Theory of photo-induced Floquet topological states in graphene and beyond

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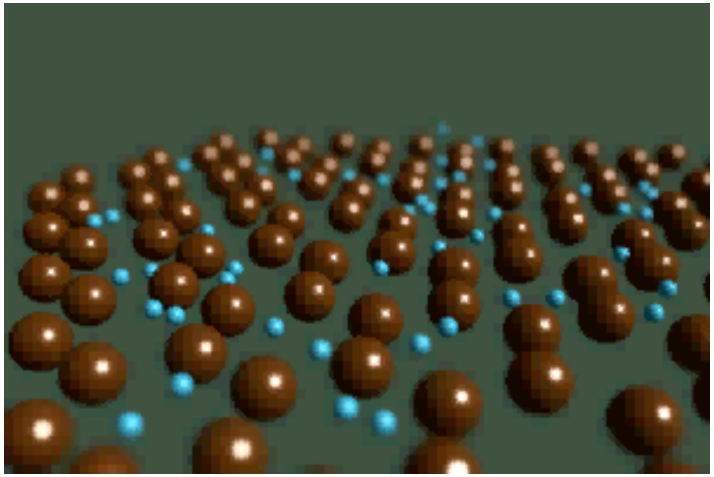
Michael Sentef

Photonics West

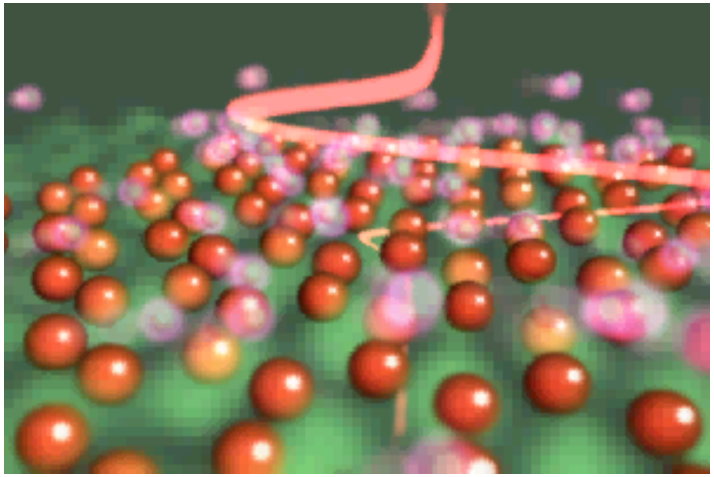
San Francisco, February 16, 2016

Artistic view of Floquet states

by Koichiro Tanaka (Kyoto university)



electrons in solids



Floquet state (photo-dressed state)

$$H$$

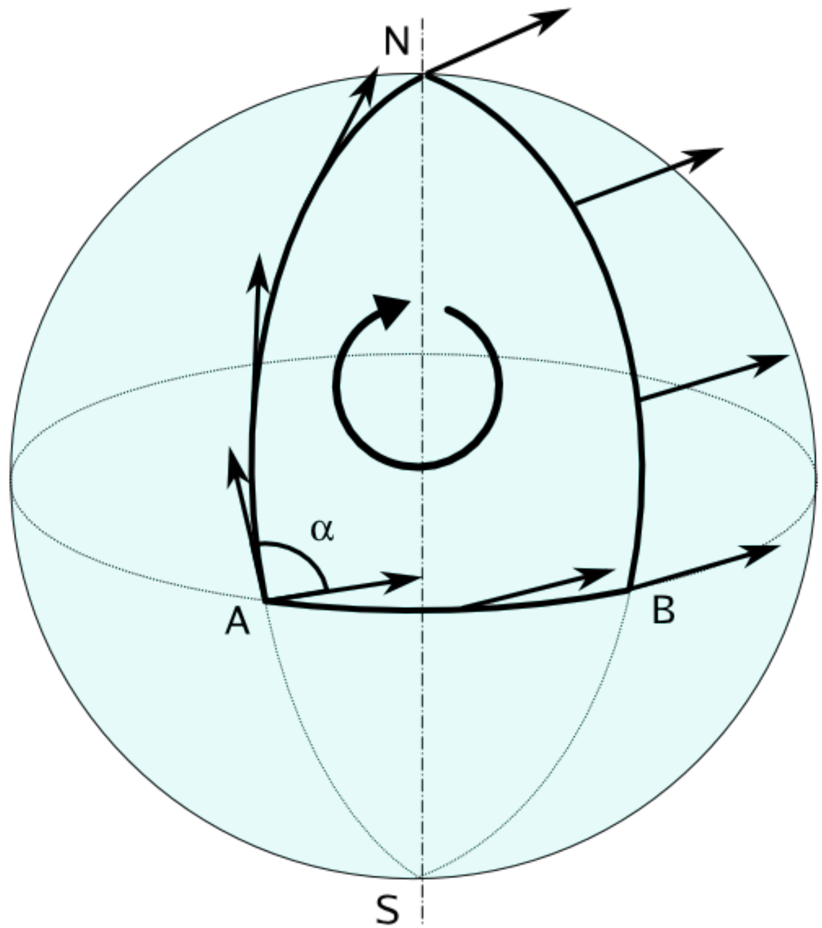
$$H_{\text{eff}}$$

- Topological band theory
- Floquet states
- Graphene
- Na_3Bi

Topological states of matter

Global Change without Local Change *illustrates Berry's Phase*

M. V. Berry, Proc. R. Soc. A 392, 45 (1984)



Topological states of matter

C. Kane, "Topological band theory and the Z2 invariant", Chapter 1 in "Topological Insulators", Elsevier (2013)

mpsd

Topological band theory of solids

$$H(\mathbf{k}) = e^{i\mathbf{k}\cdot\mathbf{r}} H e^{-i\mathbf{k}\cdot\mathbf{r}}$$

eigenvalues $E_n(\mathbf{k})$ and eigenvectors $|u_n(\mathbf{k})\rangle$

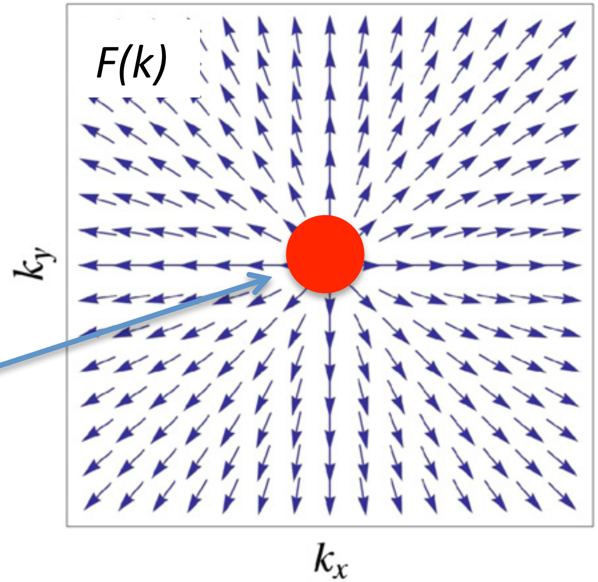
Berry connection $\mathbf{A} = -i\langle u(\mathbf{k})|\nabla_{\mathbf{k}}|u(\mathbf{k})\rangle$

Berry phase $\gamma_C = \oint_C \mathbf{A}\cdot d\mathbf{k} = \int_S \mathcal{F} d^2\mathbf{k}$

Berry phase is gauge-invariant and can be measured!

$\mathcal{F} = \nabla \times \mathbf{A}$ defines the Berry curvature

closed surface S $n = \frac{1}{2\pi}\int_S \mathcal{F} d^2\mathbf{k}$

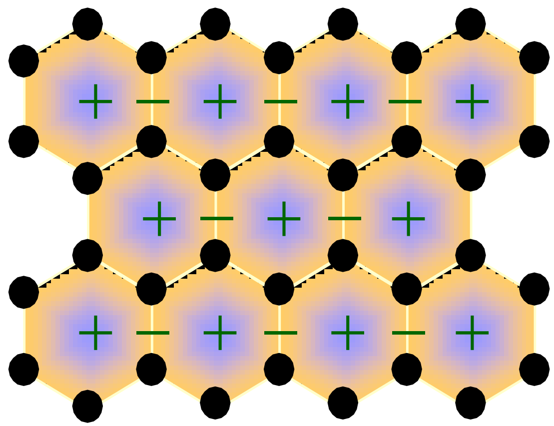


n = Chern number = # Dirac monopoles

Topological states of matter

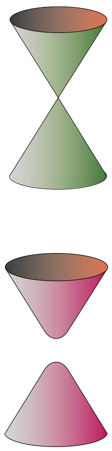
Integer Quantum Hall Effect in zero net magnetic field

Graphene with a periodic magnetic field B(r) (Haldane PRL 1988)



B(r) = 0
Zero gap,
Dirac point

B(r) ≠ 0
Energy gap
$\sigma_{xy} = e^2/h$



Topological states of matter

Dirac fermions in pseudospin representation

$$H(K+q) = \begin{pmatrix} m_K & q_x + iq_y \\ q_x - iq_y & -m_K \end{pmatrix}$$

$$= p_x\sigma_x + p_y\sigma_y + p_z\sigma_z$$

$$\boxed{\begin{array}{l} p_x = q_x \\ p_y = q_y \\ p_z = m_K \end{array}}$$

Quantized Berry phase = sign(m_K) π

+/- ½ Dirac monopole

Chern number C = sum of Dirac monopoles

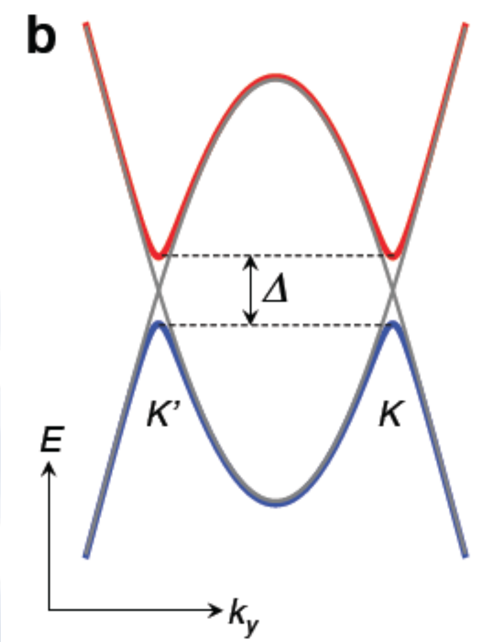
Topological states of matter

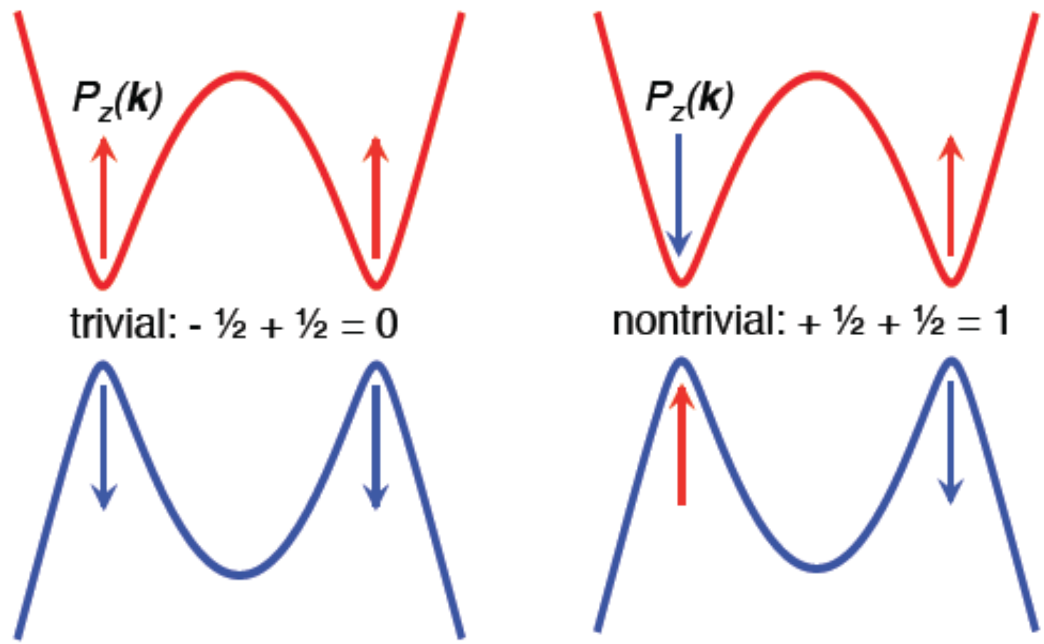
$$H(K'+q) = \begin{pmatrix} \boxed{m_{K'}} & q_x \boxed{-} iq_y \\ q_x + iq_y & -m_{K'} \end{pmatrix} \qquad H(K+q) = \begin{pmatrix} \boxed{m_K} & q_x \boxed{+} iq_y \\ q_x - iq_y & -m_K \end{pmatrix}$$

***K* vs. *K'*: opposite winding of in-plane pseudospin**

***m*$_K$ = *m*$_{K'}$**
trivial insulator

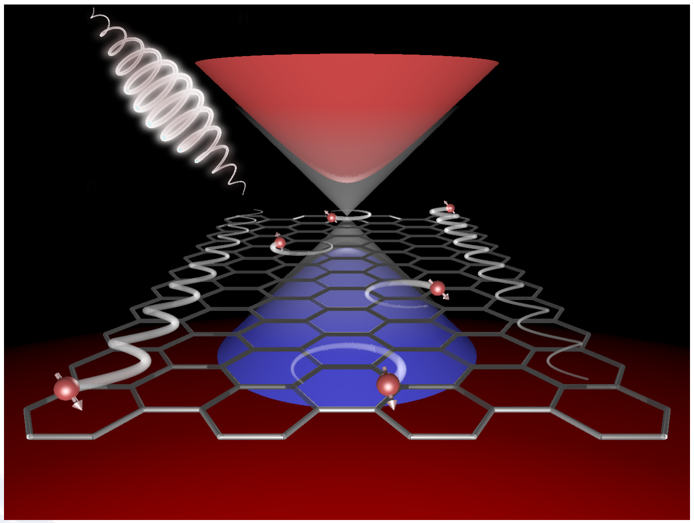
***m*$_K$ = − *m*$_{K'}$**
nontrivial insulator





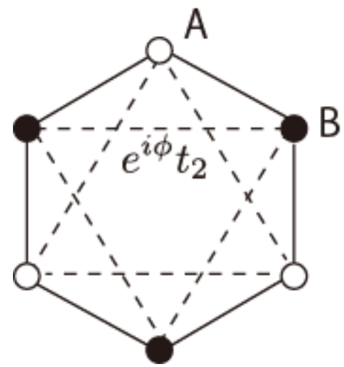
Floquet topological states

Graphene + circularly polarized light
(breaks time-reversal)



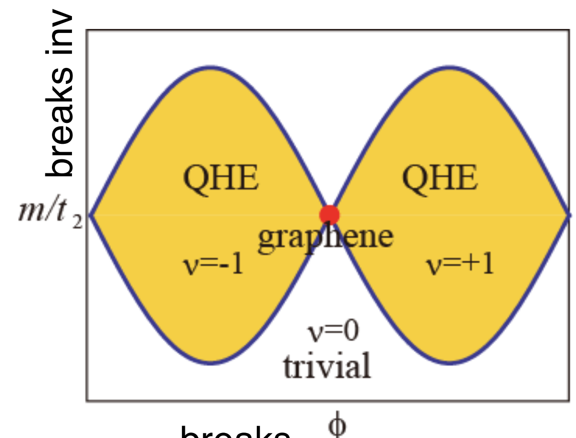
?

Haldane model (PRL 61, 2015 (1988))



Local flux ϕ
Staggered field *m*

Fictitious fields!



breaks
time-reversal

Floquet states of matter

time periodic system

$$i\partial_t \psi = H(t)\psi \qquad H(t) = H(t+T) \qquad \Omega = 2\pi/T$$

"Floquet mapping"

$$\Psi(t) = e^{-i\varepsilon t} \sum_m \phi^m e^{-im\Omega t}$$

Floquet Hamiltonian (static eigenvalue problem)

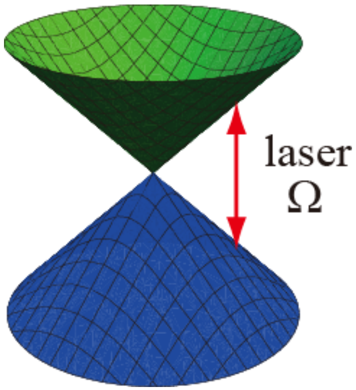
$$\sum_{m=-\infty}^{\infty} \mathcal{H}^{mn} \phi_\alpha^m = \varepsilon_\alpha \phi_\alpha^n$$

ε: Floquet quasi-energy

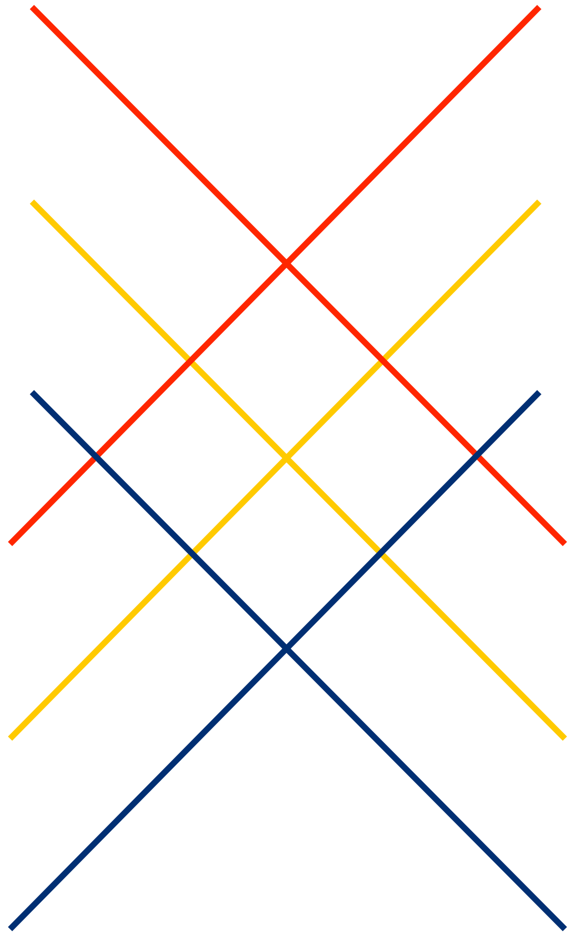
$$(\mathcal{H})^{mn} = \frac{1}{T}\int_0^T dt H(t) e^{i(m-n)\Omega t} \boxed{+ m\delta_{mn}\Omega I}$$

~ absorption of m "photons"

Dirac fermion + circularly polarized laser



$$H^{\text{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$



coupling to AC field

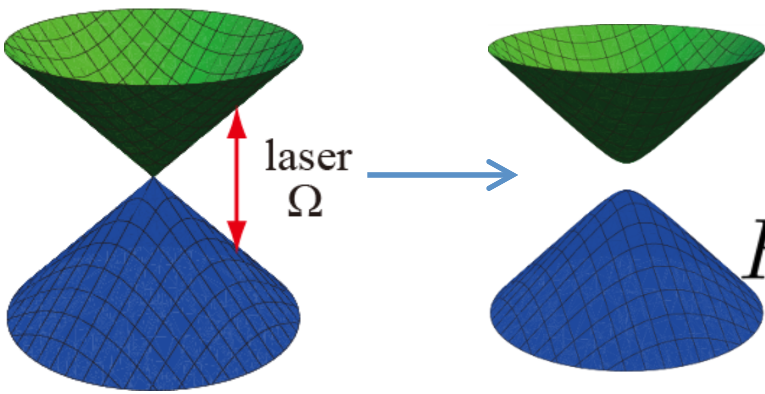
$$\boldsymbol{k} \to \boldsymbol{k} + \boldsymbol{A}(t)$$

1-photon absorbed state

0-photon absorbed state

-1-photon absorbed state

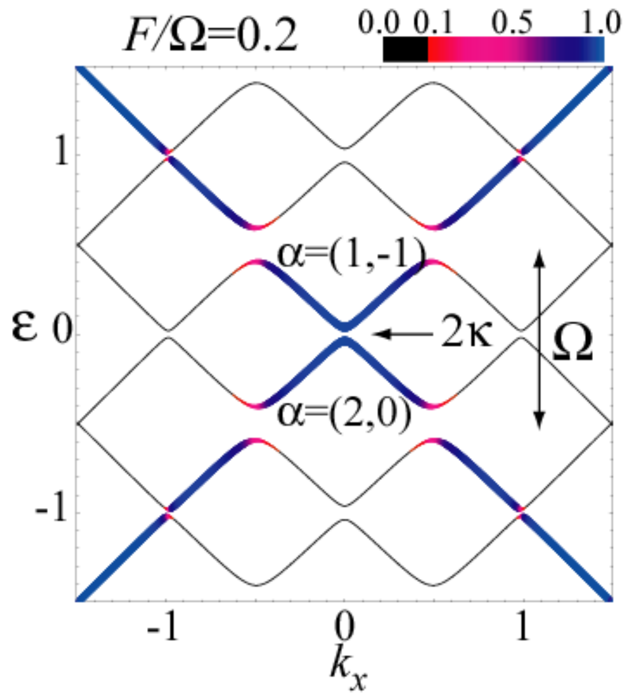
Dirac fermion + circularly polarized laser



Mass term = energy gap =
synthetic field stemming from a
real time-dependent field A(t)

$$H_{\text{eff}} = H_0 + \frac{[\overbrace{H_{-1}}^{\sim A\sigma_-}, \overbrace{H_1}^{\sim A\sigma_+}]}{\Omega} + \mathcal{O}(A^4)$$

$$H^{\text{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$



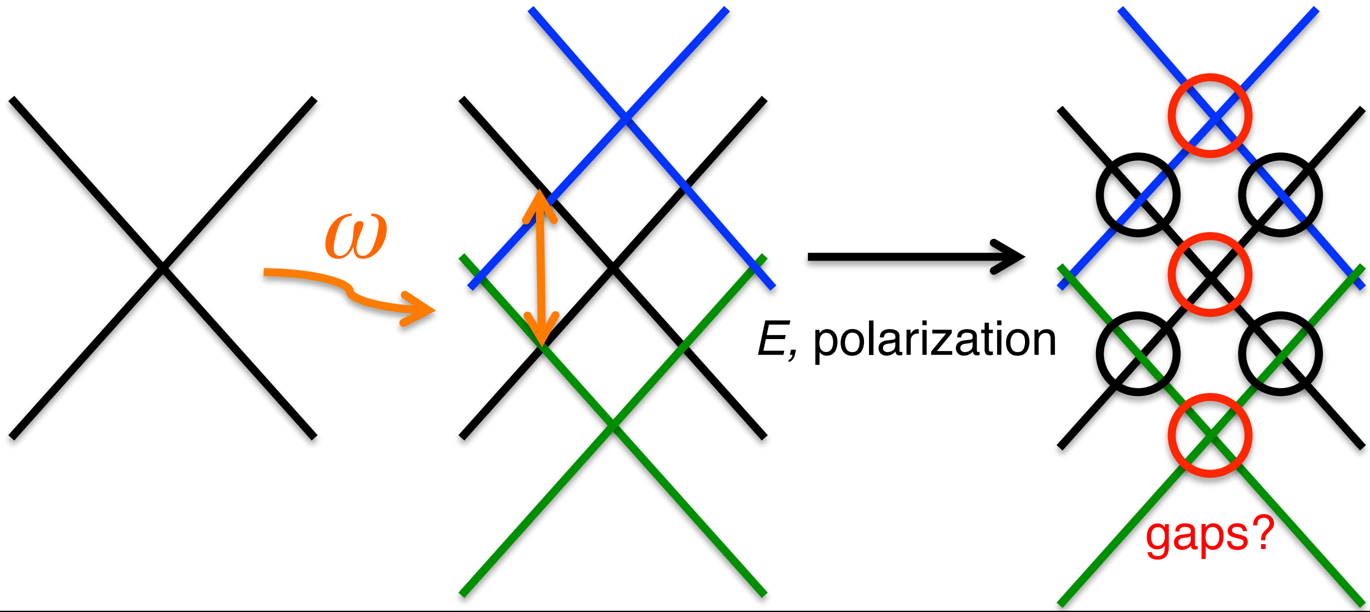
1-photon absorbed state

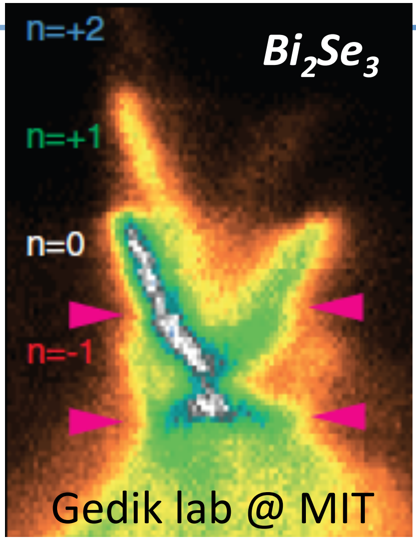
0-photon absorbed state

-1-photon absorbed state

Oka and Aoki,
PRB 79, 081406 (2009)

Floquet topological states





Wang et al., Science 342, 453 (2013)

Floquet + topology in ac driven systems:

Oka&Aoki PRB 79, 081406 (09), Kitagawa et al PRB 82, 235114 (10), Kitagawa et al PRB 84, 235108 (11), Lindner et al Nature Phys 7, 490 (11), Gu et al PRL 107, 216601 (11), Calvo et al APL 98, 232103 (11), Dora et al PRL 108, 056602 (12), Suarez Morell et al PRB 86, 125449 (12), Rudner et al PRX 3, 031005 (13), Iadecola et al, PRL 110, 176603 (13), Gomez-Leon&Platero PRL 110, 200403 (13), Fregoso et al PRB 88, 155129 (13), Perez-Piskunow et al, arXiv:1308.4362, Grushin et al, arXiv:1309.3571 … INCOMPLETE

Our work:

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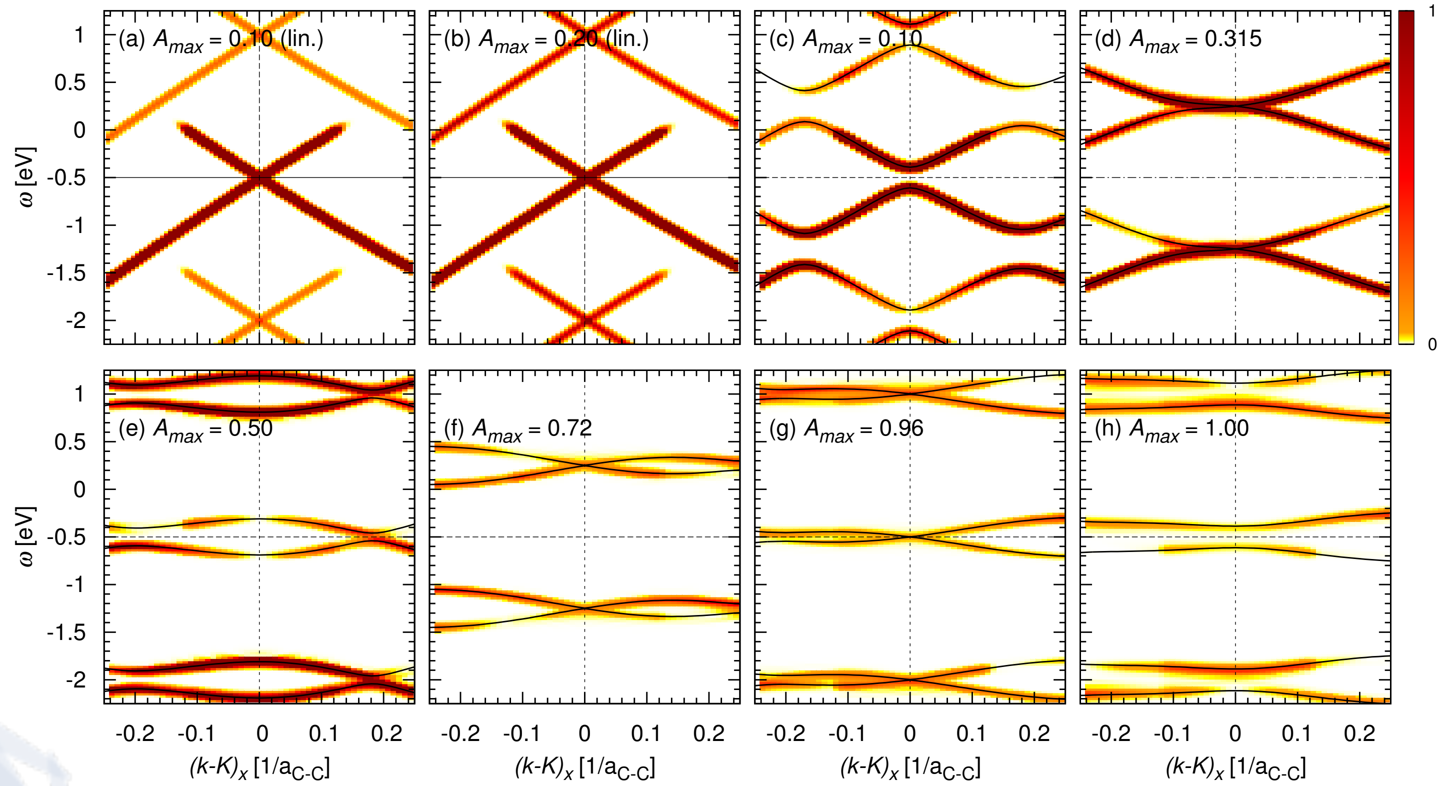
- continuous field ⟶ pulsed field (100 fs)
- Floquet states in pump-probe ARPES

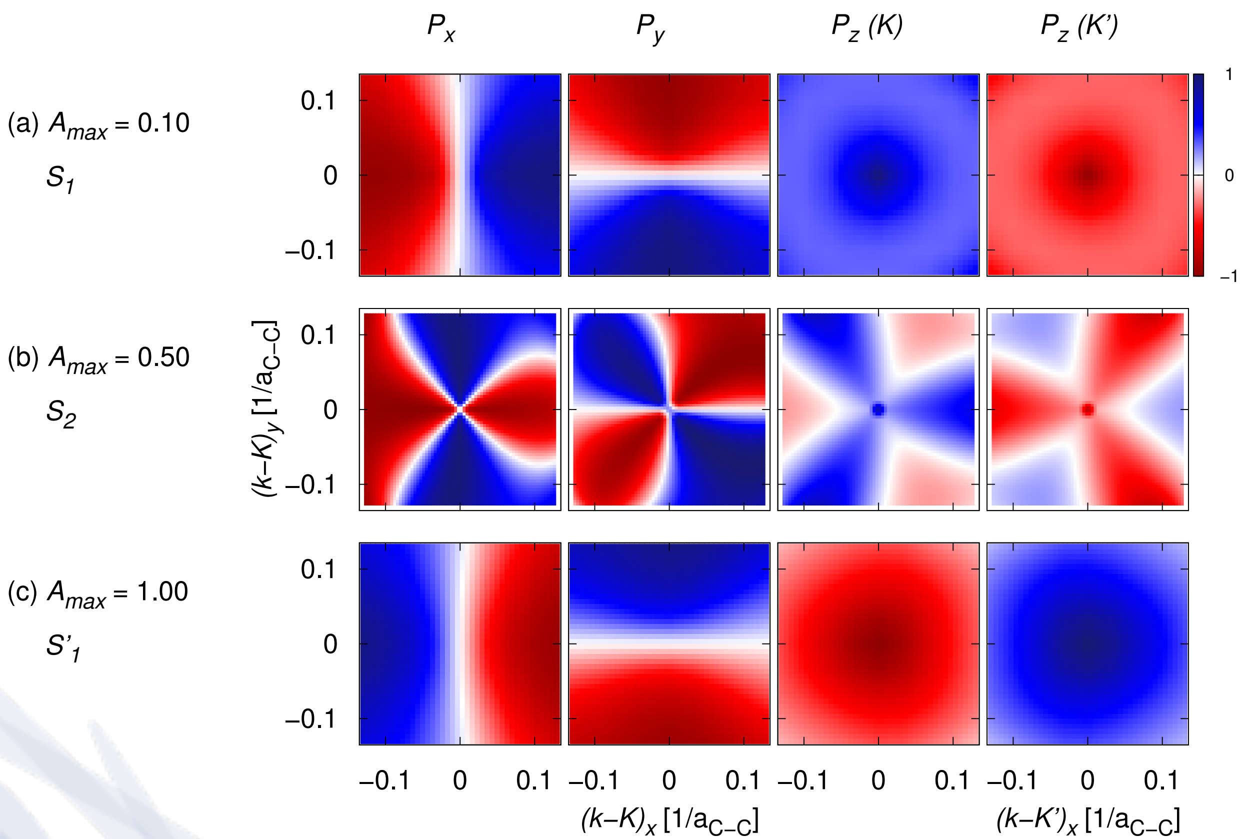
Floquet topological states in graphene

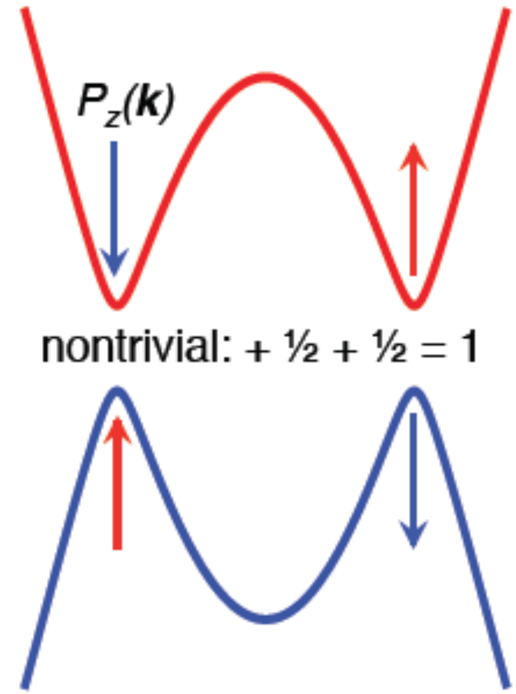
Time-resolved ARPES during 1.5 eV laser pulse



- Circularly polarized laser induces energy gap
- Good agreement with Floquet band structure

Floquet topological states in graphene

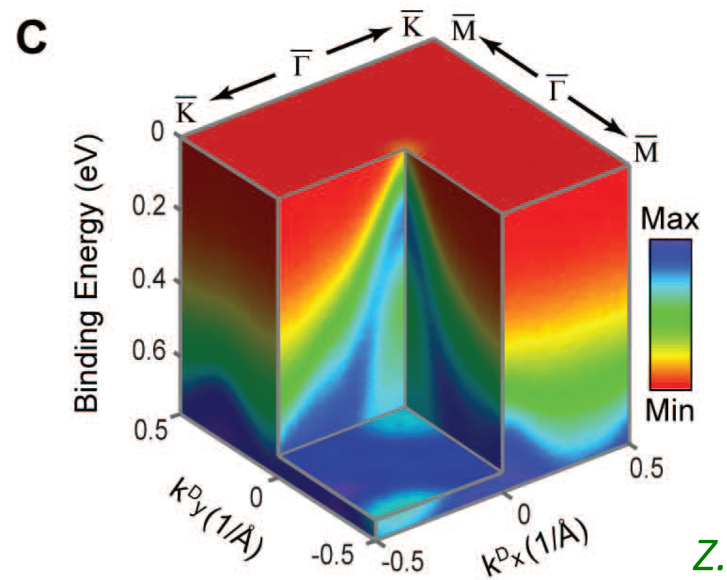




- Pseudospin changes sign between *K* and *K'*
- Light-controlled Berry phase

Beyond graphene: 3D Na_3Bi

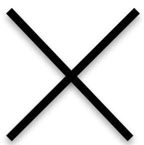
- 3D Dirac semimetal
- Dirac point with spin-orbit = 2 degenerate Weyl points of opposite chirality



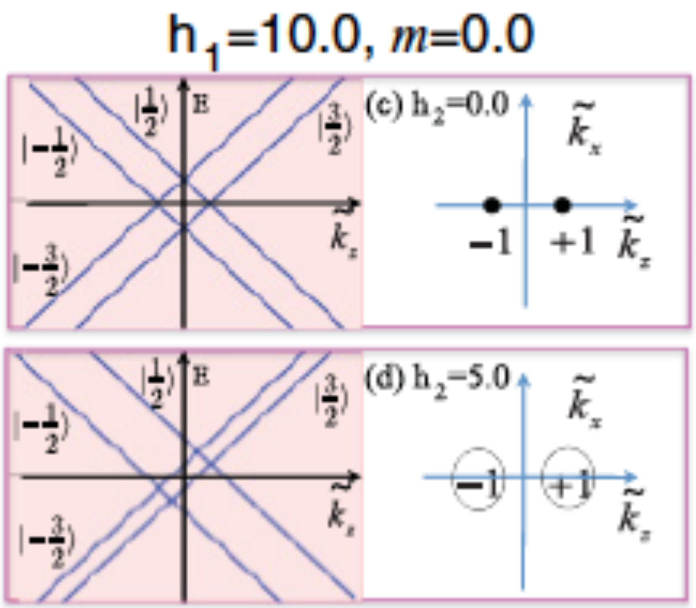
Z. K. Liu et al., Science 343, 864 (2014)

Beyond graphene: 3D Na_3Bi

- Proposed engineering of topological states via fictitious fields h_1, h_2 (analogue of Haldane model)

2x 

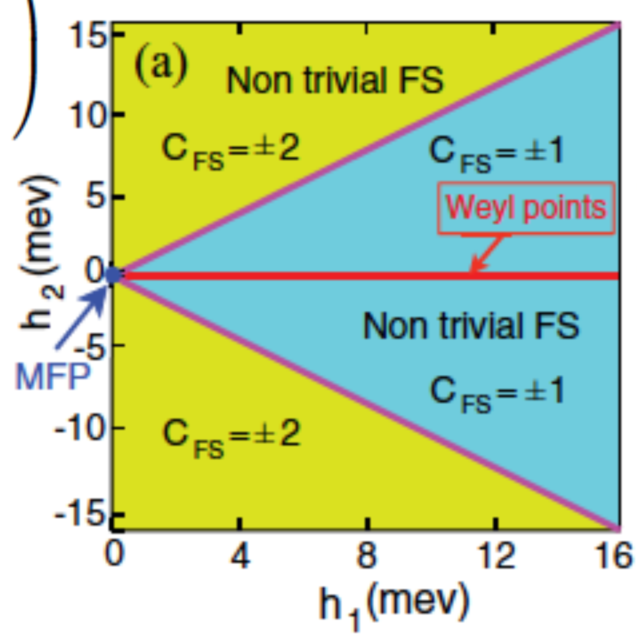
$$\mathcal{H} = \epsilon_0(\mathbf{k}) + \begin{pmatrix} M(\mathbf{k}) & Dk_+ & 0 & B^*(\mathbf{k}) \\ Dk_- & -M(\mathbf{k}) & B^*(\mathbf{k}) & 0 \\ 0 & B(\mathbf{k}) & M(\mathbf{k}) & -Dk_- \\ B(\mathbf{k}) & 0 & -Dk_+ & -M(\mathbf{k}) \end{pmatrix}$$



Fictitious fields:

$$M_1 = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & 1 \end{pmatrix}$$

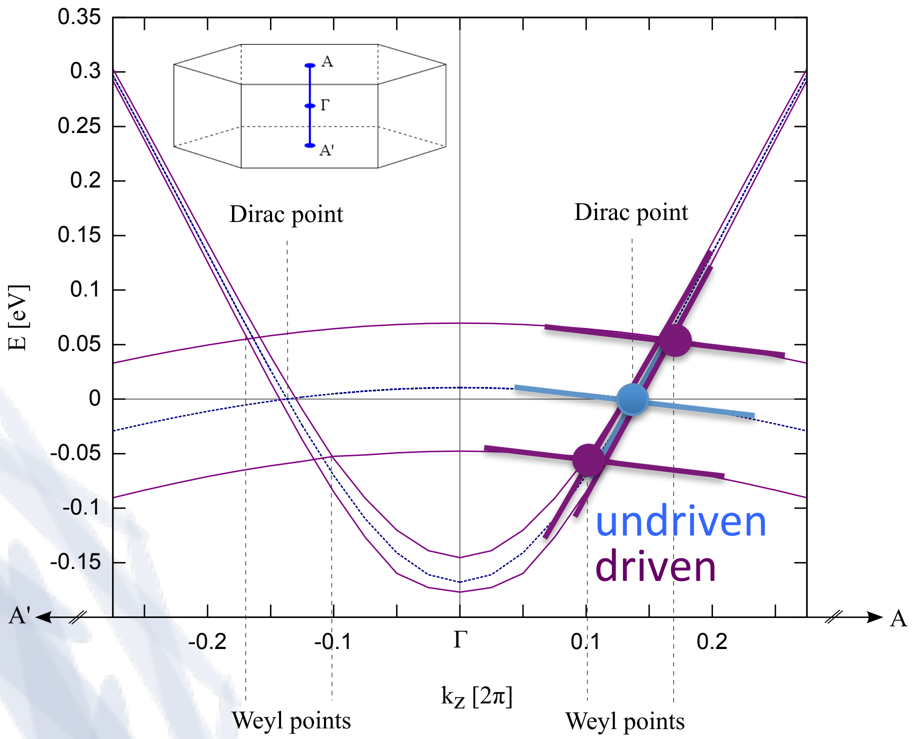
$$M_2 = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix}$$



Z. Wang et al., PRB 85, 195320 (2012)

Beyond graphene: 3D Na_3Bi

- Question: Can these fictitious fields be generated with lasers?
- Preliminary result (ab initio TDDFT): yes



Splitting of two 3D Dirac points into two pairs of Weyl points

Project with H. Hübener, A. F. Kemper, U. de Giovannini, A. Rubio

Summary

- Floquet states: engineering of fictitious gauge fields with real laser fields
- laser control of topological states of matter
- examples: 2D graphene, 3D Dirac semimetal

THANK YOU!