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Light-matter interactions in quantum plasmonic lattices

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Quantum Plasmonics, Benasque, Spain
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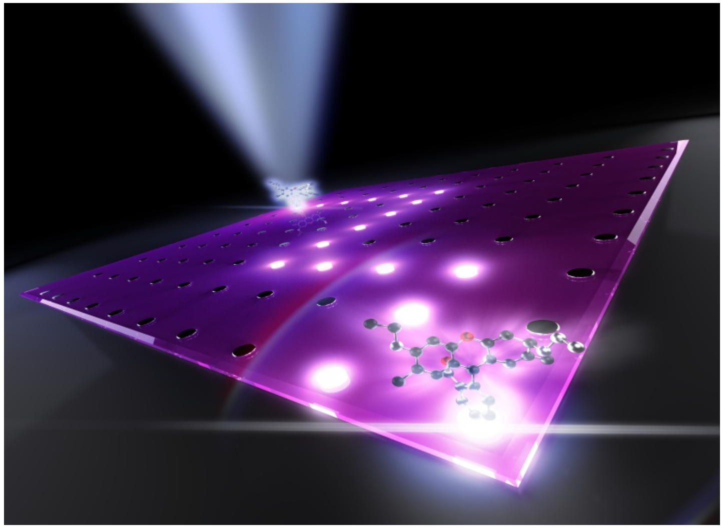
ACADEMY OF FINLAND

erc

(Periodic) spatial order and quantum physics

By nature:
- Crystal structure in matter
- Quantum objects (electrons) feeling a peridic structure: bands, …
- (Quantum) objects forming structures: Wigner crystals, …



By us:
- Semiconductor superlattices, …
- Photonic crystals, …
- Optical lattices, …

Fundamental influence on
- ***Classical***
- ***Quantum***
- ***Quantum many-body phenomena***

Also topological properties can be designed

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Surface lattice resonances (SLRs)

Markel, J. Mod. Optics 40, 2281–2291 (1993)

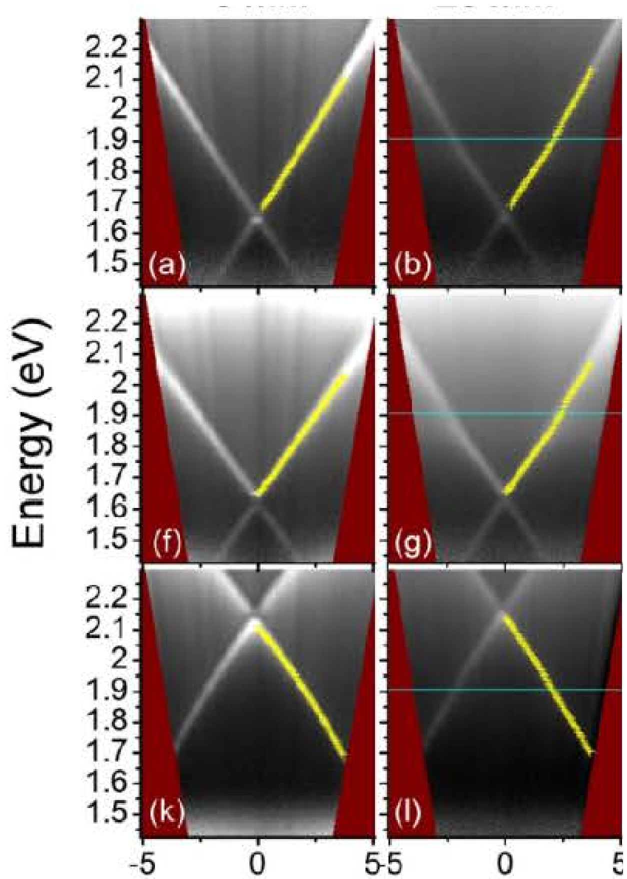
Zou, Janel, Schatz, J. Chem. Phys. 120, 10871–10875 (2004)

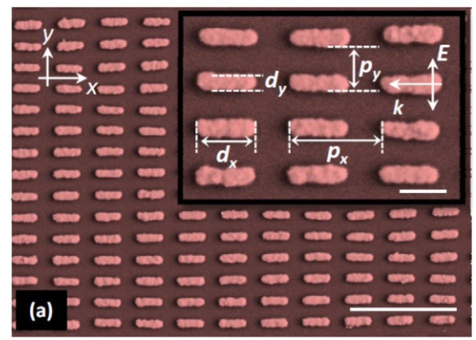
García de Abajo, Rev. Mod. Phys. 79, 1267 (2007)

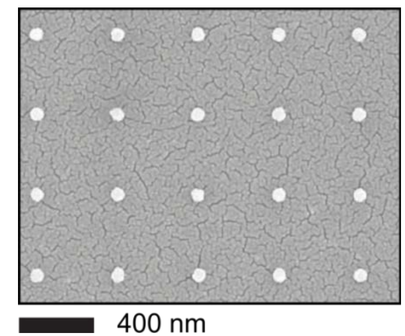
Auguié, Barnes, Phys. Rev. Lett. 101, 143902 (2008)

Kravets, Schedin, Grigorenko, Phys. Rev. Lett. 101, 087403 (2008)

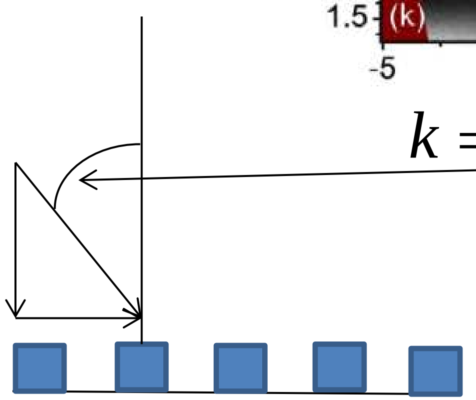
Rodriguez, Abass, Maes, Janssen, Vecchi, Gómez Rivas, Phys. Rev. X 1, 021019 (2011)



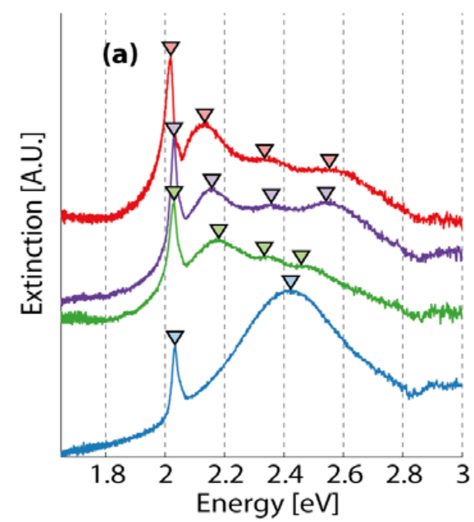




$$k = 2\pi / \lambda \sin(\theta)$$



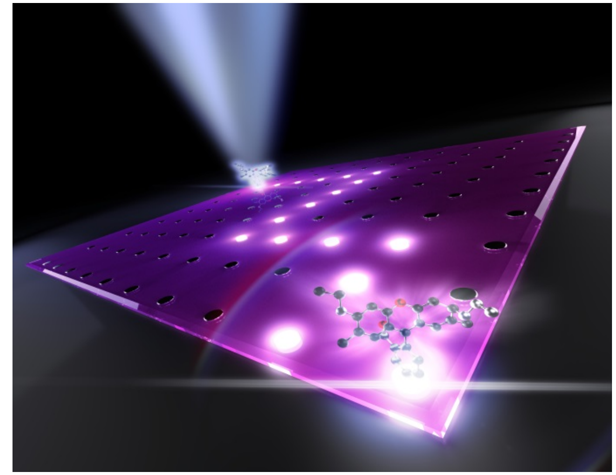
$$d\left(\sin\theta_i + \sin\theta_m\right) = m\lambda$$



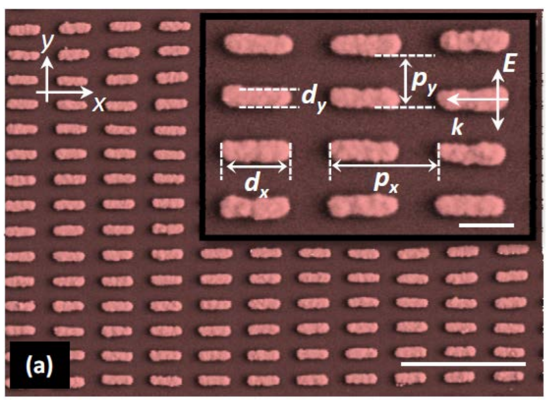
Goal:
a new concept - *quantum plasmonic lattices*

J.-P. Martikainen, M.O.J. Heikkinen, PT, Phys. Rev. A 90, 053604 (2014)

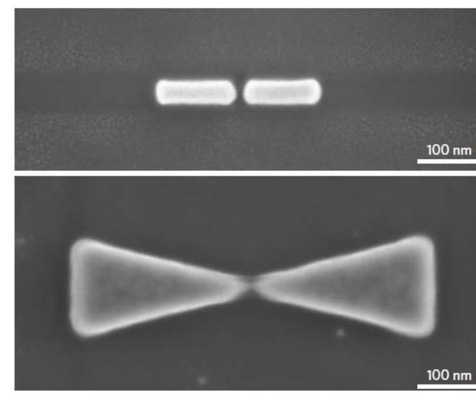
Room T
Nanoscale
On-chip
Ultrafast



$m_{eff} \sim 10^{-8} \ldots 10^{-5} m_e$ → BEC at room T (?)

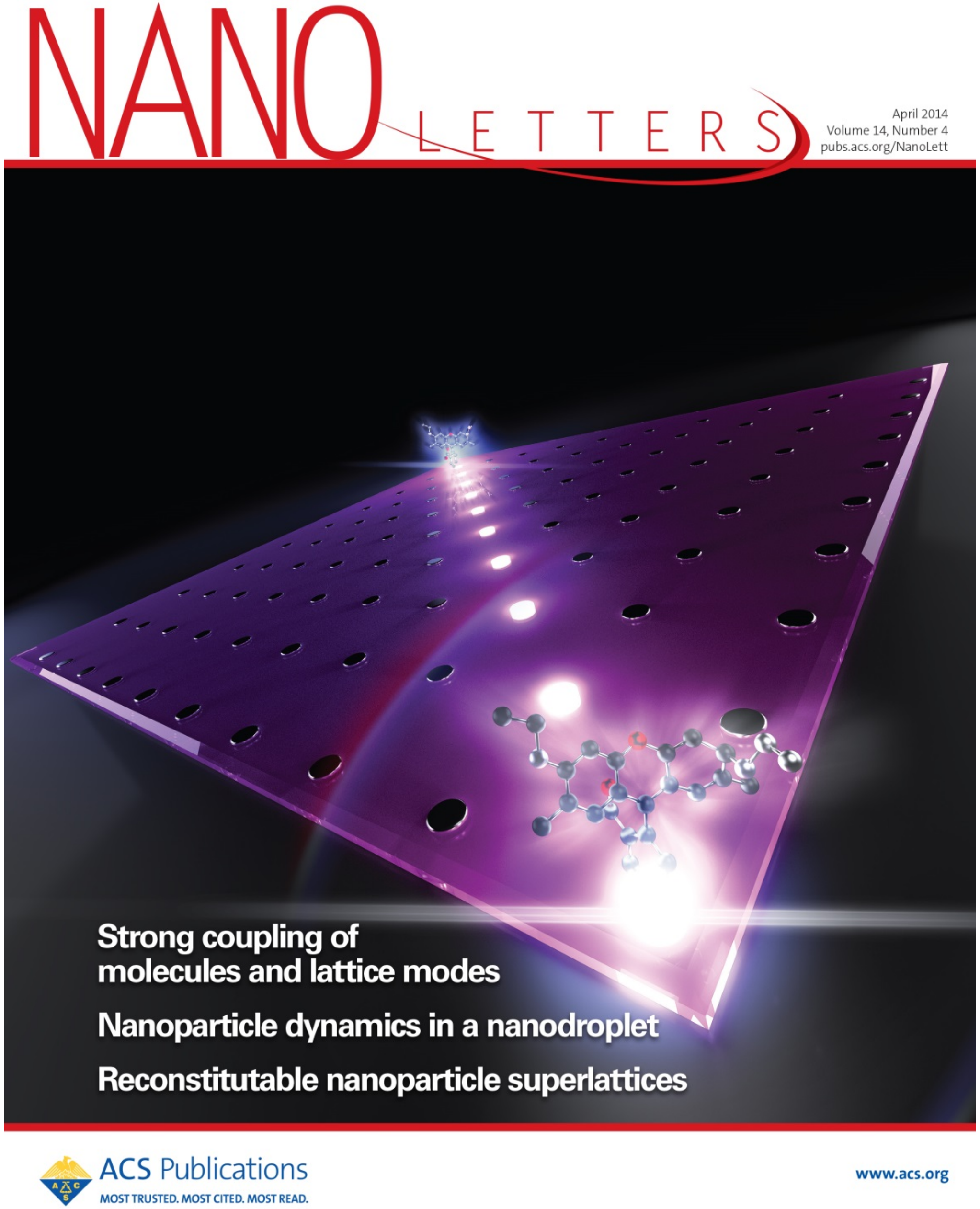


Single-emitter strong coupling predicted for hot-spots



Novotny, van Hulst, Nature Photonics 5, (2011)

Quantum statistics? Interactions between SLR photons? Quantum fluids?



Strong coupling in array

A.I. Väkeväinen, R.J. Moerland, H.T. Rekola, A.-P. Eskelinen, J.-P. Martikainen, D.-H. Kim, PT, Nano Lett. 14, 1721 (2014)

Coherence of the hybrids

L. Shi, T.K. Hakala, H. T. Rekola, J.-P. Martikainen, R.J. Moerland, PT, Phys. Rev. Lett. 112, 153002 (2014)

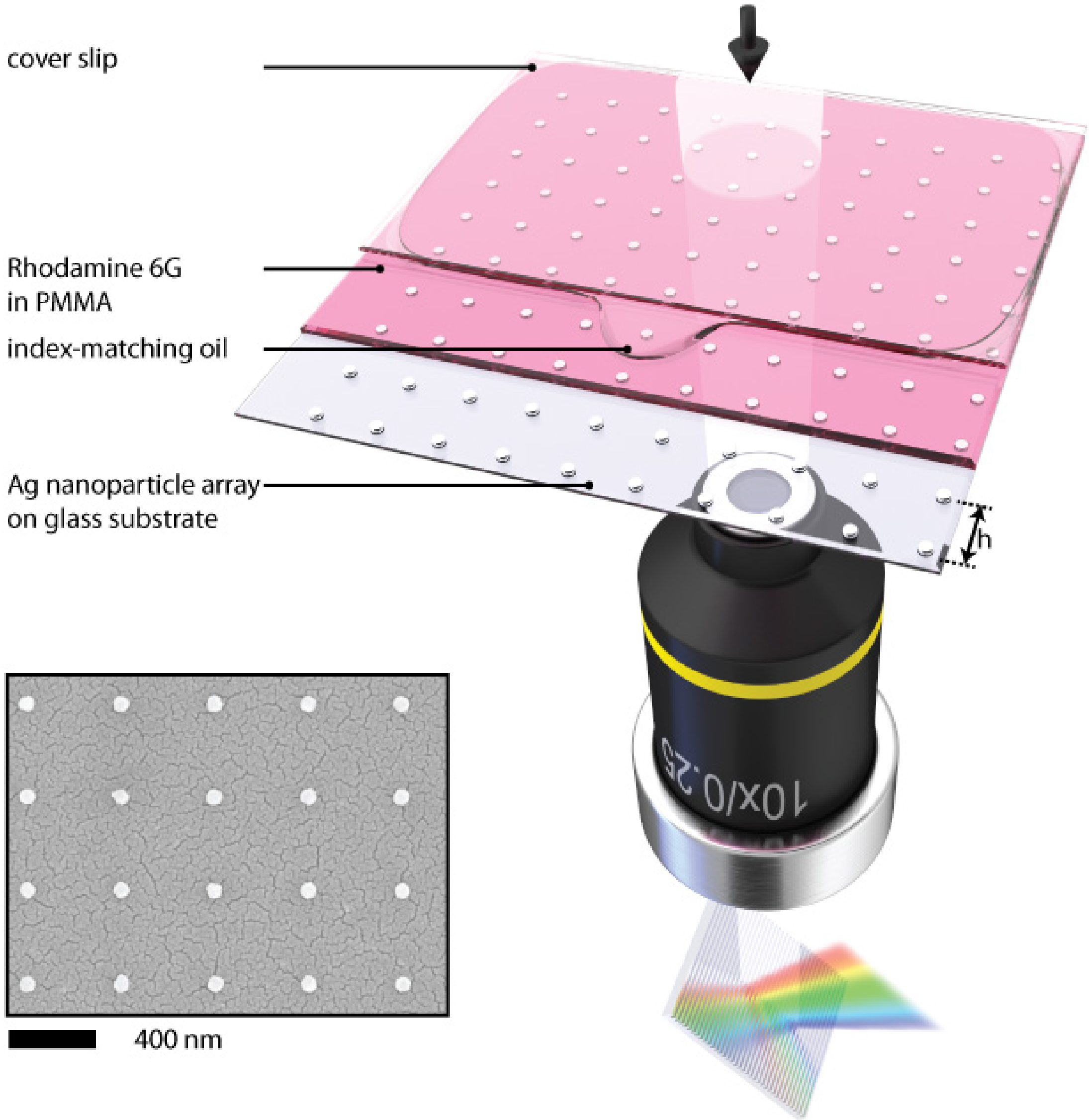
SLRs for magnetic particles

M. Kataja, T.K. Hakala, A. Julku, M. Huttunen, S. van Dijken, PT, Nature Comm. in review (2015)

SLR condensation (theory)

J.-P. Martikainen, M.O.J. Heikkinen, PT, Phys. Rev. A 90, 053604 (2014)

The measurements

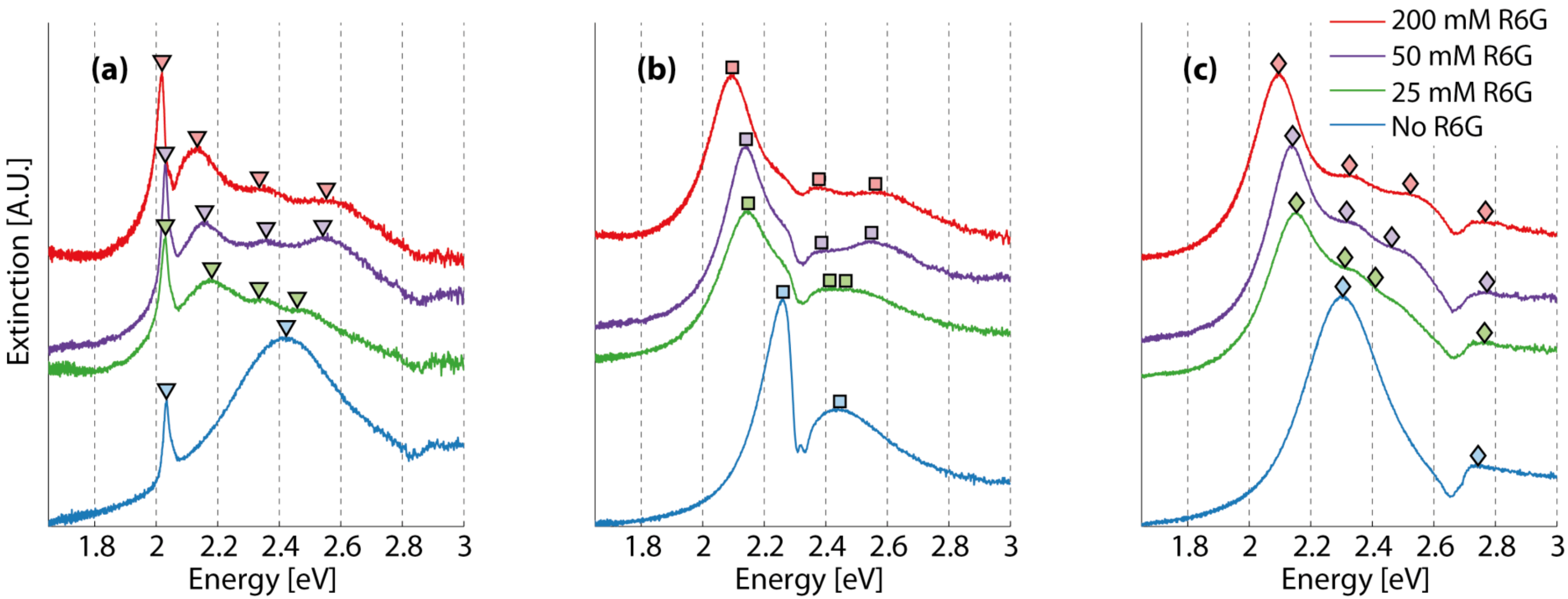


Transmission measurements with inverted optical microscope

- Symmetrical index environment
- White light incident on from top
- Transmitted light guided to a spectrometer

C.f. experiments in S. Rodriguez and J. Gomez Rivas, Opt. Express 21, 27411 (2013)

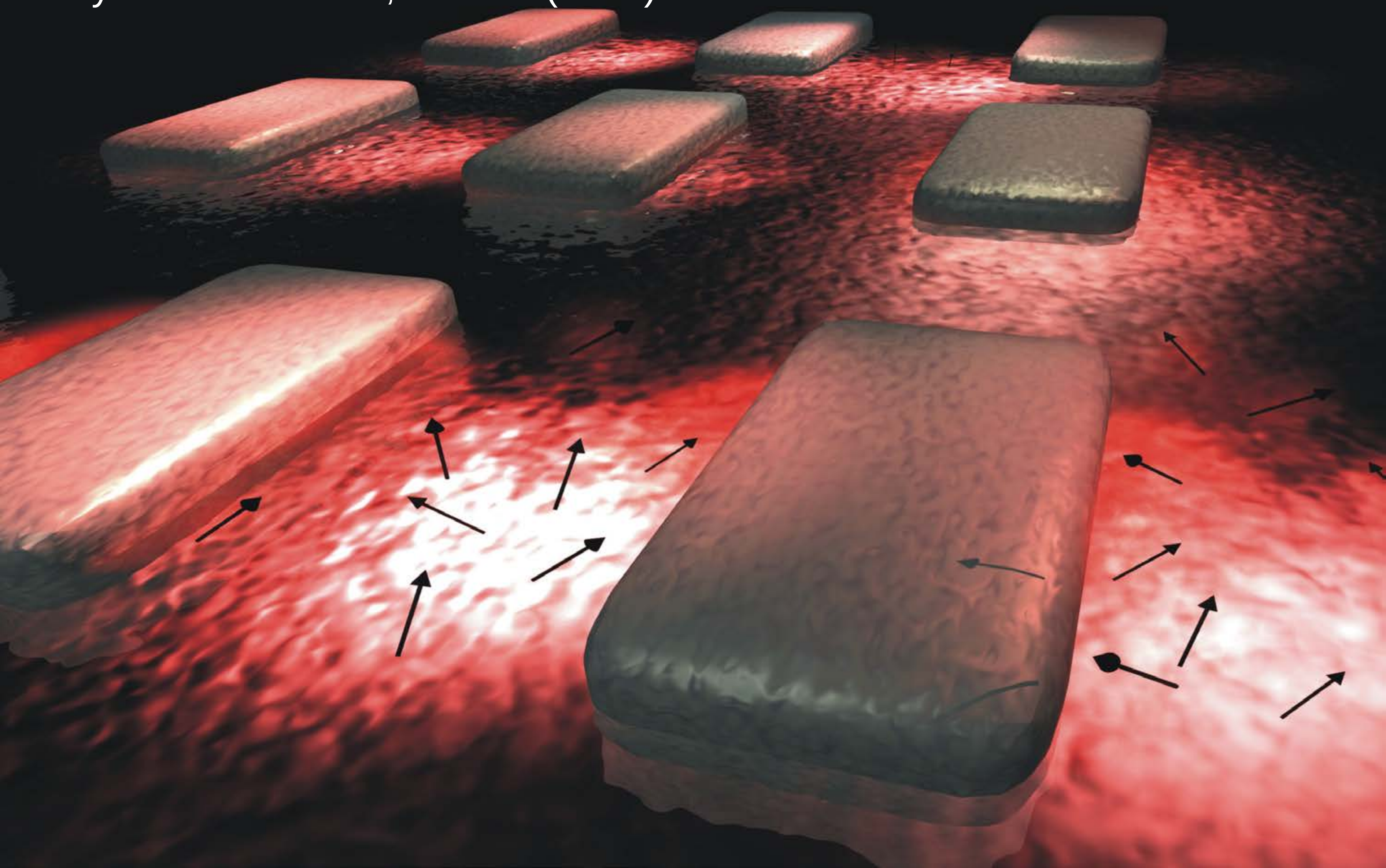
Results (with R6G)



a), b), c): different periods

The splitting grows as $\propto \sqrt{N/V}\, d$

L. Shi, T. K. Hakala, H. T. Rekola, J.-P. Martikainen,
R. J. Moerland, and P. Törmä,
Phys. Rev. Lett. 112, 153002 (2014)



Spatial coherence

Localized excitons in molecules/quantum dots:
No long-range spatial coherence

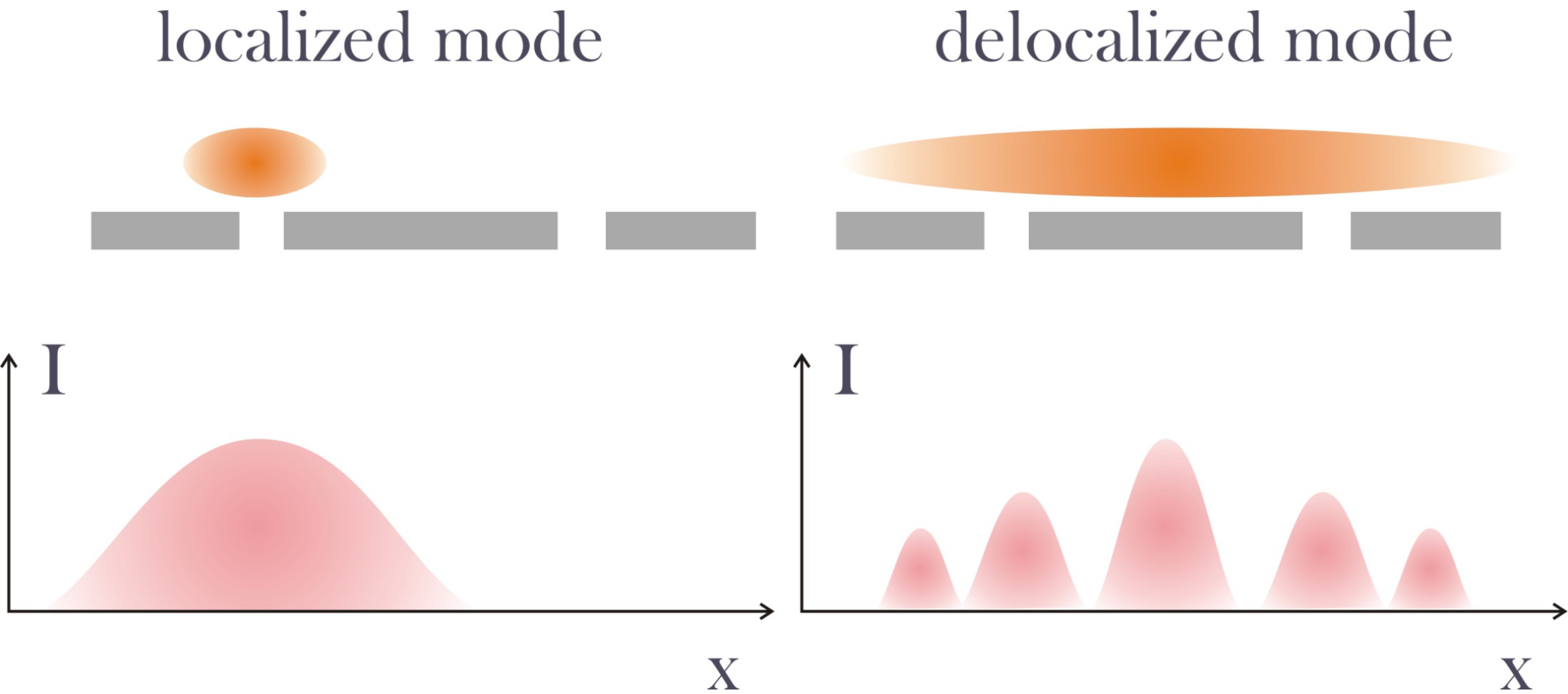
Light-matter hybrids: coherence?

$$c_l \left| light \right\rangle + c_m \left| matter \right\rangle$$

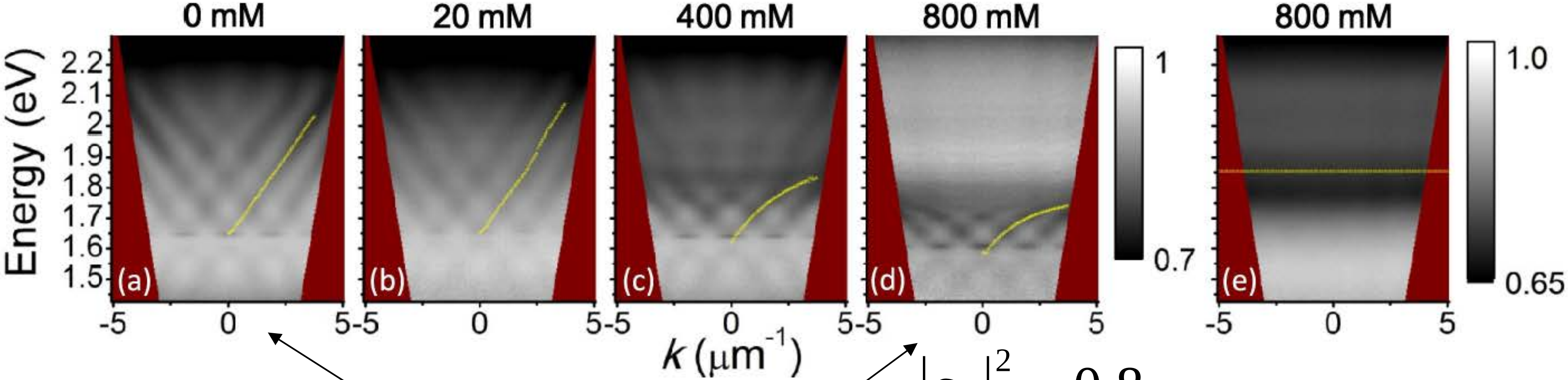
Study the spacial and coherence properties of the hybrid wavefunction; interference

c.f. Aberra Guebrou, Symonds, Homeyer, Plenet, Gartstein, Agranovich, Bellessa, Phys. Rev. Lett. 108, 066401 (2012); strong coupling regime (weak coupling reference by a different system), planar metal

A double slit experiment

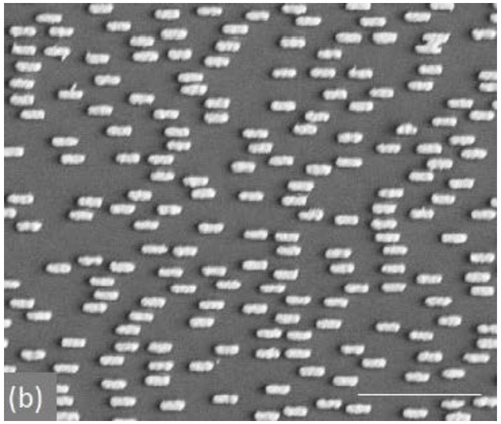


Double slit

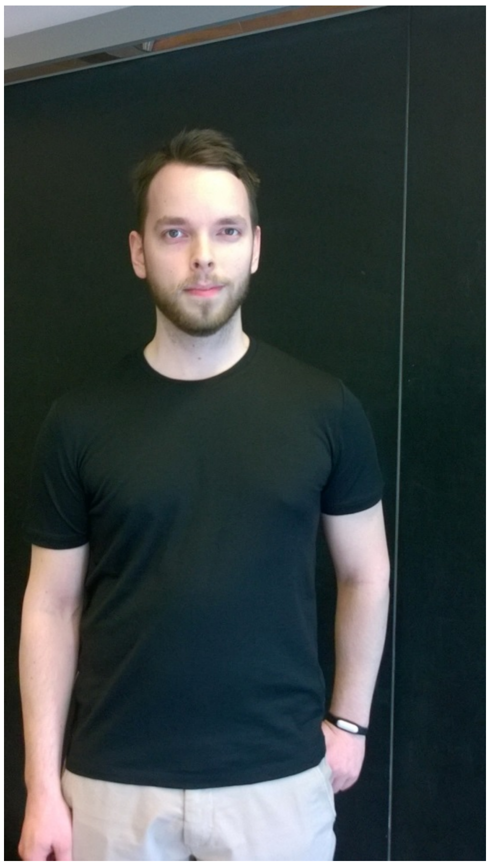


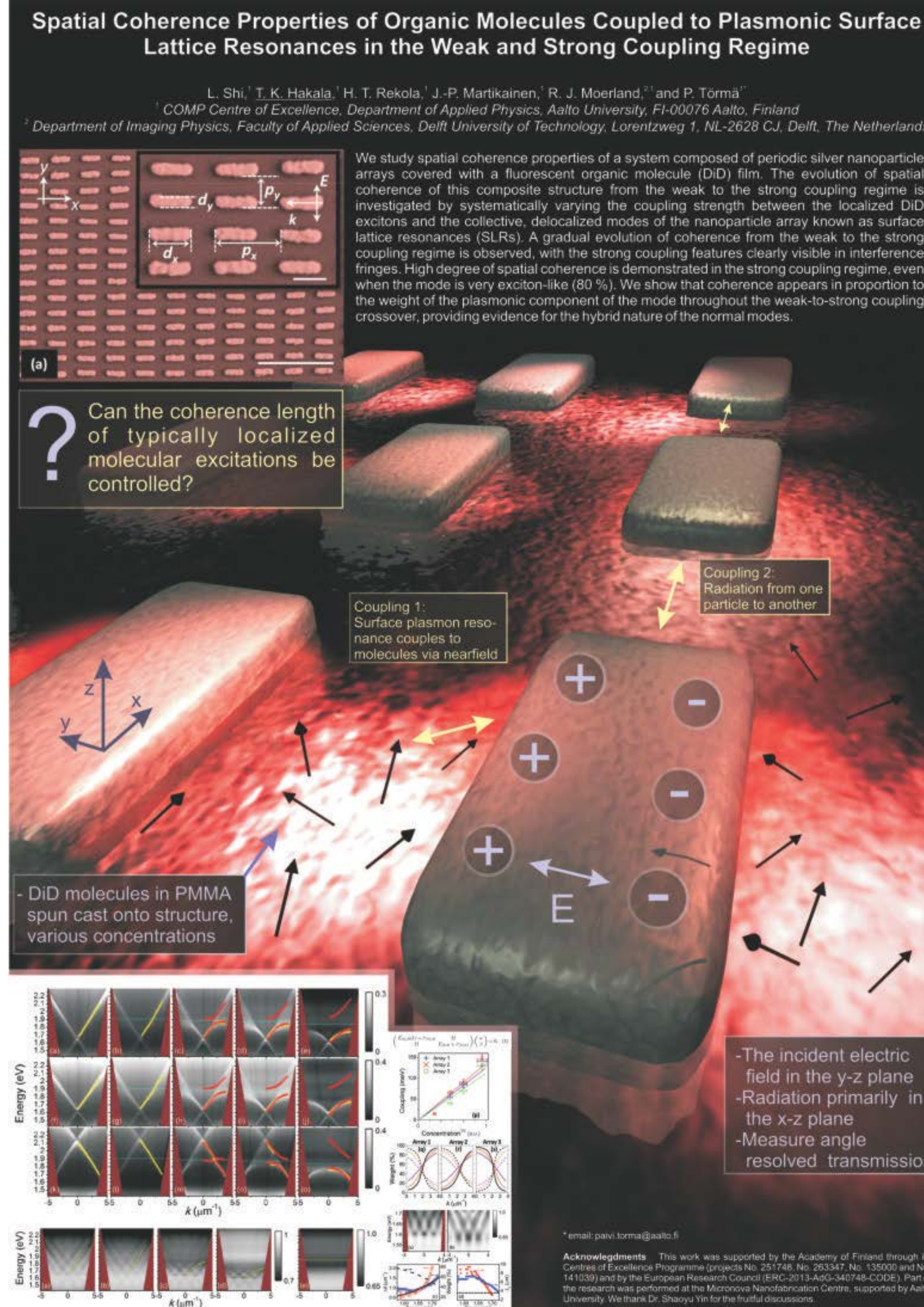
$$|c_m|^2 \approx 0.8$$

$$c_l|light\rangle + c_m|matter\rangle$$



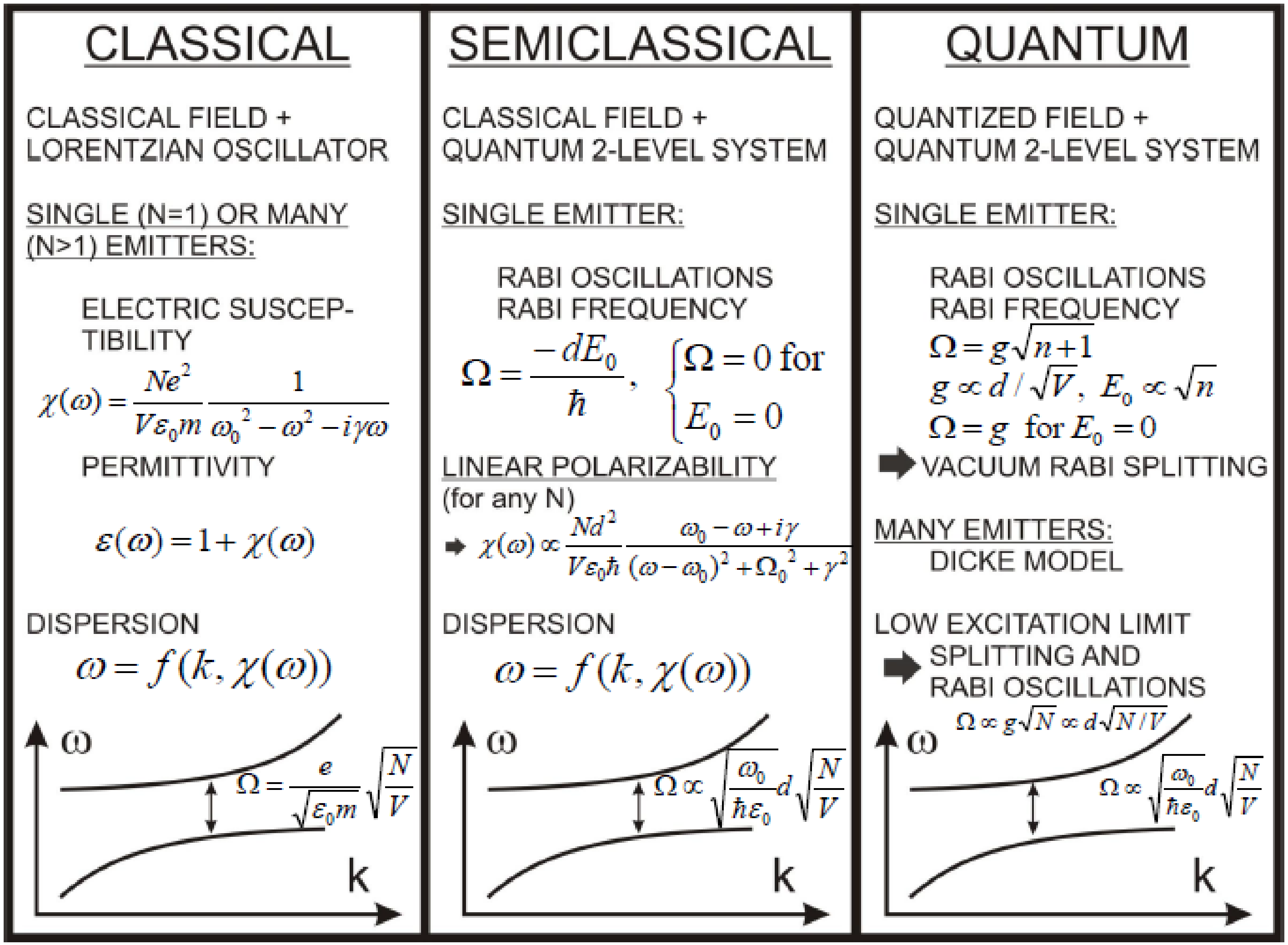
Poster on the spatial coherence experiment by Heikki Rekola





Strong coupling of surface plasmon polaritons and emitters: a review

PT and W.L. Barnes, Rep. Prog. Phys. 78, 013901 (2015)



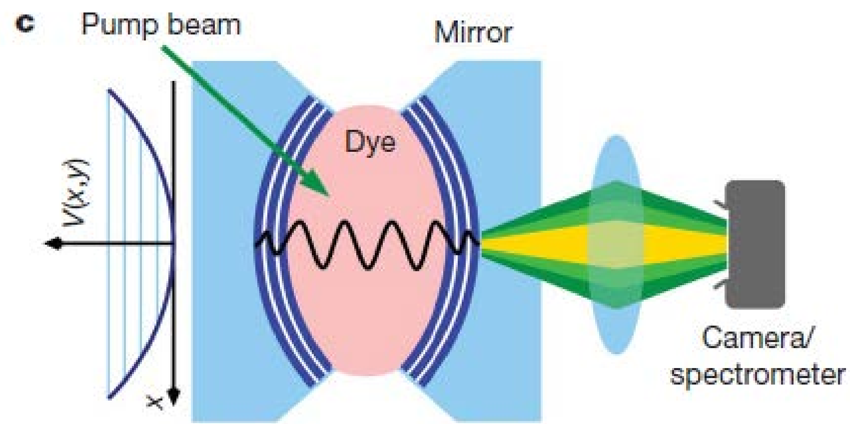
Photon BEC

LETTER

doi:10.1038/nature09567

Bose–Einstein condensation of photons in an optical microcavity

Jan Klaers, Julian Schmitt, Frank Vewinger & Martin Weitz



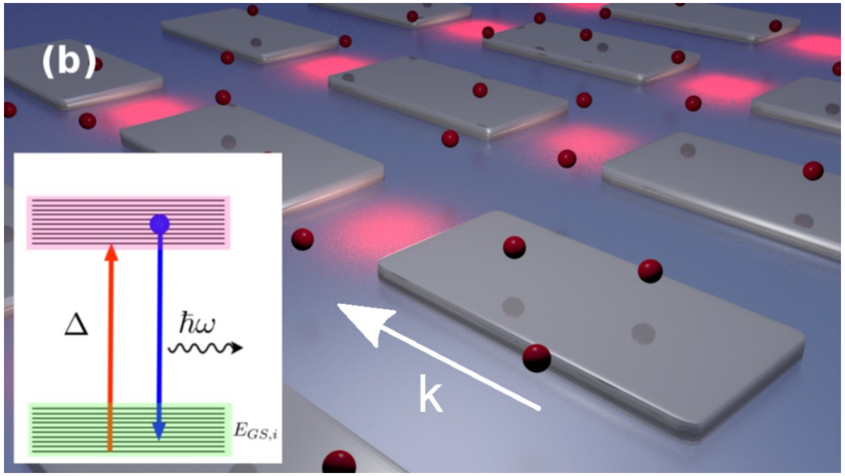
Black body

$$\frac{1}{e^{\hbar\omega/(k_B T)} - 1}$$

BEC

$$\frac{1}{e^{(\hbar\omega-\mu)/(k_B T)} - 1}$$

Question: are similar condensation phenomena possible in plasmonic systems?



J.-P. Martikainen, M.O.J. Heikkinen and PT, Condensation phenomena in plasmonics,
Phys. Rev. A 90, 053604 (2014)

Main conceptual question: the role of losses

Rate equations, steady state: BEC-like distribution at certain conditions

$$n(k) = \frac{1}{g(\omega)e^{\beta(\hbar\omega - \Delta)} - 1}$$

$$g(\omega(k)) = [MB(\omega)R_{abs} + \Gamma(\omega)]/(MR_{spon}B(\omega))$$

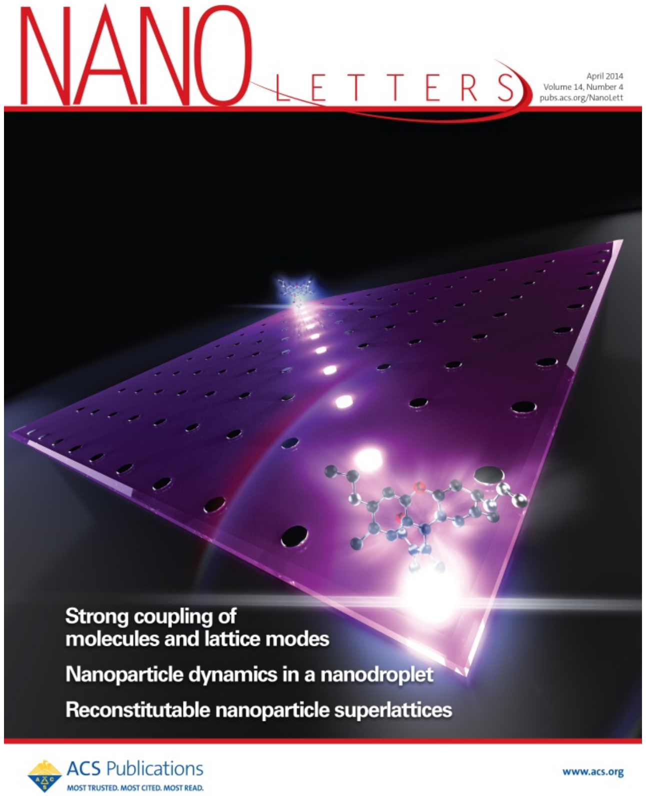
$$\mu(\omega) = \Delta - \frac{1}{\beta}\ln g(\omega)$$ Effective chemical potential

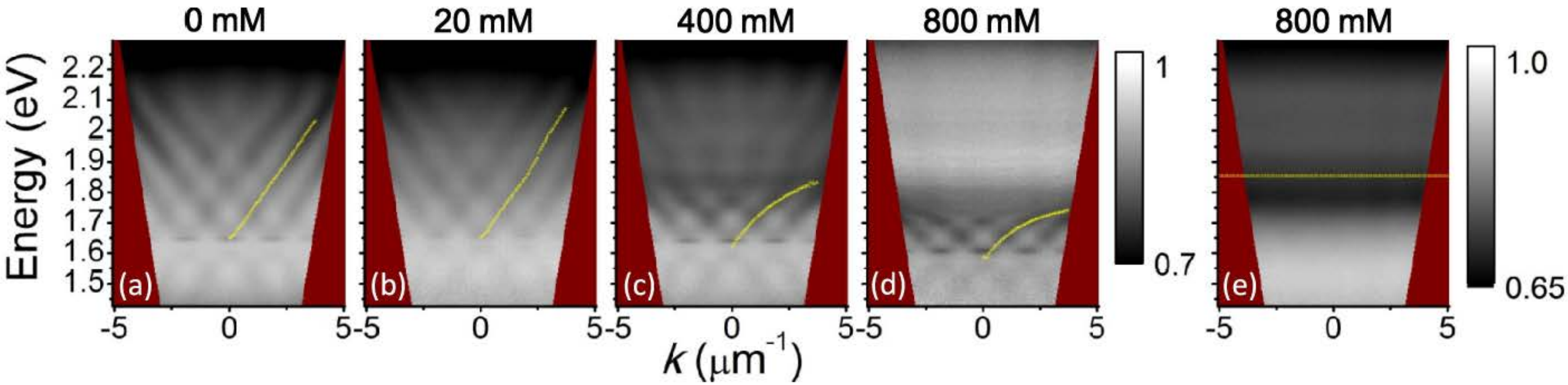
Condition for diverging population

$$\frac{N_e \Phi}{N_g} \geq \frac{1}{1 - \Gamma(\omega)\tau / (MFN_e B(\omega))}$$

Summary

- Goal: quantum plasmonic lattices
- Strong coupling of SLRs
  and molecules
- Coherence of light-matter hybrids
  throughout the weak to strong coupling
  crossover
- Lattice resonances for magnetic
  particles
- Towards BEC physics





VOL. 3

Quantum Gas Experiments

Exploring Many-Body States

This book thoroughly describes the most important experimental techniques in the growing field of ultracold gases, with emphasis on methods especially relevant for studies of many-body quantum physics. As a background for the rest of the book, brief reviews on the many-body physics of optical lattices, and of the BCS-BEC crossover in ultracold Fermi gases are provided. The book then gives in-depth and detailed descriptions of basic experimental techniques for manipulating fermionic atoms, and for the creation of complex optical lattice structures both for bosonic and fermionic gases. Various spectroscopies (RF, Bragg and lattice modulation) are thoroughly covered. The basic physics of emerging research topics such as dipolar gases and ion-atom gas systems is presented. The book covers advanced techniques especially important for probing many-body aspects of the systems, such as correlation measurements and the newly developed single-site imaging techniques. Most topics are covered both from the theoretical and experimental viewpoint, with interrelated chapters written by theorists and experimentalists.

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