Aalto University
School of Science

Topological Photonics with Plasmonic Lattices

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Quantum Nanophotonics, Benasque, Spain

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Institute Q

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HORIZON2020
Marie Skłodowska-Curie actions

ACADEMY OF FINLAND

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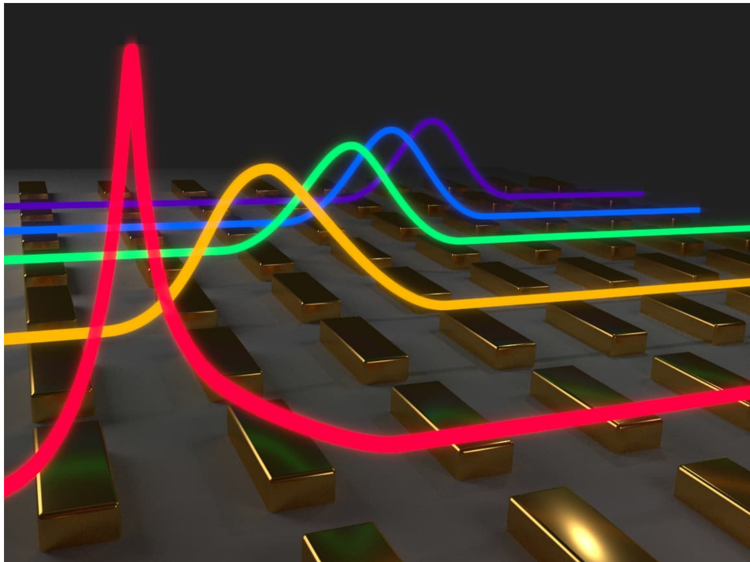

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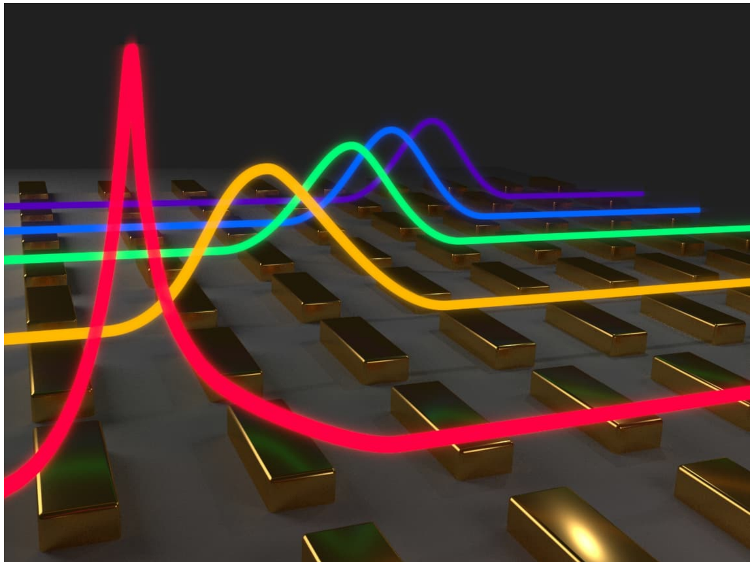
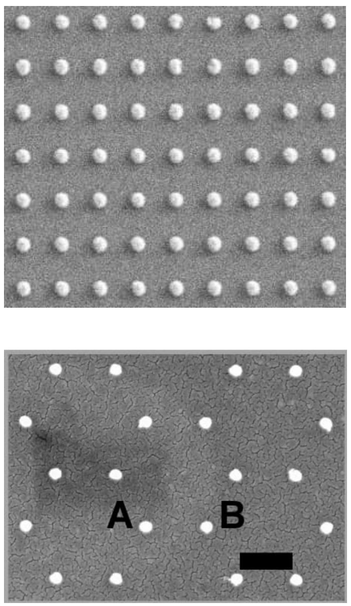
Bose-Einstein condensation (BEC) in a plasmonic lattice

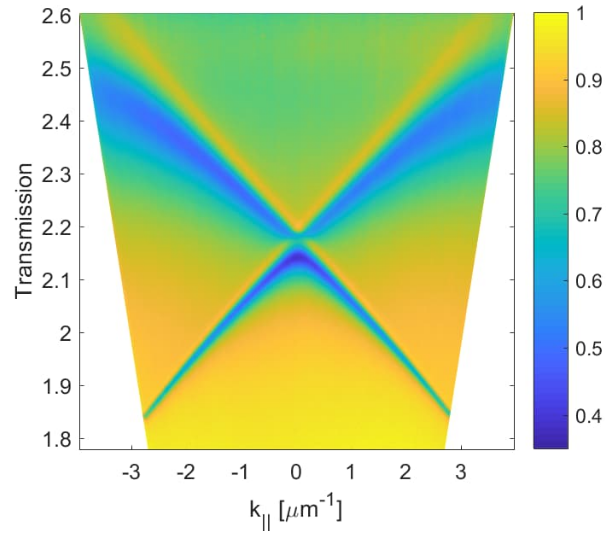
- **Background**
- BEC at weak and strong coupling
- Spatial and temporal coherence
- Polarization textures

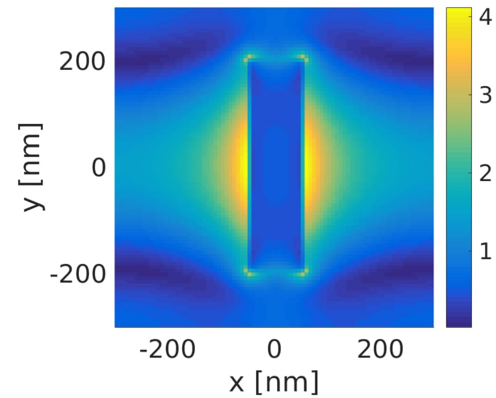
Quasi-BIC mode lasing and topological transitions



Plasmonic lattices
light-matter interaction at new regimes

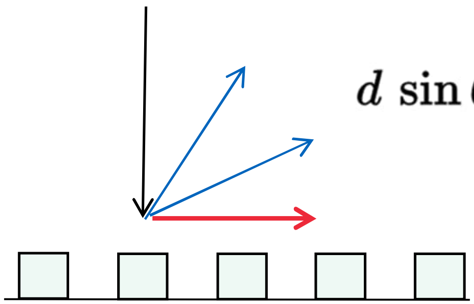




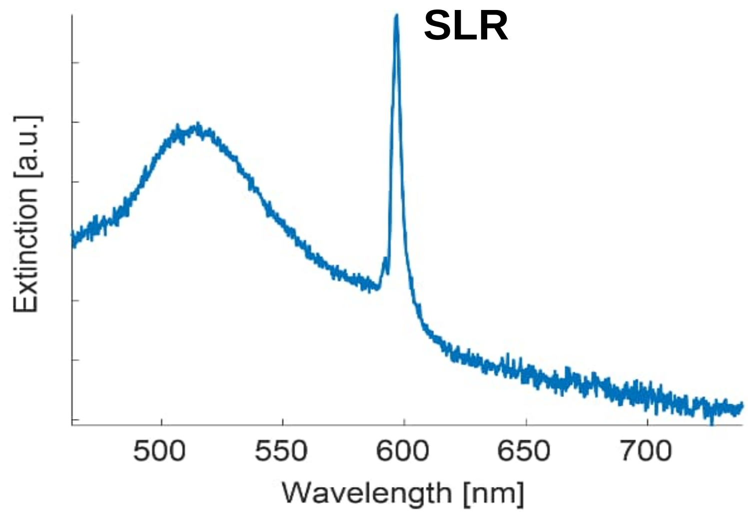


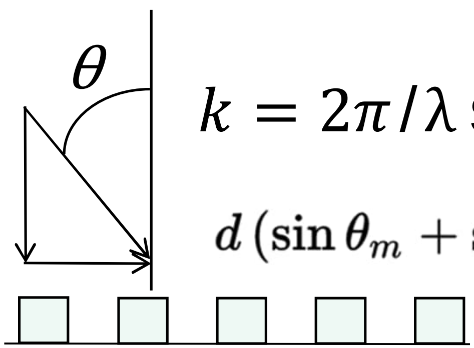
Reviews
Garcia de Abajo, Rev. Mod. Phys. 2007
Wang, Ramezani, Väkeväinen, PT, Gomez-Rivas, Odom, Materials Today 2018
Kravets, Kabashin, Barnes, Grigorenko, Chemical Reviews 2018

Surface lattice resonance (SLR)



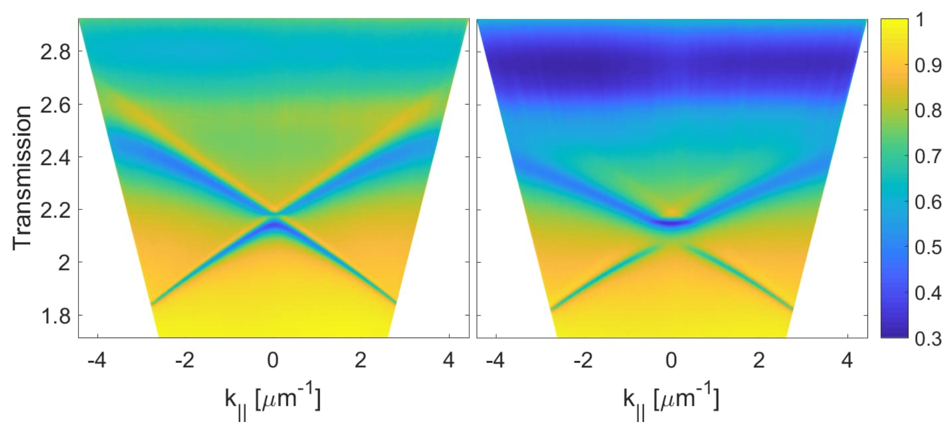
$$d \sin\theta_n = n\lambda$$



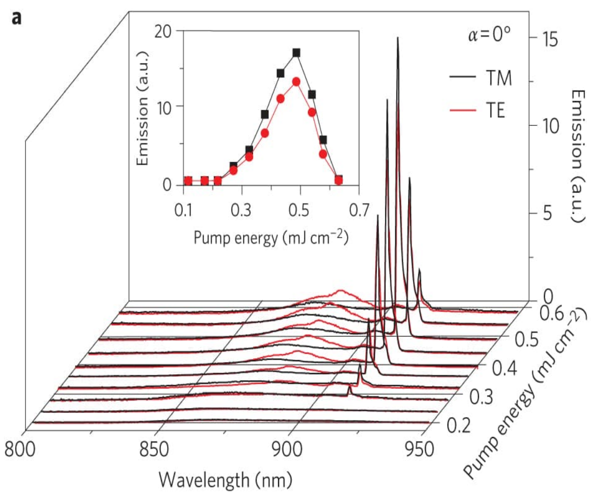


$$k = 2\pi/\lambda \sin(\theta)$$

$$d\,(\sin\theta_m + \sin\theta_i) = m\lambda$$

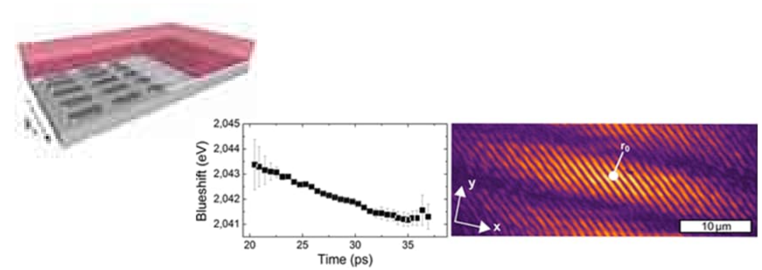


Nanoparticle arrays combined with organic molecules: lasing, strong coupling



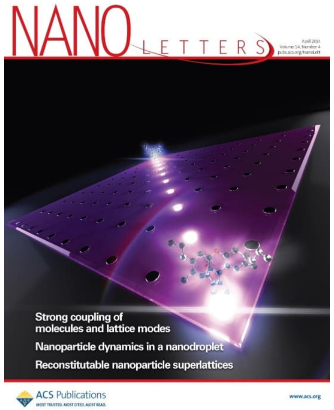
Picture from
Odom, Schatz, Nat. Nanotech. 2013

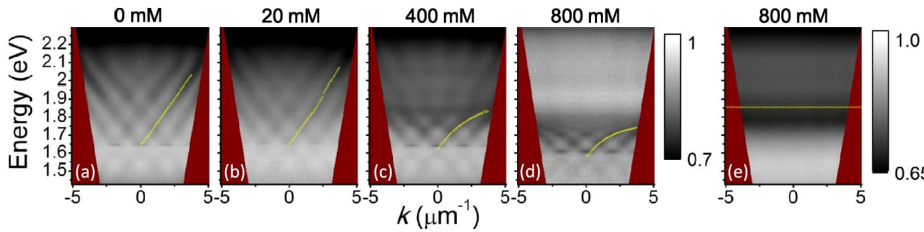
Reviews
Small lasers, the spaser concept:
Hill and Gather, Nat. Phot. 8, 908 (2014)
Focus on nanoparticle arrays:
Wang et al., Chem. Rev.118, 2865 (2018)
Wang et al., Materials Today 21, 303 (2018)



Polariton lasing/condensation
Ramezani, Halpin, Fernández-Domínguez, Feist, Rodriguez, Garcia-Vidal, Gomez-Rivas, Optica 2017,
Gomez-Rivas, Sanvitto groups
ACS Photonics 2018, Nano Letters 2019

Our previous SLR work

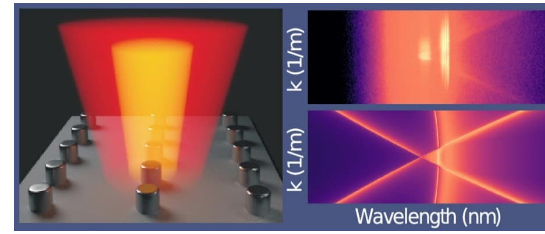




Spatial coherence at strong coupling
Shi et al. Phys Rev Lett 2014

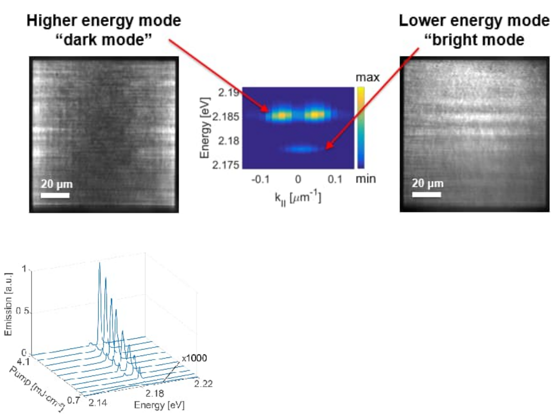
Strong coupling in a plasmonic lattice
Väkeväinen et al. Nano Lett 2014

Strong coupling in dielectric particle array
Heilmann et al. Nanophot. 2020

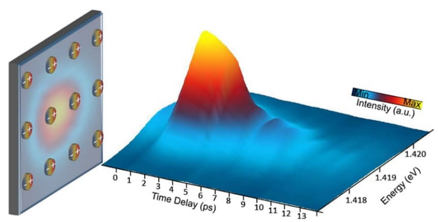


Lasing in Ni nanodisk arrays
Pourjamal et al. ACS Nano 2019

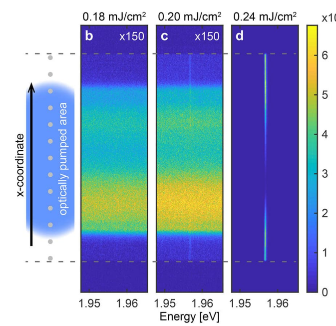
Magnetoplasmonic lattices
Kataja et al. Nature Comm 2015



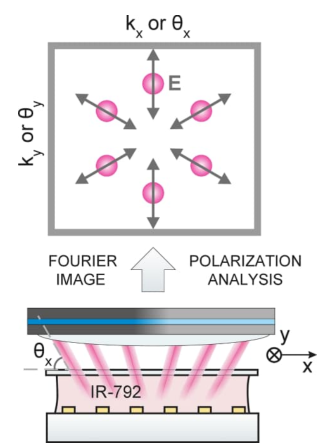
Lasing in dark (BIC)
and bright modes
Hakala et al. Nature Comm 2017



Ultrafast pulse generation
Daskalakis et al. Nano Lett 2018



1D plasmonic lasing
Rekola et al. ACS Phot 2018



K-point lasing in a honeycomb
lattice
Guo et al. Phys Rev Lett 2019

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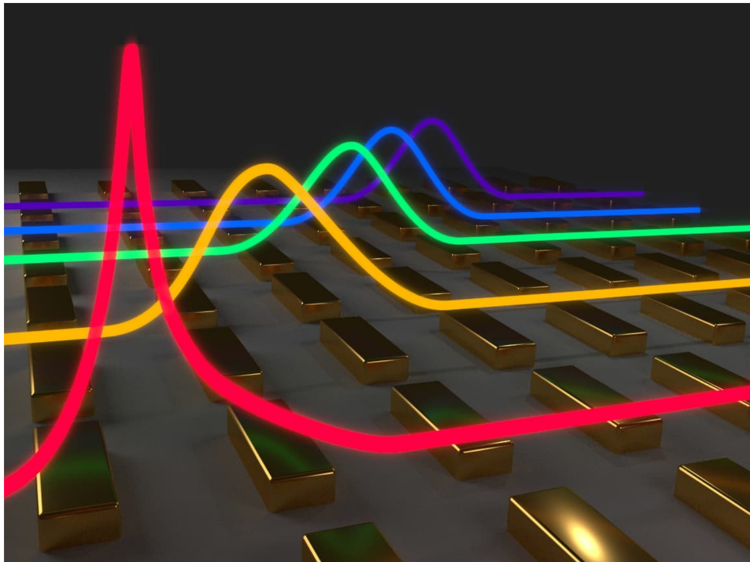


Bose-Einstein condensation in a plasmonic lattice

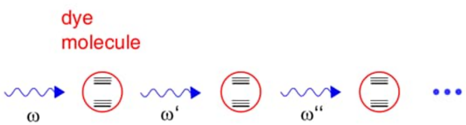
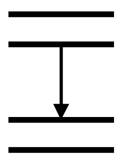
Hakala, Moilanen, Väkeväinen, Guo, Martikainen, Daskalakis, Rekola, Julku, PT, Nature Physics 2018

Väkeväinen, Moilanen, Necada, Hakala, Daskalakis, PT, Nature Communications 2020

Moilanen, Daskalakis, Taskinen, PT, PRL 2021

Taskinen, Kliuiev, Moilanen, PT, Nano Letters 2021

Photon and/or exciton condensation

	Light	Polariton $c_l\|light\rangle + c_m\|matter\rangle$	Matter
Thermalization by emission/absorption cycles 	Photon BEC *Plasmonic BEC weak coupling Hakala et al. Nat.Phys.2018*	*Plasmonic BEC strong coupling Väkeväinen et al. Nat.Comm.2020*	
Relaxation by emission of a vibrational quantum 		Organic polariton condensate/lasing	
Coulomb relaxation/ thermalization		Inorganic polariton condensate/BEC/ lasing	Exciton BEC

Literature: Byrnes, Kim, Yamamoto, Nat. Phys. 2014; Klaers, Schmitt, Vewinger, Weitz, Nature 2010
Keeling, Kena-Cohen, Ann. Rev. Phys. Chem. 2020

Plasmonic BEC: weak coupling

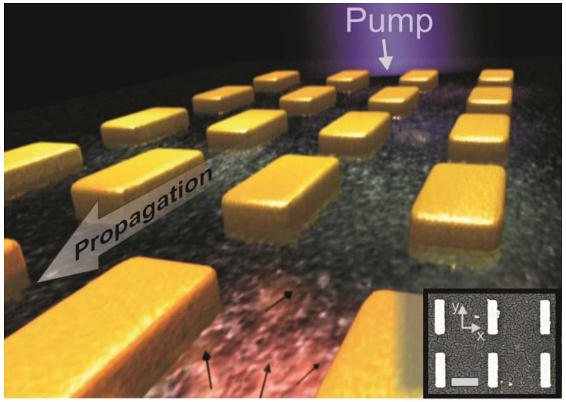
Tommi Hakala

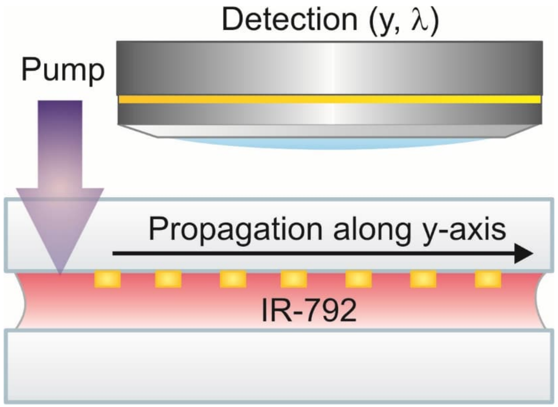
Antti Moilanen

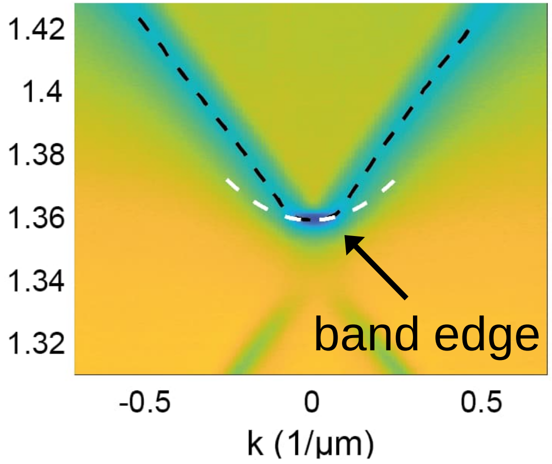
Aaro Väkeväinen

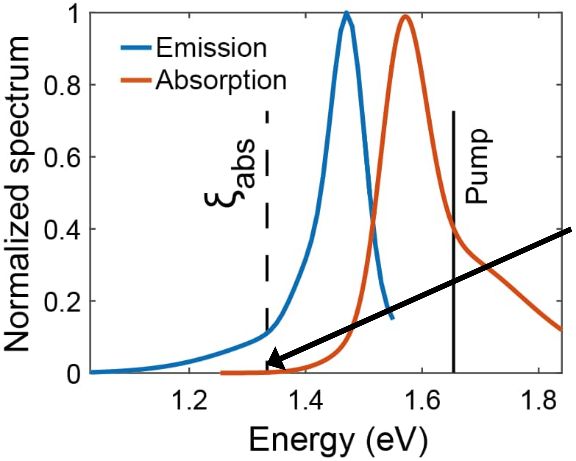
Hakala, Moilanen, Väkeväinen, Guo, Martikainen, Daskalakis, Rekola, Julku, PT, Nature Physics 2018

Nanoparticle array + molecules (weak coupling)



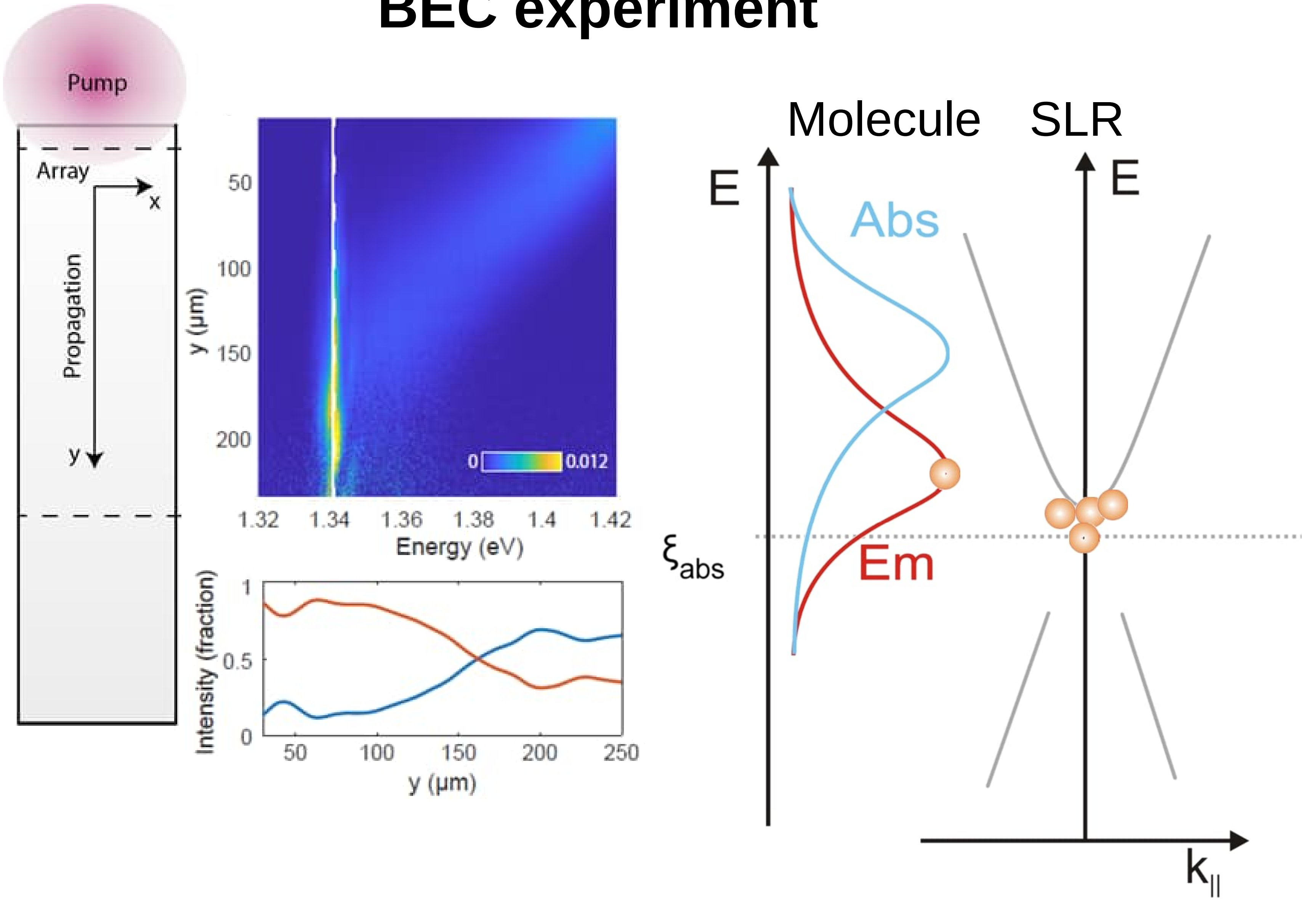






Energy where absorption rate is effectively zero (i.e. smaller than the loss rate)

BEC experiment



Plasmonic BEC: strong coupling

Aaro Väkeväinen

Antti Moilanen

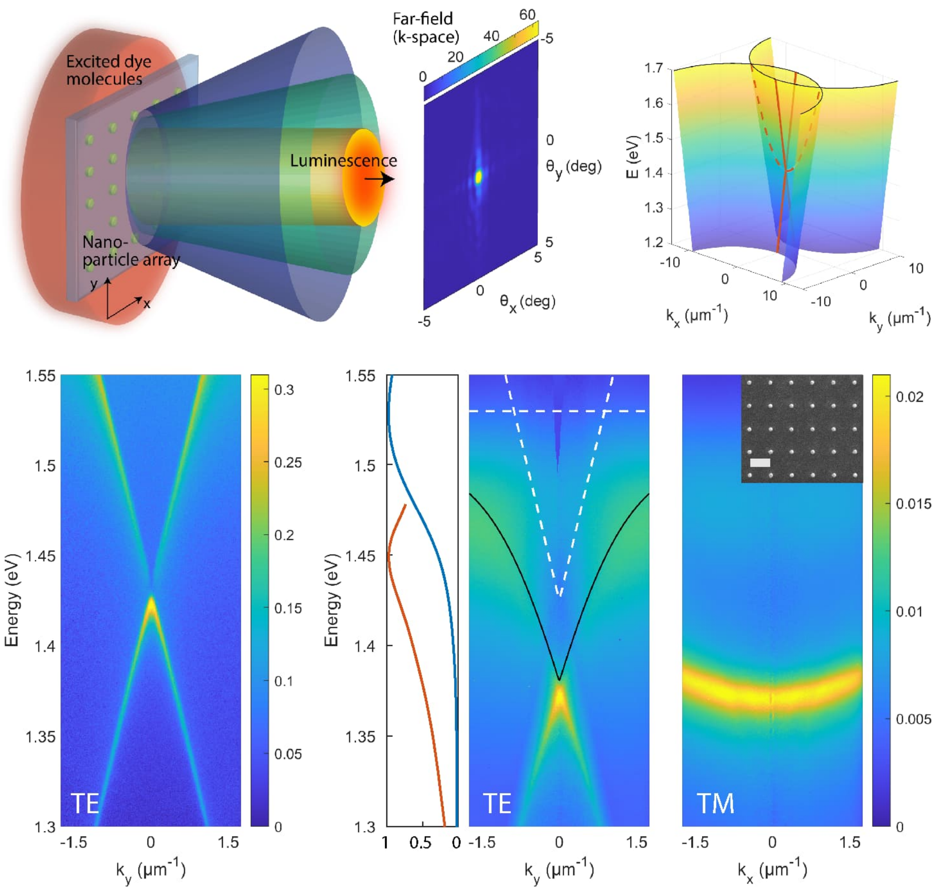
Marek Necada

Väkeväinen, Moilanen, Necada, Hakala, Daskalakis, PT, Nature Communications 2020

Sub-picosecond thermalization dynamics of the condensate

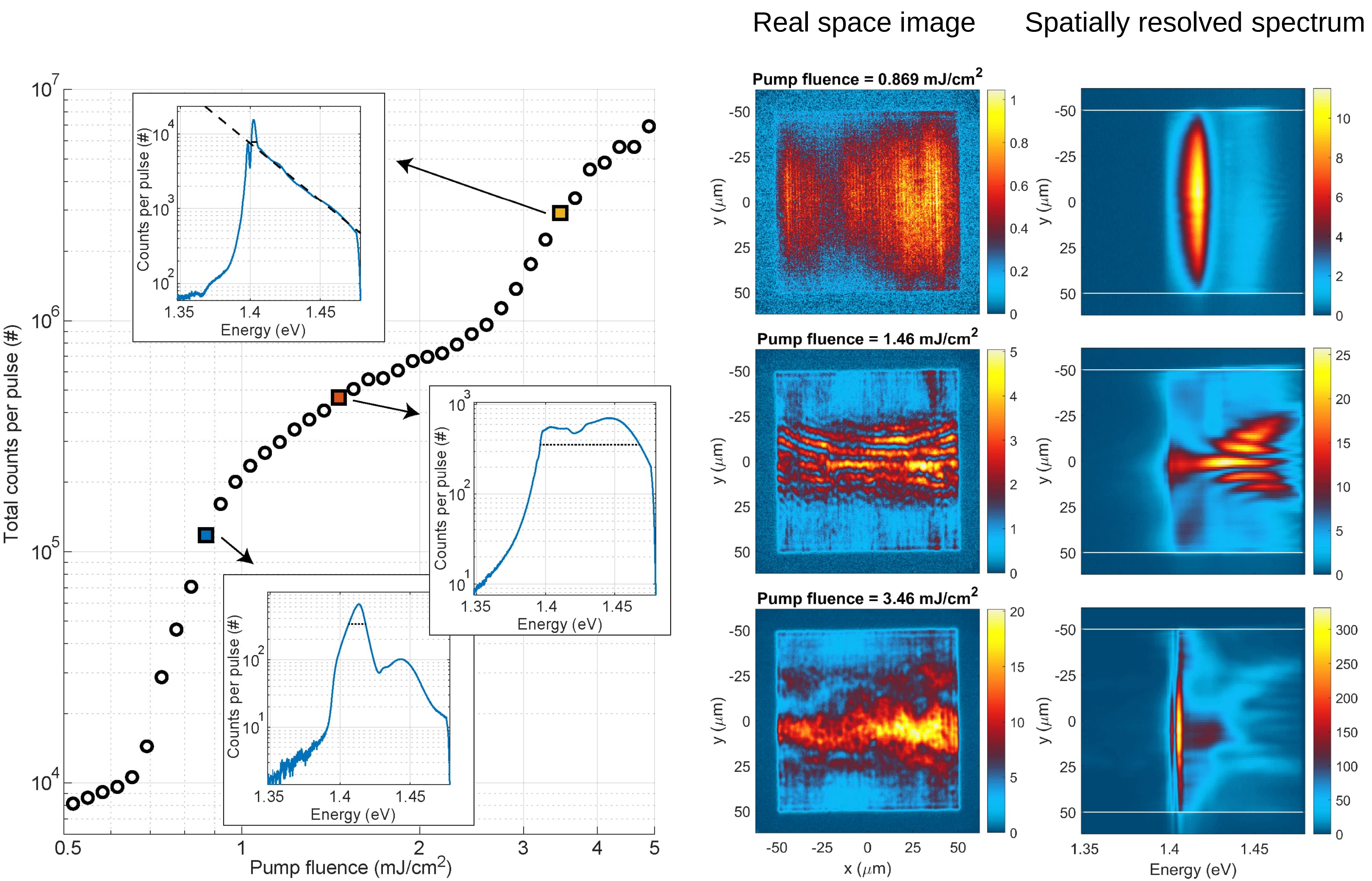
Strong coupling regime: Polariton
= SLR excitation (“light”)
+ dyes molecules (“matter”)

Pump over the whole sample



Väkeväinen, Moilanen, Necada, Hakala, Daskalakis, PT, Nat. Commun. 2020

Three regimes:
polariton lasing, stimulated thermalization, BEC



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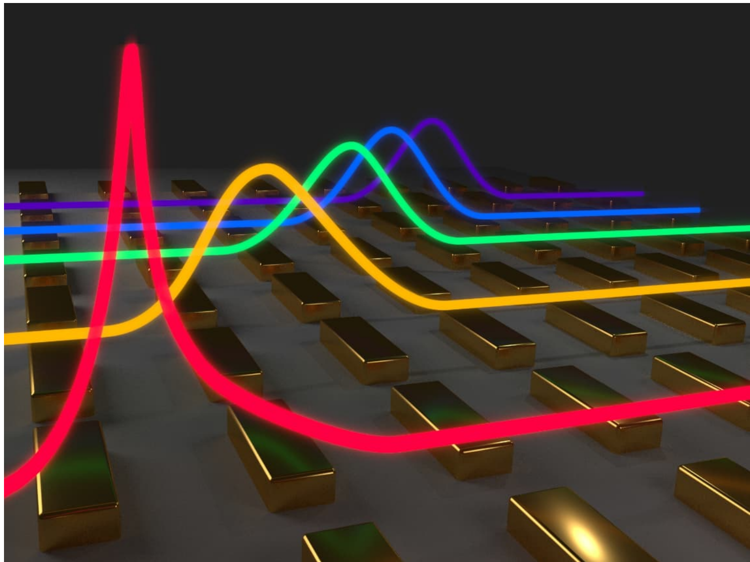
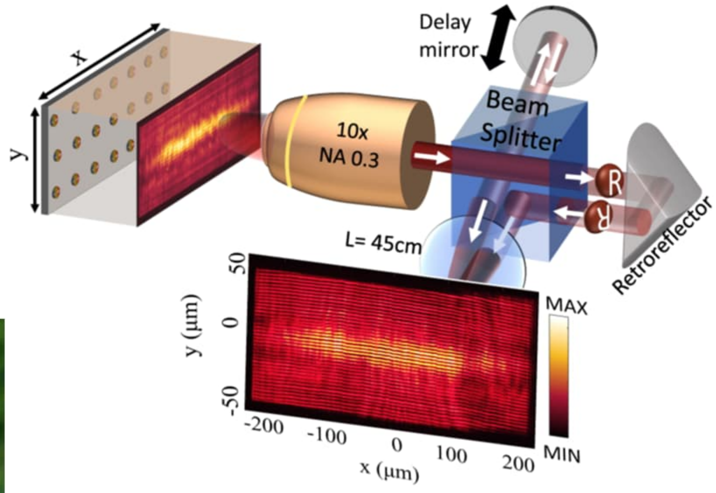
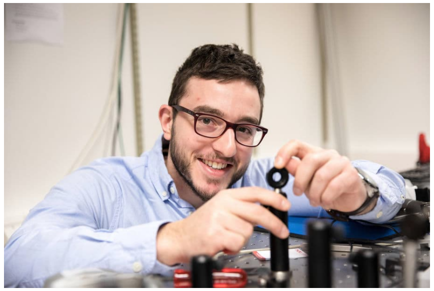


Spatial and temporal coherence of the strong coupling BEC





Antti Moilanen   Konstantinos Daskalakis   Jani Taskinen

Moilanen, Daskalakis, Taskinen, PT, PRL 2021

Long-range order in 2D BECs

Mermin-Wagner:
- thermal fluctuations prevent ODLRO in 2D at any finite T

Berezinskii–Kosterlitz–Thouless (BKT):
- vortex-antivortex pairing
- quasi-long-range order
- algebraic decay: $b < 0.25$

$g^{(1)}(x) = ax^{-b}$

How about non-equilibrium condensates?

Non-equilibrium BKT
- algebraic decay; different exponents for spatial and temporal coherence[2,3]

$b_s = 2b_t$

Kardar–Parisi–Zhang (KPZ)
- dynamical phase ordering; decay by stretched exponential with universal exponents[4,5,6]

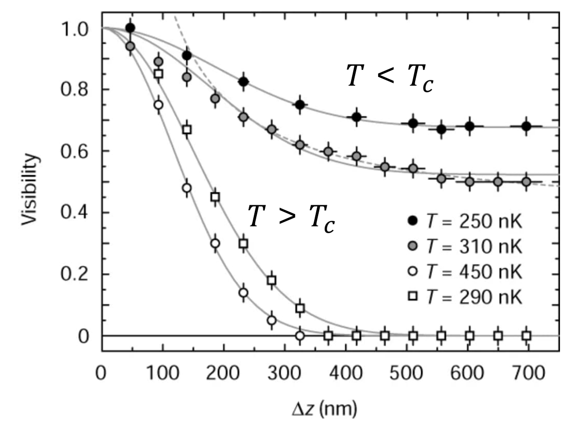
$g^{(1)}(x) = ae^{-(x/d)^{\beta}}$

$\beta_s = 0.78$
$\beta_t = 0.48$

BKT–KPZ crossover by system anisotropy[4,7]

In 3D BEC at equilibrium, off-diagonal long-range order (ODLRO)

Spatial correlation function of a trapped Bose gas [1]:



[1] Bloch, Hänsch & Esslinger, Nature 403, 166–170 (2000)
[2] Szymanska, Keeling & Littlewood, PRB 75, 195331 (2007)
[3] Comaron, Carusotto, Szymanska & Proukakis, EPL 133, 17002 (2021)
[4] Altman, Sieberer, Chen, Diehl & Toner, PRX 5, 011017 (2015)
[5] Ferrier, Zamora, Dagvadorj & Szymanska, arXiv:2009.05177 (2020)
[6] Comaron, Dagvadorj, Zamora, Carusotto, Proukakis & Szymanska, PRL 121, 095302 (2018)
[7] Zamora, Sieberer, Dunnett, Diehl & Szymanska, PRX 7, 041006 (2017)

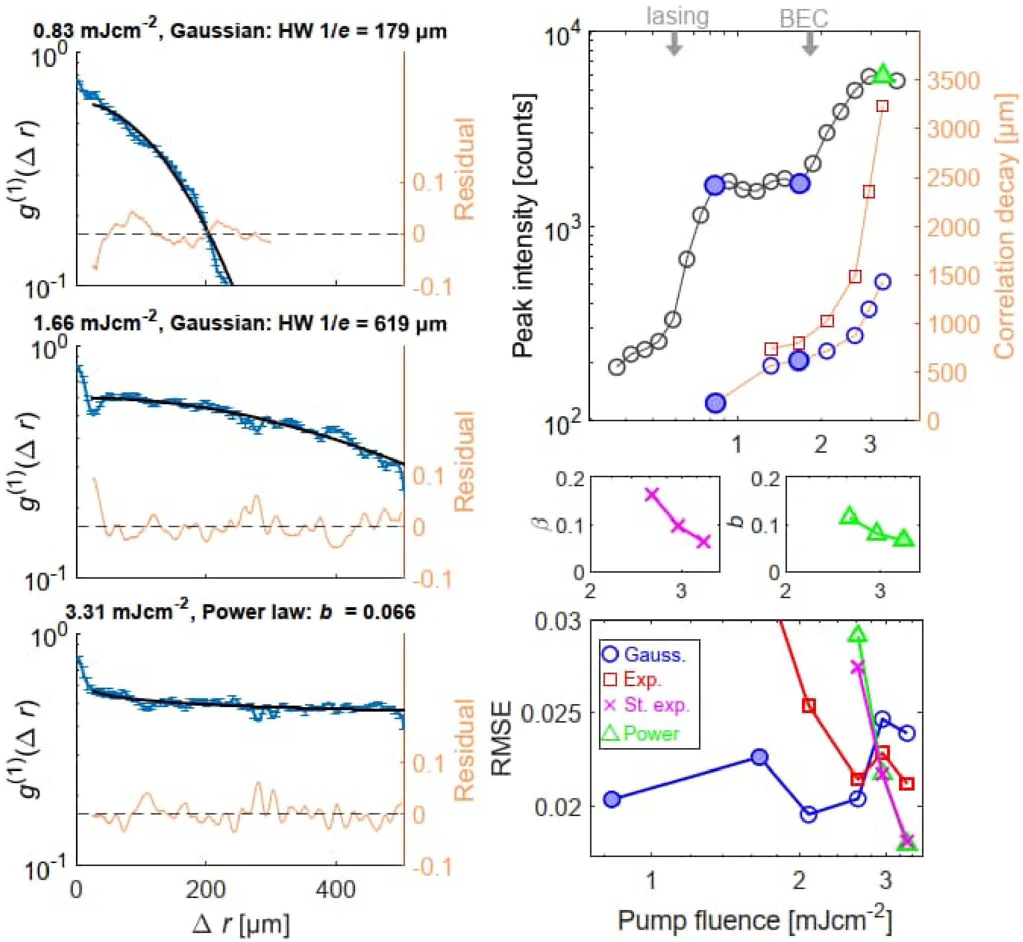
KPZ and polaritons in 1D: J. Bloch group, Nature 2022

Spatial coherence decay laws

Gaussian	$g^{(1)}(\Delta r) = ae^{-(\Delta r/d)^2}$
Exponential	$g^{(1)}(\Delta r) = ae^{-\Delta r/d}$
Str. Exponential	$g^{(1)}(\Delta r) = ae^{-(\frac{\Delta r}{d})^{\beta}}$
Power law	$g^{(1)}(\Delta r) = a(\Delta r)^{b}$

Below BEC threshold (polariton lasing): Gaussian decay

Above BEC threshold, power law **(b_t = 0.066)** *fits well, stretched exponential gives* **β_t ~ 0.095**



Temporal coherence decay laws

Gaussian $g^{(1)}(\Delta r) = ae^{-(\Delta r/d)^2}$

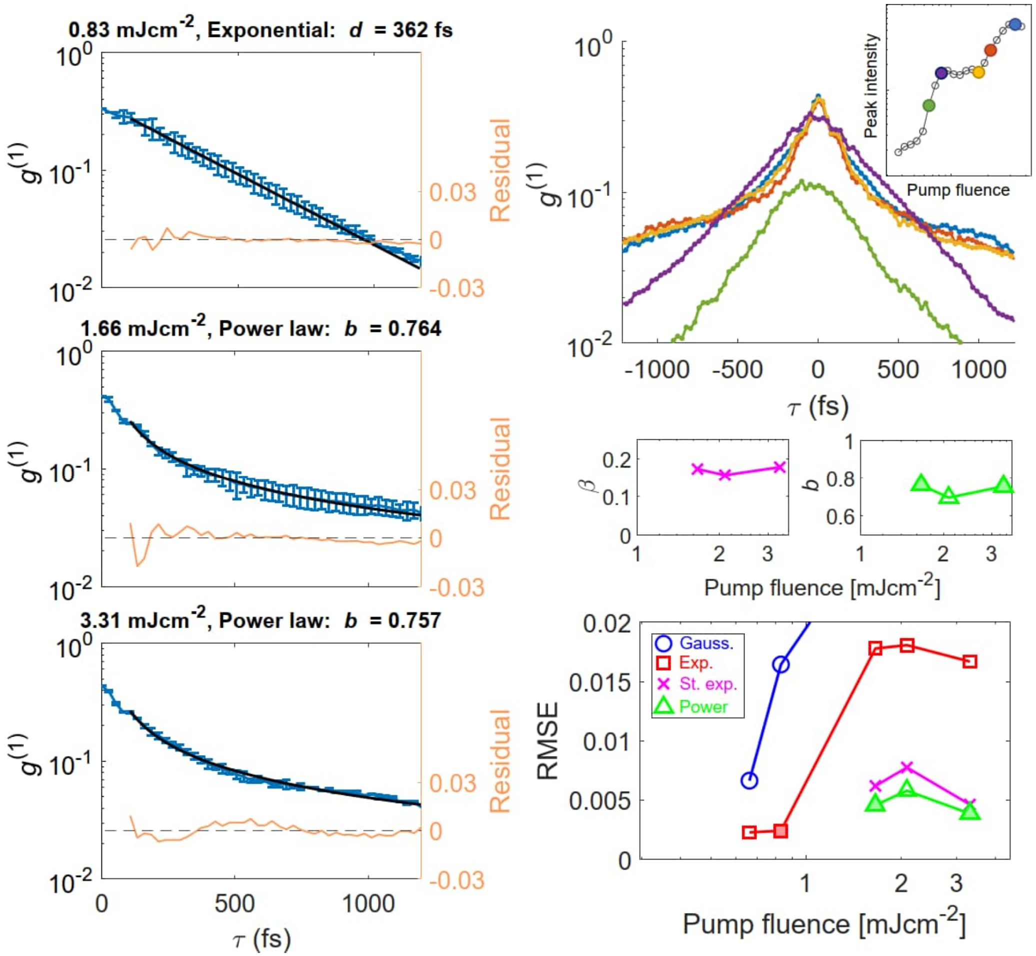
Exponential $g^{(1)}(\Delta r) = ae^{-\Delta r/d}$

Str. Exponential $g^{(1)}(\Delta r) = ae^{-(\frac{\Delta r}{d})^\beta}$

Power law $g^{(1)}(\Delta r) = a(\Delta r)^b$

Below BEC threshold (polariton lasing): exponential decay (d=366 fs)

Above BEC threshold: power law **(b_t = 0.756)** *fits well, stretched exponential gives* **β_t ~ 0.2**



Conclusion BEC clearly different from (polariton) lasing; no KPZ; power law observed – BKT-type physics but with exponents not given by present theory

Theory of strongly coupled vibrational system interacting with many modes needed; Arnardottir, Moilanen, Strashko, PT, Keeling, PRL 2020

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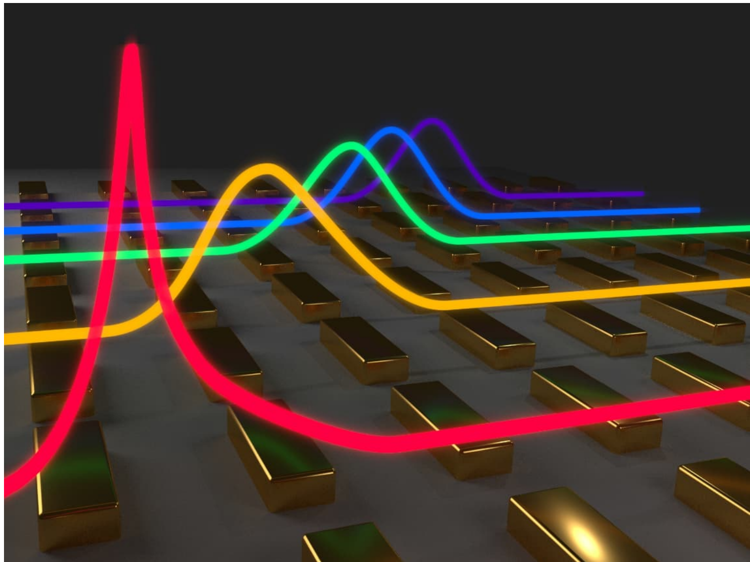


Plasmonic BEC: polarization textures

Jani Taskinen

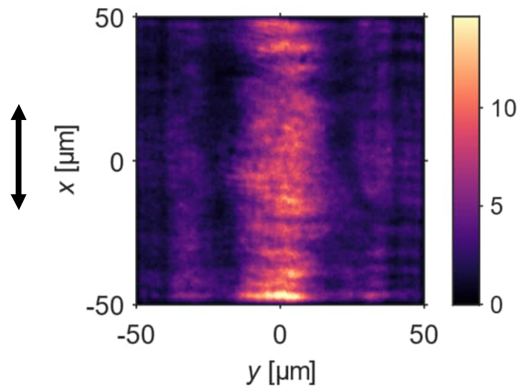
Pavel Kliuiev

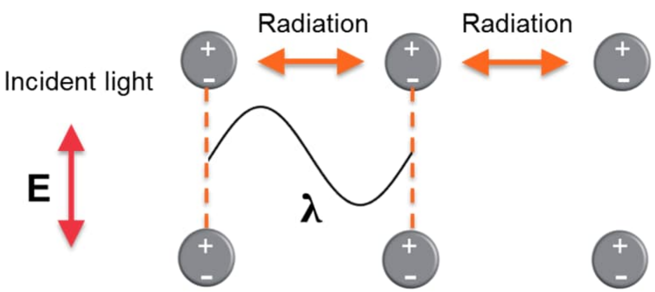
Antti Moilanen

Taskinen, Kliuiev, Moilanen, PT, Nano Letters 2021

Condensate of a vector field

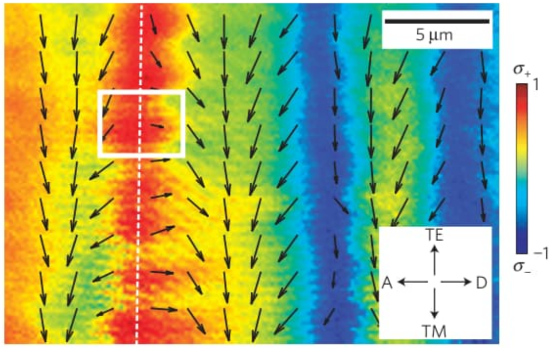
So far, pump and emission x-polarized; essentially a scalar condensate





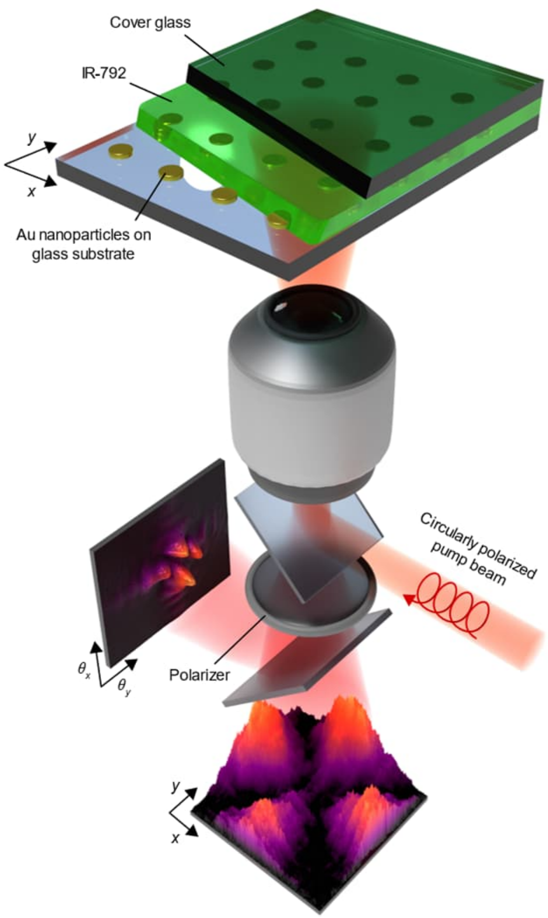
(Pseudo)spin textures in quantum or classical vector fields:

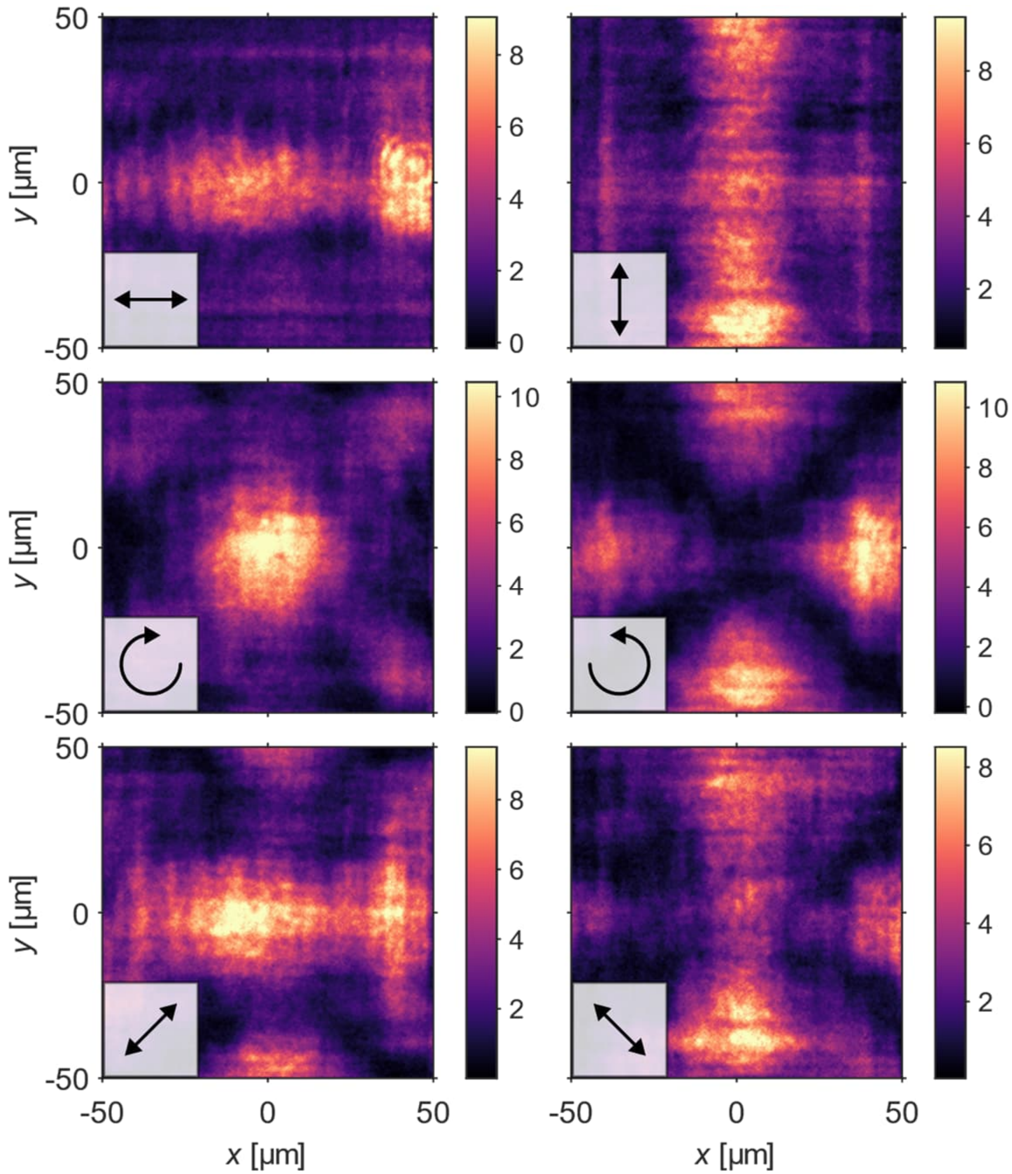
- Liquid Helium
- Atomic spinor BECs
- Semiconductor polariton condensates (at low T)
- Solid state magnetic systems
- Photonic crystals
- Metamaterials
- Liquid crystals



Hivet et al. Nat Phys 2020
(Bloch, Bramati, Malpuech, Amo)

Polarization resolved detection (strong coupling BEC)



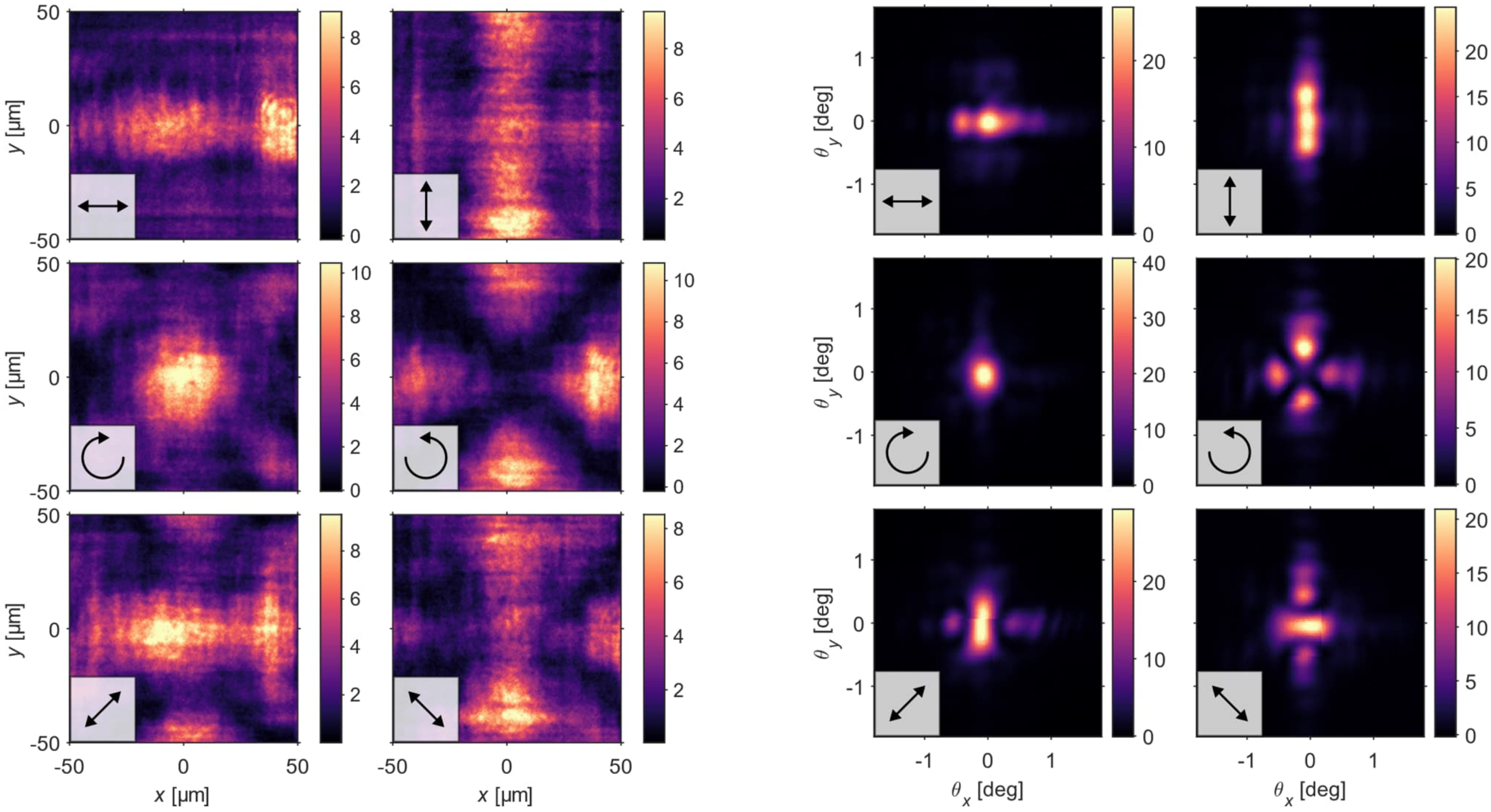


$$\frac{|\updownarrow\rangle + i e^{i\varphi_{R/L}} |\leftrightarrow\rangle}{\sqrt{2}}$$

$$\varphi_R = \pi, \quad \varphi_L = 0$$

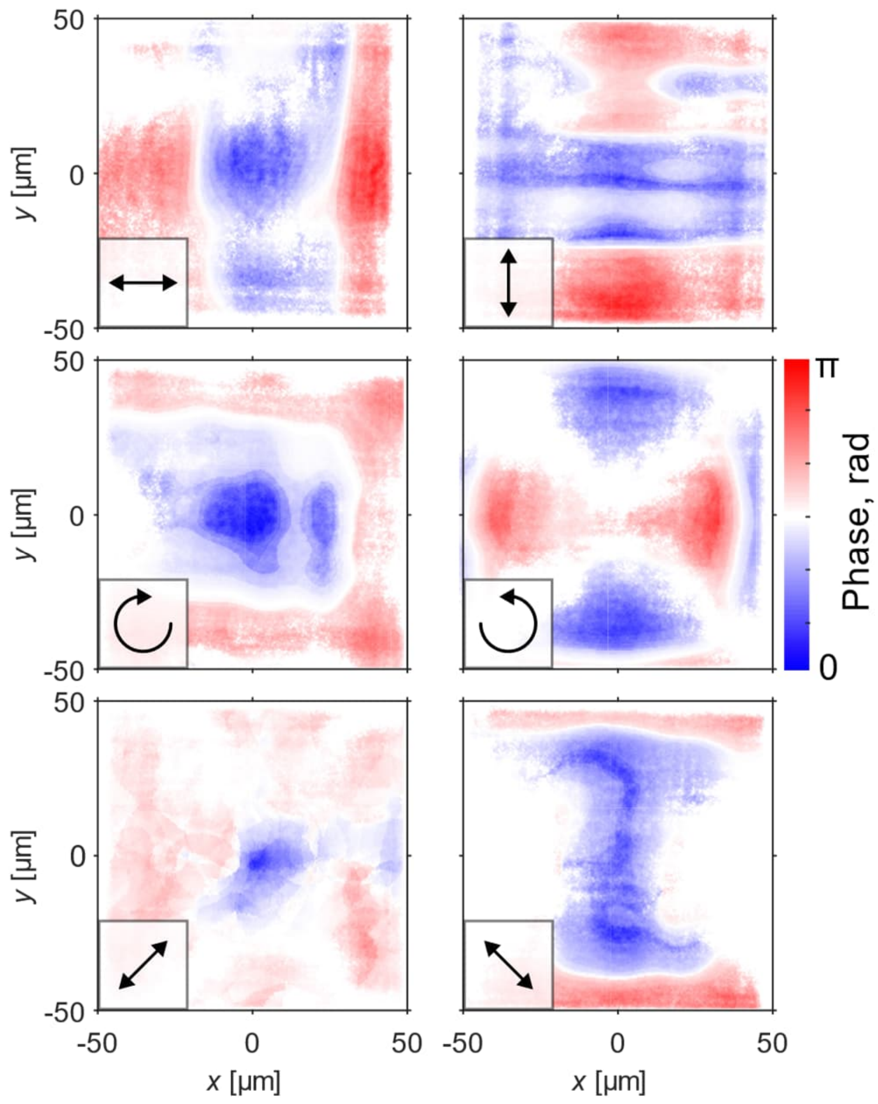
Real space

k-space

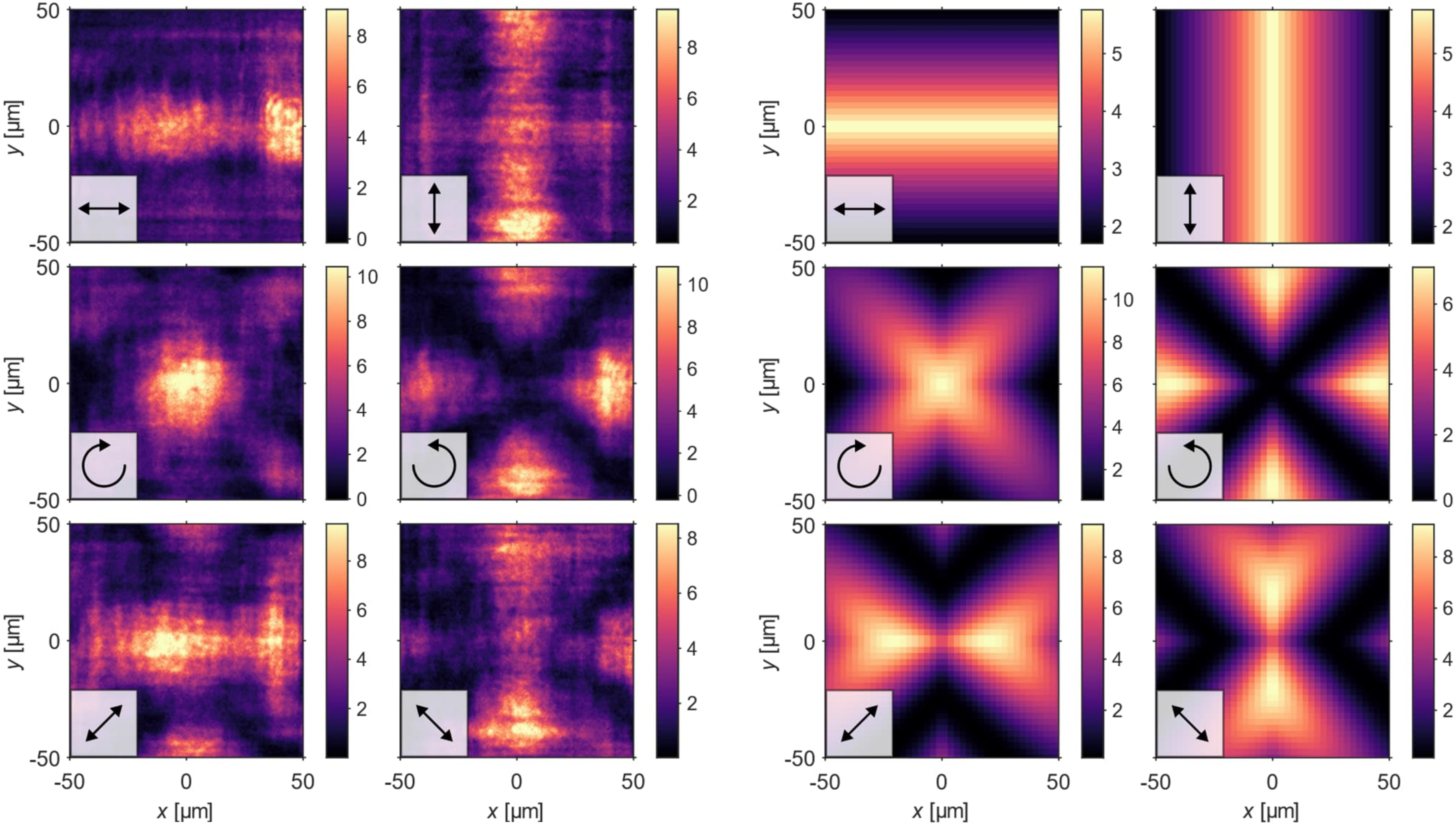


BEC phase by Gerchberg-Saxton algorithm

Condensate phase determined for the first time by phase retrieval



Polarization textures: experiment vs theory



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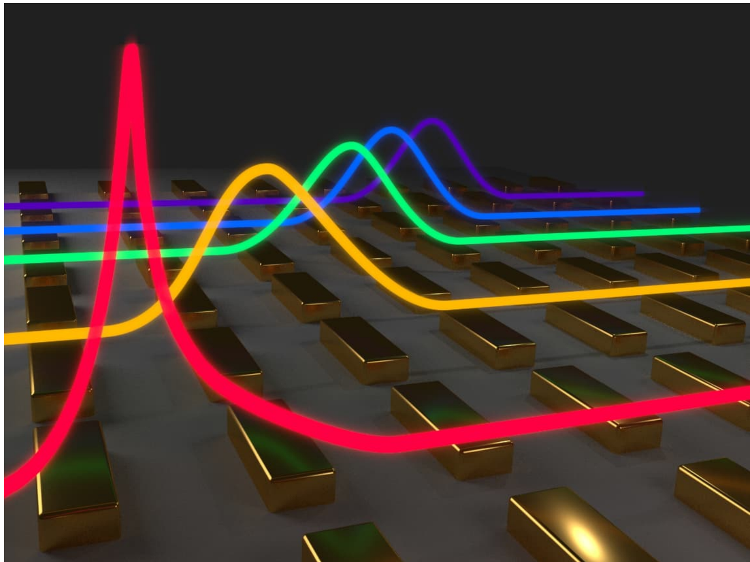


Quasi-BIC mode lasing

Heilmann, Salerno, Cuerda, Hakala, PT, ACS Photonics 2022

Salerno, Heilmann, Arjas, Aronen, Martikainen, PT, PRL 2022

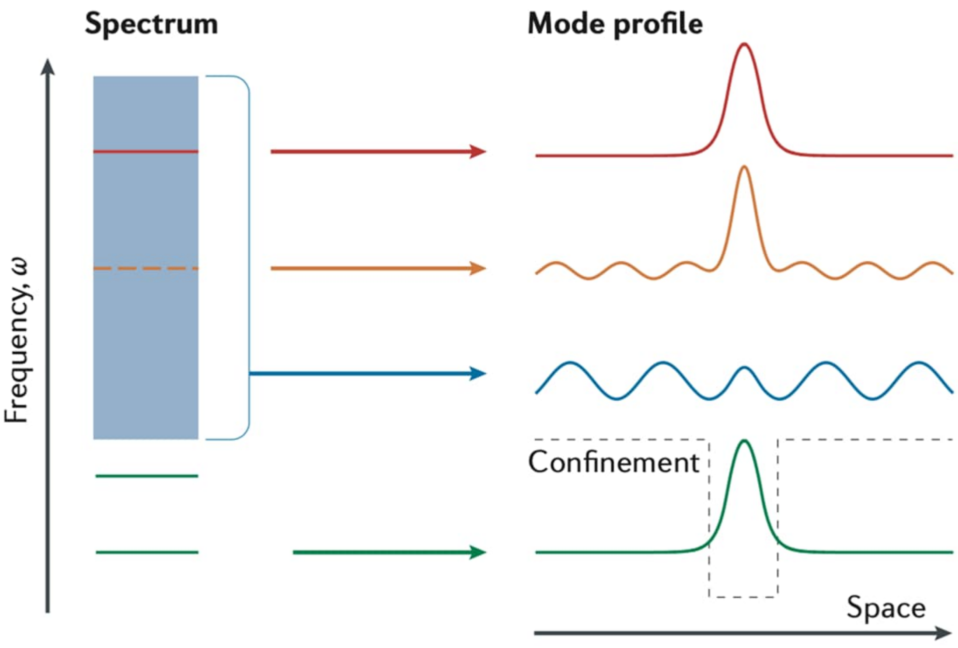
Rebecca Heilmann

Grazia Salerno

Javier Cuerda

Kristian Arjas

Bound states in continuum (BICs)



Hsu *et al., Nat Rev Mater* **1,** 16048 (2016)

BICs are *embedded eigenvalues,* decoupled from the continuum spectrum

BICs have infinite Q-factor, i.e. zero linewidth

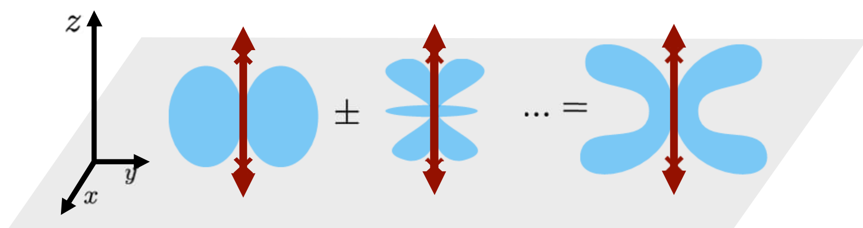
BICs are totally invisible in the radiation field (hence dark mode)

Marinica *et al.*, *Phys. Rev. Lett.* **100**, 183902 (2008)
Hsu *et al.*, *Nature* **499**, 188–191 (2013)
Doeleman *et al.*, *Nat. Phot.* ***2***, 397 (2018)
Azzam & Kildishev, *Adv Opt Mater* **9,** 2001469 (2021)

What type of BICs?

Realized in many systems, including waveguides, metasurfaces, plasmonic and photonic crystals.

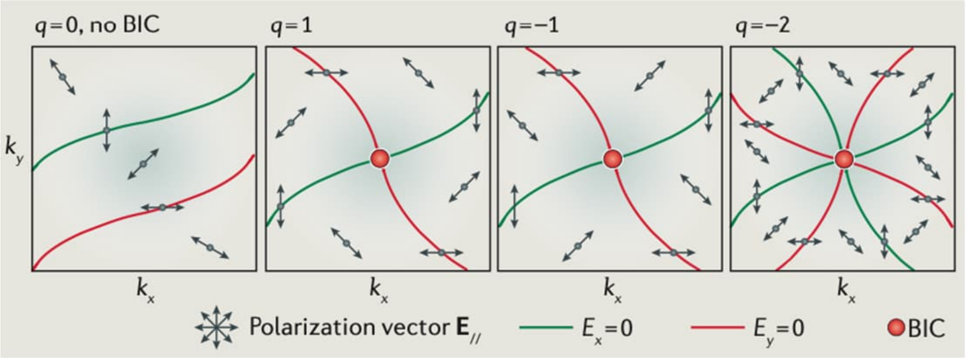
They can be symmetry-protected, “accidental”, and even topological.



Marinica *et al.*, *Phys. Rev. Lett.* **100**, 183902 (2008)
Hsu *et al.*, *Nature* **499**, 188–191 (2013)

Doeleman *et al.*, *Nat. Phot.* ***2***, 397 (2018)
Azzam & Kildishev, *Adv Opt Mater* **9,** 2001469 (2021)

Topological BICs are polarization vortices



Zhen *et al., Phys. Rev. Lett.* **113**, 257401 (2014)

Hsu *et al., Nat Rev Mater* **1,** 16048 (2016)

Topological BICs cannot radiate because **there is no way to assign a far-field polarization** that is consistent with neighbouring k points.

Robust BICs are possible when there is vorticity in the polarization field, protected by the existence of a non-trivial topological invariant, the vortex charge:

$$q = \frac{1}{2\pi} \int \mathrm{d}\mathbf{k} \cdot \nabla_{\mathbf{k}} \phi(\mathbf{k})$$

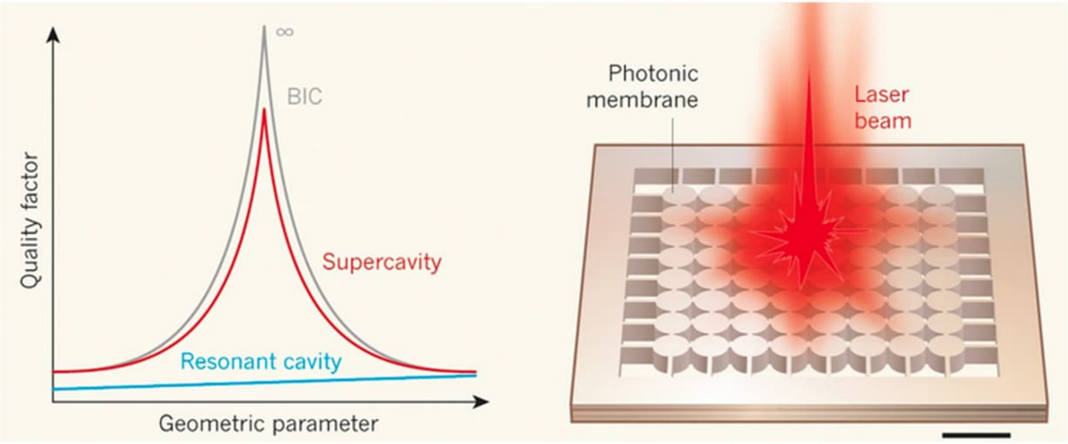
$$\Phi(\mathbf{k}) = \arg[\mathbf{p}(\mathbf{k}) \cdot \hat{x} + i\mathbf{p}(\mathbf{k}) \cdot \hat{y}]$$

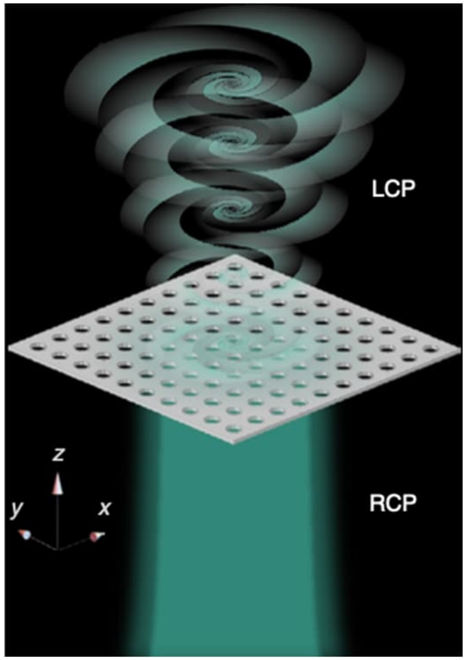
$$\mathbf{p}(\mathbf{k}) = (\hat{x} \cdot \langle \mathbf{u_k}(\mathbf{r}, z) \rangle)\hat{x} + (\hat{y} \cdot \langle \mathbf{u_k}(\mathbf{r}, z) \rangle)\hat{y}$$

Lasing and vortex beams from BICs

High-Q BICs support lasing

They directly offer large quantum numbers of optical angular momentum for the generation of optical vortex beam

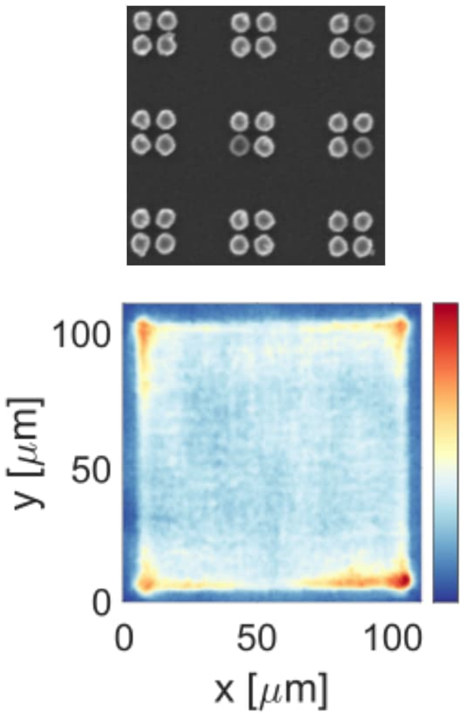


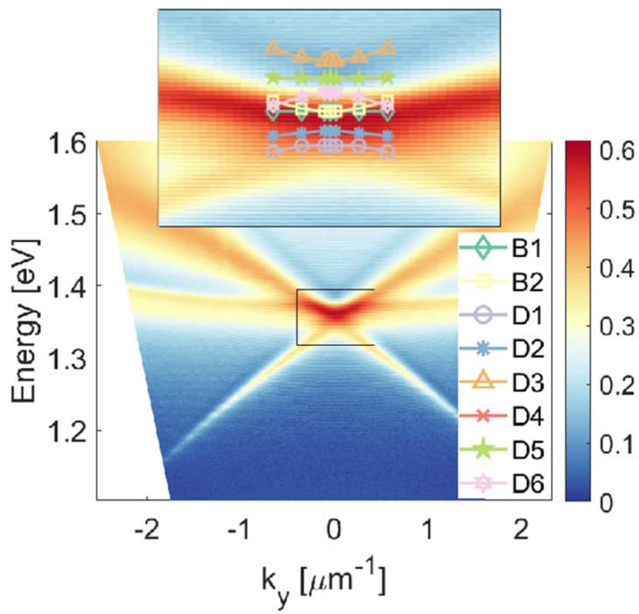


Rybin and Kivshar, *Nature* **541**, 164 (2017)
Kodigala *et al.*, *Nature* **541**, 196 (2017)
Ha *et al., Nat. Nanotechnol.* **13**, 1042 (2018)
Huang *et al.*, *Science* **367**, 1018 (2020)

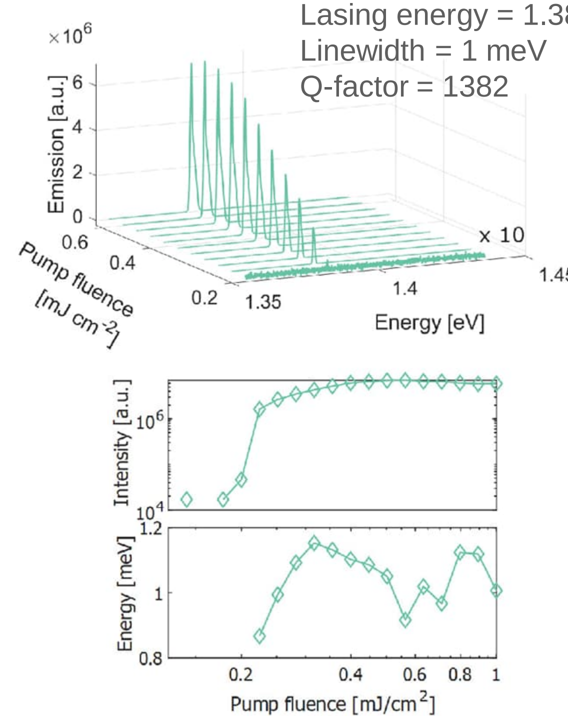
Wang *et al., Nat. Phot.* **14**, 623 (2020)
Wu *et al., New J. Phys.* **24**, 033002 (2022)
Kang *et al., Adv. Optical Mater.* **10**, 2101497 (2022)

Lasing from a plasmonic lattice: 4-fold rotational symmetry



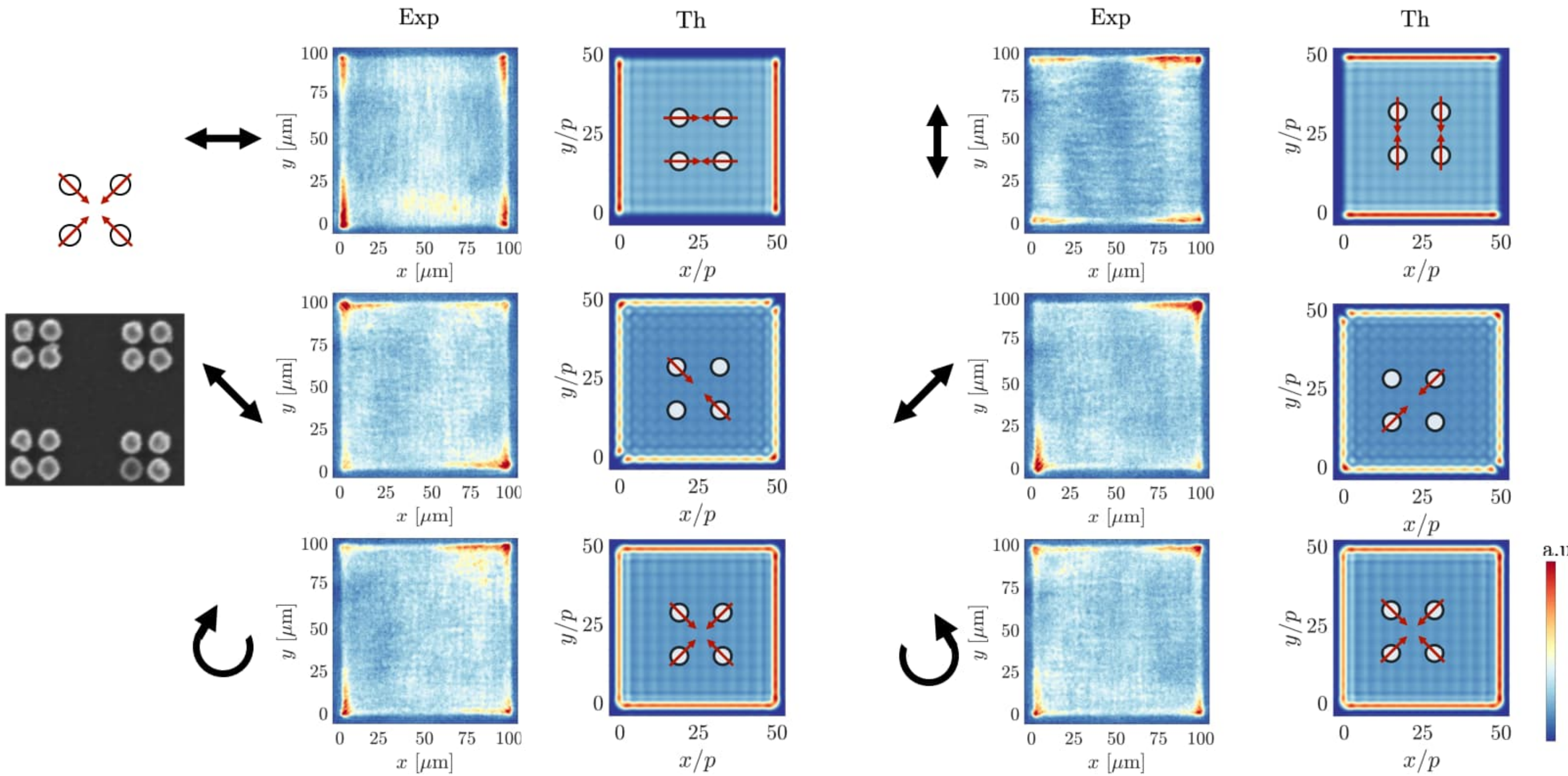


Lasing energy = 1.382 eV
Linewidth = 1 meV
Q-factor = 1382



Heilmann *et al.*, *ACS Photonics* ***9*** 224 (2022)

Polarization-resolved images: the vortex

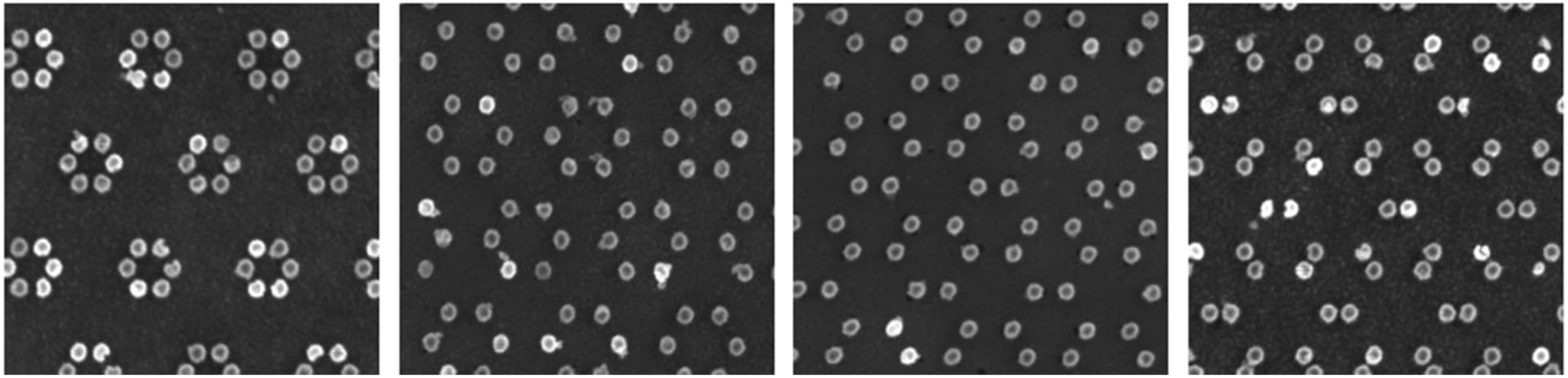


Heilmann *et al., ACS Photonics* ***9*** 224 (2022)

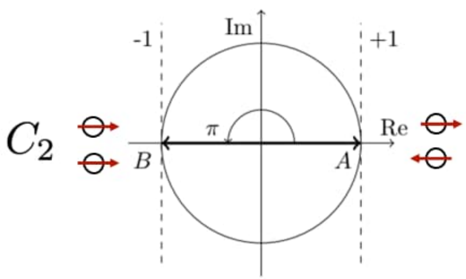
Loss-induced topological transition

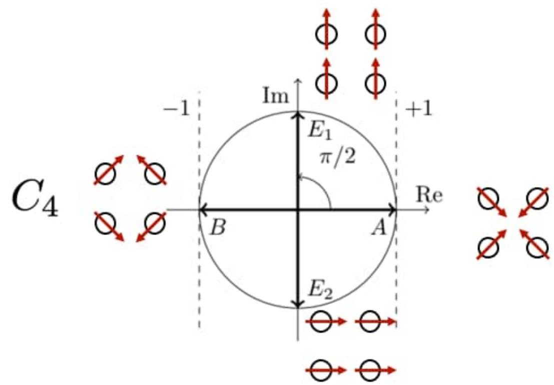
Salerno, Heilmann, Arjas, Aronen, Martikainen, PT, PRL 2022

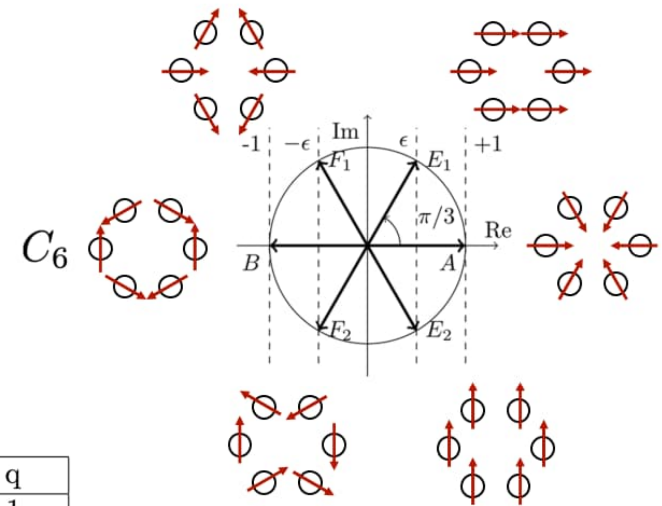
Tuning interparticle distance in a hexamer nanoparticle array

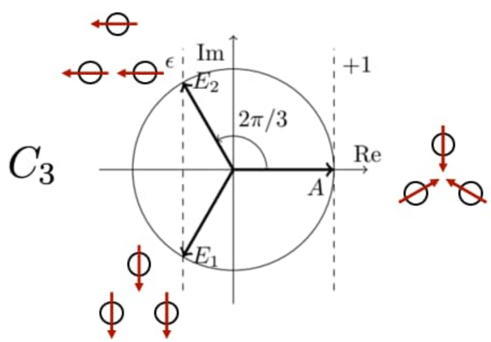


Rotational symmetries and irreducible representations







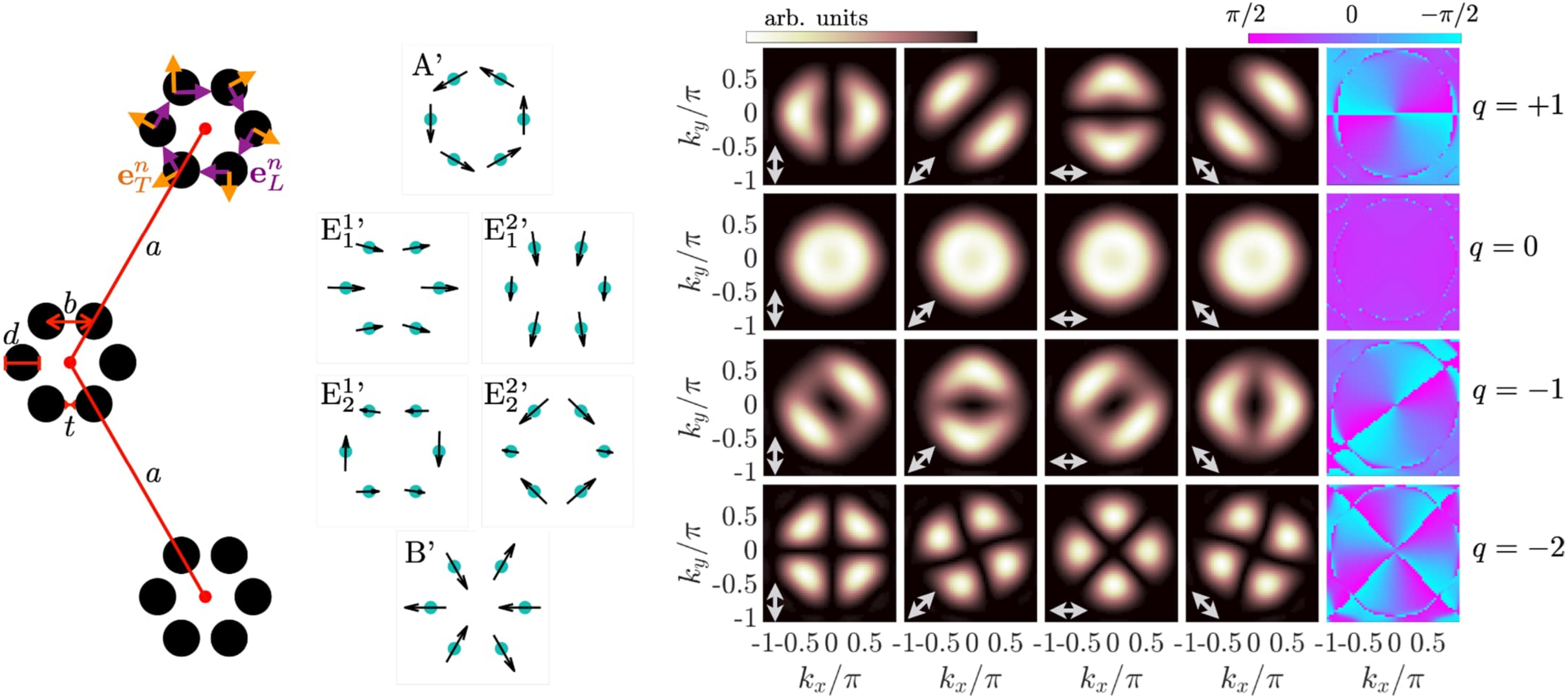


Symmetry	IR	$\arg(\epsilon_{\mathrm{IR}})$	q
C_2	A	0	+1
	B	π	0
C_3	A	0	+1
	E^*	$2\pi/3$	0
C_4	A	0	+1
	B	π	−1
	E^*	$\pi/2$	0
C_6	A	0	+1
	B	π	−2
	E_1^*	$\pi/3$	0
	E_2^*	$2\pi/3$	−1

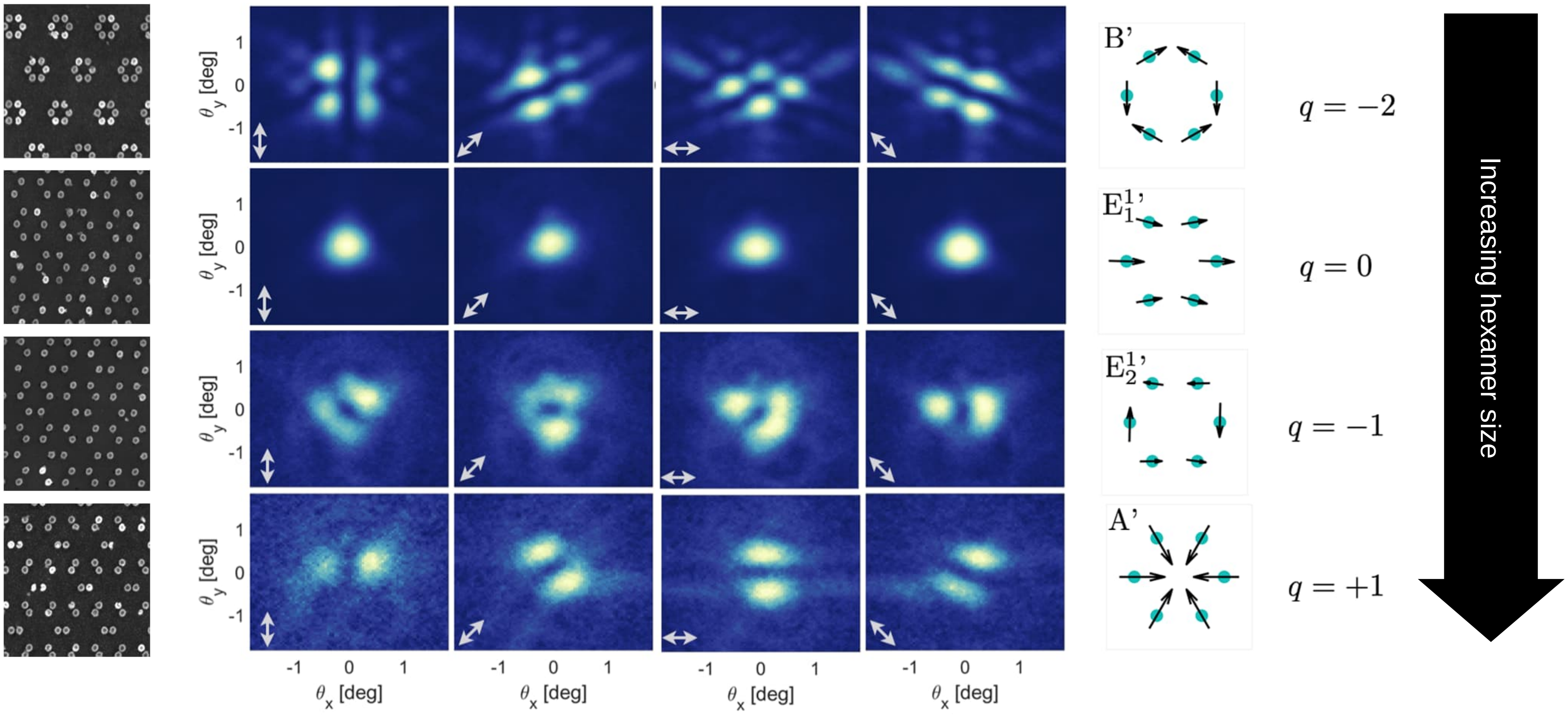
$$q_{\mathrm{irrep}} = 1 - \frac{n}{2\pi}\arg(\epsilon_{\mathrm{irrep}})$$

Salerno *et al.*, *Phys. Rev. Lett.* **129** 173901 (2022)

Modes of a single hexamer: real and k-space

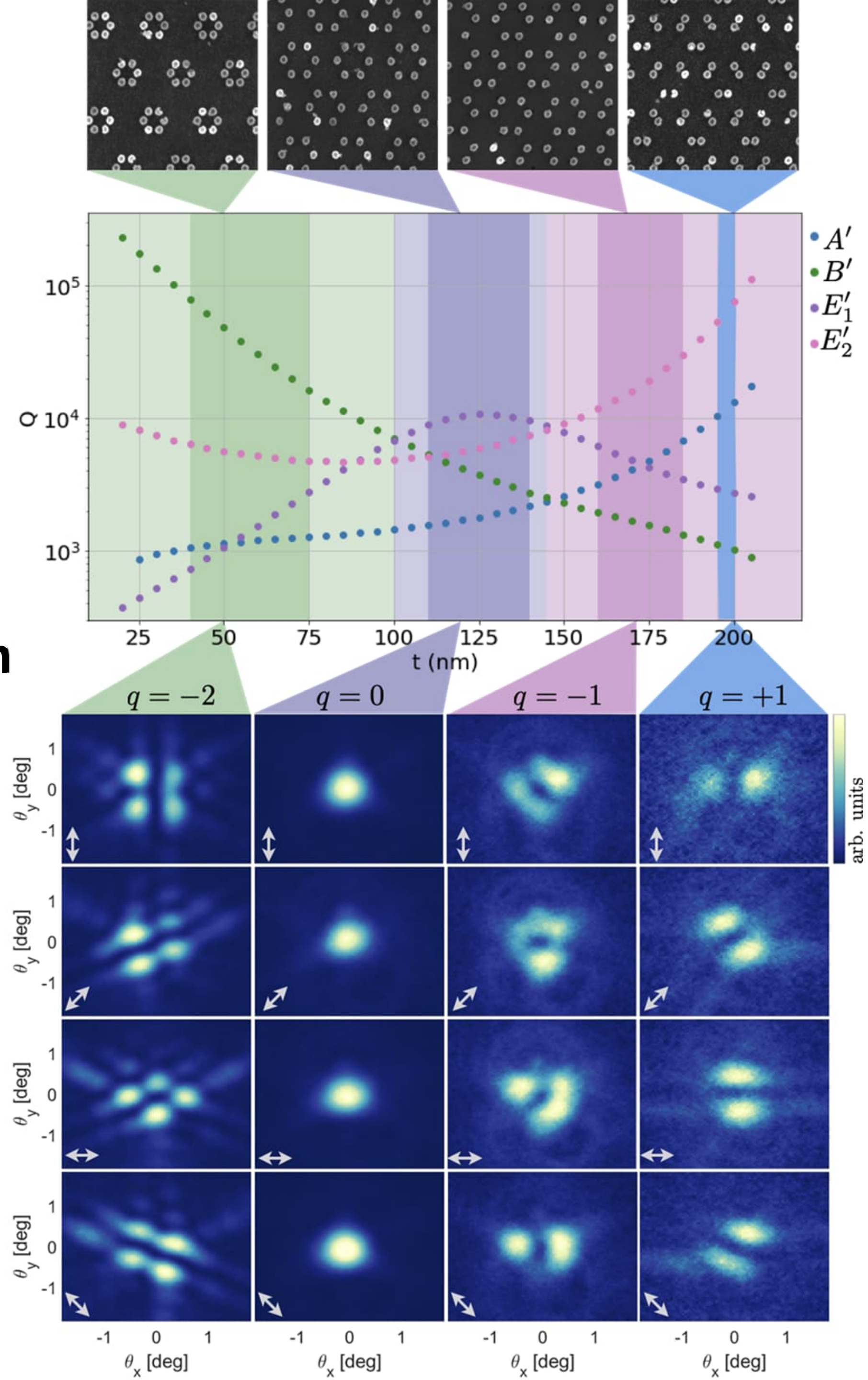


Lasing mode changes with geometry: topological transition

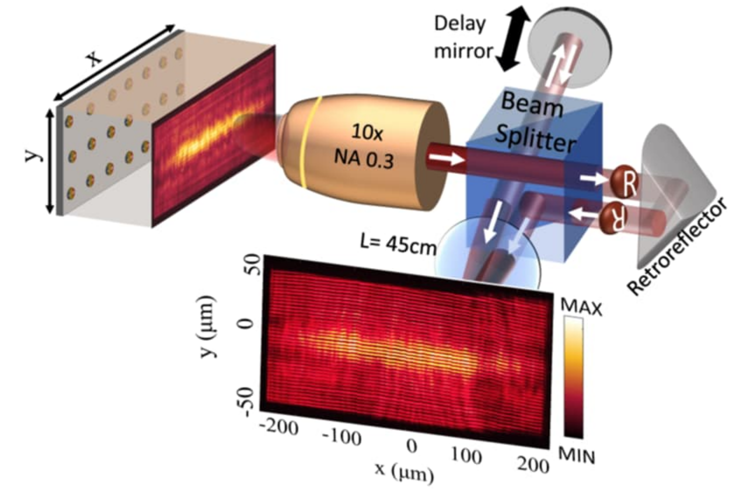


T-matrix simulations:
Q-factors of the modes vary

Topological transitions driven by losses (gain)



Summary



Bose-Einstein condensation
in a plasmonic lattice; spatial and temporal
coherence show power law; polarization
and phase textures

Quasi-BIC lasing with a quadrumer and hexamer lattice;
topological transitions driven by losses

Outlook

Interplay of quantum geometry, topology
and interactions in photonic systems