Topological photonics

Ling Lu (陆凌)

Mathematics

New degree of freedom

Robust, nearly-perfect properties

2 reviews:

Lu, Joannopoulos, Soljačić *Nat. Photonics* (Nov. 2014)

Lu, Joannopoulos, Soljačić *Nat. Physics* (July, 2016)

2016

2016-10-04

The Nobel Prize in Physics 2016

© Trinity Hall, Cambridge University. Photo: Kiloran Howard

David J. Thouless

Prize share: 1/2

Photo: Princeton University, Comms. Office, D. Applewhite

F. Duncan M. Haldane

Prize share: 1/4

Ill: N. Elmehed. © Nobel Media 2016

J. Michael Kosterlitz

Prize share: 1/4

The Nobel Prize in Physics 2016 was divided, one half awarded to David J. Thouless, the other half jointly to F. Duncan M. Haldane and J. Michael Kosterlitz *"for theoretical discoveries of topological phase transitions and topological phases of matter"*.

2016-10-11

Oliver E. Buckley Condensed Matter Prize

2017 Recipients

Alexei Kitaev
California Institute of Technology

Xiao-Gang Wen
Massachusetts Institute of Technology

"*For theories of topological order and its consequences in a broad range of physical systems.*"

The Nobel Prize in Physics 2016

© Trinity Hall, Cambridge University. Photo: Kiloran Howard

David J. Thouless

Prize share: 1/2

Ill: N. Elmehed. © Nobel Media 2016

J. Michael Kosterlitz

Prize share: 1/4

The Nobel Prize in Physics 2016 was divided, one half awarded to David J. Thouless, the other half jointly to F. Duncan M. Haldane and J. Michael Kosterlitz *"for theoretical discoveries of topological phase transitions and topological phases of matter"*.

Vortices

Zhen, Hsu, **Lu**, Stone, Soljačić *Phys. Rev. Lett.* (2014)

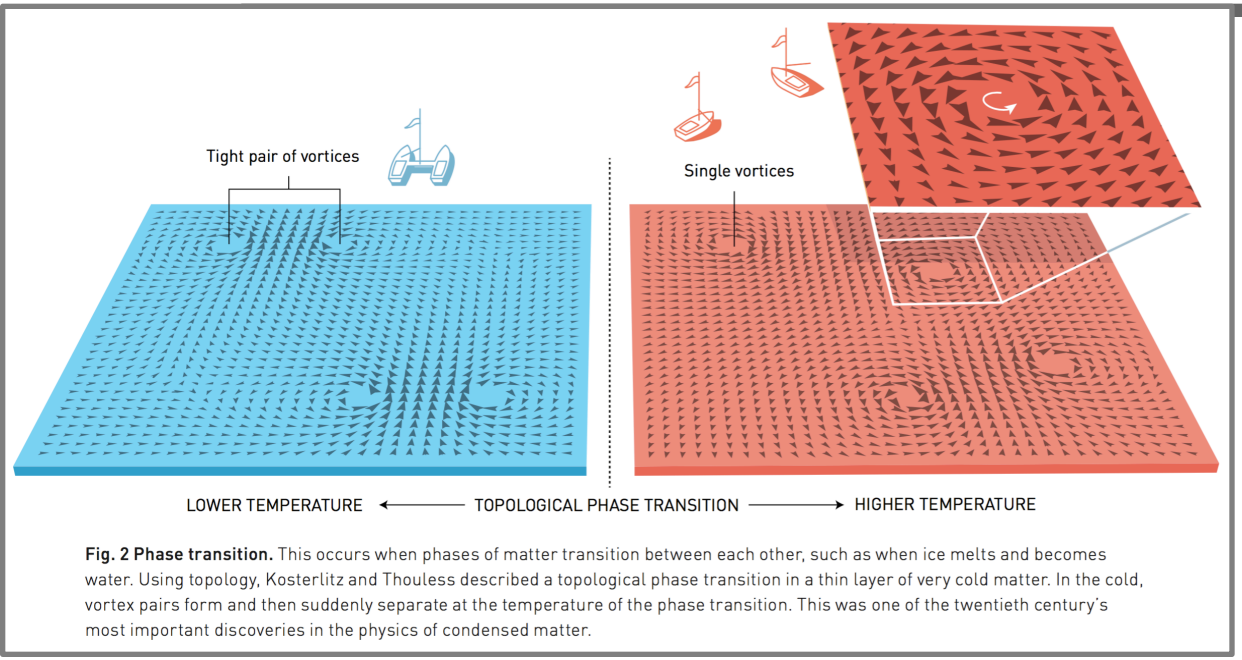
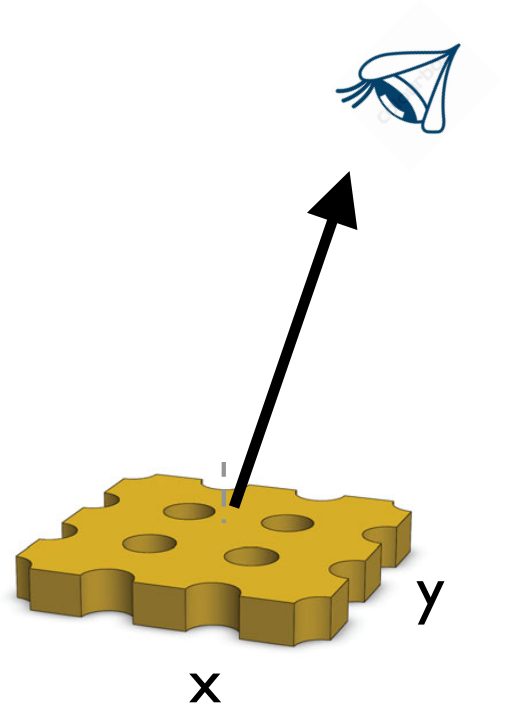
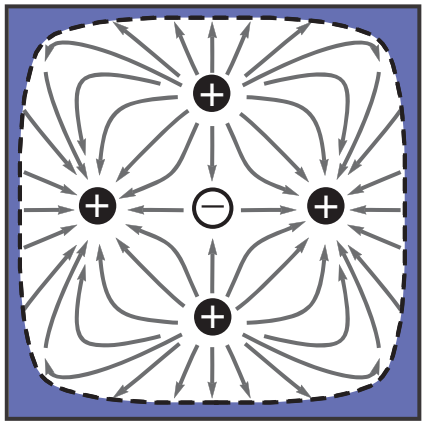


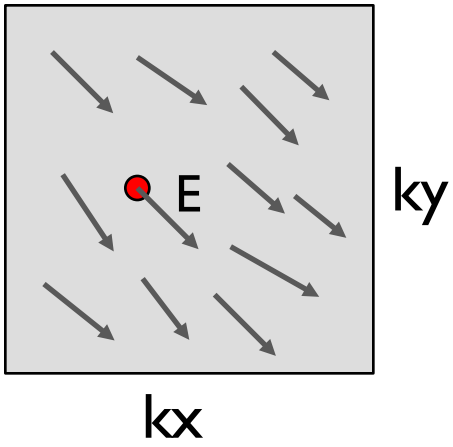
Fig. 2 Phase transition. This occurs when phases of matter transition between each other, such as when ice melts and becomes water. Using topology, Kosterlitz and Thouless described a topological phase transition in a thin layer of very cold matter. In the cold, vortex pairs form and then suddenly separate at the temperature of the phase transition. This was one of the twentieth century's most important discoveries in the physics of condensed matter.



Polarization vector field, $\boldsymbol{c}(\boldsymbol{k})$



$u_k(r)$



Bound states in continuum

The Nobel Prize in Physics 2016

Photo: Princeton University, Comms. Office, D. Applewhite

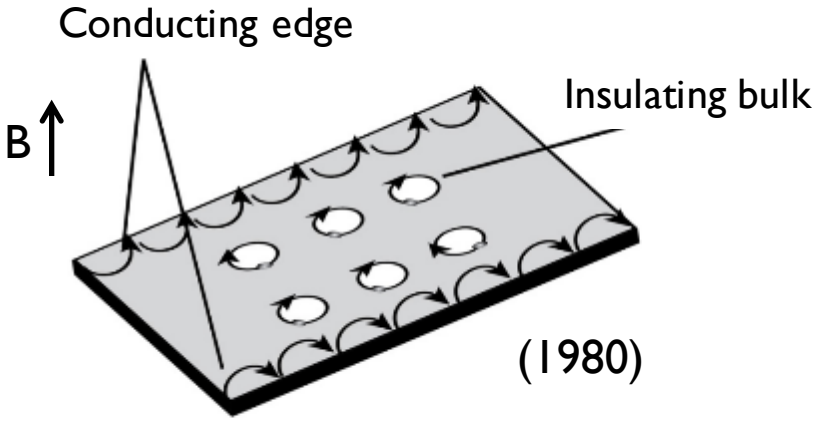
F. Duncan M. Haldane

Prize share: 1/4

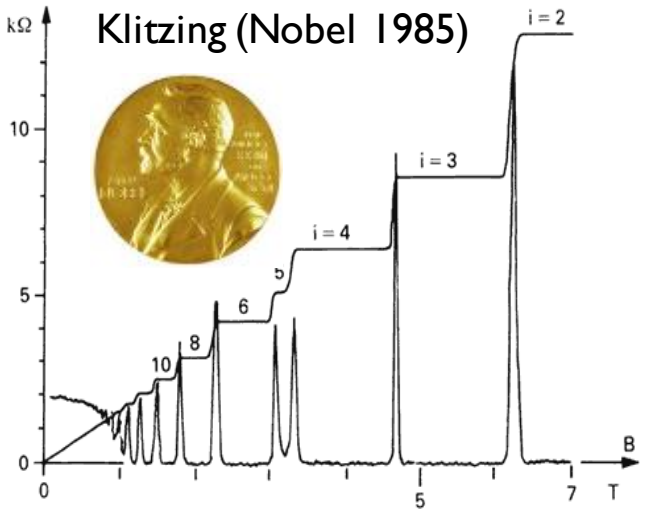
The Nobel Prize in Physics 2016 was divided, one half awarded to David J. Thouless, the other half jointly to F. Duncan M. Haldane and J. Michael Kosterlitz *"for theoretical discoveries of topological phase transitions and topological phases of matter"*.

Quantum Hall phase

Integer quantum Hall

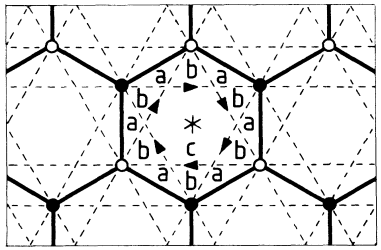


(1980)



Quantum anomalous Hall

Haldane model (1988)



Zhang, et al. *Science* (2013)

Photonic realization

Haldane, Raghu, *arXiv/PRL/PRA* (2005-2008)
Wang, Chong, Joannopoulos, Soljačić, *Nature* (2009)
Hafezi, Demler, Lukin, Taylor, *Nat. Phys.* (2011)
Fang, Yu & Fan, *Nat. Photon.* (2012)
Kraus, et al. *Phys. Rev. Lett.* (2012)
Khanikaev, et al. *Nat. Mater.* (2013)
Rechtsman, et al. *Nature* (2013)
…….

Photonic crystals

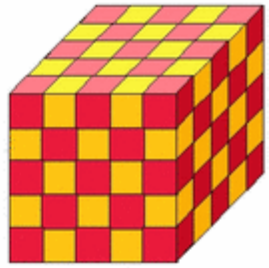
Lord Rayleigh (1887)

Yablonovitch and John (1987)

1D

2D

3D



Well-known

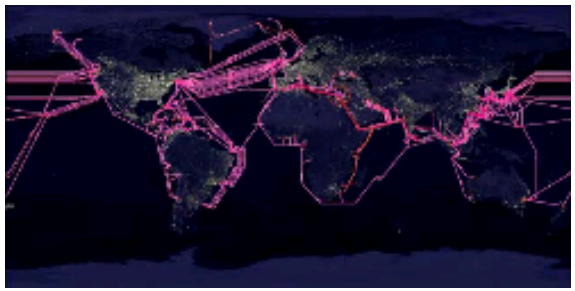
gratings,DBR,DFB,VCSEL

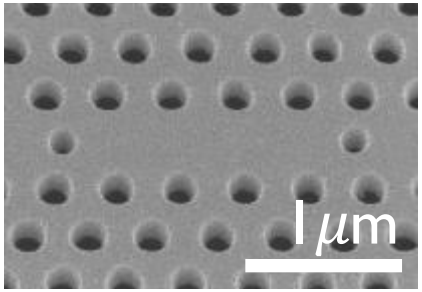
……

Fabricable devices

photonic crystal fibers

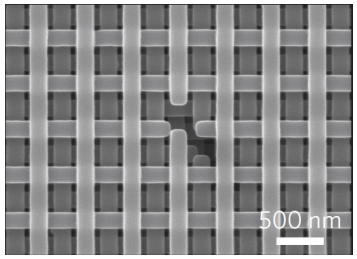
Difficult to make



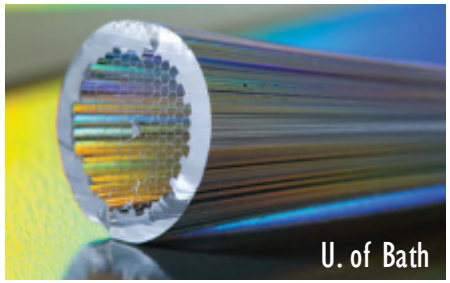


Pouya et al. (2012)

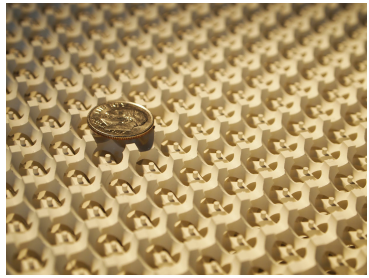
Optical



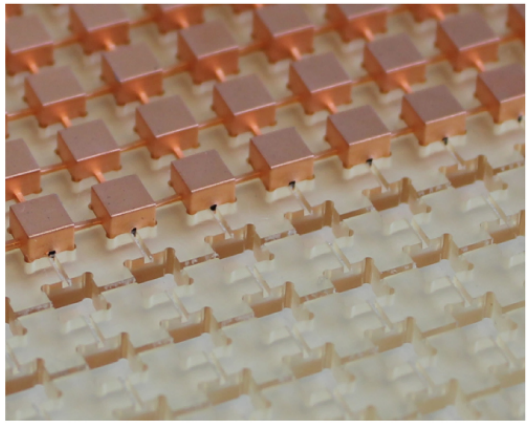
Noda et al. (2012)

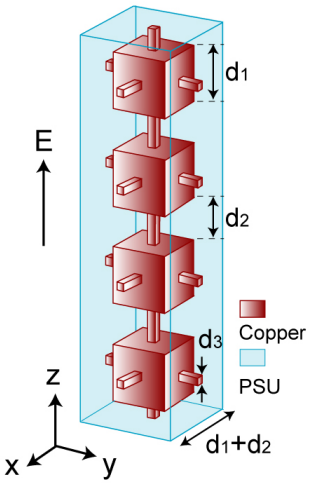


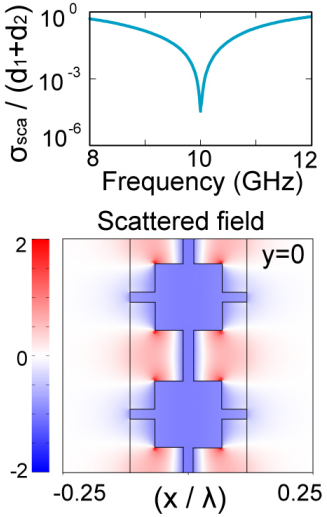
Microwave



Invisible material







Single polarization
Single frequency
All angles

Ye, **Lu**, Joannopoulos, Soljačić, Ran arXiv:1510.00016

Eigen-value problem

Lu, Joannopoulos, Soljačić
Nat. Photon. (2014) Review

$$\mathrm{i}\begin{pmatrix} 0 & \nabla\times \\ -\nabla\times & 0 \end{pmatrix}\begin{pmatrix} E \\ H \end{pmatrix}=\omega\begin{pmatrix} \epsilon & 0 \\ 0 & \mu \end{pmatrix}\begin{pmatrix} E \\ H \end{pmatrix}$$

Time-reversal symmetry

$$T=\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}^{*}$$

$$T^2=+1$$

Boson

T - breaking

$$\mu=\begin{pmatrix} \mu & iv & 0 \\ -iv & \mu & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Ferrimagnetic (gyromagnetic) material as Yttrium iron garnet (YIG)

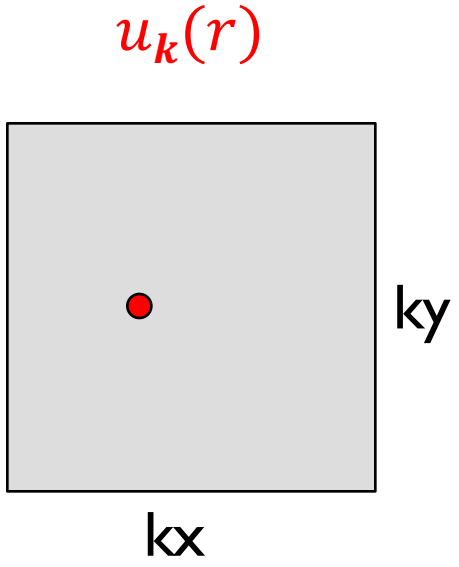
Bloch solutions

$$\psi_{\boldsymbol{k}}(r)=\begin{pmatrix} E(r) \\ H(r) \end{pmatrix}=\mathbf{u}_{\boldsymbol{k}}(r)e^{-ikr}$$

Topology of u_k in k space (B.Z.)

Band topology

波函数 如何 连续历遍 整个布里渊区



Infinite variation

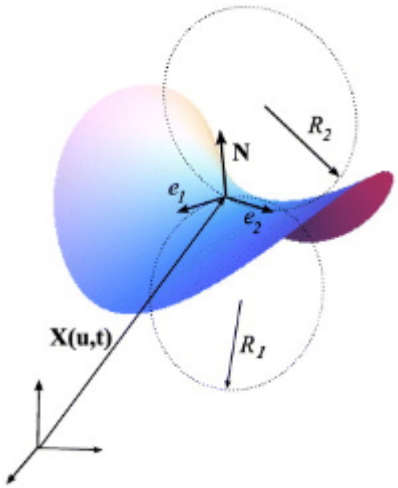
New degree of freedom

Gauss-Bonnet theorem

Lu, Joannopoulos, Soljačić
Nat. Photon. (2014) Review

Genus (g) =0 g=1 g=2

$$K=\frac{1}{R_1 R_2}$$



$$\frac{1}{2\pi}\int_{surface} \mathrm{K}\, dA = 2(1-g)$$

$\mathrm{K}=\kappa_1\kappa_2$ Gaussian curvature

Discrete values = robustness

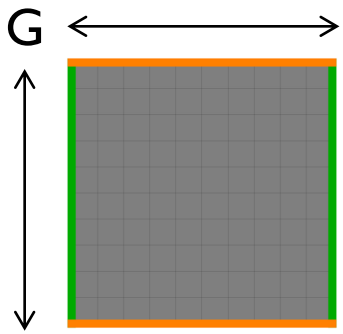
Berry curvature

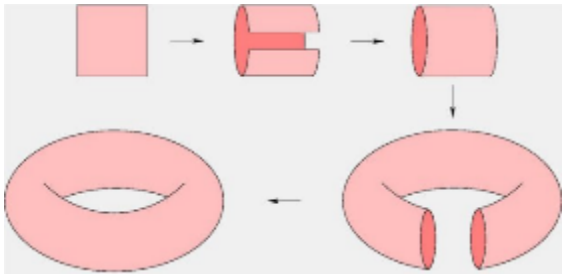
Lu, Joannopoulos, Soljačić
Nat. Photon. (2014) Review

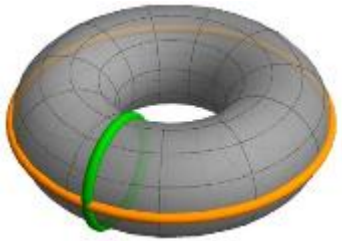
Brillouin zones

1D loop

2D torus



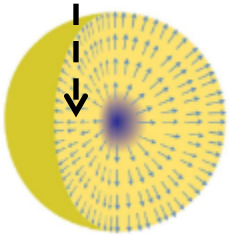




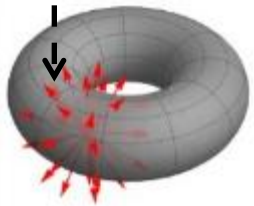
$$\psi_{\boldsymbol{k}}(\boldsymbol{r}) = u_{\boldsymbol{k}}(\boldsymbol{r})e^{-i\boldsymbol{k}\cdot\boldsymbol{r}}$$

Table B1 | Comparison of the Berry phase for Bloch wavefunctions and the Aharonov–Bohm phase.

$\mathcal{A}(\mathbf{k}) = \langle u(\mathbf{k})\|i\nabla_{\mathbf{k}}\|u(\mathbf{k})\rangle$	Berry connection
$\oint \mathcal{A}(\mathbf{k}) \cdot \mathrm{dl}$	Berry phase
$\mathcal{F}(\mathbf{k}) = \nabla_{\mathbf{k}} \times \mathcal{A}(\mathbf{k})$	Berry curvature
$\iint \mathcal{F}(\mathbf{k}) \cdot \mathrm{ds}$	Berry flux
$C = \frac{1}{2\pi} \oiint \mathcal{F}(\mathbf{k}) \cdot \mathrm{ds}$	Chern number

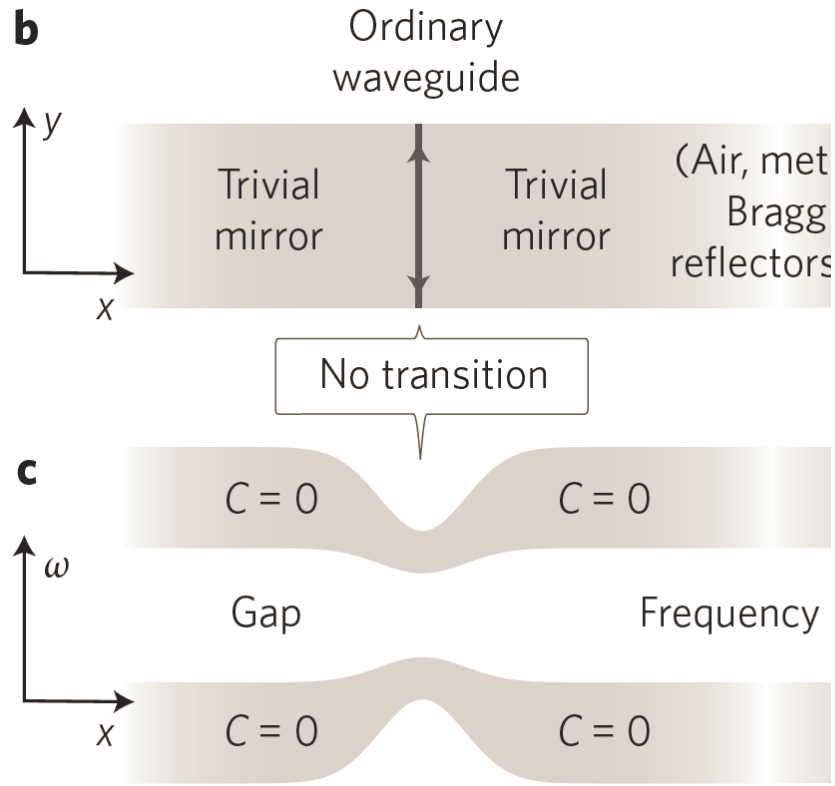


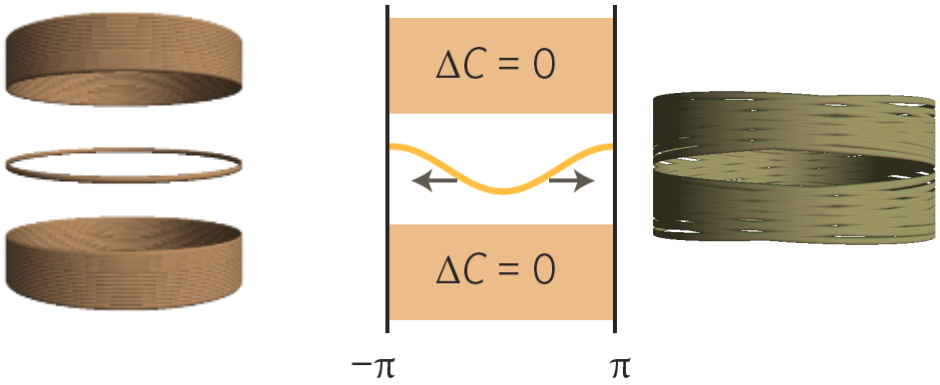
$\mathcal{F}(k)$ is *even* under ***P*** and *odd* under ***T***



Topological phase transition

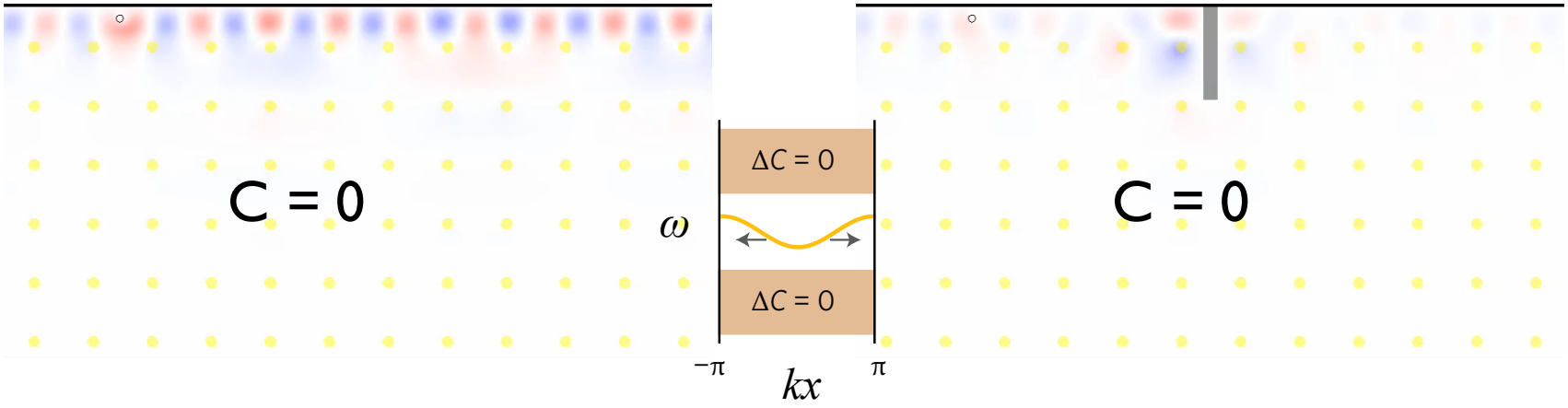
Lu, Joannopoulos, Soljačić
Nat. Photon. (2014) Review



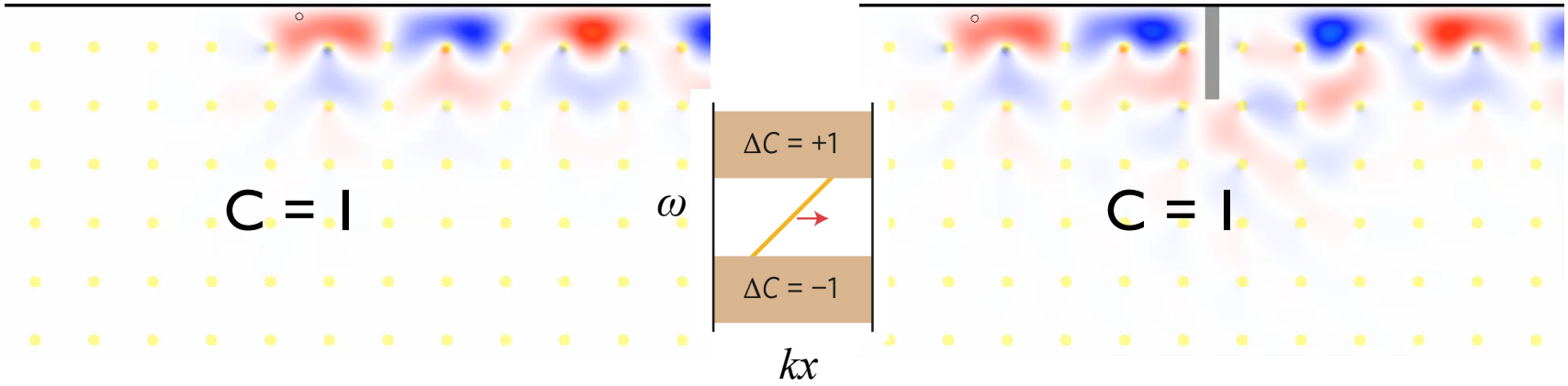


Videos

two-way waveguides

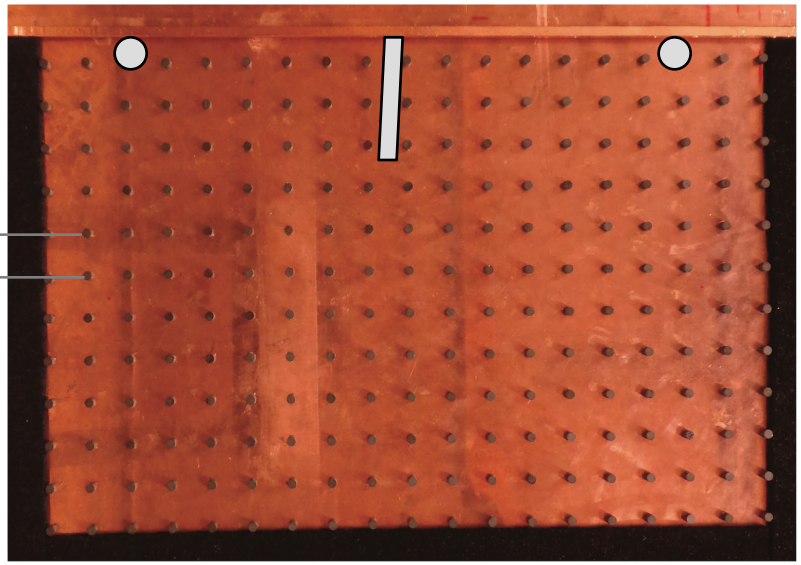


one-way waveguides

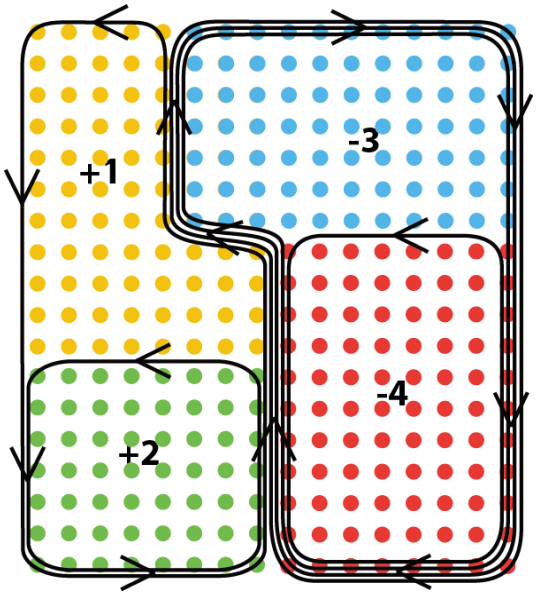


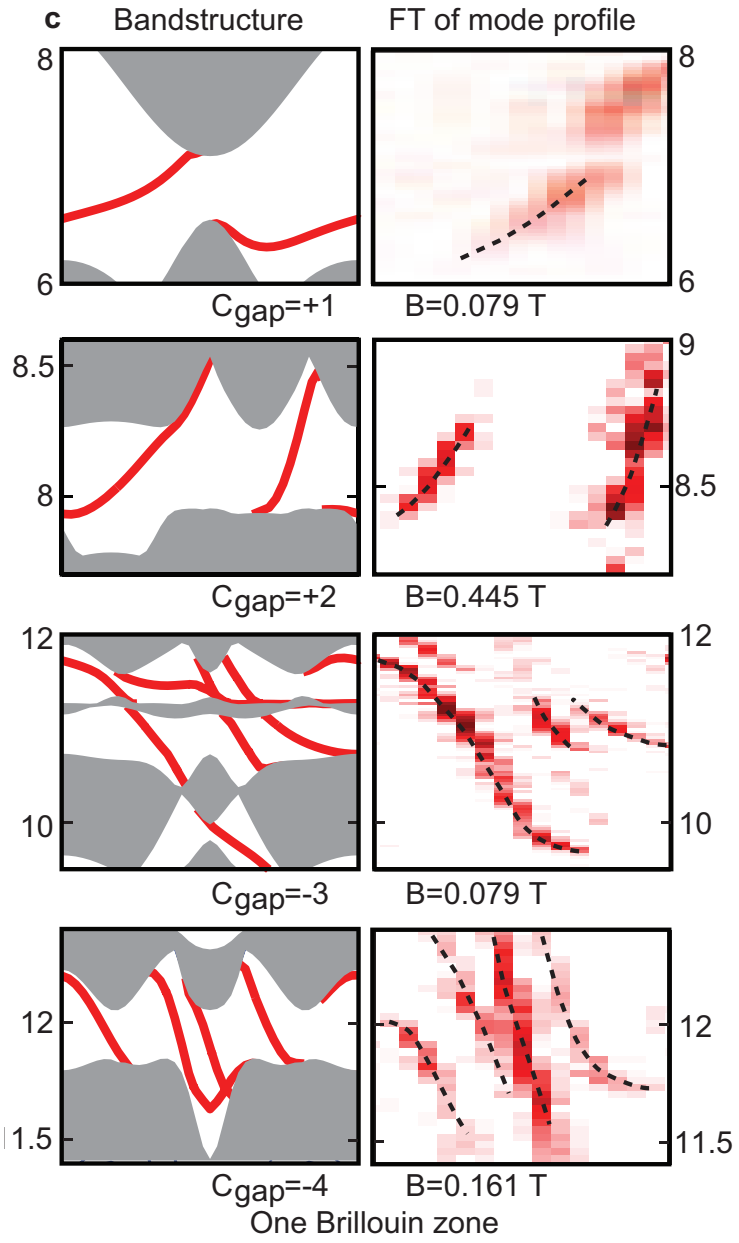
Large Chern numbers (Z)

Skirlo, **Lu**, Soljačić *PRL* (2014)
Skirlo, **Lu**, Igarashi, Yan, Joannopouls Soljačić *PRL* (2015)



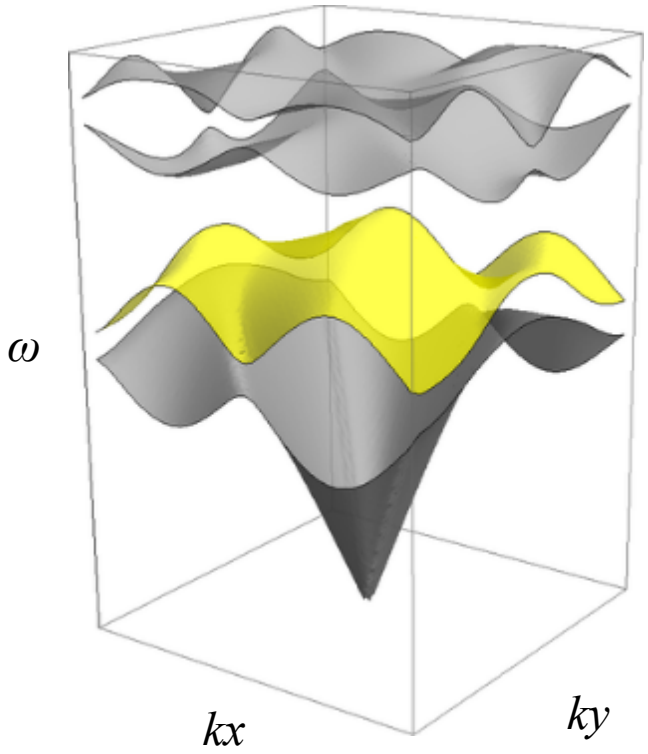
One-way photonic circuit



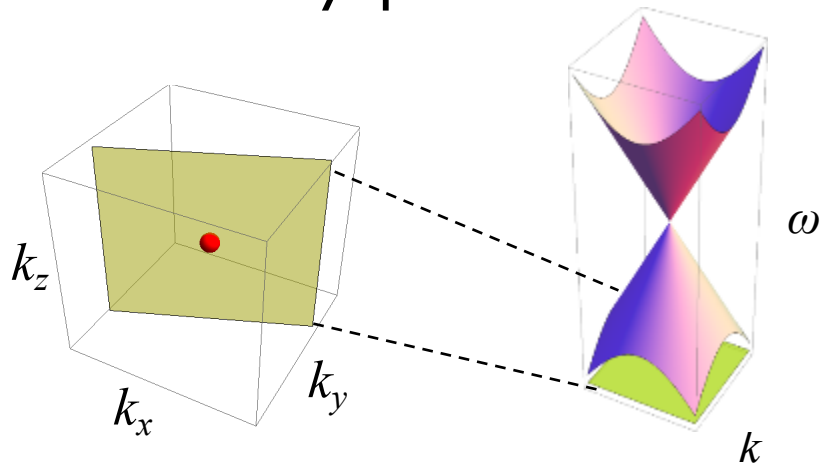


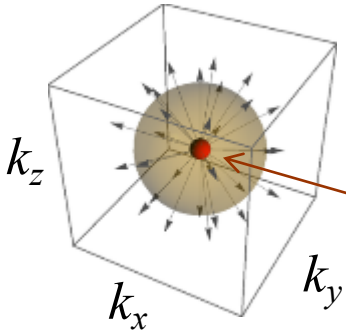
Chern monopoles in 3D

2D

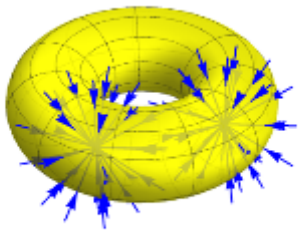


3D Weyl point

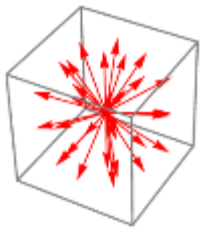


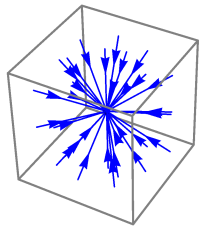


Chern number (C)=±1



"Imaginary"--- Weyl points charges





History of Weyl points

Dirac Hamiltonian (1928)

$$H(k)=\begin{pmatrix} \sigma \cdot k & m \\ m & -\sigma \cdot k \end{pmatrix} \qquad m=0$$

Proposals

Weyl (1929)

Pauli (1930) *Neutrinos (has mass)*

Volovik (2002) *3He-A*

Wan, Turner, Vishwanath, Savrasov (2011) *pyrochlore iridates*

.....

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Reviews

Turner, Vishwanath (2013)

Hosur, Qi (2013)

First experiments

February 2015

Weyl points in photonic crystals

arXiv 1502.03438 (MIT, ZJU)

Fermi arcs in TaAs

arXiv 1502.03807 (Princeton, PKU)

arXiv 1502.04684 (IOP Beijing)

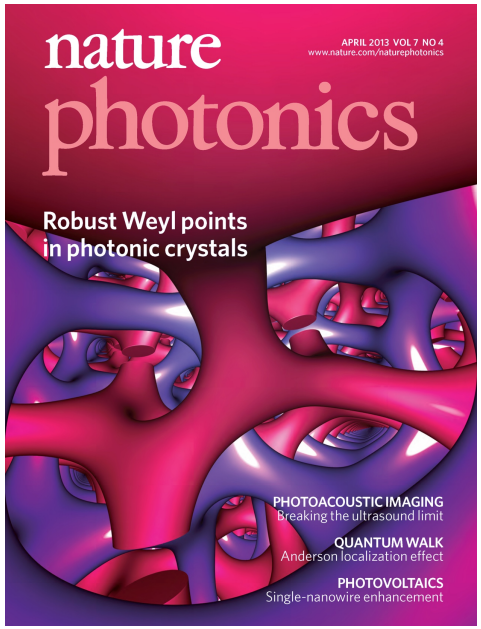
Weyl experiment

physicsworld TOP 10 BREAKTHROUGH 2015

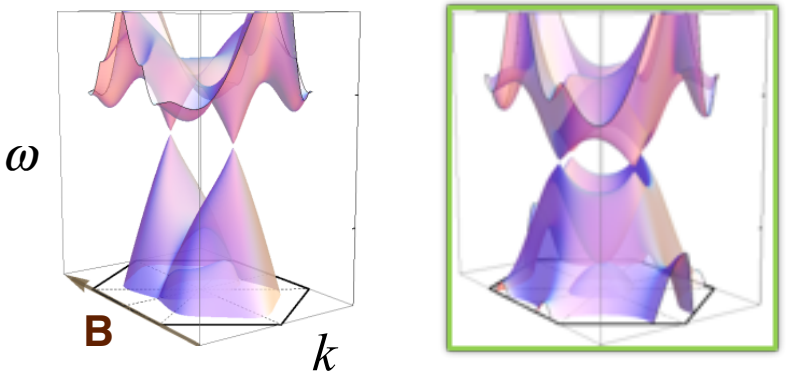
Weyl semimetal of TaAs by IOP & Princeton

APS Highlights of the year

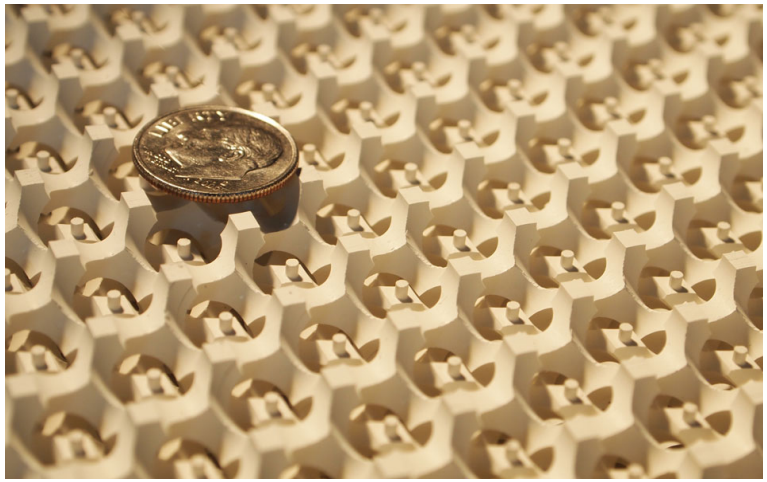
Lu, Fu, Joannopoulos, Soljačić
Nat. Photonics. 7, 294 (2013)

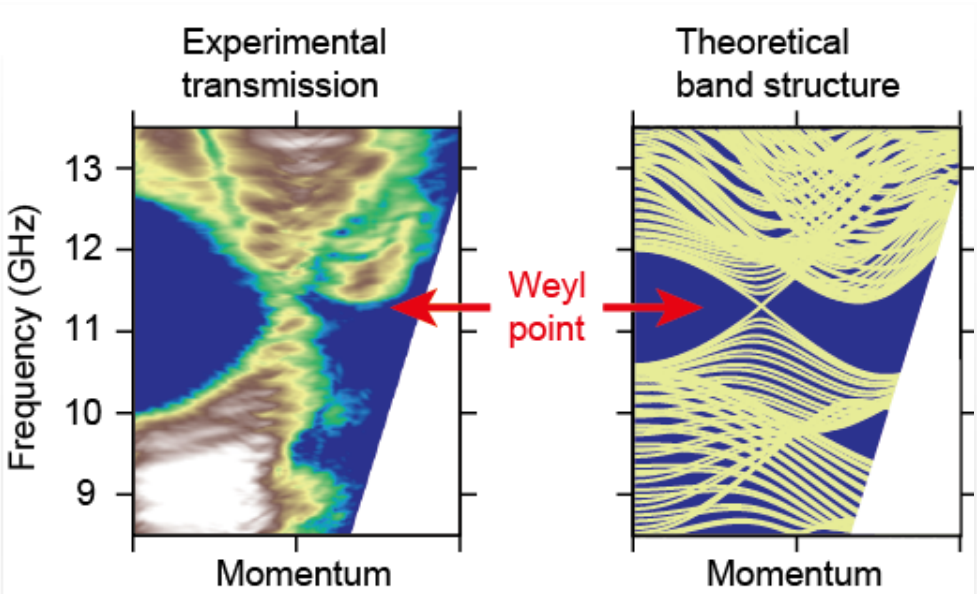


2 & 4 Weyl points



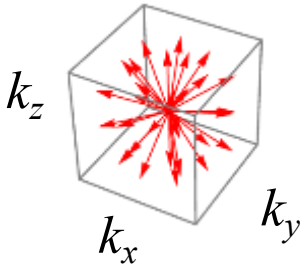
Lu, Wang, Ye, Ran, Fu, Joannopoulos, Soljačić
Science 349, 622 (2015)



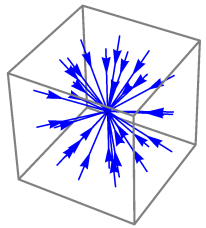


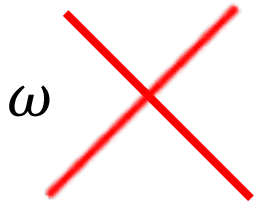
3D gapped phase

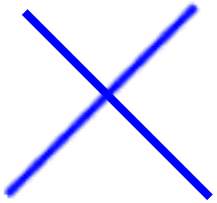
C=+1



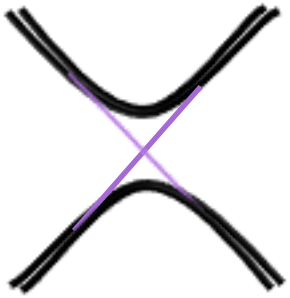
C=-1







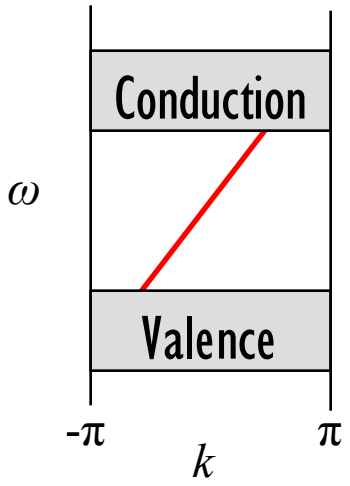
3D TI

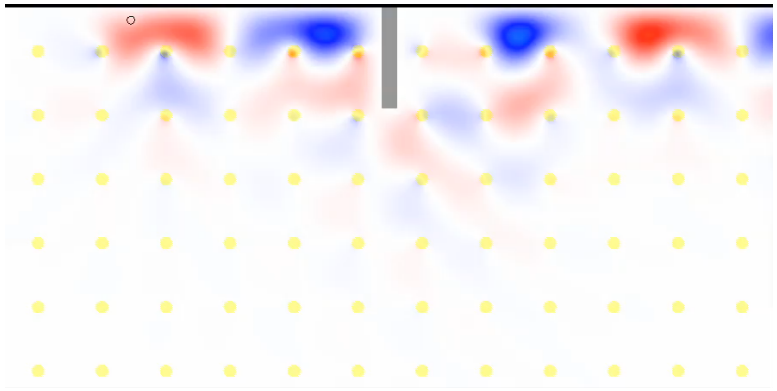


2D anti-localization

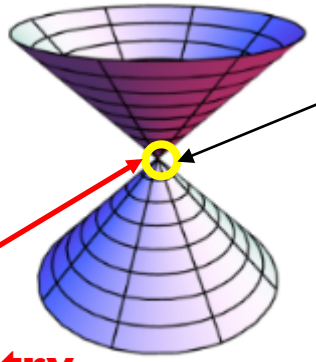
Lu, Fang, Fu, Johnson, Joannopoulos, Soljačić *Nature Phys.* (2015)

1D





2D



Time-reversal symmetry (Kramers' degeneracy for fermions)

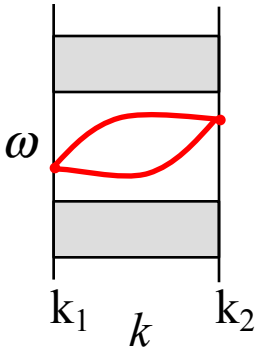
Crystal symmetry

Fu *PRL* (2011)

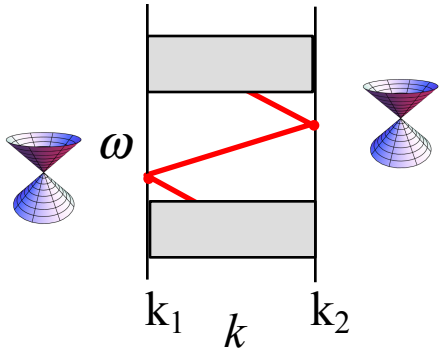
Liu, Zhang, VanLeeuwen *PRB* (2014)

Fang, Fu *PRB* (2015)

$Z_2=0$

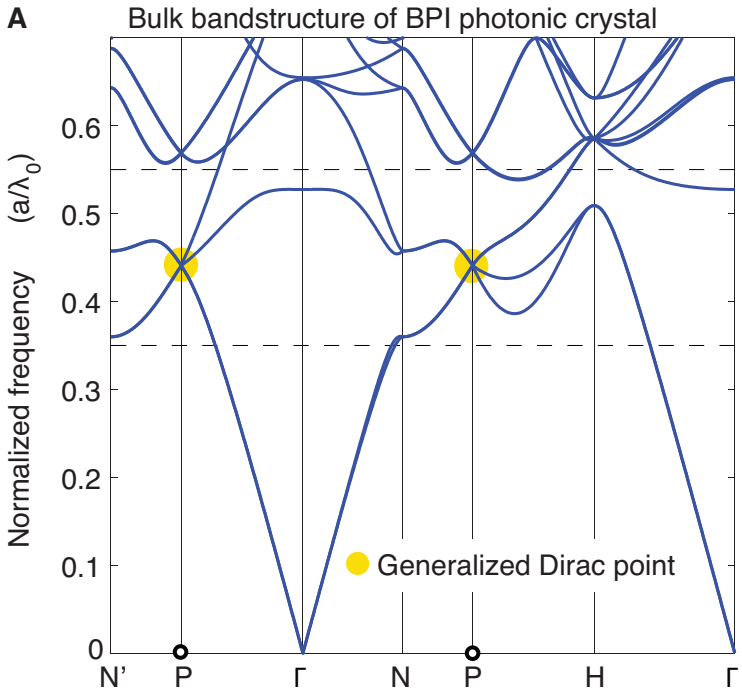


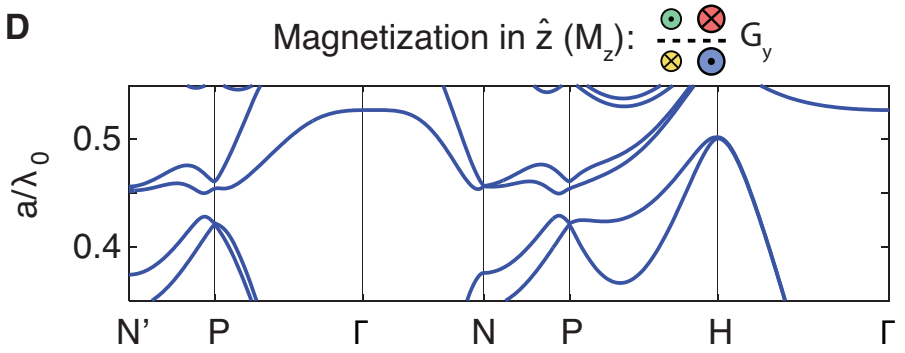
$Z_2=1$

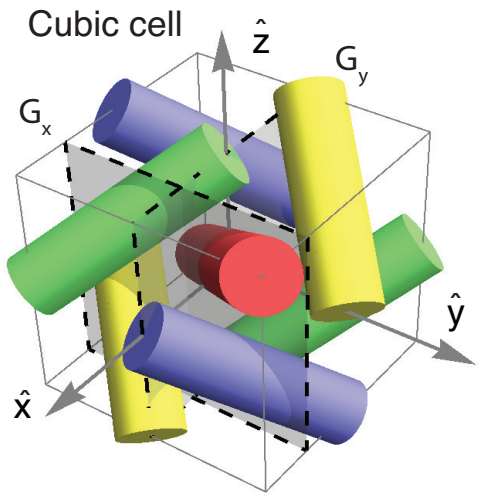


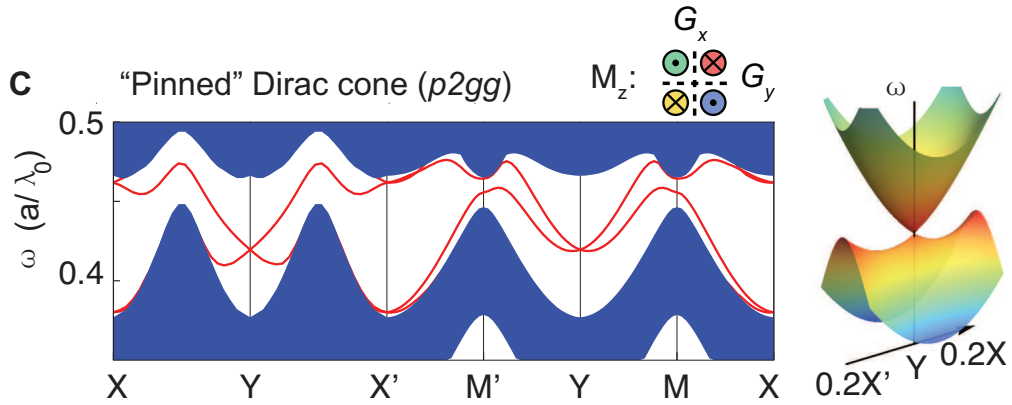
3D generalized Dirac point

Lu, Fang, Fu, Johnson, Joannopoulos, Soljačić *Nature Phys.* (2015)



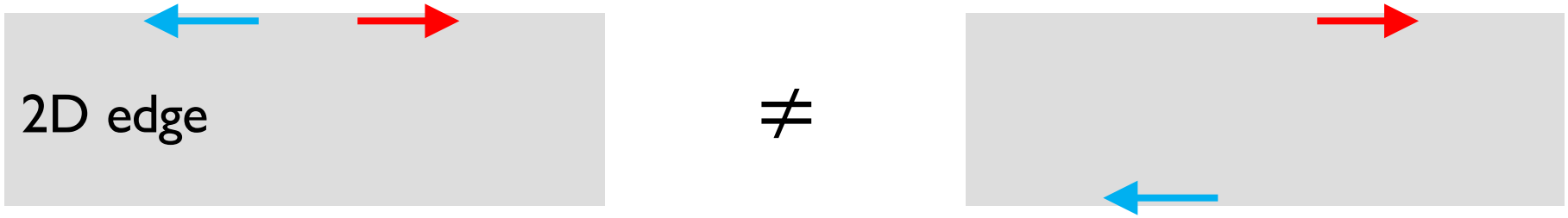




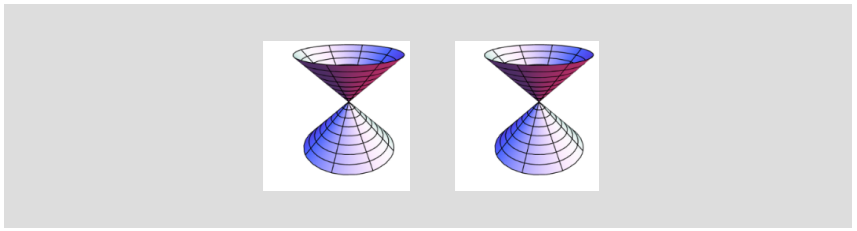


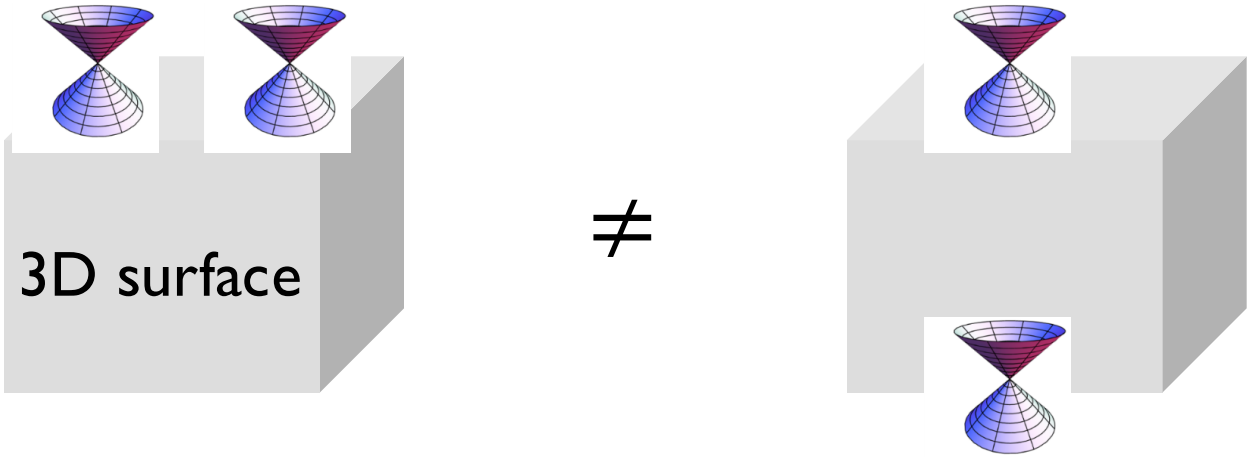
1 , 2 , 3 D

1D bulk



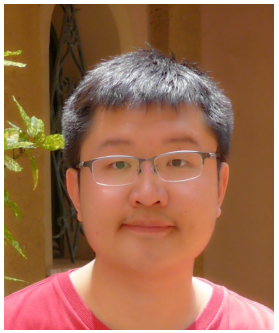
2D bulk

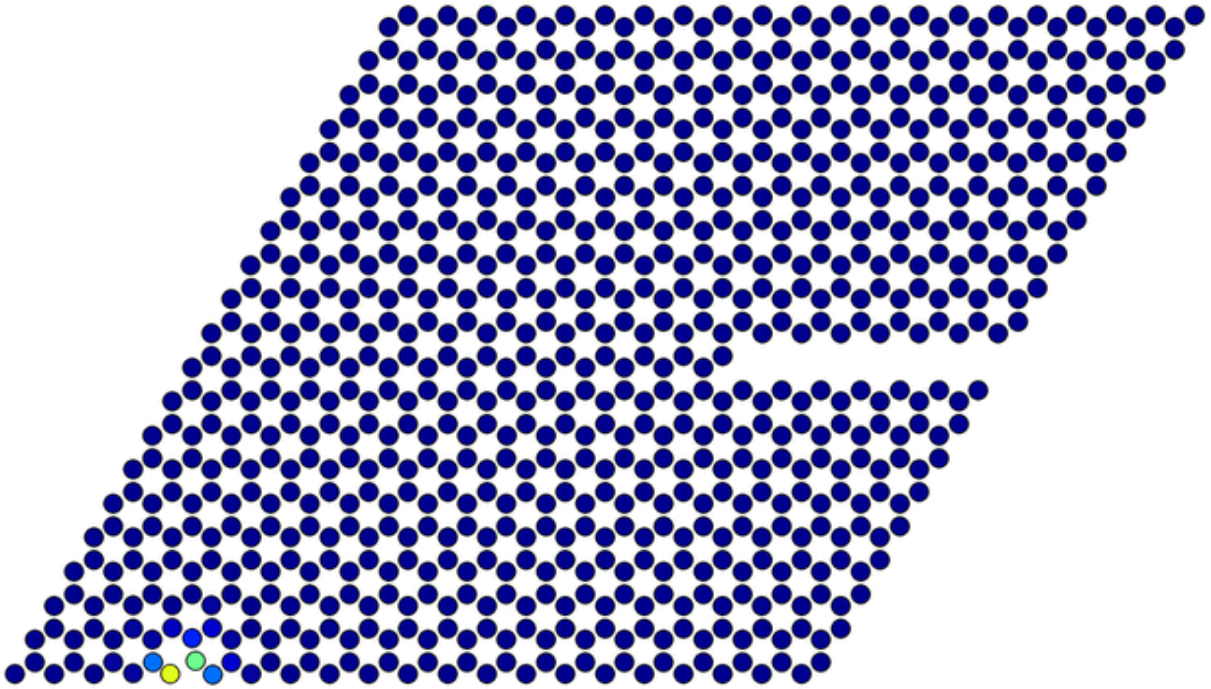


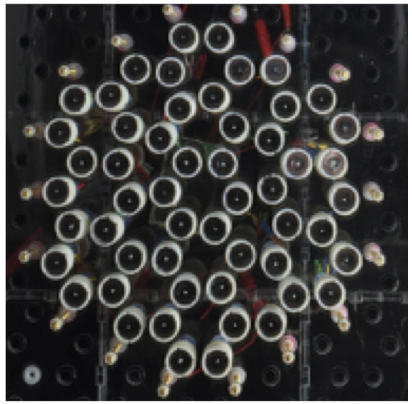


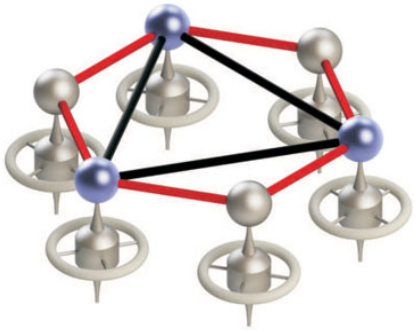
Topological **phononic** crystals

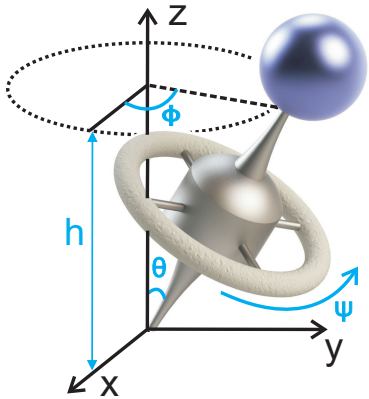
Wang, **Lu**, Bertoldi
Phys. Rev. Lett. (2015)







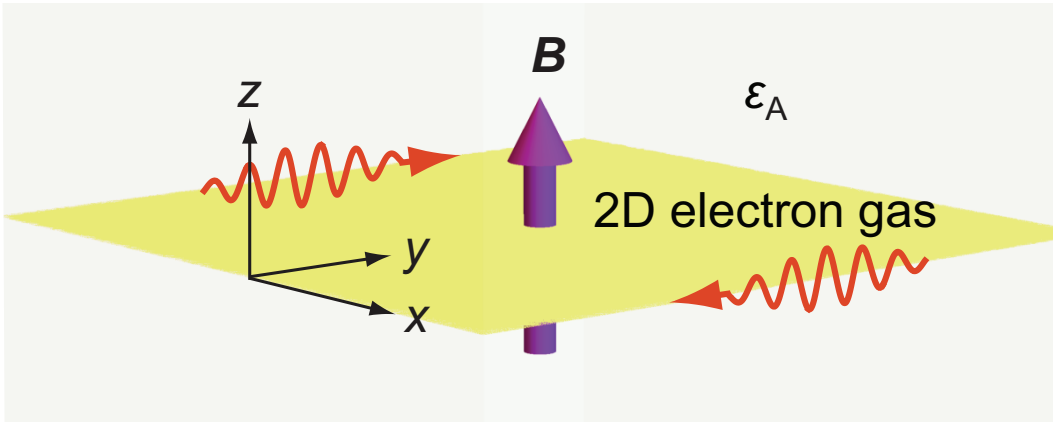


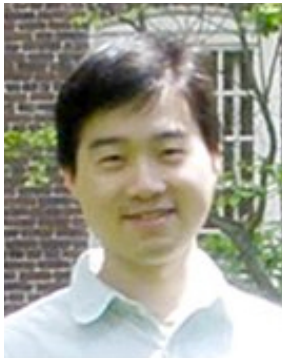


Nash, et. al arXiv:1504.03362

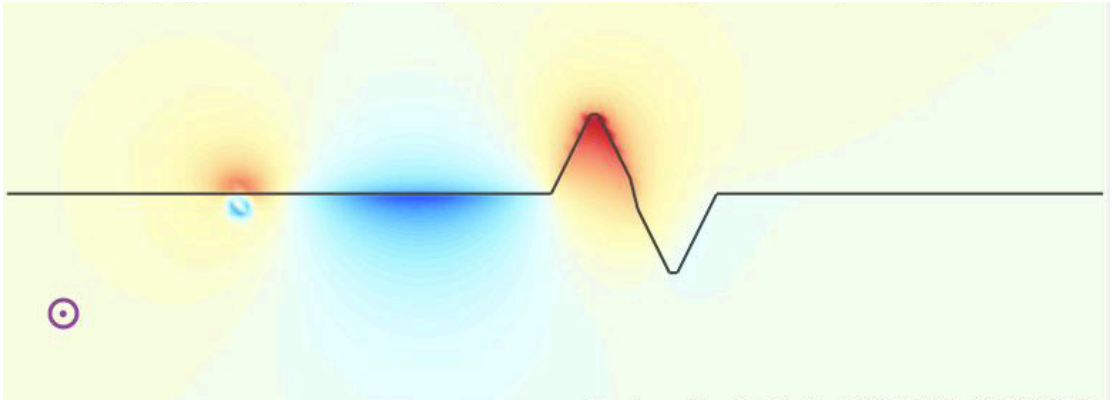
Topological magnetoplasmon

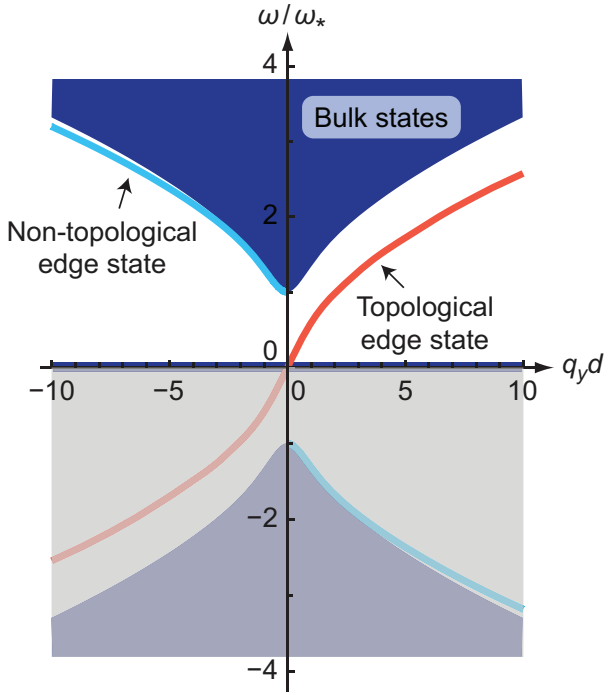
Jin, **Lu**, Wang, Fang, Joannopoulos, Soljačić, Fu, Fang *Nat. Comm.* (2016)





studied by Fetter and many others in 1970s

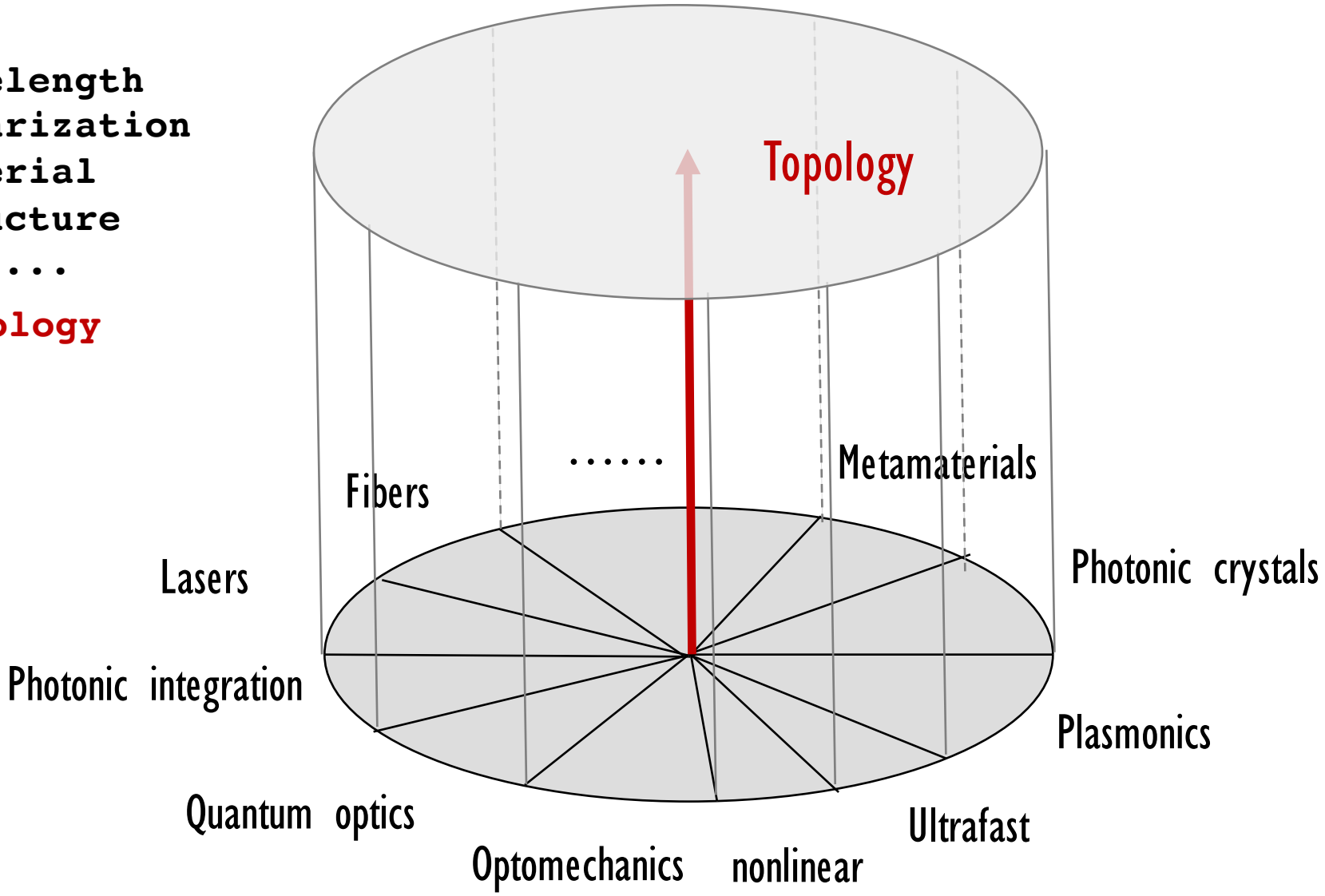




New degree of freedom for light

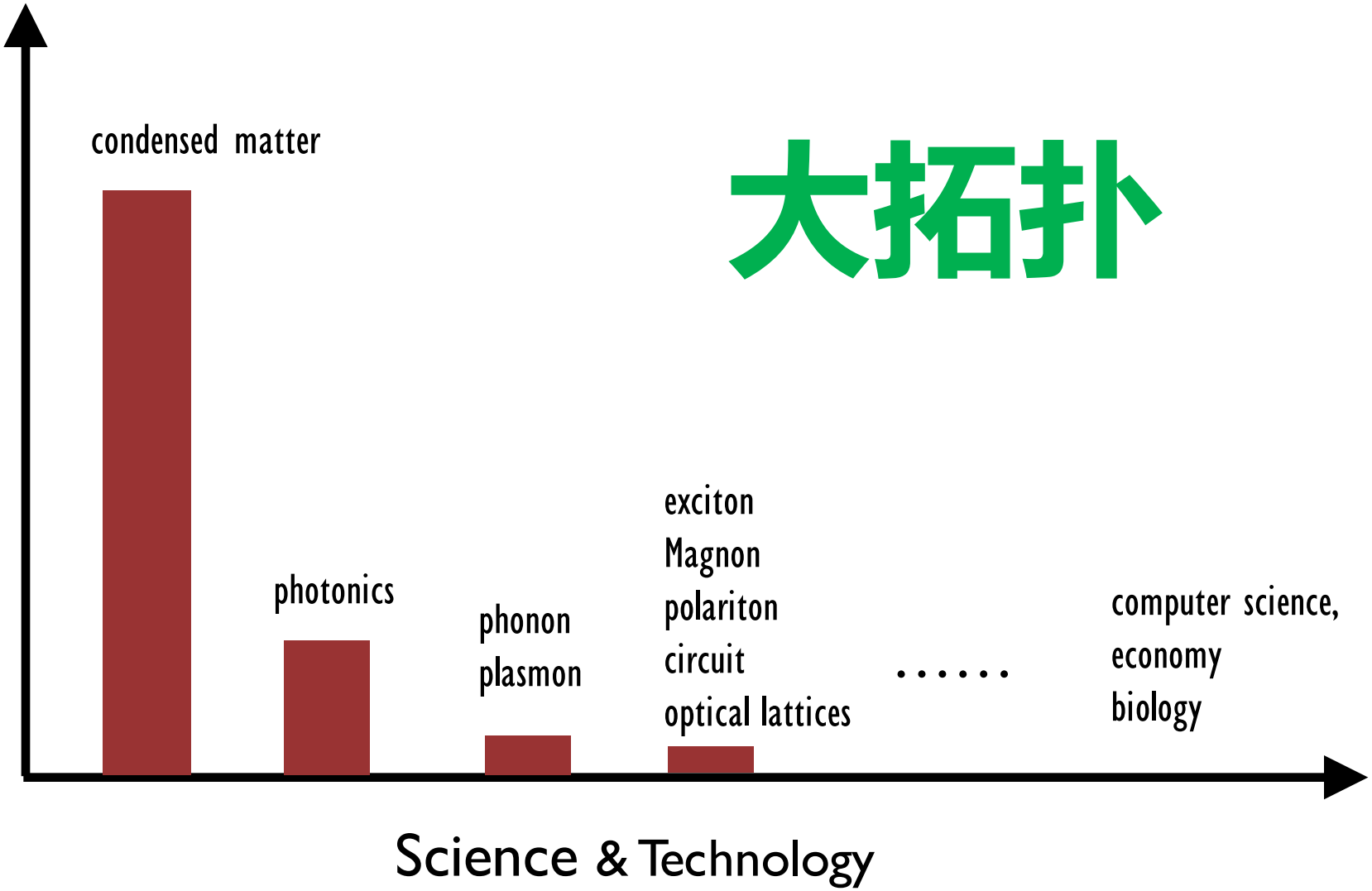
Wavelength
Polarization
Material
Structure
... ...

Topology



The language of topology

Topology (math)



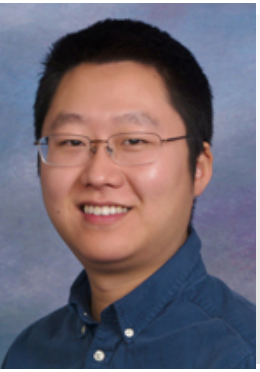
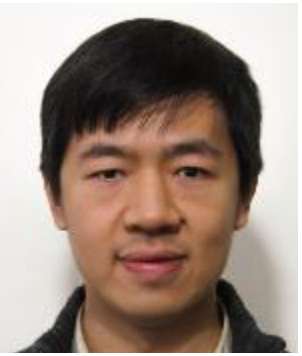
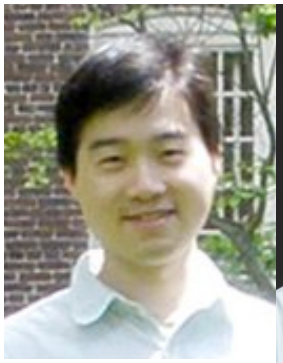
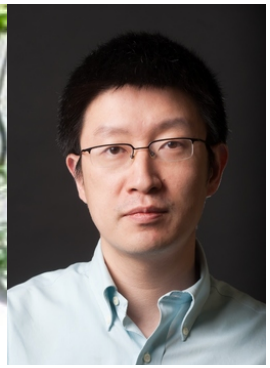
大拓扑

Acknowledgements




MIT


Harvard

MIT



ZJU

2 reviews:

Lu, Joannopoulos, Soljačić
"Topological photonics"
Nat. Photonics (Nov. 2014)

Lu, Joannopoulos, Soljačić
"Topological states in photonic systems"
Nat. Physics (July, 2016)