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Complexity and Topology in Quantum Matter

Topological physics with light: Topological edge modes in polariton lattices

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Julius-Maximilians-Universität Würzburg

Chair for Applied Physics







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Complexity and Topology in Quantum Matter

What is “Topological Photonics”?

„Science of Places“ ?! ?

Fundamental Part of Mathematics

Topological Spaces
Homeomorphism?
etc.



„Science of Light“

Opto-Electronics

Devices, Information Technology
Etc.



Topological classes

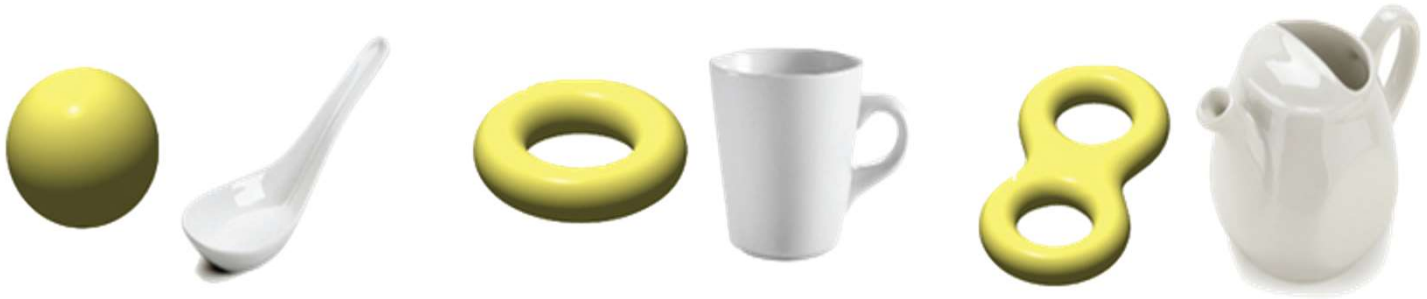


Gauss-Bonnet theorem

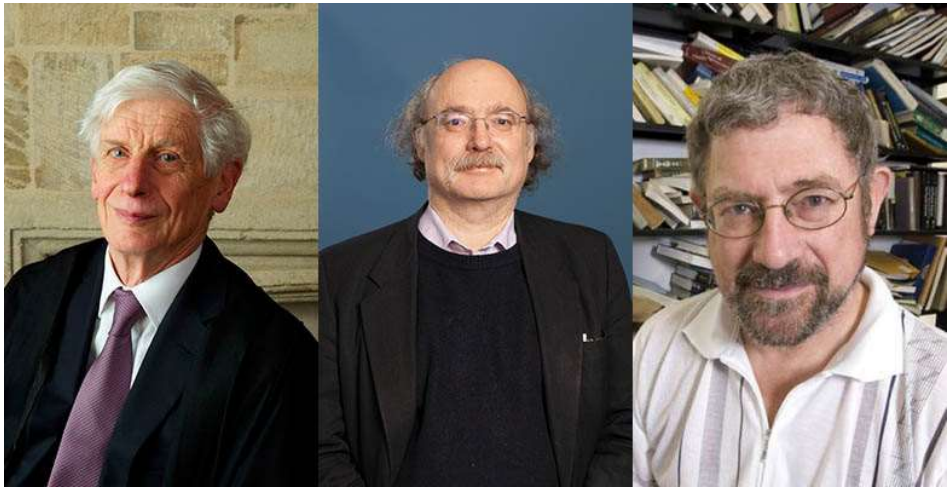
$$\frac{1}{2\pi}\int_S KdA = 2(1-g)$$

number of holes

genus 0 1 2



Nobel Price in Physics 2016





Credits: Trinity Hall/University of Cambridge; Princeton University, Office of Communications, Denise Applewhite; Brown University

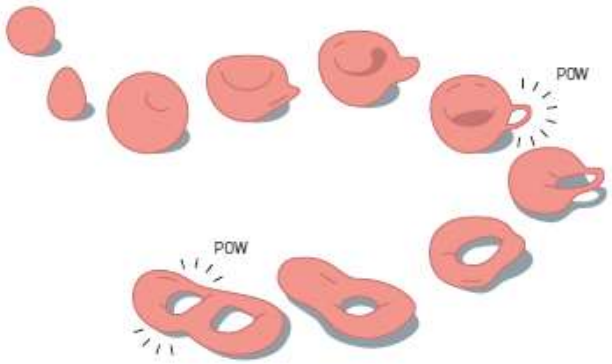
David J. Thouless

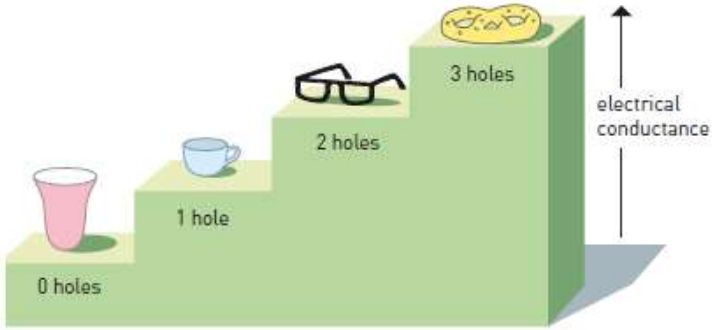
F. Duncan M. Haldane

J. Michael Kosterlitz

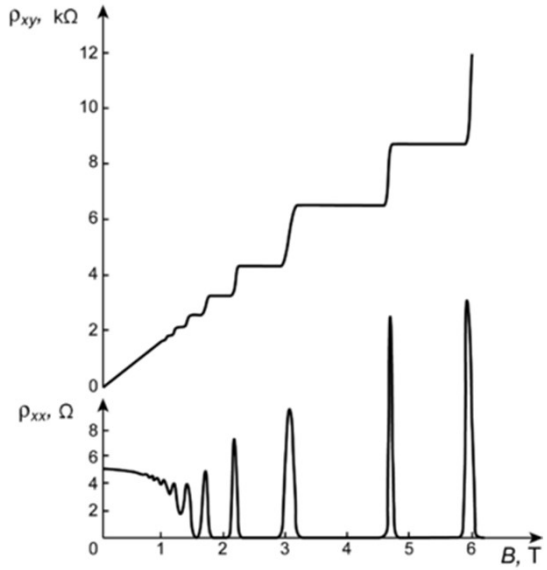
„For theoretical discoveries of topological phase transitions and topological phases of matter.“

Topological Physics



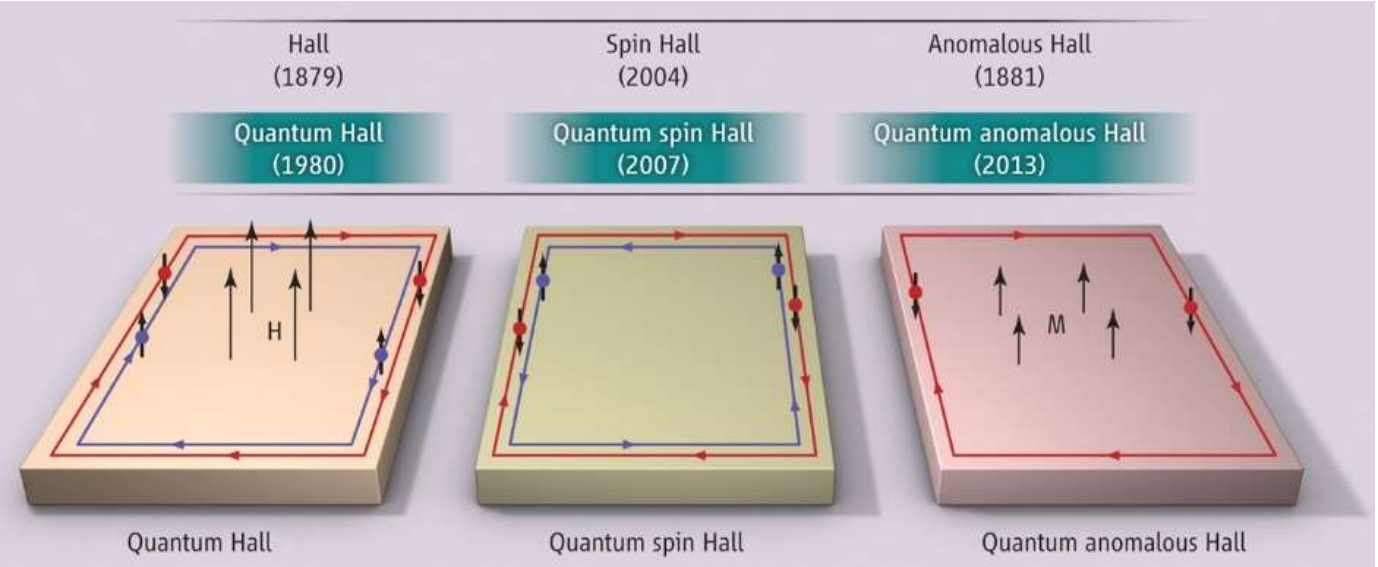


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- Properties change in defined steps.
- A system can be described by a topological order parameter – the topological invariant. These systems are endowed with a form of robustness.

Quantum Hall Physics – Topological Insulators



Seongshik Oh, The Complete Quantum Hall Trio. *Science* **340**, 153-154 (2013)

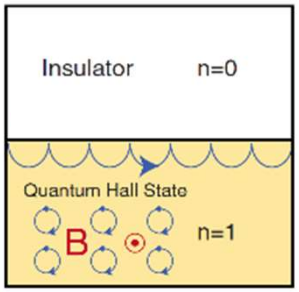


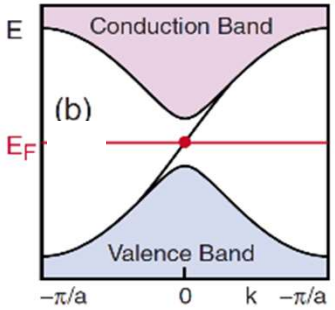
Klitzing 1985, Tsui and Störmer 2010, Geim and Novoselov 2010, Haldane, Kosterlitz and Thouless 2016, …

-> Outlook „Breaking of time-reversal sym.“, „bulk-to-edge correspondence“

Topological physics
The beginnings

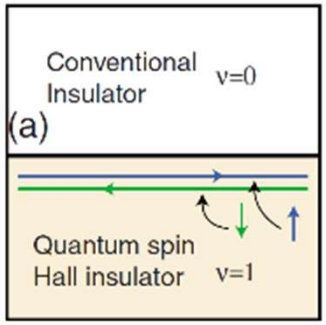
Quantum Hall effect

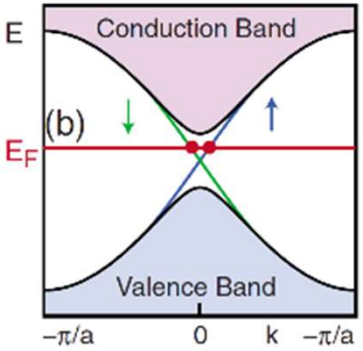


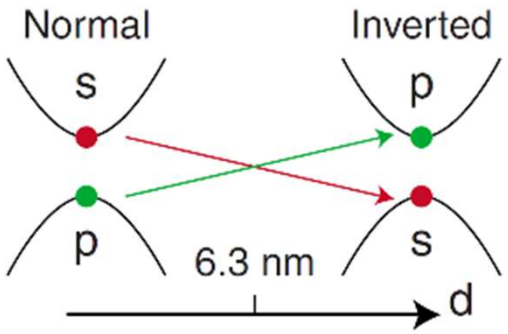


K. v. Klitzing, et al. *Phys. Rev. Lett.* **45**, 494 (1980).
M. Z. Hasan, C. L. Kane. *Rev. Mod. Phys.* **82**, 3045 (2010).

Quantum spin Hall effect







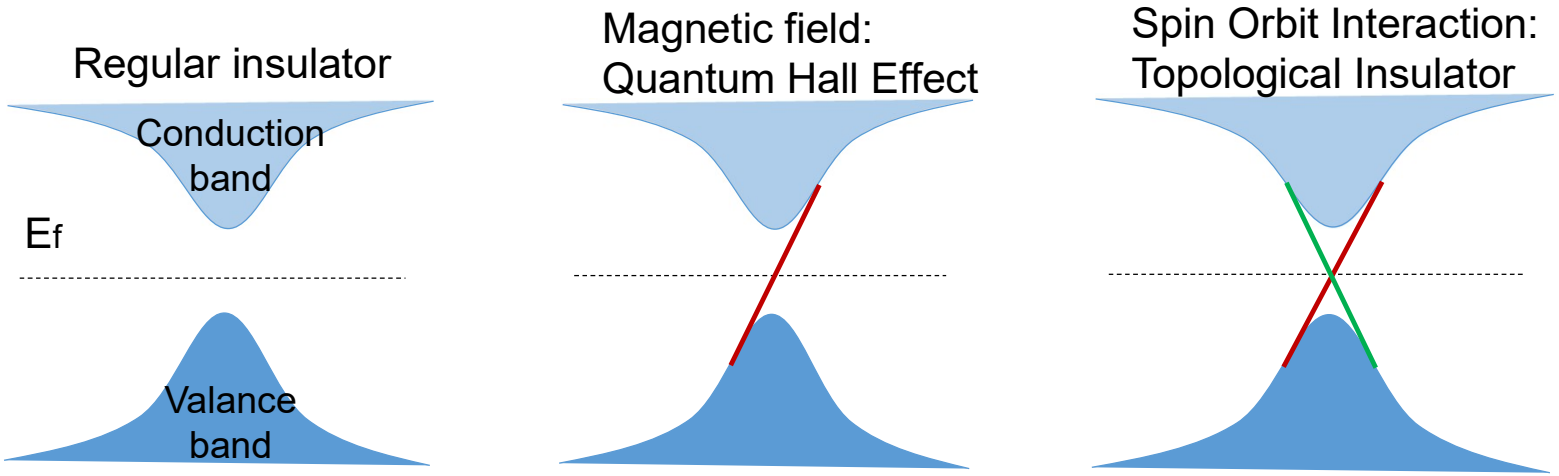
B. A. Bernevig, et al. *Science* **314**, 1757 (2006).
M. König, et al. *Science* **318**, 766 (2007).

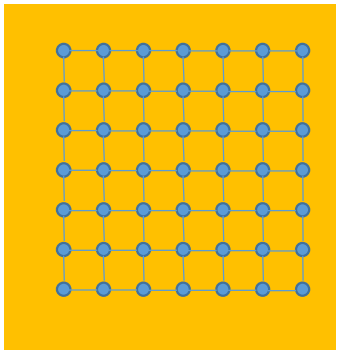
- Edge conductance only
- Protection against back-scattering and scattering into the bulk
- Robustness against local defects
- Chirality





What are Topological insulators?





Main characteristics:

- Edge conductance only
- Immune to scattering/defects:
  - No back-scattering
  - No scattering into the bulk

Only for Topological insulators:

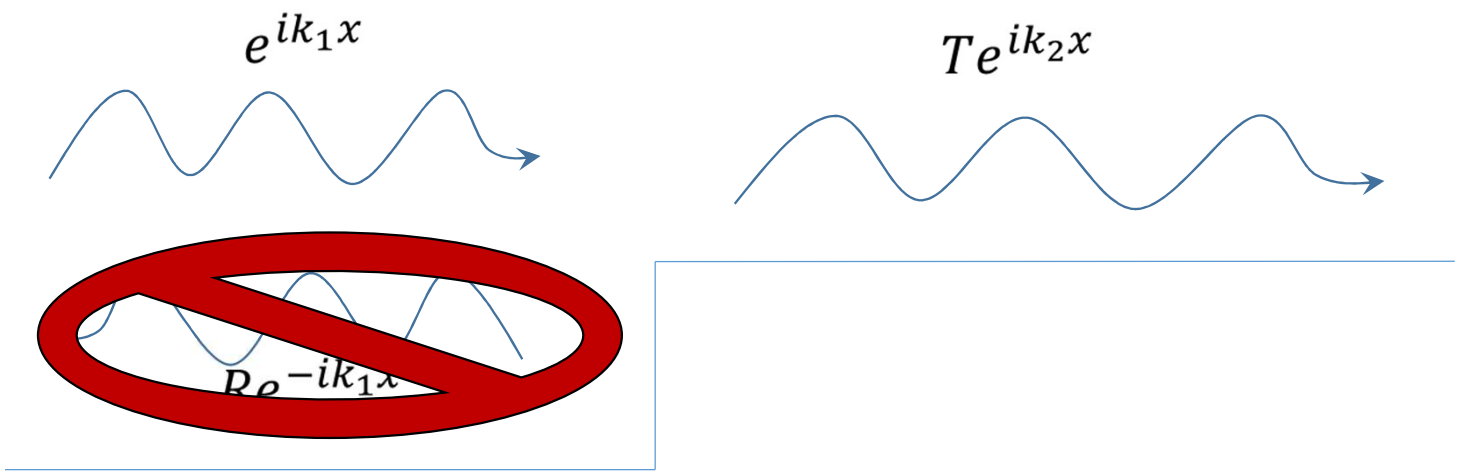
- No need for external fields

Von Klitzing

Kane and Mele, PRL (2005)

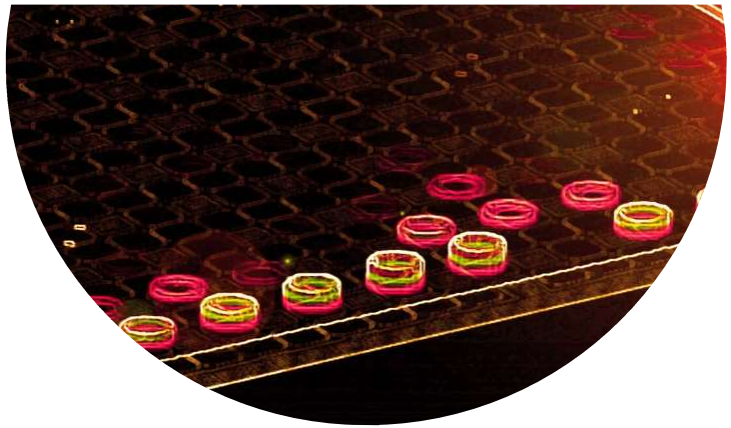
Slide courtesy of Moti Segev

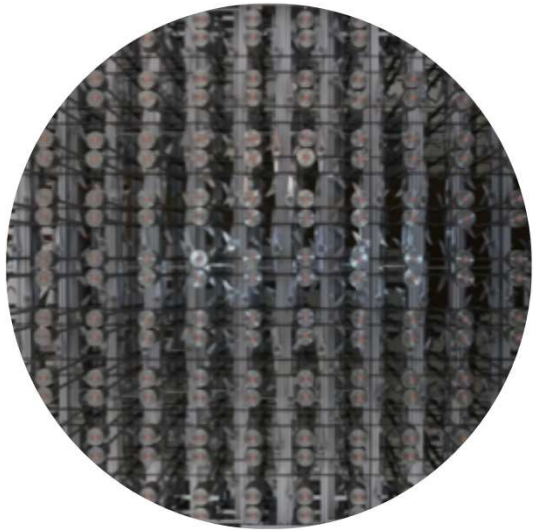
Motivation: No back scattering

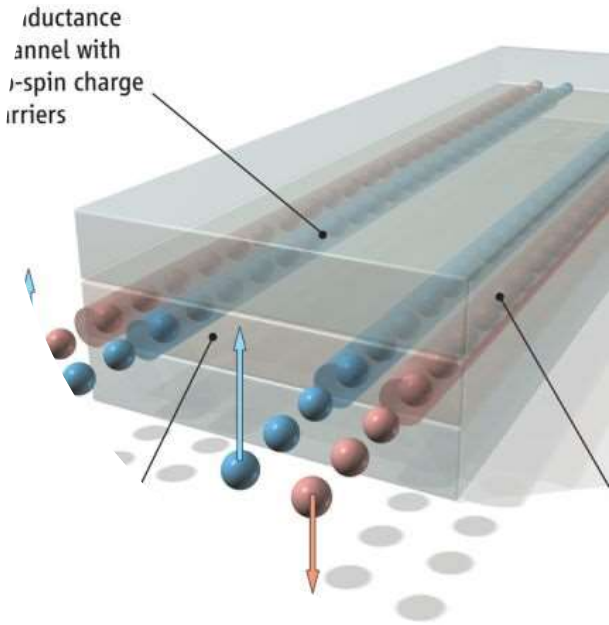


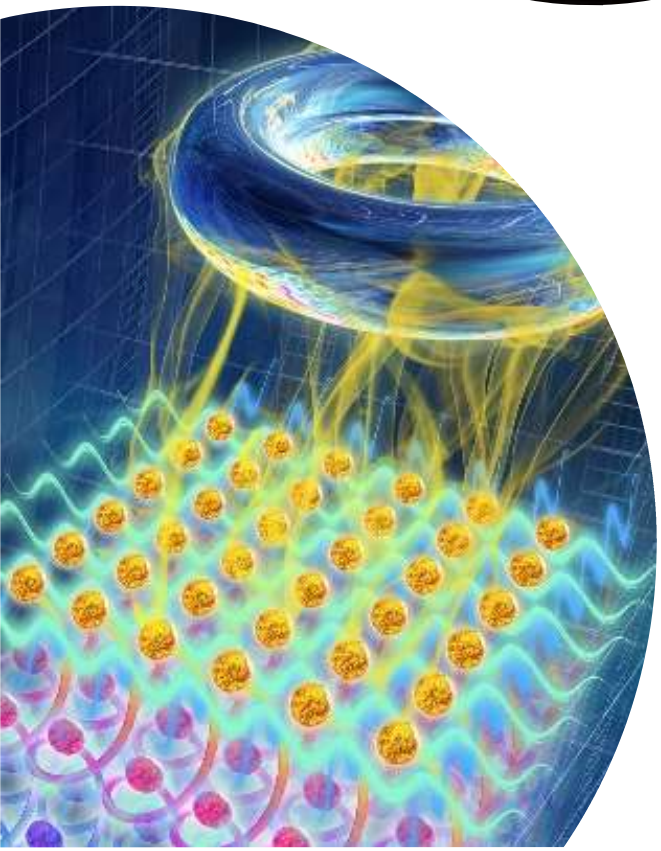
No back scattering → Robust transport!

Slide courtesy of Moti Segev

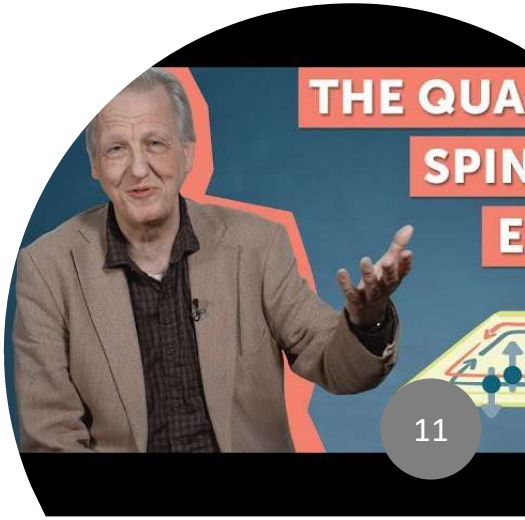






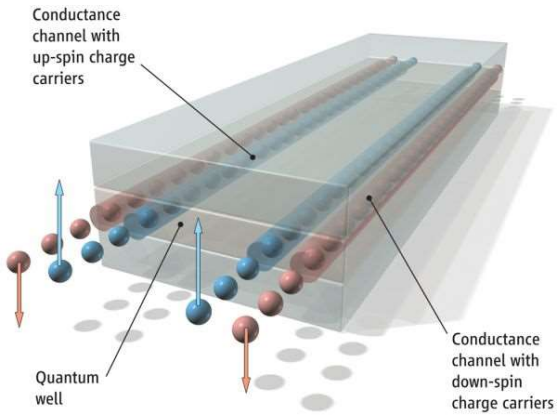


Topological physics: a broad field of research



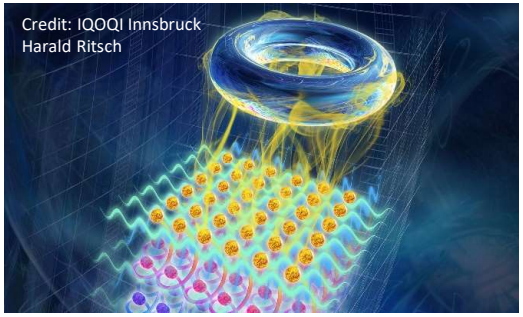
Topological physics
The platforms

Transport physics
Quantum spin Hall effect



B. A. Bernevig, et al. *Science* **314**, 1757 (2006).
M. König, et al. *Science* **318**, 766 (2007).

Cold atoms
Topological Haldane model



G. Jotzu, et al. *Nature* **515**, 237 (2014).
M. Aidelsburger, et al. *Nat. Phys.* **11**, 162 (2015).
D. T. Tran, et al. *Science Advances* **3**, e1701207 (2017).

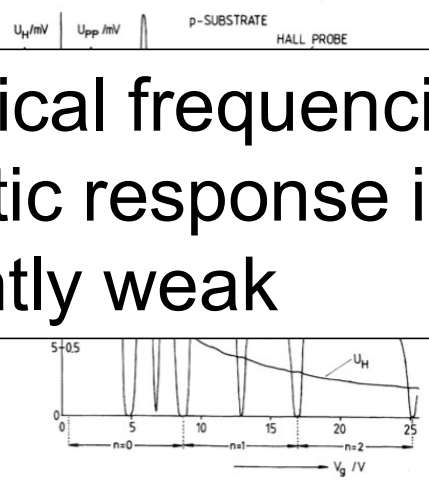
Mechanical systems
Phononic helical edge states



C. L. Kane & T. C. Lubensky *Nat. Phys.* **10**, 39 (2014).
R. Süsstrunk and S. Huber *Science* **349**, 47 (2015).

Towards topological photonics

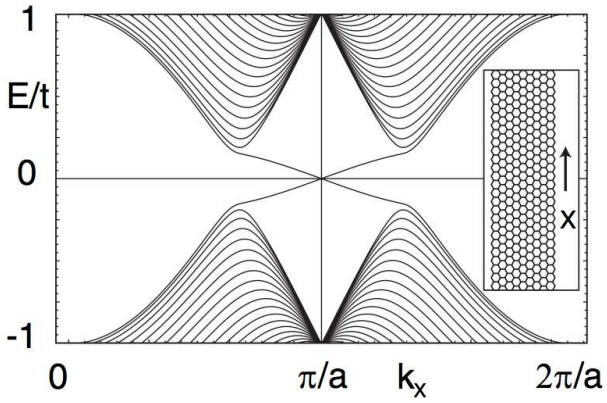
Quantum hall



von Klitzing et. al., PRL (1980)

For optical frequencies, magnetic response is inherently weak

No magnetic field Topological Insulator



Kane and Mele, PRL (2005)

We need a type of Kane-Mele transition, but how, without Kramers' degeneracy ?

(1) Hafezi, Demler, Lukin, Taylor, Nature Phys. (2011): aperiodic coupled resonator system
(2) Umucalilar and Carusotto, PRA (2011): using polarization as spin in PCs
(3) Fang, Yu, Fan, Nature Photon. (2012): electrical modulation of refractive index in PCs
(4) Khanikev et. al. Nature Mat. (2012): birefringent metamaterials

Slide courtesy of Moti Segev

Topological photonics

Experimental realizations in diverse range of platforms

PRL 100, 013904 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

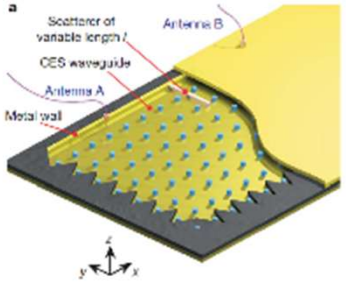
Possible Realization of Directional Optical Waveguides in Photonic Crystals with Broken Time-Reversal Symmetry

F. D. M. Haldane and S. Raghu*

Department of Physics, Princeton University, Princeton, New Jersey 08544-0708, USA

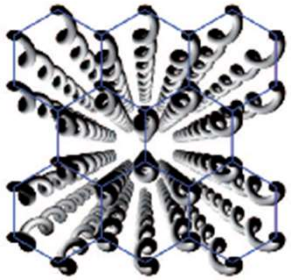
(Received 23 March 2005; revised manuscript received 30 May 2007; published 10 January 2008)

Microwaves



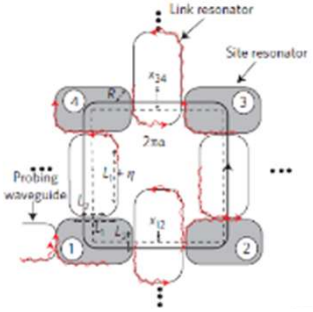
Z. Wang, et al. *Nature* **461** , 772 (2009).

Floquet Waveguides



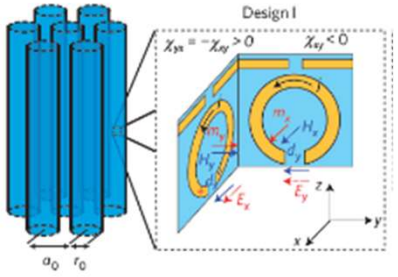
M. C. Rechtsman, et al. *Nature* **496**, 196 (2013).

Silicon Photonics



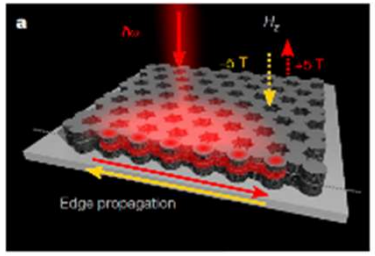
M. Hafezi, et al. *Nat. Phys.* **7**, 907 (2011).
M. Hafezi, et al. *Nat. Photon.* **7**, 1001 (2013).

Metamaterials



A. B. Khanikaev, et al. *Nat. Mater.* **12**, 233 (2013).

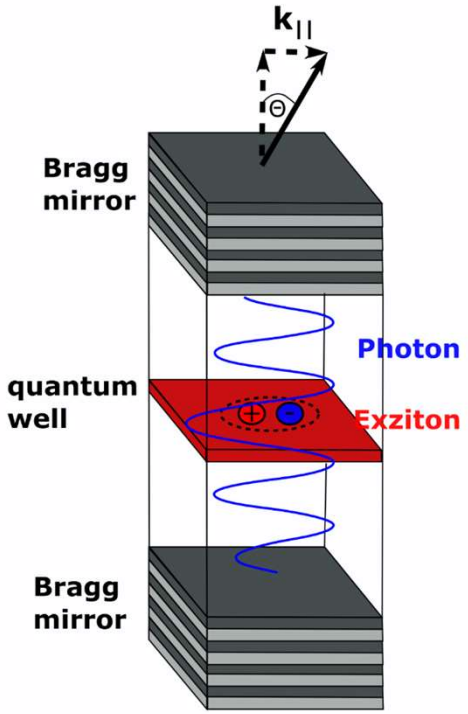
Exciton-Polaritons

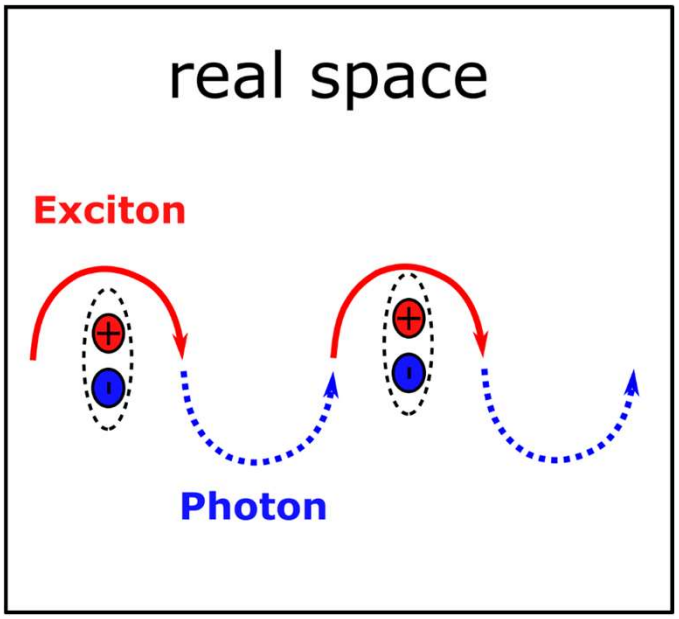


S. Klembt, et al. *Nature* **562**, 552 (2018).

Microcavity Exciton-Polaritons

Strong light-matter coupling in a microcavity





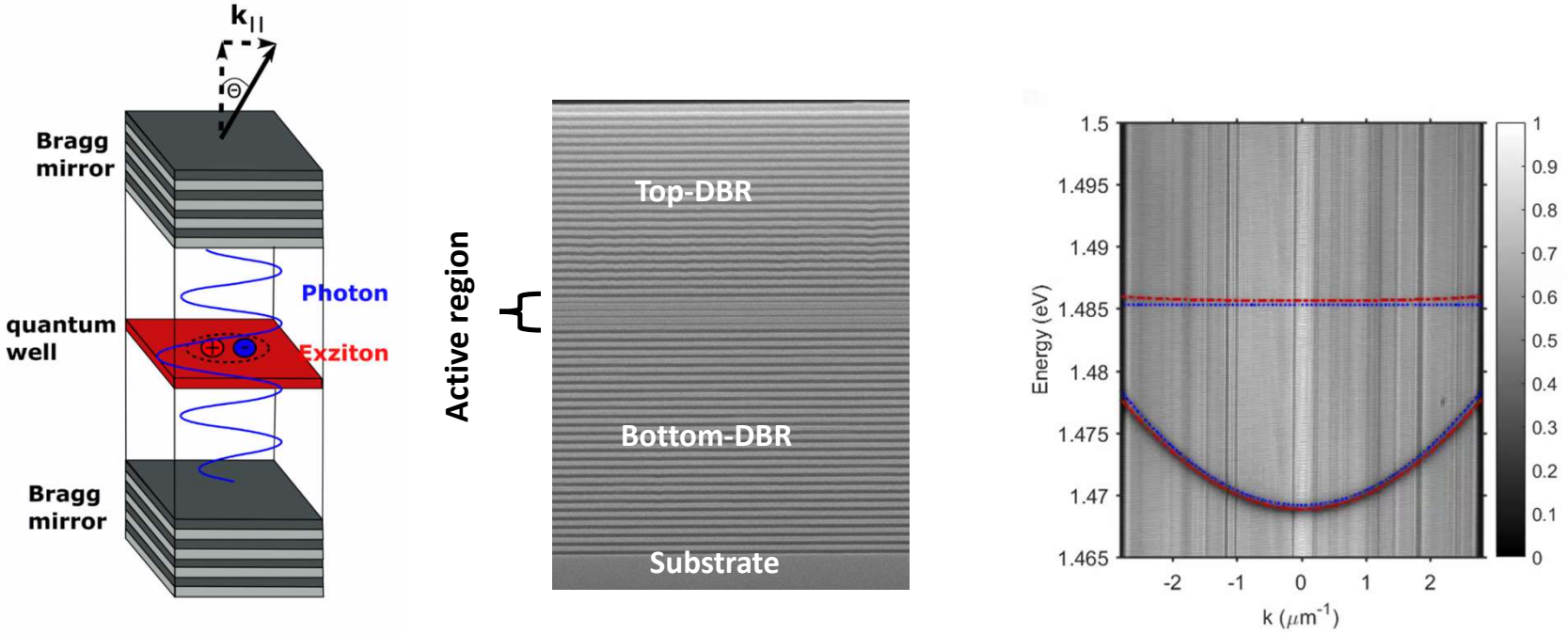
- Experimental system: exciton hosting material embedded in cavity

- Described by coupled oscillator equation:

$$\begin{bmatrix} E_C + i\hbar\Gamma_C & \hbar\,\Omega/2 \\ \hbar\,\Omega/2 & E_X + i\hbar\Gamma_X + \Delta \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = E \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

Microcavity Exciton-Polaritons

Strong light-matter coupling in a microcavity



- Experimental system: exciton hosting material embedded in cavity.
- Dipole coupling leads to normal mode splitting of the resonance

C. Weisbuch, et al. *Phys. Rev. Lett.* **69**, 3314 (1992)

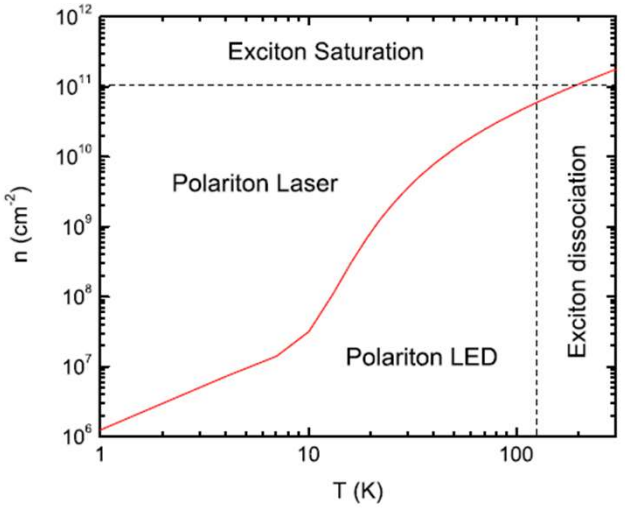
$$\begin{bmatrix} E_C + i\hbar\Gamma_C & \hbar\,\Omega/2 \\ \hbar\,\Omega/2 & E_X + i\hbar\Gamma_X + \Delta \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = E \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

Microcavity Exciton-Polaritons

Strong light-matter coupling in a microcavity

- **Bosonic system → Cavity-Polariton Physics**
- Hybridization of the dispersions:
  Polaritons as low-mass bosons
- Quasi-particle: part light / part matter
- $k_{||} = \omega/c \quad \sin(\theta)$ - directly measurable
- Light eff. Mass: $m_{pol} = 10^{-5} m_e = 10^{-9} m_{Rb}$
- Matter part gives rise to large nonlinearity

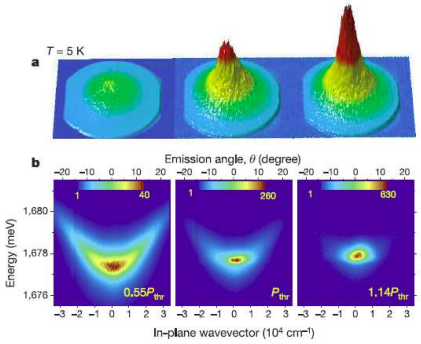
→ Testbed for condensation at elevated temperatures!



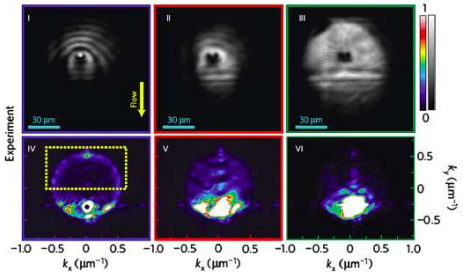
Kavokin et al. Microcavities, Oxford (2006)

Polaritonics – Quantum Fluids of Light

Strong light-matter coupling in a microcavity

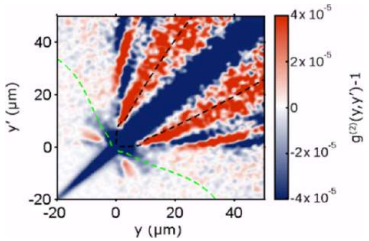


Polariton BEC – Laser-like emission:
J. Kasprzak et al., *Nature* **443**, 409 (2006)



Superfluidity:
A. Amo et al., *Nat. Phys.* **5**, 805 (2009)

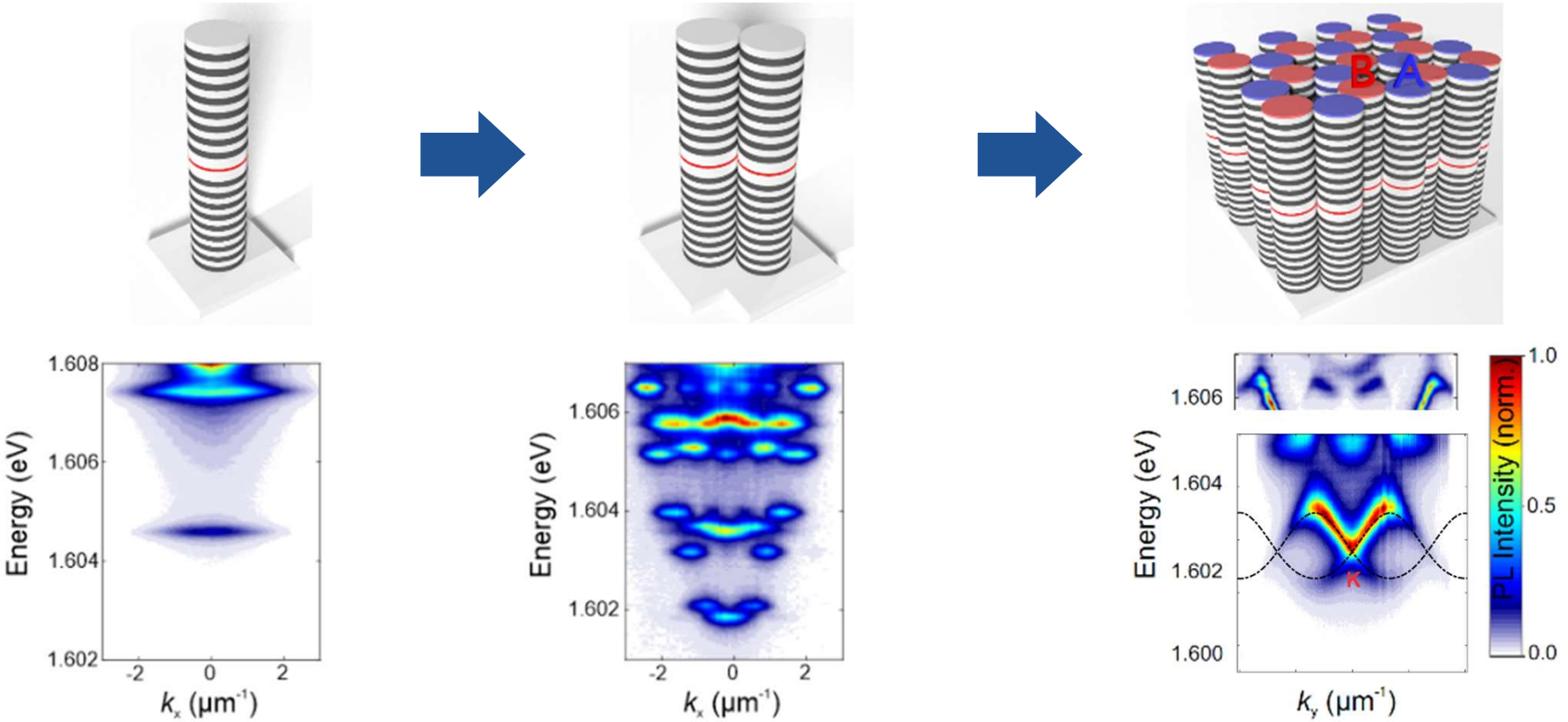
I. Carusotto and C. Ciuti
Rev. Mod. Phys. **85**, 299 (2013)
„Quantum fluids of light“



Black hole analogues:
H. S. Nguyen,et al., *Phys. Rev. Lett.* **114**, 036402 (2015)

Microcavity lasers

VCSEL arrays



Coupling micropillars into arrays

Bloch-Theorem

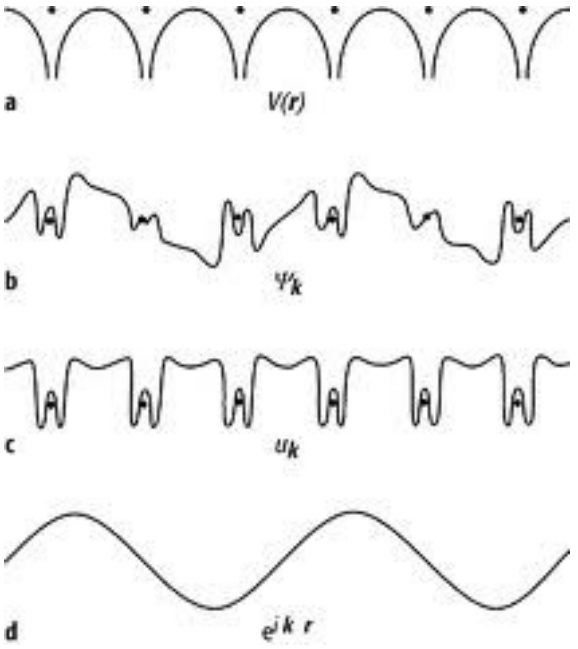
Kristallpotential: U(r)=U(r+R)

Theorem: $\psi(r+R) = e^{ikR}\psi(r)$

Blochfunktion: $\psi(r) = u_k e^{ikr}\ mit\ u_k(r+R) = u_k(r)$

$$u_{\vec{k}}(\vec{r}) = \sum_n a_{n,\vec{k}} \left| n \right\rangle$$

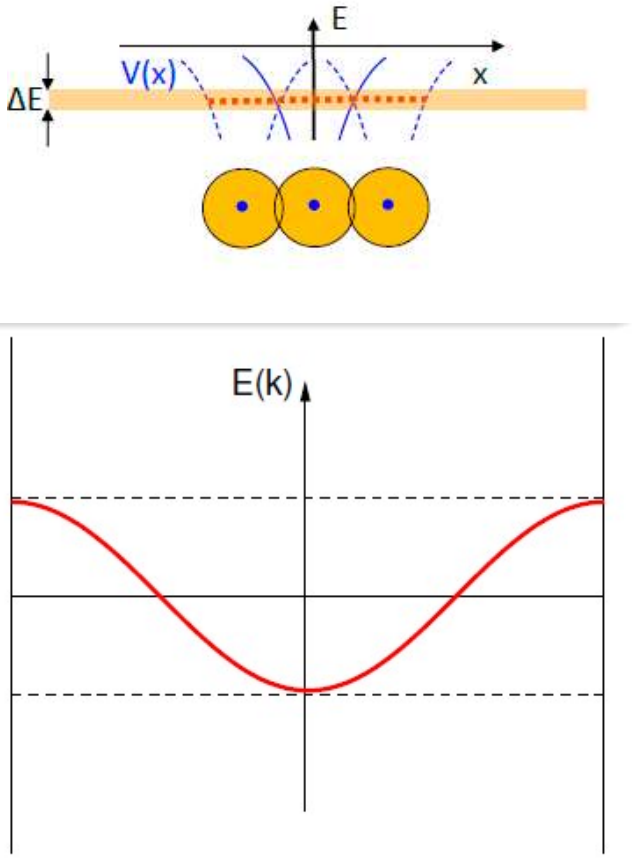
Linear combination of atomic WF



Tight binding ‚light‘

- Electrons are strongly bound to 'their' crystal atom. Interaction only with nearest neighbors.
- Suitable for shell electrons (valence band), that is, electrons that are strongly bound to the atoms.

Here, too, an energy band is created around the atomic energy levels ...

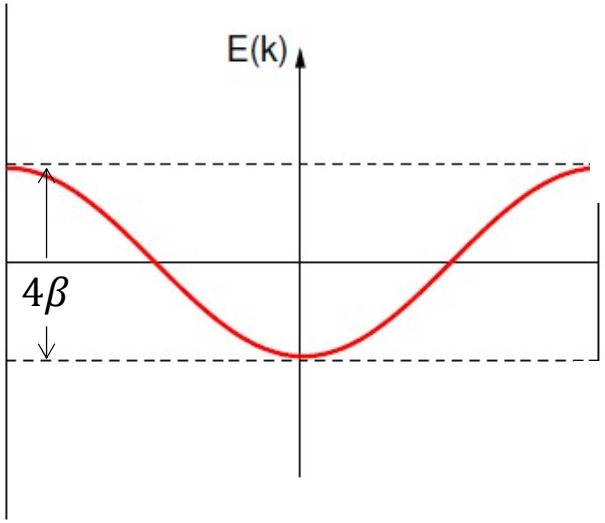


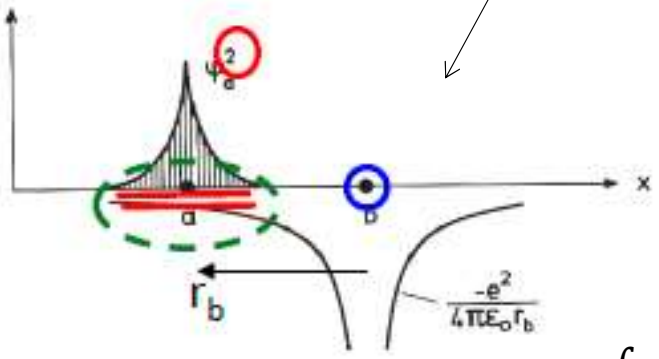
Dispersion relation

With $H = H_{at}(r - R_i) + \Delta V$

$E(k) = E_0 - \alpha - 2\beta\cos(kR)$

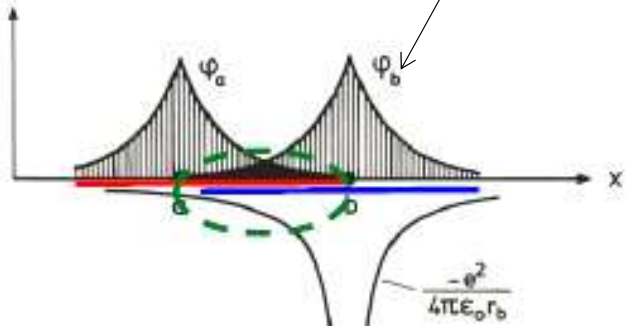
$\alpha = \int dV\ \phi(r)\Delta V\phi(r)$



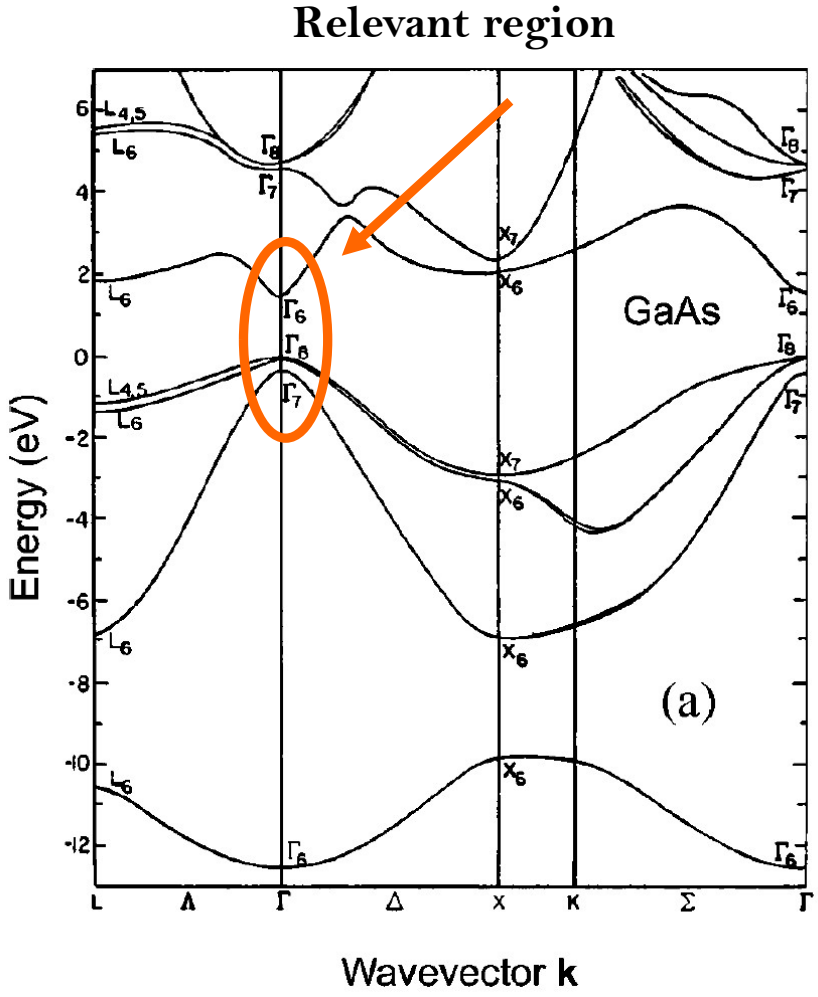


$E_o - \alpha$

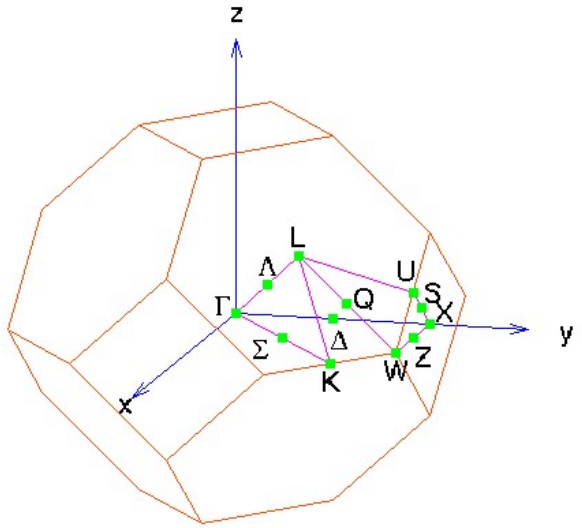
$\beta = \int dV\ \phi(r - R)\Delta V\phi(r)$



Band structure of GaAs



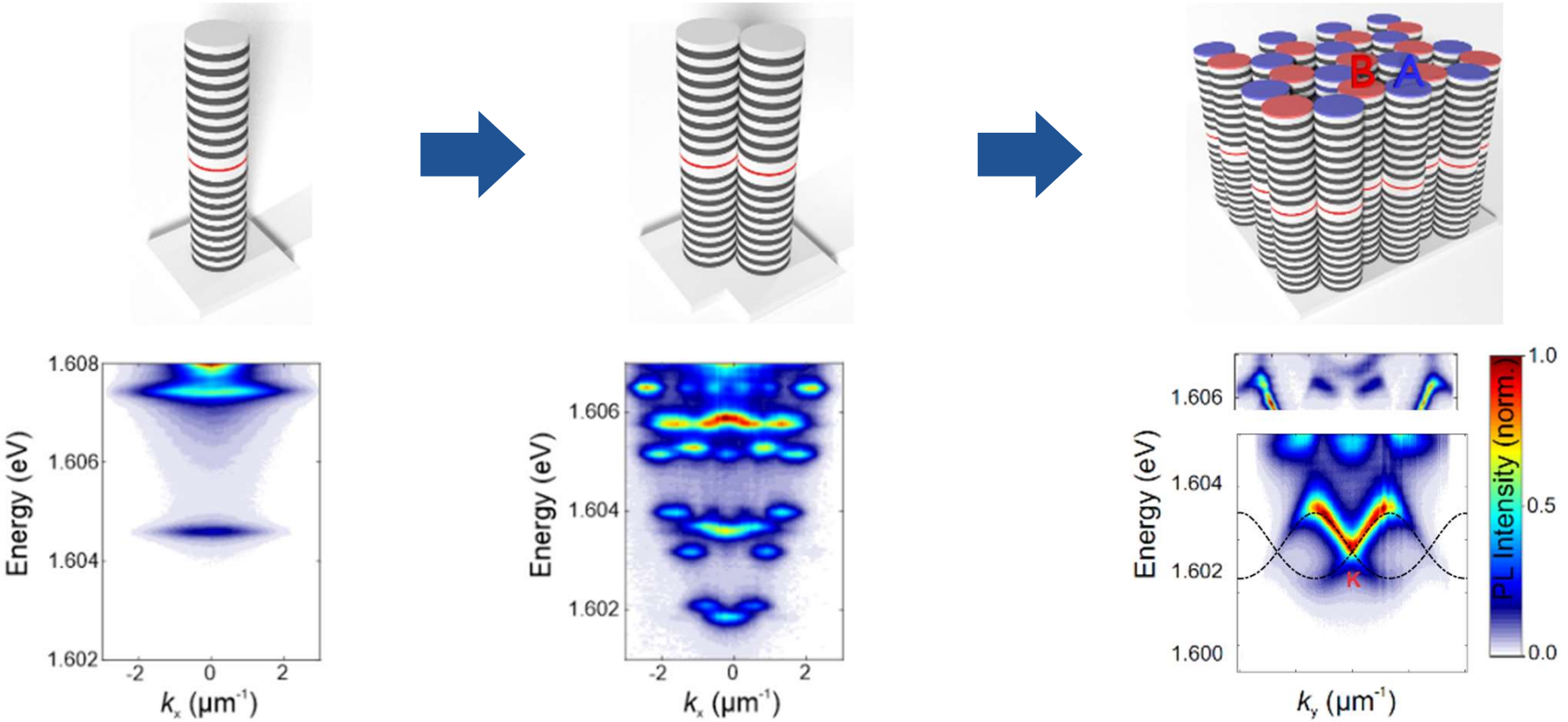
Display along distinct crystal directions



1. BZ of fcc-lattice

Microcavity lasers

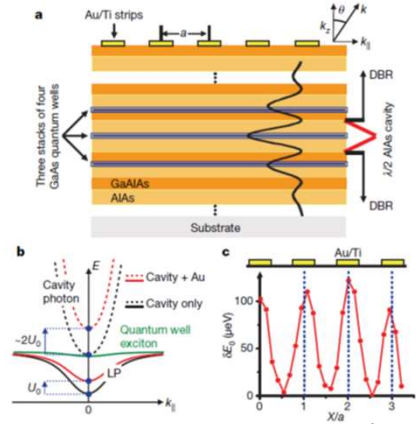
VCSEL arrays



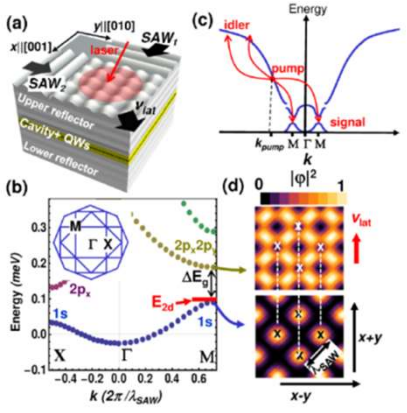
Coupling micropillars into arrays

Polariton lattices (2D)

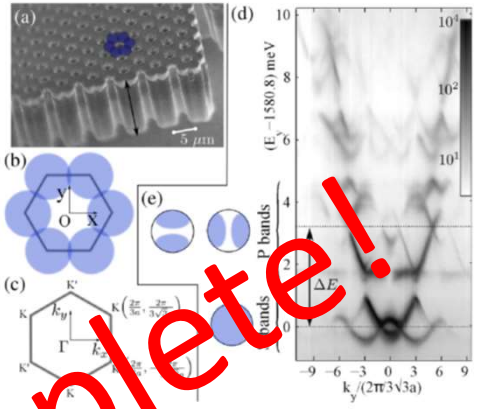
Experimental realizations in diverse range of platforms



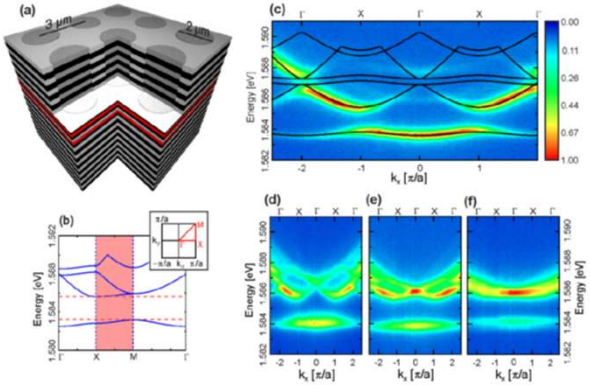
C. W. Lai et al., *Nature* **450**, 529 (2007).



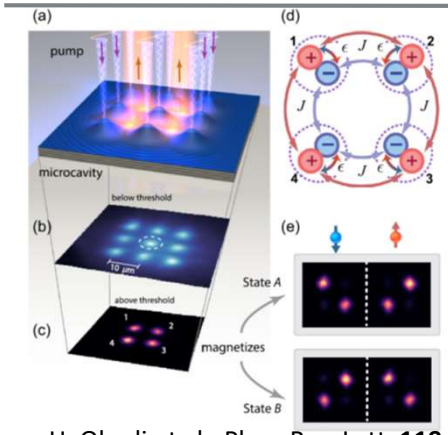
E. A. Cerda-Méndez et al., Phys. Rev. Lett. **111**, 146401 (2013).



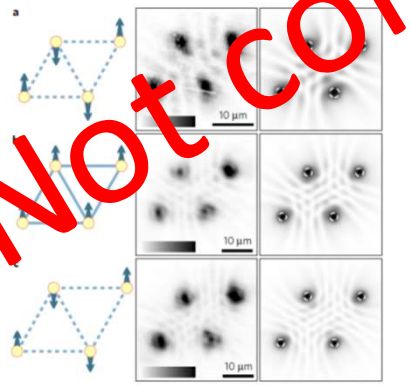
T. Jacqmin et al., Phys. Rev. Lett. **112**, 116402 (2014)



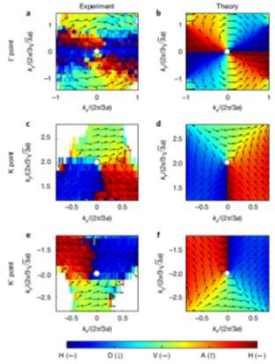
K. Winkler et al., New J. Phys. **17**, 023001 (2015).



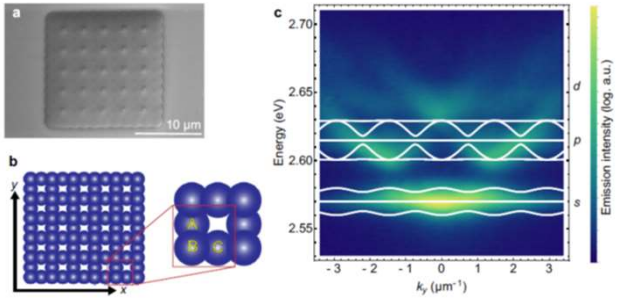
H. Ohadi et al., Phys. Rev. Lett. **119**, 067401 (2017).



N. G. Berloff et al. Nature Materials **16**, 1120 (2017).



C. E. Whittaker et al. *Nature Photonics* ***15***, 193 (2021).

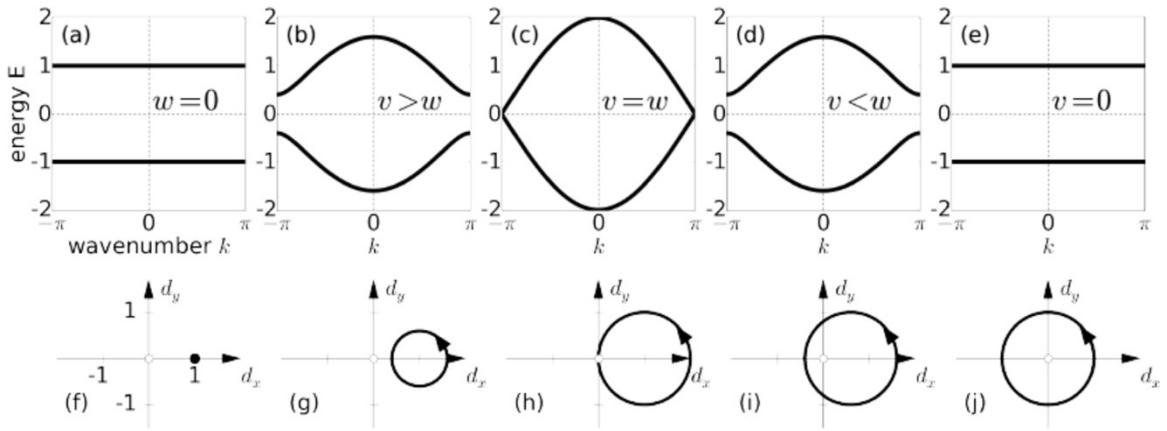


F. Scafirimuto et al., Commun. Phys. **4**, 39 (2021).

Not complete!

Considering simple topological bandstructures

Su-Schrieffer-Heeger



Inducing a (weak-weak) defect (ABABAABABA) leads to protected state in the topological gap!

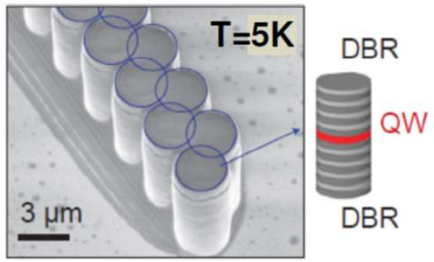
J.K. Asbóth et al., A Short Course on Topological Insulators: Band-structure topology and edge states in one and two dimensions. Lecture Notes in Physics, 919 (2016). (Preprint free on arXiv)

SSH topological defect

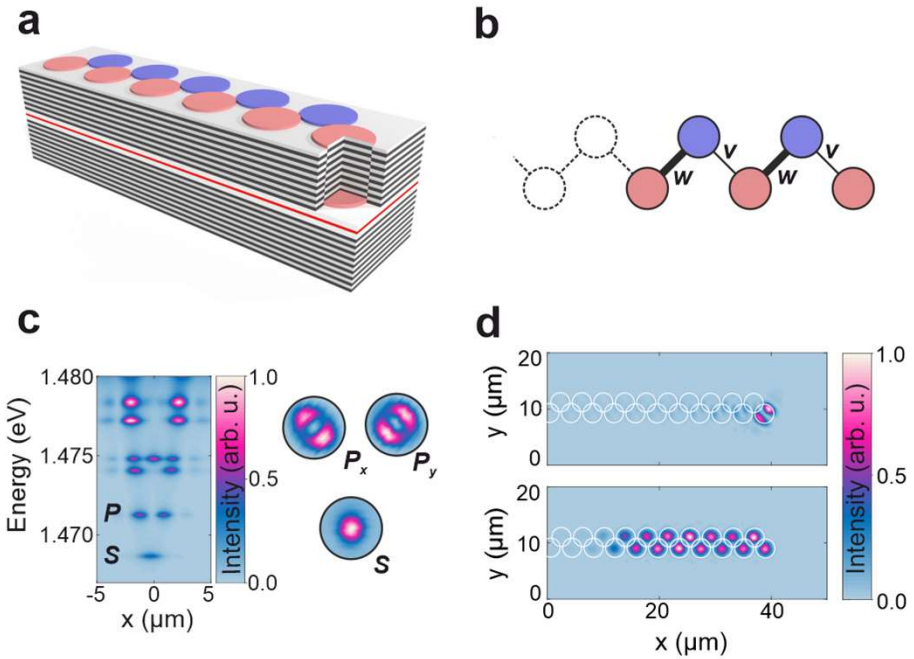
Su-Schrieffer-Heeger



Dimere coupling in the p-mode



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

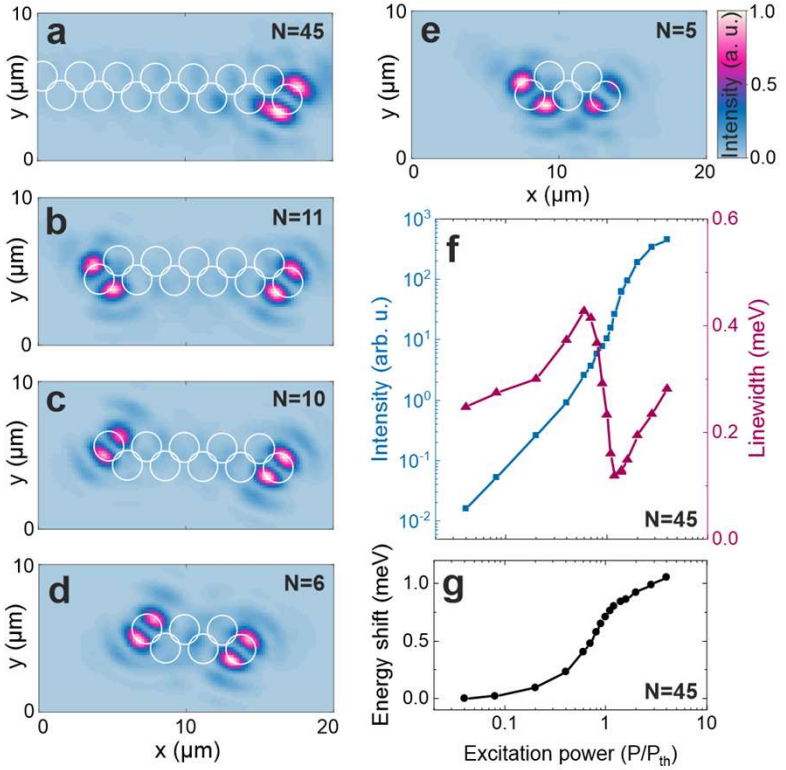


- Orbital SSH model, resulting from p_x- and p_y-modes.

T. Harder, S.K. et al., ACS Photonics **8**, 1377 (2021).

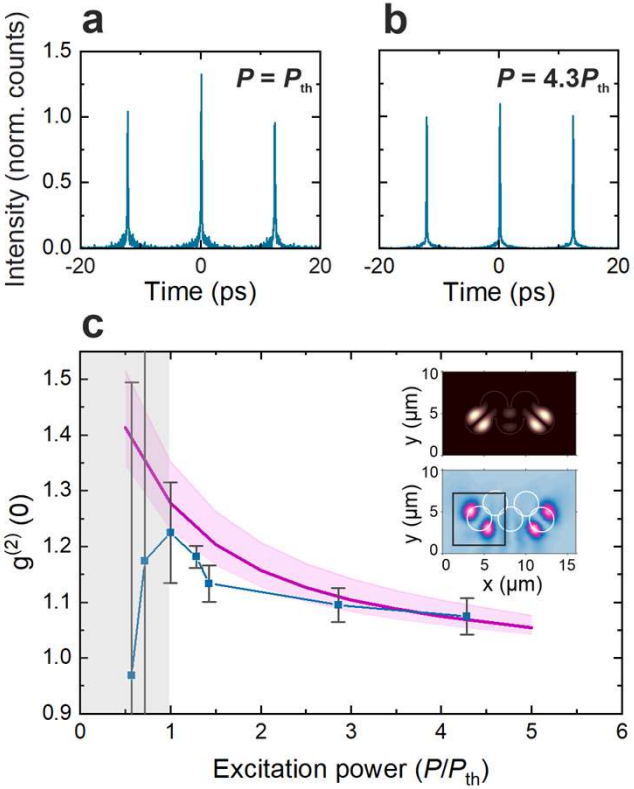
Coherent topological laser

Su-Schrieffer-Heeger



$$g^{(2)}(0) = \frac{\langle I^2(t)\rangle}{\langle I(t)\rangle^2}$$

$$g^{(2)}_{SSH}(0) \approx 1.07$$

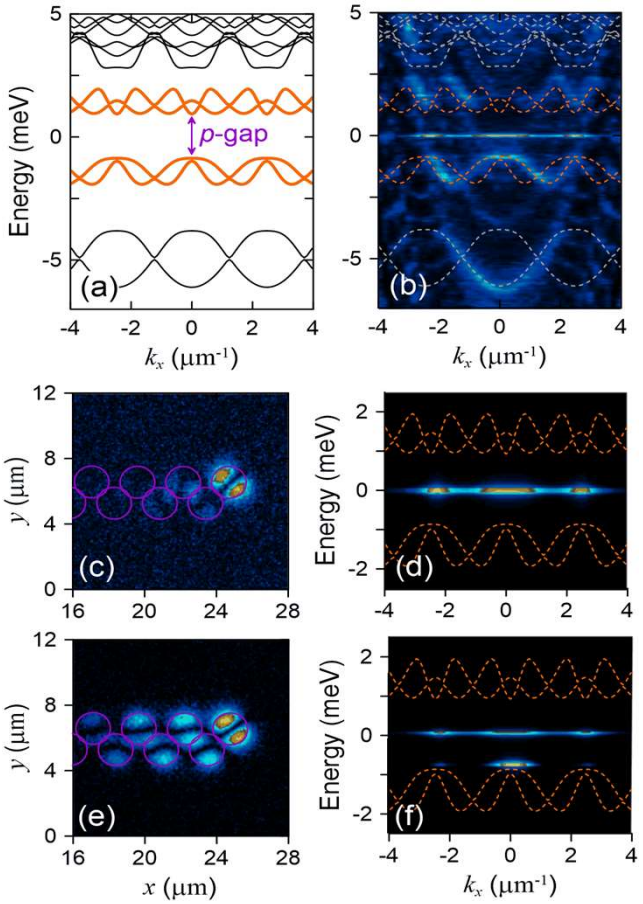


- Coherent laser emission from topo. edge mode.
- Temporal correlation measurement (HBT) reveals coherent laser emission.

T. Harder, S.K. et al., ACS Photonics **8**, 1377 (2021).

Coherent topological laser

Theory: Eigenvalue problem with 2D photonic potential



Model:

- *Modified Gross-Pitaevkii Model*
- *Incoherent Reservoir*
- Condensation of many-body-system in external potential!

$$i\hbar\frac{d}{dt}\Psi(\boldsymbol{r},t)=\left(\underbrace{-\frac{\hbar^2}{2\,m^*}\nabla_{\parallel}^2}_{\text{Density/ Velocity}}+\underbrace{V(\boldsymbol{r},t)}_{\text{Potential}}-\underbrace{i\hbar\frac{\gamma}{2}}_{\text{Decay}}+\underbrace{g|\Psi(\boldsymbol{r},t)|^2}_{\text{Interaction}}\right)\Psi(\boldsymbol{r},t)+\underbrace{F_p(\boldsymbol{r},t)}_{\text{Pump}}$$

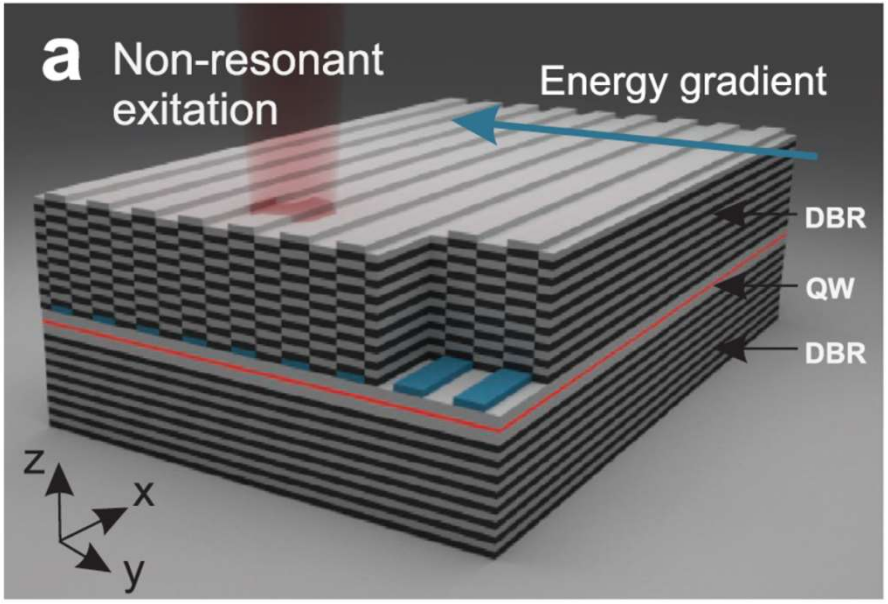
T. Harder, S.K. et al., ACS Photonics **8**, 1377 (2021).

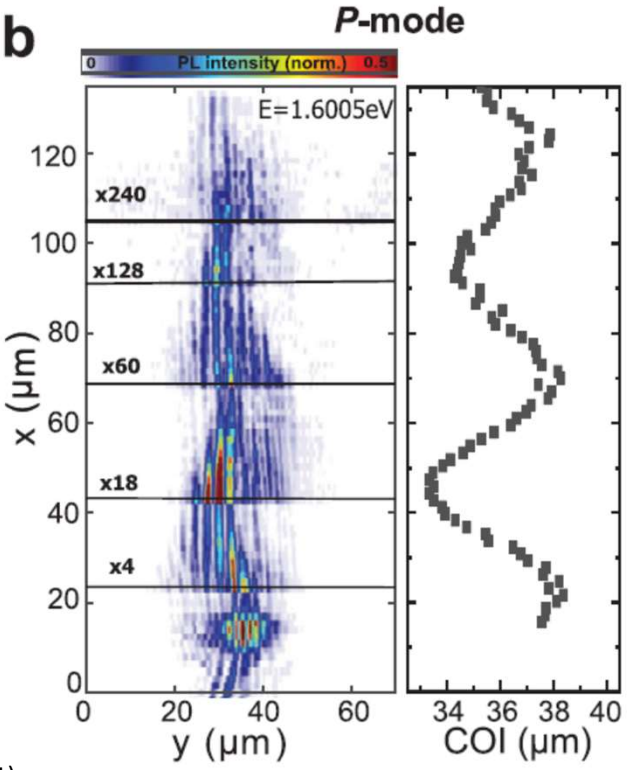
Polariton propagation

In plane – out of plane

- Polariton propagation in-plane
- Monitoring polaritons through dissipation normal to sample surface
- Example: Bloch-Oscillations in gradient waveguides





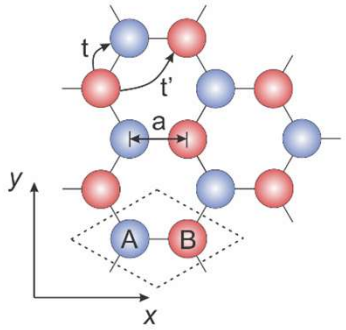


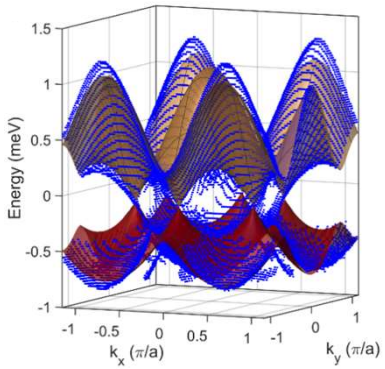
J. Beierlein, S.K. et al. Adv. Optical Mater. ***9***, 2100126 (2021).
Josephson-like oscillations -> J. Beierlein, S. K. et al., Phys. Rev. Lett. 126, 075302 (2021).

Honeycomb Lattice

Designing polariton graphene

Tight-binding Model



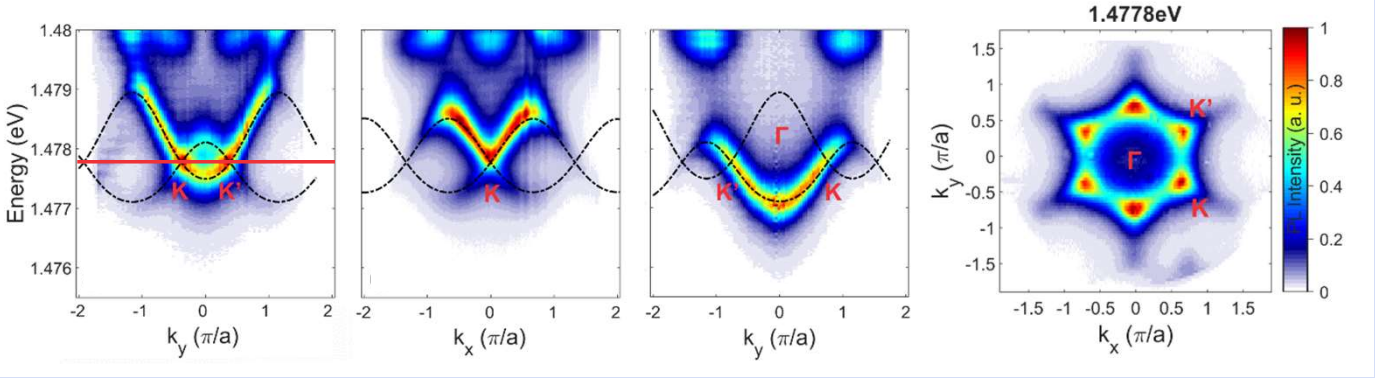


$$E(k) = \pm t\sqrt{3 + f(k)} - t' f(k)$$

$$f(k) = 2\cos(\sqrt{3}k_y a) + 4\cos\left(\frac{\sqrt{3}}{2}k_y a\right)\cos\left(\frac{3}{2}k_x a\right)$$

- Visualisation of six Dirac cones
- Good agreement with tight binding model

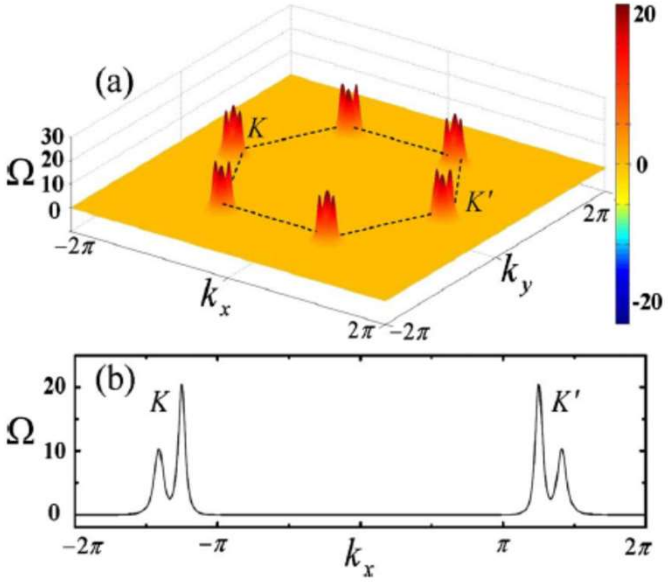
Hyperspectral Imaging



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

Topological invariants

Designing polariton graphene



Z. Qiao et al., PRB **82**, 161414(R) (2010)

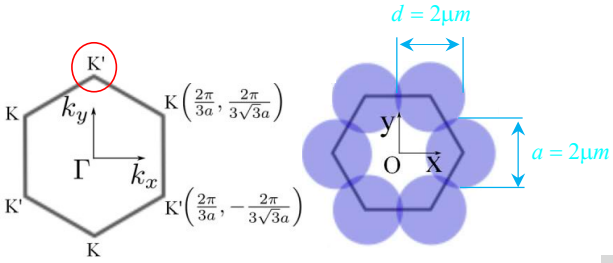


Berry curvature Ω
-> gauge-invariant local manifestation of the geometric properties

$$C^{(m)} = -\frac{1}{2\pi}\int_{BZ} \Omega^{(m)}(\boldsymbol{k})\, d\boldsymbol{k} \rightarrow graphene\ C = \frac{6}{3} = 2$$

Exciton-polariton TI

Band structure engineering

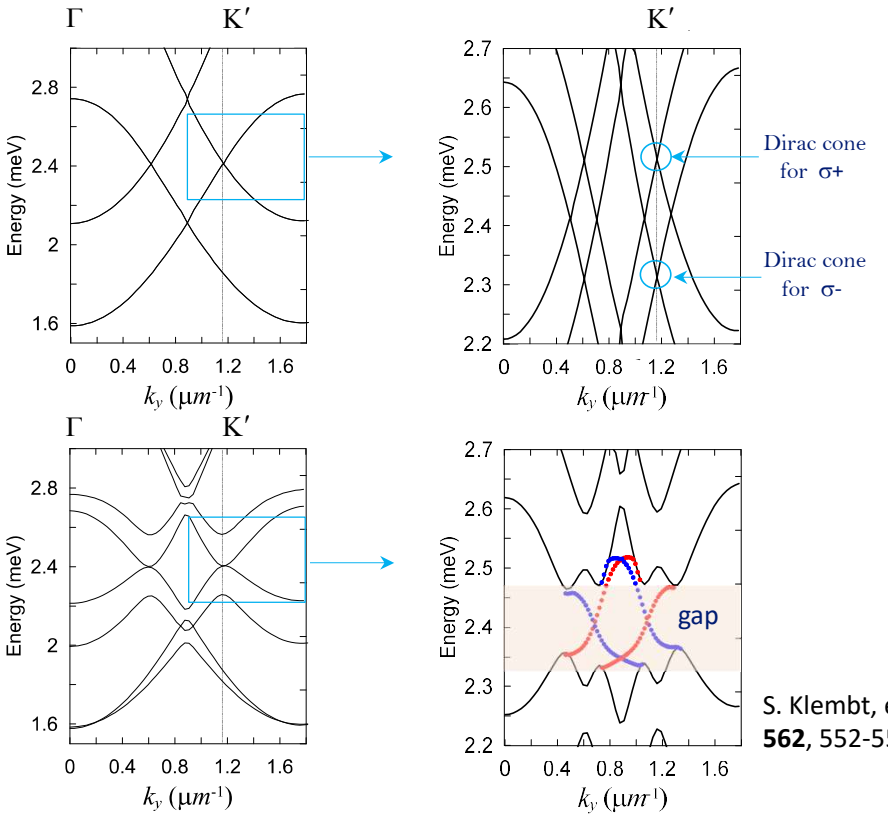


TE-TM mode splitting in benzene behaves like spin-orbit interaction

TE-TM mode splitting
$\beta_{eff} = 0$

TE-TM mode splitting
$\beta_{eff} = 0.1\, meV\mu m^2$

magnet field
$\Delta_{eff} = 0.2meV$



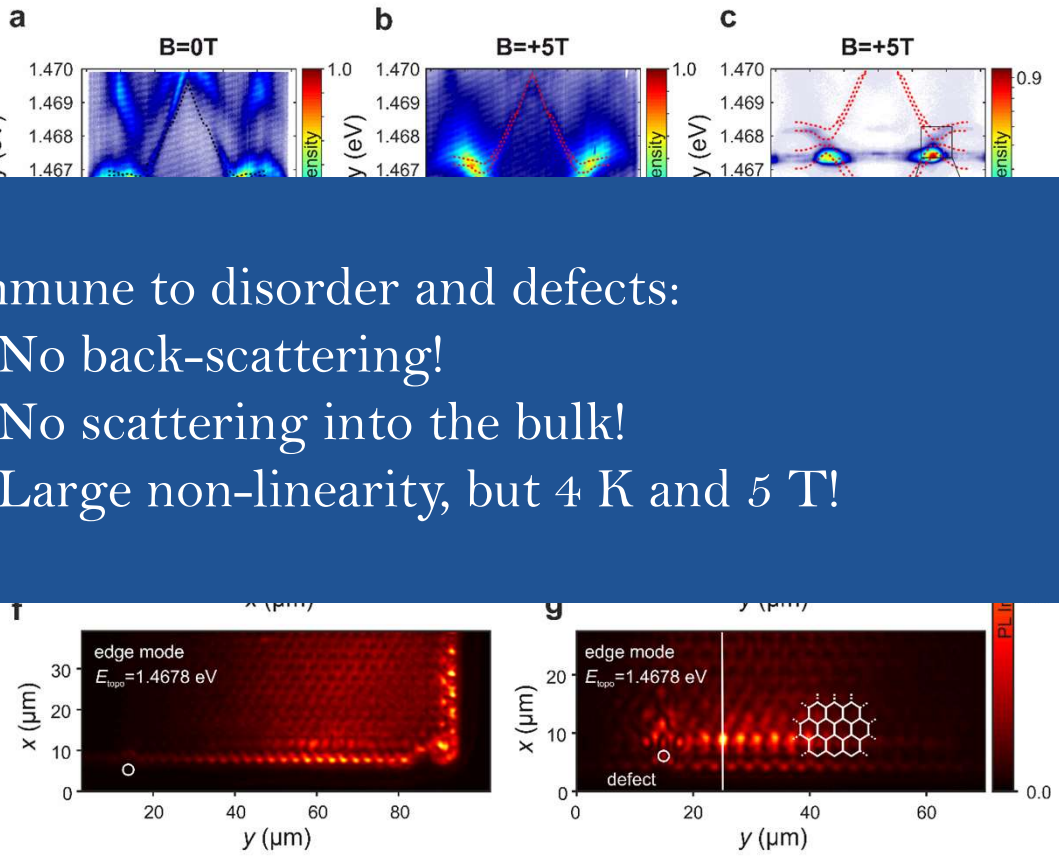
Kane and Mele, *Phys. Rev. Lett.* **95**, 226801 (2005)
Bardyn, et al. Phys. Rev. B 91, 161413(R) (2015)
Nalitov, et al. *Phys. Rev. Lett.* **114**, 116401 (2015)

S. Klembt, et al. *Nature* **562**, 552-556 (2018).

Exciton-polariton TI

Edge modes

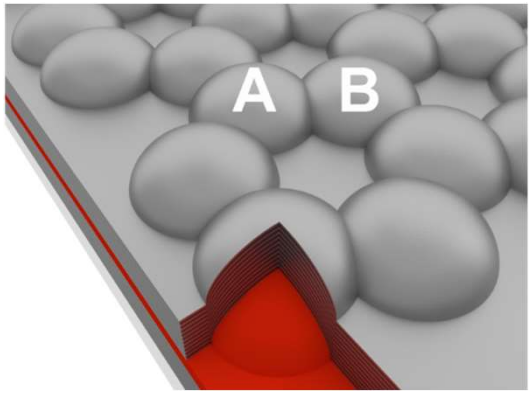
- Mode in the topological gap at the edge of t
- No bulk scatter intentional defe
- Modes go arou from Zigzag in



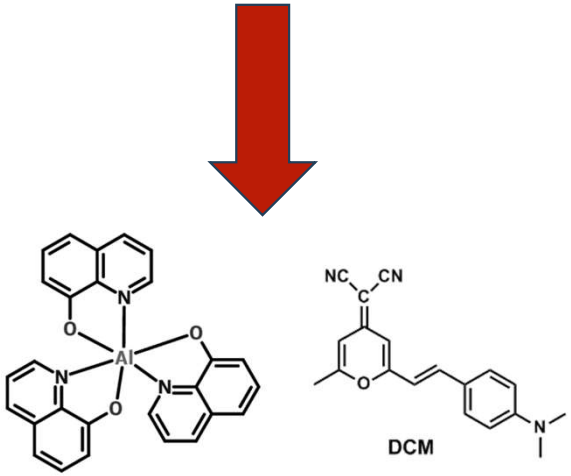
- Immune to disorder and defects:
  - No back-scattering!
  - No scattering into the bulk!
  - Large non-linearity, but 4 K and 5 T!

S. Klembt, et al. *Nature* **562**, 552-556 (2018).

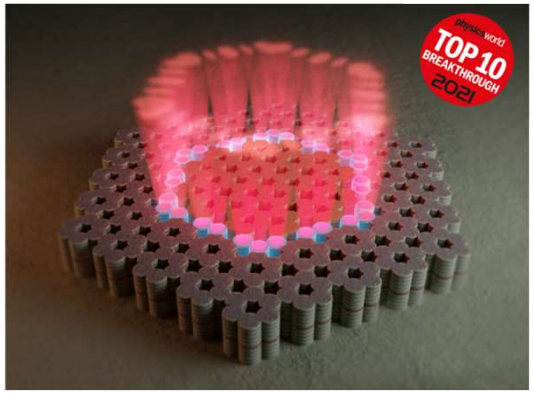
Dirac Cones and Room Temperature Polariton Lasing Evidenced in an Organic Honeycomb Lattice



S. Betzold, SK et al., *Adv. Sci.* (2024).



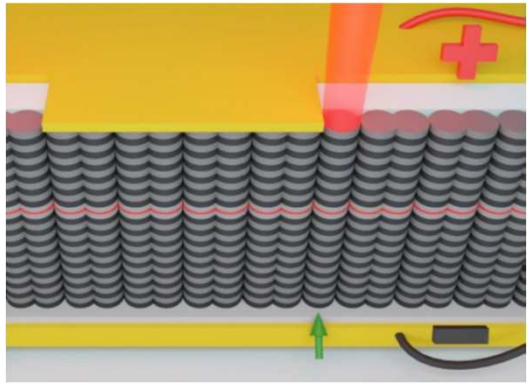
Topological insulator vertical-cavity laser array



A. Dikopoltsev, SK et al., *Science* (2021)

Patent: Topologic insulator surface emitting laser system. M. Segev, S. Hofling, S. Klembt, A. Dikopoltsev, T. Harder, E. Lustig, Y. Lumer US20230223735A1 (2023).

An electrically pumped topological polariton laser



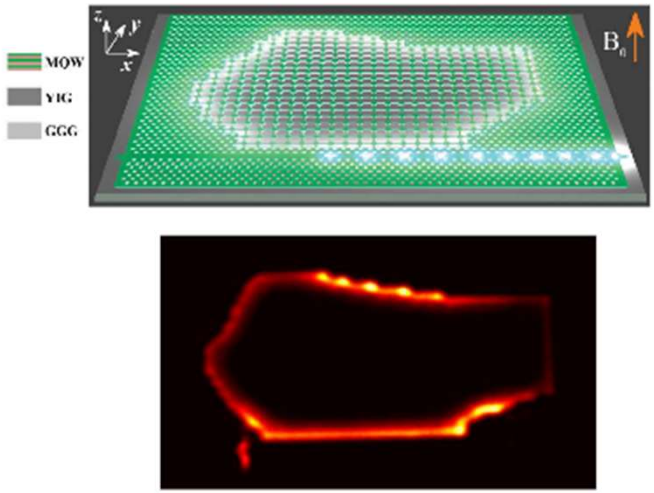
P. Gagel, SK et al., *Nano Lett.* (2024).

Topological Lasers

injection-locking and coherent light emission from coupled laser arrays

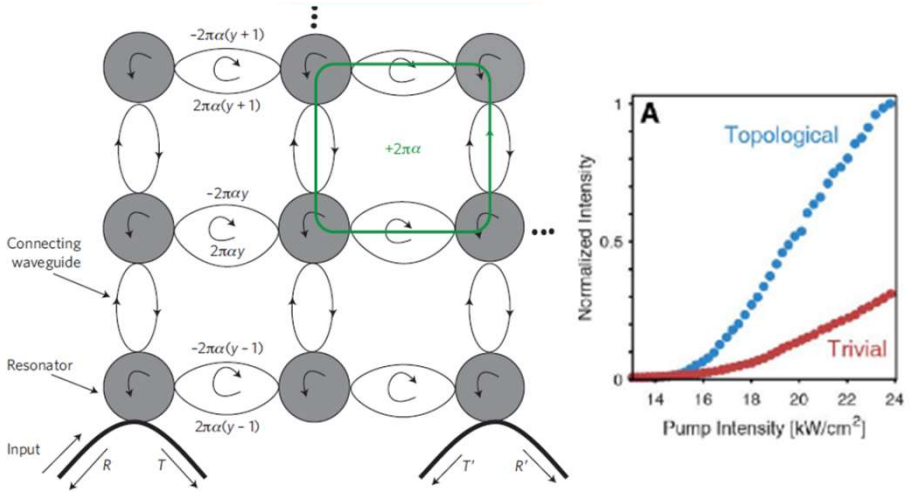
Topological photonics

First implementations of topological lasers



- Photonic crystal at $\lambda \approx 1.5\mu m$
- Broken time reversal symmetry through magnetic field and gyrotropic material Gadolinium Gallium Garnett

B. Bahari, et al. *Science* **358**, 636-640 (2017).



- Coupled ring resonators at $\lambda \approx 1.5\mu m$
- Synthetic gauge field (magnetic field) created by spatial offset of the link resonators that results in phase shifts

G. Harari, et al. in CLEO, OSA Technical Digest, paper FM3A.3 (2016).
M. A. Bandres, et al. *Science* **359** (6381), eaar4005 (2018).
G. Harari, et al. *Science* **359** (6381), eaar4003 (2018).

So far, all topological lasers featured in-plane geometries

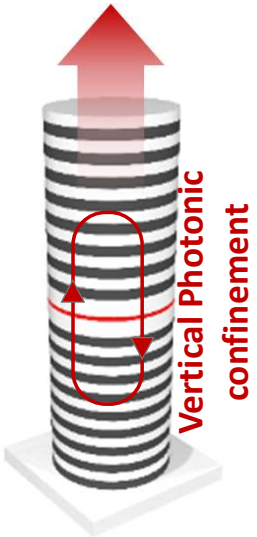
Microcavity lasers

Vertical cavity surface emitting laser (VCSEL)

Distributed Bragg Mirror
29 pairs AlAs/GaAs

GaAs cavity with
$In_{0.30}Ga_{0.70}As$ quantum dots
as active material

Distributed Bragg Mirror
33.5 pairs AlAs/GaAs





Advantages

- Vertical emission
- Compact design
- Collimated output beam
- Industry friendly
- Modulation at ~100GHz

Main Challenge: limited output power

Large VCSEL Arrays

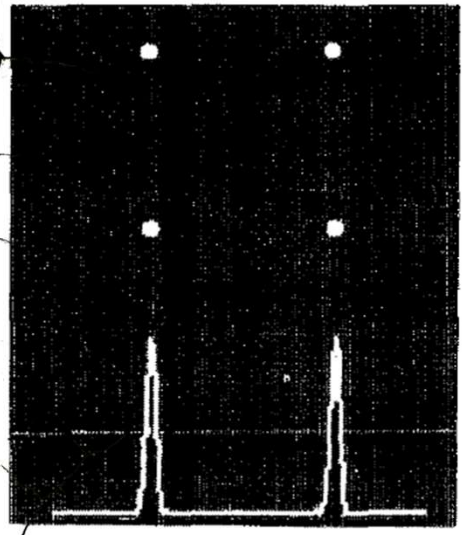
A Long Sought Dream…

Large two-dimensional arrays of phase-locked vertical cavity surface emitting lasers

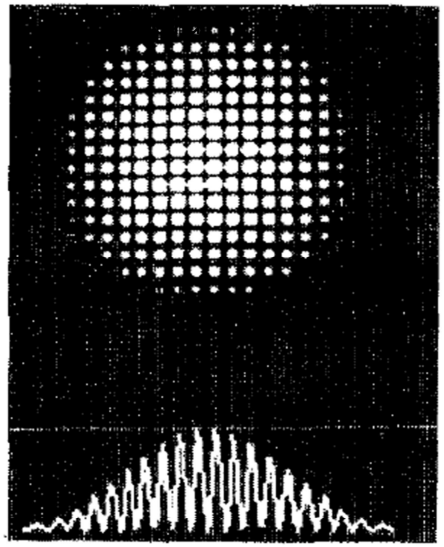
Cite as: Appl. Phys. Lett. **60**, 1535 (1992); https://doi.org/10.1063/1.107243
Submitted: 06 September 1991 . Accepted: 24 January 1992 . Published Online: 04 August 1998

M. Orenstein, E. Kapon, J. P. Harbison, L. T. Florez, and N. G. Stoffel

Far Field



Near



Large VCSEL Arrays

A Long Sought Dream…

As the array size grows, it becomes nearly impossible to force a VCSEL array to lock coherently at lasing



Injection locking of many lasers using properties of topological insulators:

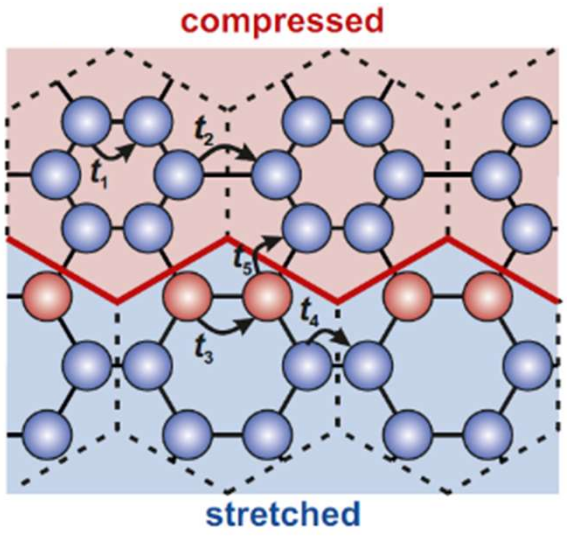
a) Non-zero group velocity
b) Suppression of localization of modes
c) Robustness to disorder and defects

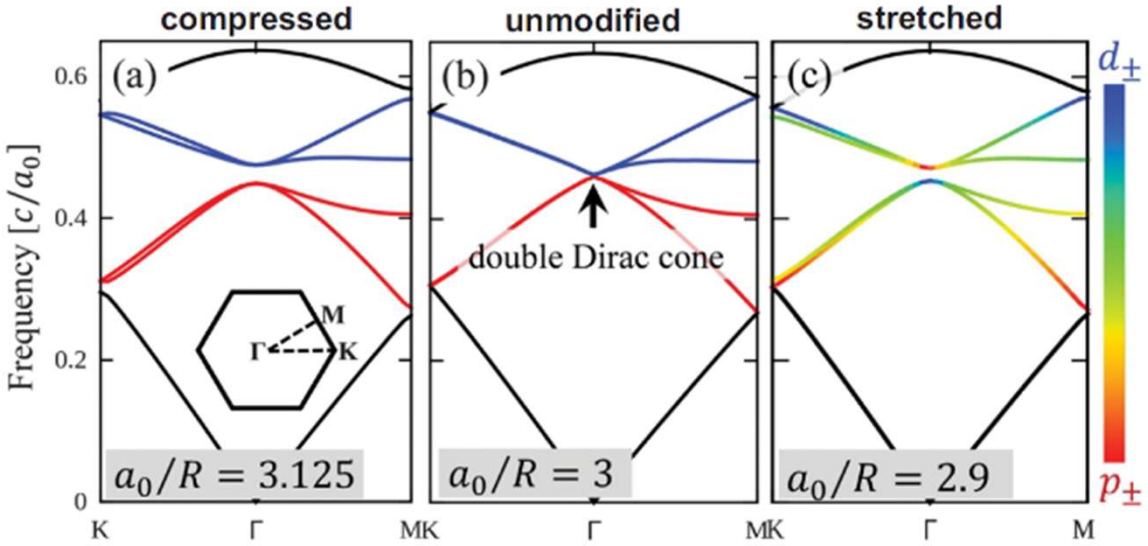


H. G. Winful and S. S. Wang (1988).

Vertically emitting topological insulator laser

Topological crystalline insulator (TCI)



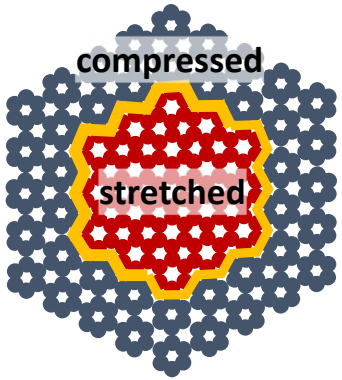


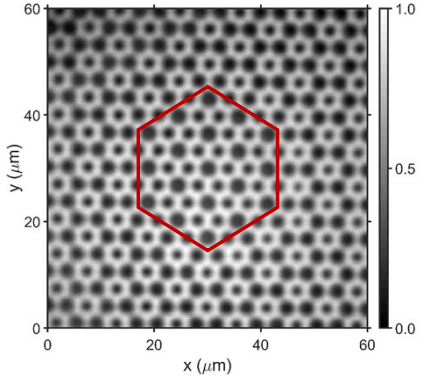
L.-H. Wu, X. Hu. *Phys. Rev. Lett.* **114** (22), 223901 (2015).

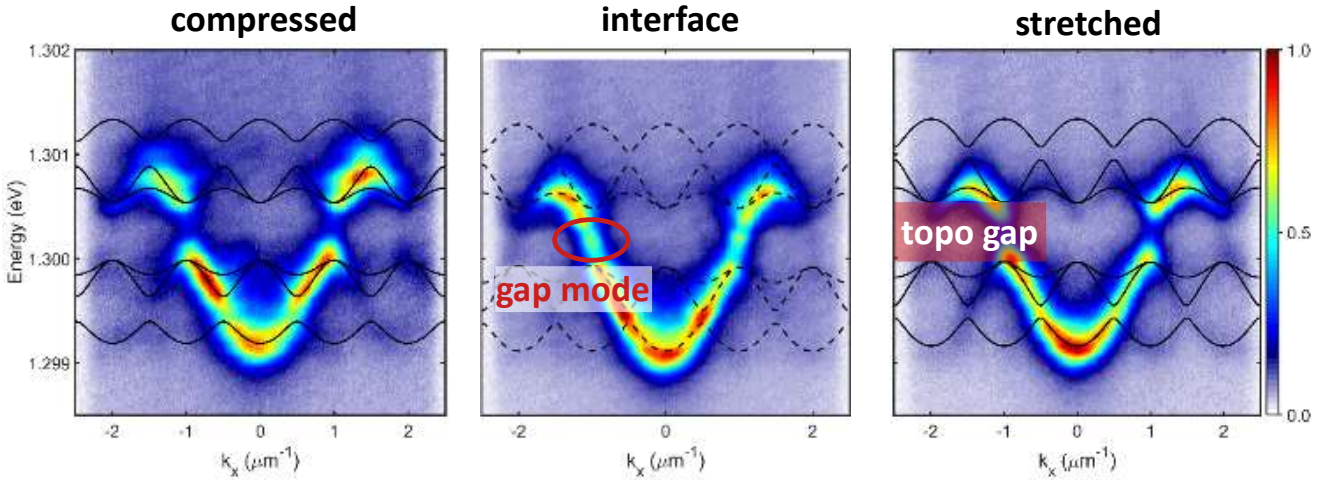
- Honeycomb lattice with extended unit cell that is compressed / stretched
- Band inversion in the stretched domain leads to topological interface mode

Vertically emitting topological insulator laser

TCI lattice with VCSELs







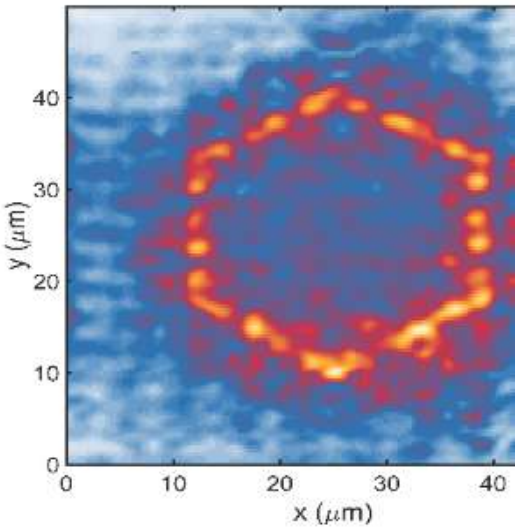
- Topological band gaps of 553µeV and 565µeV in the compressed and stretched domains
- Topological interface (red line) mode within the gap

Vertically emitting topological insulator laser

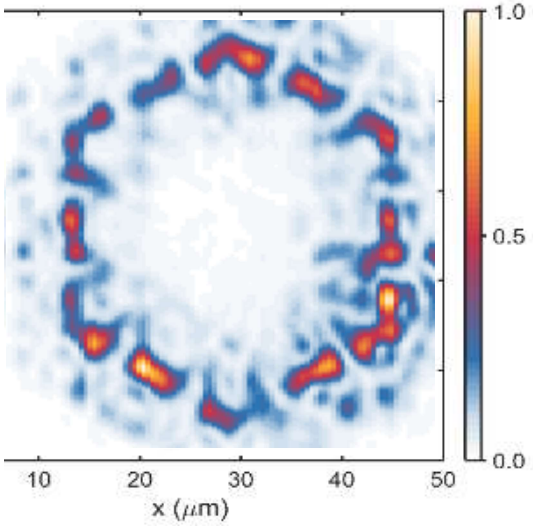
Input-output characteristics and spectral analysis

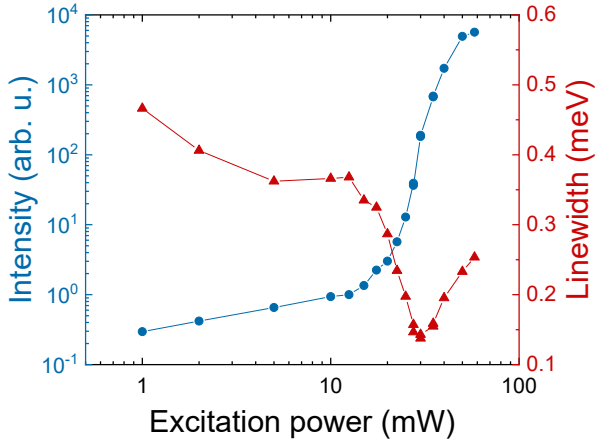
4K

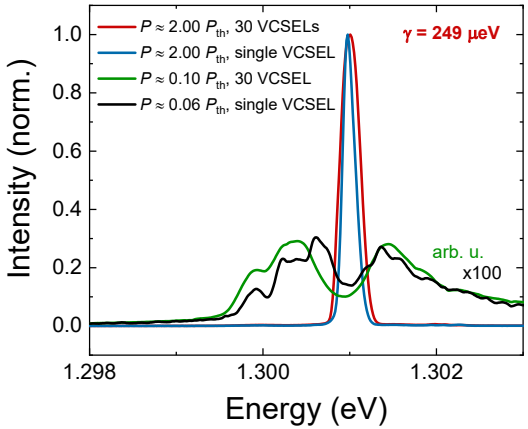
Below threshold



Above threshold







Single mode lasing with a linewidth of 249μeV, considerably **narrower than the topological gap**

Vertically emitting topological insulator laser

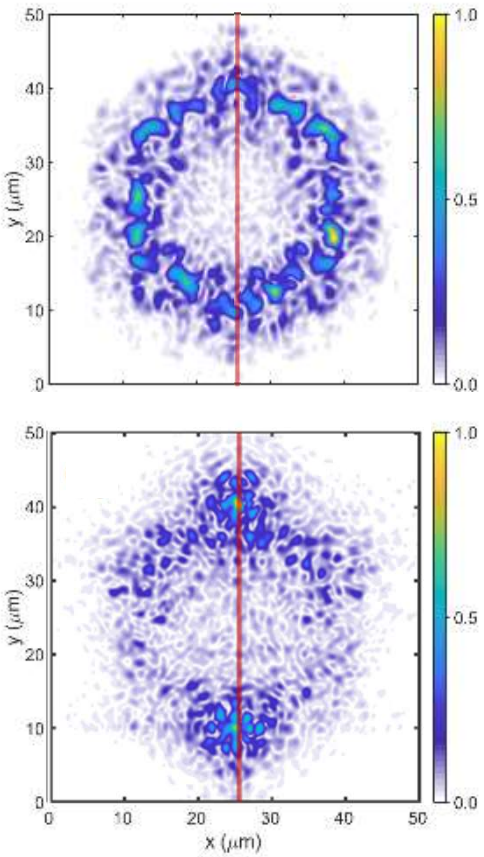
Topological vs. trivial lasing

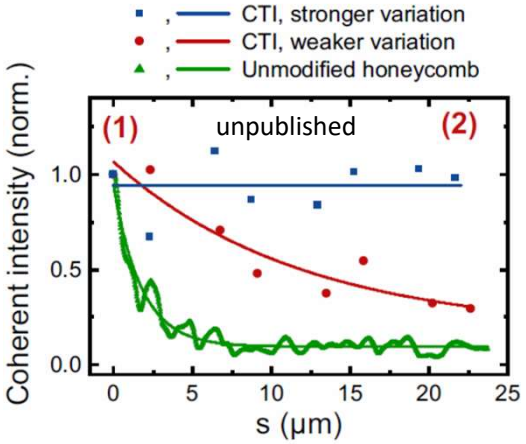
4K

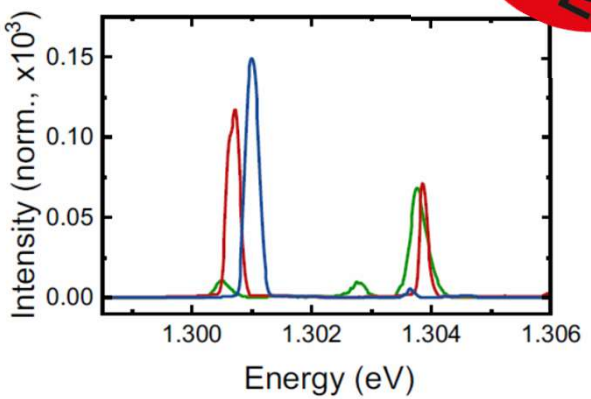
Topological

Trivial

Coherent emission







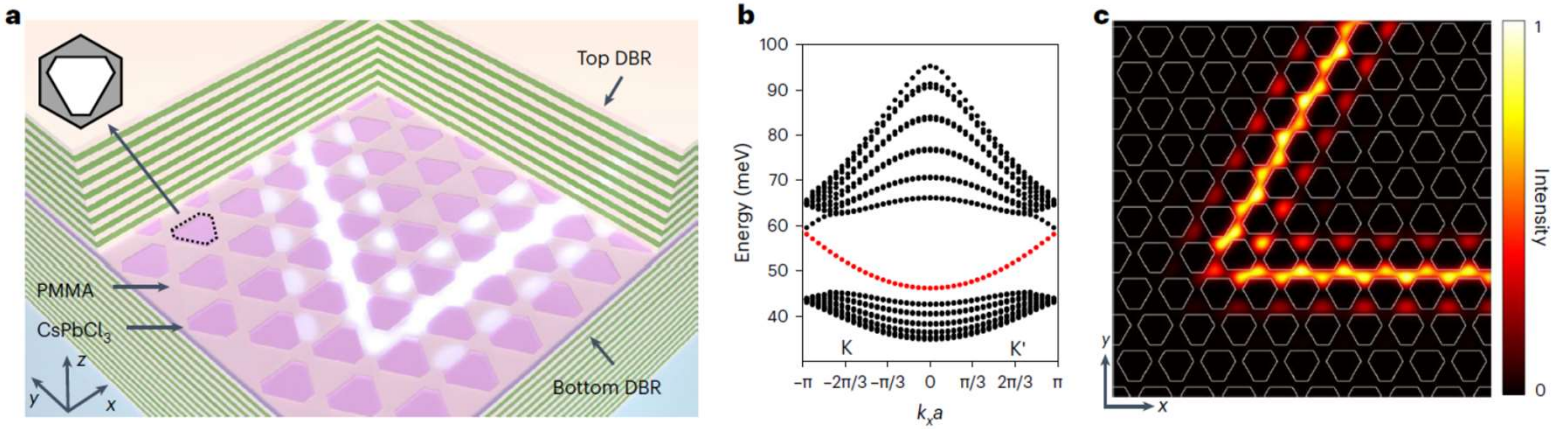
physicsworld TOP 10 BREAKTHROUGH 2021

- **The topological laser array features superior coherence to a trivial honeycomb array**
- **Reduction of topological gap deminishes coherence properties**



A. Dikopoltsev, S.K. et al., *Science* **373**, 1514-1517 (2021).

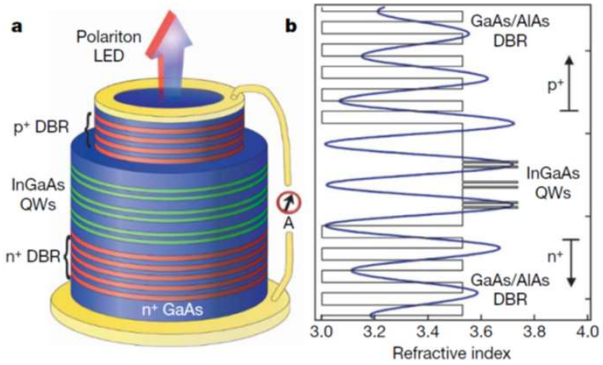
Topo. edge modes in vertical emitters



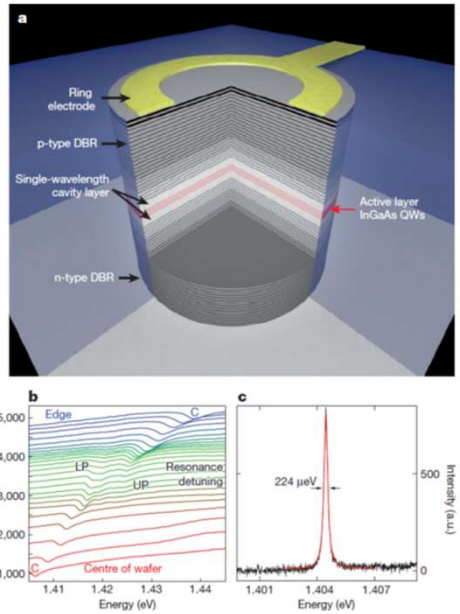
Peng, K., Li, W., Sun, M. *et al.* Topological valley Hall polariton condensation. *Nat. Nanotechnol.* (2024).



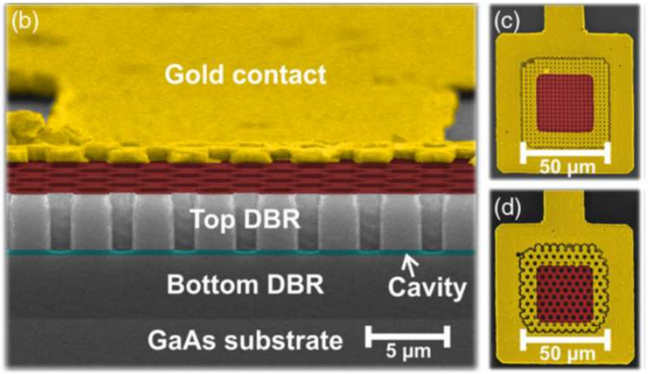
Electrically pumped polaritons & lattices



- S. Tsintzos et al., *A GaAs polariton light-emitting diode operating near room temperature.* Nature 453, 372–375 (2008).

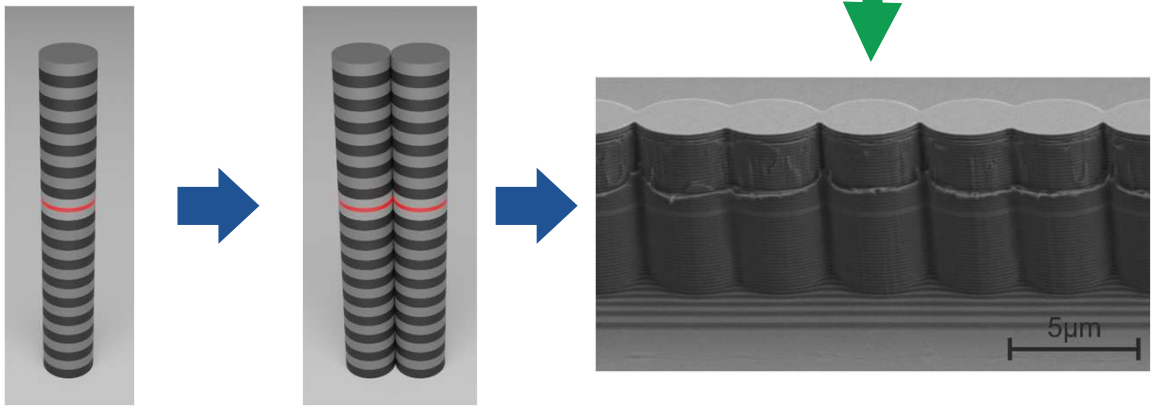


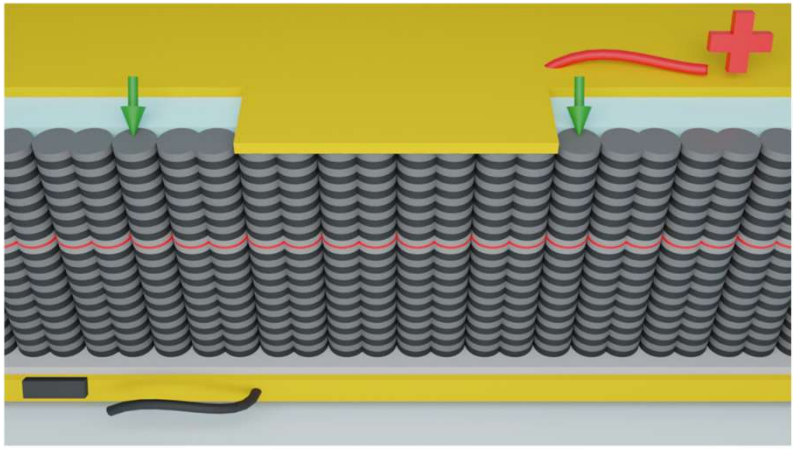
- C. Schneider *et al., An electrically pumped polariton laser.* Nature **497**, 348–352 (2013).

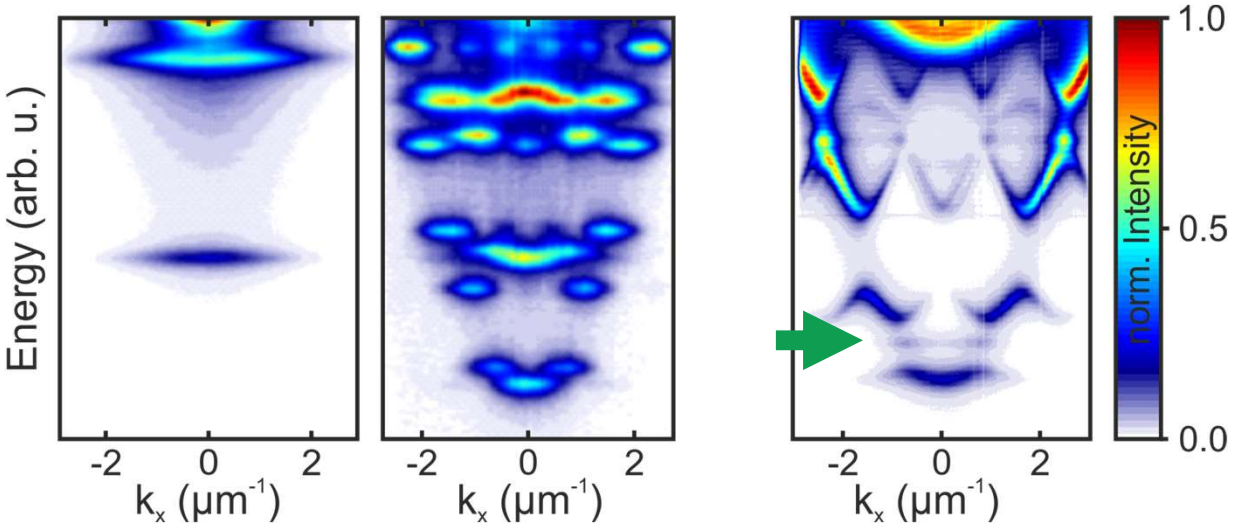


- H. Suchomel et al., *Platform for Electrically Pumped Polariton Simulators and Topological Lasers.* Phys. Rev. Lett. **121**, 257402 (2018).

Coupling of micropillars: Sample layout for EL



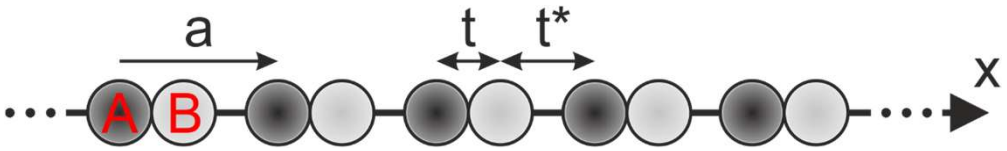


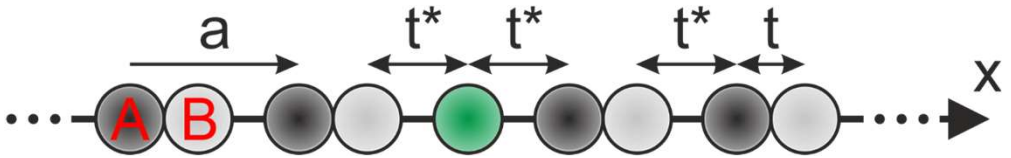




ELectrically driven POLariton Lasers based On LOCal topological Order
DFG Project: EL POLLO LOCO

Electrical operation: Topological defect in a SSH-chain

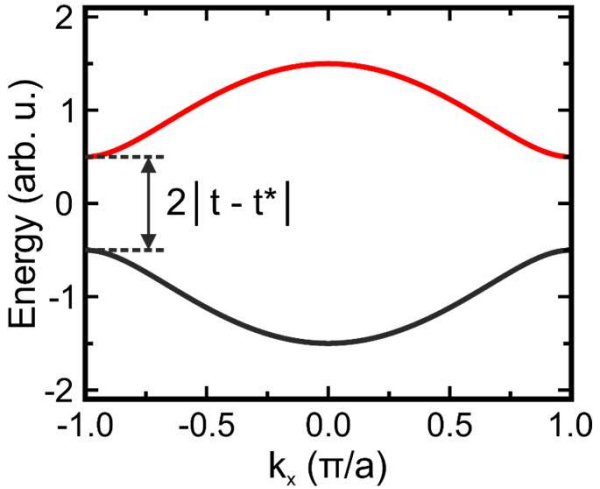


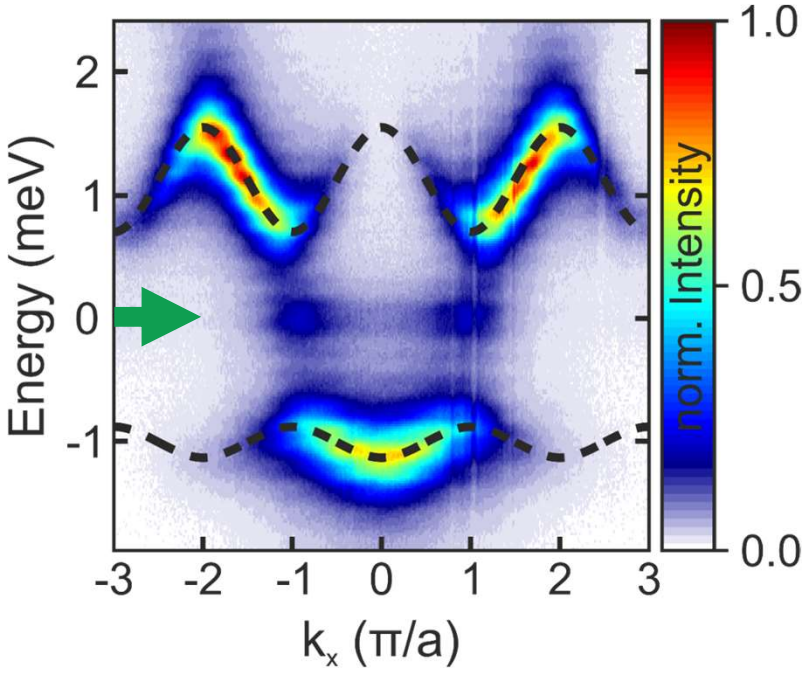


$$H(k) = \begin{bmatrix} 0 & t + t^* e^{-ik} \\ t + t^* e^{+i} & 0 \end{bmatrix}$$

$$E(k) = \pm\sqrt{t^{\,2} + t^{*2} + 2tt^* \cos(k)}$$

t* = 0.5, t = 1





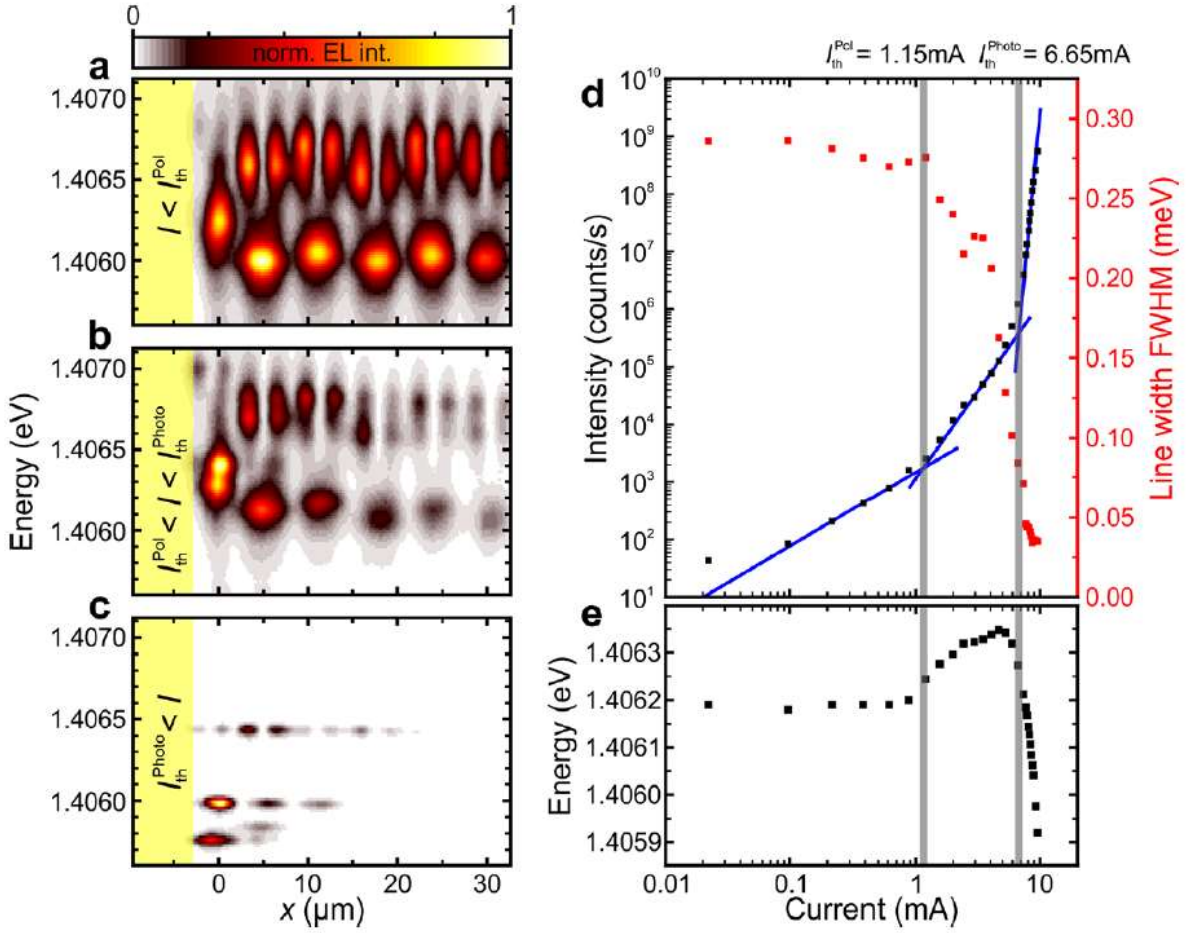
J.K. Asbóth, et al. “A Short Course on Topological Insulators”, *Lecture Notes in Physics* **919**, 166 (2016).

Topological laser: Input output characteristics

4K

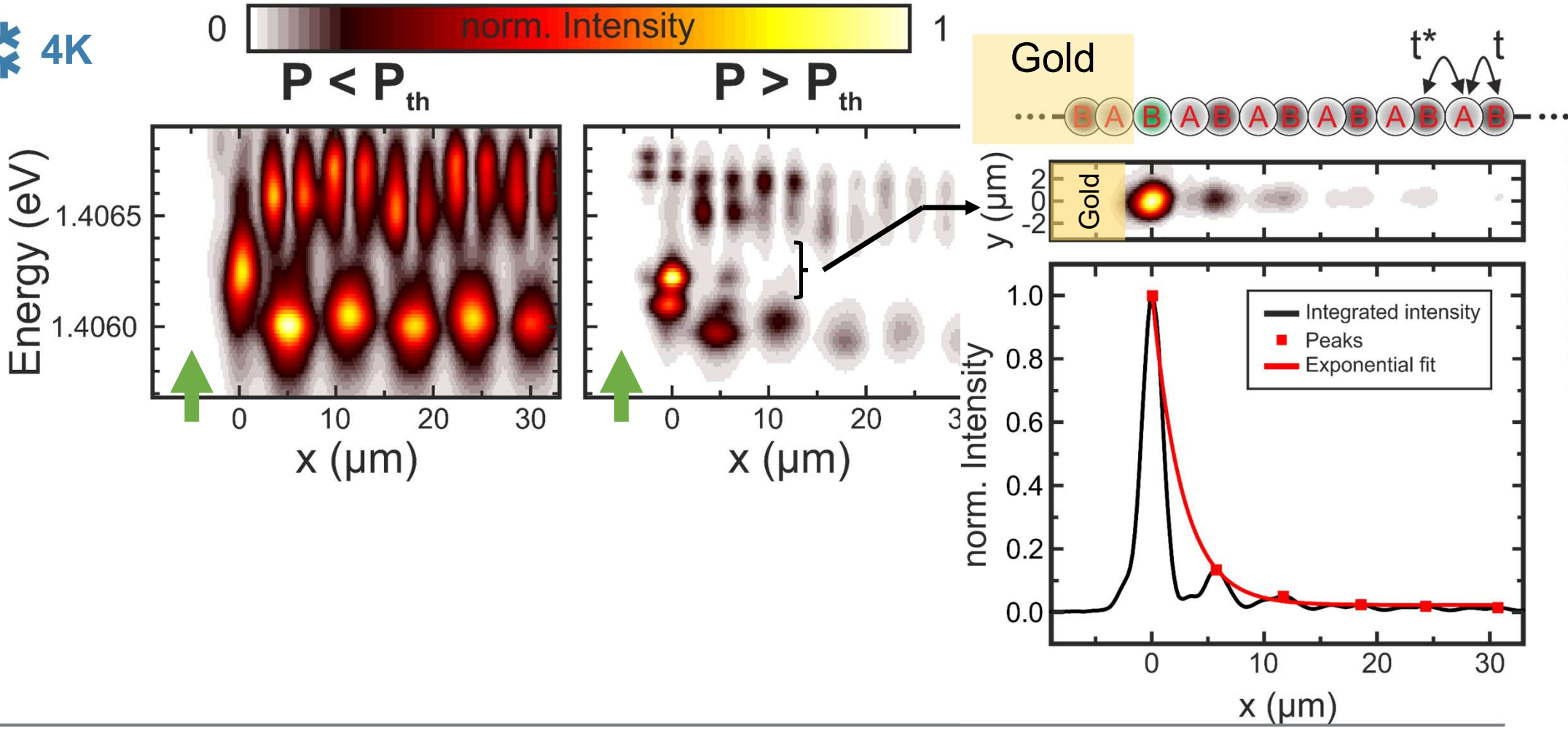
- Topological defect within the topological gap
- Two distinct threshold behaviors associated with lasing in strong and weak coupling under electrical injection

DC pumping



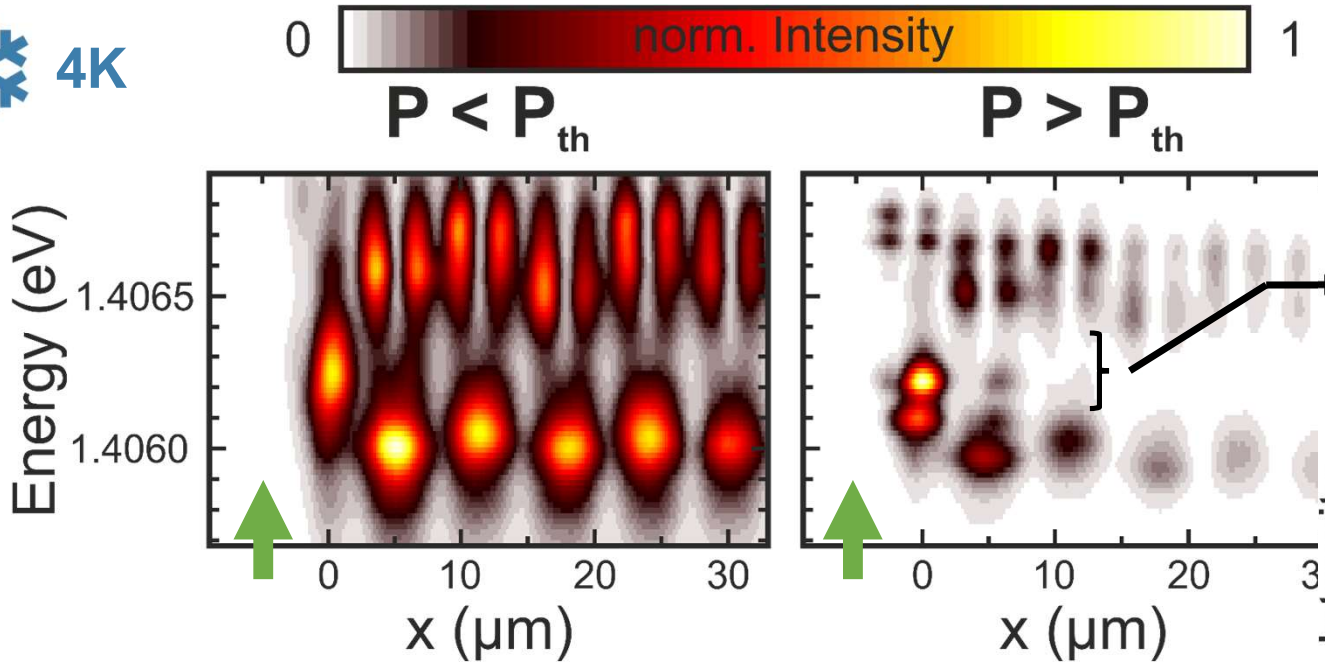
Topological laser: Input output characteristics

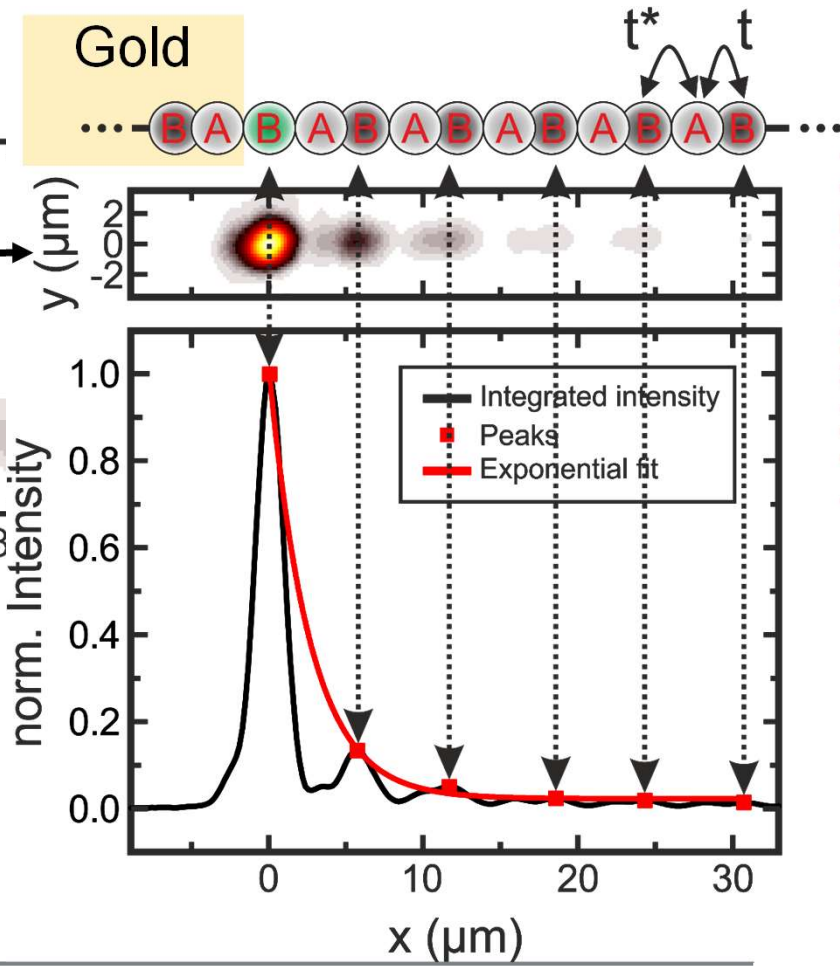
4K



Topological laser: Input output characteristics

4K

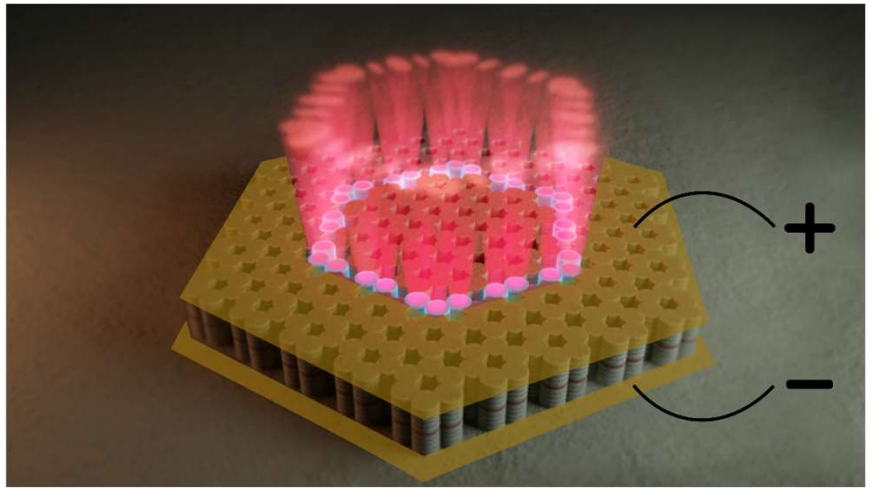




P. Gagel, SK et al., Nano Lett. **24**, 6538 (2024).

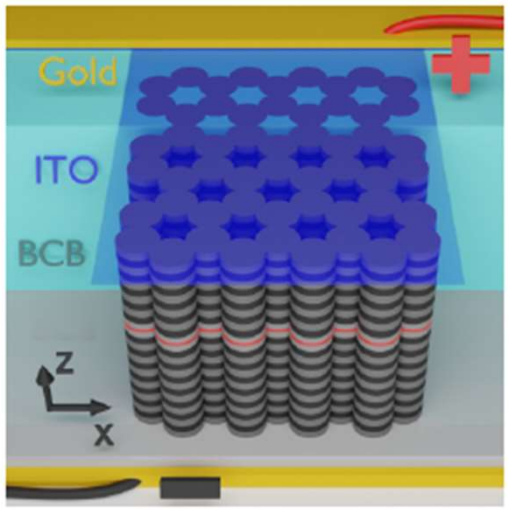
Outlook

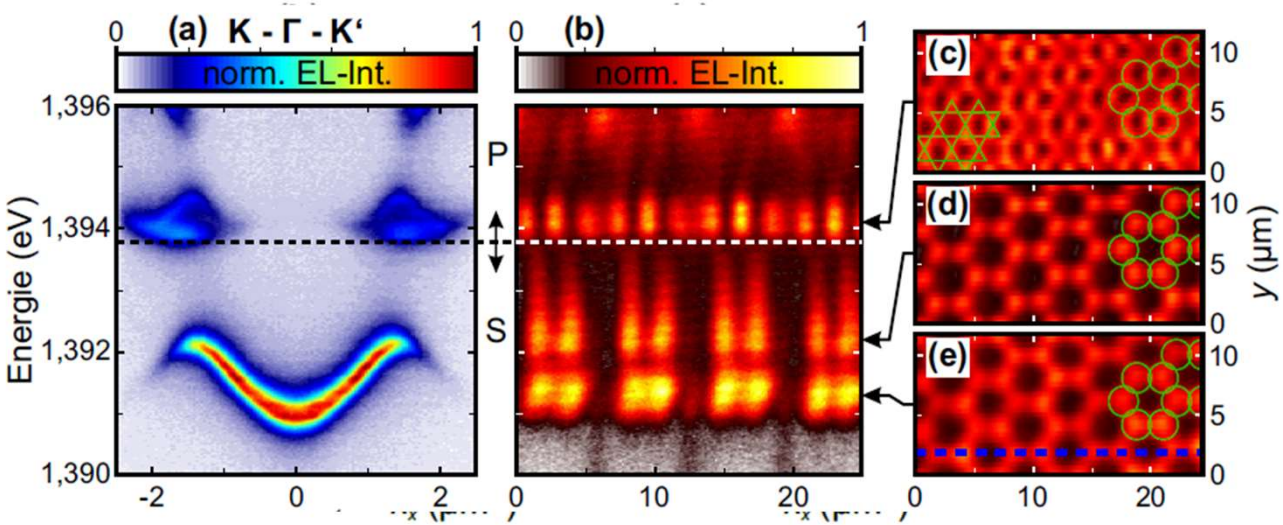
Electrically pumped topological laser

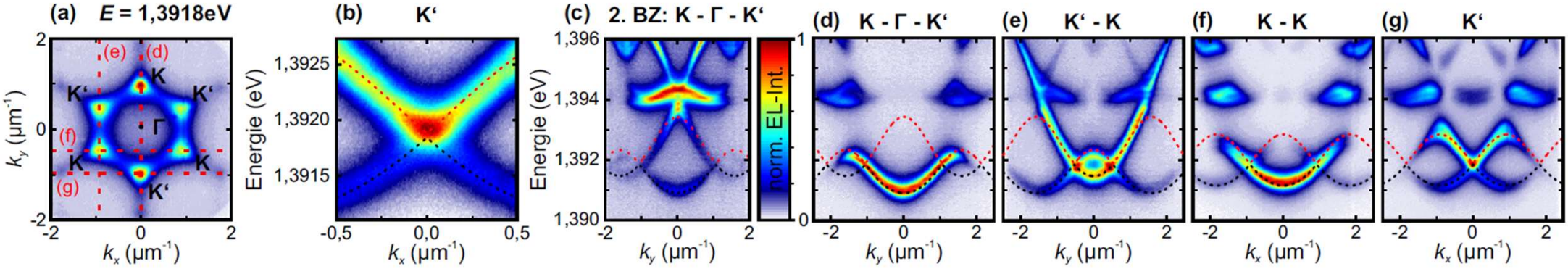


- Topological defect within the topological gap
- Distinct threshold behavior of the defect under electrical injection

ITO for efficient transparent contacts



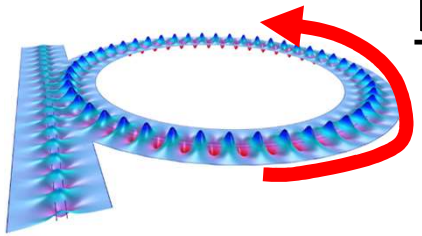


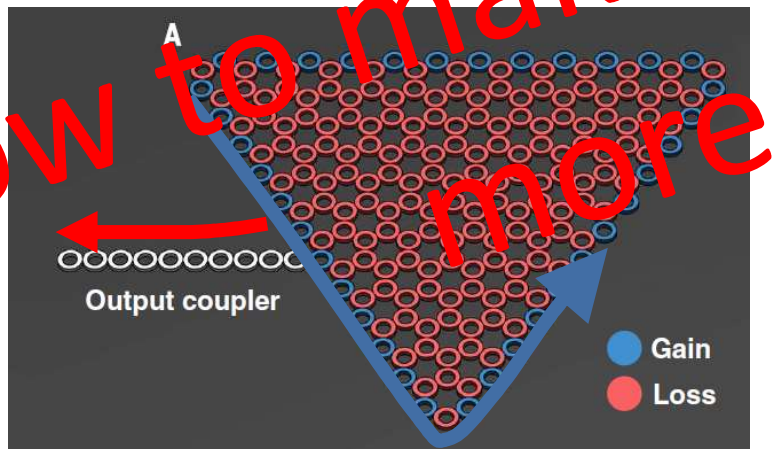


Conceptual Difference

Topological Insulator Lasers

In-plane lasing and in-plane coupling

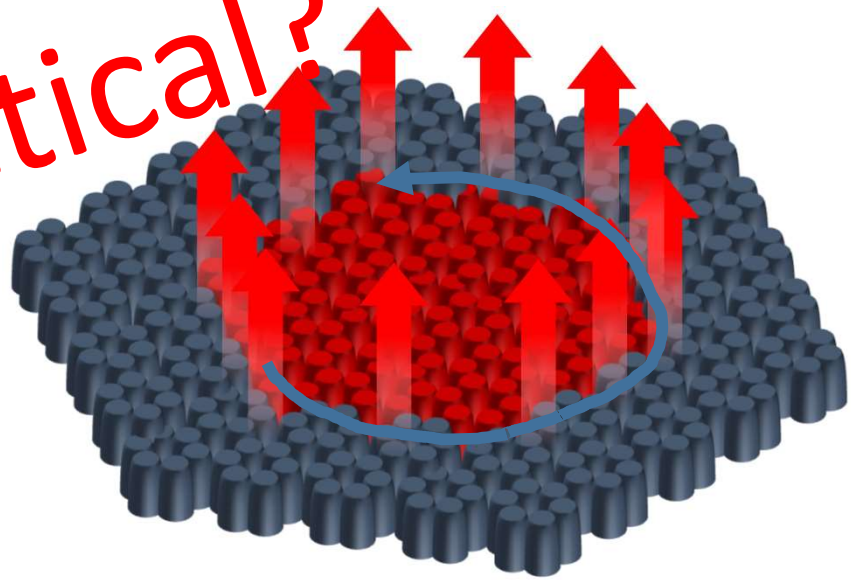




Harari et al., Science **359**, eaar4003 (2018)

Out-of-plane lasing and in-plane coupling



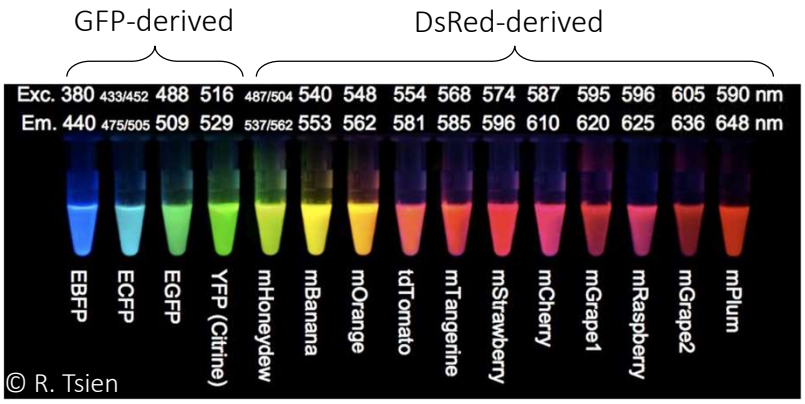


How to make topological lasers more practical?

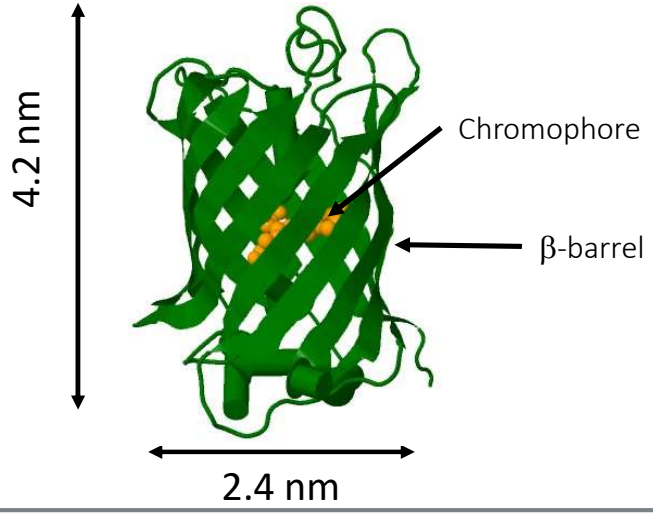
Fluorescent proteins

Organics for room temp. stable excitons



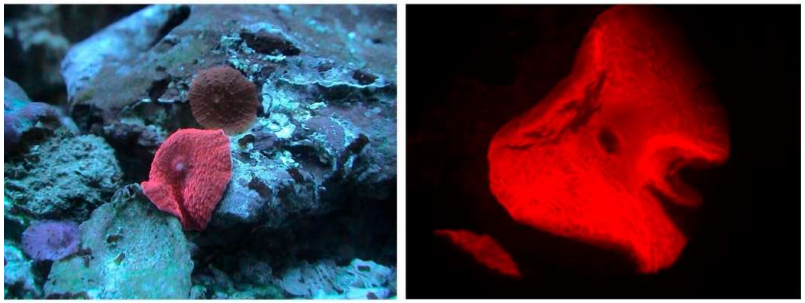


- Nobel Prize in Chemistry (2008) for the discovery and development of GFP
- Biological marker, e.g. for microscopy and single cell imaging
- Can be expressed by various cell types
- Unique, barrel-like molecular structur
- High quantum yield
- High extinction coefficients

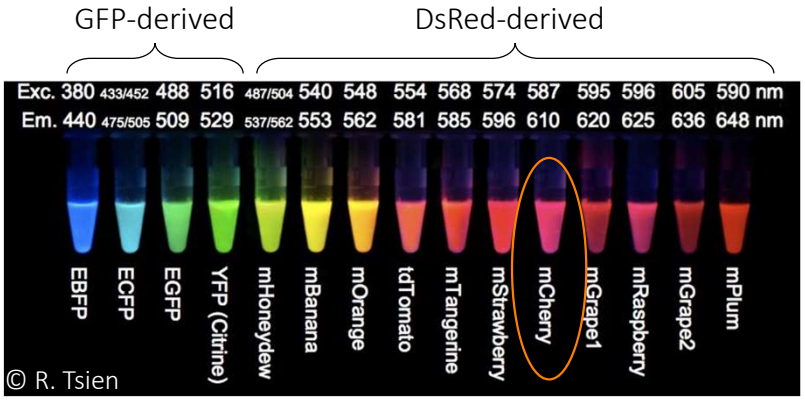


Fluorescent proteins

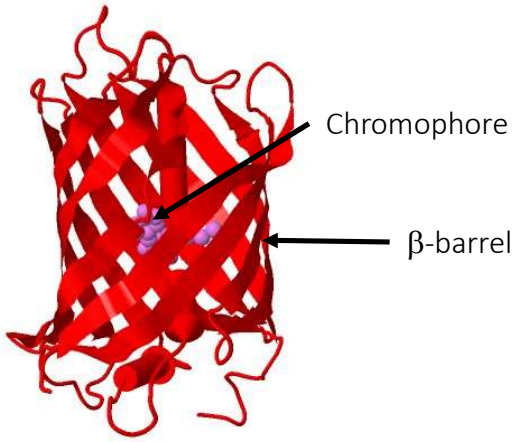
Organics for room temp. stable excitons



Discosoma striata (Mushroom Coral)

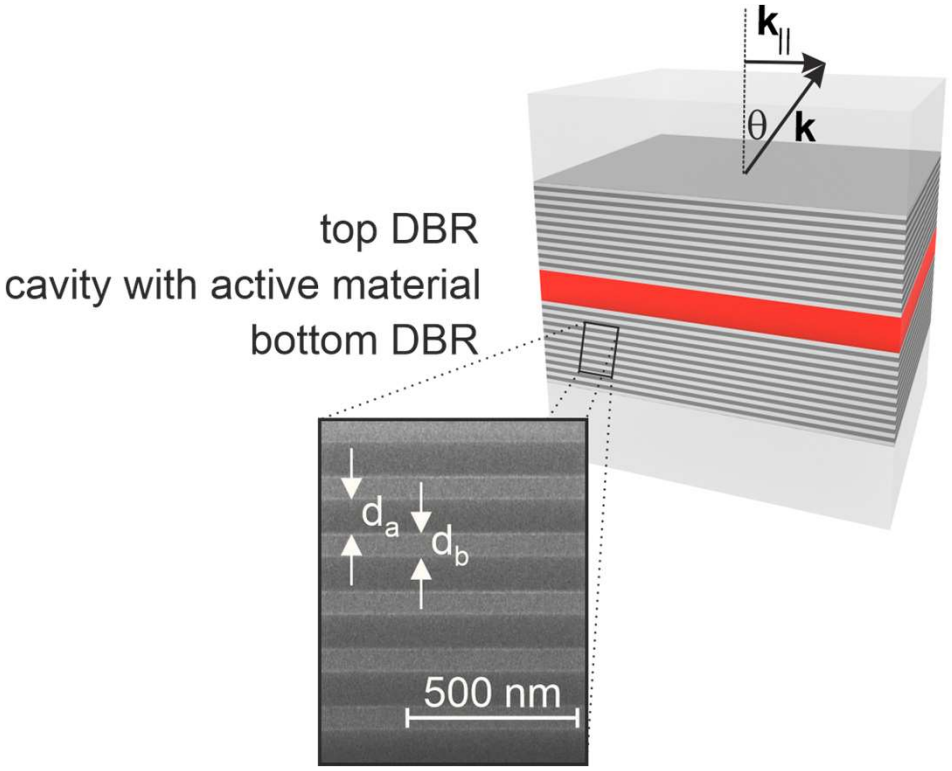


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- Can be expressed by various cell types
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- High extinction coefficients



Povarova et al., *Int. J. Mol. Sci.* **18**, 1503 (2017)

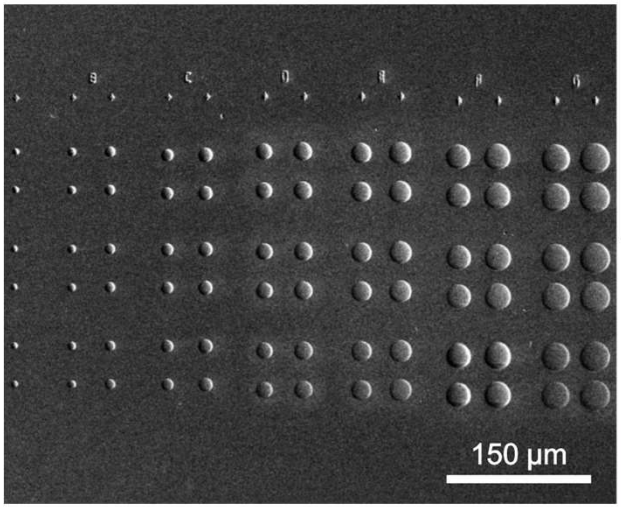
Microcavity with embedded mCherry

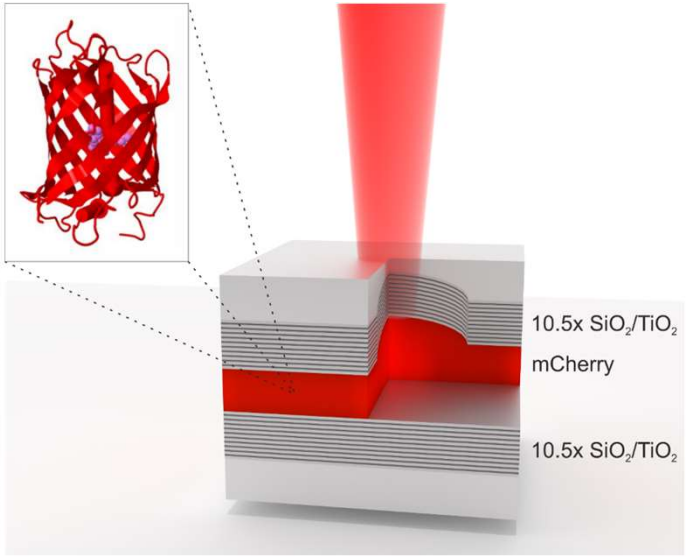


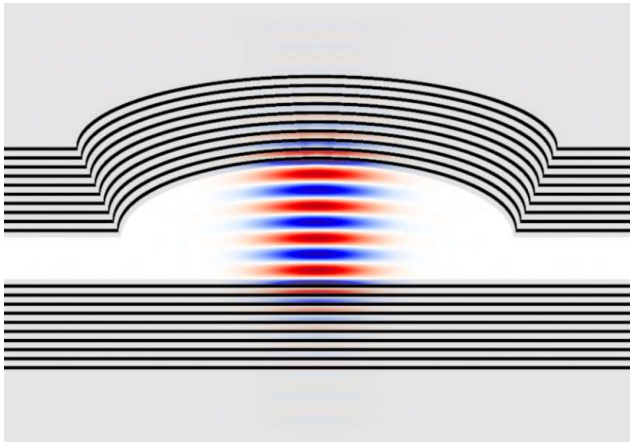
- Dielectric mirror (10.5 pairs of SiO_2/TiO_2, λ_c=620nm) on glass substrate
- highly concentrated mCherry solution (175 g/l)
- Second dielectric mirror (10.5 pairs of SiO_2/TiO_2, λ_c=620nm) on glass substrate
- Cavity modes with Q >5000

Hemispherical microcavity

- Additional trapping potential for polaritons
  - Strongly localized polaritons
  - Reduced mode volume
- Patterning of the glass substrate before coating with the DBR-layers using FIB lithography
- Various Radius of curvature of the lenses possible (normally RoC$\sim 5..20$ µm)



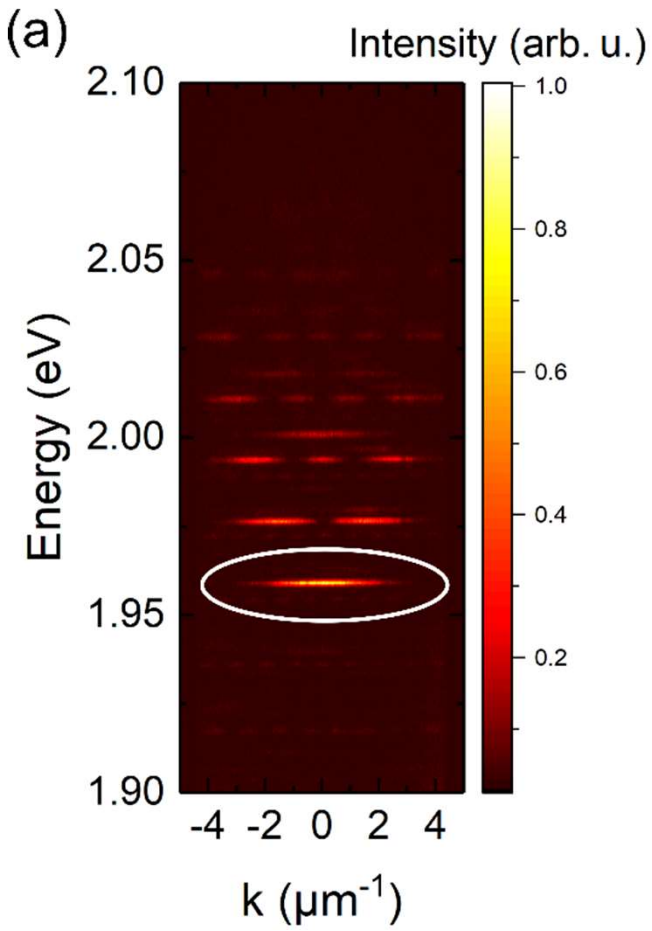


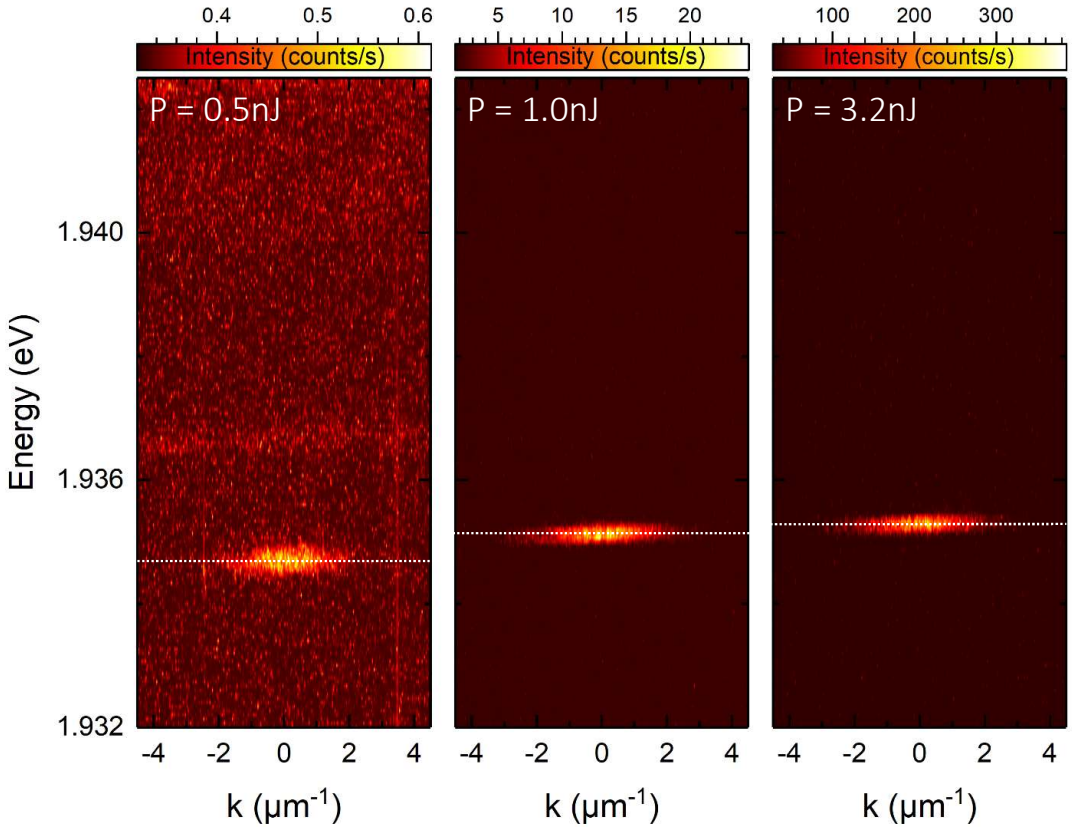


S. Betzold et al., *ACS Photonics* **7**, 384 (2020) S. Betzold et. al, *Proc. SPIE* **10540**, 105401V (2018)

Hemispherical microcavity

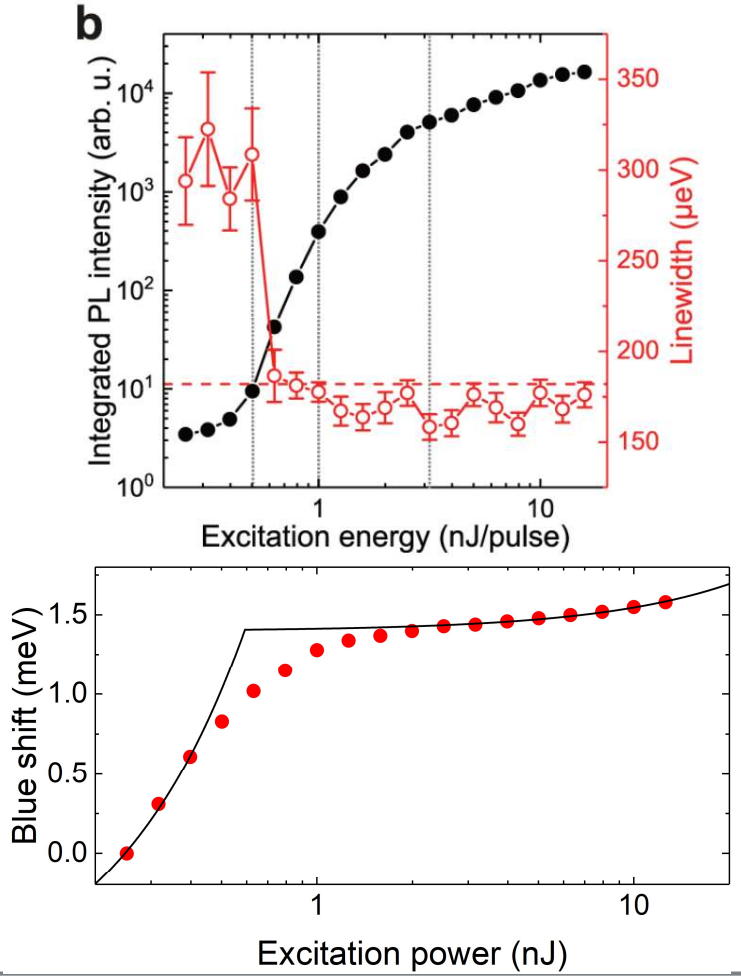
Trap: 4µm diameter, ~8µm radius of curverture
Excitation: OPO @ 532nm (first bragg minimum), 7ns pulses, 2 Hz rep. rate





S. Betzold et al., *ACS Photonics* **7**, 384-392 (2019)

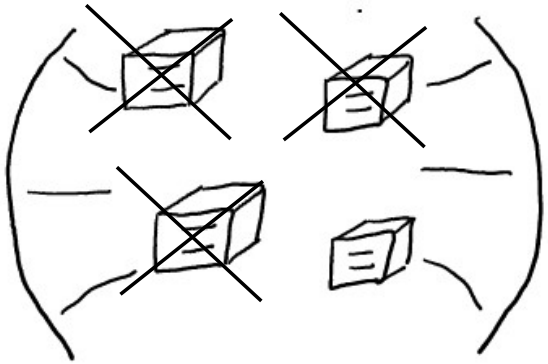
Input-output characteristic



- Key signatures for polariton condensation are shown
  - Nonlinearity
  - Sharp drop in linewidth (below detector resolution)
  - Power dependent blueshift
- Energy shift is normaly described by two different interaction regimes[2,3]
  - Polariton-reservoir interaction below threshold
  - Predominantly polariton-polariton interaction above threshold

Also valid for Polariton Condensates with Frenkel Excitons?

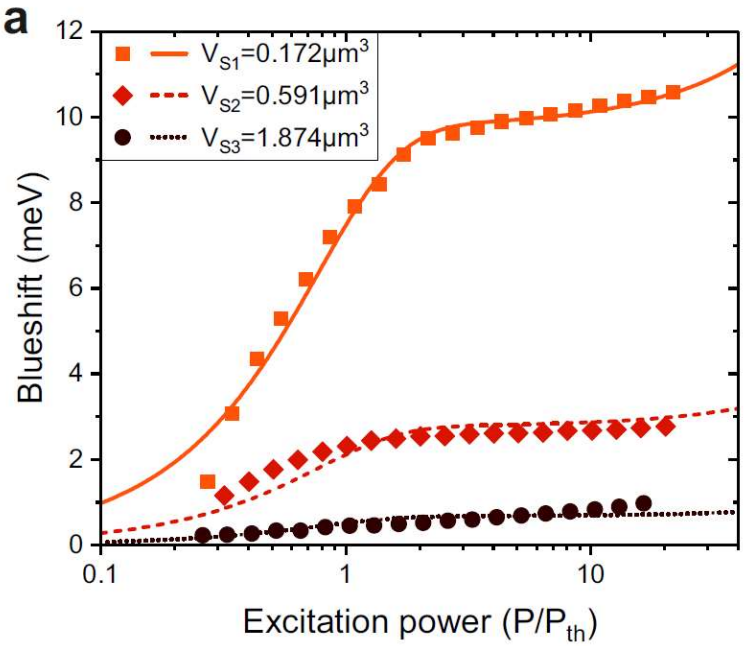
„Interactions“ with Frenkel Excitons



Excitons within the light cone

$$g(N_{\mathrm{PL}}^{X}) = g(0)\left[1 - \frac{2N_{X}^{\mathrm{PL}}}{N_s}\right]$$

$$g(0) = |\mathbf{d}_X \cdot \mathbf{E}|\sqrt{N_s} = |\mathbf{d}_X \cdot \mathbf{e}_{\mathrm{EM}}|\sqrt{\frac{\hbar\omega_{c,0}}{2\varepsilon_0 V_{\mathrm{EM}}}}\sqrt{n_s V_s}$$



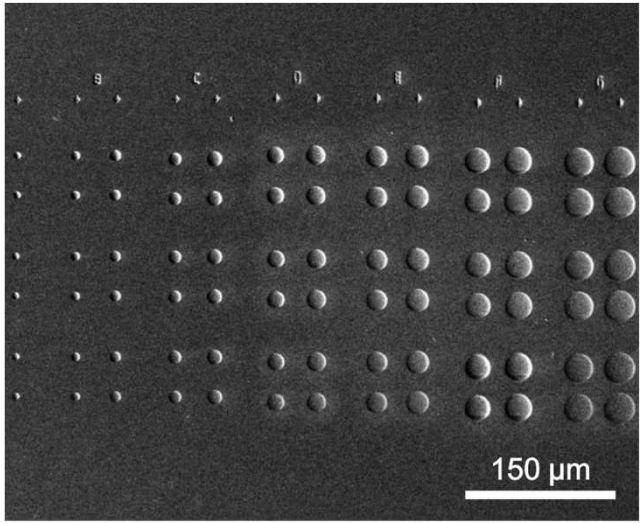
Theory by I. Shelykh and O. Kyrienko

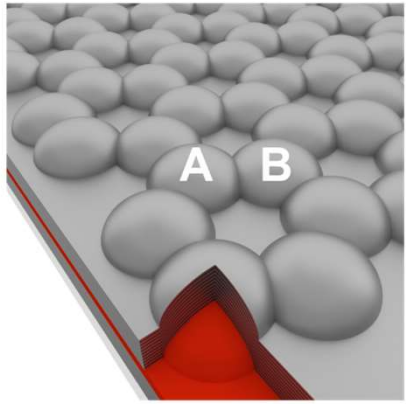
[1]S. Betzold et al., *ACS Photonics* **7**, 384-392 (2019)

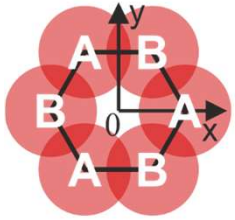
[2]T. Yagafarov et al., *Commun. Phys.* **3,** 18 (2020)

Organic Honeycomb lattice

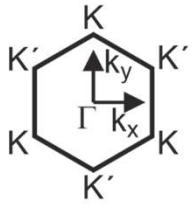
… bringing lattice emulation to room temperature



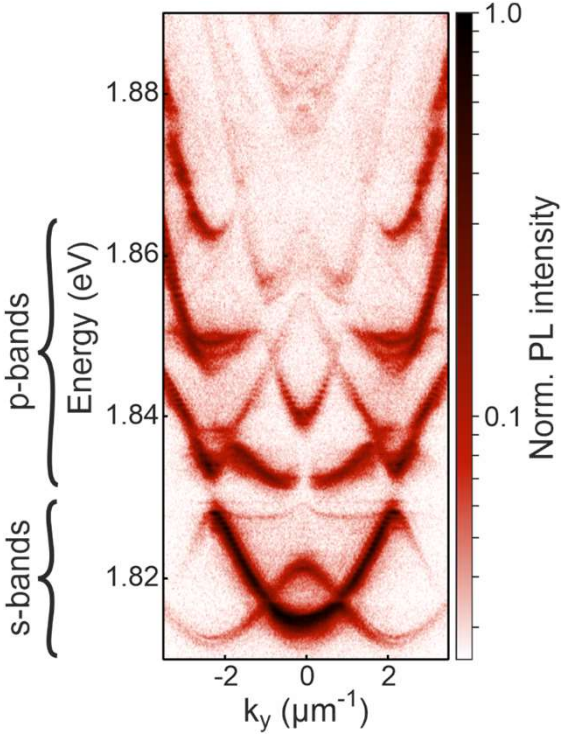




Real space



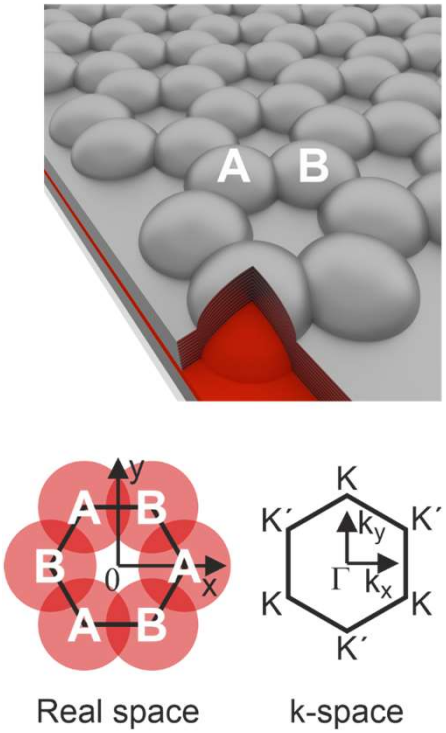
k-space

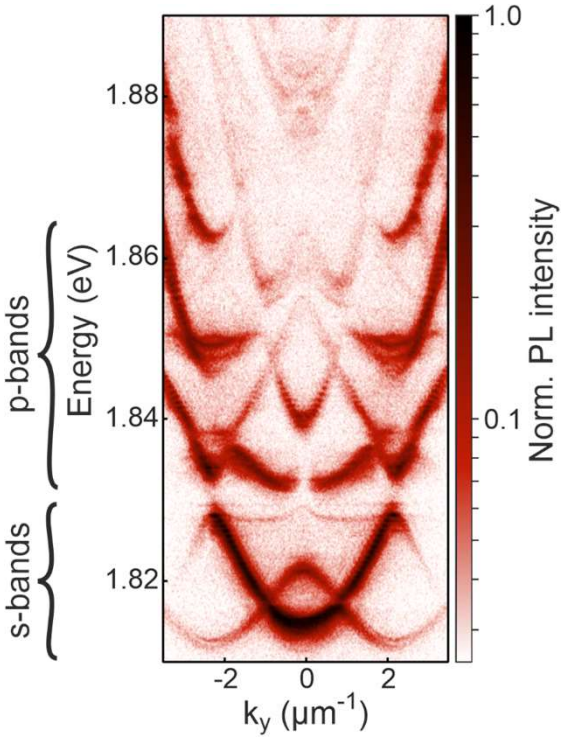


- Versatile platform for photonic lattices using various emitter materials
- Coupling strength and quality-factors comparable to state-of-the-art SC
- Allows for fundaments as well as applied studies

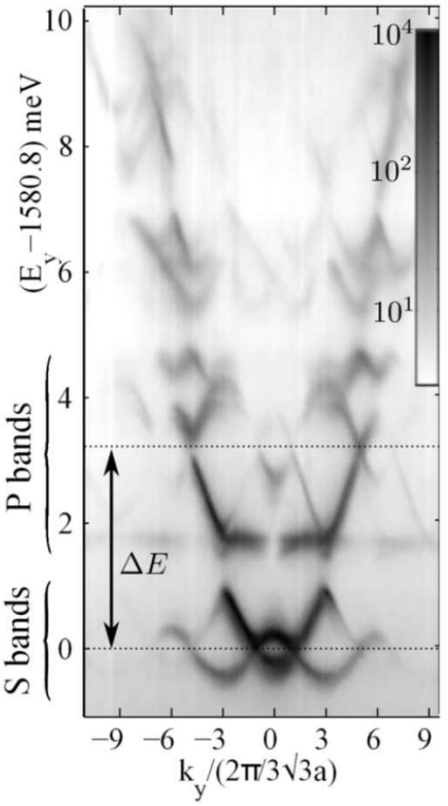
S. Betzold, SK et al., *Adv. Sci.* (2024).

Honeycomb lattice as a descriptive example for a 2D lattice



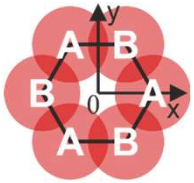


S. Betzold, SK et al., *Adv. Sci.* **11**, 2400672 (2024).

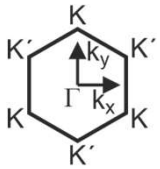


T. Jacqmin et al., *Phys. Rev. Lett.* **112**, 116402 (2014)

Bandstructure formation



Real space



k-space

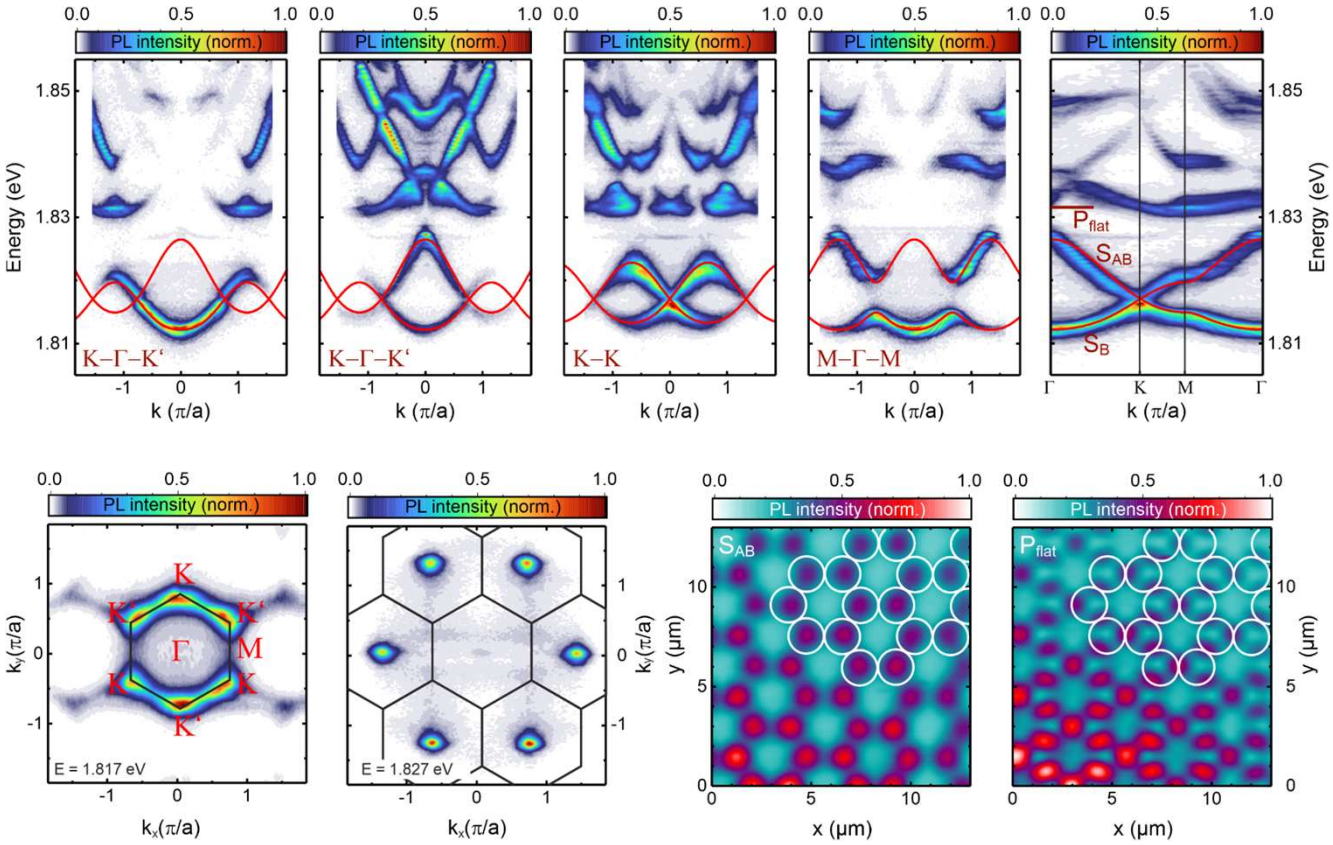
Tight binding fits considering nearest neighbor coupling t_1 and next-nearest neighbor coupling t_2

$$E(k) = \pm t_1 \cdot \sqrt{3 + f(k)} - t_2 \cdot f(k)$$

with $f(k) = 2\cos(\sqrt{3}k_y a) +$

$$+4\cos\left(\frac{\sqrt{3}}{2}k_y a\right)\cos\left(\frac{3}{2}k_x a\right)$$

	t1 (meV)	t2 (meV)	t2/t1
This work	2.38	0.25	0.11
Tristans thesis	0.356	0.044	0.12
Jacqmin et al.[1]	0.25	0.02	0.08



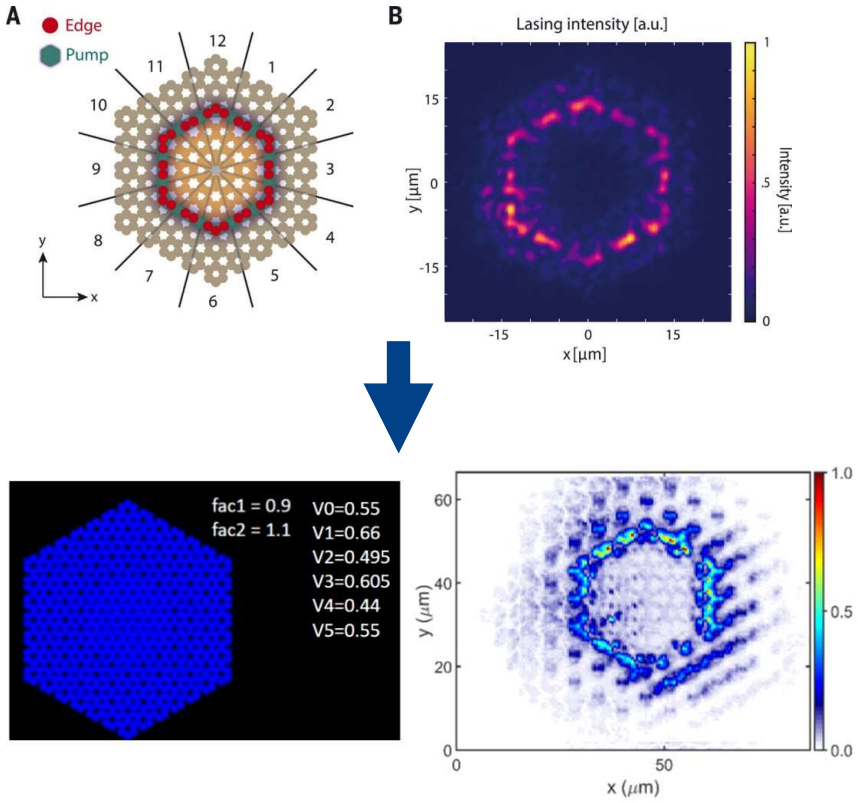
S. Betzold, SK et al., *Adv. Sci.* **11**, 2400672 (2024).

[1]T. Jacqmin et al., *Phys. Rev. Lett.* **112**, 116402 (2014)

Coupled hemispheric cavities as versatile platform

- Outlook: more complex and interesting lattices

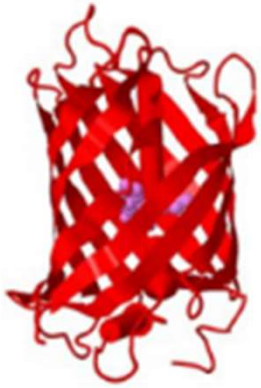
A. Dikopoltsev, …, SK, Science **373**, 6562 (2021).



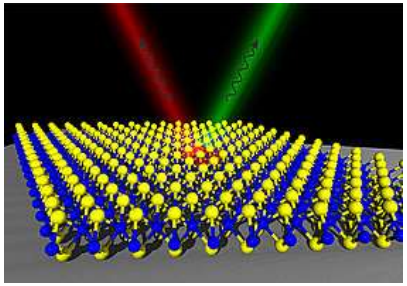
Use various organic emitter materials

- mCherry (Fischer)
- Perylene Bisimides (Würthner)
- Alq3:DCM (Leo, Pflaum)

Novel materials for RT cavities

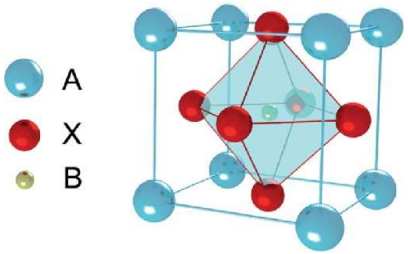


- S. Betzold, S.K. et al., ACS Photon. **7**, 384 (2019)
- M. Dusel, S.K. et al., Nat. Commun. **11** , 1-7 (2020)
- M. Dusel, R. Thomale, S.K. et al., Nano Lett. 21, 6398 (2021)
- Strong light matter coupling with Perylene Bisimides (in preparation)



- N. Lundt, S.K. et al., *Nat. Nano.* **14** , 770 (2019)
- C. Anton-Solanas, S.K. et al. *Nat. Mater.* **20**, 1233 (2021)
- H. Shan, S.K. et al. *Nat. Commun.* **12**, 1-7 (2021)

  … with Prof. Schneider, Uni Oldenburg



ABX_3

Collaboration TEP – EP VI

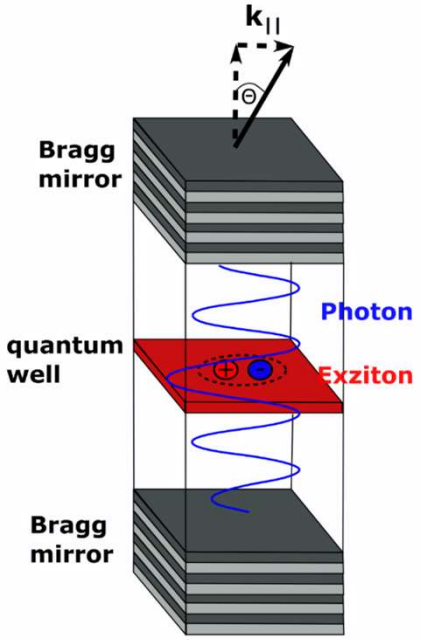
- peroskite layers as emitter material
- MAPI/$MAPbBr_3$ or novel $Cs_2AgBiBr_6$ double perovskite

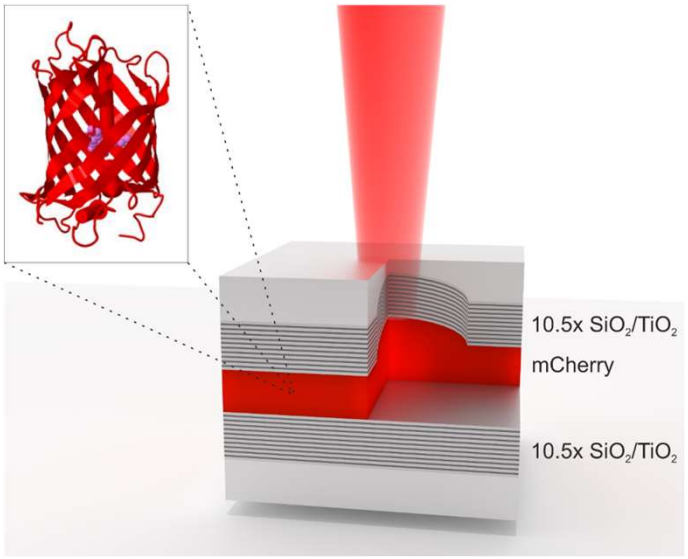
… with Prof. Dyakonov, Uni Würzburg

Towards topological photonics with a versatile emitter platform

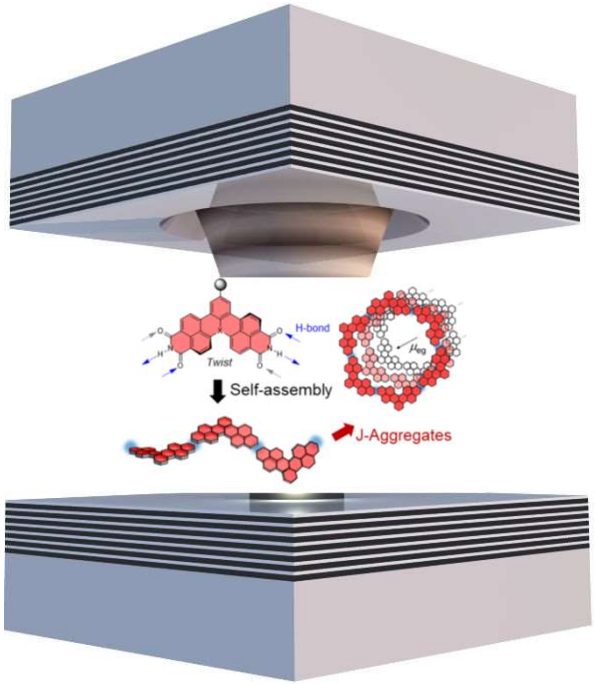
From semiconductors to dielectric cavities

Organic emitters and novel 2D materials





S. Betzold, SK et al., *ACS Photonics* (2020).



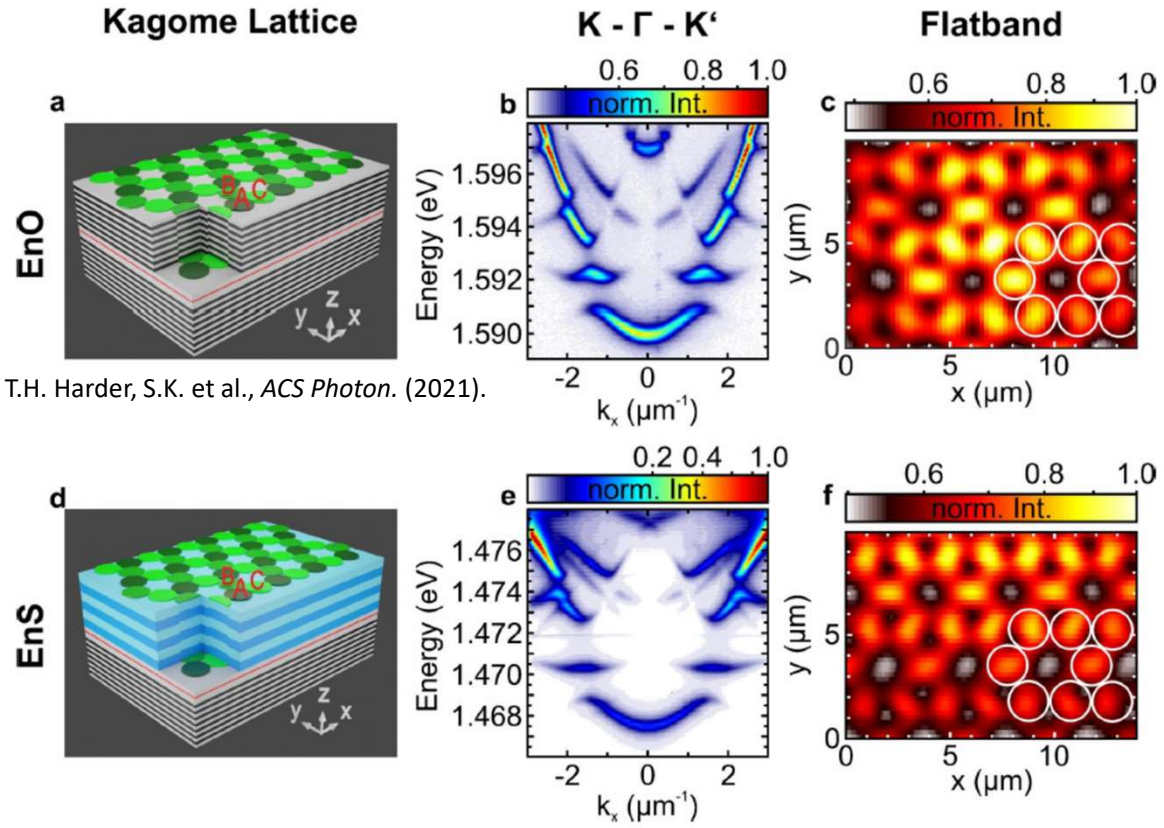
H. Shan, SK et al., Nat. Commun. (2022).

D. Horneber, SK et al., in preparation (2024).

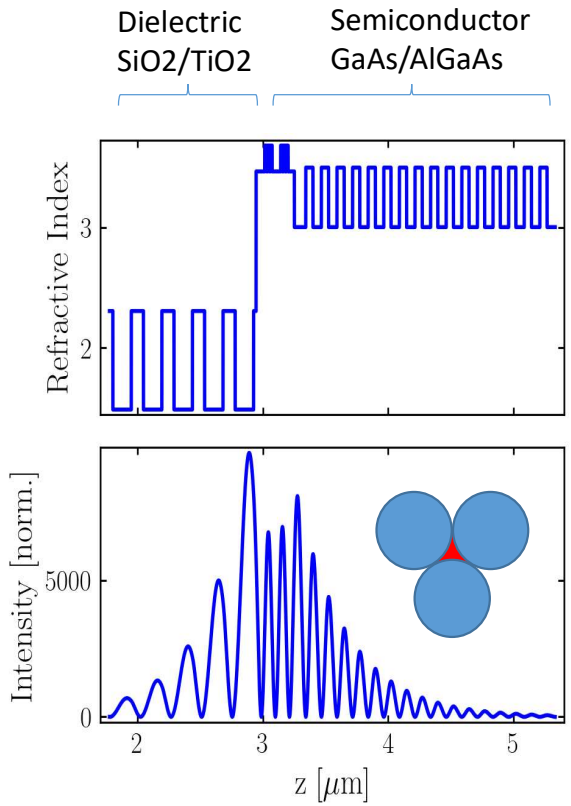
- Strong light matter interactions in tailered microcavities
- A wide range of novel quantum materials and organic emitters can be studied
- Use of supramolecular engineered materials
- Study reaction kinetics under the presence of strong light fields

Novel technique for polariton lattices

Hybrid III/V & Dielectric Microcavities



T.H. Harder, S.K. et al., *ACS Photon.* (2021).

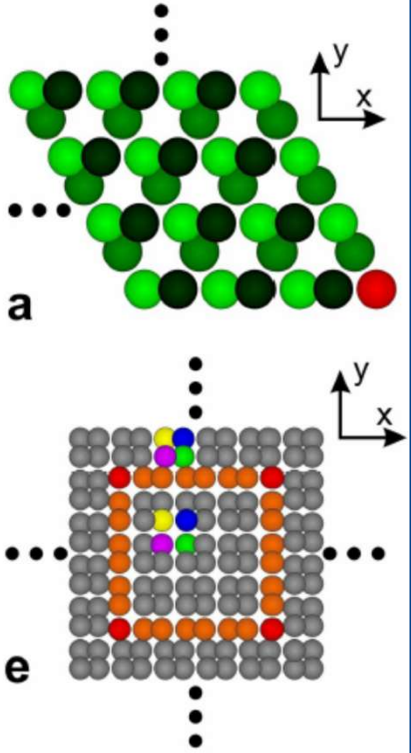


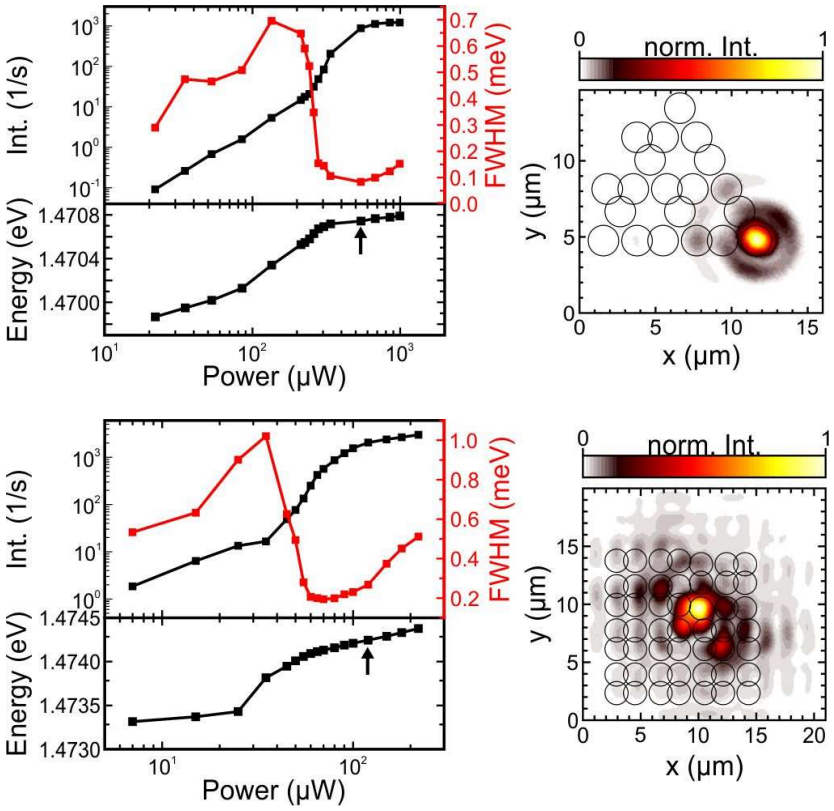
- Very similar couplings
- No change in bandstructure
- Same levels of homogeniety
- Realization of lattices with high packing density

Higher-order polariton TIs

Coupling, dimensionality and disorder

- Realization of a **breathing Kagome lattice**, a hexagonal lattice with tri-atomic unit cell
- … and a **2D-SSH lattice**, featuring bulk regions with compressed and stretched unit cells, as well as a boundary between them
- Studies of disorder, robustness, symmetry breaking, …

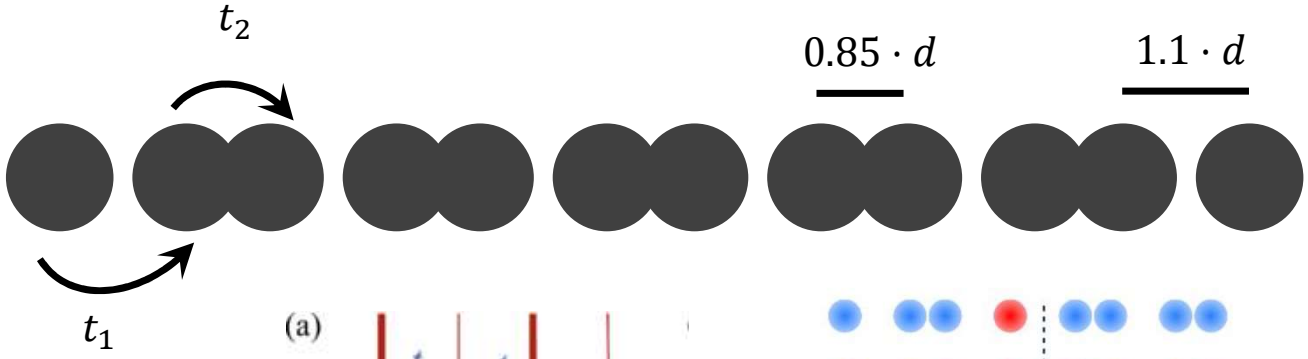




P. Gagel, J. Düreth, SK et al., *in preparation* (2024).

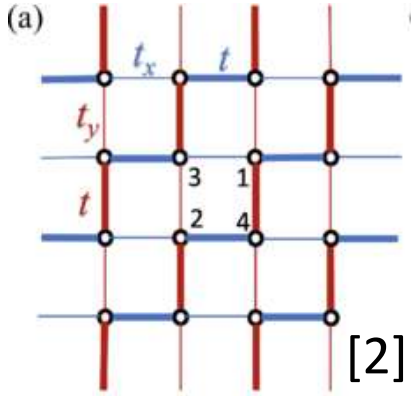
SSH-Lattice

- Staggered hopping -> Dimerization [1]

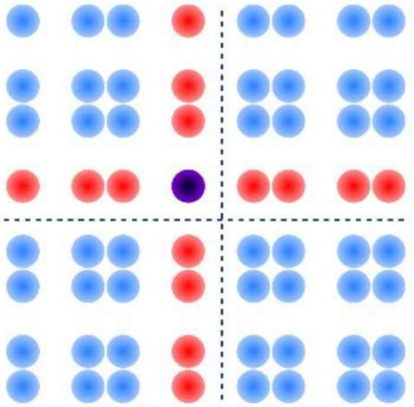


$d = 2\mu m$

- Extension to 2D



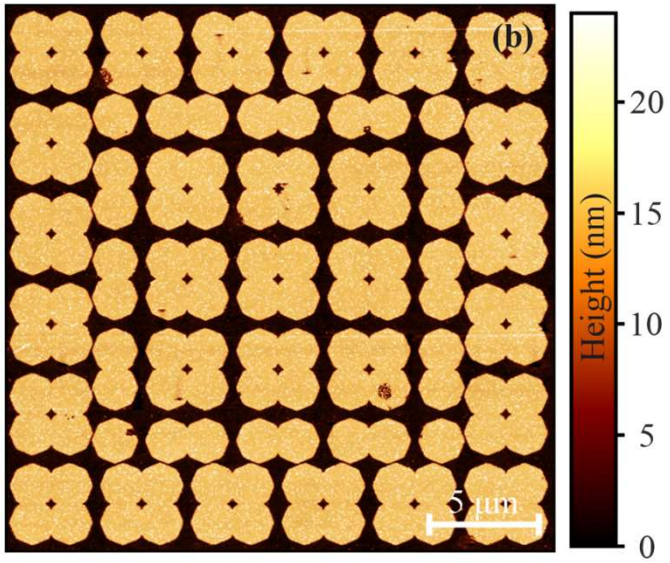
[2]

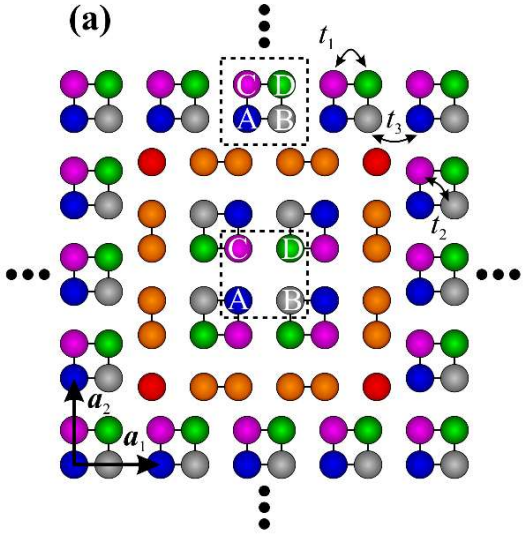


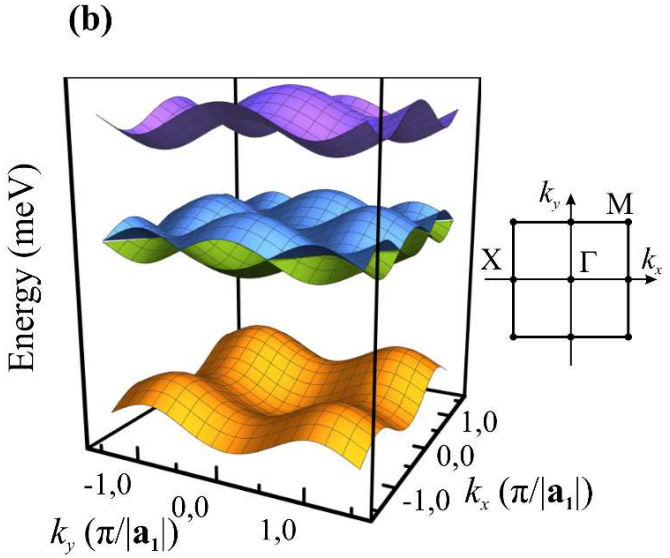
[3]

[1] W. P. Su, J. R. Schrieffer, and A. J. Heeger, Phys. Rev. Lett. **42**, 1698 (1979)
[2] Chang-An Li et al., Phys. Rev. Research 4, 023193 (2022)
[3] https://arxiv.org/abs/2401.06267

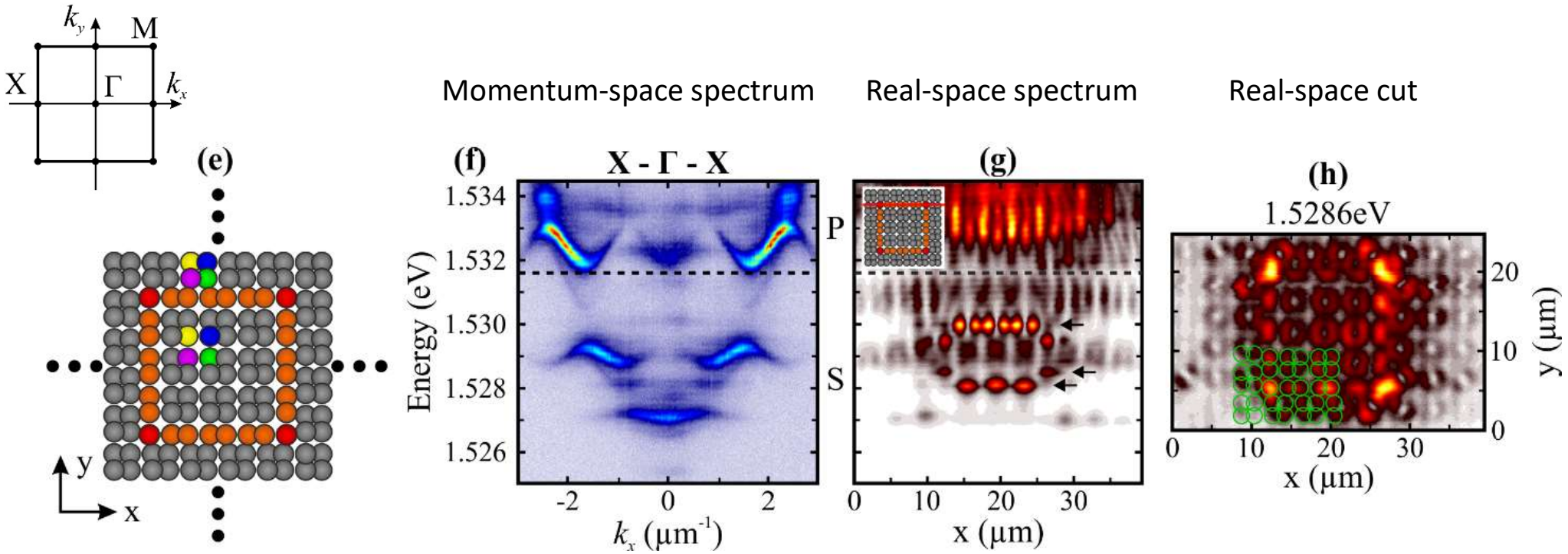
2D-SSH Lattice



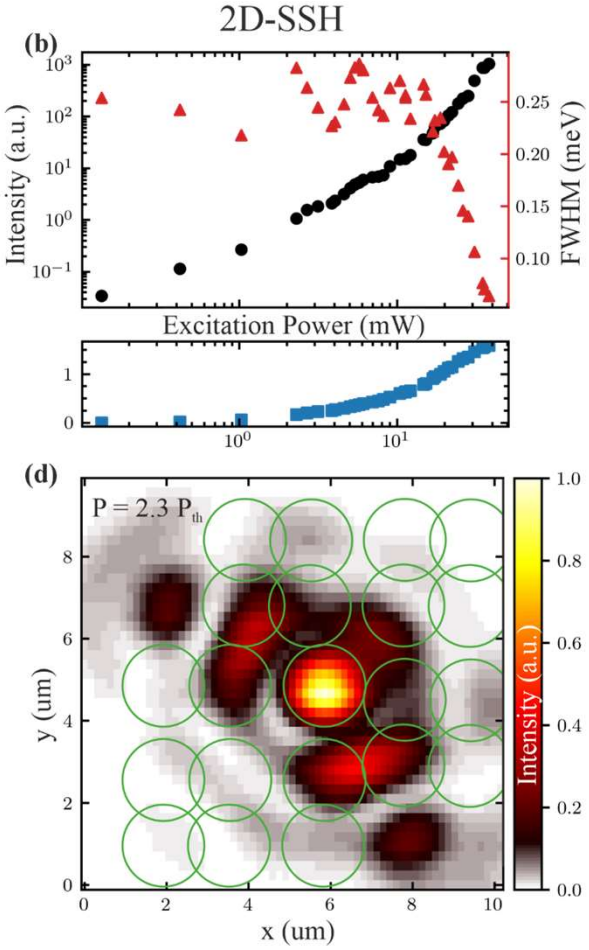


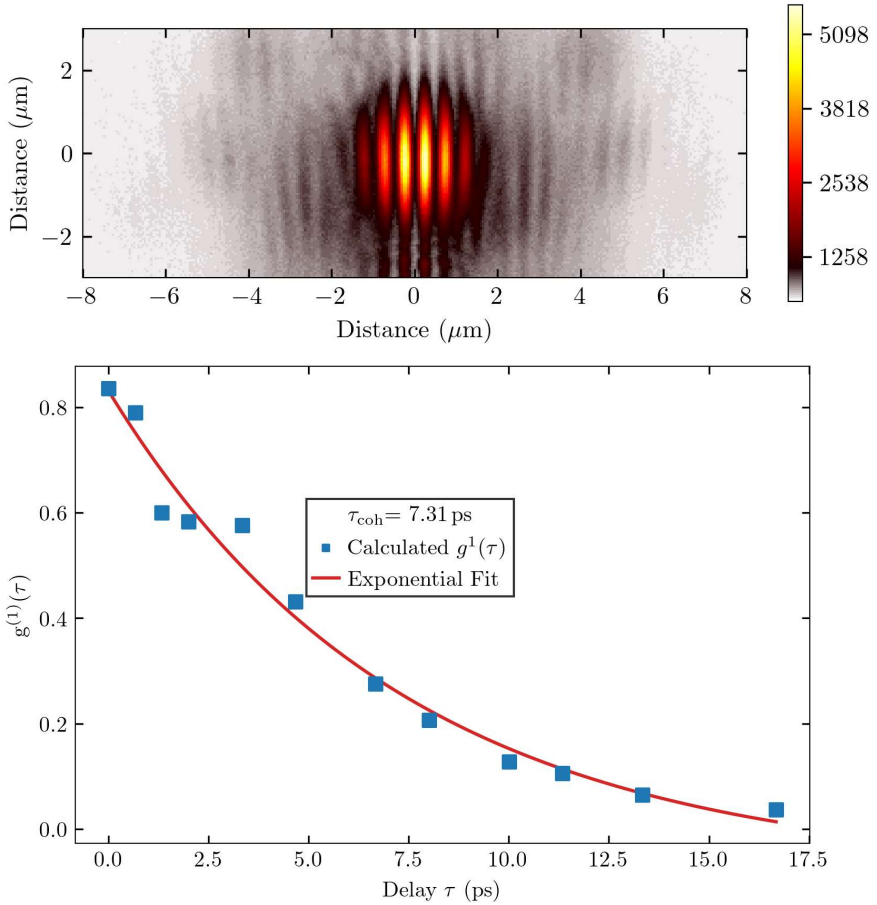


2D-SSH Lattice

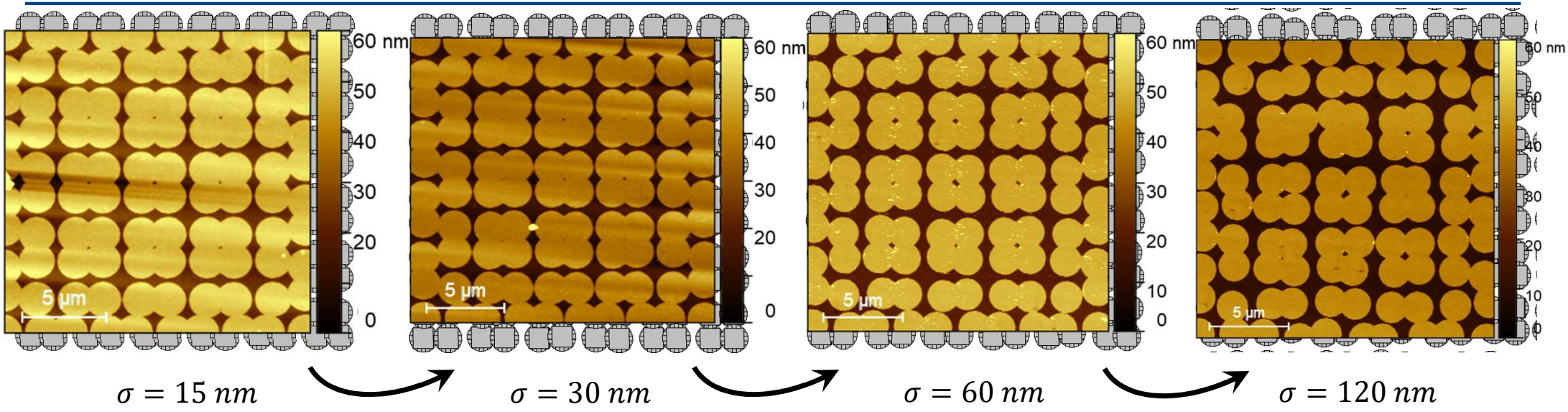


Corner Mode Lasing and Coherence

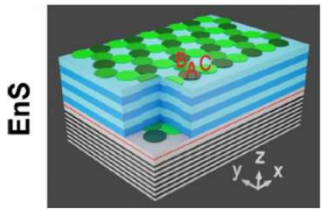


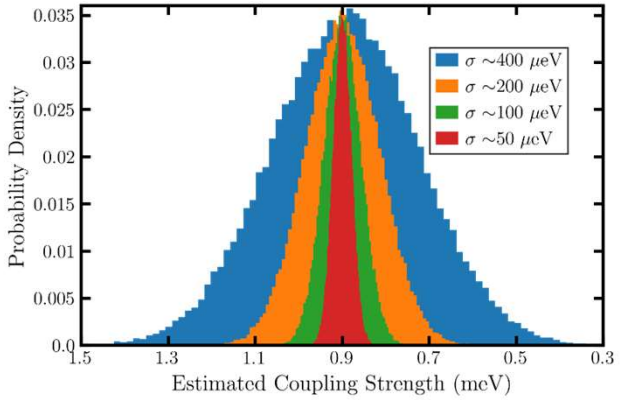


Disorder and Protection?

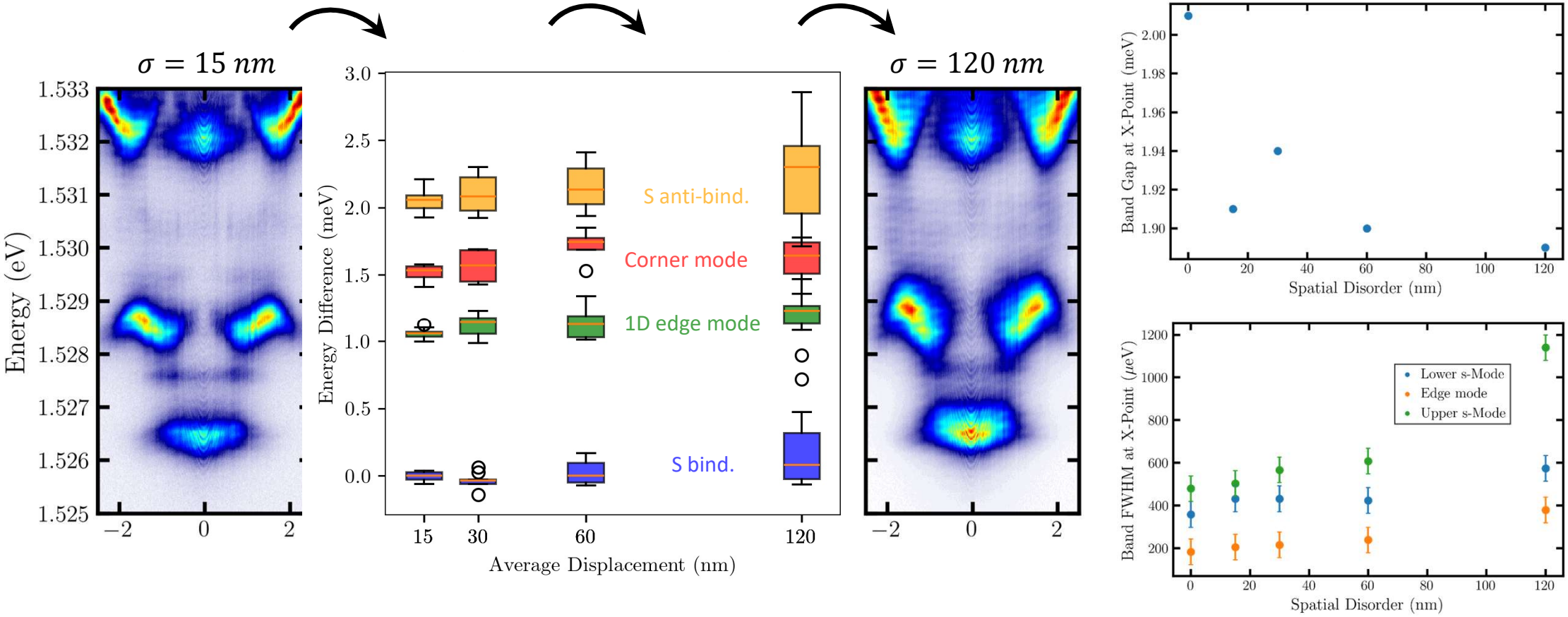


- Intentionally manufacture disordered lattice
- Displacement of position in x- and y





Disorder and Protection?

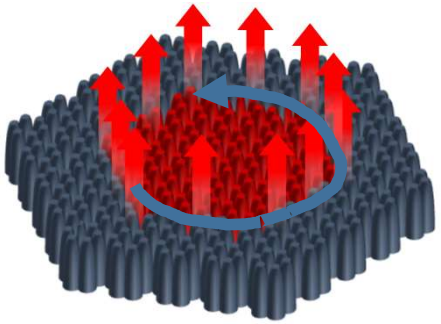


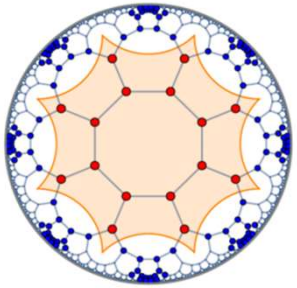
P. Gagel, J. Düreth, SK et al., *in preparation* (2024).

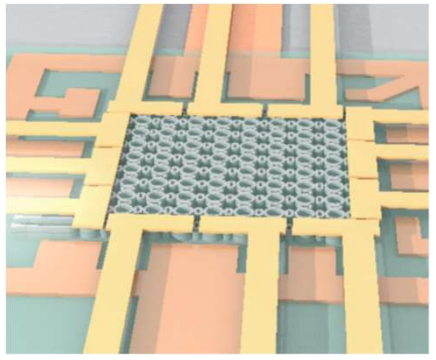
Summary

Topological Photonics

- Topologically protected edge and corner modes
- Exciton-polariton lattices offer possibilities to go into the strong interaction many-body regime
- BEC-BCS-BKT Physics accessible
- Novel topological devices







Jae-Hyuck Choi et al., Nat. Commun. **12**, 3434 (2021).

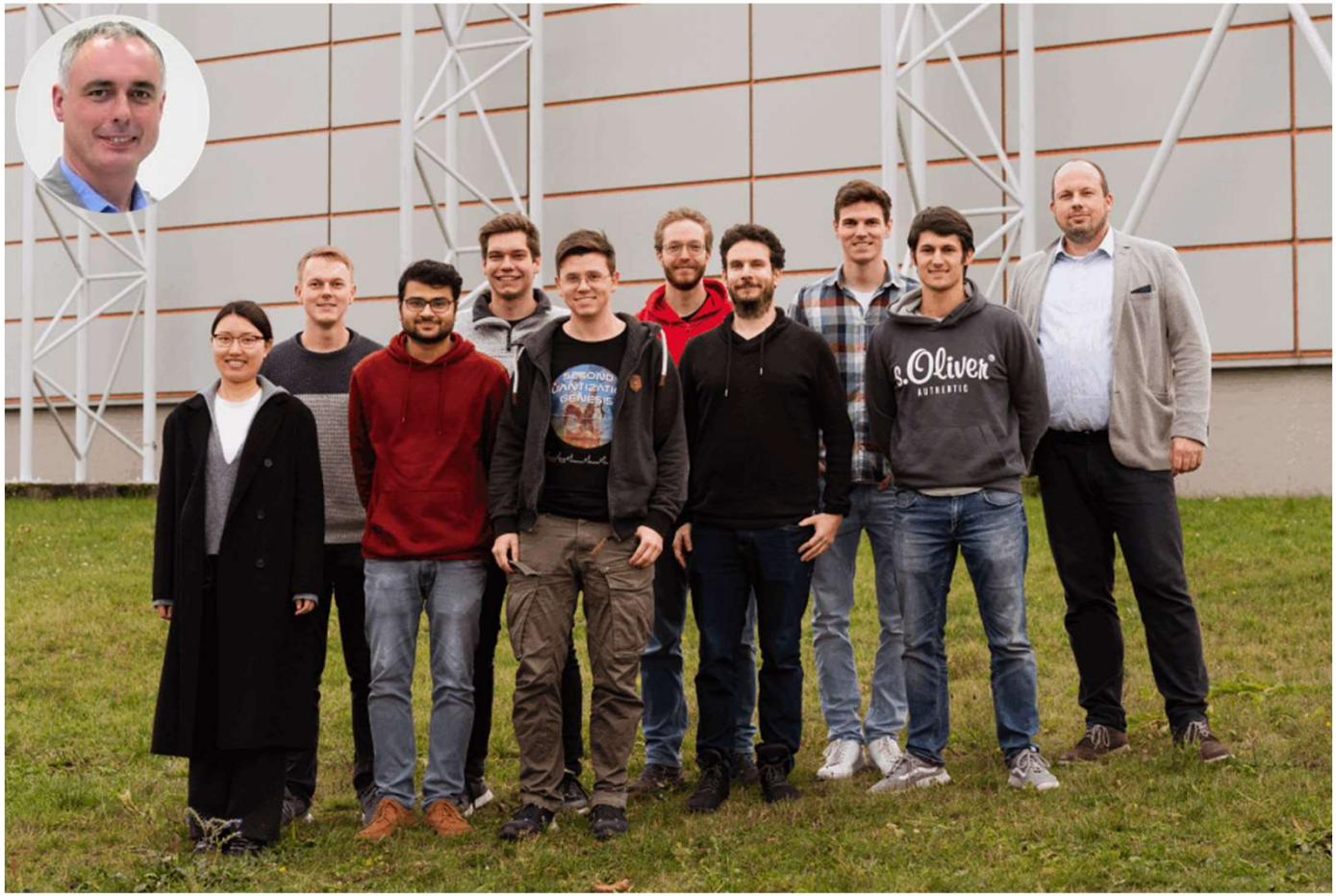
Questions?



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Seigo Tarucha



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