Exciton-polariton based topological photonics and topological lasers

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Collaboration: J.Bloch's group, *C2N, CNRS Paris,* A. Amo, Phlam, Lille

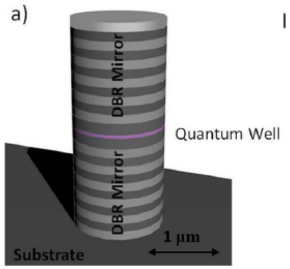
- **Introduction.**
- **Z topological insulator.**
- **Quantum Valley Hall effect.**
- **Quantum fluids: Z_2 Topological Insulator for vortices.**
- **Topological Lasers**

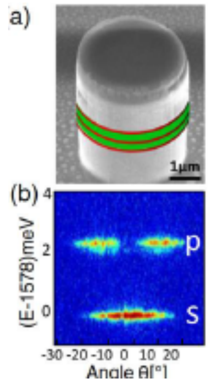
2D lattices (photonic)

→ Planar Fabry Perot cavity:
2D parabolic dispersion for radiative photon modes

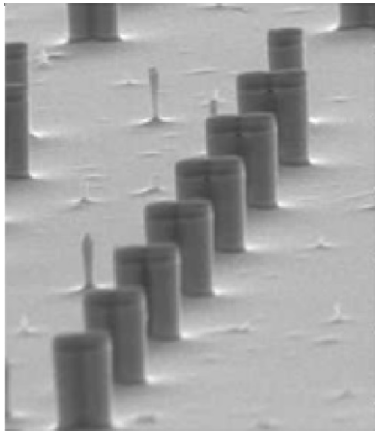
$$E_C\left(k\right)=E_C\left(0\right)+\frac{\hbar^2k^2}{2m_C}$$

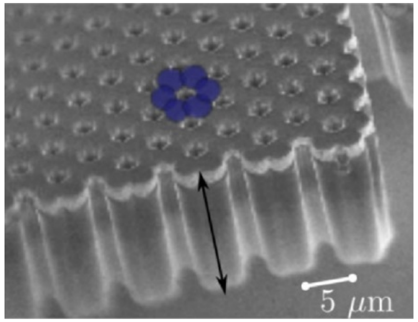
→ Lateral etching: 0D modes (photonic atoms).

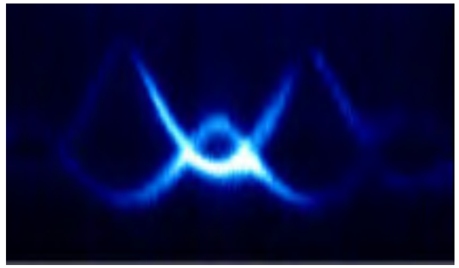




→ Coupled cavities:
Molecules, Lattices.
Each atomic states gives a dispersive branch.







T. Jacqmin & al, Phys. Rev. Lett. 112, 116402 (2014) - C2N

Good description with tight binding approach.
but
Radiative modes
TE and TM modes are close.

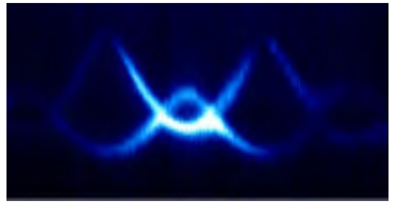
Exciton+photon→ Exciton-Polariton

- Interacting photons.

- Zeeman splitting under magnetic field.

Berry curvature and Chern number

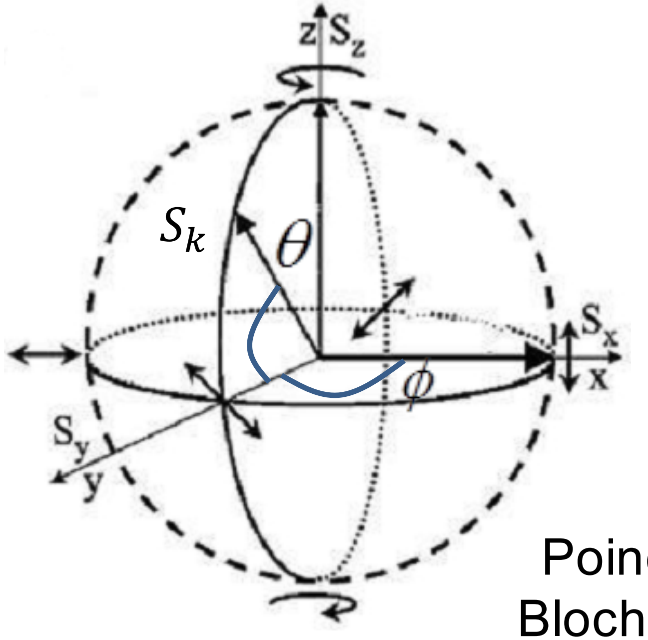
- Spinor Wave function in a lattice: $\psi_k = \begin{pmatrix} u_k^+ \\ u_k^- \end{pmatrix} e^{ikr} = \begin{pmatrix} \cos\frac{\theta_k}{2} e^{i\phi_k} \\ \sin\frac{\theta_k}{2} \end{pmatrix} e^{ikr}$



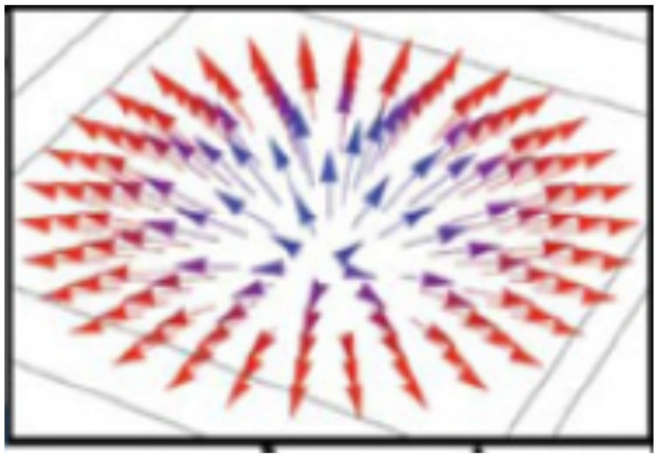
- Pseudo spin vector S_k associated to the wave function.

- Berry curvature is related to the change of S_k in reciprocal space:

$$B = \frac{1}{2}\sin\theta(\partial_x\theta\partial_y\phi - \partial_y\theta\partial_x\phi)$$



Poincaré or Bloch Sphere



Pseudo spin texture in k-space
Non-zero Berry curvature.

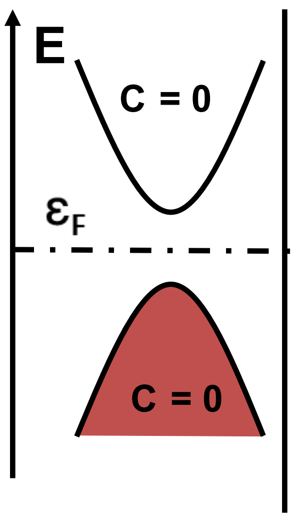
Chern Number: Integral of the Berry curvature over a band in the first Brillouin zone.

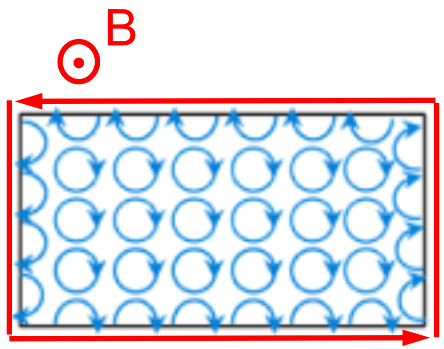
$\mathbb{Z}$ topological insulator

Chern number of bands is a non-zero integer.

Quantum Hall Effect (1980).
Quantum Anomalous Hall Effect (1988).
Broken Time Reversal symmetry (magnetic field).

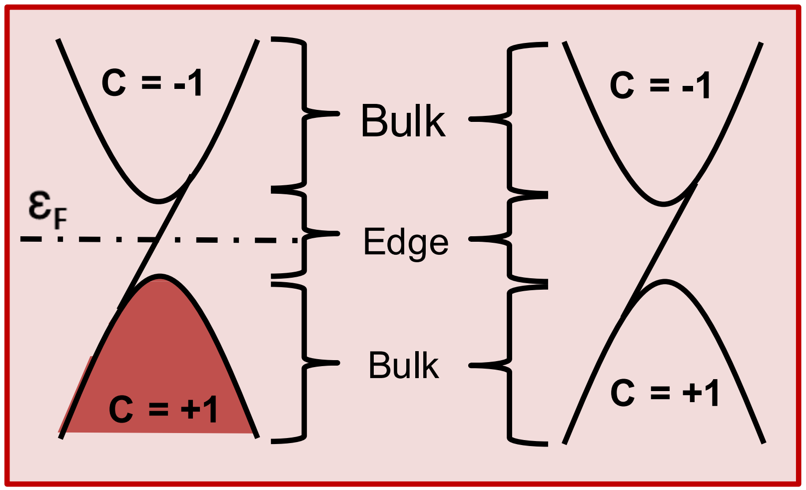
e- insulator





ex: Quantum Hall Effect
K.v.Klitzing (1980)

e- $\mathbb{Z}$ topological *insulator* *Photonic C-I*

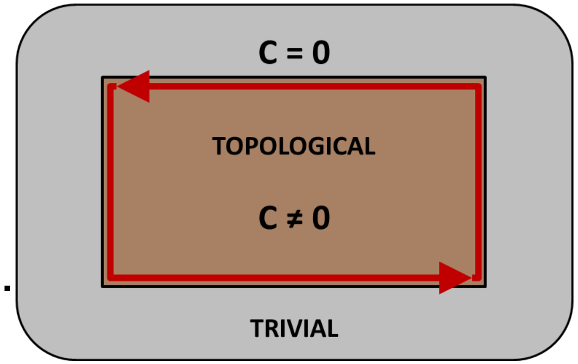


$$C_n = \frac{1}{2\pi i} \int_{BZ} \mathbf{F}_n(\mathbf{k}) d\mathbf{k}$$

Chirality Edge modes

A gap should close to change topology.
The vacuum is trivial. Gap Closure on the interface.

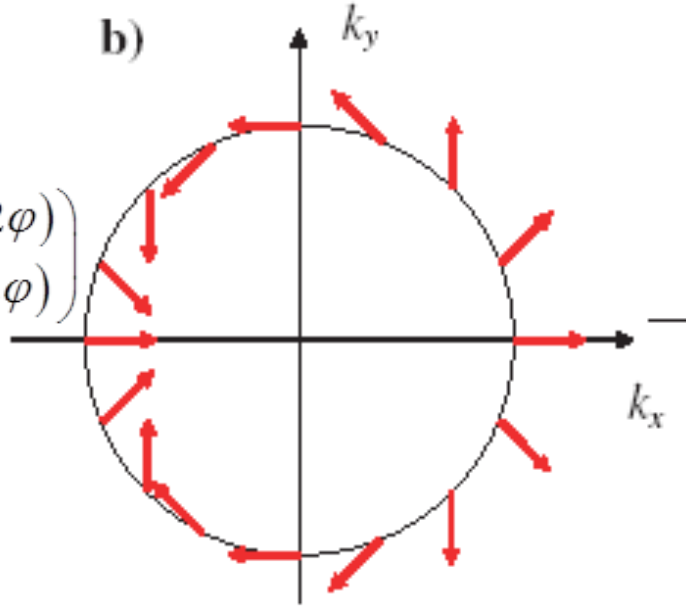
One way edge modes, which cannot be elastically scattered.



Intrinsic Chirality of Photons
2 spin projections coupled by TE-TM Splitting

$$H = \begin{pmatrix} H_0(k) & \Omega_{LT}(k)e^{-2i\varphi} \\ \Omega_{LT}(k)e^{2i\varphi} & H_0(k) \end{pmatrix} = H_0\mathbf{I} + \vec{\Omega}_{LT}\cdot\vec{\boldsymbol{\sigma}}$$

$$\Omega_{LT} \sim \beta k^2 \begin{pmatrix} \cos(2\varphi) \\ \sin(2\varphi) \end{pmatrix}$$



Spin-orbit coupling for light

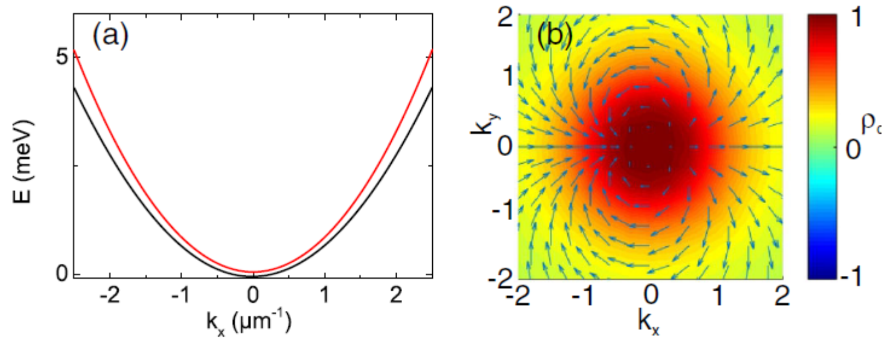
Optical Spin Hall effect

A. Kavokin, G. Malpuech, M. Glazov, PRL, 95, 136601 (2005).
Nature Phys. 3, 628, (2007) .

TE-TM + Zeeman splitting

Berry curvature for photons *(PRL 102, 046407, 2009)*

$$H_0 = \begin{pmatrix} \frac{\hbar^2 k^2}{2m^*} + \Delta & \beta k^2 e^{2i\varphi} \\ \beta k^2 e^{-2i\varphi} & \frac{\hbar^2 k^2}{2m^*} - \Delta \end{pmatrix},$$



Photon/Polariton anomalous Hall effect in a planar cavity

Arxiv 2016, PRL 121, 020401 (2018). See O. Bleu Poster

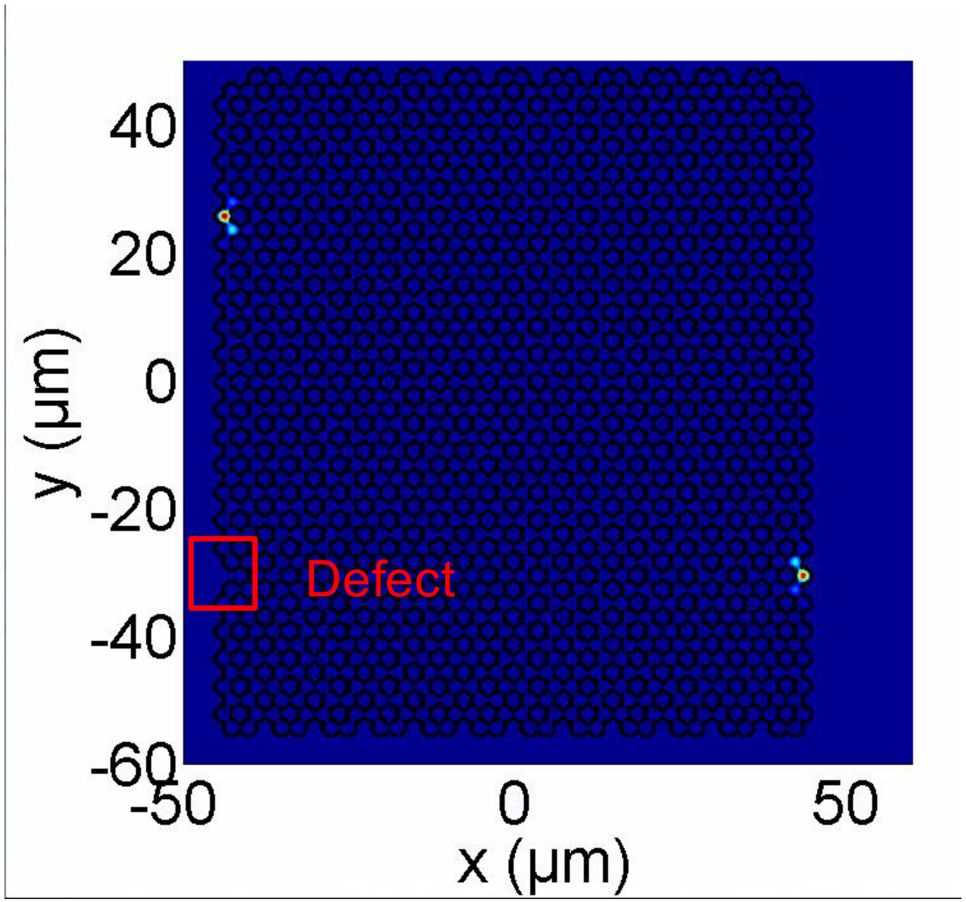
Chiral photons combined with a good lattice→ Topological gaps

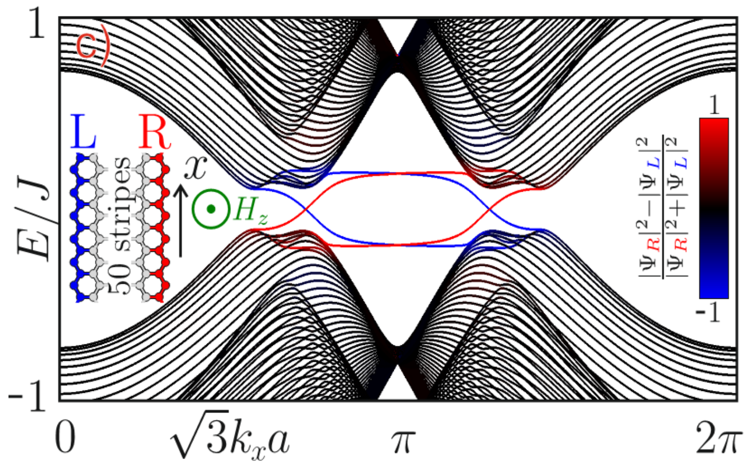
→ Initial proposal Haldane-Raghu PRL 100, 013904 (2008).
→ Observed at GHz frequencies Soljacic Group Nature 2009.

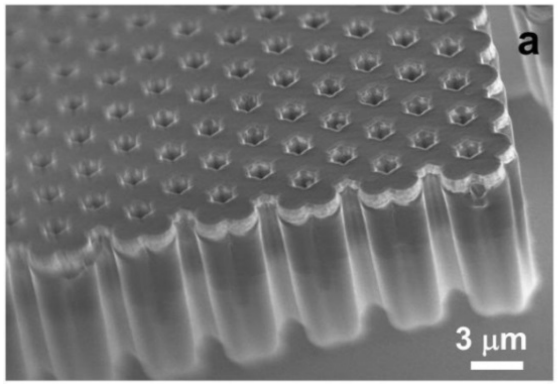
Proposal for Exciton-polaritons at optical frequencies

A.Nalitov, D. Solnyshkov, and G. Malpuech, PRL 114, 116401, (2015).
O. Bleu, D. Solnyshkov, G. Malpuech, PRB, 95, 115415 (2017).

For realistic parameters
Chern number +-2



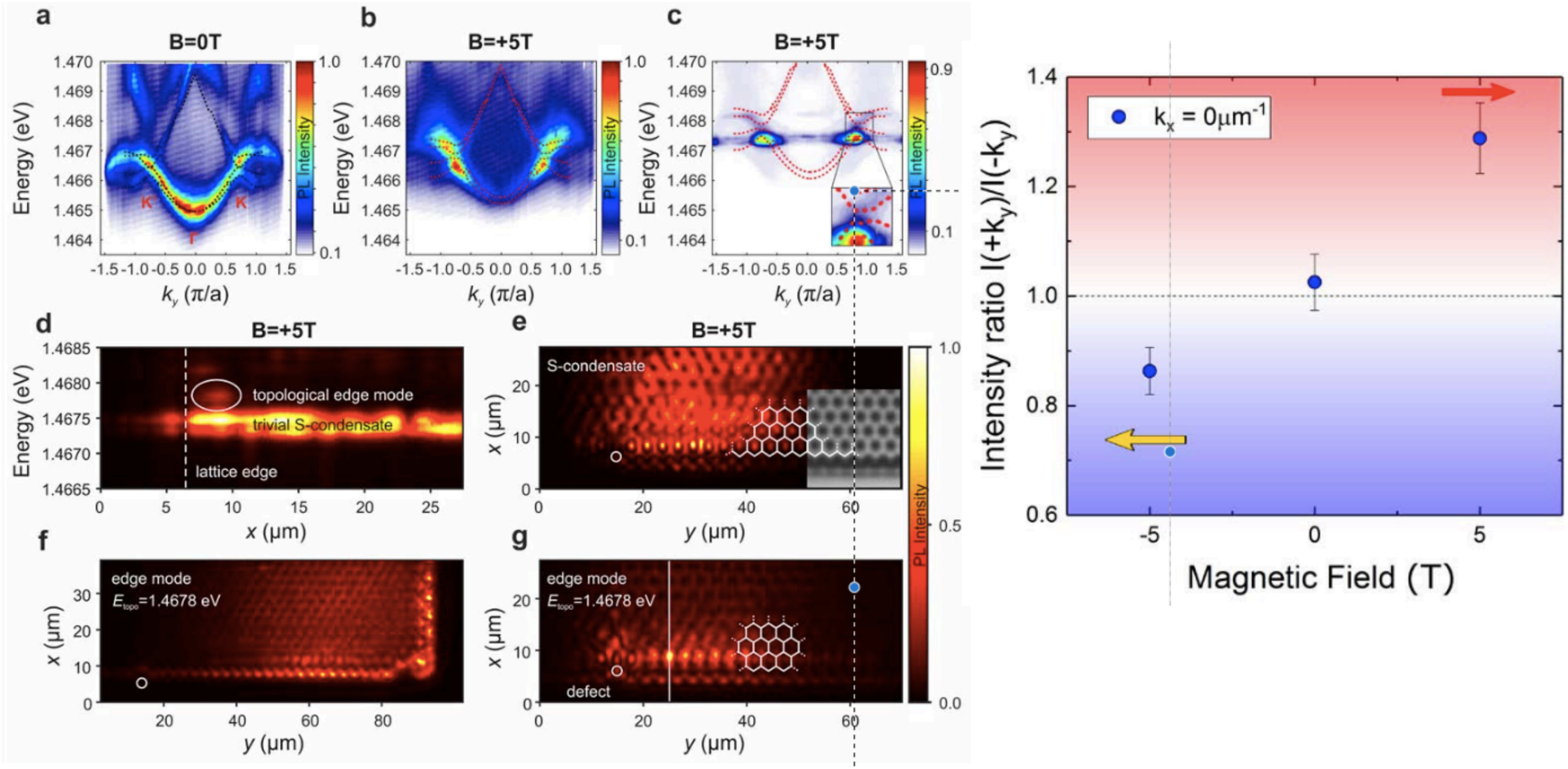




T. Jacqmin & al,
Phys. Rev. Lett. 112, 116402 (2014)

Edge modes under magnetic field reported in

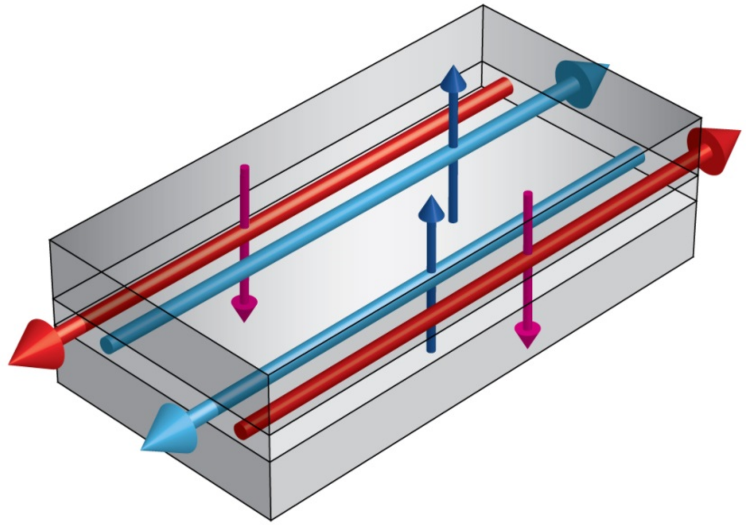
S. Klembt et al. (Hofling group) Nature 562, 552, (2018).



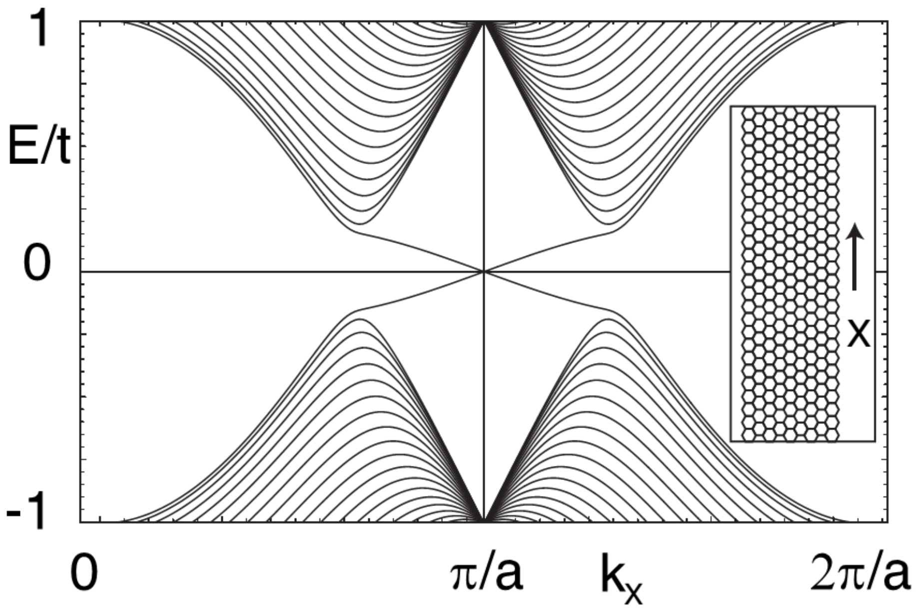
$\mathbb{Z}_2$ topological insulator

Quantum **Spin** Hall Effect (2005)

Total Chern number of Bands is zero.
But Spin Chern number $1/2(C_+ - C_-)$ is 1.
Spin current on the sample edge.
Time Reversal Symmetry (No magnetic field).
No spin conversion for electrons.



Does not work for any spinor !!
(for instance polarised photons)



C.L.Kane, E.J.Mele,
Phys. Rev. Lett. **95**, 226801 (2005)

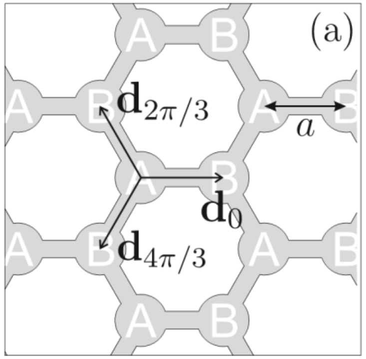
Quantum (pseudo)-spin Hall effect

Quantum Valley Hall Effect

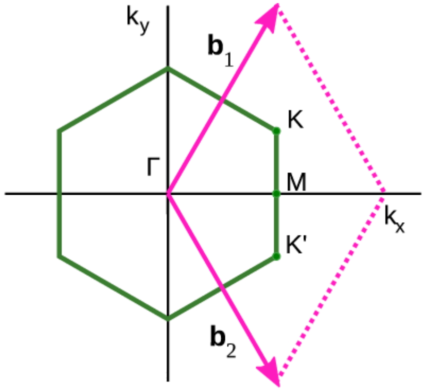
How to make it robust (against disorder scattering for instance) ?

Honeycomb lattice (scalar case)

real space



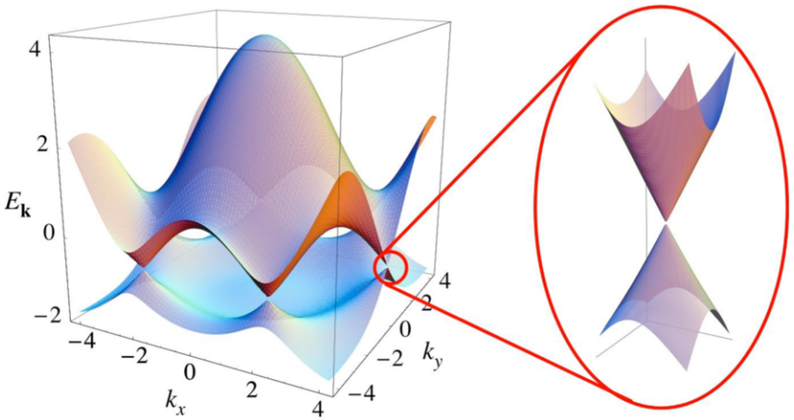
reciprocal space



Tight-Binding Hamiltonian

$$H_{graphene} = -\begin{pmatrix} 0 & Jf_k \\ Jf_k^* & 0 \end{pmatrix} \begin{matrix} \mathrm{A} \\ \mathrm{B} \end{matrix} \qquad f_{\mathbf{k}} = \sum_{j=1}^{3} \exp(-i\mathbf{k}\mathbf{d}_{\varphi_j})$$

dispersion:



Close to K or K'

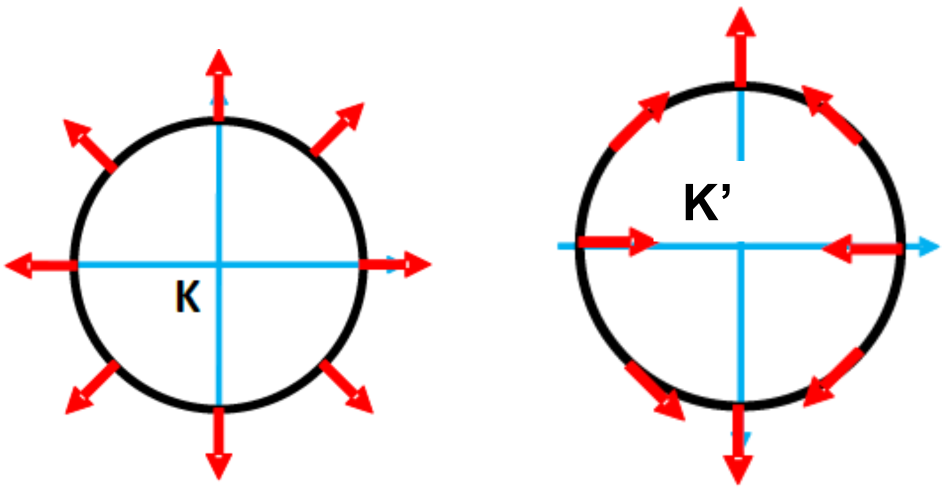
$$H \sim \tau_z \sigma_x k_x + \sigma_y k_y$$

Effective field representation

$$H = \Omega_{eff} \hat{\sigma}$$

Sub-lattice pseudo-spin

$$\tau_z = \pm 1 \qquad \vec{\Omega}_{eff} \approx v\left(\tau_z k_x, k_y, 0\right)^T$$



Monopolar Dresselhaus

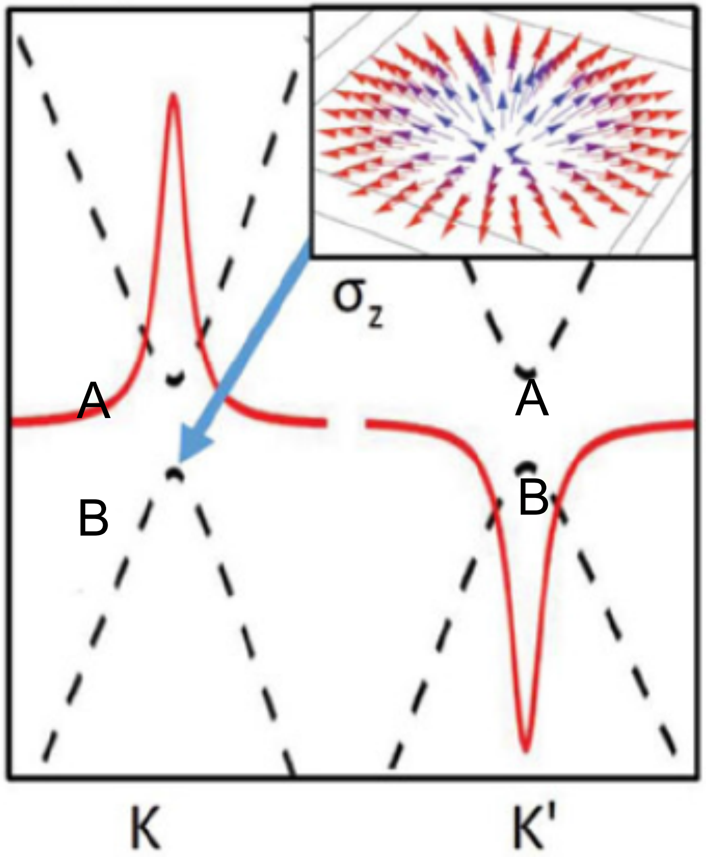
Opposite winding at K and K'

Quantum Valley Hall Effect

Let us make A and B different (staggered lattice).

$$H_{staggered} = -\begin{pmatrix} -\Delta & Jf_k \\ Jf_k^+ & \Delta \end{pmatrix} \approx -\left(J\left(\tau_z k_x \sigma_x + k_y \sigma_y\right) + \Delta \sigma_z\right)$$

Di Xiao, Wang Yao, and Qian Niu, Phys. Rev. Lett. 99, 236809, (2007).



- Massive Dirac Hamiltonian.

- Gap opening.
- Berry curvature of opposite sign at K and K'.
- Valley dependent angular momentum.

Valley = pseudo-spin

-Definition of a Valley Chern Number $C_K = -C_{K'}$

$C_{KK'} = C_K - C_{K'} = 1$ Z_2 topological invariant, like in the Quantum Spin Hall effect at the zigzag interface between lattices of opposite staggering.

Valley current of topological origin.

Remark

Topological states, but unprotected from inter-valley scattering.
Same as QSHE, un-protected from inter-spin scattering.

Photonic Quantum Valley Hall Effect

In photonic crystal slabs:

- L.-H. Wu and X. Hu, Phys. Rev. Lett. 114 , 223901 (2015).
- T. Ma, A. B. Khanikaev, S. H. Mousavi, and G. Shvets, Phys. Rev. Lett. 114 , 127401 (2015).
- T. Ma and G. Shvets, New Journal of Physics, 18, 025012 (2016).
- L. Xu, H. Wang, Y. D. Xu, H. Y. Chen, and J.-H. Jiang, Optics Express 24, 18059 (2016).
- X.-D. Chen and J.-W. Dong, arXiv:1602.03352.
- … ,Hafezi, New J. Phys. 18, 113013 (2016).
- …..
- Fan Zhang, *« Topological Valleytronics brought to light »* Nature Physics **14**, 111 (2018).

Direct analog of Quantum Spin Hall Effect cannot be made for photons.

because

Photon (pseudo)-spin is not protected by Time Reversal Symmetry.

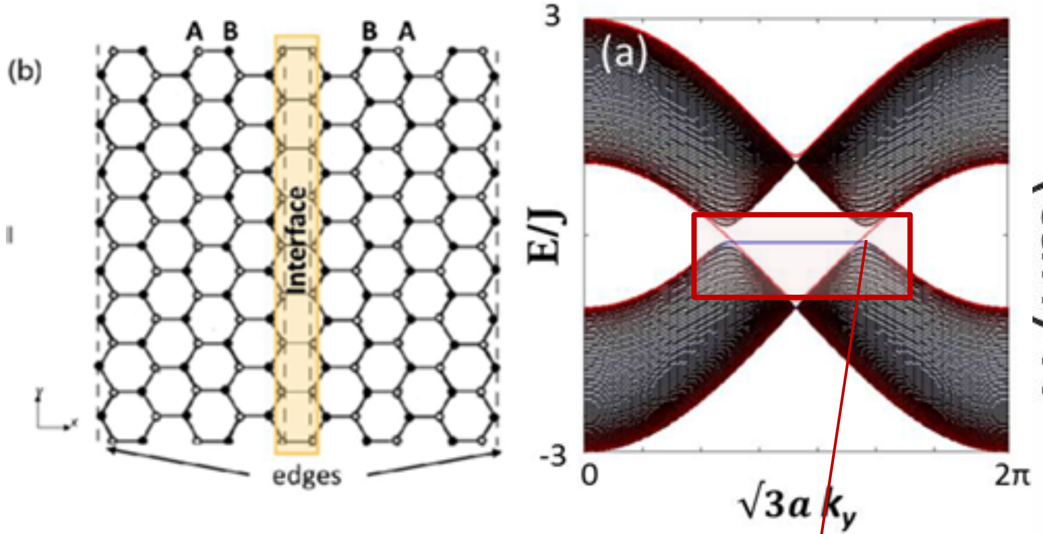
TE-TM splitting couples counter propagating spin states.

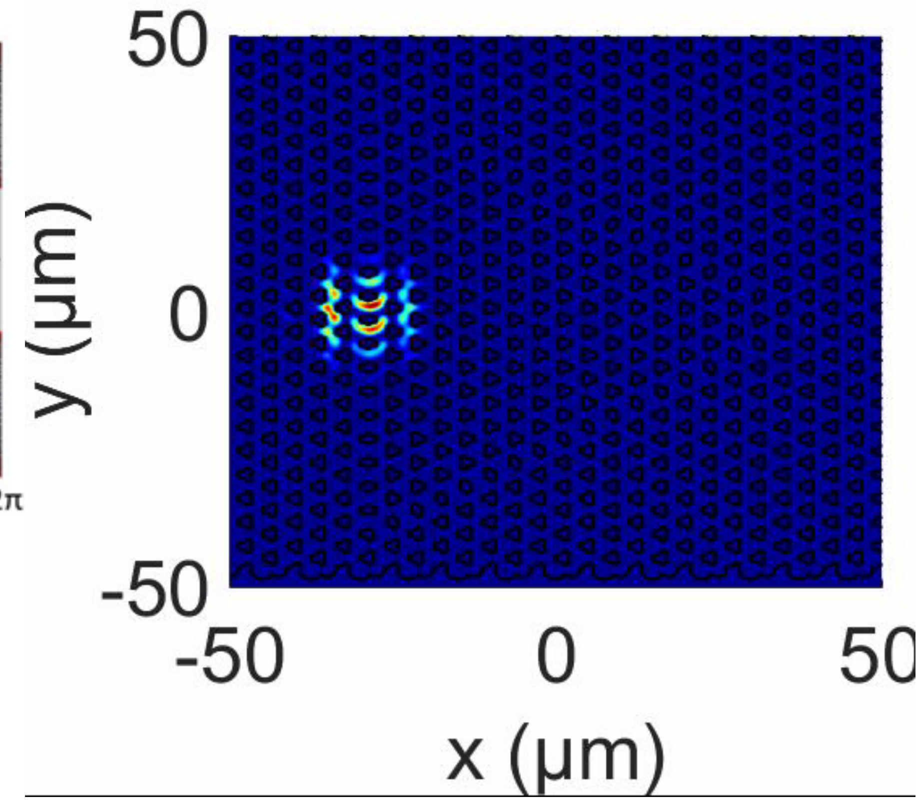
One needs to cancel competly TE-TM, which is demanding.

A.B Khanikaev et al., Nature Materials 12, 233 (2013). Nat. Phot. 2017.

Photonic Quantum Valley Hall effect

Zig-zag interface between 2 opposite staggered lattices





Domain wall topological invariant*

$$N_{K,K'} = C_{K,K'}(l) - C_{K,K'}(r) = \pm 1$$

→ 1 interface state in each valley

→ One valley, one group velocity.

However, no protection against inter-valley scattering !!

Valley pseudo-spin is protected by a spatial symetry which is not fulfilled by random disorder.

O. Bleu et al. Phys. Rev. B ***95****, 235431 (2017).*

Interacting Quantum fluids in topological lattices

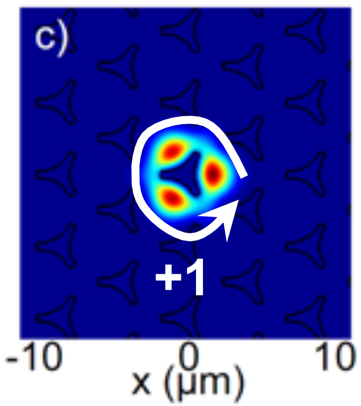
Condition: Presence of a **Bose Einstein Condensate** of exciton-polaritons at the Gamma point.

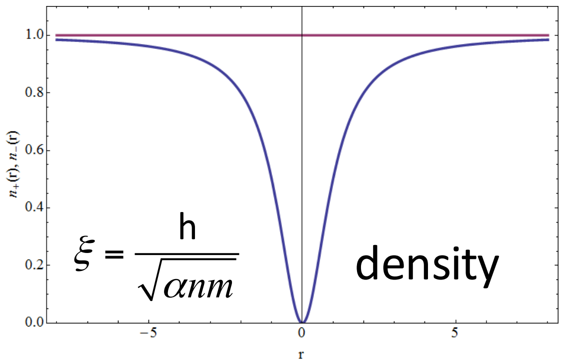
Quantized vortex

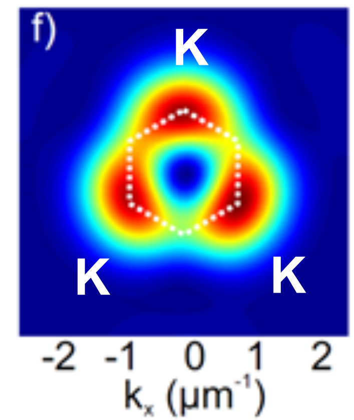
$$\psi = \sqrt{n(r)}e^{ip\theta}$$

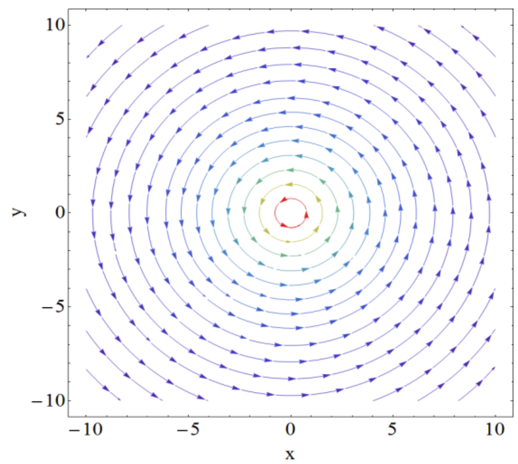
BEC excitation: Quantized vortices in 2D.

Vortex Core









Staggered honeycomb lattice.

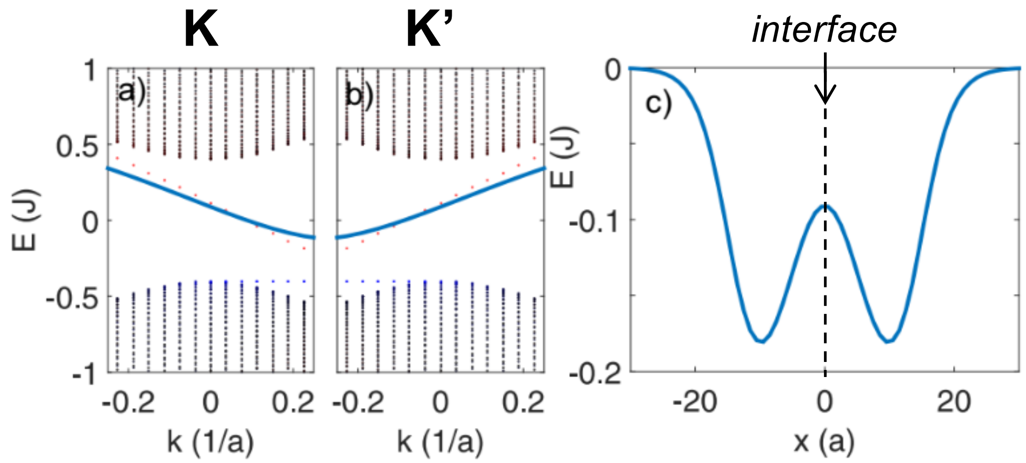
- Vortex core composed by states near K and K' possesing an angular momentum.
- The quantum vortex winding is linked with the Valley.
- The Valley imposes a well defined propagation direction.

Winding - Valley coupling

Valley – Propagation direction coupling.

Robust Quantum Valley Hall effect

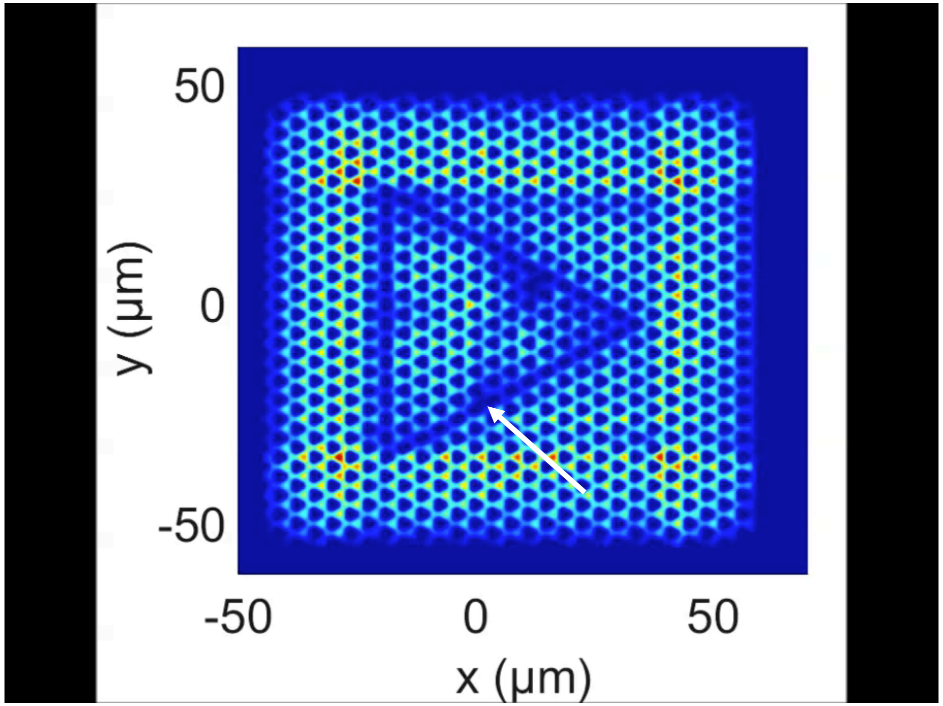
Vortex core inherits linear states chirality



Valley chirality

Potential seen by the core

Simulation of chiral vortex propagation



GPE equation

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\Delta\psi + \alpha|\psi|^2\psi + U\psi - \mu\psi$$

Nat. Com. 9, 3991, (2018).

→ **Robust chiral propagation** thanks to combination of real and momentum space topologies

Non-linear analog of QSHE : **vortex winding** replacing **electron spin**

Topological protection of vortex winding replaces the TRS protection of electron spin.

Topological lasers

Get Lasing in a topological mode.

Not evident in the microwave range where a lot of experiments are carried out…

Initial proposal for a 1D topological laser

PRL **116,** 046402 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Kibble-Zurek Mechanism in Topologically Nontrivial Zigzag Chains of Polariton Micropillars

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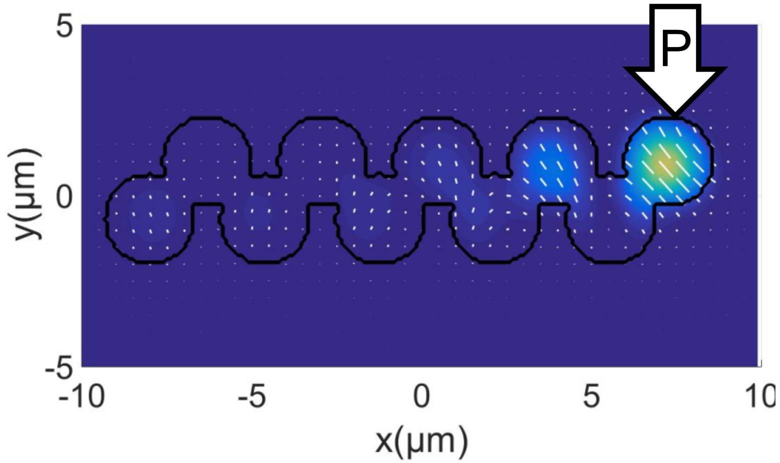
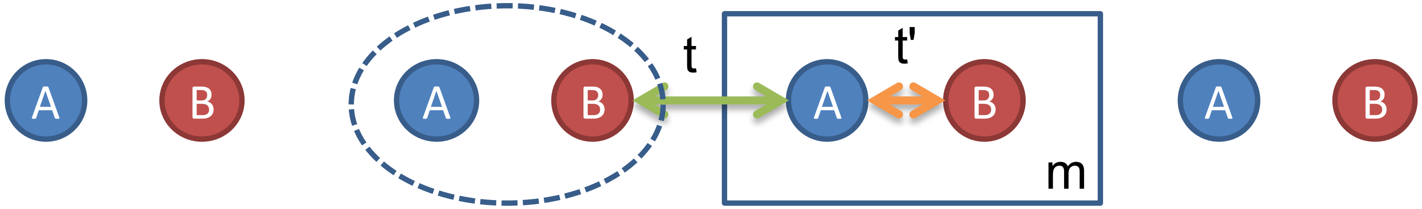
[2]*School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom*
(Received 15 June 2015; revised manuscript received 7 October 2015; published 29 January 2016)

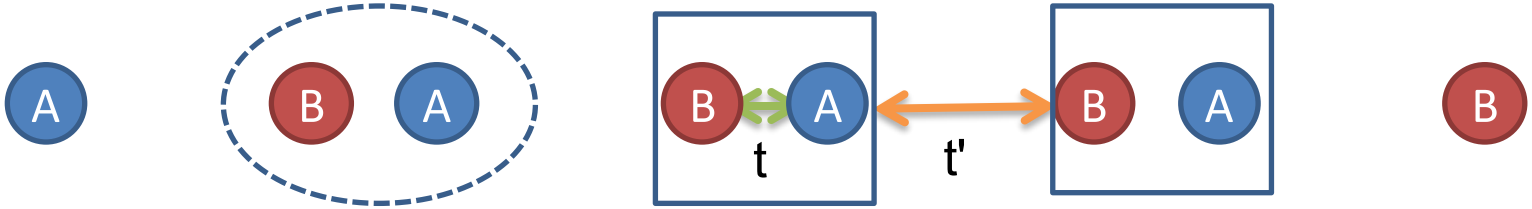


Pump on the edge.
Condensation in the edge state.

1D: Dimer chain and edge states



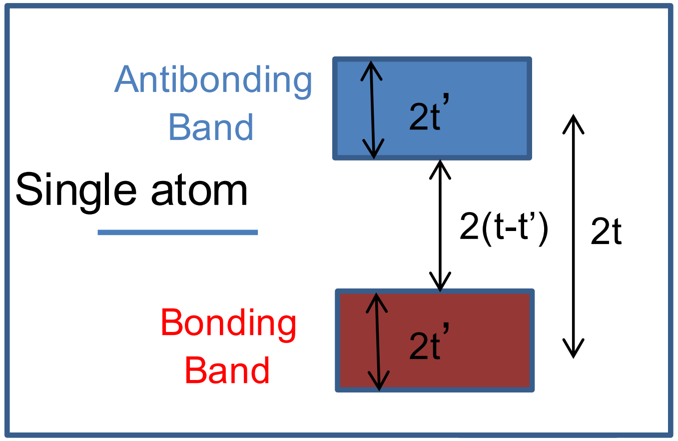
t'>t: tightly bound pairs = "molecules" **<u>AB</u>**, no «extra» atoms
Two bands: AB in phase/out of phase (like s and p states of a single site)



t'<t: tightly bound "molecules" **<u>BA</u>**; two «extra» atoms on the edges

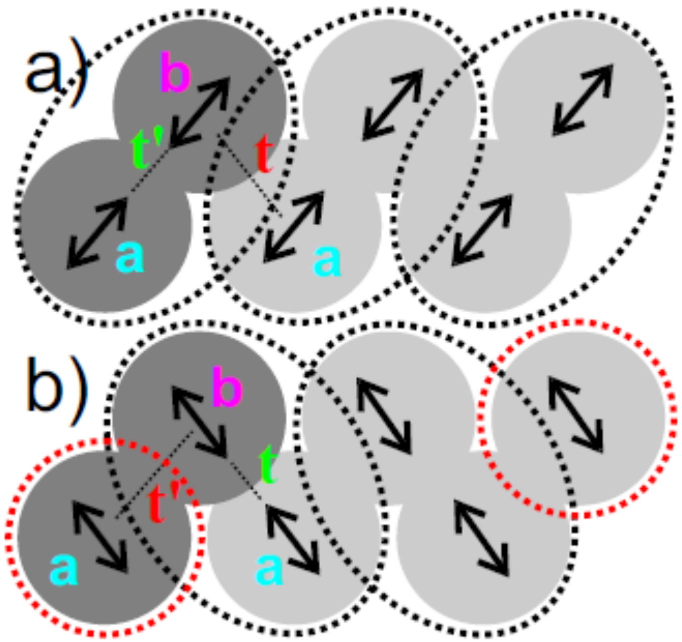
Topological quantity characterizing edge states –
the **Zak phase**

$$\gamma_n = \int_{-\pi/a}^{\pi/a} \frac{2\pi}{a} \int_0^a u_{nk}^*(x)\, i \frac{\partial u_{nk}(x)}{\partial k}\, dx\, dk$$

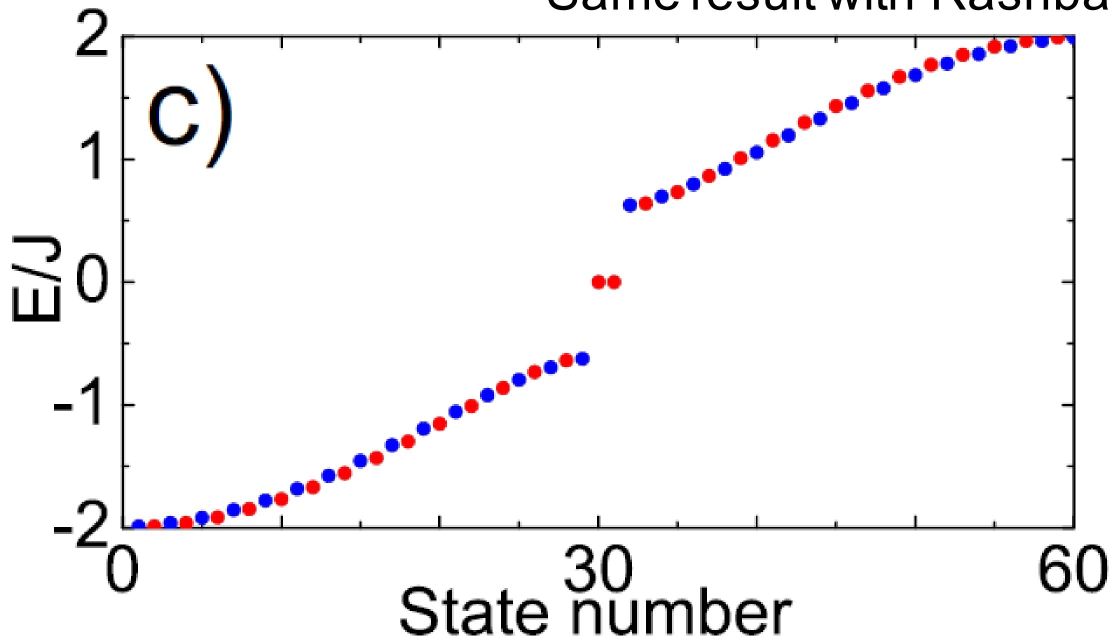


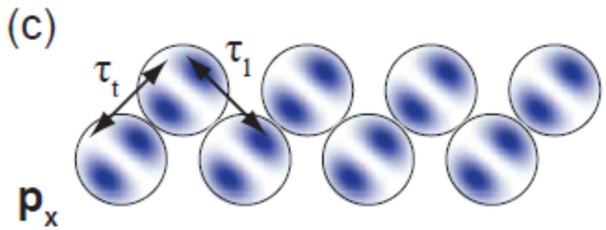
Dimerization of a zigzag chain for polaritons

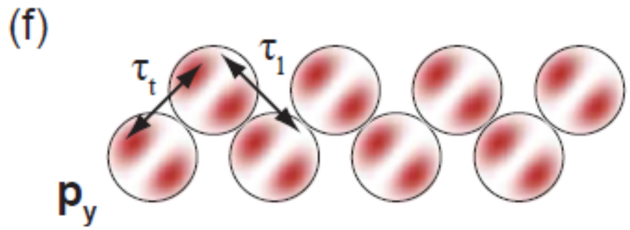
- Polarization-dependent coefficients t and t'
- Tight-binding calculation of the eigenstates
- 0 edge states in D-polar, 2 edge states in A-polar



Same result with Rashba field







Same can be done with p-orbitals

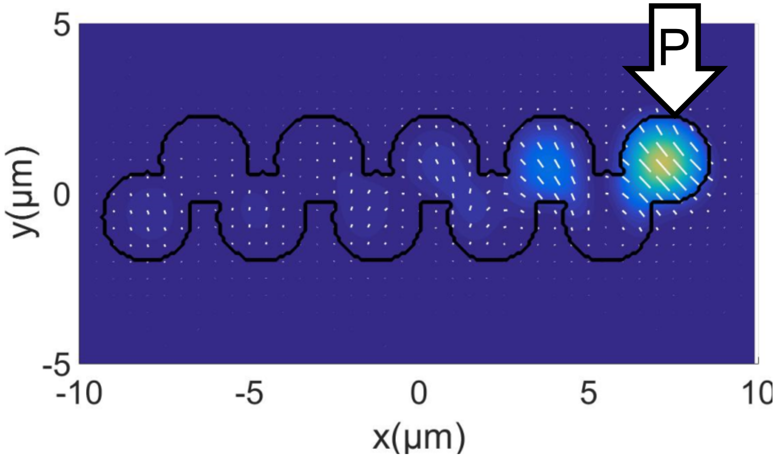
Edge states in the condensation

- Edge states favored by higher overlap
- Localized pumping

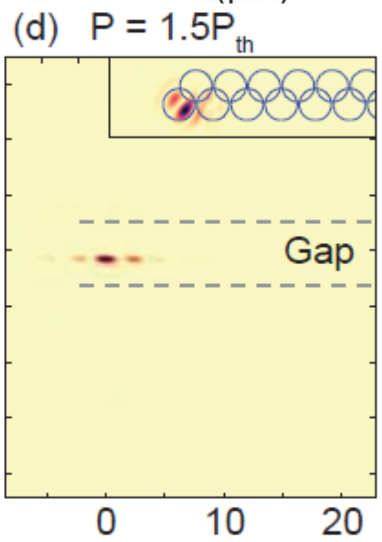
$$i\hbar\frac{\partial\psi_\pm}{\partial t} = -(1-i\Lambda)\frac{\hbar^2}{2m}\Delta\psi_\pm + \beta\left(\frac{\partial}{\partial x}\mp i\frac{\partial}{\partial y}\right)^2\psi_\mp \qquad (4)$$

$$+U\psi_\pm - \frac{i\hbar}{2\tau}\psi_\pm + \left(\left(U_R+i\gamma(n)\right)\psi_\pm+\xi\right)\exp\left(-\frac{(\mathbf{r}-\mathbf{r}_0)^2}{\sigma^2}\right)$$

D. Solnyshkov et al., PRA 89, 033626 (2014).



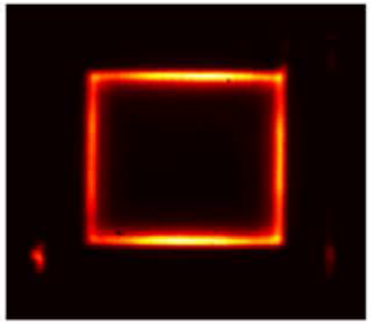
Pump on the edge.
Condensation in the edge state.

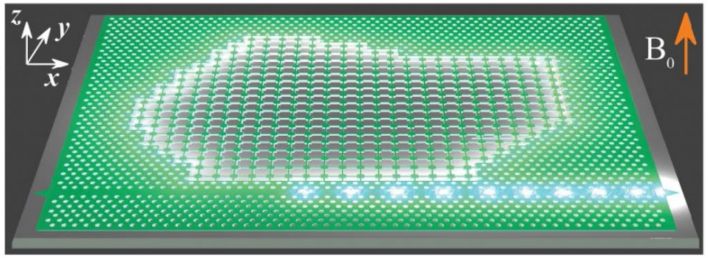


Observation of a 1D topological laser

P. Saint Jean et al. Nature Photonics, 11,651, (2017).

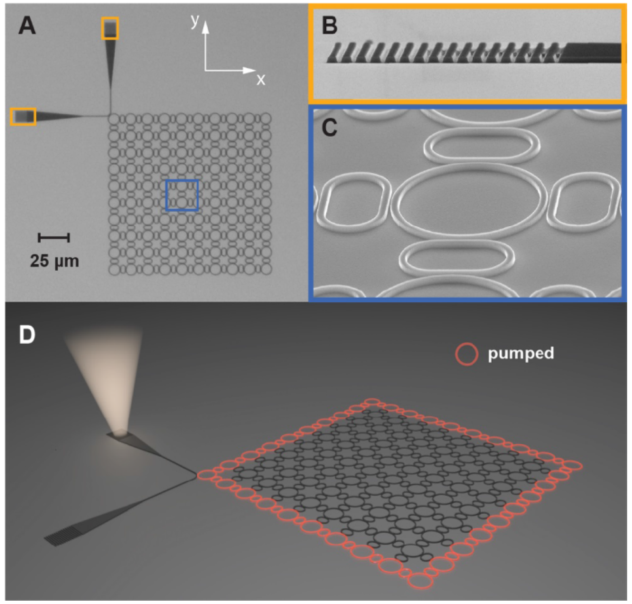
2D Topological Lasers





Based on Quantum Anomalous Hall Effect

Bahari et al, Science, 10.1126/scienceaa04551 (2017).



Based on Quantum Spin Hall Effect

Brandes et al, Science, 10,1126/Scienceaar4005 (2018).

Conclusion

- **Intrinsic chirality of Photon modes→ Z topological insulator.**
- **Quantum fluids makes Quantum Valley Hall effect robust.**
- **Topological lasers in 1D-chains.**