Topologie avec des fluides quantiques de lumière (polaritons de cavité)

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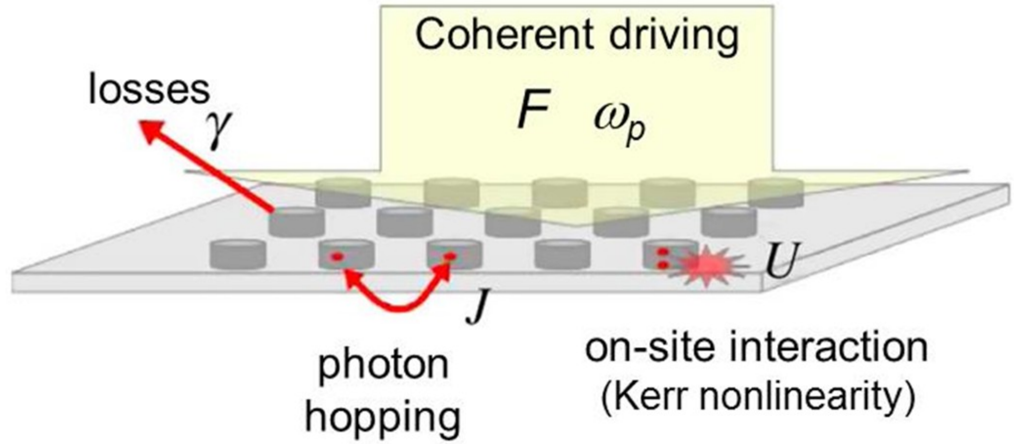
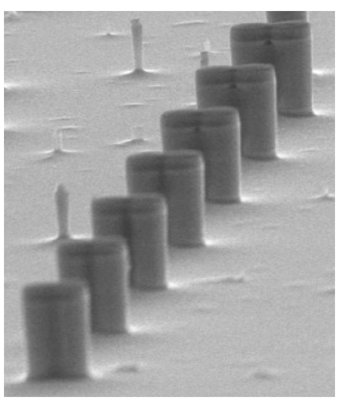
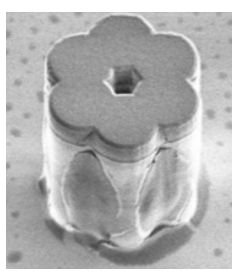
Driven dissipative polariton lattices

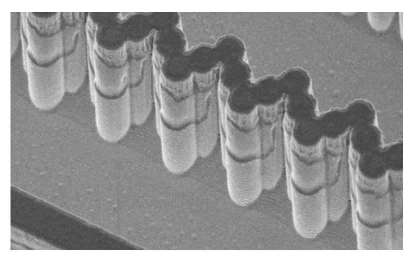
Use of nanotechnology to emulate different Hamiltonians with lattices of coupled resonators

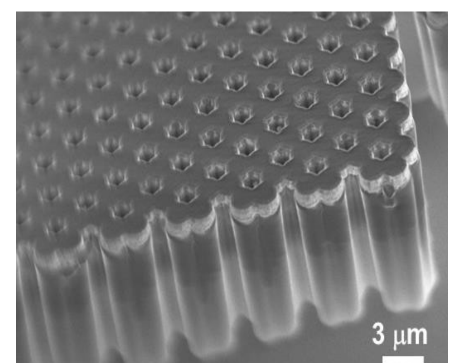
Incoherent drive



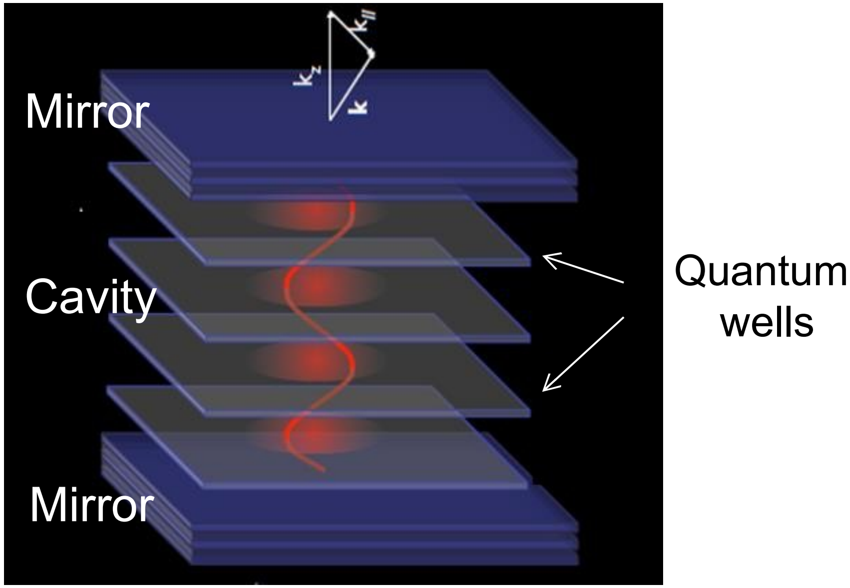


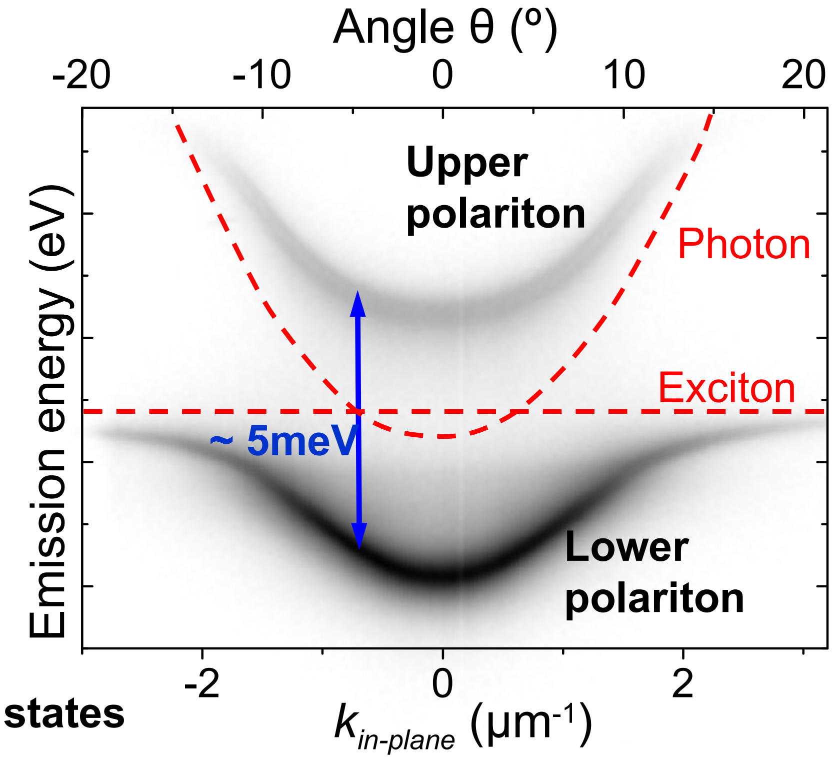




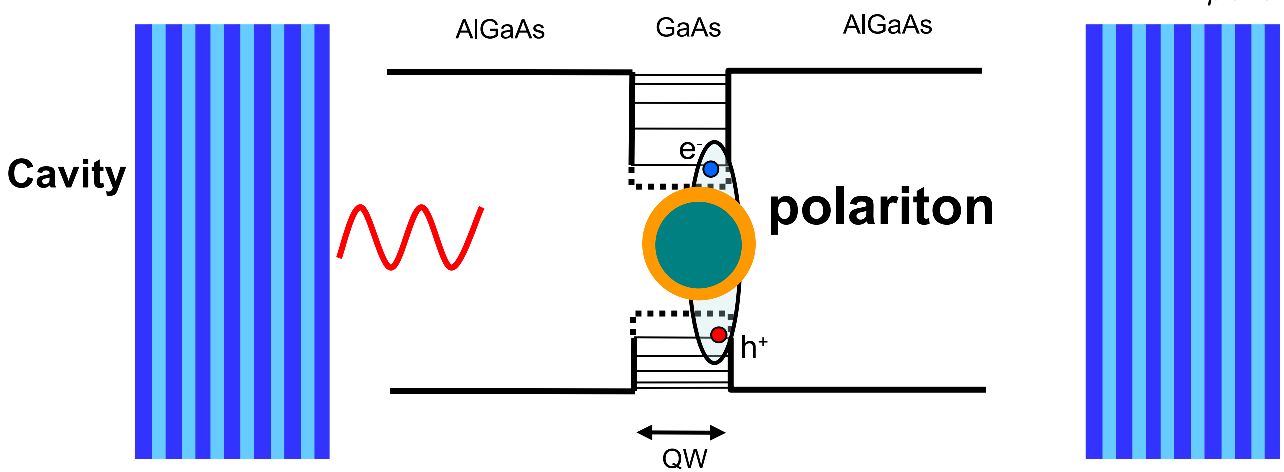


Microcavity polaritons





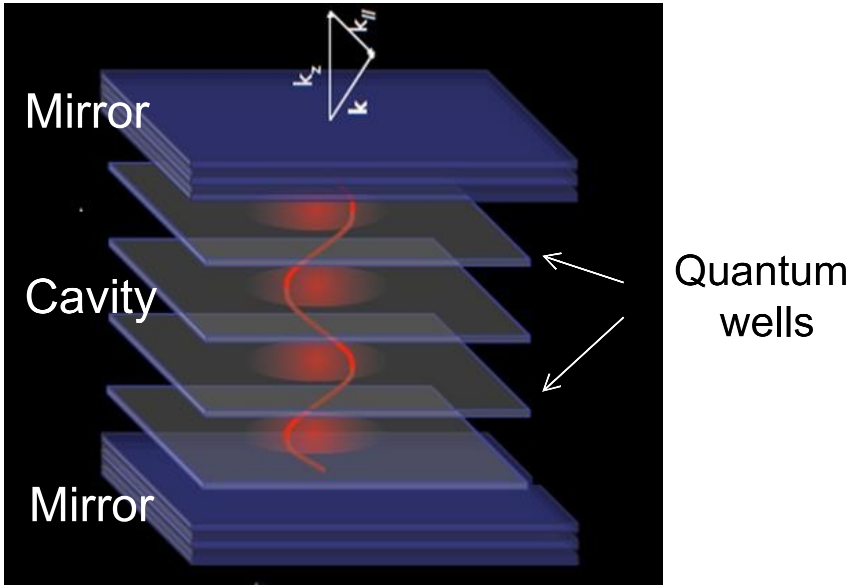
Microcavity polaritons : mixed exciton-photon states

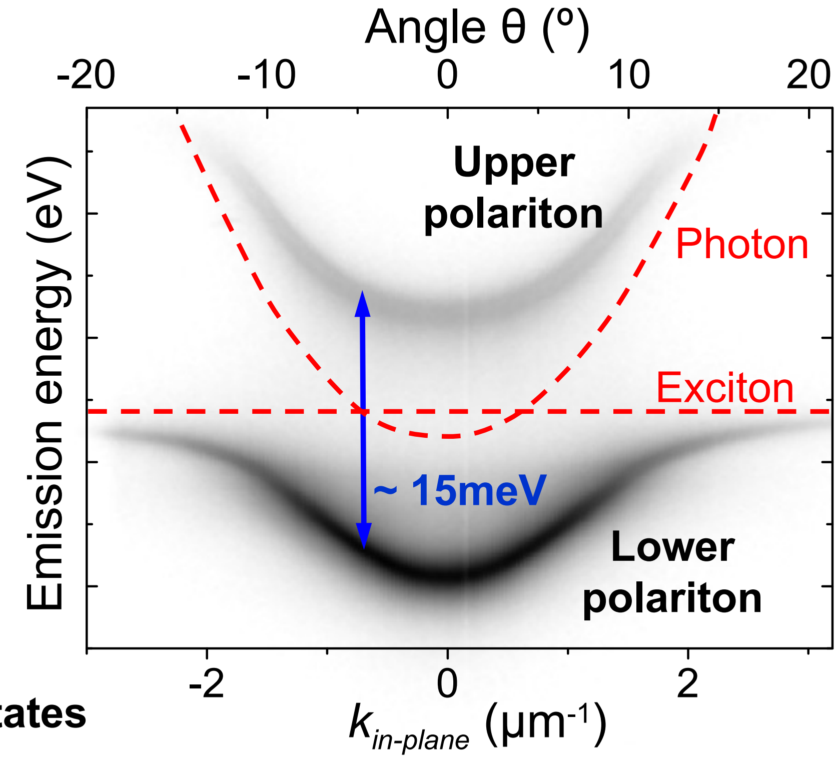


Courtesy D.Sanvitto

Claude Weisbuch
PRL **69**, 3314 (1992)

Microcavity polaritons



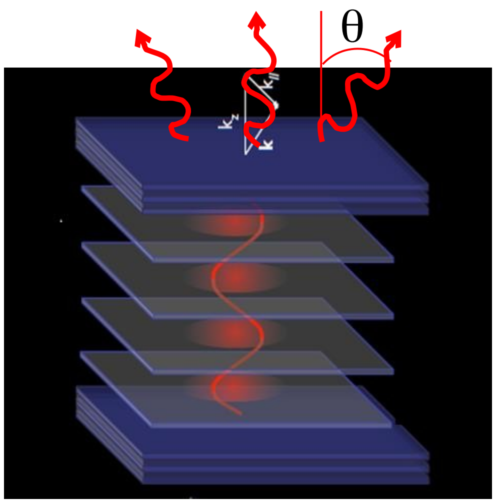


Microcavity polaritons : mixed exciton-photon states

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

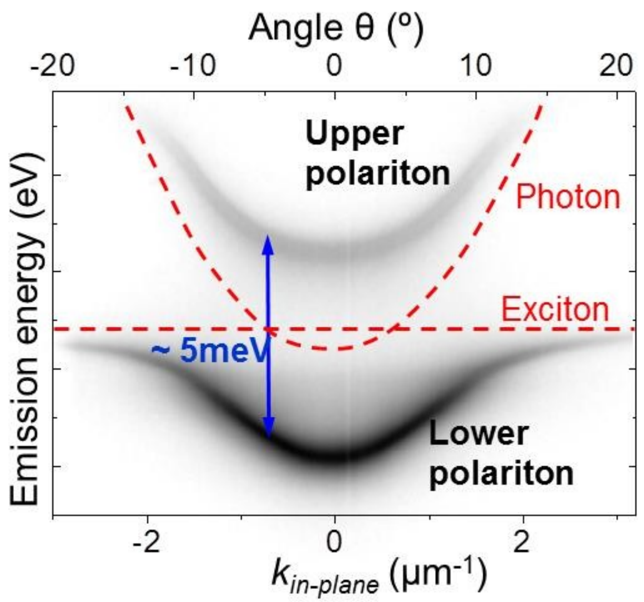
- Photonic component ➡ confinement in microstructures
  dissipation
- Excitonic component ➡
  - Interactions - $\chi^{(3)}$ (dominated by exchange)
  - Gain (lasing)
  - Sensitivity to magnetic field

Probing polariton states

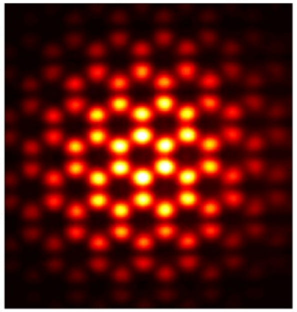


$k_{//} = \omega/c \sin(\theta)$

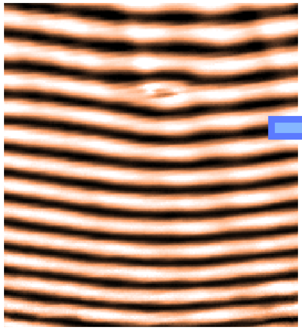
Imaging of k-space



Imaging of real space

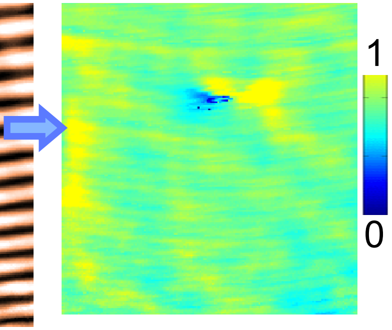


Density



Interferometry

- vortices
- solitons

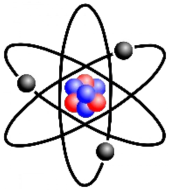


Coherence

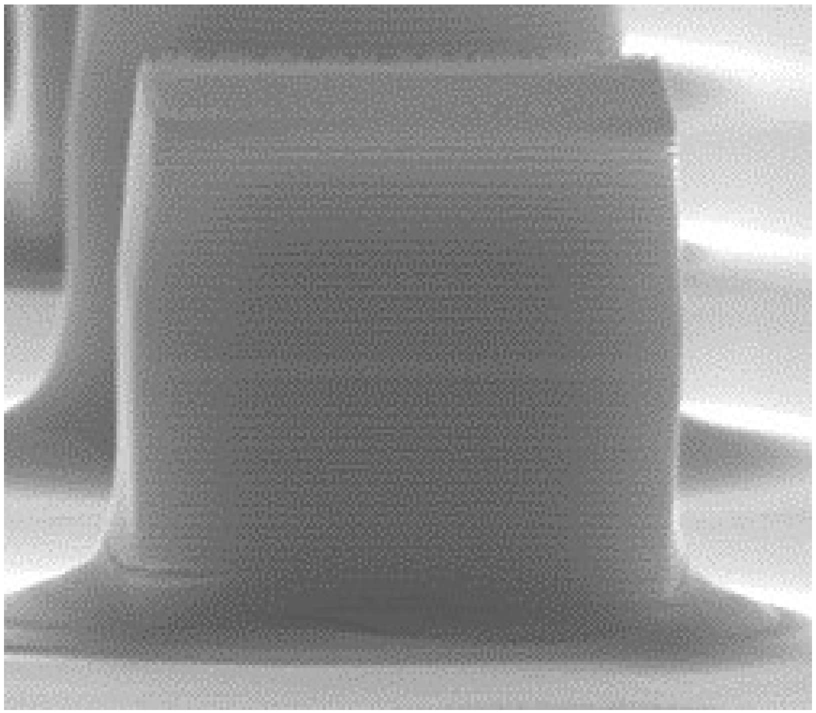
$g^{(1)}$

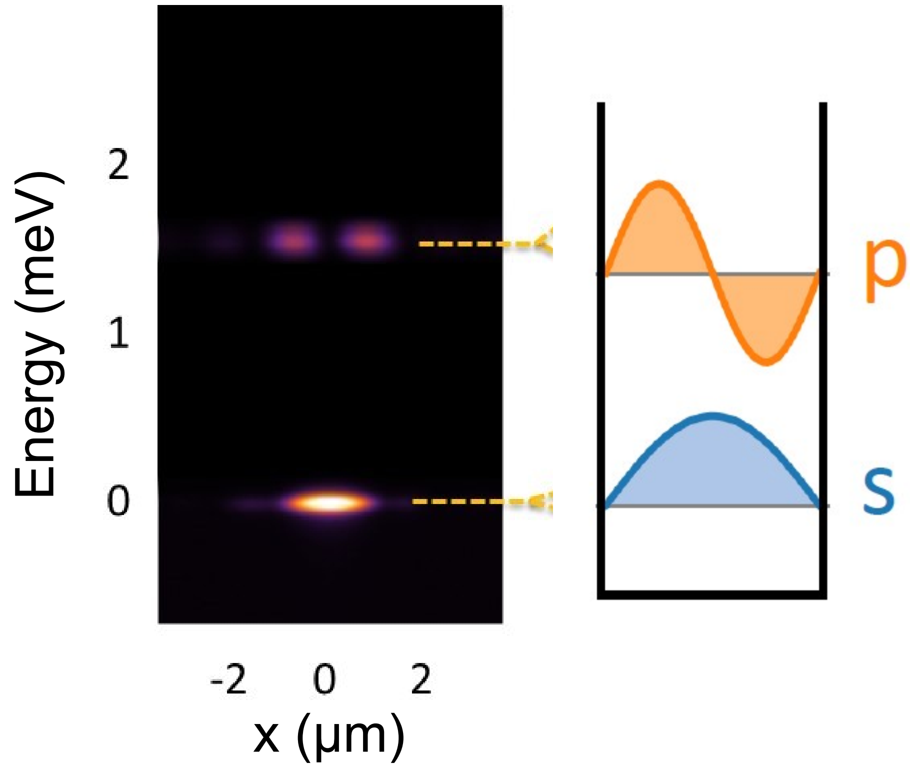
$g^{(2)}$

Lattices of coupled micropillars

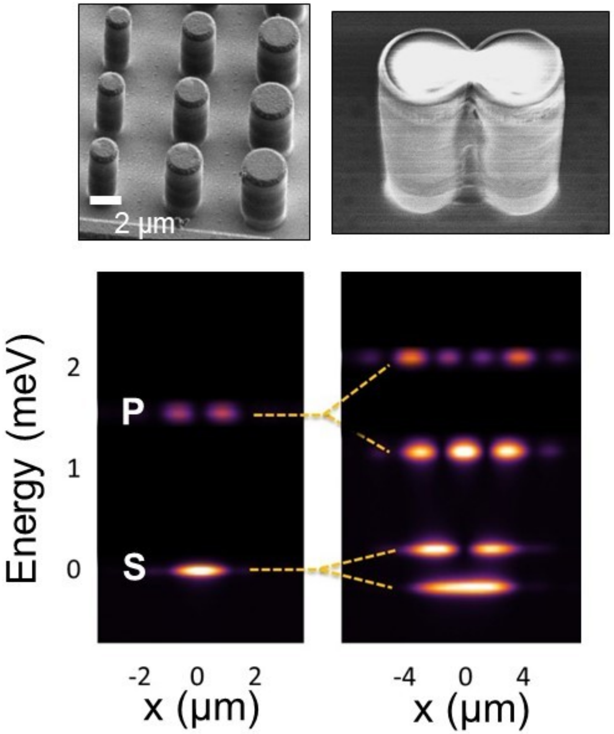


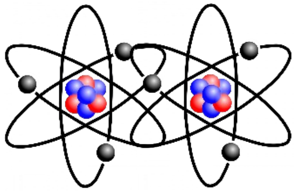
Building block



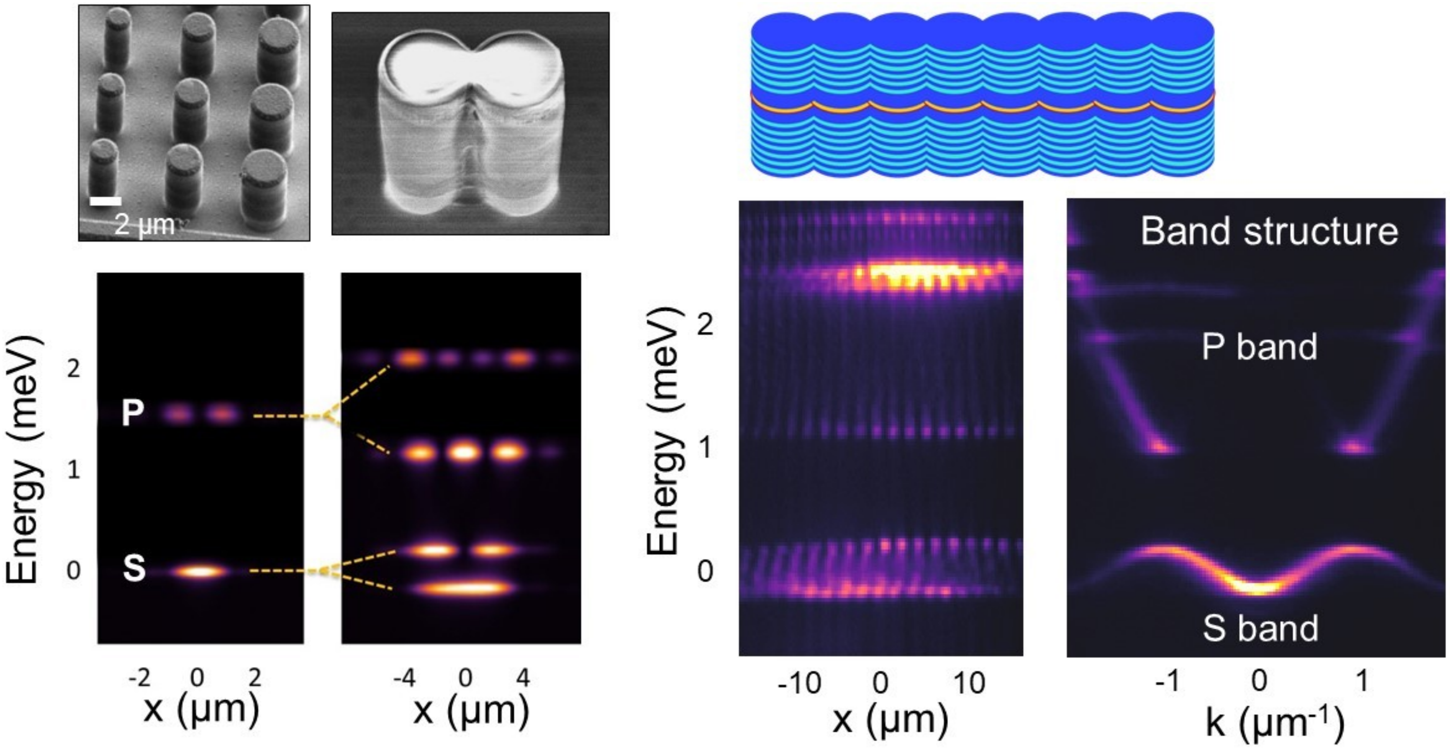


Lattices of coupled micropillars





Des réseaux de cavités: des cristaux pour la lumière

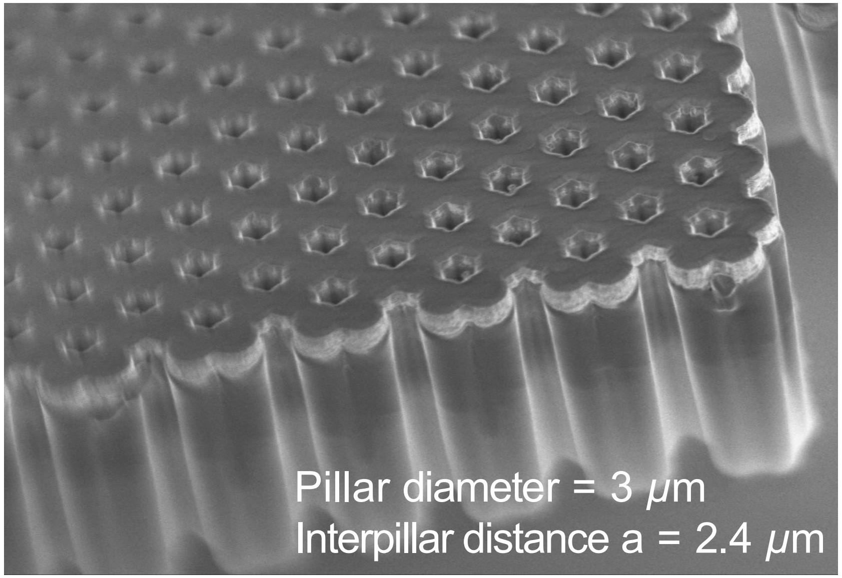


Correspondance : Wavefunction = electric field

Spin = Polarisation

C. Ciuti & I. Carusotto, Rev. Mod. Phys. **85**, 299 (2013)
Compte Rendus Physique Vol. 17, Issue 8, Pages 805-956 (2016)
Physique des polaritons: Edité par A. Amo, J. Bloch and I. Carusotto

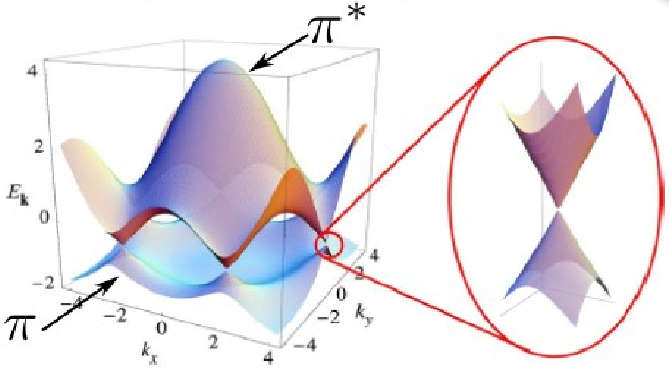
Polariton honeycomb lattice



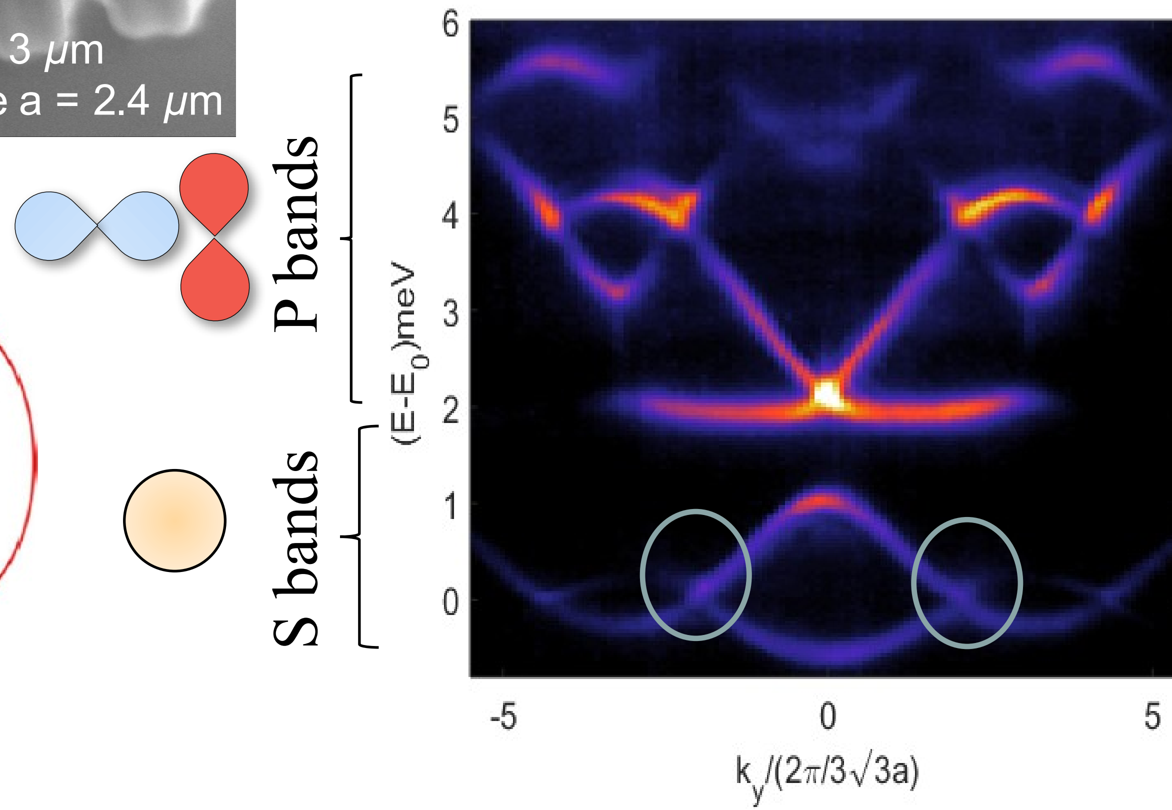
$k_y/(2\pi/3\sqrt{3}a)$

$k_x/(2\pi/3a)$

Graphene energy bands



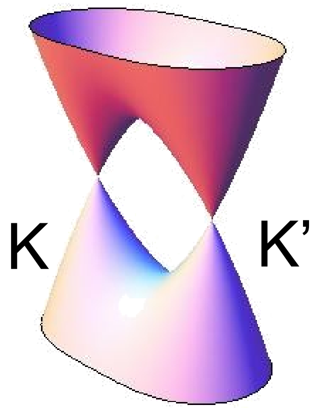
Castro Neto et al., Rev. Mod. Phys. 81 (2009)



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

Topological properties of Dirac cones

Topological charge: **Winding number**

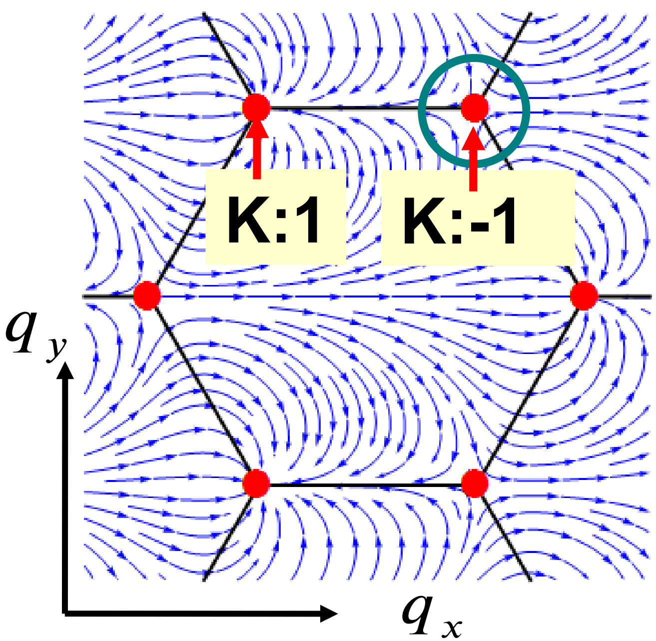


ψ

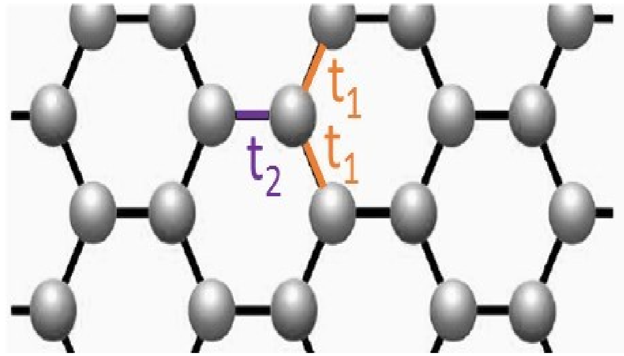
ω-Number of times phase of the wave function winds around the Dirac cone

ω

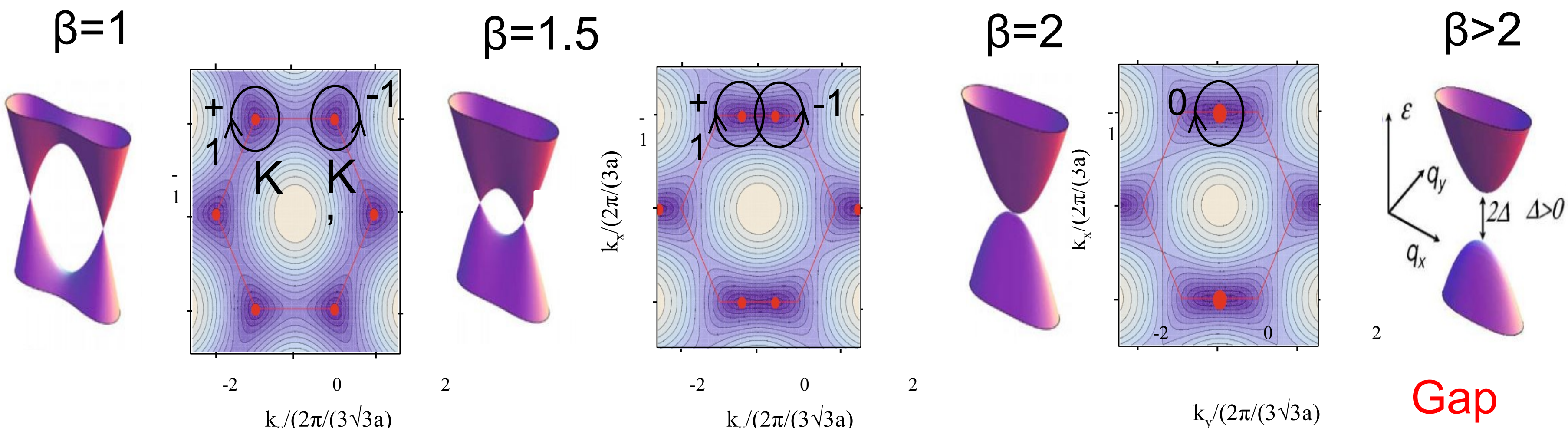
$$\frac{1}{2\pi}\oint \partial_q \Phi(q)\cdot dq$$



Uniaxial strain in graphene



$\beta = t_2/t_1$



Gap opens!

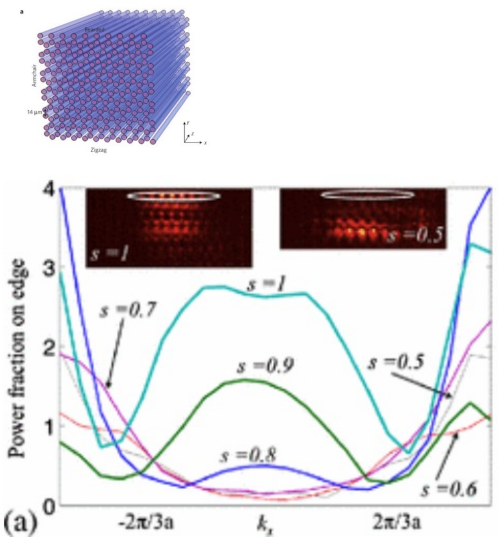
$$H_{\pm} = \left(\frac{1}{2} - \frac{1}{\beta} + \frac{q_x^2}{2m}\right)\sigma_x + c q_y \sigma_y$$

Hamiltonian at merging of +1 and -1 Dirac cones

Montambaux G. et al., *Phys. Rev. B* **80**, 153412 (2009)

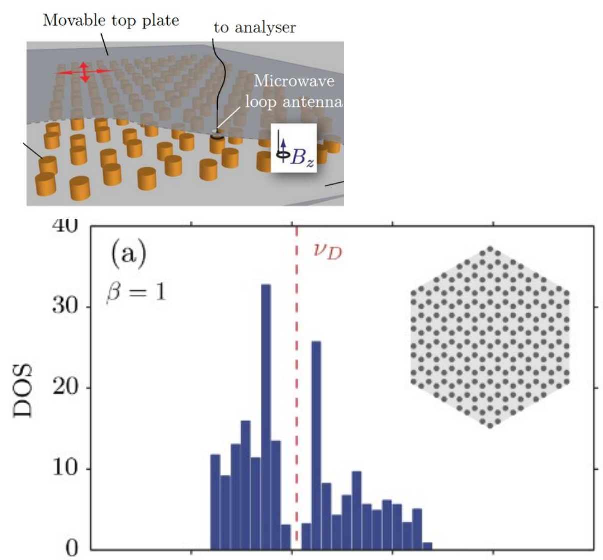
Artificial graphene: topological phase transition

Coupled Waveguides



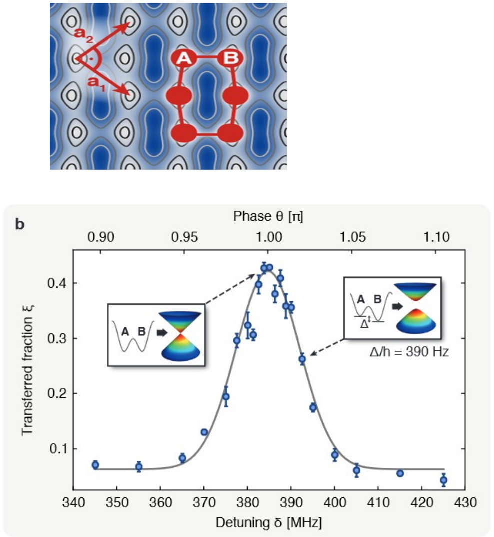
Rechtsman et al., Phys. Rev. Lett, 111, 103901 (2013)
Noh et al., Nature Physics, 13, 6 (2017).

Microwave resonators



Bellec et al., Phys. Rev. Lett, 3, 033902 (2013)

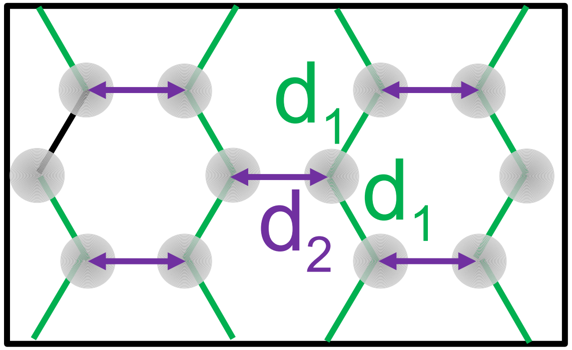
Cold atoms



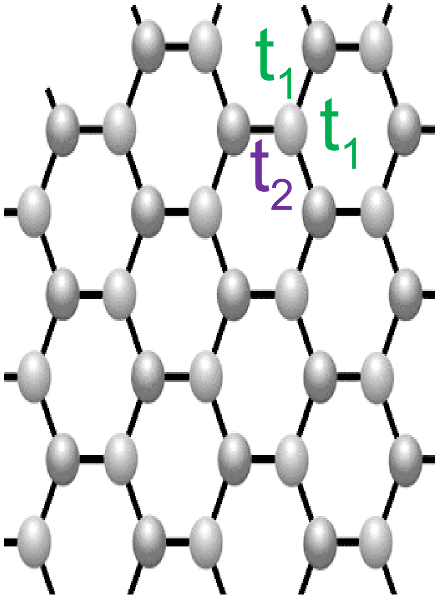
Tarruell et al., Nature, 483, 7389 (2012)

Strain engineering with micropillars

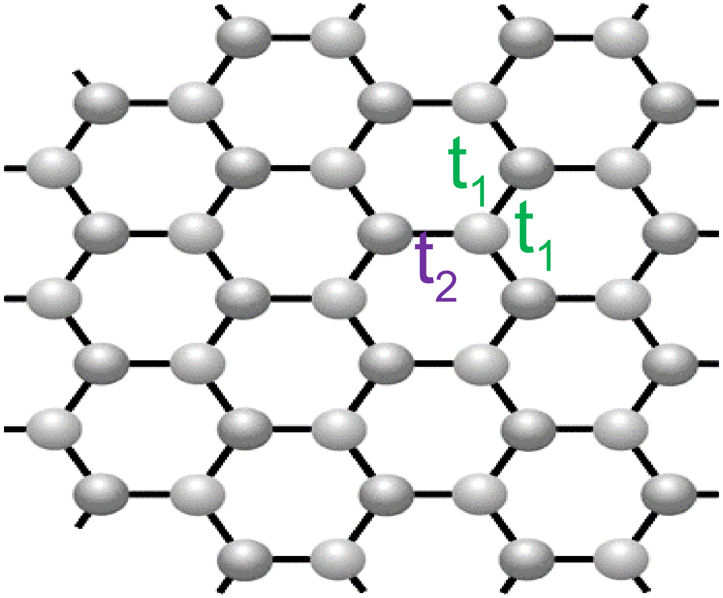
$\beta = t_2/t_1$



$\beta > 1$



$\beta < 1$



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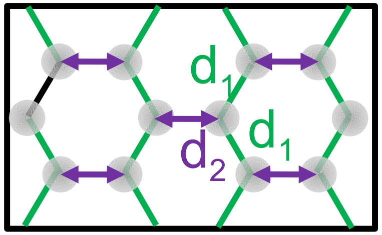
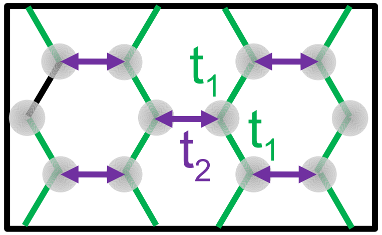
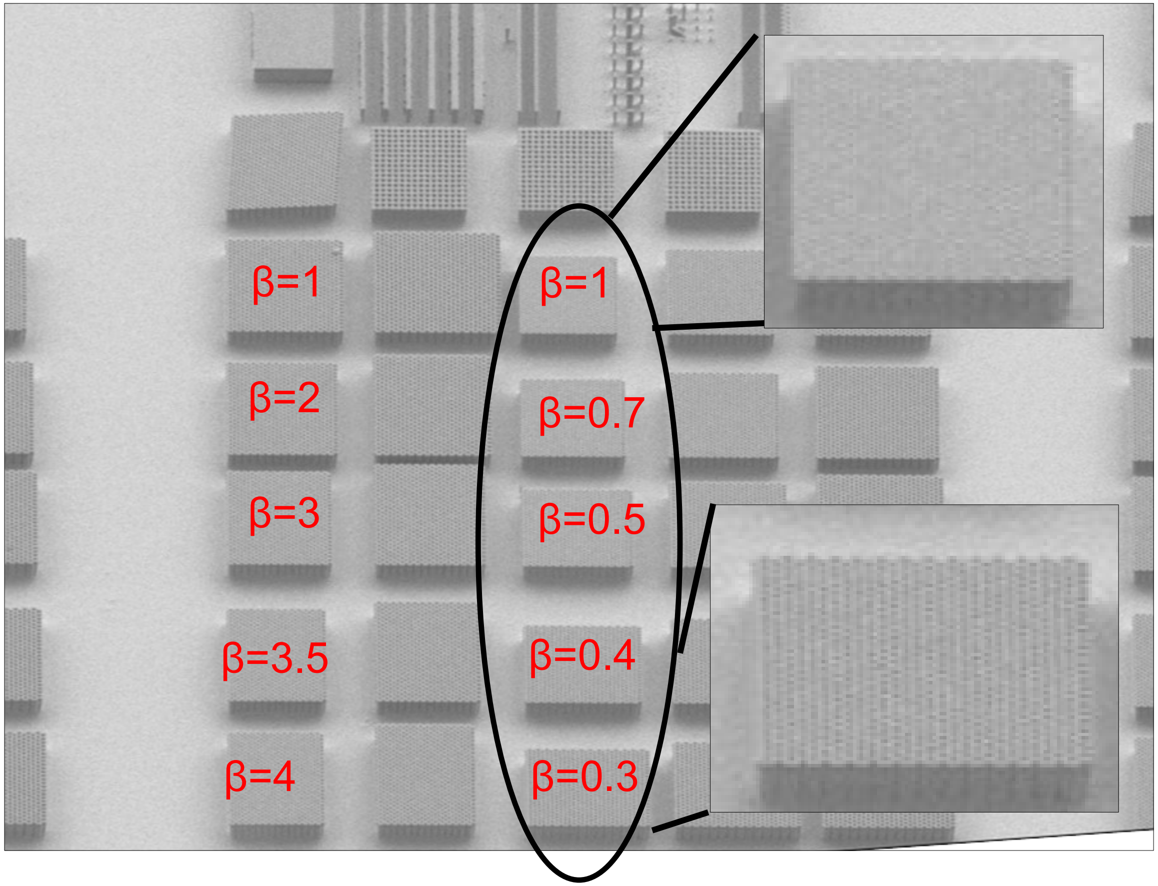
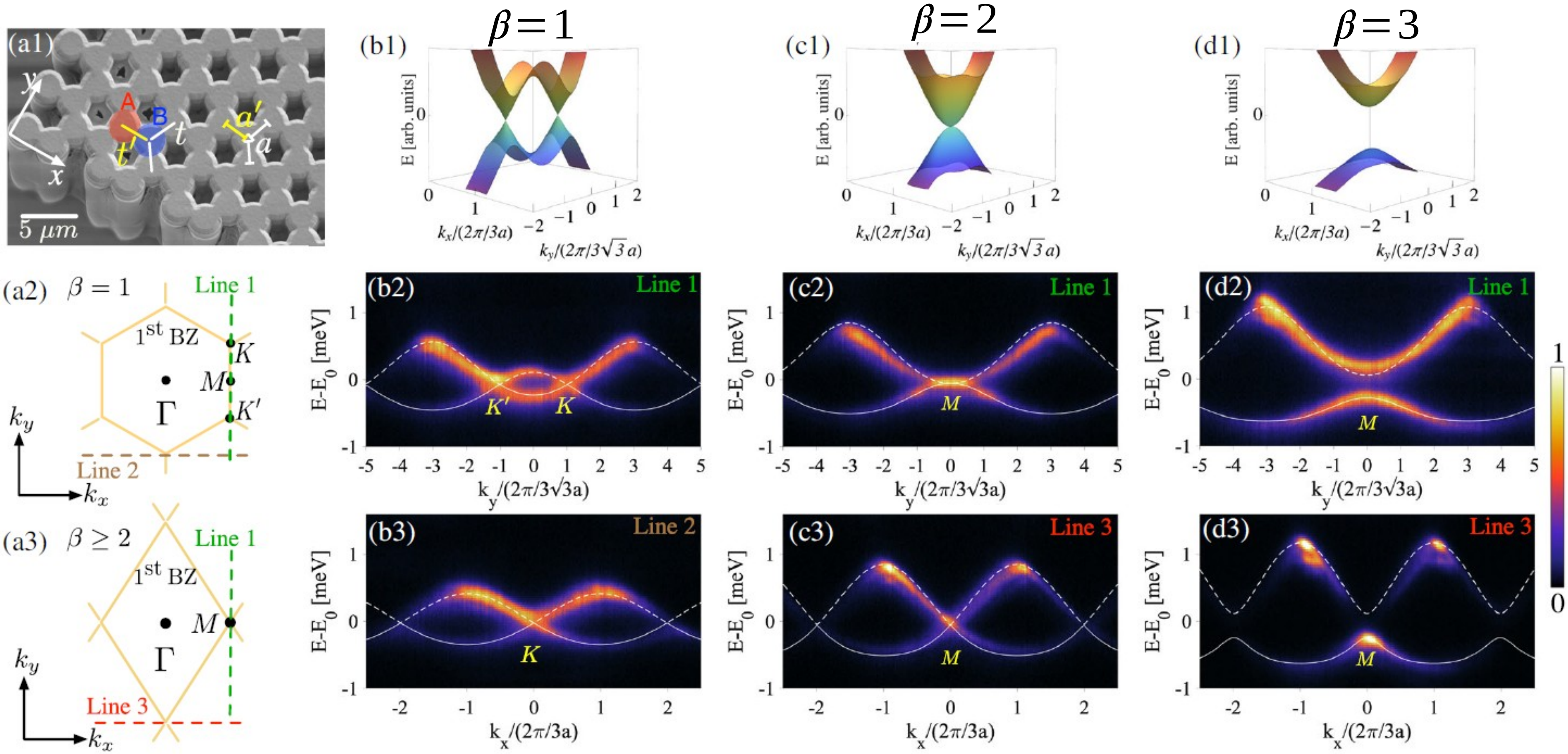






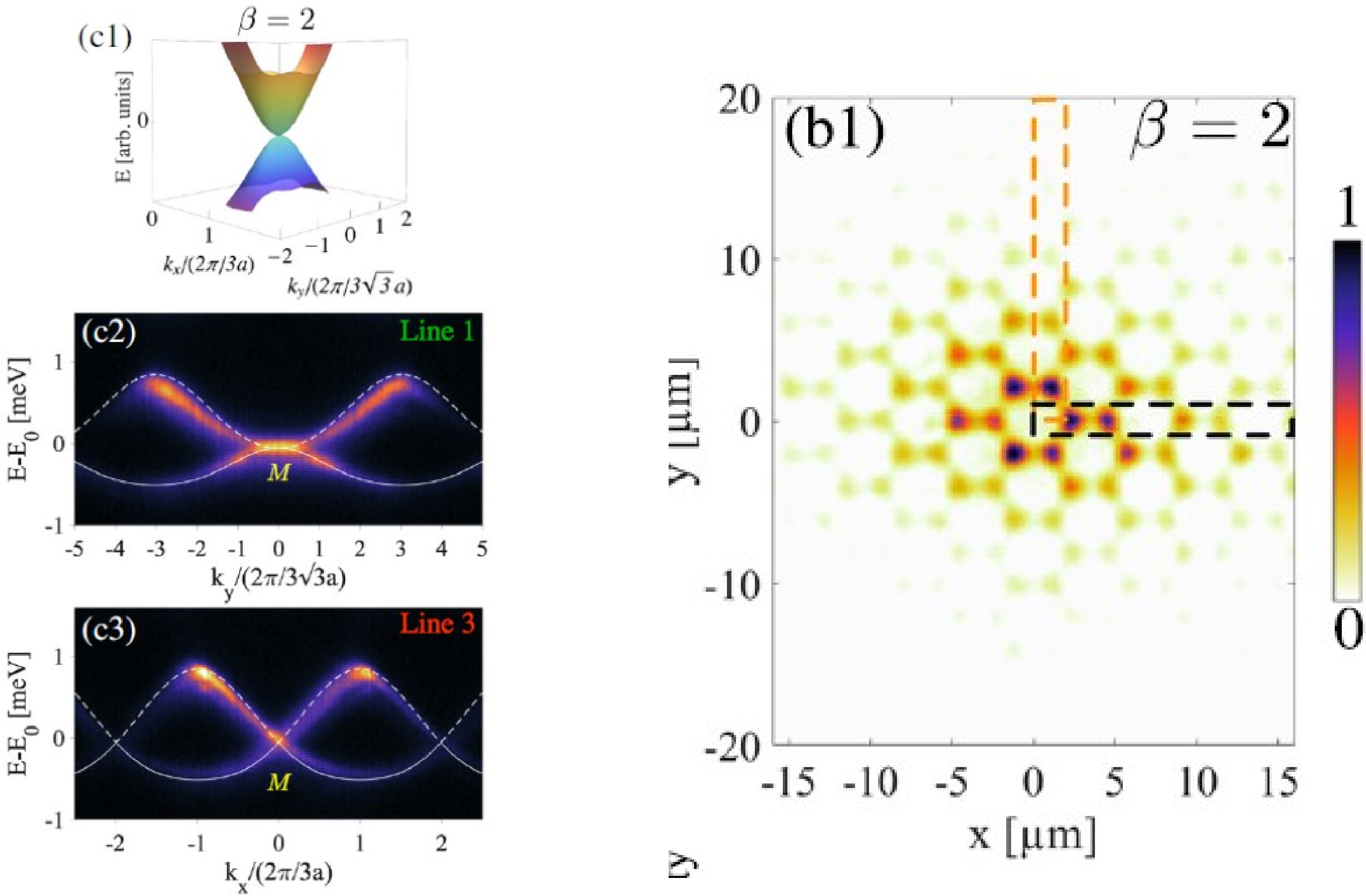
Merging of +1 and -1 Dirac cones

$\beta = t_2/t_1$



Semi-Dirac Transport and Anisotropic Localization in Polariton Honeycomb Lattices, B. Real, ….. G. Montambaux, et al., Physical Review Letters **125** 186601 (2020)

Anisotropic transport of semi-Dirac polaritons



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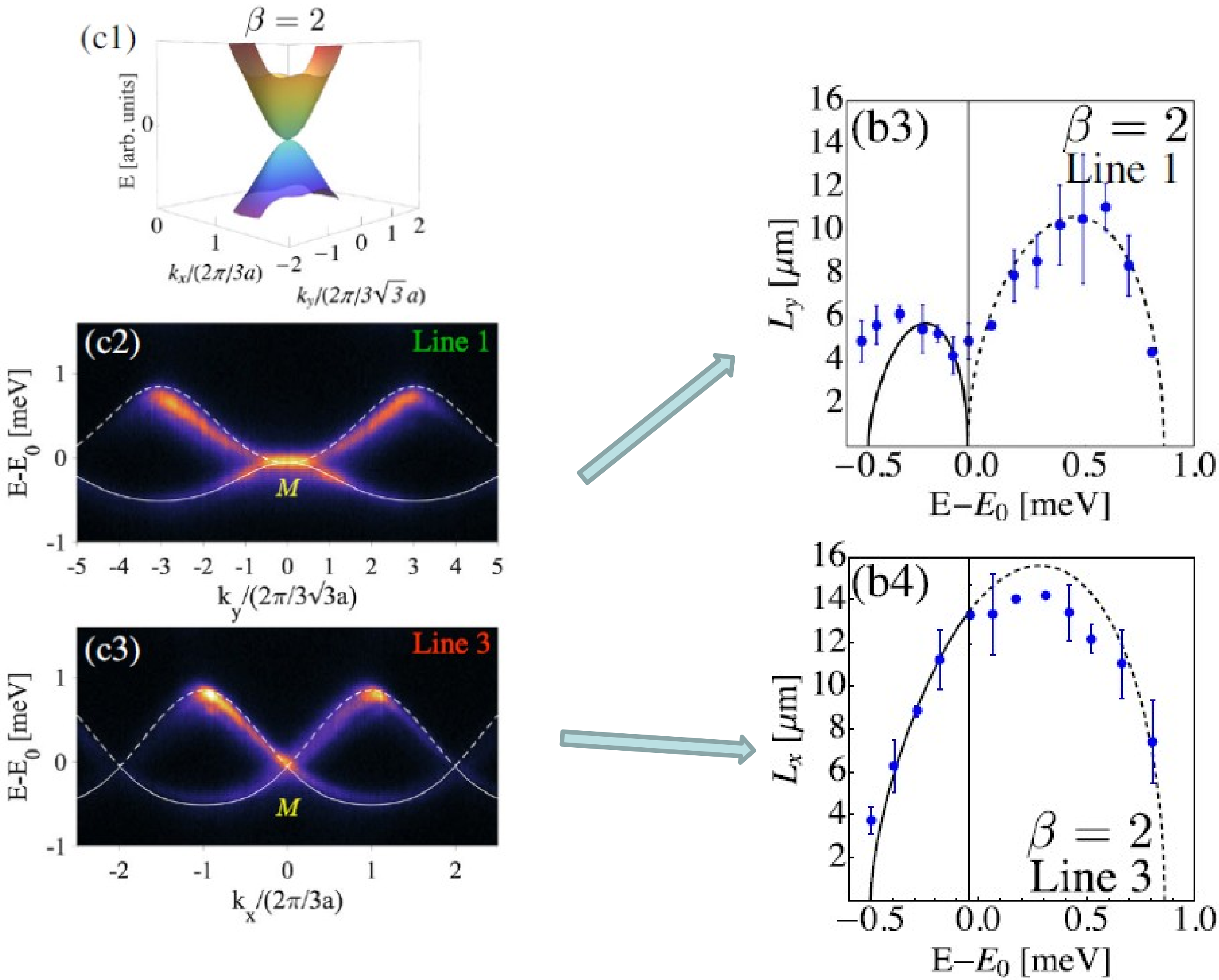
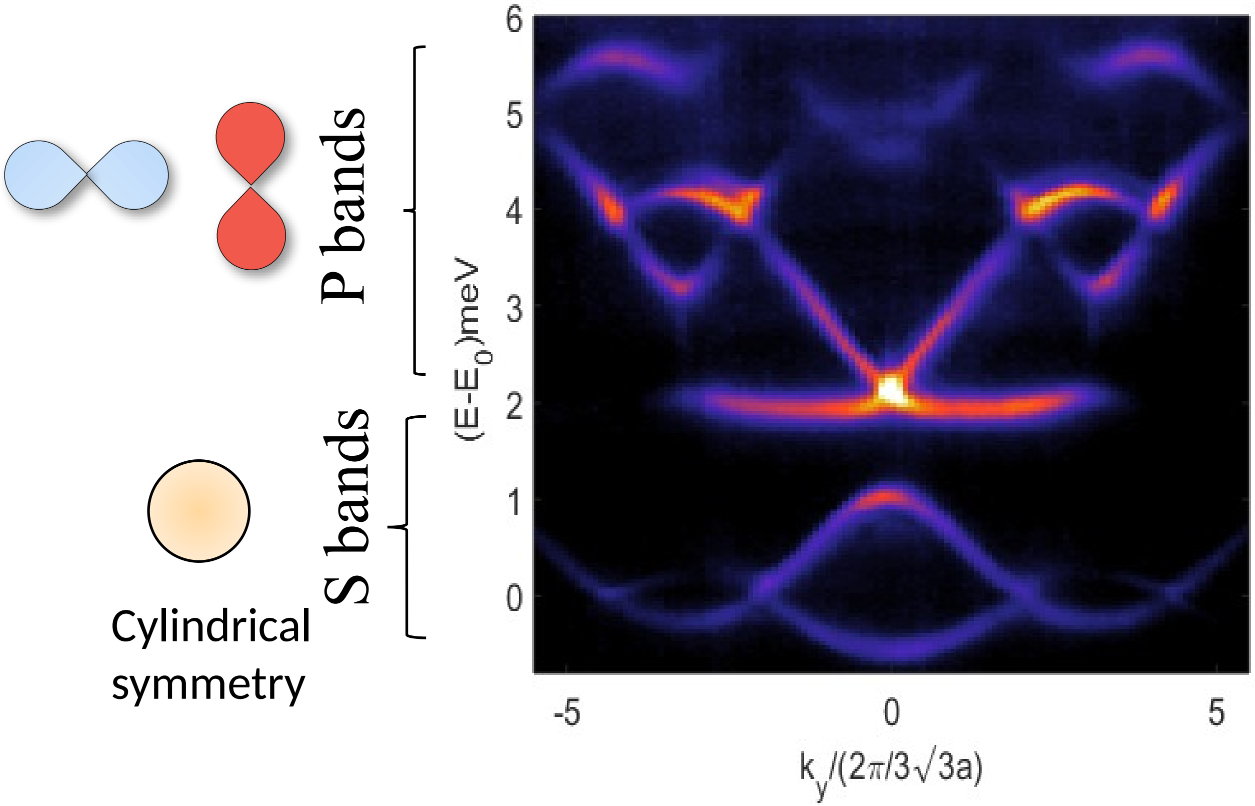
Anisotropic transport of semi-Dirac polaritons



Semi-Dirac Transport and Anisotropic Localization in Polariton Honeycomb Lattices, B. Real, ….. G. Montambaux, et al., Physical Review Letters **125** 186601 (2020)

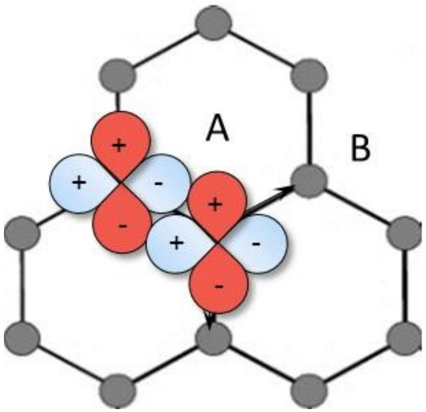
A new playground for Gilles : the p-bands!!!!

Orbital bands

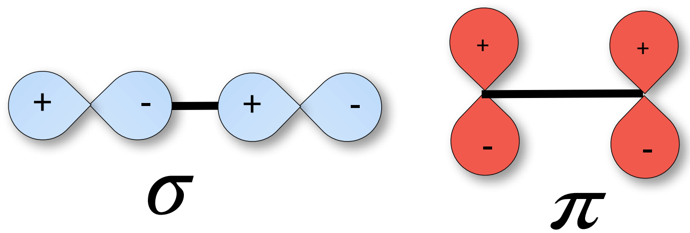


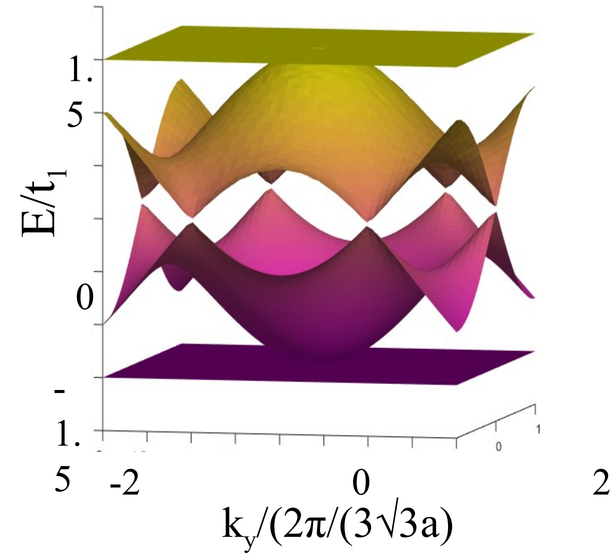
Type-III and Tilted Dirac Cones Emerging from Flat Bands in Photonic Orbital Graphene; M. Milićević, G. Montambaux et al., Phys. Rev. X 9, 031010 (2019)

Orbital graphene



$t_\sigma >> t_\pi$

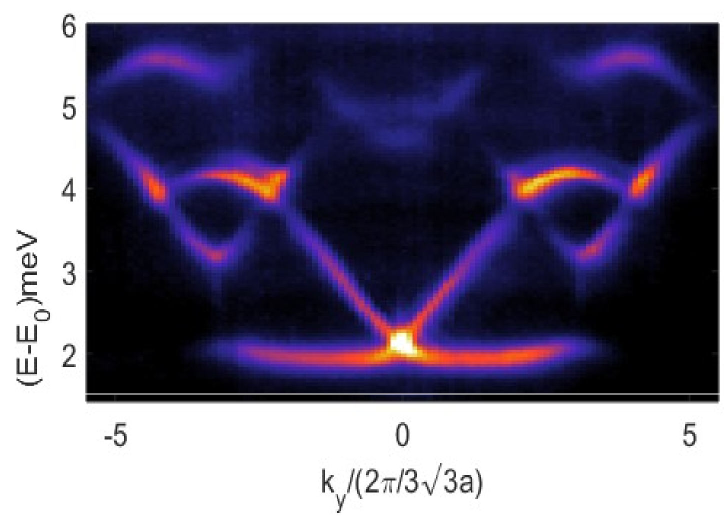




Tight-binding Hamiltonian

$$\hat{H} = -\sum_{\langle i,j\rangle}[t_\sigma(\hat{\vec{\psi}}_i^\dagger \cdot e_{ij}^{(L)})(e_{ij}^{(L)\dagger} \cdot \hat{\vec{\psi}}_j)$$

$$+ t_\pi(\hat{\vec{\psi}}_i^\dagger \cdot e_{ij}^{(T)})(e_{ij}^{(T)\dagger} \cdot \hat{\vec{\psi}}_j^\dagger) + \mathrm{H.c.}]$$



Wu, D. Bergman, L. Balents, and S. Das Sarma, Phys. Rev. Lett. **99**, 070401 (2007)

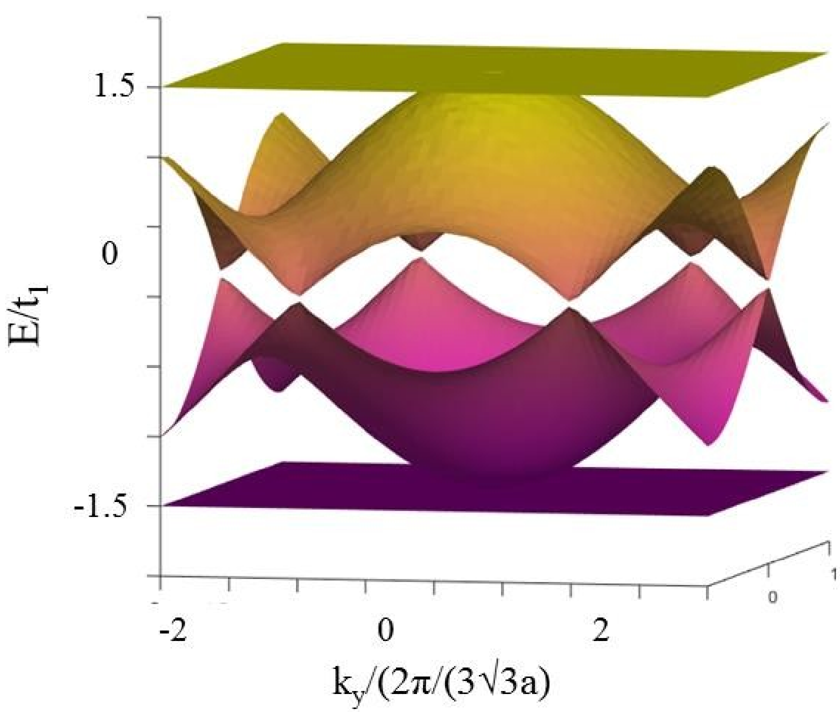
PHYSICAL REVIEW X **9**, 031010 (2019)

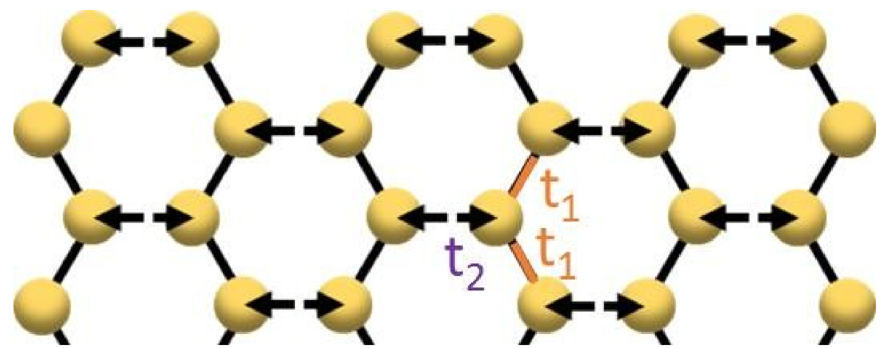
Featured in Physics

Type-III and Tilted Dirac Cones Emerging from Flat Bands in Photonic Orbital Graphene

M. Milićević,[1] G. Montambaux,[2] T. Ozawa,[3] O. Jamadi,[4] B. Real,[4] I. Sagnes,[1] A. Lemaître,[1]
L. Le Gratiet,[1] A. Harouri,[1] J. Bloch,[1] and A. Amo[4]

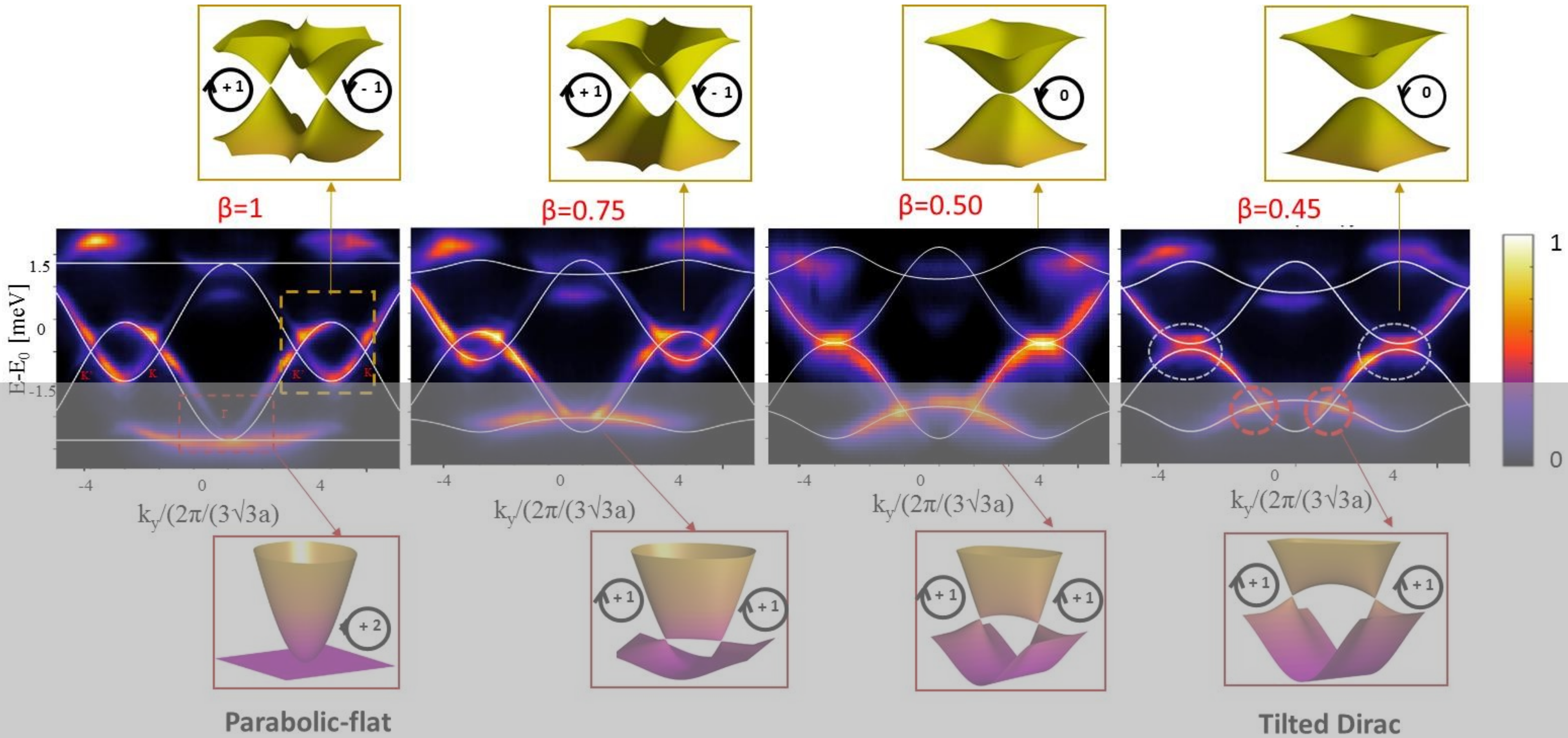
$\beta = t_2/t_1$





Manipulation of P bands

$\beta = t_2/t_1$



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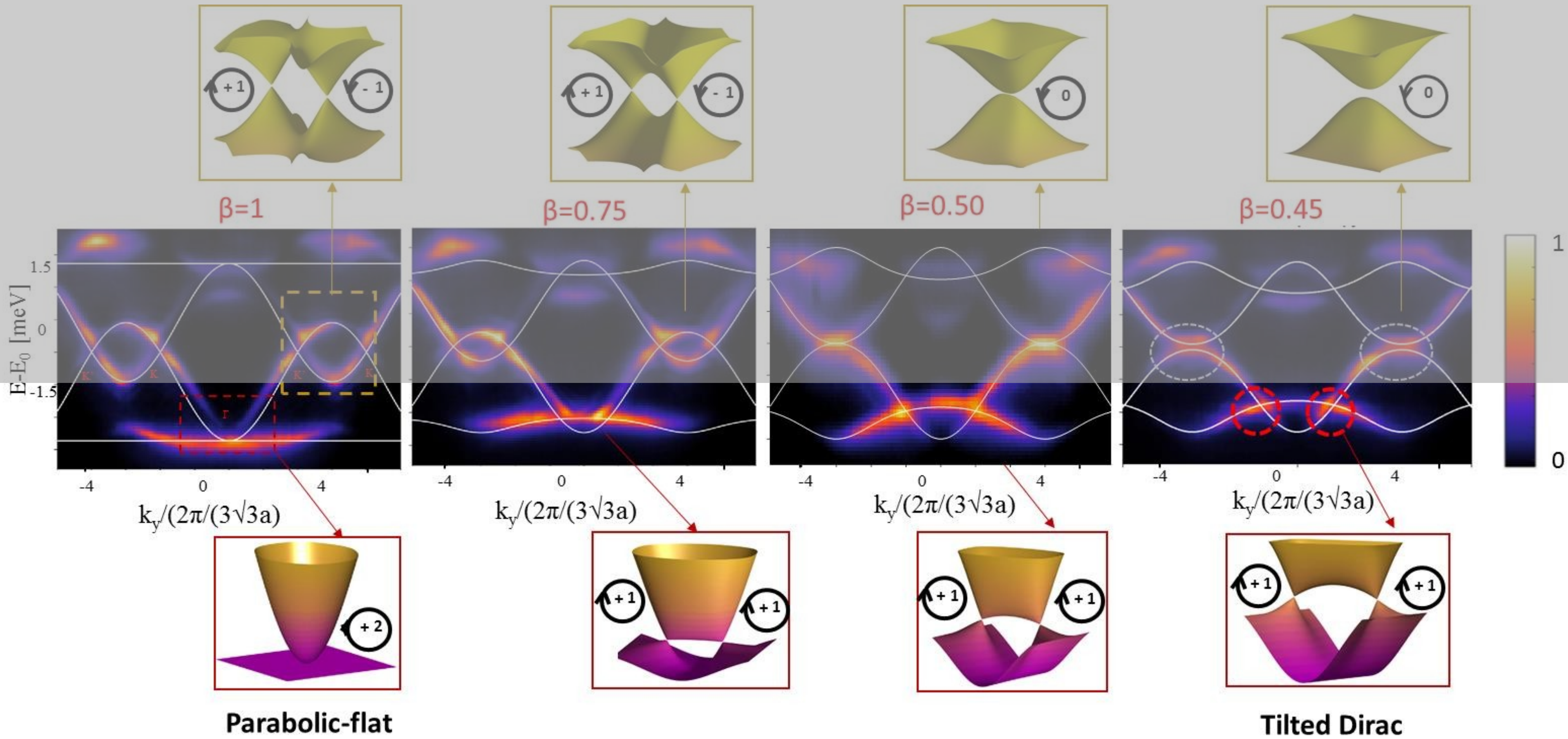
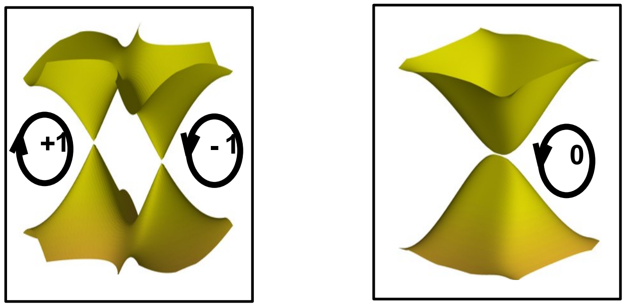


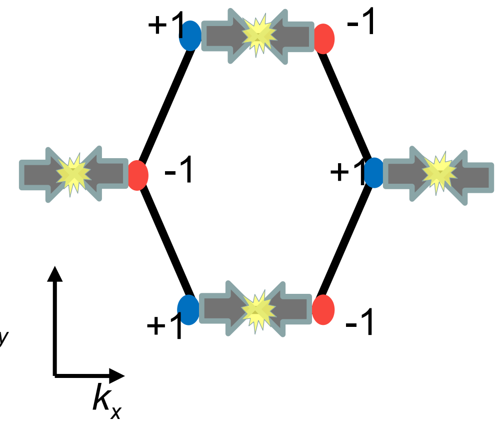
Type-III and Tilted Dirac Cones Emerging from Flat Bands in Photonic Orbital Graphene; M. Milićević, G. Montambaux et al., Phys. Rev. X 9, 031010 (2019)

Two types of merging of Dirac points

Opposite topological charge ➡ **gap opens**



Expansion



Two types of merging of Dirac points

PHYSICAL REVIEW LETTERS **121**, 256402 (2018)

Winding Vector: How to Annihilate Two Dirac Points with the Same Charge

Gilles Montambaux,[1] Lih-King Lim,[2,3,*] Jean-Noël Fuchs,[1,4] and Frédéric Piéchon[1]
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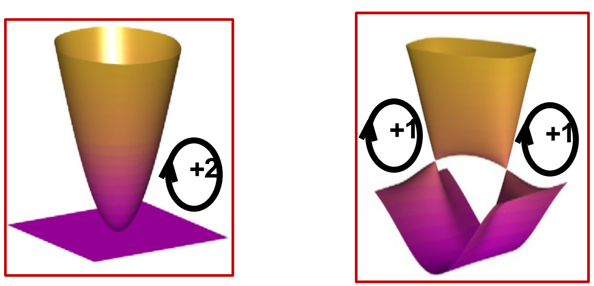
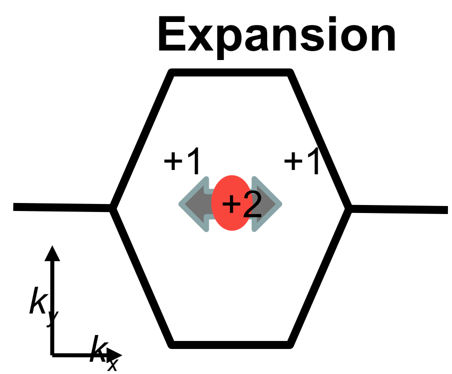
[2]*Zhejiang Institute of Modern Physics, Department of Physics, Zhejiang University, Hangzhou, Zhejiang 310027, People's Republic of China*
[3]*Institute for Advanced Study, Tsinghua University, Beijing 100084, People's Republic of China*
[4]*Sorbonne Université, CNRS, Laboratoire de Physique Théorique de la Matière Condensée, LPTMC, F-75005 Paris, France*

(Received 11 April 2018; published 18 December 2018)





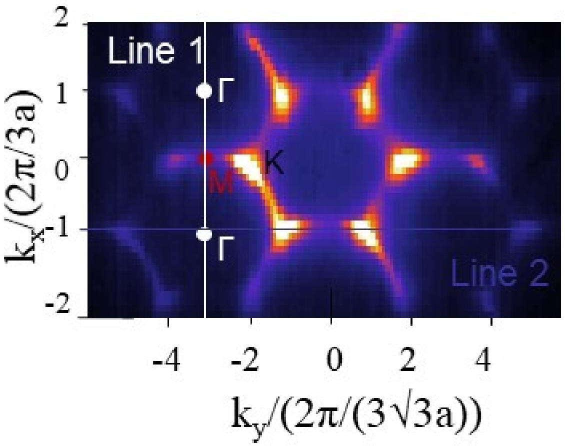
Both kinds of merging are observed in orbital photonic graphene

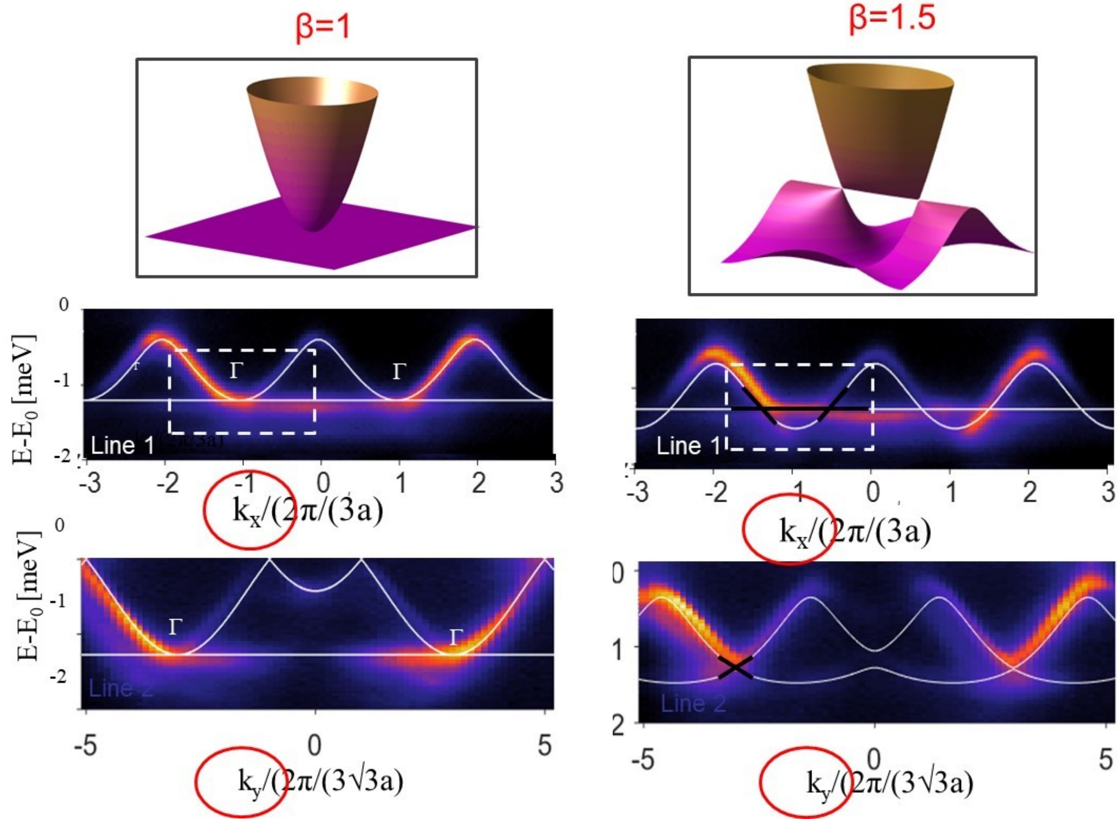
G. Montambaux et al, Phys. Rev. Lett. 121, 256402 (2018)

Duplantier et al , Dirac Matter, Birkauser (2017)

Manipulation of P bands: type III Dirac Cones

Uniaxial compression





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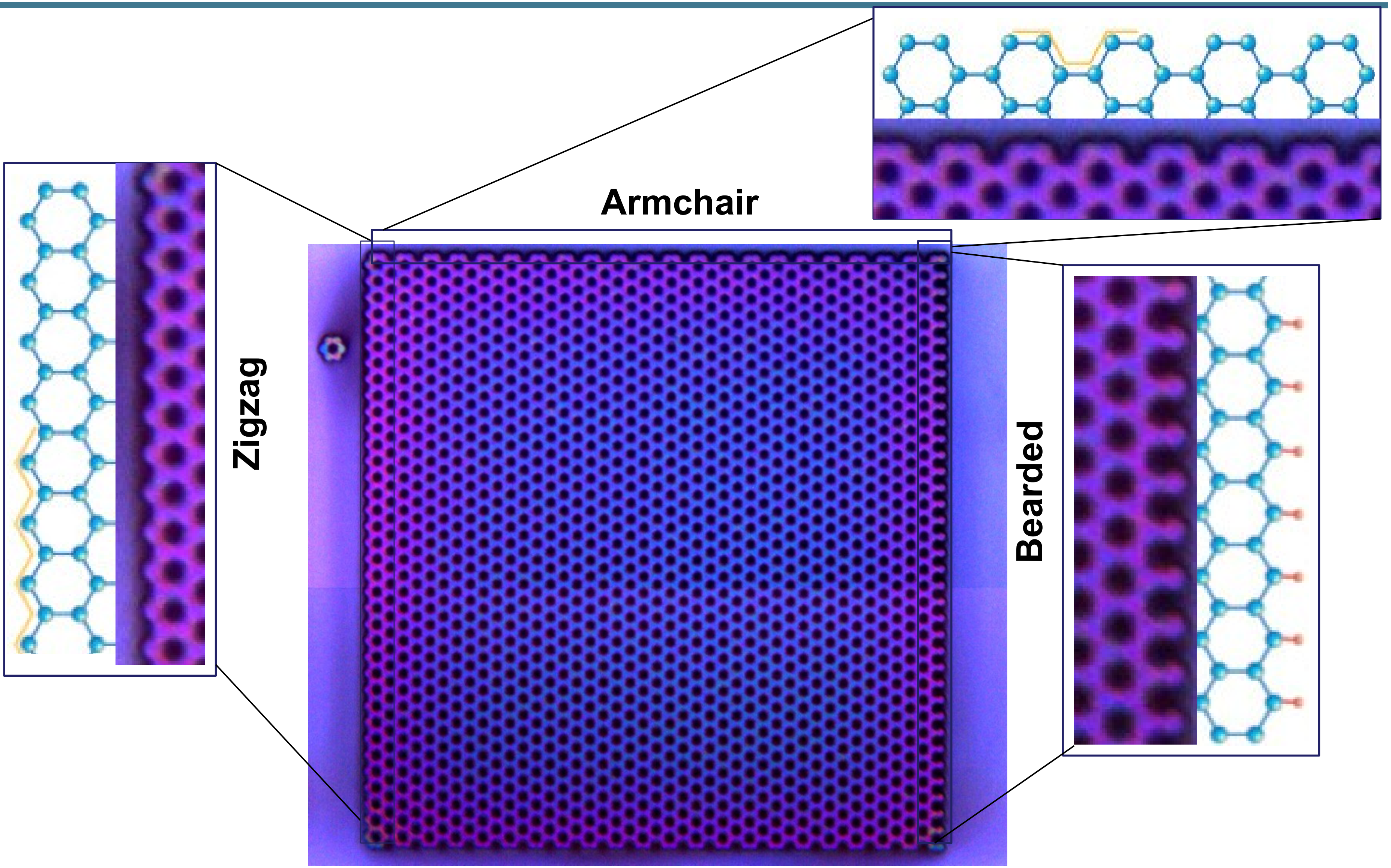
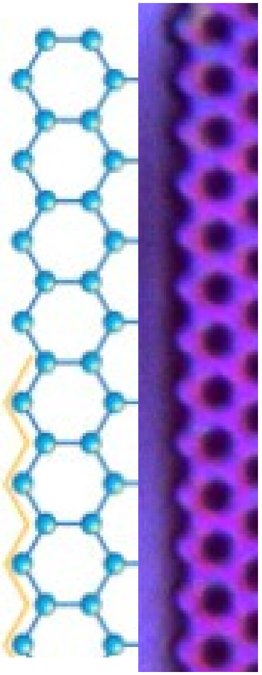
Polariton honeycomb lattice: edges



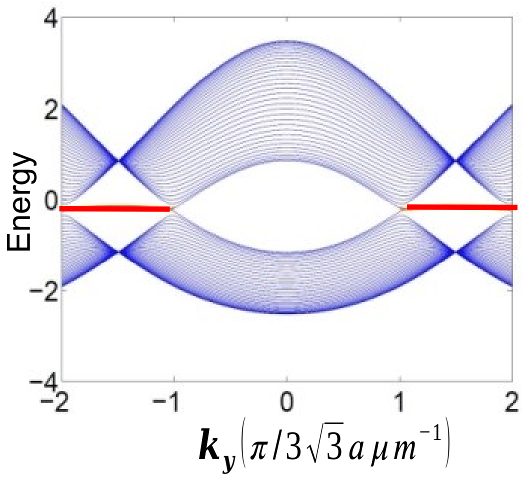
Milicevic et al, 2D Mater. **2,** 034012 (2015)

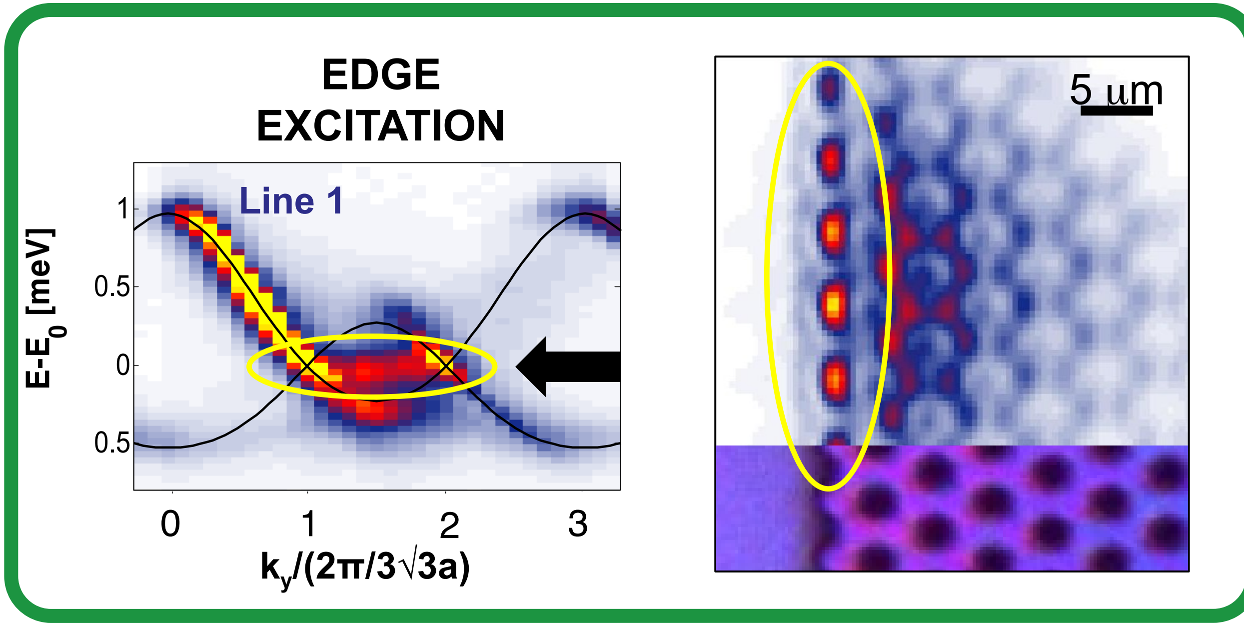
See also Plotnik et al, Nat. Mater. ***13****, 57 (2014)*

Polariton honeycomb lattice: edges



Zigzag edge





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

PHYSICAL REVIEW B 84, 195452 (2011)

Zak phase and the existence of edge states in graphene

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(Received 22 September 2011; revised manuscript received 30 October 2011; published 23 November 2011)

Graphene

$$H(\vec{k}) = \begin{bmatrix} 0 & t+2t\cos\left(\frac{\sqrt{3}}{2}ak_x\right)e^{\left(i\frac{3}{2}ak_y\right)} \\ t+2t\cos\left(\frac{\sqrt{3}}{2}ak_x\right)e^{\left(-i\frac{3}{2}ak_y\right)} & 0 \end{bmatrix}$$

SSH

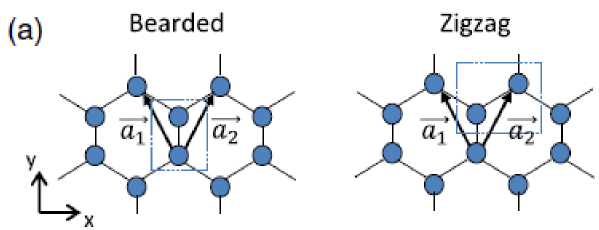
$$H(k) = \begin{bmatrix} 0 & t+t'e^{(+ika)} \\ t+t'e^{(-ika)} & 0 \end{bmatrix}$$

Correspondance:

$$t_{SSH} \rightarrow t \qquad\qquad t'_{SSH} \rightarrow 2t\cos\left(\frac{\sqrt{3}}{2}ak_x\right)$$

intra-cell — inter-cell

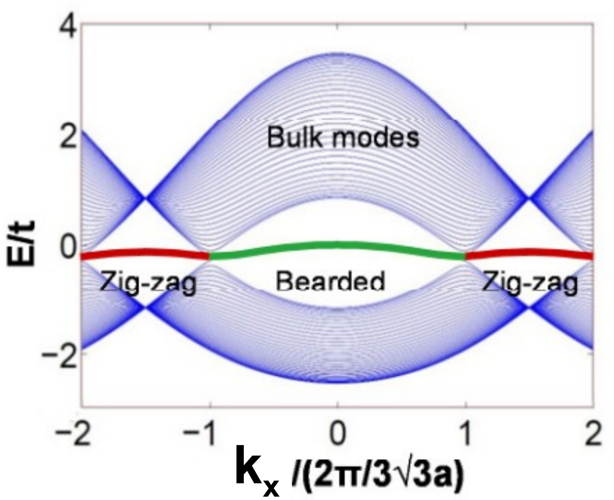
Conditions for edge states in graphene (bearded)



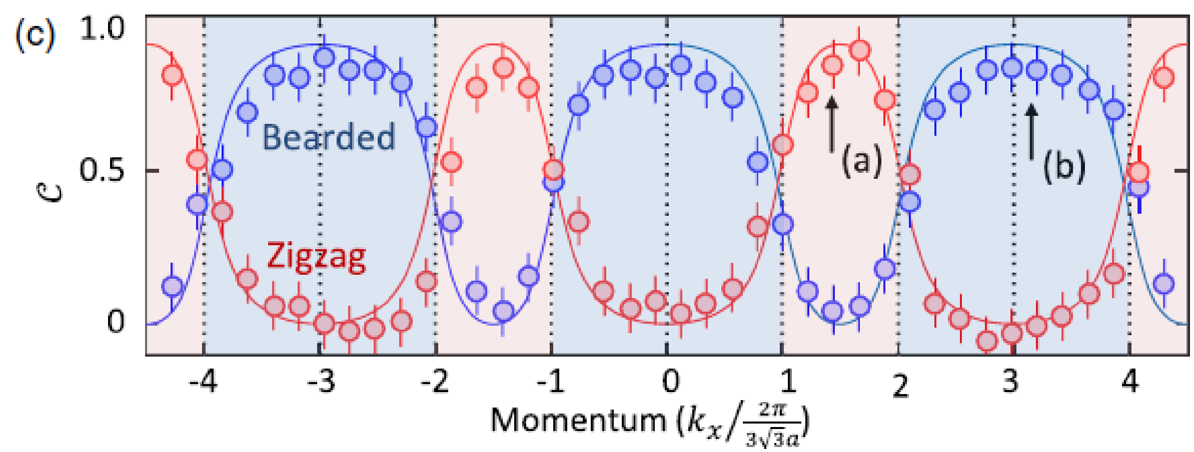
$$t_{SSH} \rightarrow t \qquad t'_{SSH} \rightarrow 2t\cos\left(\frac{\sqrt{3}}{2}ak_x\right)$$

intra-cell inter-cell

$$2t\cos\left(\frac{\sqrt{3}}{2}ak_x\right) > t \rightarrow |k_x| < \frac{2\pi}{3\sqrt{3}a}$$

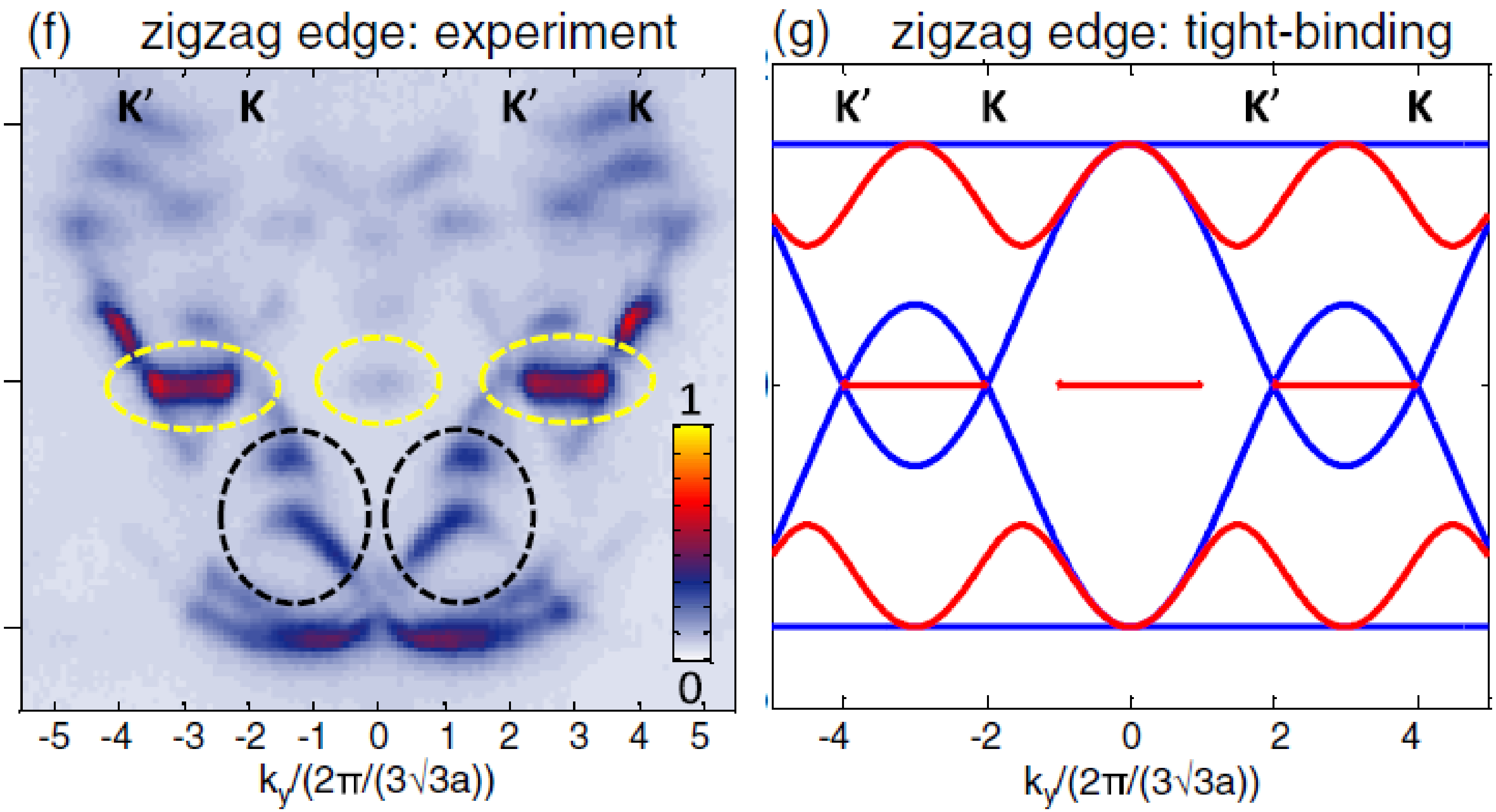


Experimental measurements of the topological invariants of graphene



P. St-Jean et al., **Phys. Rev. Lett. 126, 127403 (2021)**

Gilles, what about p-band edge states?



Orbital Edge States in a Photonic Honeycomb Lattice
M. Milićević, T. Ozawa, G. Montambaux, et al., Phys. Rev. Lett. 118, 107403 (2017)

Gilles, what about p-band edge states?

$$\hat{\mathcal{H}}_p = -t_L \begin{pmatrix} 0_{2\times2} & Q^\dagger \\ Q & 0_{2\times2} \end{pmatrix}$$

$$Q = \begin{pmatrix} f_1 & g \\ g & f_2 \end{pmatrix}$$

$$f_1 = \tfrac{3}{4}(e^{i\mathbf{k}\cdot\mathbf{u}_1} + e^{i\mathbf{k}\cdot\mathbf{u}_2})$$

$$f_2 = 1 + \tfrac{1}{4}(e^{i\mathbf{k}\cdot\mathbf{u}_1} + e^{i\mathbf{k}\cdot\mathbf{u}_2})$$

$$g = (\sqrt{3}/4)(e^{i\mathbf{k}\cdot\mathbf{u}_1} - e^{i\mathbf{k}\cdot\mathbf{u}_2})$$

$$f_p \equiv \det Q = |\det Q| e^{i\phi(\mathbf{k})}$$

$$f_p(\text{zigzag}) = \frac{3}{4} e^{i\mathbf{k}\cdot(\mathbf{a}_1-\mathbf{a}_2)} f_s(\text{bearded})$$

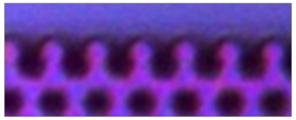
$$f_p(\text{bearded}) = \frac{3}{4} e^{i\mathbf{k}\cdot\mathbf{a}_2} f_s(\text{zigzag}),$$

Winding of f(k) => number of edge states

Orbital Edge States in a Photonic Honeycomb Lattice
M. Milićević, T. Ozawa, G. Montambaux, et al., Phys. Rev. Lett. 118, 107403 (2017)

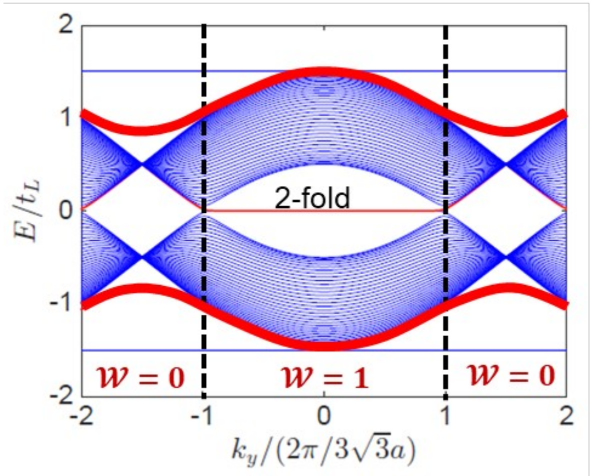
Gilles, what about p-band edge states?

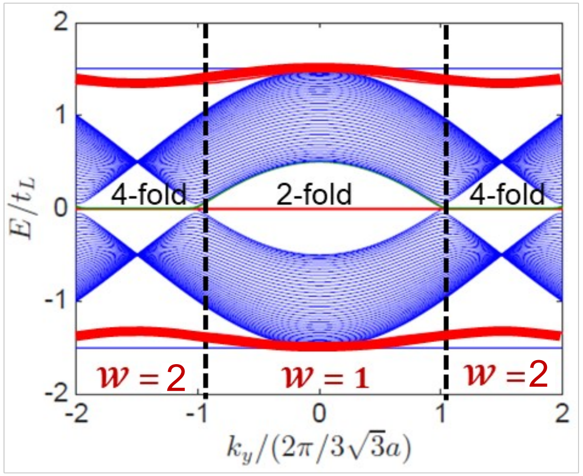
Zigzag edges

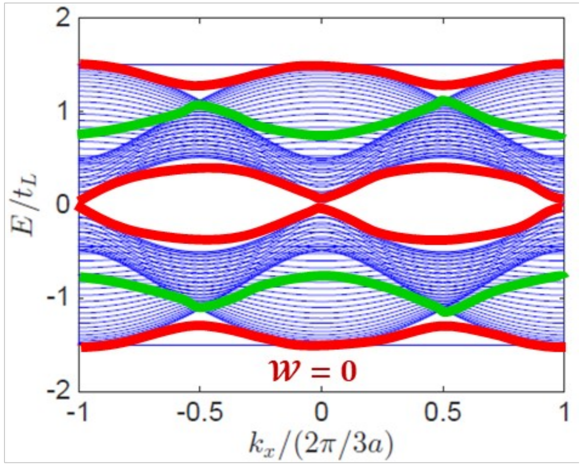


Bearded edges

Armchair edges



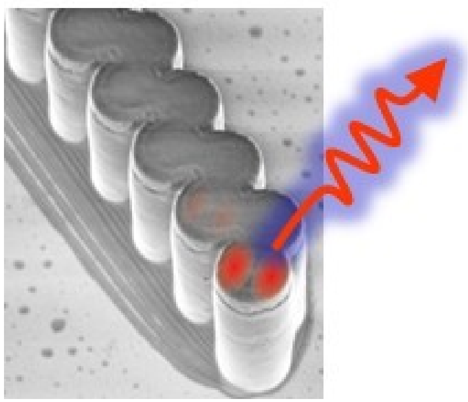




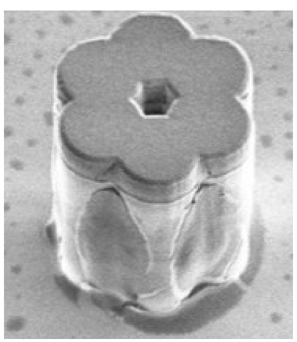
Orbital Edge States in a Photonic Honeycomb Lattice
M. Milićević, T. Ozawa, G. Montambaux, et al., Phys. Rev. Lett. 118, 107403 (2017)

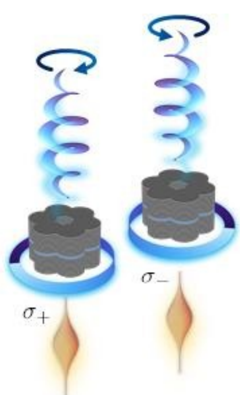
Why using polaritons?

Excitons provide gain



St-Jean et al., Nature Photonics 11, 651 (2017)

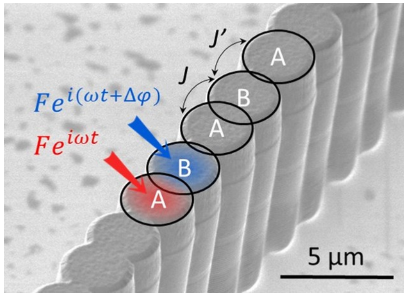


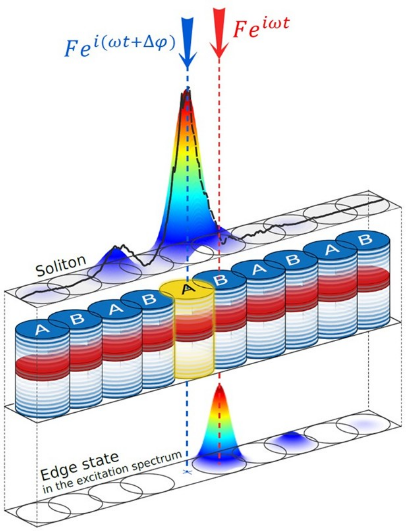


Sala *et al.*,
Phys. Rev. X **5**, 011034 (2015)

N Carlon Zambon et al.,
Nature Photonics 13, 283 (2019)

Excitons provide huge Kerr non-linearity : driven topology

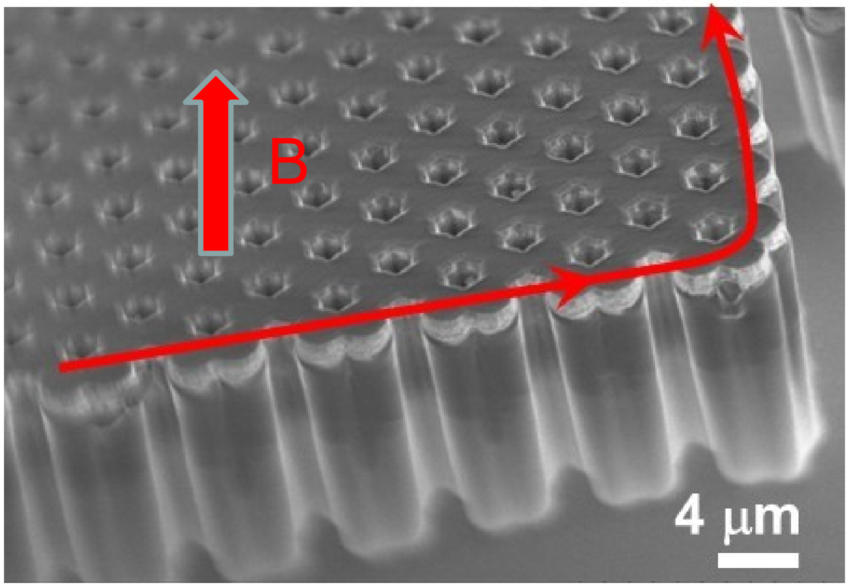




N. Pernet et al.,
Nature Physics18, 678 (2022)

Soon a new problem for Gilles!!!

Polariton topological insulator: s and p bands!



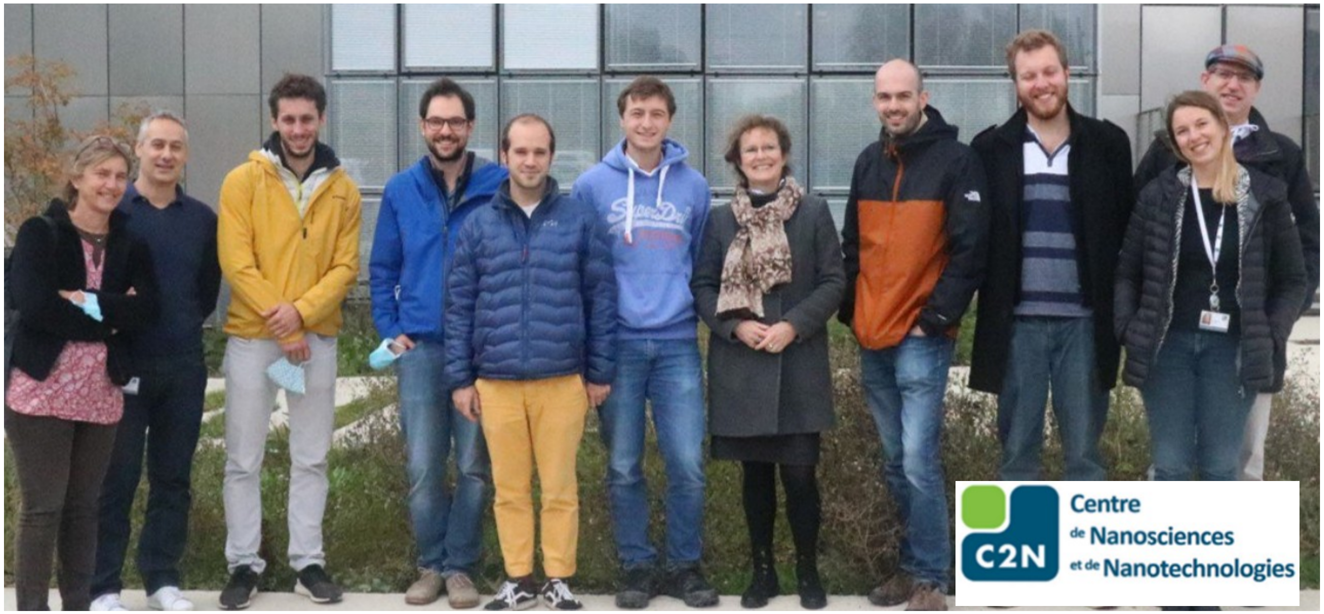
Exciton: Zeeman splitting

Photon: spin orbit coupling

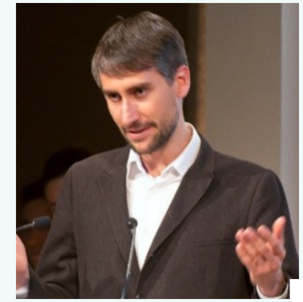
Nalitov, et al., Physical Review Letters **114**, 116401 (2015)
Bardyn et al., Physical Review B **91,** 161413(R) (2015)
S. Klembt et al. Nature 562, 552 (2018)

Acknowledgements

Group picture (2020):



Left to right: I. Sagnes, L. le Gratiet, Q. Fontaine, P. St-Jean, N. Carlon-Zambon, M. Guillot, J. Bloch, S. Ravets, N. Pernet, M. Morassi, A. Lemaître.

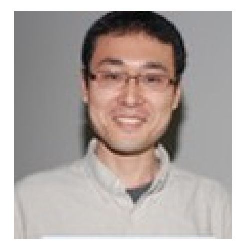


Alberto Amo's group (Lille)

OmarJamadi

Bastian Real

Iacopo Carusotto Trento



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