

Des réseaux de microcavités pour simuler la matière condensée avec de la lumière

Microcavity lattices to simulate
condensed matter with light

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<http://www.polaritonquantumfluid.fr>

Inspiration: Emerging physics in the condensed matter

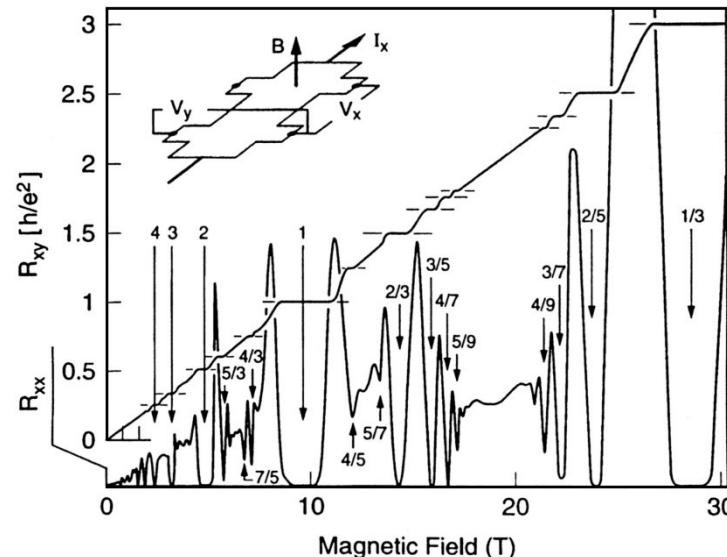
Superfluidity



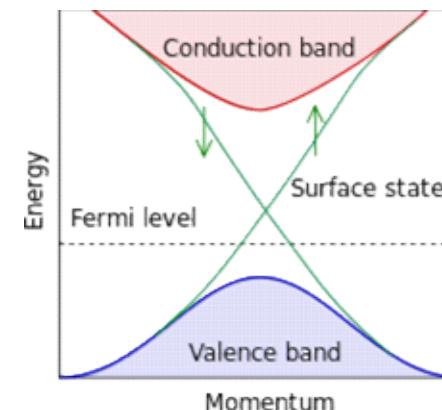
Graphene



Fractional Quantum Hall effect



Topological insulators



Quantum fluids of light as an analogous system

$$i\hbar \frac{\partial \psi}{\partial t} = H\psi$$

Same Hamiltonian => Same physical properties

See plenary talk by Antoine Browaeys
Séance Parallèle (4.3 Simulateurs quantiques)

Why use synthetic quantum material?

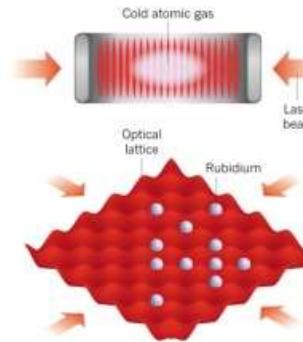
- System « easier » to probe, manipulate
- Create new geometries, new properties => Applications
- Realize experiments impossible to predict because of complexity of numerical simulations (many body physics): **quantum simulations**

QUANTUM BOARD GAMES

The set-ups of quantum simulators are different, but the concept is the same: first take atoms, ions or electrons, cool them to cryogenic temperatures and arrange them in an orderly grid. Then tune the interactions on the grid to mimic a more complex material.

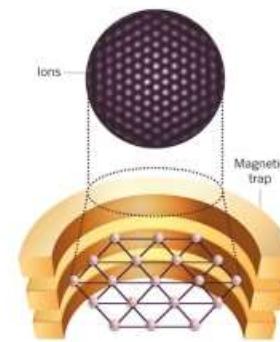
COLD ATOMS

Rubidium atoms are held in place by criss-crossed laser beams, which can also be used to tweak individual particles. A single pair of lasers holds the atoms in a one-dimensional column (top), whereas two pairs hold them in a grid (bottom). Some excitations in the grid system behave like the Higgs particle.



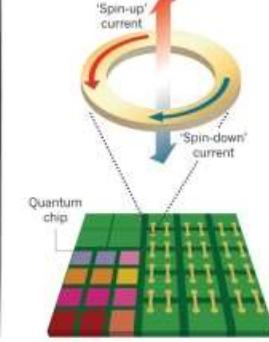
TRAPPED IONS

A combination of electric and magnetic fields trap charged, ionized atoms in an orderly grid. The ions wiggle and rotate in a way that mimics the interactions of quantum magnetism — a phenomenon that can't be simulated in classical systems.



SUPERCONDUCTING LOOPS

A quantized loop of current can flow clockwise, anticlockwise or in a superposition of both in a superconducting circuit (top). An array of such loops (bottom) can be manipulated to simulate various quantum systems — and perhaps even biological processes such as photosynthesis.



Nature 14 November 2012

Original idea: [R. Feynman., Int. J. Theor. Phys. 21, 467 (1982)]

Quantum fluids of light as an analogous system

- Photons have no mass !
- Photons have no charge !
- Photons do not interact (or so weakly) !
- Photons are bosons (not fermions like electrons !)



Quantum fluids of light as an analogous system

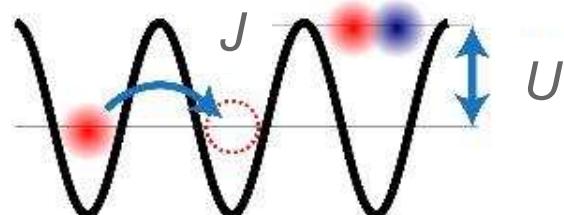
- Photons have no mass ! **Effective mass in a cavity**
- Photons have no charge ! **Artificial gauge field**
(see for neutral atoms J. Dalibard et al., RMP 83, 1523 2011)

- Photons do not interact (or so weakly) ! **When coupled to electronic excitations**

- Photons are bosons (not fermions like electrons !) **Nobody is perfect!**

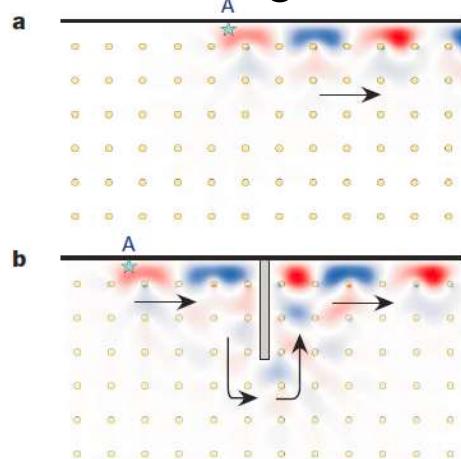


Bose-Hubbard $\hat{H} = -J \sum_{\langle m,n \rangle} \hat{a}_m^\dagger \hat{a}_n + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)$



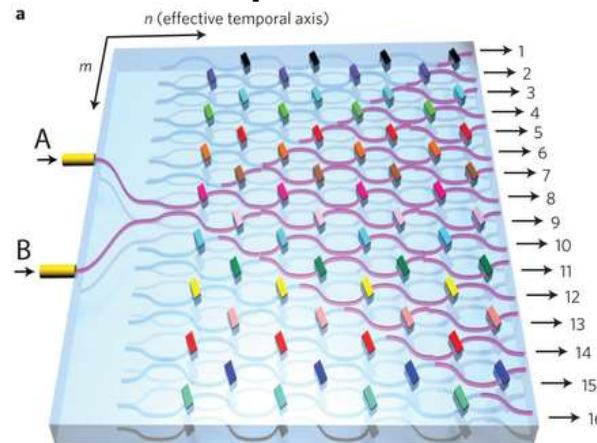
Emulation with light

Chiral edge states



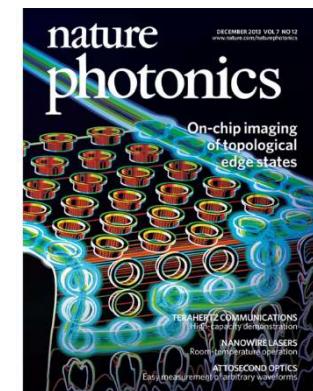
Zheng Wang et al.,
Nature **461** 772 (2009)

Random quantum walk



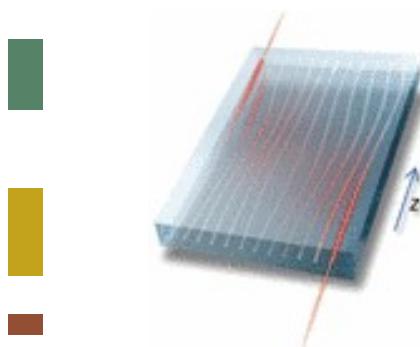
A. Crespi, Nature Photonics **7**, 322 (2013)

Topological edge states Si



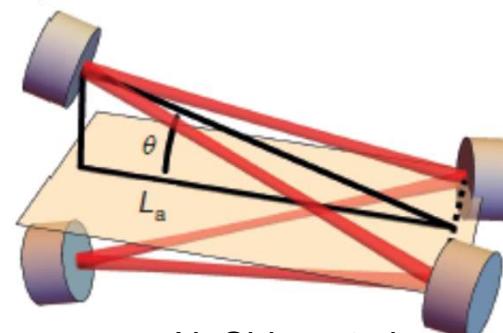
M. Hafezi,
Nat. Phot. **7** 1001 (2013)

Quasi crystal



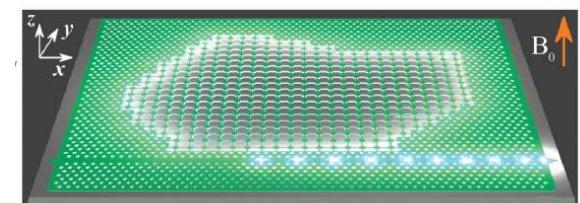
Kraus et al., PRL **109**, 106402 (2012)
Levi et al., Science **332**, 1541 (2011)

Synthetic Landau levels



N. Shine et al.
Nature **354**, 671 (2016)

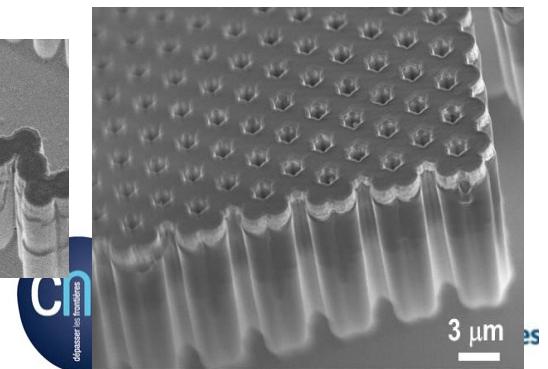
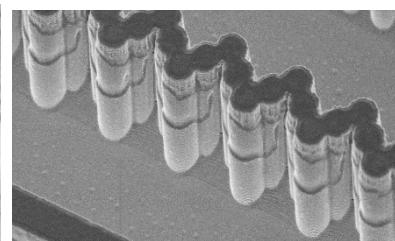
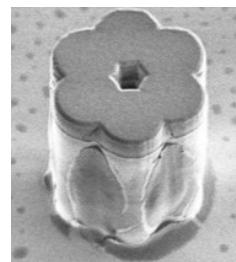
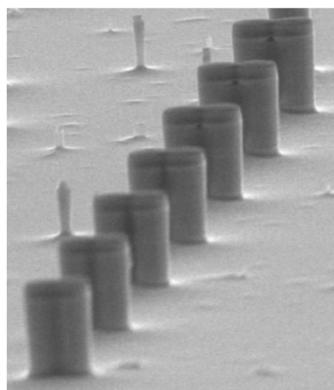
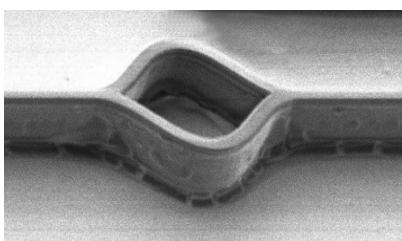
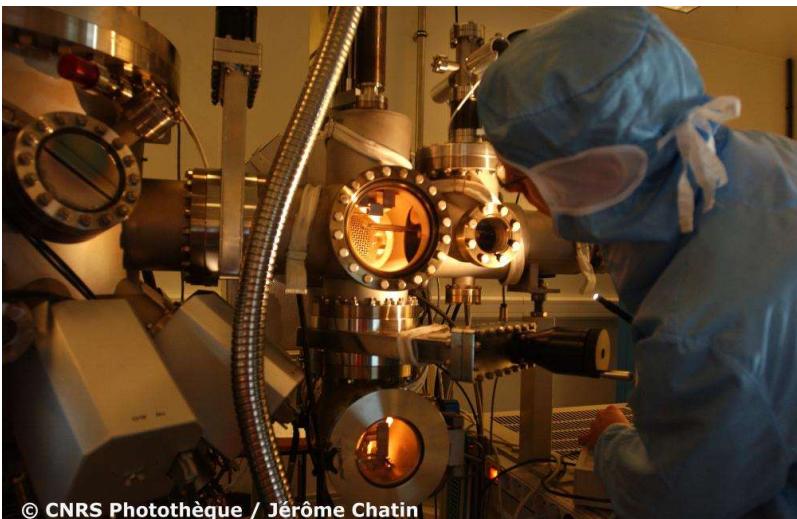
Non reciprocal lasing



B.Bahari et al., Science
10.1126/science.aao4551(2017)
M. A. Bandres et al. Science
10.1126/science.aar4005 (2018)

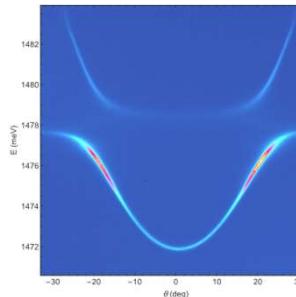
Our research at C2N

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

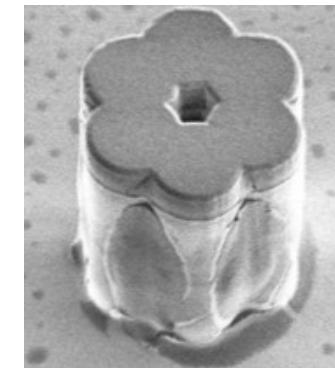
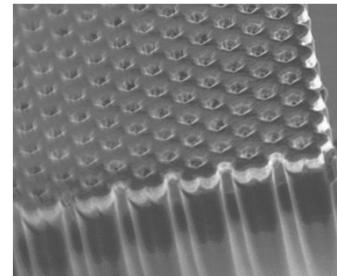


Outline

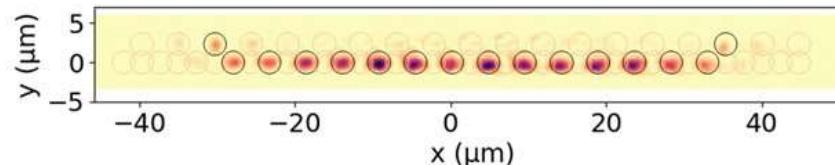
- Introduction to polariton quantum fluids
- Benzene photonic molecule: lasing with angular momentum



- Emulating graphene physics

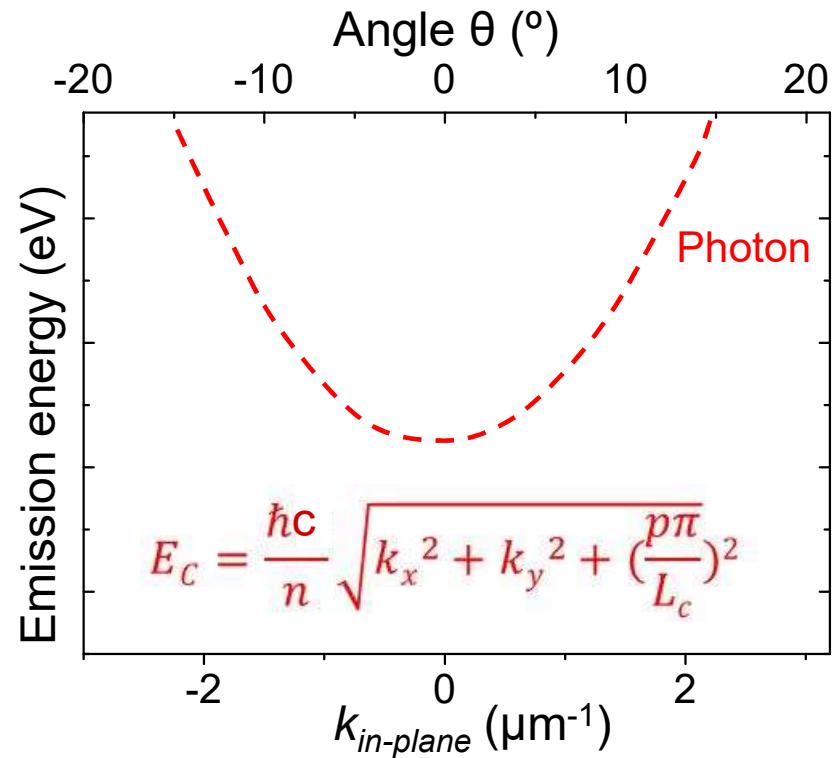
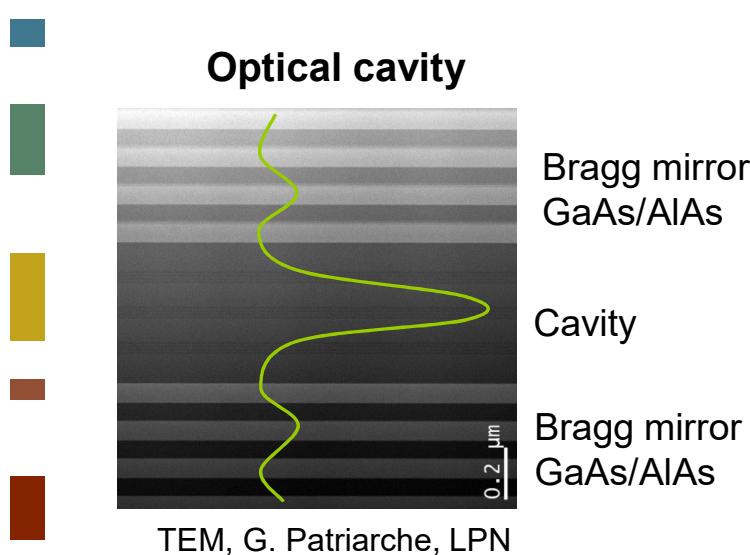
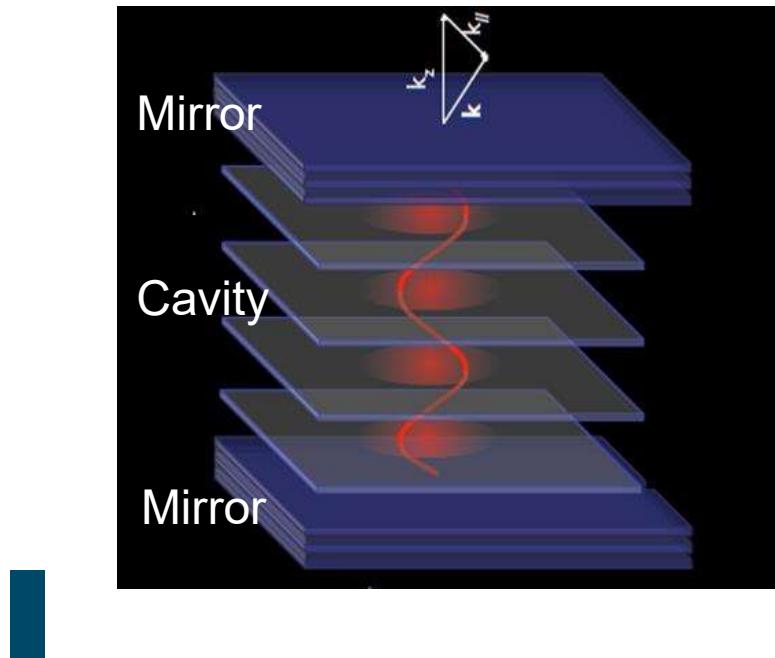


- Non linearities in a flat band



- Toward many quantum many body physics

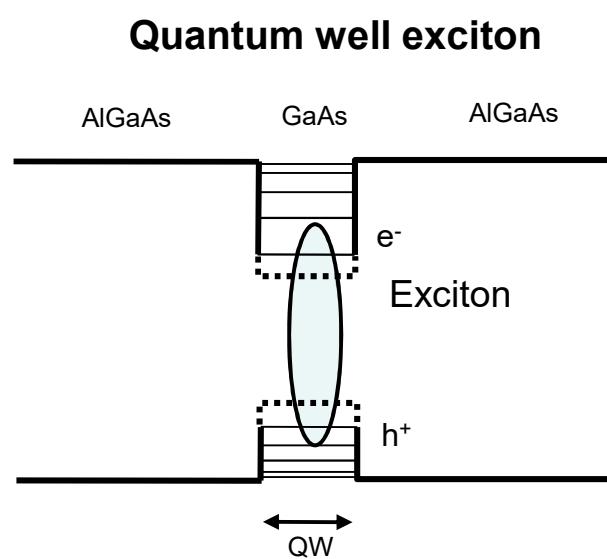
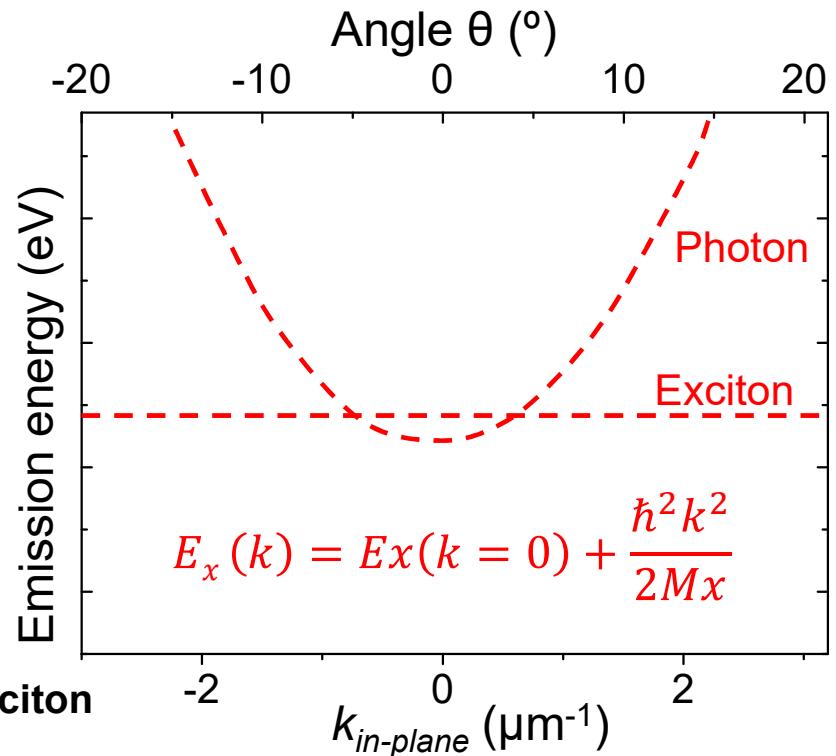
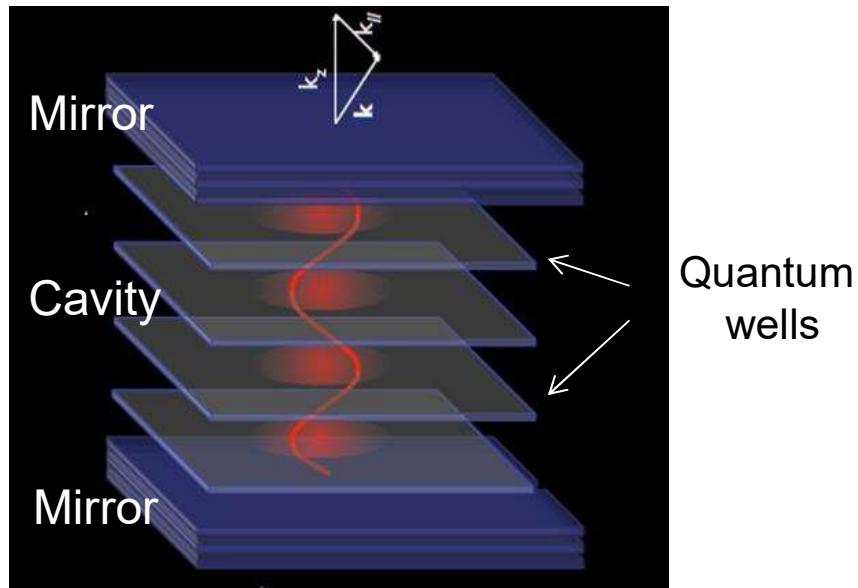
Microcavity polaritons



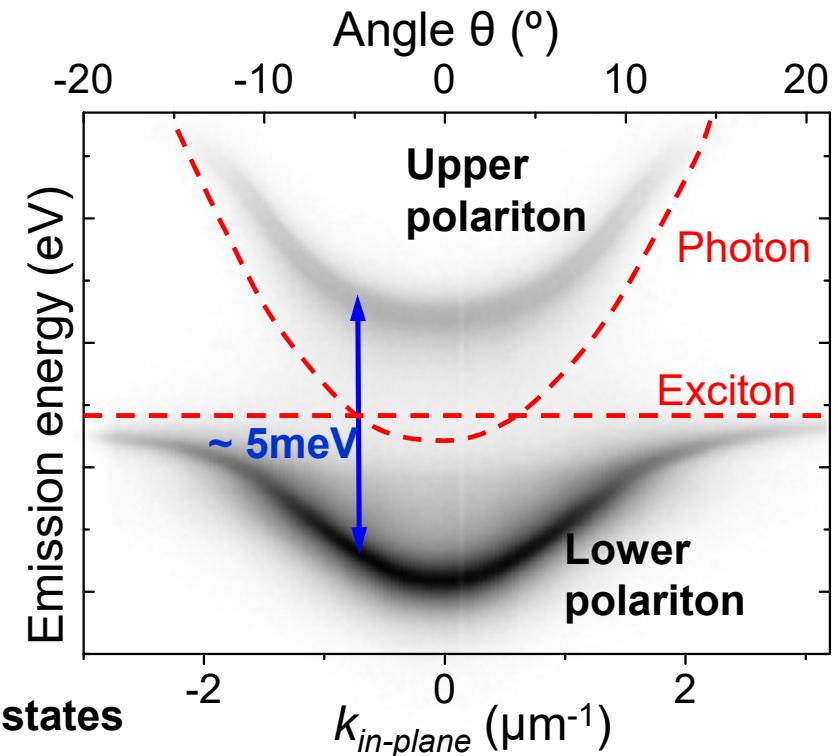
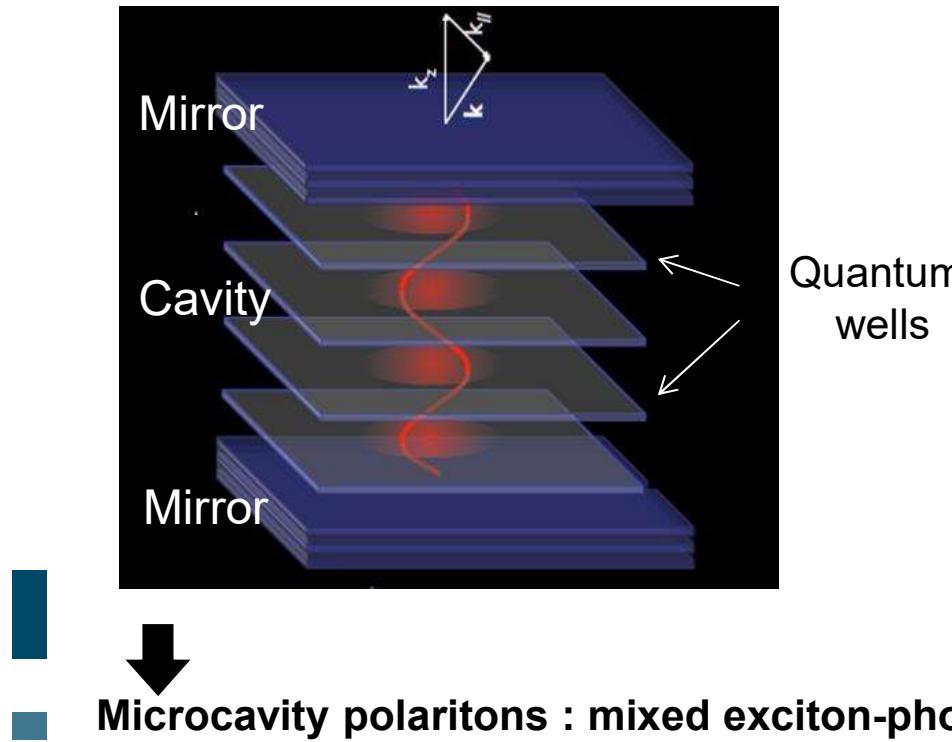
$$E_C(k) = E_C(k=0) + \frac{\hbar^2 k^2}{2 M p_{hot}}$$

$$\text{with } M_{phot} = \frac{p^2 \pi^2 \hbar^2}{L_c^2 n^2}$$

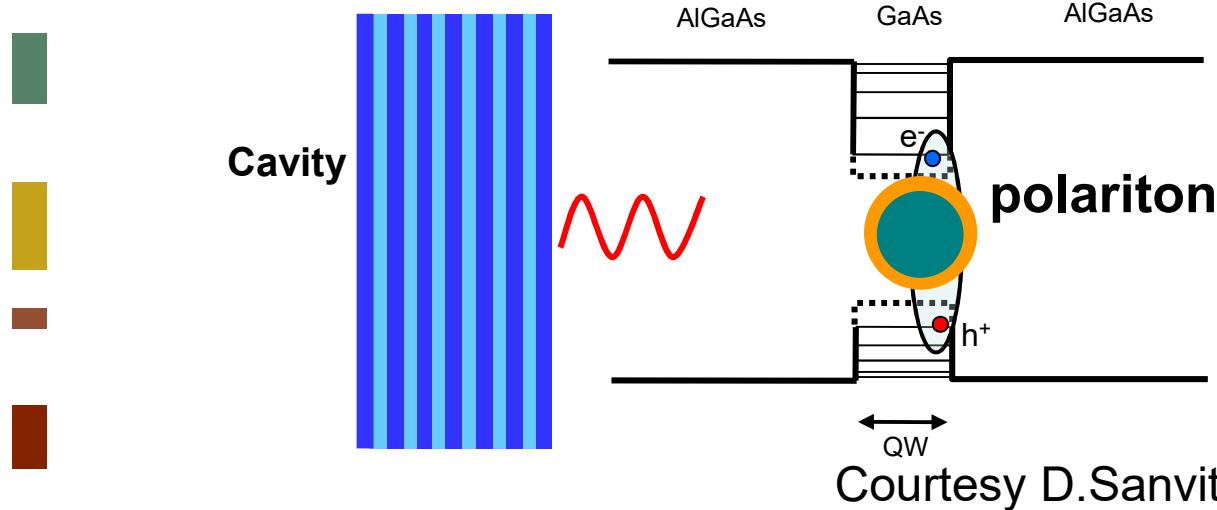
Microcavity polaritons



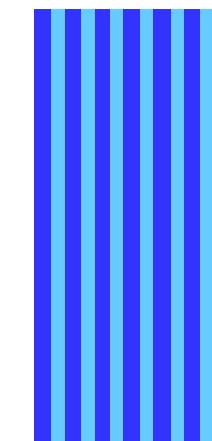
Microcavity polaritons



■ Microcavity polaritons : mixed exciton-photon states

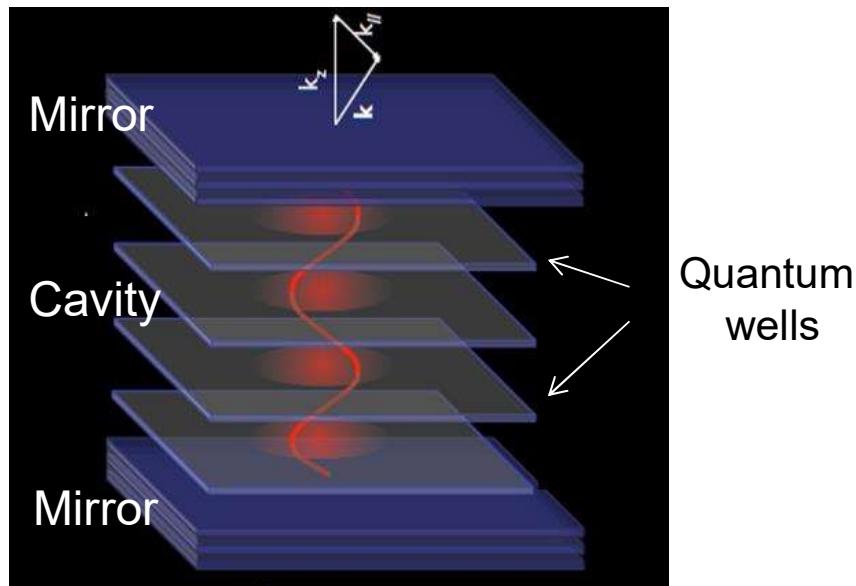


Courtesy D.Sanvitto

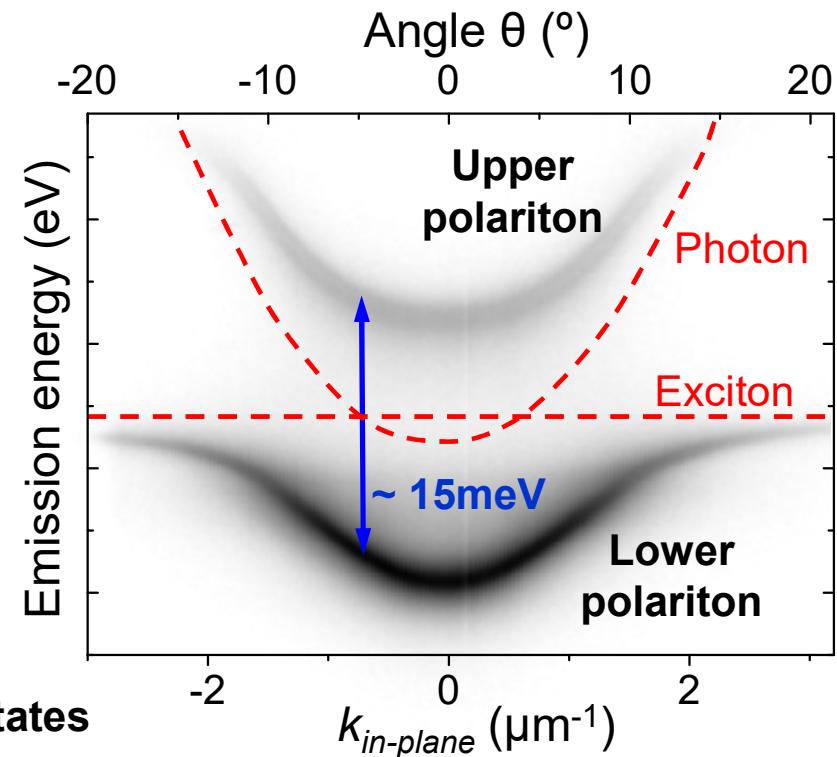


Claude Weisbuch
PRL 69, 3314 (1992)

Microcavity polaritons



■ Microcavity polaritons : mixed exciton-photon states

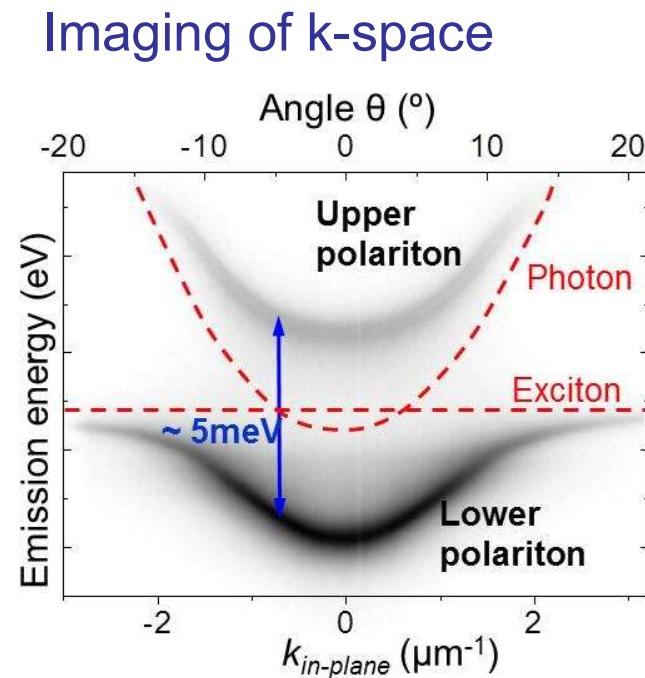
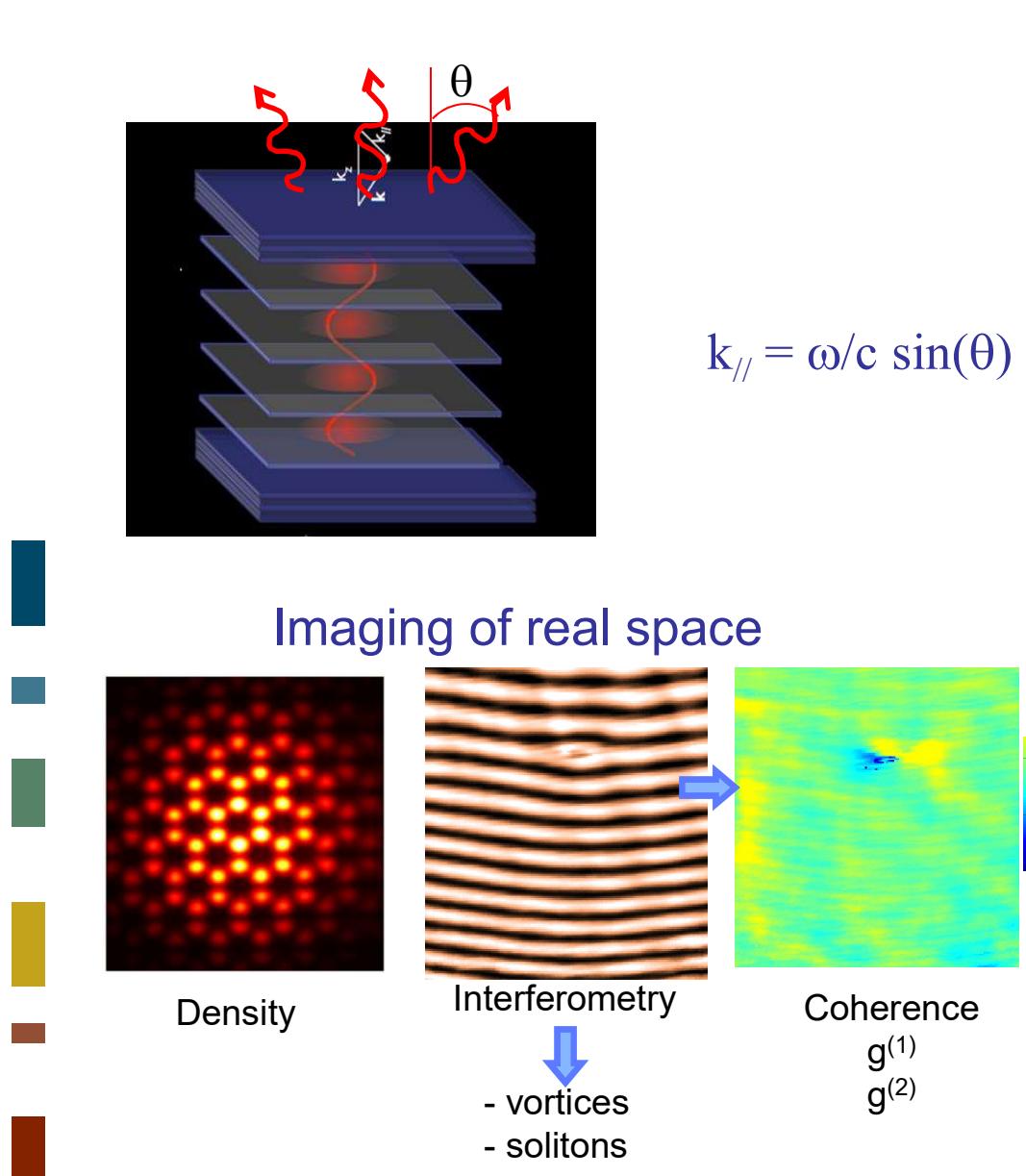


Properties

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

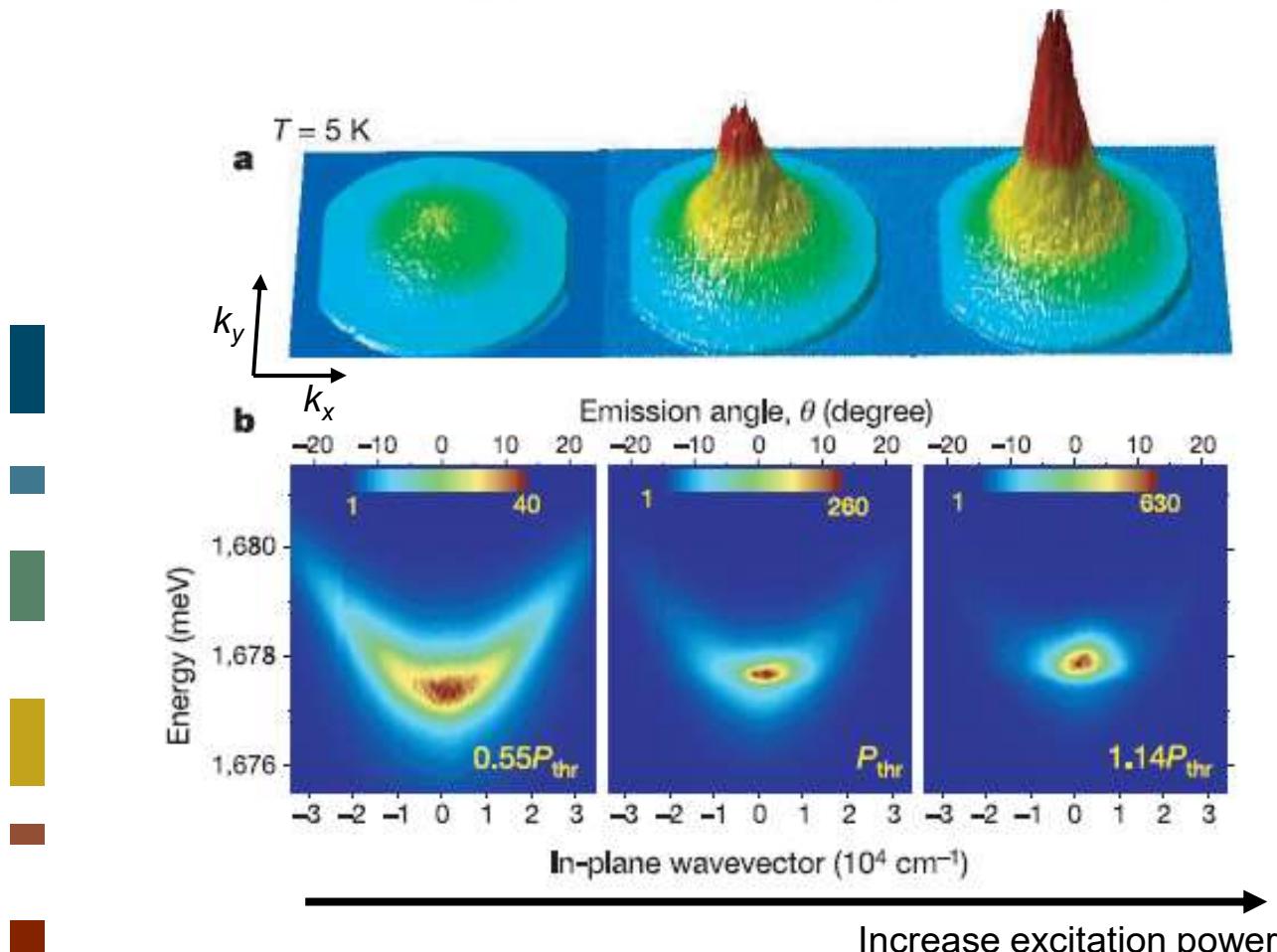
- Photonic component \rightarrow confinement in microstructures
real space, k-space imaging
- Excitonic component \rightarrow
 - Interactions - $\chi^{(3)}$ (dominated by exchange)
 - Gain (lasing)
 - Sensitivity to magnetic field

Probing polariton states



Bose-Einstein condensation of exciton polaritons

J. Kasprzak¹, M. Richard², S. Kundermann², A. Baas², P. Jeambrun², J. M. J. Keeling³, F. M. Marchetti⁴, M. H. Szymańska⁵, R. André¹, J. L. Staehli², V. Savona², P. B. Littlewood⁴, B. Deveaud² & Le Si Dang¹



Kasprzak et al. Nature, 443, 409 (2006)



Benoit Deveaud



Le Si Dang

Polariton superfluidity



Iacopo Carusotto



Cristiano Ciuti



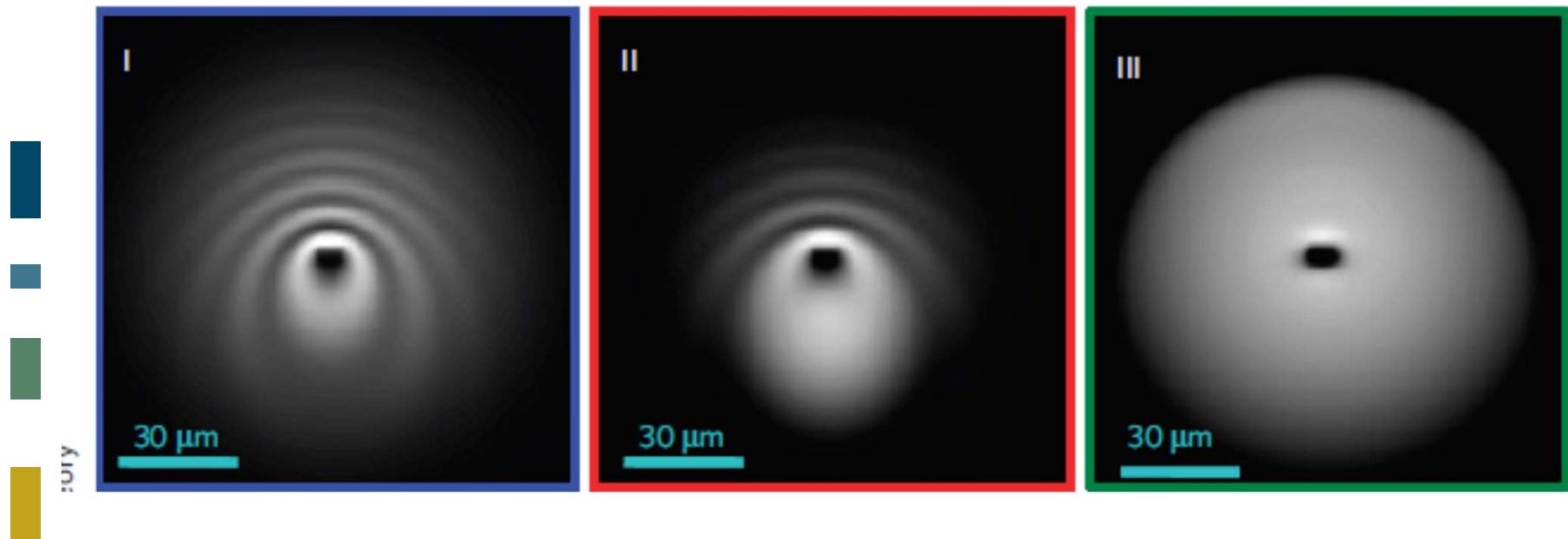
Alberto Amo



Alberto Bramati



Elisabeth Giacobino



C. Ciuti and I. Carusotto PRL 242, 2224 (2005)

A. Amo et al. Nature Physics 5, 805 (2009)

C. Ciuti & I. Carusotto, Rev. Mod. Phys. 85, 299 (2013)

Emulation of many body systems with lattices of polaritons

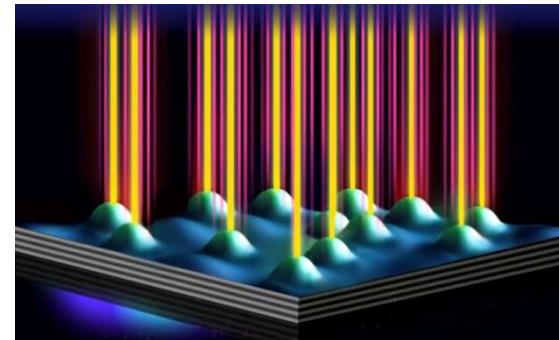
Phase locking of polariton condensates



Pavlos Lagoudakis



Natalia Berloff



Realizing the classical XY Hamiltonian in polariton simulators, Natalia G. Berloff et al., Nature Materials 16, 1120 (2017)

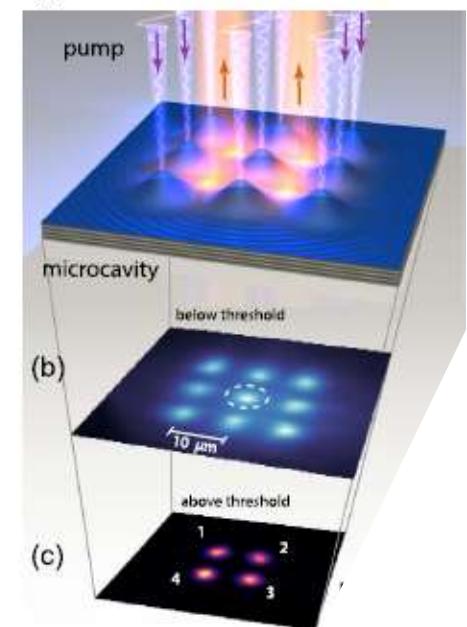
Polarization instability in coupled polariton condensates



Jeremy Baumberg

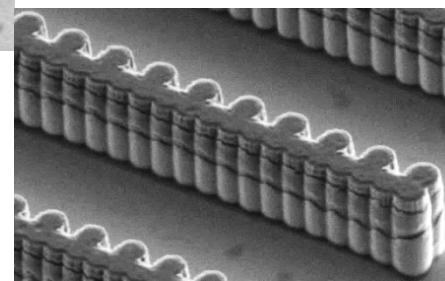
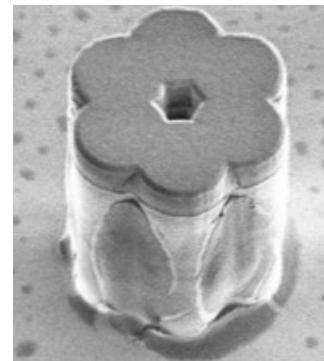
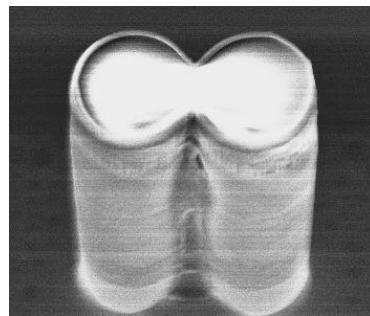
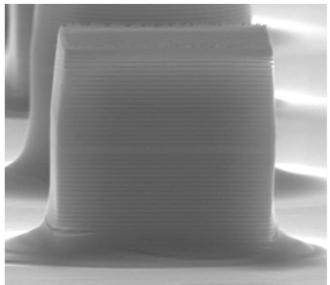


Hamid Ohadi

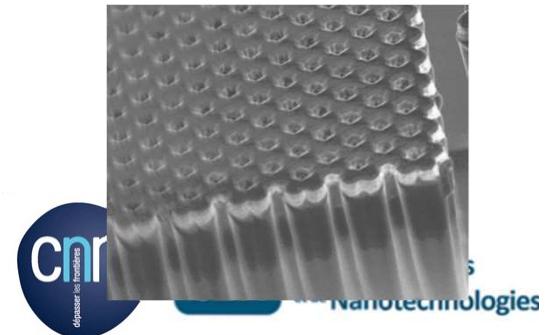


Spin order and phase transitions in chains of polariton condensates,
H. Ohadi, et al., Phys. Rev. Lett.. 119, 067401 (2017)

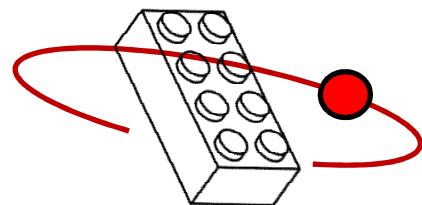
Polariton lattices:Tight binding approach



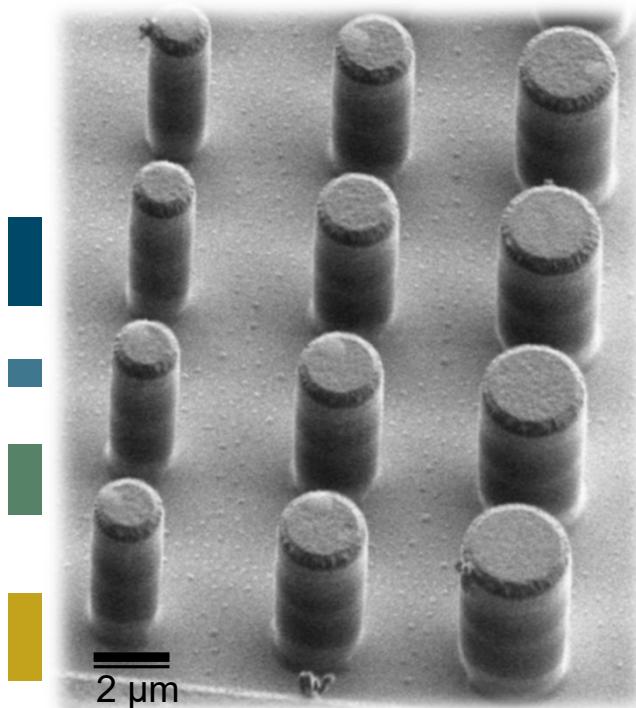
Review: C. Schneider et al., Rep. Prog. Phys. 80, 16503 (2017)



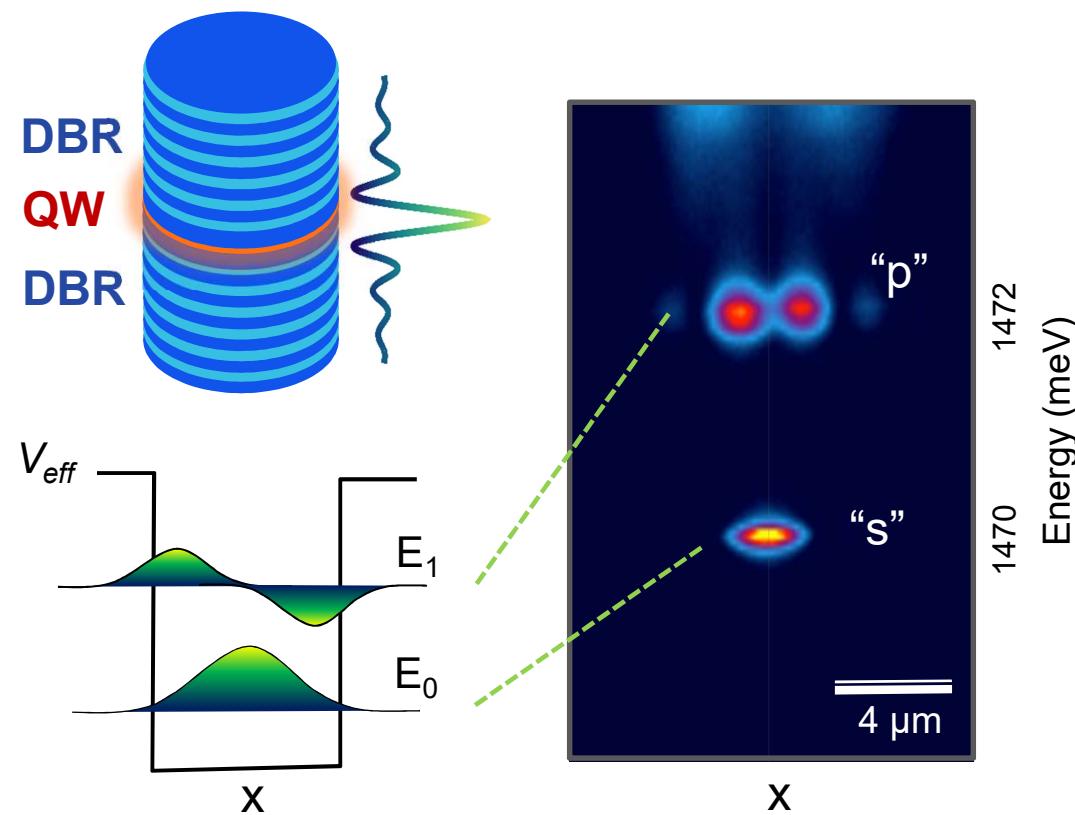
Engineering the photonic wavefunction



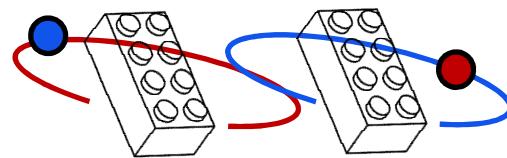
➤ Our bricks: Semiconductor micropillars



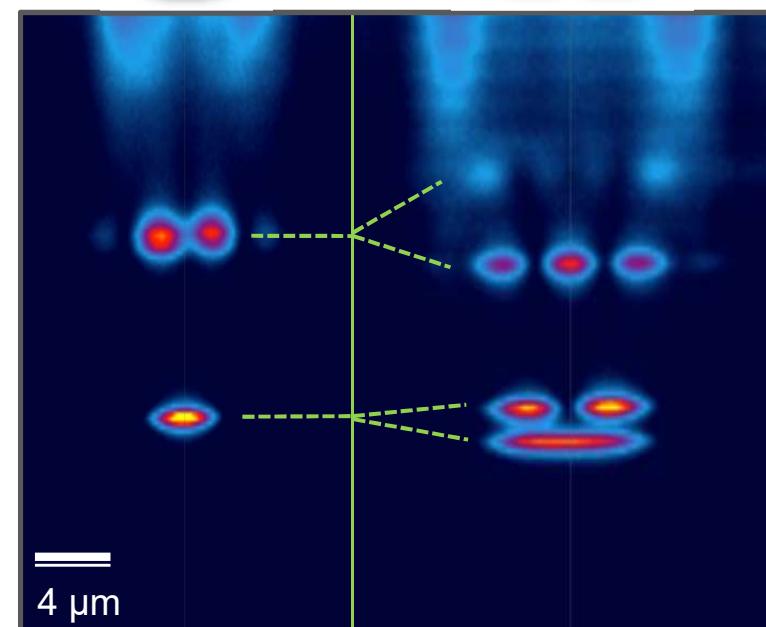
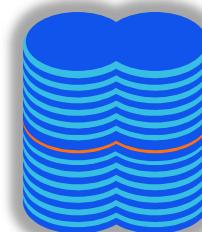
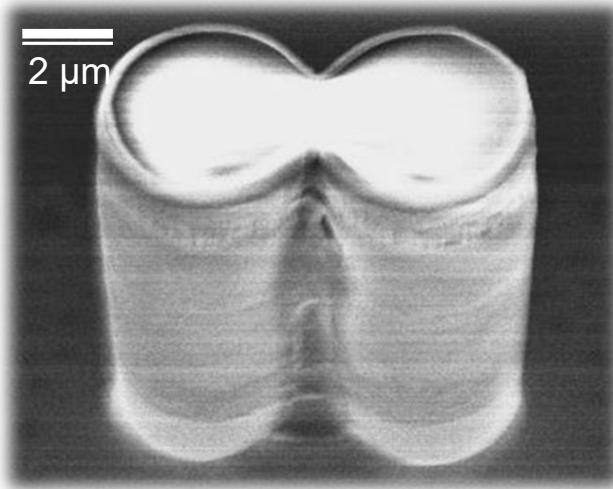
— 2 μm —



Engineering the photonic wavefunction



➤ Coupling the briks



Energy (meV)

1470

1472

x

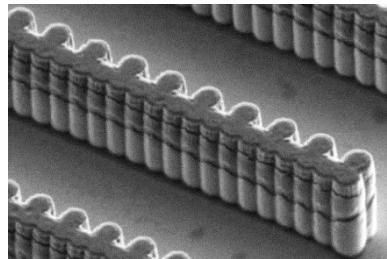


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Galbiati et al., PRL 108, 126403 (2012)

Emulation with polaritons

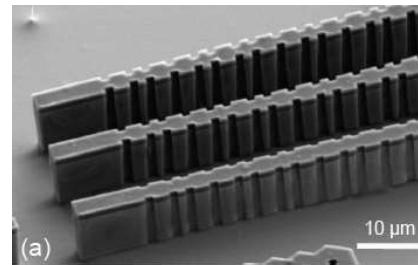
Flat band physics



F. Baboux et al.
PRL116, 066402 (2016)

V. Goblot et al. arXiv:1905.03759

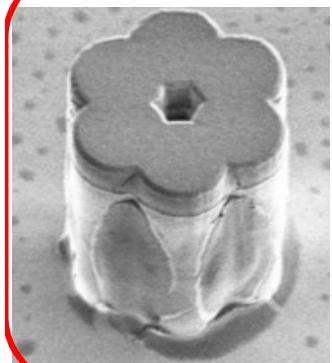
Quasi-periodic 1D lattice



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

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

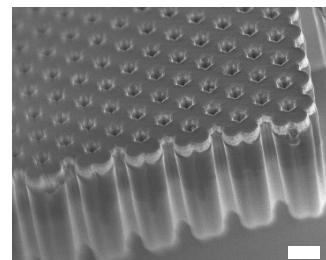
Spin orbit coupling



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

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

N. Carlon Zambon et al., arXiv:1812.06163



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

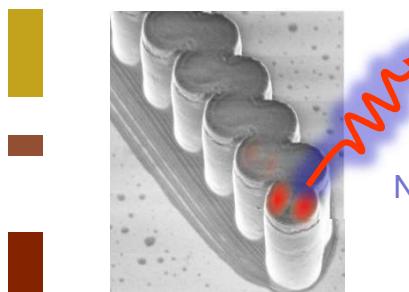
M. Milicevic et al, 2D Mater. 2, 034012 (2016)

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

M. Milicevic et al., Arxiv1807.08650

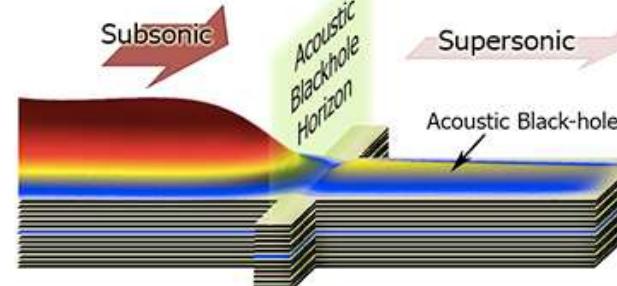
Dirac physics

SSH chain and topological lasing



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

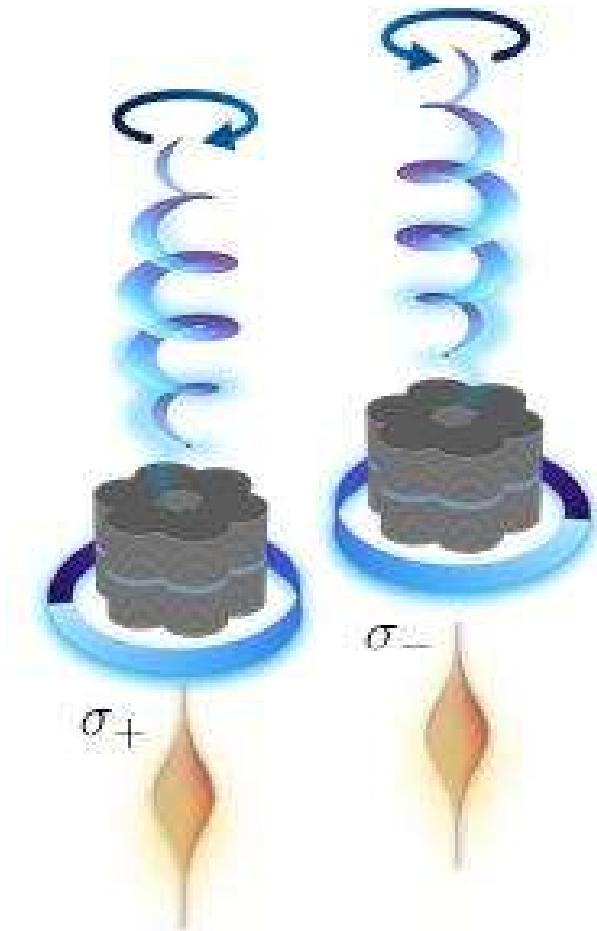
Hawking physics



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

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A microlaser with optically controlled chirality



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-
-
-
-

■ N Carlon Zambon, P. St-Jean et al., Nature Photonics 13, 283 (2019)

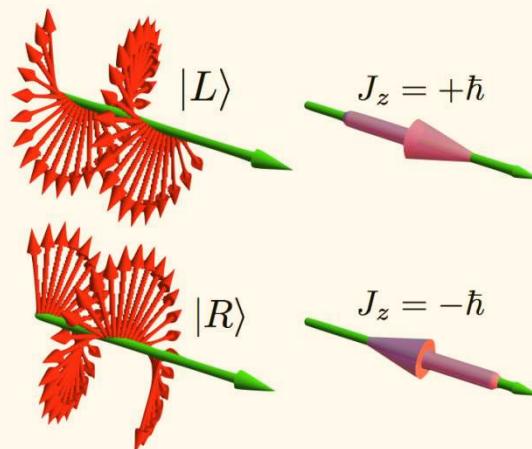


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Angular Momentum of Light

For a single tone:

$$\mathbf{J} \propto \int d^3\mathbf{r} (\mathbf{E}^* \times \mathbf{E}) + \int d^3\mathbf{r} [\mathbf{E}^* \cdot (\mathbf{r} \times \nabla) \mathbf{E}]$$



Spin Angular Momentum:

- associated to polarization
- zero for linearly polarized light

C.V. Raman and S. Bhagavantam *Nature* **129**, 22 (1932)

$$\phi = \text{const}$$



Orbital Angular Momentum:

- Associated to the wavefront twist
- non-zero for helical wavefronts
- Unbounded integer charge

L. Allen et al., *Phys. Rev. A* **45**, 8185 (1992)

Generating Light with OAM

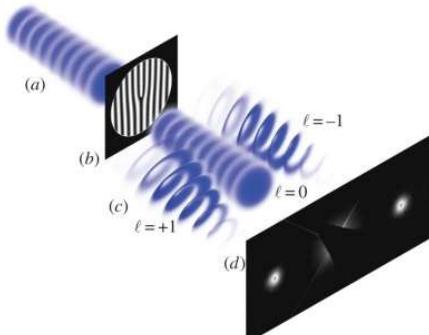
Relevance

- Classical and quantum information
- Sensing
- Nano-manipulation,
- Biological processes

F. Cardano and L. Marrucci,
Nature Photonics 9, 776 (2015)
K.Y. Bliokh et al.,
Nature Photonics 9, 796 (2015)

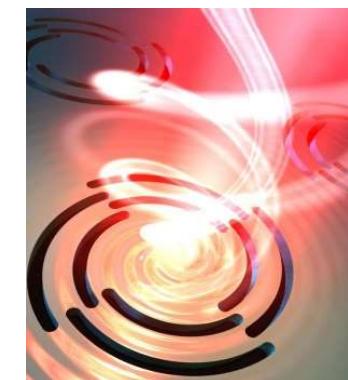
Bulk Optics

- Versatile ✓
- slow ✓
- difficult to scale ✓



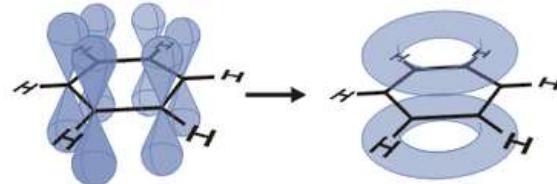
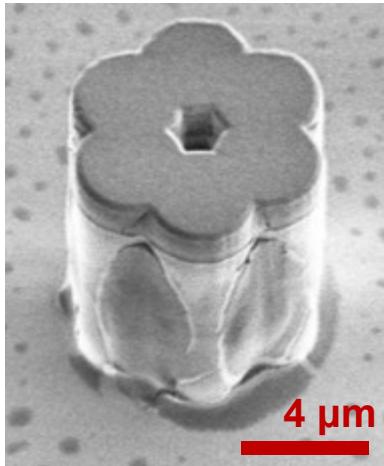
Integrated Devices, metamaterials

- Easily scalable ✓
- Efficient ✓
- limited versatility ✓



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Periodic structures: photonic benzene



Periodic boundary conditions

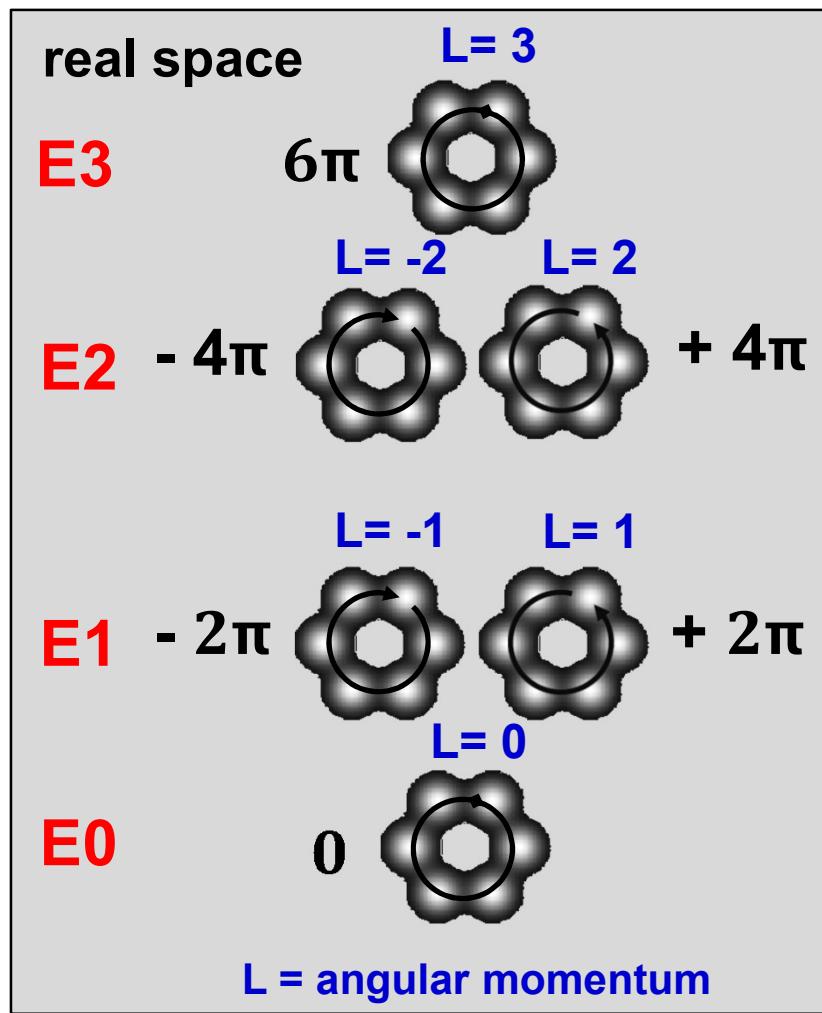
Tight binding model

$$H = -t \sum_{j=1}^6 (|\phi_j\rangle\langle\phi_{j+1}| + |\phi_{j+1}\rangle\langle\phi_j|)$$

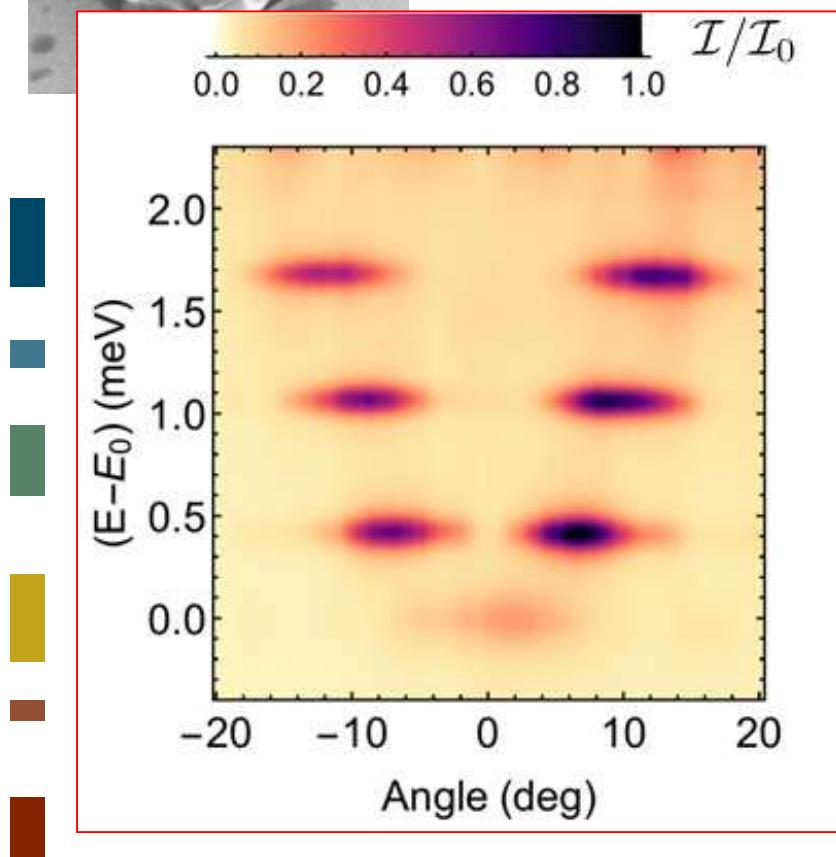
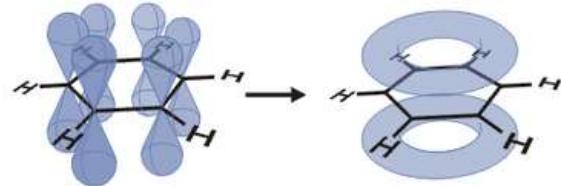
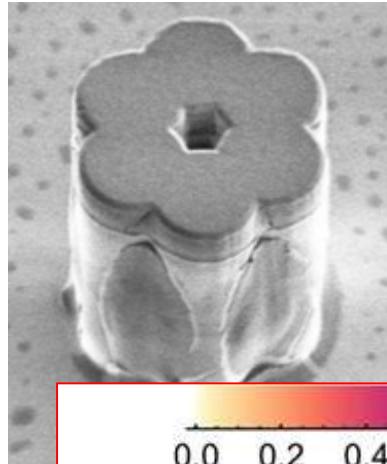
vortical eigenstates

$$|\Psi_L\rangle = \frac{1}{\sqrt{6}} \sum_{v=1}^6 e^{i\frac{L\pi v}{3}} |\phi_v\rangle$$

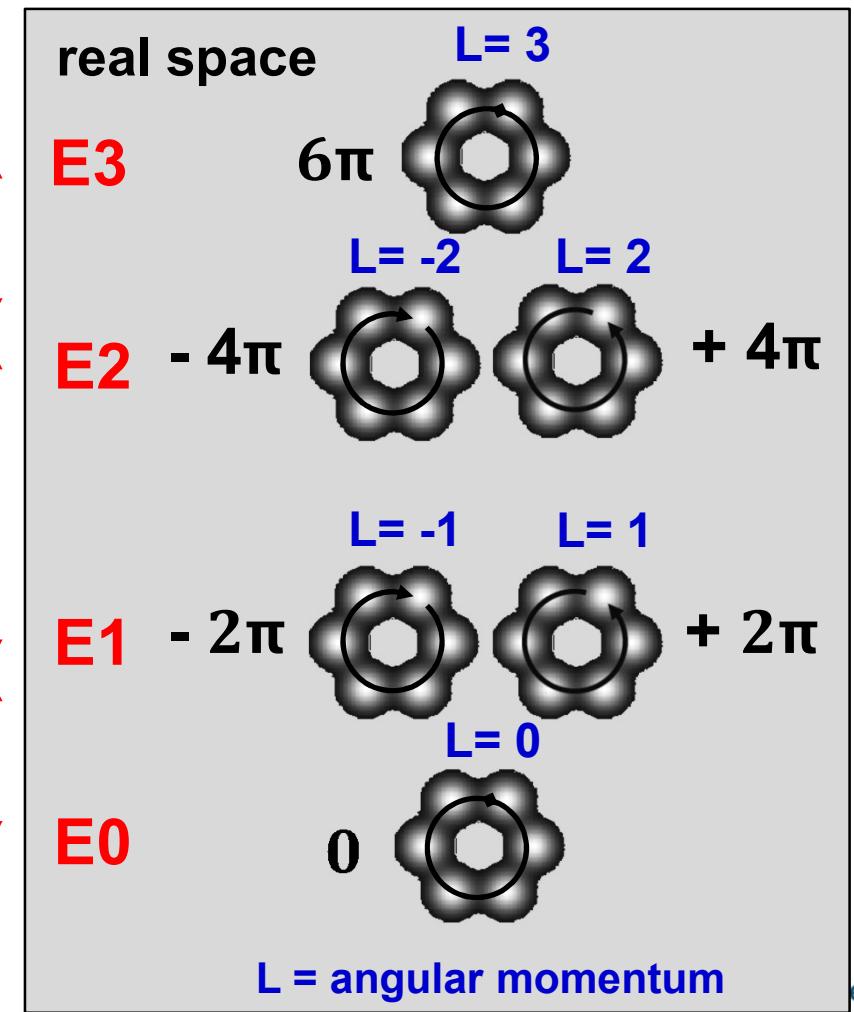
J
 $2J$
 J



Periodic structures: photonic benzene

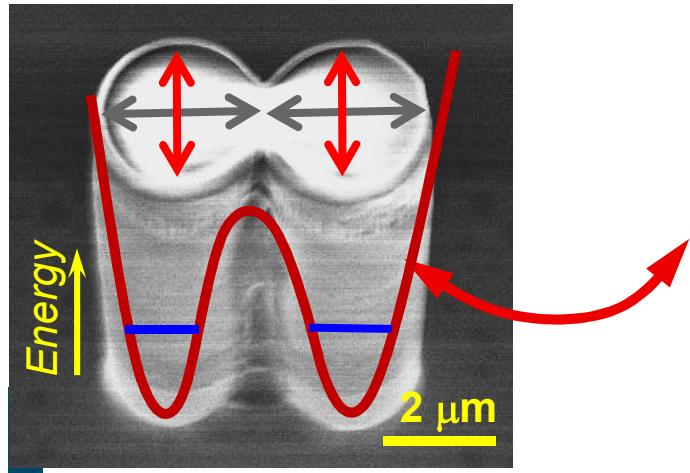


J
 $2J$
 J

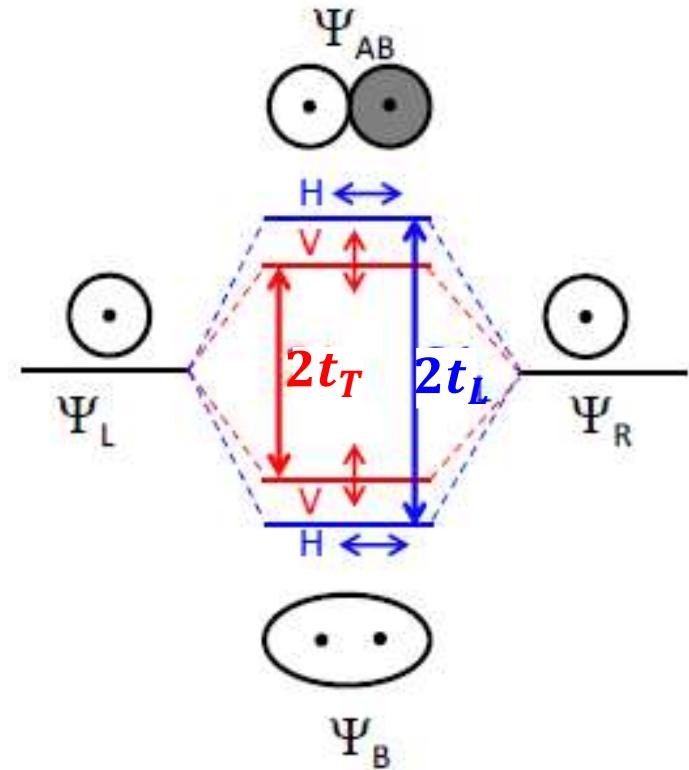
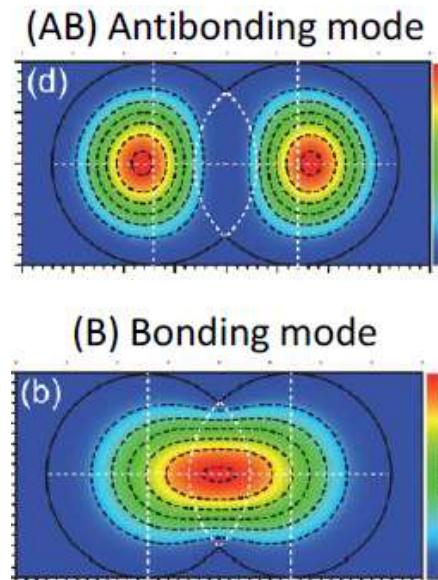


Polarisation dependent tunneling

Polarisation dependent tunneling



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

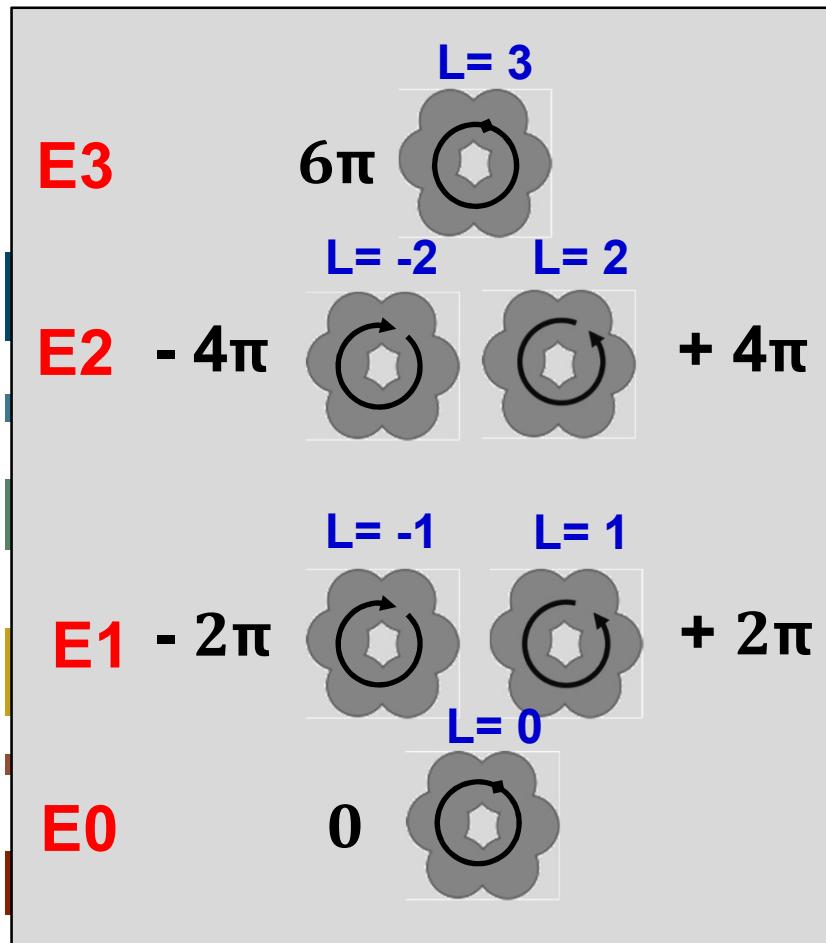


$$t_L \neq t_T$$

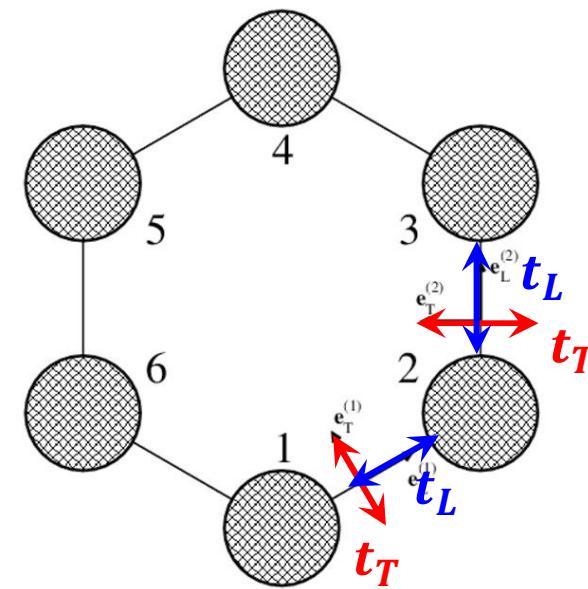


Spin-orbit coupling

double degeneracy σ^+ , σ^-



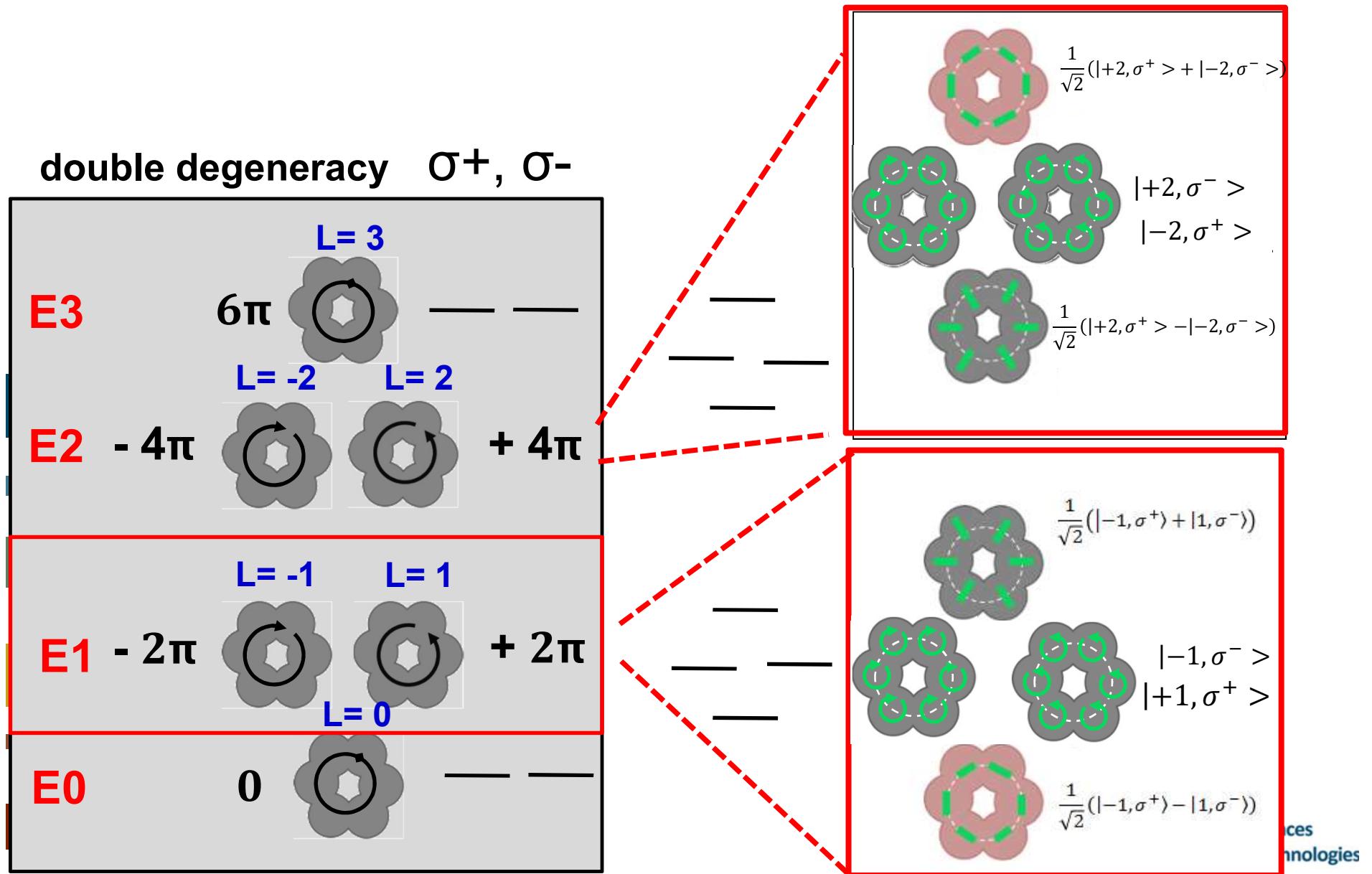
$$H = - \sum_{i=1}^M \{ [\hbar t_L (\hat{\mathbf{a}}_{i+1}^\dagger \cdot \mathbf{e}_L^{(i)}) (\mathbf{e}_L^{(i)\dagger} \cdot \hat{\mathbf{a}}_i) + \\ + \hbar t_T (\hat{\mathbf{a}}_{i+1}^\dagger \cdot \mathbf{e}_T^{(i)}) (\mathbf{e}_T^{(i)\dagger} \cdot \hat{\mathbf{a}}_i)] + \text{h.c.} \}$$



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



Spin-orbit coupling

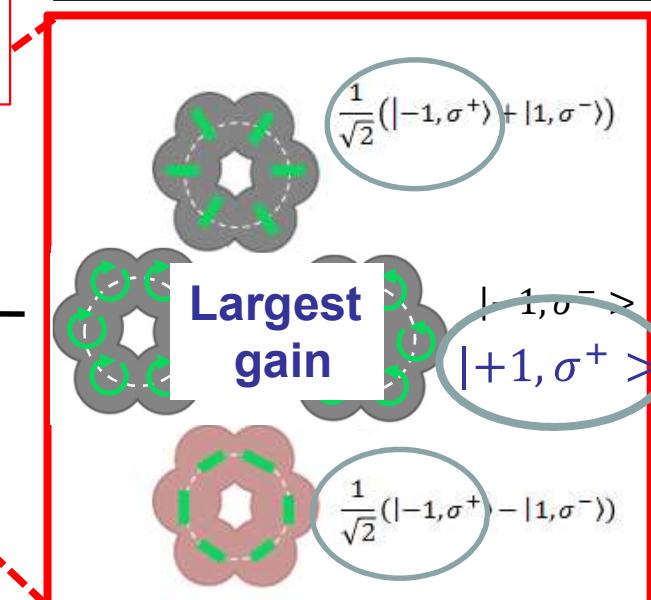
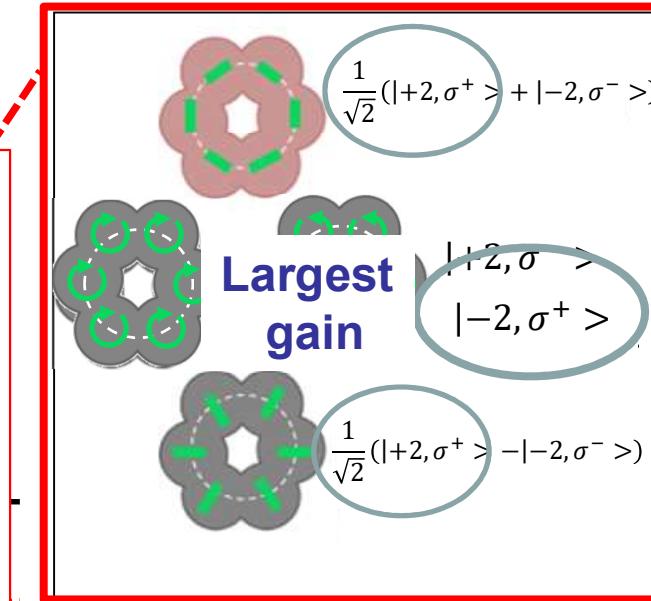
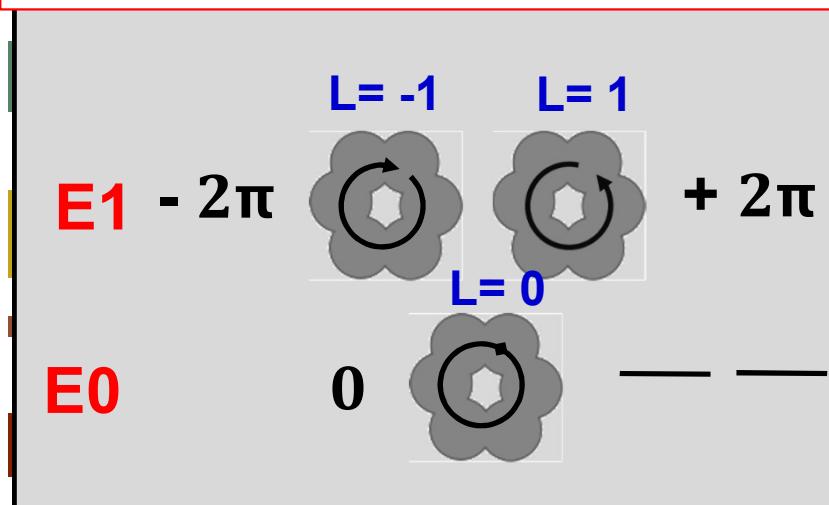


Spin-orbit coupling

Breaking of time reversal symmetry:

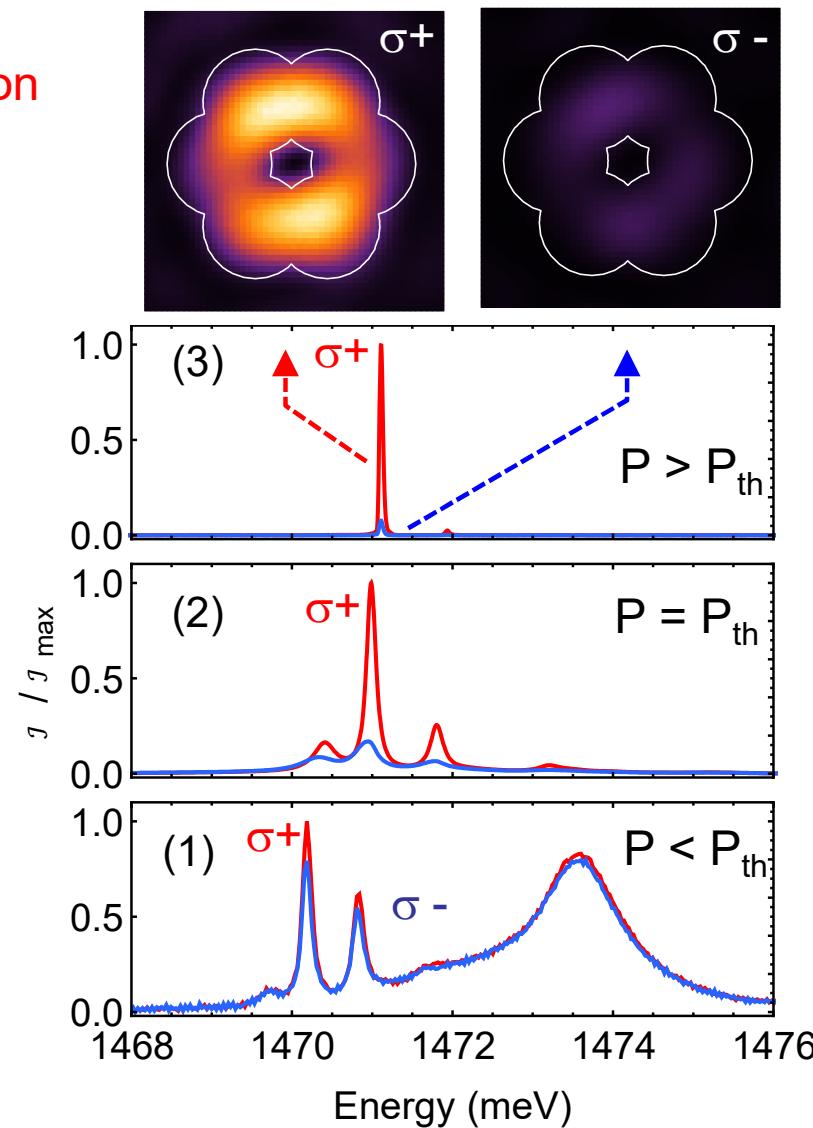
Spin polarize the gain medium

Non resonant pumping with σ^+ polarization



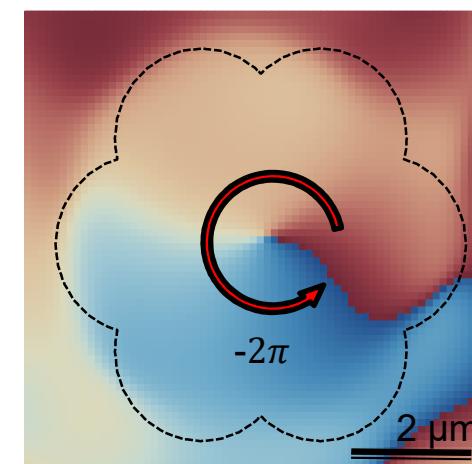
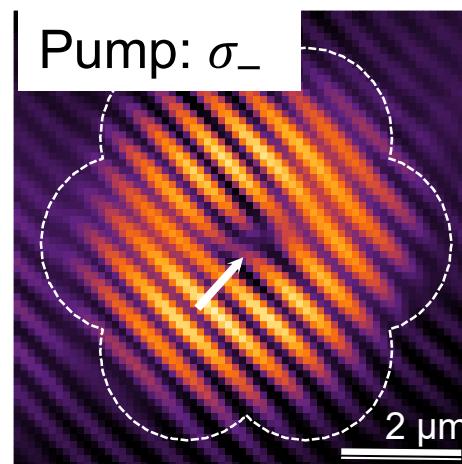
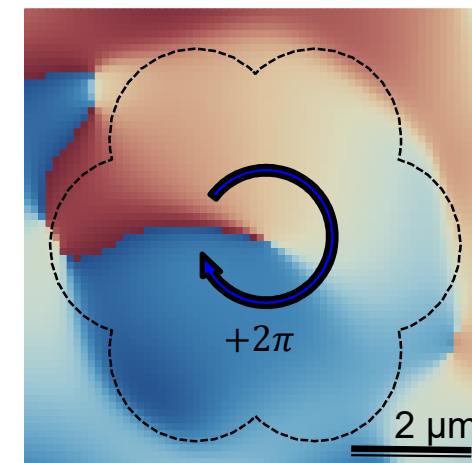
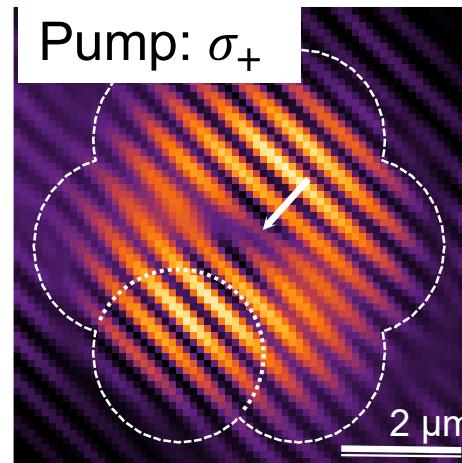
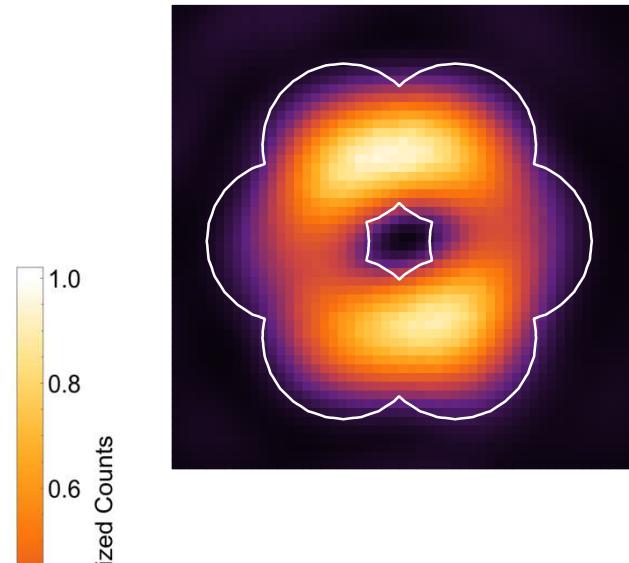
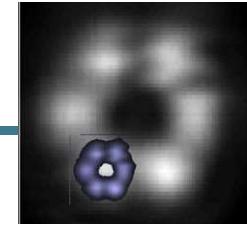
Orbital Angular Momentum Lasing

σ^+ polarized
non-resonant excitation



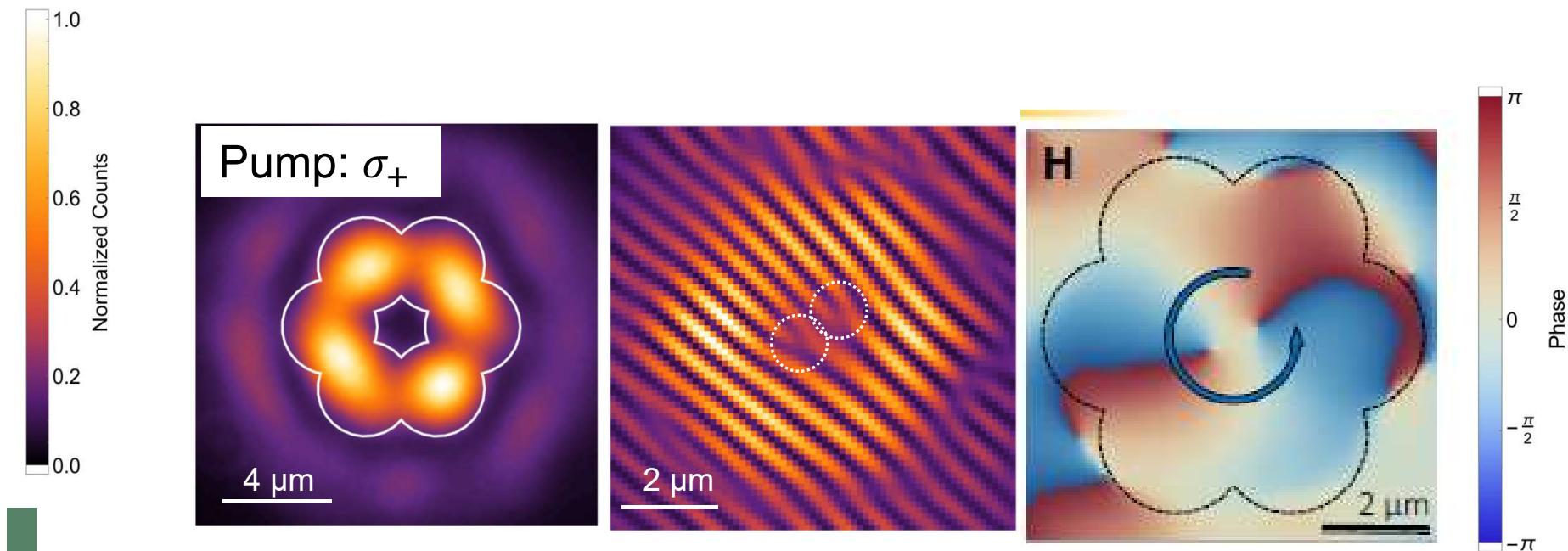
Orbital Angular Momentum Lasing

L=1 Angular momentum



Orbital Angular Momentum Lasing

L=2 Angular momentum

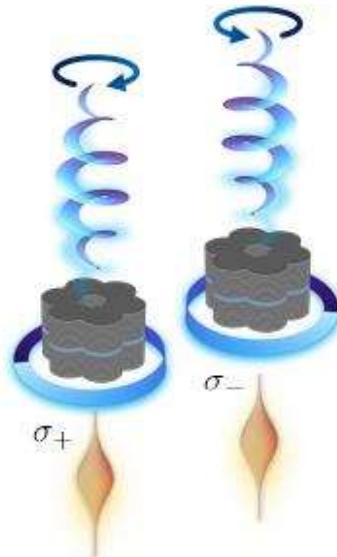


N Carlon Zambon, P. St-Jean et al., Nature Photonics 13, 283 (2019)



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Generating Light with OAM



- Optical control of the helicity ✓

- Scalable ✓

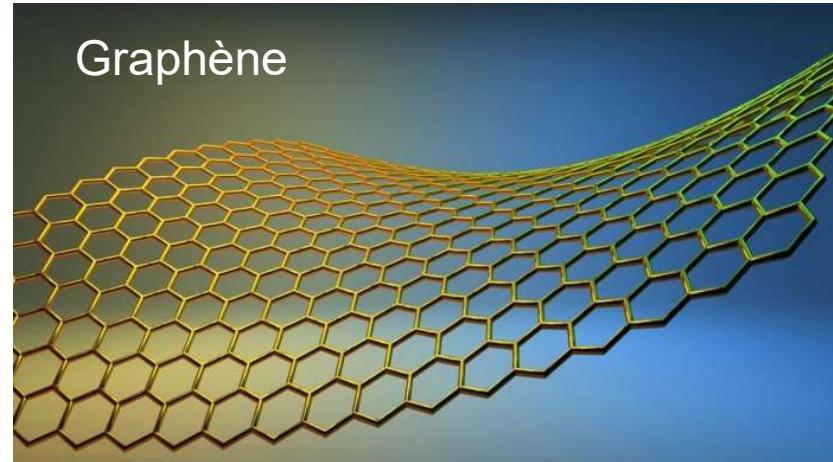
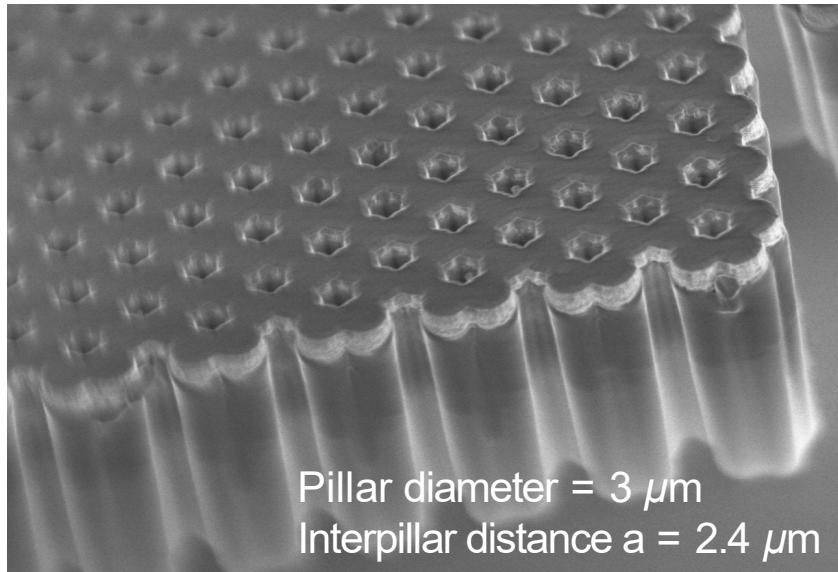
But

- Operation up to 80 K ✓

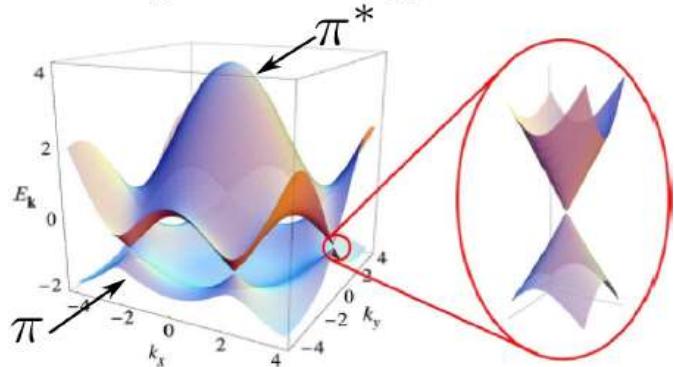
- Could be implemented with different active material for room temperature operation ?

N Carlon Zambon, P. St-Jean et al., Nature Photonics 13, 283 (2019)

Polariton honeycomb lattice



Graphene energy bands



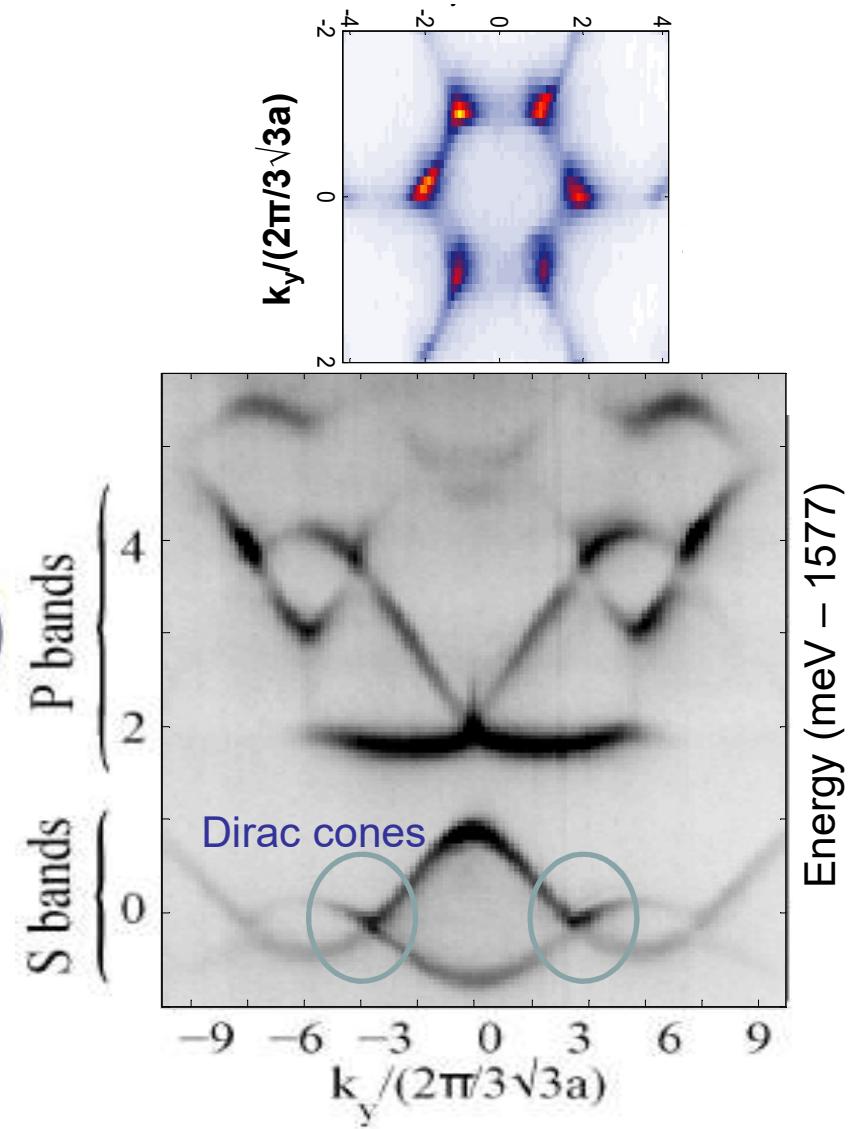
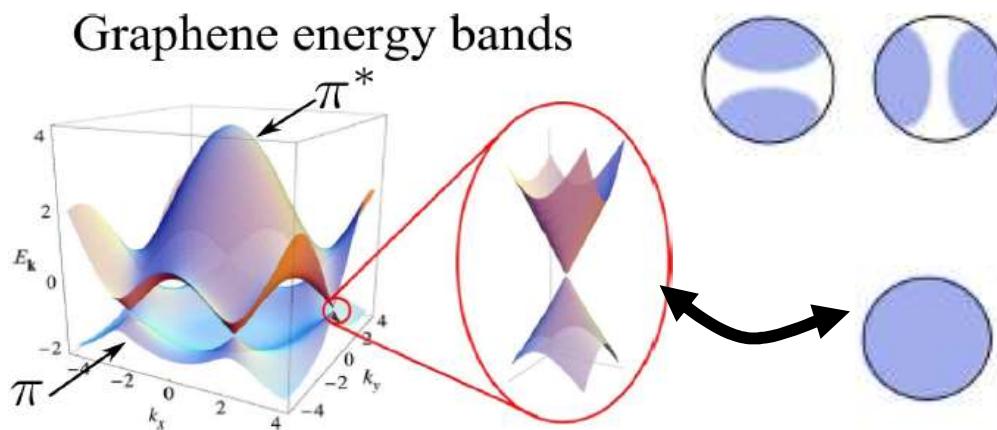
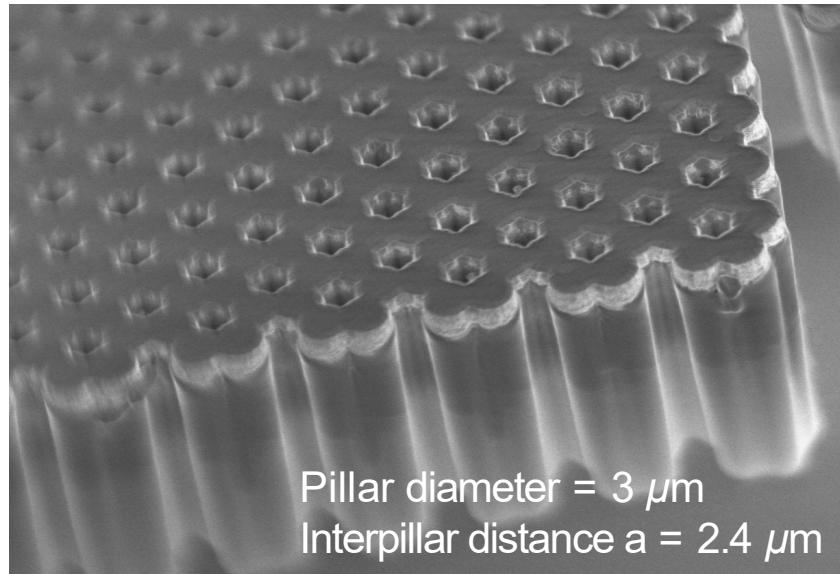
Castro Neto et al., Rev. Mod. Phys. 81 (2009)

Jacqmin et al., PRL 112, 116402 (2014)
See also Yamamoto (Stanford), Krizhanovskii (Sheffield)



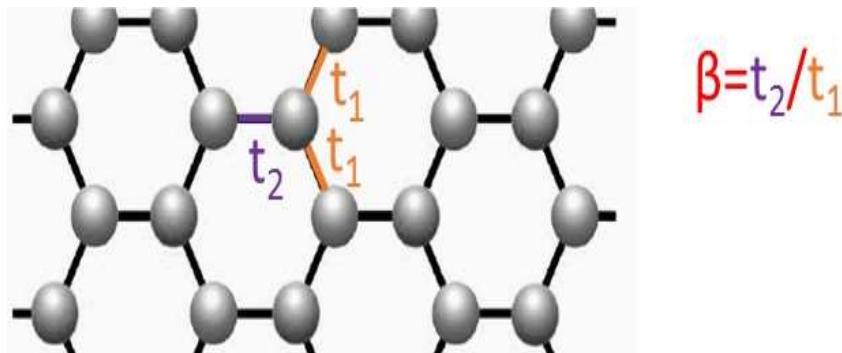
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Polariton honeycomb lattice

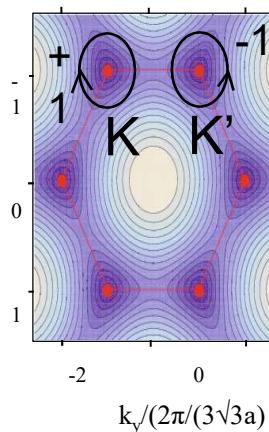


Jacqmin et al., PRL 112, 116402 (2014)
See also Yamamoto (Stanford), Krizhanovskii (Sheffield)

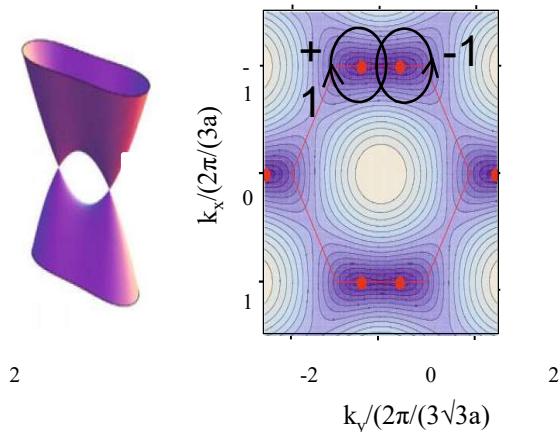
Uniaxial strain in graphene



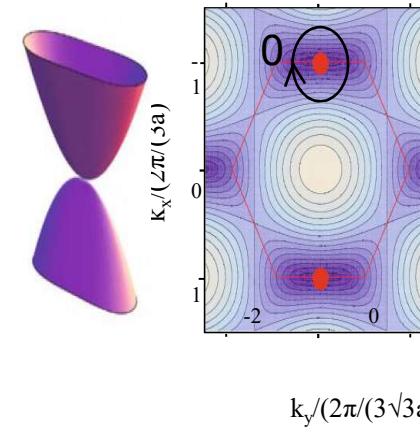
$\beta=1$



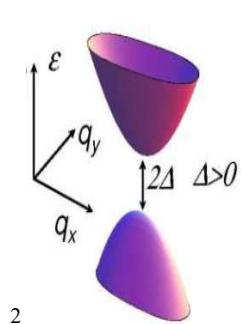
$\beta=1.5$



$\beta=2$



$\beta>2$



Gap
opens!



$$\mathcal{W} = \oint i \langle \psi | \partial_k | \psi \rangle \cdot dk = \frac{1}{2\pi} \oint \partial_k \phi(k) \cdot dk$$

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



Hamiltonian at merging of +1 and -1 Dirac cones

Y. Hasegawa et al., Phys. Rev. B, **74**, 033413 (2006)

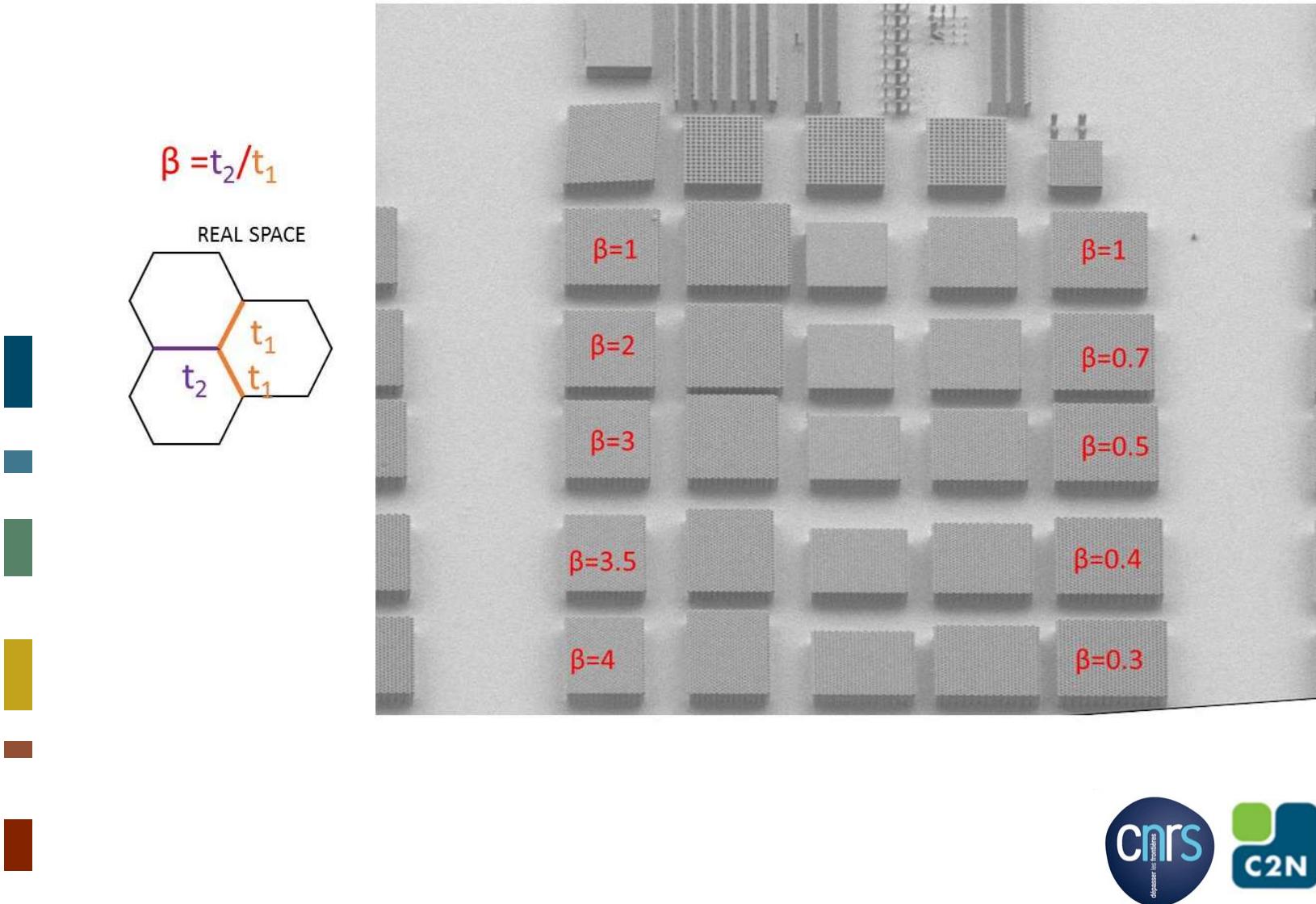
S-L. Zhu et al., Phys. Rev. Lett. **98**, 260402 (2007)

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



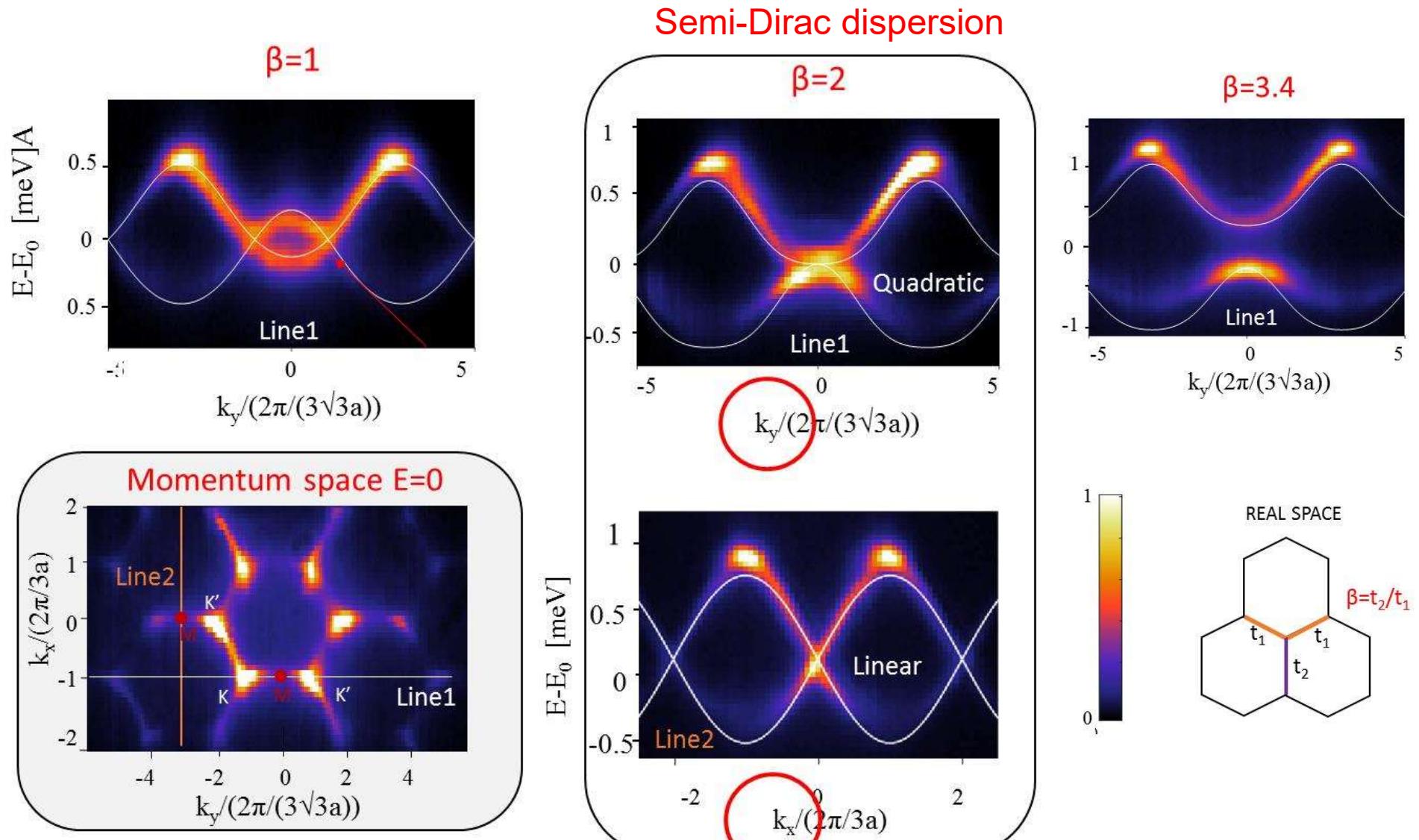
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Strain engineering with micropillars



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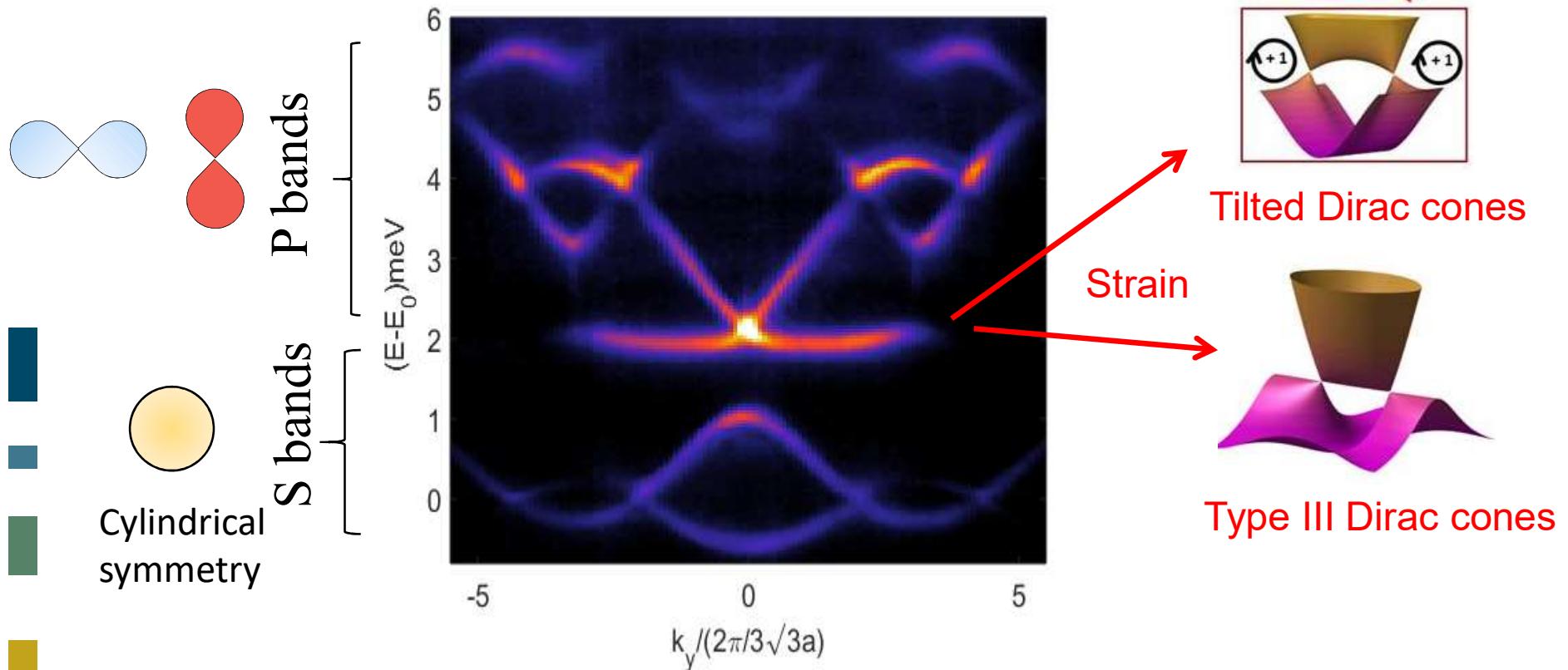
Merging of +1 and -1 Dirac cones



see also: Kim et al., Science, 349, 6249 (2015)
 M. Bellec et al., PRL 110, 033902 (2013)
 L. Tarruell et al., Nature, 483, 7389 (2012)

Orbital graphene

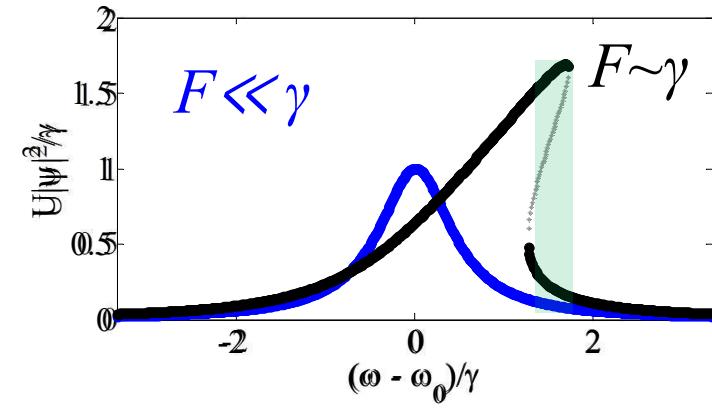
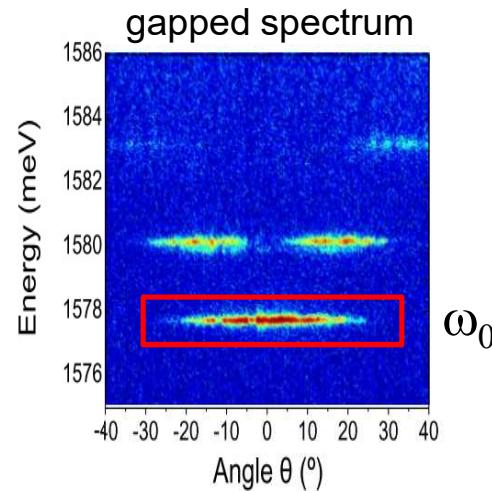
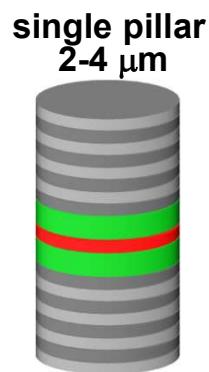
Strain : New types of Dirac cones emerge from the flat band



M. Milicevic et al., to appear in PRX (Arxiv1807.08650)



Nonlinear micropillar



Optical bistability

H.M. Gibbs et al., PRL 36, 1135 (1976)

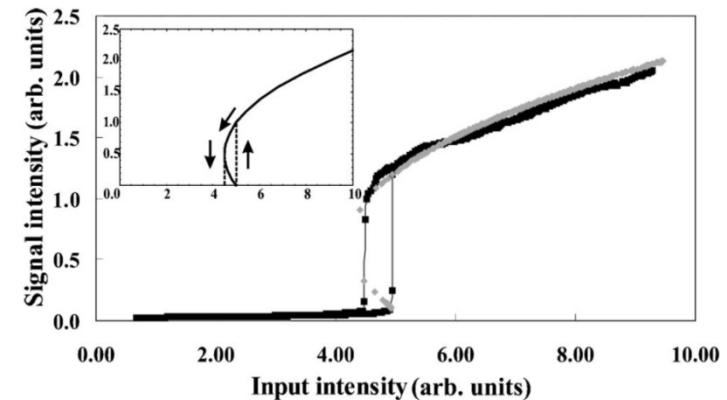
$$i\hbar \frac{d\Psi}{dt} = (E + U|\Psi|^2 - i\gamma)\Psi + Fe^{i\omega t}$$

Interaction energy Decay

CW pumping

The equation shows the time evolution of the wavefunction Ψ . It includes terms for the interaction energy $U|\Psi|^2$, decay $-i\gamma$, and continuous-wave pumping $Fe^{i\omega t}$.

- Repulsive interactions lead to resonance blue-shift



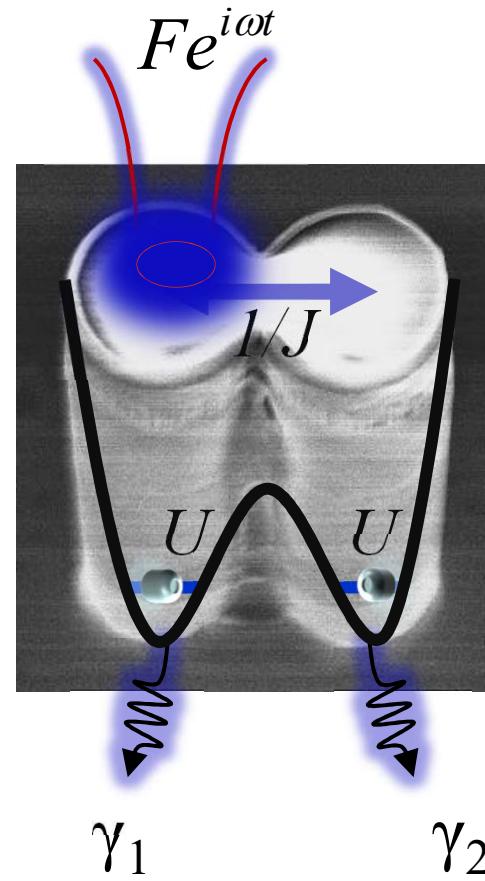
Baas et al., PRB. 70, 161307(R) (2004)
Baas et al., PRA 69, 023809 (2004)



Nonlinear dimer

$$i\hbar \frac{d\Psi_1}{dt} = (E_1 + U|\Psi_1|^2 - i\gamma_1)\Psi_1 - J\Psi_2 + Fe^{i\omega t}$$

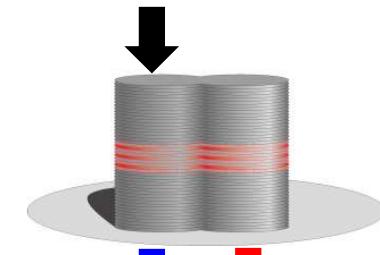
$$i\hbar \frac{d\Psi_2}{dt} = (E_2 + U|\Psi_2|^2 - i\gamma_2)\Psi_2 - J\Psi_1$$



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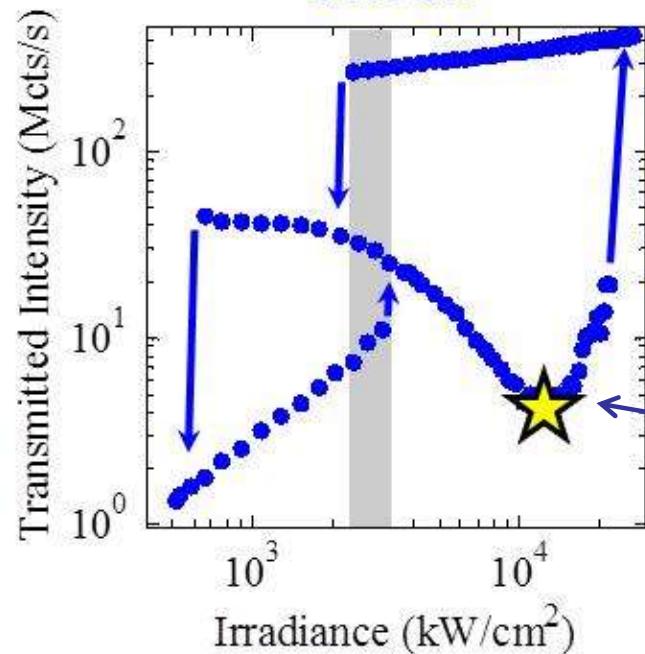
Nonlinear dimer

CW excitation of left micropillar

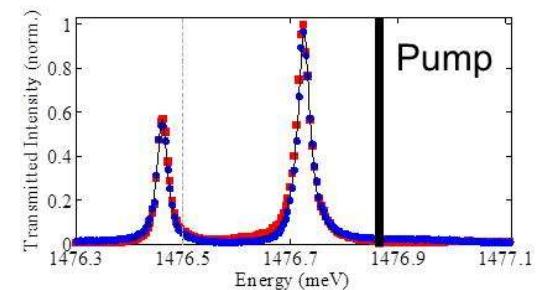


Tristability

Driven



Destructive interference
Non-linear hopping phase



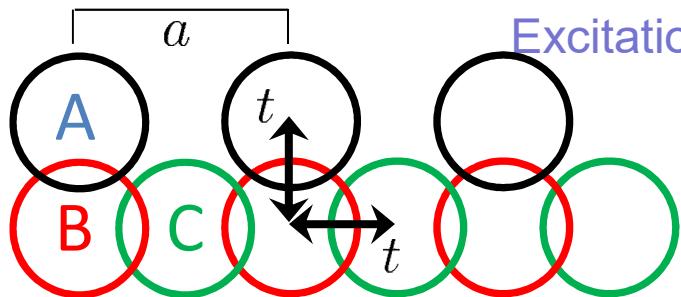
S. Rodriguez et al., Nature Commun. 7, 11887 (2016)

See also Paraïso et al., Nature Materials 9, 655 (2010)

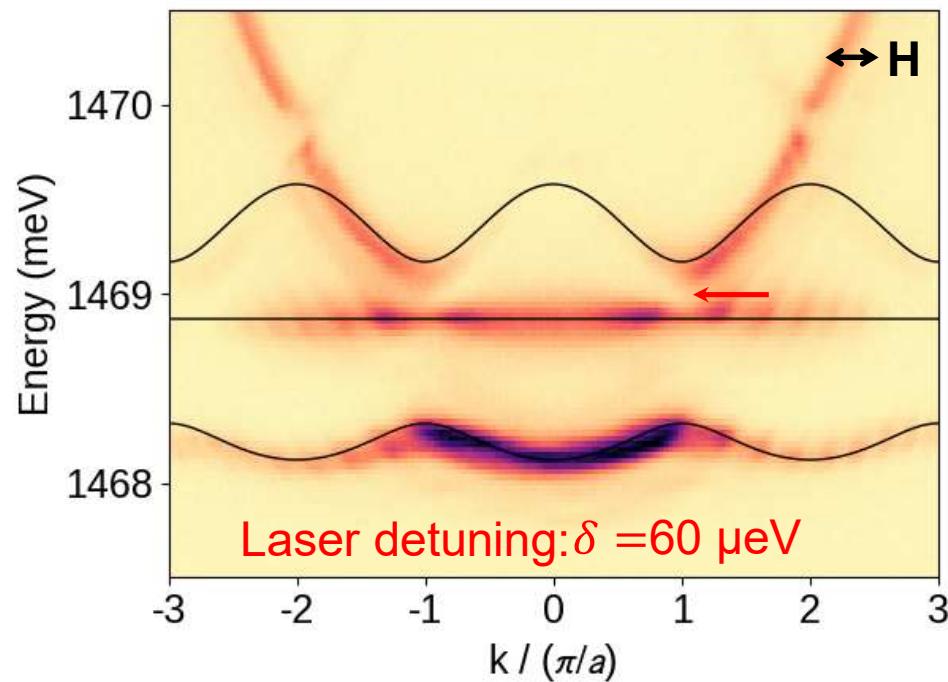
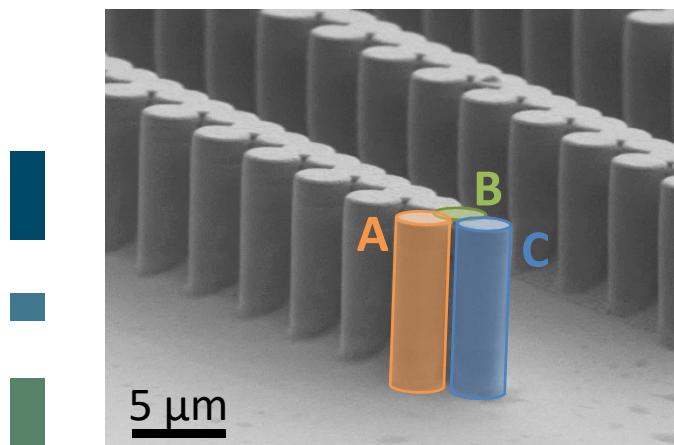


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Non-linearity in a flat band



Excitation in the gap: laser detuning = interaction energy



V. Goblot et al, arXiv:1905.03759

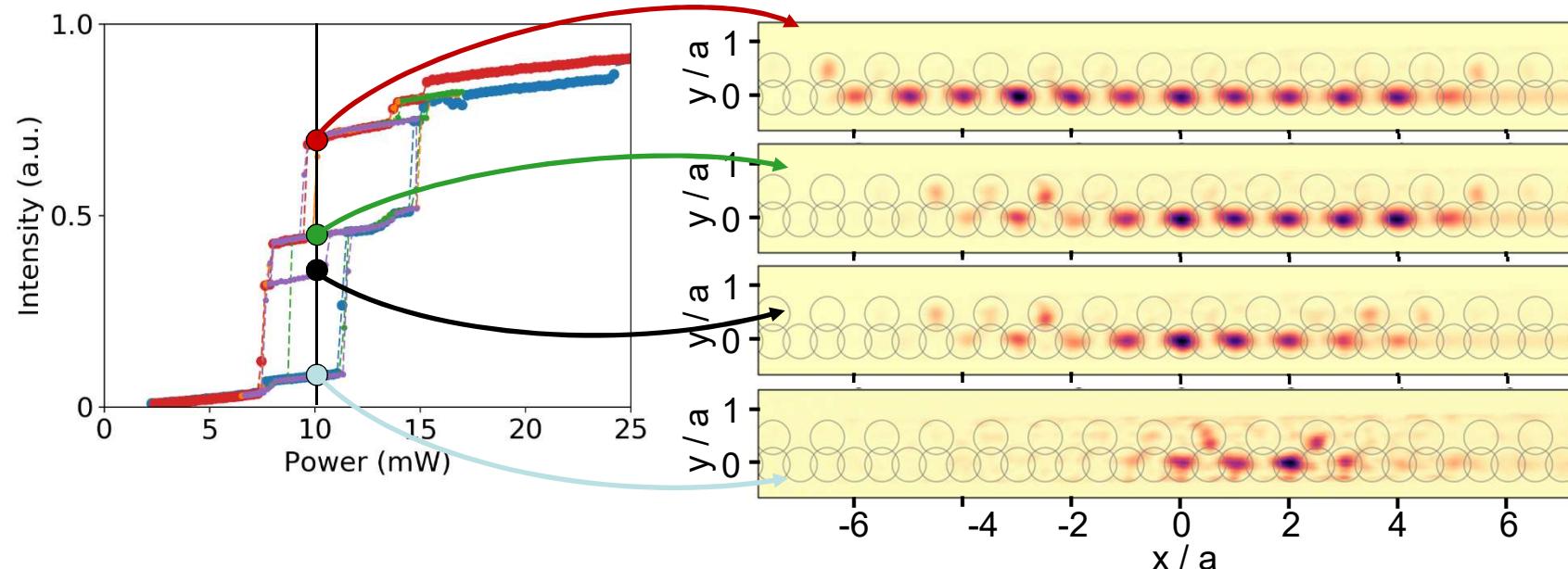
F. Baboux et al. PRL116, 066402 (2016)

See also Yamamoto (Stanford), Krizhanovskii (Sheffield)



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Multistability of Non-linear domains



V. Goblot et al, arXiv:1905.03759



Summary

- Emulation of different Hamiltonians with lattices of coupled cavities
- New concepts for photonic devices
- Light behaves as a highly non-linear quantum fluid

Potential for Applications

Important developments for room temperature operation of polariton devices

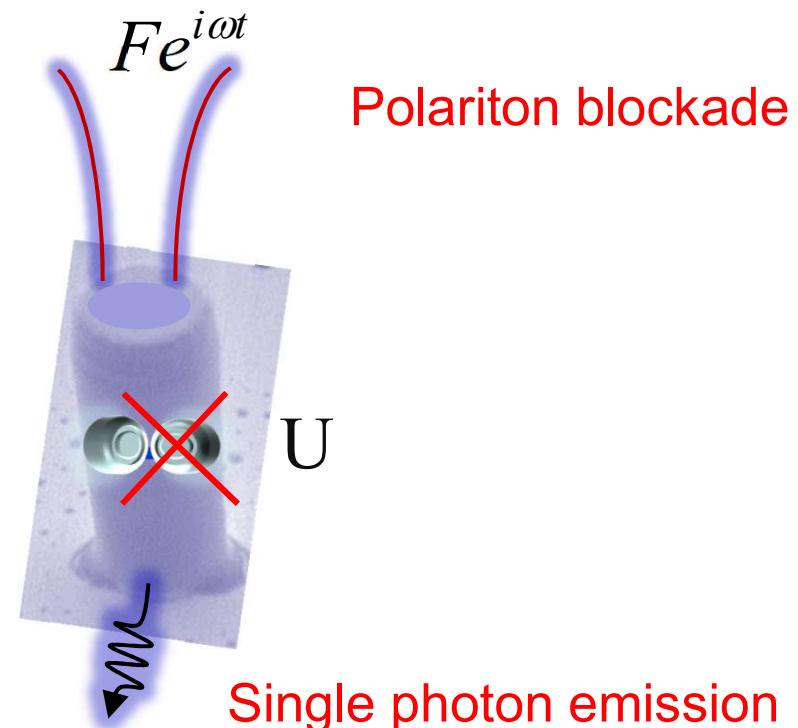
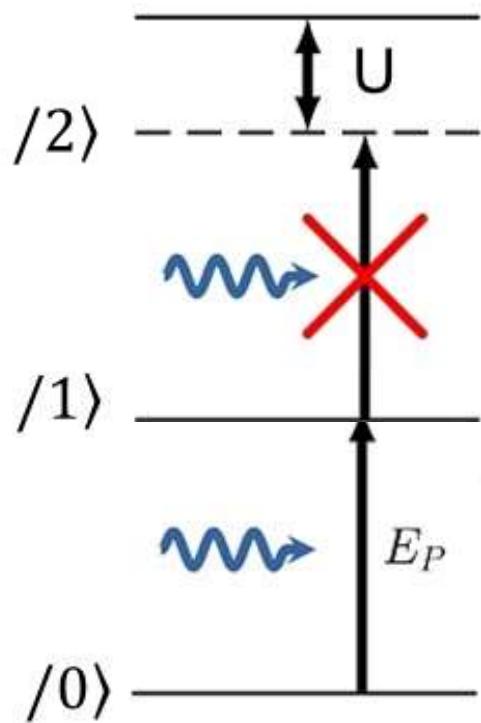
ZnO, 2D materials, Perovskite.....

Séance Parallèle (2.3 Fluides Quantiques de Lumière)

- Non-linearity and topology?
- How far from quantum regime? Beyond mean field?

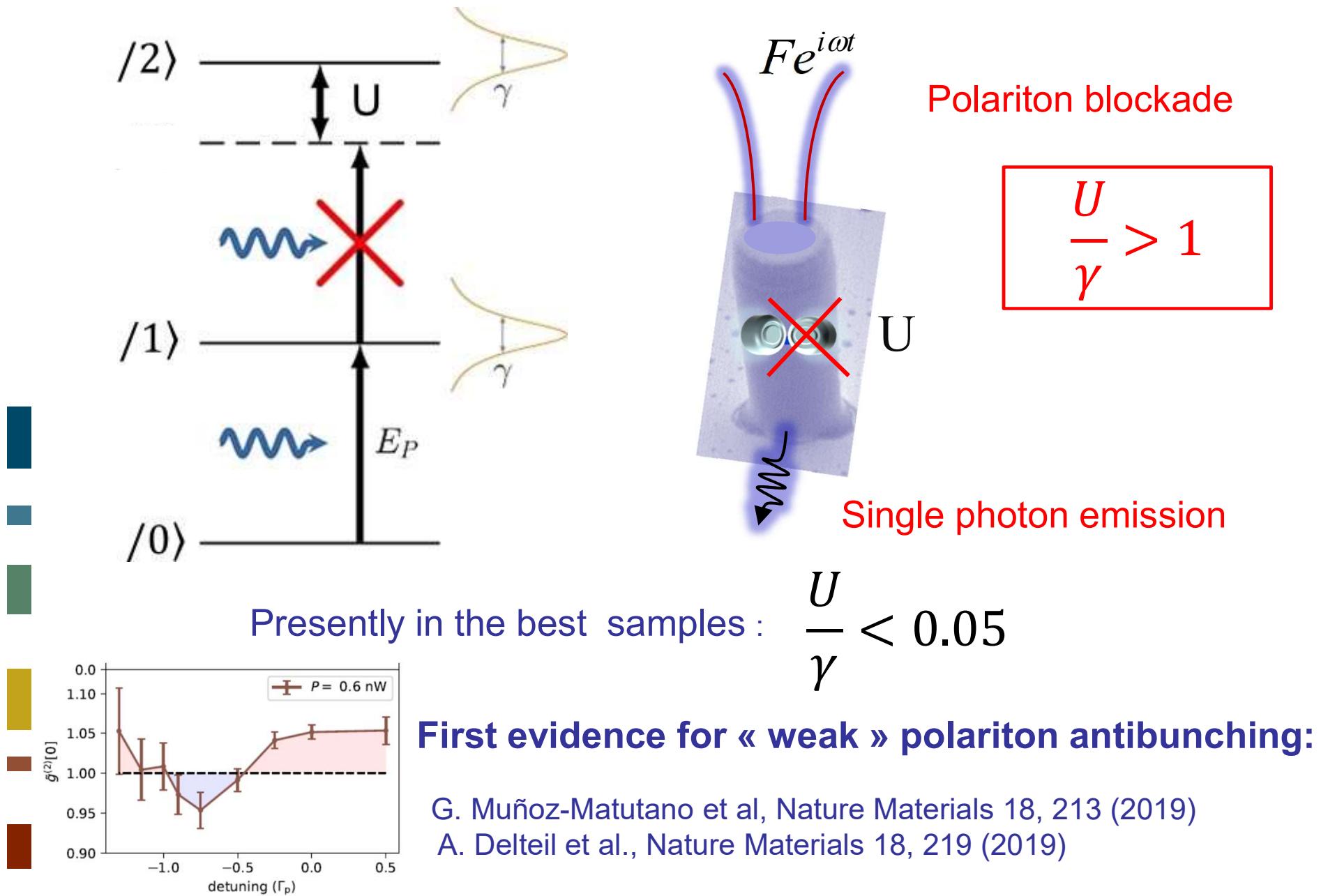


How far from quantum regime ? Polariton blockade?



A. Verger et al., Phys. Rev. B 73, 193306 (2006)
Exp J. Simon's group: Nature Physics 14, 550, (2018)

How far from quantum regime ? Polariton blockade?



How to increase interactions? Couple to different excitations

- **Dipolar polaritons:**

P. Cristofolini et al., Science 336, 704 (2012)

E. Togan et al., Physical Review Letters 121, 227402 (2018)

Atac
Imamoglu
ETH

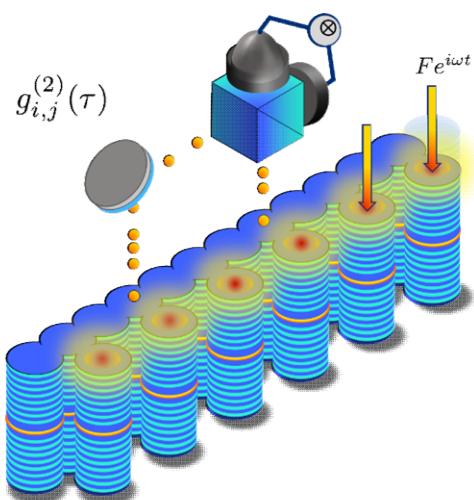


- **Polaron polaritons:** S. Ravets et al., Phys. Rev. Lett. 120, 057401 (2018)

- **Photons coupled to fractional quantum Hall states,**

P. Knüppel et al., arXiv:1903.09256

Bose-Hubbard



$$\hat{H} = -J \sum_{\langle m,n \rangle} \hat{a}_m^\dagger \hat{a}_n + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)$$

Strongly correlated
photon phases
Within reach!!!

Acknowledgment to our theoretician collaborators



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Ozawa



Eric Akkermans



Oded
Zilberberg



Antonio
Štrkalj



Jose
Lado



Gilles Montambaux



Cristiano Ciuti



Wim Casteels



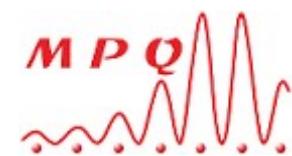
Florent Storme



Filippo Vincentini



Alexandre Le Boit 



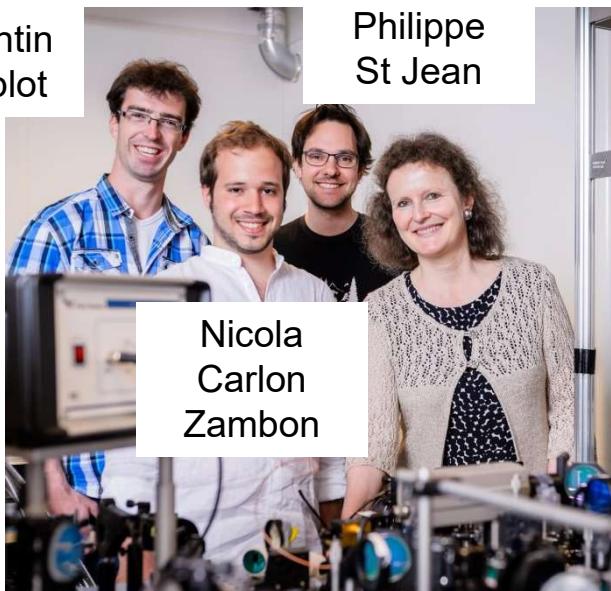
Paris

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Carlon
Zambon

Philippe
St Jean



Sylvain
Ravets



Alberto Amo
Lilles University



Nicolas
Pernet



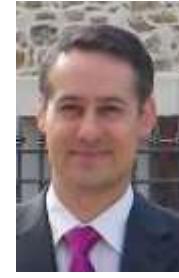
Aristide Lemaitre



Carmen Gomez



Isabelle Sagnes



Luc Legratiet



Abdou Herouri



This project is funded
by the European Union

