Orbital edge states in photonic lattices

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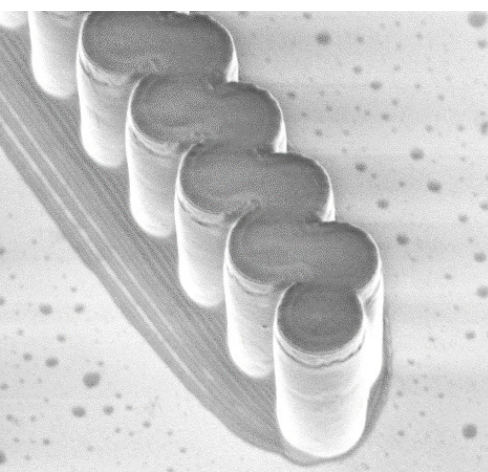

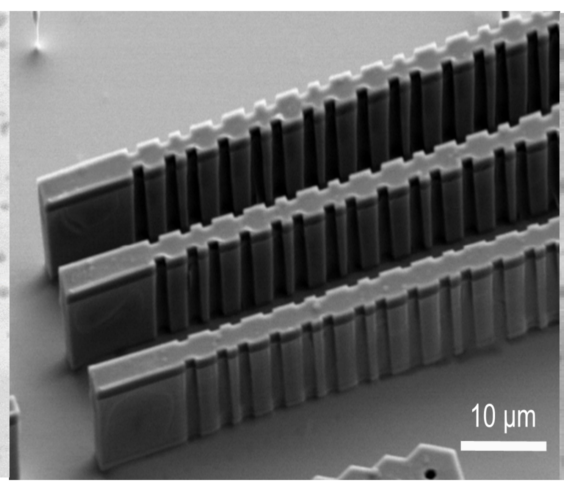

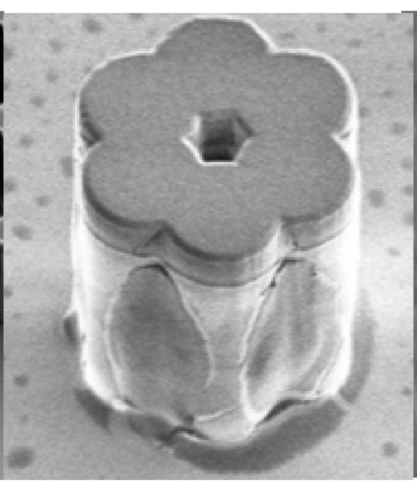

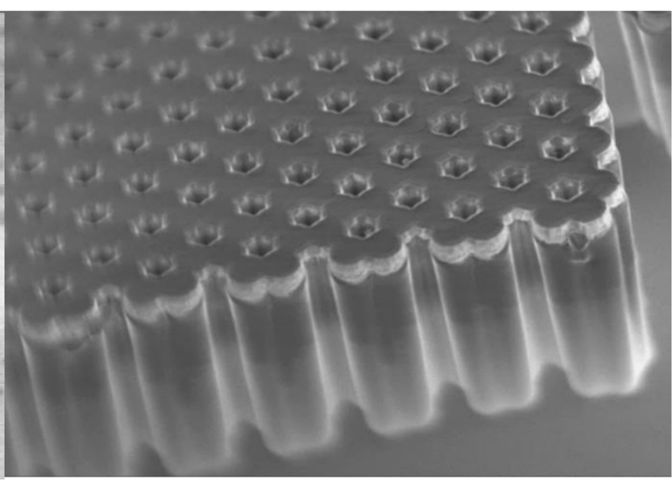

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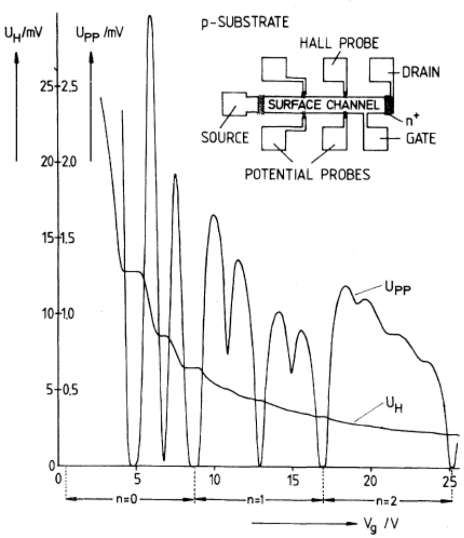
ANALOG QUANTUM SIMULATORS FOR MANY-BODY DYNAMICS

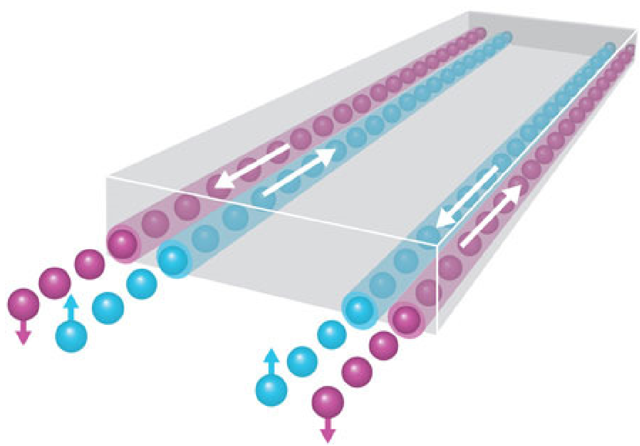
Emerging physics in the solid state

Quantum Hall effect



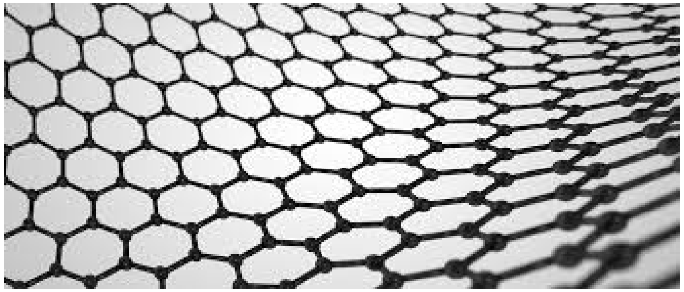
K. v. Klitzing, et al.,
PRL **45,** 494 (1980)

Topological insulators



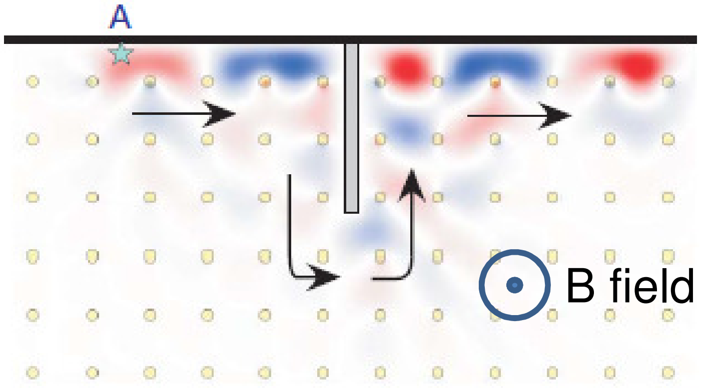
T. Dube, ScienceNews

Graphene and 2D materials



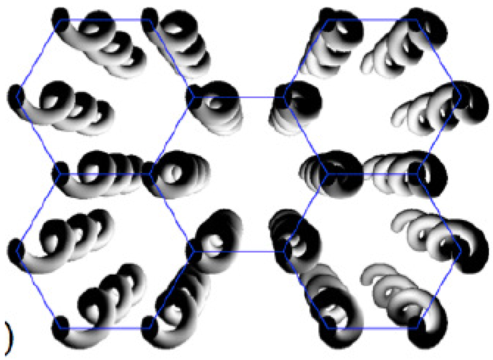
Topological photonics: edge states

Chiral transport for microwaves



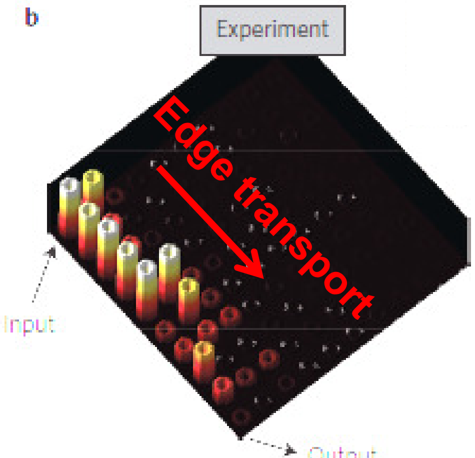
Z. Wang et al., Nature **461**, 772 (2009)

Floquet topological insulators



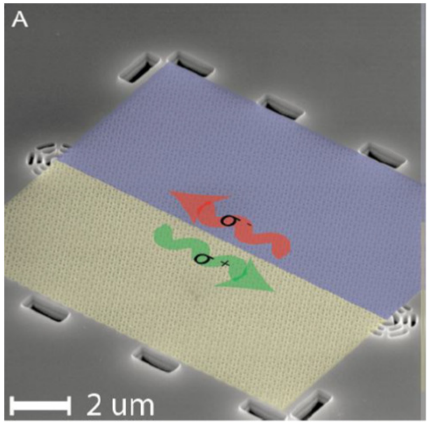
M. C. Rechtsman et al.,
Nature **496**, 196 (2013)

Edge transport in Si resonators



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

Pseudo $\mathbb{Z}_2$ topological insulator

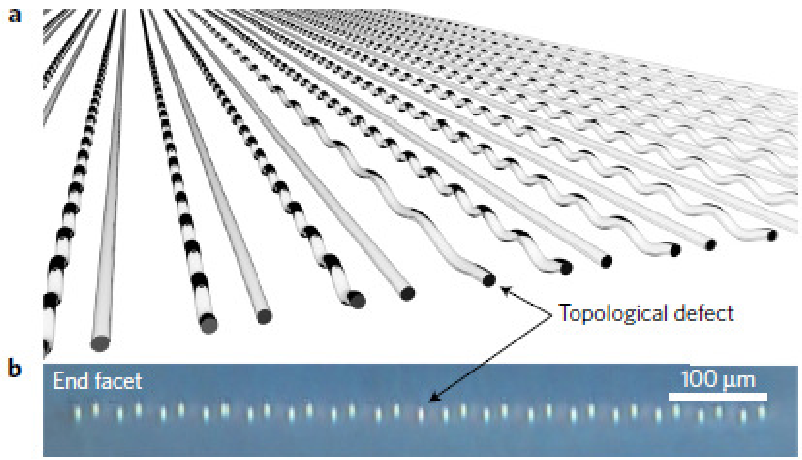


S. Barik et al., arxiv:1711.00478
L.Wu and X. Hu, PRL 114 , 223901 (2015)

For a review: L. Lu, J. D. Joannopoulos, and M. Soljačić, Nat. Photon. **8**, 821 (2014), Nat. Phys. **12**, 626 (2016).

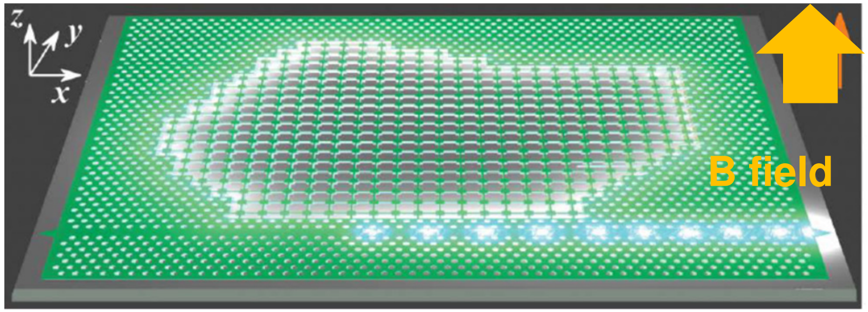
Photonic lattices: new opportunities

PT symmetric bound states



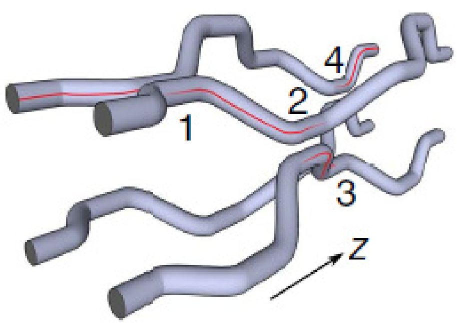
S. Weimann et al., Nat. Mater. 16, 433 (2017)

Topological insulator lasers



B. Bahari et al., Science **358**, 636 (2017)

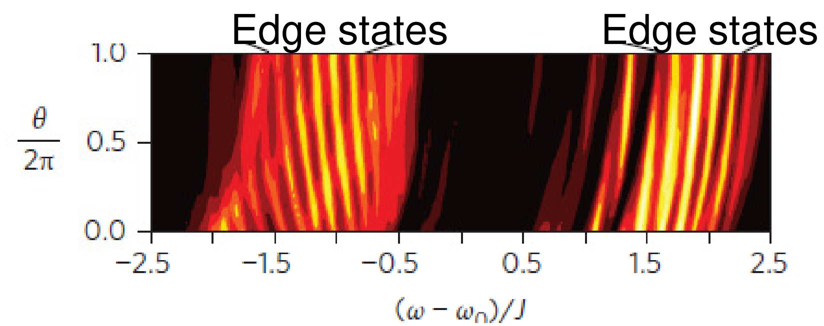
Topological pumps



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

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

Measurement of topological invariants



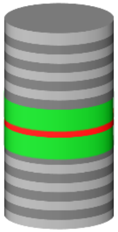
S. Mittal et al., Nat. Photonics 10, 180 (2016)

W. Hu et al., PRX 5, 011012 (2015)

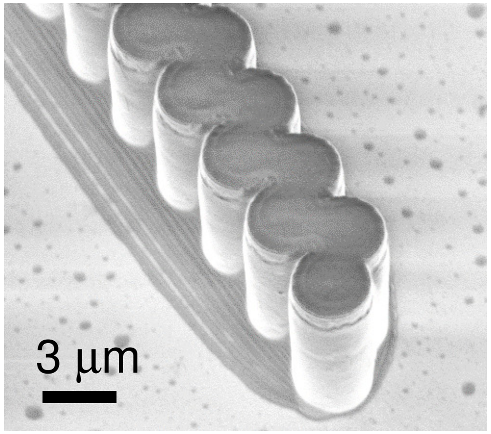
F. Cardano, et al., Nat. Commun. 8, 15516 (2017)

Outline

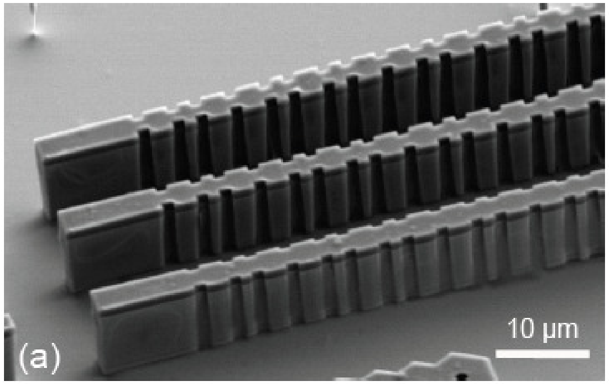
➡ **Hamiltonian engineering in a polariton system**



➡ **Lasing in orbital SSH edge states**



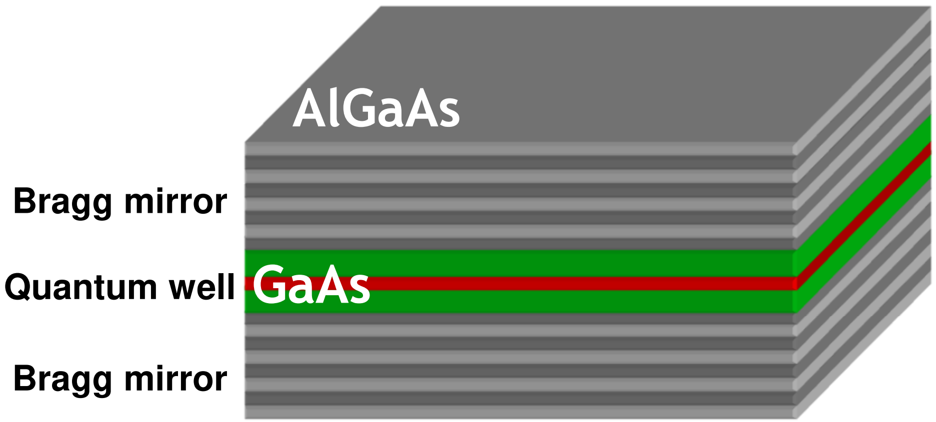
➡ **Measuring topological invariants in quasicrystals**



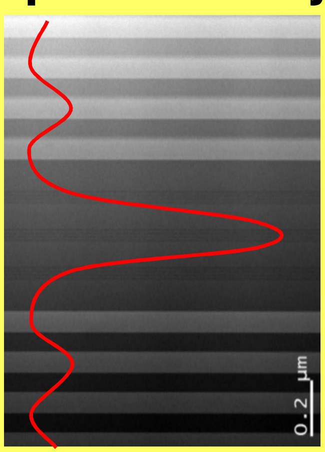
Microcavity polaritons

T=5K

2D (MBE grown)

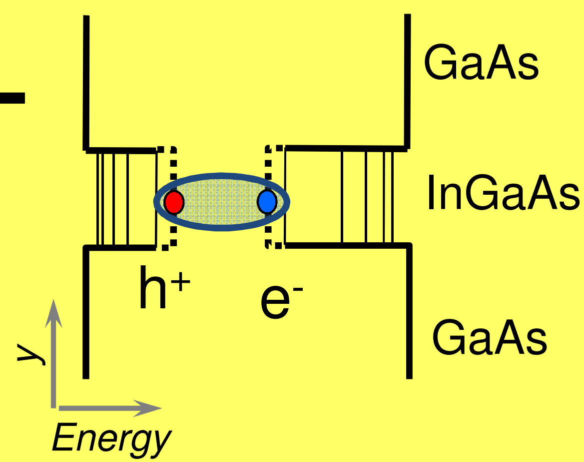


Optical Cavity



+

Quantum well

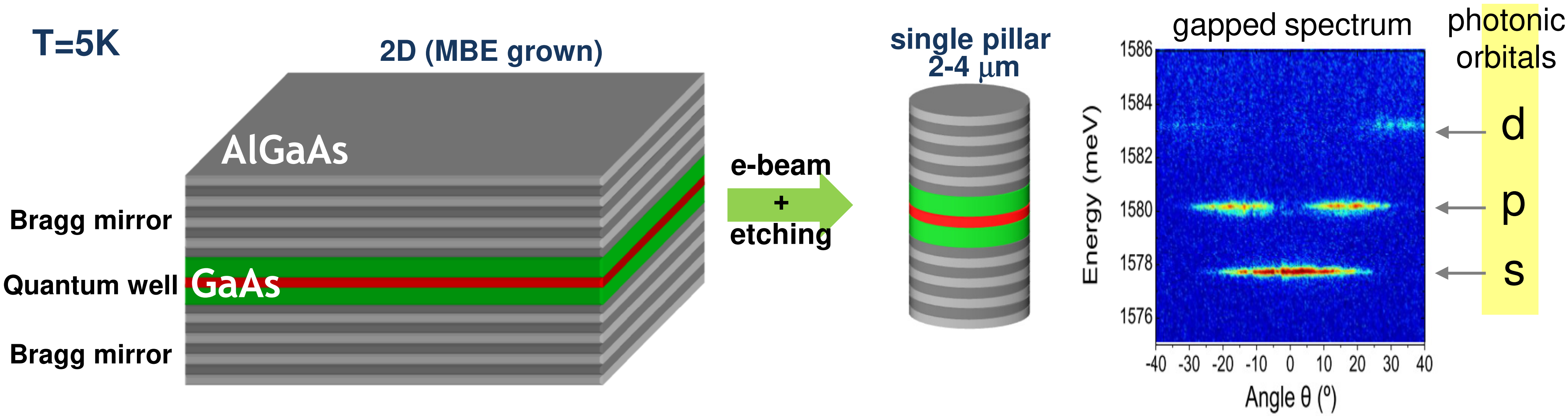


$$|pol\rangle = X_k|exc\rangle + C_k|phot\rangle$$

- **Confinement**

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

Confined polaritons



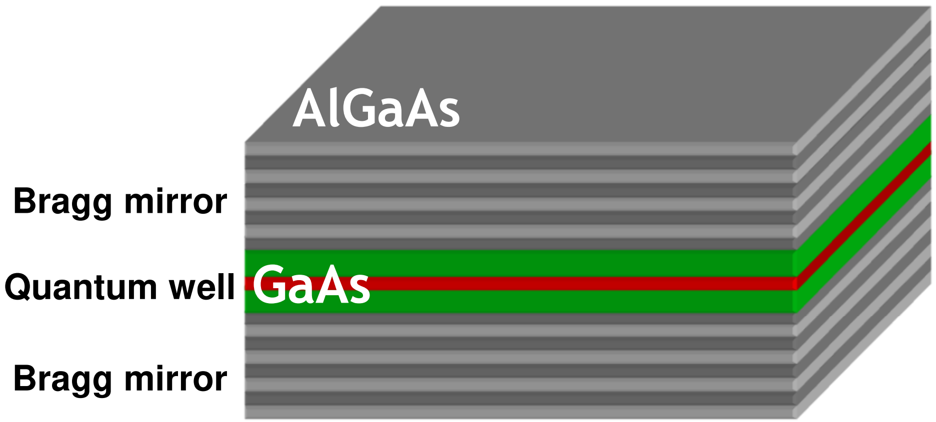
Other techniques: Stanford, Lausanne, Würzburg, Berlin, Sheffield, Cambridge, Southampton, Crete, Michigan…

C. Schneider et al., Rep. Prog. Phys. 80, 16503 (2017)

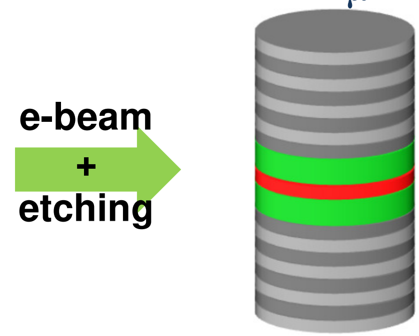
Confined polaritons

T=5K

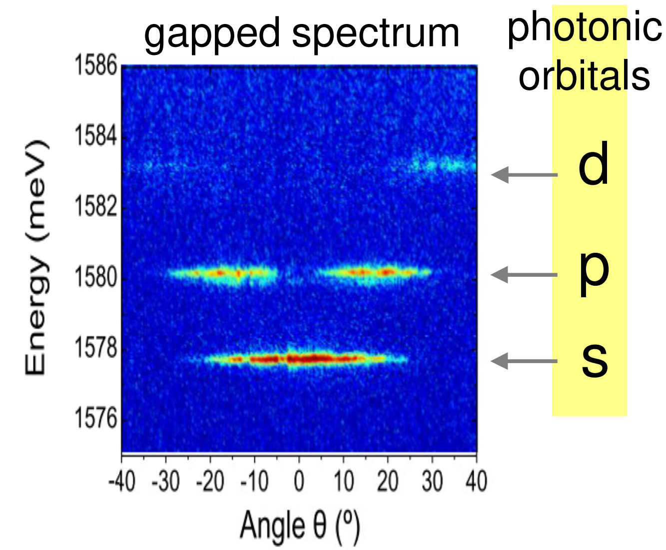
2D (MBE grown)



single pillar
2-4 μm



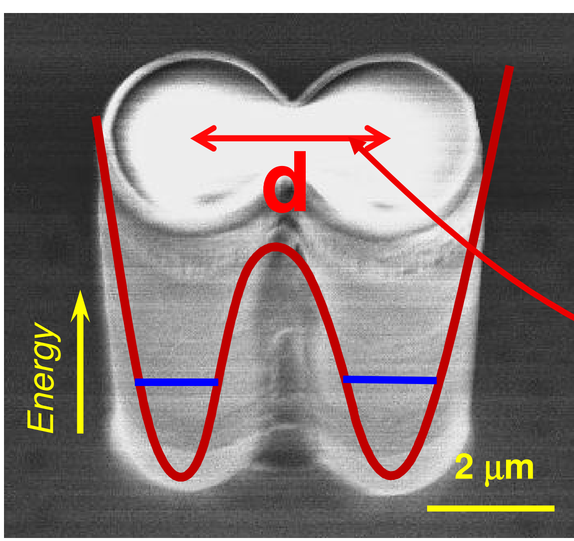
gapped spectrum



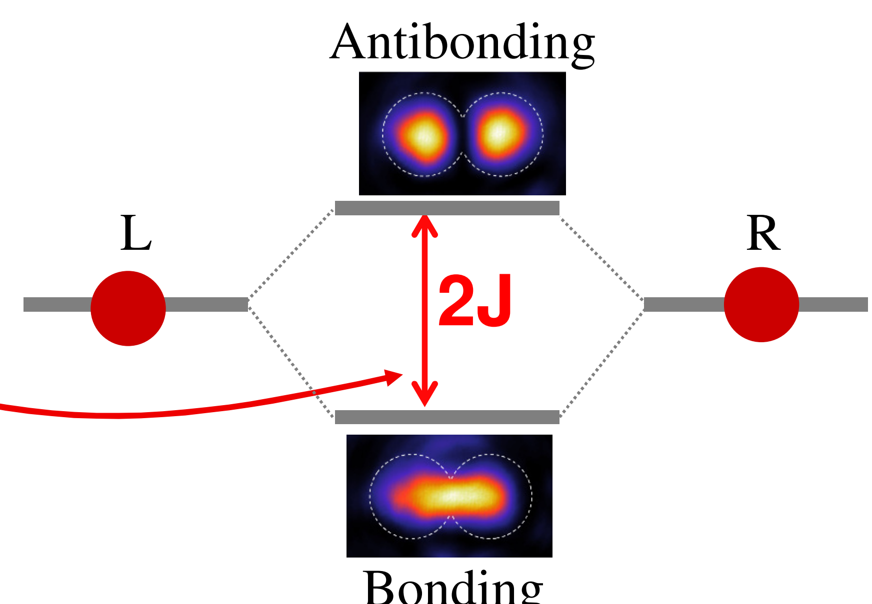
Coupled micropillars

Photonic tunneling

Tight-binding building block (orbital)



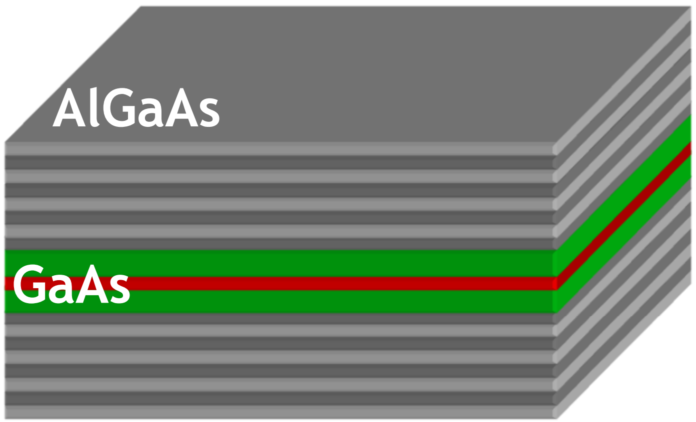
Michaelis de Vasconcellos et al., APL **99**, 101103 (2011)



Confined polaritons

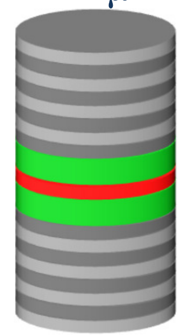
T=5K

2D (MBE grown)

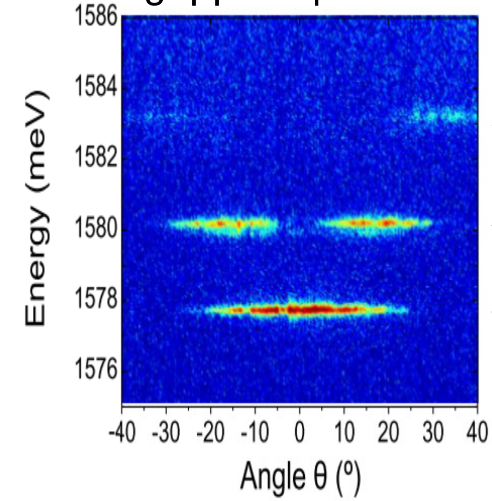


e-beam
+
etching

single pillar
2-4 μm



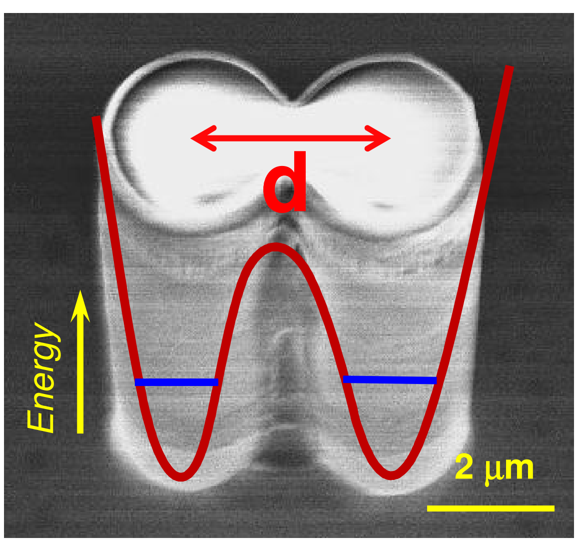
gapped spectrum



photonic orbitals
d
p
s

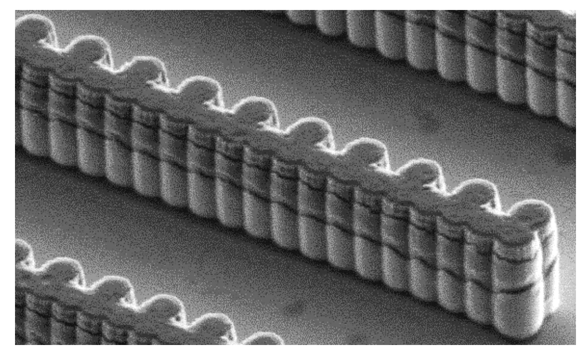
Coupled micropillars

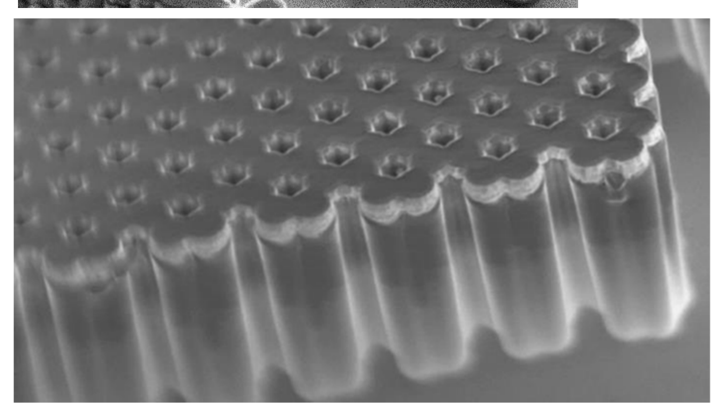
Photonic tunneling



Michaelis de Vasconcellos et al.,
APL **99**, 101103 (2011)

Extension to lattices

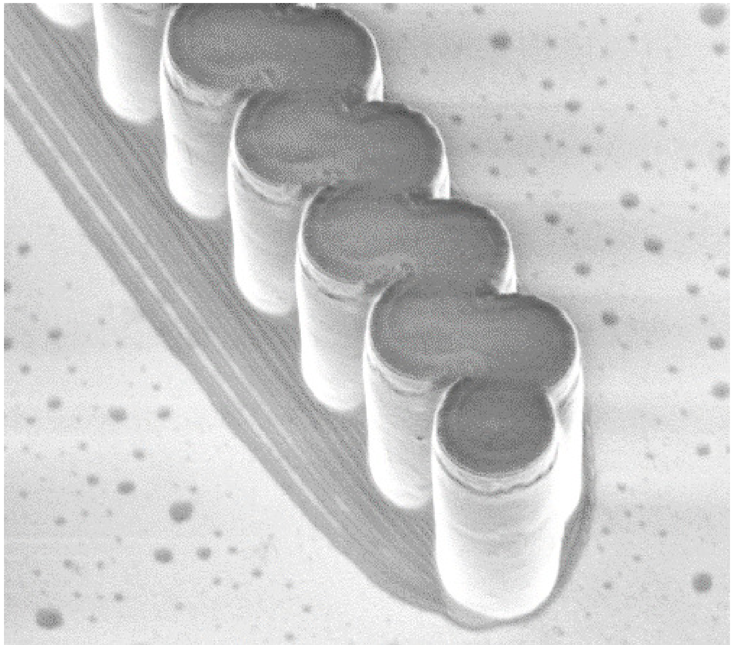




Lasing in topological edge modes

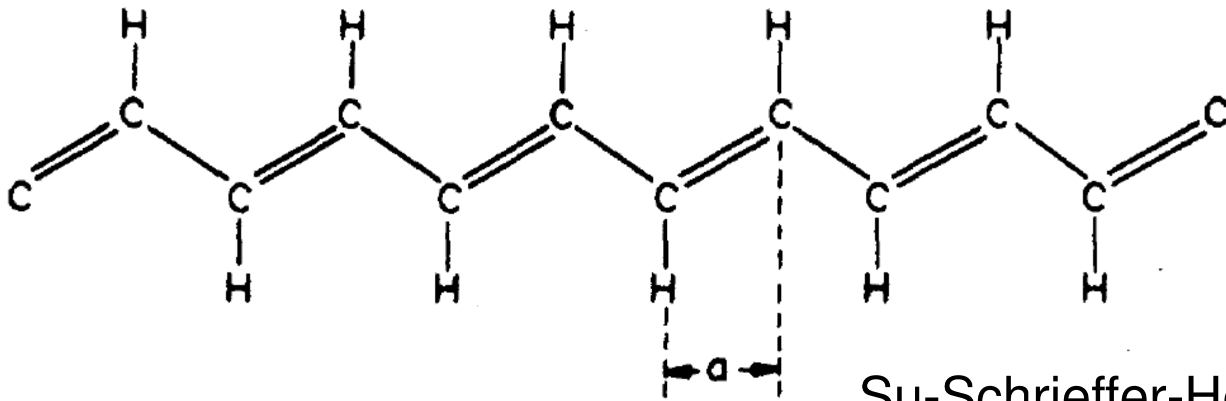
- Photonic structure with topological edge modes

- Cavity with gain

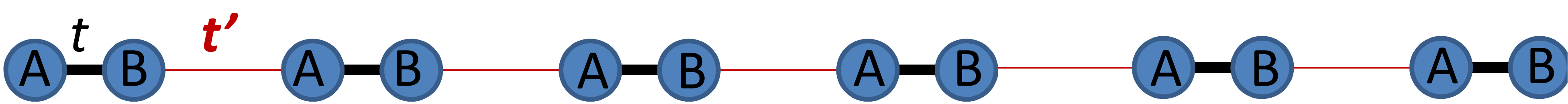


1D lattice with topological edge states

Polyacetylene



Su-Schrieffer-Heeger, PRL **42**, 1698 (1979)

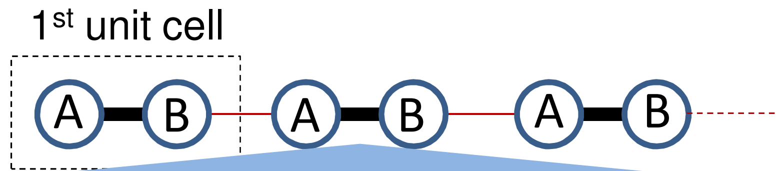


$t \neq t'$

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

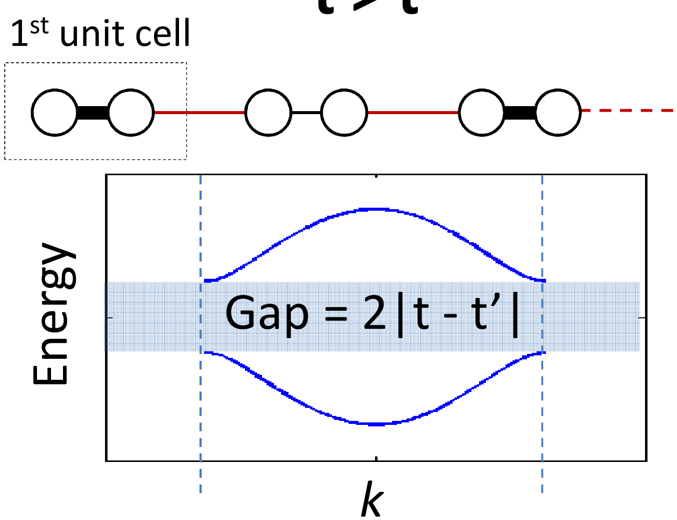
The SSH Hamiltonian

SSH lattice



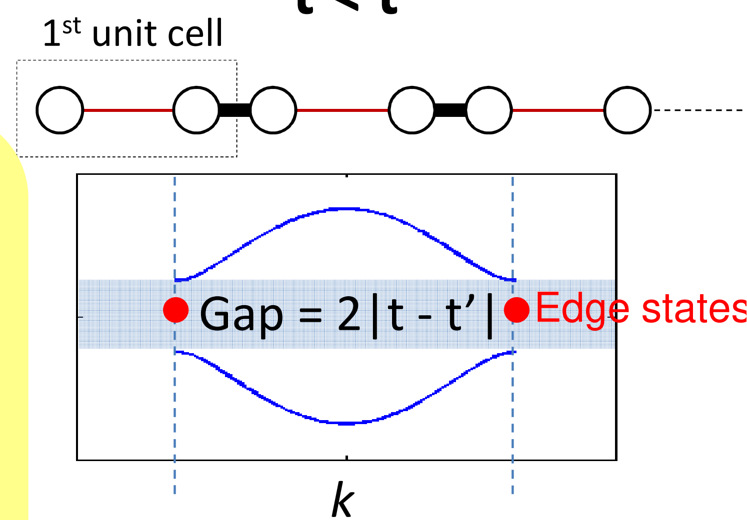
Dimerization 1

t > t'



Dimerization 2

t < t'



Same dispersion

Eigenfunctions are different

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

$$\cot\phi(k) = \frac{t'/t}{\sin ka} + \cot ka$$

Winding number:

$$\mathcal{W} = \oint_{BZ} i\langle\pm|\partial_k|\pm\rangle\, dk = 0$$

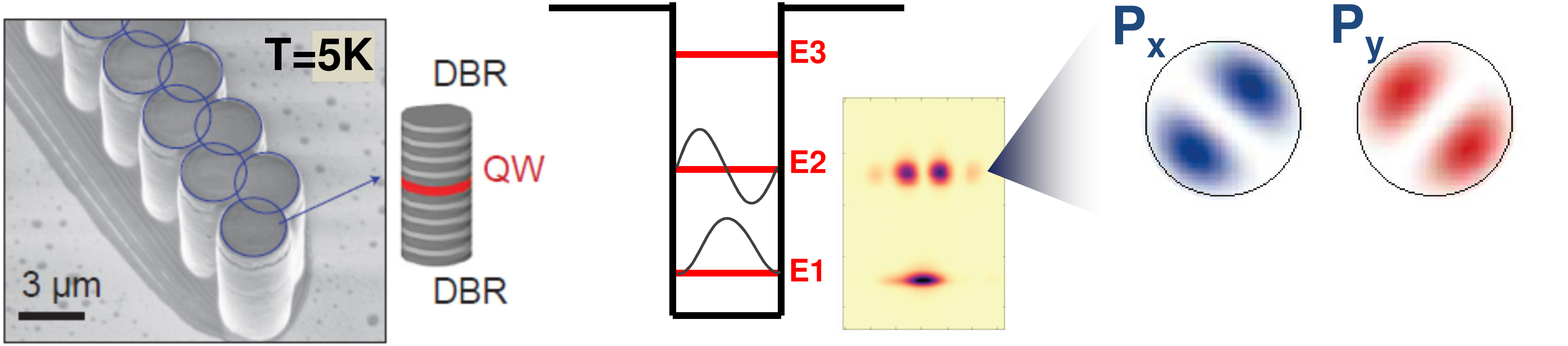
NO edge state

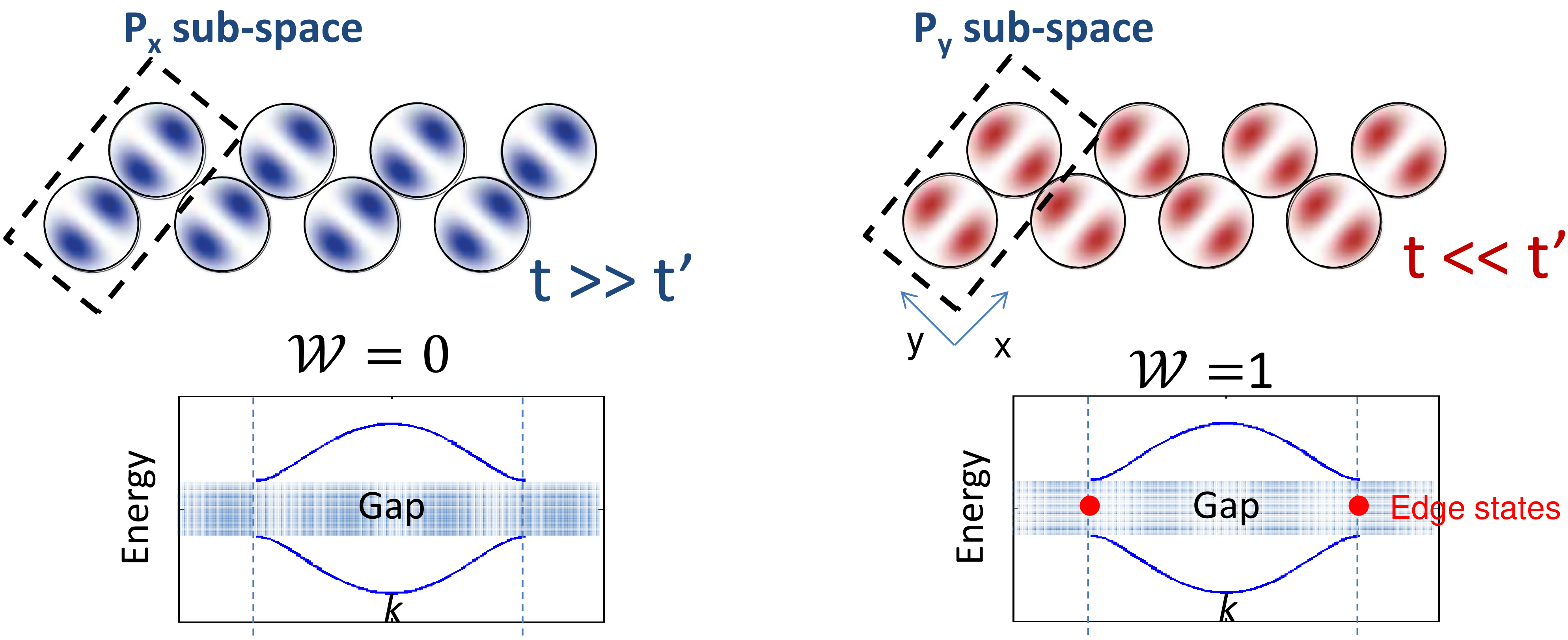
Winding number:

$$\mathcal{W} = 1$$

Edge states

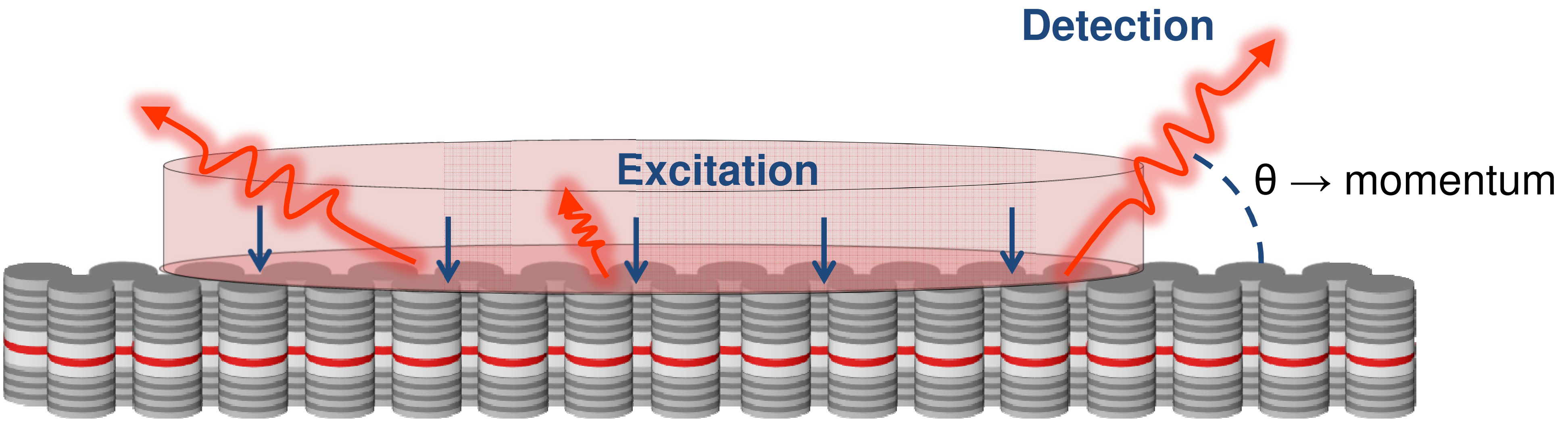
The SSH Hamiltonian with polaritons

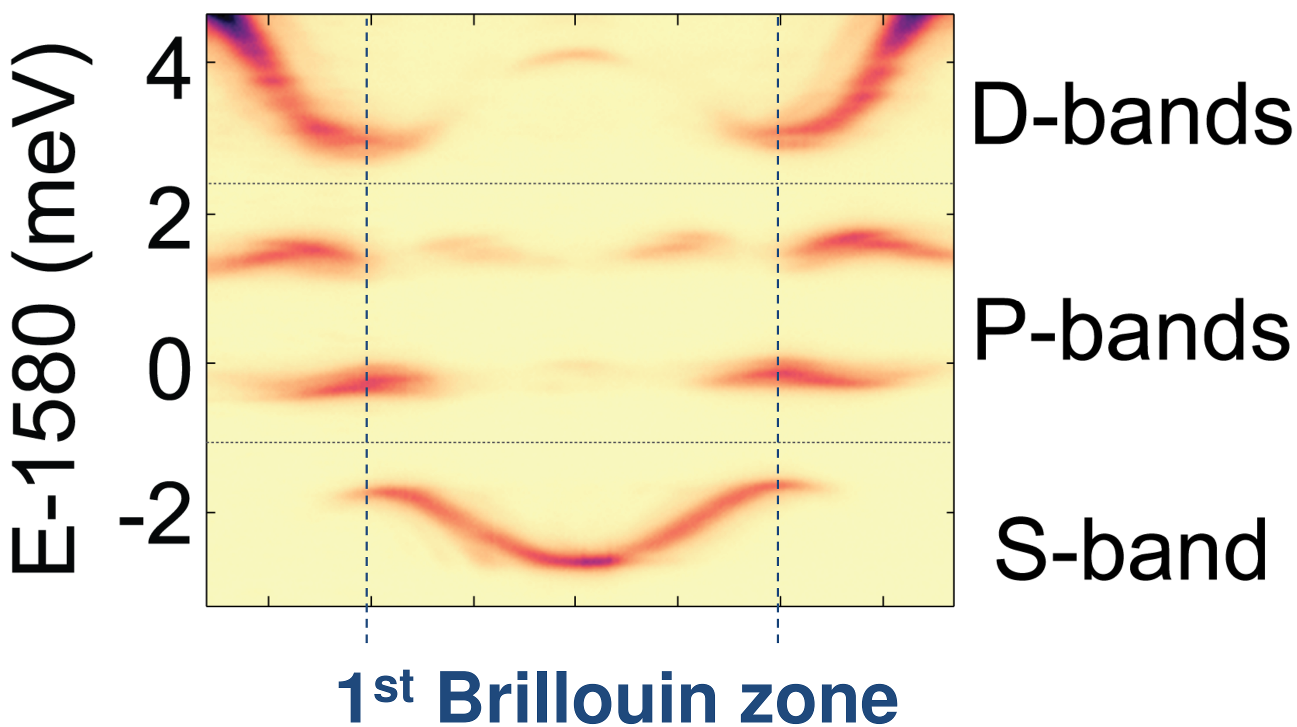


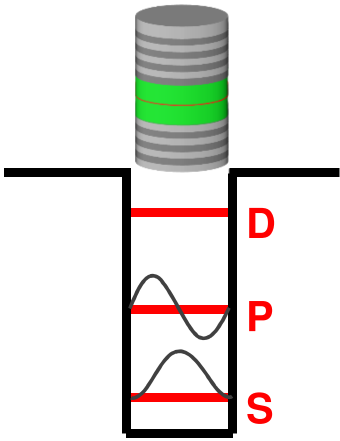


Both simultaneously present in the same chain

Orbital bands

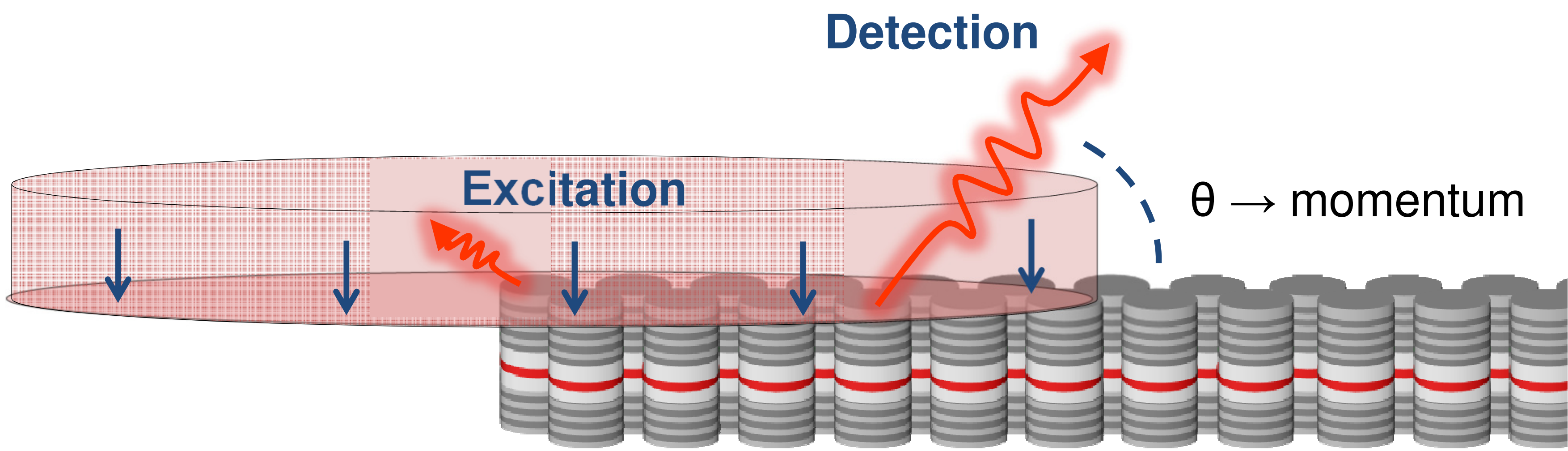


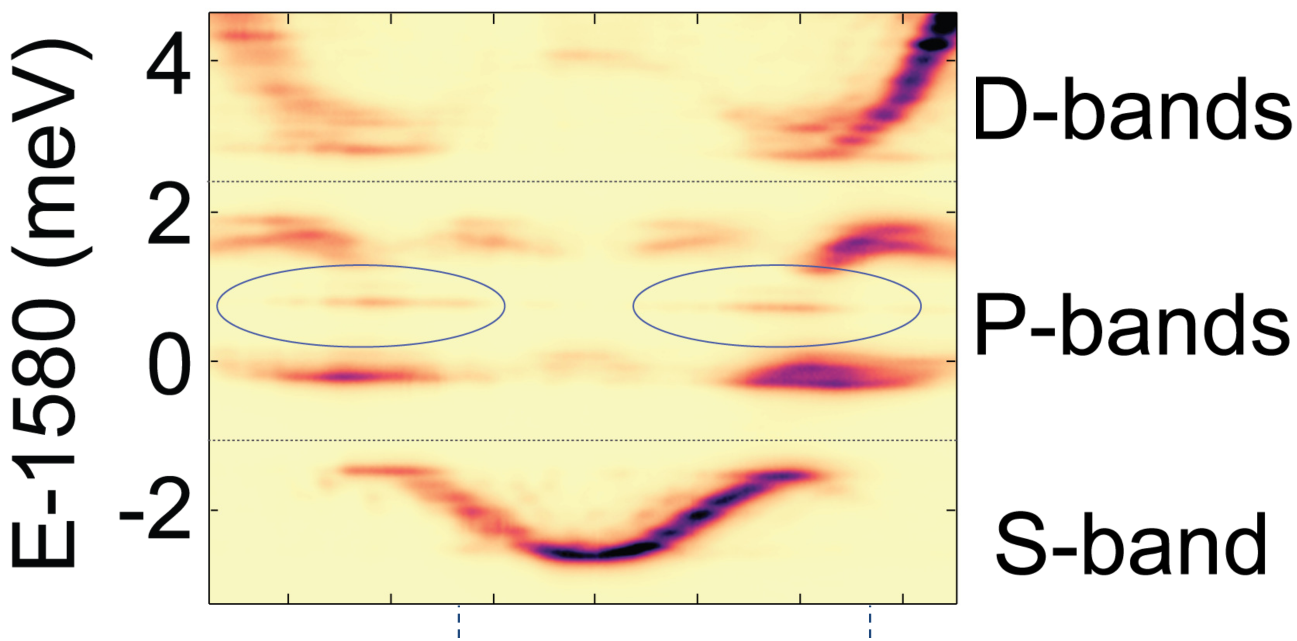




P. St-Jean et al., Nat. Photon. **11**, 651 (2017)

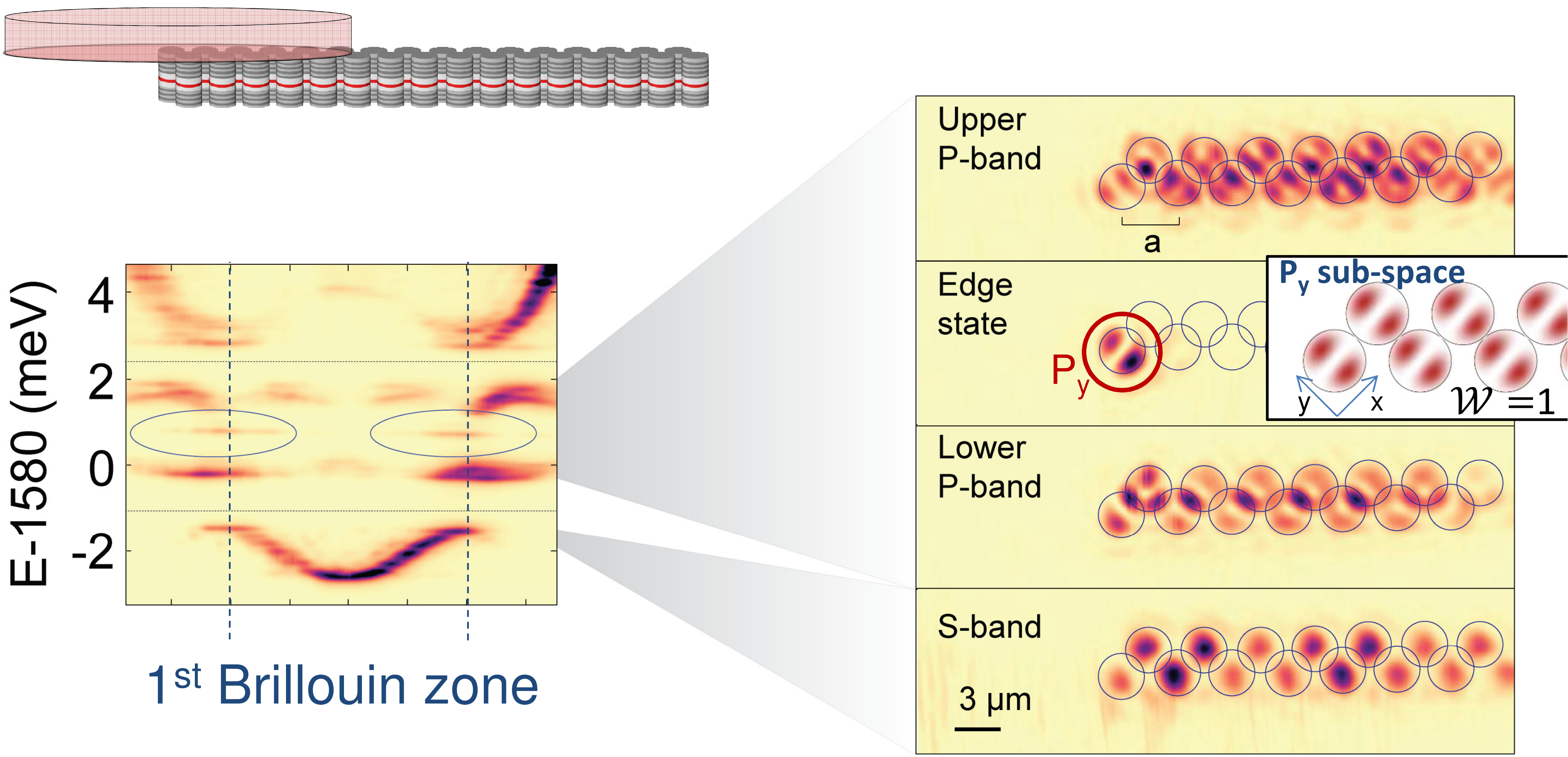
Orbital bands: edge states





P. St-Jean et al., Nat. Photon. **11**, 651 (2017)

Orbital bands: edge states

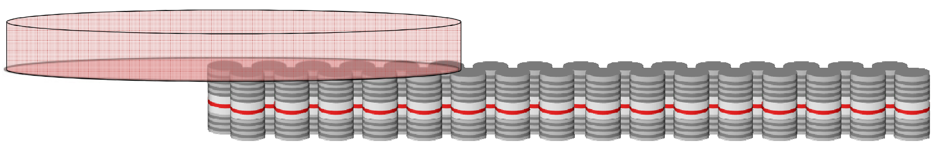


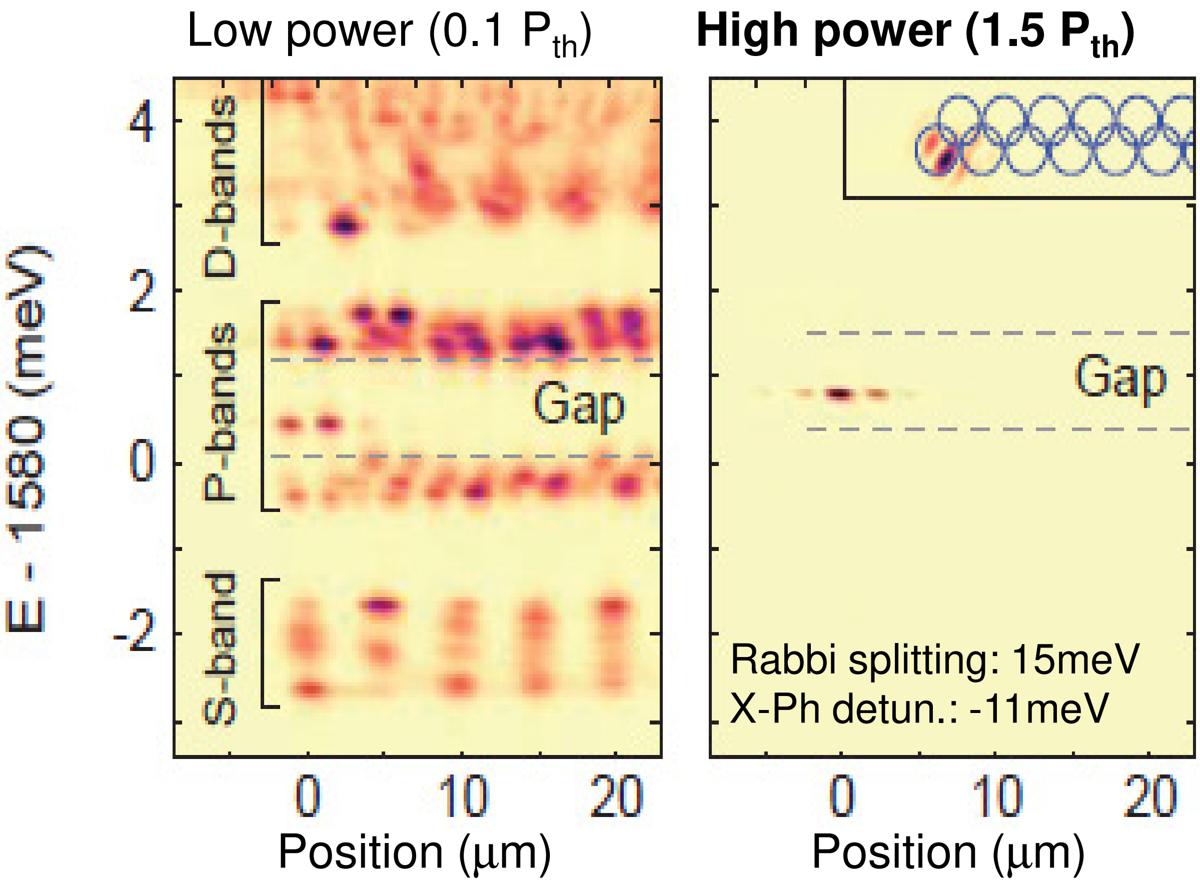
Momentum space

Real space

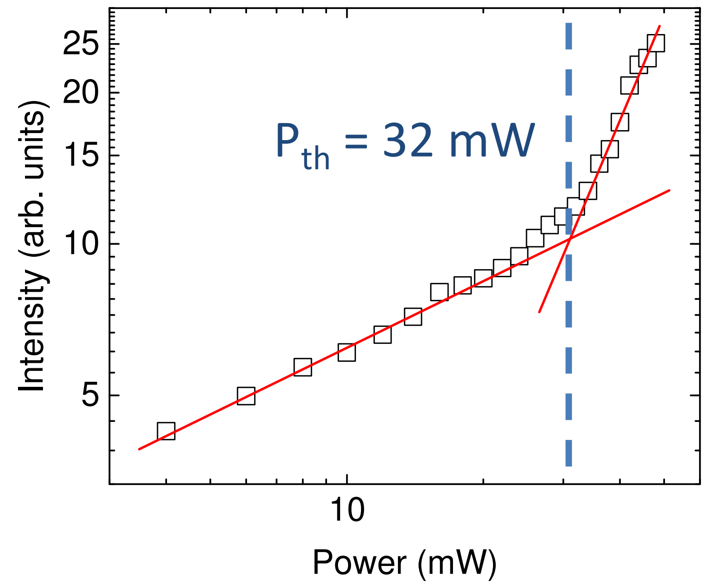
P. St-Jean et al., Nat. Photon. **11**, 651 (2017)

Lasing in topological edge states

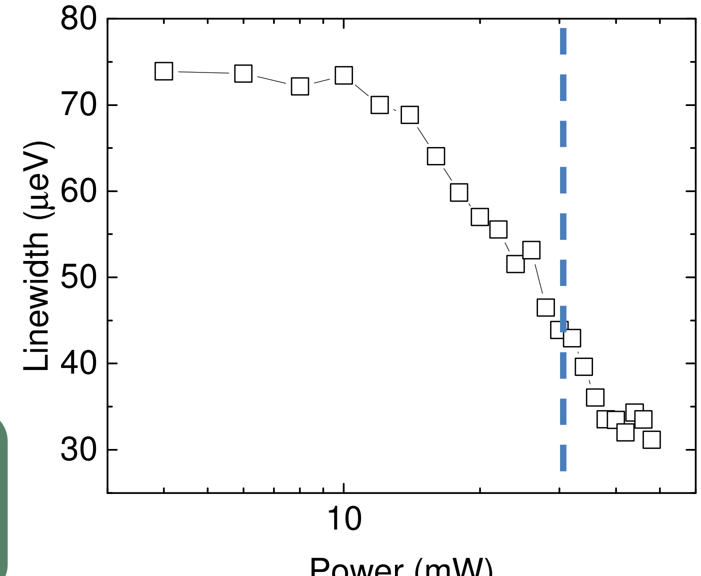




Threshold behaviour



Temporal coherence



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

P. St-Jean et a

Topological robustness of lasing

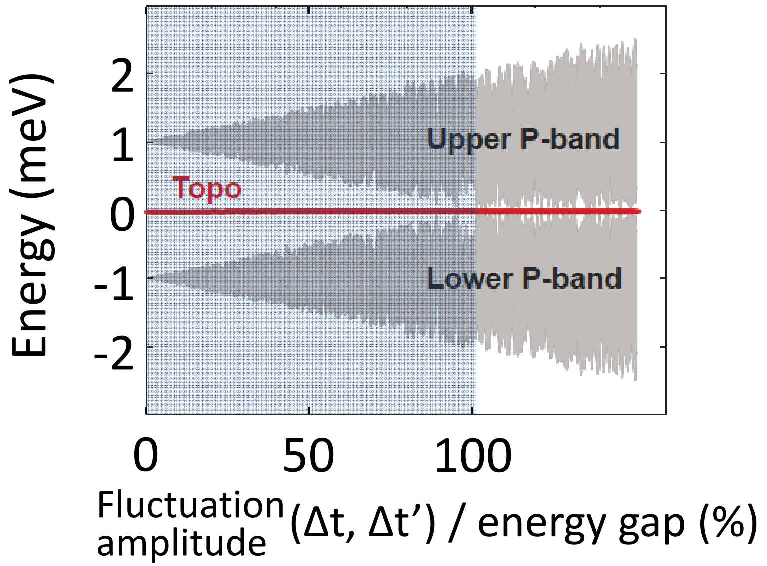
$$H(k) = \begin{pmatrix} 0 & t + t'e^{ika} \\ t + t'e^{-ika} & 0 \end{pmatrix}$$

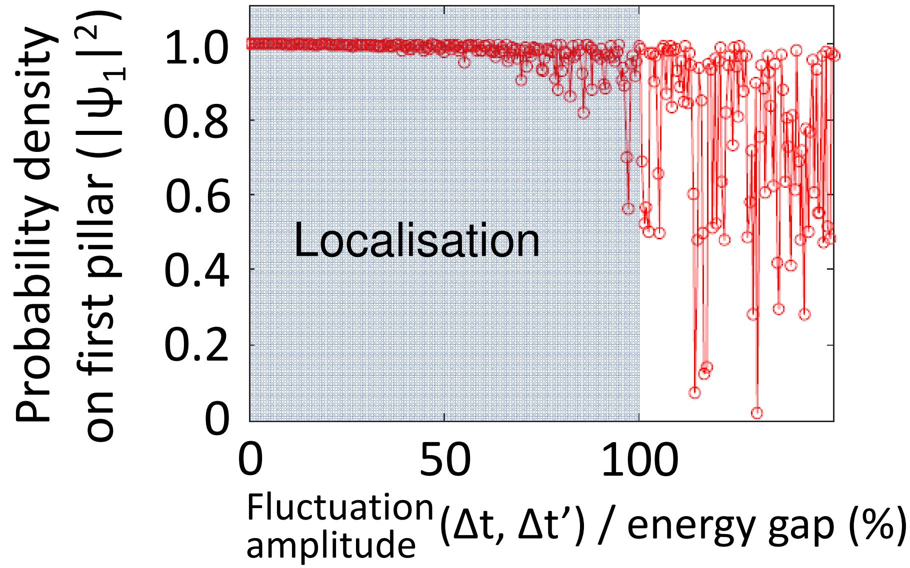
$\{H, \sigma_z\} = 0$ (chiral symmetry)

1. Eigenspectrum is symmetric around E=0;
2. **Localized states have energy E=0**

Theoretical calculations

Random fluctuations in t, t'



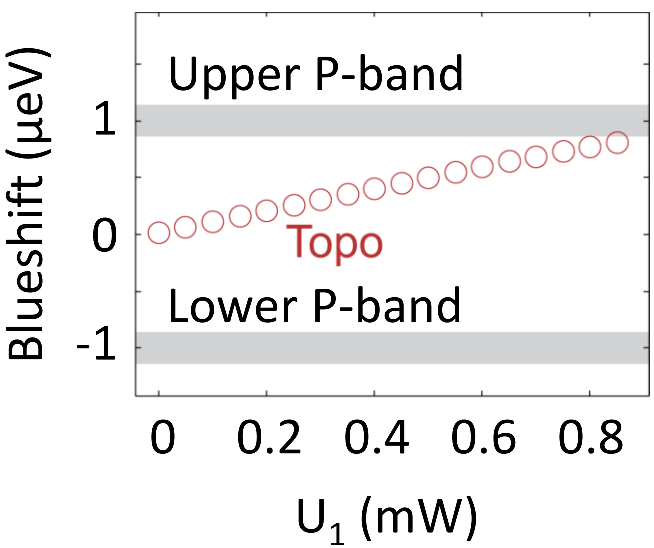


Energy and **localization** of the edge state
are robust against hopping energy fluctuations

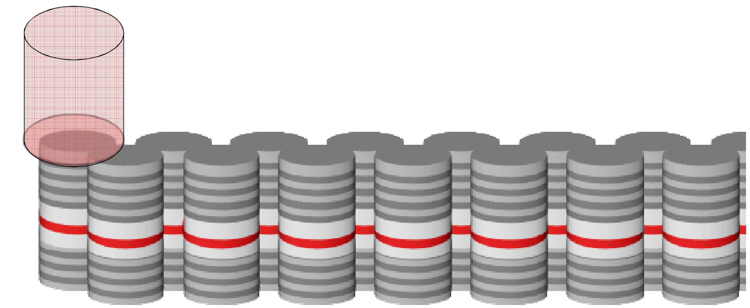
Robustness to break down of chiral symmetry

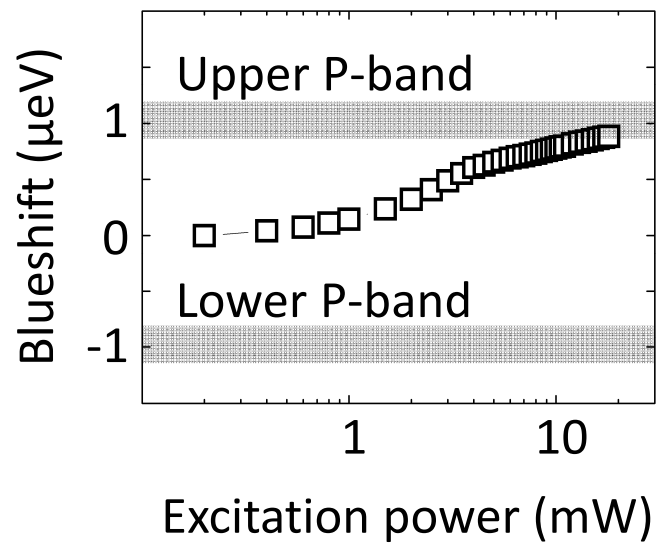
Theoretical calculation

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



Experimental observation

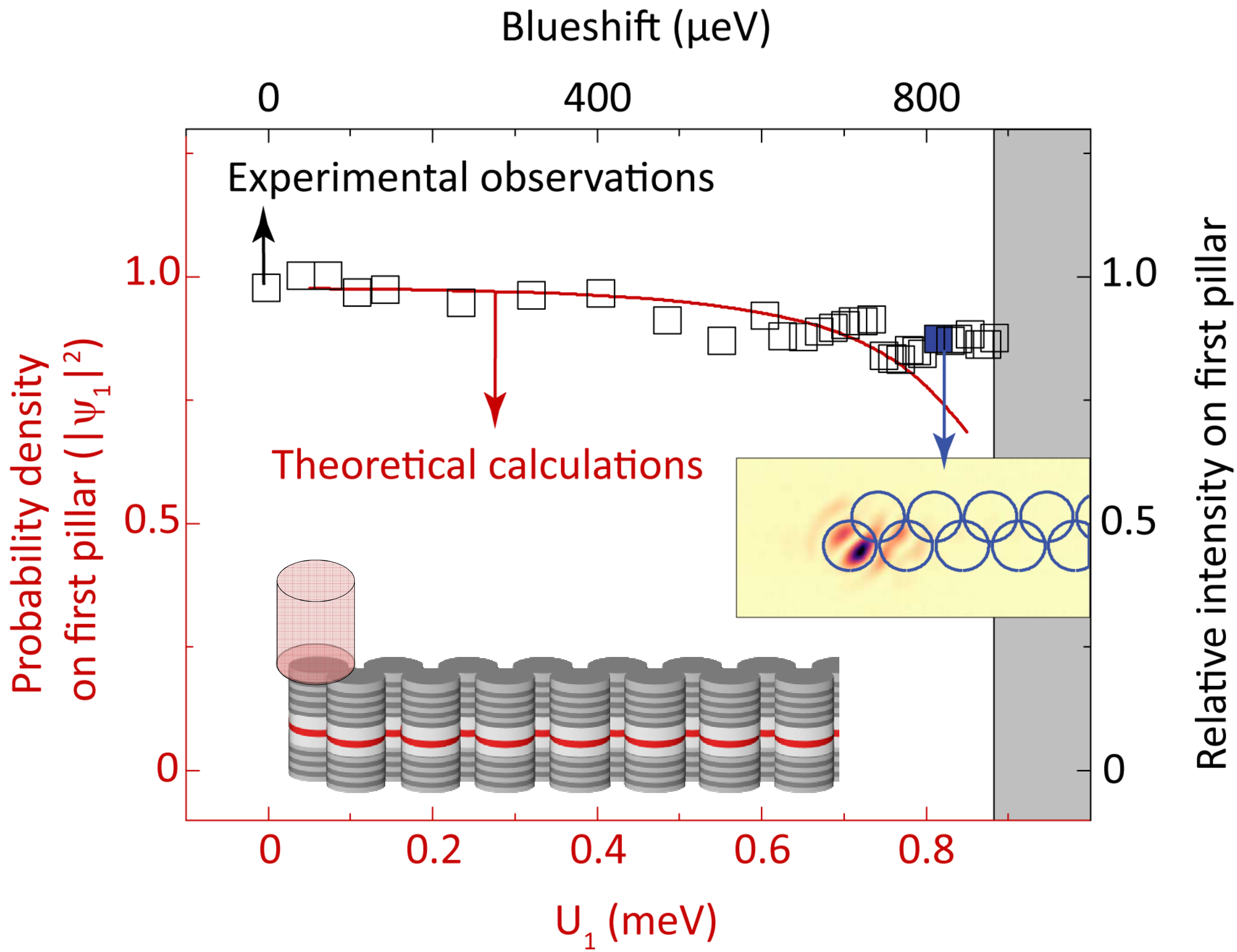




Gapped states robust against on-site energy perturbation

P. St-Jean et al., Nat. Photon. **11**, 651 (2017)

Robustness to break down of chiral symmetry



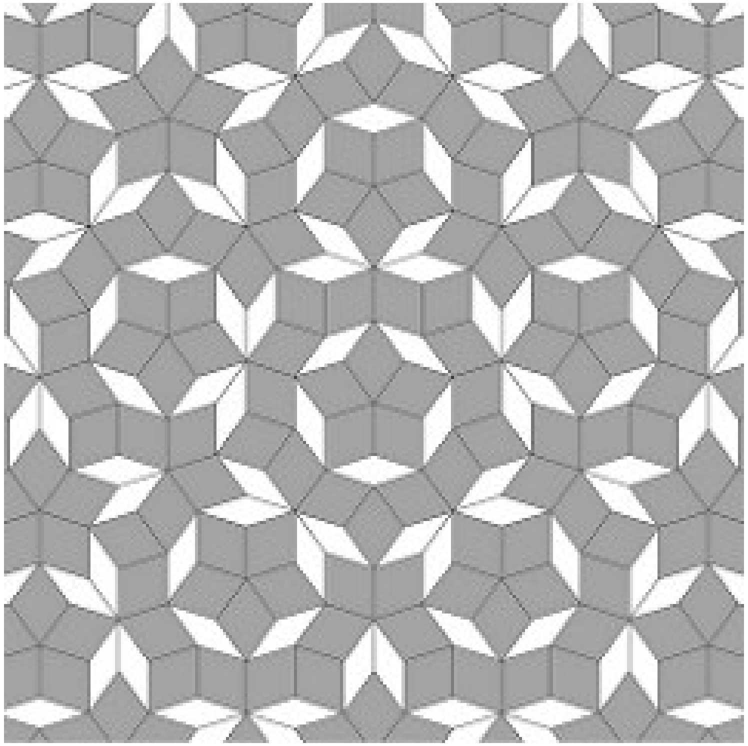
Localization only weakly affected by on-site disorder

P. St-Jean et al

Measuring topological invariants

Quasi-crystals

- **no translational symmetry**
- **long range order**
- **topological properties (high windings)**



Penrose tiling

Fibonacci sequence

1175-1250

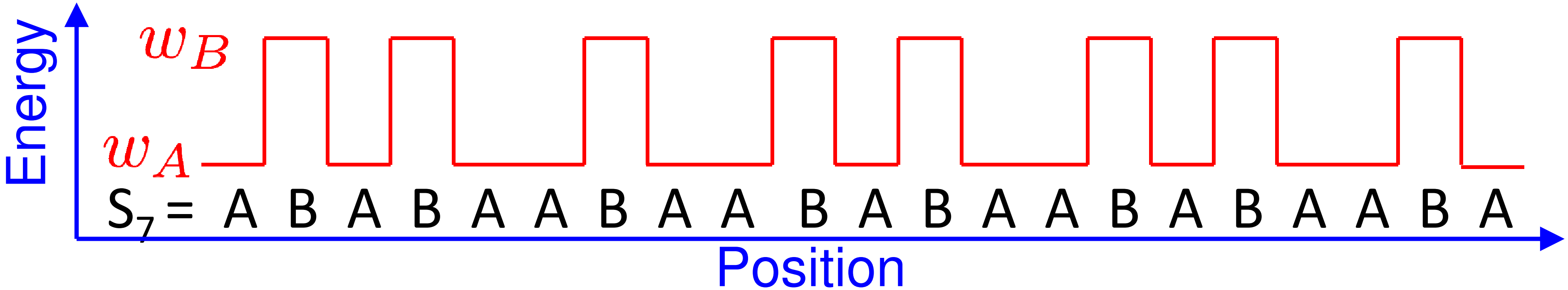
Substitution method

$$A \to BA$$
$$B \to A$$

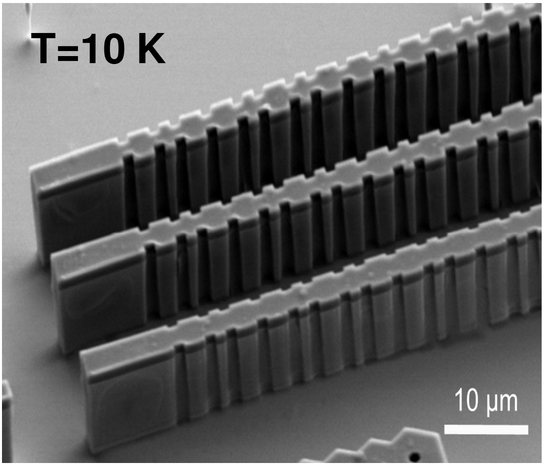
$S_1 = A$ 1 ← Length of the Fibonacci "word"

$S_2 = BA$ 2

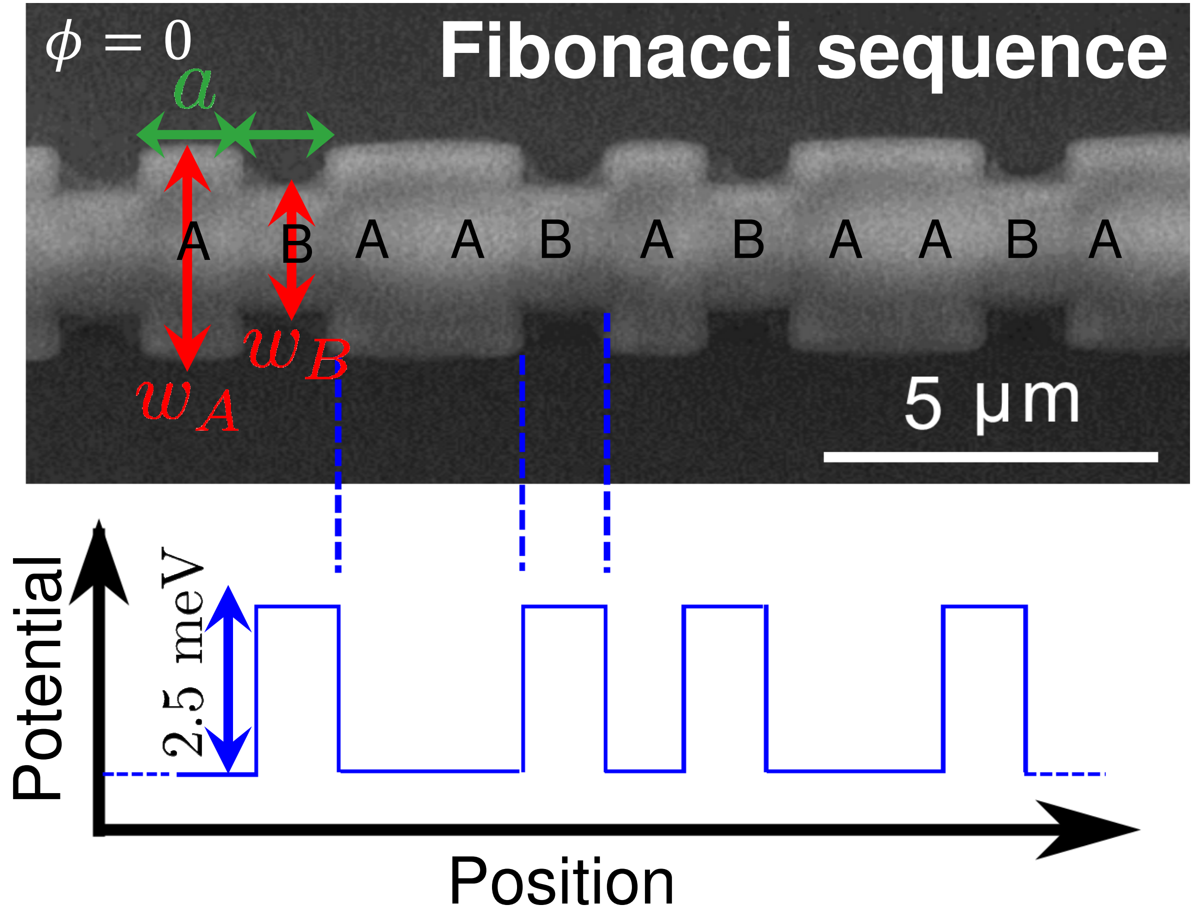
Let A and B be the 2 values of an energy potential:



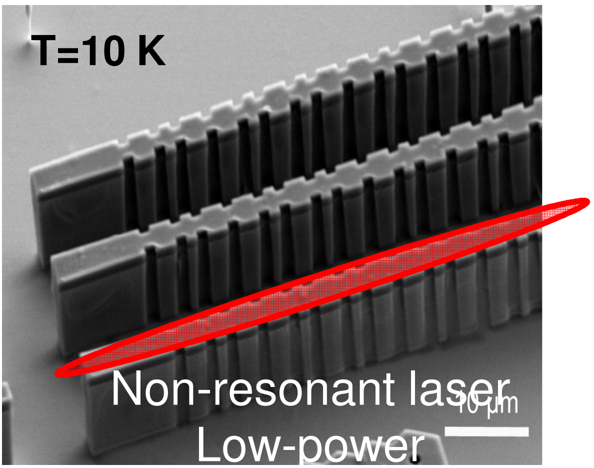
Fibonacci potential



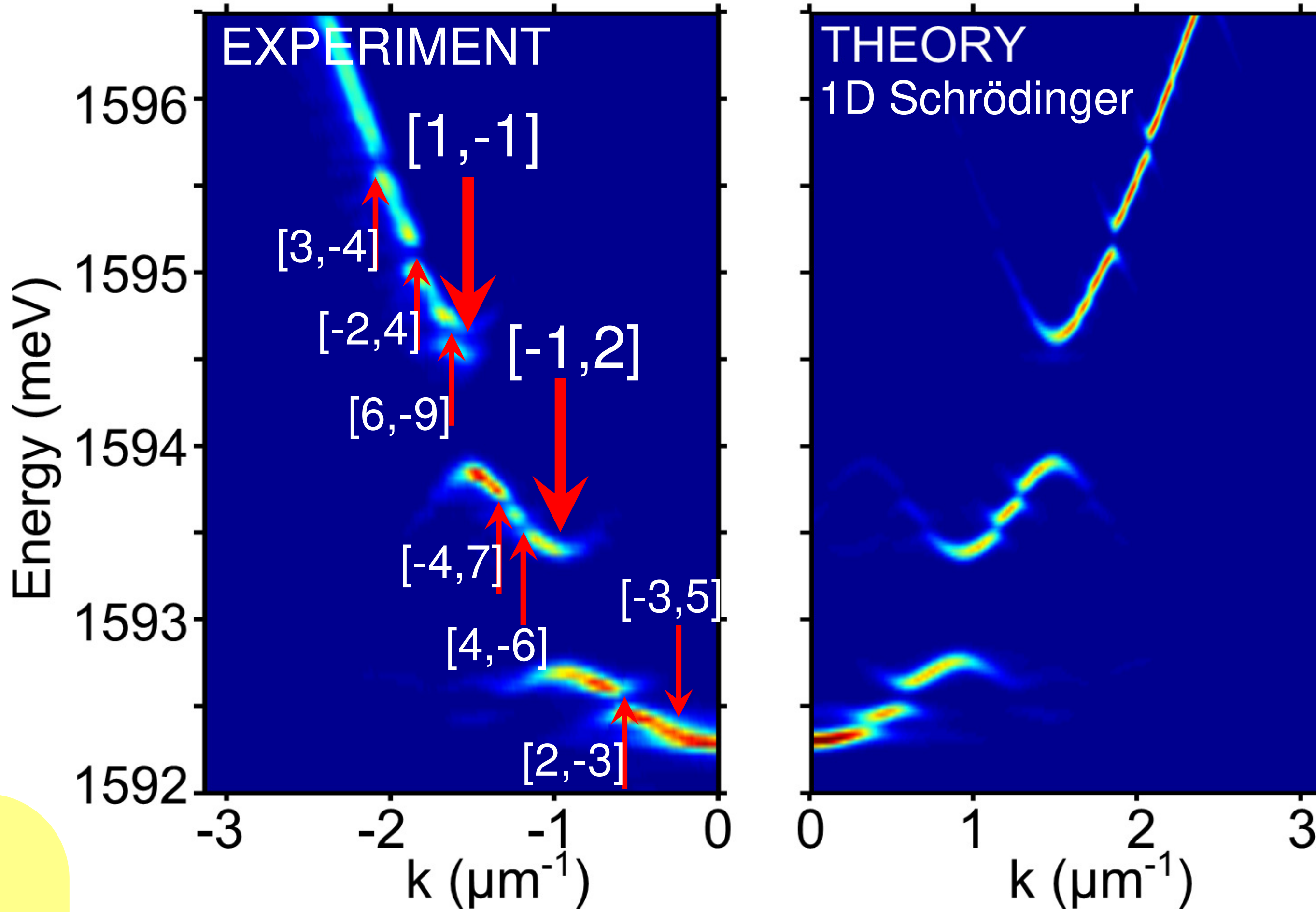
Top view



Fractal spectrum



$\phi = 0$



Gap-labelling thorem

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

Golden mean

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

- **No Brillouin zone**
- **Topological gap invariants?**

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

Synthetic dimension in 1D quasi-crystals

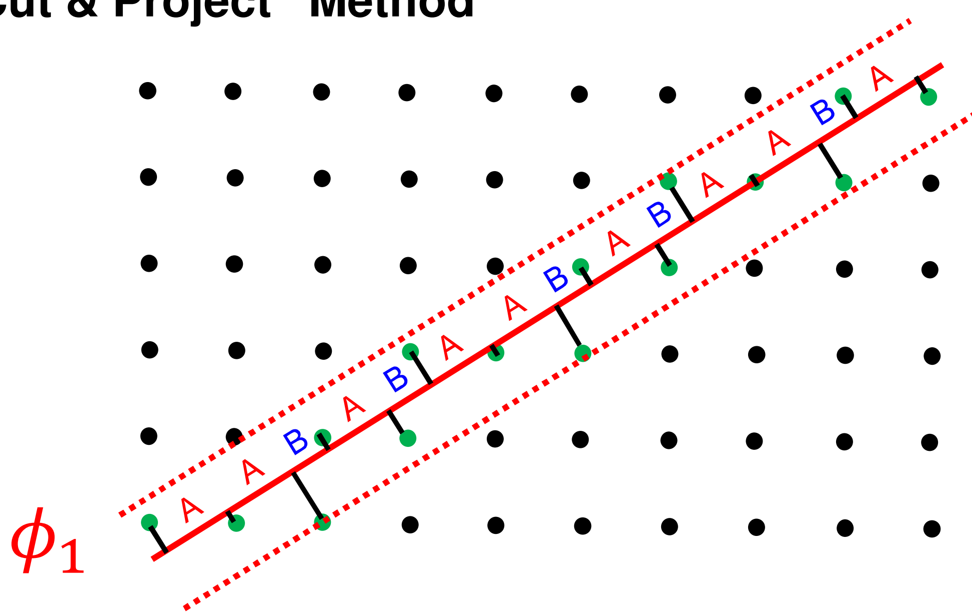
Characteristic function: periodic in ϕ

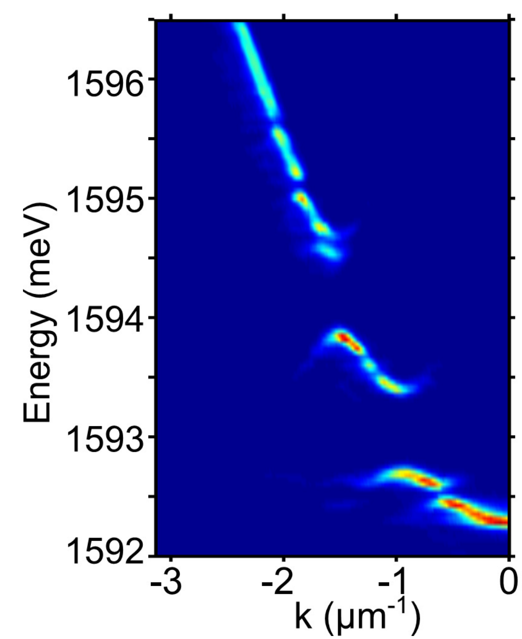
Y. E. Kraus et al., PRL 109, 106402 (2012)

$$\chi_j = \mathrm{sgn}[\cos(2\pi j \sigma^{-1} + \phi) - \cos(\pi\sigma^{-1})] \rightarrow \begin{cases} +1 & w_A \\ -1 & w_B \end{cases}$$

site (j) **phason ("synthetic" dimension)** (ϕ) **Golden mean** (σ)

"Cut & Project" Method





Synthetic dimension in 1D quasi-crystals

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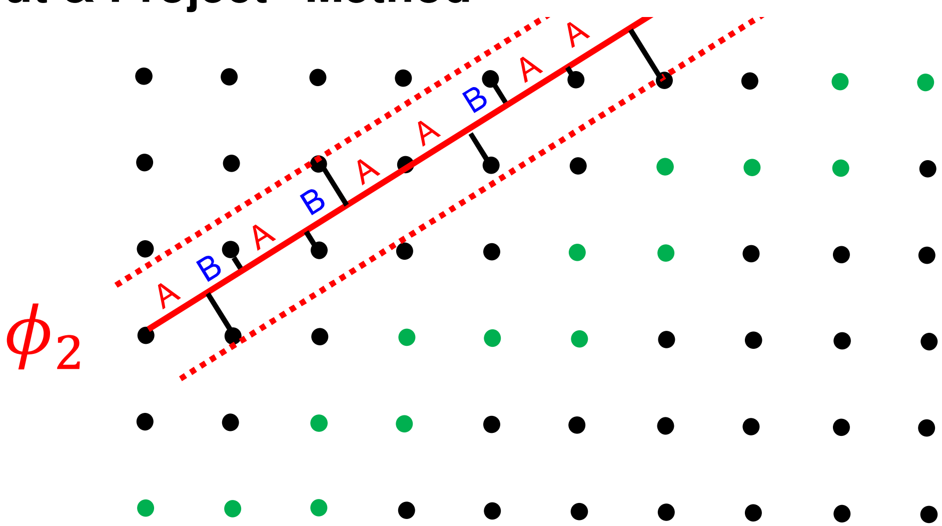
$$\chi_j = \mathrm{sgn}[\cos(2\pi j\sigma^{-1} + \phi) - \cos(\pi\sigma^{-1})]$$

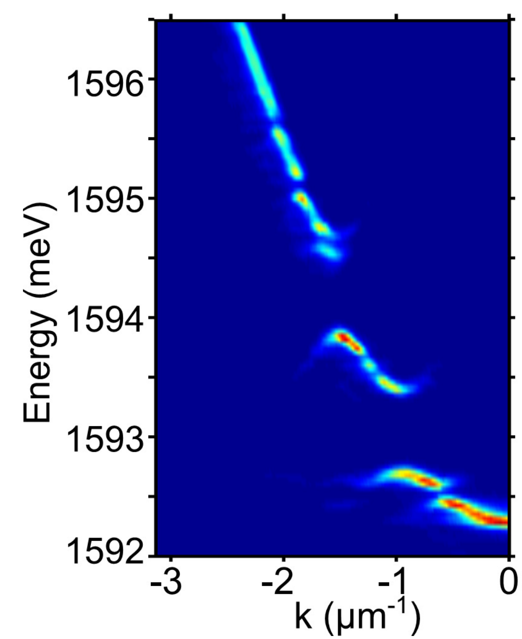
site phason Golden mean

+1 w_A

-1 w_B

"Cut & Project" Method





Fibonacci potential: periodic in ϕ

Synthetic dimension in 1D quasi-crystals

Characteristic function: periodic in ϕ

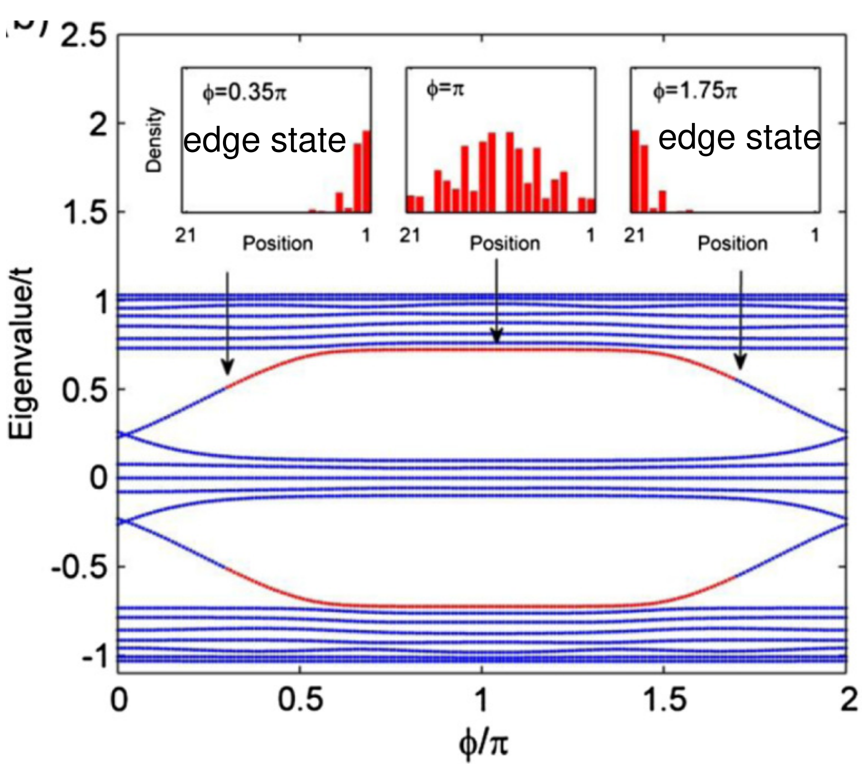
Y. E. Kraus et al., PRL 109, 106402 (2012)

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

site — phason — Golden mean

+1 w_A

-1 w_B



Quasi-crystal bands can be associated topological invariants

Appearance of edge states

Traverse the gap when varying ϕ

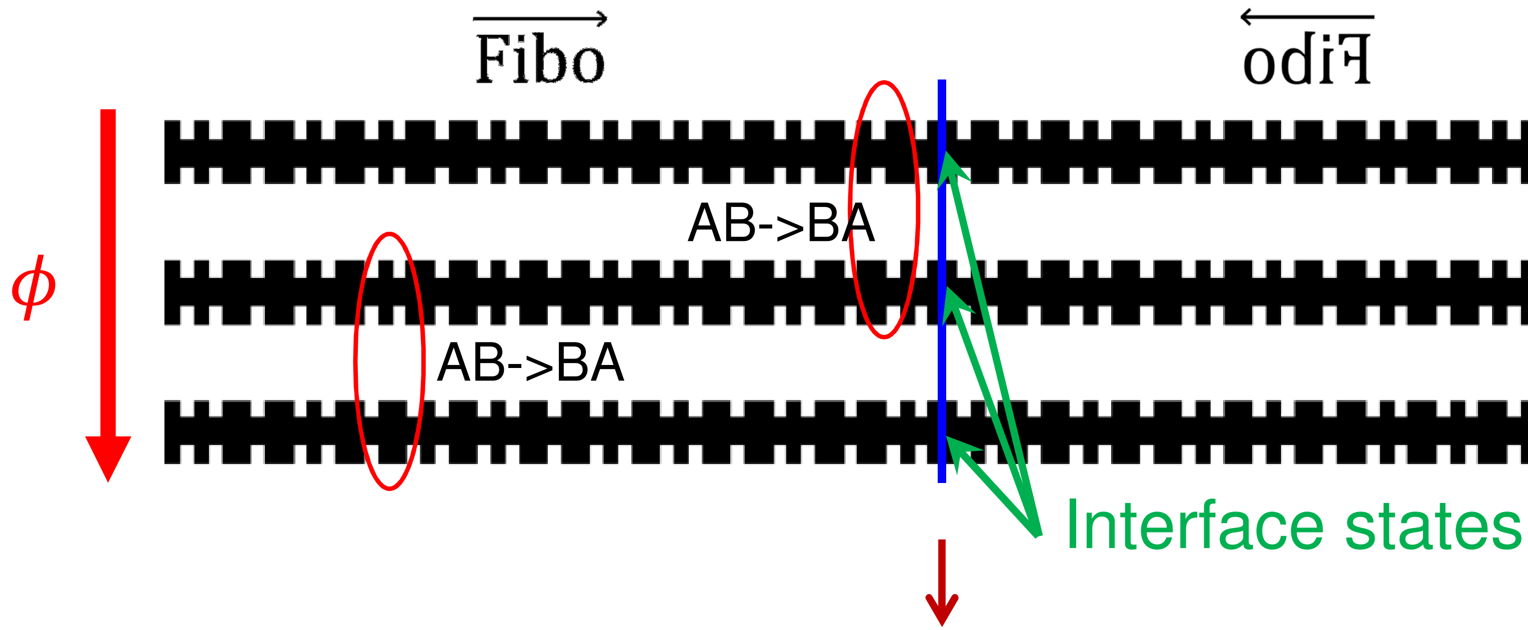
Fibonacci cavity

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

site

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

Golden mean



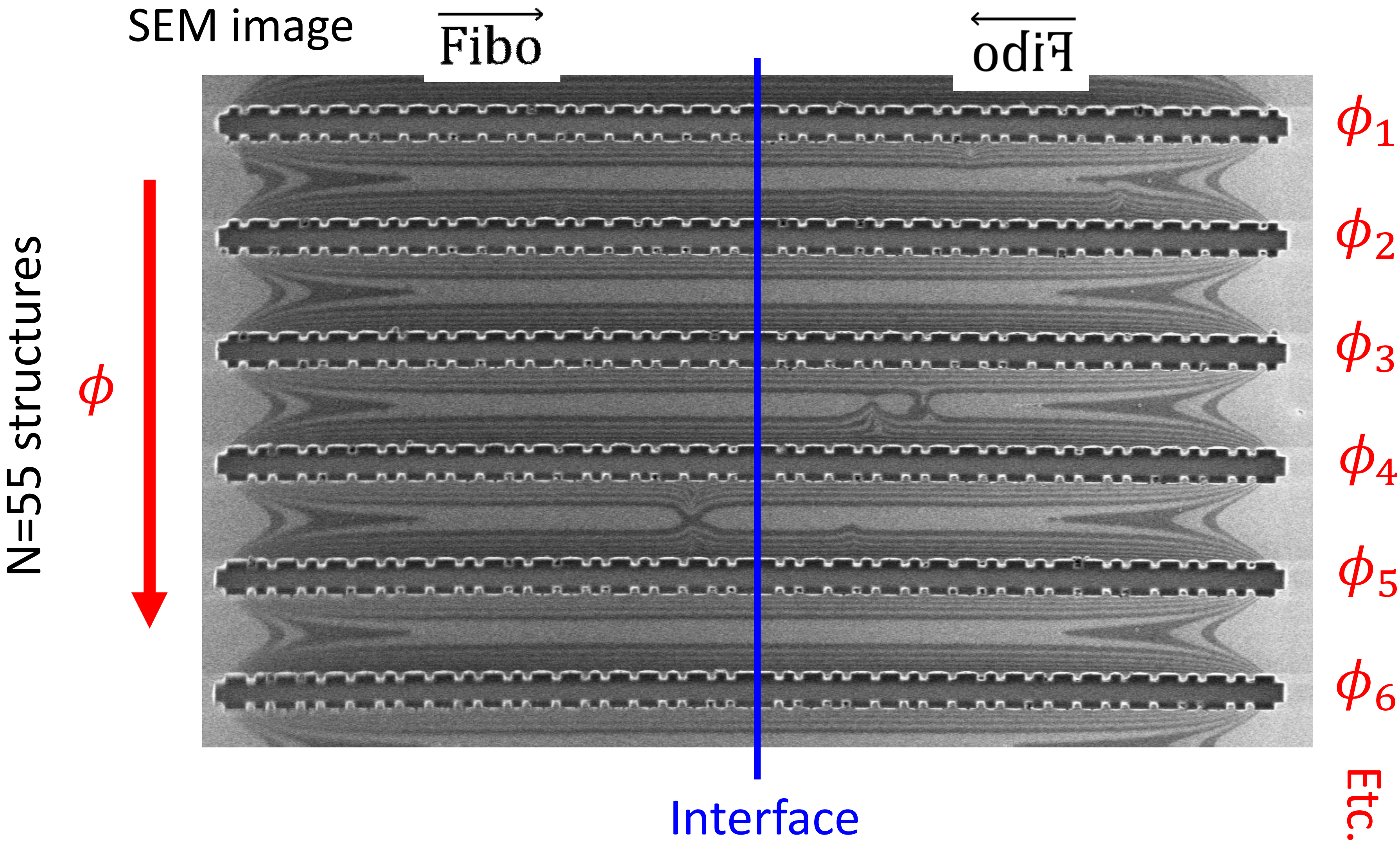
Effective Fabry-Pérot cavity of zero length but finite round-trip phase θ_{cav}

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

Accessible in the spectral properties

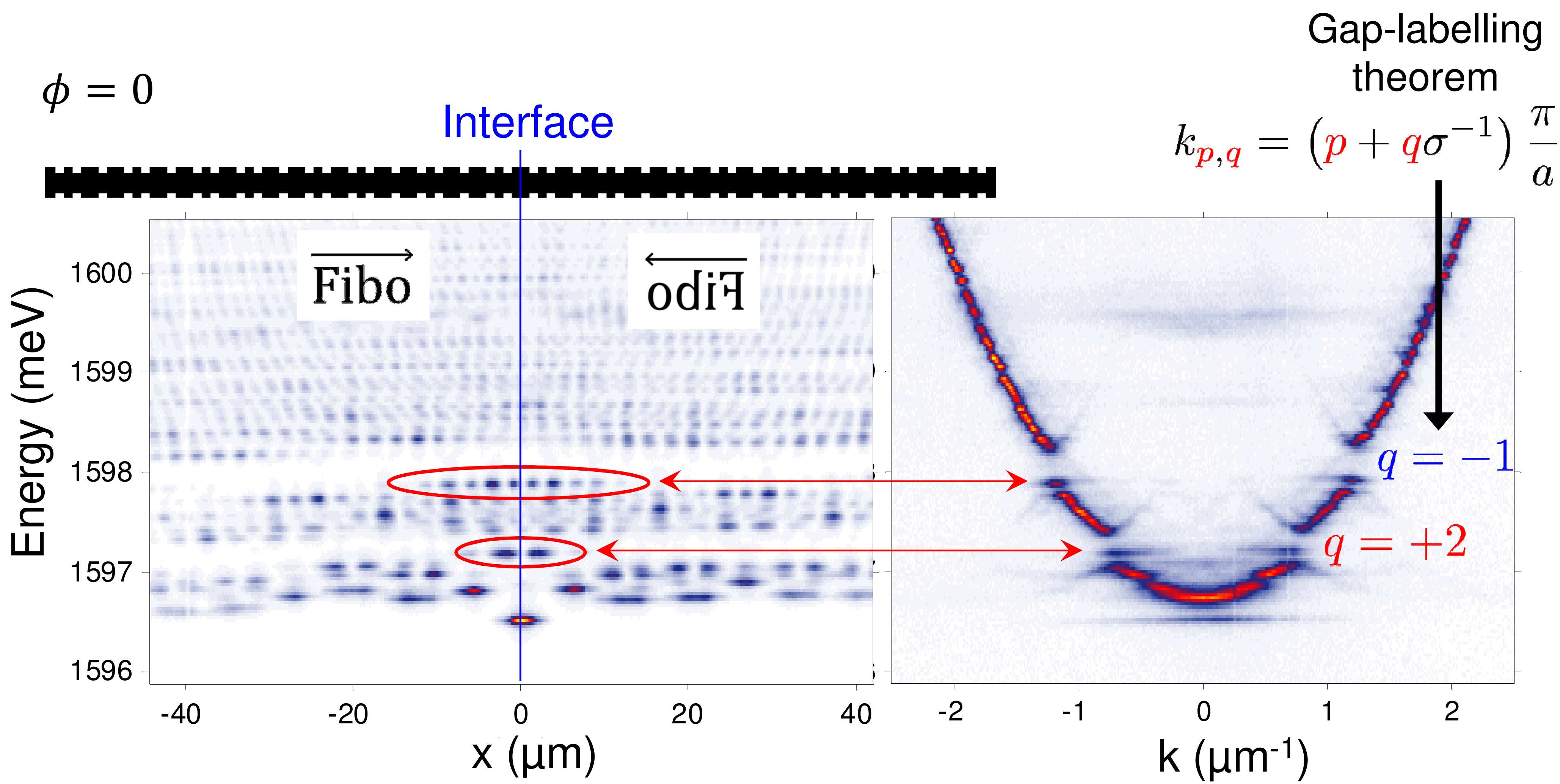
E. Levy et al., arxiv:1509.04028 (2015)
J. Kellendonk & E. Prodan arXiv:1710.07681

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

Measurement of topological invariants in a quasi-crystal

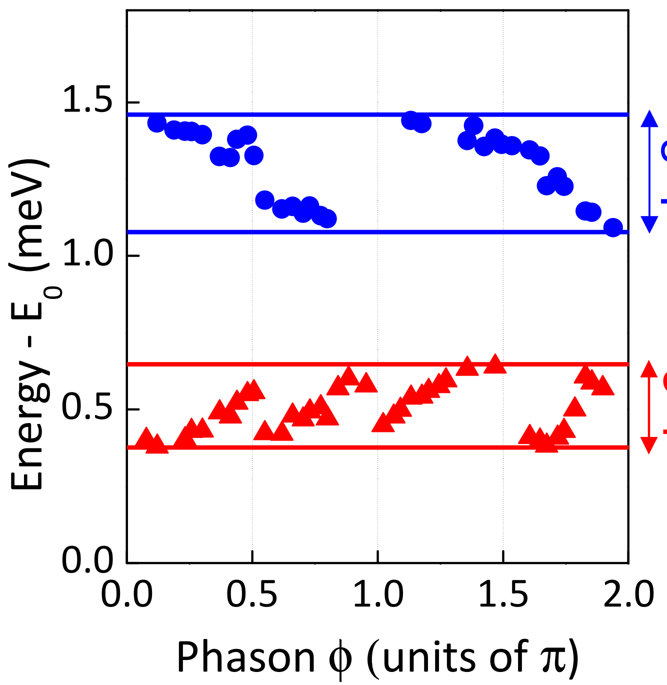
Gap-labelling theorem

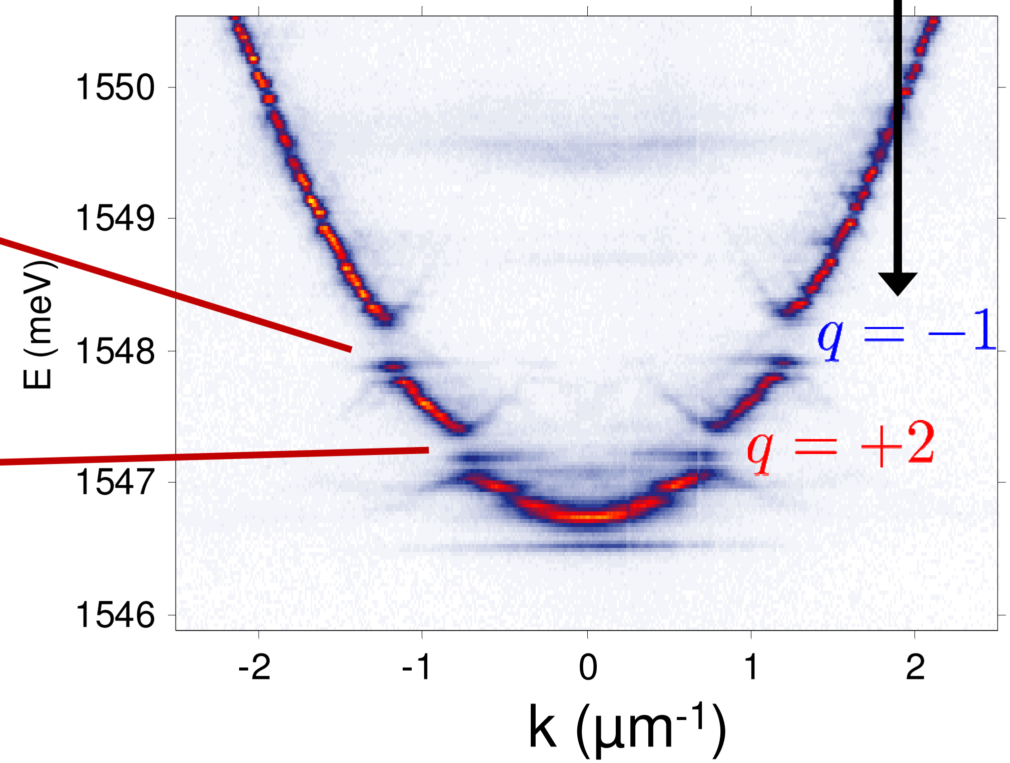
$$k_{p,q} = \left(p + q\sigma^{-1}\right)\frac{\pi}{a}$$

Experiment

$\mathcal{W} = -2$

$\mathcal{W} = +4$





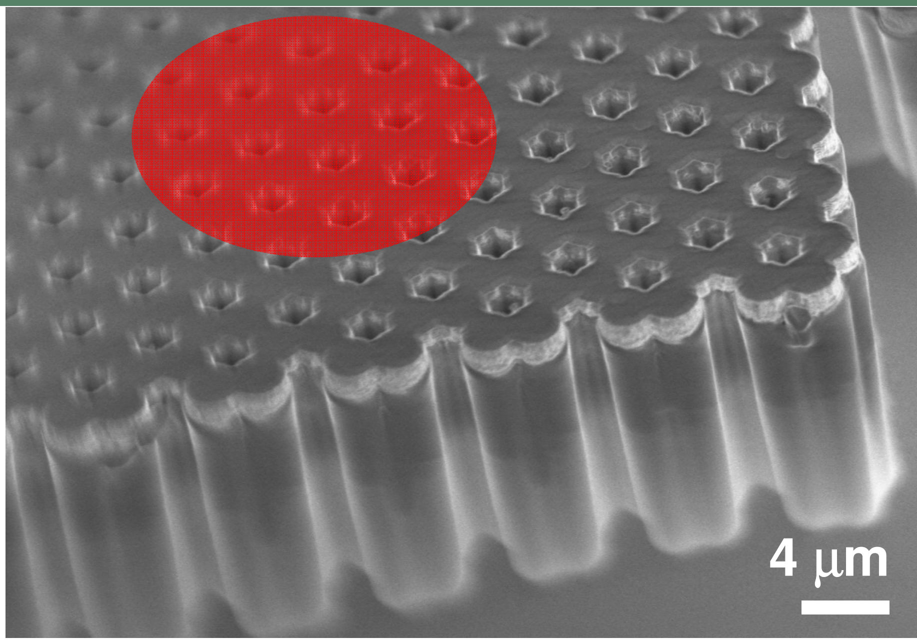
The interface states traverse periodically the gaps

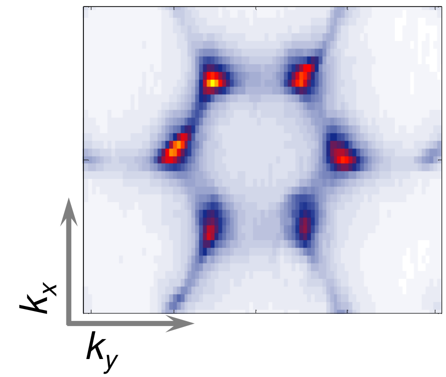
$$\boldsymbol{\mathcal{W}(\theta_{cav}) = 2q}$$

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

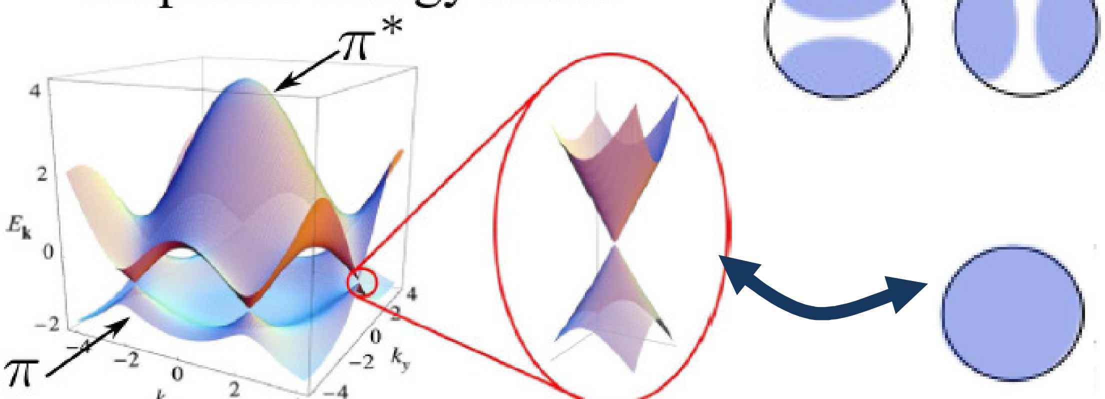
J. Kellendonk & E. Prodan arXiv:1710.07681

Polariton honeycomb lattice

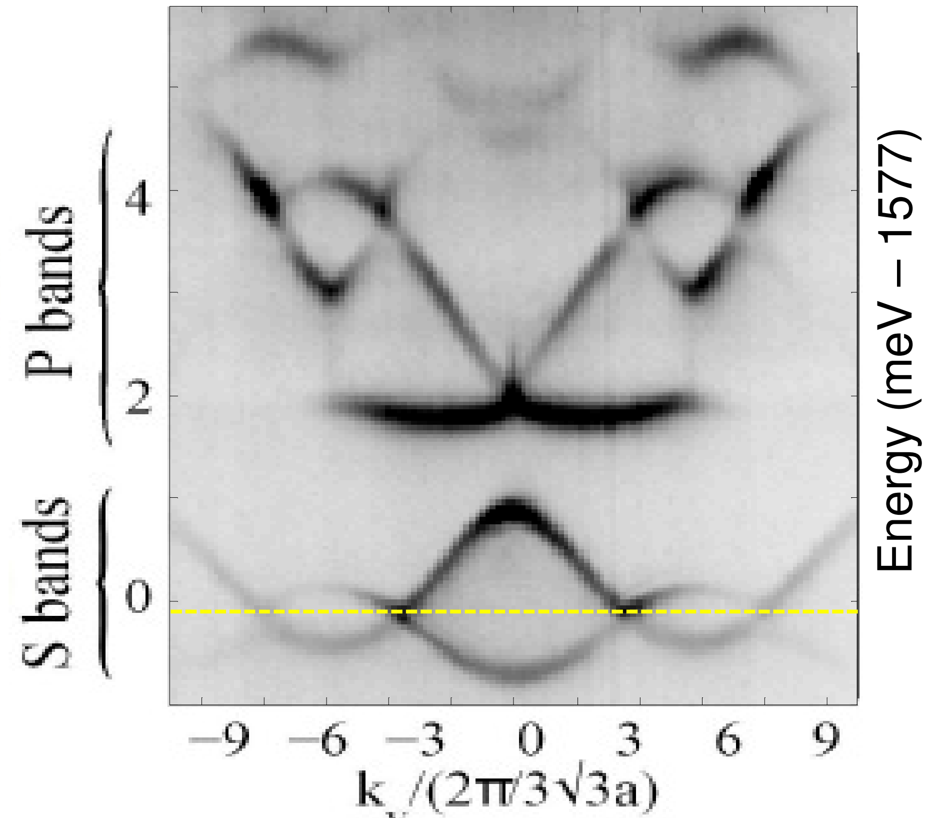




Graphene energy bands



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

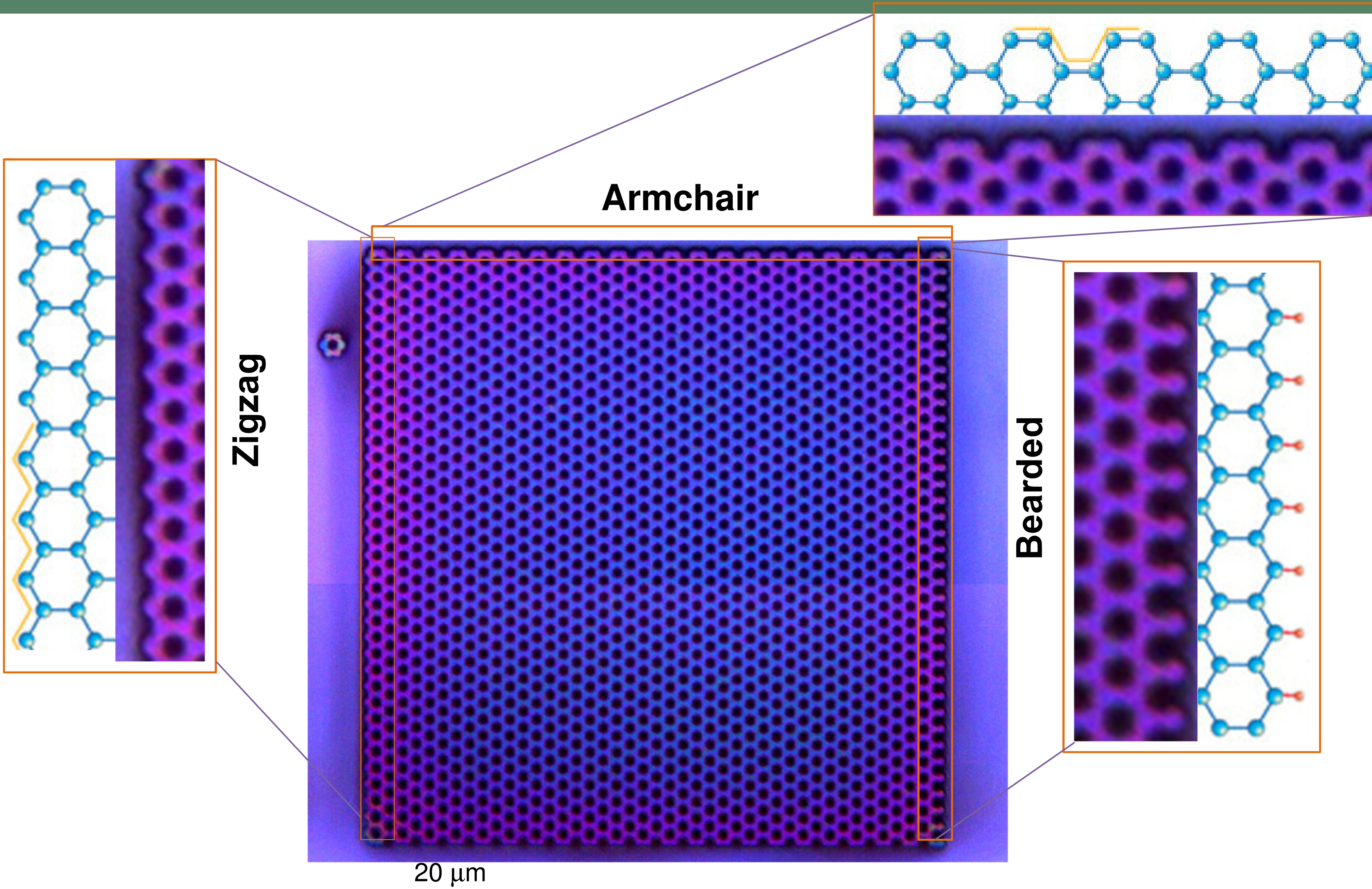


Polariton Dirac cones

See also: N. Y. Kim, et al. NJP **15**, 35032 (2013)
K. Kusudo et al., PRB **87**, 214503 (2013).

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

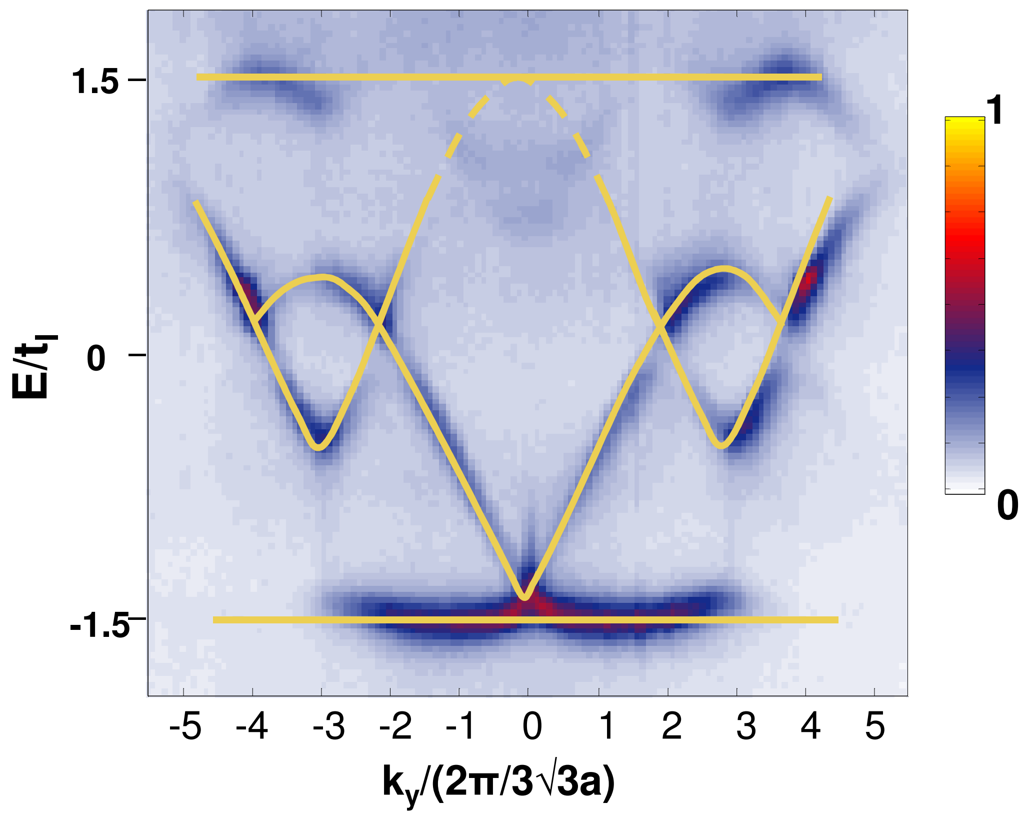
Polariton honeycomb lattice: edges



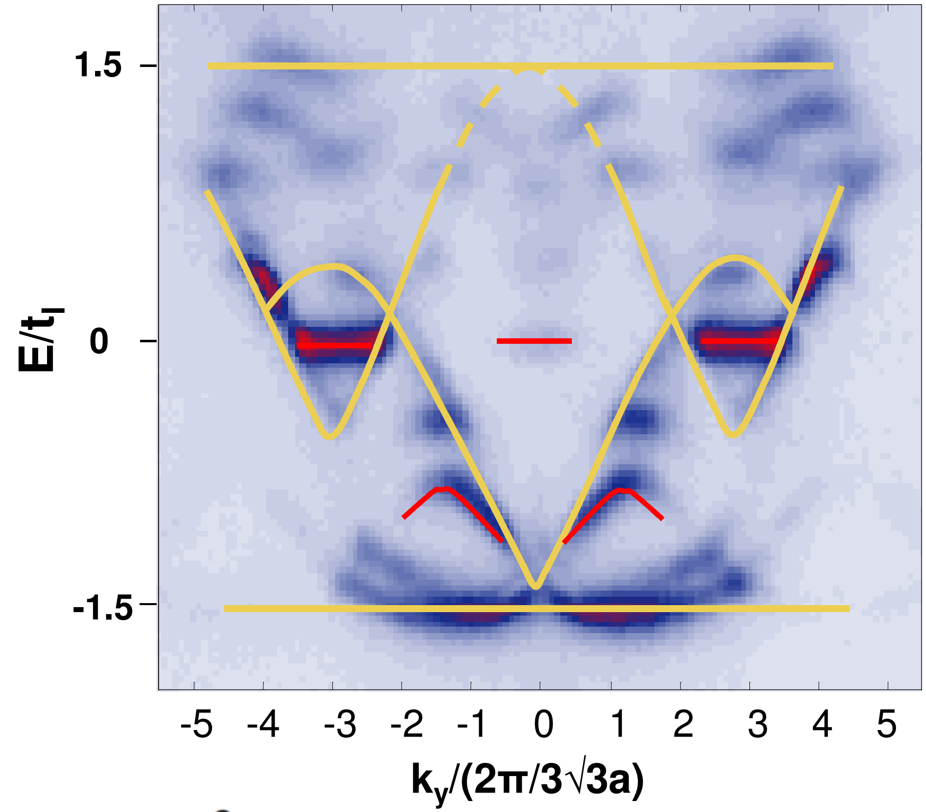
Milicevic et al, 2D Mater. **2,** 034012 (2015)

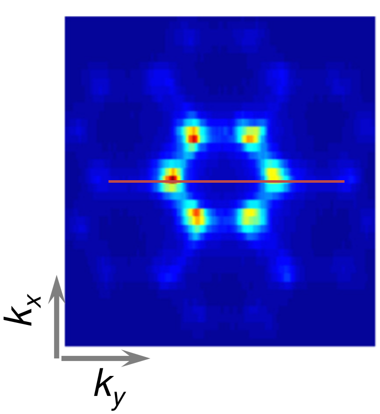
p-bands – zigzag edge

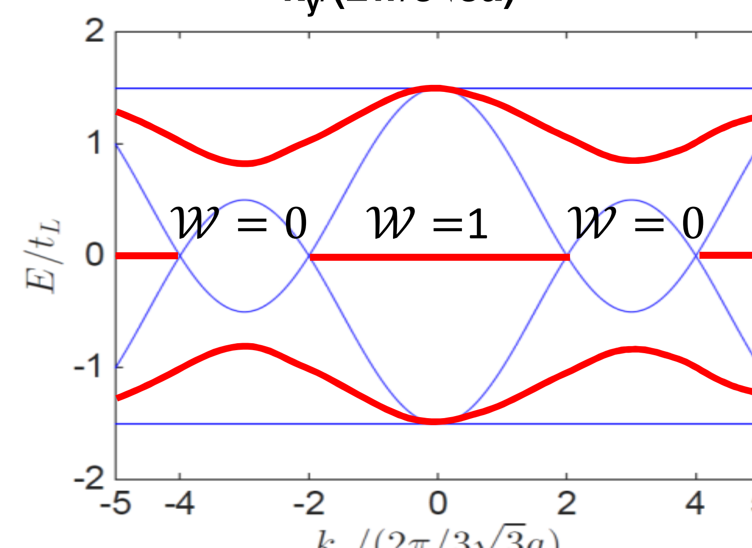
Bulk



zigzag edge



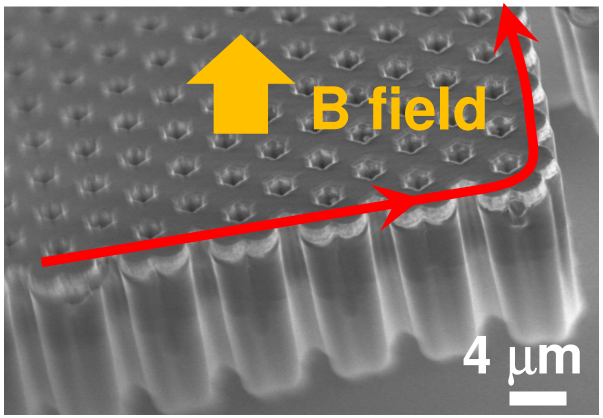




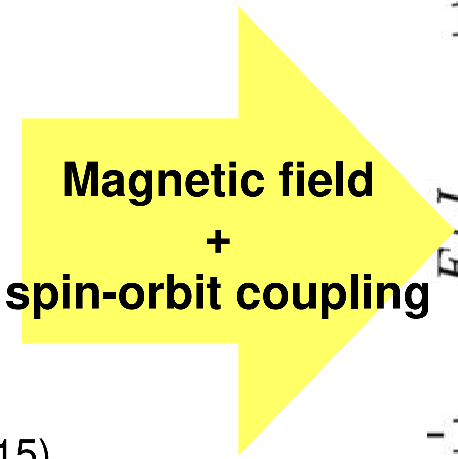
Milicevic et al., PRL **118**, 107403 (2017)

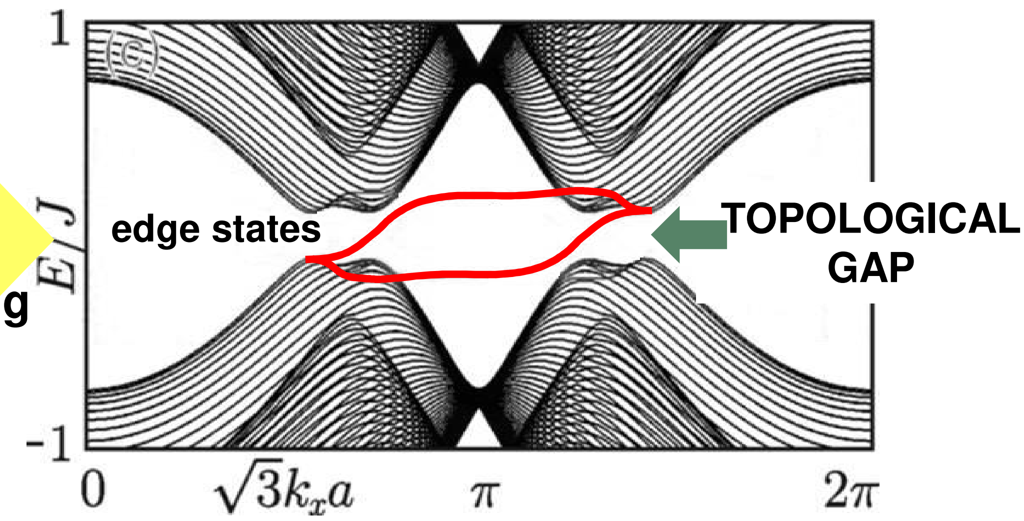
Perspectives: polariton Chern insulator

Polariton Chern insulator

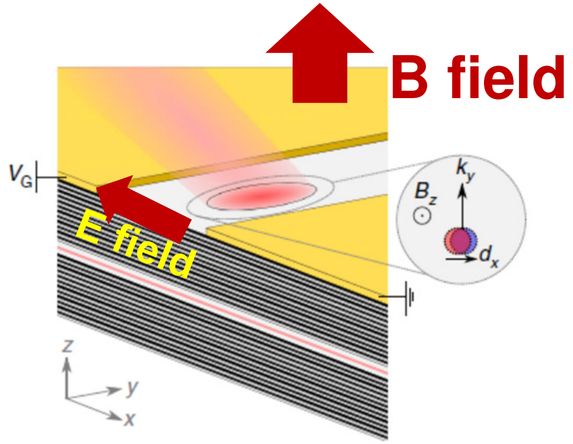


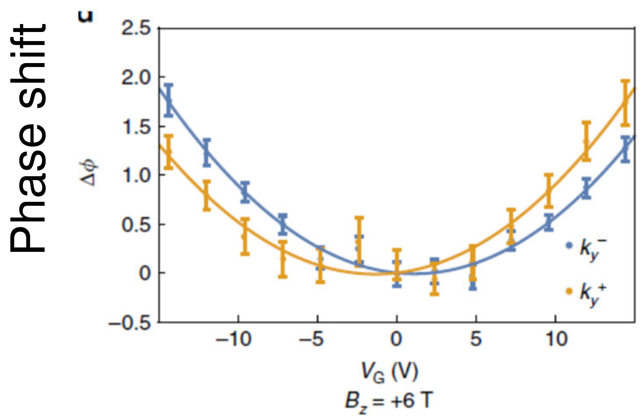
Nalitov, et al., PRL **114**, 116401 (2015)
Bardyn et al., PRB **91,** 161413(R) (2015)





Artificial gauge potential





H.-T. Lim et al., Nat. Commun. **8**, 14540 (2017)

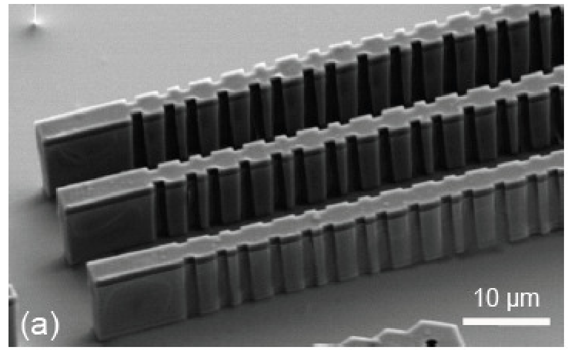
Emulation with polaritons

honeypol.eu

Lasing in topological edge states

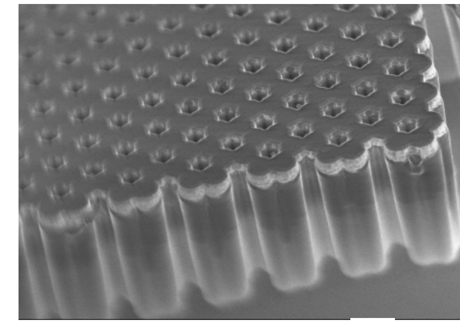
P. St-Jean et al.,
Nat. Photon. **11**, 651 (2017)

Topological invariants in Fibonacci quasi-crystal



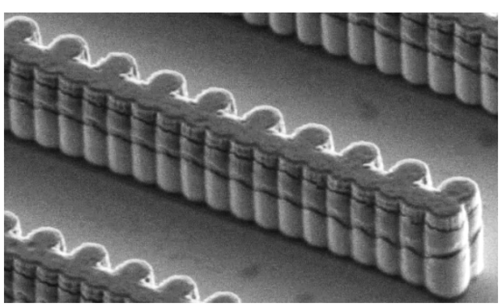
D. Tanese et al., PRL 112, 146404 (2014)
F. Baboux et al., PRB 95, 161114(R) (2017)

Dirac physics



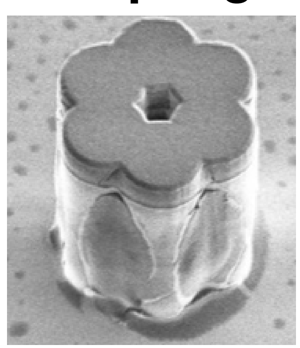
T. Jacqmin et al., PRL **112**, 116402 (2014)
M. Milicevic et al., 2D Mater. **2,** 034012 (2015)
M. Milićević et al., PRL **118,** 107403 (2017)

Flat band physics



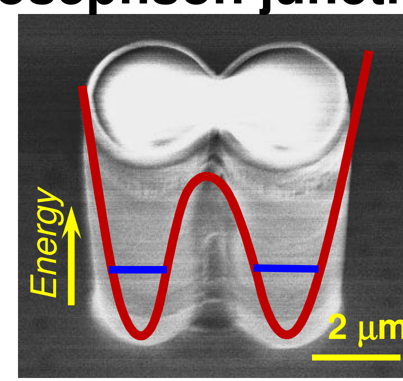
F. Baboux et al.,
PRL **116**, 066402 (2016)

Spin-orbit coupling



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

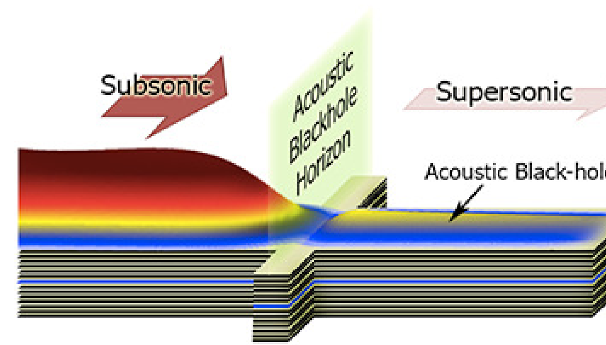
Nonlinear Josephson junction



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)