# Photonic topological insulators and Type-II Weyl points

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*Columbia, May 2017*

# Part 1: Background on photonic topological insulators

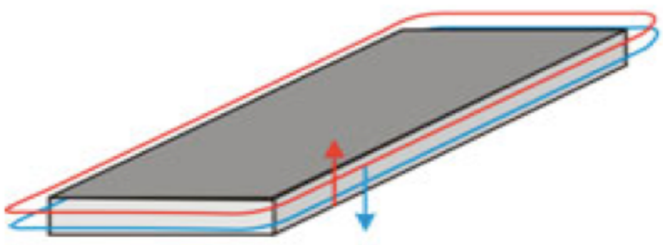
*(collaboration with Segev group, Technion and Szameit group, Jena)*

MCR et al., Nature 496, 196-200 (2013)

# What are topological insulators?

- Topological insulators are insulators in the bulk but metallic on the edges.

- Most importantly: **the edge states are scatter-free!**



Kane and Mele, Phys. Rev. Lett. 95, 226801 (2005)

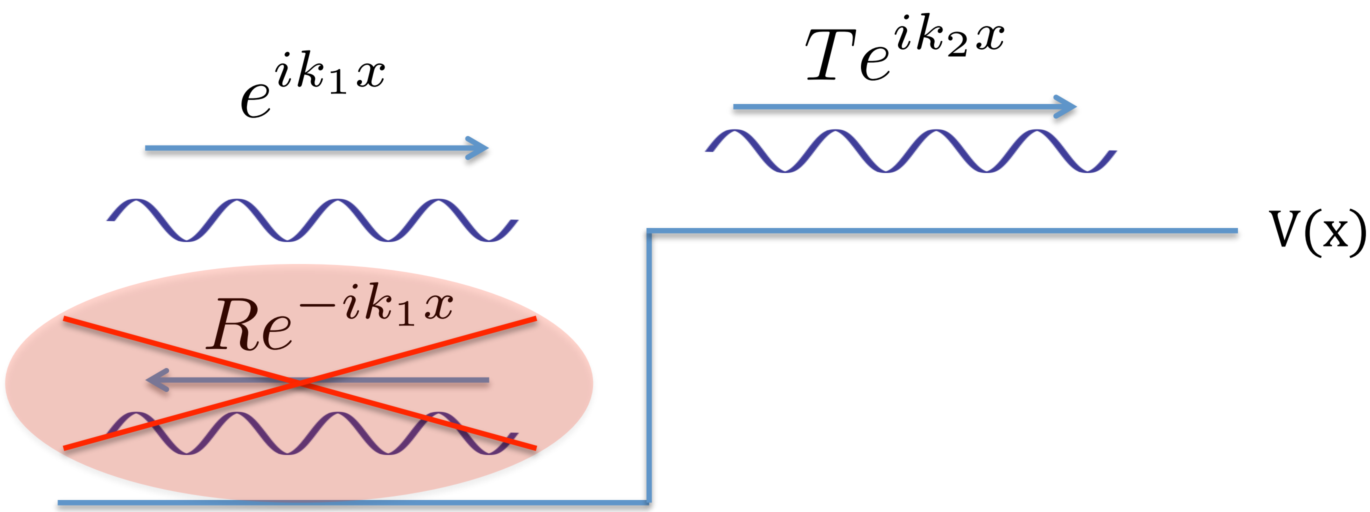
Hughes et al., Science 314, 5806, 1757-1761 (2006)

Hsieh et al., Nature 452, 970-974 (2008)

Chen et al., Science 325 (5937) 178-181 (2009)

Hsieh et al., Nature 460, 1101-1105 (2009)

- Why?

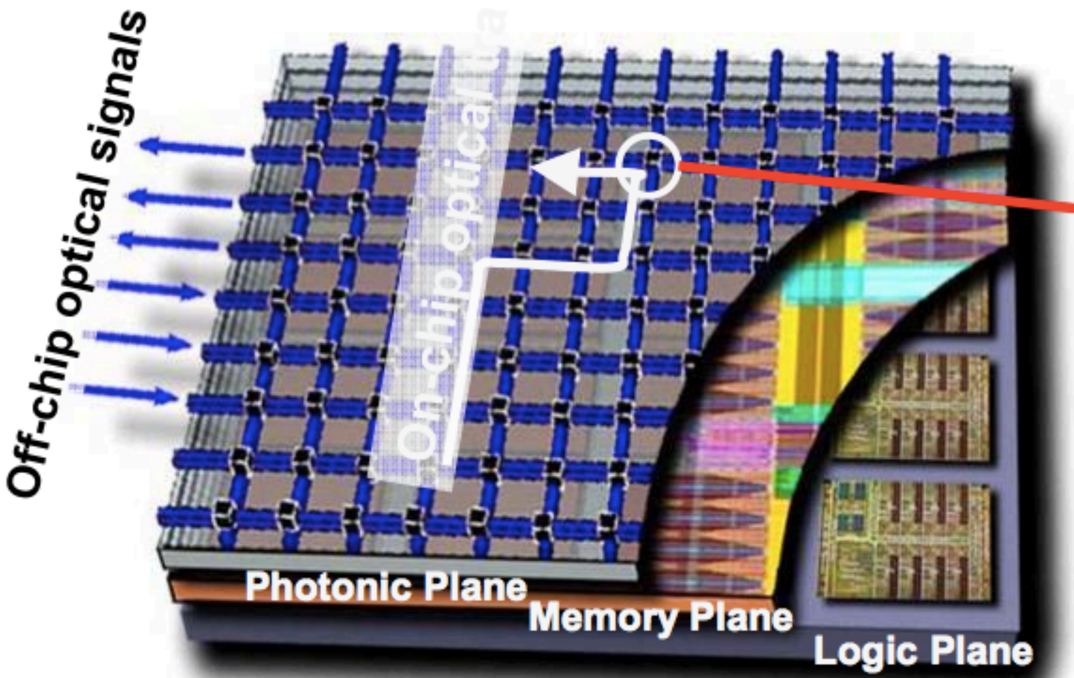


# Motivation

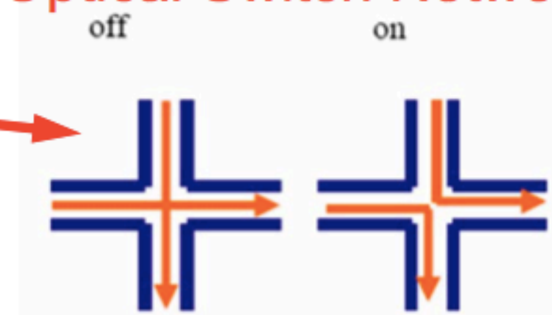
VOLUME 45, NUMBER 6 PHYSICAL REVIEW LETTERS 11 AUGUST 1980

**New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance**

K. v. Klitzing
*Physikalisches Institut der Universität Würzburg, D-8700 Würzburg, Federal Republic of Germany, and Hochfeld-Magnetlabor des Max-Planck-Instituts für Festkörperforschung, F-38042 Grenoble, France*




## Optical Switch Network



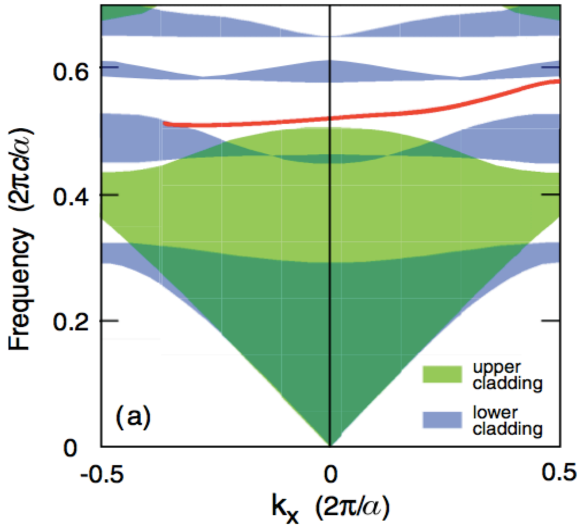

Photonic layer not only connects various cores, but also routes the traffic

Dr. Gary Patton, IBM: "Innovations for Next Generation Scaling" Industry Strategy Symposium, Napa, CA, Jan 15, 2013

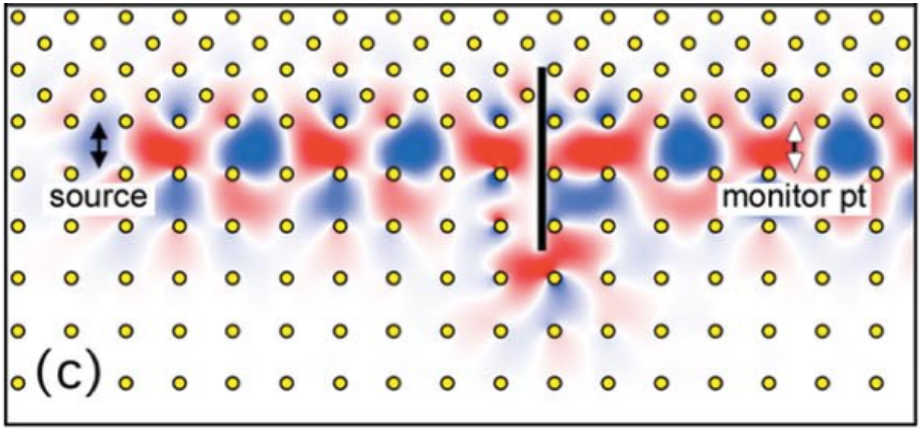
# Background: photonic topological protection

Raghu, Haldane PRL (2008)

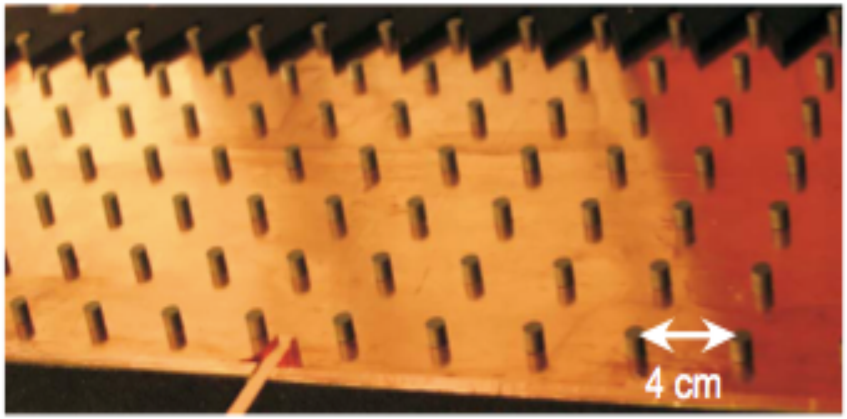
$$\tilde{\mu} = \begin{pmatrix} \mu_1 & i\mu_2 & 0 \\ -i\mu_2 & \mu_1 & 0 \\ 0 & 0 & \mu_1 \end{pmatrix}$$



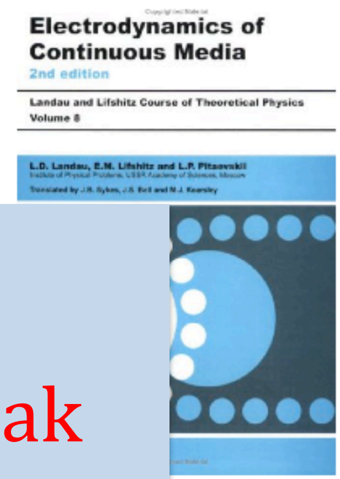

Wang et. al., PRL (2008)




Wang et. al., Nature (2009)



# Magnetism in photonics




**The big question:**
**How can we strongly break time-reversal symmetry in optics?**

Thus there is … cal frequencies
onward, and in … uish between **B**
and **H** in this fre… ame is true for

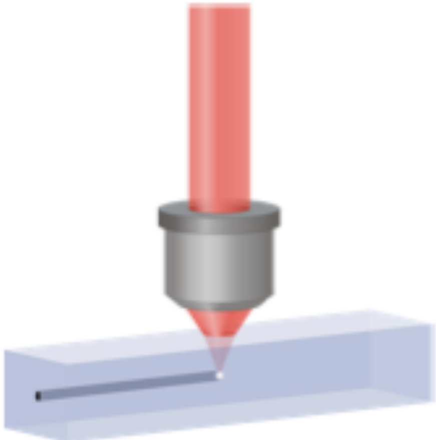
Magnetic response is inherently weak at optical frequencies

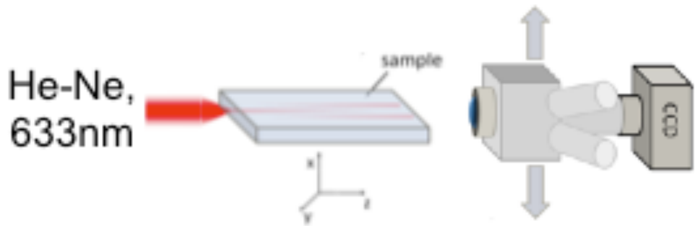
(1) Koch, Houck, Le Hur, Girvin, PRA (2010): circuit QED system
(2) Hafezi, Demler, Lukin, Taylor, Nature Phys. (2011): CROWS [+ Nature Photon. (2013)]
(3) Umucalilar and Carusotto, PRA (2011): using spin as polarization in PCs
(4) Fang, Yu, Fan, Nature Photon. (2012): electrical modulation of refractive index in PCs
(5) Khanikev et. al. Nature Mat. (2012): birefringent metamaterials

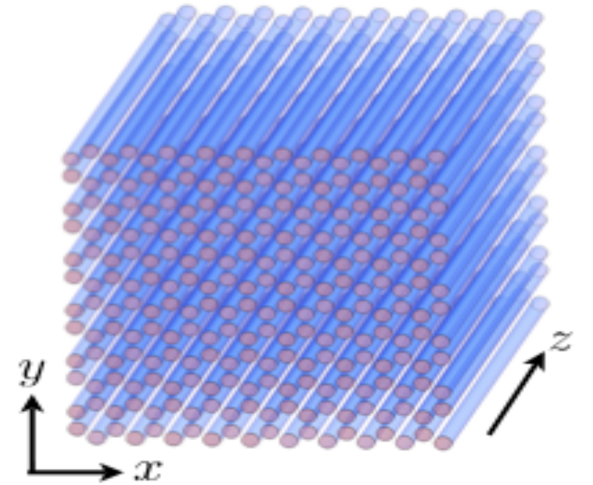
… also in cold atoms

# Experimental system: photonic lattices

Array of coupled waveguides






Peleg et. al., PRL (2007)

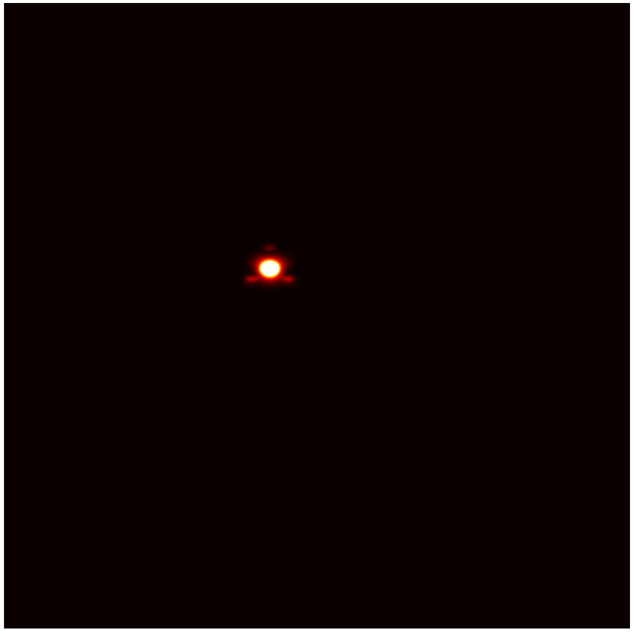
Envelope approximation for electric field:

$$\mathbf{E}(x,y,z) = \hat{x}\psi(x,y,z)e^{i(k_0 z - \omega t)}$$

$$|\partial_z^2 \psi| \ll 2k|\partial_z \psi|$$

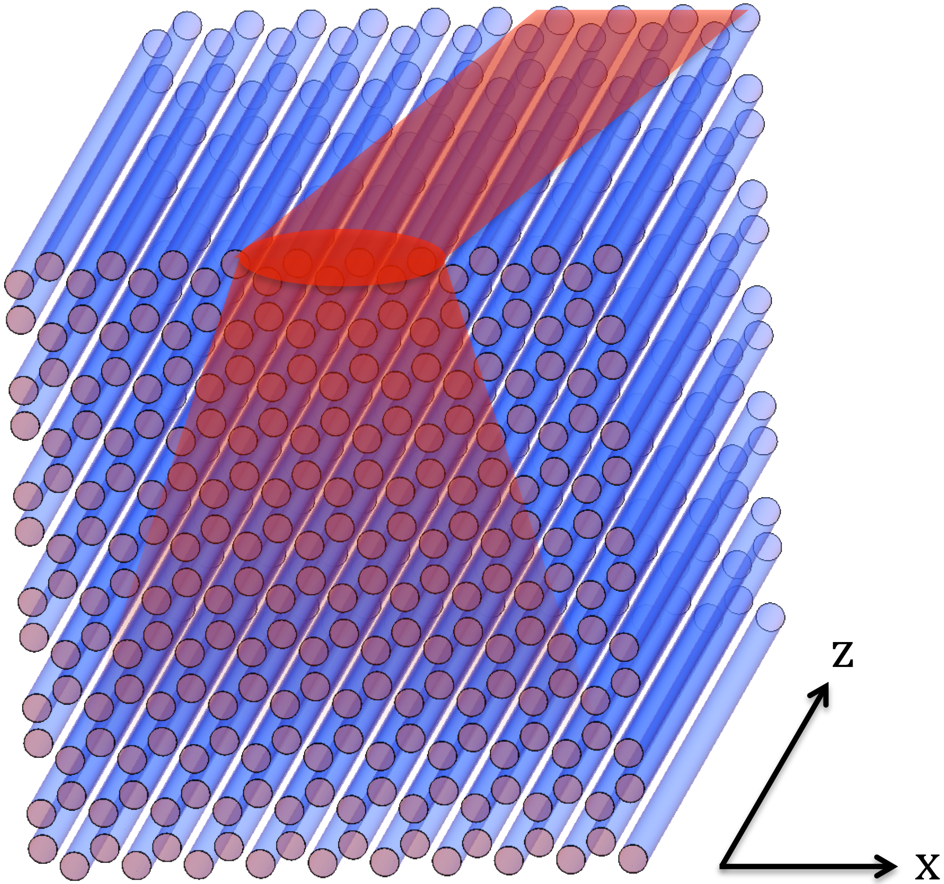
Paraxial Schrödinger equation:

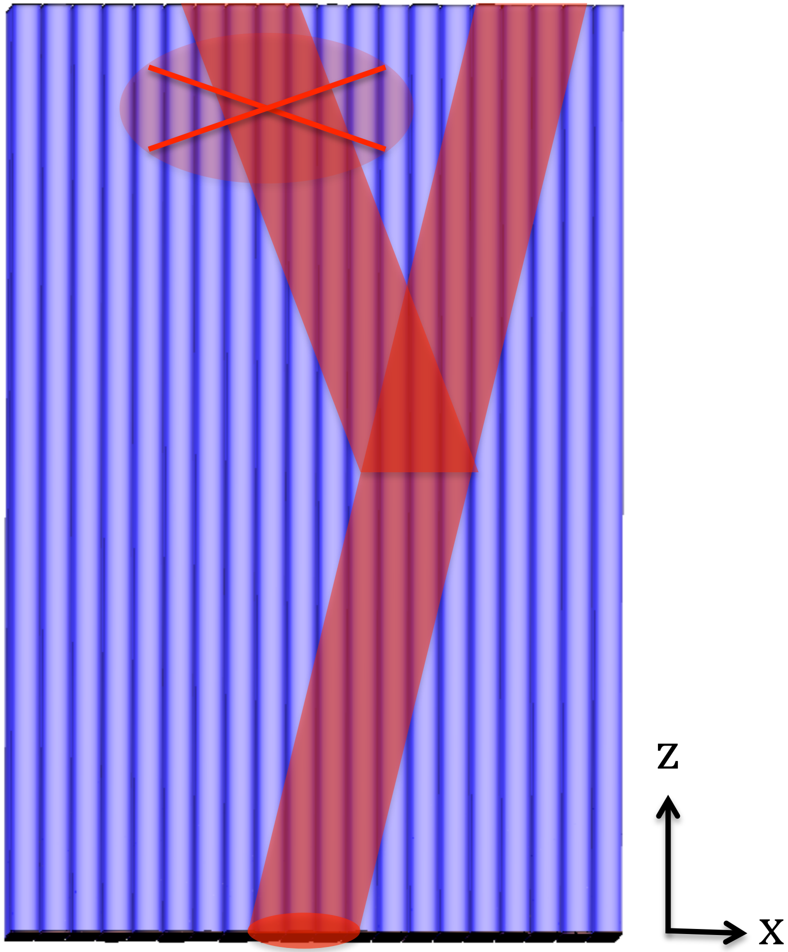
$$i\partial_z \psi = -\frac{1}{2k}\nabla^2\psi - \frac{k}{n_0}\Delta n(x,y,\mathbf{z})\psi$$



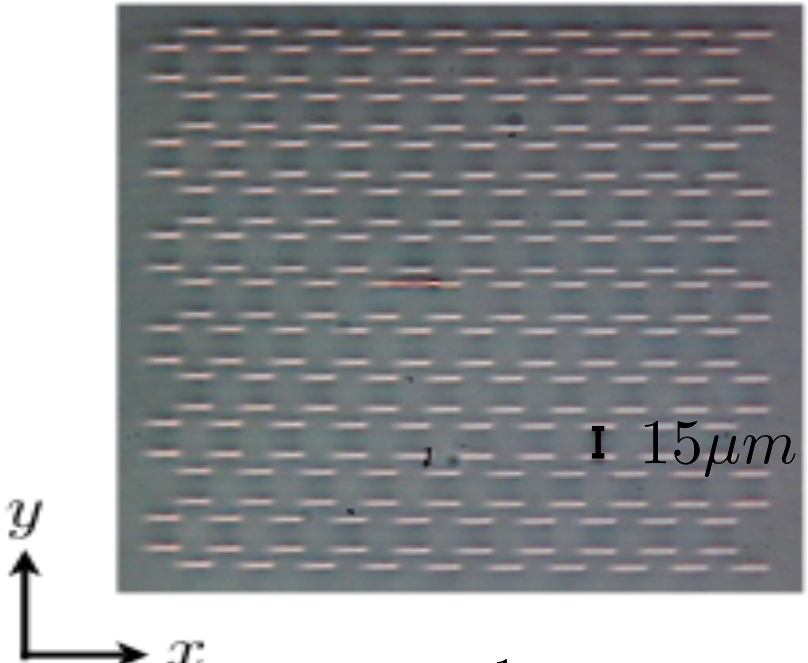
# Experimental system: photonic lattices

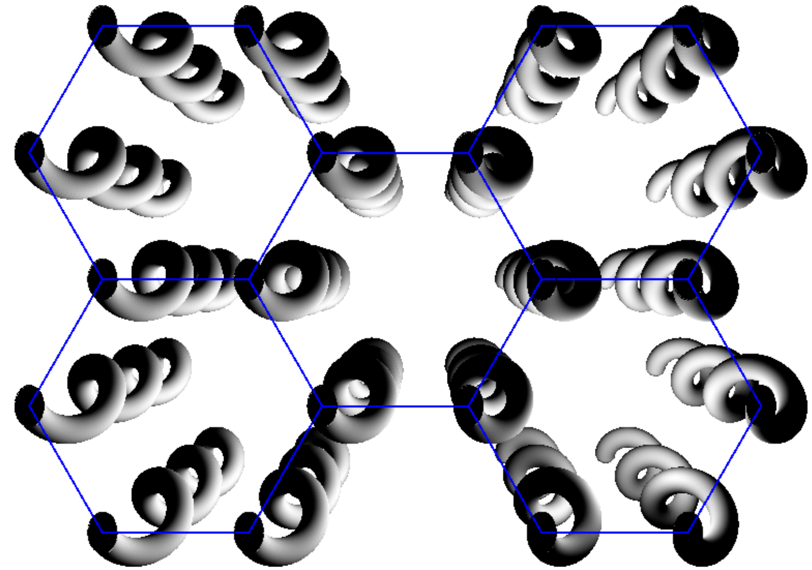
Our system: topological protection against **transverse** backscattering



# Helical rotation induces a gauge field



$$i\partial_z\psi = \frac{1}{2k_0}\left(i\nabla + \mathbf{A}(z)\right)^2\psi - \frac{k_0\Delta n(x,y)}{n_0}\psi - \frac{k_0 R^2\Omega^2}{2}\psi$$

$$A(z) = k_0 R\Omega(\sin\Omega z, \cos\Omega z)$$

$$x' = x + R\cos\Omega z$$
$$y' = y + R\sin\Omega z$$
$$z' = z$$

$$\mathcal{H}(z) = \sum_{m,\langle n\rangle} e^{i\mathbf{A}(z)\cdot\mathbf{r}_{mn}}\psi_n^\dagger\psi_m$$

- Floquet TIs: Kitagawa et al., PRB (2010); Lindner et al., Nature Phys. (2011).

# Calculating the Floquet band structure

We use Floquet theory (quasiperiodic solutions):

$$\psi_n(z = Z) = e^{-iEZ}\psi_n(z = 0)$$

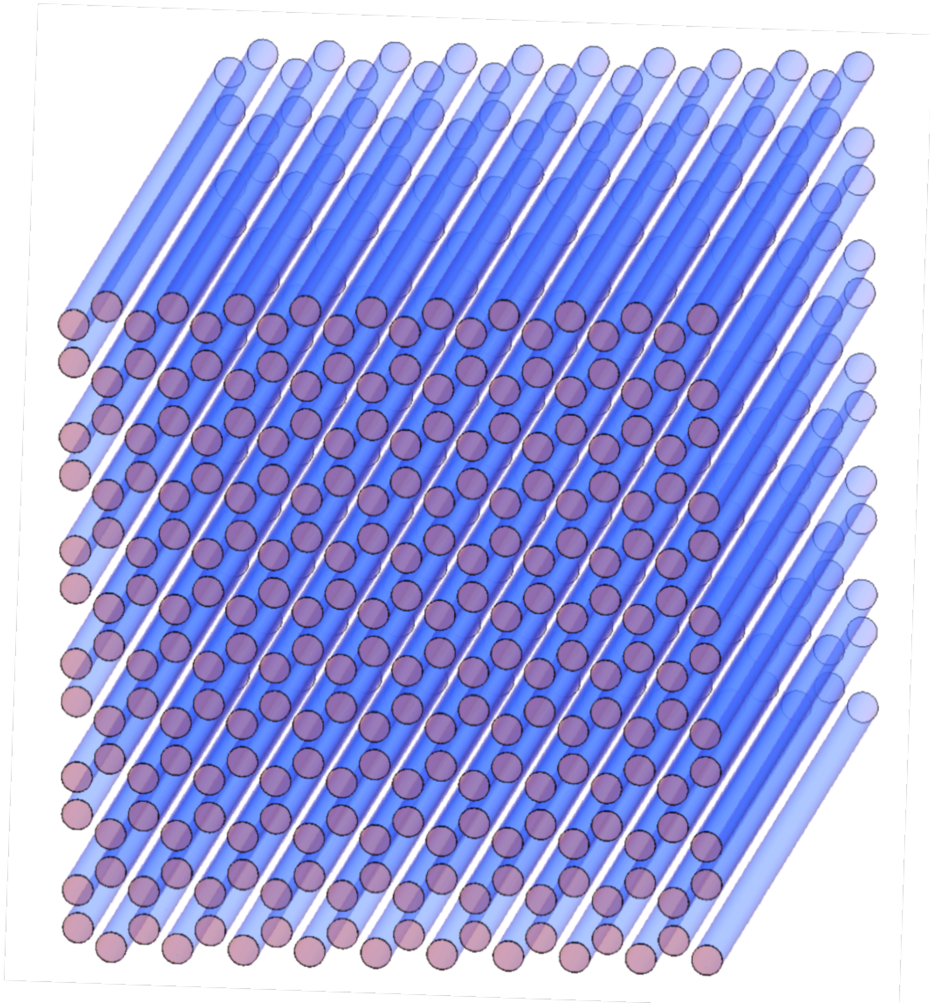
Calculate the propagator through one period, *Z*:

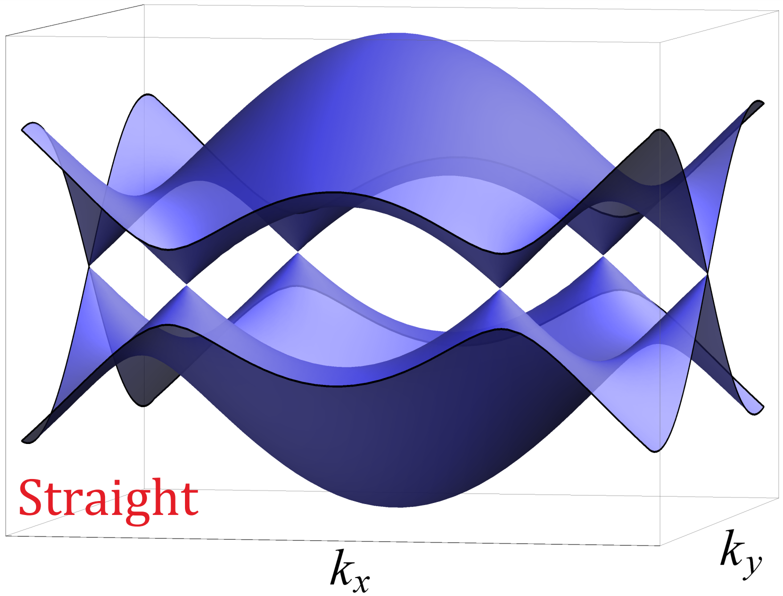
$$U(Z) = \prod_z e^{-iH(z)dz}$$

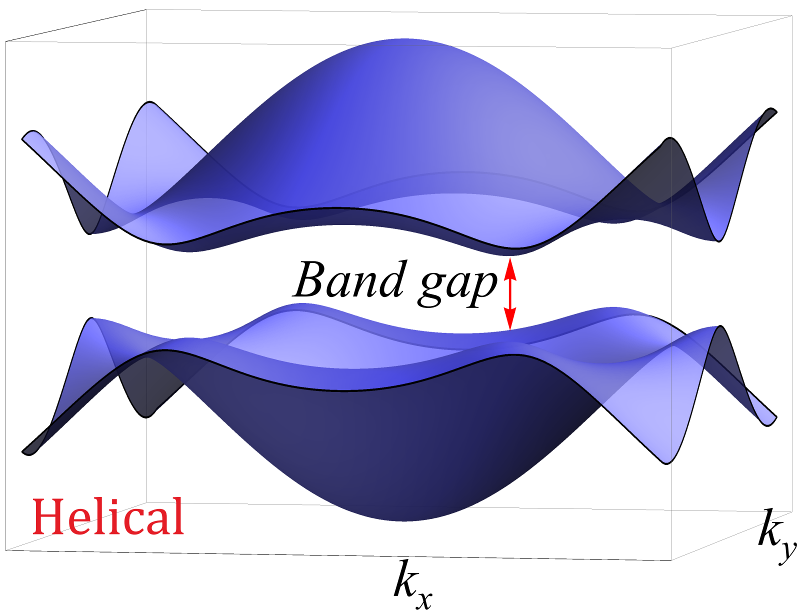
This gives an effective Floquet Hamiltonian:

$$\mathbf{H}_F = \frac{i}{Z}\log U(Z)$$

# Graphene opens a Floquet gap for helical waveguides





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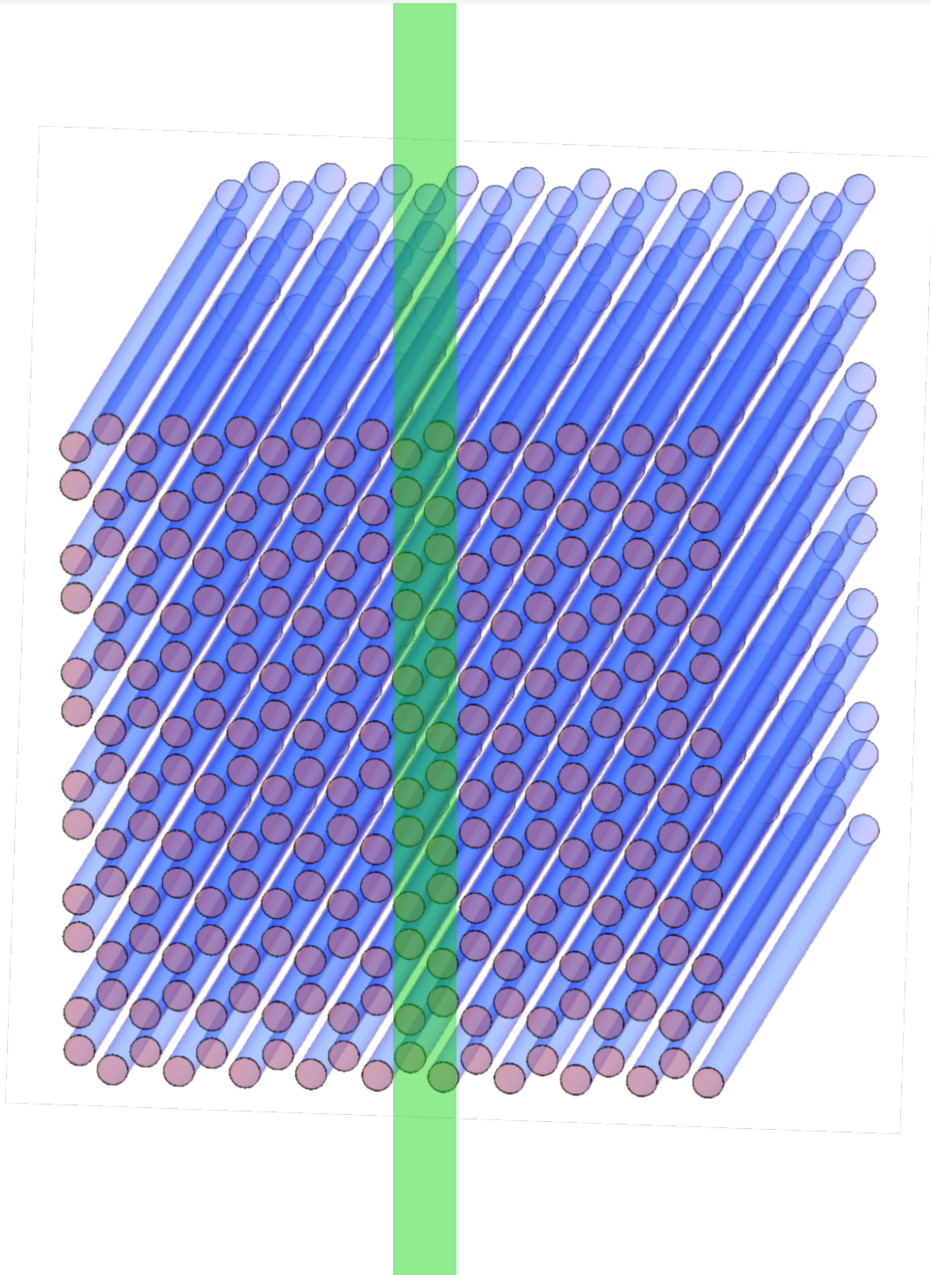
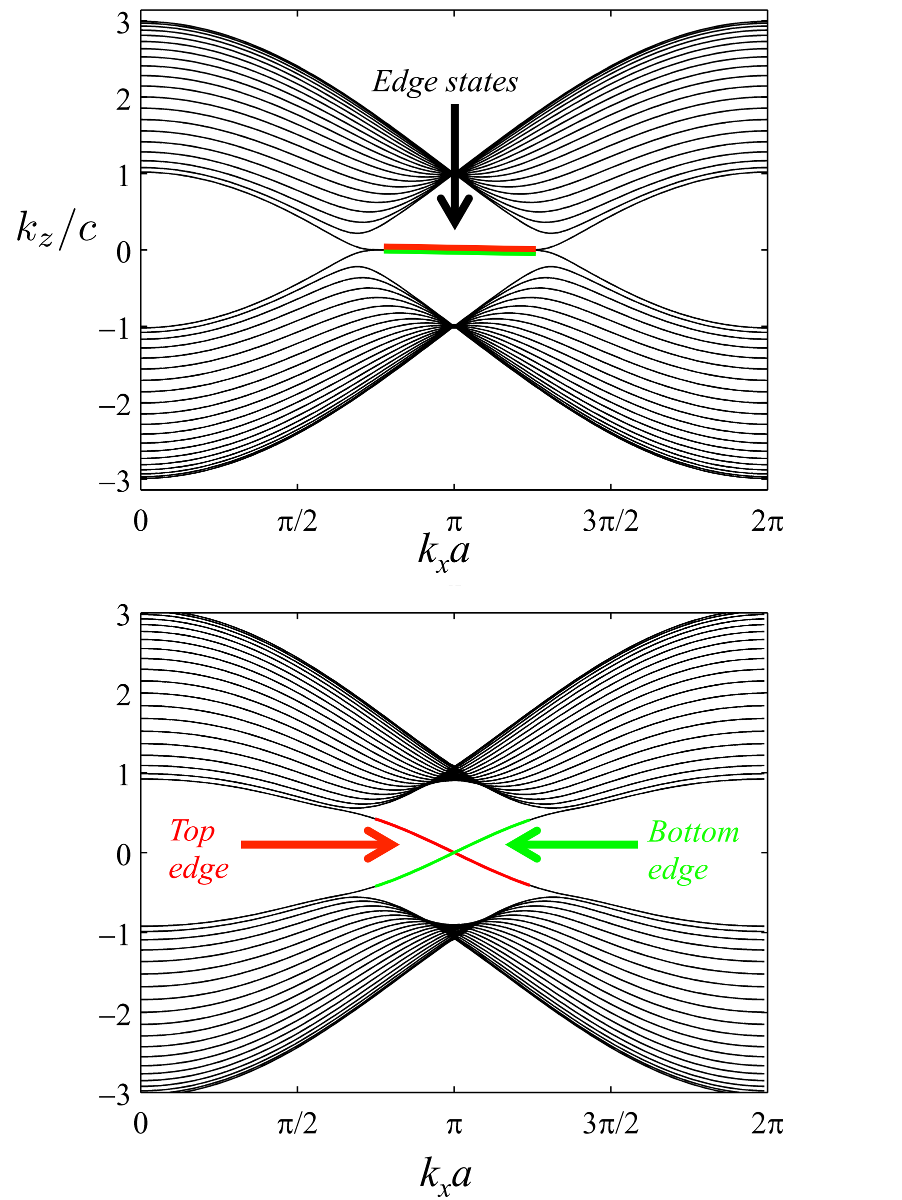
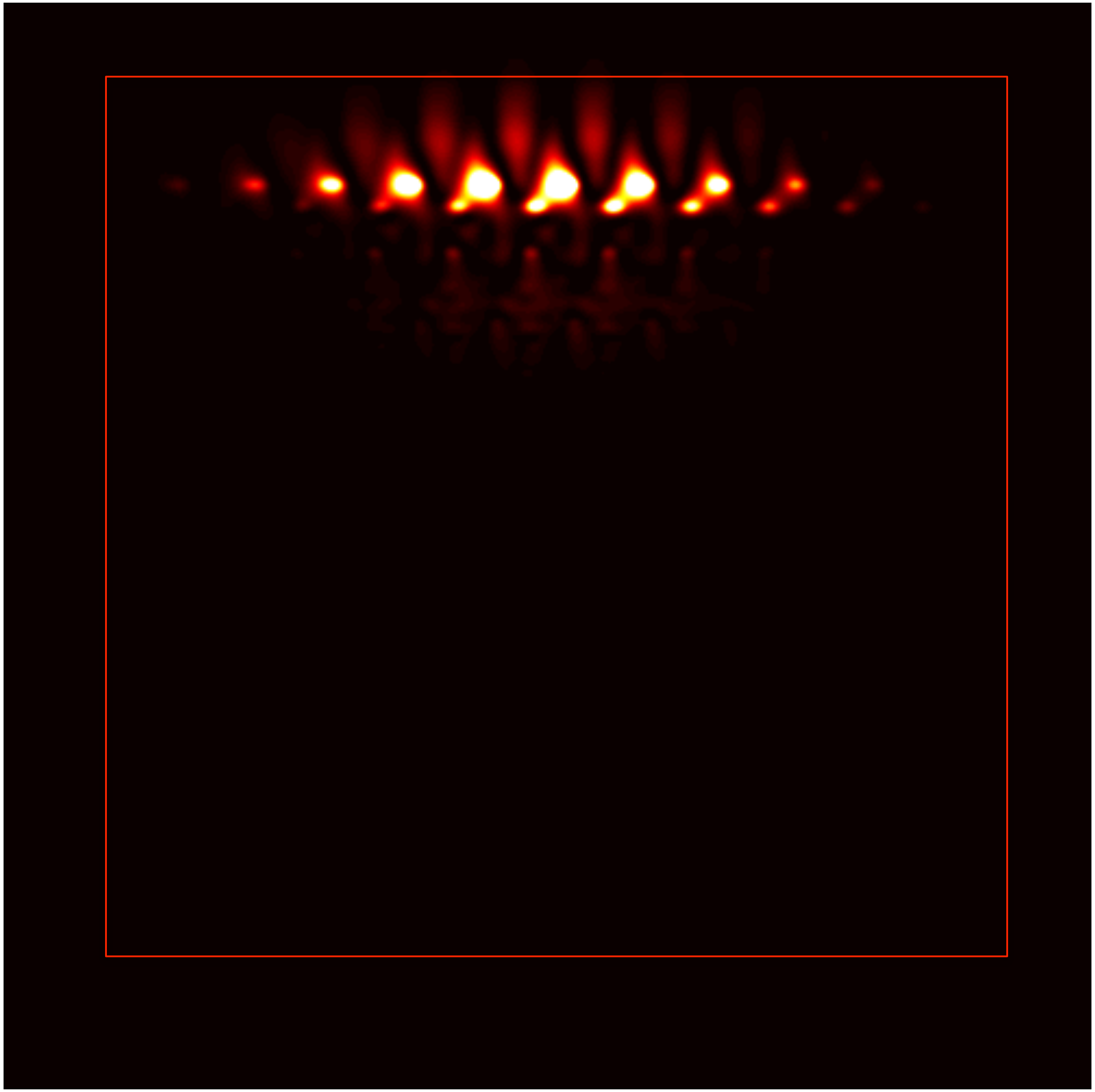


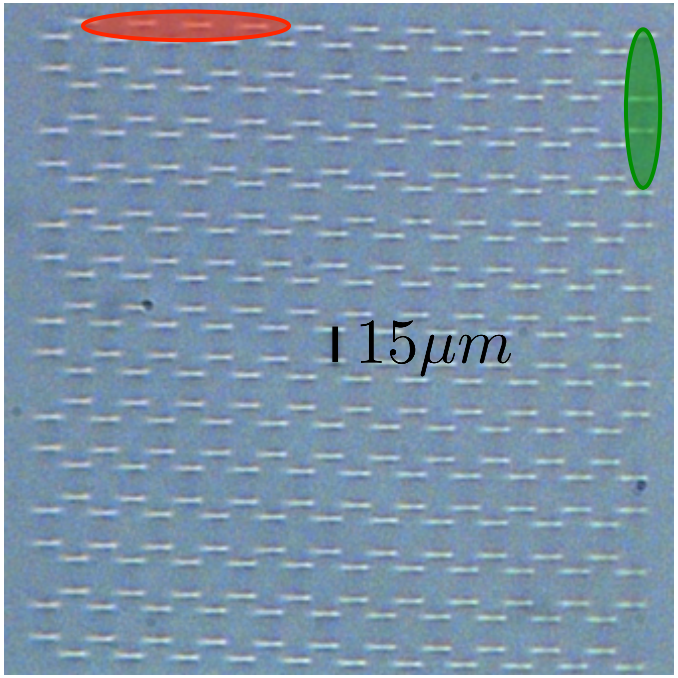


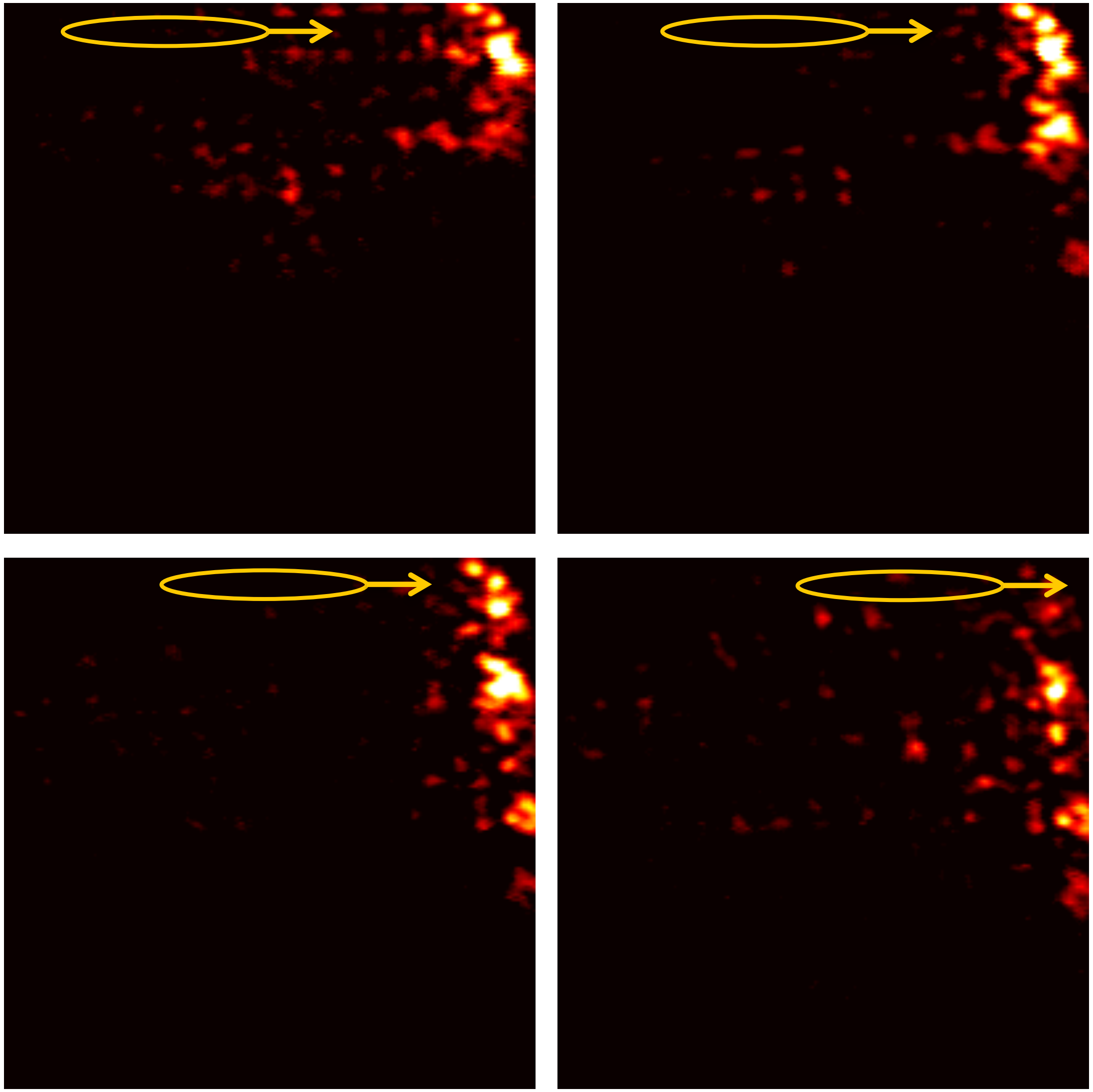
# “Time”-domain continuous simulations



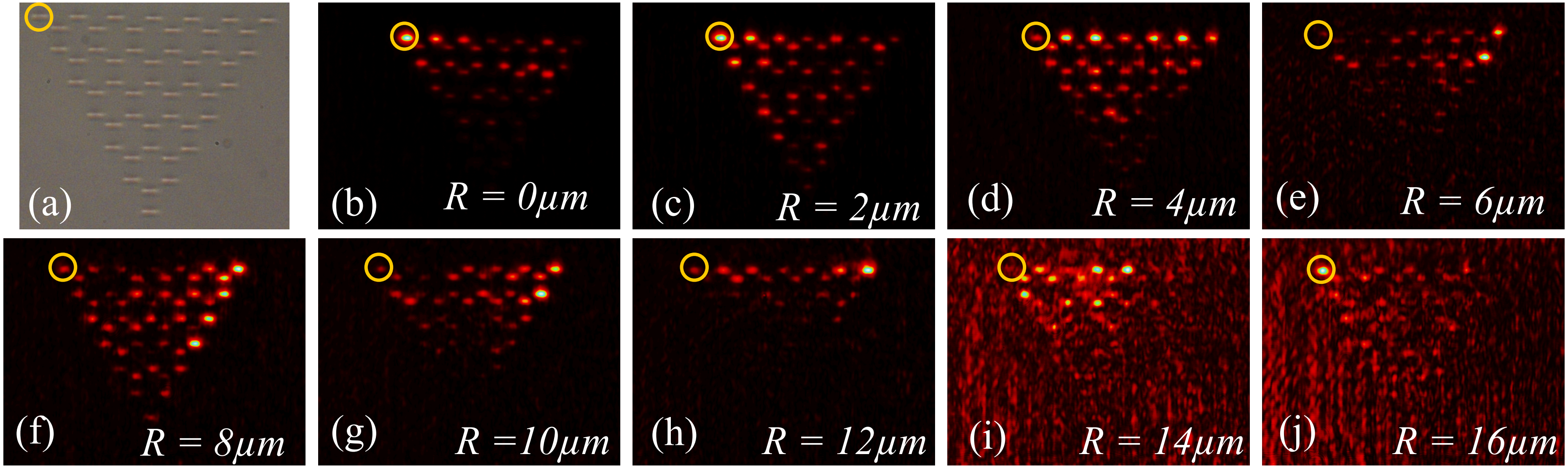
# Experimental results: rectangular arrays

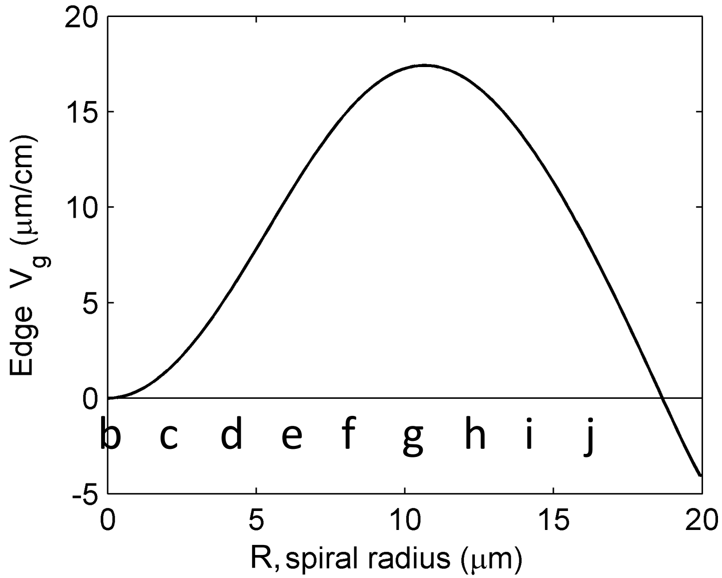
Microscope image



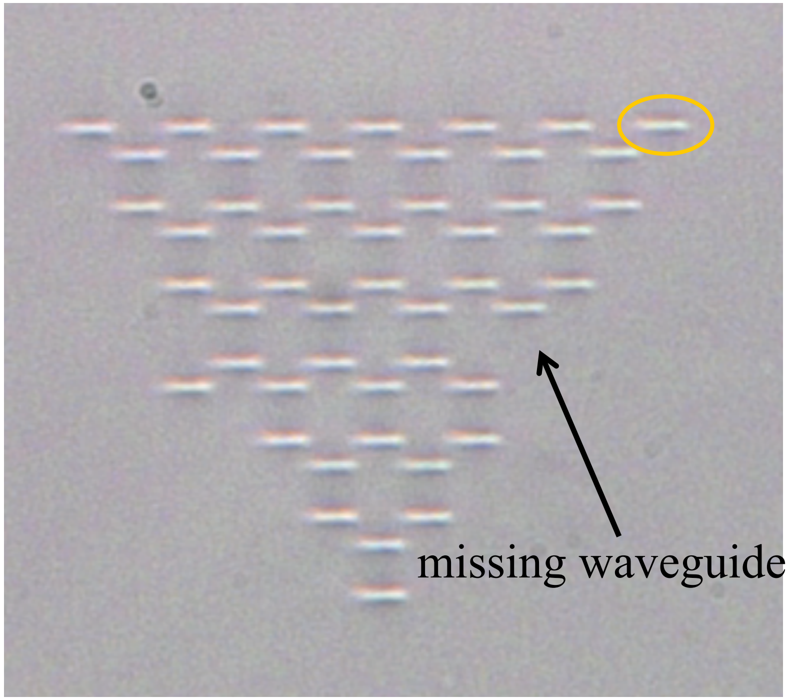



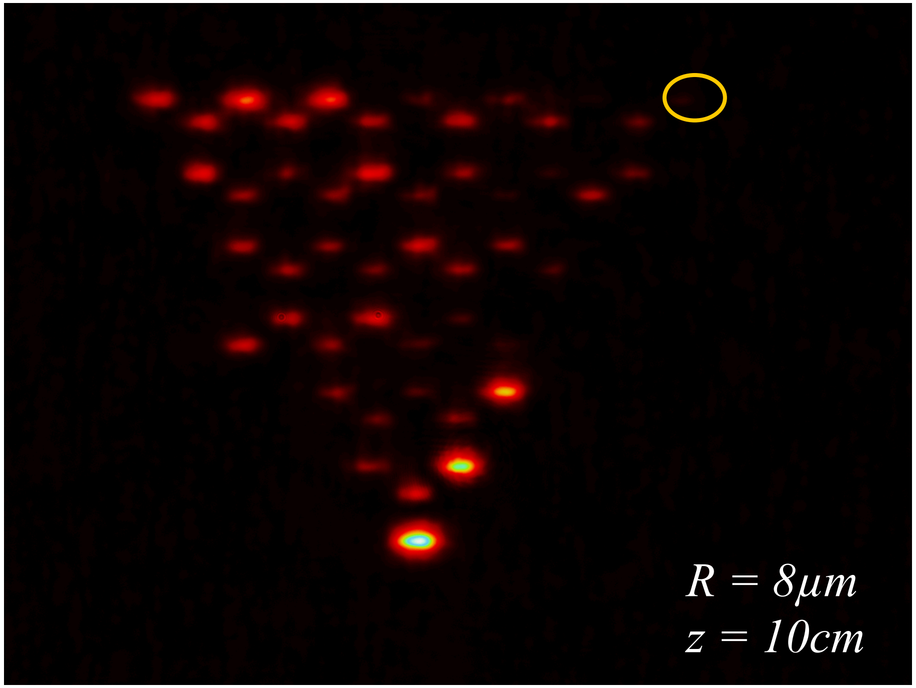
# Experimental results: group velocity vs. helix radius, R



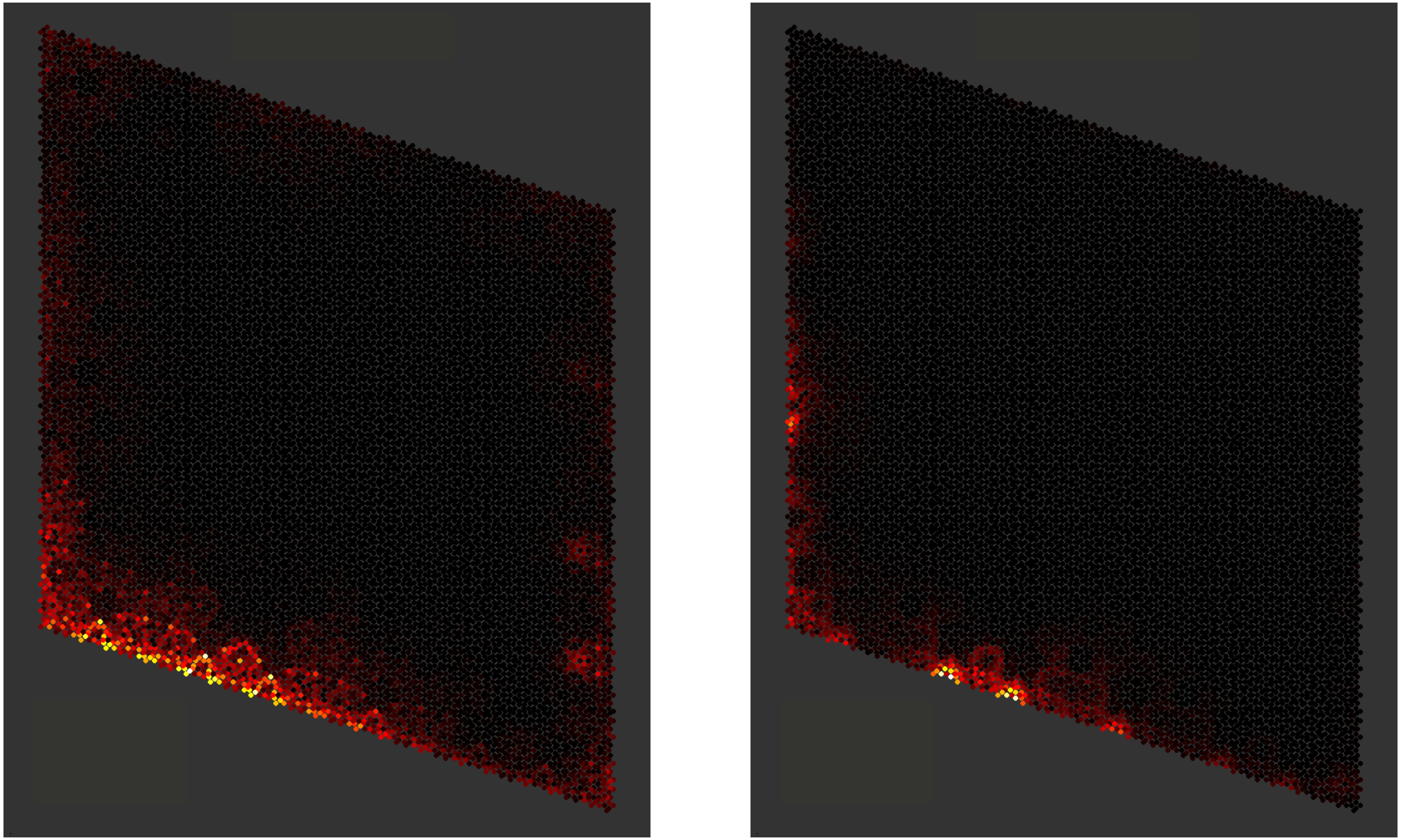



# Experimental results: triangular arrays with defects

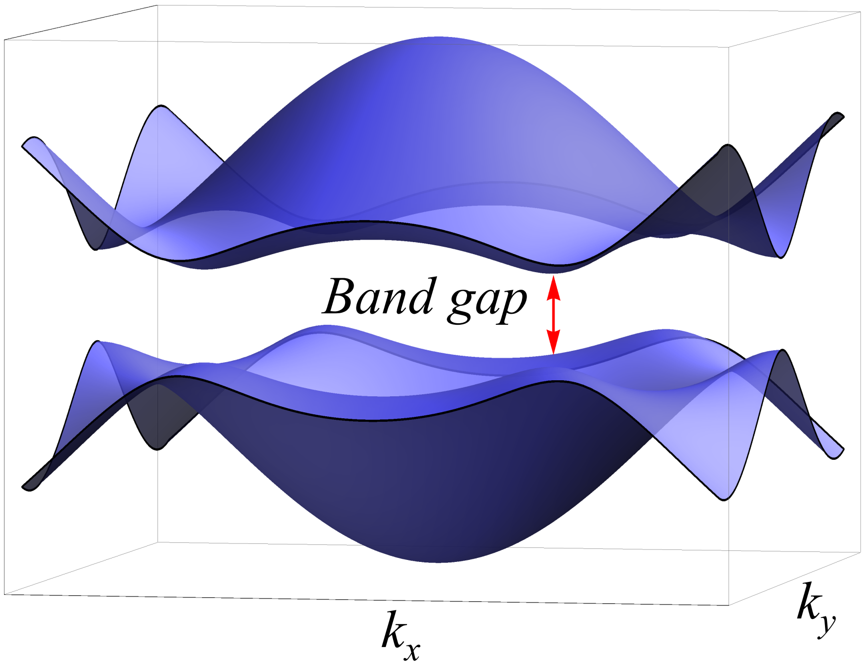


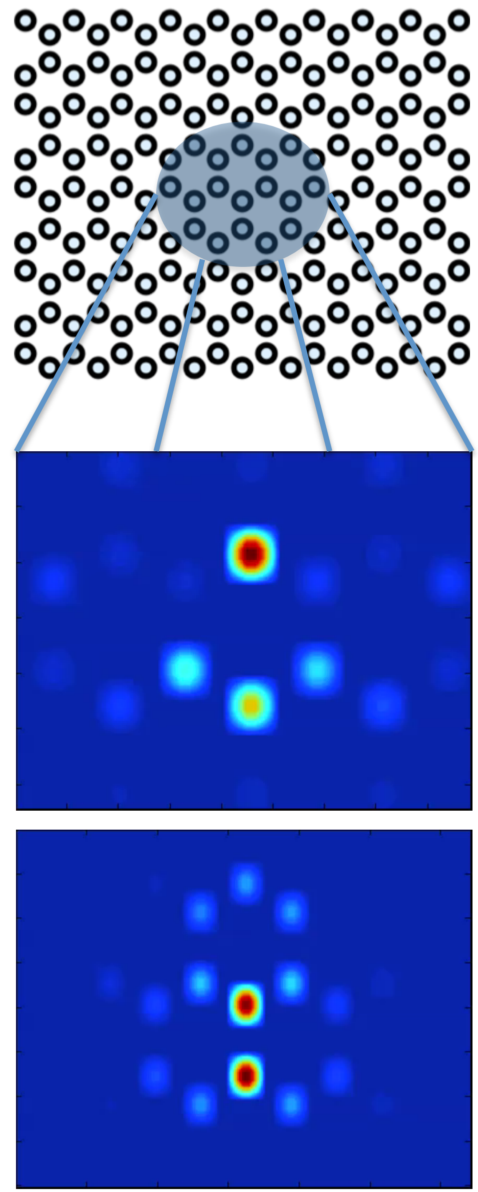



# Numerics: topological states in quasicrystals



# Nonlinearity yields topological solitons



$$i\partial_z \psi_n = \sum_{\langle m \rangle} H_{nm}\psi_m \pm |\psi_n^2|\psi_n$$

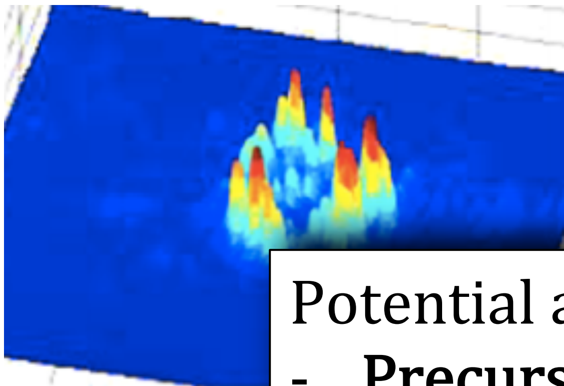
Y. Lumer, Y. Plotnik, M. Rechtsman, M. Segev,
Phys. Rev. Lett., 111, 243905 (2013).

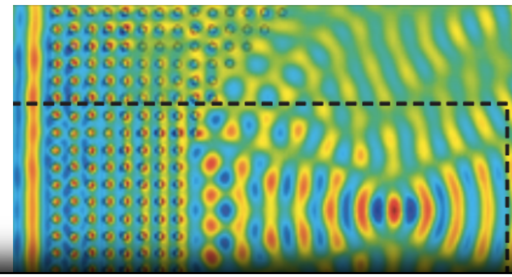
# Part 2: Experimental observation of optical Weyl points

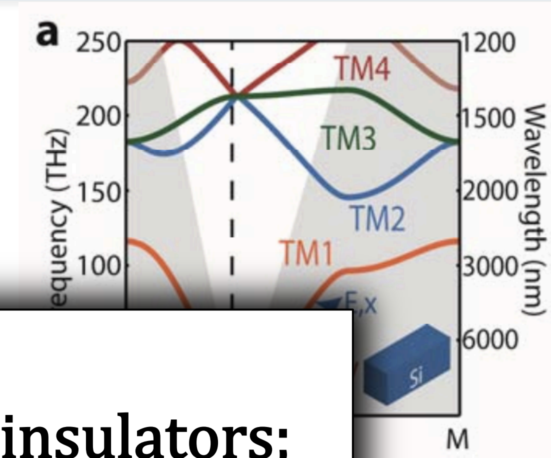
*(collaboration with Chong group, NTU-Singapore and Chen group, Pittsburgh)*

Noh et al., Nature Physics (online, 2017)

# Some more background on Dirac points





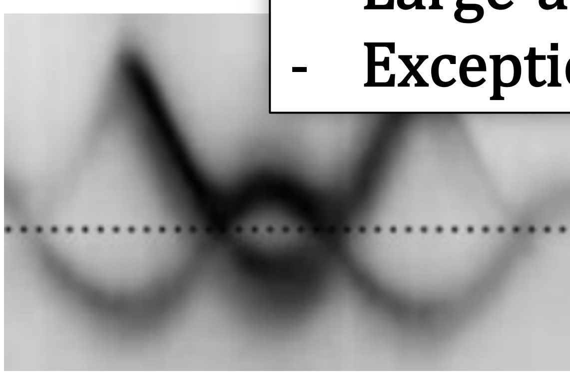



Potential applications in 2D:

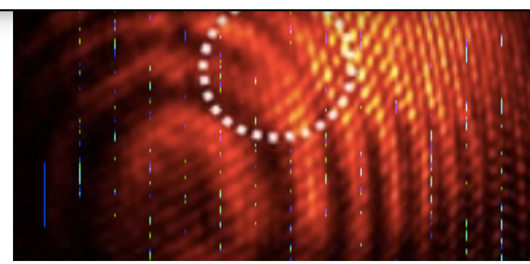
- **Precursor to photonic topological insulators;**
- **ENZ Materials;**
- **Large-area single-mode lasers**
- **Exceptional rings and photonic tachyons…**

Peleg et al., PRL 98
Segev

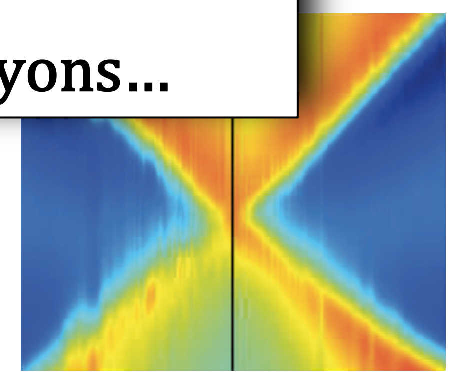
…t. Photon.
…ntine group



Jacqmin et al., PRL 112, 116402 (2014): Bloch/Amo group



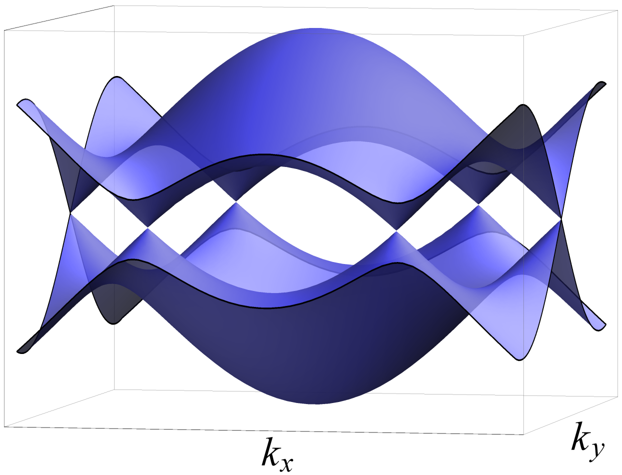
Song et al., Nat. Comm. 6, 6272 (2014): Z. Chen group

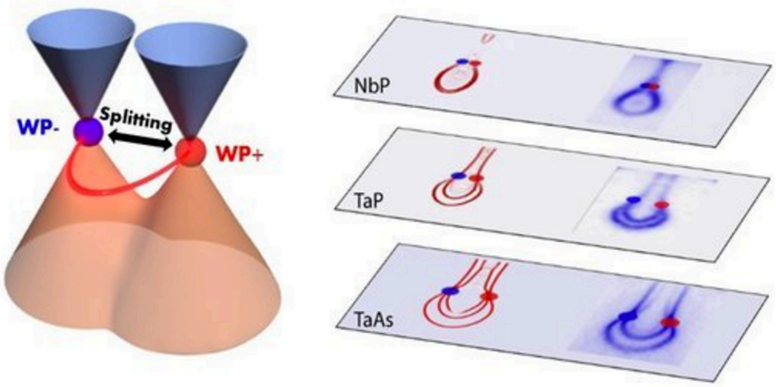


Zhen et al., Nature 525, 354 (2015): Soljacic group

# Weyl points: 3d Dirac points

- Amazing properties of graphene arise from its Dirac point:



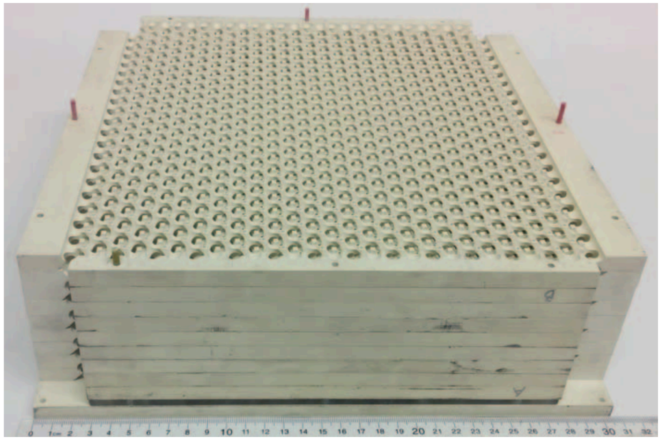



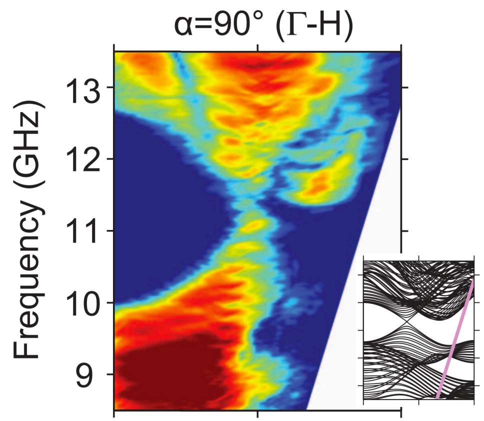

Attribution: Max Planck for the Science of Light, press release

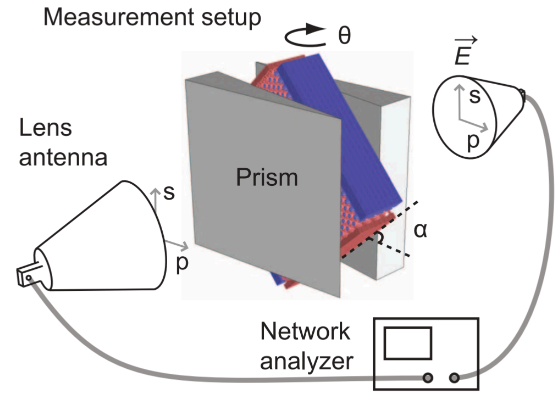
$$H = k_x\sigma_x + k_y\sigma_y \; + \underbrace{k_z\sigma_z}$$

- In 3d, Weyl point cannot be lifted!
- Associated with magnetic monopole of the Berry curvature.
- Novel behavior in condensed matter systems (Fermi arcs, …)
- Associated with a topological phase transition
- Large-volume single-mode lasing? (Bravo-Abad et al., PNAS: 9761 (2012))

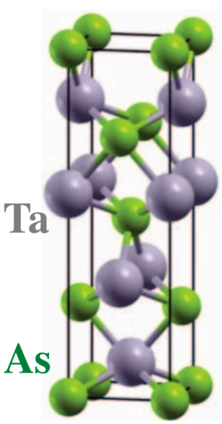
# Weyl points: previous work

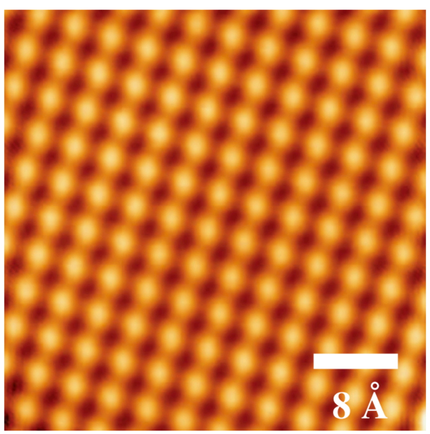


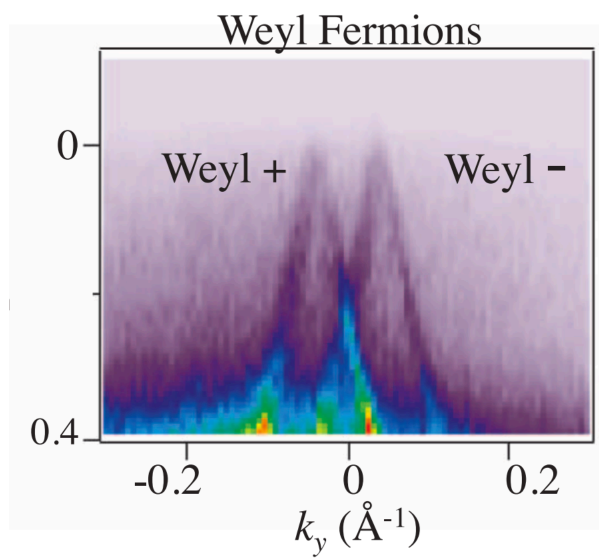


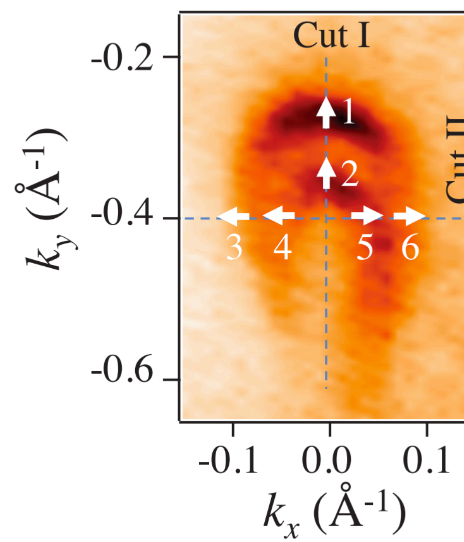




Lu et al., *Science* 349, 622 (2015) [prediction: Lu et al., *Nature Photonics* 7, 294 (2013)]



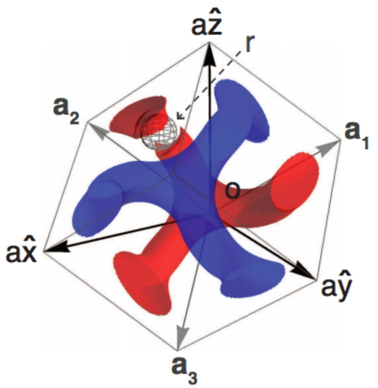



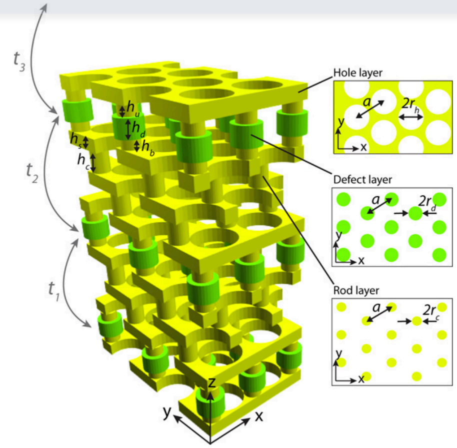




Xu et al., *Science* 349, 613 (2015)

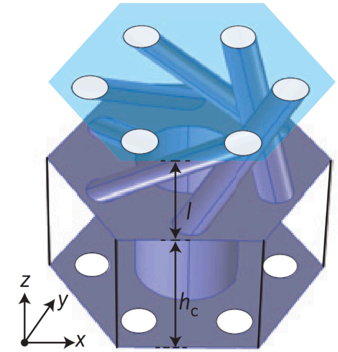
# Weyl points: previous work in photonics




Lu et al., *Nat. Photon* 7, 294 (2013)



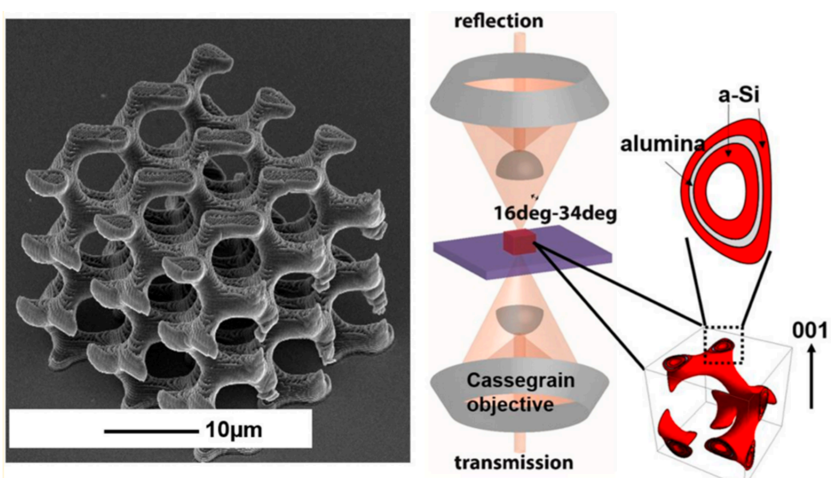

Bravo-Abad et al., *2D Mat.*, 2, 034013 (2015)



Xiao et al., *Nat. Physics.*, 11, 920 (2015)

- Gao et al., arXiv: 1511.04875 (2015)
- Yang et al., arXiv: 1601.07966 (2015)
- Xiao et al., *PRL.*, 117, 057401 (2016)
- Chen et al., arXiv: 1612.04681 (2016)

Also, 3D topological insulators: Lu et al., (Soljacic group) Nat. Phys. 12, 337 (2016);
Slobozhanyuk et al. (Khanikaev group), Nat. Photon. 11, 130 (2017)




Peng et al., *ACS Photonics* 3, 1131 (2016)

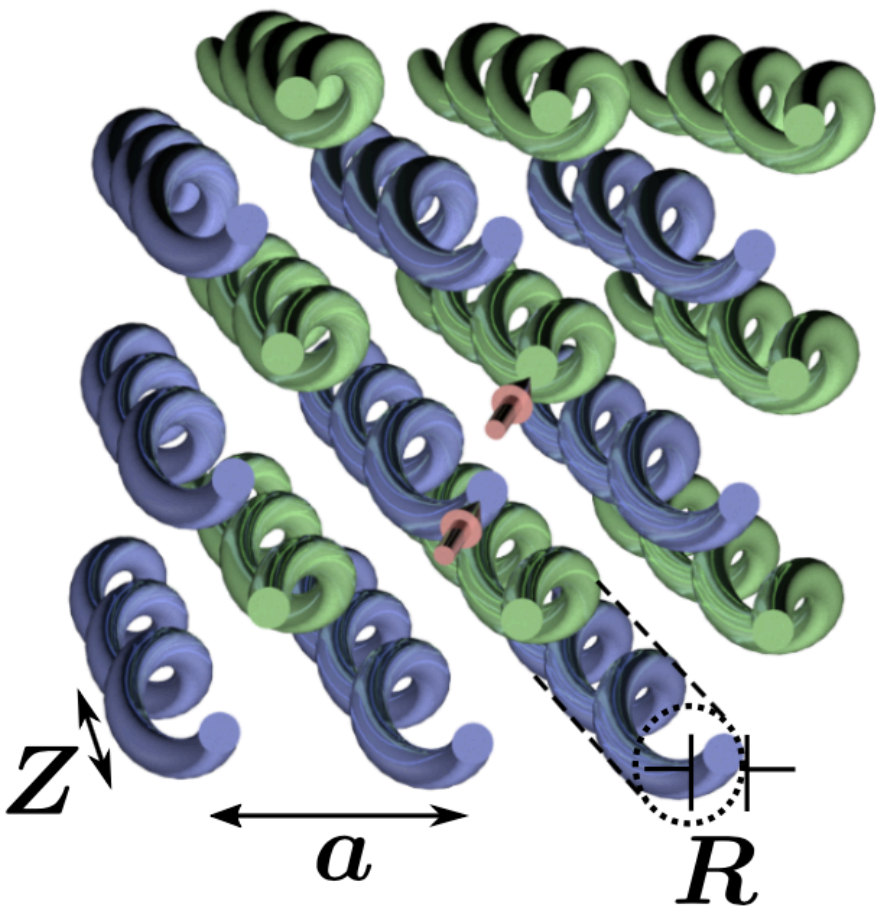
Progress towards mid-infrared Weyl points:

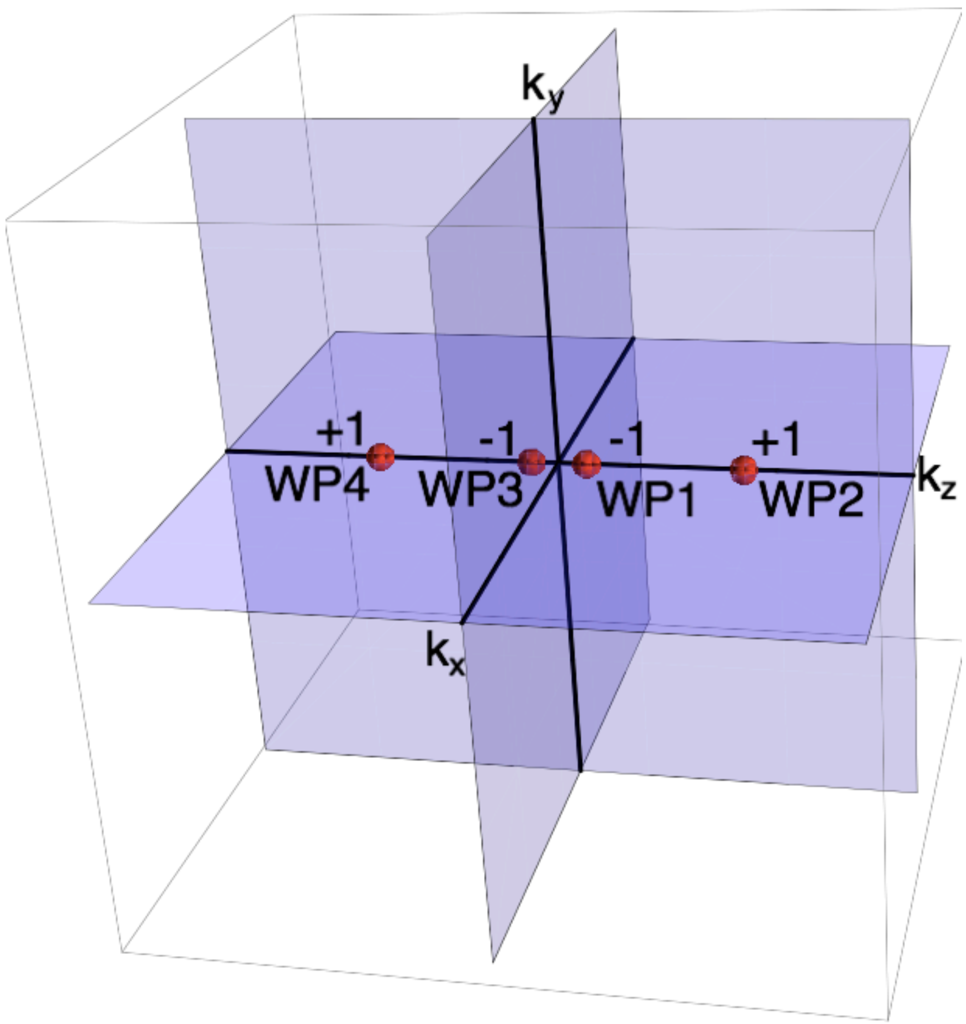
- Peng et al, APS-MM H1.00296 (2015)
- Peng et al., APS-MM S52.00013 (2016)
- Goi et al., CLEO, JTu5A.101 (2015)
- Goi et al., CLEO-2016, SM3R.3 (2016)

How can we get Weyl points?

Well… $2 + 1 = 3$.

# Our system: photonic TI with a topological transition



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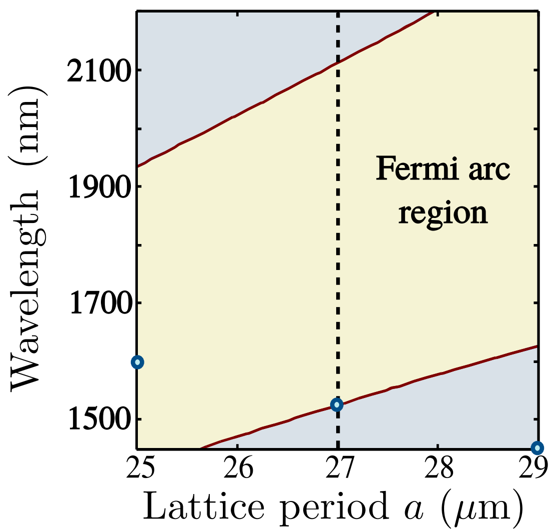
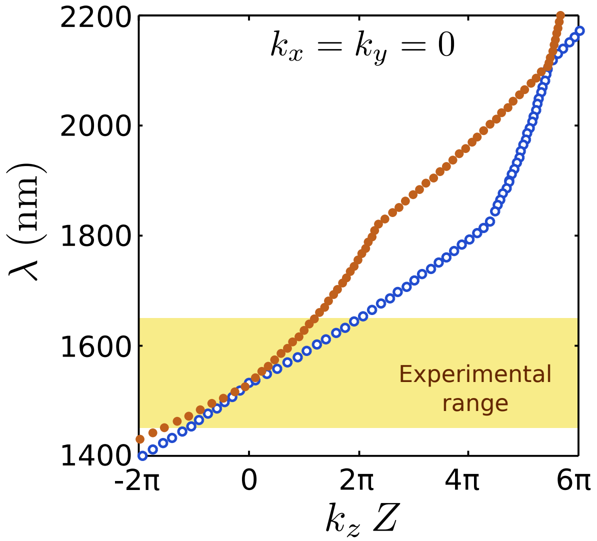
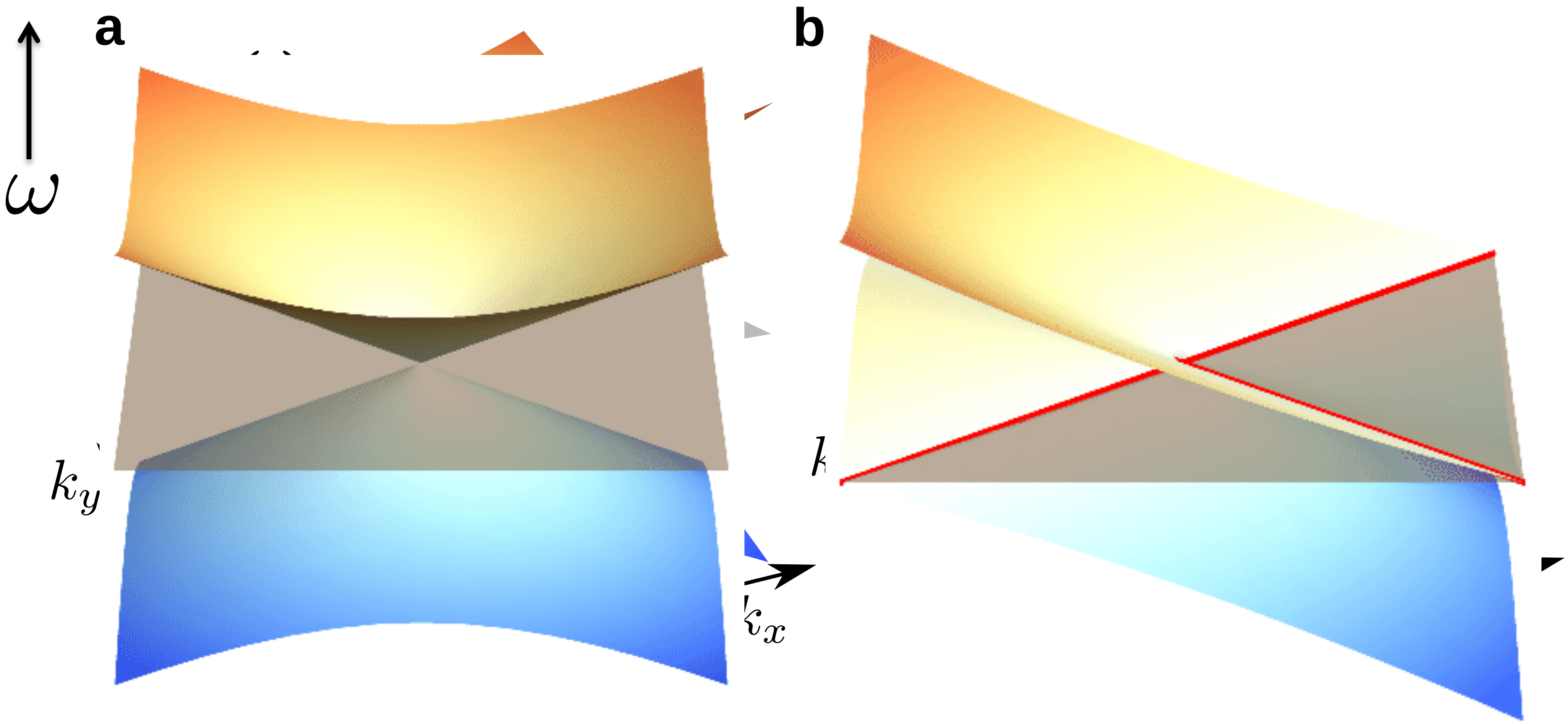


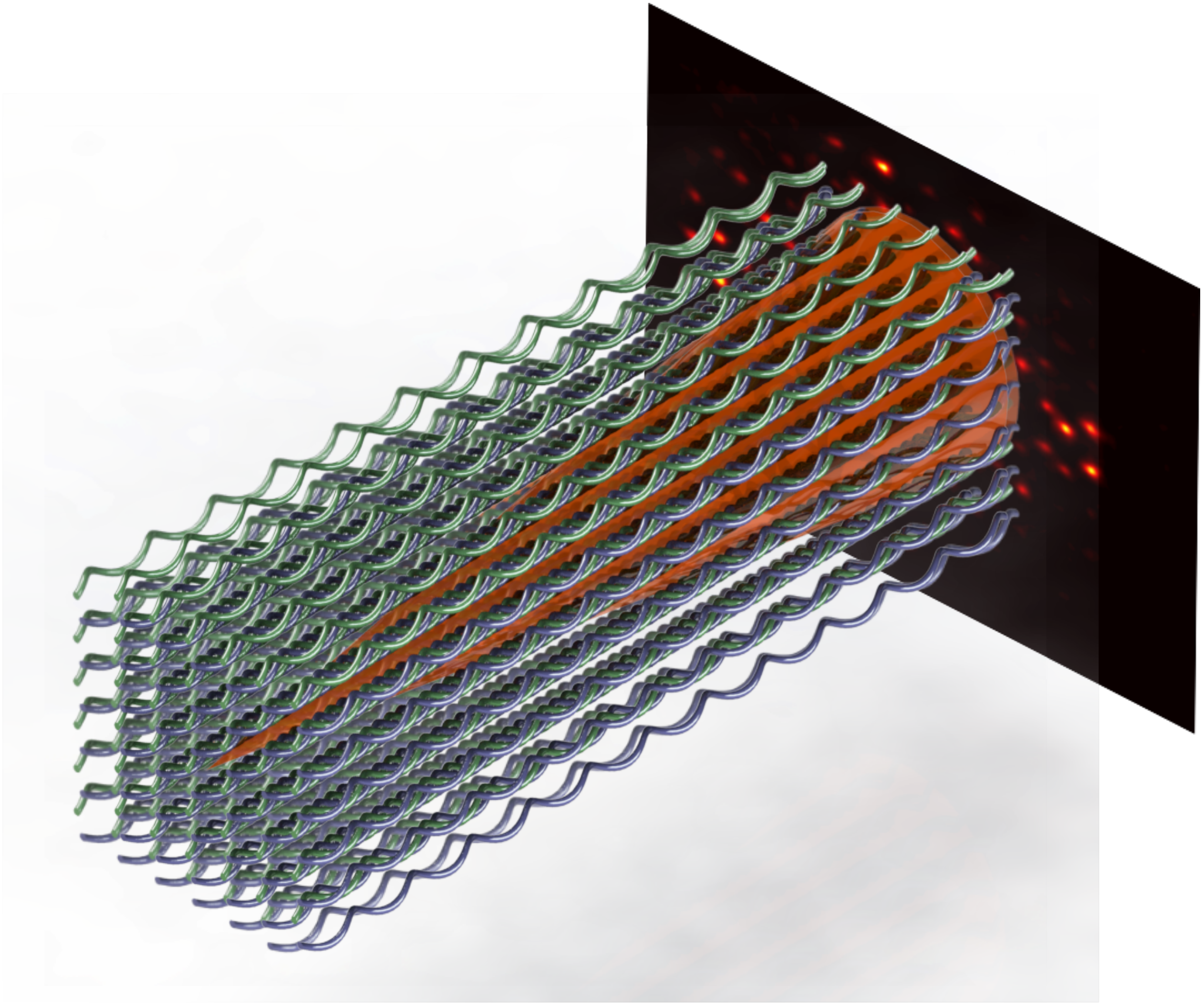
# Type-II Weyl points



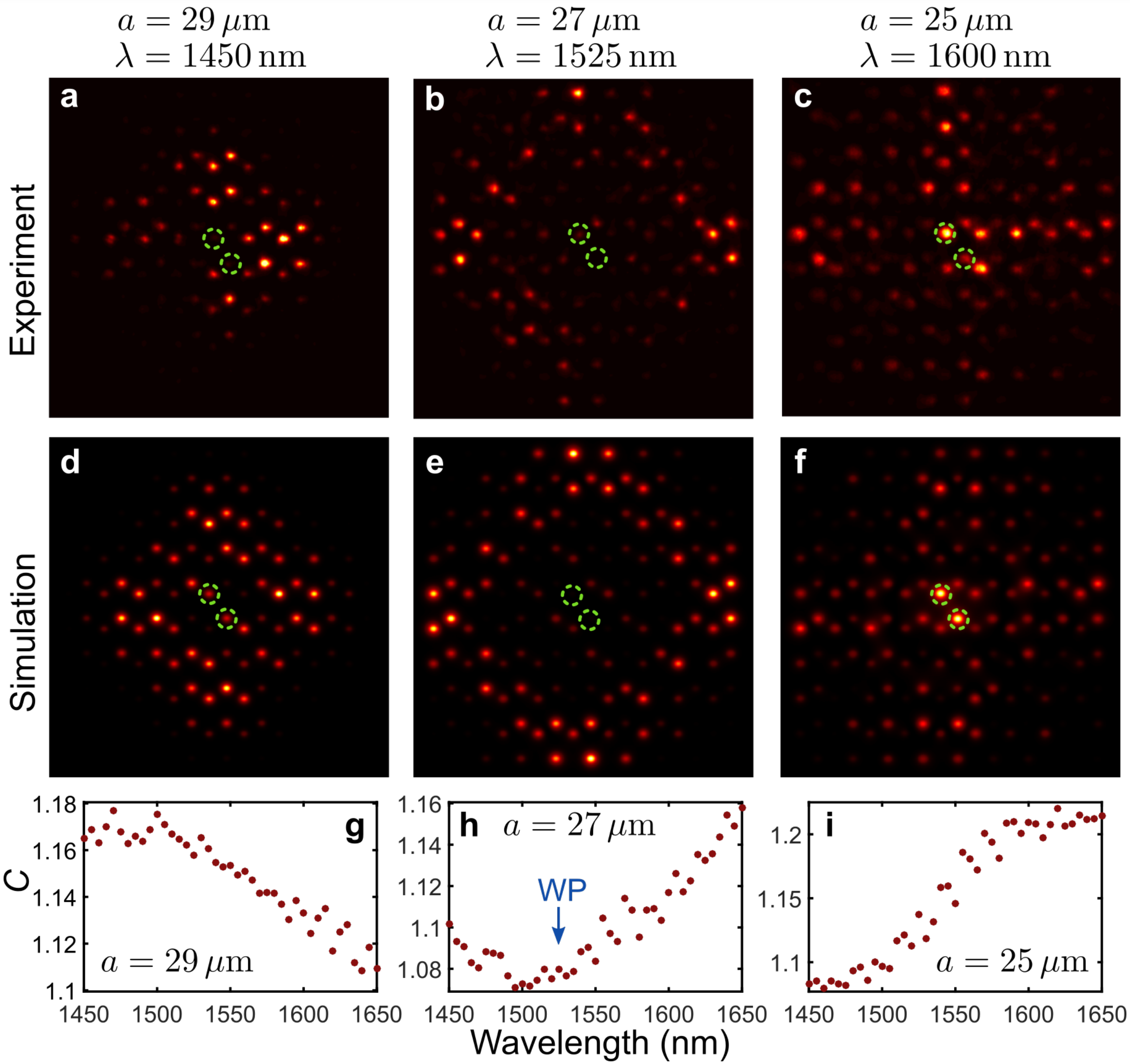

$k_z = 0$

$k_y = 0$

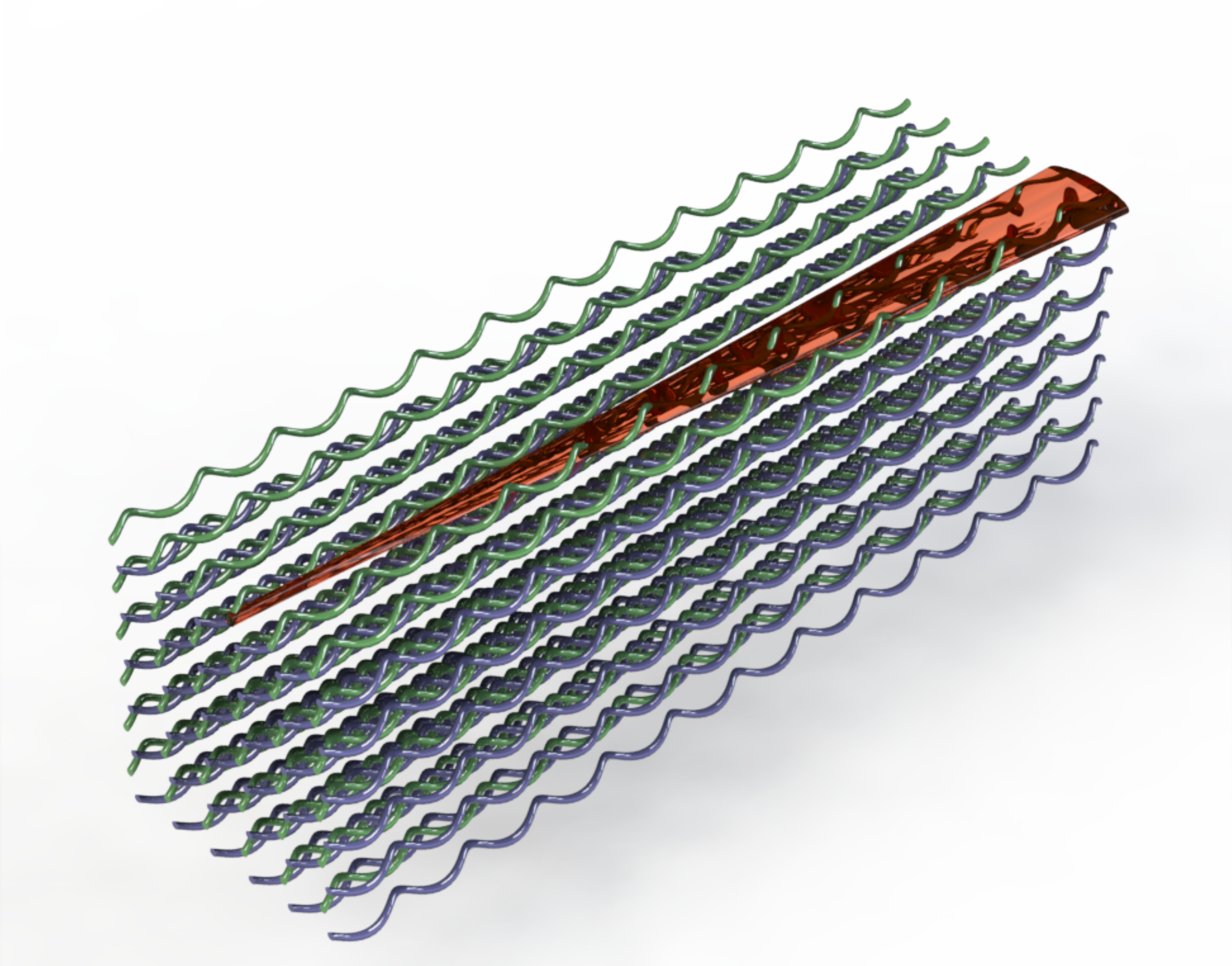
# Type-II Weyl points implies conical diffraction



# Experimental results: conical diffraction at Weyl point

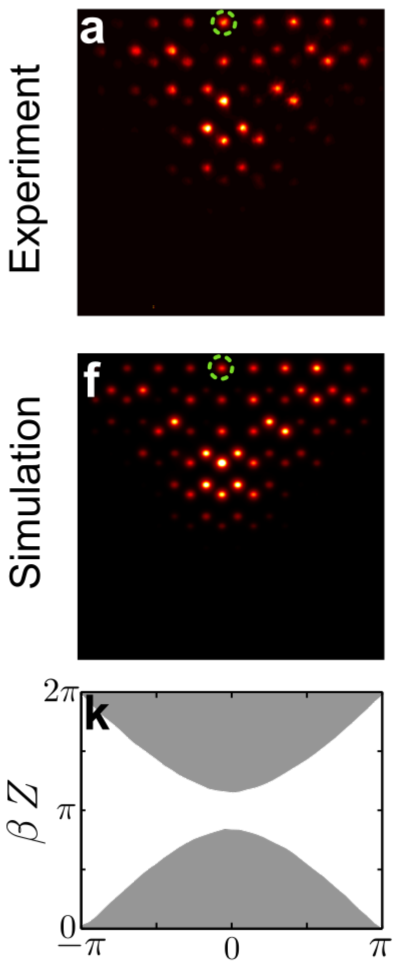


# 2d edge states are 3d “Fermi arc” surface states



# Experimental observation of Fermi arc surface states

$a = 29\,\mu\text{m}$



# Thanks

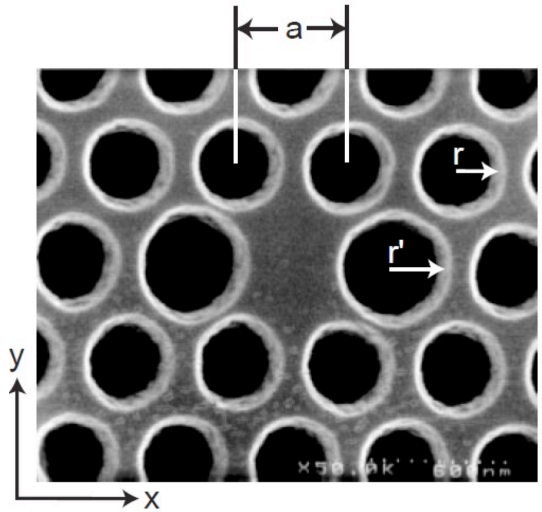
# Part 3: Topologically protected zero-modes in 2d systems

*(collaboration with Taylor Hughes' group, UIUC and Chen group, Pittsburgh)*

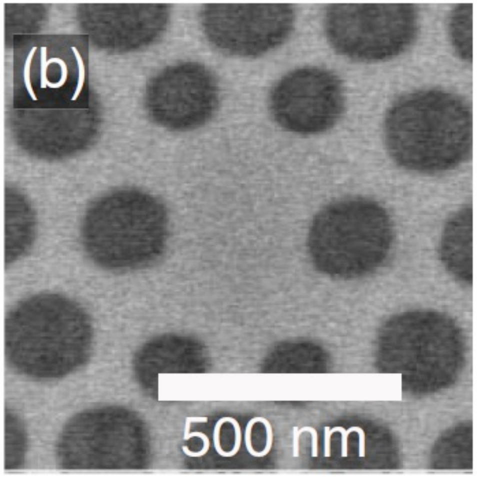
How else can we use topology to protect states?

# Motivation: protecting modes in two-dimensional photonics

Photonic crystal slabs

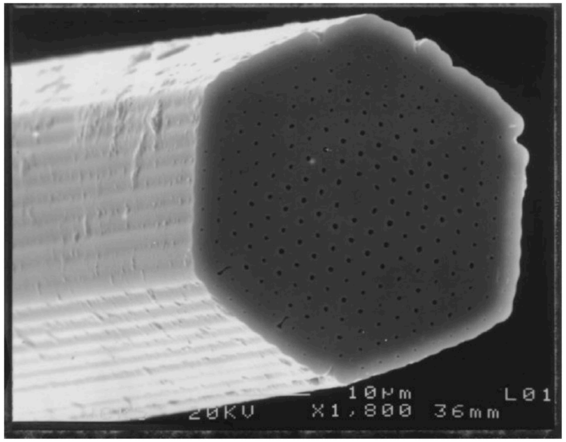



O. Painter *et al*. *Science* **284**, 1819 (1999)

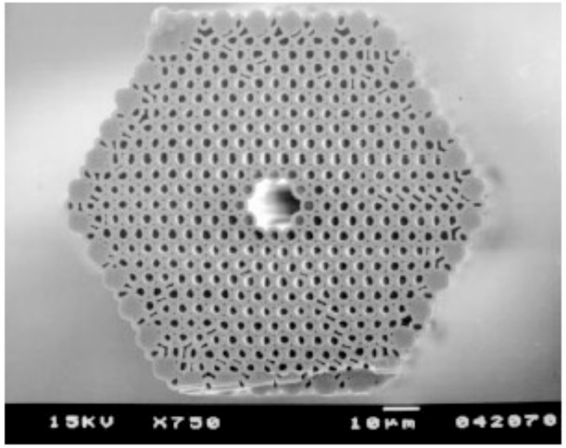



D. Englund *et al*. *Phys. Rev. Lett.* **95** (2005)

Photonic crystal fibers

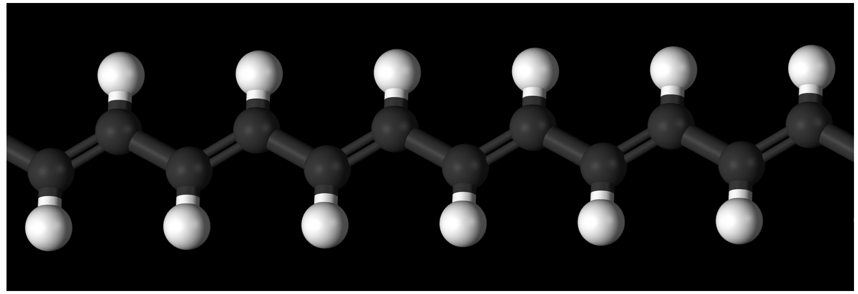


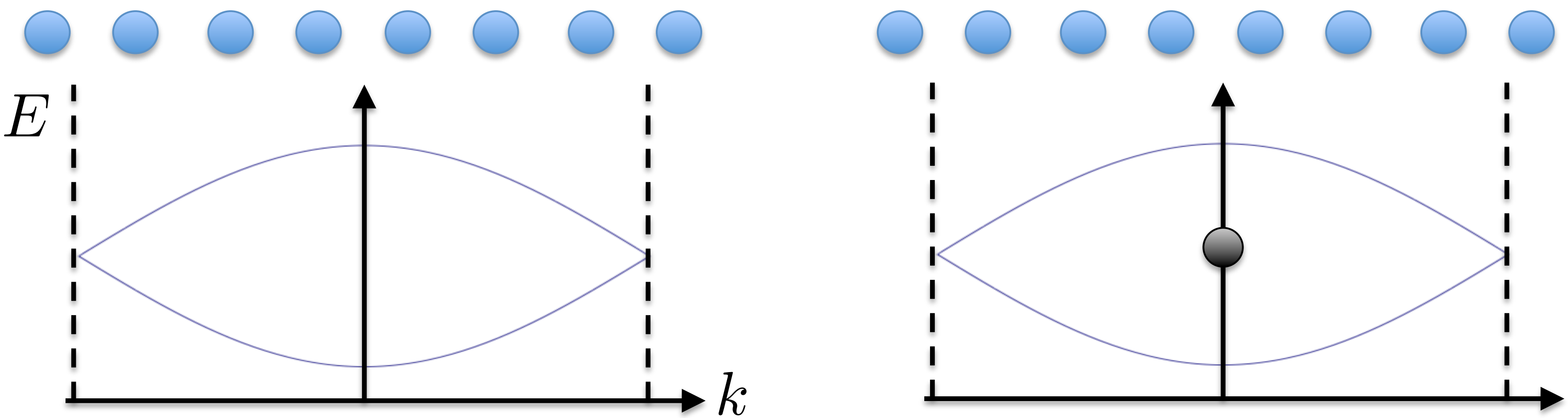

J.C. Knight *et al*. *Science* **284**, 1819 (1999)




R.F. Cregan *et al*. *Science* **285**, 1537 (1999)

# FAQ: what's the simplest TI model? Polyacetelene!






$\gamma = 0$ $\gamma = \pi$

Zak phase / Winding number:

$$\gamma = i \int \langle \psi_k | \nabla_k | \psi_k \rangle \cdot d\mathbf{k}$$

# Shockley / SSH states in 1d

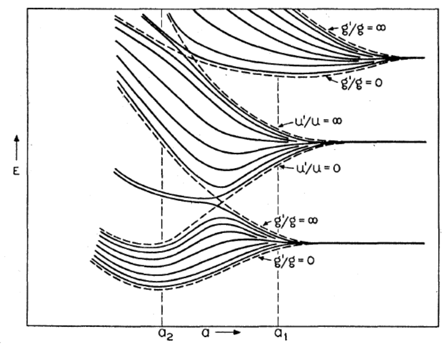
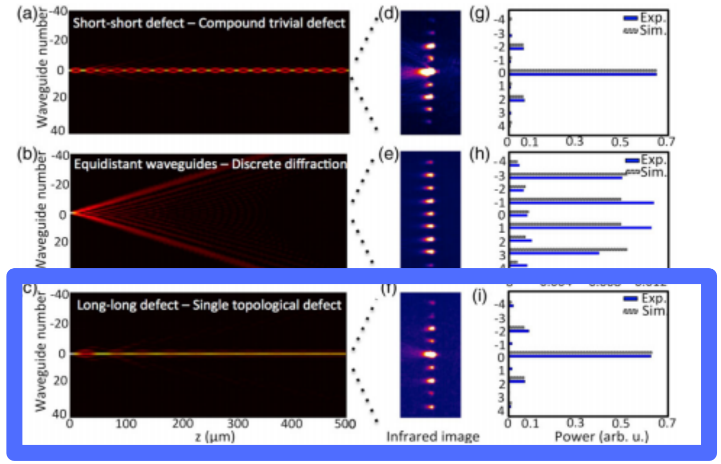
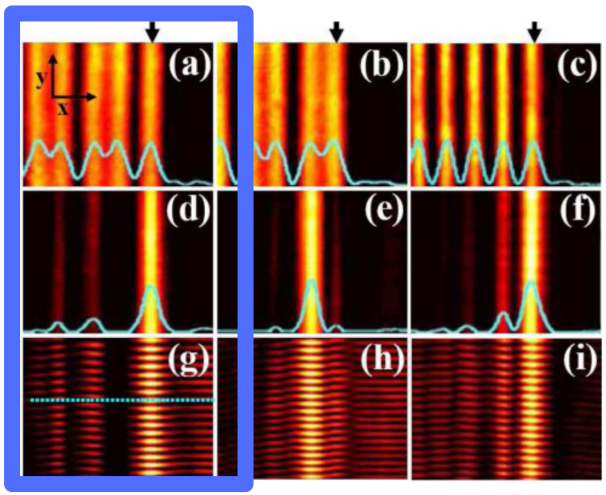



FIG. 2. Energy spectrum for a one-dimensional lattice with eight atoms.

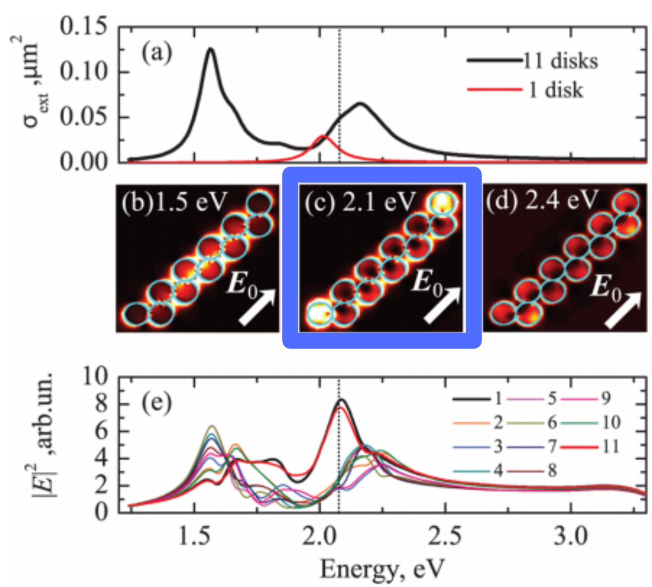
W. Shockley *Phys. Rev.* **56,** 317 (1939)




A. Blanco-Redondo *et al.*,
*Phys. Rev. Lett.* **116,** 163901 (2016)

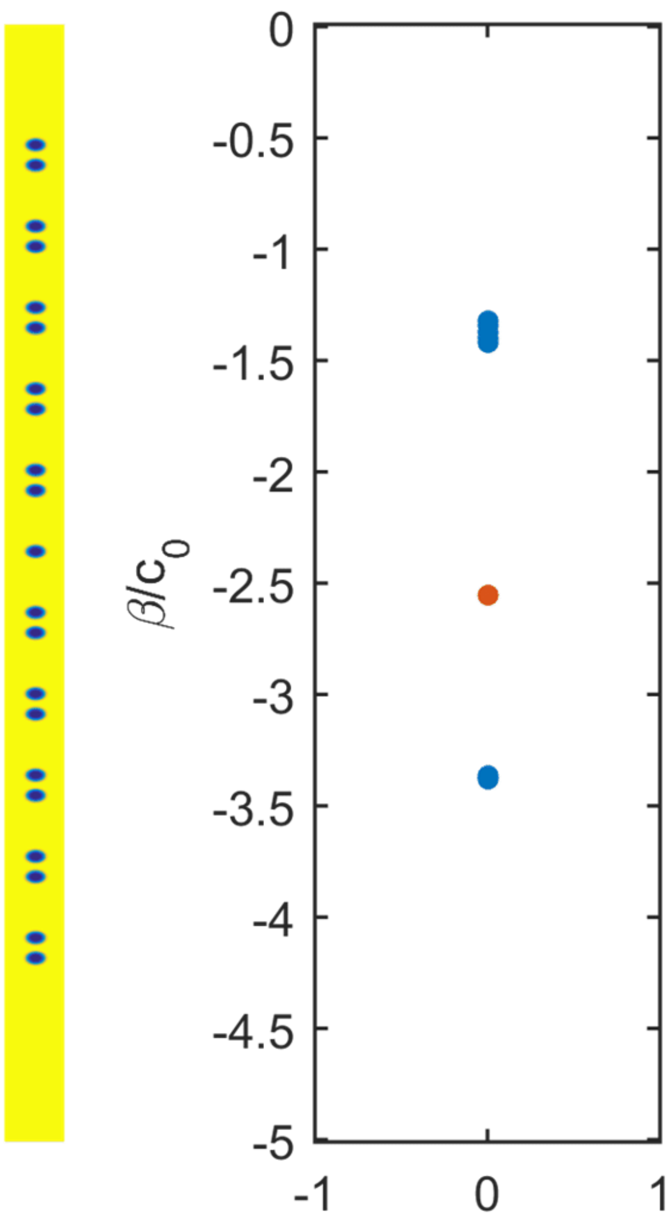



N. Malkova *et al.*, *Opt. Lett.* **34,** 1633 (2009)




A. Poddubny *et al.*, *ACS Photonics* **5,** 101 (2014)

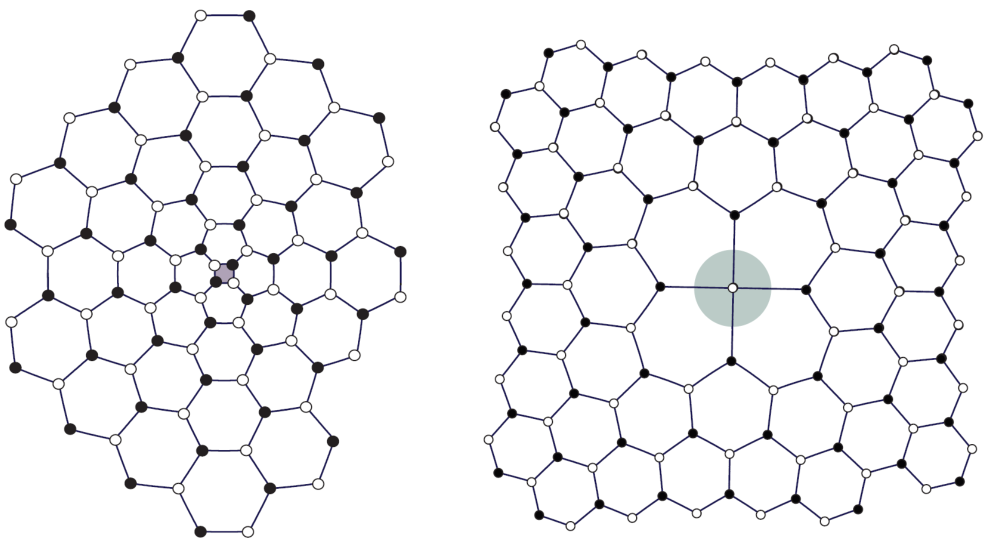
# Shockley / SSH states in 1d




Protection against off-site disorder!

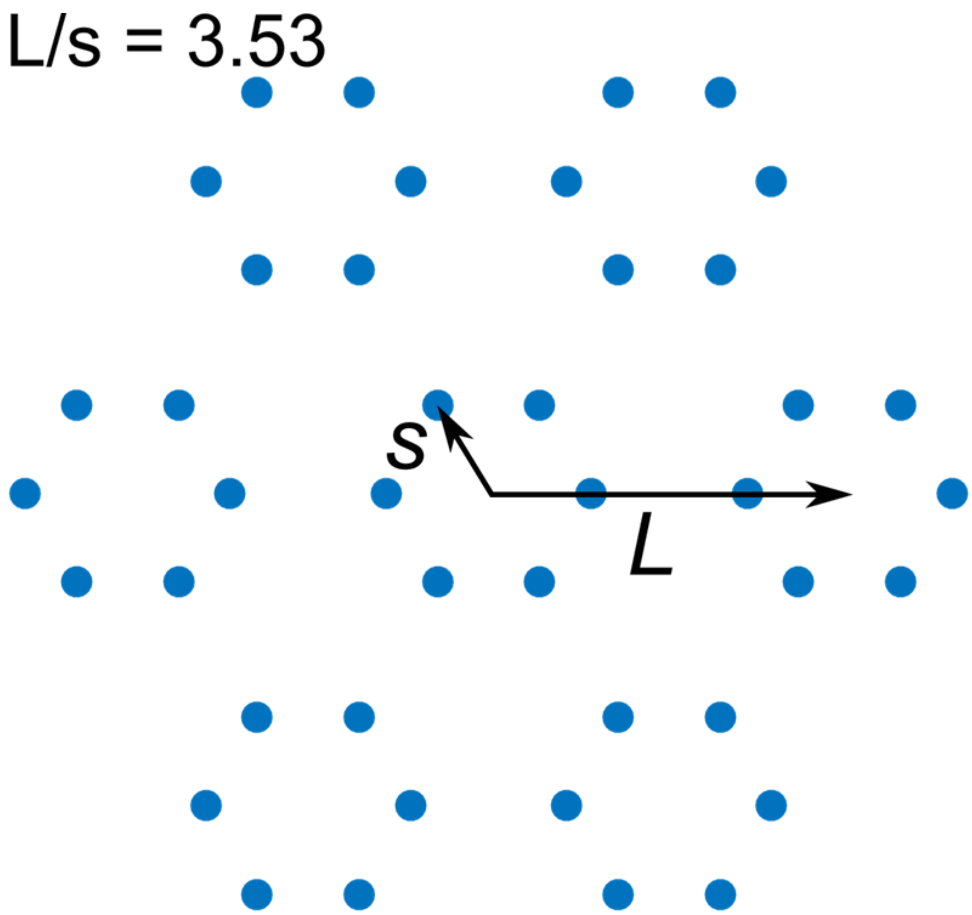
# SSH in 2d?

- Finding realizations of topological states that manifest themselves via defect states, e.g., corner or disclination localized modes
- Zero-dimensional defect modes in time-reversal invariant topological insulator structures:



W. A. Benalcazar *et al.*, *Phys. Rev. B* **89** 224503 (2014) (T. Hughes Group)

# Paraxial propagation and our structure

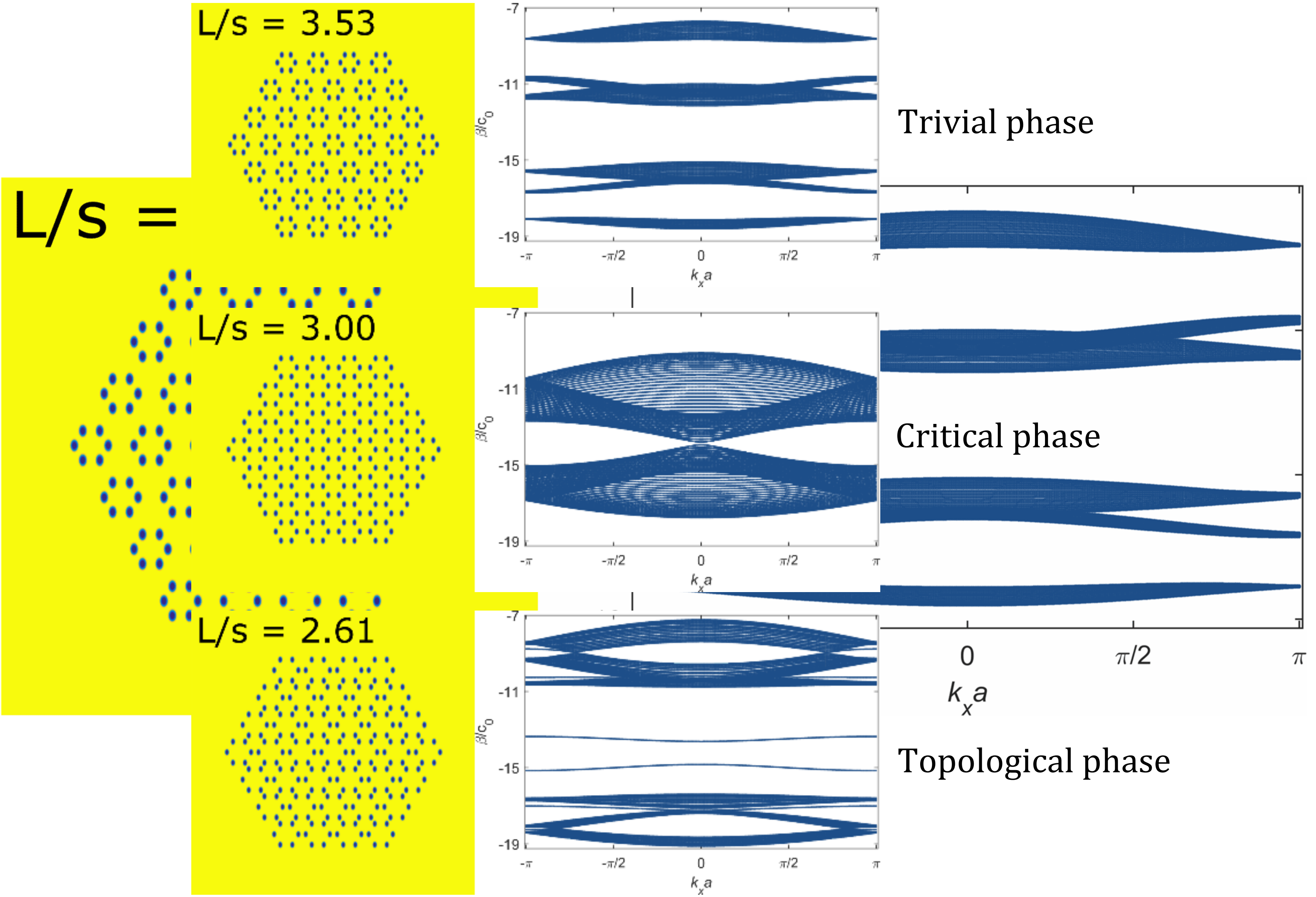



W. A. Benalcazar *et al., Phys. Rev. B* **89** 224503 (2014)

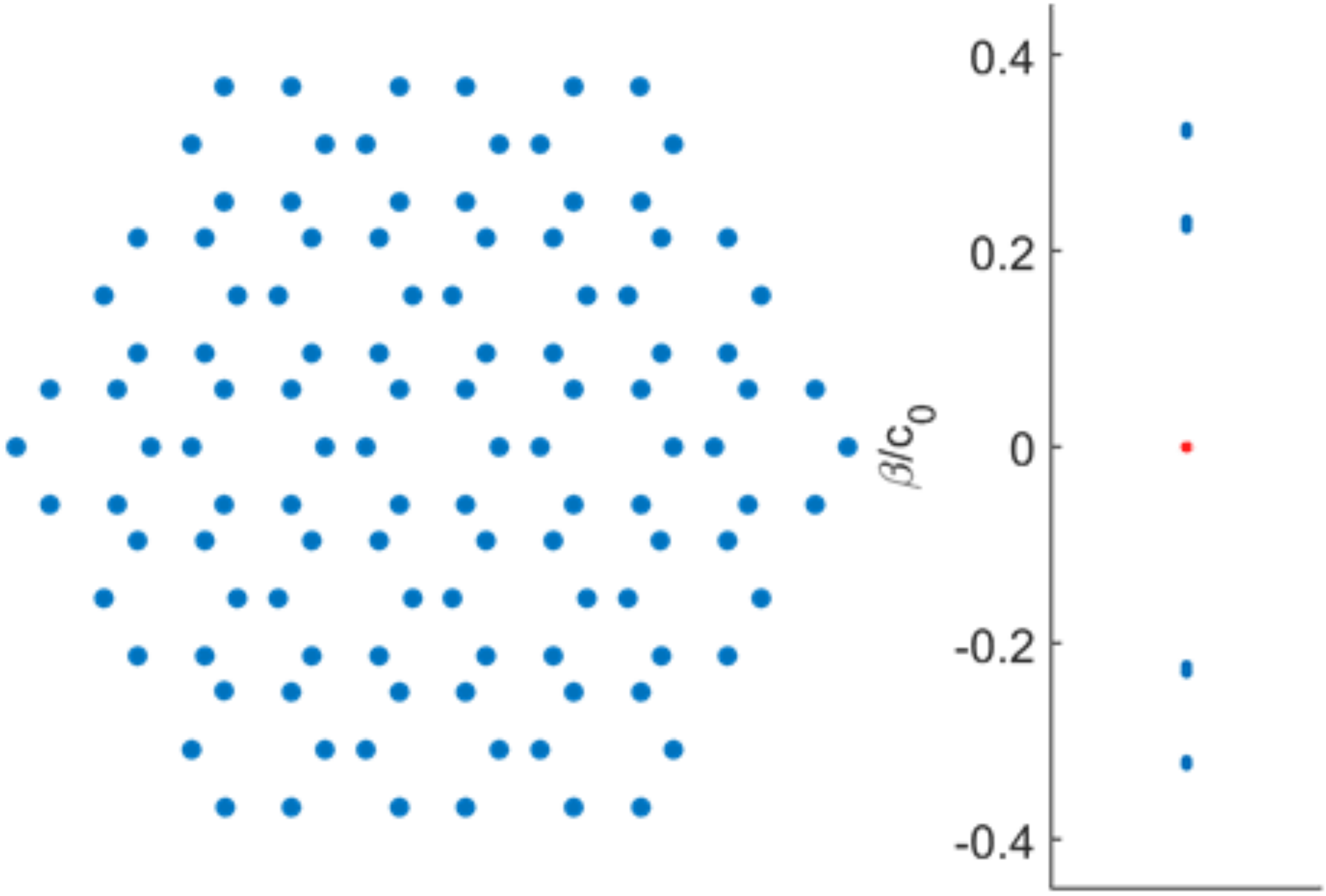
L.-H. Wu *et al., Phys. Rev. Lett.* **114,** 223901 (2015)

Barik *et al., arXiv. 1605.08822* (2016)

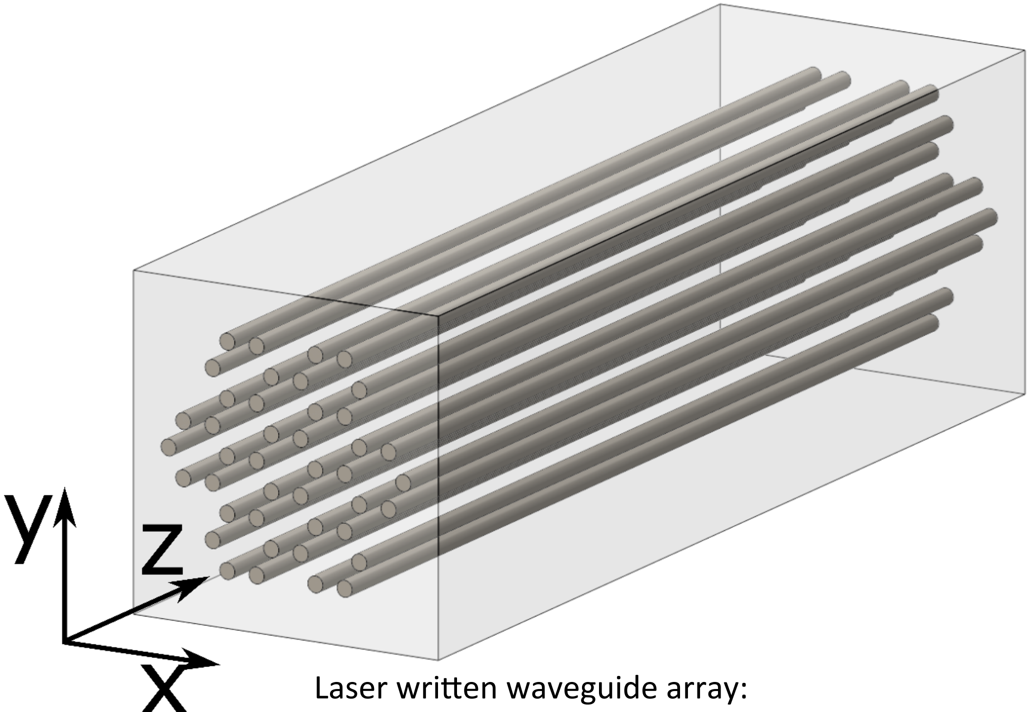
# Paraxial propagation and our structure



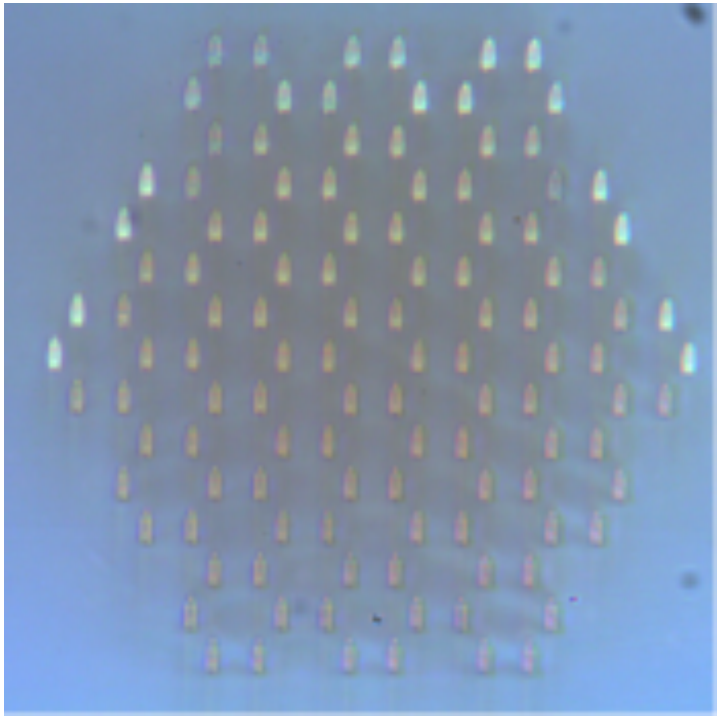
# Protection of defect modes



# Paraxial propagation and our structure



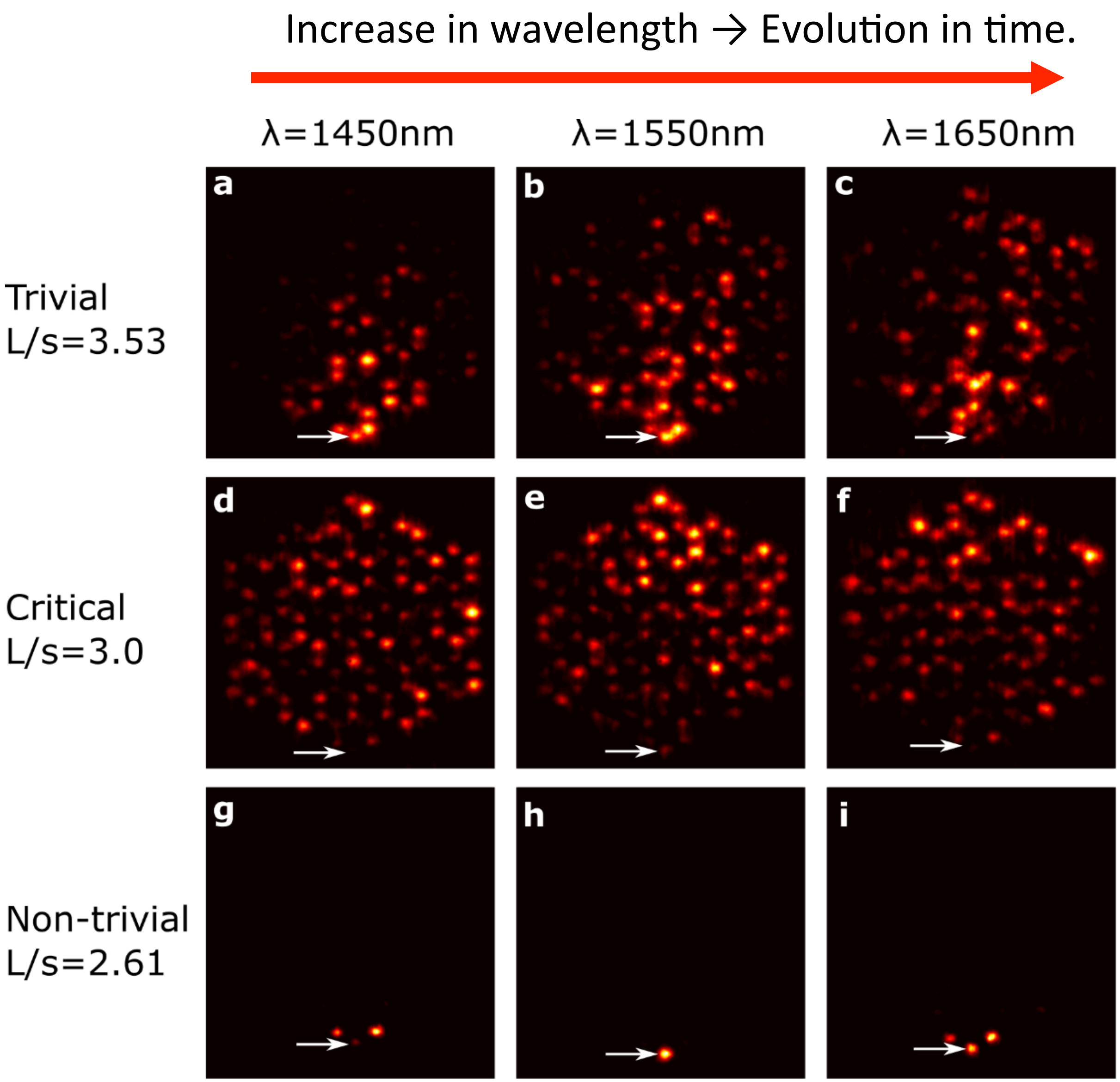

Laser written waveguide array:
A. Szameit *et al.*, *Opt. Express* **13,** 10552 (2005)



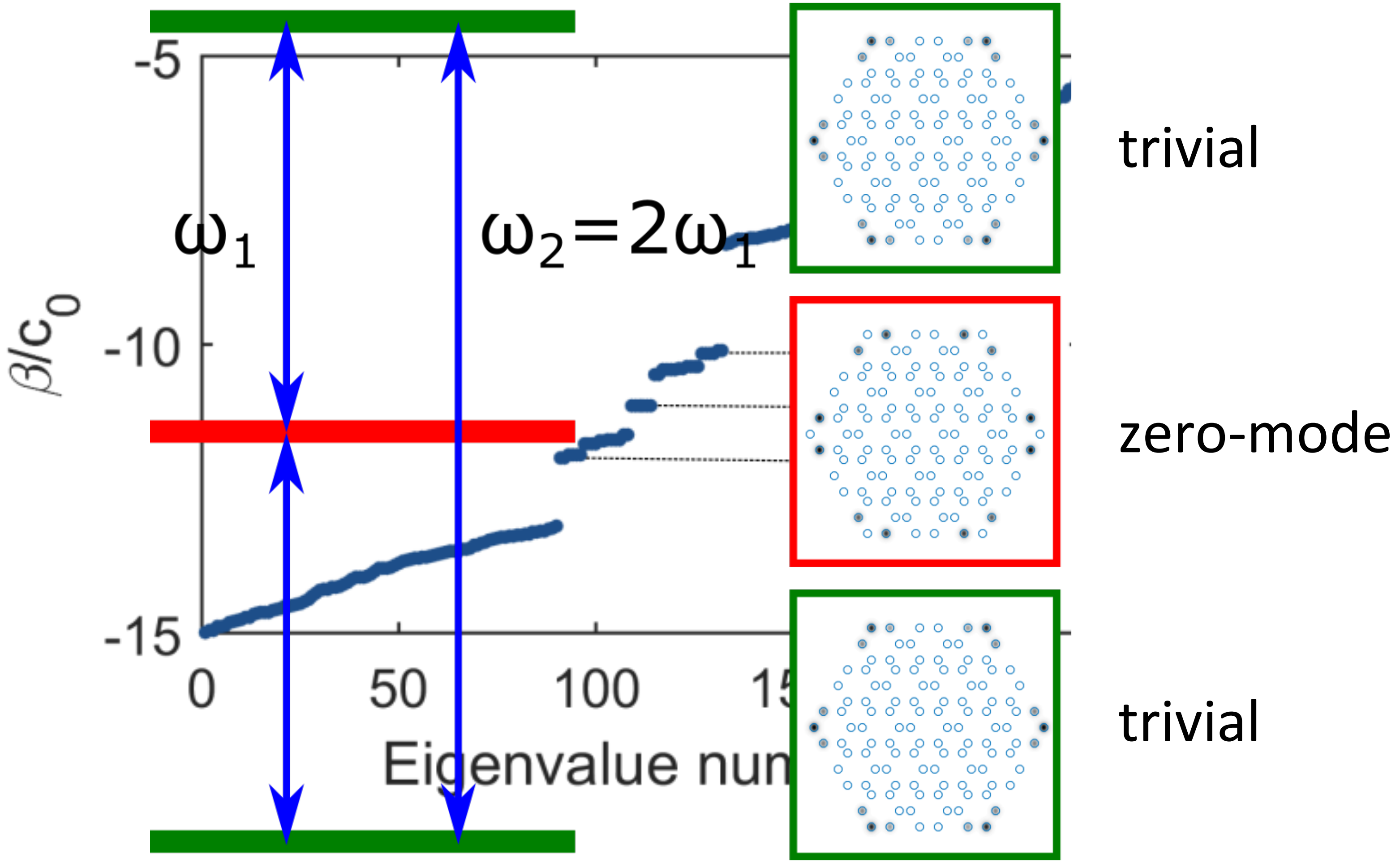
$$i\partial_z \psi(\mathbf{r}, z) = -\frac{1}{2k_0}\nabla^2_{\mathbf{r}}\psi(\mathbf{r}, z) - \frac{k_0 \Delta n(\mathbf{r})}{n_0}\psi(\mathbf{r}, z)$$

$$i\partial_z \psi_i(z) = \sum_z c_{ij}(\lambda)\psi_j(z)$$

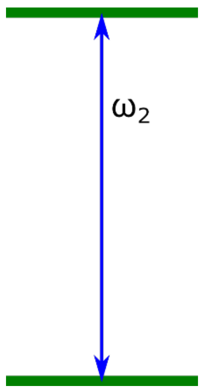
# Experimental results

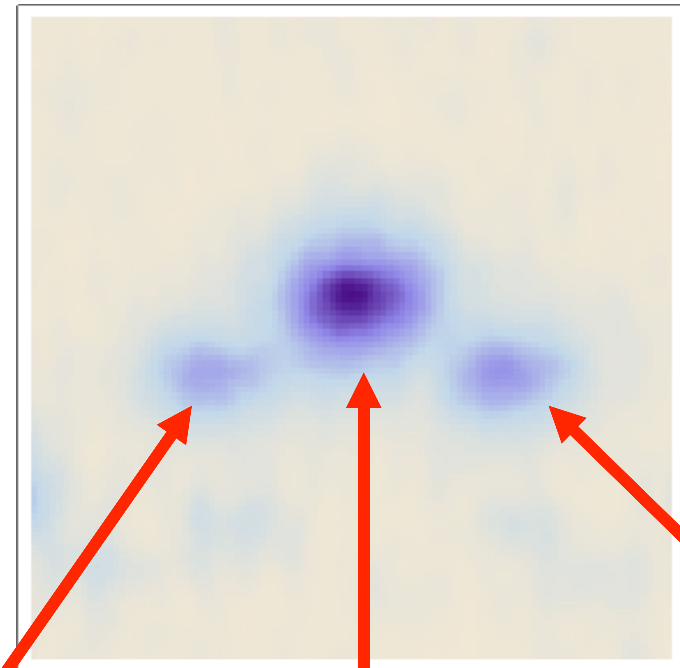


# Our experimental observables



# Experimental results

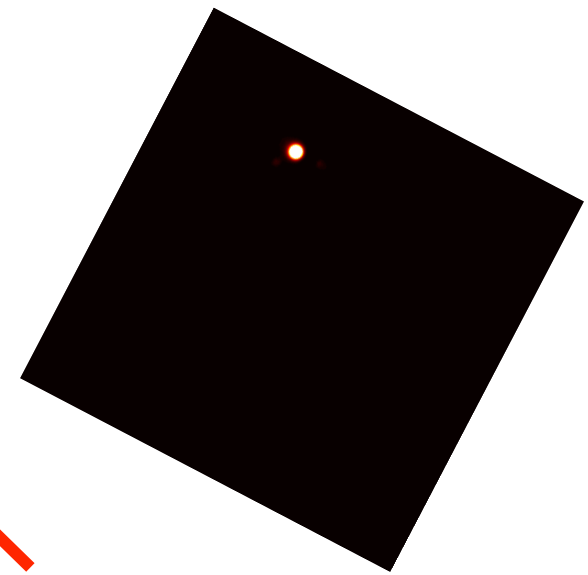


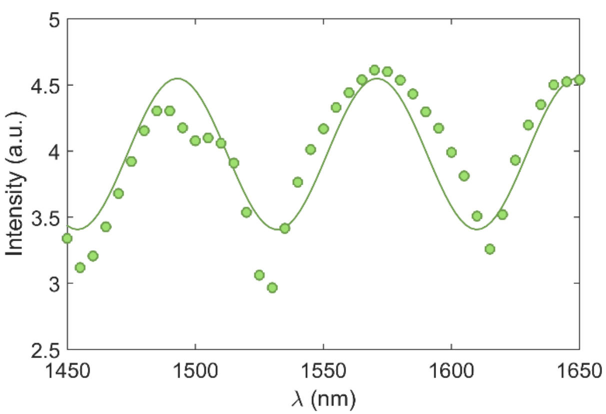



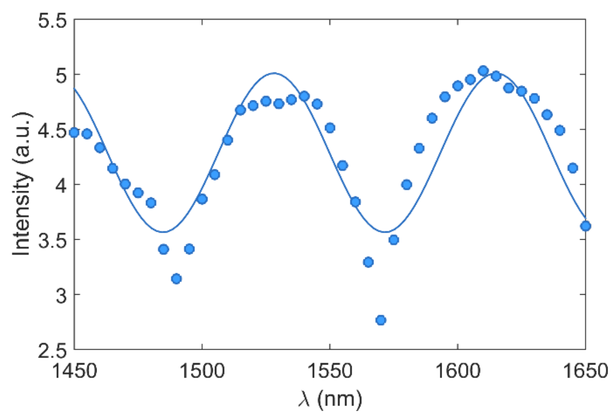
**Frequency ratio:**

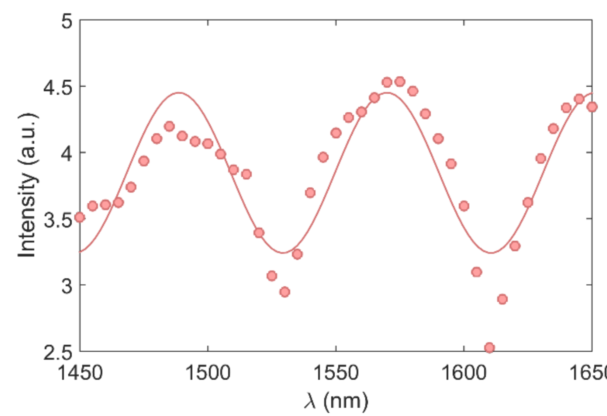
Measured: 0.98 ± 0.09

Theory: 1.00

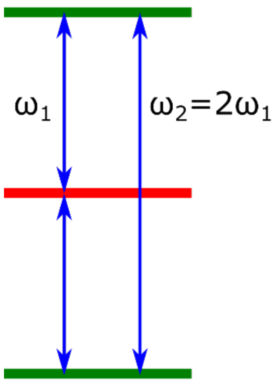


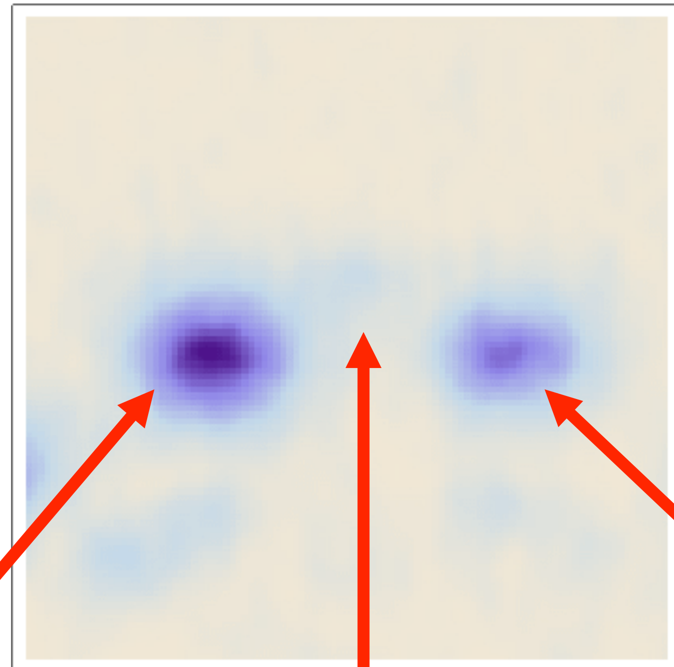


# Experimental results

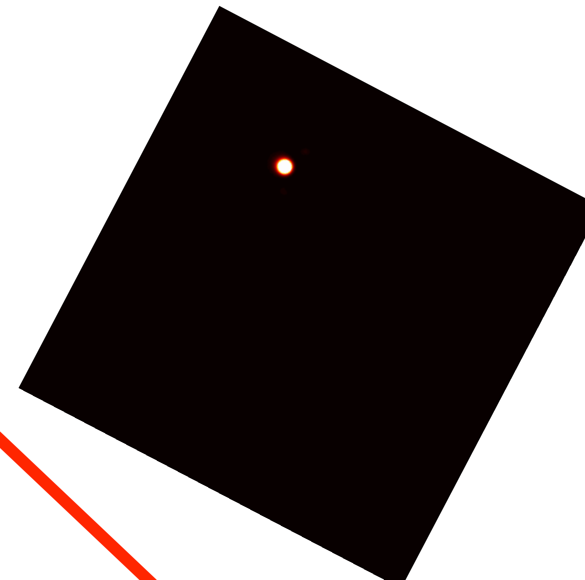


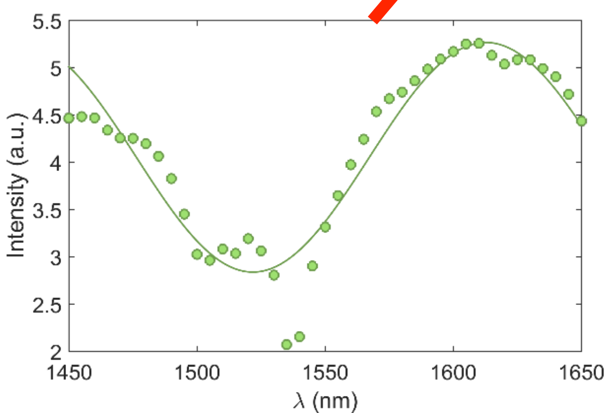



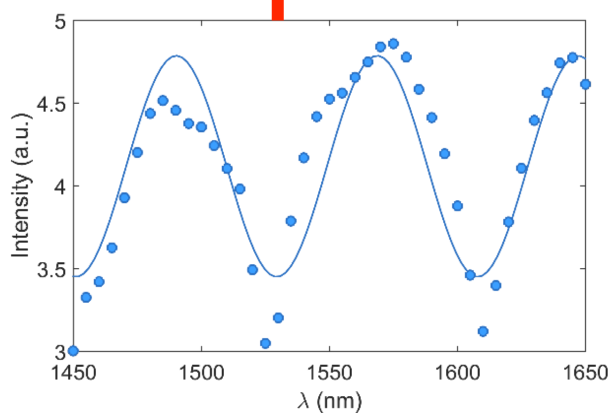
Frequency ratio:

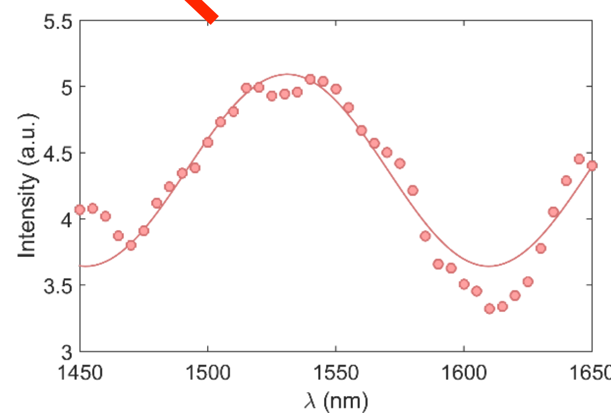
Experiment: 1.99 $\pm$ 0.27

Theory: 2.00





# Thanks