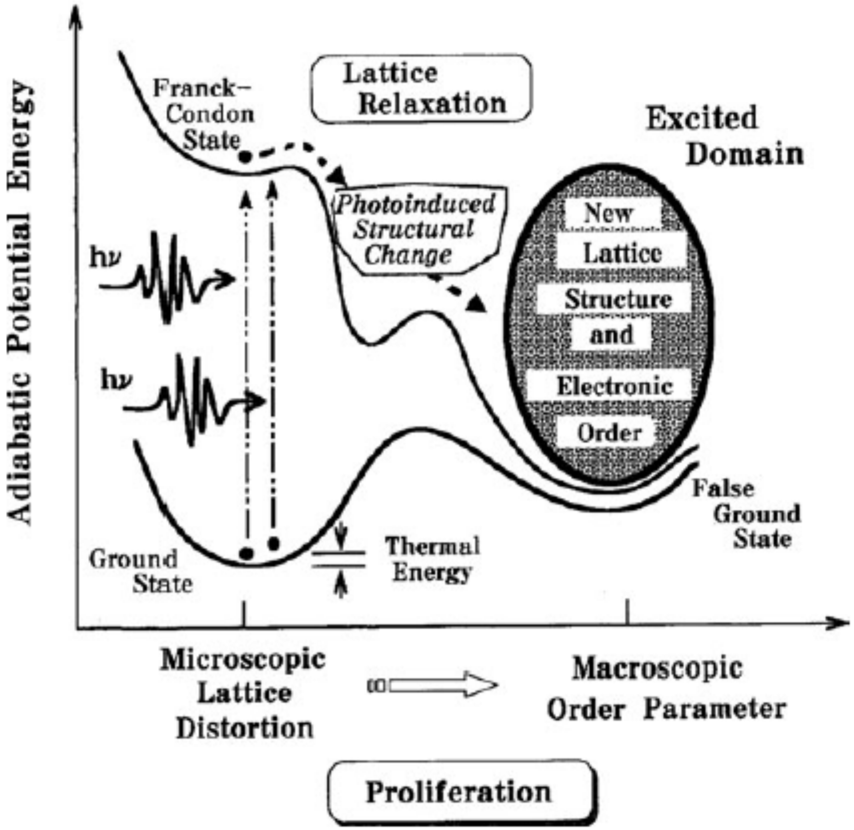
Manganites



Different types of light matter interaction



Direct electronic excitation



Can we preserve and utilize the coherence?

Outline

- Coherent light matter interaction in solids
- Observation of Floquet-Bloch states in TIs
- Breaking valley degeneracy in TMDs with light
- Outlook

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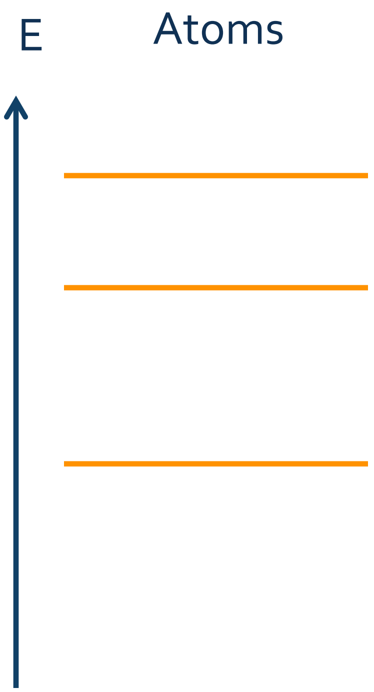
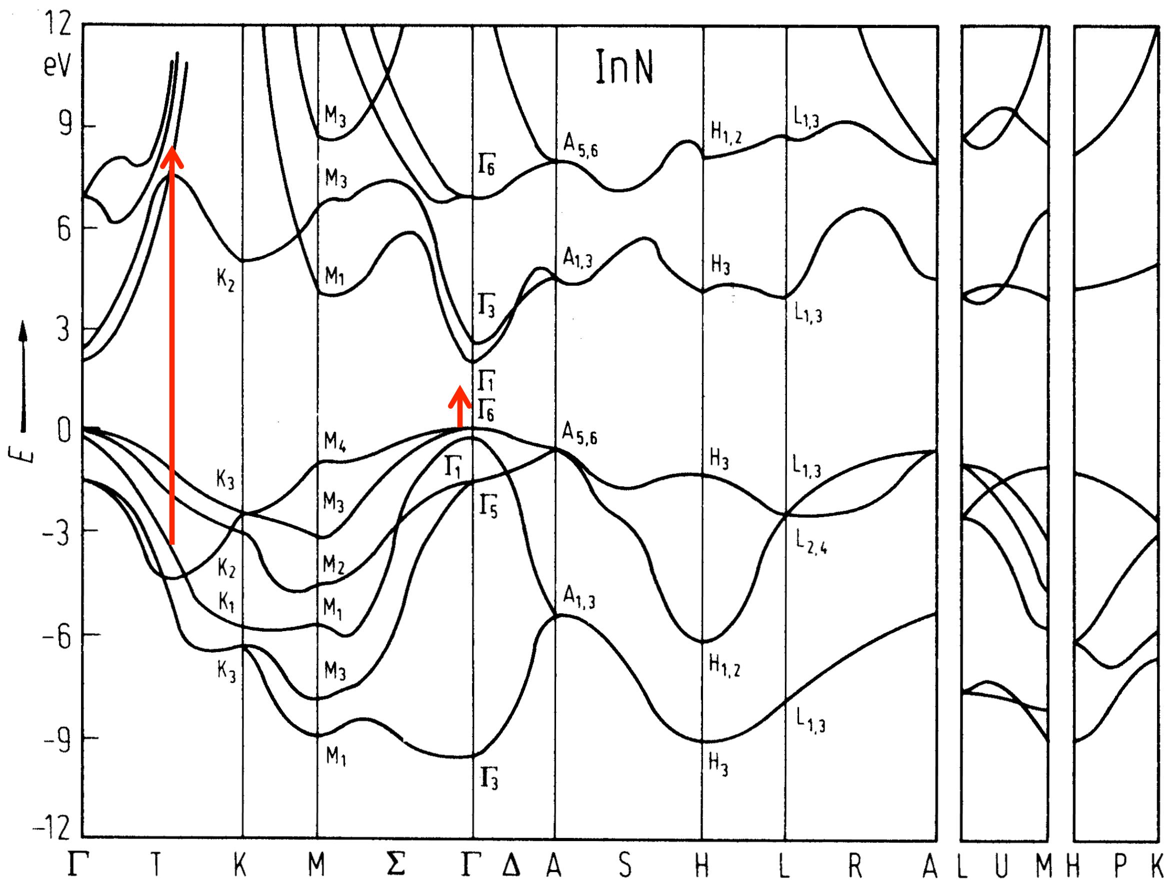
How to preserve coherence?

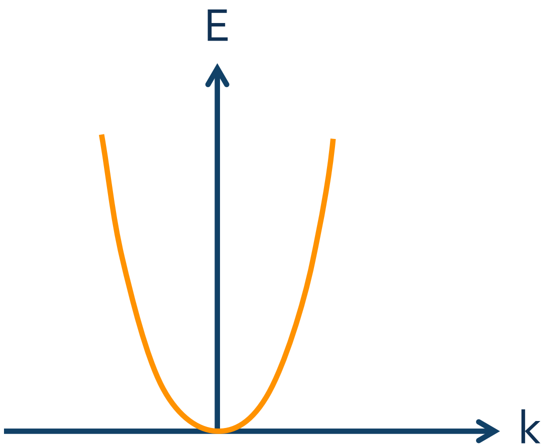




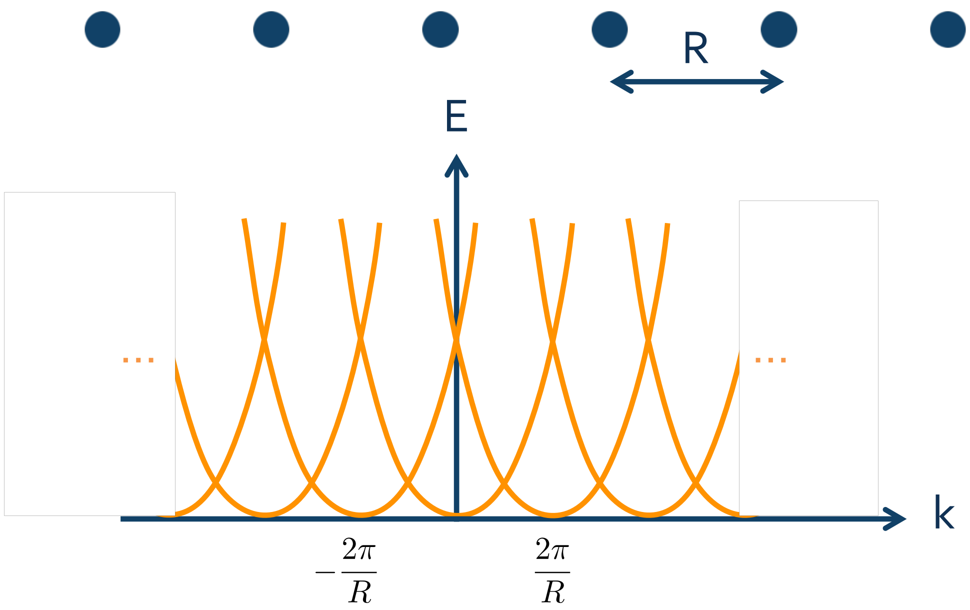
Foley &Tansley (1986)

Electrons in a periodic potential

Free electrons

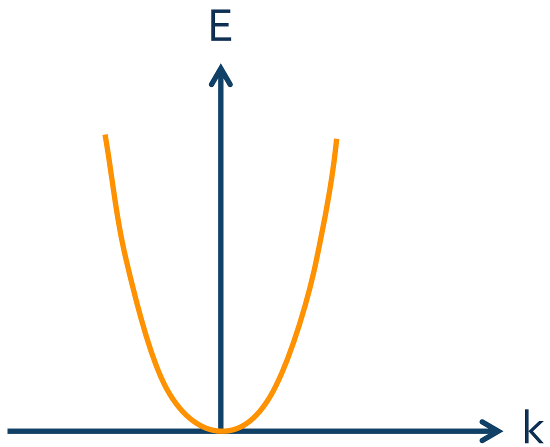


In a solid, potential is **periodic in space**



Electrons in a periodic potential

Free electrons



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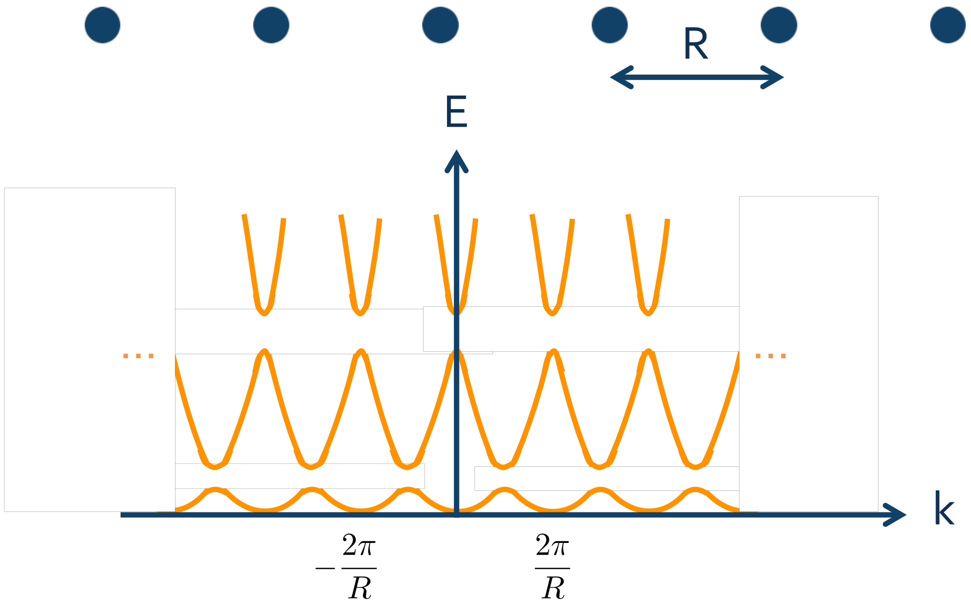


Electrons in a periodic potential

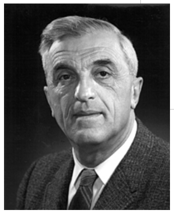
- Spatially periodic:

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

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

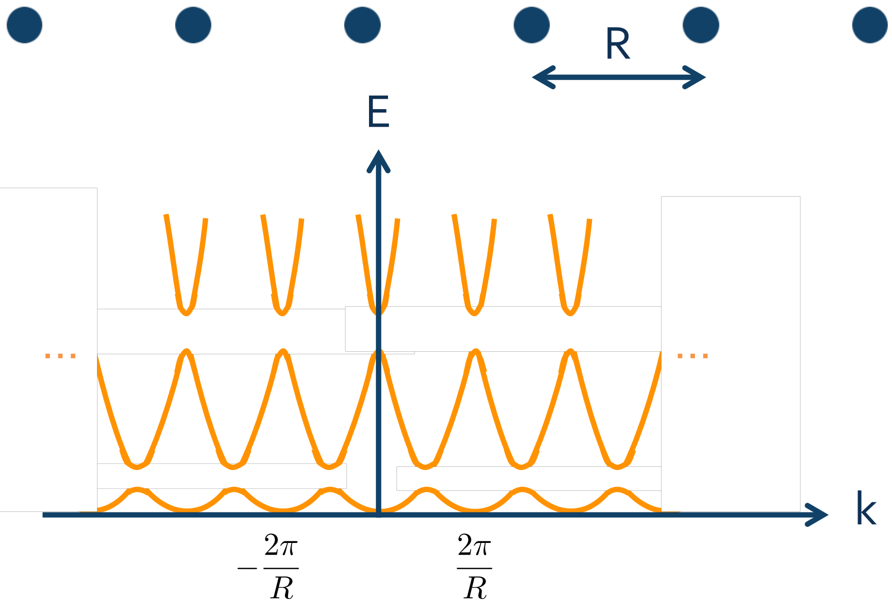
$$u_{nk}(r+R) = u_{nk}(r)$$

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



Bloch States

In a solid, potential is **periodic in space**



Electrons in a periodic potential

+ Spatially periodic:

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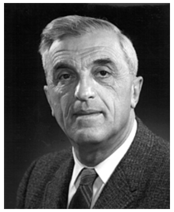

+ Temporally periodic

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

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

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

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

Bloch States

Floquet States

Floquet-Bloch States

Can we directly observe these states in solids?

Outline

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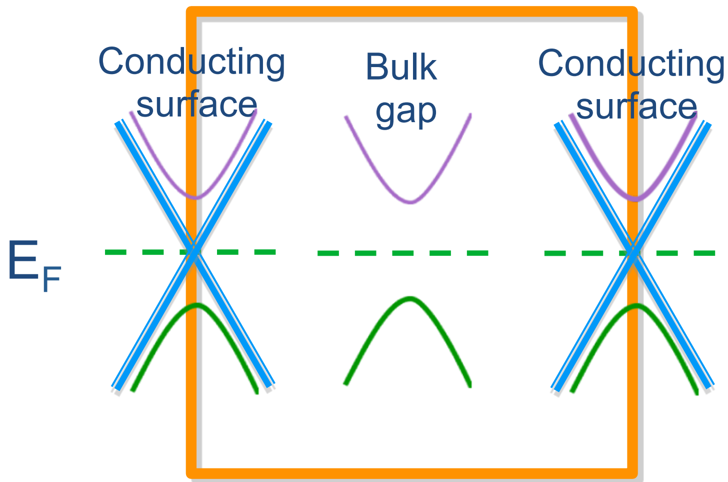
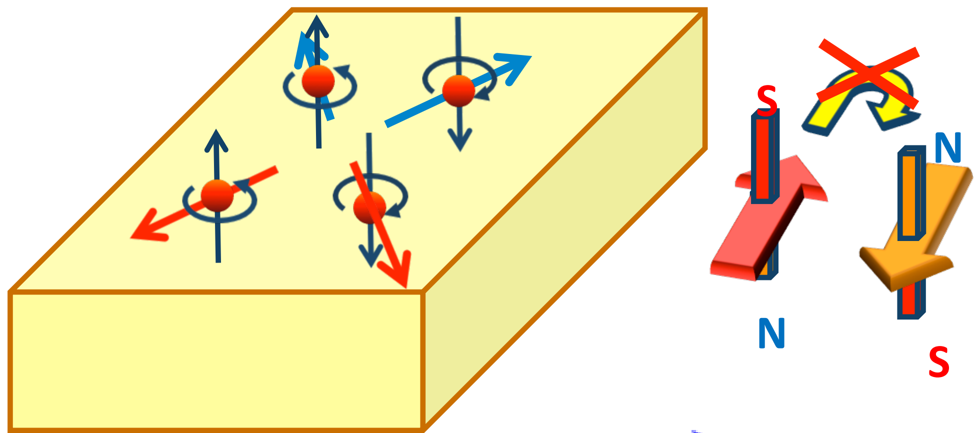
The 3D topological insulator



Theoretical prediction

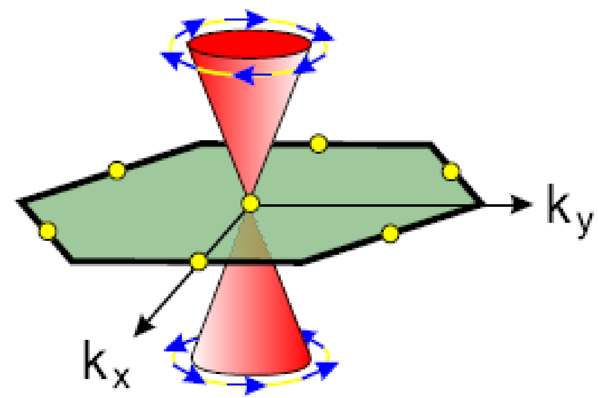
Fu & Kane (2006)
Moore & Balents (2006)
Roy (2006)



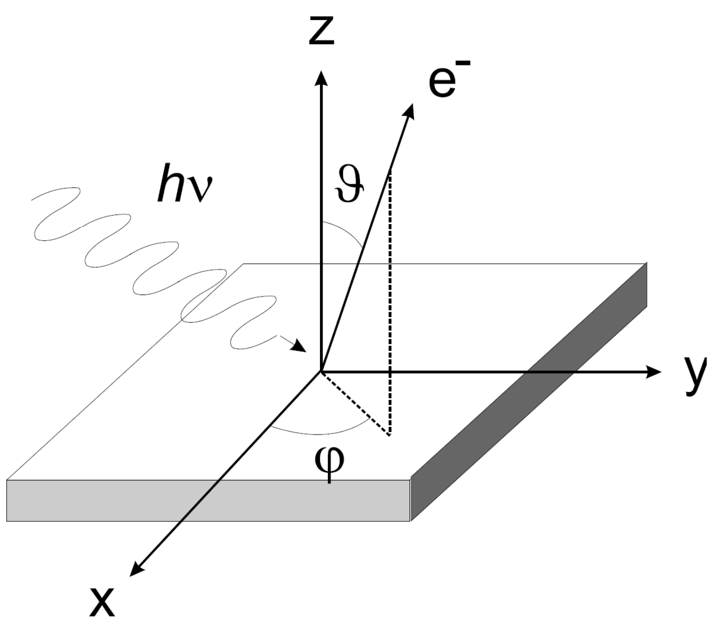
Some known TI materials:

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

Hundreds other materials recently proposed



Angle Resolved Photo-Emission Spectroscopy



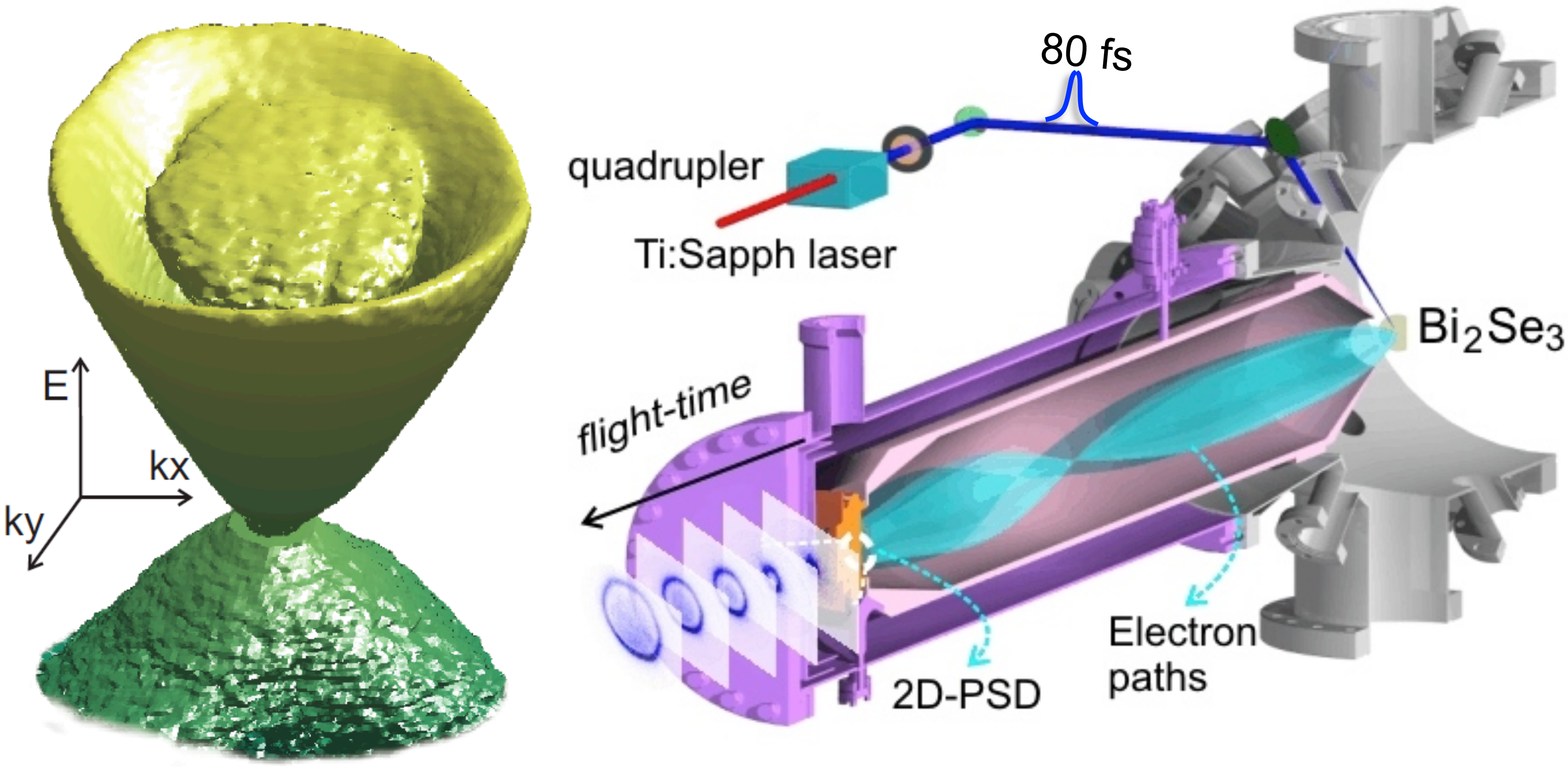
$$K_x = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\cos\varphi$$

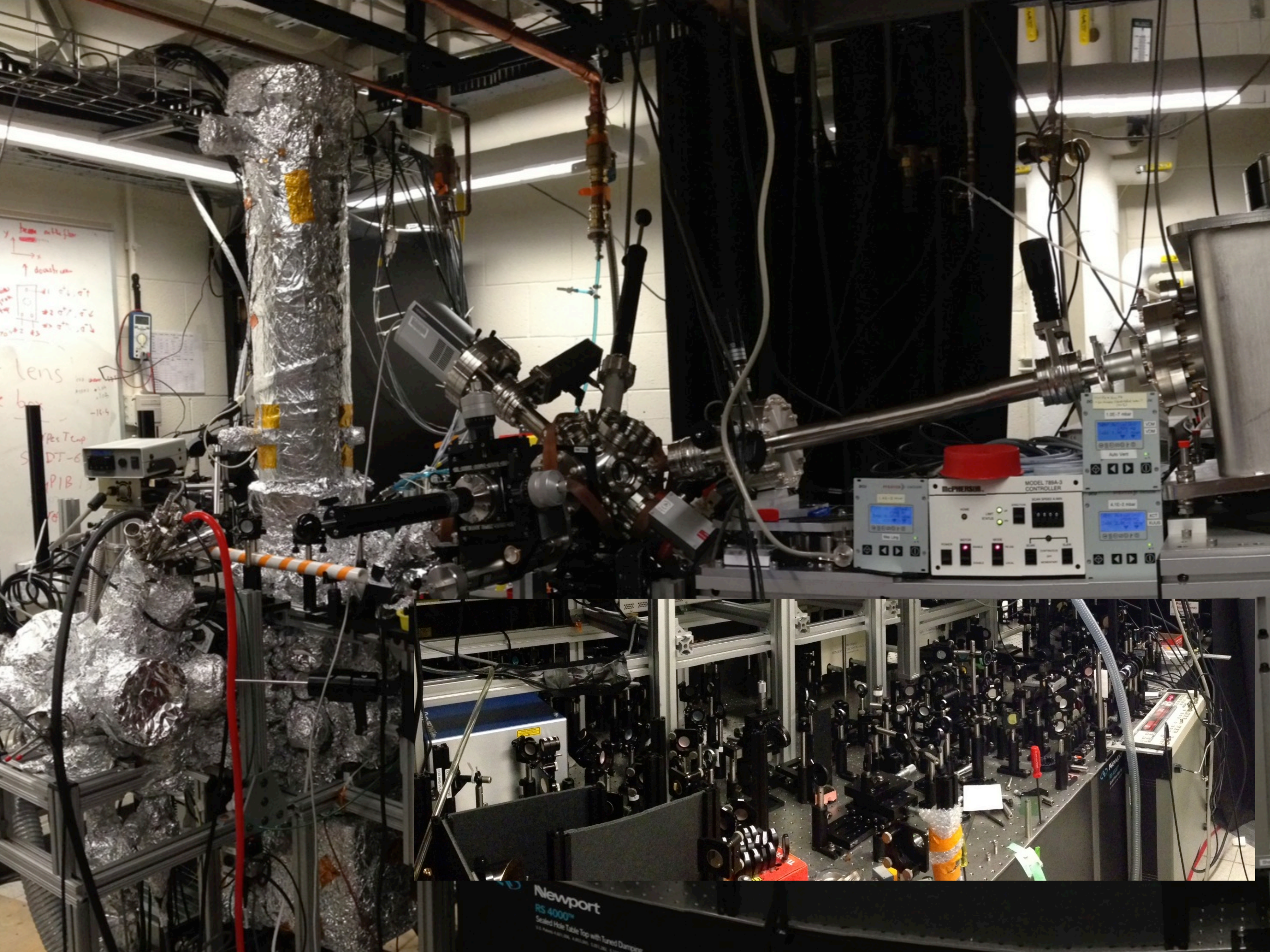
$$K_y = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\sin\varphi$$

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

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

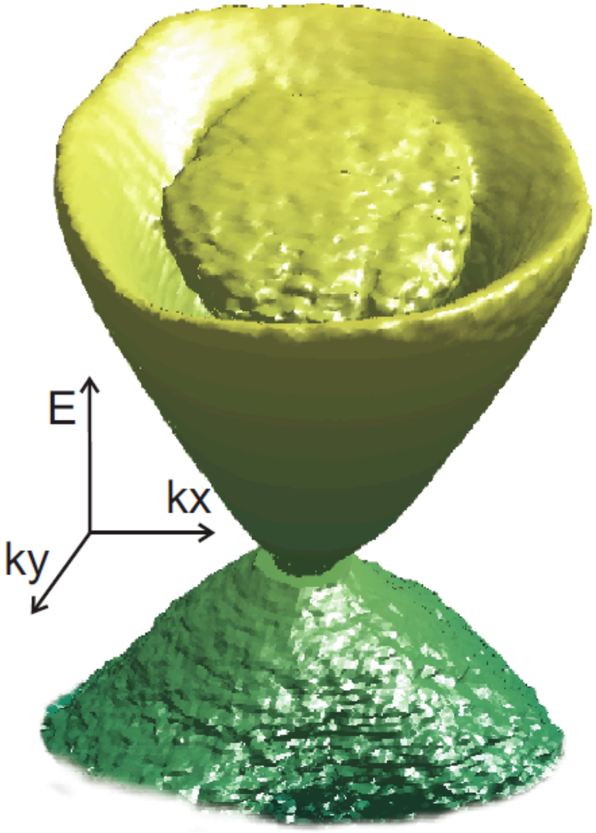
Novel Time-of-flight ARPES

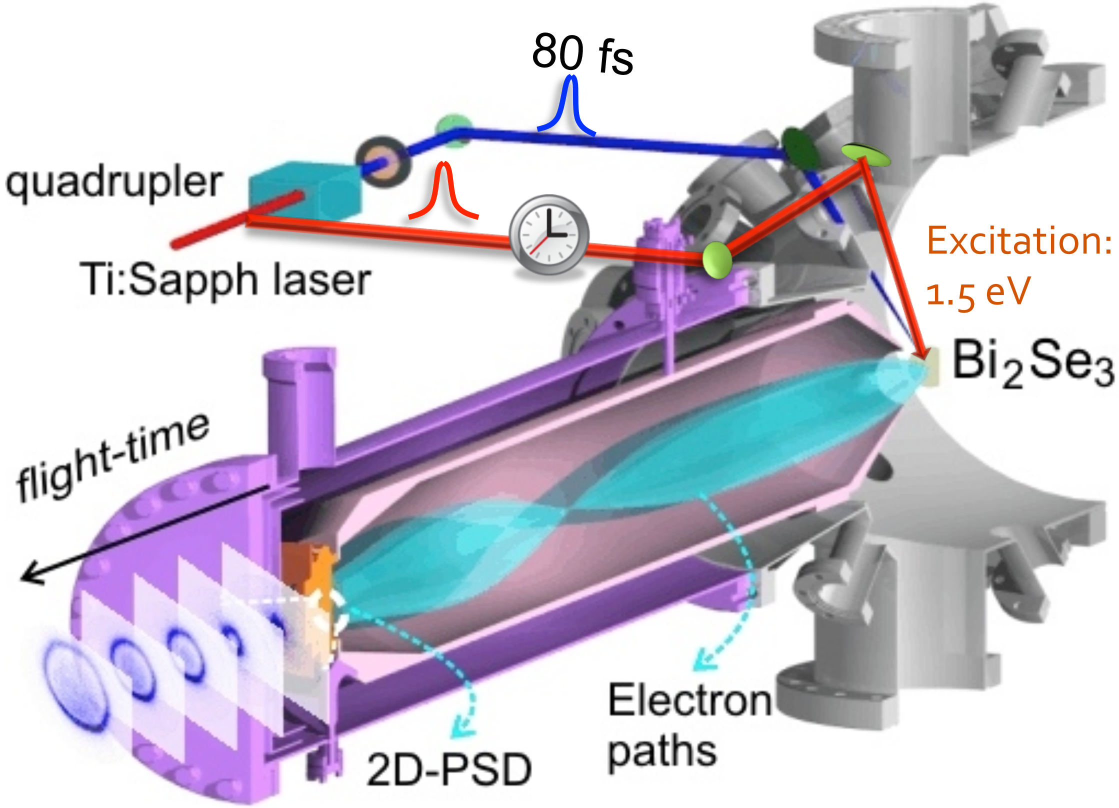



Newport
RS 4000
Sealed Hole Table Top with Tuned Damping
McPHERSON
MODEL 789A-3
CONTROLLER
Auto Vent

Time resolved ARPES

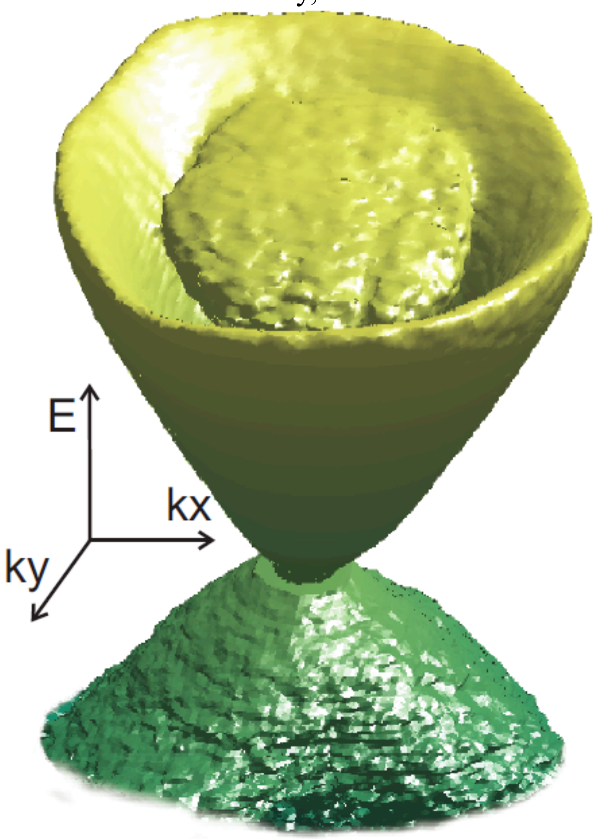
$I(E, k_x, k_{y,} t<0)$



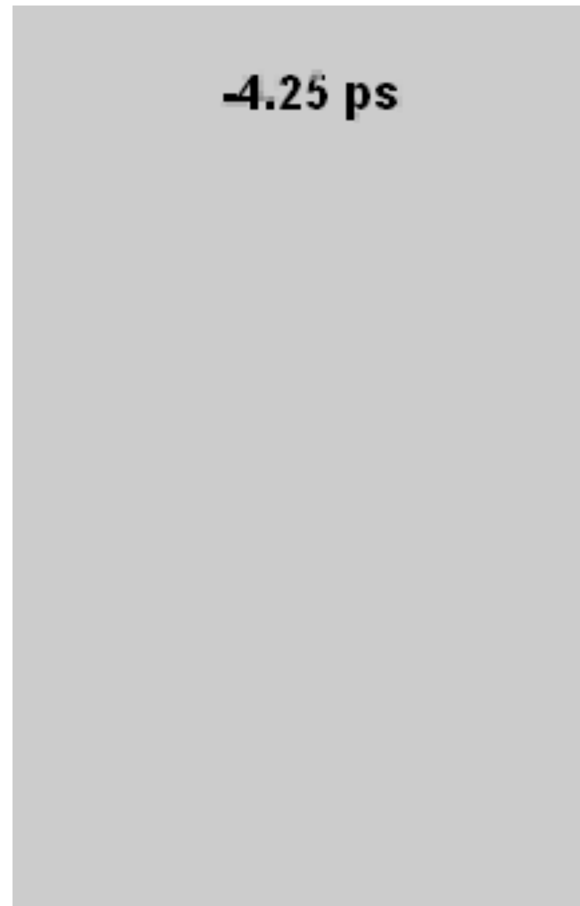


Movie of the 3D electronic band structure

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



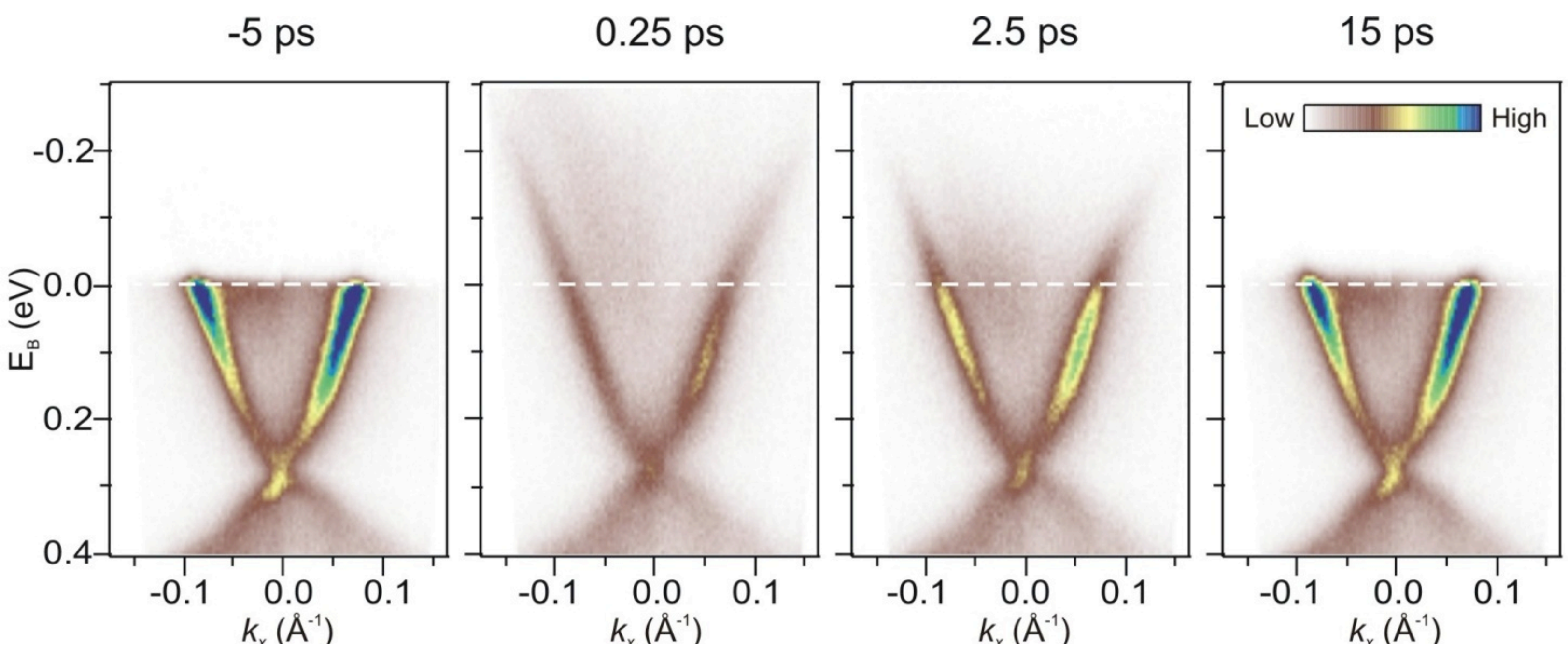
$I(E, k_x, k_y, t>0) - I(E, k_x, k_y, t<0)$



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:



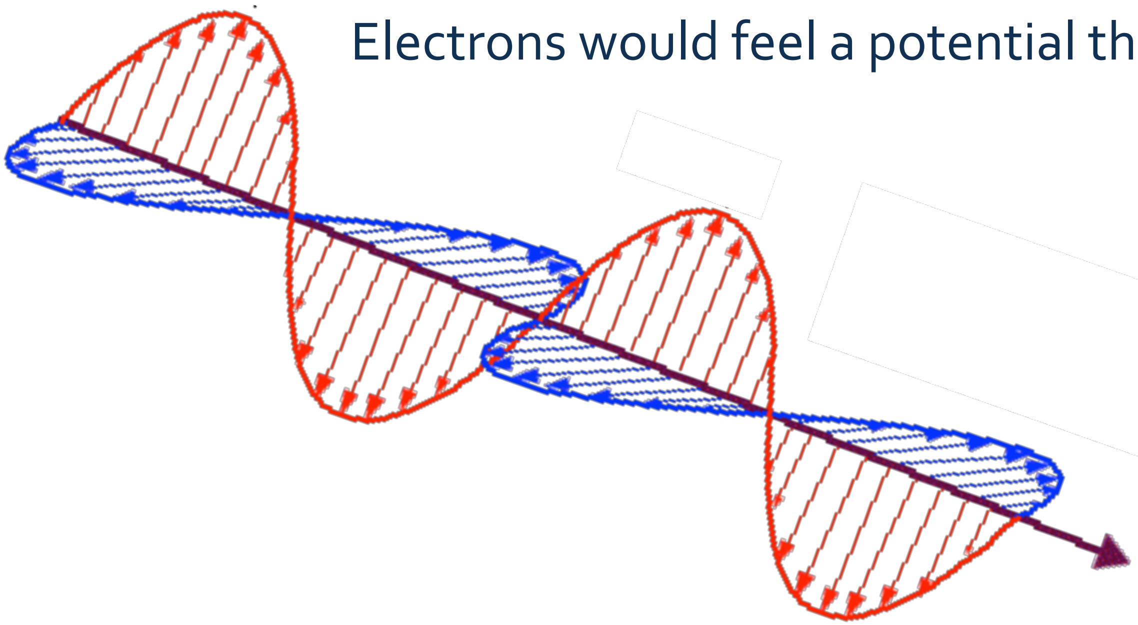
Excitation Energy = 1.5 eV

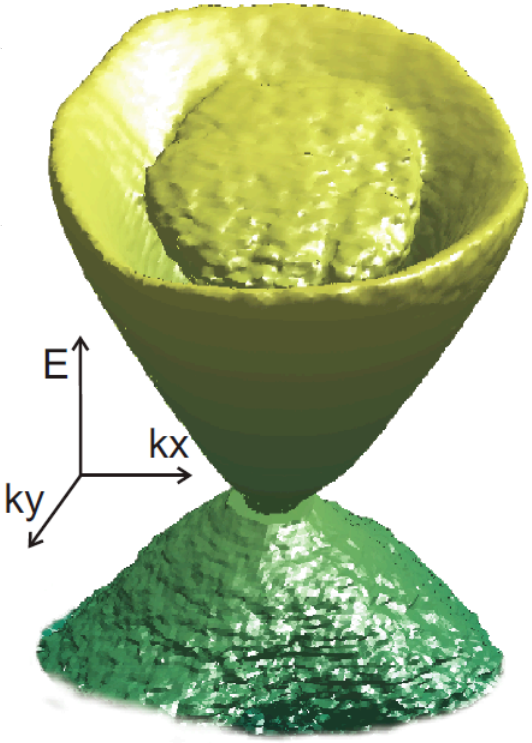
What would happen if I excite below bulk bandgap?

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

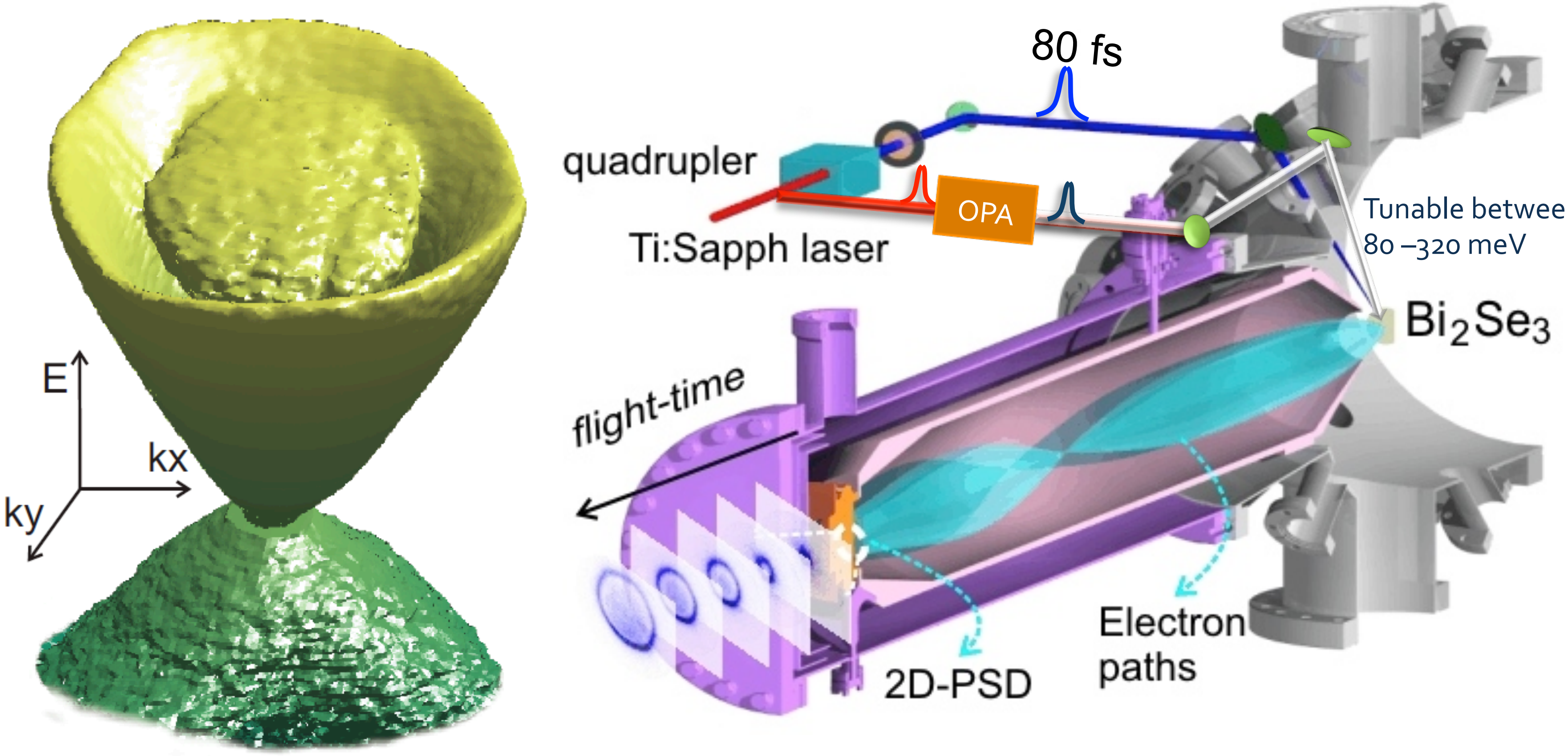
What would happen if I excite below bulk bandgap?

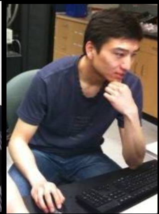
Electrons would feel a potential that is **periodic in time!**



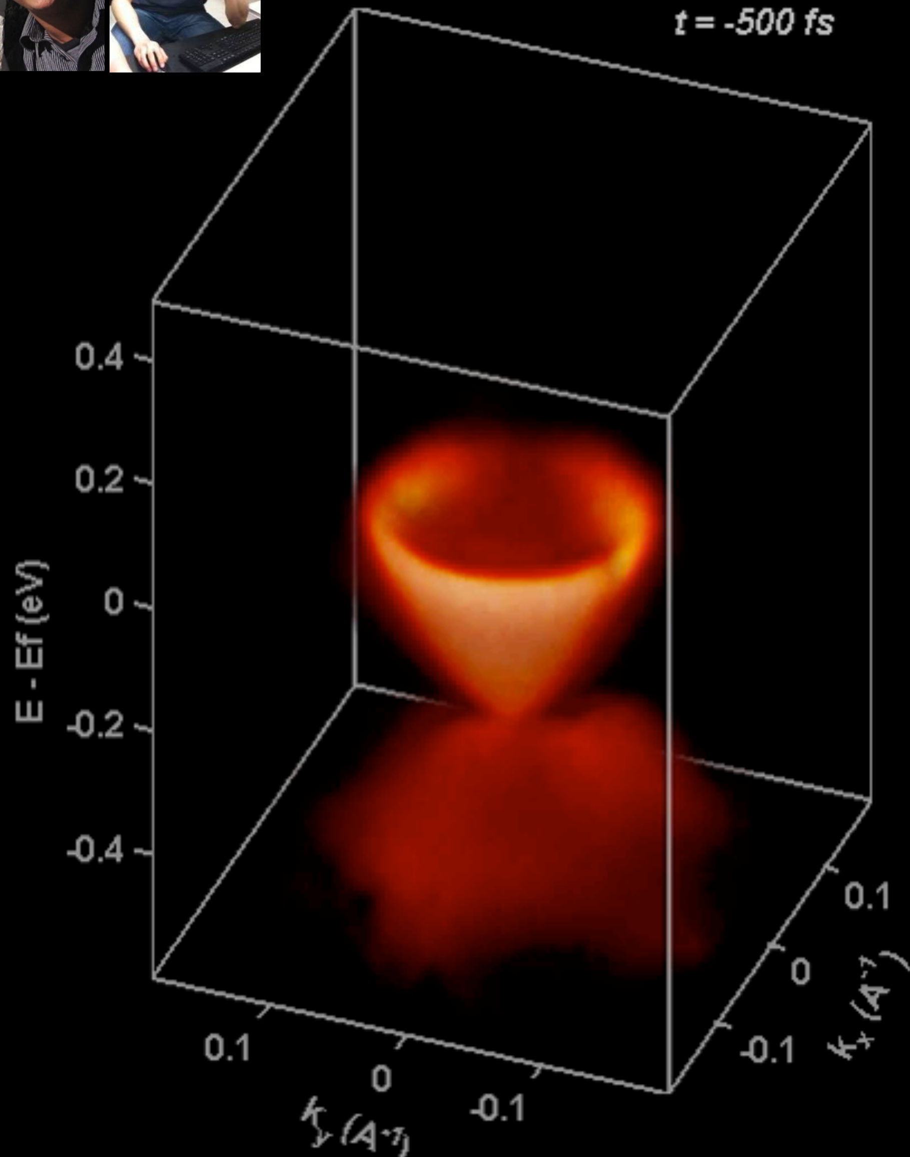


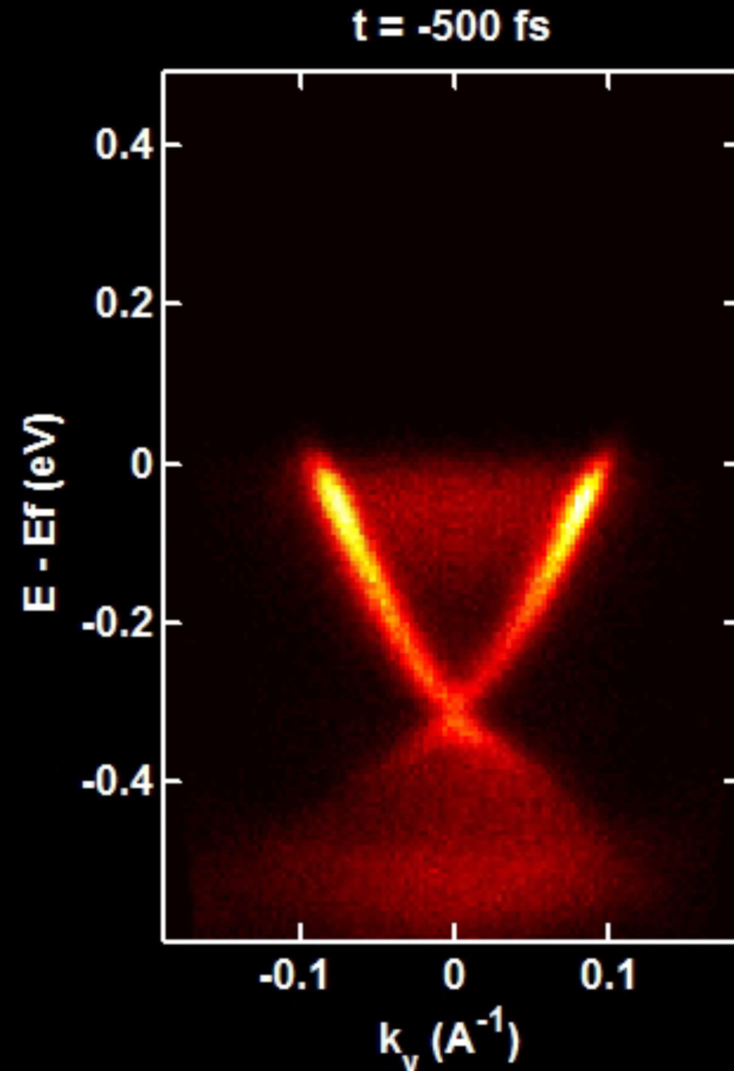
Time resolved ARPES



Horizontal cut at t = 0 fs
Vertical cut at t = 0 fs

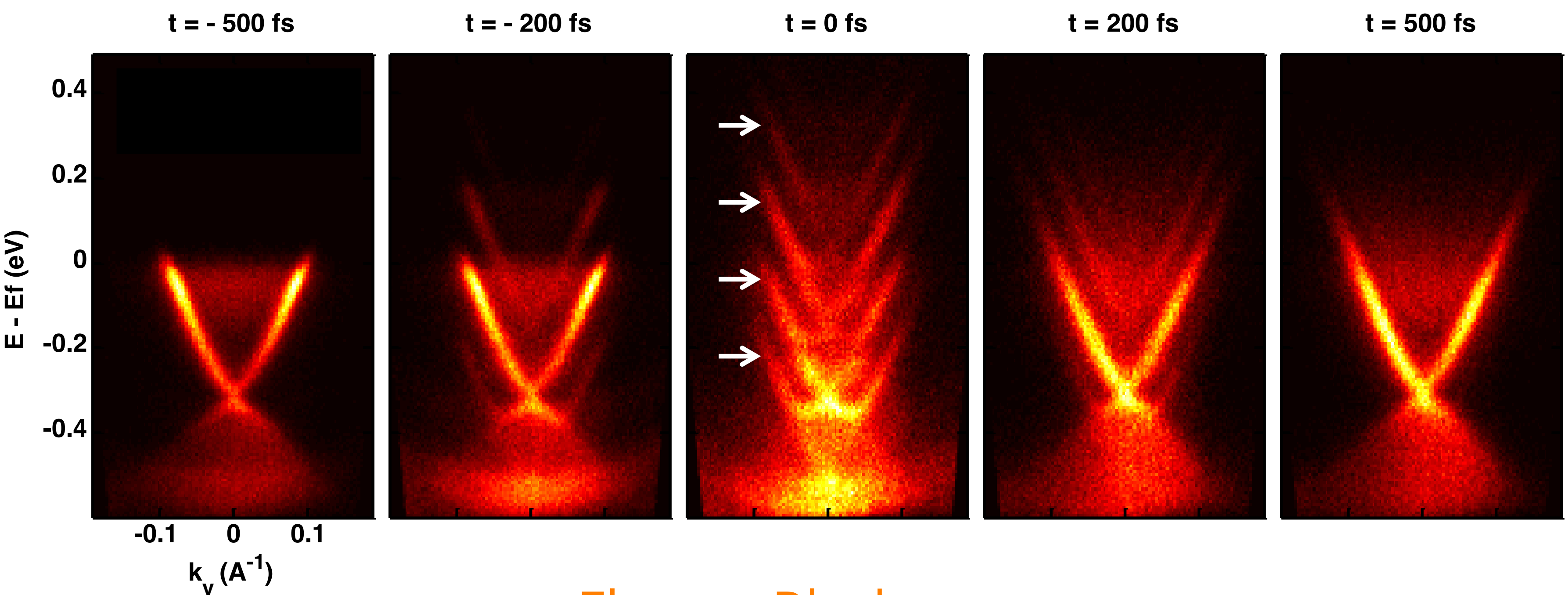




Science 342, 453 (2013)   Nature Physics 12, 306 (2016)

Photoexcitation of TI with light $E<E_g$

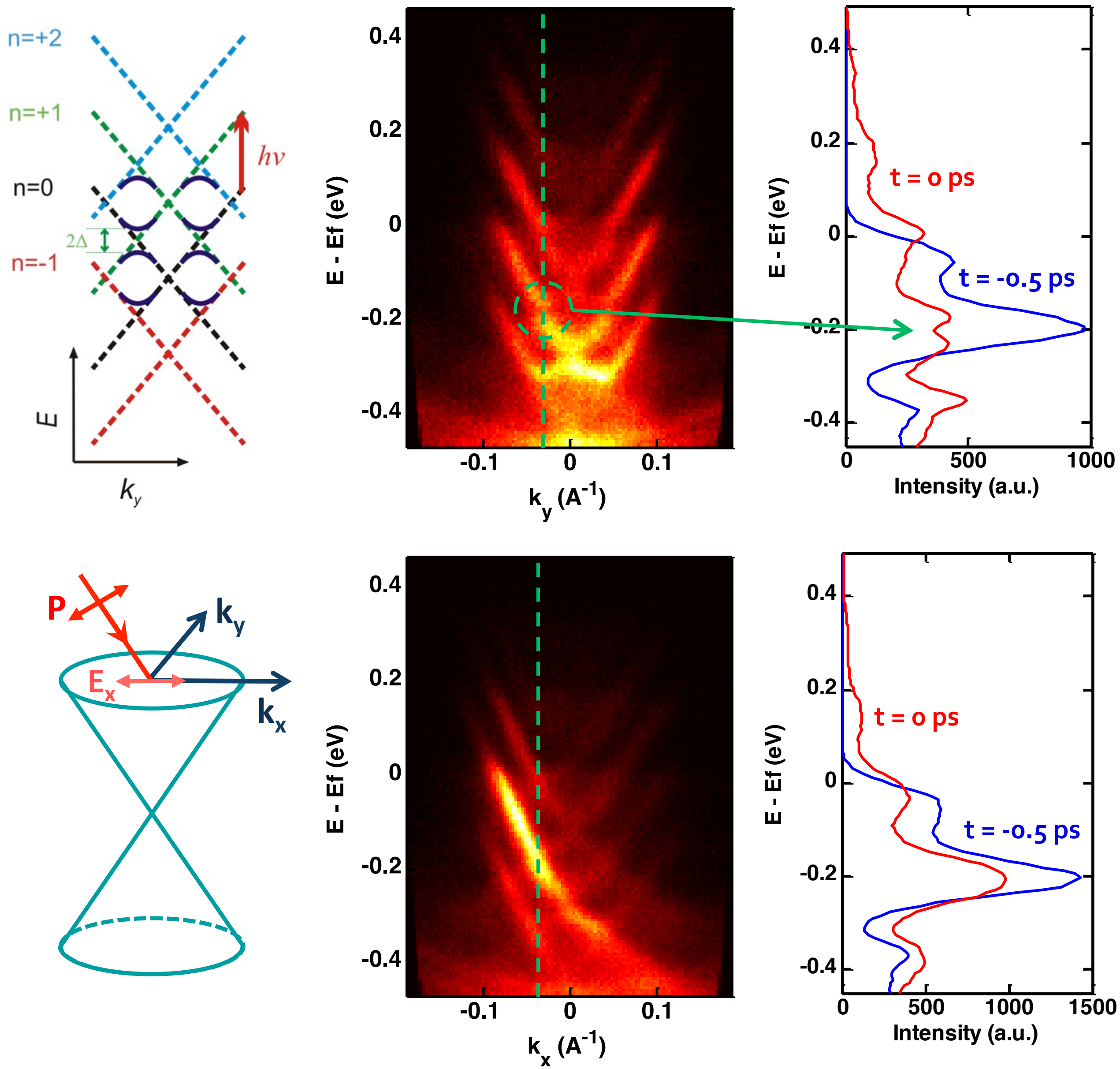
- Excitation light energy is **smaller** than the bulk band gap



Floquet-Bloch states

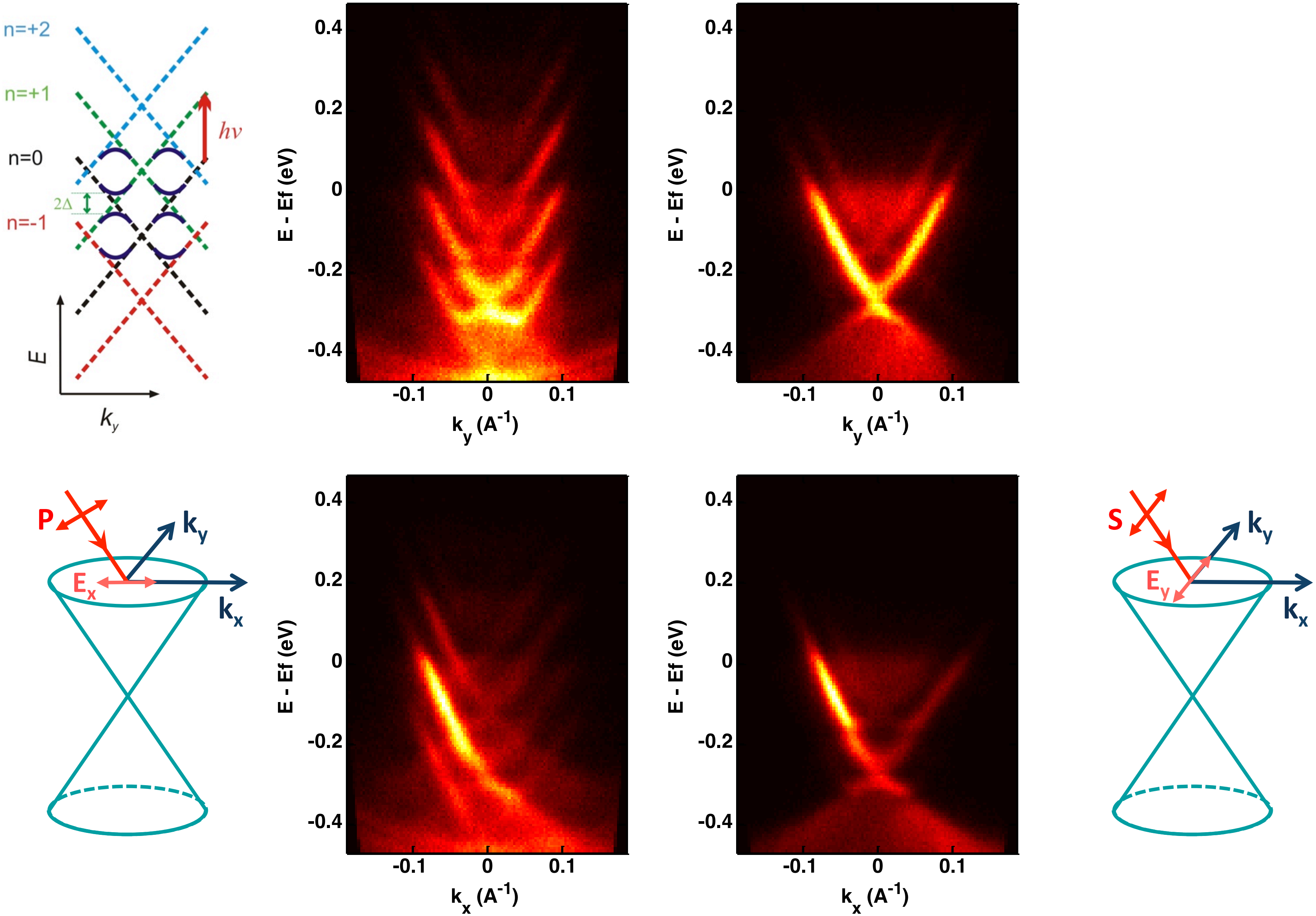
Science 342, 453 (2013)   Nature Physics 12, 306 (2016)

Dependence on momentum direction



Science 342, 453 (2013)   Nature Physics 12, 306 (2016)

Dependence on momentum direction



Science 342, 453 (2013)   Nature Physics 12, 306 (2016)

Theory of coherent light interaction with TI

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

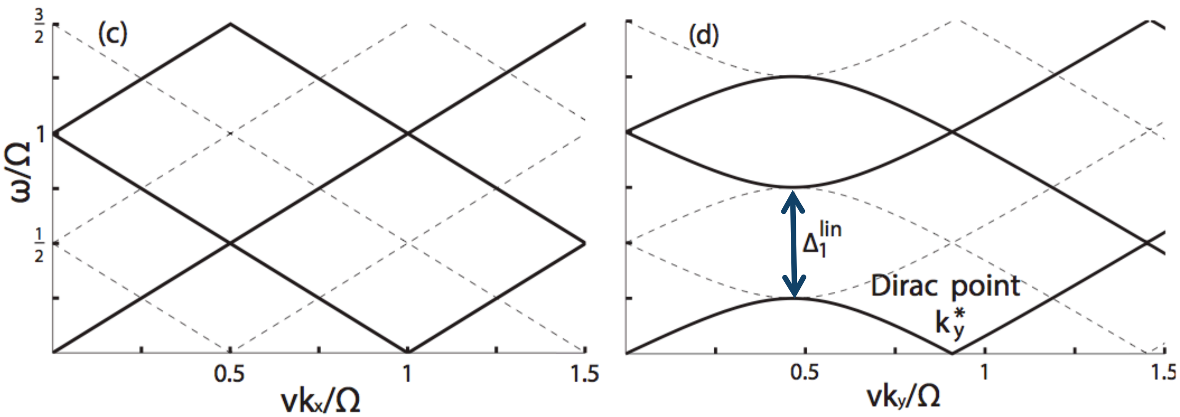
$$H(\mathbf{k},t) = H_0(\mathbf{k}) + H_{ext}(t)$$

$$H_{ext}(t) = V\Theta(t-t_0)(A_x(t)\sigma_y - A_y(t)\sigma_x)$$

$$\text{Linear:}\ \ A(t) \propto (\cos\omega t, 0)$$

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

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



Theory:

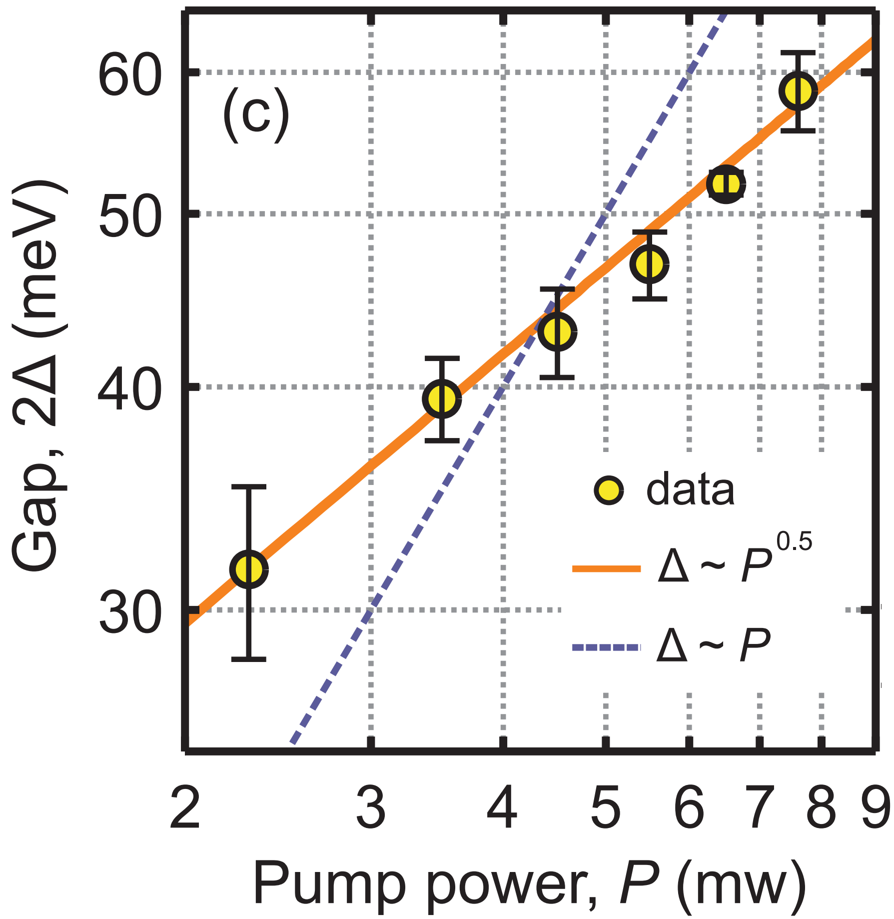
$2\Delta = 66\,meV$

Exp:

$2\Delta = 68\,meV$

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

Theory of coherent light interaction with TI



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

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

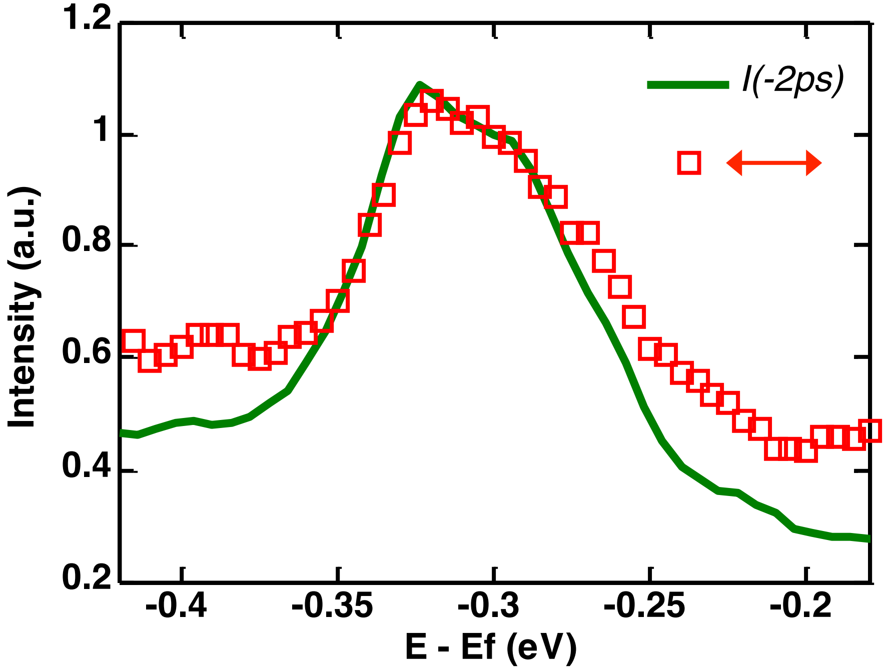
Nature Physics 12, 306 (2016)

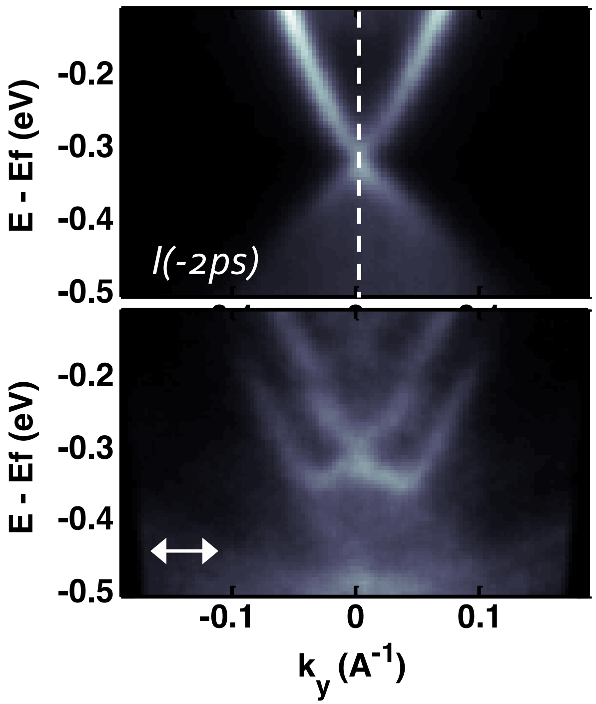
Can we break TRS in TIs with light?

- Topological phase is protected by time reversal symmetry (TRS)
- Breaking TRS in TIs is predicted to lead to fascinating effects
- It will open a band gap and make the Dirac fermions massive

- Traditional methods rely on coating with ferromagnet or doping with magnetic impurities both of which are difficult
- Could we use circularly polarized light to break TRS in TIs?

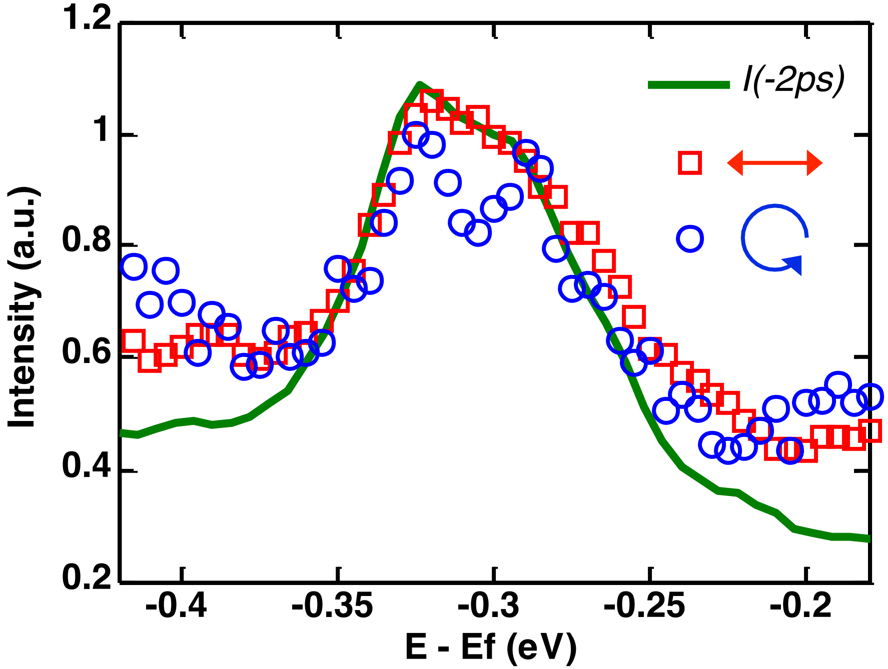
Linear Polarization:
No Gap at the Dirac Point!

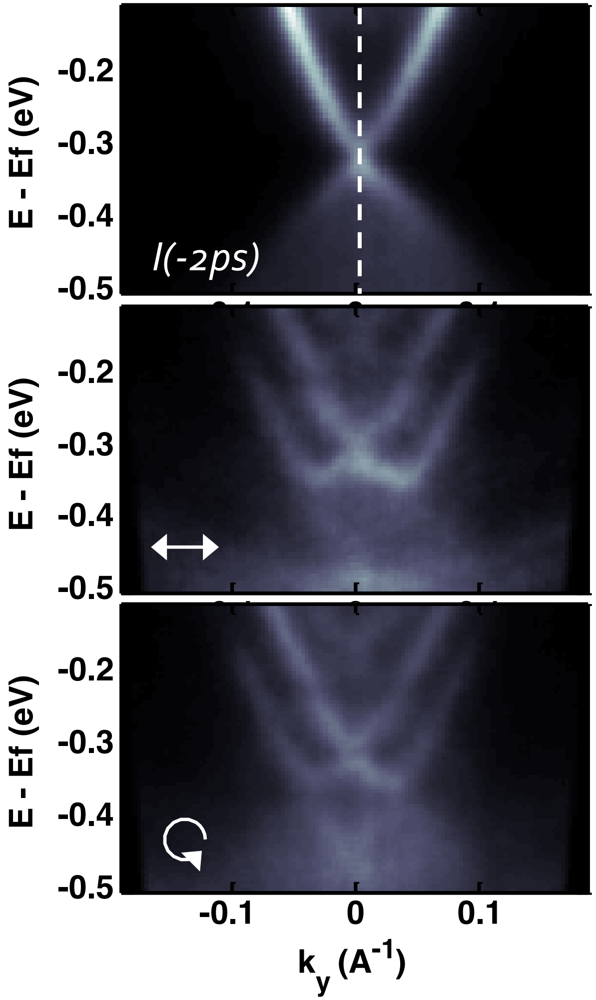




Science 342, 453 (2013) Nature Physics 12, 306 (2016)

Circular Polarization: Photoinduced Gap at the Dirac Point!





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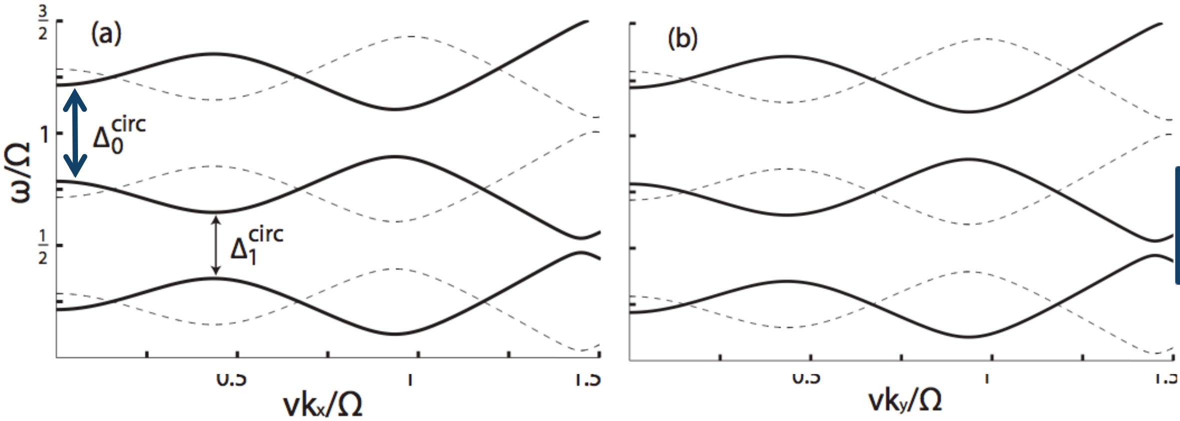
$$H(\mathbf{k},t) = H_0(\mathbf{k}) + H_{ext}(t)$$

$$H_{ext}(t) = V\Theta(t-t_0)(A_x(t)\sigma_y - A_y(t)\sigma_x)$$

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

Linear: $A(t) \propto (\cos\omega t, 0)$

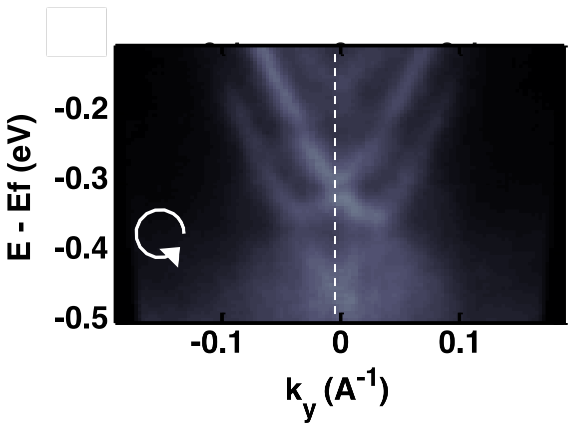
Circular: $A(t) \propto (\pm\cos\omega t, \sin\omega t)$



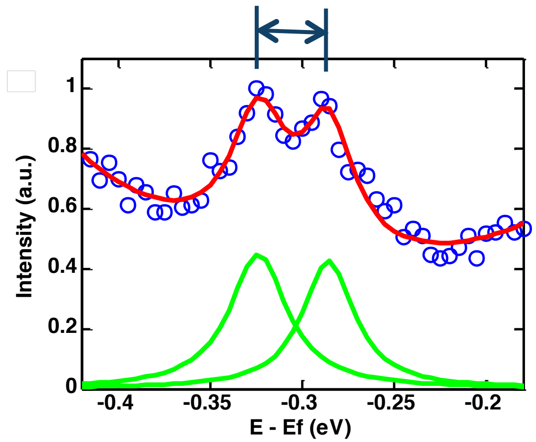
$$2\kappa = \sqrt{4V^2 + (\hbar\omega)^2} - \hbar\omega$$

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

Theory: Circular polarization



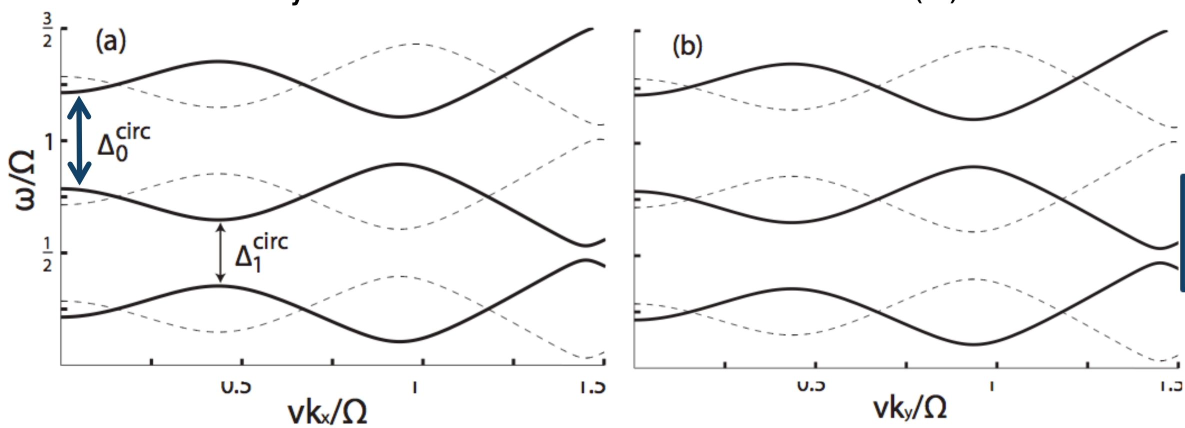
$2\kappa = 39\, meV$



$$V = evE_0/\omega$$

Theory:

$$2\kappa = 48\, meV$$



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

Small Coupling $V \ll \hbar\omega$

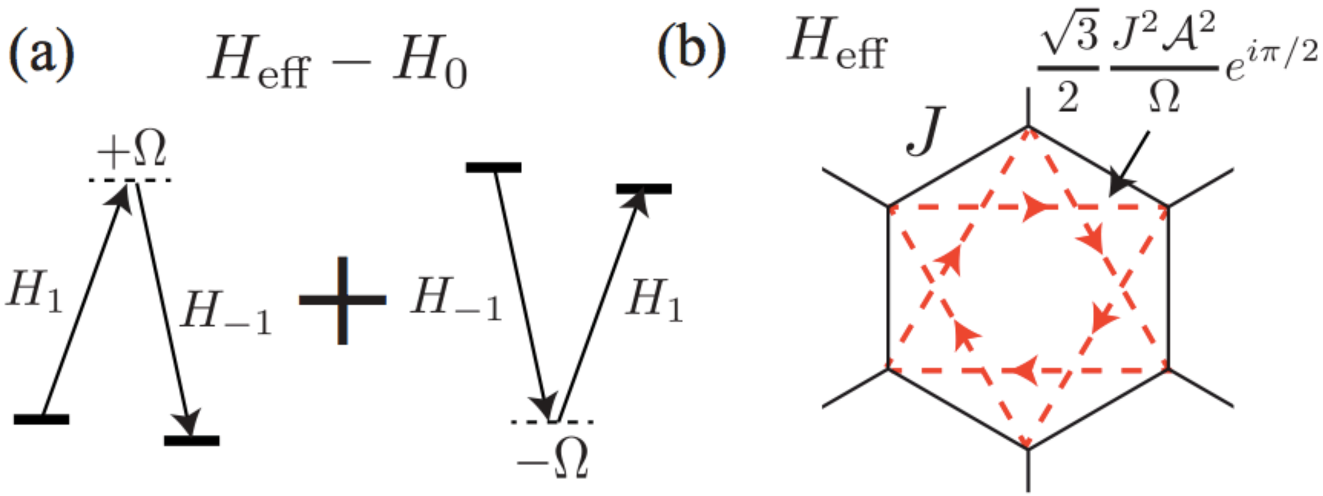
$$2\kappa \approx \frac{2V^2}{\hbar\omega}$$

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

Science 342, 453 (2013) Nature Physics 12, 306 (2016)

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!!!

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

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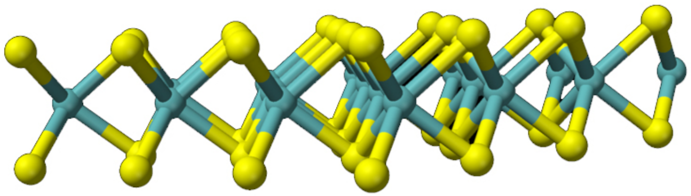
Transition metal dichalcogenides (TMD)



(MX_2 with M: Mo, W and X: S, Se, Te)

Broken inversion symmetry

↓

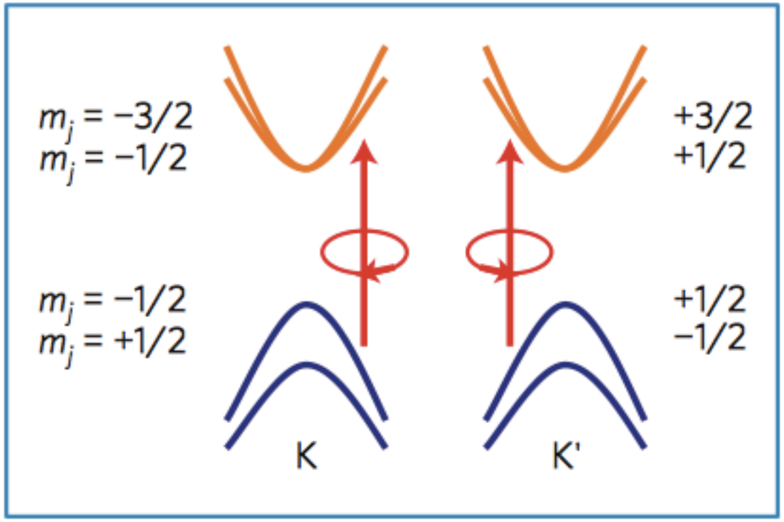
coupling of spin and valley

Time reversal symmetry

↓

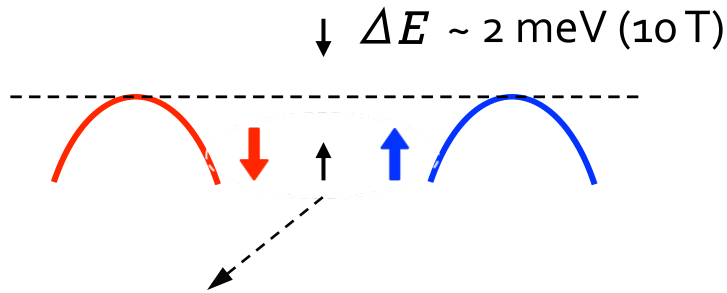
Degenerate valley at K and K′

Mak et al. Nature Nanotech. 7, 494–498 (2012).



Valley degeneracy in TMDs

Applying magnetic field



Time-reversed partner

Zeeman effect, see:

- MacNeill *et al*, PRL
- Li *et al*, PRL
- Srivastava *et al*, Nature Phys
- Aivazian *et al*, Nature Phys

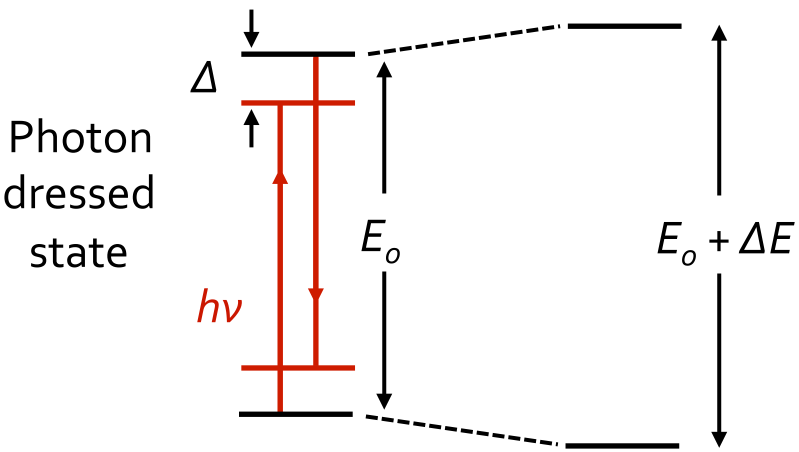
Energetically degenerate

Break time-reversal symmetry

Locked by time-reversal symmetry

Can <u>light</u> be used to lift the valley degeneracy?

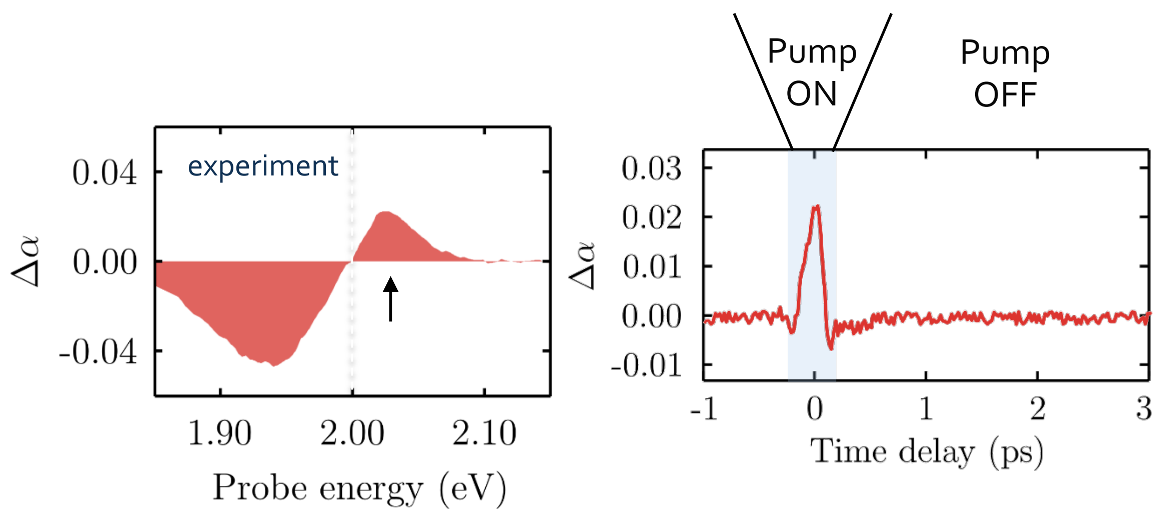
The optical Stark effect (WS2)



Laser Fluence

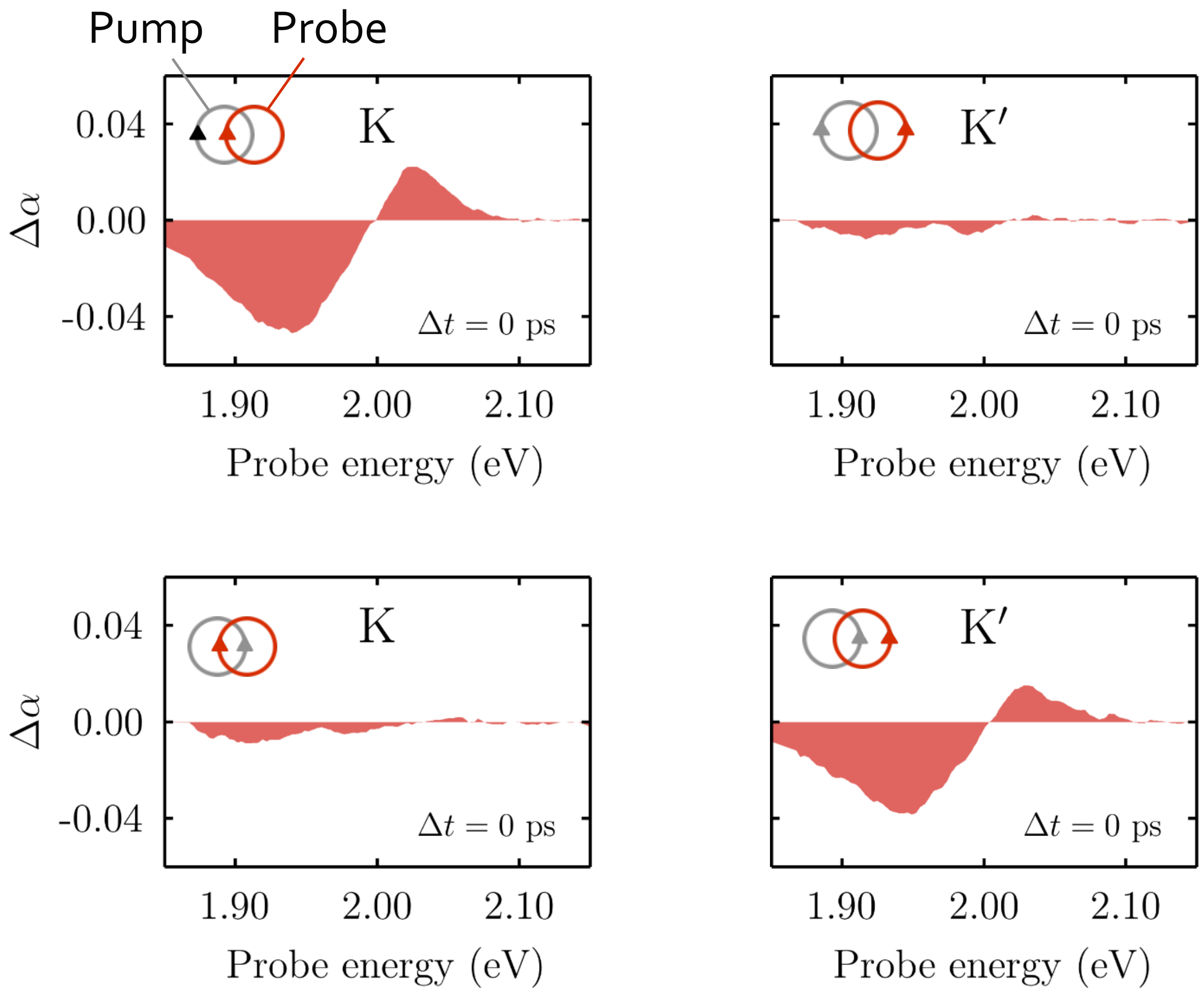
$$\boxed{\Delta E_{\mathrm{OS}} \propto \frac{\mathcal{E}_0^2}{E_0 - \hbar\omega}}$$

energy detuning (Δ)



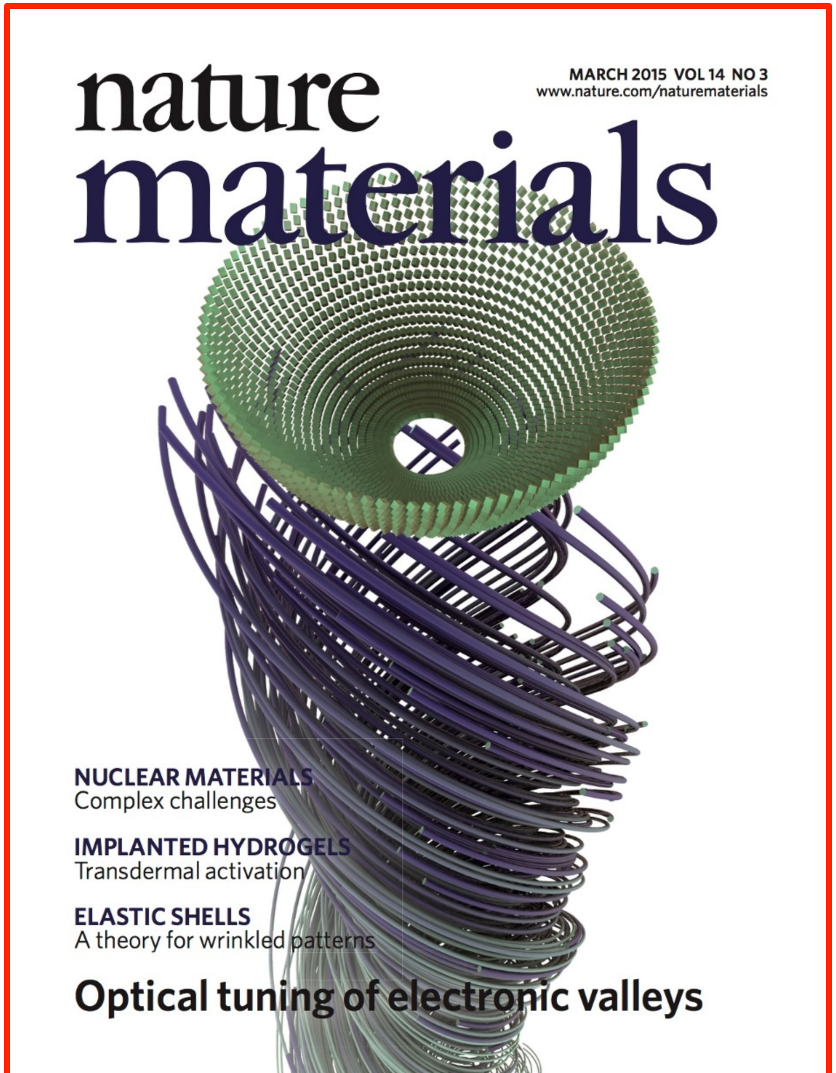
E J Sie *et al*, Nature Materials 14, 290 (2015)
Kim et al. Science

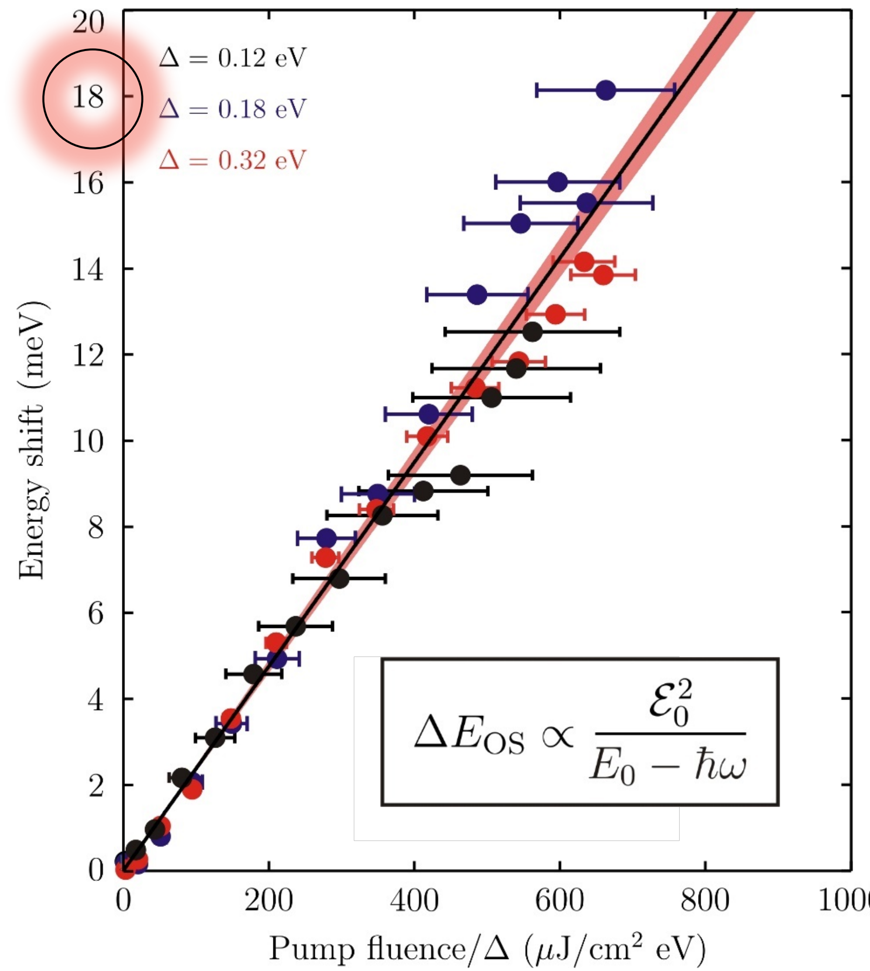
Valley selectivity



E J Sie *et al*, Nature Materials 14, 290 (2015)

Laser tunability

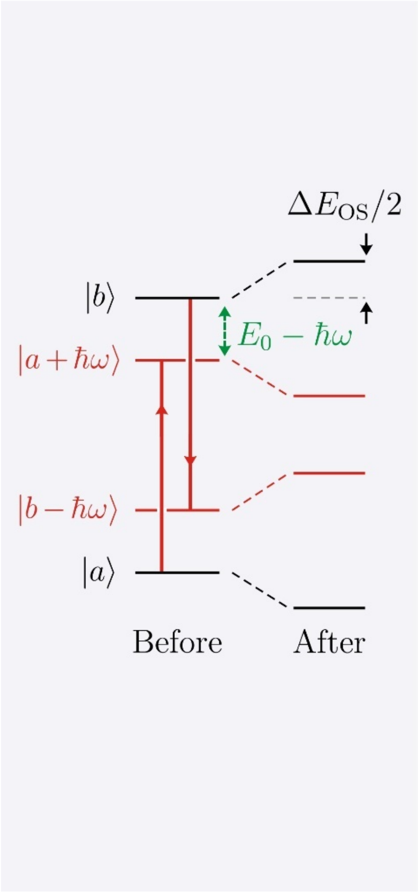


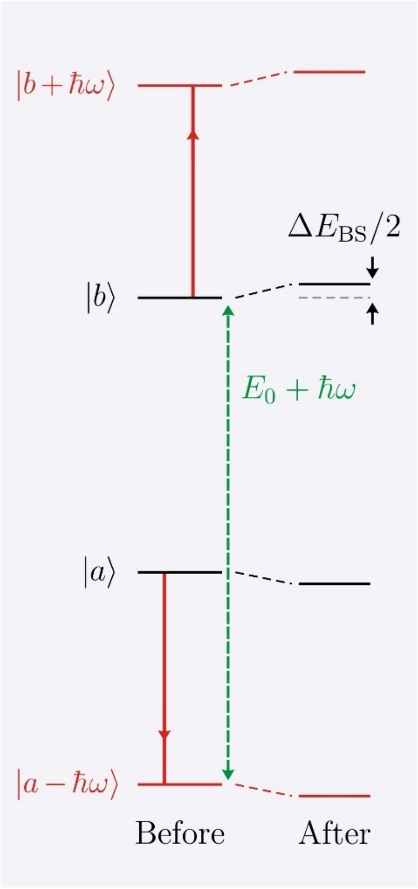


EJ Sie *et al*, Nature Mater 14, 290 (2015)
Kim et al. Science

What would happen in large detuning?

Bloch-Siegert shift





Optical Stark effect

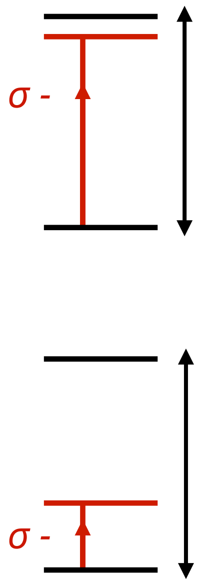
$$\boxed{\Delta E_{OS} \propto \frac{\mathcal{E}_0^2}{E_0 - \hbar\omega}}$$

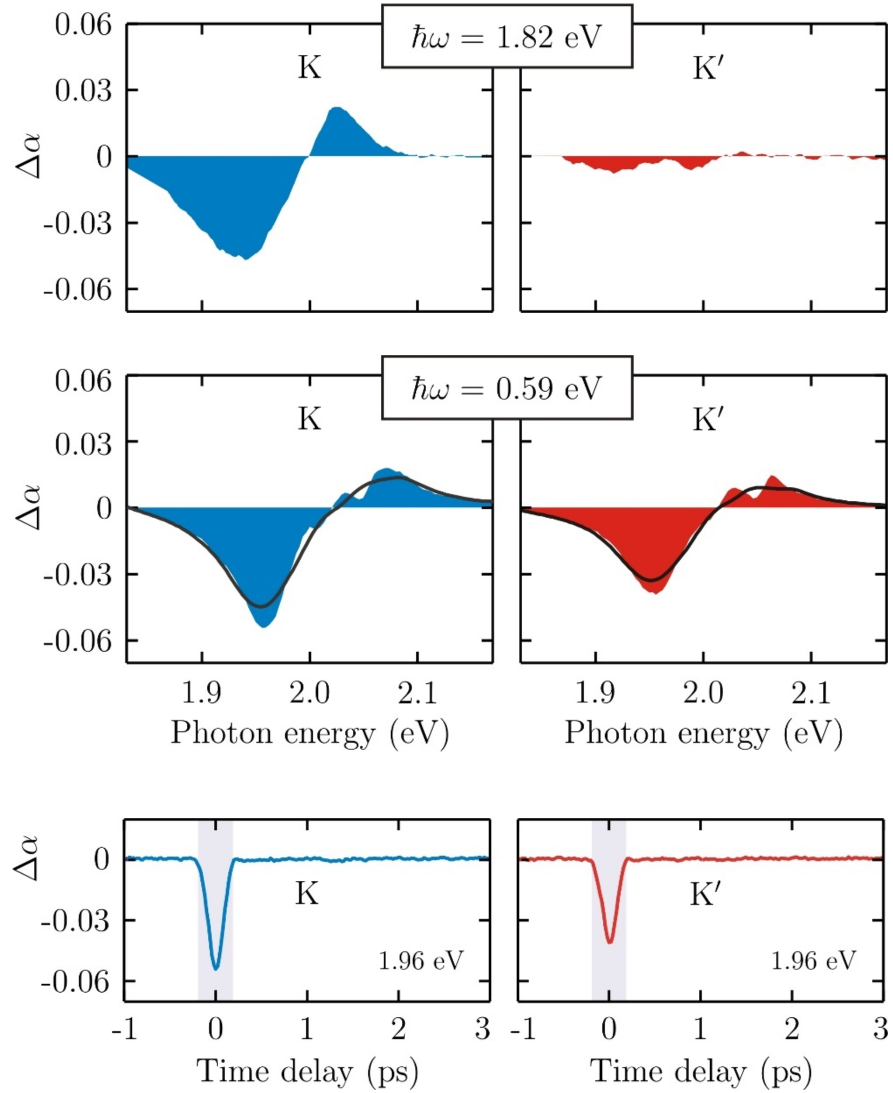
Bloch-Siegert shift

$$\boxed{\Delta E_{BS} \propto \frac{\mathcal{E}_0^2}{E_0 + \hbar\omega}}$$

EJ Sie *et al*, in review (2016)

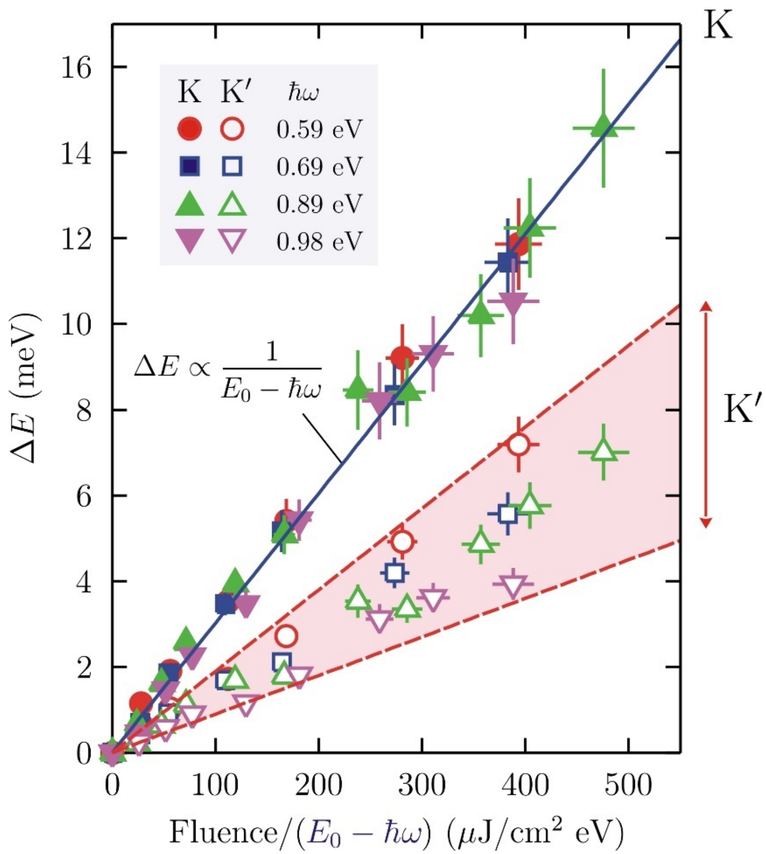
Small-to-Large detuning

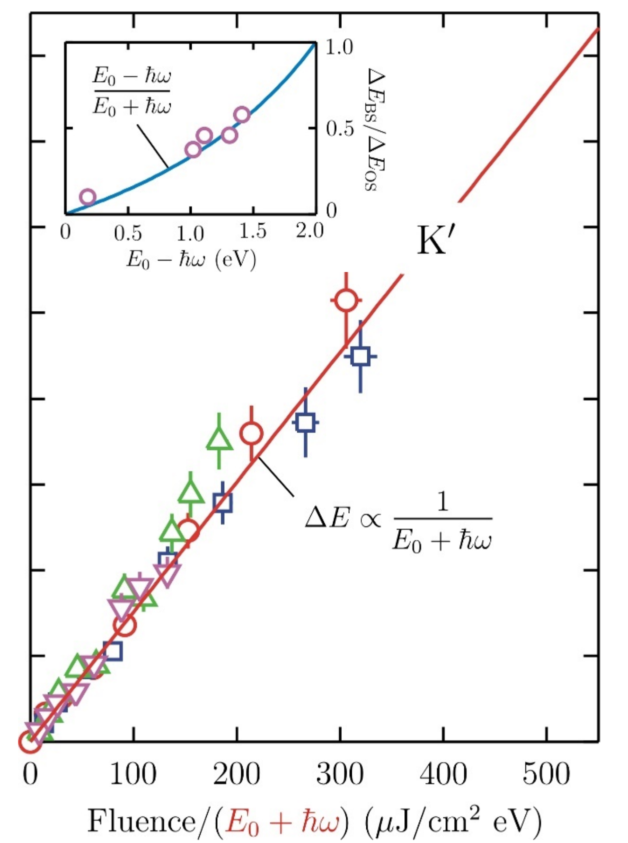




EJ Sie *et al*, in review (2016)

Fluence and detuning dependence



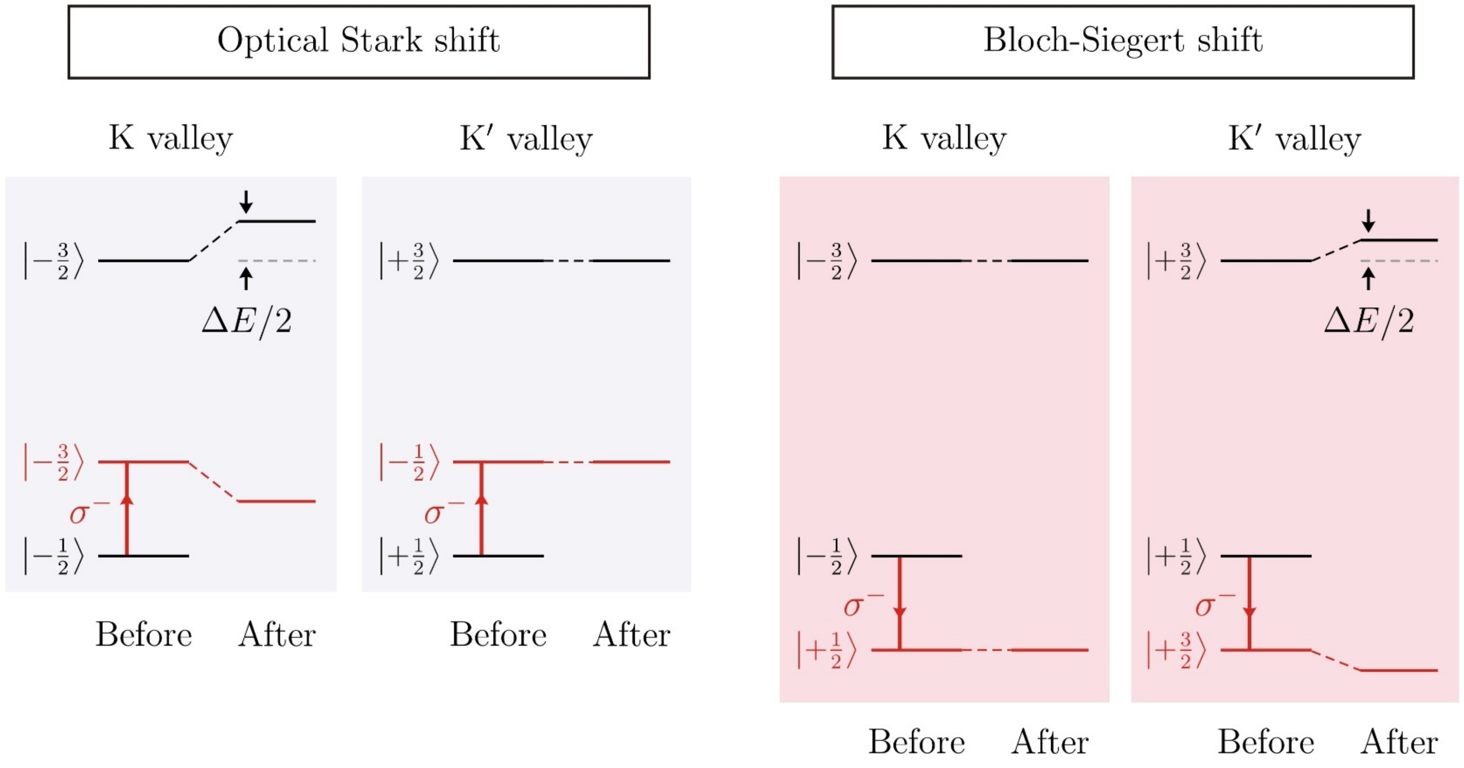


$$\boxed{\Delta E_{OS} \propto \frac{\mathcal{E}_0^2}{E_0 - \hbar\omega}}$$ Optical Stark effect

$$\boxed{\Delta E_{BS} \propto \frac{\mathcal{E}_0^2}{E_0 + \hbar\omega}}$$ Bloch-Siegert shift

EJ Sie *et al*, in review (2016)

Physical picture



EJ Sie *et al*, in review (2016)

Summary

- 3D visualization of bulk and surface dynamics
- Observation of Floquet-Bloch states in solids!
- Breaking of TRS with light in a TI!
- Breaking valley degeneracy with light in TMDs
- Observation of Bloch-Siegert shift in solids

Current Group Members