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erc

Exciton-polaritons in 2D Lieb lattice with spin-orbit coupling

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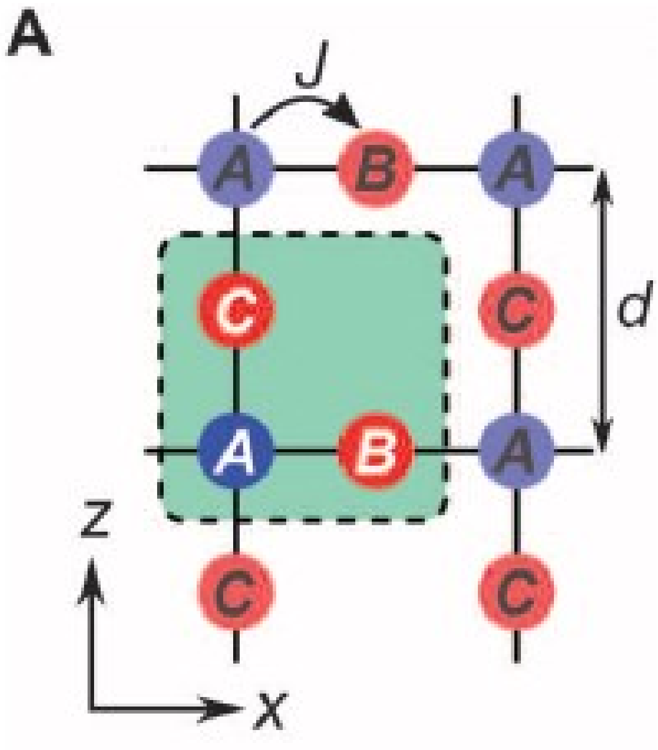
The University of Sheffield

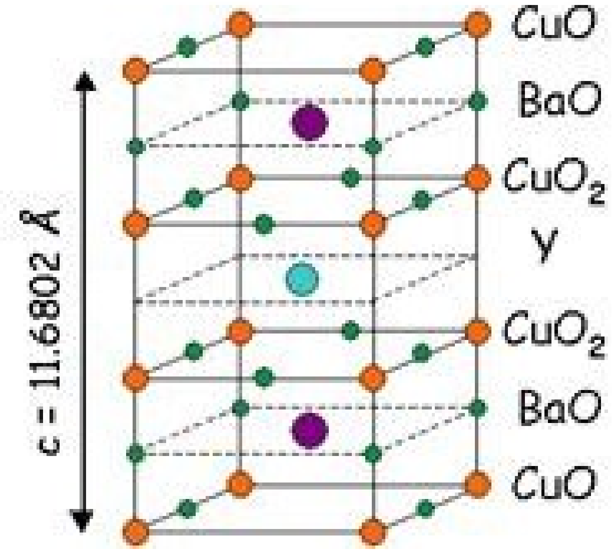
Outline

- Intoduction to Lieb lattices. Importance of flat bands
- Methods of polariton confinement. Photonic spin-orbit coupling
- Polariton 2D Lieb lattice
- Real space patterns with polarisation textures of S and P type flat band condensates
- Condensate fragmentation and effects of interactions
- Conclusions

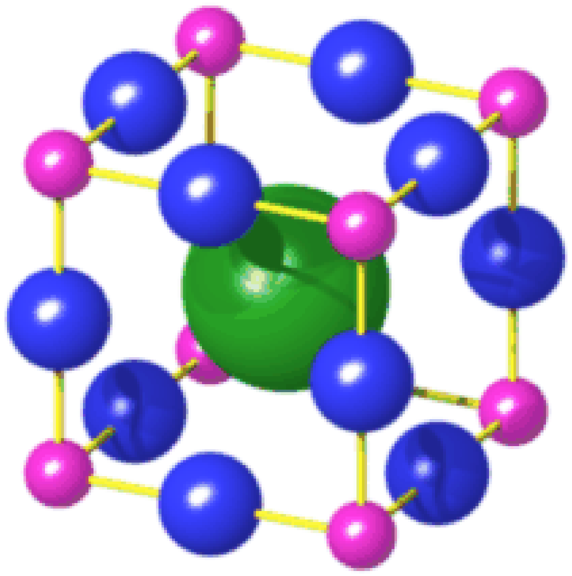
2D Lieb lattice



$YBa_2Cu_3O_7$



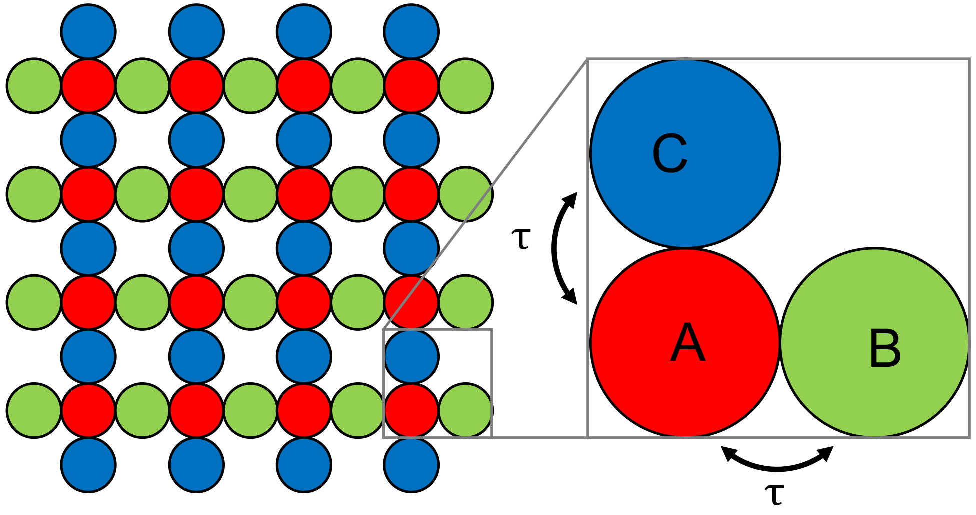
$SrTiO_3$

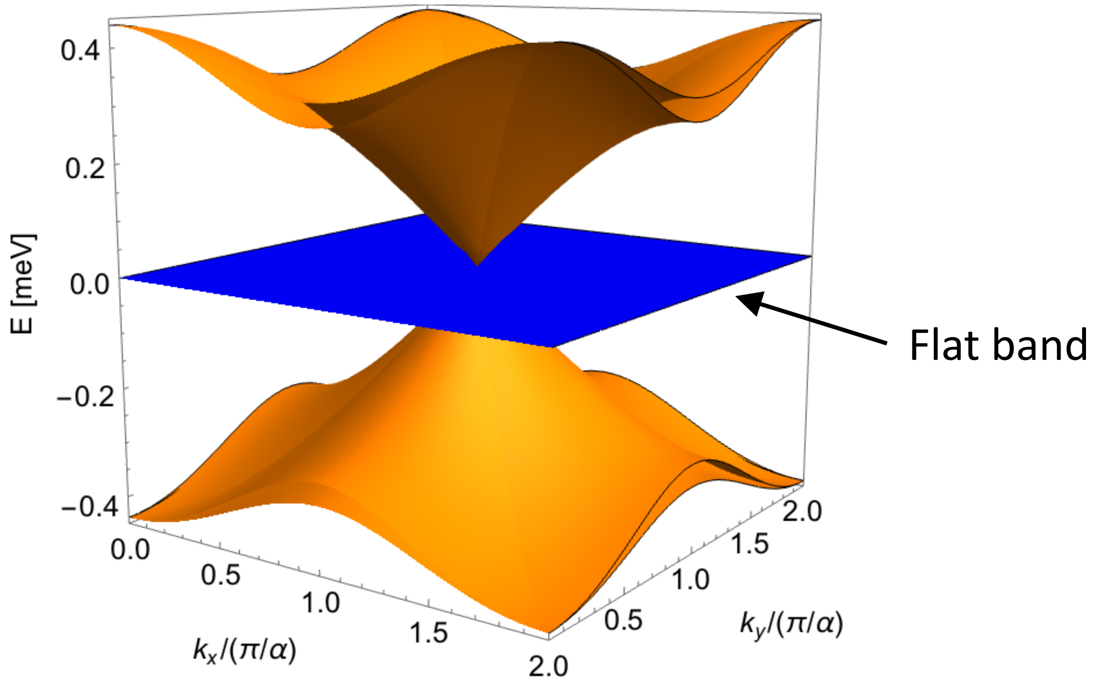


Decorated square lattice (A) with another sublattice centered on each side of the square

Lieb lattice oobserved in layered perovskites materials
CuO_2 weakly bound layer in high T superconductor $YBa_2Cu_3O_7$

Energy band structure and flat bands



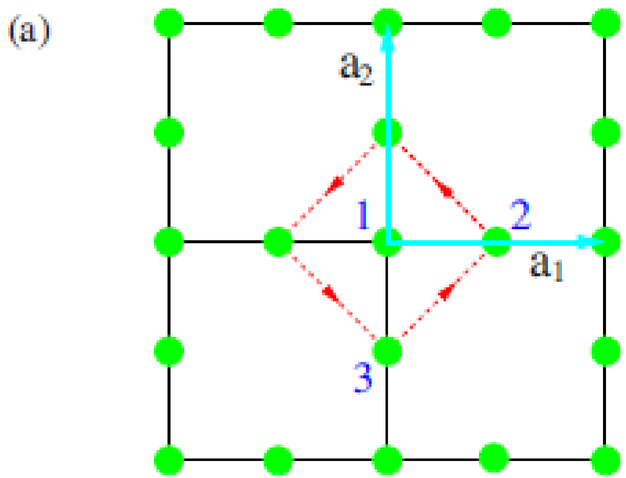


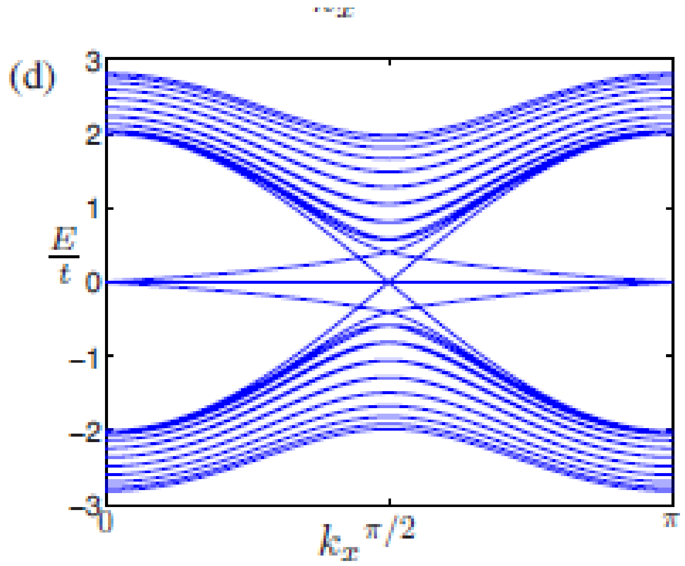
- Ferromagnetic ordering
- Quantum Hall phases
- Linear and nonlinear self-trapped wave packets (compactons)

Flat band arises from destructive interference between quasiparticles tunnelling from C to A and from B to A.

Linear dispersion crossing flat band at the edge of BZ

Topological and correlated phases in Lieb Lattice

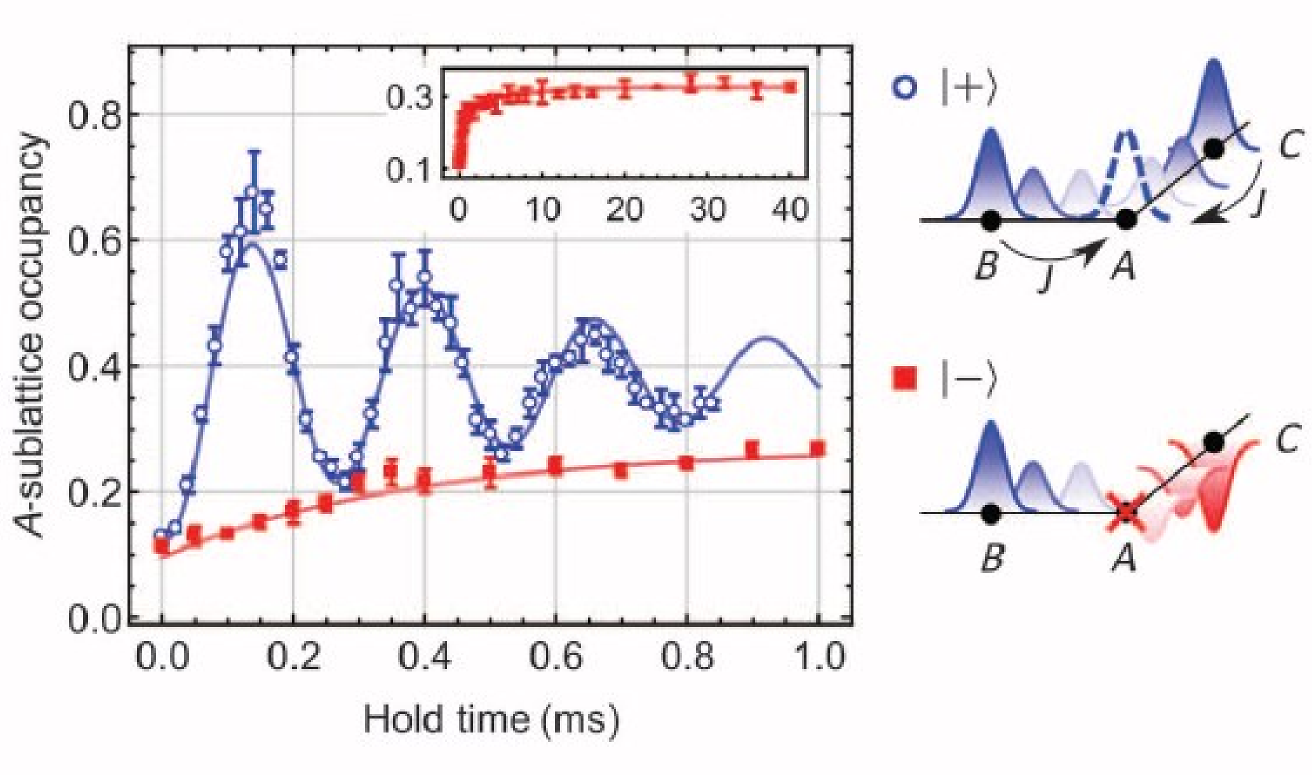




Spin-orbit induced next nearest neighbour coupling opens gap

Formation of topologically protected edge states
PRB 82, 085310 (2010)

BEC of cold atoms in Lieb lattice

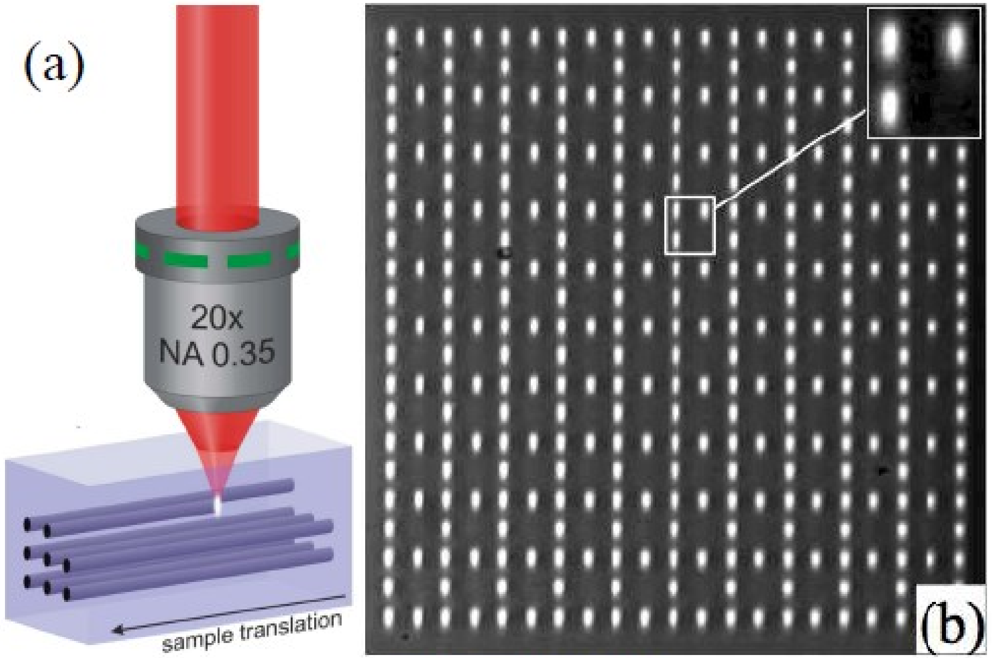


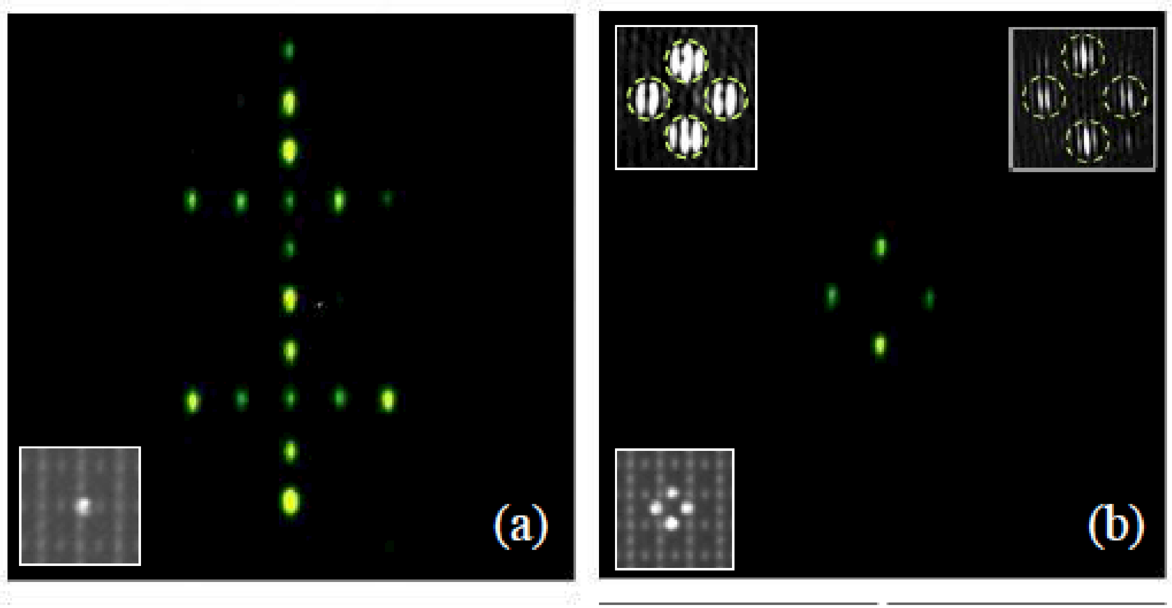
Atomic BEC in optically induced Lieb lattice

Localisation in a flat band

Science Advances 1, 10, (2015)

Compactons in Lieb lattice of coupled waveguides



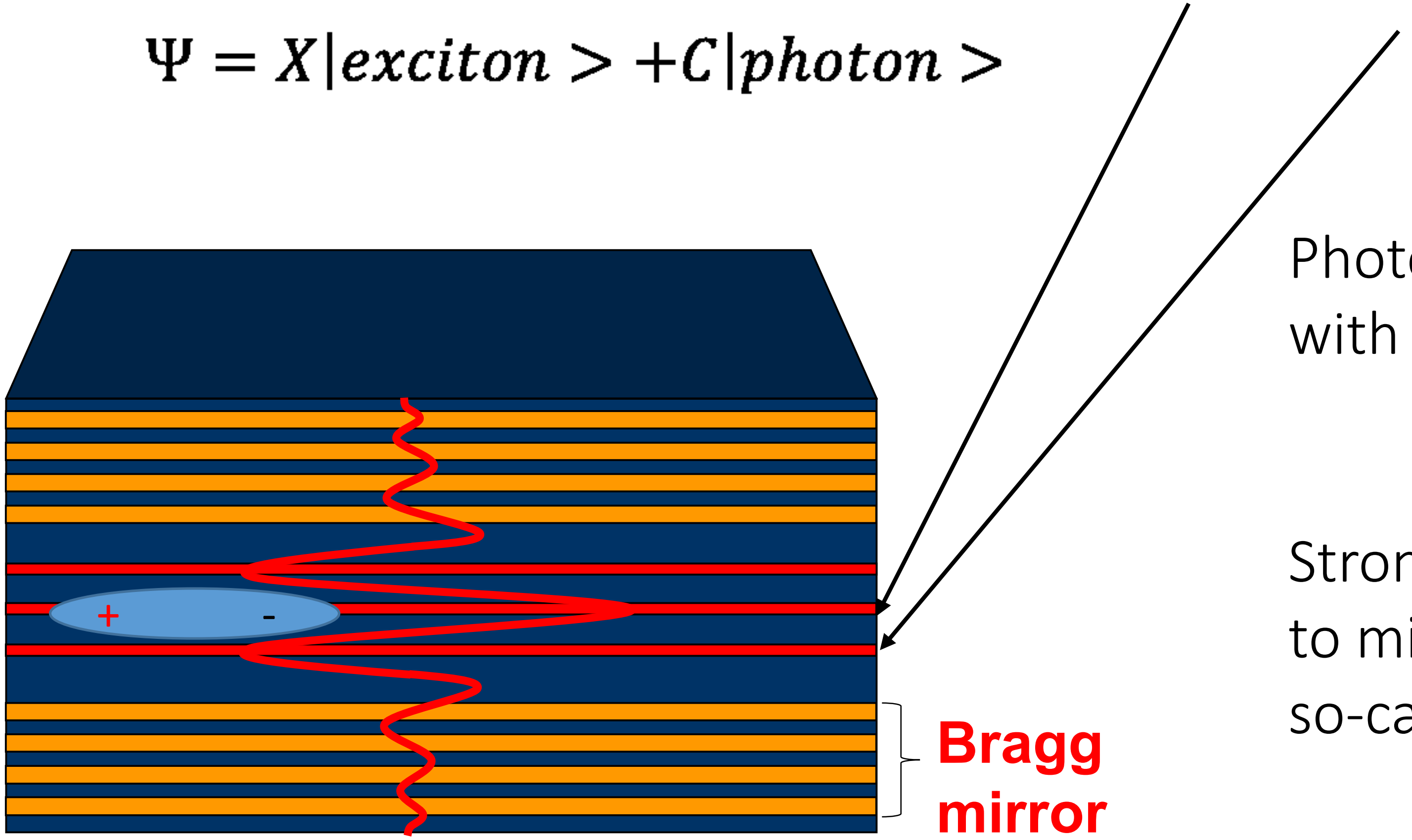


PRL 114, 245503 (2015)

STRONG EXCITON-PHOTON COUPLING IN SEMICONDUCTOR MICROCAVITIES

quantum well (III-V, II-VI or 2D materials of $MoSe_2$, WSe_2.)

$$\Psi = X|exciton> + C|photon>$$

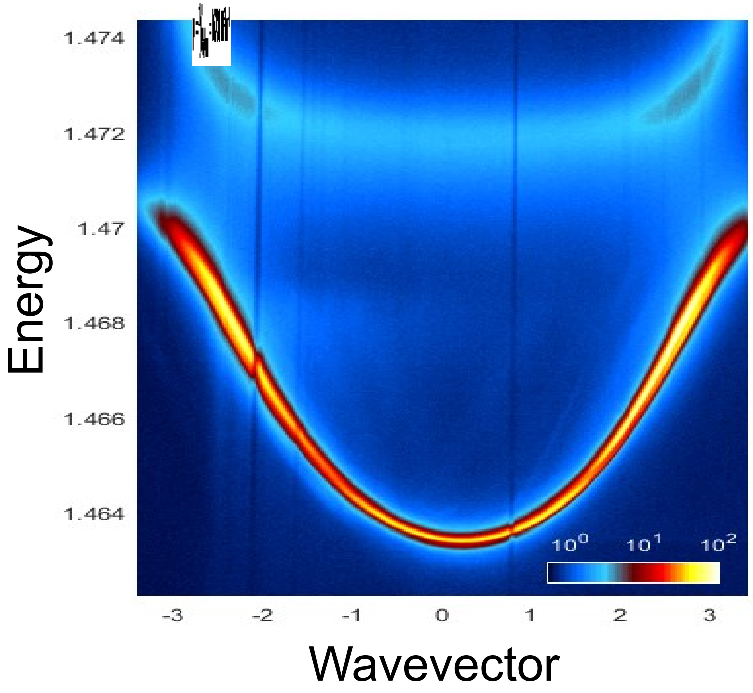


Photon mode is in resonance with quantum well exciton

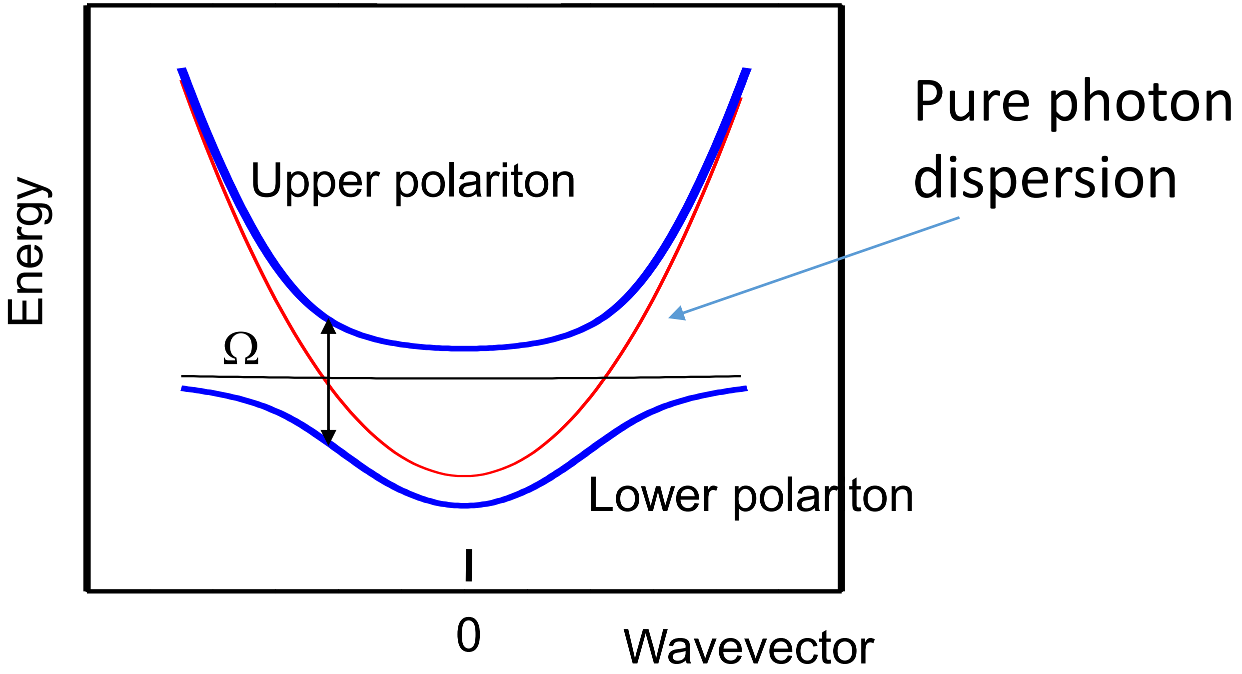
Strong exciton-photon coupling leads to mixed exciton-photon states, so-called 2D polaritons

MICROCAVITY POLARITON DISPERSION

experiment



theory

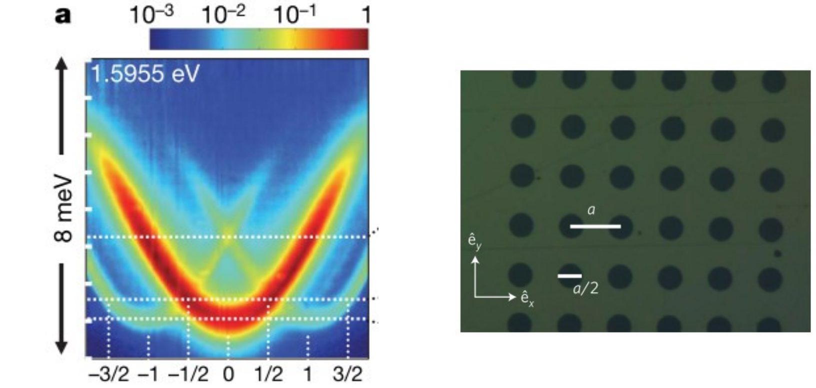


- Strong polariton-polariton interactions due to exciton
- Fast response on ps timescale=> suitable for optical signal processing
- Low mass (low density of state). $10^{8\text{-}9}$ times smaller than an atom mass

Polariton Bose-Einstein condensation at high T can be observed

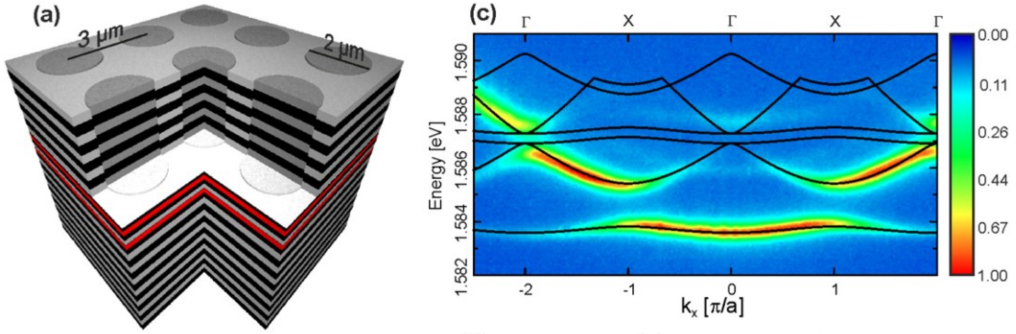
Methods of exciton-polariton confinement

Metal deposition (100’s μeV)



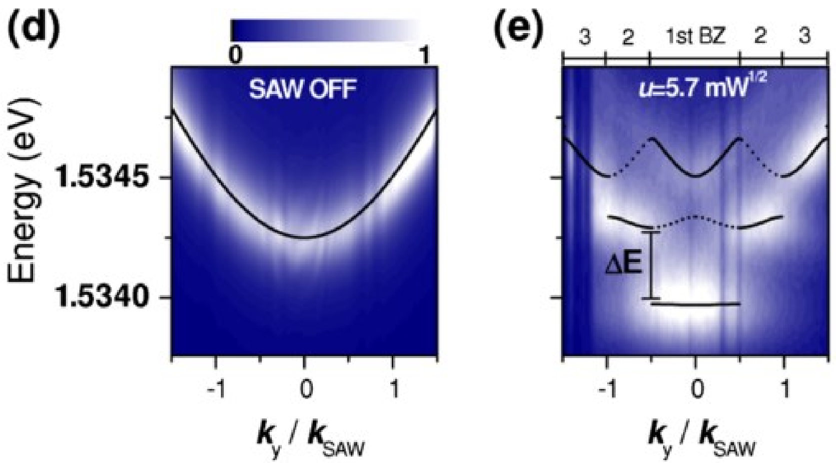
Nature **450**, 529-532 (2007); *Nature Phys.* **7**, 681-686 (2011)

Mesa traps (several meV)



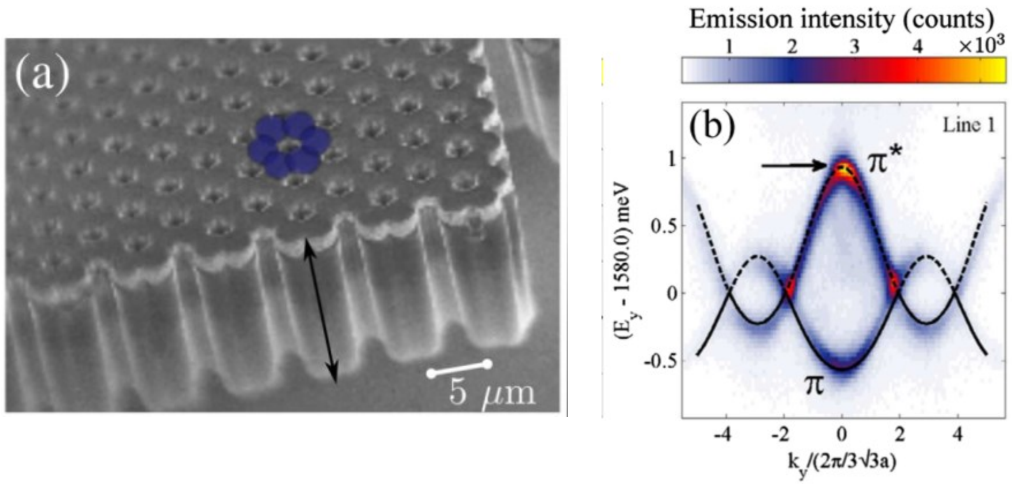
New J. Phys. **17**, 023001 (2015)

Surface acoustic waves (100’s μeV)



Phys. Rev. Lett. **105**, 116402 (2010)

Etched micropillars (10’s meV)



Phys. Rev. Lett. **112**, 116402 (2014)

Photonic spin-orbit coupling

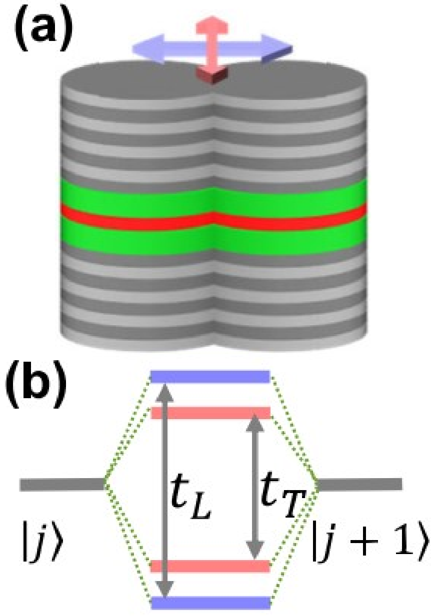
- Strong TE-TM splitting of photonic mode
- Introduces effective magnetic field acting on polariton pseudospin (polarisation)

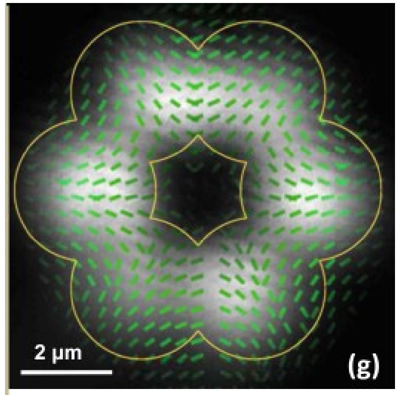
$$\begin{pmatrix} H(\boldsymbol{k}) & \Omega_{LT}(\boldsymbol{k})e^{-2i\theta} \\ \Omega_{LT}(\boldsymbol{k})e^{+2i\theta} & H(\boldsymbol{k}) \end{pmatrix} = H(\boldsymbol{k})I + \boldsymbol{\Omega}_{LT} \cdot \boldsymbol{\sigma}$$

C. R. Physique **17**, 920-933 (2016)

Phys. Rev. Lett. **115**, 116402 (2015)

Polarization-dependent hopping in micropillars





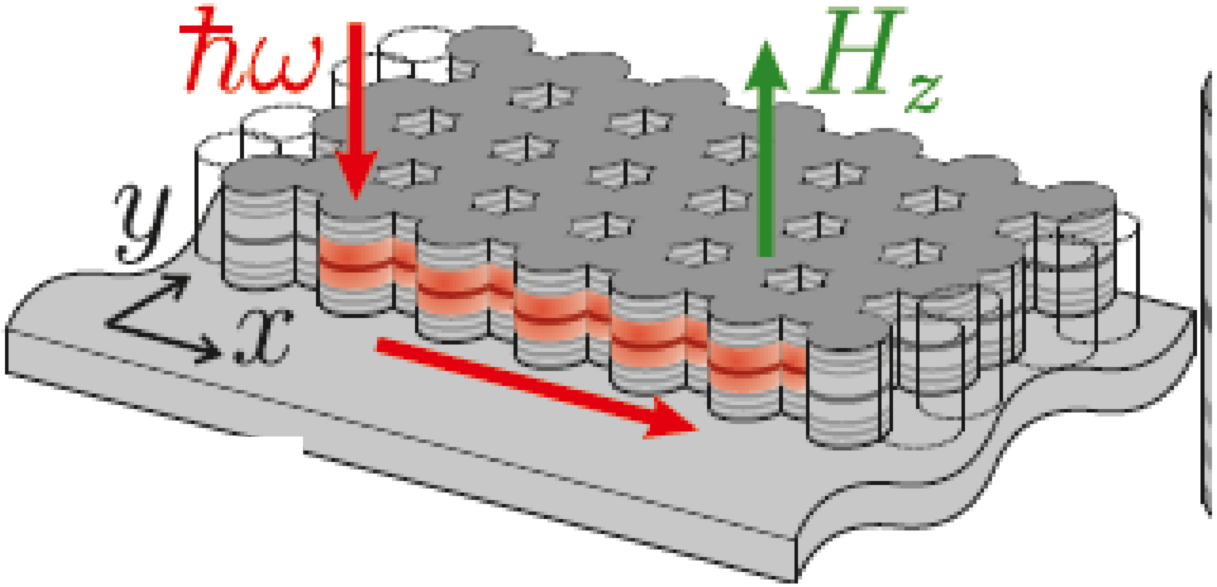
Phys. Rev. X **5**, 011034 (2015)

- One way to realize SSH Hamiltonian
- Large SOC + Zeeman splitting → opening of a topologically non-trivial gap in honeycomb lattices

PSEUDOMAGNETIC FIELDS IN POLARITON SYSTEM

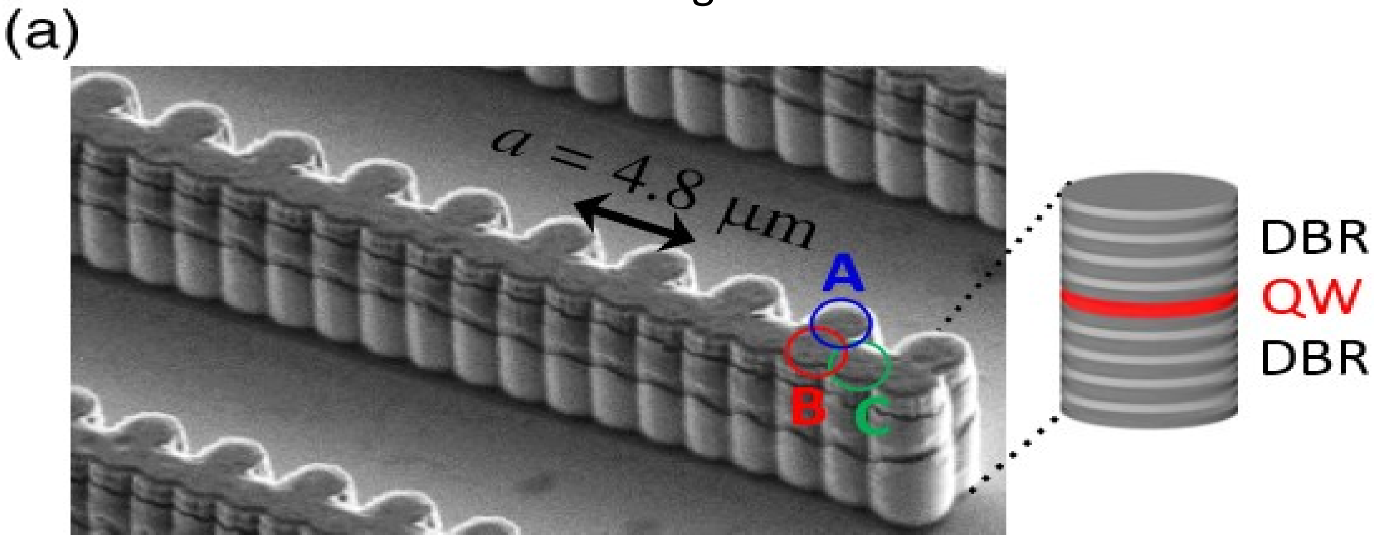
Large spin-orbit interaction for photons + real magnetic field acting on excitons

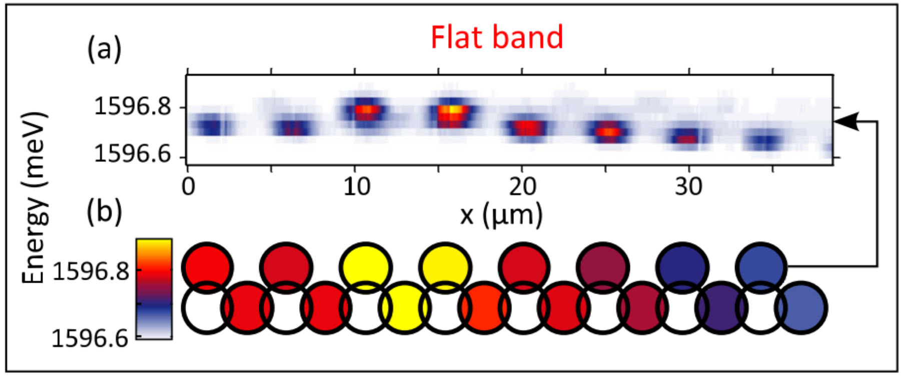
Phys. Rev. Lett. 114, 116401 (2015)



1D Lieb lattice

1D analog





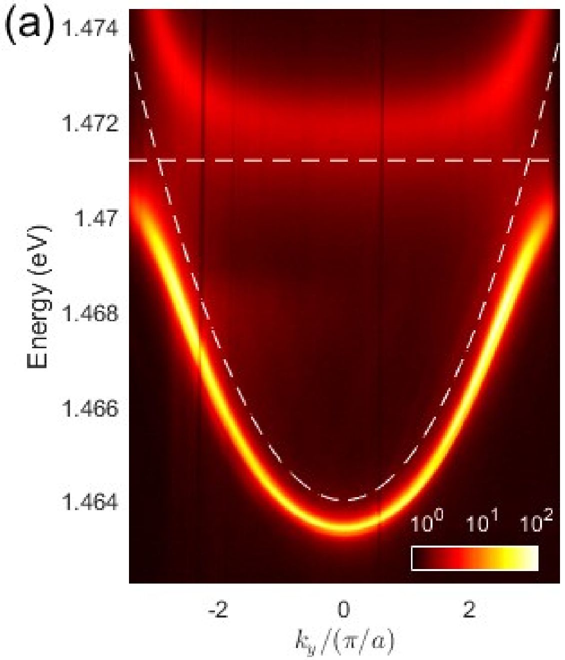
Phys. Rev. Lett. **116**, 066402 (2016)

Condensation into S type flat band.

Orbital flat bands and effects of spin orbit coupling unexplored

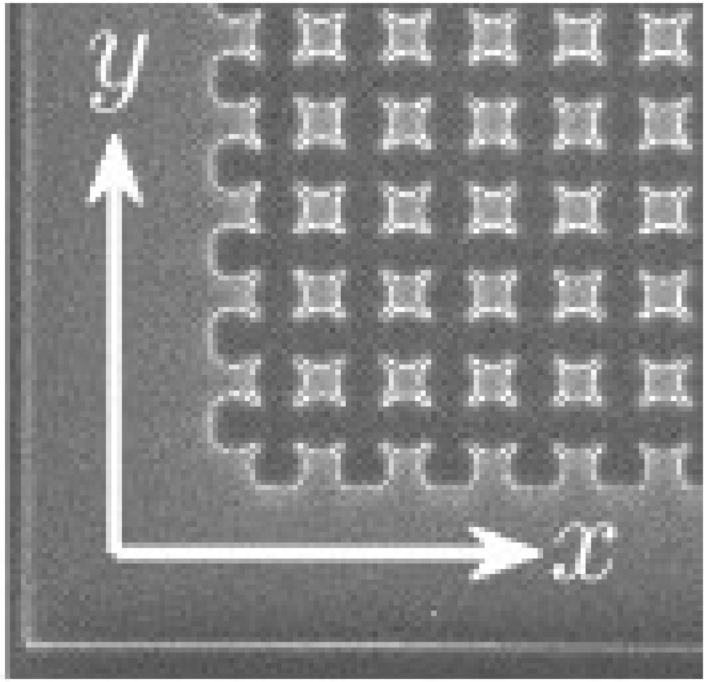
Our system

Unetched wafer



EBL + plasma dry etching

2D lattice

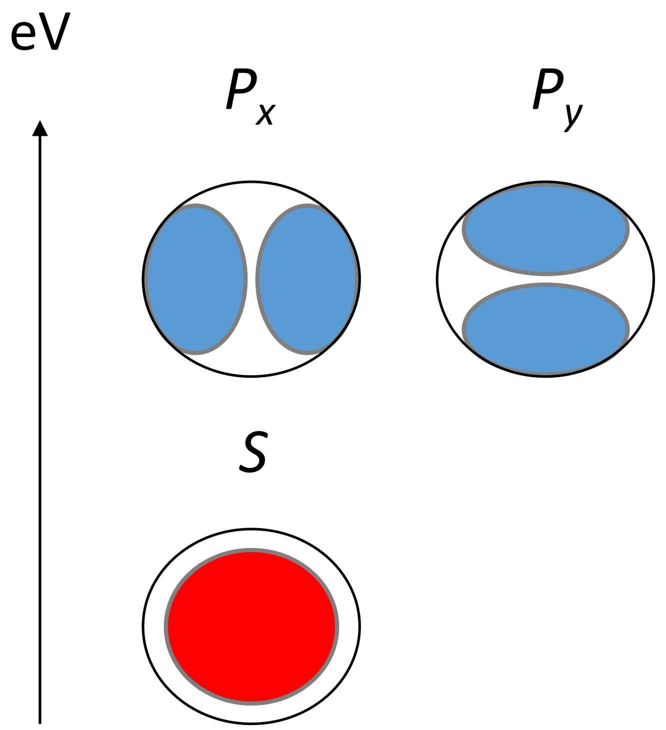


- λ/2 GaAs microcavity with 3x $In_{0.4}Ga_{0.96}As$ QWs
- Rabi splitting of 4.7 meV
- Linewidth ~0.1 meV
- Photon-exciton detuning of -7.2 meV

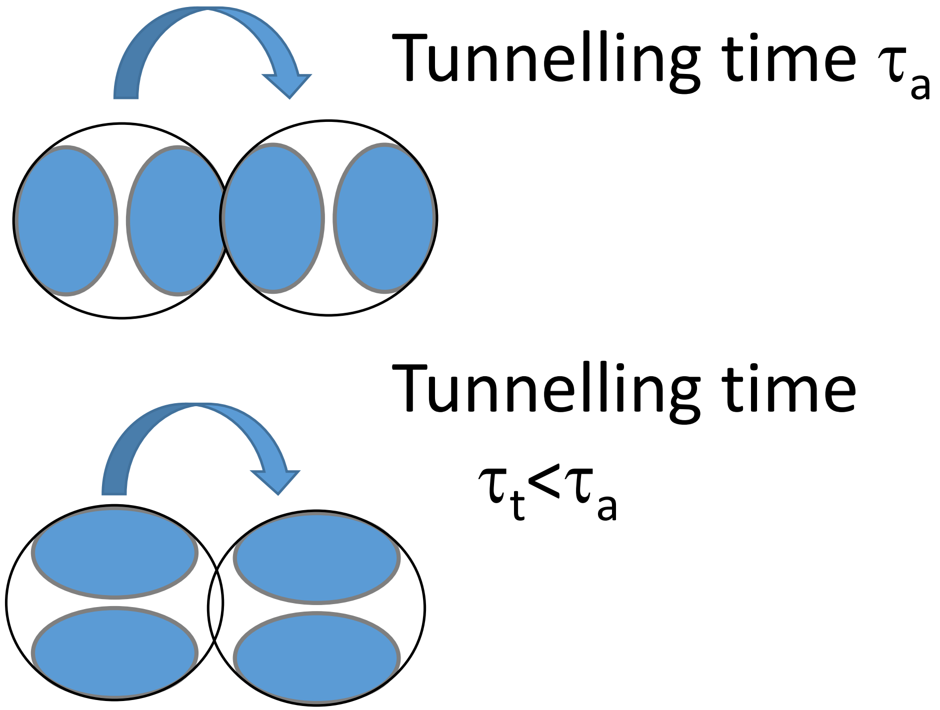
- 14x14 unit cells (~100 μm^2)
- 3 μm pillar diameter and 2.9 μm separation
- 5.8 μm lattice constant

S and P type orbitals in micropillars
(for now neglect polarisation degree of freedom)

Orbitals in single pillar

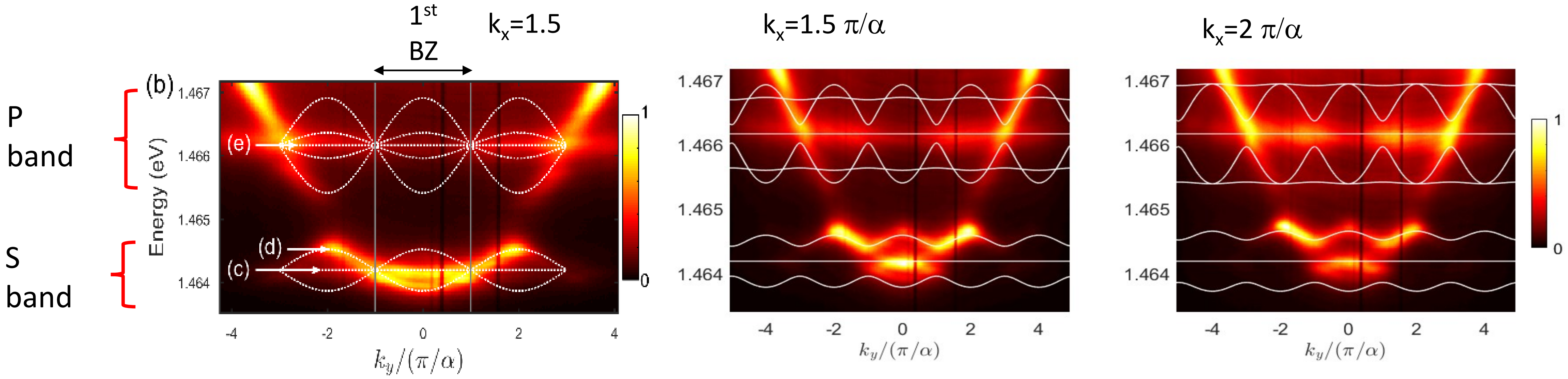


Tunneling of P orbitals between coupled pillars



Energy-momentum relation

Experimental *E-k* relations with tight-binding curves



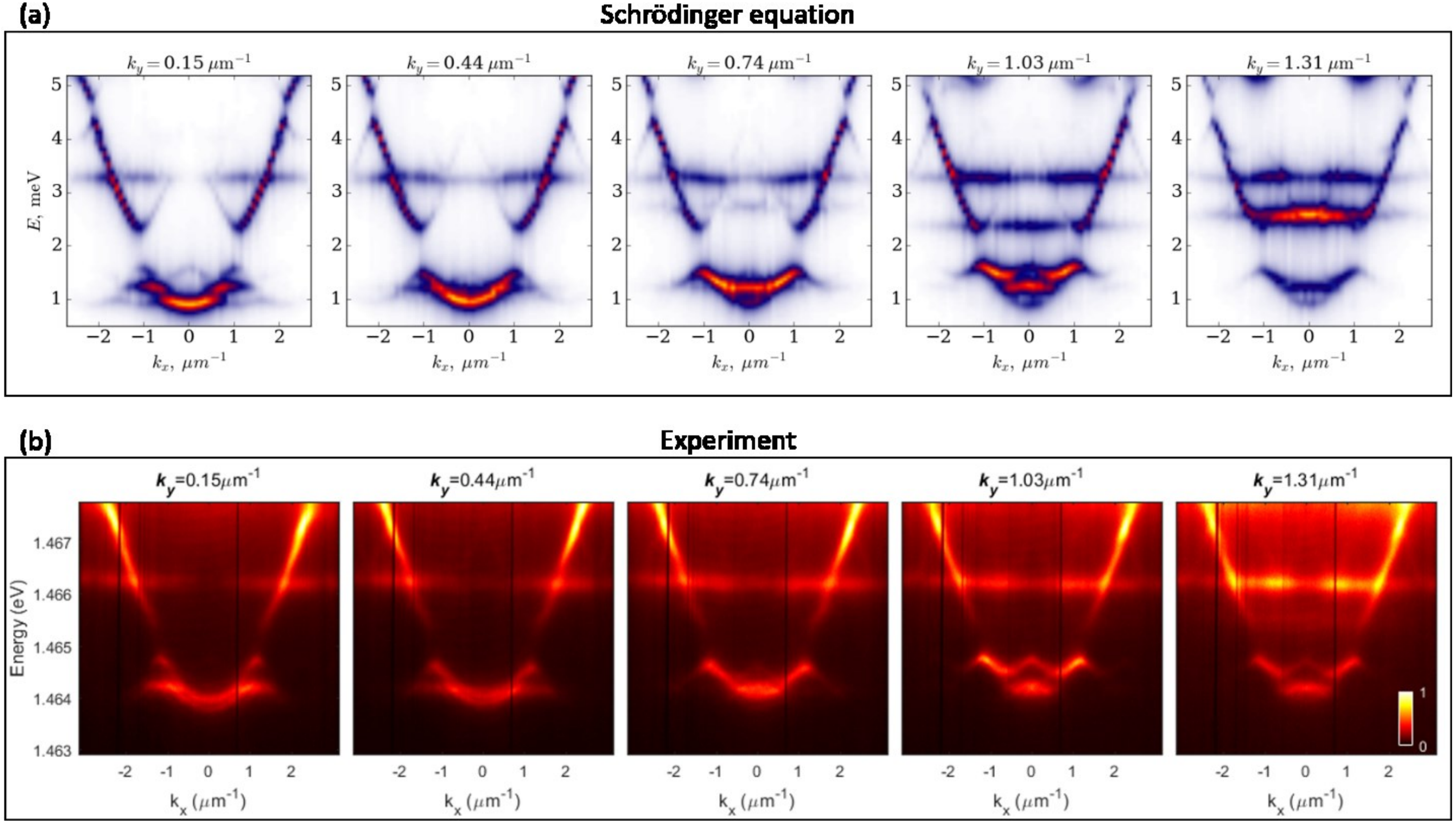
Emission from Flat S and P type band is pronounced

Emission from some dispersive bands is supressed probably due to far-field destructive intereference of different modes

Tight-binding model:

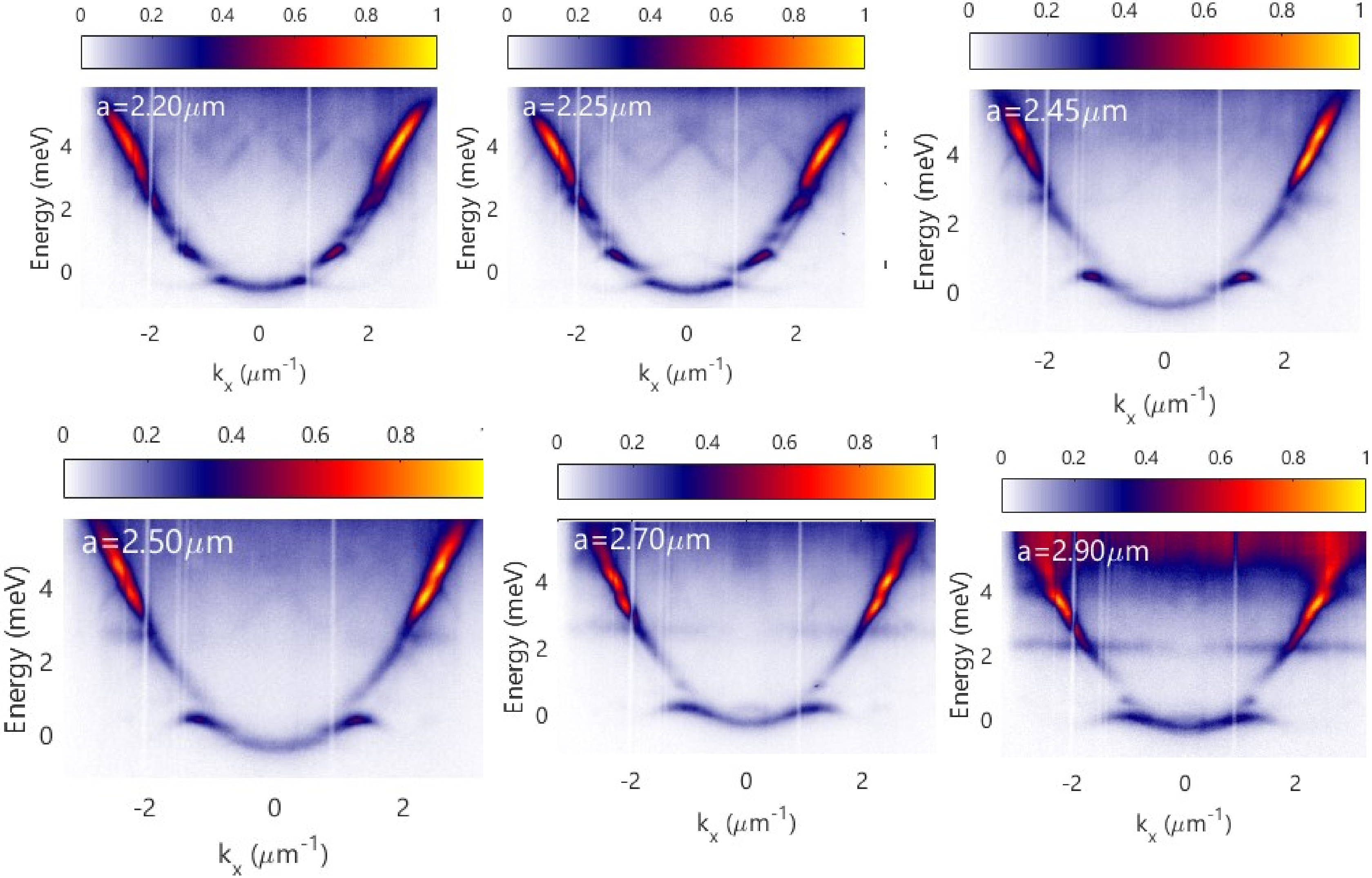
- *S* band: τ = 0.165 meV
- *P* band: τ^a = 0.375 meV; τ^t = 0.1 meV

Schrödinger equation in 2D Lieb potential



- 10 meV confinement potential
- $m^* = 5 \times 10^{-5} m_0$
- 0.1 meV lifetime

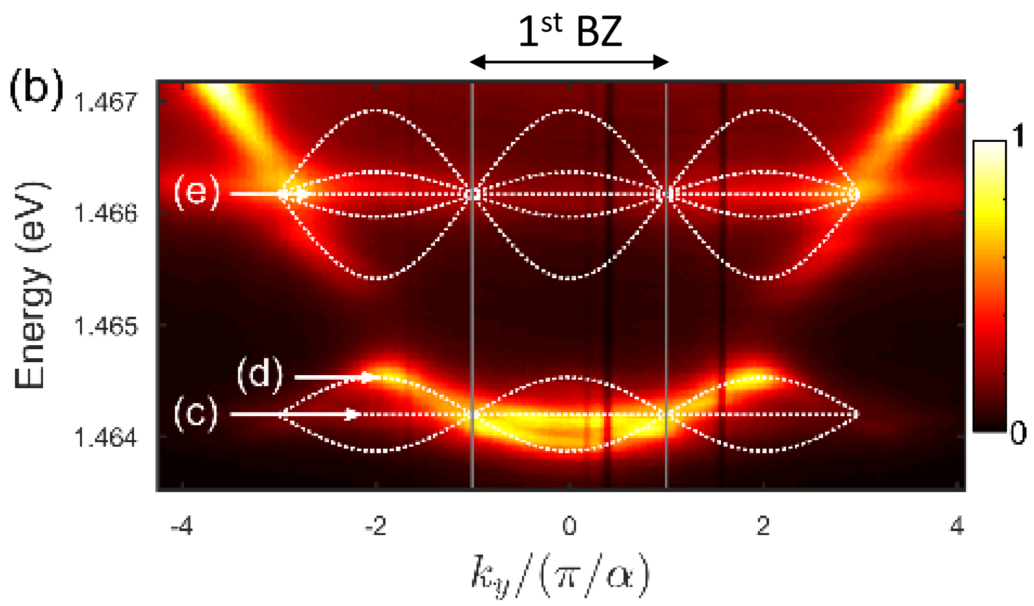
Band structure for different lattice constants



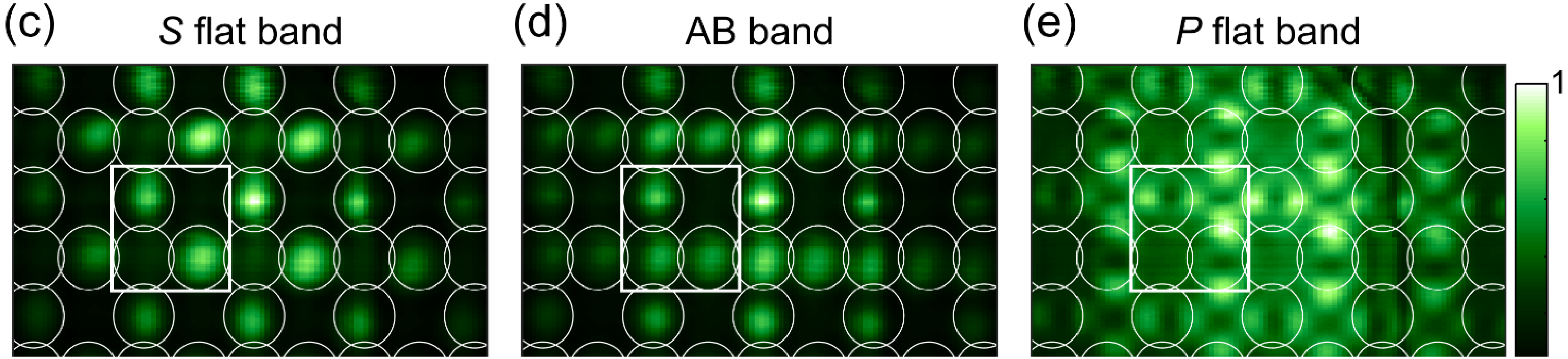
At smaller lattice constants energy gaps become smaller

Flat bands disappear

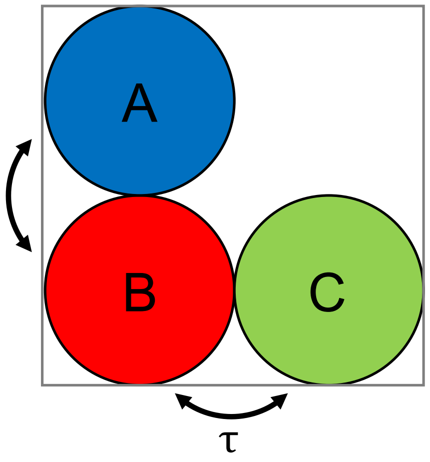
Real space emission

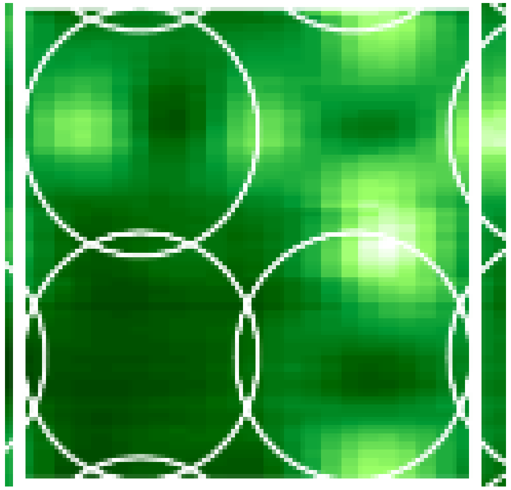


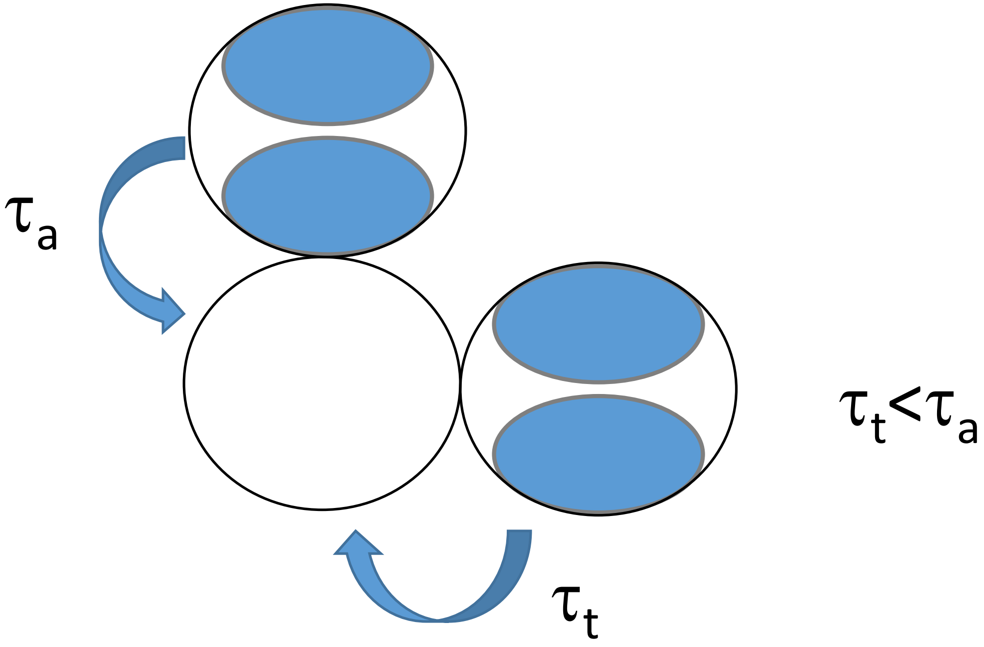
- Flat bands show suppressed emission from *B* sublattices due to destructive wave interference
- AB (dispersive) band eigenmodes are delocalized



P-flat band real space pattern







A site has higher proportion of Px orbital (Px/Py~6)

C site has higher proportion of Py orbital

Population on B site close to zero as expected for flat band

Py (A) τ_a= Py (C) τ_t

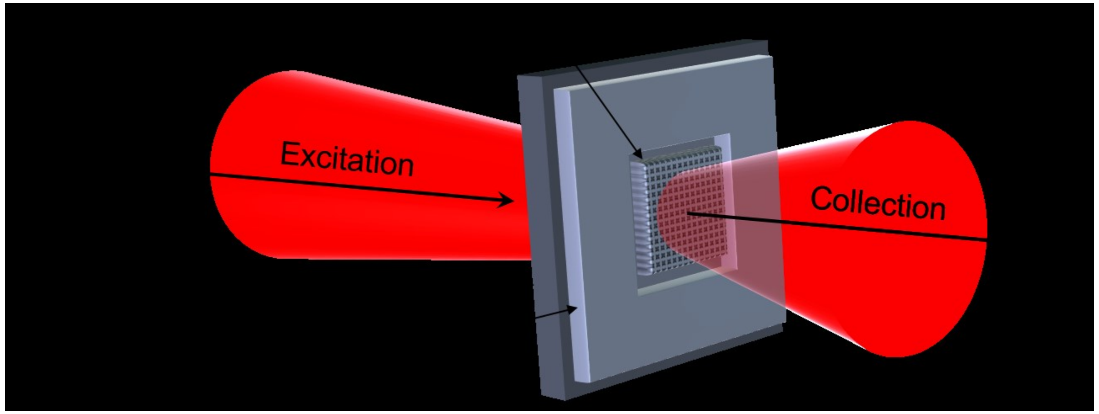
⇓

Py (A)< Py (C)

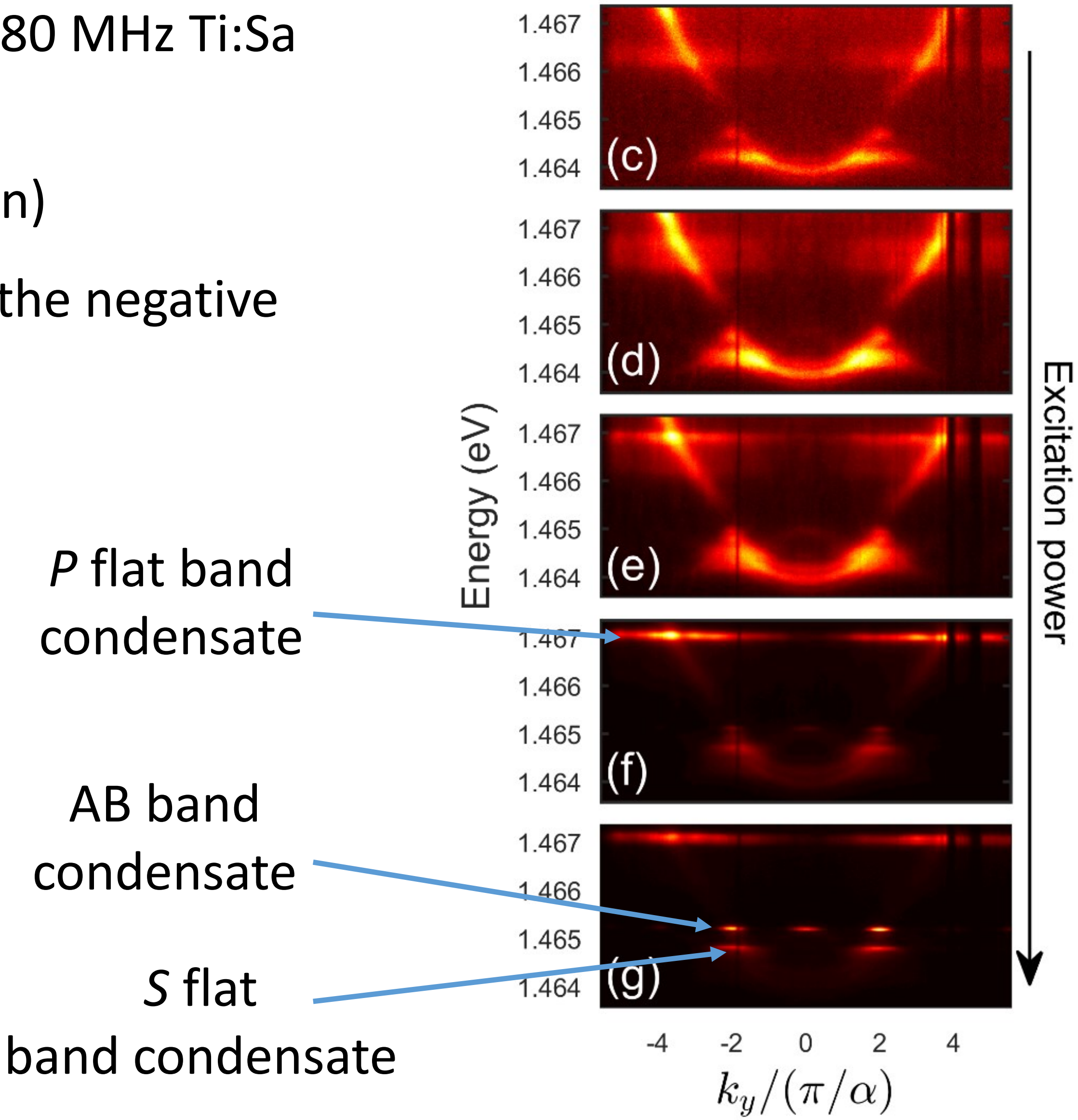
Polariton condensation

- 100 ps horizontally-polarized pulses from an 80 MHz Ti:Sa laser
- Laser tuned to 843 nm (~1 meV below exciton)
- Polaritons condense into two flat bands and the negative effective mass states at the AB band maxima

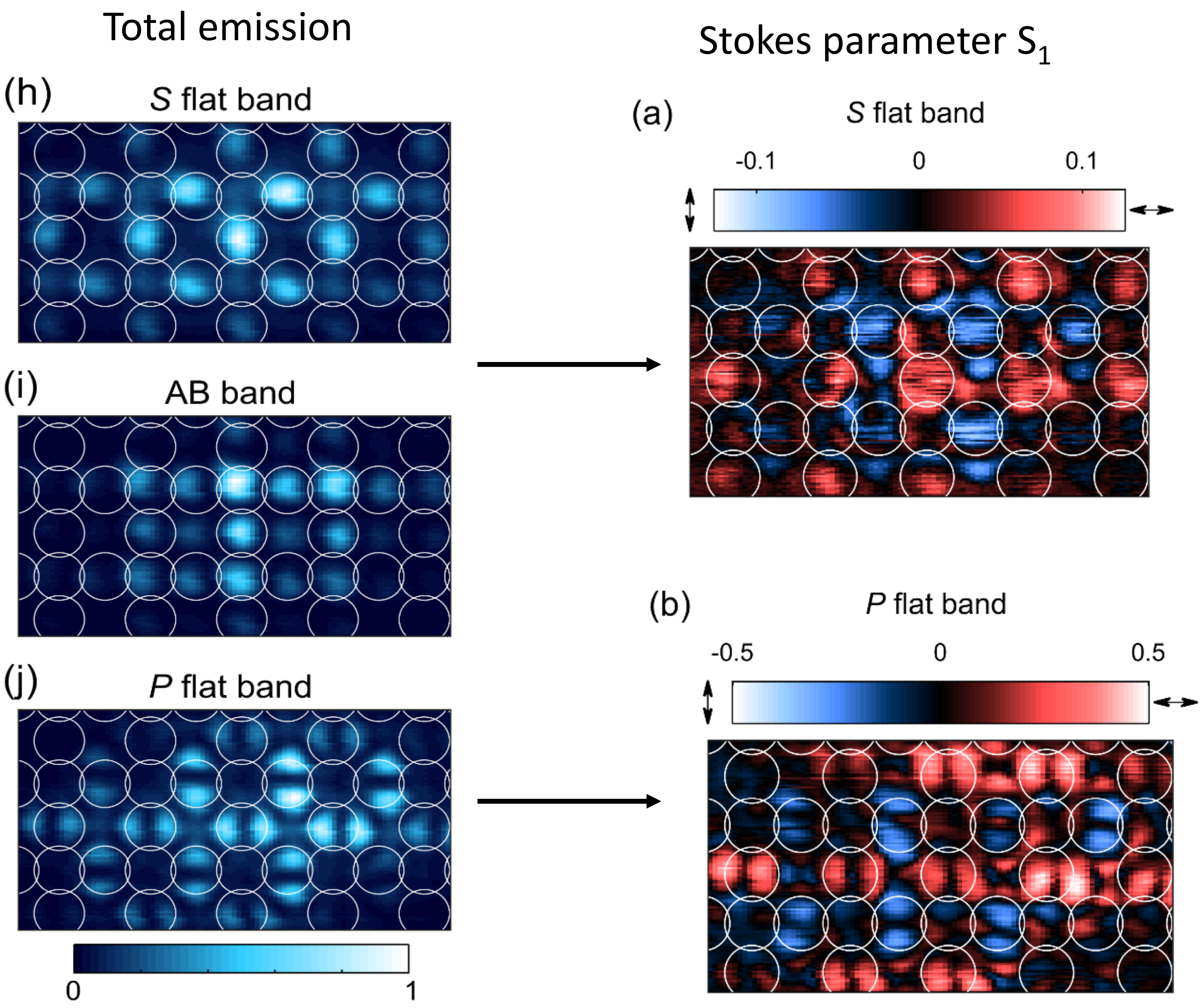
Excitation scheme



Power dependence at $k = 0$



Real space emission patterns

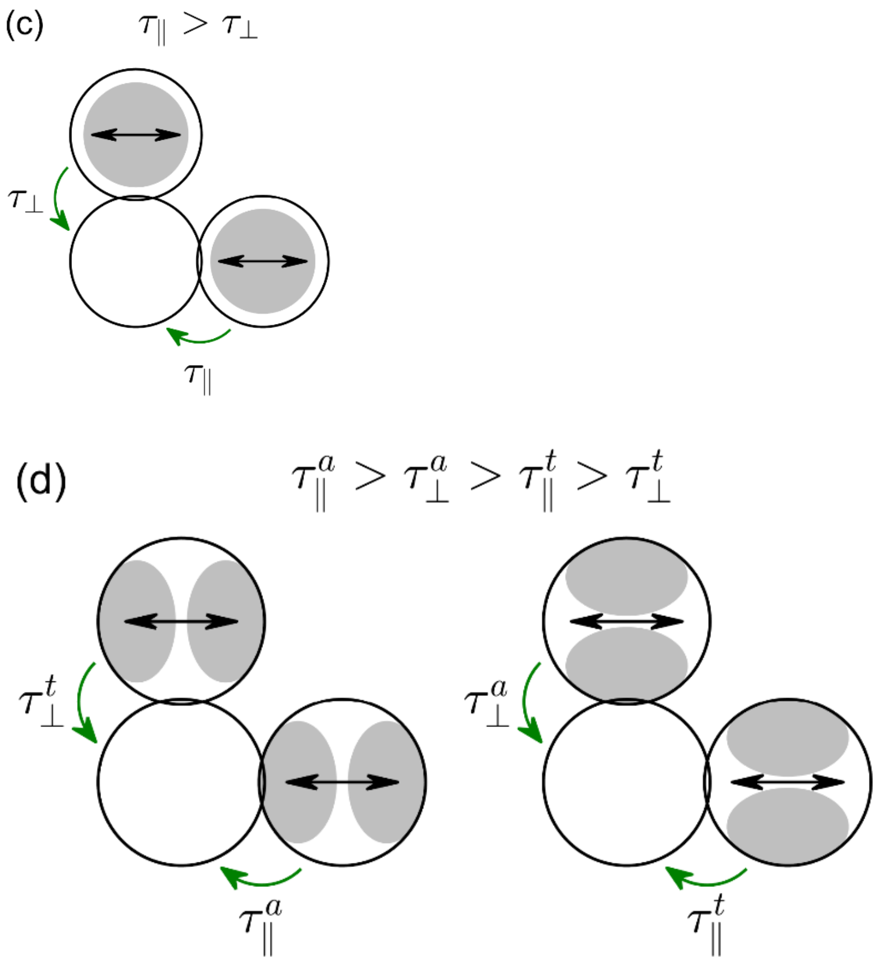


- Condensates formed on flat bands are localized on *A* and *C* sublattices
- Photonic spin-orbit coupling gives rise to pseudospin texture in flat band condensates

Polarisation dependent tunnelling

S

P



Tight-binding model:

- *S* band:

  $\tau_{||}$ = 0.165 meV; $\tau_{\perp}$ = 0.145 meV

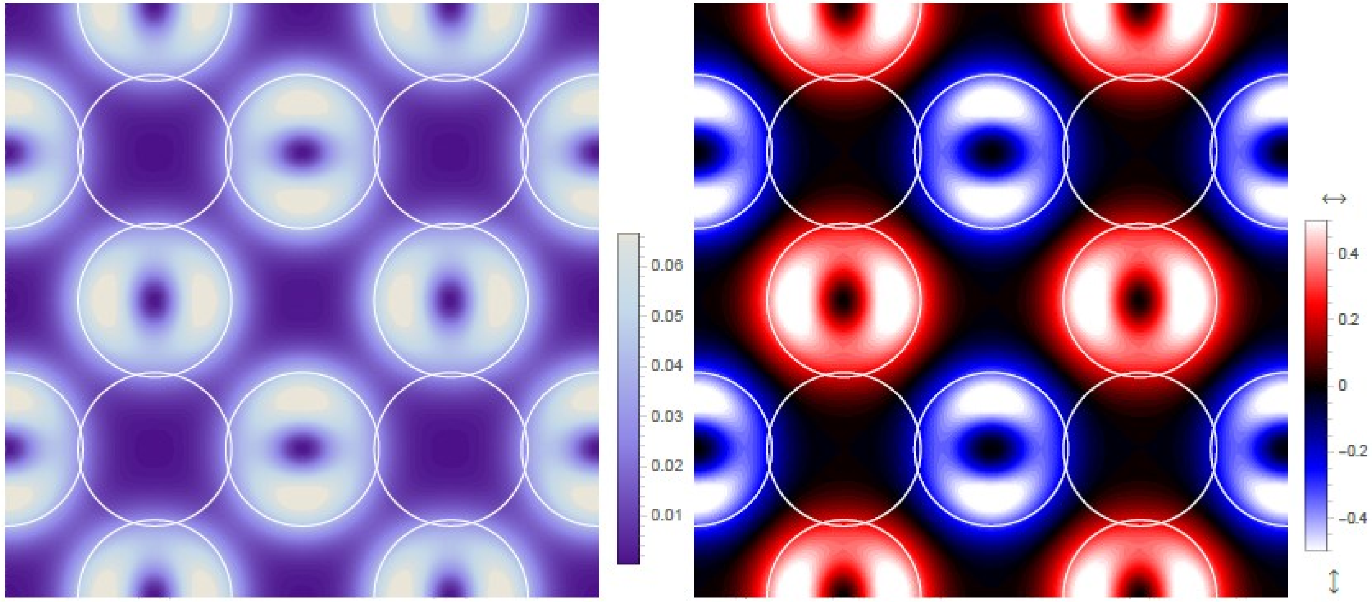
- *P* band:

  $\tau^a_{||}$ = 0.375 meV; $\tau^t_{||}$ = 0.1 meV

  $\tau^a_{\perp}$ = 0.125 meV; $\tau^t_{\perp}$ = 0.033 meV

Calculated real space emission patterns with polarisation

Calculated patterns for P flat band



Ratio of orbital populations: 6

$$\left|\Psi_{P_x}\right|^2 / \left|\Psi_{P_y}\right|^2 \ (A \text{ sites})$$

$$\left|\Psi_{P_y}\right|^2 / \left|\Psi_{P_x}\right|^2 \ (C \text{ sites})$$

Linear Polarisation degree

~0.5 for P flat bandand
~0.13 for S flat band

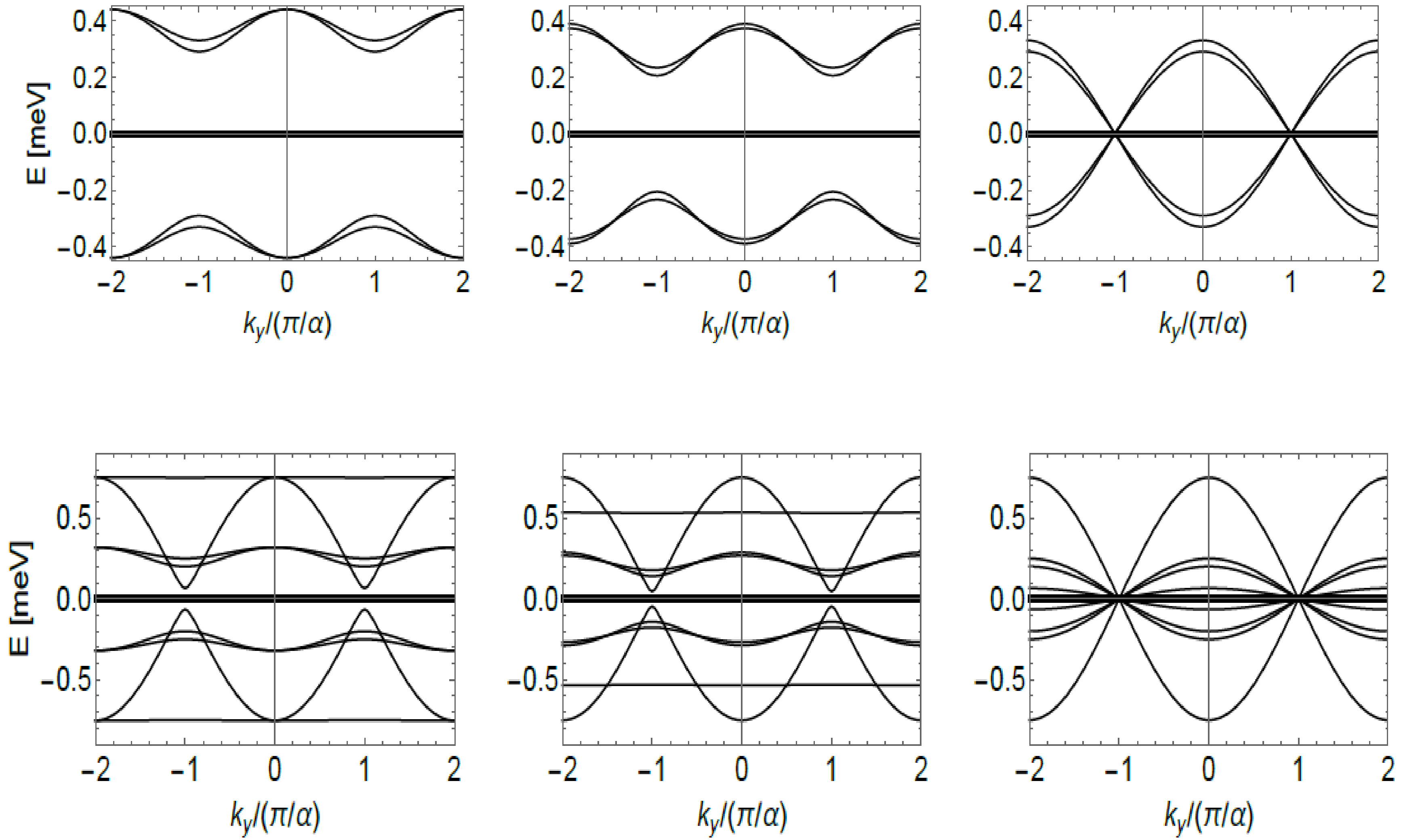
in agreement with the experiment

Calculated Energy-momentum dispersions

TB model with polarization

S

P

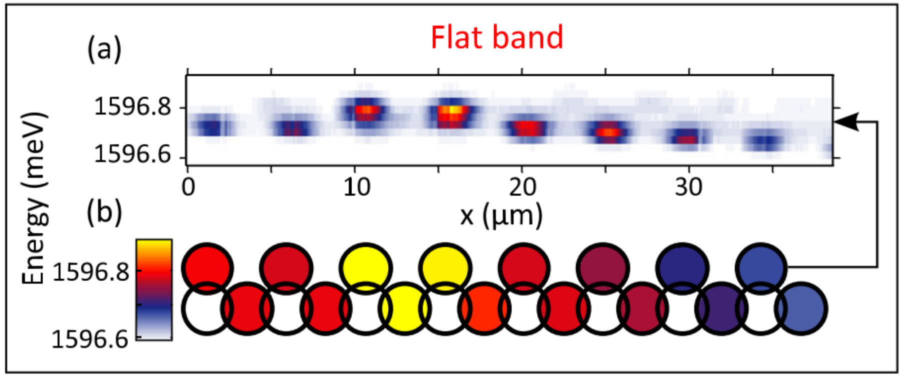


Dispersive bands are polarisaion split

Flat bands are unaffected by polarisation dependent tunneling

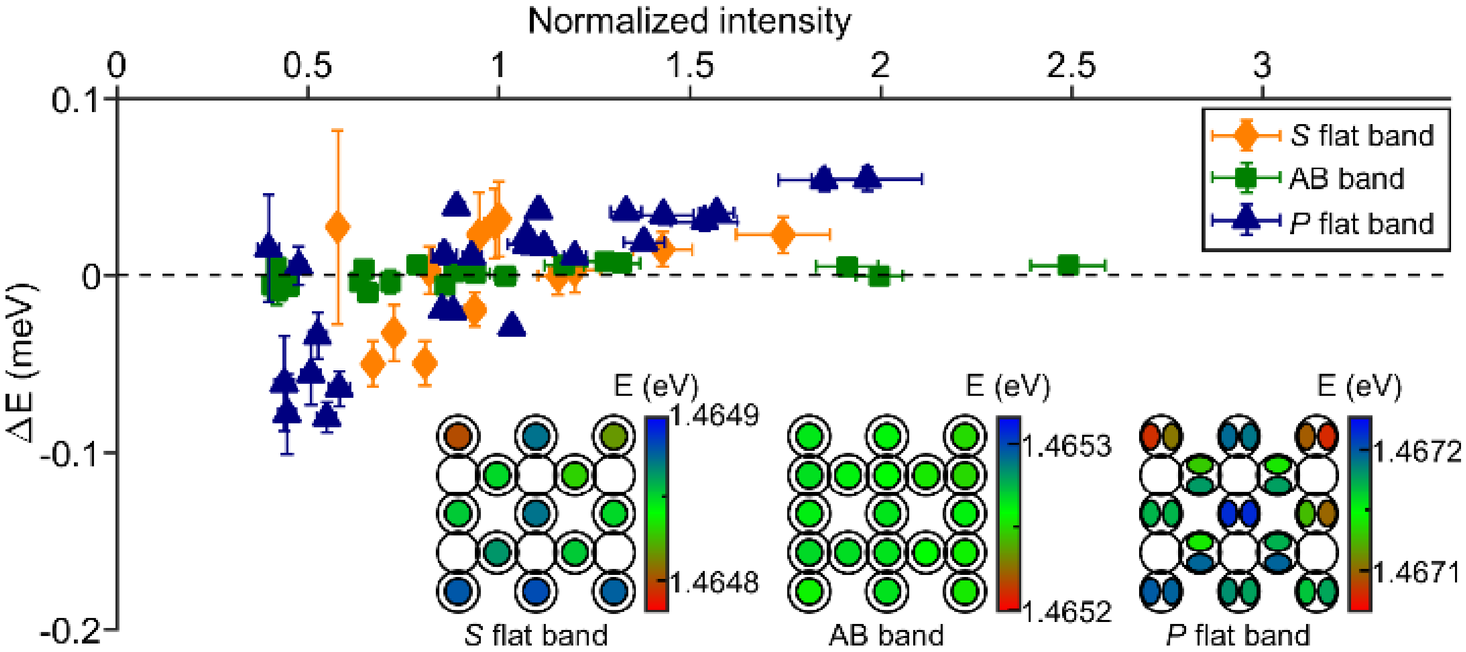
Condensate fragmentation

1D case



Phys. Rev. Lett. **116**, 066402 (2016)

2D case



- Spatially-dependent blueshift of pillar modes seen in flat-band condensates
- Correlation between population and blueshift of orbitals shows role of interactions in spectral fragmentation. Interactions with reservoir are dominant

Strength of polariton-polariton interaction

Polariton density

Blueshift of polariton energy at given k $E_{shift}=g_{pol-pol}N_{pol}$

Exciton fraction

Photon fraction

$$E_{shift}=g_{pol-pol}N_{pol}=g_{xx}N_{pol}|X|^4/N_{QW} + \Delta\Omega|C|^2$$

Blueshift of exciton resonance

Strength of exciton-exciton interactions g_{xx}

Number of quantum wells N_{QW}

Reduction of Rabi splitting due to screening of exciton resonance by exction-exciton interactions $\Delta\Omega=\beta_{xx}N_{pol}|X|^2/N_{QW}$

$g_{pol\text{-}pol}$ and g_{xx} from literature

Measuring blueshift of polariton high density phase (condensate) in microcavities pumped resonantly or nonresonantly

SRK Rodriguez, A Amo et al.arXiv preprint arXiv:1602.07114, Nature Comm (2016)

$g_{pol-pol} = 0.8\ \mu eV\ \mu m^{2\cdot}$; g_{xx}=30 $\mu eV\ \mu m^{2\cdot}$

Lydie Ferrier, et aland Jacqueline Bloch Phys. Rev. Lett. ***106****, 126401 (2011)*

$g_{pol-pol} = 2 - 10\ \mu eV\ \mu m^{2\cdot}$; g_{xx}>100 $\mu eV\ \mu m^{2\cdot}$

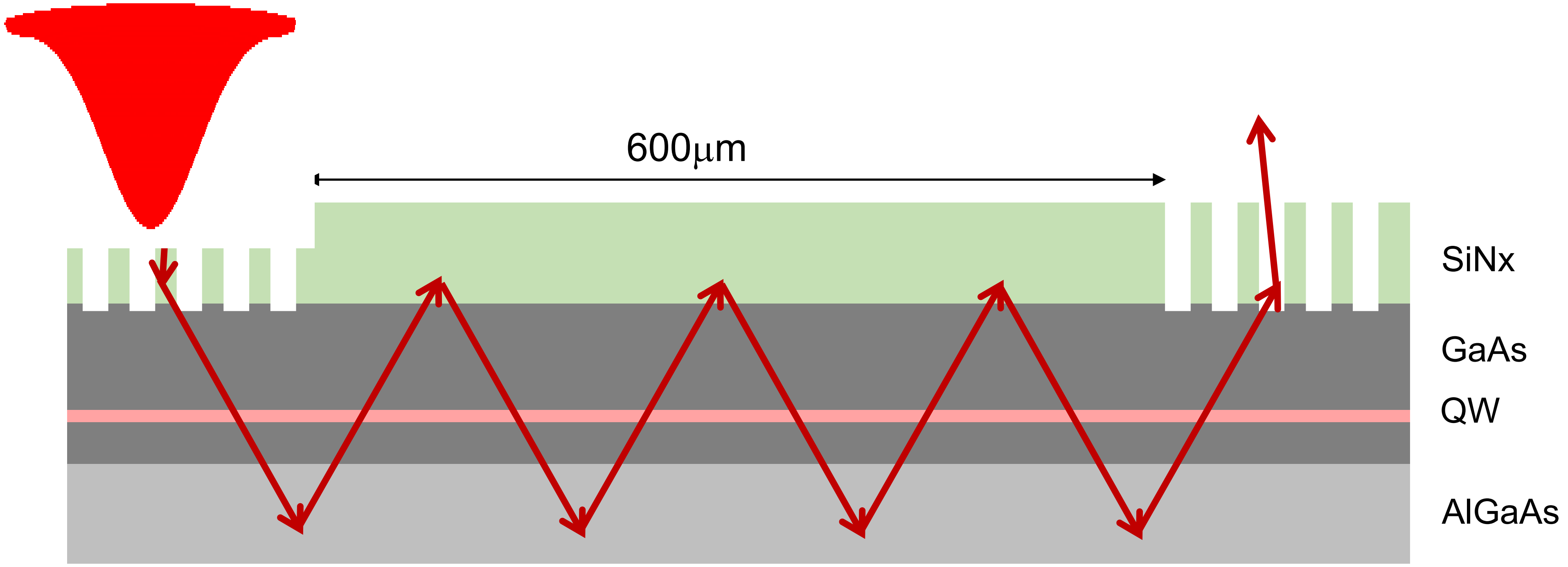
A.S. Brichkin et al PRB, 84, 195301 (2011)

$g_{pol-pol} = 0.07\ \mu eV\ \mu m^{2\cdot}$; g_{xx}~2-3 $\mu eV\ \mu m^{2\cdot}$-
consistent with theoretical estimate $g_{xx} \sim 3 a_B^2 E_B$

Bright Temporal Solitons

http://arxiv.org/abs/1409.0725 *P.Walker et al., DNK Nature Comm. 2015*

Inject 350fs pulse through a grating. Let it propagate
600 μm and extract it through a second grating.



Comparison with other photonic systems

From soliton threshold estimate the nonlinear parameter and nonlinear refractive index: *P.Walker, et al., DN Krizhanovskii Nature Comm.* 6, 8317 *(2015)*

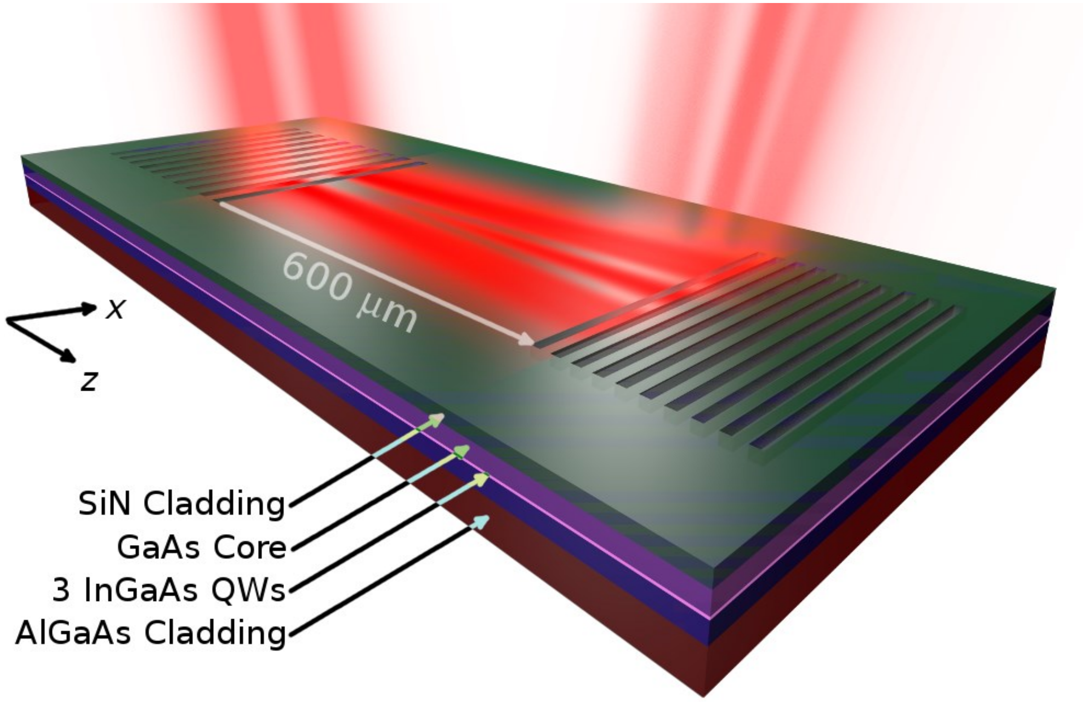
$$L_{NL} \approx \frac{1}{\Delta k} = \frac{v_g \hbar}{E_{shift}}$$ - the length over which nonlinear phase is 1 rad

$$L_{NL} \approx L_D \approx 40 - 50\ \mu\text{m}$$

Excitonic nonlinearity g_{XX} = 4-12 μeV μm^2

	Polariton GaAs system	AlGaAs waveguides	Silicon PhC	InGaP PhC
Nonlinear Index n_2 ($W^{-1}m^2$)	**10^{-14} - 10^{-13}**	1.8×10^{-17}	6×10^{-18}	6×10^{-18}

Strength of polariton-polariton interactions for CW pump



- Inject fluids containing amplitude and phase defects.
- Vary the density of the polariton fluid and observe the changes after nonlinear propagation.
- Formation of dark polariton solitons

P.Walker, et al., DN Krizhanovskii Nature Comm. 6, 8317 (2015)
P.Walker et al., DN Krizhanovskii, arXiv preprint arXiv:1703.08351 (2016)

Estimation of $g_{pol\text{-}pol}$ from CW dark soliton

$$g_{pol-pol} = \frac{\hbar^2}{2M_{x\_eff}\xi^2 N_{pol}}$$

M_{x_eff} - polariton effective mass in transverse direction of waveguide
ξ- dark soliton FWHM or healing length
N_{pol} – polariton density of dark soliton background

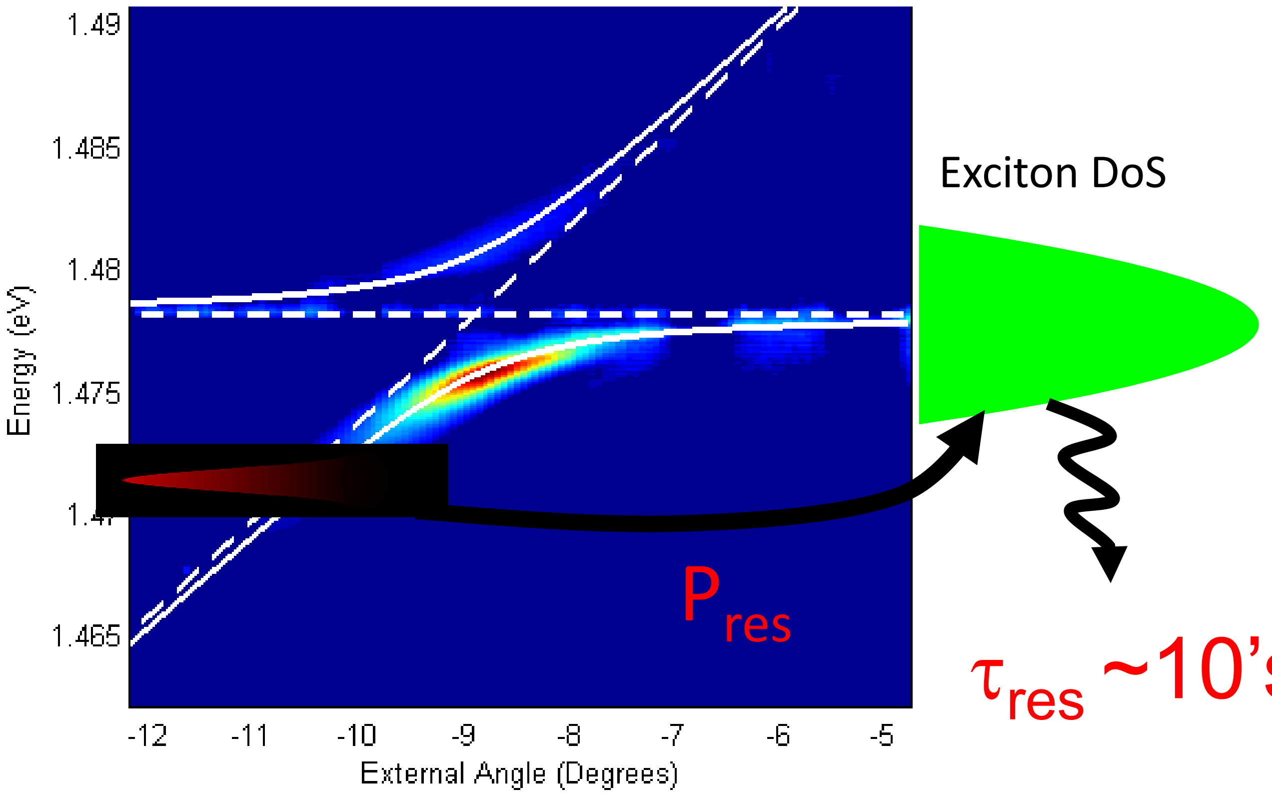
$\boldsymbol{g_{pol-pol} \approx 5\ \mu eV\ \mu m^2}$ Taking into account $|X|^2$=0.5 and N_{QW}=3

g_{xx}~60 μeV μm² → An order of magnitude larger than in case of ps pulsed excitation

Population of exciton reservoir under CW pump

D Sarkar, SS Gavrilov, Physical review letters 105 (21), 216402 (2010)

DN Krizhanovskii, et alSolid state communications 119 (7), 435-439 (2001)



τ_{res} ~10’s-100’s ps

Exciton reservoir:

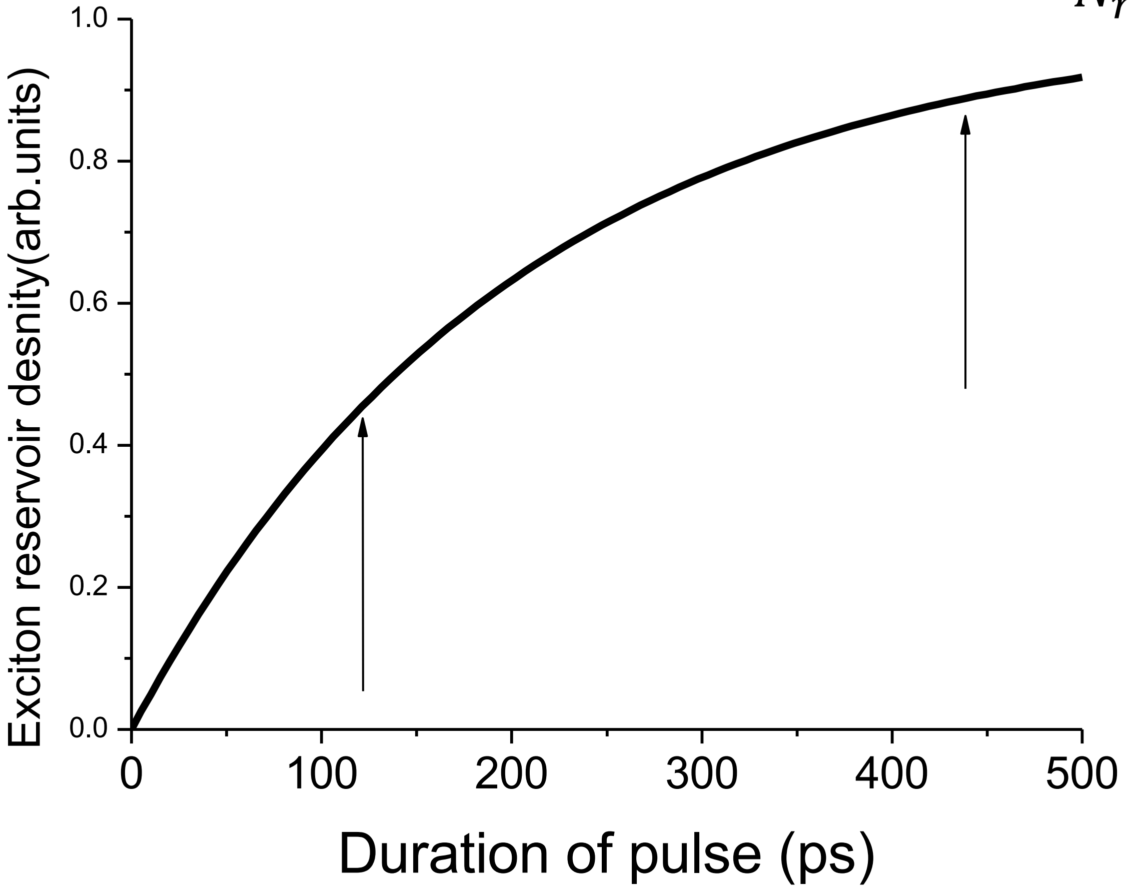
Localised excitons not coupled to cavity mode

Dark excitons

Excitons with high momenta

Pumping of reservoir directly or via excitation of biexcitons with two linearly polarised polaritons

Reservoir density vs duration of excitation



$$N_{res} = Const * P_{peak}(1 - \exp(-t_{pulse}/\tau_{res}))$$

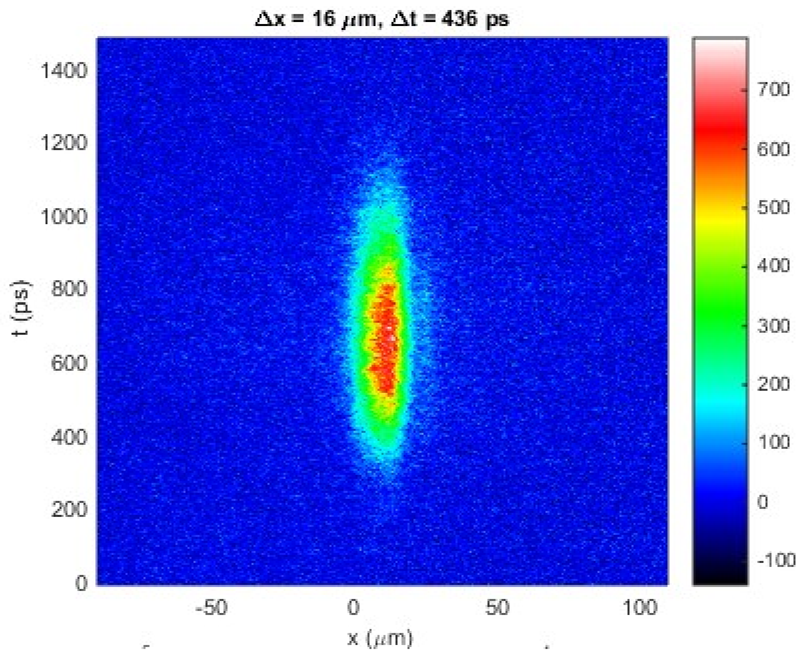
P_{peak} – peak power or excitation

t_{pulse} *-duration of pulse*

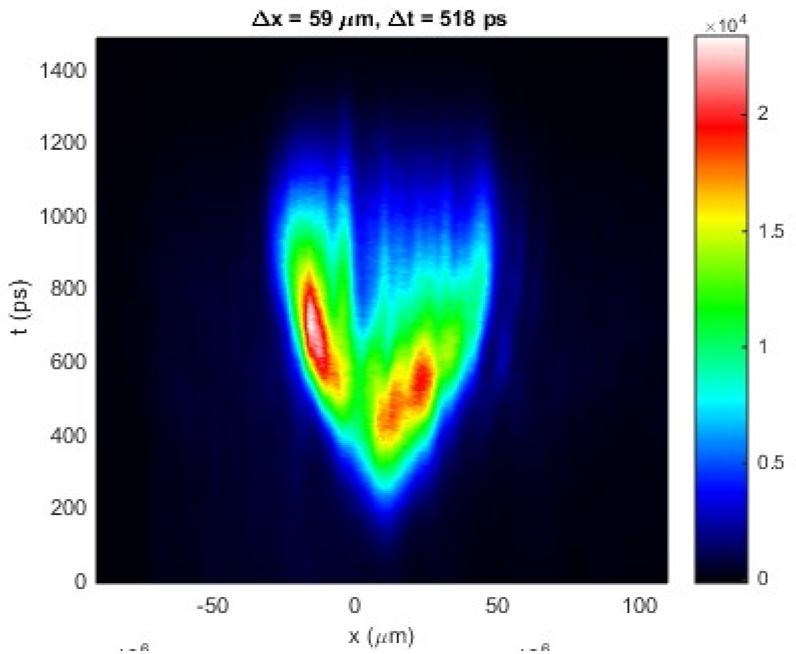
τ_{res} *= 200 ps*

450-ps Pulse Spatial Defocussing

13 mW



1.3 W



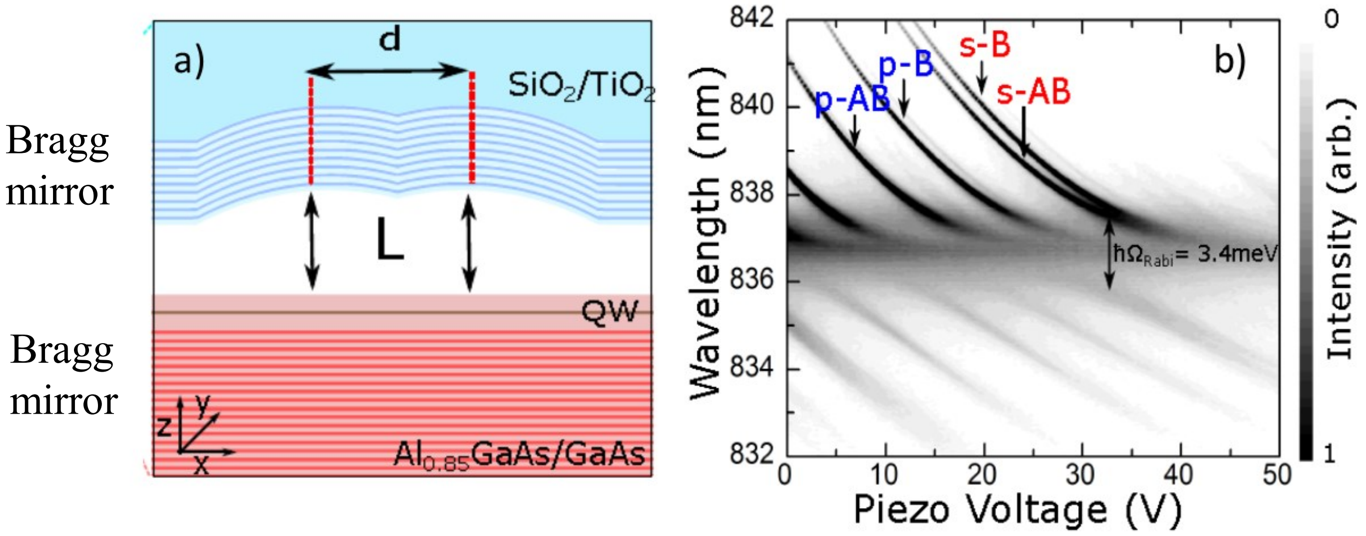
450 ps long pulse

Temporal offset of outer spatial harmonics by 100-200 ps.

Surprisingly tail of the pulse experiences large defocusing

TOWARDS QUANTUM POLARITONS IN LATTICES

Active media- GaAs-based quantum well



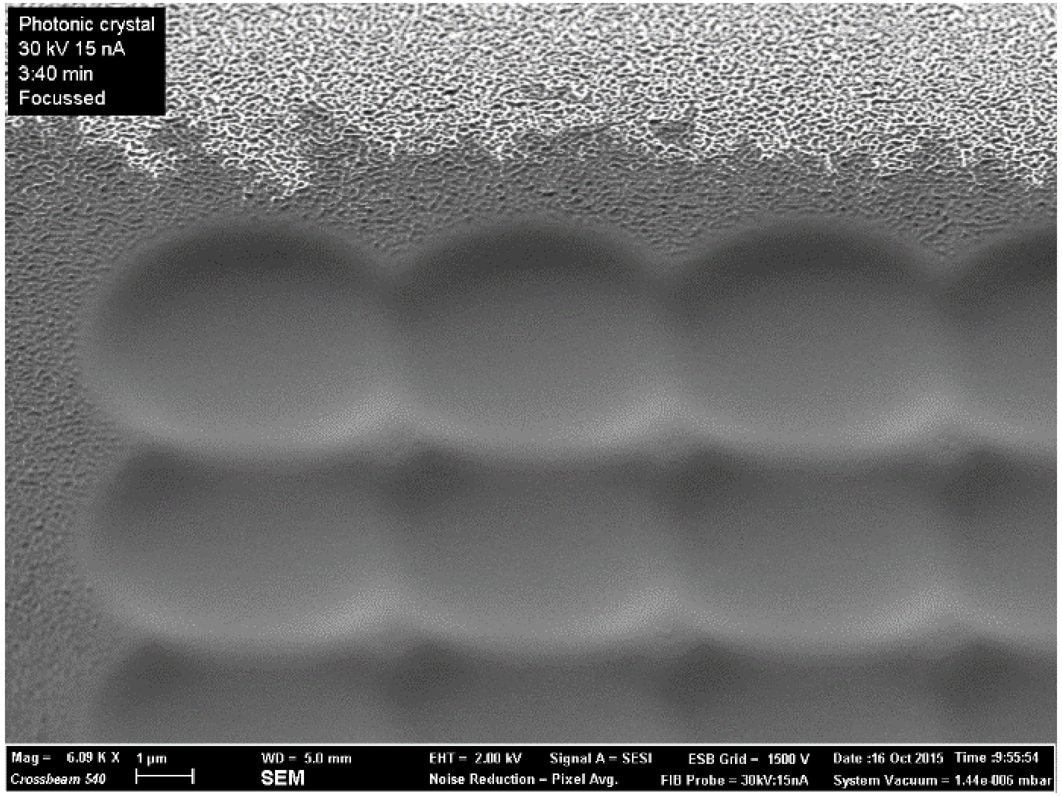
Q-factor ~ up to 150 000 .

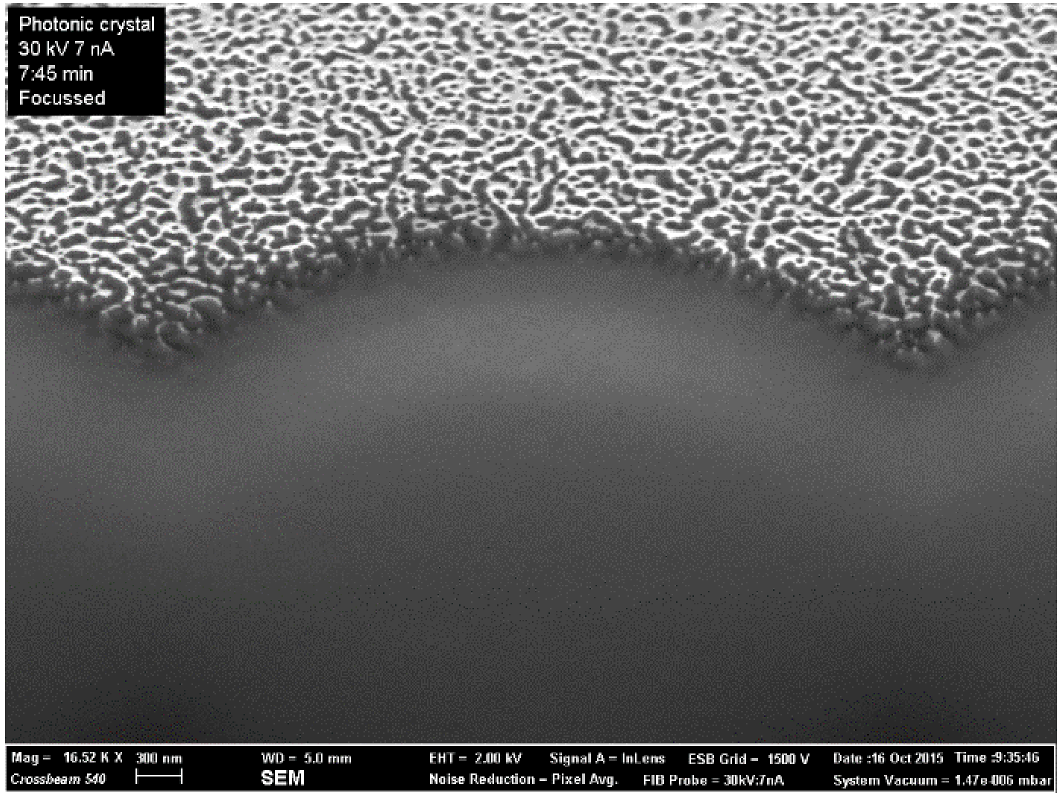
*Dufferwiel, DNK et al Applied Physics Letters 107 (20), 201106 (2015); Phys. Rev. Applied **3**, 014008 (2015)*

Strong **lateral** confinement (~500 nm) => strong polariton-polariton interactions in lattice sites U~20 μeV (maybe further increased up to 100's **μeV**)

Scalable system=> My group in collaboration with J Smith (Oxford) demonstrated high-quality photonic molecules, lattices of 3D boxes in progress.

Fabrication of open MC lattices for topological photonics (Oxford, J Smith’s group)





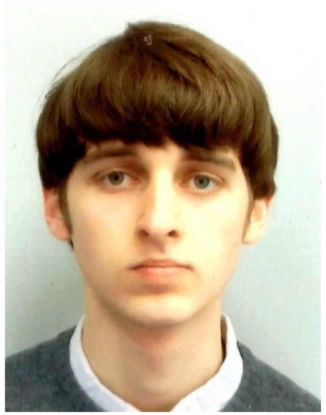
Summary

- Full 2D Lieb lattice of etched micropillars
- Flat bands formed by *S* and *P* orbitals
- Condensation observed in both flat bands and AB band
- Photonic spin-orbit coupling provides pseudospin texture
- Spectral profiles of condensates are spatially-inhomogeneous for flat bands
- Interactions are not very strong and there is effect of reservoir

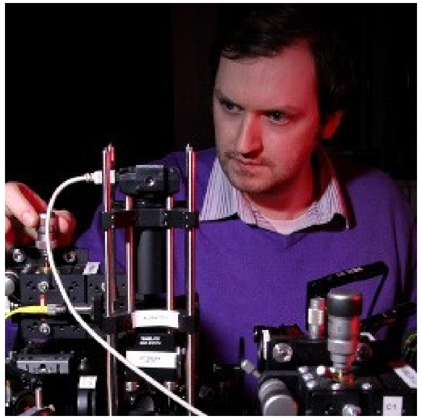
Acknowledgements

The University Of Sheffield.

Experiment



Charles Whittaker (Sheffield)



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Theory

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Prof. D. M. Whittaker (Sheffield)

ITMO, St Petersburg

Ivan Shelykh
Ivan Iorsh

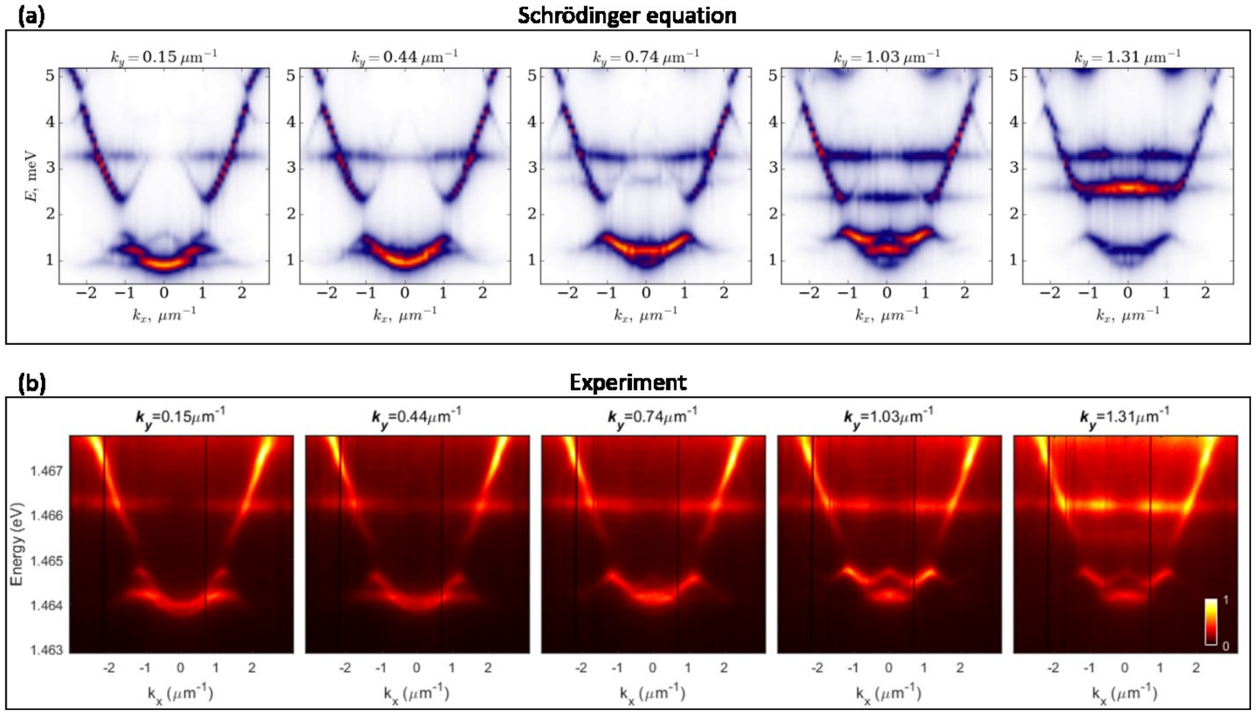
Samples, Sheffield University:
Ed Clarke
Ben Royal
Deivis Vaietikis

Thanks for listening!

Supplementary material

Schrödinger equation

- 10 meV confinement potential
- $m^* = 5x10^{-5}m_0$
- 0.1 meV lifetime



Fourier space emission

S flat band | AB band | *P* flat band

Below threshold

Above threshold