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Bose-Einstein condensation and K-point lasing in plasmonic lattices

Päivi Törmä
Aalto University

Quantum Nanophotonics

Benasque, Spain

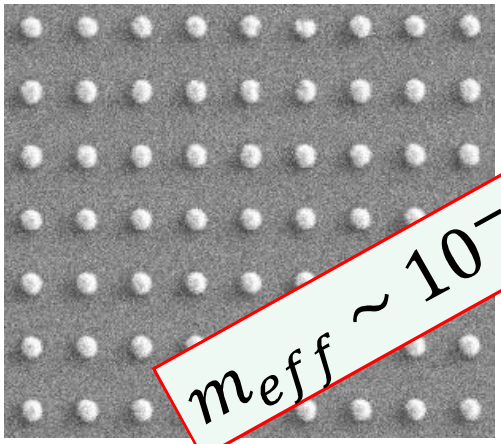
22.3.2019

erc
HORIZON2020
Marie Skłodowska-Curie actions
ACADEMY OF FINLAND

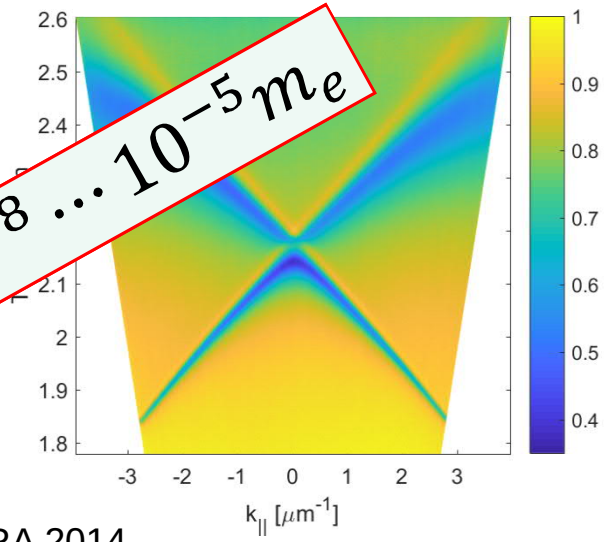
Plasmonic lattices

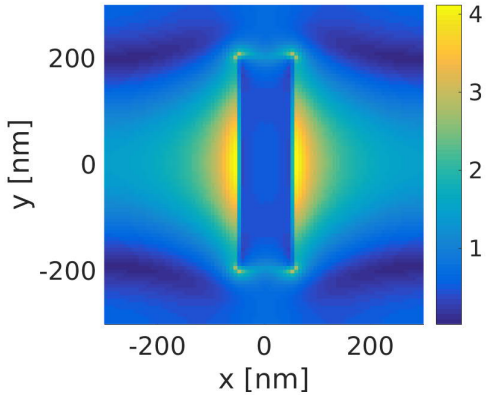
Pushing quantum many-body physics
- smaller
- faster
- hotter
- towards new applications

Combine with emitters: strong coupling
Ebbesen, Barnes, Bellessa, et al. 2004-2005
Hakala et al. (PT) 2009
PT, Barnes, Rep Prog Phys 2015
Shegai, Käll, et al. 2015
Baumberg, Haran, et al. 2016



$m_{eff} \sim 10^{-8} \ldots 10^{-5} m_e$

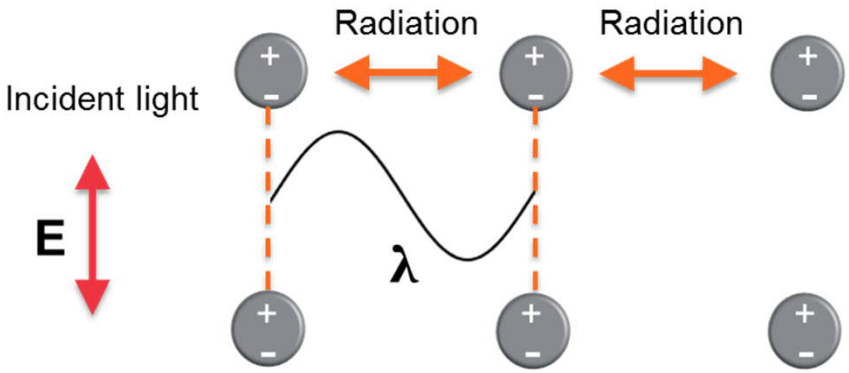


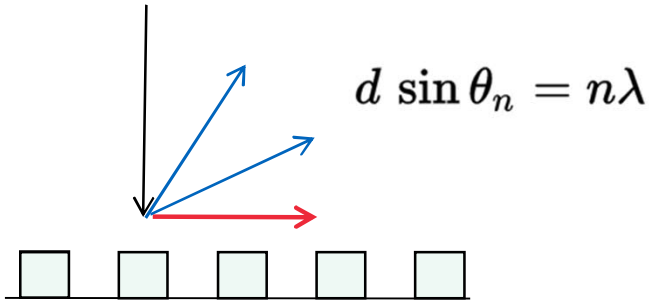


→ BEC at room T

Martikainen, Heikkinen, PT, PRA 2014

Plasmonic lattices





Surface lattice resonance (SLR)

= single particle resonance (SPR) + diffraction order

= ***light + electron plasma oscillations***

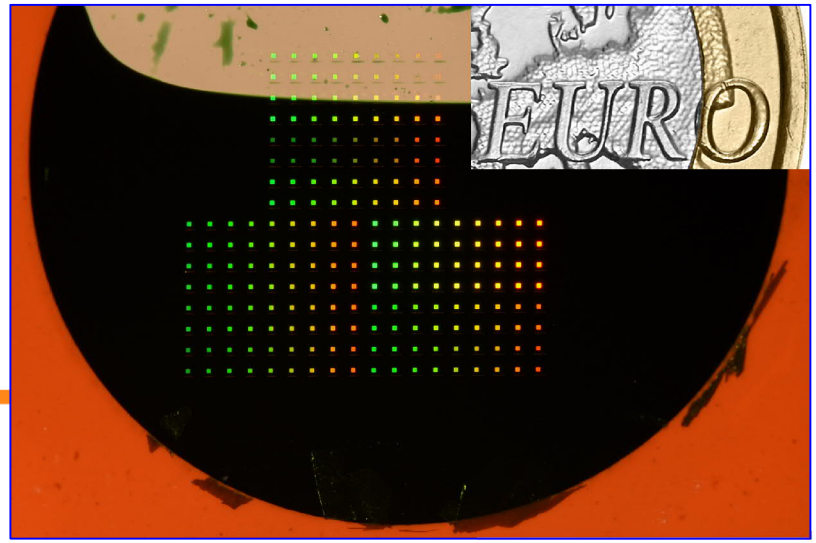
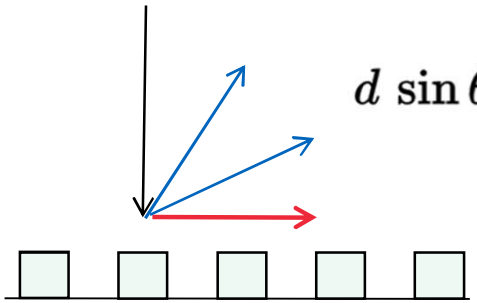
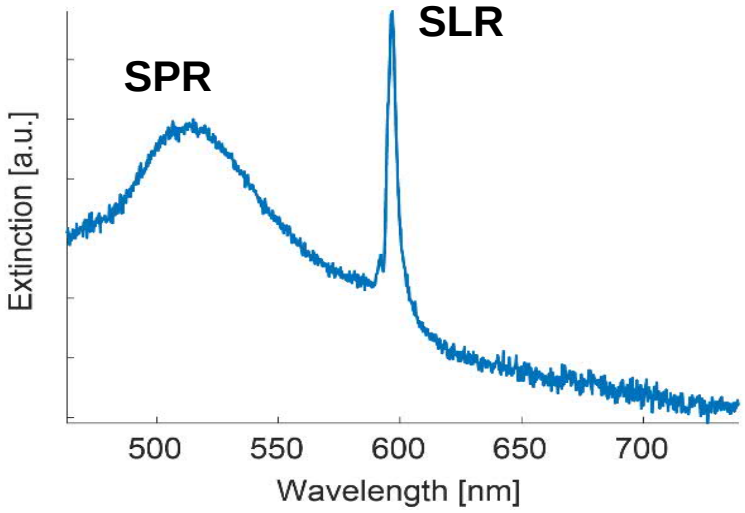
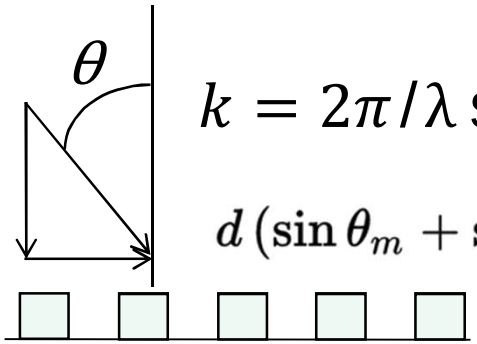


Photo Credit: Aaro Väkeväinen



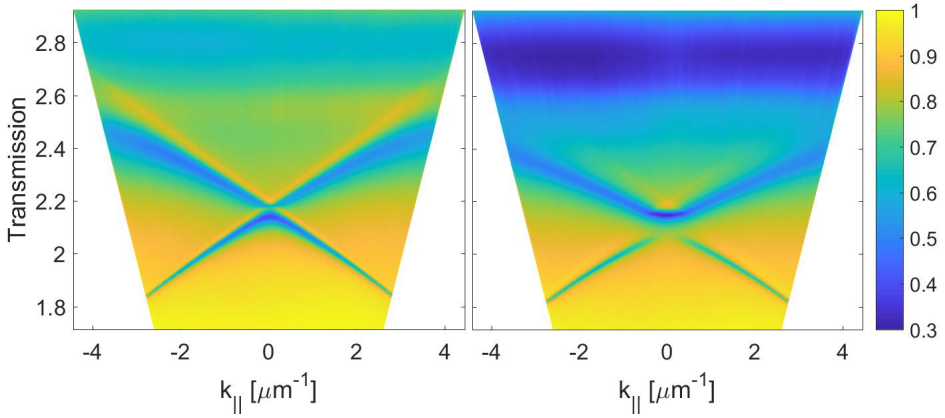
$$d \sin\theta_n = n\lambda$$





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

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



Nanoparticle arrays - dispersions, strong coupling, lasing, etc.: Barnes, Garcia de Abajo, Giannini, Gomez-Rivas, Grigorenko, Odom, Schatz, Shalaev, etc. groups

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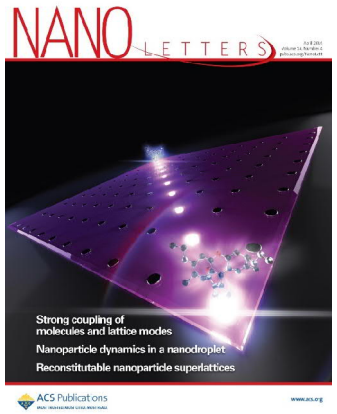
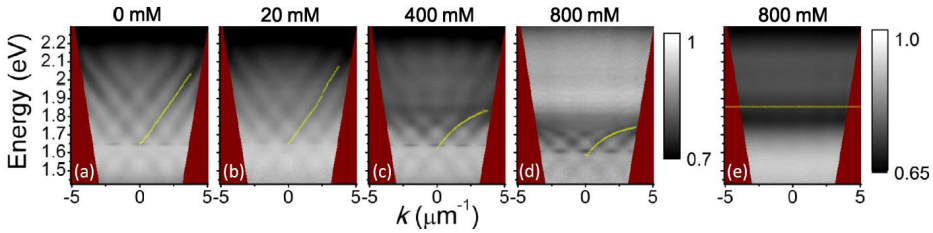
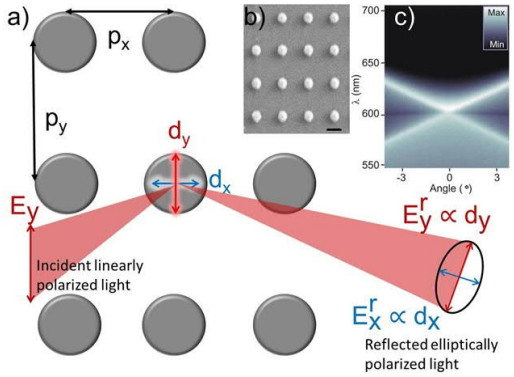
Recent review by Odom, Gomez-Rivas, PT groups
Materials Today 21, 303 (2018)





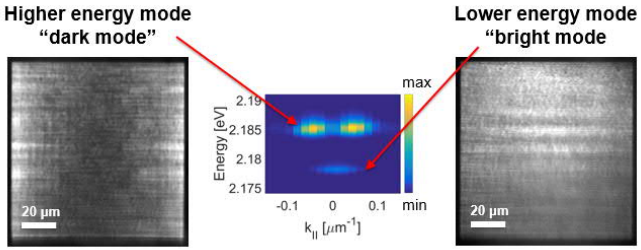
Spatial coherence at strong coupling
Shi et al. Phys Rev Lett 2014

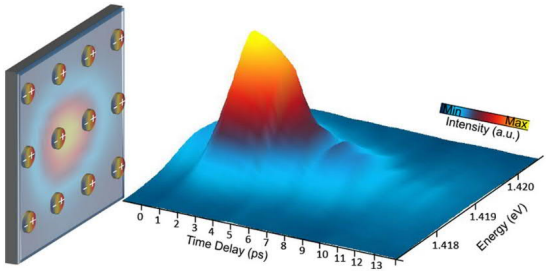


Magnetoplasmonic lattices
Kataja et al. Nature Comm 2015

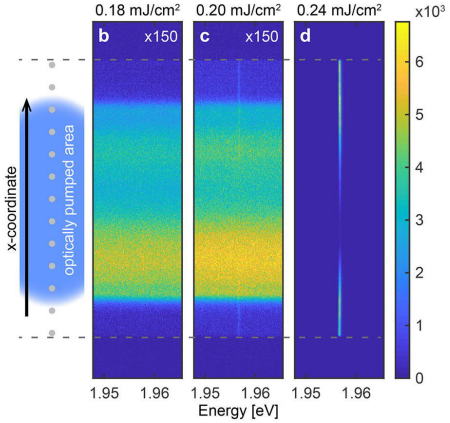
Strong coupling in a plasmonic lattice
Väkeväinen et al. Nano Lett 2014

Our previous SRL work

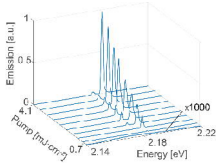




Ultrafast pulse generation
Daskalakis et al. Nano Lett 2018



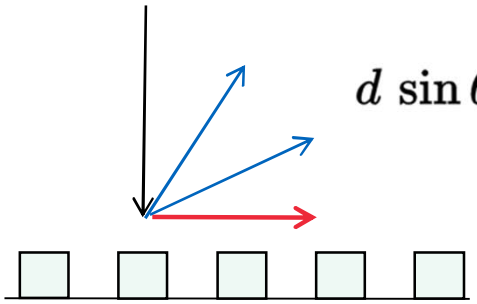
1D plasmonic lasing
Rekola et al. ACS Phot 2018



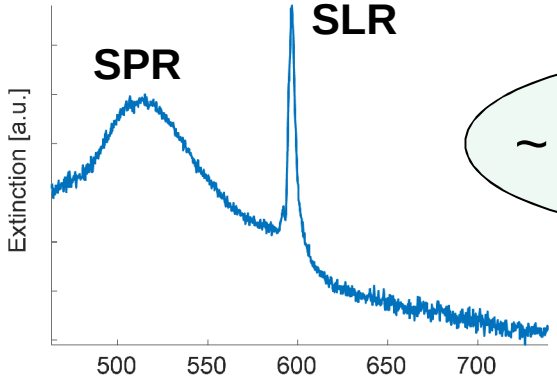
Lasing in dark and bright modes
Hakala et al. Nature Comm 2017

Surface lattice resonance (SLR)
= diffractive order + single particle resonance (SPR)
= *light + electron plasma oscillations*

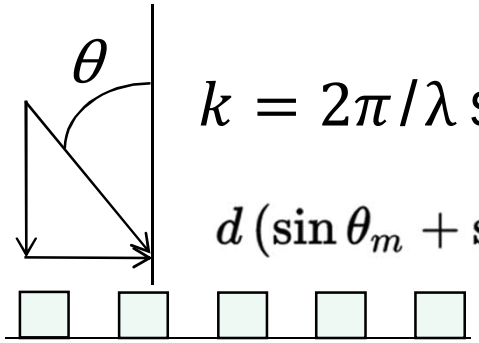
← This is the quasiparticle to condense



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



~ 100 fs lifetime



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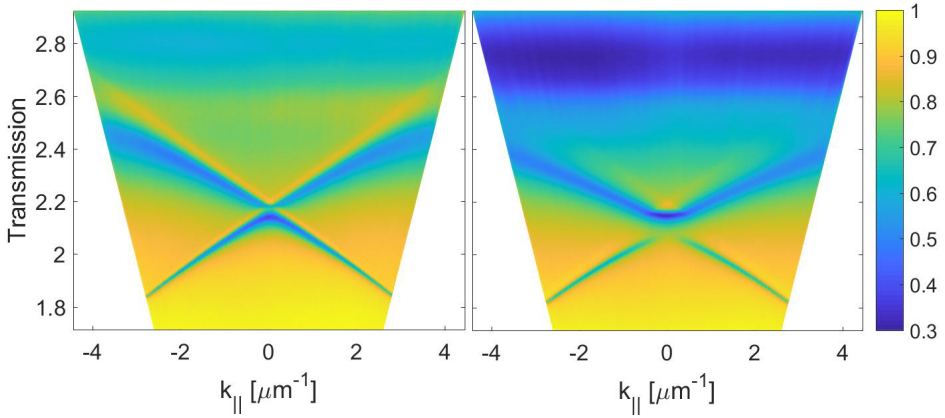

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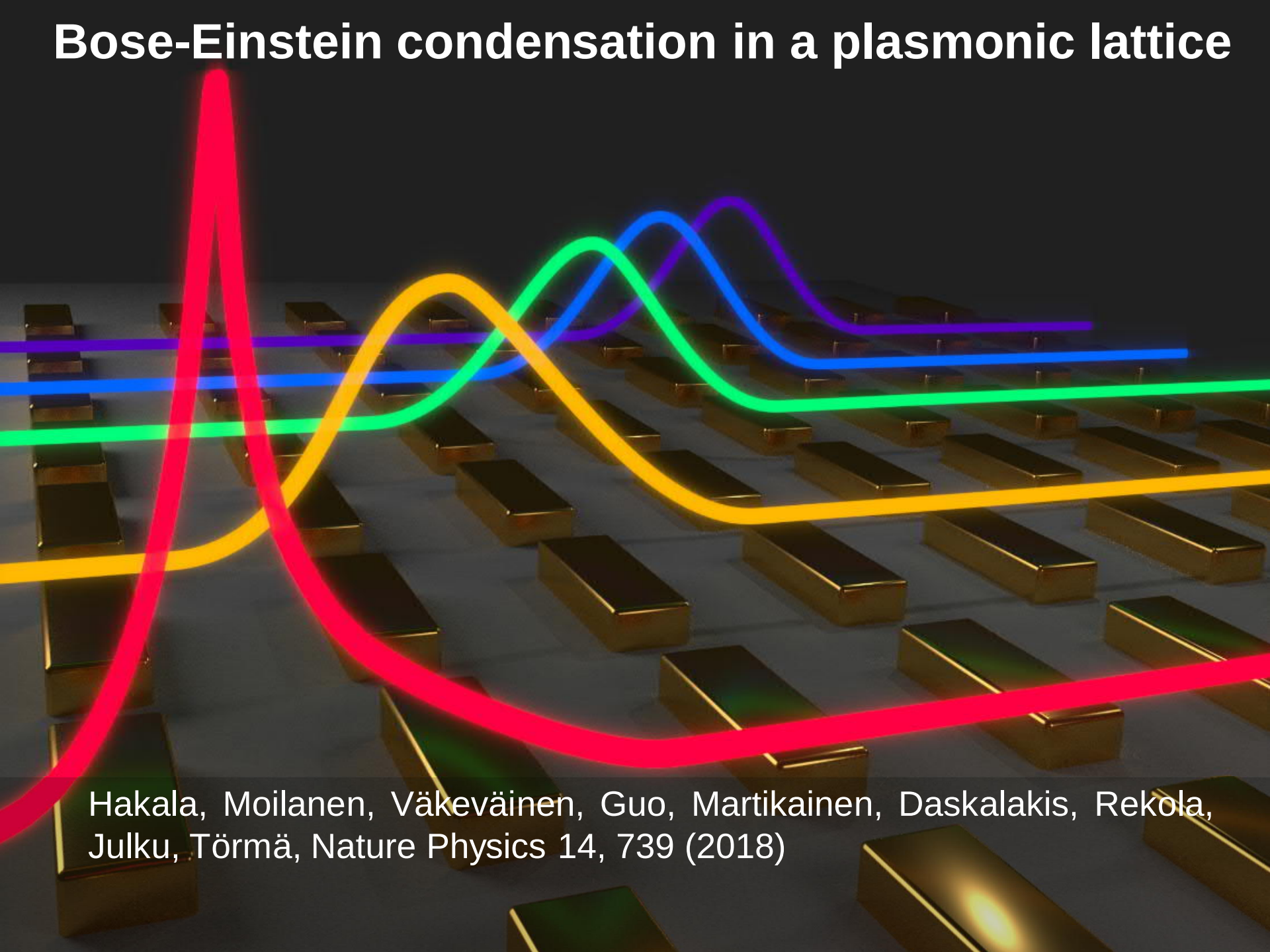
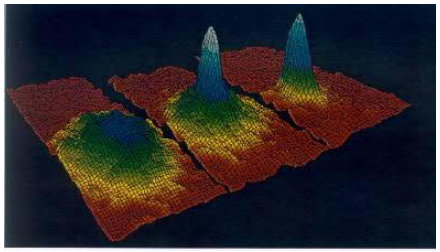
Recent review by Odom, Gomez-Rivas, PT groups
Materials Today 21, 303 (2018)

Bose-Einstein condensation in a plasmonic lattice



Hakala, Moilanen, Väkeväinen, Guo, Martikainen, Daskalakis, Rekola, Julku, Törmä, Nature Physics 14, 739 (2018)

Family of condensates



Helium superfluids[1,2]

Magnon BECs[3,4]

Ultracold gas superfluids[5,6]

Photon condensates[7,8]

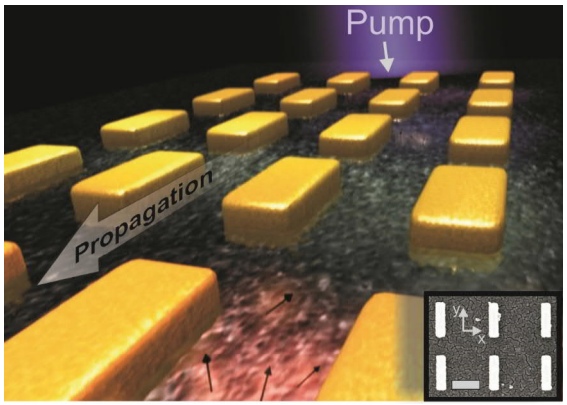
Inorganic and organic polariton condensates[9,10,11,12]

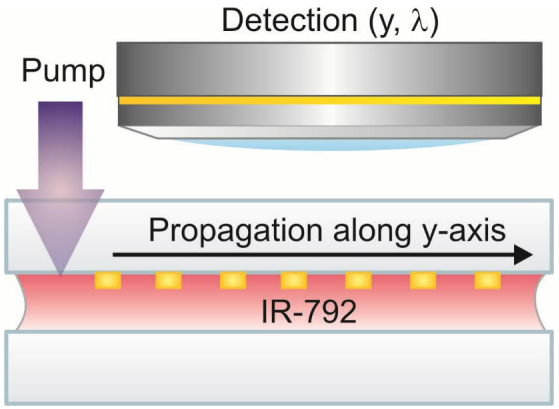
Superconductors[13,14]

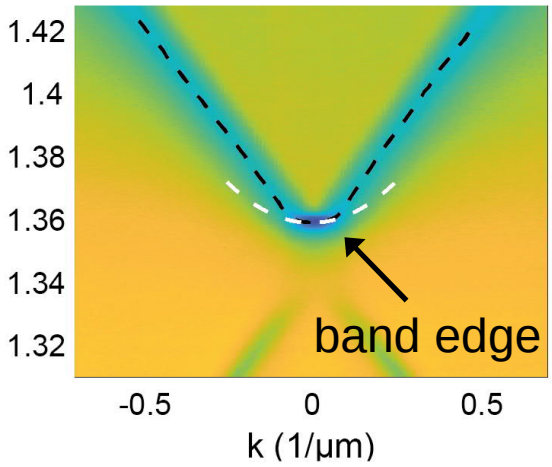
New member: plasmonic BEC

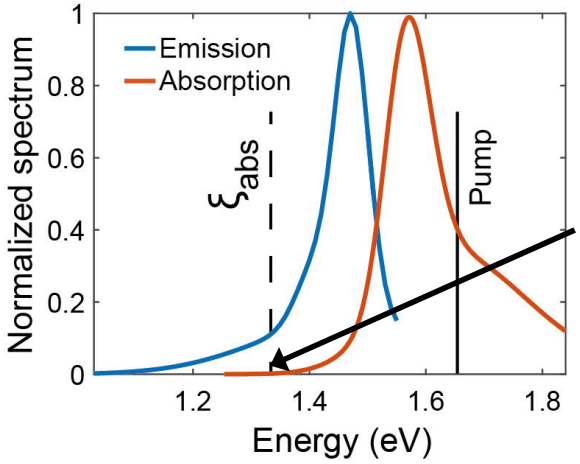
[1] P. Kapitsa, Nature 141, 74 (1938)
[2] J.F. Allen , A.D. Misener, Nature 141, 75 (1938)
[3] S. O. Demokritov *et al.*, Nature 443, 430 (2006)
[4] T. Giamarchi, C. Regg, O. Tchernyshyov, Nature Physics 4, 198 (2008)
[5] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, E. Cornell, Science 269, 198 (1995)
[6] K. B. Davis, M. O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, W. Ketterle, Phys. Rev. Lett. 75, 3969 (1995)
[7] J. Klaers, J. Schmitt, F. Vewinger, M. Weitz, Nature 468, 545 (2010)
[8] J. Marelic, R.A. Nyman, Phys. Rev. A 91, 033813 (2015)
[9] H. Deng, G. Weihs, C. Santori, J. Bloch, Y. Yamamoto, Science 298, 199 (2002)
[10] J. Kasprzak *et al.*, Nature 443, 409 (2006)
[11] J.D. Plumhof *et al.*, Nature Materials 13, 247 (2014)
[12] K. S. Daskalakis *et al.*, Nature Materials 13, 271 (2014)
[13] H. K. Onnes, Comm. Phys. Lab. Univ. Leiden, Nos. 119, 120, 122 (1911).
[14] J. Bardeen, L. N. Cooper, J. R. Schrieffer, Phys. Rev 108, 1175 (1957).

Nanoparticle array + molecules (weak coupling)



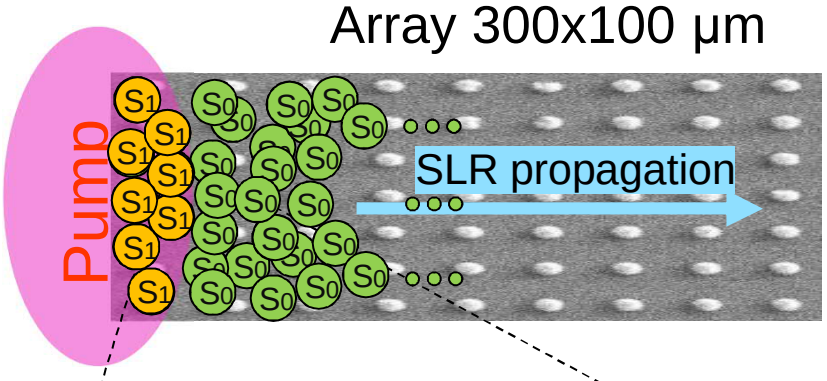


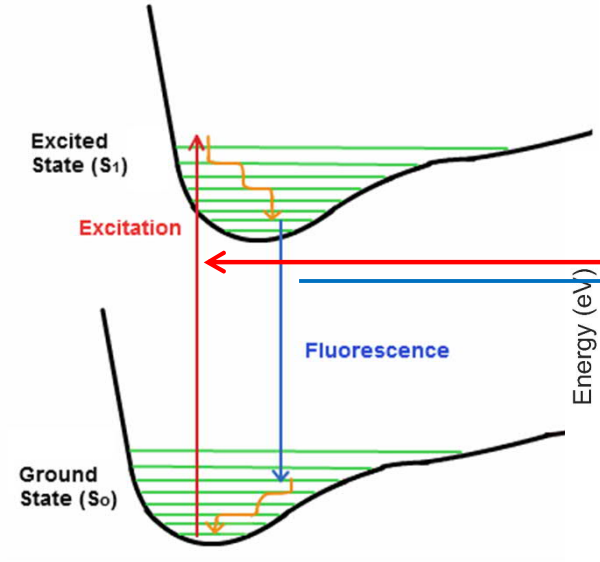




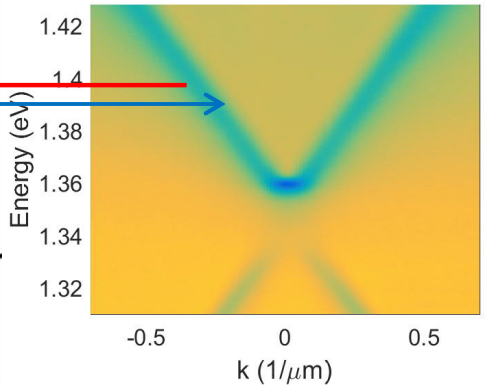
Energy where absorption rate is effectively zero (i.e. smaller than the loss rate)

Thermalization process

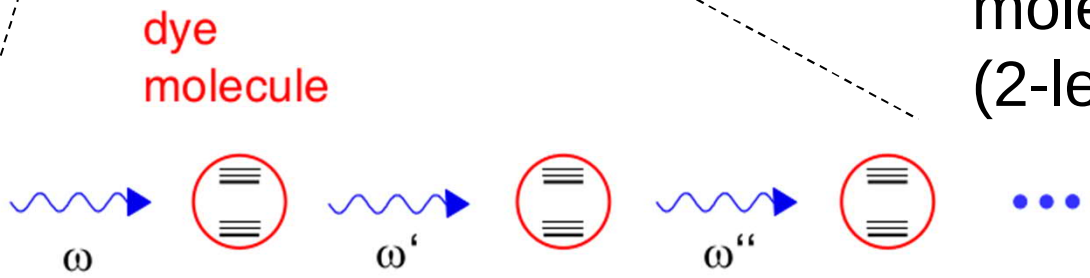




molecule
(2-level system)



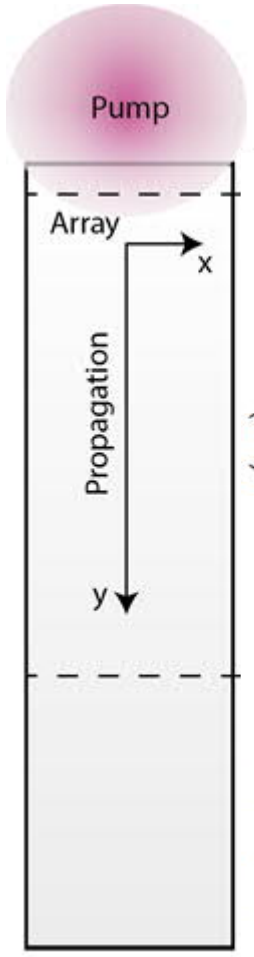
SLR

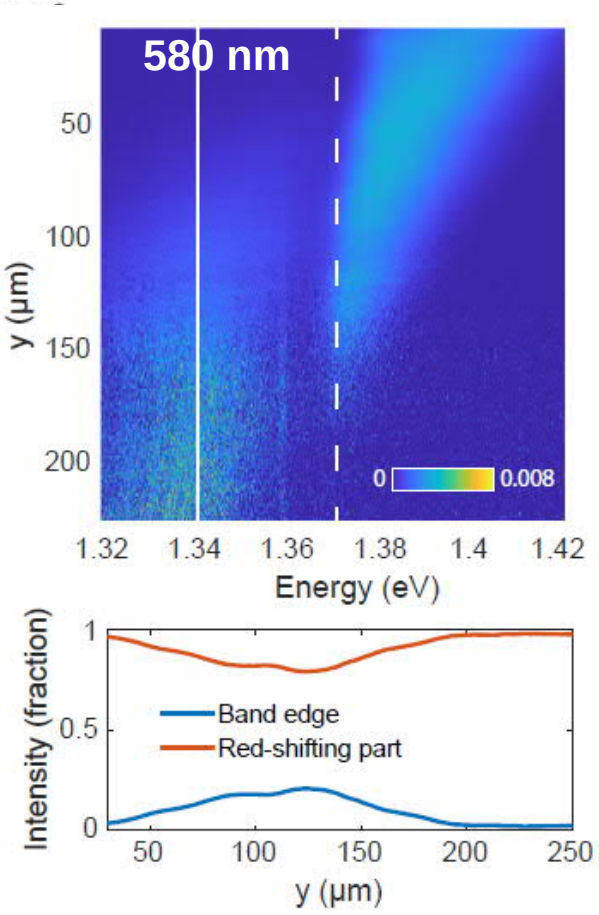


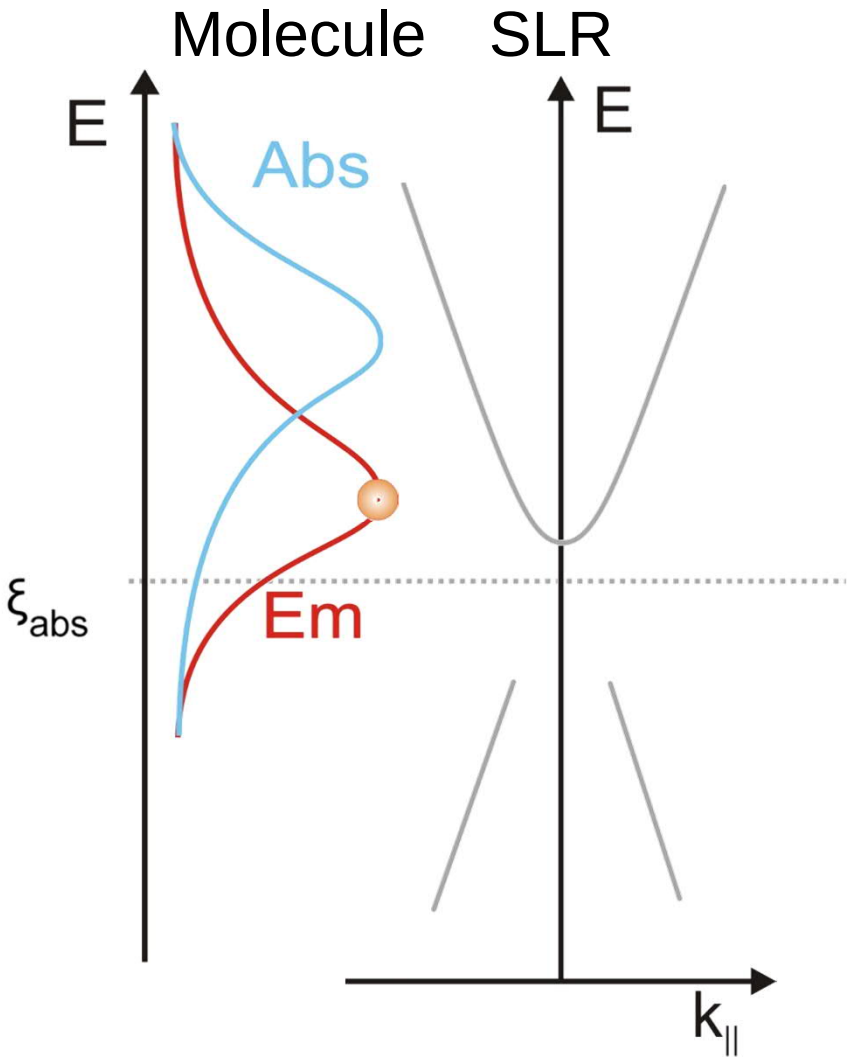
ω > ω’ ω' > ω” ω" > … == Red-shift

Thermalization mechanism similar to Klaers, Vewinger, Weitz, Nat. Phys. 2010

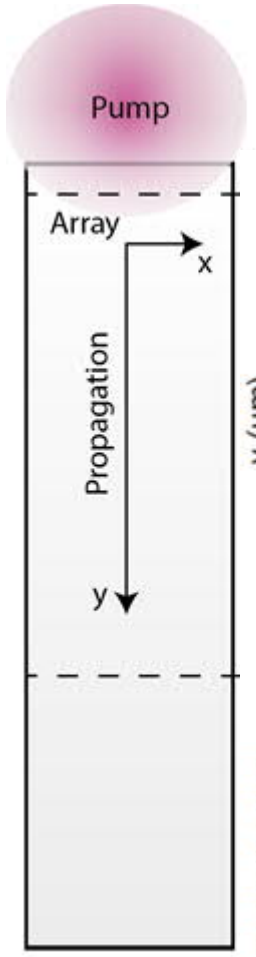
Thermalization experiment p = 580 nm

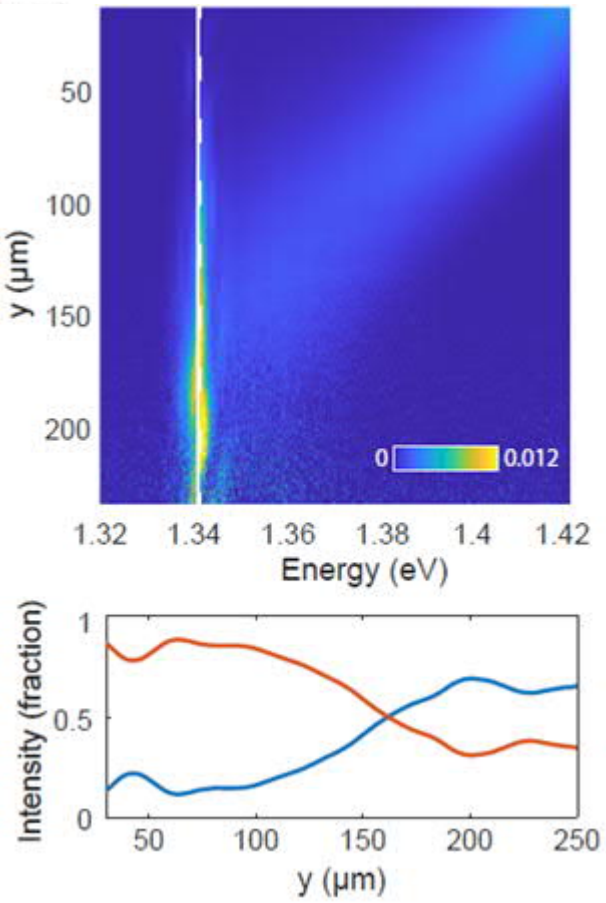


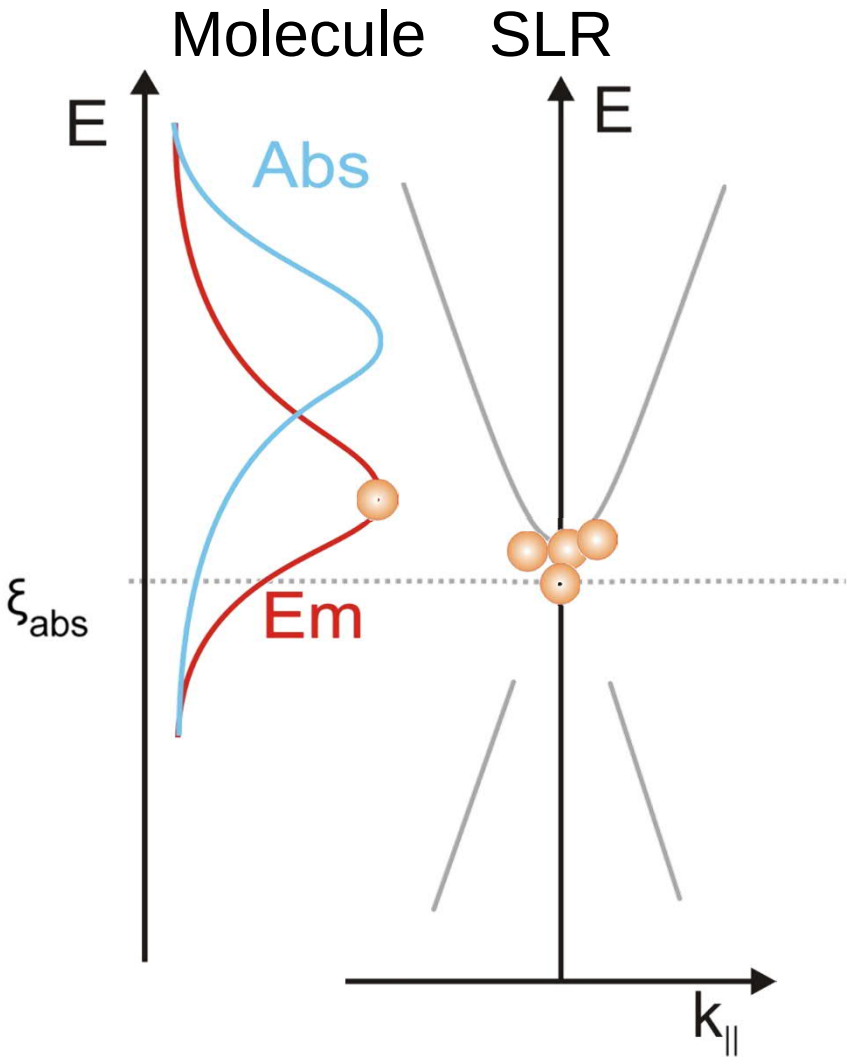




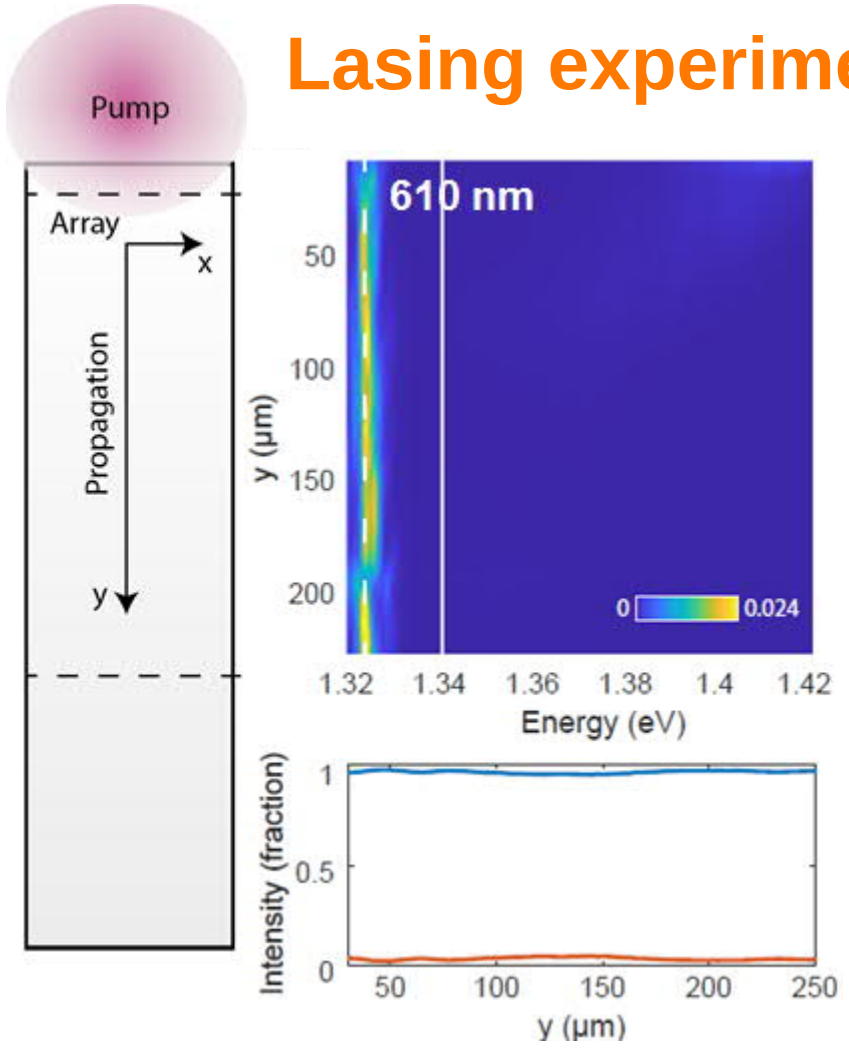
BEC experiment p = 600 nm

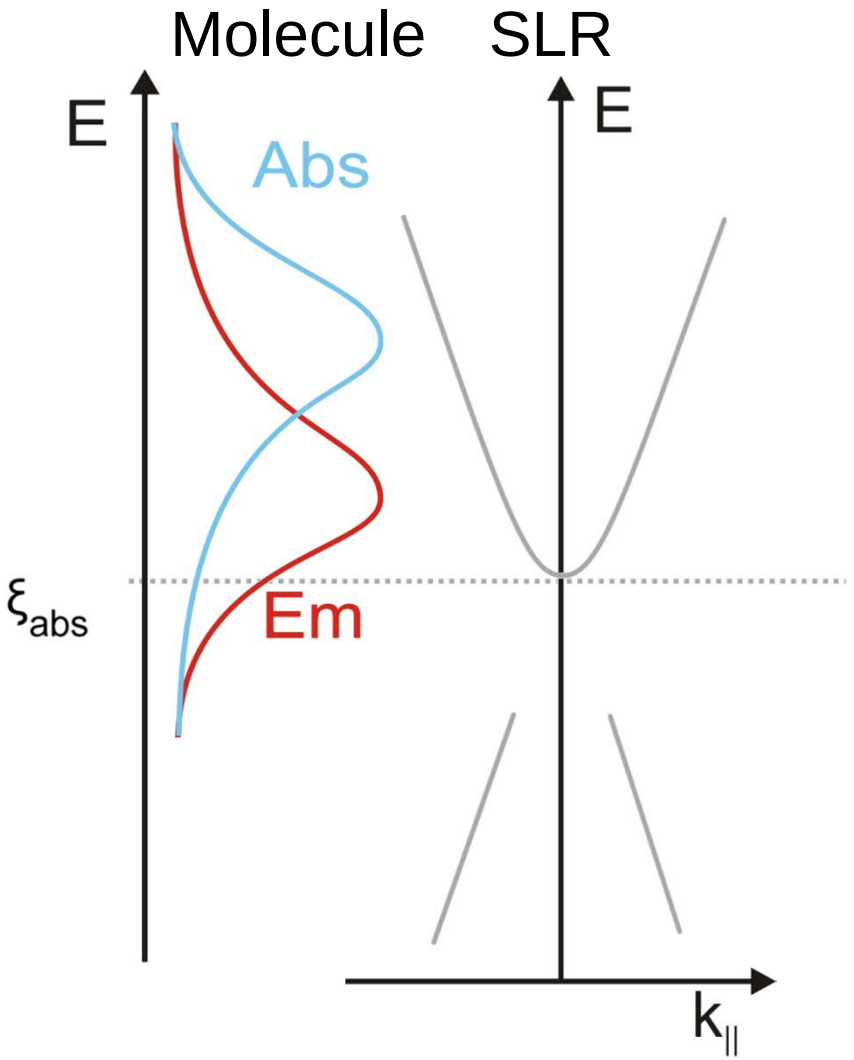




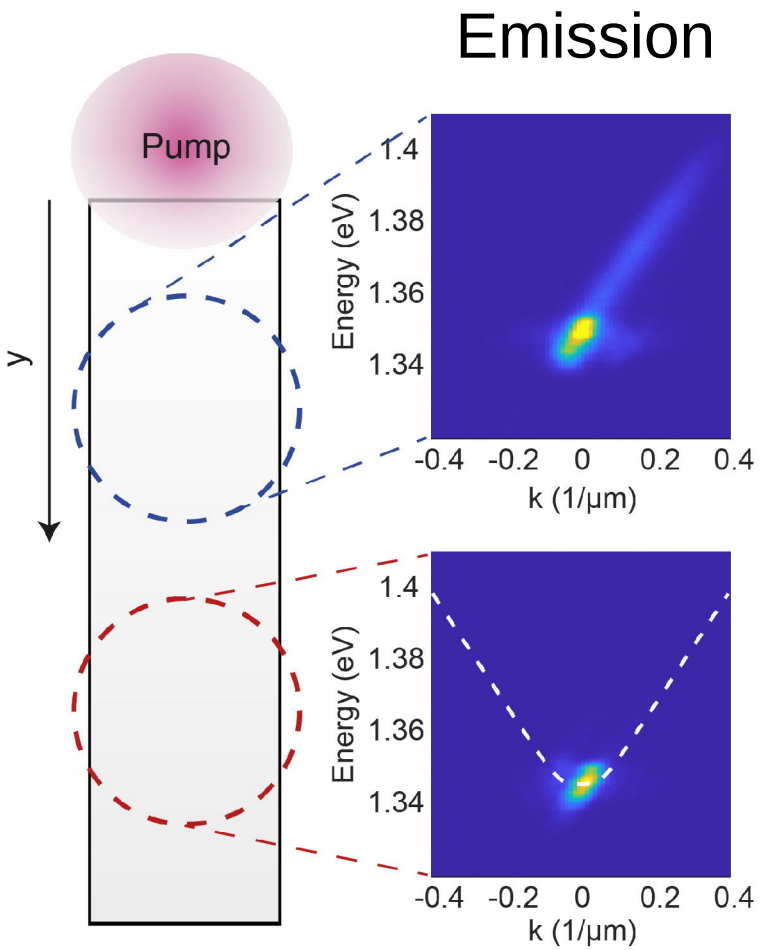


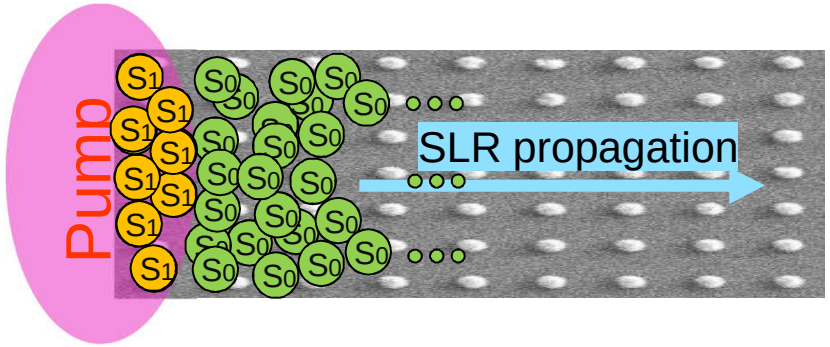
Lasing experiment p = 610 nm

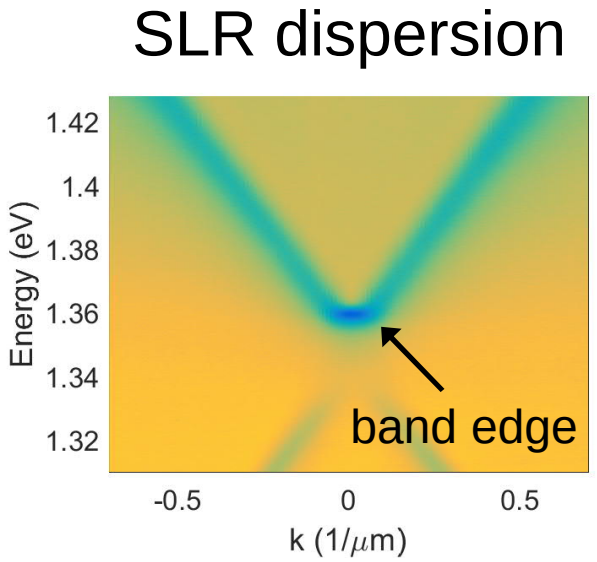




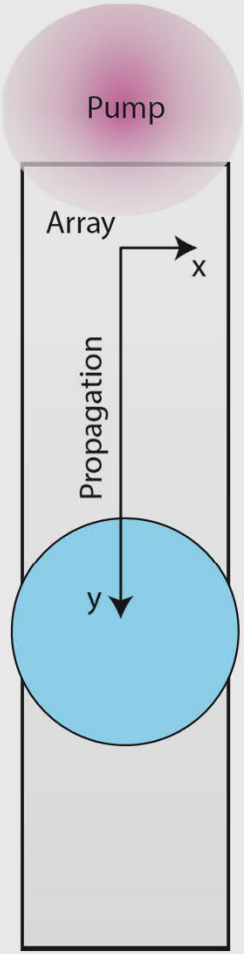
Thermalizing population follows the SLR dispersion



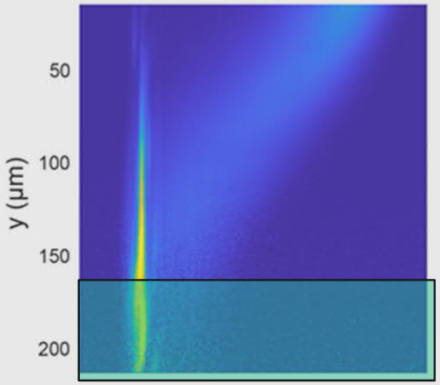




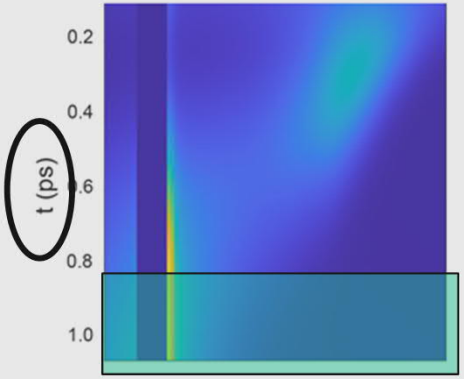
Bose-Einstein distribution at room temperature

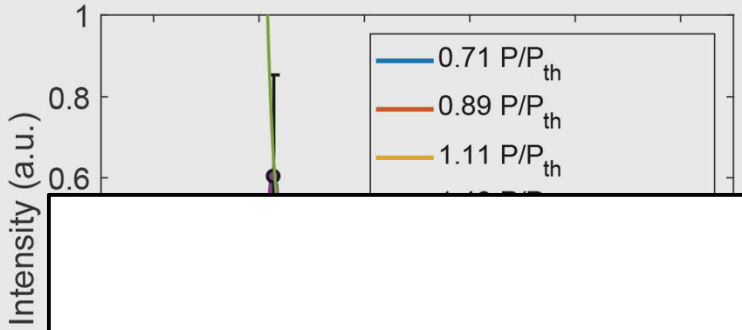


Experiment

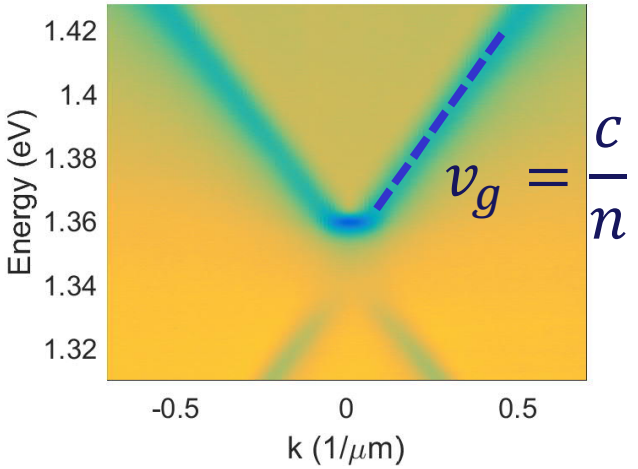


Rate equation simulation



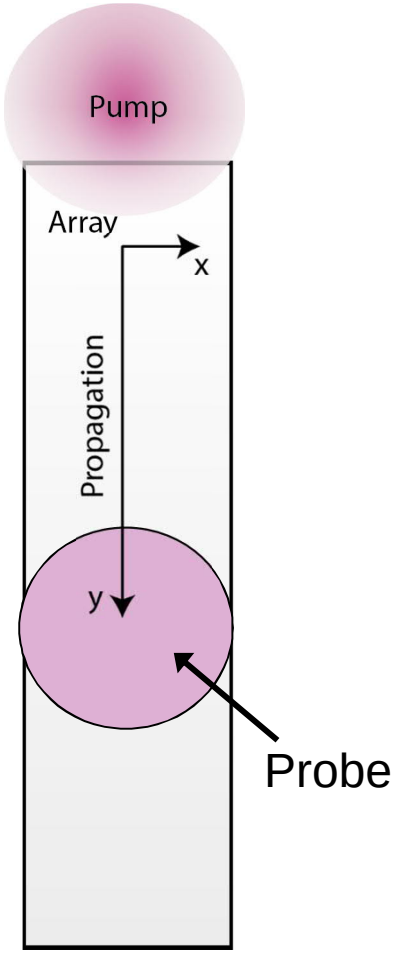


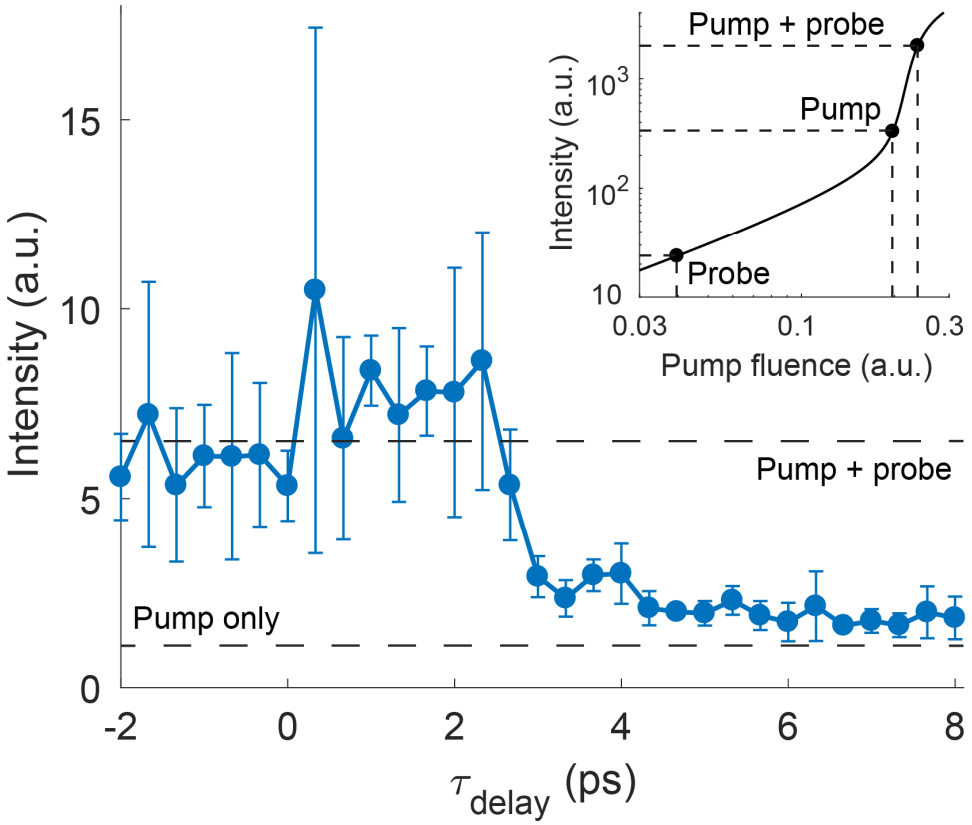
SLR dispersion



Intensity (a.u.)

Pump-probe: confirms the picosecond dynamics





Spatial coherence properties

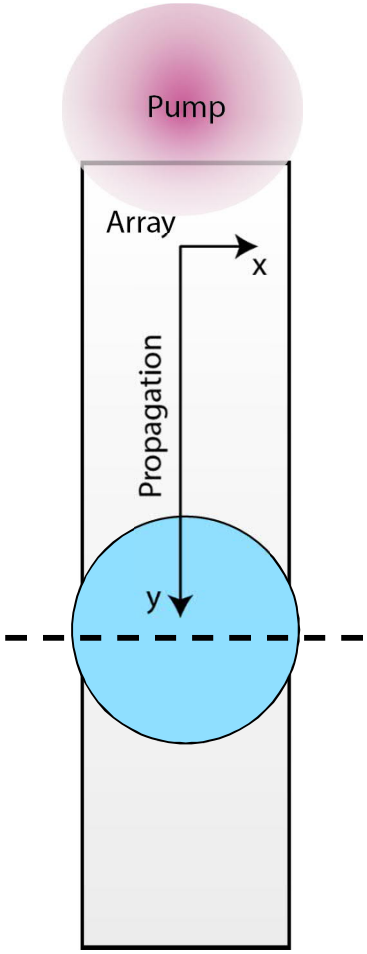
We have a finite-size condensate (dissipative system)

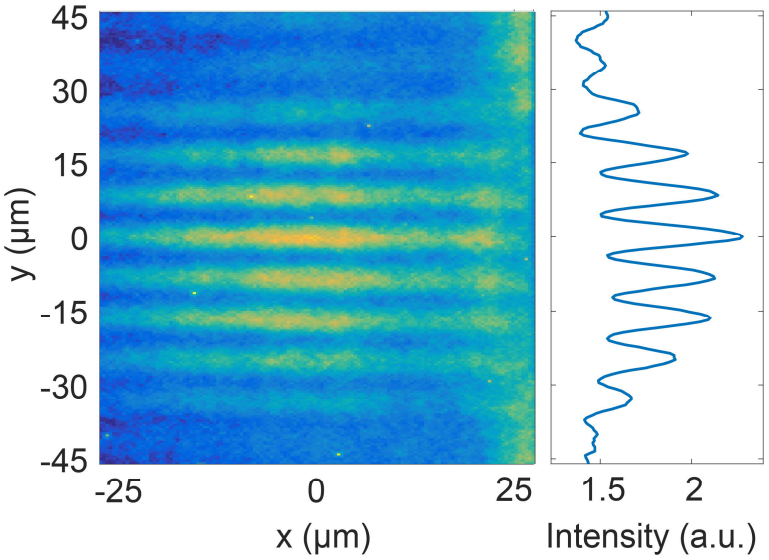
Long-range order limited in low dimensions (Mermin-Wagner-Hohenberg)

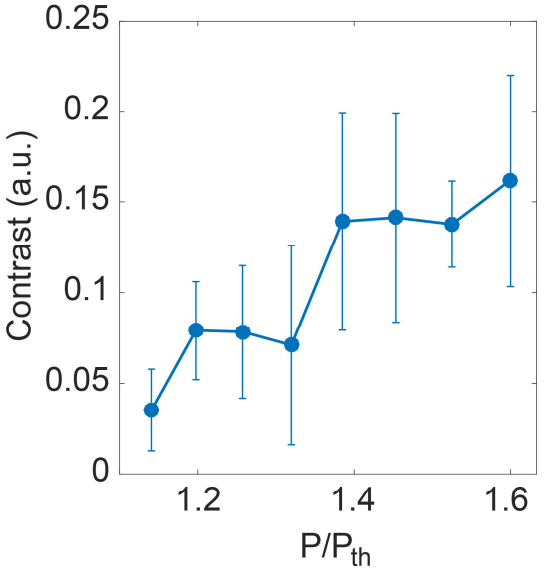
Long-range order subtle in driven-dissipative condensates
Sieberer, Huber, Altman, Diehl, PRL 2013

Spatial coherence

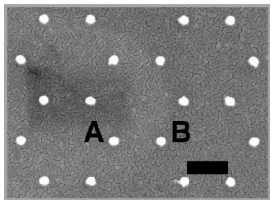
Michelson interferometer in retro-reflector configuration



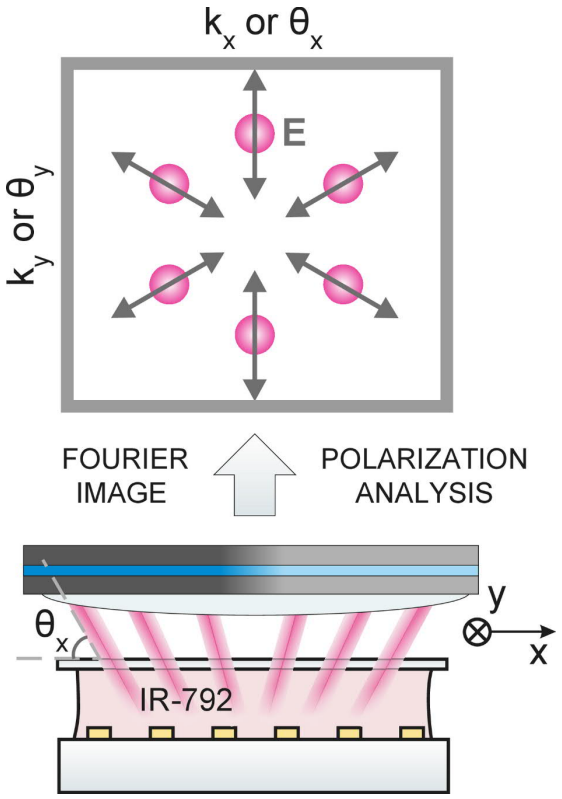


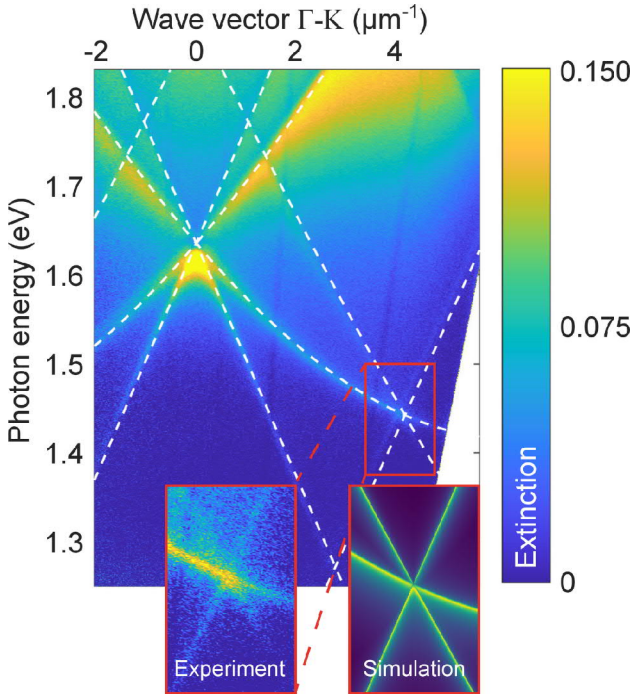


Lasing at the K-points of a honeycomb plasmonic lattice

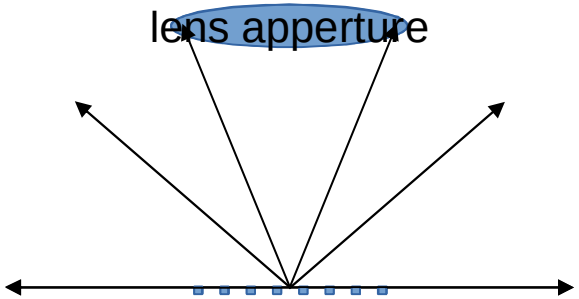


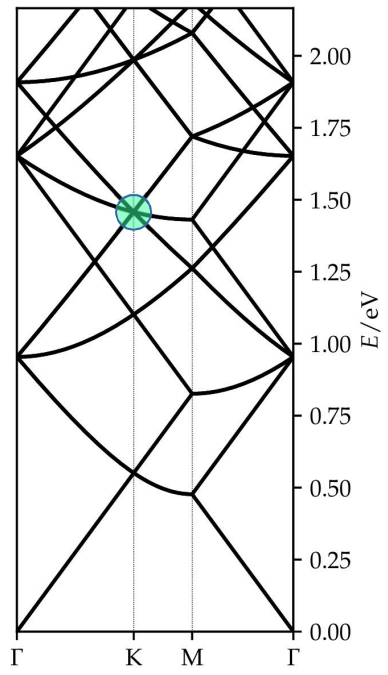
Guo, Necada, Hakala, Väkeväinen, PT, Phys Rev Lett (2019)

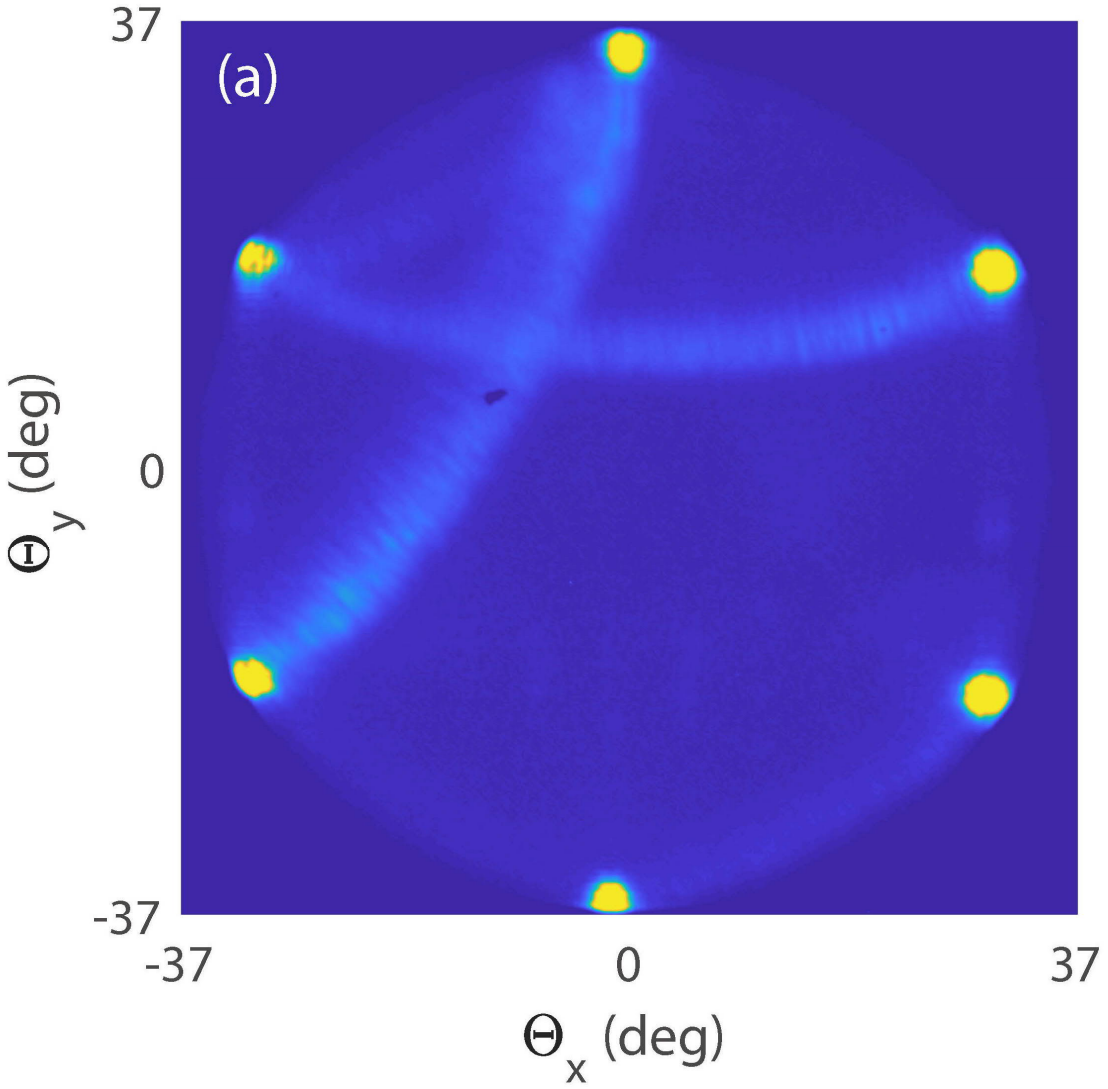




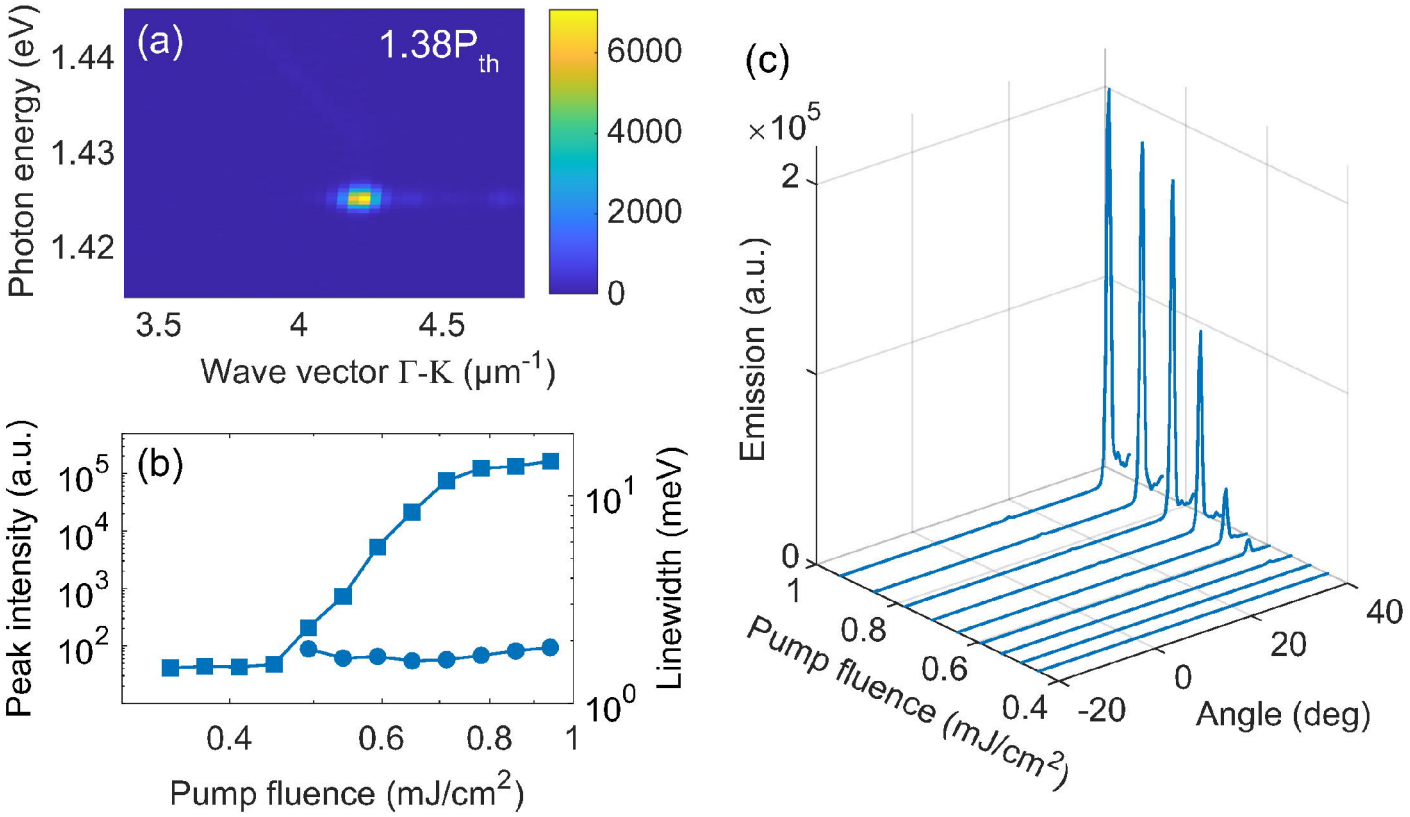
Seeing the whole Brillouin zone





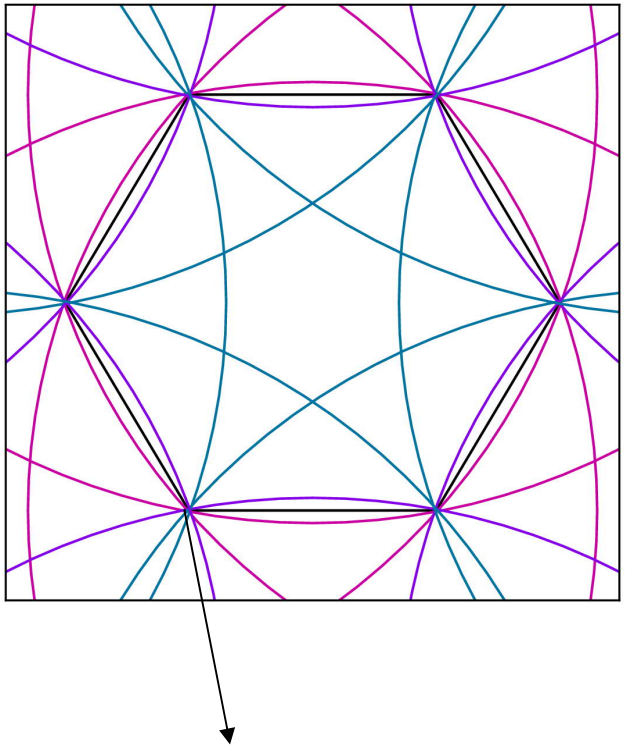


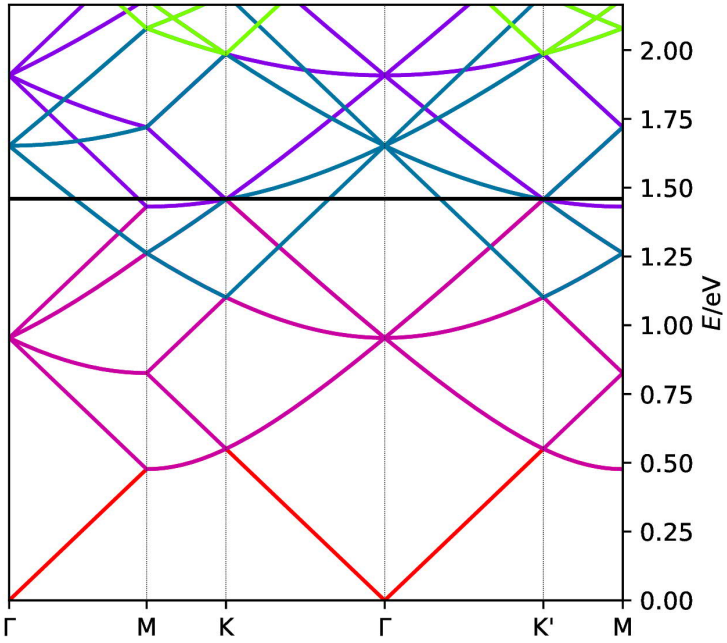
Threshold behaviour



Apparently lasing (with emission in non-normal direction).

Mode structure: empty lattice model

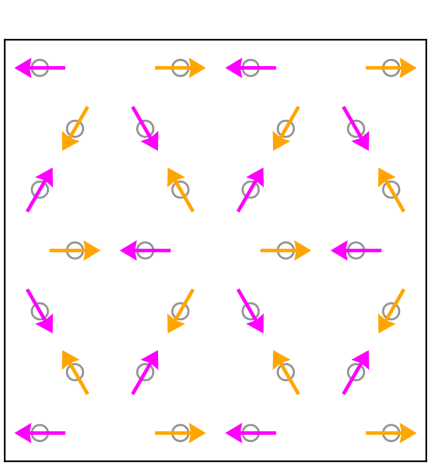




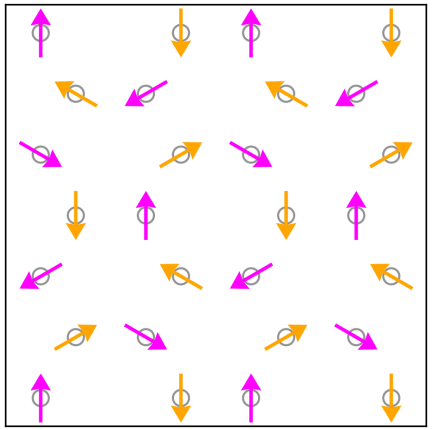
Six diffracted modes crossing at *K*-points.
What is their actual degeneracy in the real system?

Mode structure: Group-theoretical classification

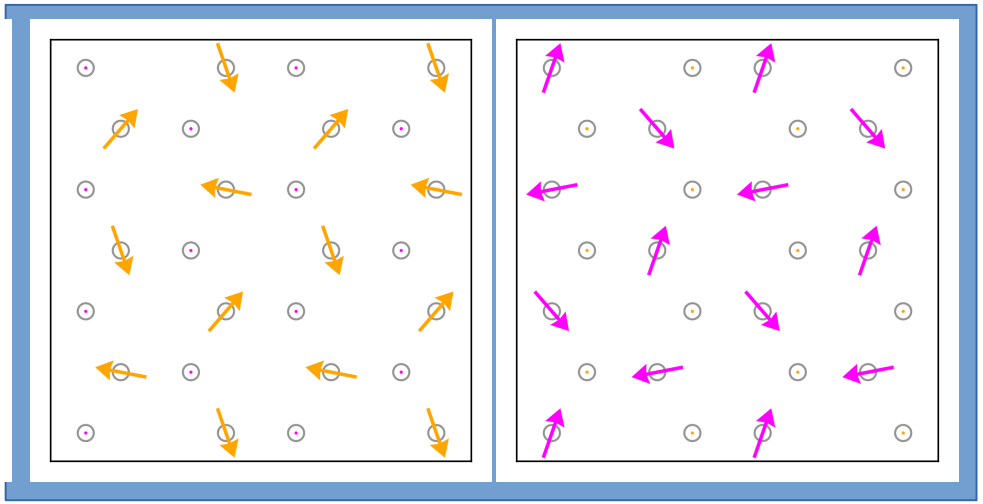
- D_3 point group symmetry at *K*-points
- one and two dimensional irreducible representations possible → singlets and (degenerate) doublets
- irreducible representations with non-trivial in-plane electric dipoles:



singlet

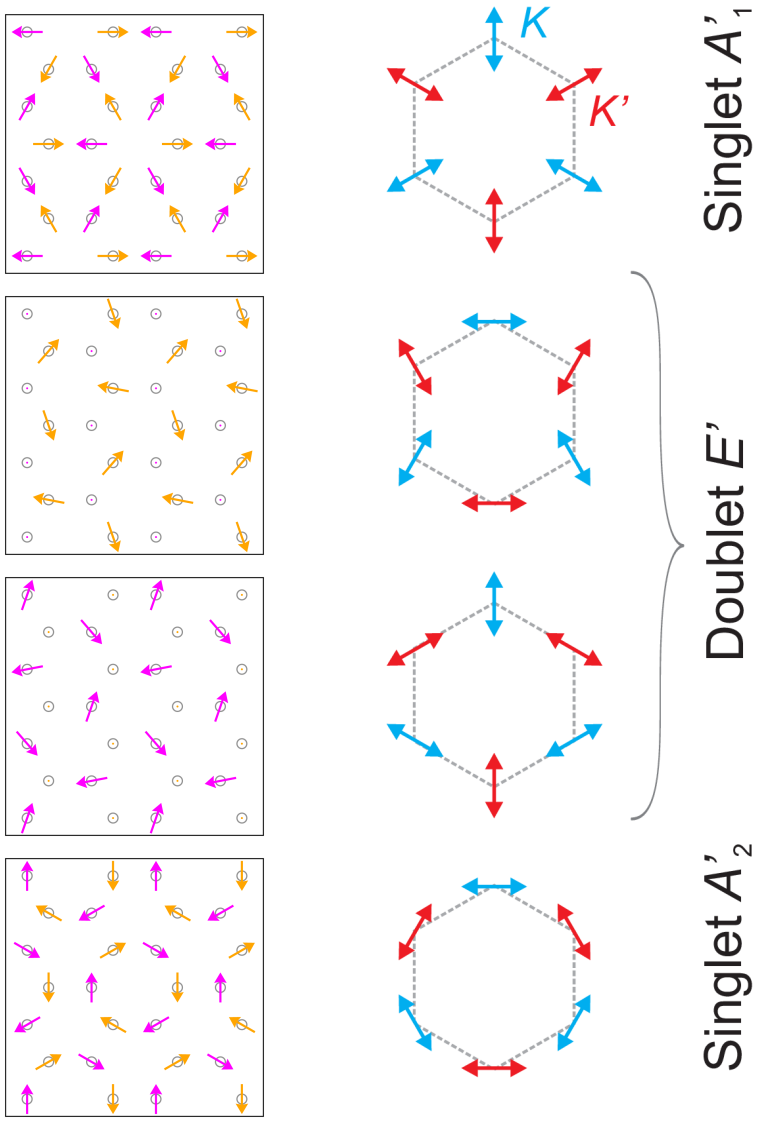


singlet

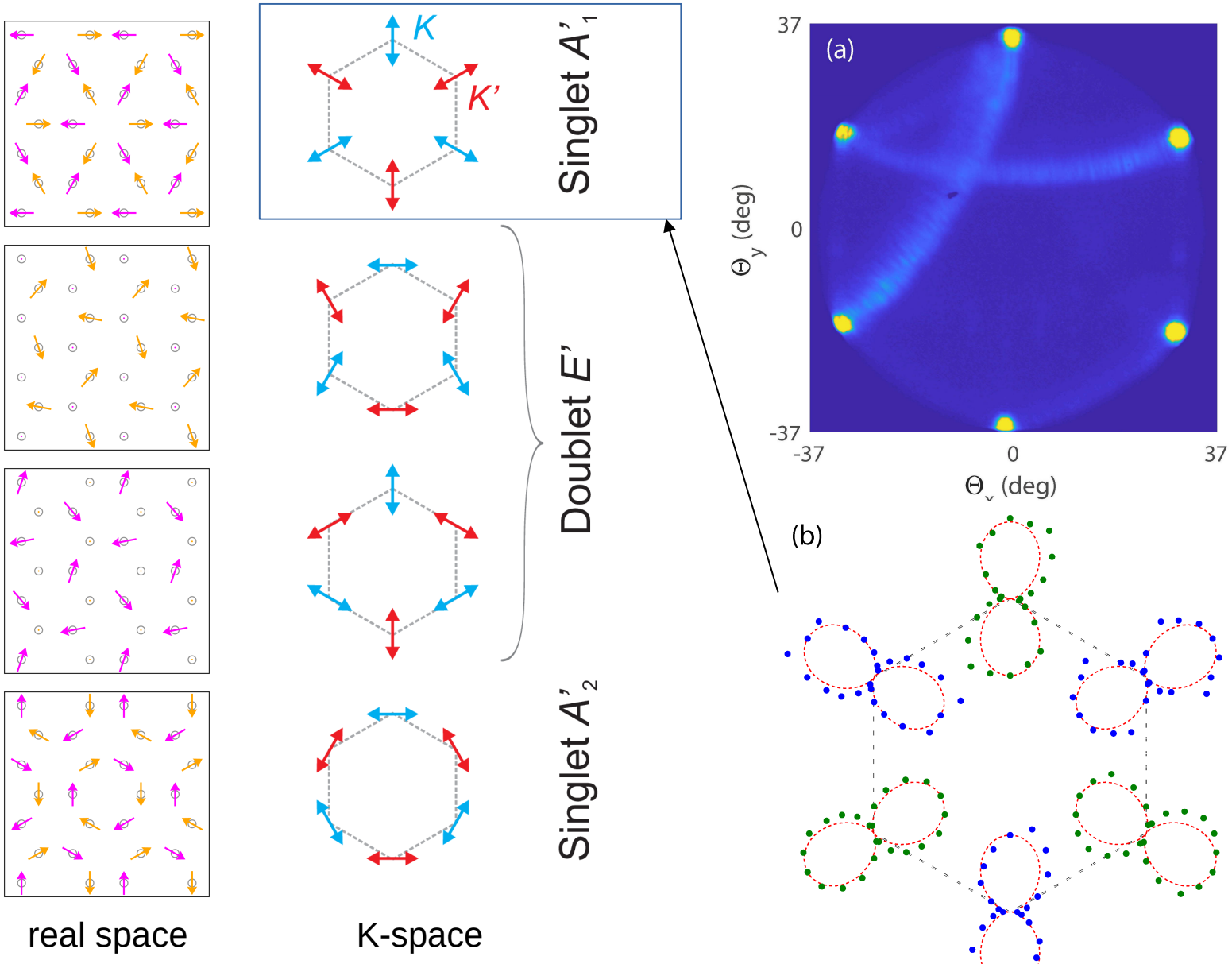


doublet

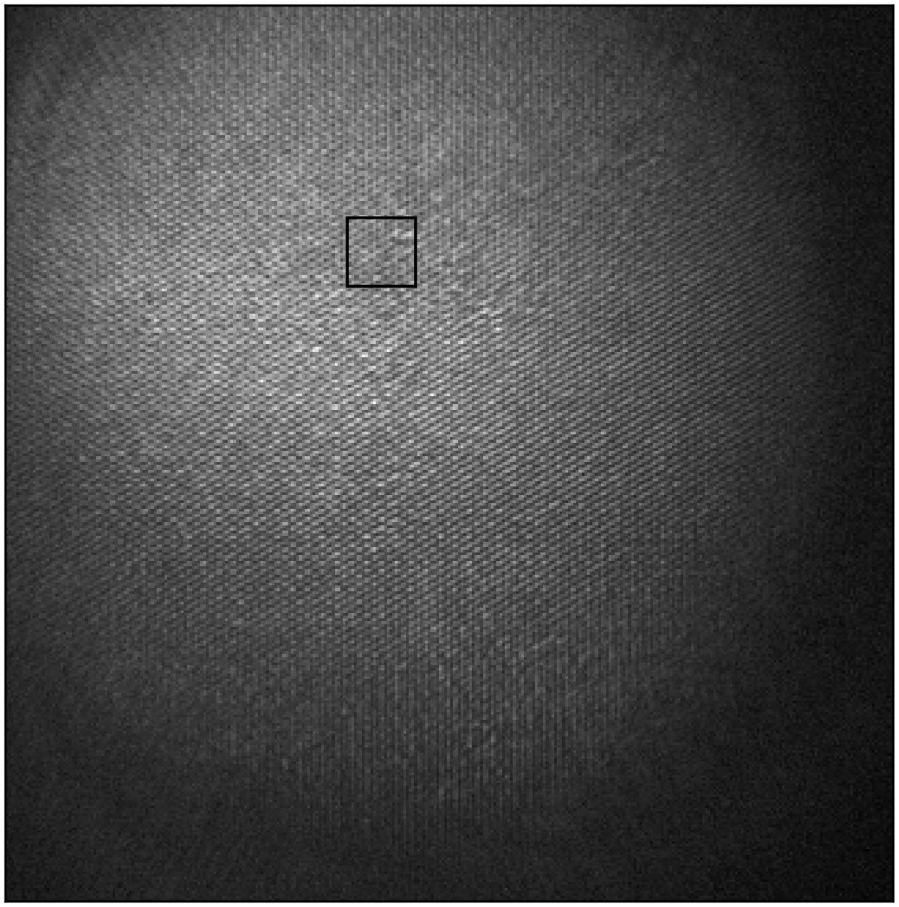
Irreps in *K*-space

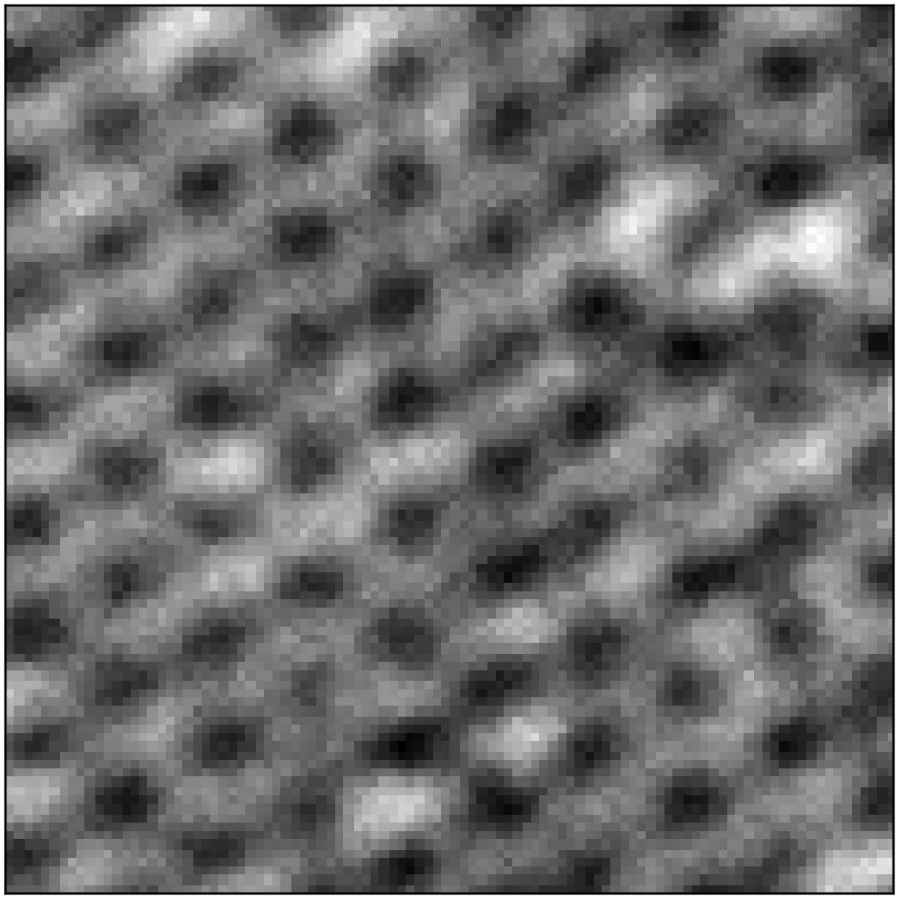


K-space classification with polarisation measurements



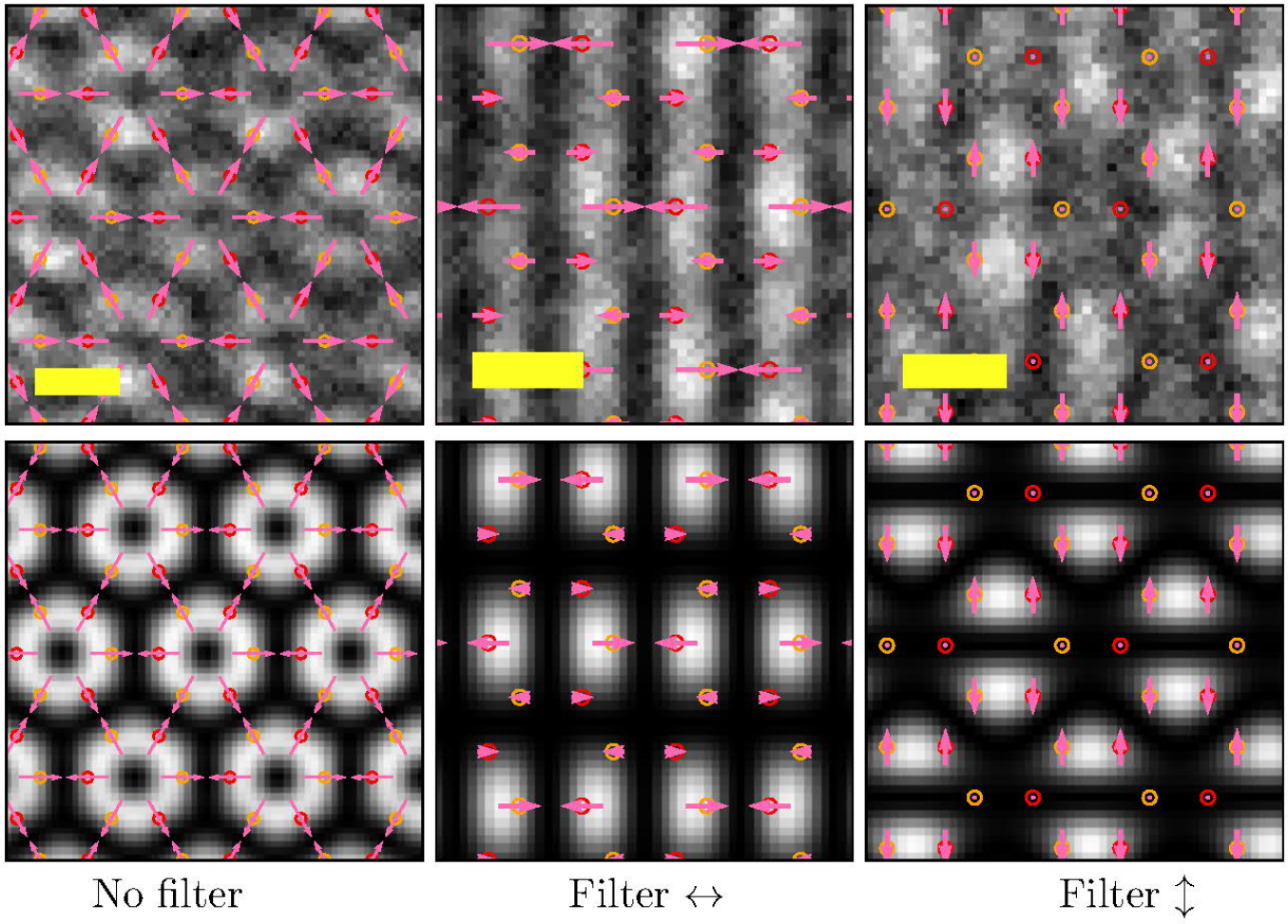
Real space images





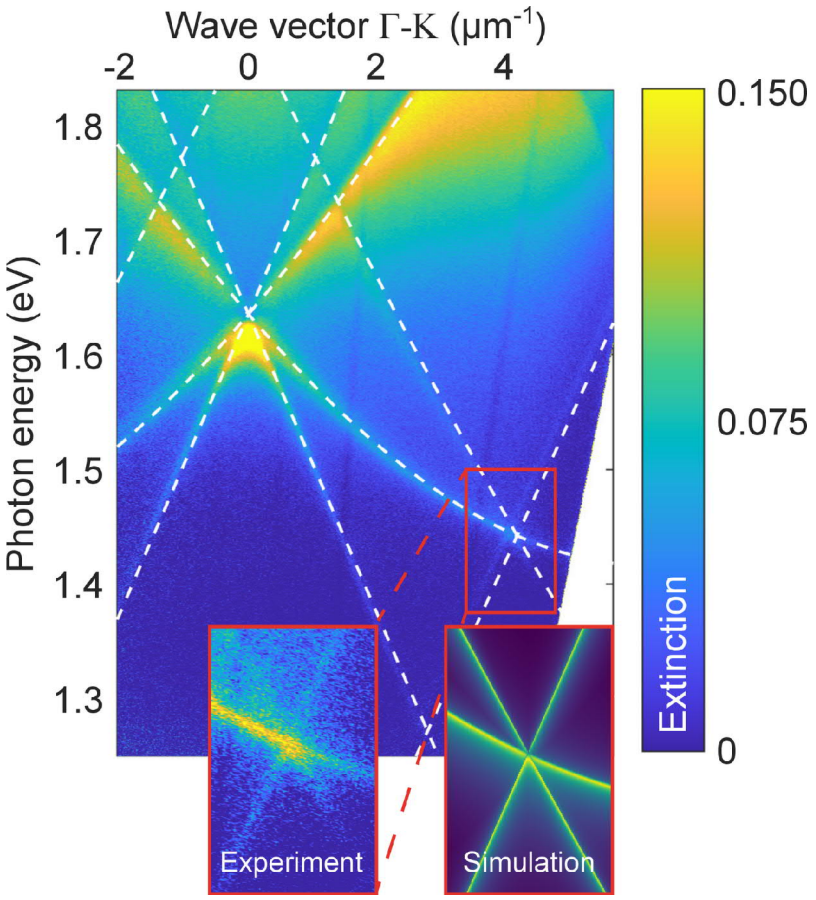
without filter

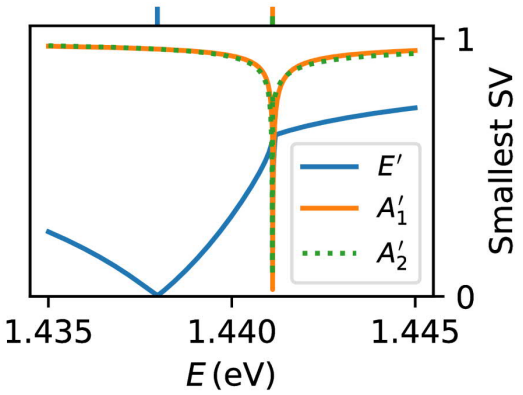
Mode classification in real space

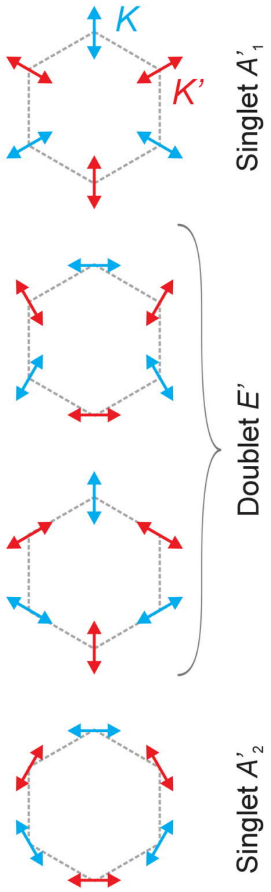


Consistent with A_1'

Lasing occurs despite a gap too small to be visible in the dispersion - promising for topological studies

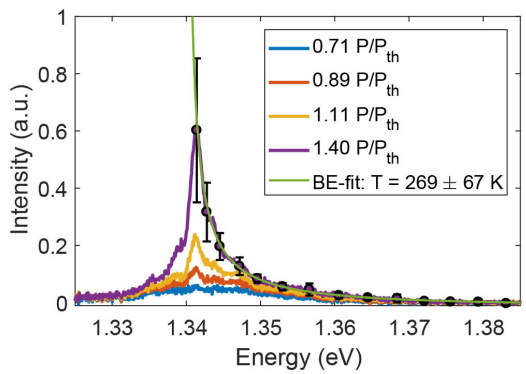


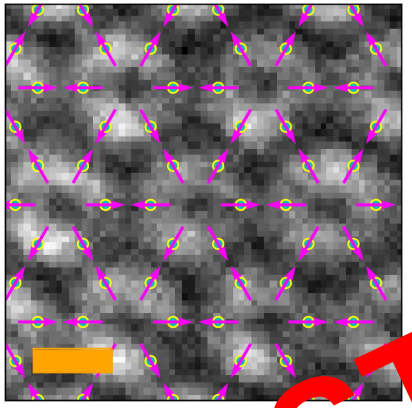




BEC and K-point lasing in plasmonic lattices

Tommi Hakala, Antti Moilanen, Rui Guo, Marek Necada,
Aaro Väkeväinen, Jani-Petri Martikainen, Konstantinos Daskalakis,
Heikki Rekola, Aleksi Julku





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