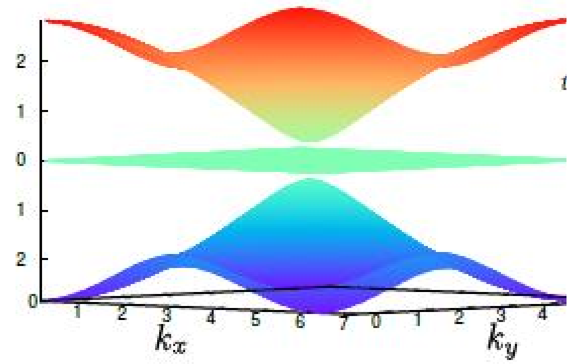
Many-body quantum physics with ultracold gases (theory)

Quantum Dynamics group
Prof. Päivi Törmä



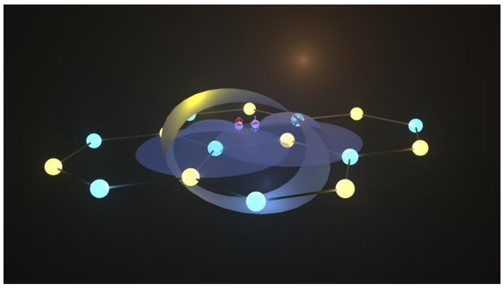
There is one theory project available.

The system and the questions

Ultracold quantum gases are exceptionally powerful systems for creating and studying interesting and novel quantum many-body systems. They are envisioned to be actually so called “quantum simulators” where quantum phenomena that are impossible to approach by conventional computers can be efficiently simulated. Researchers all around the world try to use these systems to solve outstanding questions, such as whether superconductivity can exist at high temperature, even at room temperature. Answering such questions would be a breakthrough in basic science and, technologically, could lead to, for instance, computers that use superconducting components and therefore radically reduce the energy consumption needed for information processing worldwide.

Our research has direct relevance to ultracold quantum gas systems, but it also contributes to understanding superconductivity and superfluidity in other systems, such as high-T_c superconducting materials and novel graphene-based materials which have been suggested as candidates for even room temperature superconductivity.

A recent highlight of our work is the discovery that superfluidity is possible even in a flat band (i.e. band where the group velocity is zero), if the band if topologically non-trivial, see the news http://sci.aalto.fi/en/current/news/2015-11-20/
and further publications on the topic from our web-pages
http://physics.aalto.fi/en/groups/qd/publications/
such as http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.117.045303

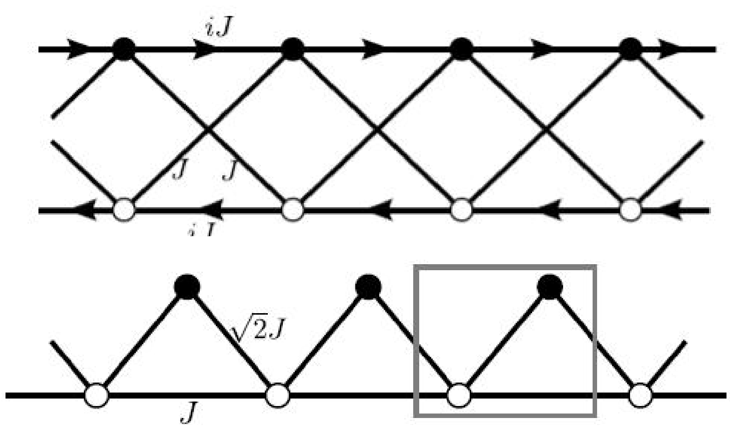


We discovered that flat band superfluidity is intimately connected to so called quantum metric, which measures distances between quantum states. Since in a flat band the group velocity is zero, intuitively one might think that there cannot be any supercurrent, i.e. superconductivity. However, we have theoretically shown that this is possible for lattices with certain quantum geometric properties.

Flat band superfluidity and its connection to the quantum metric, and thereby to quantum information science, is a very new topic and there are a large number of open questions. One of the key questions is how the flat band features appear in reduced dimensions, that is, in quasi-1D systems. Another one is to find out in which experimental system flat band superfluidity could be best observed. The summer trainee project is related to these outstanding questions.

The Project

The goal is to find, by detailed simulations, how particle transport through a quasi-1D ultracold optical lattice takes place and predict experimentally observable signatures of the flat band characteristics. The project involves understanding the quantum physics of flat bands, and how ultracold quantum gas setups work. The main part of the simulations will be done with the Kwant software that is tailored to describe quantum transport in arbitrary geometry. This part of the project suits for a special assignment or a B.Sc. thesis. The work belongs to a collaboration with experimentalists at ETH Zurich where P. Törmä was an invited guest professor in 2015 and the second supervisor of the project, Sebastiono Peotta, a visiting scientist in 2017 and 2018. For a M.Sc. thesis project, or a special assignment done after passing the Quantum Physics course (second quantization needed), the project can include also analytical calculations exploring whether the exotic Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) state could occur in special quasi-1D lattices which have flat bands. A student who wants even more challenge can try to find out how the quantum metric reflects in the FFLO state. Our group is one of the world leading ones in the research on the FFLO state, and we have recently published a related review article http://iopscience.iop.org/article/10.1088/1361-6633/aaa4ad



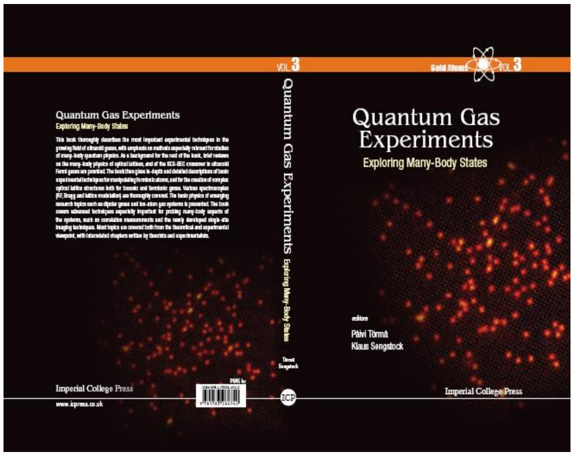
What will you learn from the project

You will learn the physics of frontline research in superfluidity and superconductivity, and about the field of ultracold quantum gases in general. You will learn how to do quantum simulations for a free software (Kwant). If you have passed (by the time the work starts) the course Quantum Physics lectured by P. Törmä, you will be able to use the second quantization and mean-field techniques that you learned there in a real-world research problem, and thereby deepen

$$\hat{\mathcal{H}} - \mu\hat{N} = \sum_{\mathrm{i}\alpha,\mathrm{j}\beta}\sum_{\sigma}\hat{c}^{\dagger}_{\mathrm{i}\alpha\sigma}K^{\sigma}_{\mathrm{i}\alpha,\mathrm{j}\beta}e^{\mathrm{i}\mathbf{q}\cdot(\mathbf{r}_{\mathrm{i}\alpha}-\mathbf{r}_{\mathrm{j}\beta})}\hat{c}_{\mathrm{j}\beta\sigma} - U\sum_{\mathrm{i},\alpha}\hat{c}^{\dagger}_{\mathrm{i}\alpha\uparrow}\hat{c}_{\mathrm{i}\alpha\uparrow}\hat{c}^{\dagger}_{\mathrm{i}\alpha\downarrow}\hat{c}_{\mathrm{i}\alpha\downarrow} - \mu\hat{N}.$$

your knowledge. Your scientific communication and collaboration skills are developed since you will work as a member of an active group.

Who supervises you and how



You will be supervised by P. Törmä and her group members.
The group leader P. Törmä is one of the leading theorists in the field of ultracold gases; more information about these systems can be obtained from a book that she has edited:
http://www.worldscientific.com/worldscibooks/10.1142/p945
An ebook version is available for anybody with an Aalto account via Aalto library http://lib.aalto.fi/en/ click "Alli" and enter Quantum Gas Experiments into the search, then click the World Scientific Ekirja, this directs you to the site of the publisher where you can download pdfs of any of the chapters (for instance the Introduction provides a brief summary).

The group publishes in the topmost scientific journals such as Science, Nature Communications, Physical Review Letters and Nano Letters. In the autumn 2013, P. Törmä obtained the prestigious ERC Advanced Grant (1.6 Meuros),
http://sci.aalto.fi/en/current/current_archive/news/2013-09-26/
and in 2017 the Academy Professorship
http://www.aalto.fi/en/current/news/2016-06-22-002/
reflecting that the group and the research topics are evaluated as being at the very top European level. By working in the group, you get a direct access to the frontline of research, and your work will get visibility.

The group member supervising this project, in addition to P. Törmä, is Dr. Sebastiano Peotta, who is a postdoc and recipient of the highly competitive Marie Curie grant of EU, obtained Ph.D. from Scuola Normale Superiore di Pisa and had a previous postdoc period at the University of California San Diego.

You will meet the group leader at least once per week, and the second supervisor (instructor) (Sebastiano) almost daily. We have a system of writing your special assignment/B.Sc thesis/M.Sc. piecewise during the summer, so that you will be able to complete it promptly after the summer.

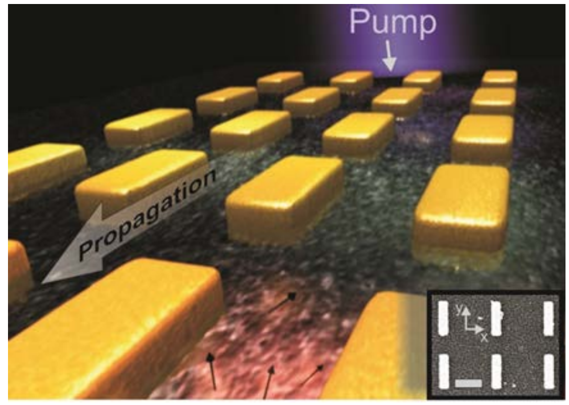
More information about the group and the research:
http://physics.aalto.fi/groups/comp/qd/
Our group in Helsingin Sanomat: http://www.hs.fi/tiede/art-2000002917734.html

You can also ask for more information from paivi.torma@aalto.fi

Interested in your future? See from
http://physics.aalto.fi/en/groups/qd/members/alumni/
where people who worked in our group have ended up, both in academia and industry.

Päivi Sebastiano

Quantum plasmonics and nano-optics (experiments)



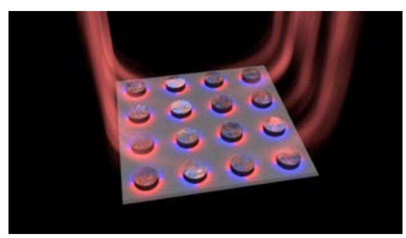
Quantum Dynamics group/Academy Prof. Päivi Törmä

There are two experimental projects available.

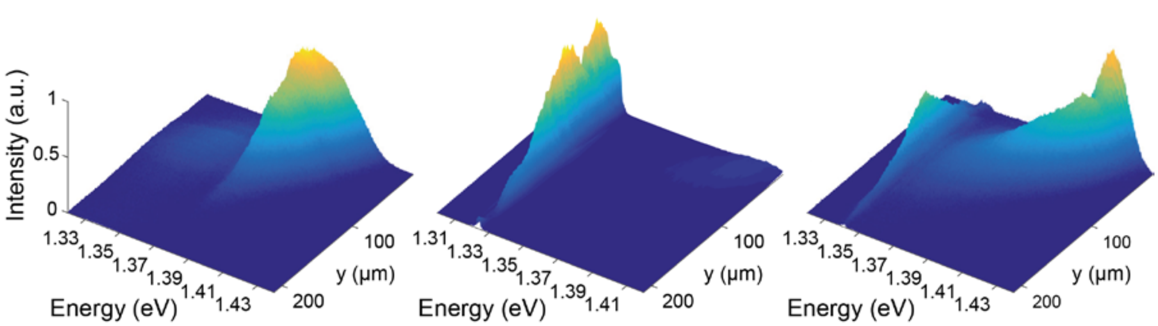
Nanoscale Bose-Einstein Condensates and lasers

Nanoplasmonics deals with surface plasmon polaritons (SPPs) which are light bound on the surface of a metal. The special feature is that such light can be confined to smaller scales than the wavelength of light (which is in micrometers): it can be called "nanolight". "Nanolight" has special properties such as extremely high field intensity. SPPs are already applied in biosensors, and the most important future applications are envisioned to be novel light sources, solar energy harvesting, and cancer therapy. Our group has been pioneering the use of plasmonics to create novel types of coherent light sources, such as nanoscale lasers and, very recently, ***Bose-Einstein condenstates (BEC).***

The review article by P. Törmä and W.L. Barnes on these systems contains a video abstract that discusses exciting prospects of these systems, and also shows how our lab looks like, see http://iopscience.iop.org/article/10.1088/0034-4885/78/1/013901



Recently, we achieved ***nanoscale lasing*** in nanoparticle arrays, see the Aalto News and an article in Helsingin Sanomat (both contain a video, in English in the former and Finnish in the latter):
http://comp.aalto.fi/en/current/news/2017-01-03/
http://www.hs.fi/tiede/art-2000005034015.html
We have a world record in the linewidth of such lasers, only 0.09 nanometers.



Spatial evolution of (from left) thermalization, lasing, and Bose-Einstein condensation.

Our very recent breakthrough is the observation of a first plasmonic Bose-Einstein condensate. Bose-Einstein condensation is a phenomenon predicted by Bose and Einstein more than hundred years ago, and observed in a few different systems ever since. Our

BEC produces coherent light somewhat similar to laser light, and is one of the fastest BECs known (dynamics in the sub-picosecond range). The BEC observation results can be found in https://arxiv.org/abs/1706.01528

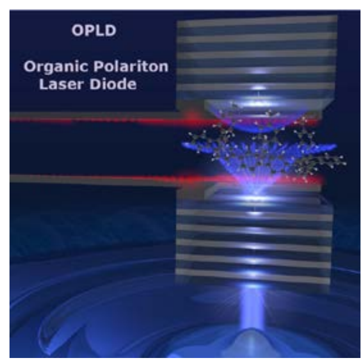
Such novel nanoscale lasers and BECs offer unprecedented access to fundamental understanding of how light and matter interact in the sub-wavelength and ultrafast scales. And they provide a way to realize nanoscale light sources with unique properties, such as small footprint, ultrafast operation and low energy consumption, essential for future quantum technologies.

Now, a crucial *question* is: can the pumping (i.e. input of energy) of these systems be realized with low-intensity light sources, such as lamps, even sunlight, or by electrical injection? So far, all condensates and lasers of this type have been pumped with massive, expensive lasers. ***Achieving pumping by a low-cost, compact energy source would be a major achievement both scientifically and concerning the potential applications.*** In these projects, first steps towards this goal will be taken.

The Project 1 (experiment)

The goal is to pump a lasing sample and a BEC sample utilizing a low-intensity light source. You will plan and construct the optical setup needed for this, fabricate the samples and analyze the measurement results. You will use the nanofabrication tools available at Micronova cleanroom and the measurements are carried out in the state-of-the-art ultrafast dynamics laboratory of the QD group. This work constitutes a Bachelor of Science thesis or a special assignment. If you wish to do a Master's thesis, integration of the light source on the sample can be included, as well as rate-equation modelling of the BEC and lasing dynamics if you wish to combine experimental and theoretical/computational work. This project is related to the ERC (European Research Council) Proof of Concept grant obtained by P. Törmä in 2017.

The Project 2 (experiment)

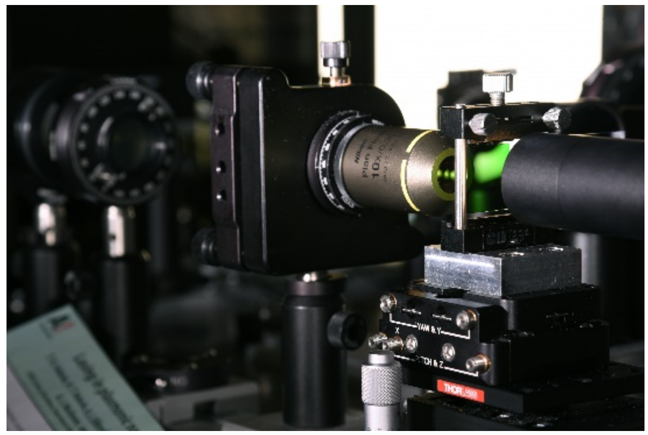


The goal is to realize electrical pumping of an organic microcavity condensate. First observation of such a condensate has been published in Nature Materials by Kostas Daskalakis, a Marie Curie postdoctoral fellow in our group https://www.nature.com/articles/nmat3874
The project involves sample fabrication by thin film growth techniques, measurements in the QD group ultrafast laboratory, and analysis of measurement results. The project is related to the OPLD Marie Curie postdoctoral grant of Kostas Daskalakis funded by the European Commission. The project can be adapted to produce a M.Sc. or B.Sc. thesis, or a special assignment.

What will you learn in the projects

In the fabrication work you will learn a set of state-of-the-art nanofabrication methods and how to work in a cleanroom environment. You will also learn how to plan an experiment and perform it with an advanced optical measurement setup, and how to innovate a solution to a challenging problem. Your scientific communication and collaboration skills will develop since you will work as a member of an active group.

Who supervises you and how



You will be supervised by P. Törmä and her group members. The group leader P. Törmä is one of the highly regarded scientists in the world in the fields of ultra-cold gases and nanoplasmonics. The group publishes in the topmost scientific journals such as Science, Nature Communications, Physical Review Letters and Nano Letters. In the autumn 2013, P. Törmä obtained the prestigious ERC Advanced Grant (1.6 Meuros),
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reflecting that the group and the research topics are evaluated as being at the very top level. By working in the group, you get a direct access to the frontline of research, and your work will get visibility.

The group members supervising these projects are Dr. Tommi Hakala, who is a staff scientist at Aalto and worked previously at the Harvard University, USA, Ph.D. student Aaro Väkeväinen, and Marie Curie postdoc Kostas Daskalakis who did his Ph.D. in Imperial College London.

You will meet the group leader at least once per week, and the second supervisor (Tommi, Aaro, Kostas) almost daily. We have a system of writing your special assignment/B.Sc thesis/M.Sc. piecewise during the summer, so that you will be able to complete it promptly after the summer.

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You can also ask for more information from paivi.torma@aalto.fi

Interested in your future? See from
http://physics.aalto.fi/en/groups/qd/members/alumni/
where people who worked in our group have ended up, both in academia and industry.