Quantum fluids of light in semiconductor lattices

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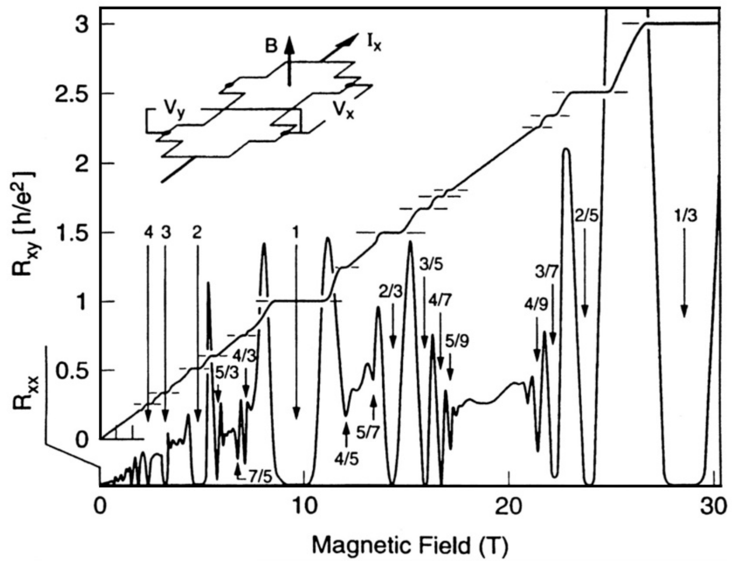
http://www.polaritonquantumfluid.fr

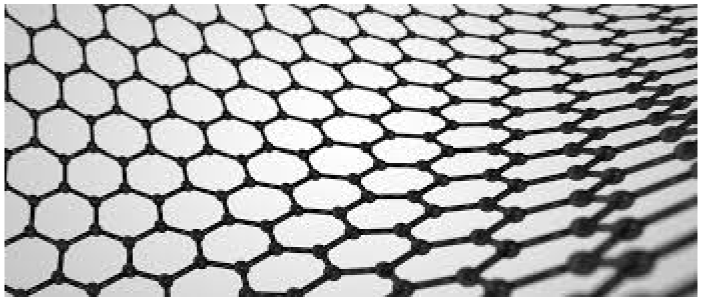
Inspiration: Emerging physics in the solid state

Superfluidity

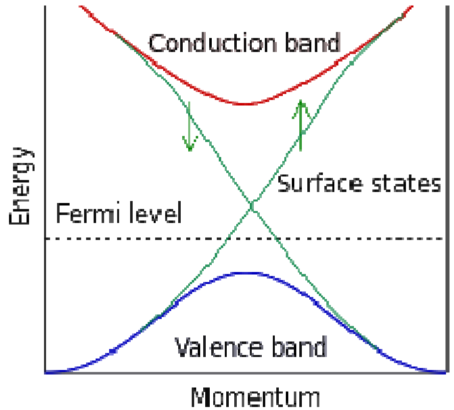
Fractional Quantum Hall effect



Graphene

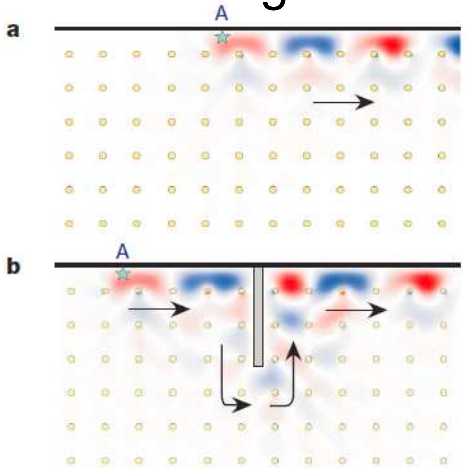


Topological insulators



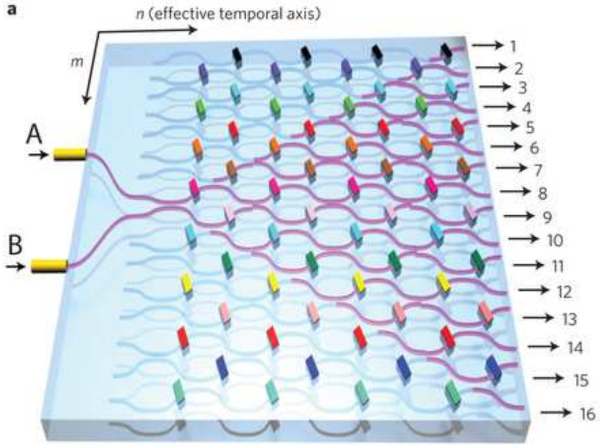
Emulation with light

Chiral edge states



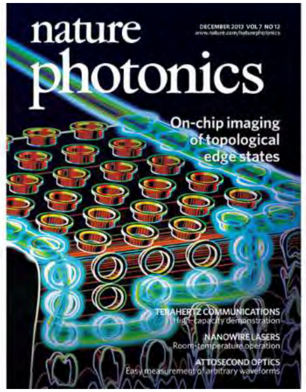
Zheng Wang et al.,
Nature **461** 772 (2009)

Randon quantum walk



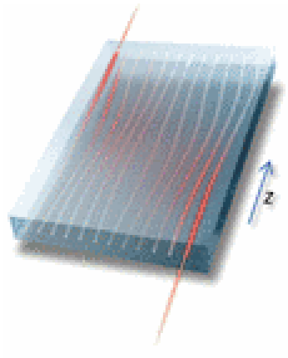
A. Crespi, Nature Photonics 7, 322 (2013)

Topological edge states Si



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

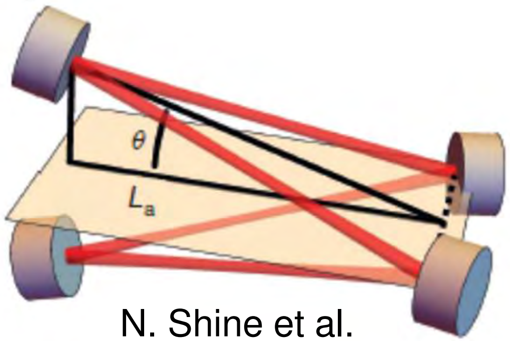
Quasi crystal



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

Levi *et al.*, Science **332**, 1541 (2011)

Synthetic Landau levels

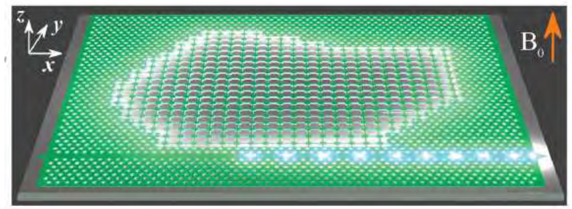


N. Shine et al.
Nature 354, 671 (2016)

2 photon Laughling state

Arxiv 1907.05872

Non reciprocal lasing



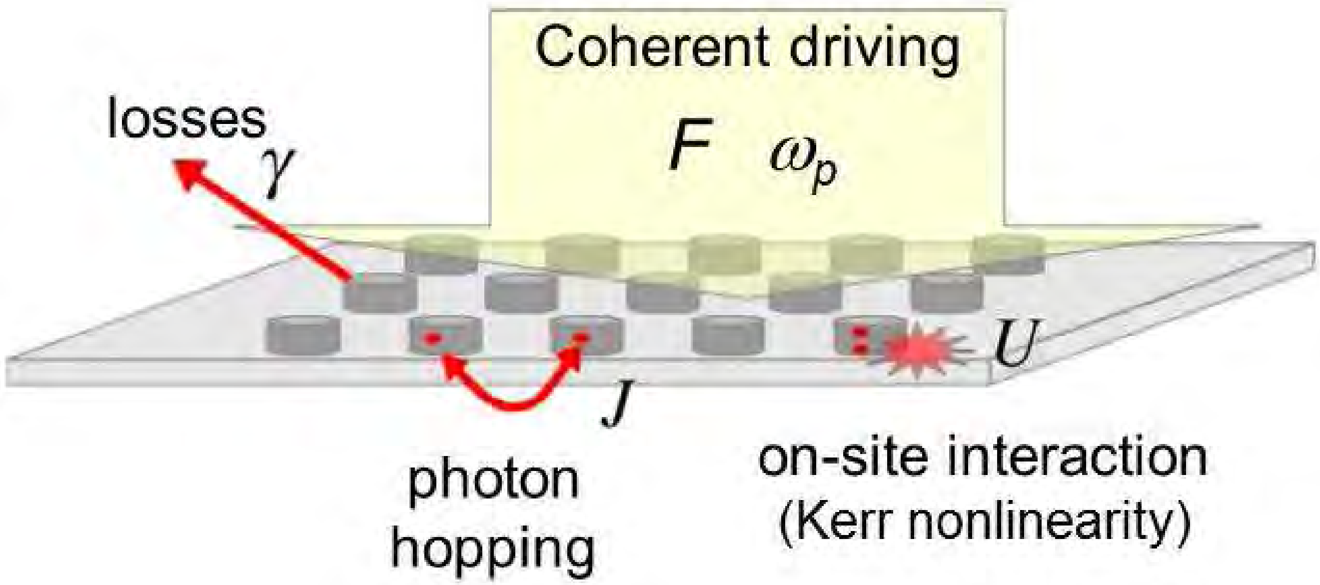
B.Bahari et al., Science
10.1126/science.aao4551(2017)

M. A. Bandres et al. Science
10.1126/science.aar4005 (2018)

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

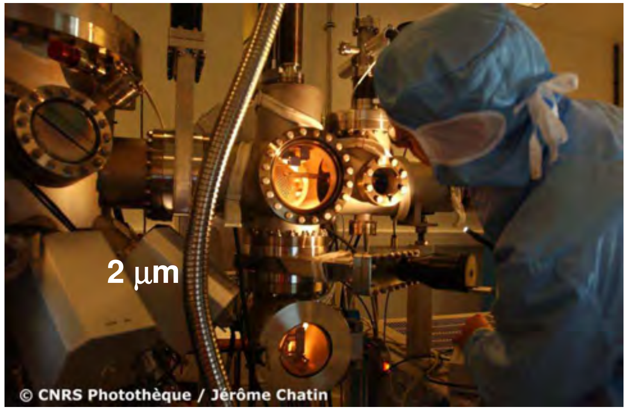
Driven-dissipative photonic Bose-Hubbard model

Out of equilibrium quantum physics



Ciuti & Carusotto, Rev. Mod. Phys. **85**, 299 (2013)
M.J. Hartman, Journal of Optics (2016)
C.Noh and DG Angelakis, Report on progress in Physics (2016)
A. Biella et al., Phys. Rev. A 96, 023839 (2017)
F. Vincentini et al., Phys. Rev. A 97, 013853 (2018)

Use nanotechnology to engineer photonic lattices



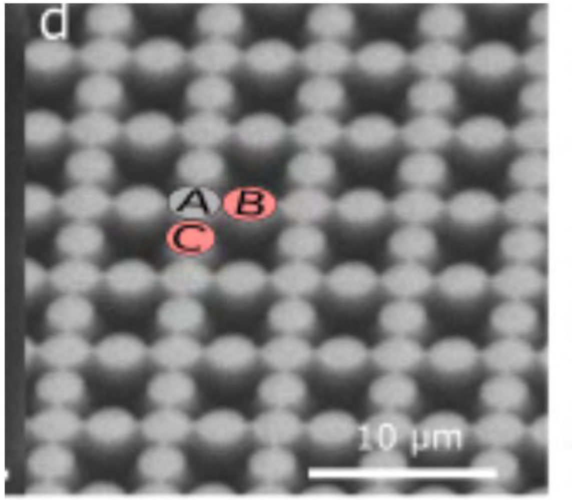
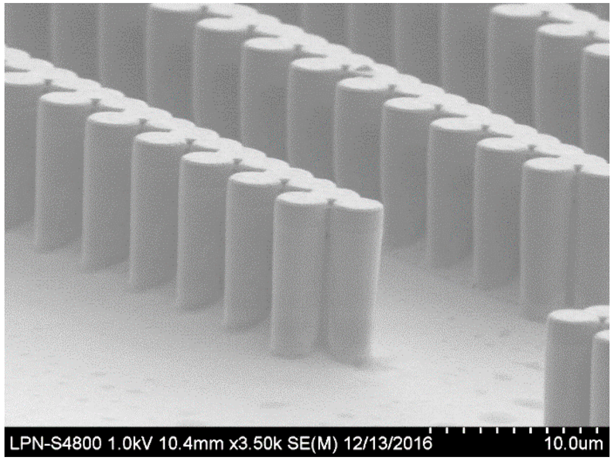
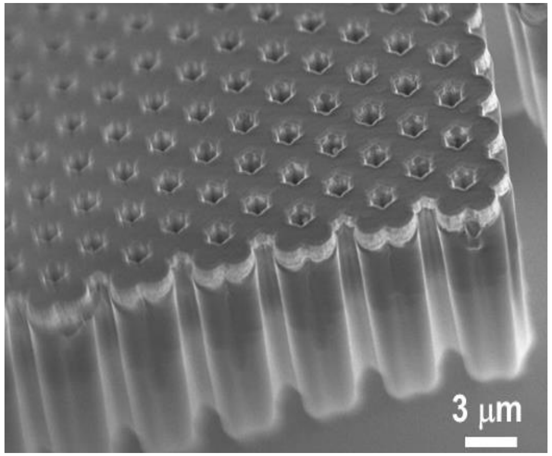


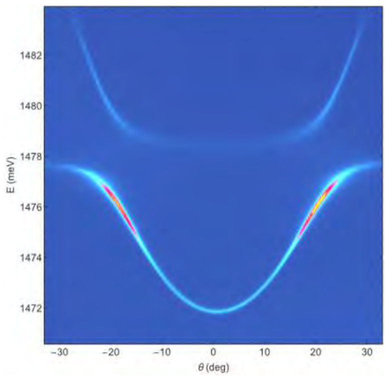
Image from Würzburg

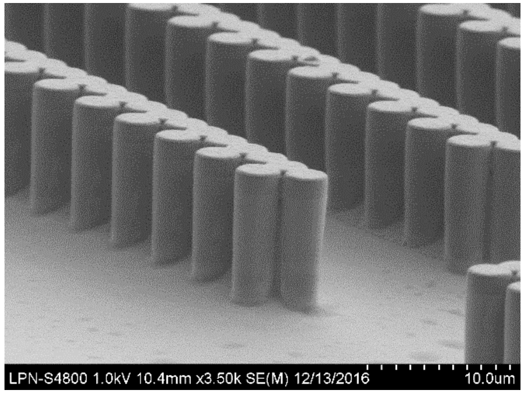




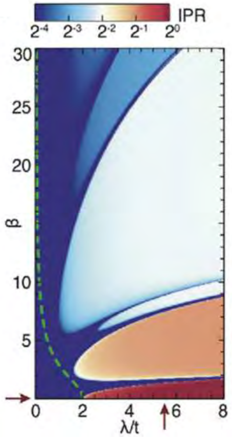
Outline

- Introduction to polariton lattices

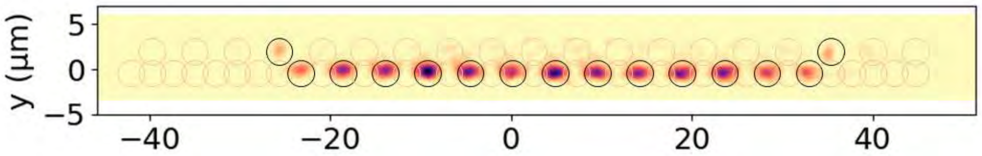




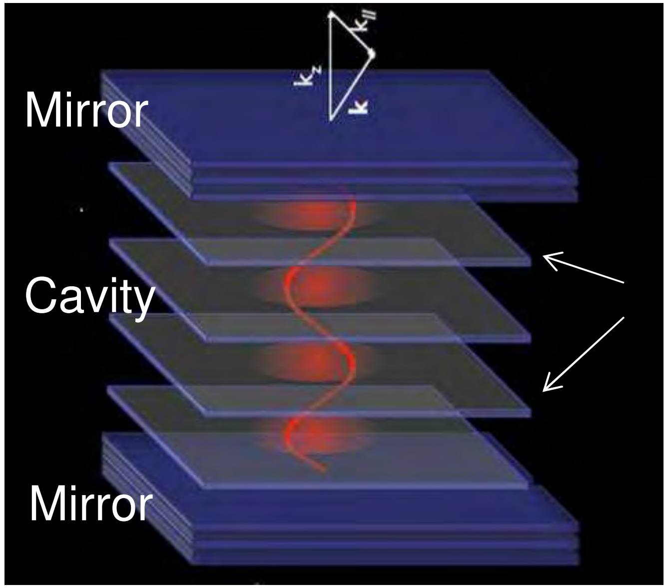
- Emergence of criticality in quasi-crystals

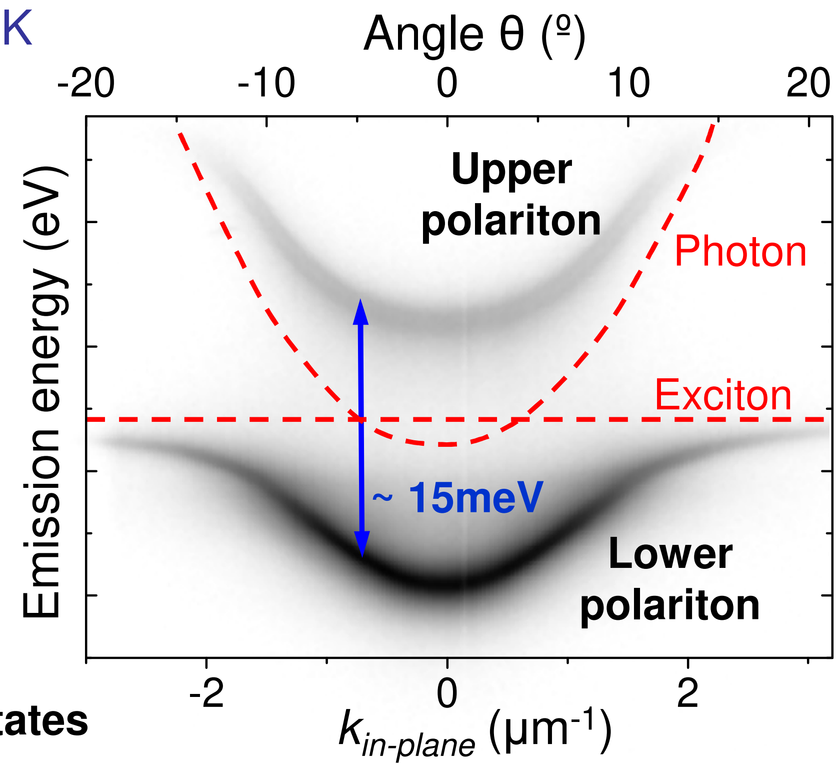


- Discrete gap solitons in a flat band



Microcavity polaritons



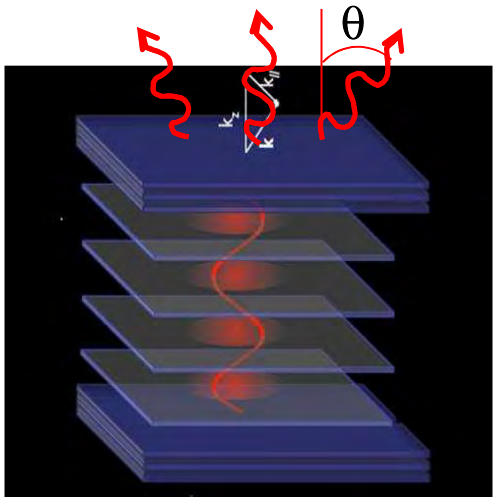


- **Microcavity polaritons : mixed exciton-photon states**

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

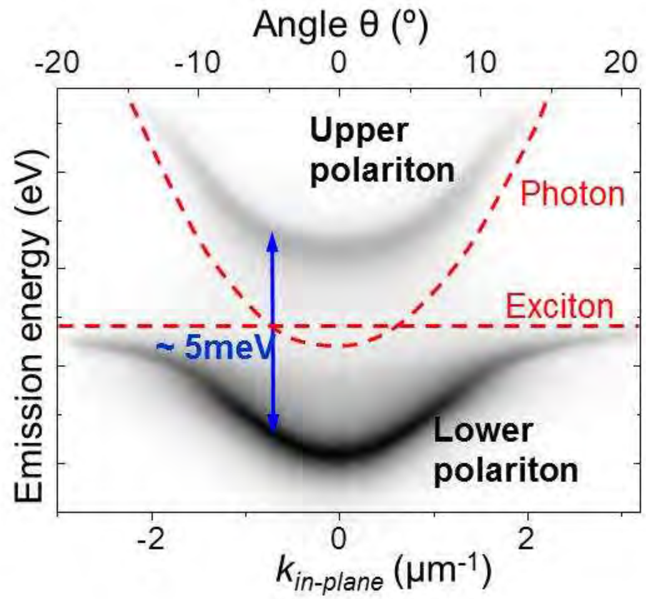
- Photonic component ➡ confinement in microstructures
  real space, k-space imaging
- Excitonic component ➡
  - Interactions - $\chi^{(3)}$ (dominated by exchange)
  - Gain (lasing)
  - Sensitivity to magnetic field

Probing polariton states

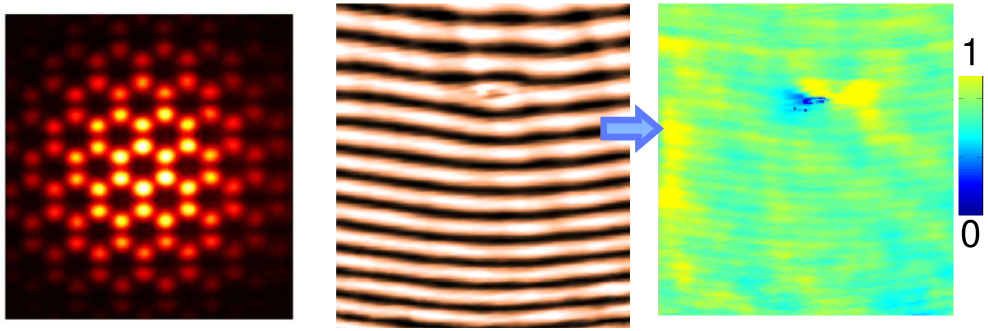


$$k_{//} = \omega/c \sin(\theta)$$

Imaging of k-space



Imaging of real space



Density

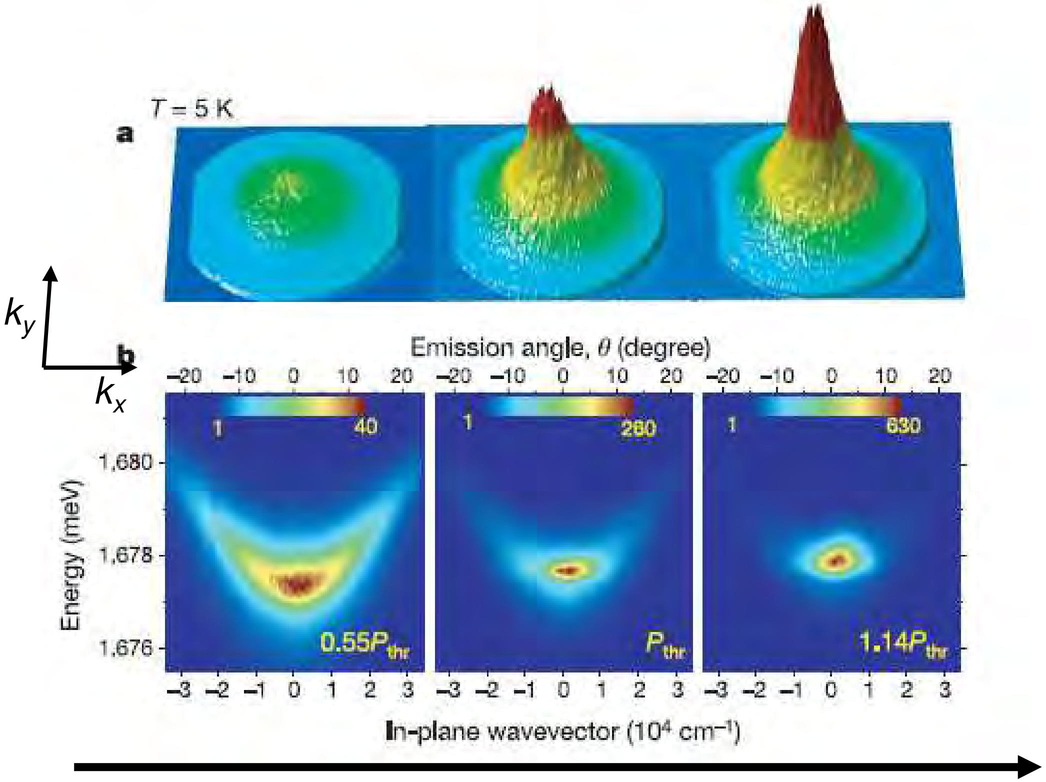
Interferometry

- vortices
- solitons

Coherence
$g^{(1)}$
$g^{(2)}$

Bose–Einstein condensation of exciton polaritons

J. Kasprzak[1], M. Richard[2], S. Kundermann[2], A. Baas[2], P. Jeambrun[2], J. M. J. Keeling[3], F. M. Marchetti[4], M. H. Szymańska[5], R. André[1], J. L. Staehli[2], V. Savona[2], P. B. Littlewood[4], B. Deveaud[2] & Le Si Dang[1]



Increase excitation power

Benoid Deveaud

Le Si Dang

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

See also H. Deng et al. Science (2002), R. Balili et al., Science (2007)

Polariton superfluidity

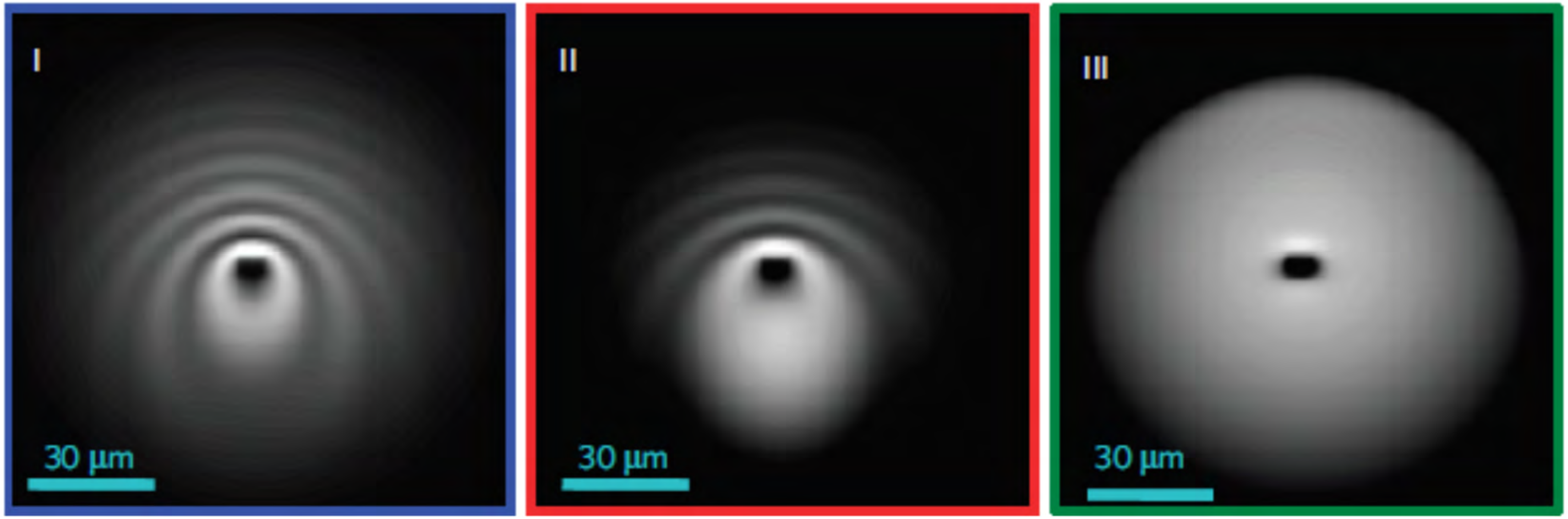
Iacopo Carusotto

Cristiano Ciuti

Alberto Amo

Alberto Bramati

Elisabeth Giacobino



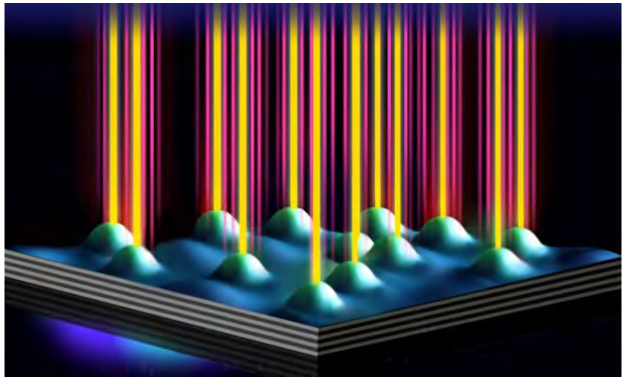
C. Ciuti and I. Carusotto PRL 242, 2224 (2005)

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



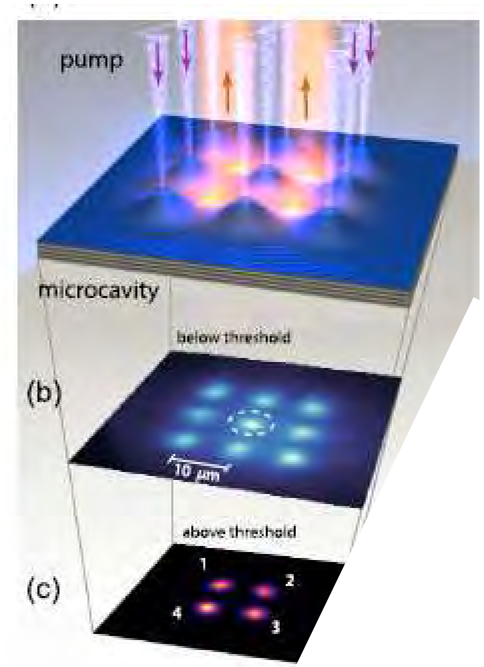
Pavlos Lagoudakis

Southampton

Natalia Berloff

Cambridge

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



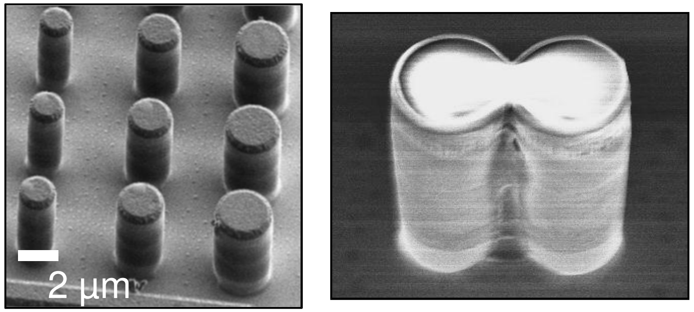
Polarization instability in coupled polariton condensates

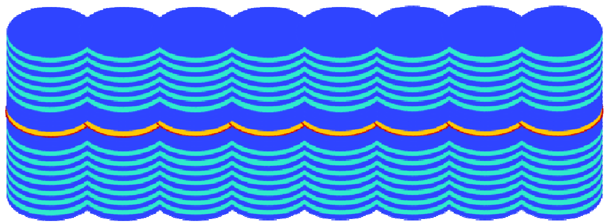
Spin order and phase transitions in chains of polariton condensates, H. Ohadi, et al., Phys. Rev. Lett.. 119, 067401 (2017)

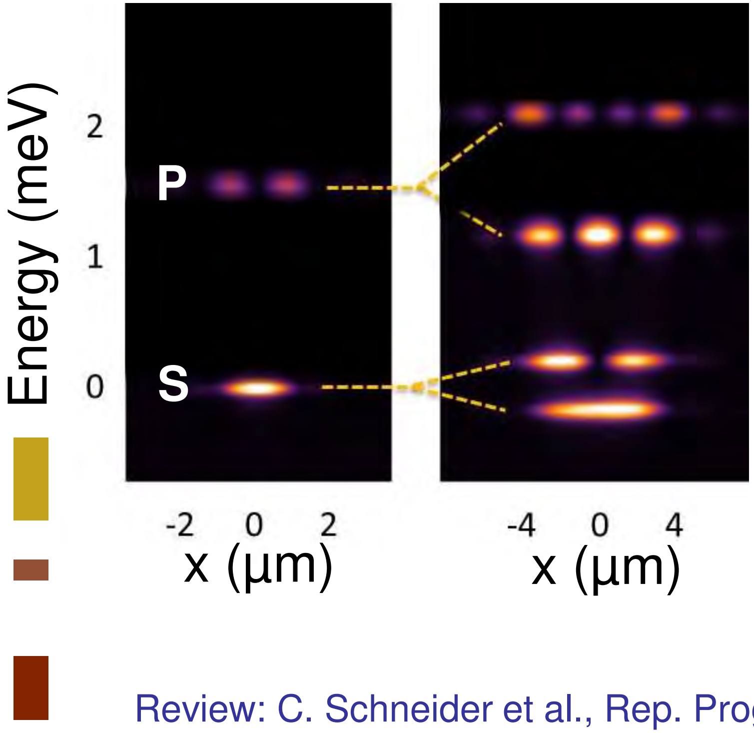
Jeremy Baumberg

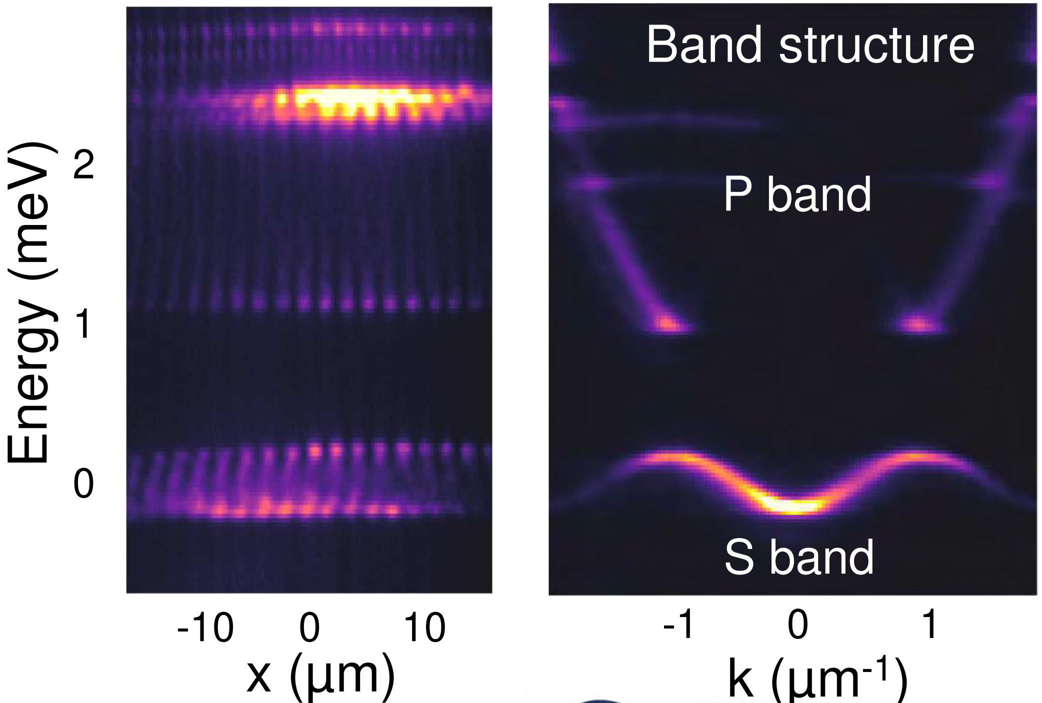
Cambridge

Polariton lattices:Tight binding approach



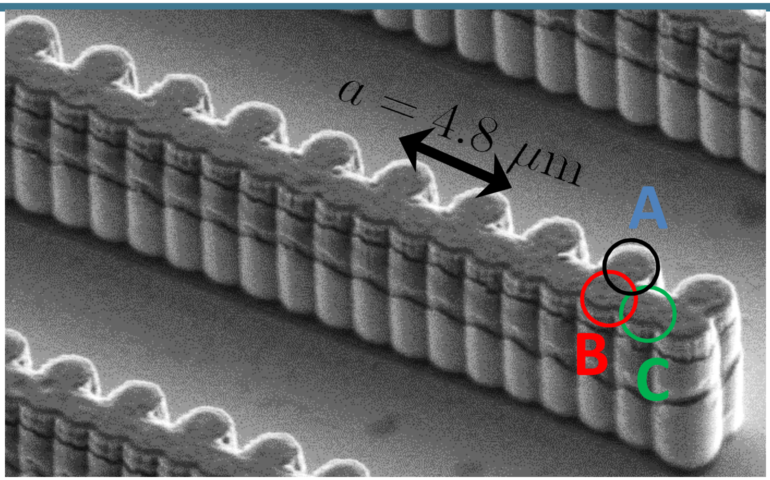


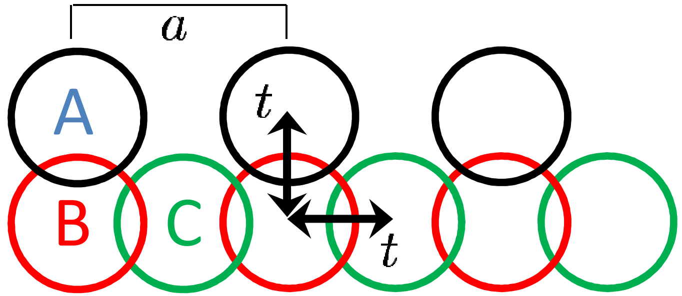




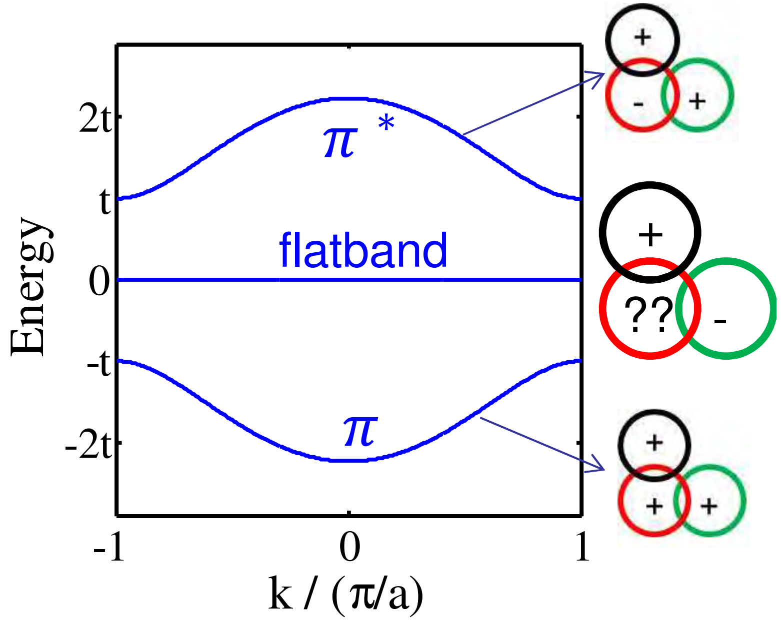
Review: C. Schneider et al., Rep. Prog. Phys. 80, 16503 (2017)

Engineering of a 1D flatband : “comb” lattice

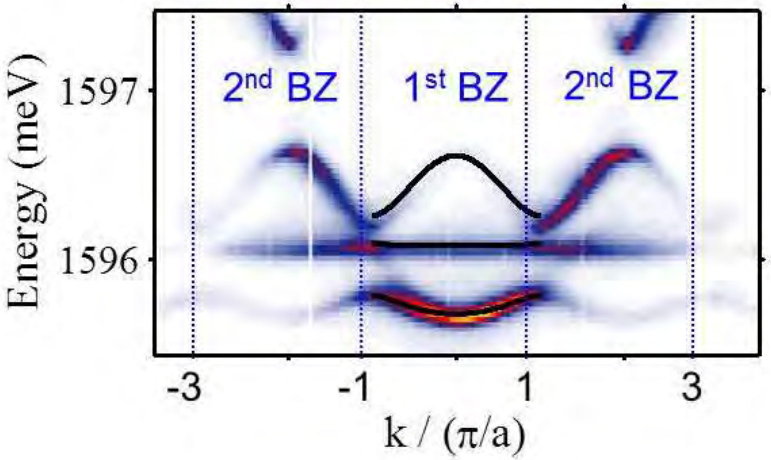




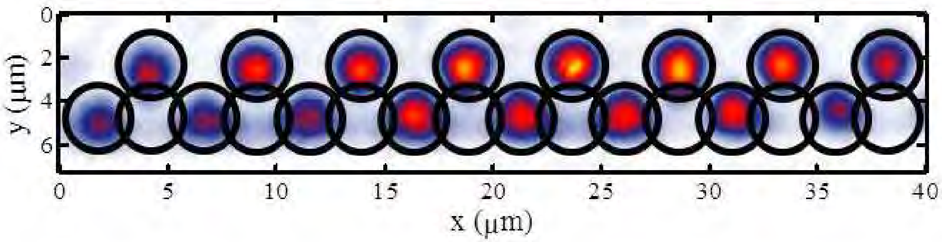
Pillar diameter = 3 µm
Interpillar distance= 2,4 µm



Far field emission

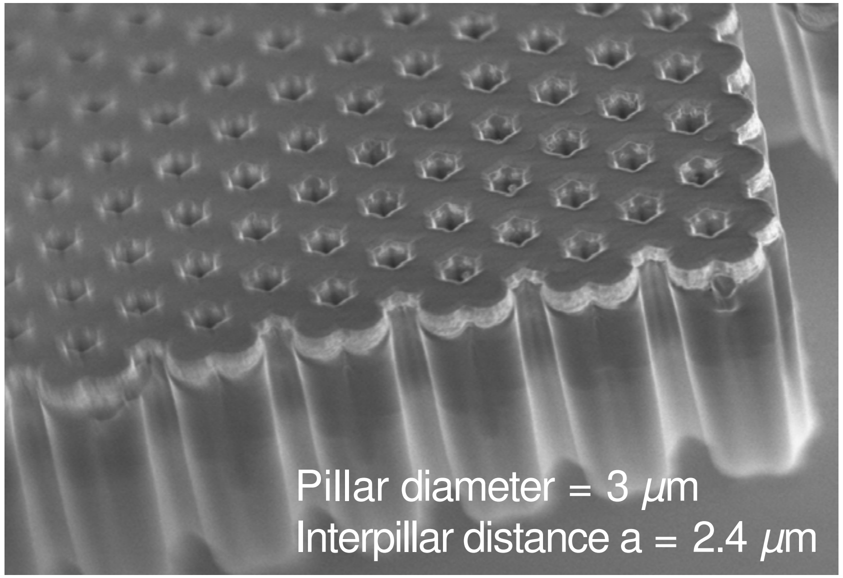


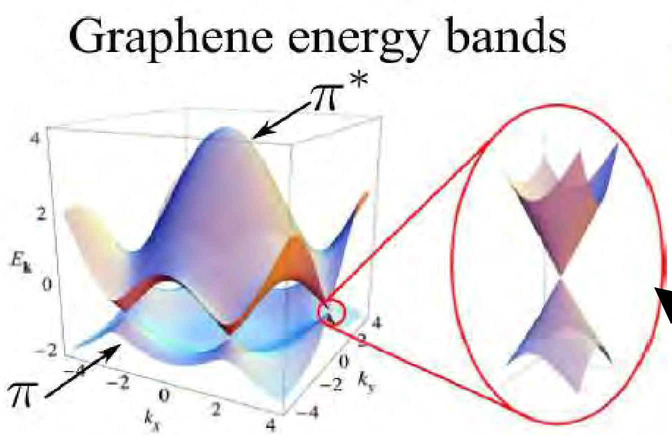
Emission of flat band in real space



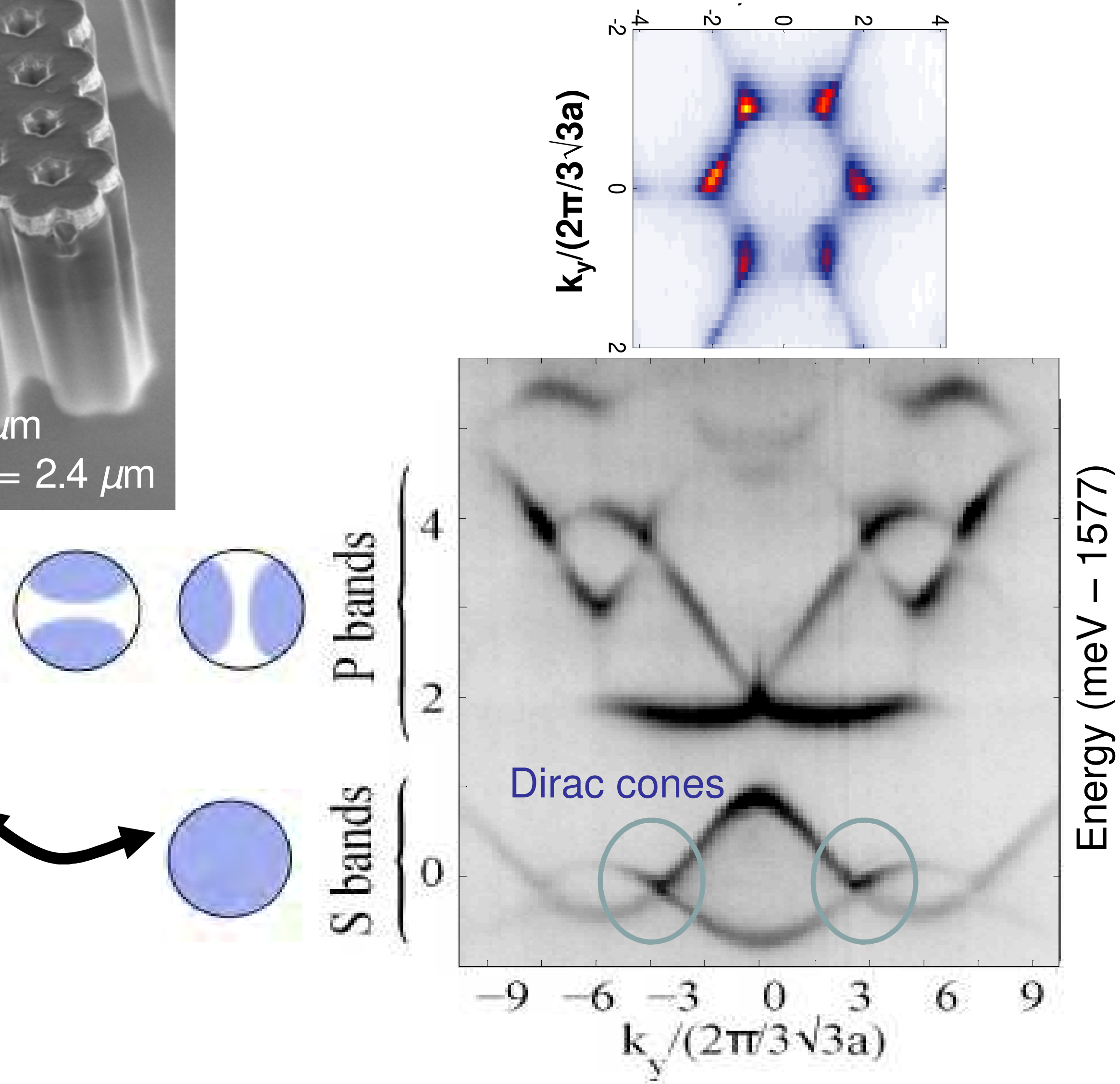
F. Baboux et al. PRL116, 066402 (2016)
See also Stanford, Sheffield, Würzburg

Polariton honeycomb lattice





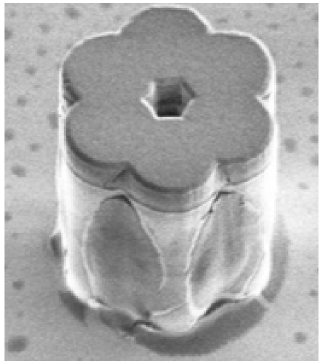
Castro Neto et al., Rev. Mod. Phys. 81 (2009)



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

Polaritonics at C2N

Spin orbit coupling

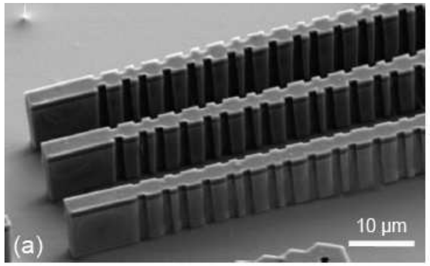


Sala et al.,
Phys. Rev. X 5, 011034 (2015)

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

N. Carlon Zambon et al.,
Opt. Lett. 44, 4531 (2019)

Quasi-periodic 1D lattice

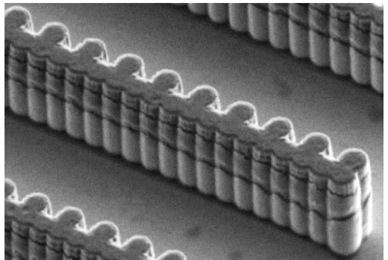


D. Tanese et al.,
PRL 112, 146404 (2014)

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

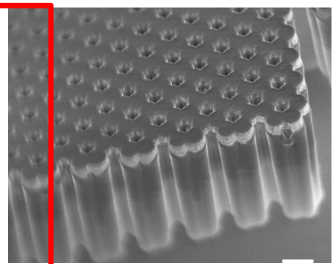
V. Goblot et al., Arxiv1911.07809

Flat band physics



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

V. Goblot et al.
Phys. Rev. Lett. 123, 113901
(2019)

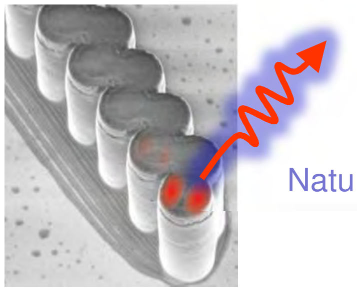


Dirac physics

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., Phys. Rev. X 9, 31010 (2019)

O. Jamadi et al., arXiv:2001.10395
P. St-Jean et al., arXiv:2002.09528

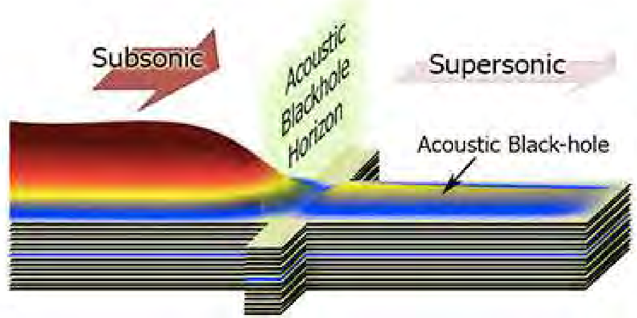
SSH chain and topological lasing



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

Hawking physics

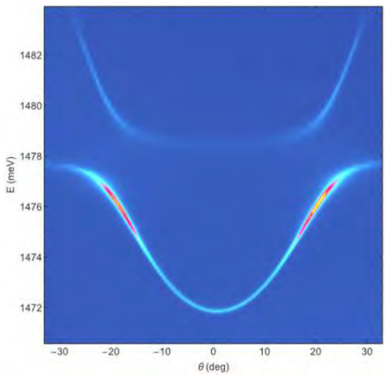
H.S. Nguyen et al.,
PRL. 114, 036402 (2015)

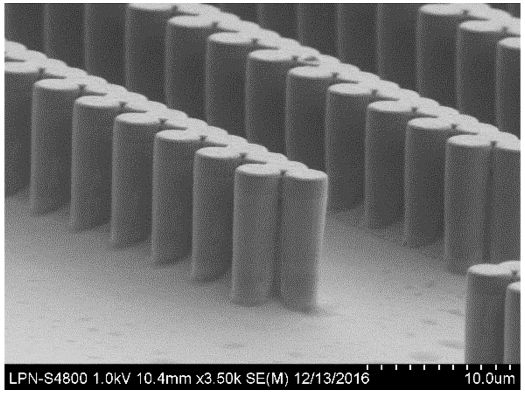


Centre de Nanosciences et de Nanotechnologies

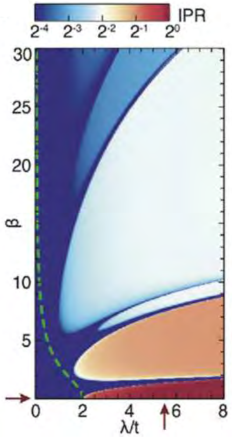
Outline

- Introduction to polariton lattices

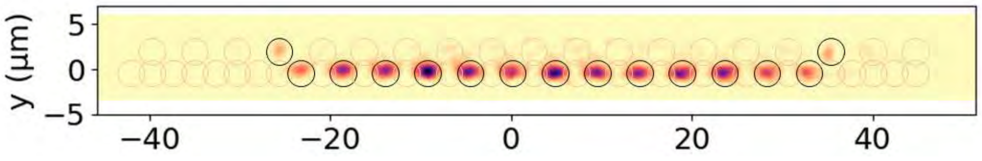




- Emergence of criticality in quasi-crystals



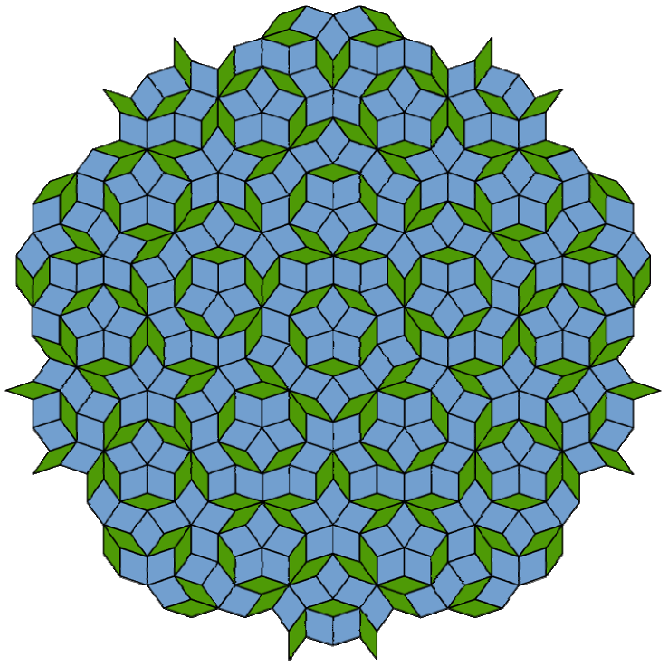
- Discrete gap solitons in a flat band



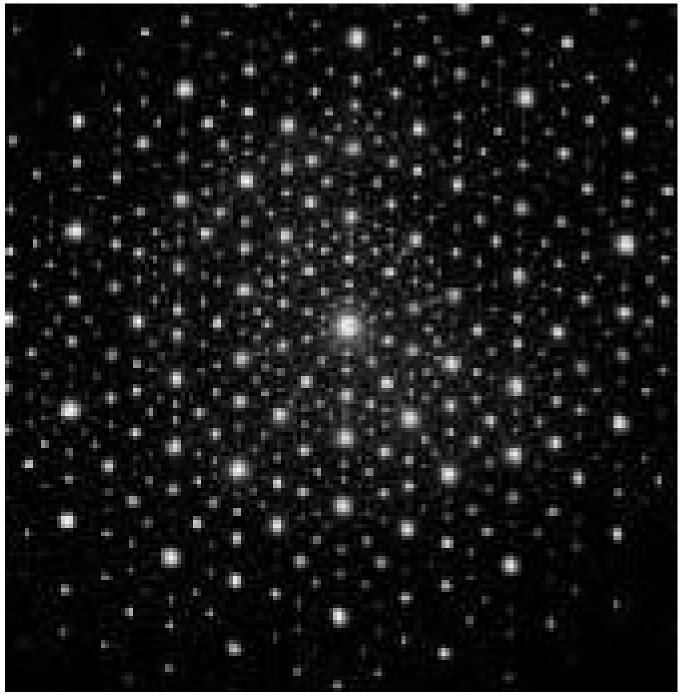
Quasicrystals

- **Quasicrystal:** aperiodic system with long-range order

- Penrose tilings



- Diffraction peaks of AlMn alloys:

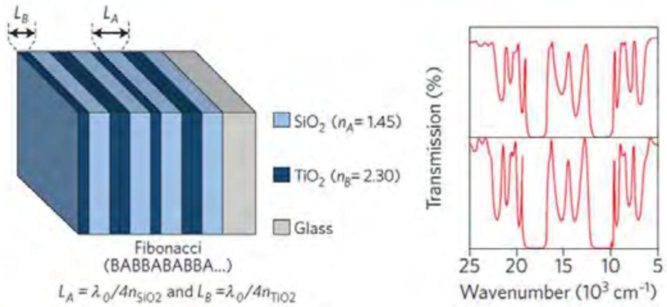


Shechtman *et al.*, PRL, 1984
Levine, Steinhardt, PRL, 1984

(2011)

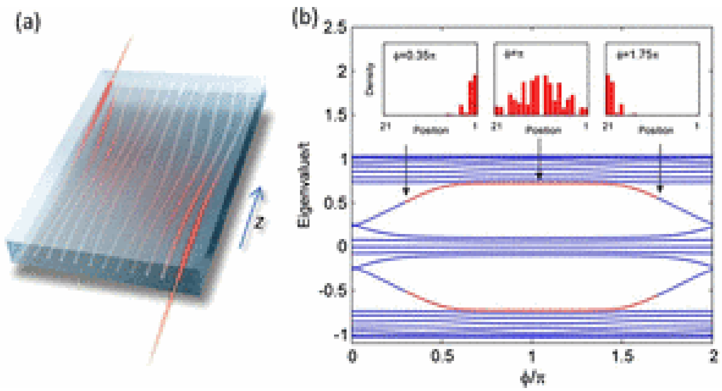
Synthetic Quasicrystals

Multilayer structures



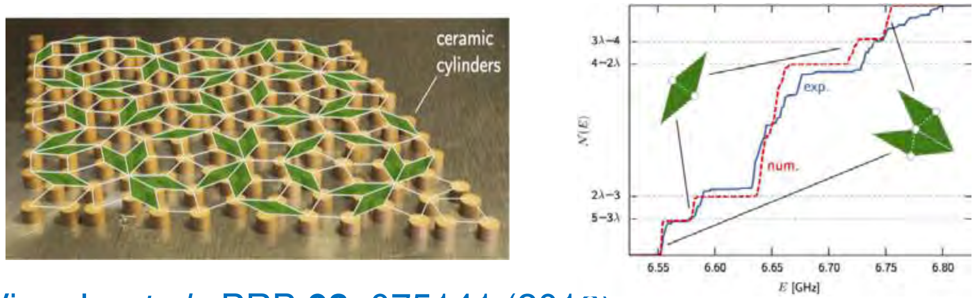
Gellermann *et al.*, PRL **72**, 633 (1994)
Hattori *et al.*, PRB **50**, 4220 (1994)

Coupled waveguides



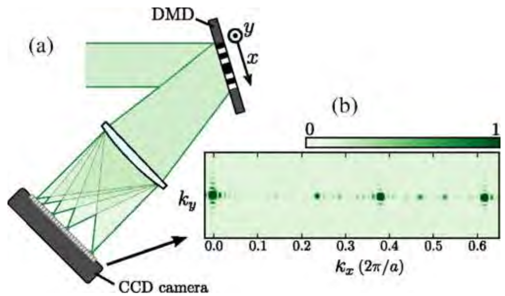
Levi *et al.*, Science **332**, 1541 (2011)
Lahini *et al.*, PRL **103**, 013901 (2012)
Kraus *et al.*, PRL **109**, 106402 (2012)

Microwave resonators



Vignolo *et al.*, PRB **93**, 075141 (2016)

Digital Mirror Device array



Dareau *et al.*, PRL **119**, 215304 (2017)

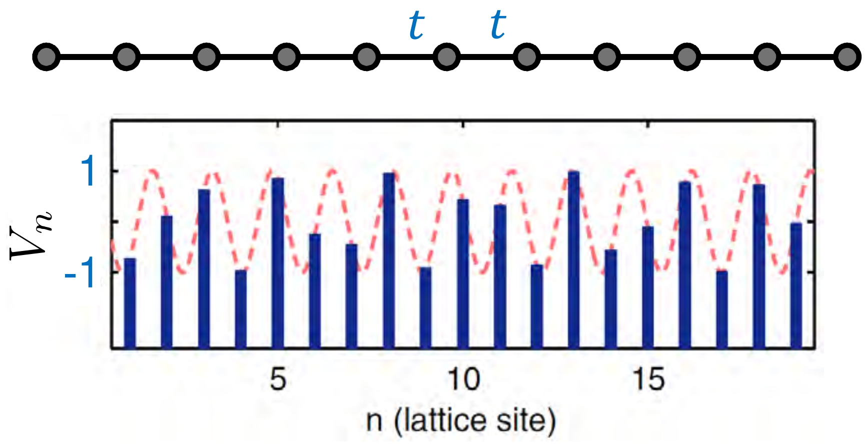
Cold atoms Roati *et al.*, Nature **453**, 895 (2008)

Henrik P. Lüschen et al., Phys. Rev. Lett. 119, 260401 (2017)

Phonons Steurer & Sutter-Widmer, J. of Phys. D: Applied Physics **40**, R229 (2007)

Aubry-André-Harper quasicrystal

- Crystal perturbed by incommensurate on-site potential: $V_n = \lambda cos(2\pi b n)$



Aubry-André-Harper quasicrystal

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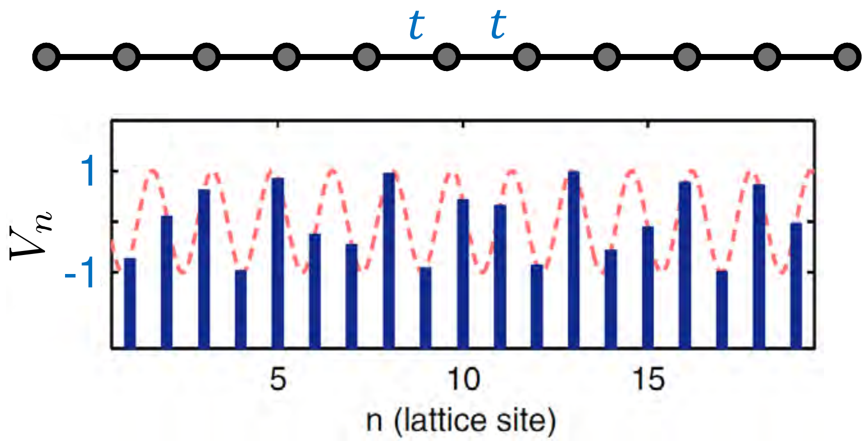
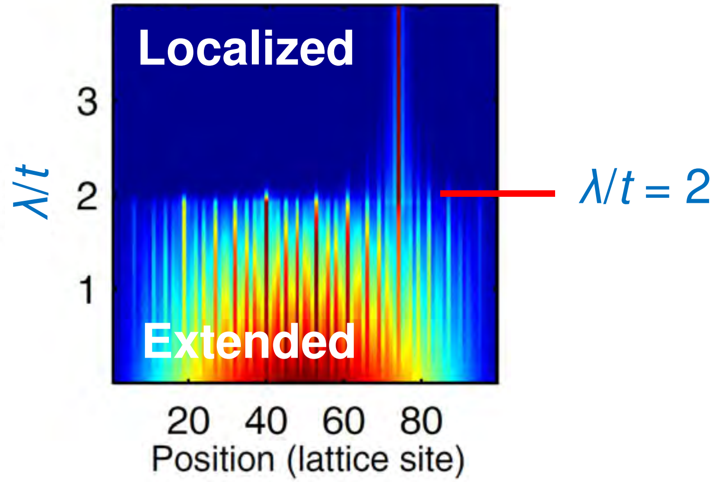


- Localization properties:



Lahini *et al.*, Phys. Rev. Lett. **103**, 013901 (2009)

- Cold atoms in optical lattices: Roati *et al.*, Nature **453**, 895 (2008)
- Also in coupled waveguides arrays: Lahini *et al.*, Phys. Rev. Lett. **103**, 013901 2009)

Fibonacci quasicrystal

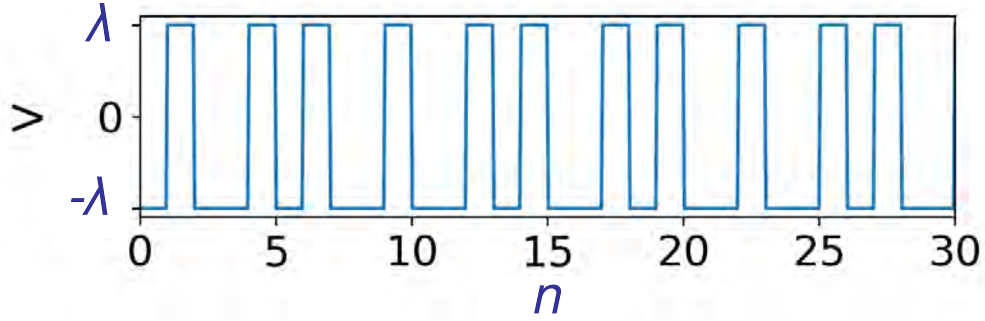
For each site $V_n = \pm\lambda$, according to: $$V_n = \lambda \times sgn[cos(2\pi nb + \phi) - cos(\pi b)]$$

site   phason   2/(1+√5)

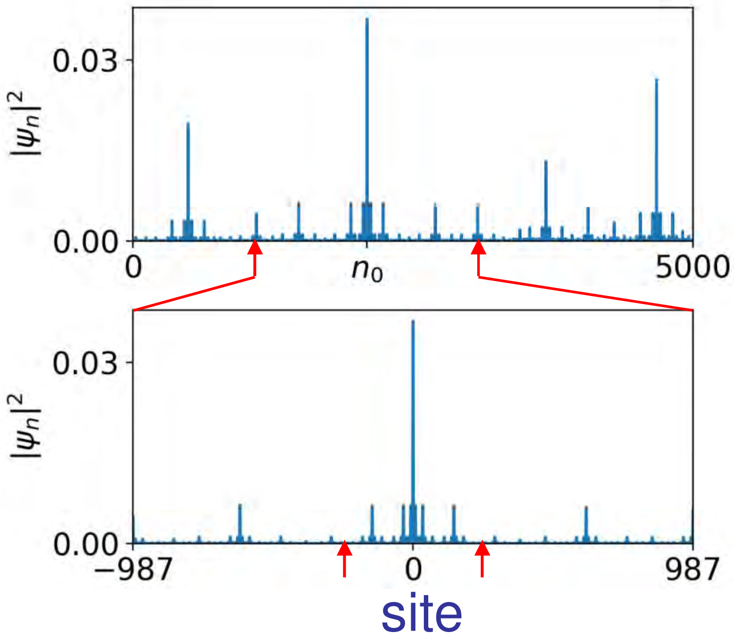
Y. E. Kraus et al., PRL 109, 106402 (2012)

- Fibonacci quasicrystal:

ABAABABAABAABABAABABAABAABABAA



- Localization properties: critical eigenstates



Continuous deformation: IAAF model

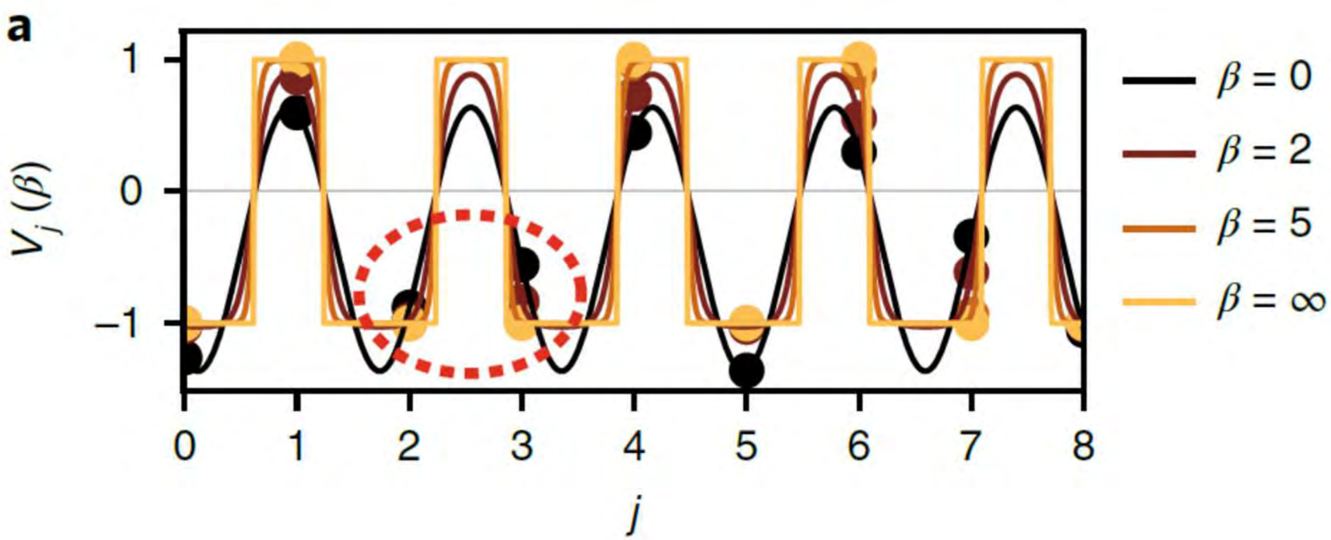
- Interpolating Aubry-André-Fibonacci model:

$$V_n(\lambda, \beta) = -\lambda \frac{\tanh \beta [\cos(2\pi n b + \phi) - \cos(\pi b)]}{\tanh \beta}$$

Modulation frequency: $b = 2/(1+\sqrt{5})$

Kraus, Zilberberg, PRL **109**, 116404 (2012)

O. Zilberberg



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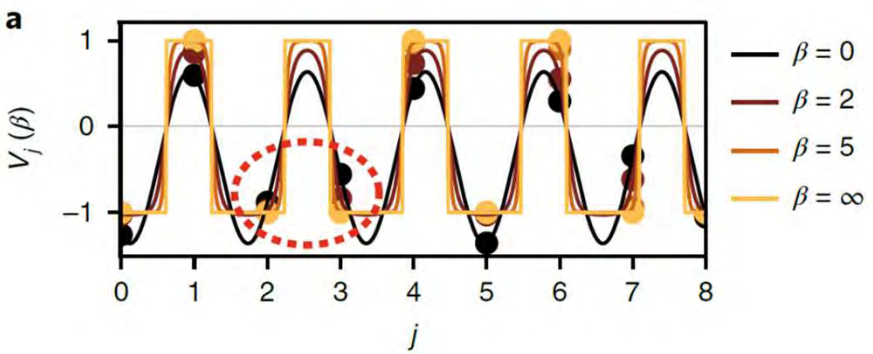
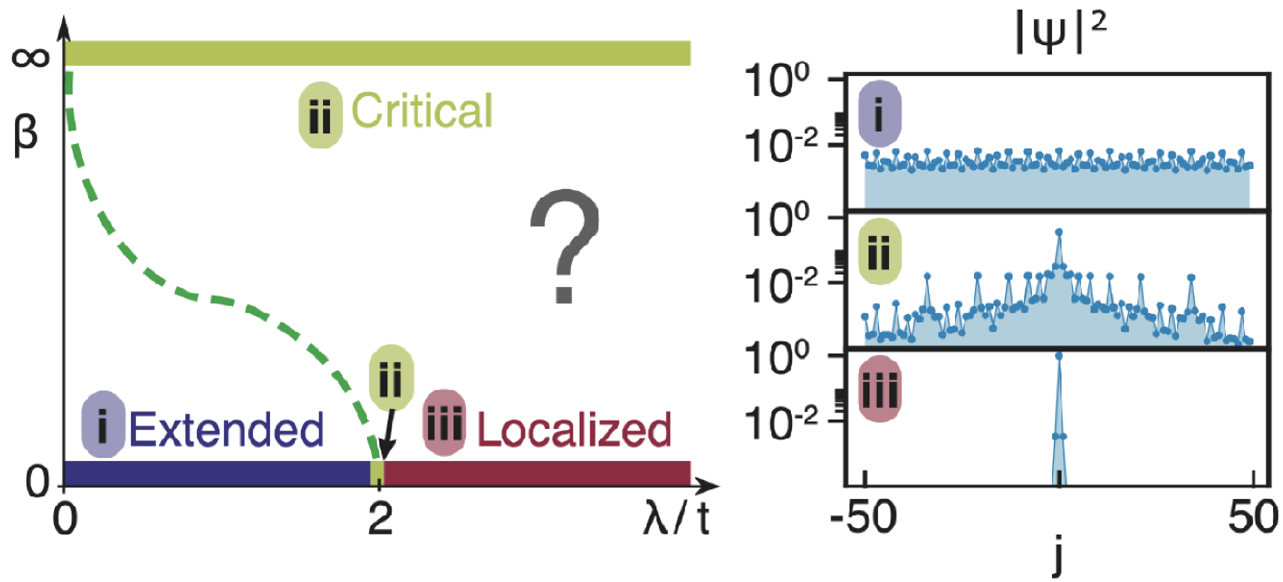
Kraus, Zilberberg, PRL **109**, 116404 (2012)

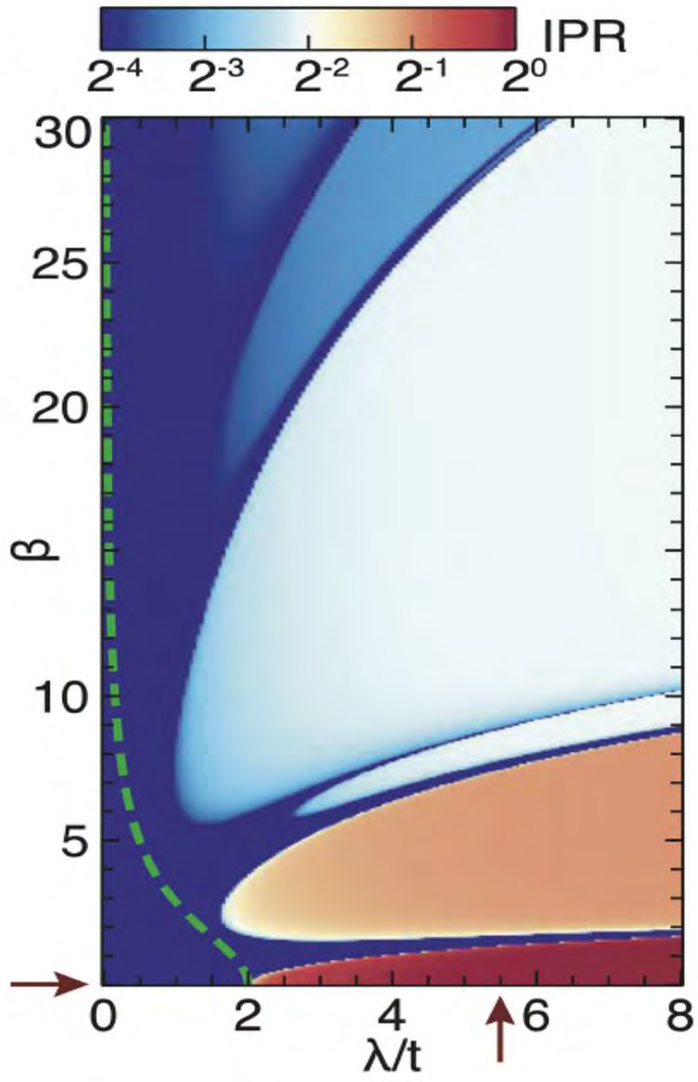


O. Zilberberg



Localization phase diagram: theory

- Tight-binding approach: $\mathcal{H}\psi_n = t(\psi_{n+1} + \psi_{n=1}) + V_n(\lambda, \beta)\psi_n$




A. Štrkalj


O. Zilberberg

- Inverse participation ratio for a state:

$$\mathrm{IPR} = \frac{\sum_{n=1}^{L} |\psi_n|^4}{\sum_{n=1}^{L} |\psi_n|^2}$$

- Extended state:

$$\mathrm{IPR} = 1/L \to 0$$

- State localized on *N* states:

$$\mathrm{IPR} = 1/N$$

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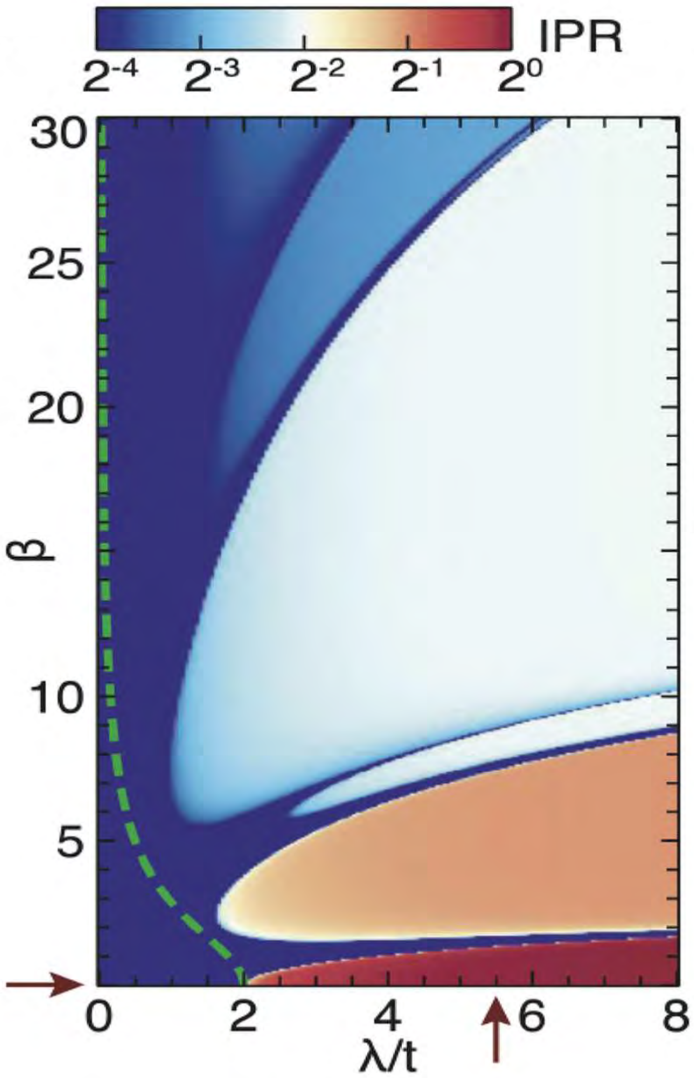
Localization phase diagram: theory

- Tight-binding approach: $\mathcal{H}\psi_n = t(\psi_{n+1} + \psi_{n=1}) + V_n(\lambda, \beta)\psi_n$



A. Štrkalj

O. Zilberberg

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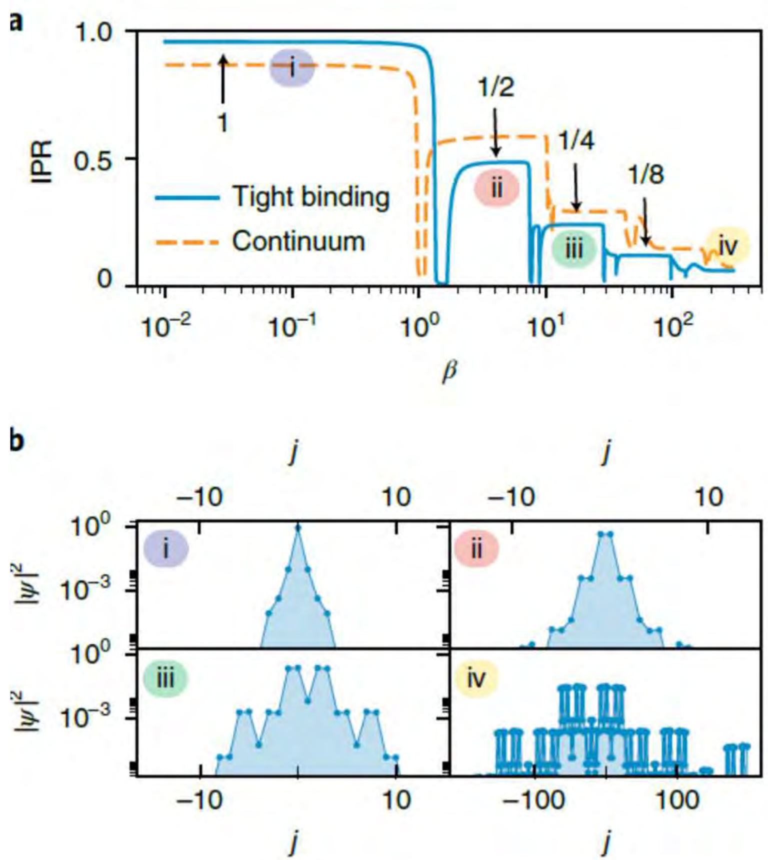
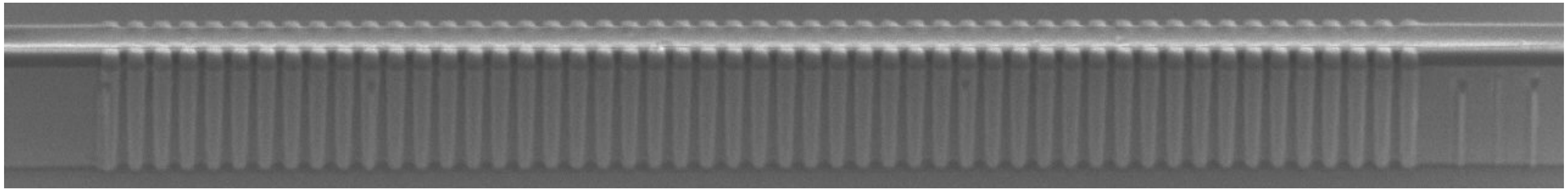


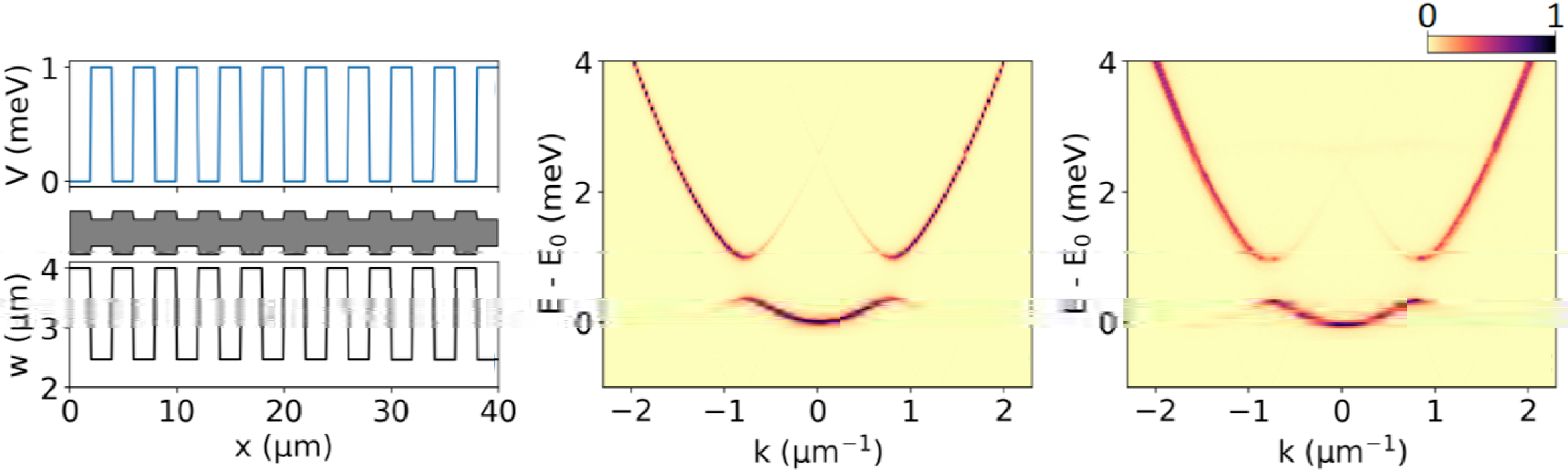
Polaritons in a 1D periodic potential



$$\boxed{E\psi(x) = -\frac{\hbar^2}{2m}\frac{\partial\psi(x)}{\partial x} + V(x)\psi(x)}$$

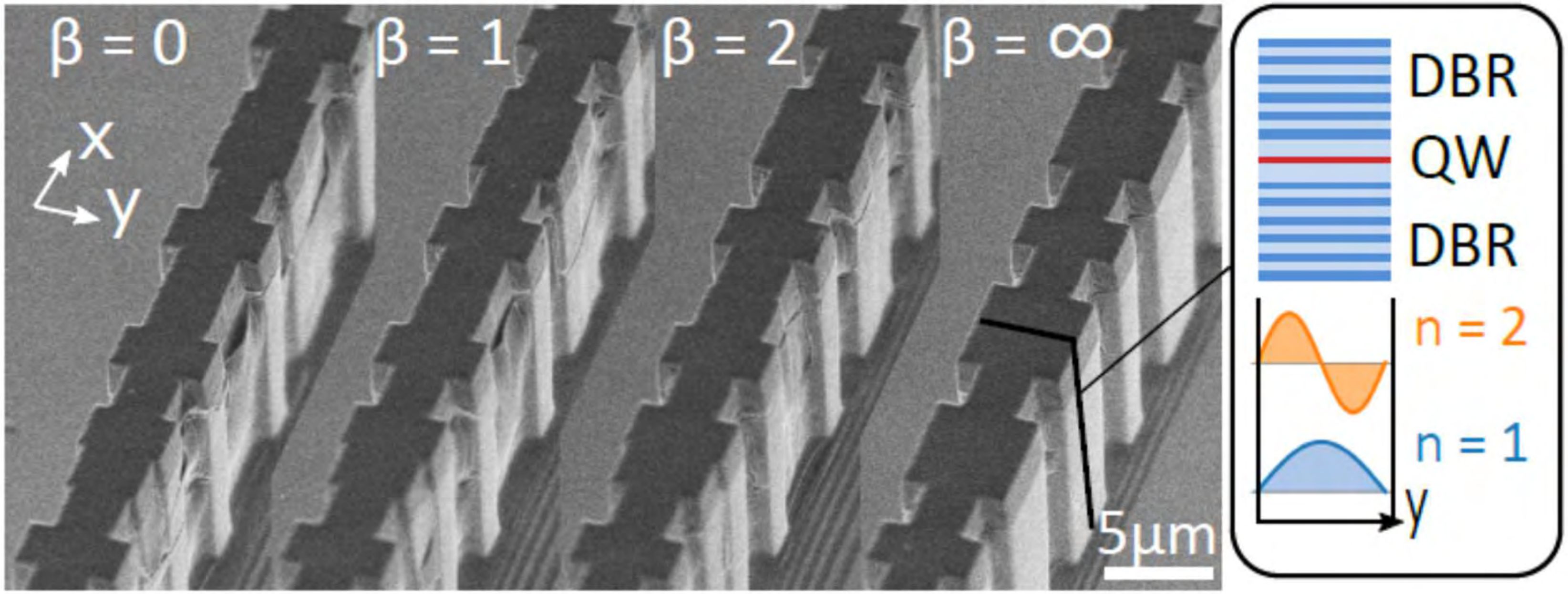
$$V(x) = \frac{\hbar^2}{2m}\frac{n^2\pi^2}{w(x)^2}$$

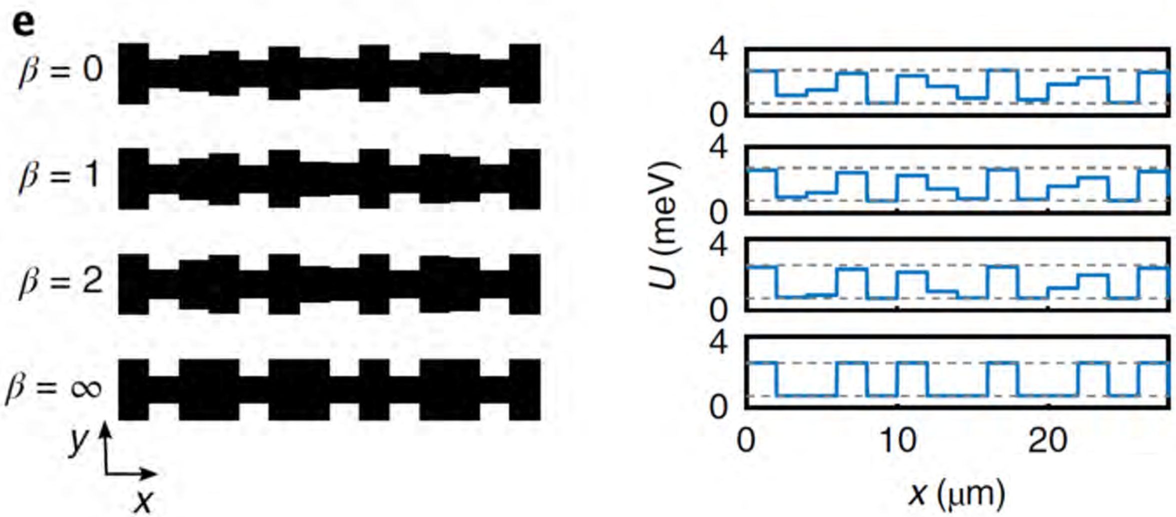
Theory Experiment



D. Tanese et al., Nature Com. **4**, 1749 (2013)

Polaritons Interpolating AA-Fibo structures





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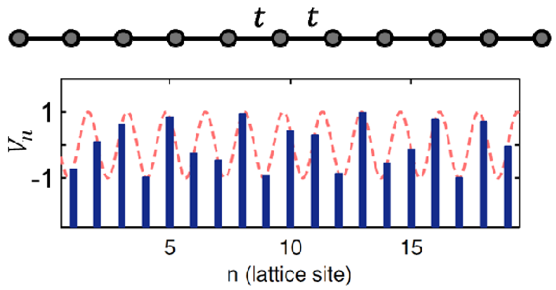
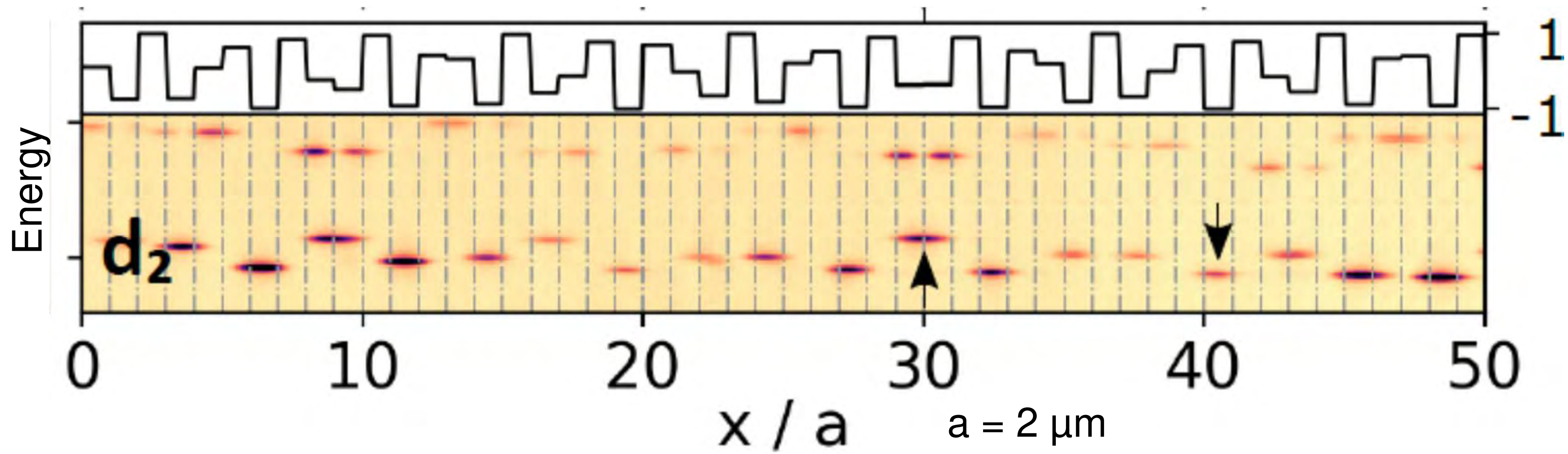
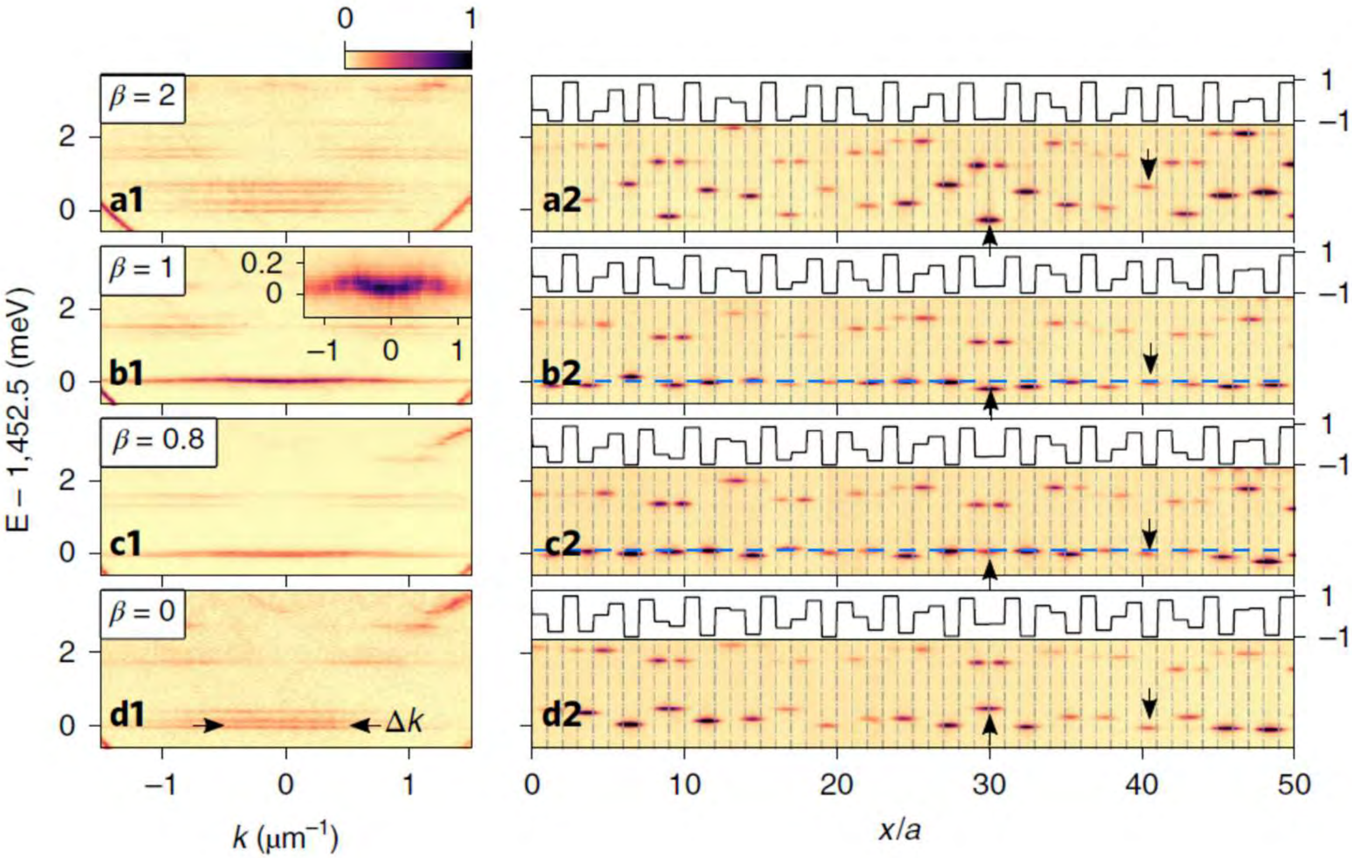
Aubry André (Harper) quasi-periodic potential

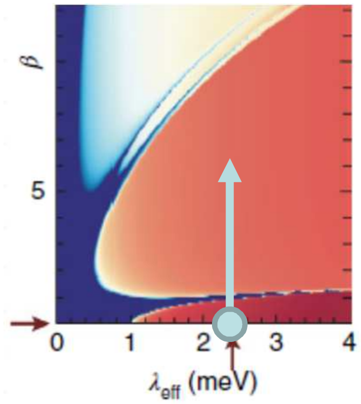
On-site potential incommensurate
with the lattice period





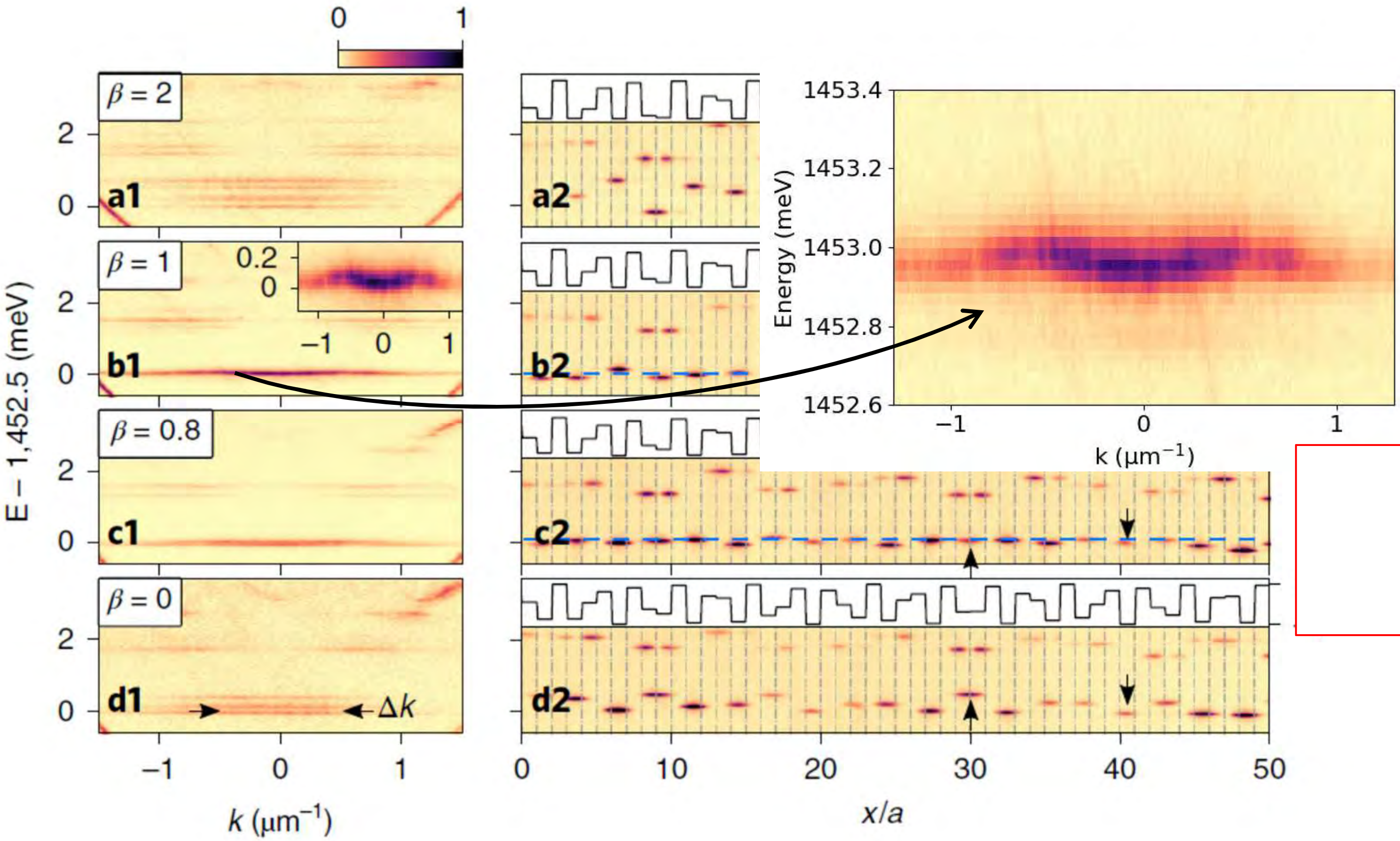
Localization in interpolating AAFibo structures

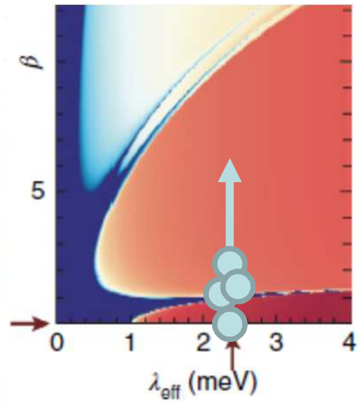




V. Goblot et al., Arxiv1911.07809

Localization in interpolating AAFibo structures





Band curvature
=
Extended states

V. Goblot et al., Arxiv1911.07809

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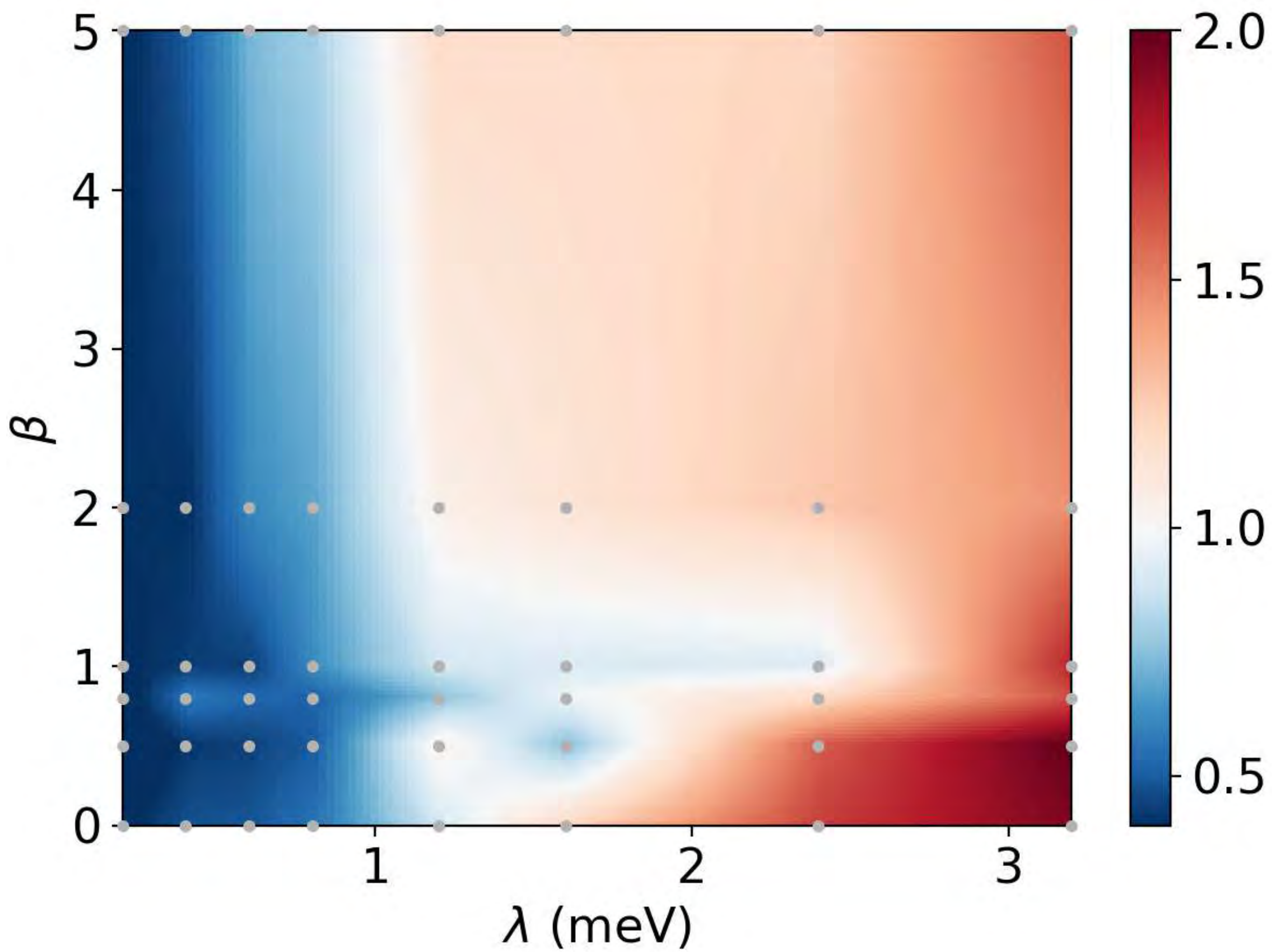
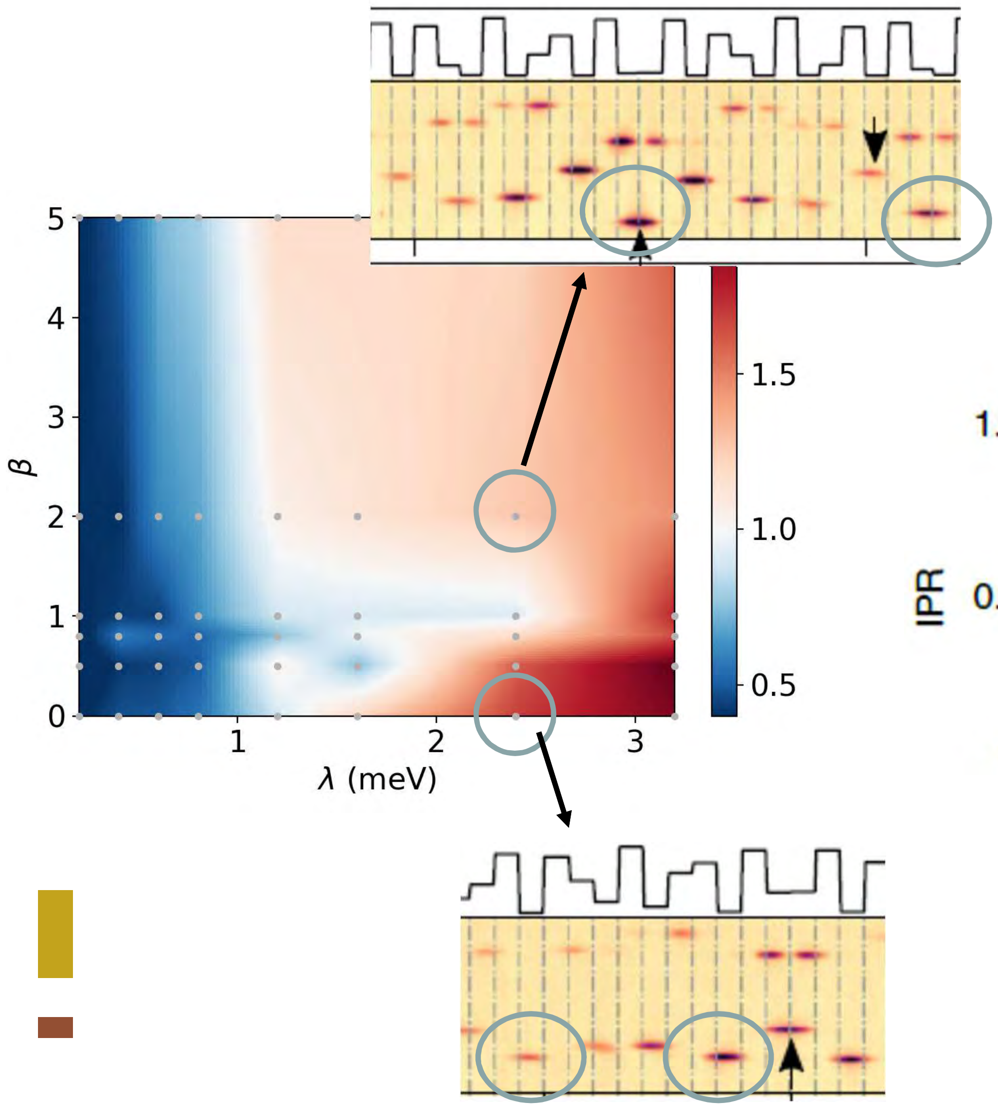
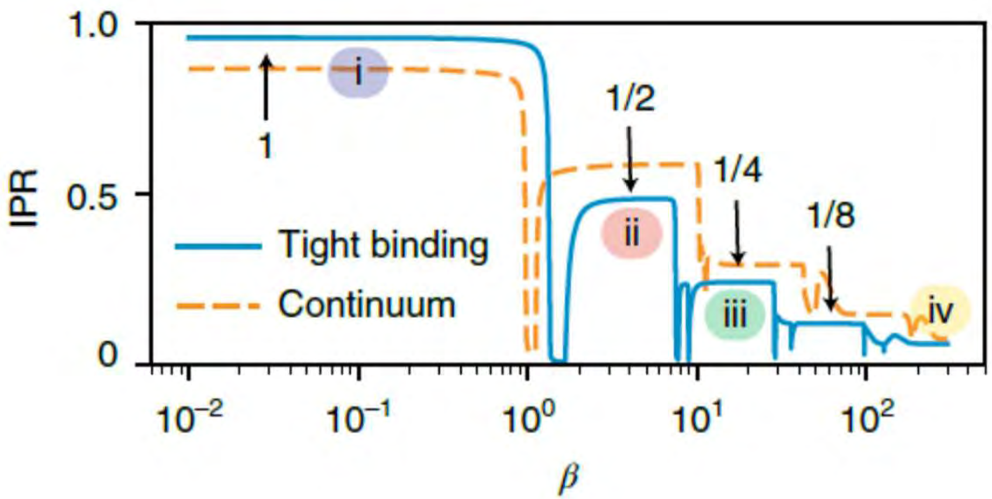
Experimental localization phase diagram



V. Goblot et al., Arxiv1911.07809

Experimental localization phase diagram

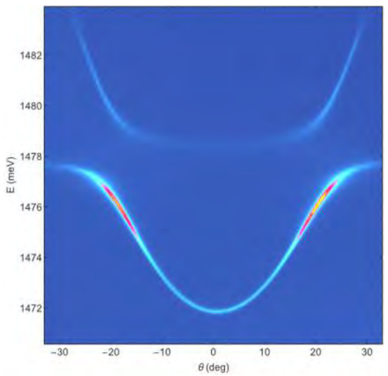


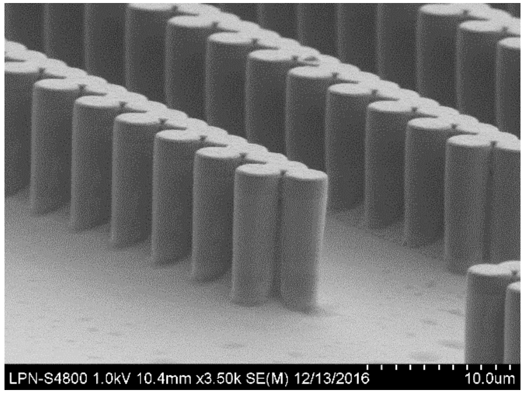


V. Goblot et al., Arxiv1911.07809

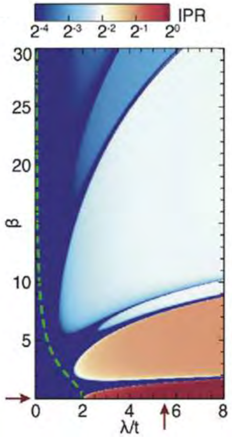
Outline

- Introduction to polariton lattices

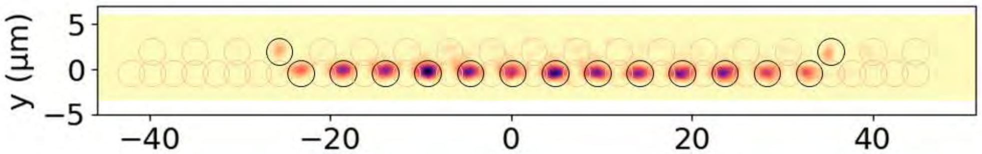




- Emergence of criticality in quasi-crystals



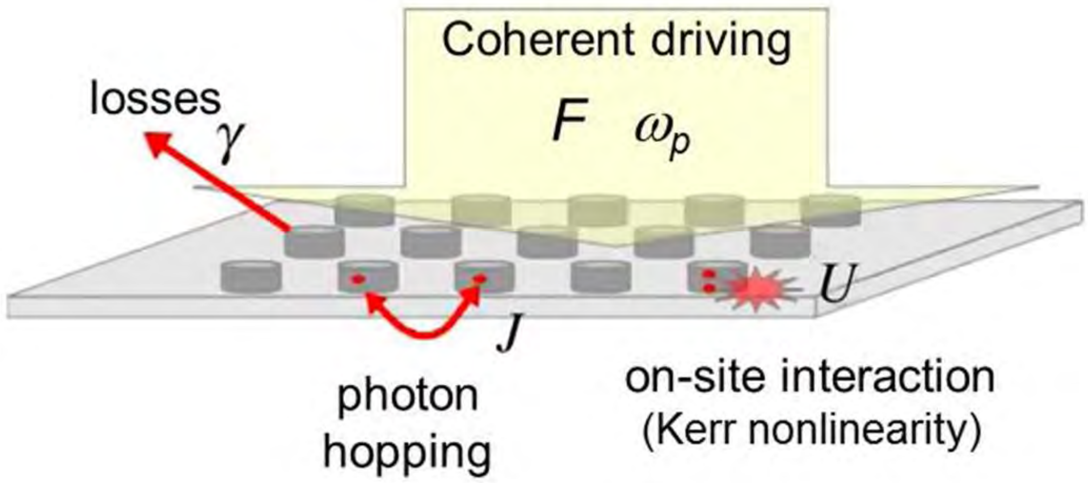
- Discrete gap solitons in a flat band



What about interactions? Non-linear physics?

Weak on-site interaction :

$$\frac{U}{\gamma} \ll 1$$

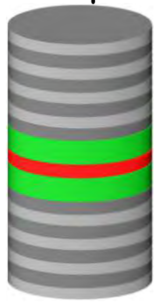


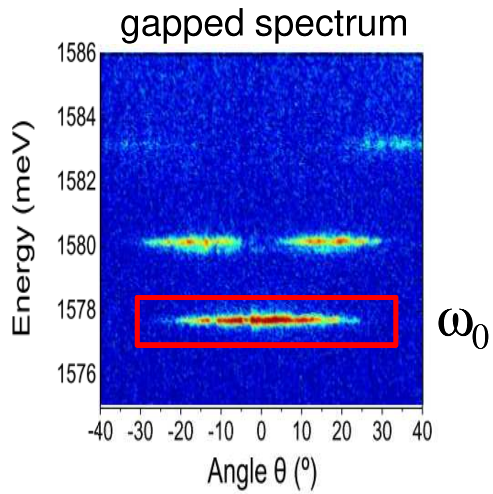
Mean field approximation :

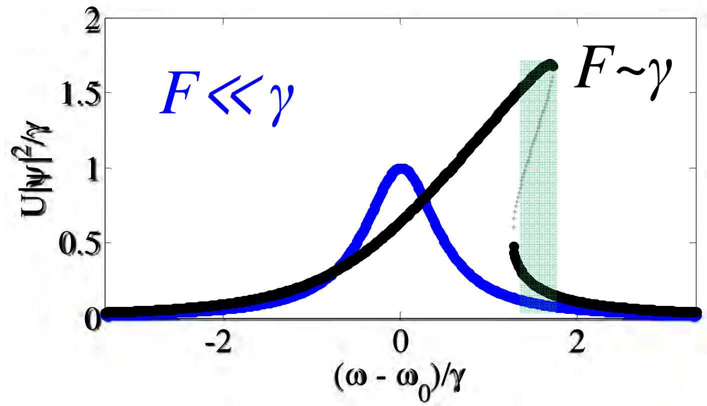
$$i\hbar \frac{\partial \Psi}{\partial t} = \left[-\frac{\hbar^2}{2m} \nabla^2 + V(x) + U|\psi|^2 - i\frac{\gamma}{2} \right] \psi + iF(x) e^{-i(\omega t - k_p x)}$$

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

Nonlinear micropillar







Optical bistabiilty

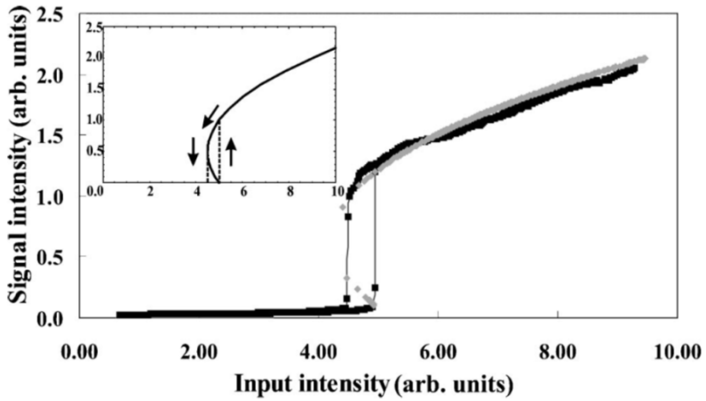
H.M. Gibbs et al., PRL 36, 1135 (1976)

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

Interaction energy

Decay

cw pumping



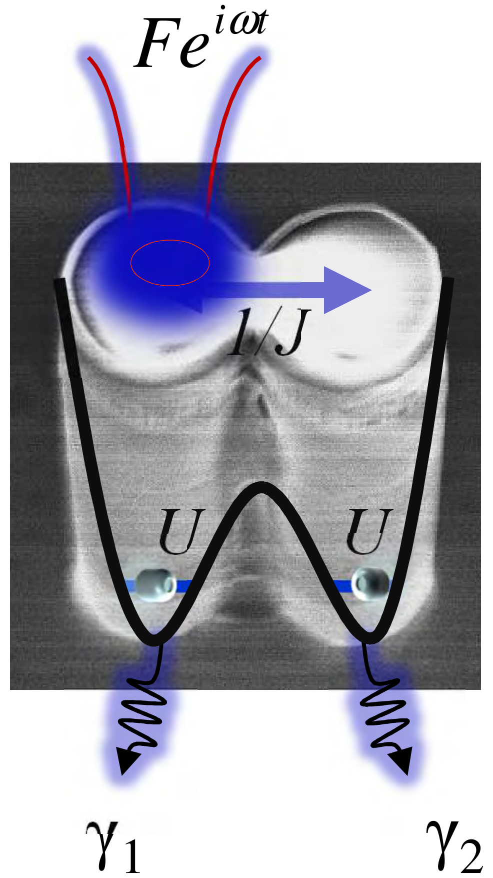
- Repulsive interactions lead to resonance blue-shift

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

Nonlinear dimer

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

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



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

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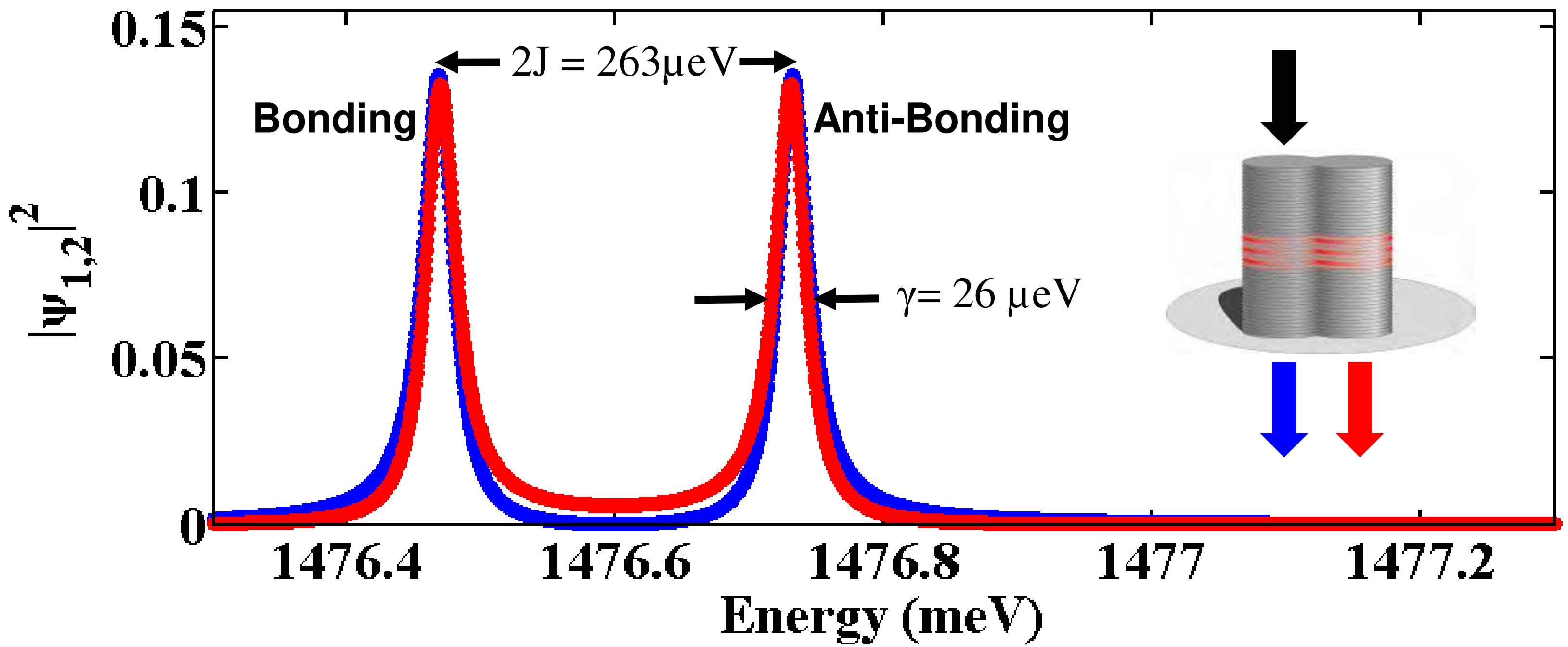
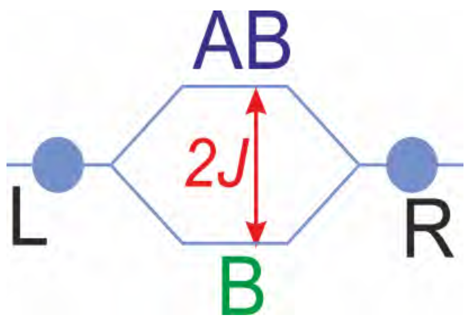
Transmission of the dimer

Weak driving: $F \ll \gamma_T$

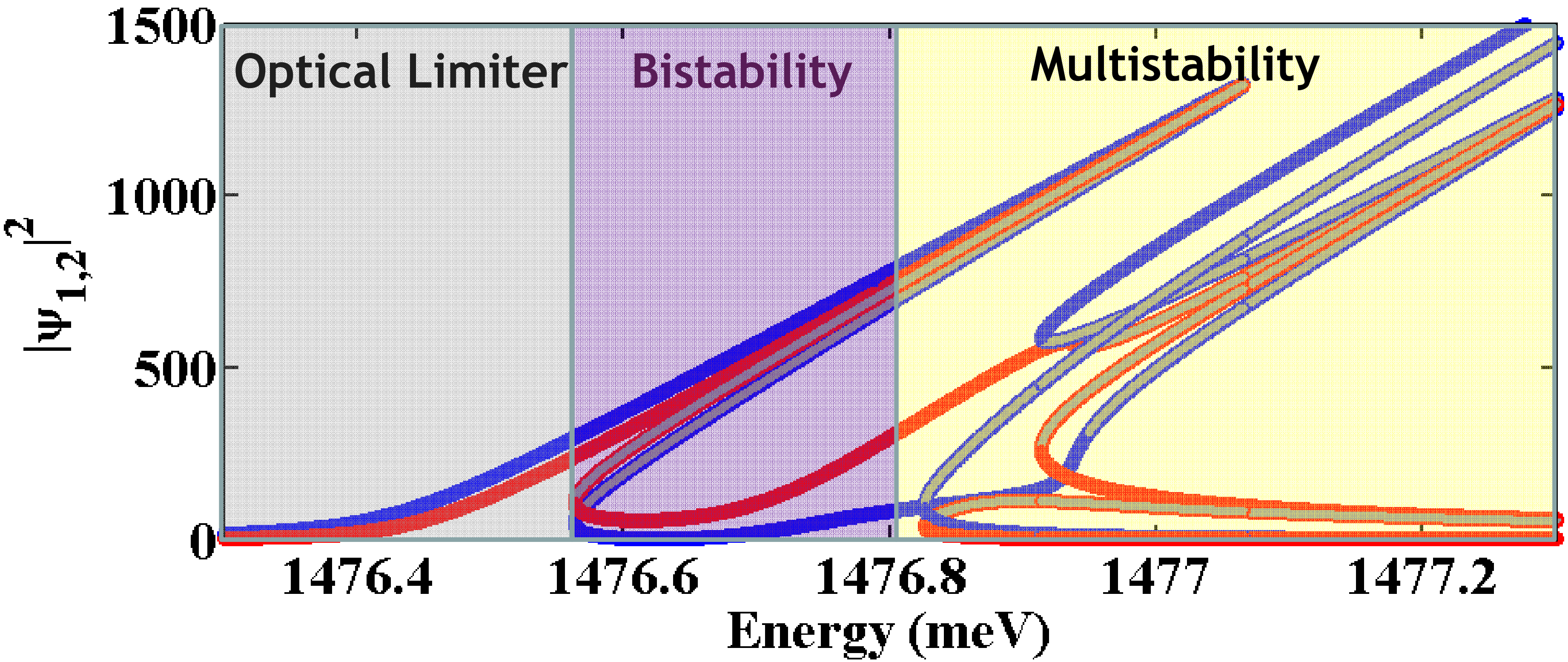
- driven (Ψ_1)
- undriven (Ψ_2)



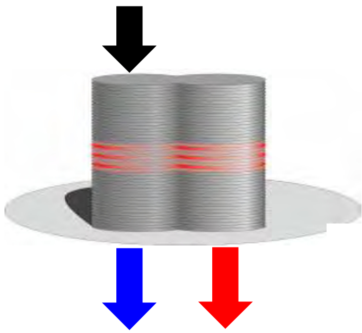


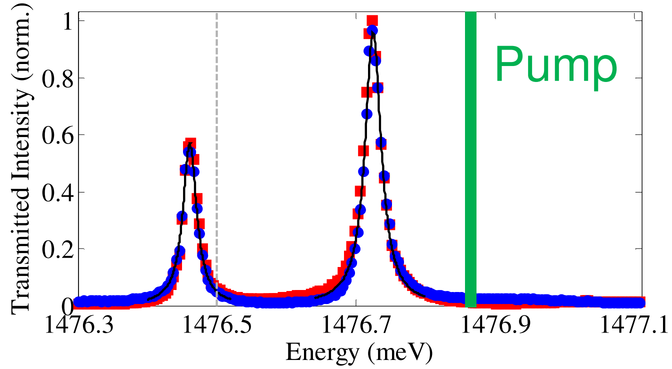
Phase diagram at strong driving

Very Strong driving: $UN_T \gg \gamma_T$, J



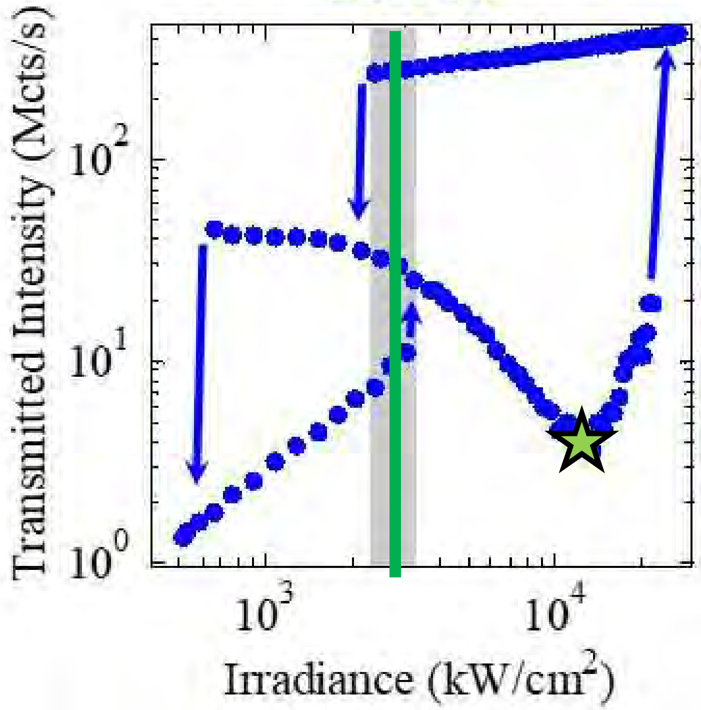
Observation of tristability





Undriven

Driven

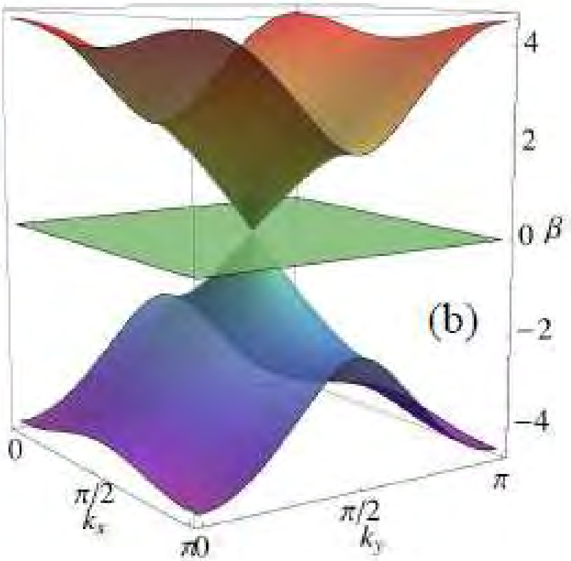


Interaction induced destructive interference

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

Non-linearity in a flat band

2D Lieb lattice



Polaritons
Naoyuki Masumoto et al., NJP 14 065002 (2012)
S. Klembt et al., Appl. Phys. Lett. 111, 231102 (2017)
C. E. Whittaker et al., Phys. Rev. Lett. 120, 97401 (2018)

Coupled lasers:
M. Nixon et al., Phys. Rev. Lett. **110**, 184102 (2013).

Coupled waveguides
D. Guzman-Silva et al., New. J. Phys. 16, 063061 (2014)
Rodrigo A. Vicencioet al., PRL 114, 245503 (2015)
S. Mukherjee et al., PRL 114, 245504 (2015)

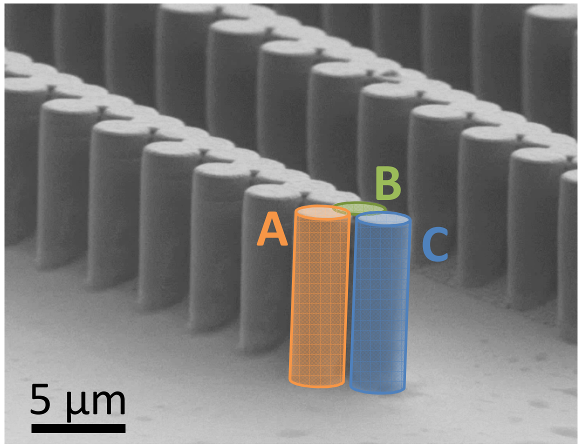
Cold atoms
Shintaro Taie et al., Sci. Adv. 1, e1500854 (2015)

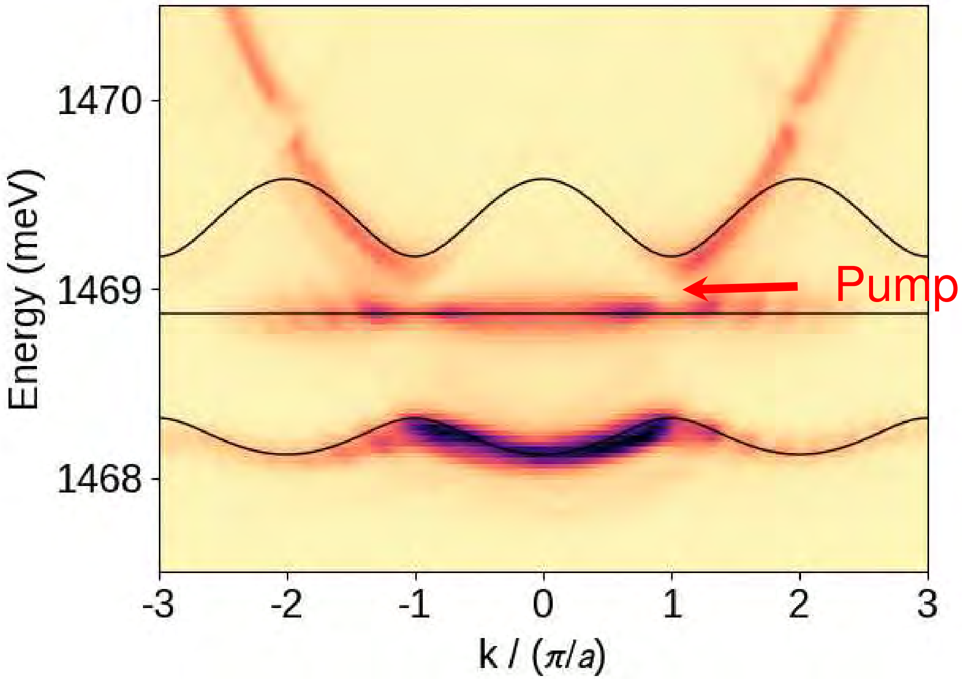
$$i\hbar\frac{\partial\Psi}{\partial t} = \left[\cancel{-\frac{\hbar^2}{2m}\nabla^2} + V(x) + U|\psi|^2 - i\frac{\gamma}{2}\right]\psi + iF(x)e^{-i(\omega t - k_p x)}$$

No kinetic energy => strong effect of disorder, of interactions

Non-linearity in a flat band

Excitation in the gap: laser detuning = interaction energy



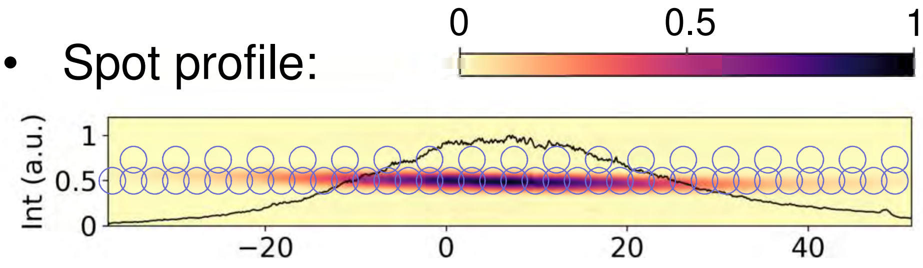


V. Goblot et al, Phys. Rev. Lett. 123, 113901 (2019)

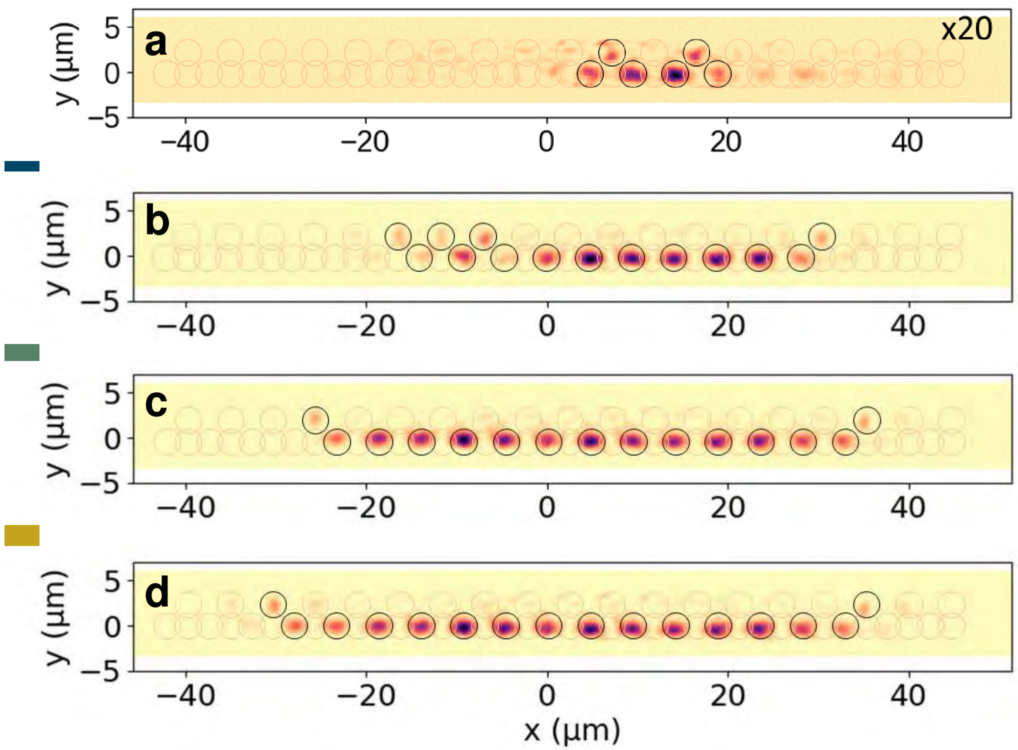
CNRS C2N Centre de Nanosciences et de Nanotechnologies

Non-linearity in a flat band

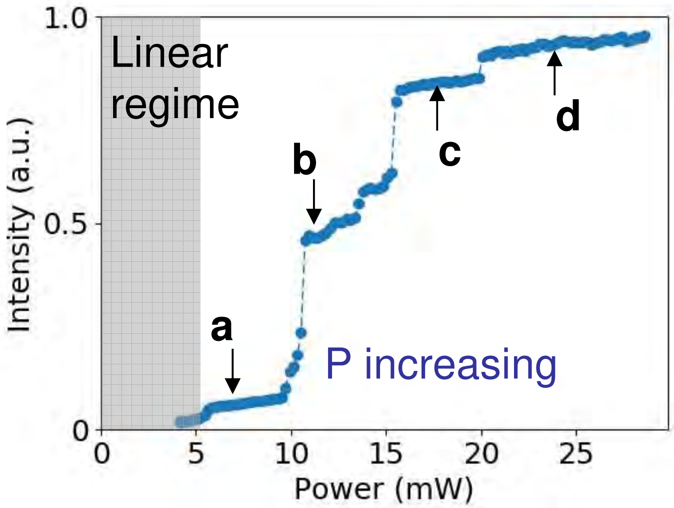
- Spot profile:



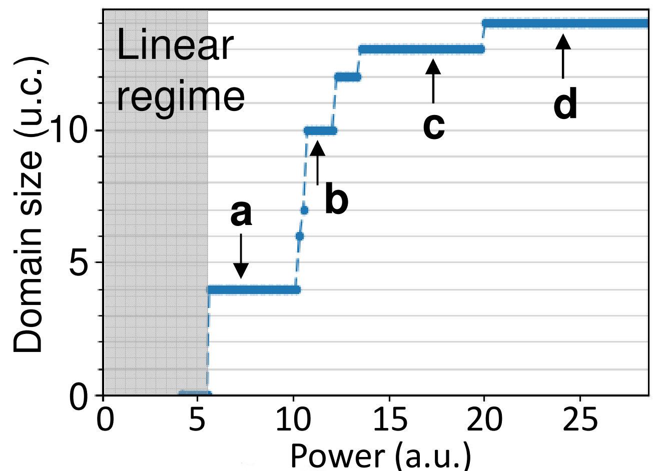
- Formation of nonlinear domains:



- Total intensity in the chain:



- Domain size:



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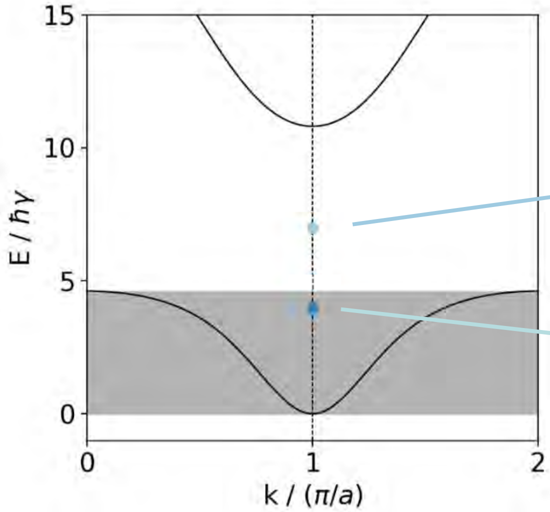
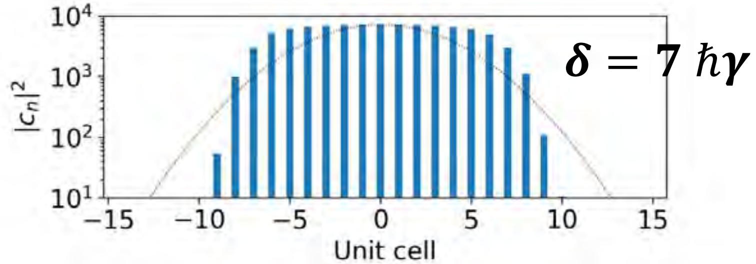
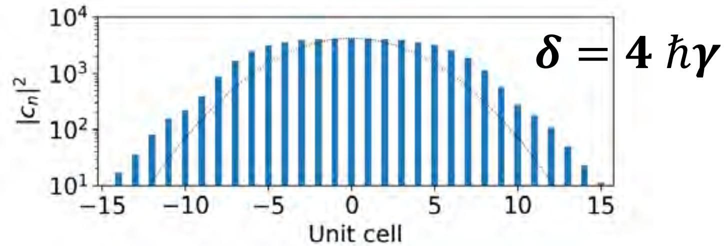
Excitation of gap solitons

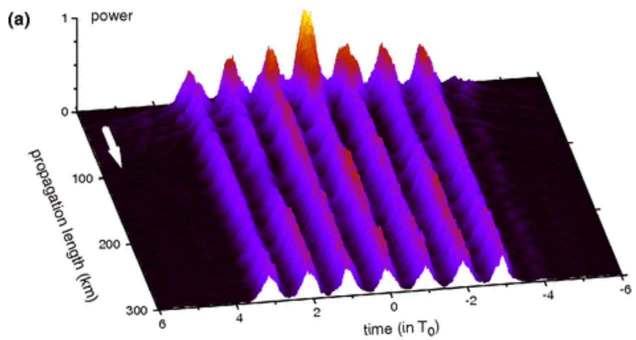
- Discretized GPE equation: $i\hbar\frac{\partial \psi_n}{\partial t} = \left[E_n + \hbar g|\psi_n|^2 - i\frac{\hbar\gamma}{2}\right]\psi_n - \sum_m t_{nm}\psi_m + iF_n e^{-i(\omega t - k_p x_n)}$







- Truncated Bloch Waves in conservative systems:



C. Bersch *et al.*, Phys. Rev. Lett. 109, 093903 (2012)
Th. Anker *et al.*, Phys. Rev. Lett. 94, 020403 (2005)
F. Bennet *et al.*, Phys. Rev. Lett. 106, 093901 (2011)

Here driven dissipative context

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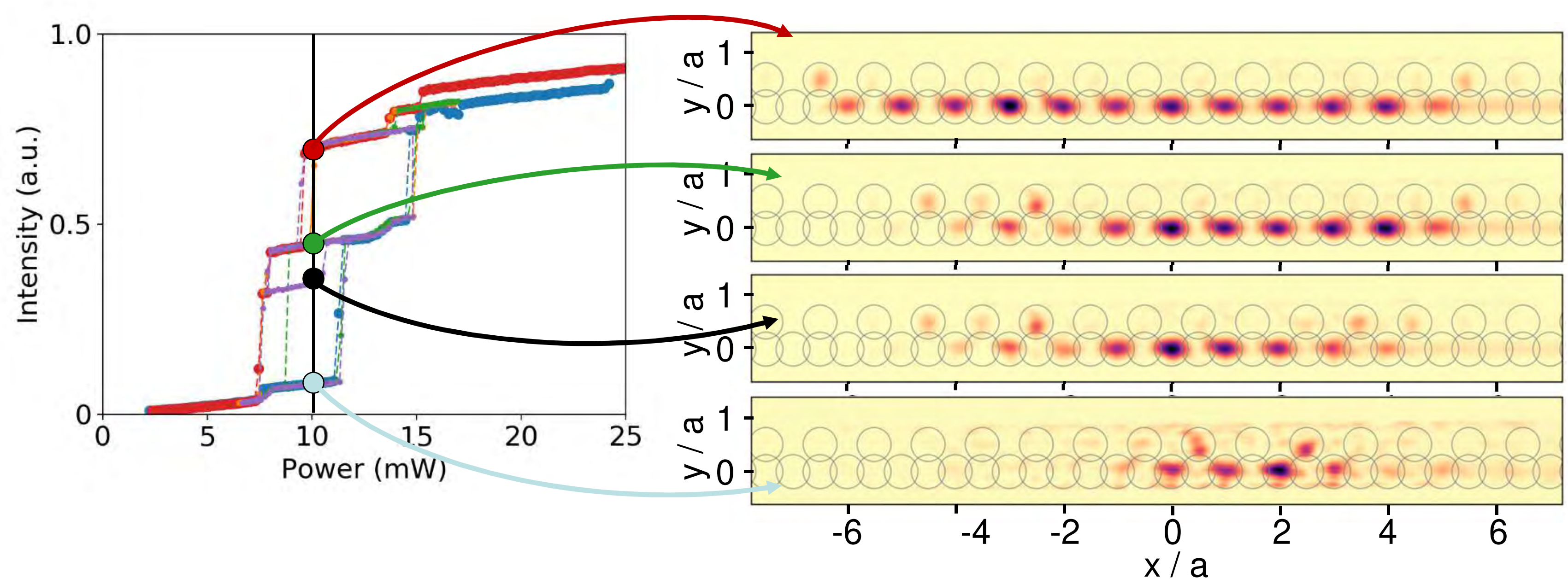
Multistability of the domains



High degeneracy (no kinetic energy) => Complex multistability

Dynamical hysteresis? Chaotic instability?

V. Goblot et al, Phys. Rev. Lett. 123, 113901 (2019)

Summary

- **Emulation of Hamiltonians with lattices of coupled cavities**

- **Potential for Applications**

Important developments for room temperature operation of polariton devices
ZnO, 2D materials, Perovskite……

- What about going beyond mean field? Blockade regime

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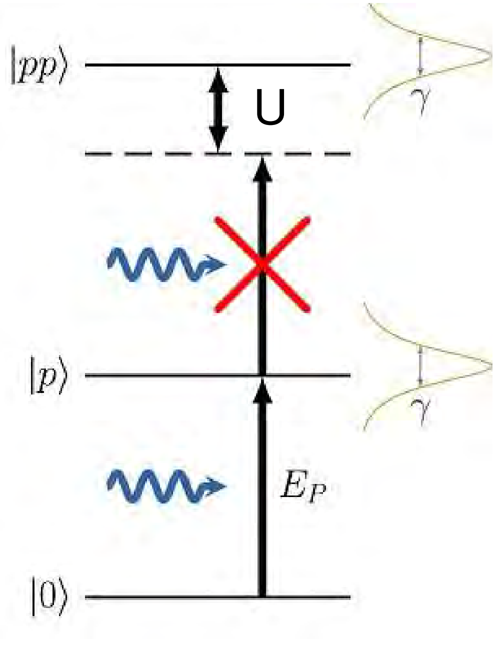
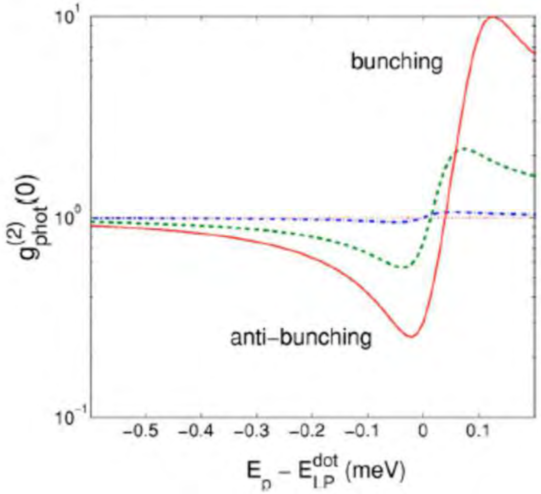
How far from quantum regime ? Quantum correlations?



Photon blockade if : $\dfrac{U}{\gamma} > 1$

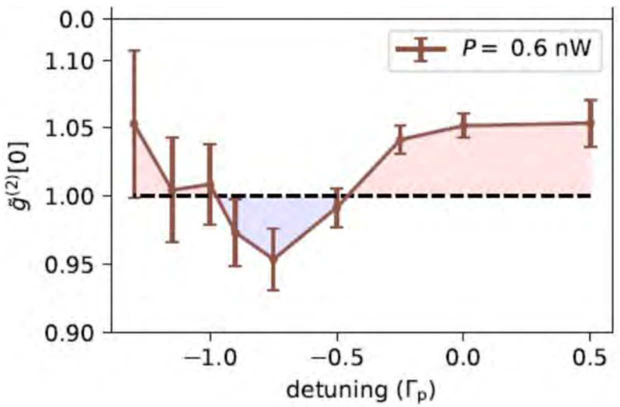


A. Verger et al.,
Phys. Rev. B 73, 193306 (2006)

See J. Simon's group:
Nature Physics 14, 550, (2018)

Presently in the best samples : $\dfrac{U}{\gamma} < 0.1$

First evidence for « weak » polariton antibunching:



G. Muñoz-Matutano et al, Nature Materials 18, 213 (2019)
A. Delteil et al., Nature Materials 18, 219 (2019)

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)
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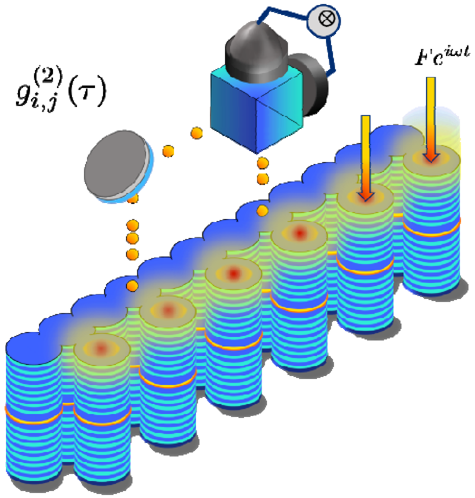
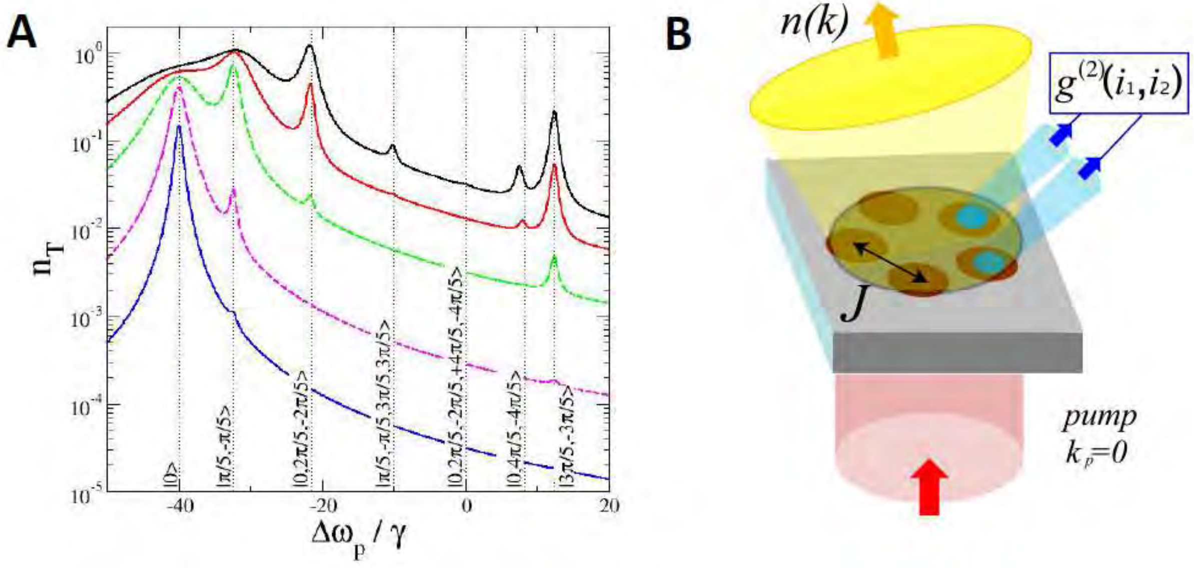
Bose-Hubbard

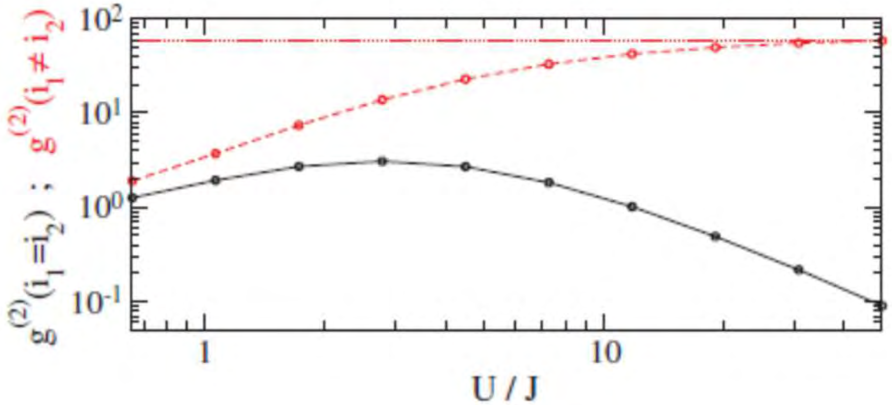
$$\hat{H} = -J \sum_{\langle m,n \rangle} \hat{a}_m^\dagger \hat{a}_n + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$



Strongly correlated photon phases within reach!!!

Generation of multi-photon correlated states





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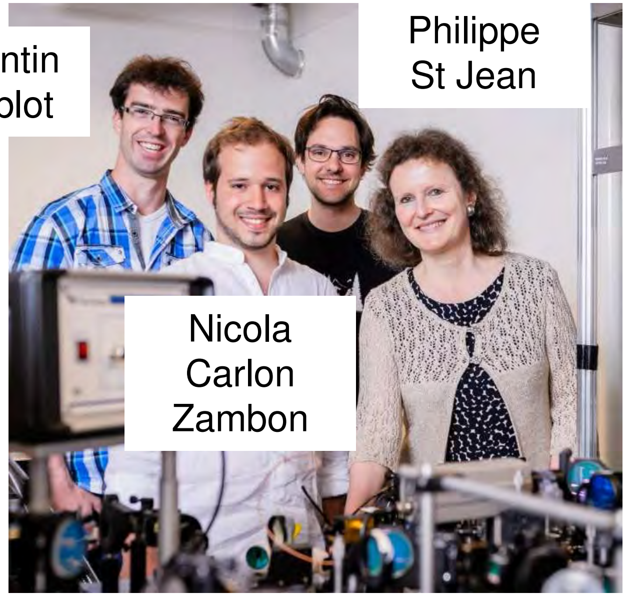

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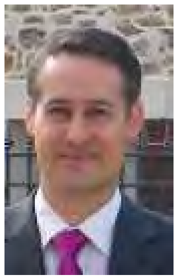

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