Topological properties of polariton lattices

P. Saint-Jean, M. Milicevic, F. Baboux, V. Goblot,

E. Galopin, L. Le Gratiet, I. Sagnes, A. Lemaître,

J. Bloch, A. Amo

http://honeypol.eu

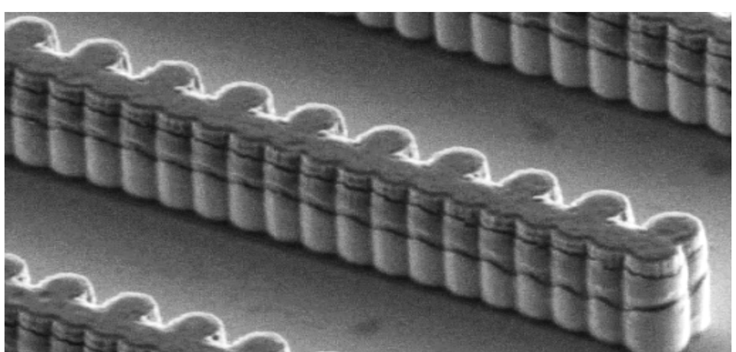
Marcoussis
France

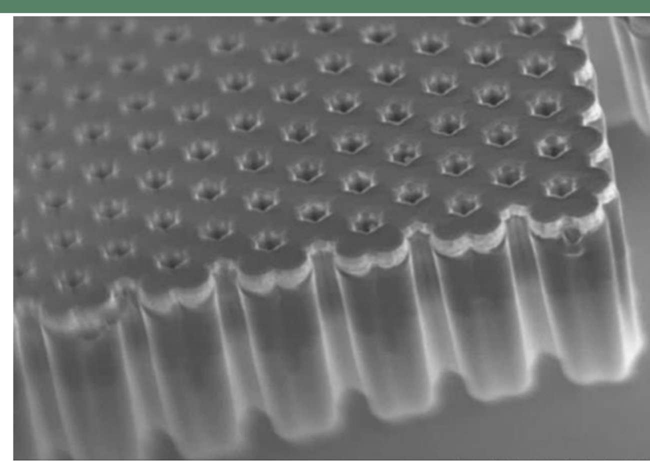
T. Ozawa
I. Carusotto
Trento

D. Solnyshkov
G. Malpuech
Clermont-Ferrand

E. Levi
E. Akkermans
Haifa

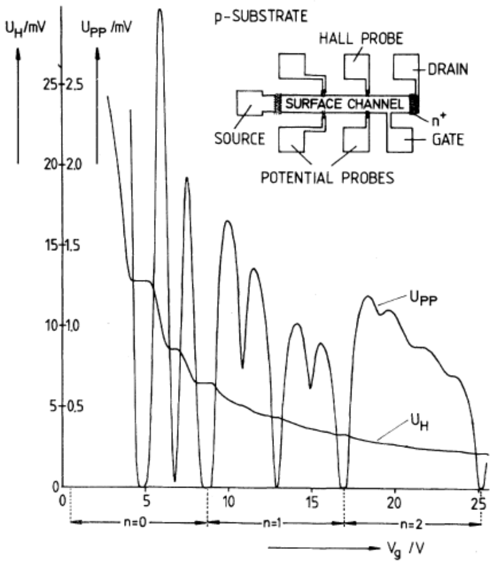
G. Montambaux
Orsay





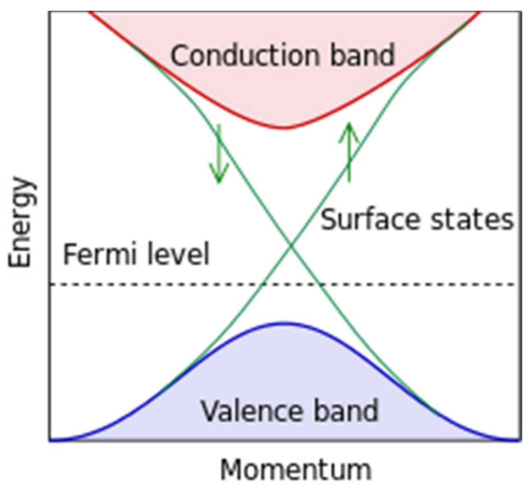
Topology: from electrons to photons

Quantum Hall effect



K. v. Klitzing, et al.,
PRL **45,** 494 (1980)

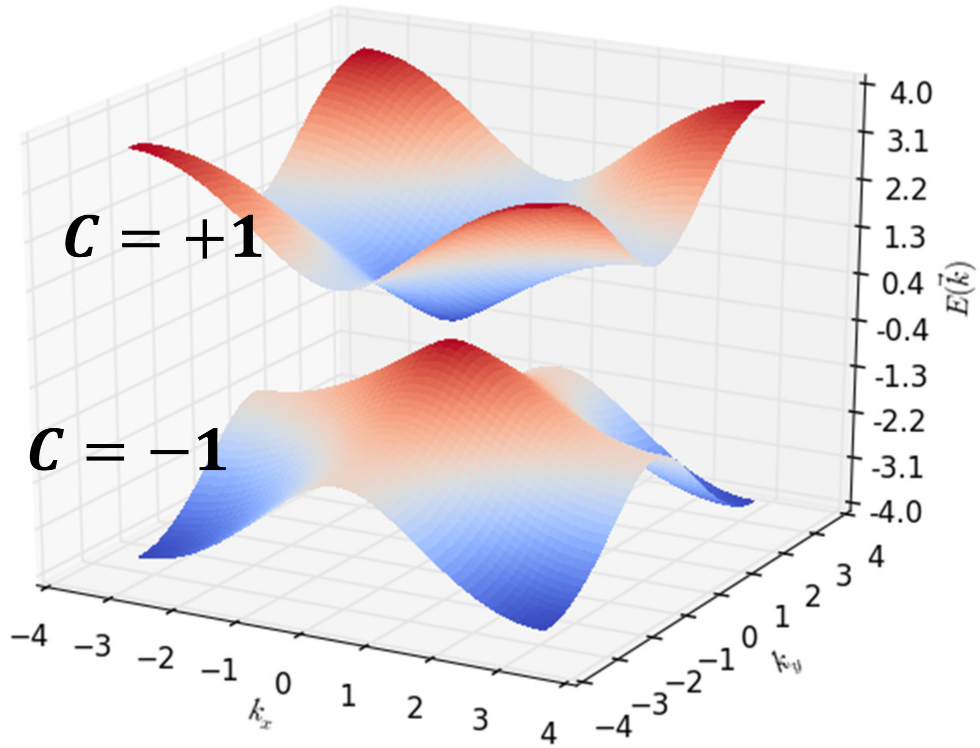
Topological insulators



Topological invariants (Chern #)

$$C = \frac{1}{2\pi} \oiint \nabla_{\boldsymbol{k}} \times \langle u(\boldsymbol{k}) | i\nabla_{\boldsymbol{k}} | u(\boldsymbol{k}) \rangle \cdot d\boldsymbol{s}$$

integral over the first Brillouin zone

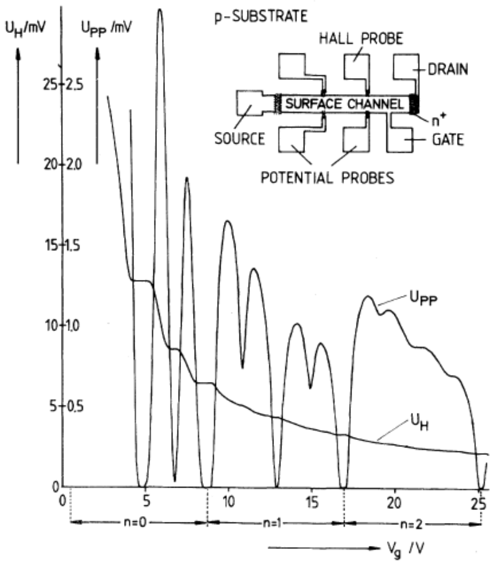


Preserved as long as gap is not closed

Topological protection

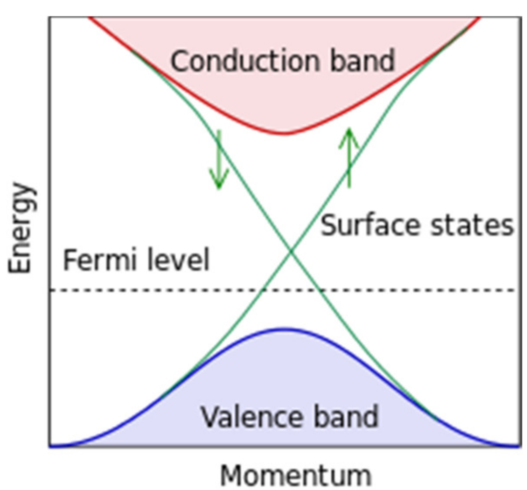
Topology: from electrons to photons

Quantum Hall effect



K. v. Klitzing, et al.,
PRL **45,** 494 (1980)

Topological insulators



Topological invariants (Chern #)

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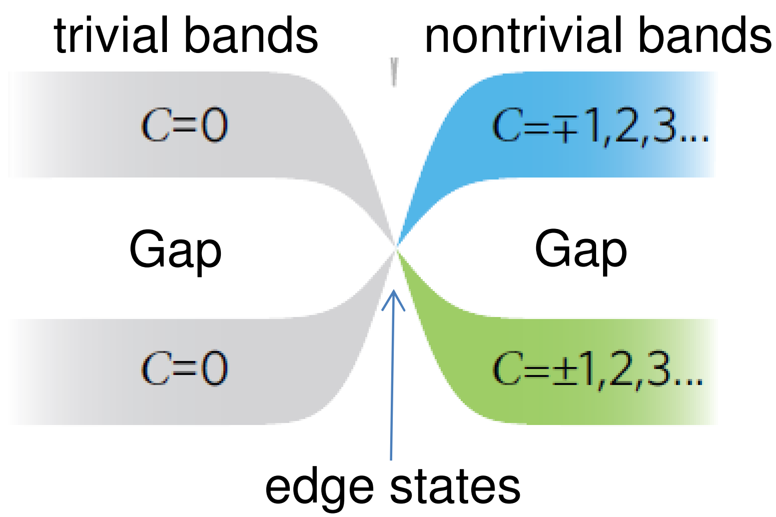
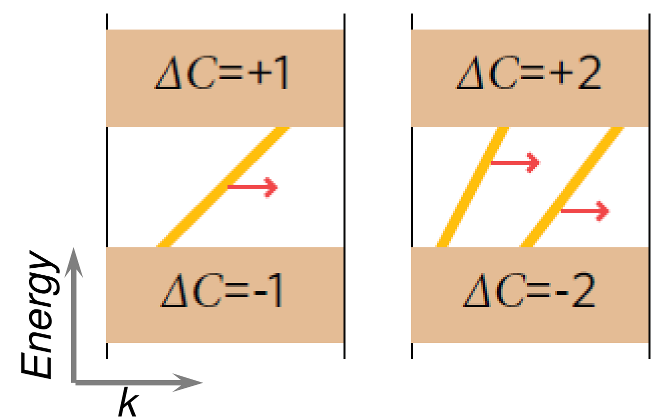


Bulk-edge correspondence

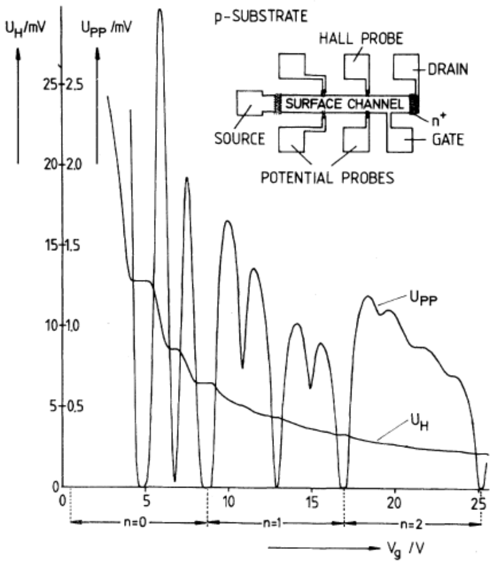


Protected chiral transport on the edges

From L. Lu et al., Nat. Photon. 8, 821 (2014)

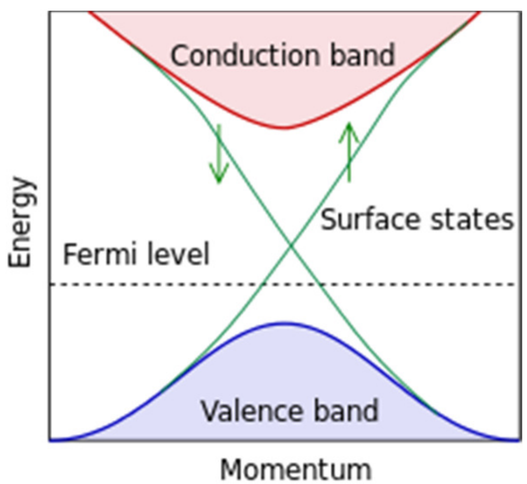
Topology: from electrons to photons

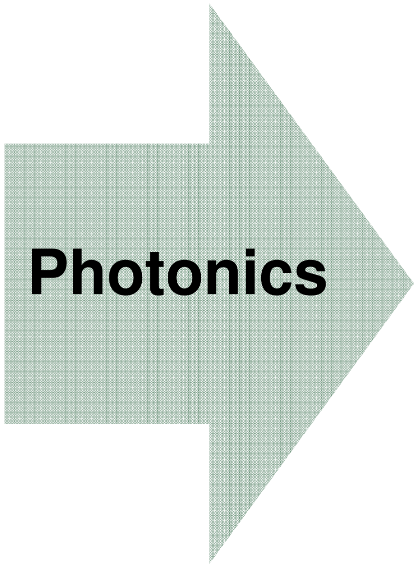
Quantum Hall effect



K. v. Klitzing, et al.,
PRL **45,** 494 (1980)

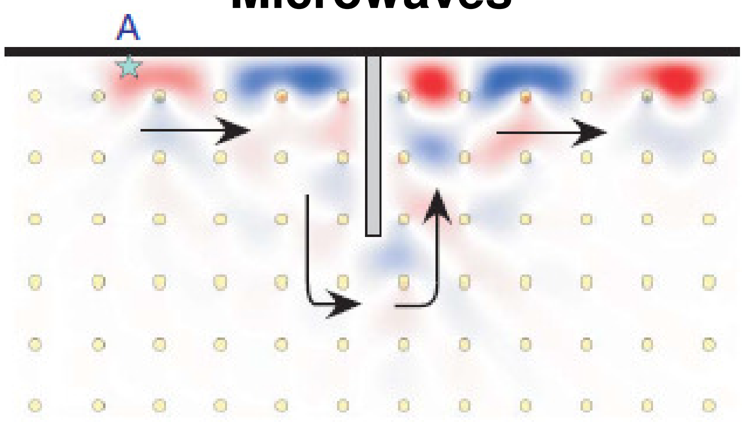
Topological insulators





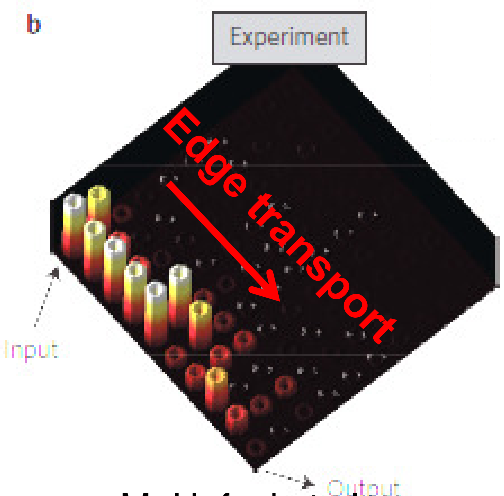
Protected chiral transport

Microwaves



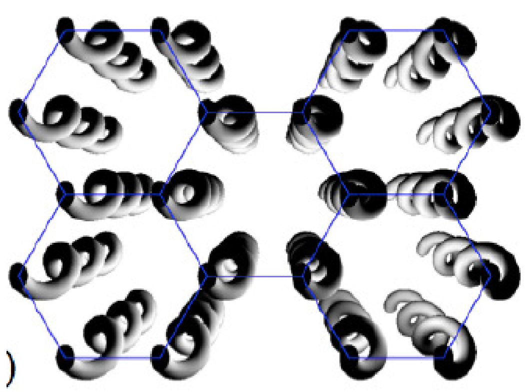
Z. Wang et al., Nature **461**, 772 (2009)

Si resonators



M. Hafezi et al.,
Nature Photonics, 7, 1001 (2013)

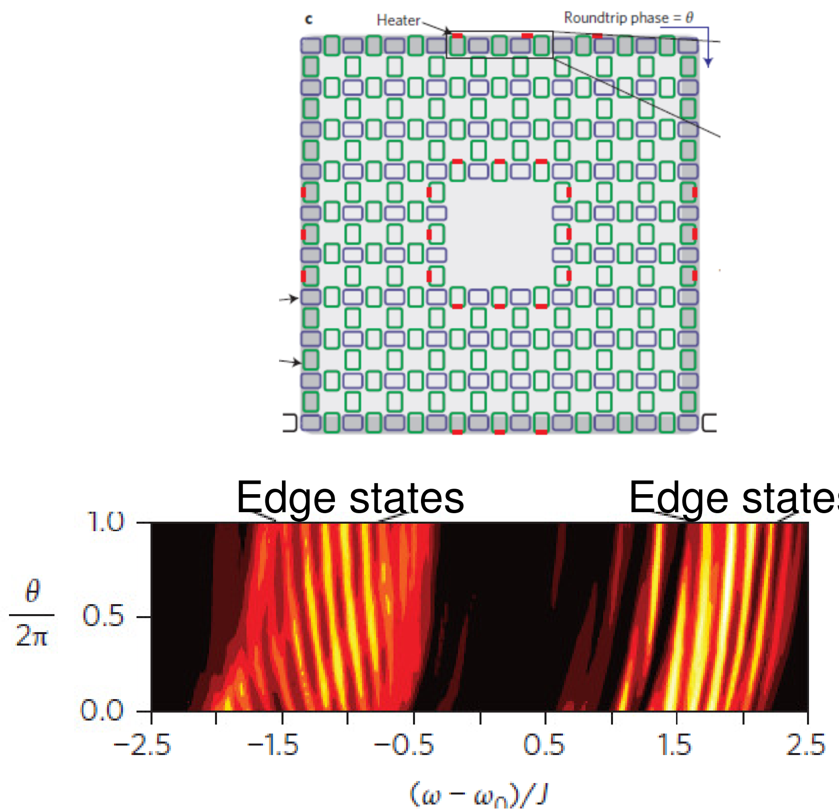
Coupled waveguides



M. C. Rechtsman et al.,
Nature **496**, 196 (2013)

Topology: from electrons to photons

Direct measurement of topological invariants

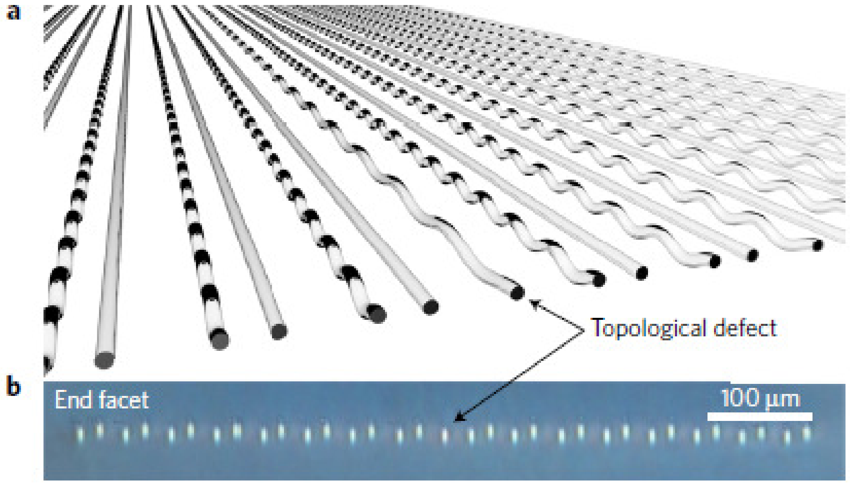


S. Mittal et al., Nat. Photonics 10, 180 (2016)

Microwaves: W. Hu et al., PRX 5, 11012 (2015)

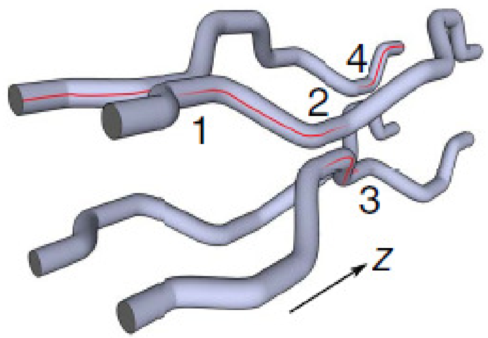
Novel photonic architectures

PT symmetric bound states



S. Weimann et al., Nat. Mater. 16, 433 (2017)

Topological pumps

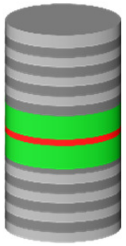


S. Mukherjee et al., Nat. Commun. 8, 13918 (2017)

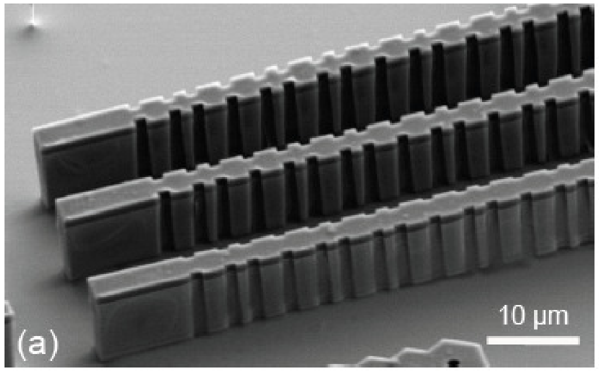
Y. E. Kraus et al., PRL 109, 106402 (2012)

Outline

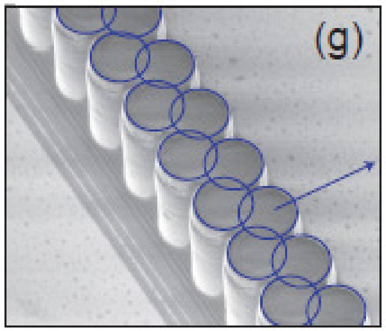
- **Hamiltonian engineering in a polariton system**



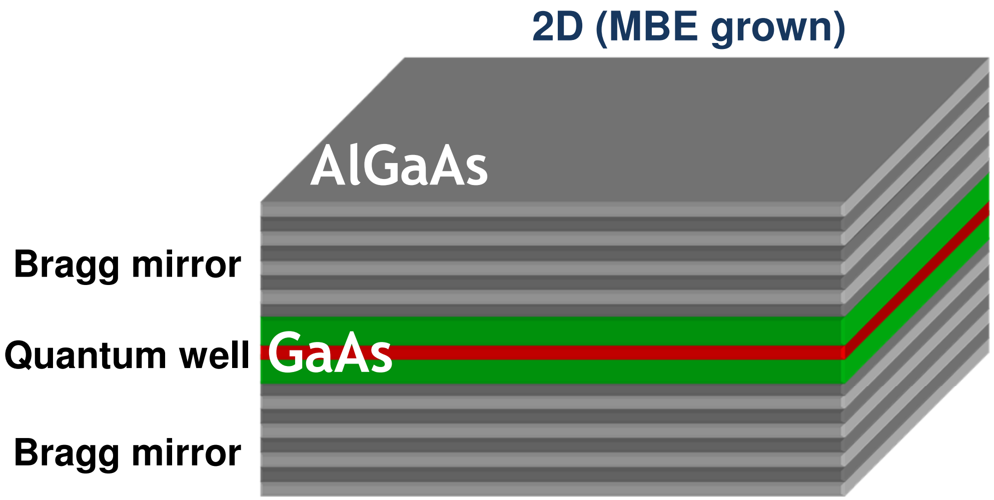
- **Measurement of topological invariants in a Fibonacci potential**



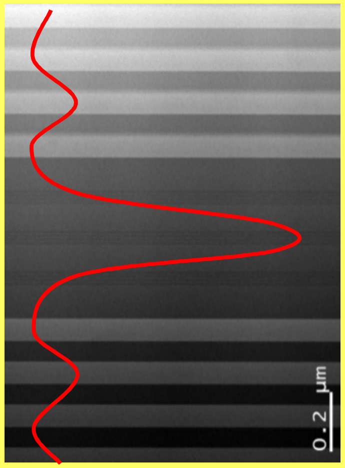
- **Lasing in topological edge states**

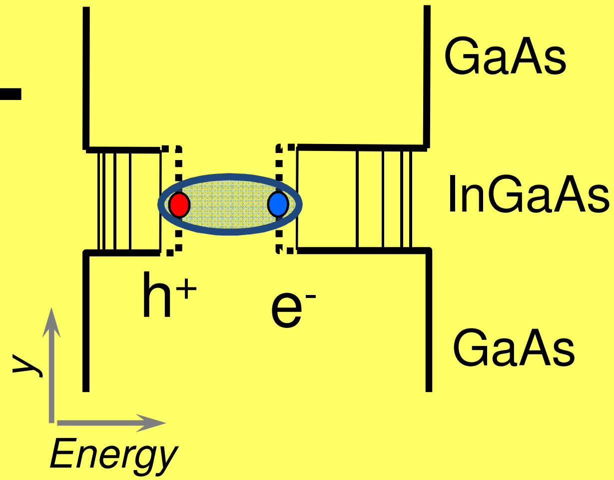


Microcavity polaritons



Optical Cavity + **Quantum well**



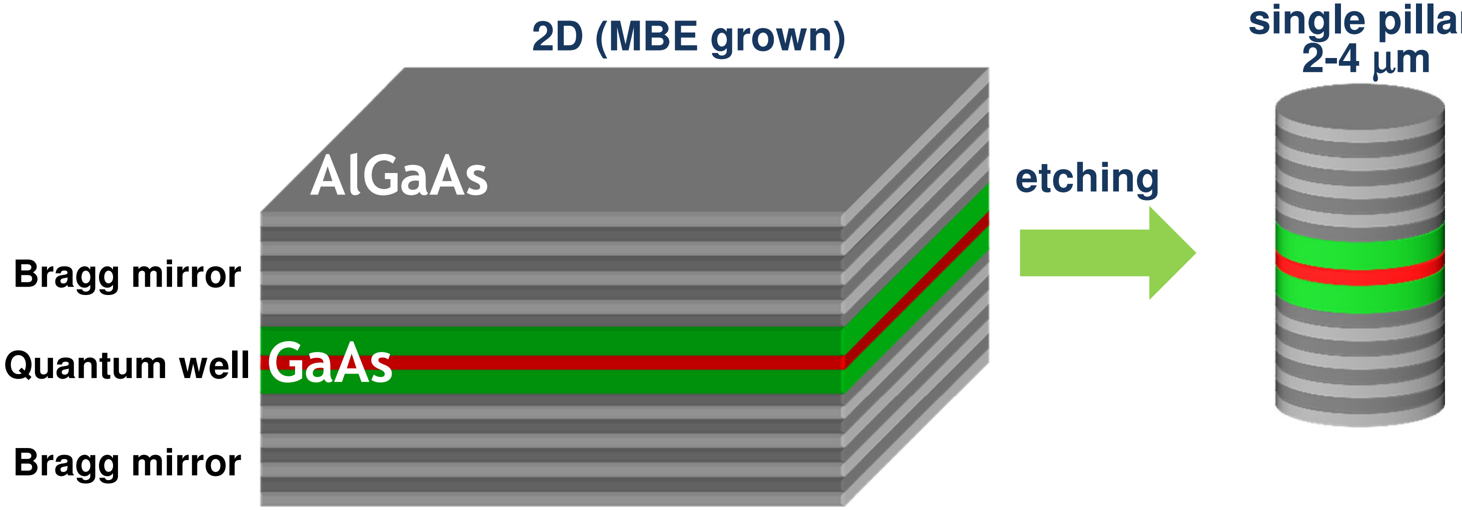


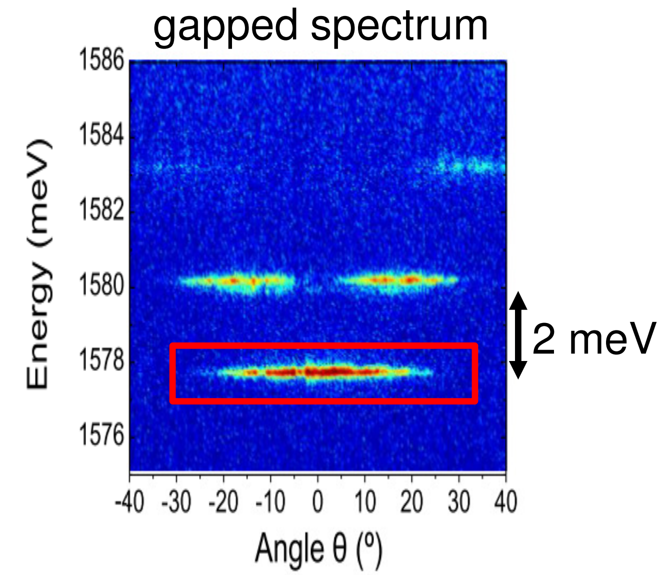
$$|pol\rangle = \boxed{X_k}|exc\rangle + \boxed{C_k}|phot\rangle$$

- Confinement

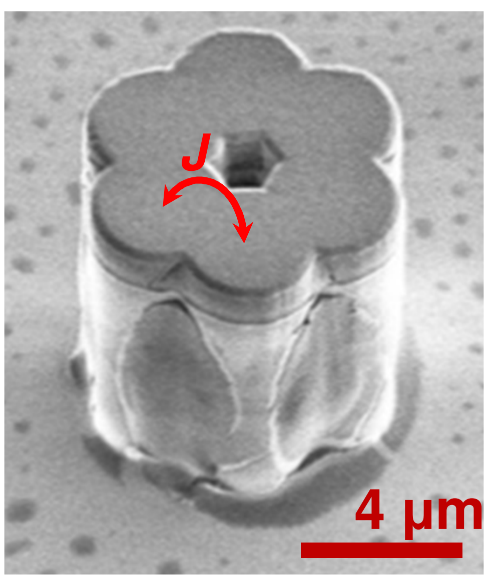
- Active element: lasing
- Interactions - $\chi^{(3)}$
- Sensitivity to magnetic field

Microcavity polaritons

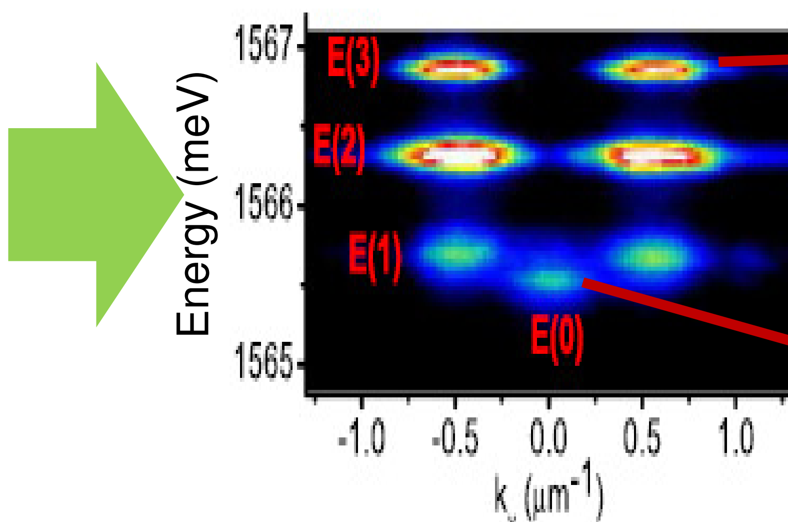




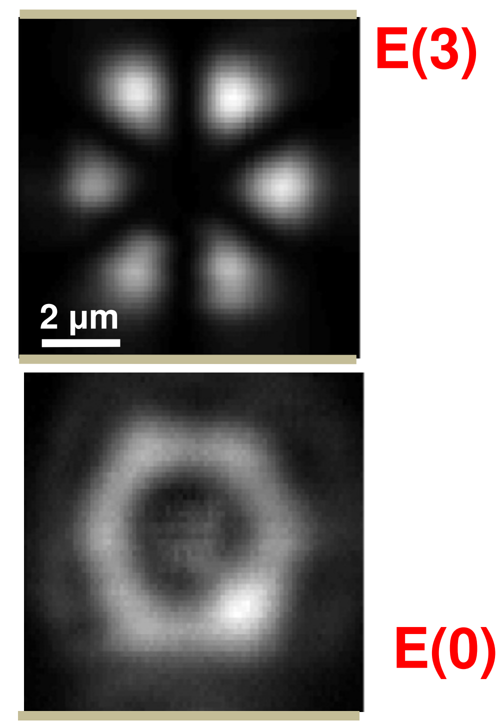
Coupled micropillars
Photonic tunneling



Spectrum



Wavefunctions



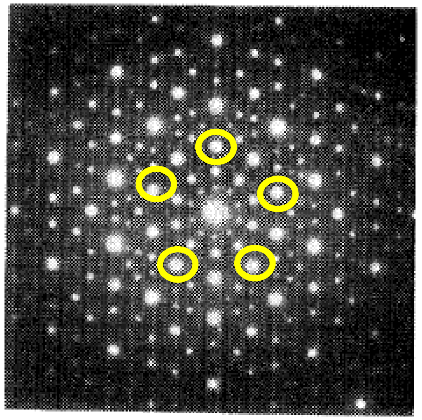
V. G. Sala et al., PRX **5**, 011034 (2015)

Quasi-crystals

Quasi-crystals → **no translational symmetry**

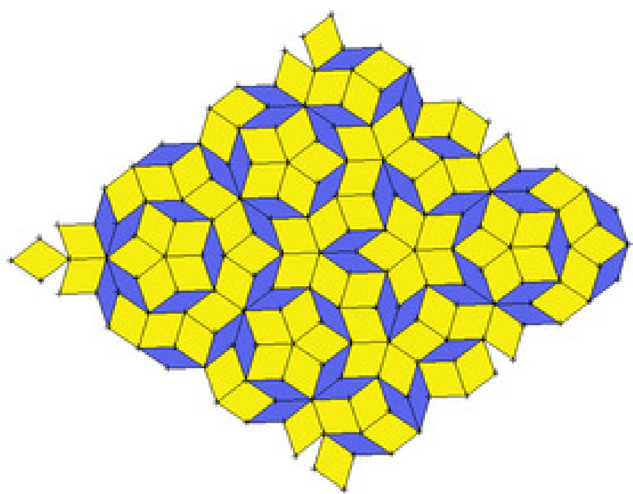
→ **long range order (we can predict the atomic position at any point)**

1st observation : Schectman *et al.* PRL **53**, 1951 (1984)



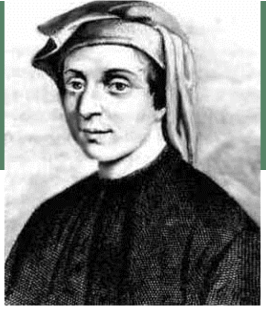
5-fold symmetry
in X-ray pattern
of AlMn alloy

Explanation by Levine and Steindhardt PRL **53**, 2477 (1984)



Penrose tiling

1D Fibonacci quasi-crystal



1175-1250

Characteristic function

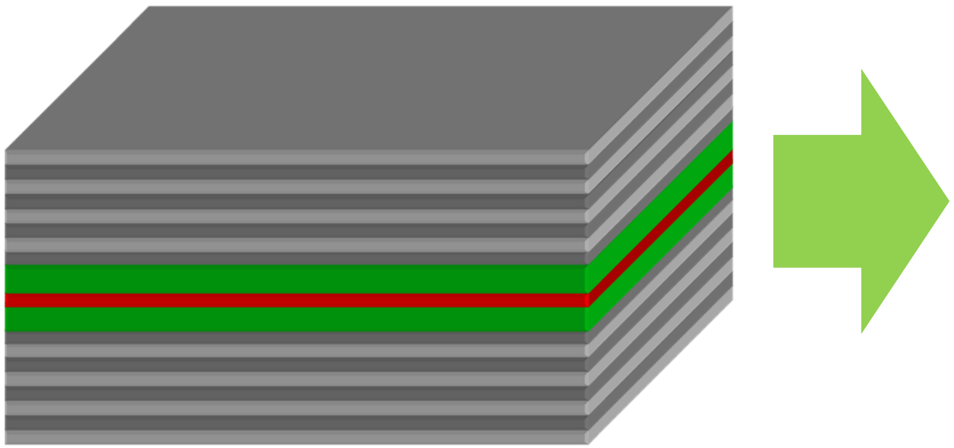
Y. E. Kraus et al., PRL 109, 106402 (2012)

$$\chi_j = \mathrm{sgn}[\cos(2\pi j \sigma^{-1} + \phi) - \cos(\pi \sigma^{-1})]$$

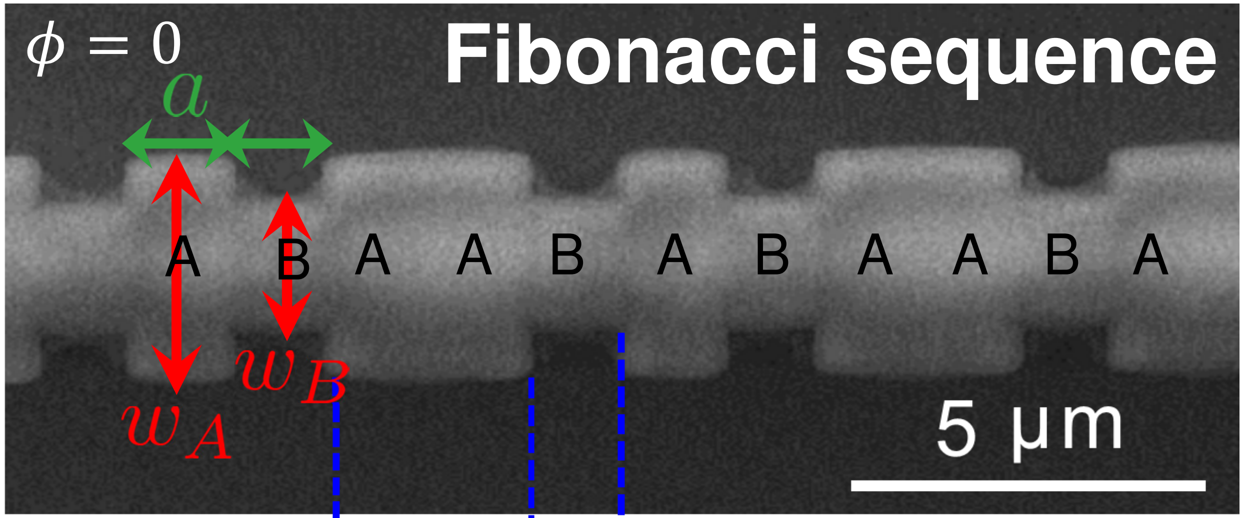
site **phason** **Golden mean**

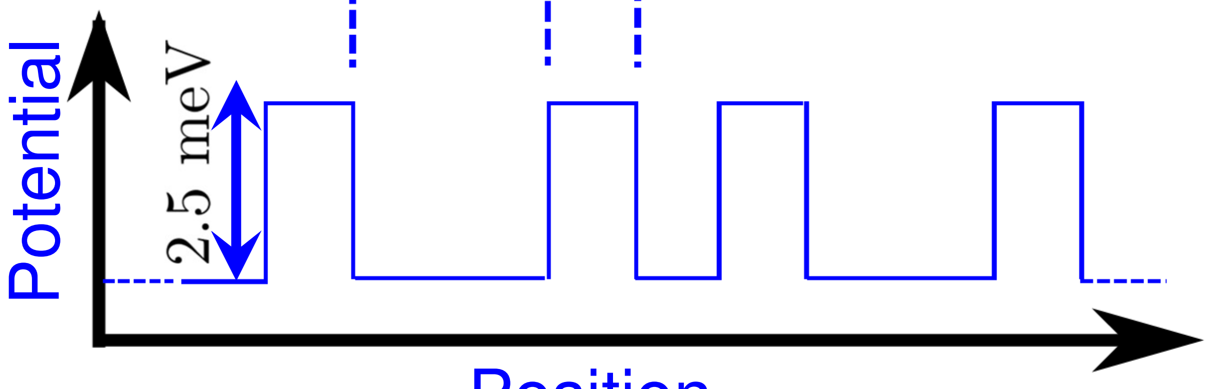
For each site → w_A, w_B

Top view

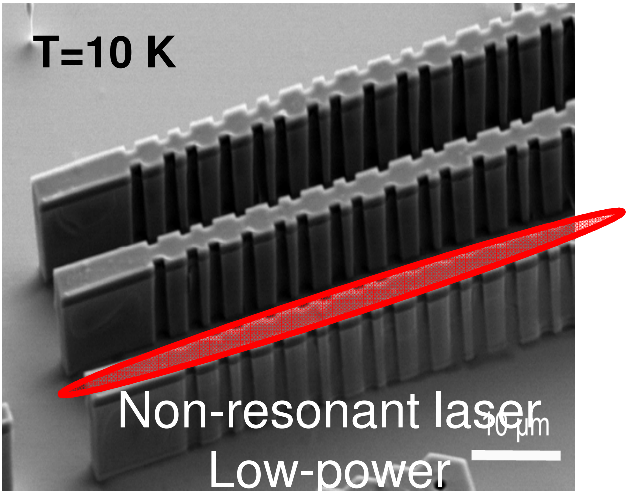


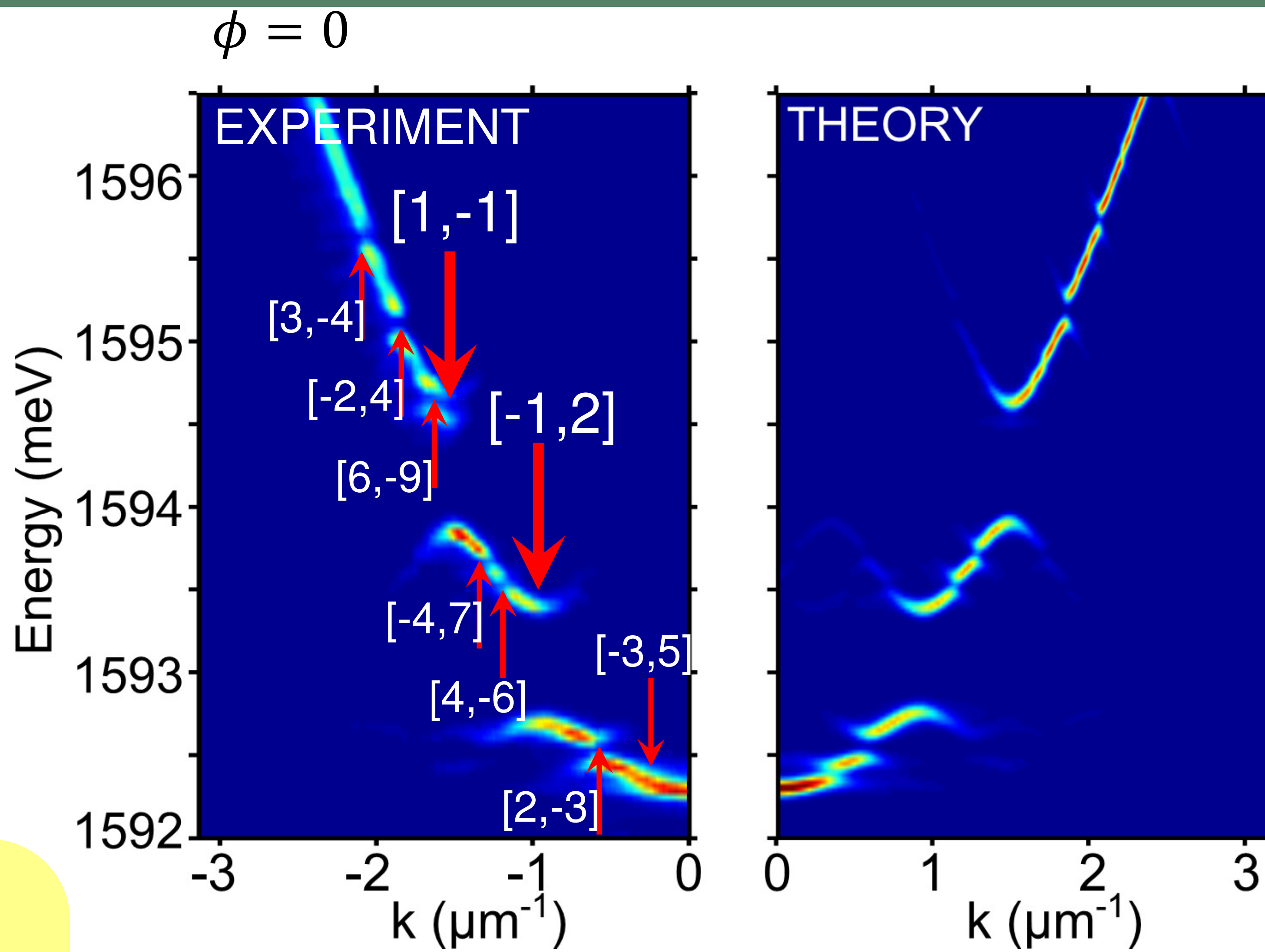
Dry-etching of a planar GaAs/AlGaAs microcavity





Fractal spectrum





Gap-labelling thorem

$$\boxed{k_{p,q} = \left(p + q\sigma^{-1}\right)\frac{\pi}{a}}$$

J. Bellissard *et al.*,
Reviews in Math. Physics **4**, 1 (1992)

- **Topological gap invariants?**
- **Periodicity?**

D. Tanese et al., PRL 112, 146404 (2014)

Topological invariants in 1D quasi-crystals

Quasi-crystals: a 1D + 1D system

Y. E. Kraus et al., PRL **109**, 106402 (2012)

Aubry-André model

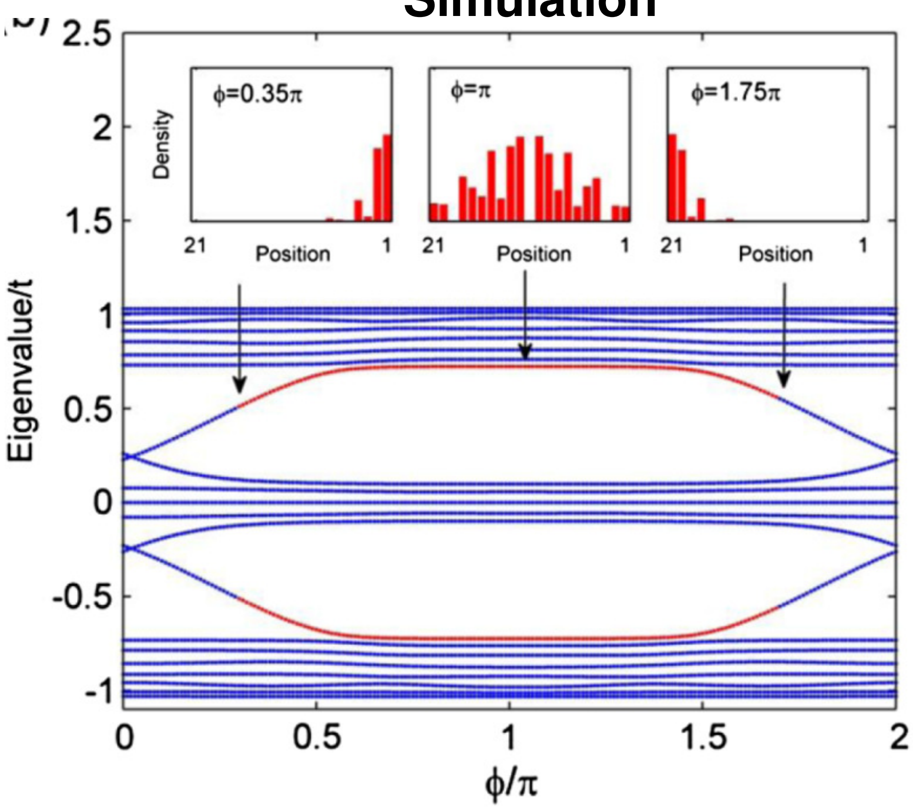
Long range order, no periodicity

$$H(\phi)\psi_n = t(\psi_{n+1} + \psi_{n-1}) + \lambda \cos(2\pi b n + \phi)\psi_n.$$

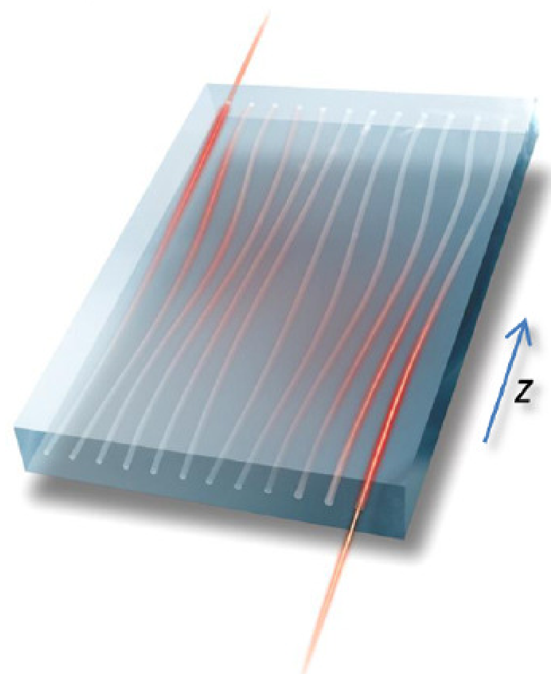
irrational number

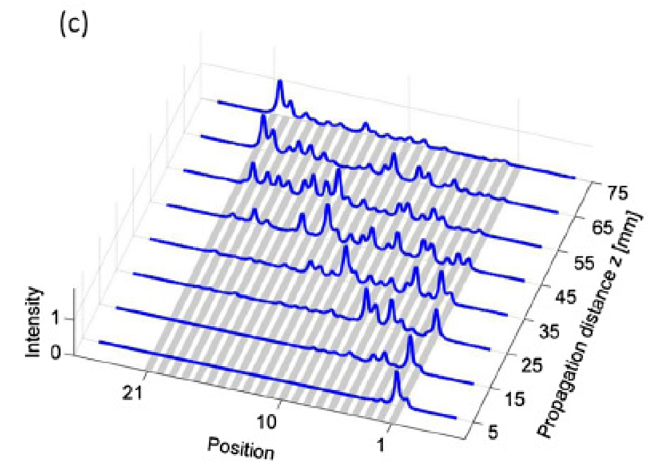
phason (extra PERIODIC dimension)

Simulation



phason (synthetic dimension)





Quasi-crystal bands can be associated a topological invariant

appearance of edge states

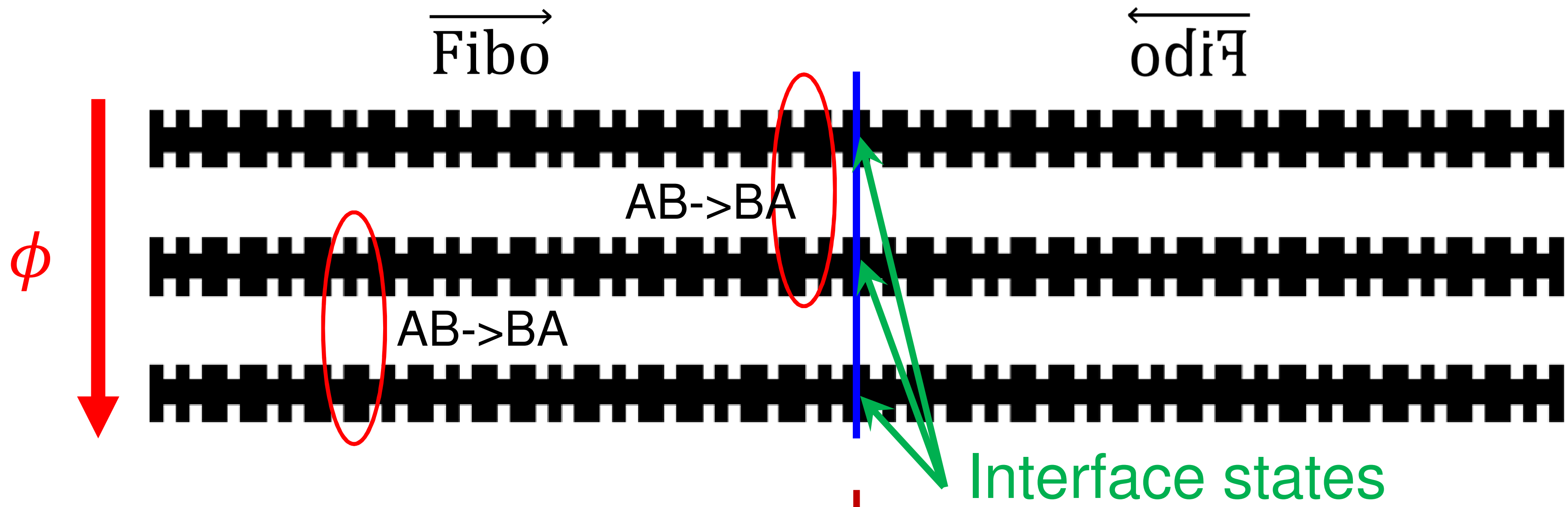
Fibonacci cavity

$$\chi_j = \mathrm{sgn}[\cos(2\pi j \sigma^{-1} + \phi) - \cos(\pi \sigma^{-1})]$$

site

phason
(PERIODIC $\in [0,2\pi]$

Golden mean

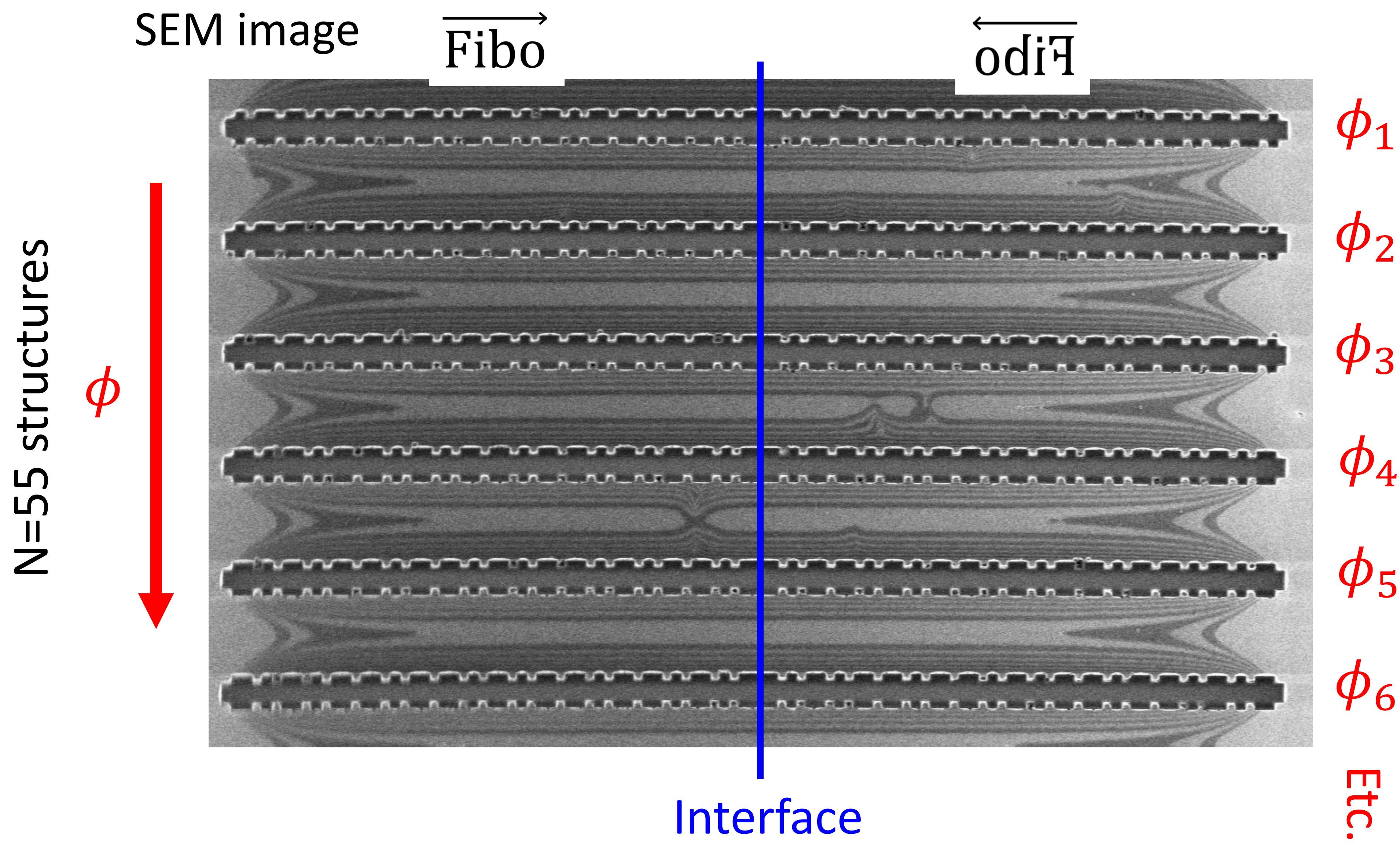


Effective Fabry-Pérot cavity of zero length but finite round-trip phase θ_{cav}

$$\mathcal{W}\left(\theta_{cav}\right) \equiv \frac{1}{2\pi} \int_0^{2\pi} d\phi \, \frac{d\theta_{cav}\left(\phi, q, k_m\right)}{d\phi} = 2\,q$$ gap label

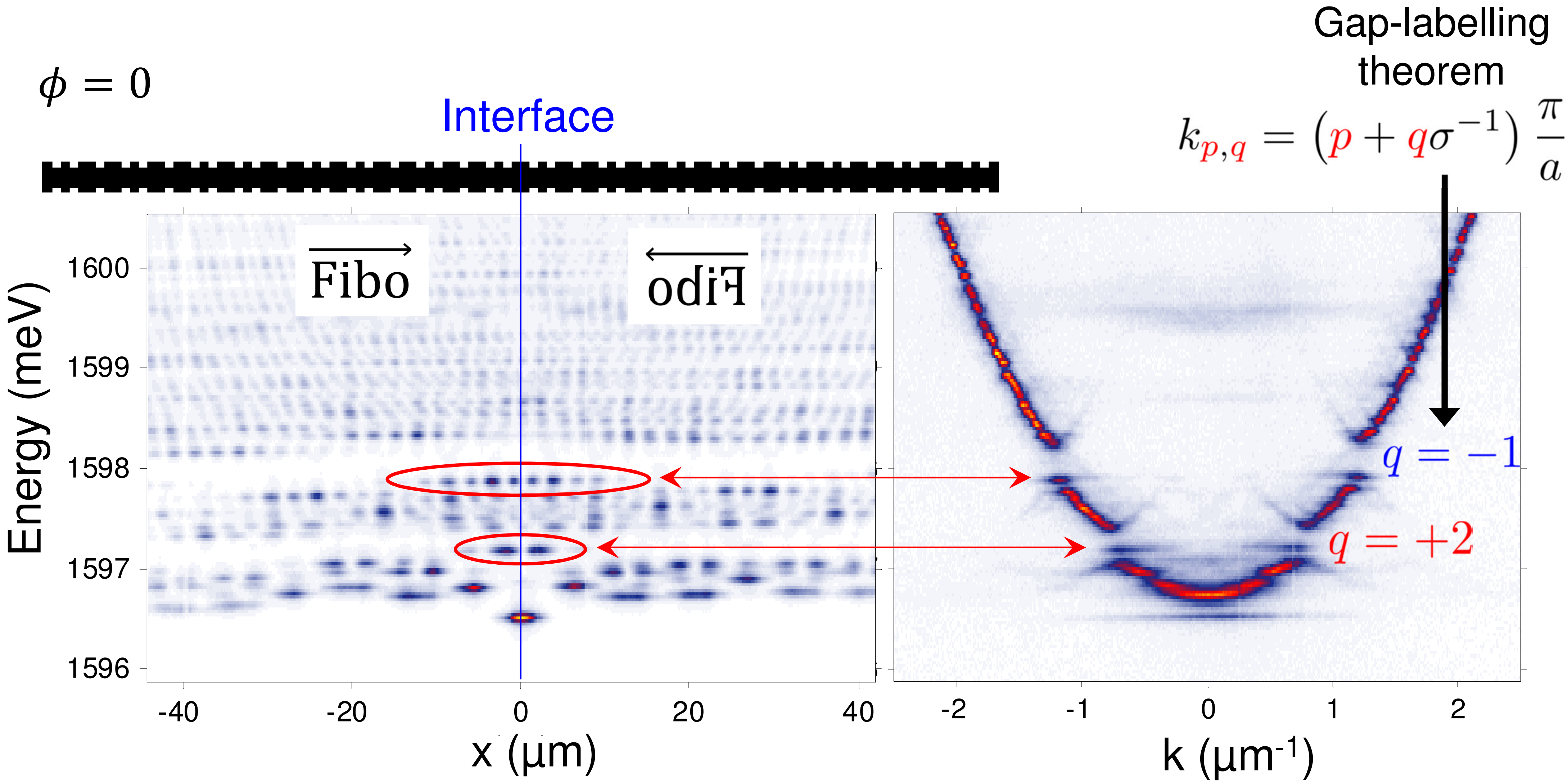
Accessible in the spectral properties

Fibonacci cavities



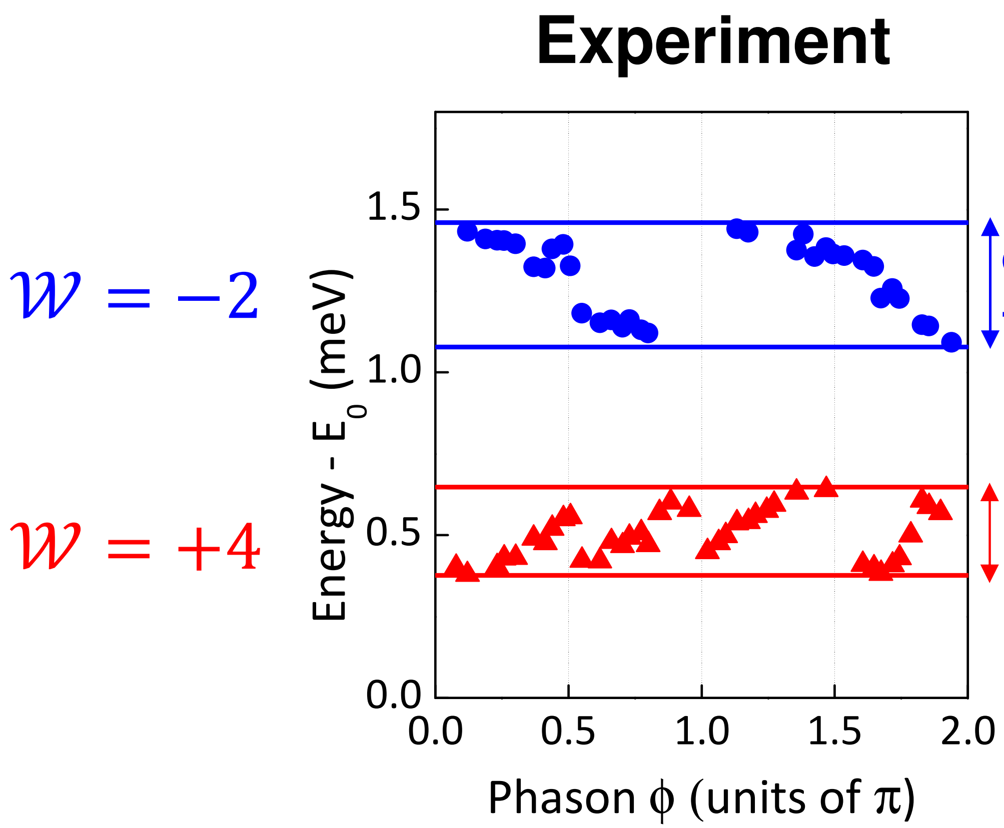
F. Baboux et al., PRB 95, 161114(R) (2017)

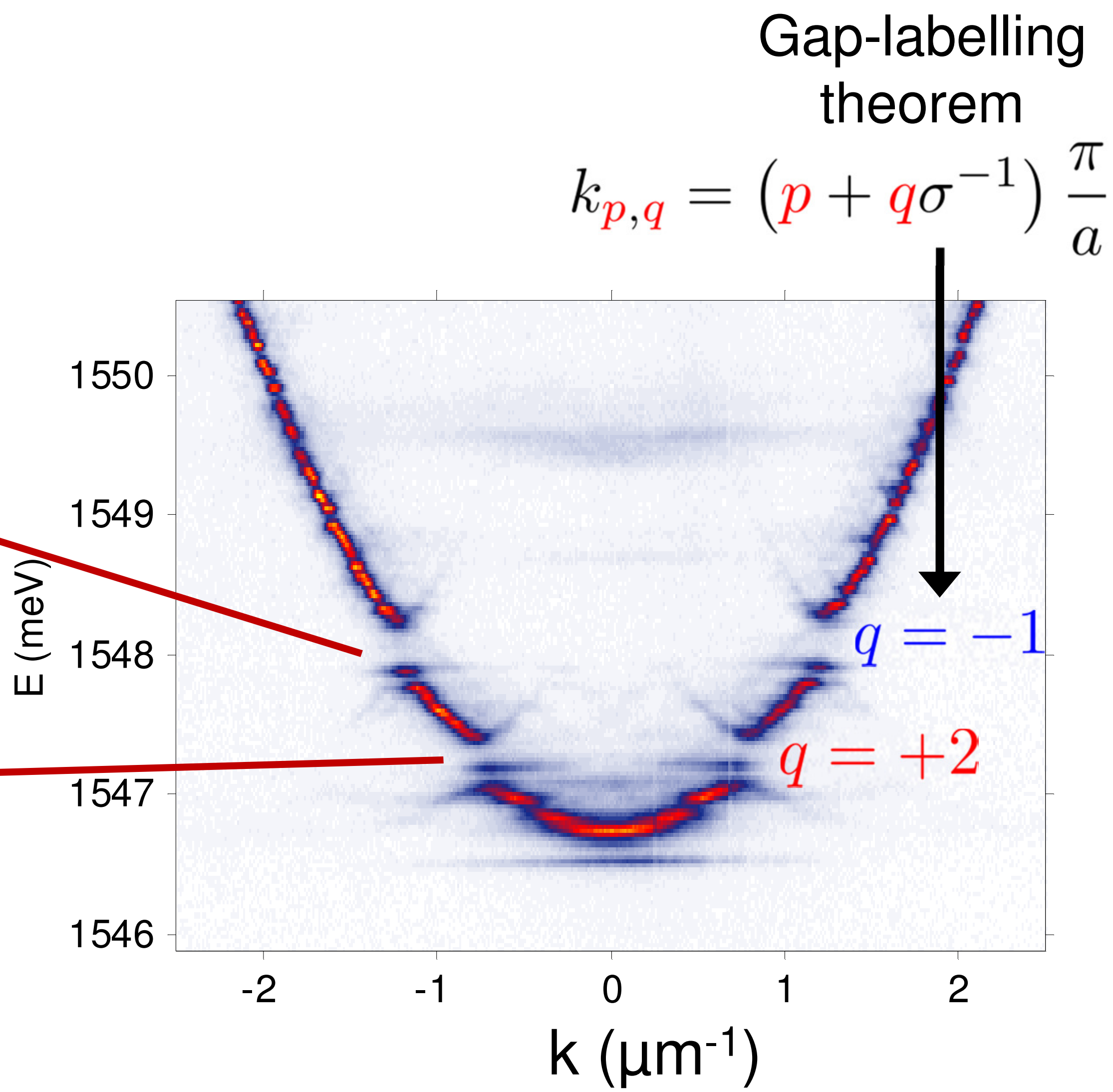
Interface states



F. Baboux et al., PRB 95, 161114(R) (2017)

Spectral winding of interface states





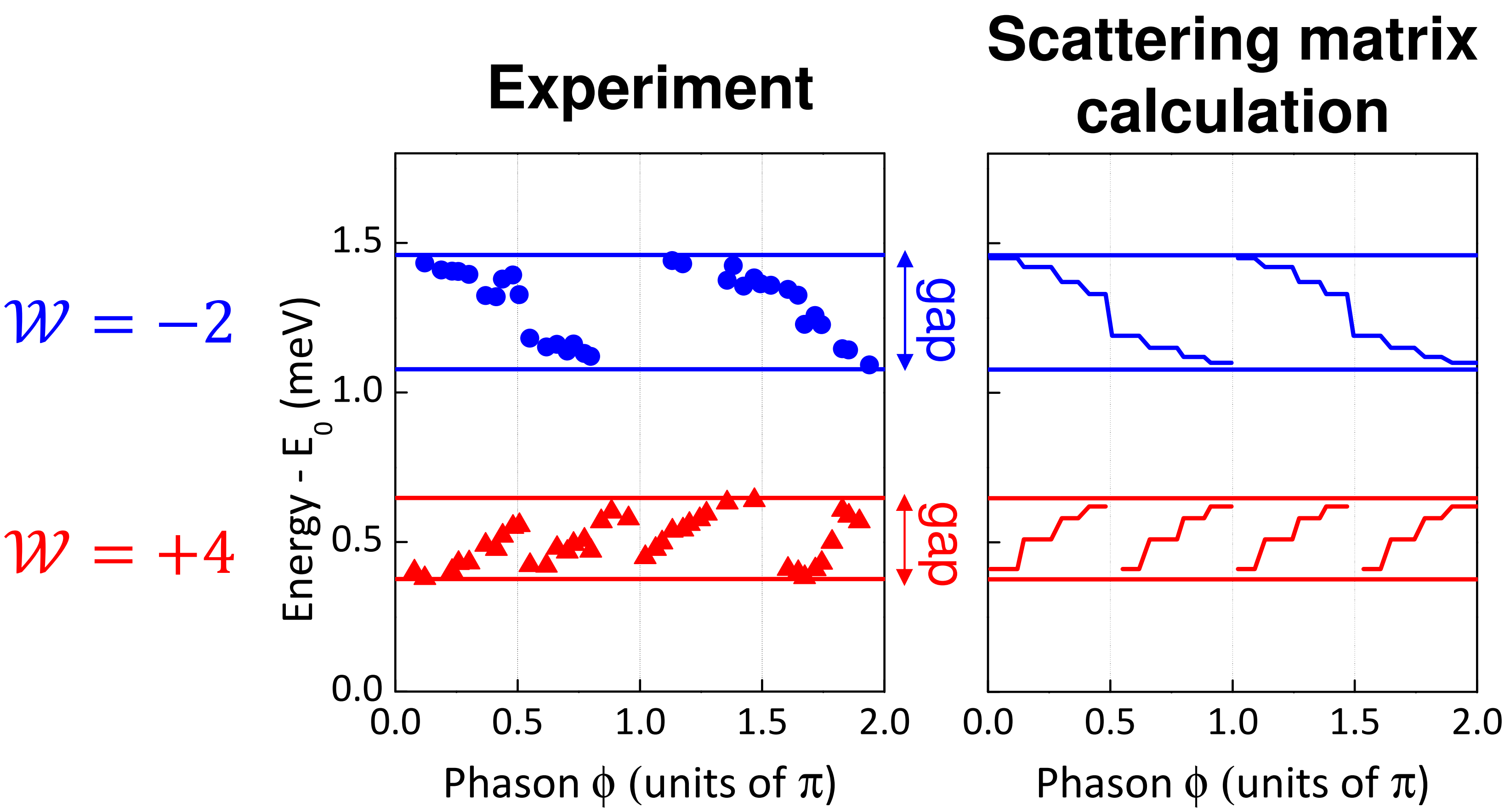
The interface states traverse periodically the gaps

$$\mathcal{W}(\theta_{cav}) = 2q$$

F. Baboux et al., PRB 95, 161114(R) (2017)

Theory: E. Levy et al., arxiv:1509.04028 (2015)

Spectral winding of interface states



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F. Baboux et al., PRB 95, 161114(R) (2017)

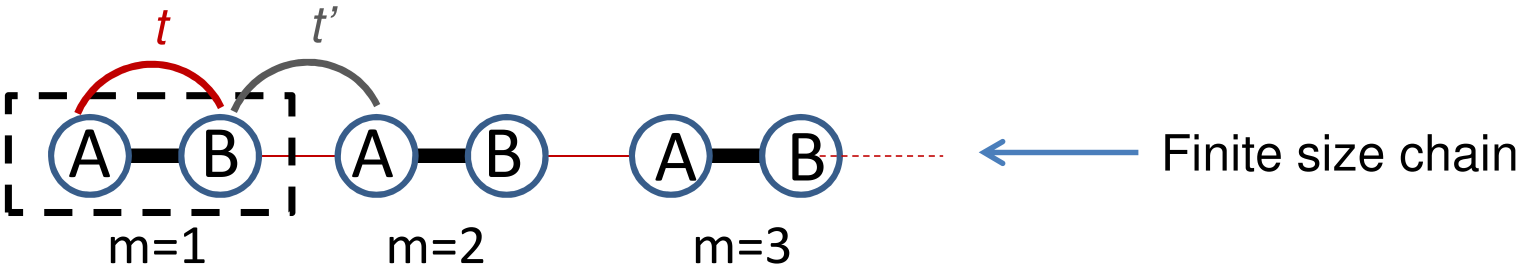
Theory: E. Levy et al., arxiv:1509.04028 (2015)

Lasing in topological edge modes

Combine:

- Photonic structure with topological edge modes
- Cavity with gain

The SSH Hamiltonian



Tight-binding Hamiltonian (real space)

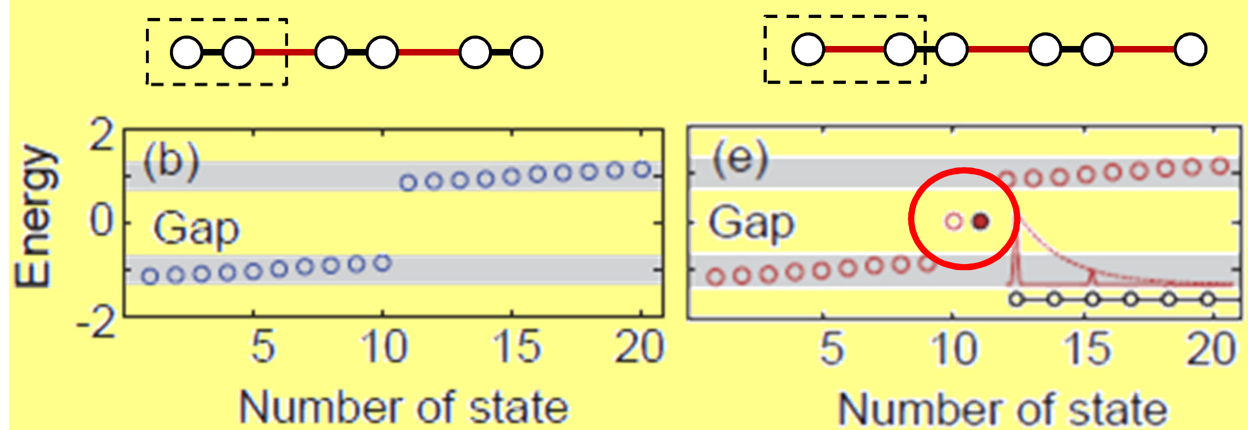
$$H = \sum_m \underbrace{t a_m b^+{}_m}_{\text{Intra-cell hopping}} + \underbrace{t' a^+{}_{m+1} b_m}_{\text{Inter-cell hopping}} + H.C.$$

Eigenstates

$$|\pm\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{-i\phi(k)} \\ \pm 1 \end{pmatrix}$$

Two possible dimerizations

t > t' | t < t'



$\mathcal{W} = 0$

NO edge states

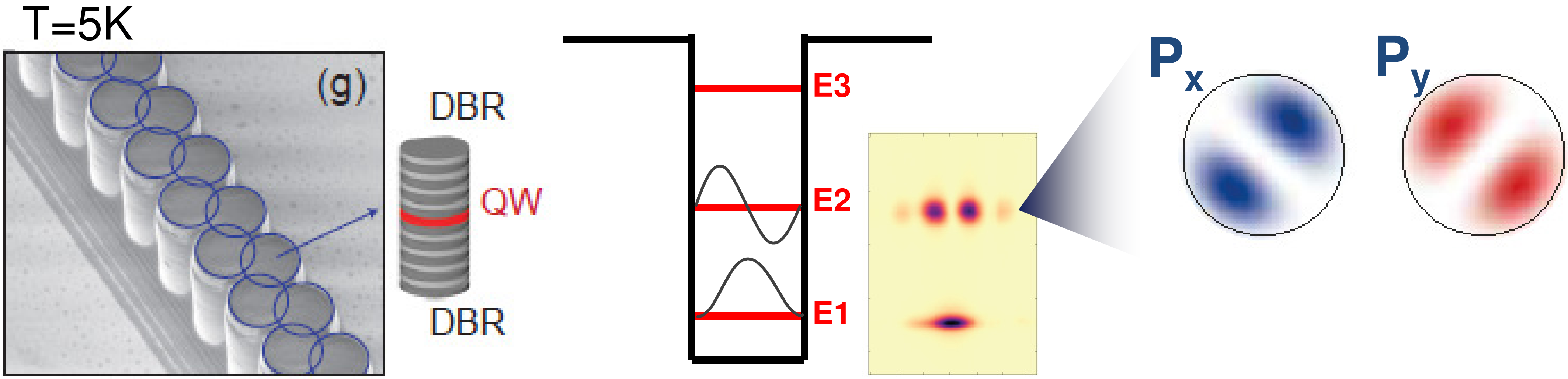
$\mathcal{W} = 1$

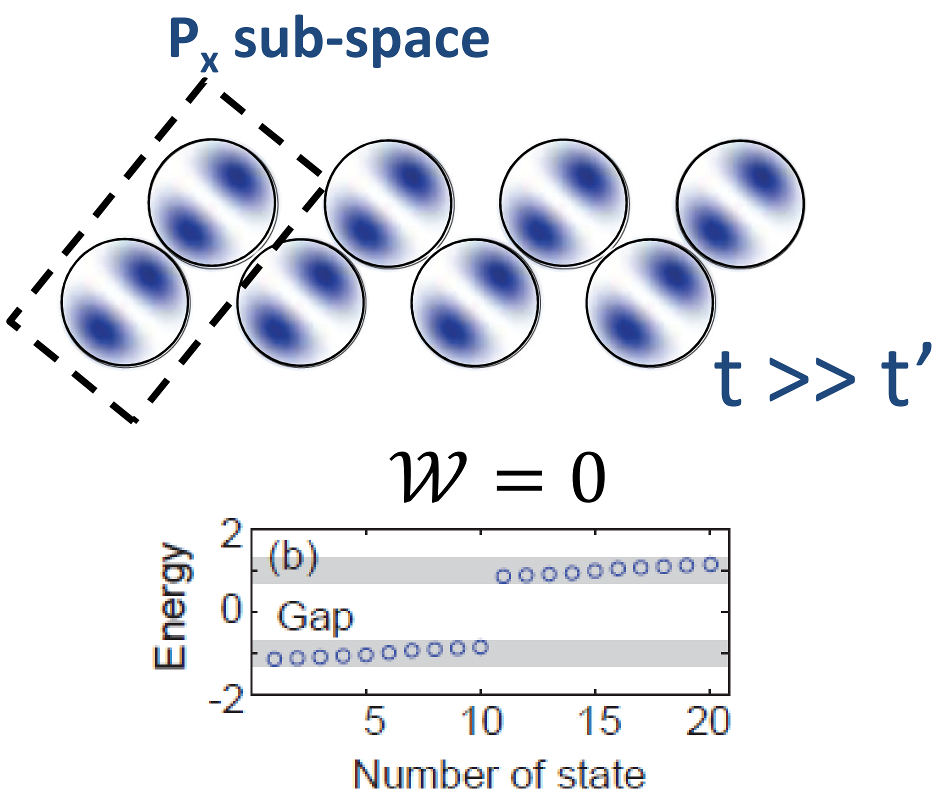
Edge states

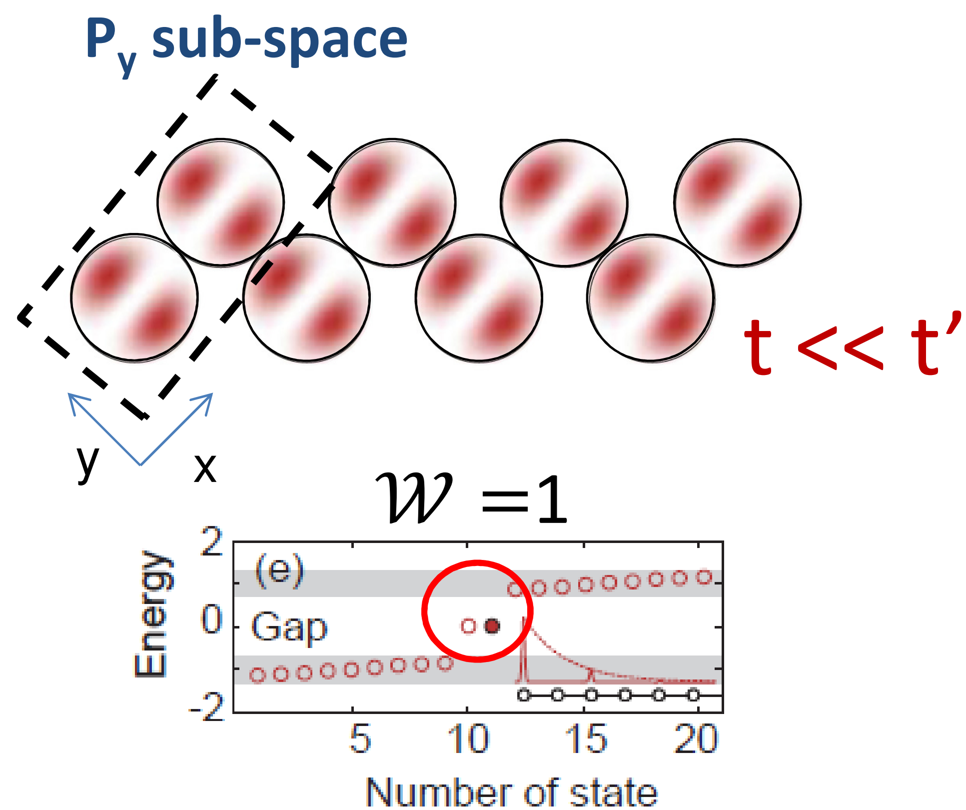
Winding number

$$\mathcal{W} = \frac{1}{2\pi} \oint \frac{\partial \phi(k)}{\partial k}\, dk$$

The SSH Hamiltonian with polaritons



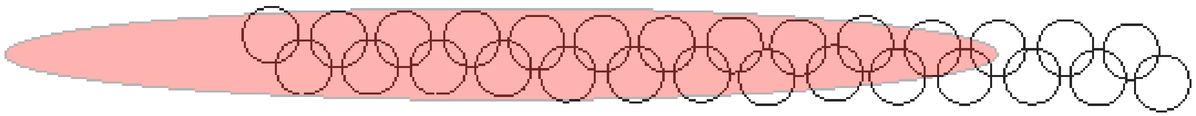


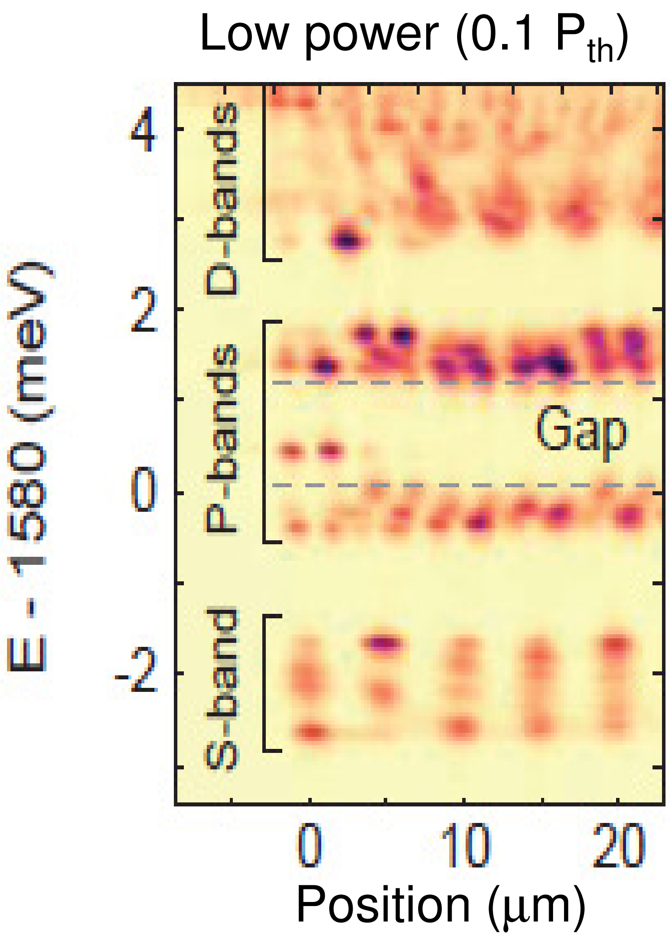


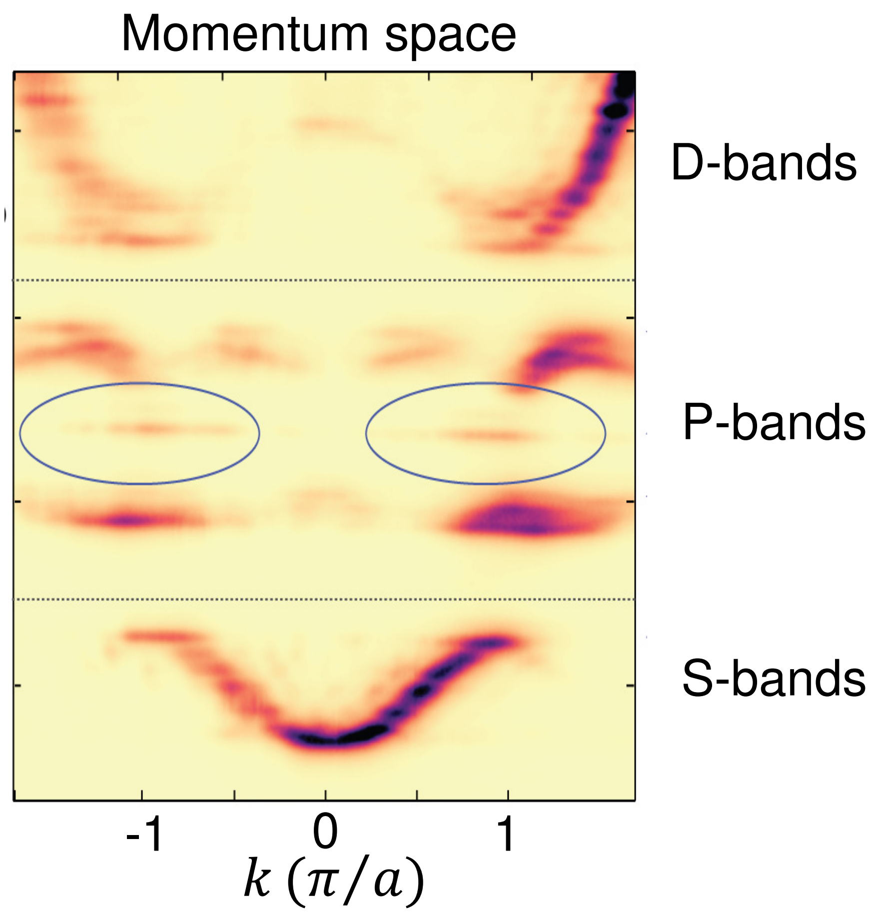
Both simultaneously present in the same chain

The SSH Hamiltonian with polaritons

T=5K



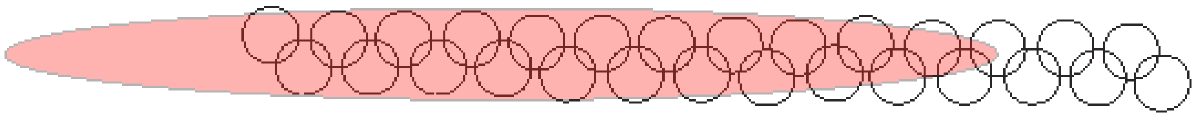


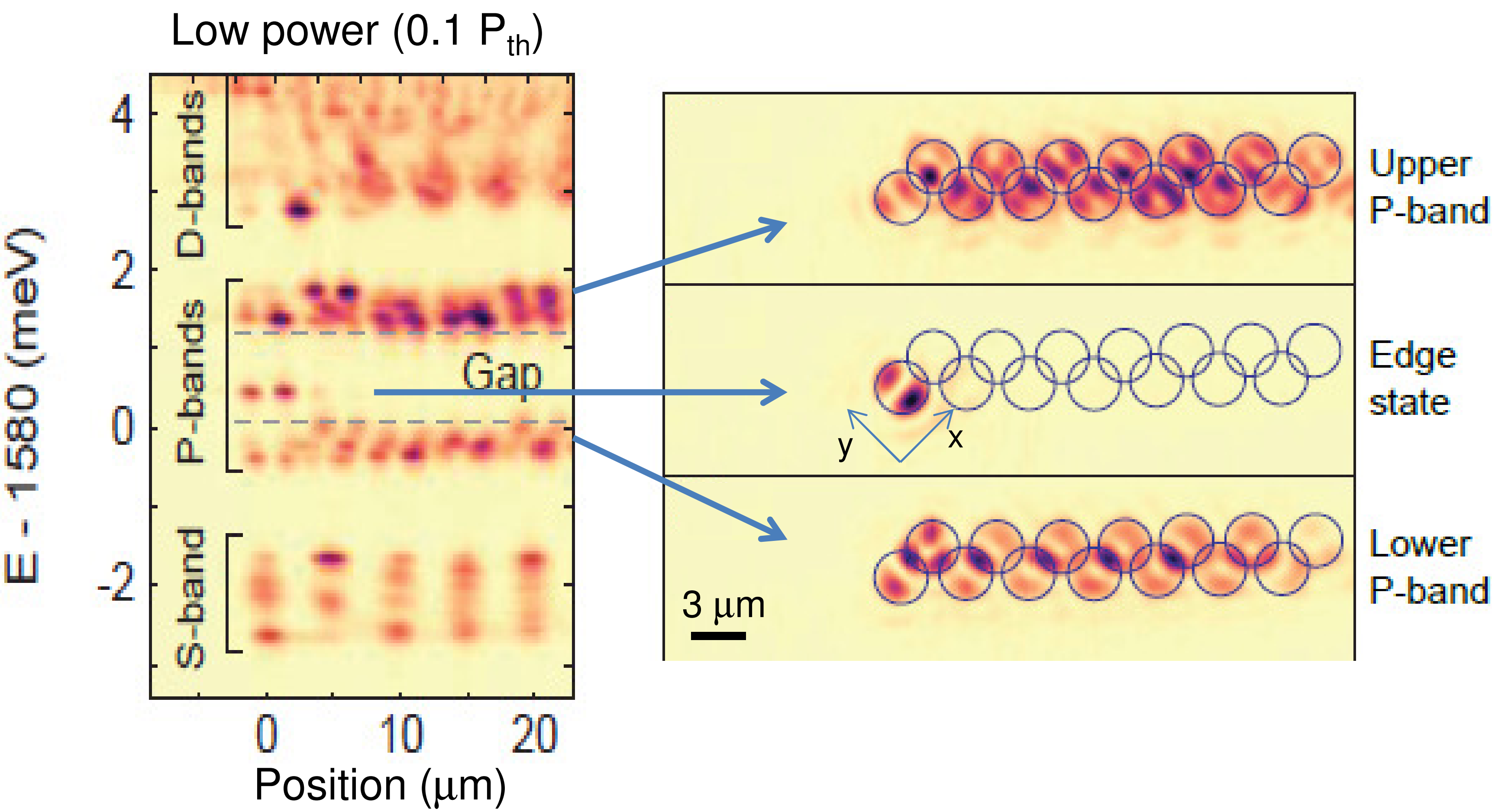


P. St-Jean et al., arXiv:1704.07310

The SSH Hamiltonian with polaritons

T=5K





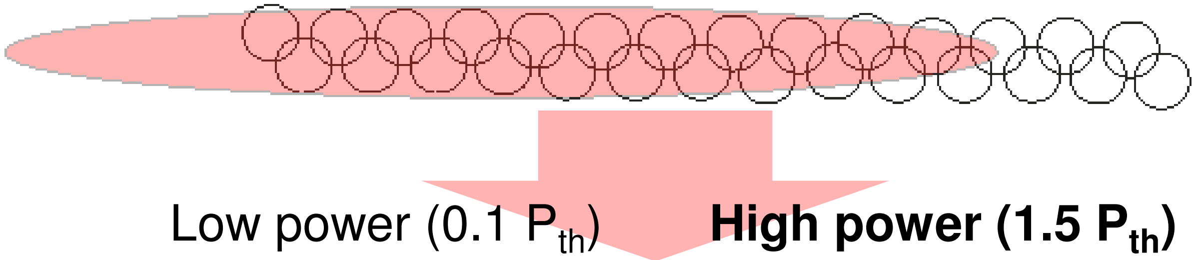
P_y sub-space strong localisation

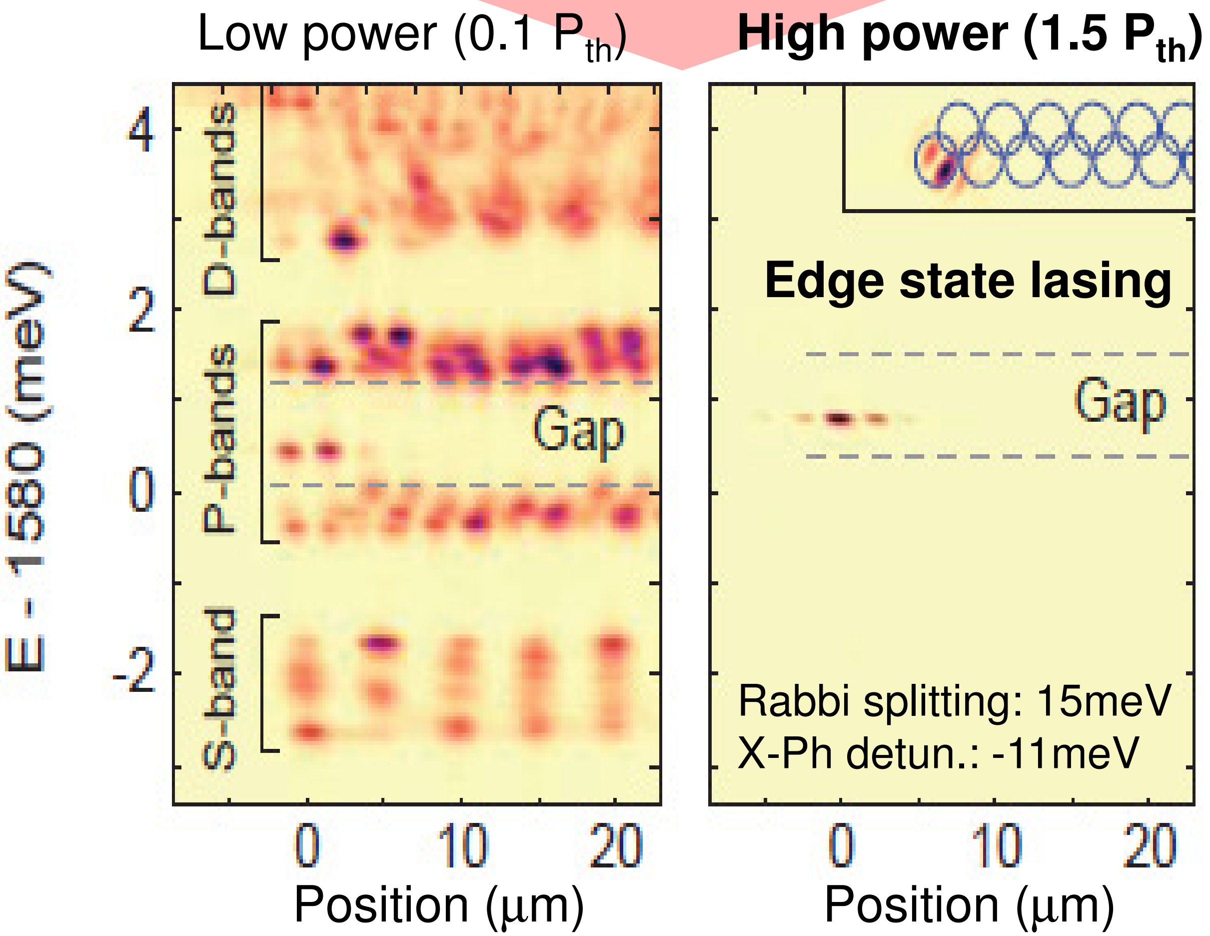
$\mathcal{W} = 1$

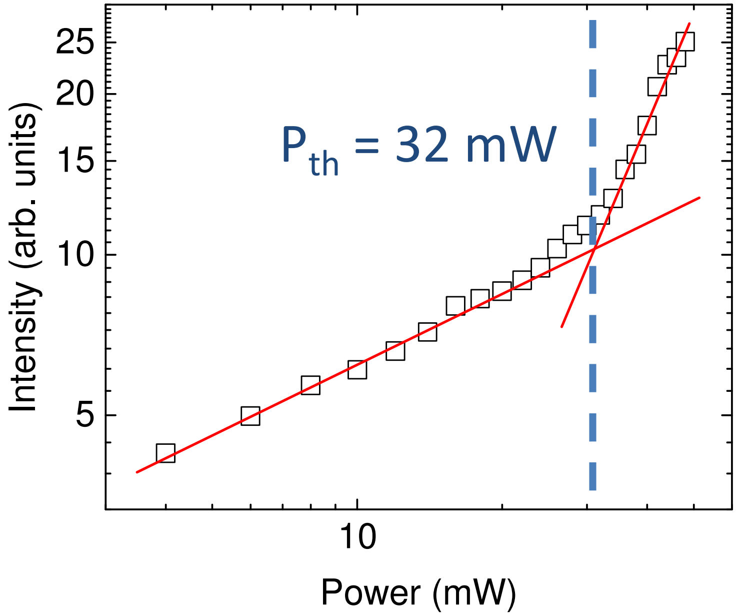
P. St-Jean et al., arXiv:1704.07310

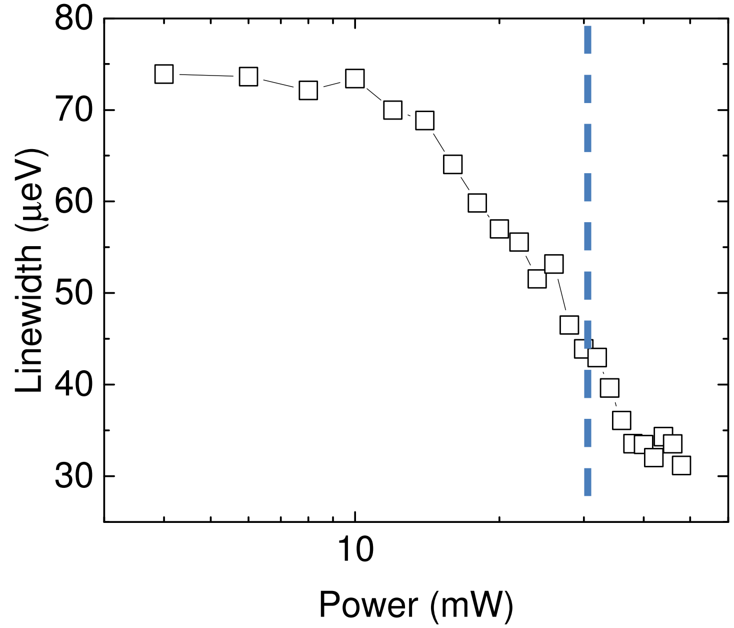
Lasing in topological state

T=5K









- Optimisation of exciton-photon denuning: gain
- Higher lifetime (localised state)

Topological robustness of lasing

Chiral symmetry of the SSH Hamiltonian

$$H(k) = \begin{pmatrix} 0 & t + t'e^{ika} \\ t + t'e^{-ika} & 0 \end{pmatrix} \qquad \{H, \sigma_z\} = 0$$

- Spectrum is symmetric around E=0
- **Localized states have energy E=0**

If <u>chiral symmetry preserved</u> (off-diagonal disorder): edge states are unaffected (no gap closing)

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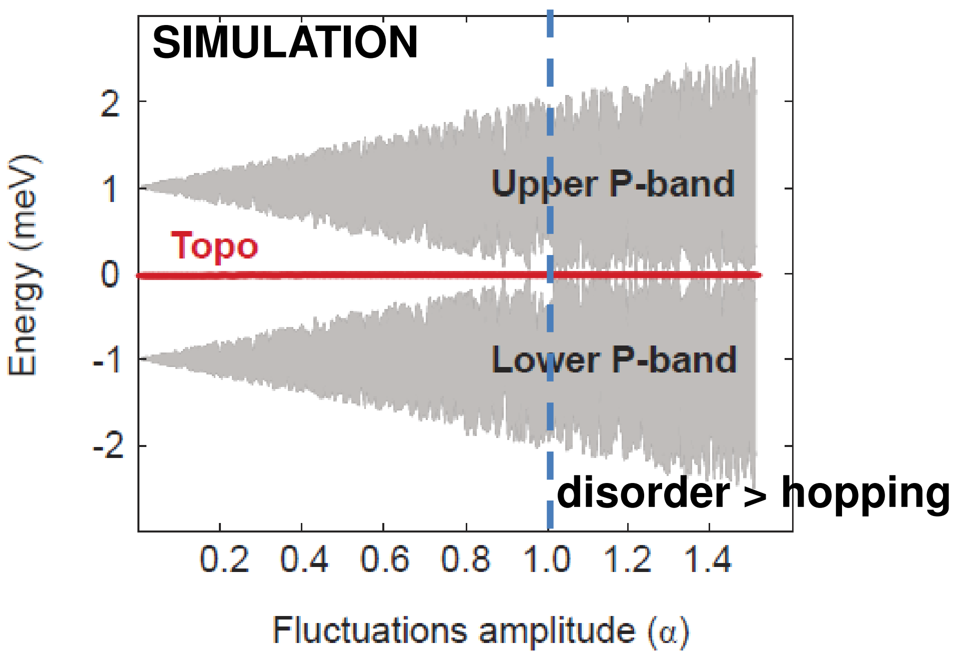
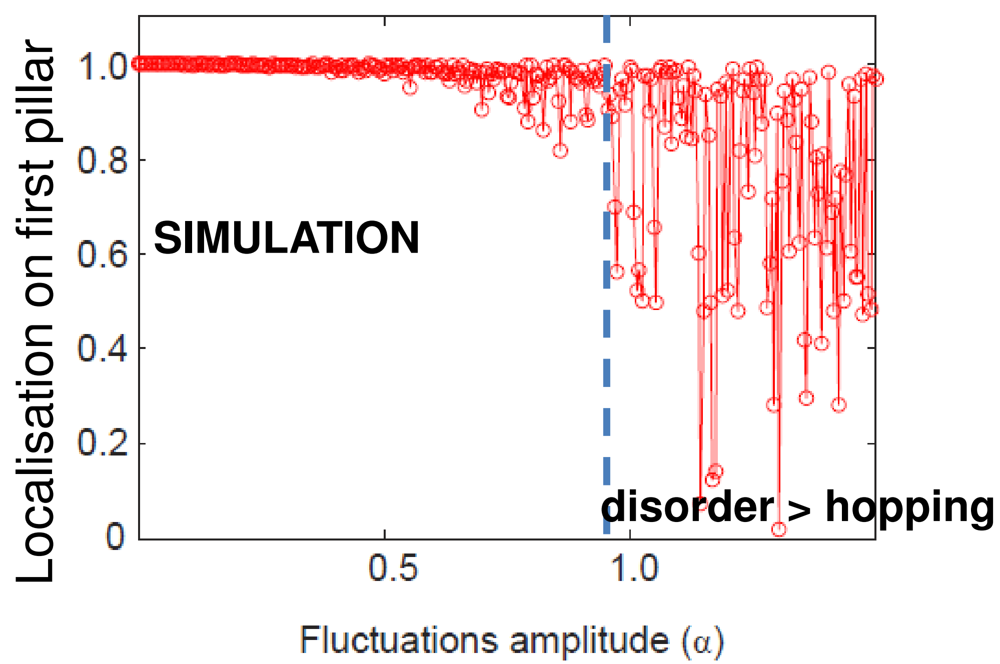
$$t_{l,t}^{(i)} \rightarrow \tilde{t}_{l,t}^{(i)}(1 + \alpha r_{l,t}^{(i)})$$

random number





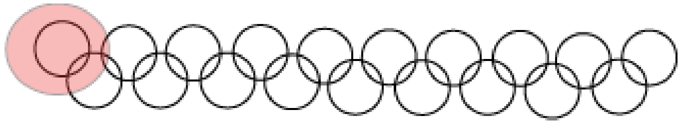
Robustness to breaking chiral symmetry

On-site disorder

$$H(k) = \begin{pmatrix} \Delta & t + t'e^{ika} \\ t + t'e^{-ika} & \Delta' \end{pmatrix}$$

Change energy of first pillar

$$H = \sum_m t a_m b^+{}_m + t' a^+{}_{m+1} b_m + H.C. + U_1 a_1 a^+{}_1$$



P. St-Jean et al., arXiv:1704.07310

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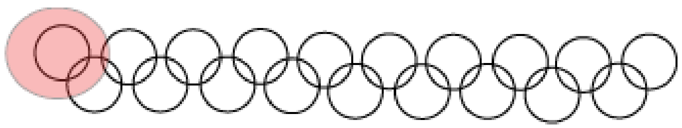
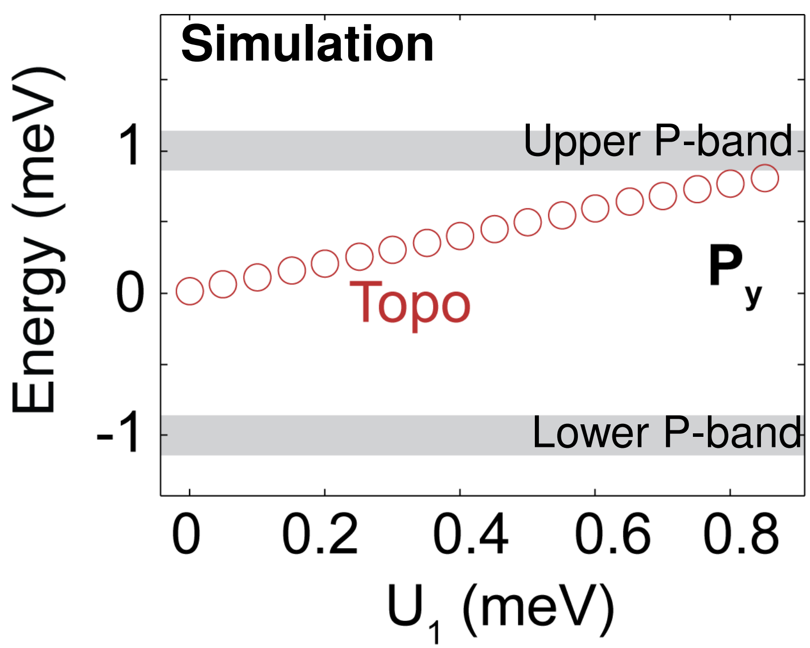
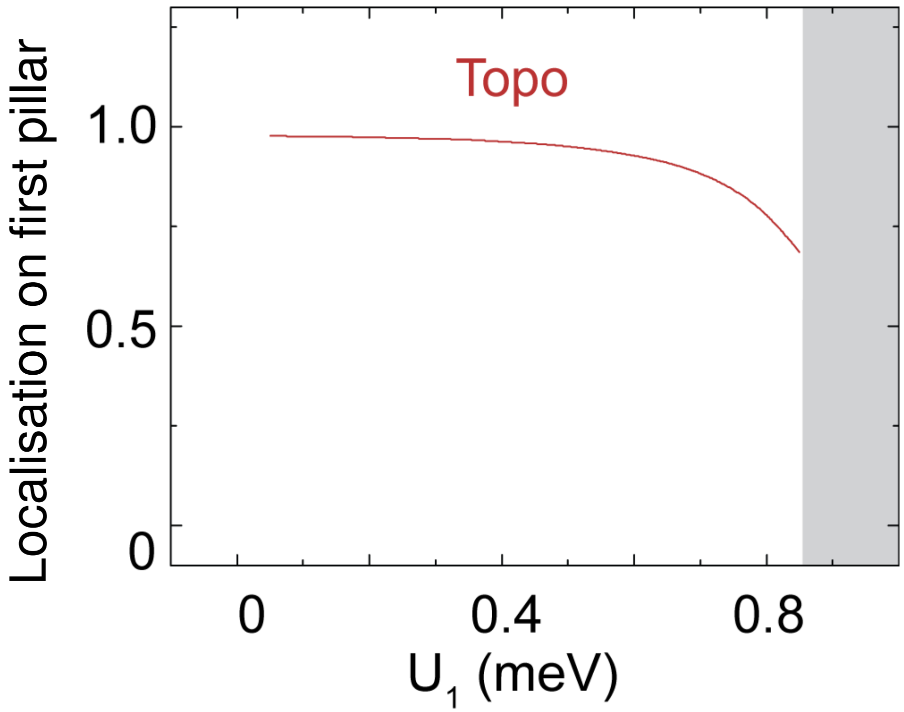


Blueshift of edge state



Keeps strong localisation



P. St-Jean et al., arXiv:1704.07310

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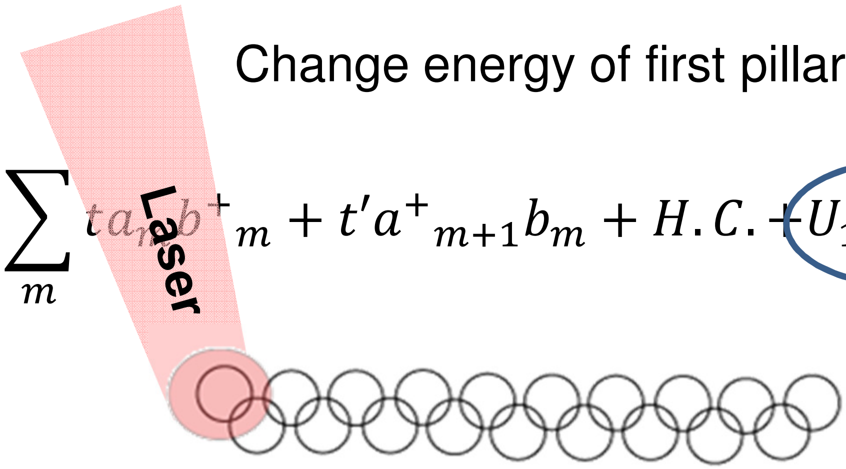
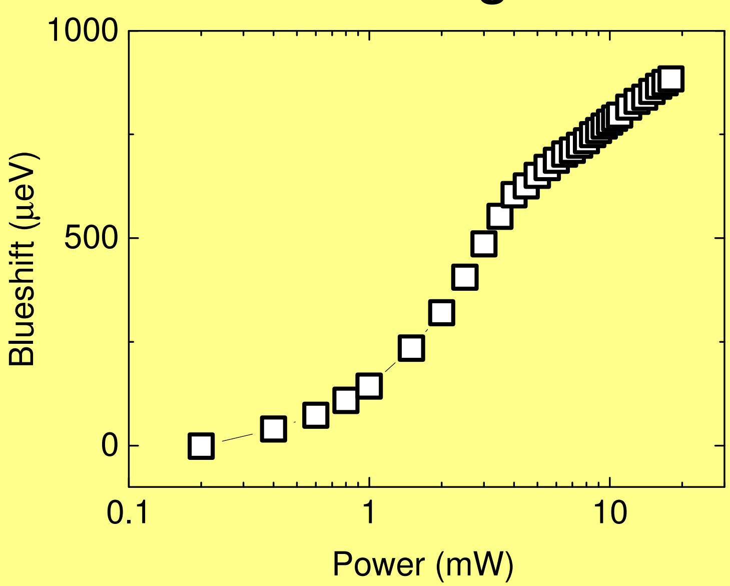


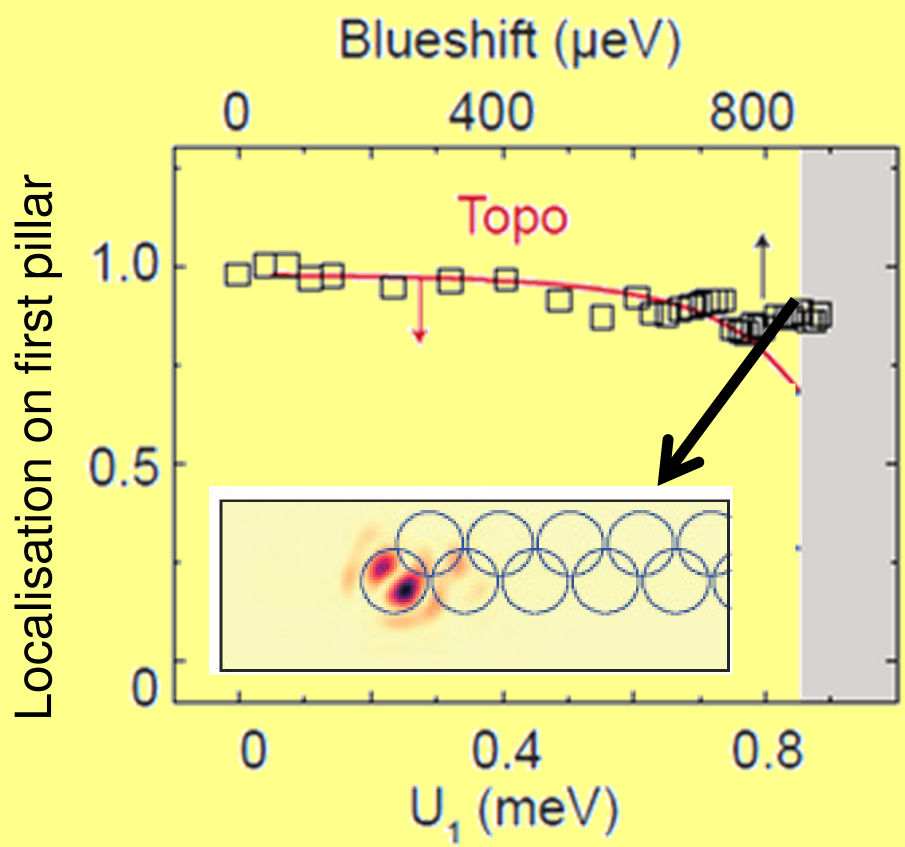
EXPERIMENT

Small excitation spot

injects **polariton reservoir in first pillar**

blueshift edge state





P. St-Jean et al., arXiv:1704.07310

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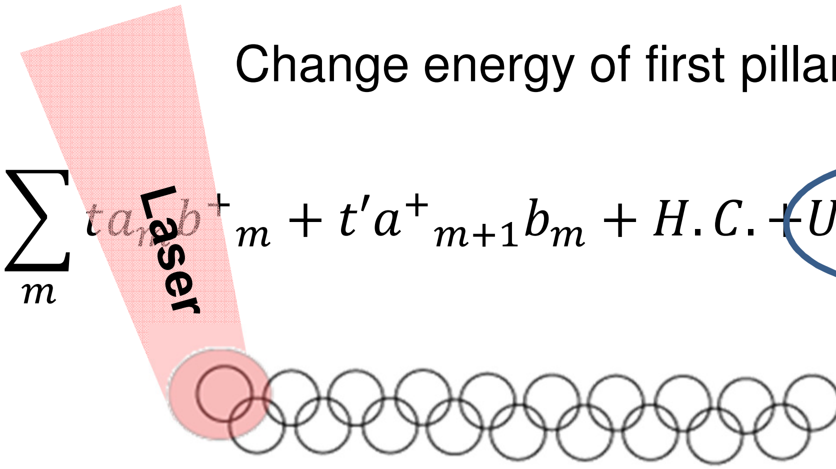


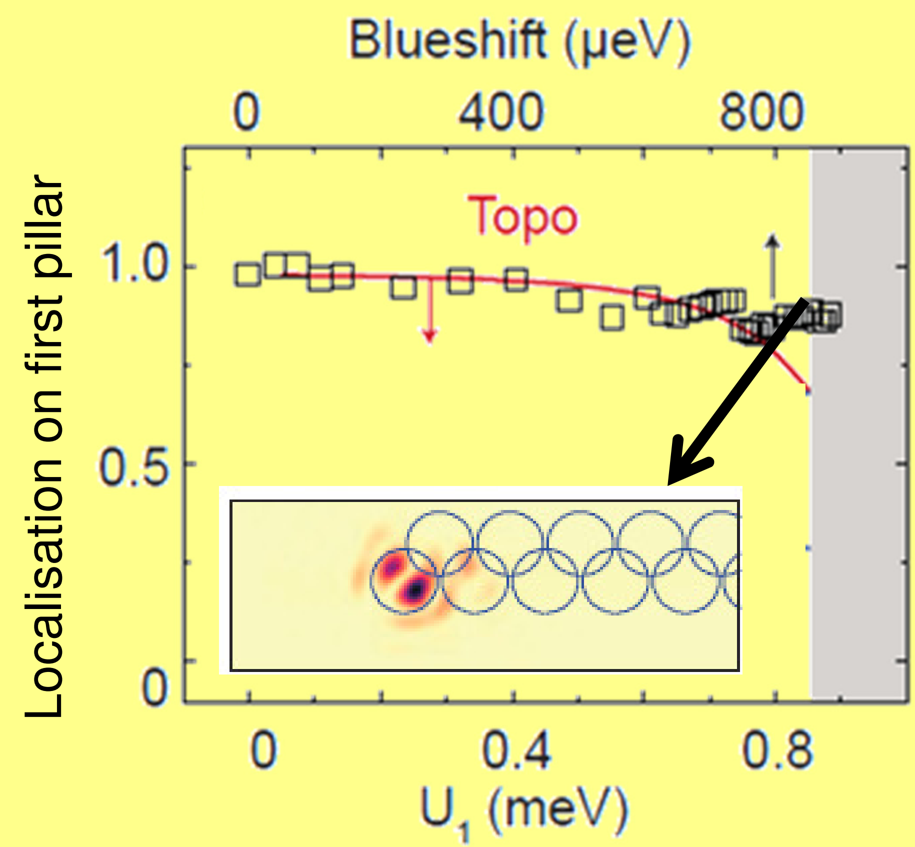
EXPERIMENT

Small excitation spot

injects **polariton reservoir in first pillar**

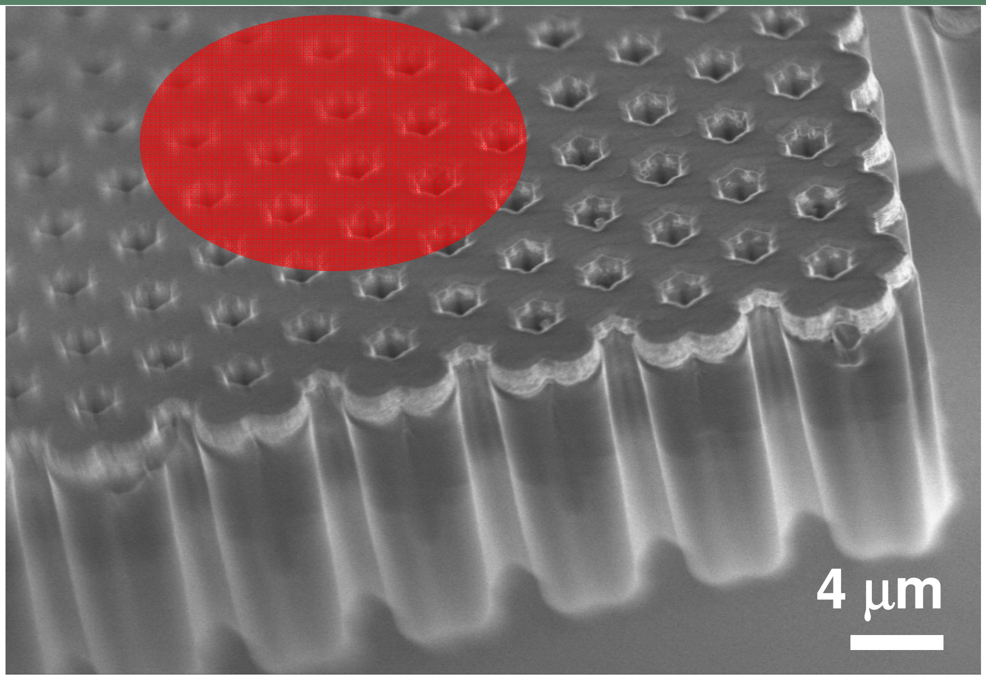
Topological robustness

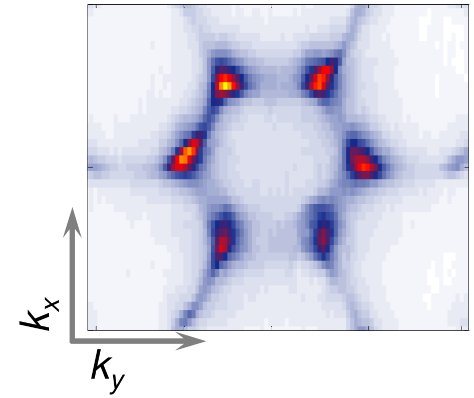
- **Disorder in hopping (chiral symmetry)**
- **On-site disorder (strong localisation)**



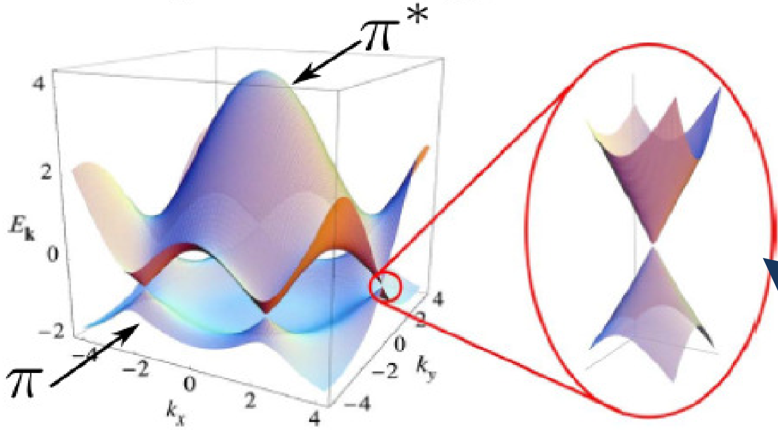
Power (mW)

Polariton honeycomb lattice

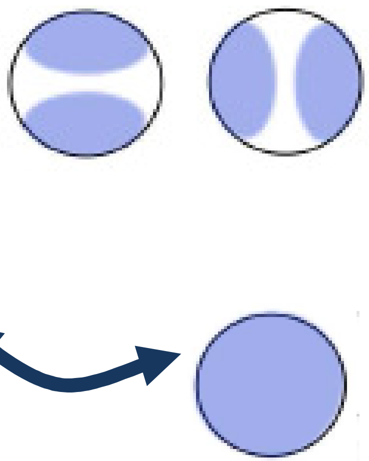


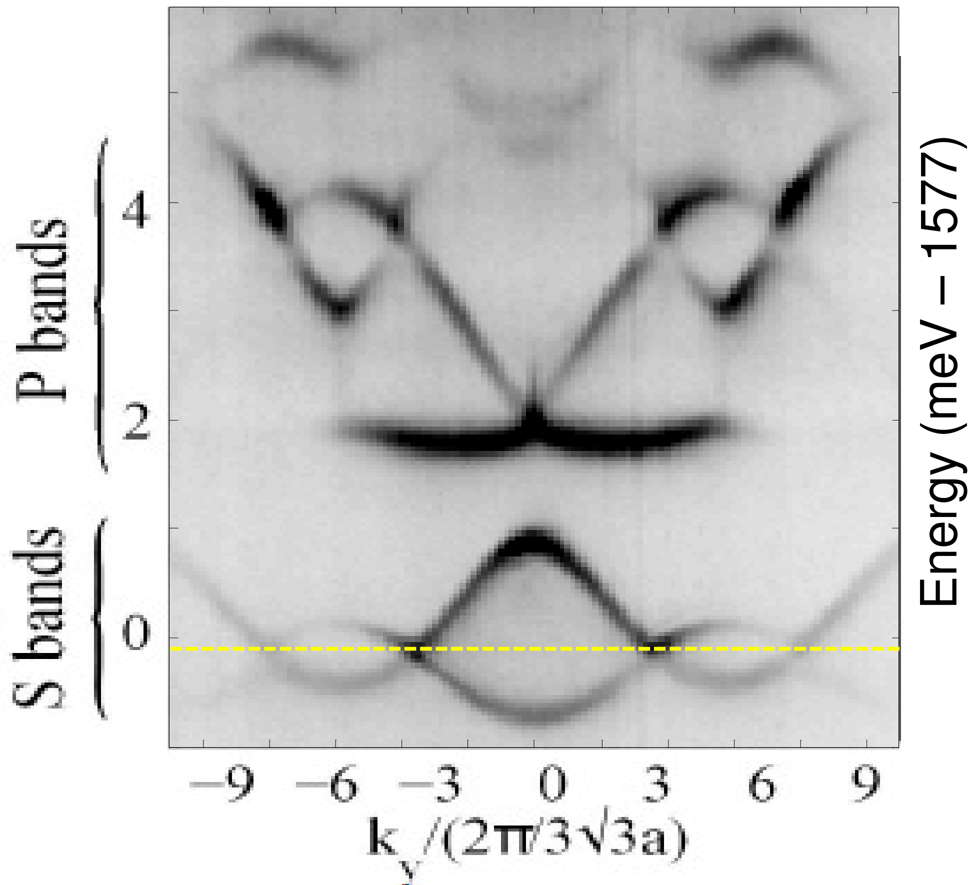


Graphene energy bands



Castro Neto et al., Rev. Mod. Phys. 81 (2009)

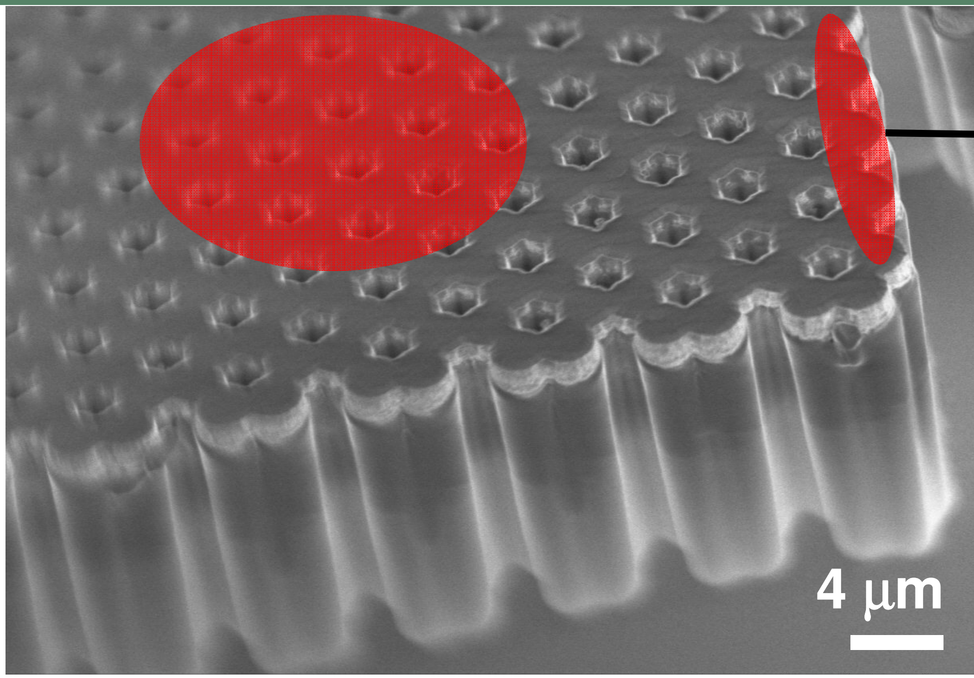




Polariton Dirac cones

Jacqmin *et al.*, PRL **112,** 116402 (2014)

Polariton honeycomb lattice

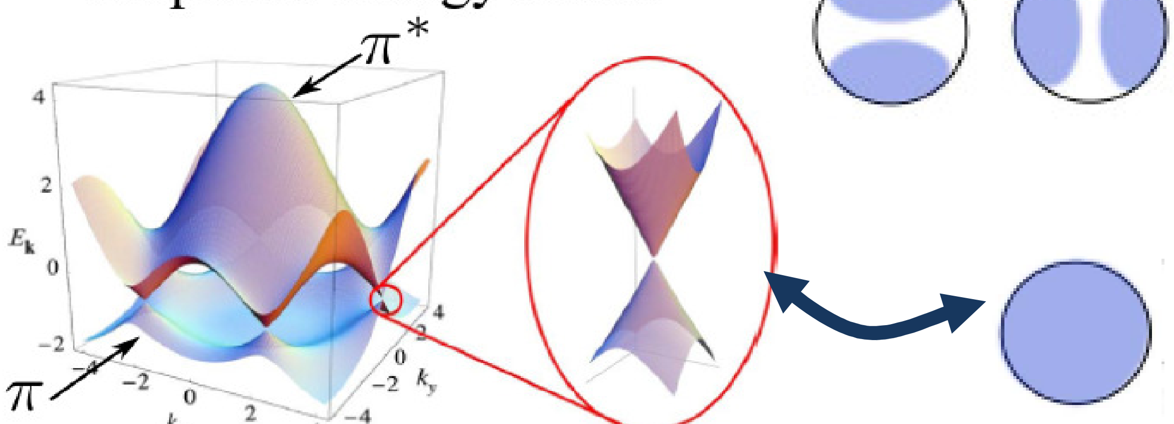


Topological edge states

Related to bulk invariants

S. Ryu and Y. Hatsugai, PRL. **89**, 077002 (2002)
P. Delplace et al., PRB **84**, 195452 (2011)

Graphene energy bands



Castro Neto et al., Rev. Mod. Phys. 81 (2009)

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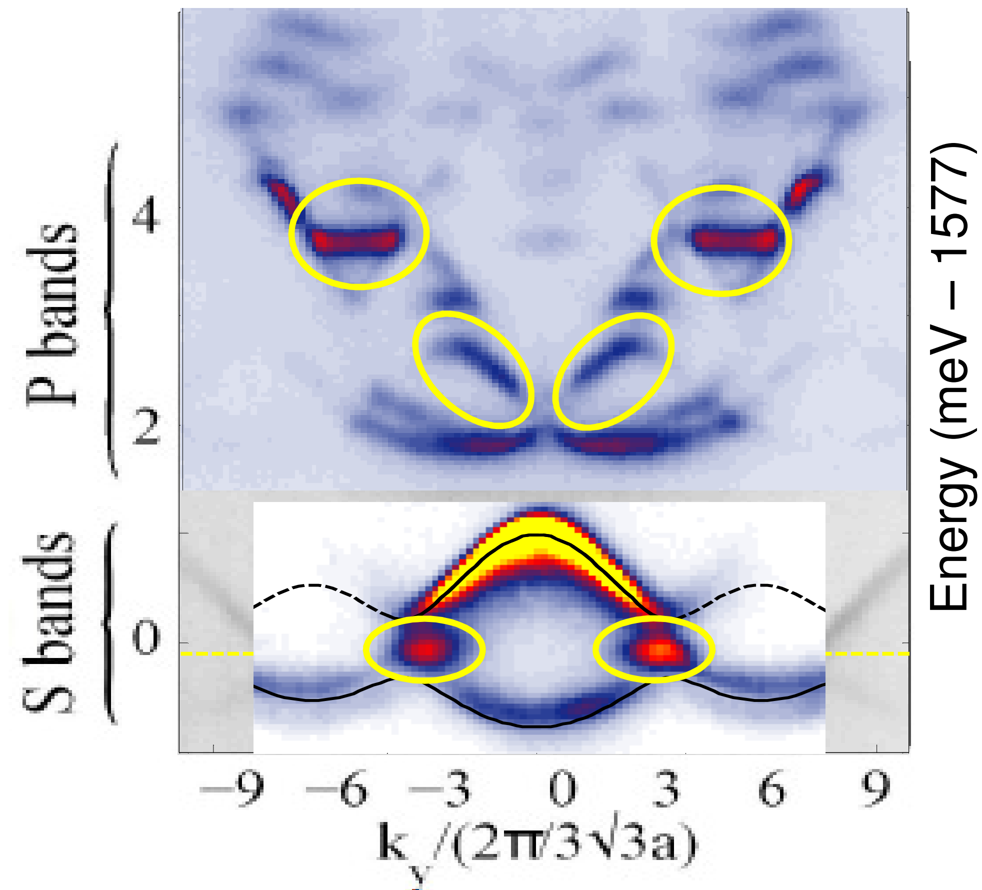
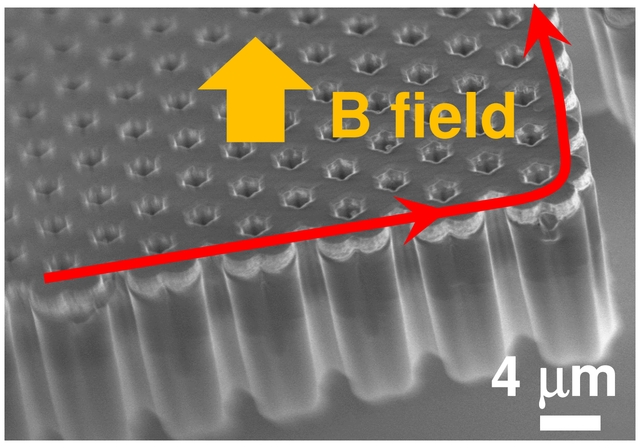


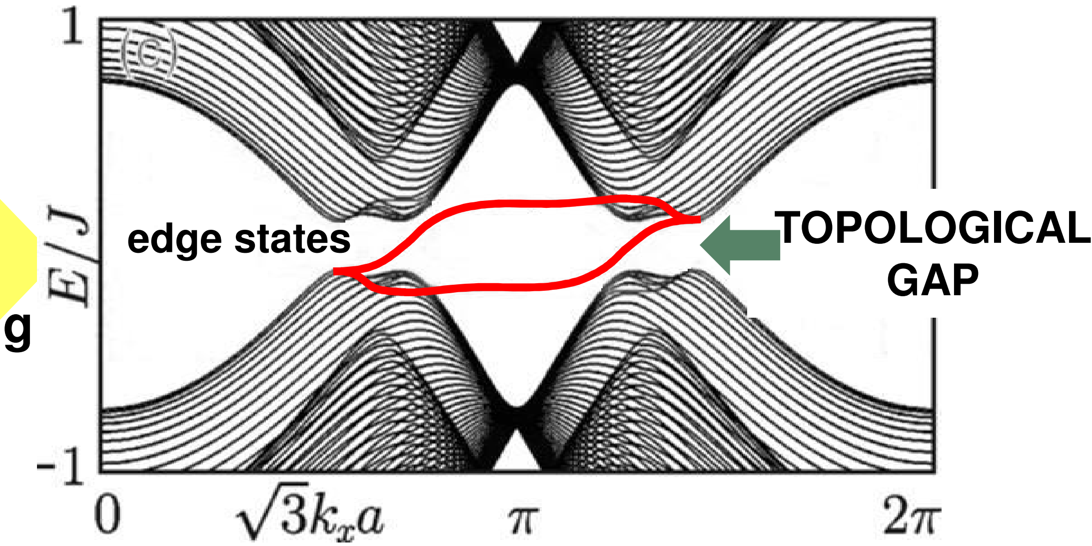
Milicevic et al., 2D Mater. **2,** 034012 (2015)
Milicevic et al., PRL **118**, 107403 (2017)

Perspectives: polariton Chern insulator

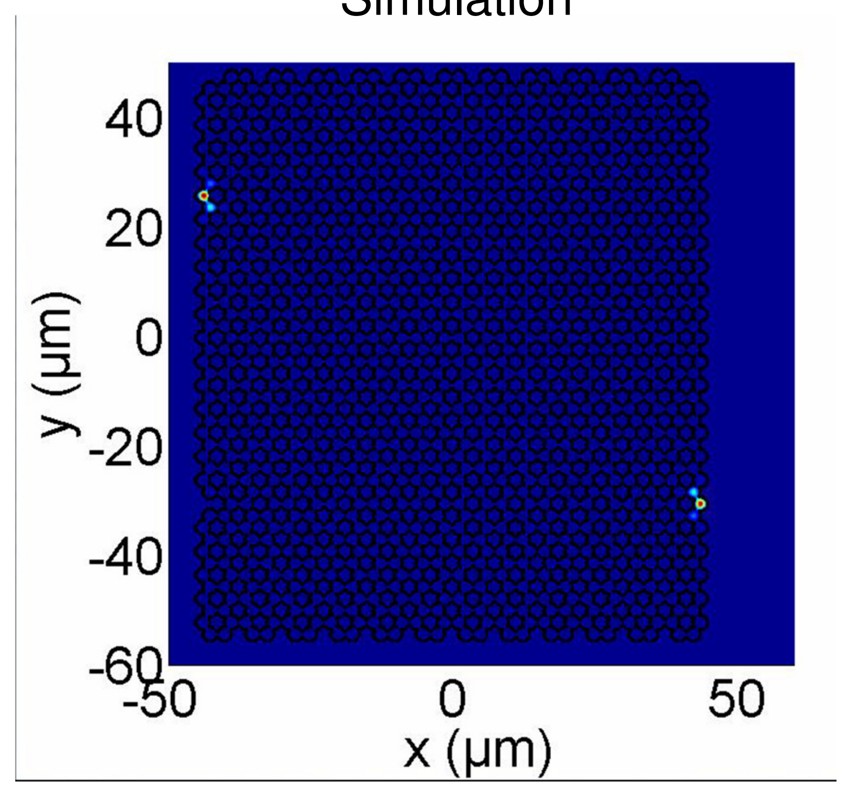


Nalitov, et al., PRL **114**, 116401 (2015)
Bardyn et al., PRB **91,** 161413(R) (2015)

Magnetic field
+
spin-orbit coupling

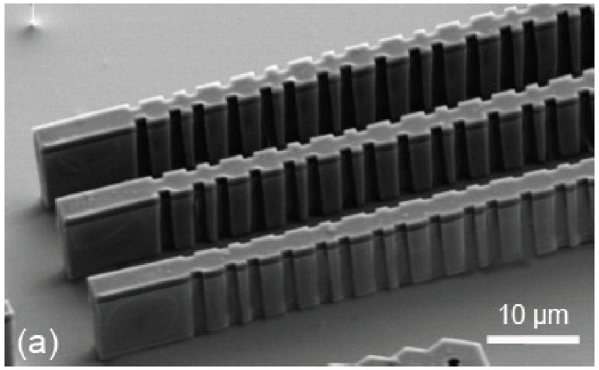


Simulation



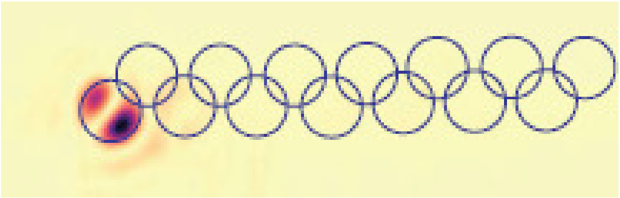
Emulation with polaritons at LPN

Topological invariants in Fibonacci quasi-crystal



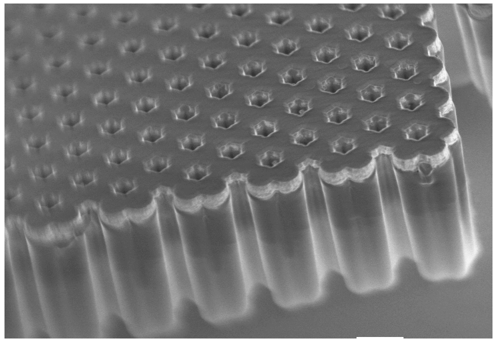
D. Tanese et al., PRL 112, 146404 (2014)
F. Baboux et al., PRB 95, 161114(R) (2017)

Lasing in topological edge states



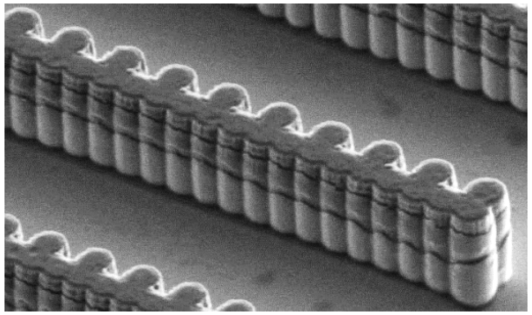
P. St-Jean et al., arXiv:1704.07310

Dirac physics



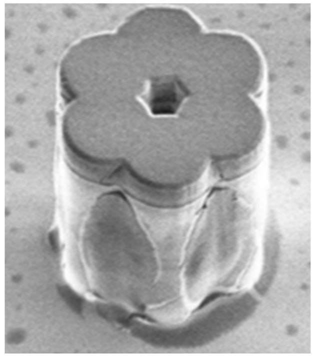
T. Jacqmin et al., PRL **112**, 116402 (2014)
M. Milicevic et al., 2D Mater. **2,** 034012 (2015)
M. Milićević et al., PRL **118,** 107403 (2017)

Flat band physics



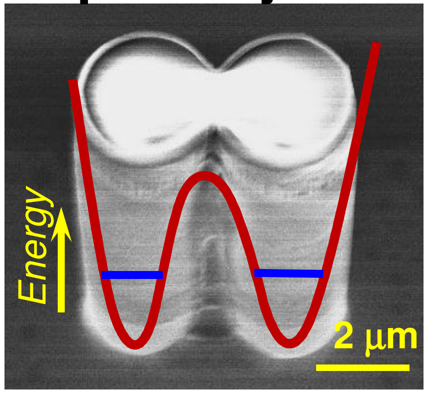
F. Baboux et al.,
PRL **116**, 066402 (2016)

Spin-orbit coupling



V. G. Sala et al.,
PRX **5**, 011034 (2015)

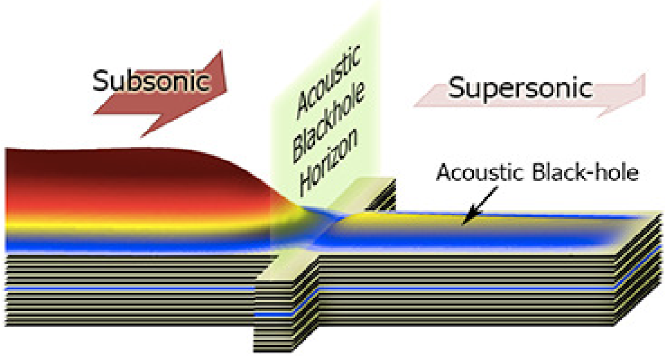
Nonlinear Josephson junction



Abbarchi et al.,
Nat. Phys. **9**, 275 (2013)

S. R. K. Rodriguez, et al.,
Nat. Commun. **7**, 11887 (2016)

Hawking physics



H.S. Nguyen et al.,
PRL **114**, 036402 (2015)