SCIENTIFIC REPORT

International Winter School and Workshop on
"Strongly correlated fluids of light and matter"
ECT*, Villazzano near Trento, January 12th-23th, 2015

ORGANIZERS

dr. Iacopo Carusotto, INO-CNR BEC Center, Trento, Italy (coordinator)
prof. Cristiano Ciuti, Universite Paris Diderot-Paris 7
prof. Rosario Fazio, SNS Pisa, Italy
prof. Atac Imamoglu, ETH Zurich, Switzerland

Number of participants: 98

Summary

The general goal of the School and Workshop on *"Strongly correlated fluids of light and matter"* was to consolidate the international community working on the young field of *Quantum Fluids of Light* and to reinforce interactions with more traditional fields of many-body physics. According to the POLATOM spirit, a special attention was paid to highlight analogies and differences between quantum gases of polaritons and of ultracold atoms.

The original plan was to have a first week with a more school-like character with top-class scientists lecturing from basic concepts up to the most recent developments, and a second week with a more workshop-like character with research seminars on a selection of hot topics. Because of the limited temporal availability of key lecturers and speakers, lectures and seminars turned out to be strongly intermixed. This unexpected feature was actually a success, as it allowed to organize the sessions according to the subject, so to give a more complete overview of the different aspects and highlight conceptual connections. Furthermore, while the lectures on the first week covered really elementary concepts, the ones on the second week were much more advanced, and brought the audience to the latest developments.

The main topics covered were:

- basics of the theory of dilute Bose gases of atoms and of photon/polaritons
- theory and experiments with polariton fluids in microcavity devices
- theory and experiments with fluids of light in cavityless propagating geometries
- strongly correlated photons in cavity arrays
- quantum hydrodynamics and artificial black holes
- non-equilibrium phase transitions
- topological effects in ultracold atoms, optics and photonics
- synthetic gauge fields for atoms and for photons
- topological protection towards topological quantum computing
- numerical simulation of quantum many-body systems, both conservative and dissipative
- entanglement in strongly correlated many-body systems
- cavity-QED and quantum devices using superconducting circuits
- non-equilibrium dynamics of atomic gases in optical cavities

Scientific content of the event and main discussion topics

Historically, most of the theoretical and experimental activities in the field of many-body physics addressed systems of material particles such as atoms, electrons, nucleons, or quarks. In the last decades, a growing community of researchers has started wondering whether in suitable circumstances light can behave as a fluid composed of a large number of corpuscular photons with sizeable photon-photon interactions. Even if this point of view is perfectly legitimate within the wave-particle duality in quantum mechanics, it is somehow at odds with our intuitive picture of light: The historical development of our understandings of matter and light have in fact followed very different paths.

The idea of matter being formed by a large number of elementary corpuscles that combine in different ways to form the variety of existing materials dates back to the ancient age with Demokritos' atomistic hypothesis, while the wavy nature of particles was put forward only in 1924 by de Broglie and experimentally demonstrated by Davisson and Germer in 1927. On the other hand, the long-standing debate between Newton's corpuscular and Huygens' undulatory theories of light appeared to be solved in the early 19th century with the observation of fringes in Young's double slit experiment and of the remarkable Arago's white spot in the shadow of a circular object. With the microscopic support of Maxwell's theory of electromagnetism, the undulatory theory was able to explain most experimental observations until the beginning of the 20th century when the corpuscular concept of a photon as a discrete quantum of light was revived by Einstein's theory of the photoelectric effect. Within the wave-particle duality, our standard interpretation of light then consists of a beam with a dual undulatory and corpuscular nature that is emitted by the source and then freely propagates through optical devices until it is absorbed.

While this intuitive picture of light is perfectly sufficient to describe most cases of interest, it is still missing a crucial element, namely, the possibility of frequent collisions between photons that might lead to collective fluid-like behaviours in the many-photon system. While photon-photon interactions have been predicted to occur even in vacuum via virtual excitation of electron-positron pairs, the cross section for such a process in vacuum is so small that can hardly be expected to play any role in realistic optical experiments. On the other hand, the nonlinear polarization of nonlinear optical media is able to mediate significant interactions between photons: Upon elimination of the matter degrees of freedom, third-order $\chi^{(3)}$ nonlinearities correspond in the language of Feynman diagrams to four-legged vertices describing, among others, binary collisions between a pair of photons. To create a stable luminous fluid, it is also crucial to give a finite effective mass to the photon. A simple strategy for this purpose involves a spatial confinement of the photon by metallic and/or dielectric planar mirrors. In a planar geometry with a pair of metallic mirrors separated by a distance l_z , the photon motion along the perpendicular z direction is quantized as $q_z = \pi M / l_z$, M being a positive integer. For each longitudinal mode, the frequency dispersion as a function of the in-plane wave vector k has the relativistic form $\omega^2(k) = c^2[q_z^2 + k^2]$ with a mass $mc^2 = h\ c\ q_z$.

In the last years, this initially speculative idea has led to impressive experimental developments, which -among other- have demonstrated superfluidity in a fluid of light, Bose-Einstein condensation of photons and polaritons (a kind of dressed photons), controlled generation and manipulation of shock waves, soliton physics, an all optical version of the Berezinski-Kosterlitz-Thouless superfluidity transition. While all these experiments were based on weakly nonlinear media where the dilute gas model based on a (generalized) Gross-Pitaevskii equation is accurate, the present theoretical experimental challenge is to achieve a strong nonlinearity regime where strongly correlated states of the photon fluid can be generated and studied. First evidences of such a regime have been obtained using single atoms in cavities, quantum dots in microcavities, atomic gases in the Rydberg-EIT regime and first reports of strong correlations reported.

As a result of these advances, the research on fluids of light is now beginning to require sophisticated many-body concepts and, in turn, to stimulate novel conceptual developments. As an example, a most remarkable novel aspect of fluids of light is that in many circumstances they far from equilibrium and their state originates from a dynamical balance between pumping and dissipation, rather than from a thermodynamical equilibrium condition: novel states of matter might thus be found with unexpected properties and both theorists and experimentalists must be prepared to deal with the new challenges.

At the same time, this research is reaching such a level of maturity that it starts offering interesting insights to other fields of many-body physics, especially ultracold atomic gases: most concepts and techniques are in fact shared by the two fields and some of the important present challenges of atomic physics might take advantage of the related success in optics. From the application side, one of the long-term goals of this research is to contribute to the development of integrated photonic platform where to use light perform quantum communication and information processing using light: introducing many-body concepts in this effort is expected to open dramatically new possibilities to improve the flexibility and the robustness of the devices.

The School and Workshop on *“Strongly correlated fluids of light and matter”* has successfully covered all the main axes of research in the broad field of Quantum Fluids of Light, trying to emphasize the interdisciplinary relations with neighbouring fields such as, e.g., non-equilibrium statistical mechanics, strongly correlated electron gases, topological quantum mechanics and, most importantly, ultracold atomic gases.

Participants have been exposed to lecture series and to seminars by world experts in the physics of ultracold atomic gases and of photon/polaritons: this intermixing of the two subjects has been fundamental to emphasize the strict connections between the two fields. In addition to that, a specific effort was made to establish interdisciplinary connections to other exciting areas of quantum condensed matter, so to further widen the scope of our POLATOM community.

The lecture series have covered:

- Basics of the theory of dilute quantum gases (Franco Dalfovo, Trento University, Italy)
- Polariton BECs and superfluids (Alberto Amo, LPN-CNRS, Marcoussis, France)
- Numerical methods for strongly correlated systems (Corinna Kollath, Bonn, Germany)
- Superconducting quantum circuits (Michel Devoret, Yale, USA)
- Topologically protected states and topological quantum computing (Ady Stern, Weizmann, Israel)
- Entanglement and simulation of strongly correlated systems (Frank Verstraete, Vienna)

The research seminars have covered a much wider range of topics (see the full program enclosed below), including Rydberg atoms, strongly correlated photon gases, optical and condensed matter analogs of gravity, non-equilibrium statistical mechanics, non-equilibrium phase transitions, nonlinear optics, strongly correlated electrons, semiconductor nanostructures, quantum simulation, synthetic gauge fields for atoms and for photons, quantum magnetism, etc.

In addition to lectures and seminars, younger participants were invited to bring a poster. These were informally shown on the walls of the conference room during the whole event, so that people could see and discuss them at will. This was an effective choice to reinforce interactions between participants.

Even if there was no special social program organized, all participants had their meals all together either at the ECT* canteen (at lunch) or in some restaurant in downtown Trento (for dinner). This is the tradition of ECT* and is -in our opinion- very successful in facilitating informal exchanges between participants in a pleasant atmosphere.

Highlights

In addition to the lectures and the research seminars, participants were invited to collectively think about the most important open problems and the most exciting future developments. This has led to the identification of a series of open problems on which -we expect- the research will focus during the next few years. Some of them are well-defined questions which only need technical work. Other call for the development of completely new concepts and may lead to unexpected changes of perspective. Some of these problems are theoretical, some other purely experimental, some other even call for a joint experimental-theoretical effort.

Here a list of some most significant questions that arose during the event. Most of them were "democratically" selected by asking participants to mark and grade their favourite open question on a dedicated sheet left by the organizers at the conference lobby.

- Is it possible to observe new kinds of (quantum) phase transitions that are made possible by the non-equilibrium driven-dissipative nature of the fluid of light in a microcavity geometry?
- What is the most efficient scheme to pump photons into the device so to faithfully generate a desired strongly correlated state of many-photons? Are these techniques able to overcome the limitations in cooling ultracold atomic gases to strongly correlated states?
- Renormalization-group calculations have anticipated that already the standard non-equilibrium BEC phase transition shows unexpected features, especially in the critical region and in 2D. Is it experimentally possible to measure them?
- What is the best experimental platform (polaritons, circuit-QED, Rydberg atoms,...) to create a spatially extended system displaying strong photon-photon interactions?
- What is the most promising system (ultracold atomic gases, microcavity devices, cavityless propagating geometries, ...) to observe analog Hawking radiation from artificial black-hole configurations in trans-sonically flowing fluids?
- What is the most efficient numerical technique to simulate the steady-state and the dynamics of strongly interacting photons in driven-dissipative configurations? In what aspects does the simulation of driven-dissipative photon/polariton systems differ from the simulation of the dynamics of conservative atomic systems?
- Is it possible to identify photonic configurations that support topologically protected quantum states? What are the advantages/disadvantages for quantum applications of working in the optical vs. microwave domain?

Impact of the event on the future directions of the field

The main success of the School and Workshop has been the contribution to the establishment of a world-wide community working on different aspects of the physics of Quantum Fluids of Light and to the reinforcement of its connection to neighbouring fields, in particular ultracold atomic gases.

Apart from a few exceptions such as the POLATOM network, so far most of the advances in this research had in fact involved several distinct groups of researchers independently working on specific aspects of this physics, while a general view was still lacking. The goal of this event was to put these sub-communities in contact and to favour and/or reinforce their mutual interactions. With respect to the core of the POLATOM network, a strong effort was made to reach a much wider community of researchers potentially interested in our subject and, more importantly, in our approach.

Just to make a few examples, in addition to the core of the POLATOM network working on ultracold atoms and polaritons, an active effort has been done to involve in our event researchers from computational quantum physics, microwave circuit-QED, classical nonlinear optics, non-equilibrium statistical mechanics, and even topological quantum computation.

As organizers, we feel that our objectives have been fully met: active and enthusiastic participation to the event has come from researchers of very different backgrounds, who have been able to communicate and interact for the duration of the event. Themes common to different fields have been illustrated from very different points of view, and unexpected connections have been drawn.

Once these connections are established and a common language is adopted, we expect that the research in all these fields will experience a sudden boost thanks to the rapid exchange of know-how between different previously separated communities. A lot of literature that was originally specific will be read again with a different eye, which is most likely to lead to completely unexpected new developments.

The active interest of researchers in this novel perspective is also witnessed by the low number of invitations that got declined and by the unexpectedly large number of spontaneous applications we received. Unfortunately, in spite of our optimization efforts, the limited space at the ECT* facilities forced us to reject several late applications.

Most remarkably, participation was not limited to European countries, but a good number of people has come from oversea. Most invited speakers accepted to pay the travel expenses on their own grants and, even more remarkably, several groups both from the US and from the Far East accepted to invest quite substantial financial resources to make their students to attend our event.

At the end of the event, several participants have proposed themselves as organizers of schools and workshops with a similar broad perspective in the next few years. This testifies the interest of the community in establishing a long-lasting series of events on these topics, which will hopefully let the relatively small POLATOM community working on photon/polaritons and ultracold atoms grow into a much larger interdisciplinary community covering all different aspects of many-body physics.

Scientific Program

(posters were shown in the conference room during the whole even)

Monday January 12th

9h00-9h30 get together + introduction by the organizers

chair i. Carusotto

9h30-11h00 Dalfovo 1 - *Basics of the theory of dilute quantum gases*
11h00-11h30 coffee
11h30-12h30 Rechtsman - *Topological effects in propagating optics*

chair C. Ciuti

14h30-16h00 Amo 1 - *Polariton BECs and superfluids*
16h00-16h30 coffee
16h30-17h15 Ramiro-Manzano - *Silicon photonics*

Tuesday January 13th

chair B. Deveaud

9h30-11h00 Dalfovo 2 - *Basics of the theory of dilute quantum gases*
11h00-11h30 coffee
11h30-13h00 Amo 2 - *Polariton BECs and superfluids*

chair D. Faccio

14h30-15h15 Deveaud - *Feshbach resonances in polariton scattering*
15h15-15h45 coffee
15h45-16h30 Wouters - *Theory of polariton fluids*
16h30-17h30 Nguyen & Gerace - *Black holes in flowing polariton fluids in microcavities*
17h30-17h50 Koghee - *Dynamical Casimir Effect in Exciton-Polariton Condensates*

Wednesday January 14th

chair M. Wouters

9h30-10h15 Faccio - *Towards analog gravity in nonlinear optics*
10h15-10h35 Larre - *Quantum fluctuations in propagating nonlinear optics*
10h35-11h00 coffee
11h00-11h45 Conti - *Quantum gravity simulation and irreversibility in nonlinear optics*
11h45-12h15 Piazza - *Ultracold Fermions inside an optical cavity*
12h15-13h00 Imamoglu - *Quantum optics with two-dimensional materials*

chair A. Amo

14h45-15h30 Ciuti - *Recent results on the theory of strongly correlated photonics systems*
15h30-16h15 Angelakis - *Simulating out of equilibrium exotic phases with strongly interacting photons*
16h15-16h45 coffee
16h45-17h30 Richard - *Experiments with exciton-polariton fluids*
17h30-18h00 Dominici - *2D+T trajectories and branching of phase singularities in a polariton fluid*

Thursday January 15th

chair D. Angelakis

9h30-10h30 Verstraete 1- *Entanglement and simulation of strongly correlated systems*
10h30-11h00 coffee
11h00-12h00 Verstraete 2 - *Entanglement and simulation of strongly correlated systems*
12h00-12h45 Fazio - *Introductory remarks to dissipative quantum phase transitions*

chair M. Richard

14h30-15h15 Diehl - *Non-equilibrium phase transitions in optics*
15h15-15h35 Dagvadorj - *Non-Equilibrium BKT transion in OPO*
15h35-16h05 coffee
16h05-16h50 Keeling - *Polariton and photon condensates in organic materials (TBC)*
16h50-17h10 Chiocchetta - *A quantum-Langevin model for non-equilibrium condensation*
17h10-17h55 Rossini - *Many-body simulations of open systems*

Friday January 16th

chair D. Gerace

9h30-10h30 Verstraete 3 - *Entanglement and simulation of strongly correlated systems*
10h30-11h00 coffee
11h00-12h00 Verstraete 4 - *Entanglement and simulation of strongly correlated systems*
12h00-12h30 Bellec - *Microwave experiments on edge states in topological and Dirac materials*

chair M. Hafezi

14h30-15h00 Bardyn - *Topological polaritons*
15h00-15h45 Simon - *Topological Photonics: Braided Microwave Circuits and Twisted Resonators*
15h45-16h15 coffee
16h15-17h00 Molina-Terriza - *Angular momentum of light*
17h00-17h20 Price - *Quantum mechanics under a momentum space artificial magnetic field*
17h20-17h40 Ozawa - *Topological effects in microcavity photonics*

Monday January 19th

chair D. Rossini

9h00-9h30 get together + introduction by the organizers
9h30-10h30 Stern 1 - *Topologically protected states and topological quantum computation*
10h30-11h00 coffee
11h00-12h00 Stern 2 - *Topologically protected states and topological quantum computation*
12h00-12h45 Bar Ad - *Black holes in propagating fluids of light*

chair C.-E. Bardyn

14h00-16h00 Devoret 1,2 - *Superconducting quantum circuits*
16h00-16h30 coffee
16h30-17h15 Bramati - *Manipulating polariton fluids with structured light*
17h15-18h00 Le Hur - *Artificial Gauge Fields and Topological Phases*

Tuesday January 20th

chair T. Ozawa
9h30-10h30 Stern 3 - *Topologically protected states and topological quantum computation*
10h30-11h00 coffee
11h00-12h00 Stern 4 - *Topologically protected states and topological quantum computation*
12h00-12h45 Tureci - *Non-equilibrium physics in lasers and polariton BECs*

chair A. Bramati
14h30-15h15 Savona - *Quantum correlations in a state-of-the-art silicon photonic crystal platform*
15h15-16h00 Hafezi - *Topological effects in silicon photonics*
16h00-16h30 coffee
16h30-17h15 Volz - *Integrated fiber-cavity devices*
17h15-18h00 Hartmann - *Strongly interacting photons*

Wednesday January 21st

chair R. Fazio
9h30-10h30 Kollath 1- *Numerical methods for strongly correlated systems*
10h30-11h00 coffee
11h00-12h00 Kollath 2 - *Numerical methods for strongly correlated systems*

chair R. Fazio
14h30-15h30 Devoret 3 - *Superconducting quantum circuits*
15h30-16h00 coffee
16h00-17h00 Devoret 4 - *Superconducting quantum circuits*
17h00-17h45 Weitz - *Bose-Einstein condensation of photons and periodic potentials for light*

Thursday January 22nd

chair C. Ciuti
9h30-10h30 Kollath 3 - *Numerical methods for strongly correlated systems*
10h30-11h00 coffee
11h00-12h00 Kollath 4 - *Numerical methods for strongly correlated systems*
12h00-12h45 Schmidt - *Towards quantum simulation with circuit QED lattices*

chair C. Ciuti
14h30-15h15 Solano - *Analog-digital quantum simulators of interacting fermions and bosons*
15h15-16h00 Mazza - *Fractional States, Helical Liquids and Topological Phases in Multicomponent 1D Fermionic Gases*
16h00-16h30 coffee
16h30-17h15 Bloch - *Cavity polaritons in 1D lattices*

Friday January 23rd

9h30-10h30 wrap-up round table
10h30-11h00 coffee
11h00-13h00 final discussion and closing

List of Speakers

(underlined the teachers of the lecture series)

Amo	Alberto	LPN-CNRS, France
Angelakis	Dimitris	Technical University of Crete, Greece and CQT Singapore
Bar-Ad	Shimshon	Tel Aviv University, Israel
Bardyn	Charles-Edouard	Caltech, USA
Bellec	Matthieu	University Nice Sophia Antipolis & CNRS, France
Bloch	Jacqueline	LPN-CNRS, France
Bramati	Alberto	LKB-UPMC, France
Chiocchetta	Alessio	SISSA, Italy
Ciuti	Cristiano	UNIVERSITE PARIS DIDEROT, France
Conti	Claudio	University College London, UK
Dagvadorj	Galbadrakh	Department of Physics, University of Warwick, UK
Dalfovo	Franco	Universita di Trento, Italy
Deveaud	Benoit	Ecole Polytechnique Federale de Lausanne, Switzerland
Devoret	Michel	Yale University, USA
Diehl	Sebastian	TU Dresden, Germany
Dominici	Lorenzo	NNL, Istituto Nanoscienze-CNR, Italy
Faccio	Daniele	Heriot-Watt University, UK
Fazio	Rosario	Scuola Normale Superiore, Italy
Gerace	Dario	University of Pavia, Italy
Hafezi	Mohammad	University of Maryland, USA
Hartmann	Michael	Heriot-Watt University, UK
Imamoglu	Atac	ETH Zurich, Switzerland
Keeling	Jonathan	University of St Andrews, UK
Koghee	Selma	Universiteit Antwerpen, Belgium
Kollath	Corinna	University of Bonn, Germany
Larre	Pierre-Elie	INO-CNR BEC Center, Trento, Italy
Le Hur	Karin	Ecole Polytechnique, CNRS France
Mazza	Leonardo	Scuola Normale Superiore, Pisa, Italy
Molina-Terriza	Gabriel	Macquarie University, Australia
Nguyen	Hai Son	Ecole Centrale de Lyon, France
Ozawa	Tomoki	INO-CNR BEC Center, Italy
Piazza	Francesco	ITP Innsbruck, Austria
Price	Hannah	INO-CNR BEC Center, Trento, Italy
Ramiro-Manzano	Fernando	Universita di Trento, Italy
Rechtsman	Mikael	Technion, Israel
Richard	Maxime	Institut Neel – CNRS, France
Rossini	Davide	Scuola Normale Superiore, Italy

Savona	Vincenzo	EPFL, Switzerland
Schmidt	Sebastian	ETH Zurich, Switzerland
Simon	Jonathan	University of Chicago, USA
Solano	Enrique	University of the Basque Country, Spain
Stern	Adiel	Weizmann Institute, Israel
Tureci	Hakan	Princeton University, USA
Verstraete	Frank	University of Vienna, Austria
Volz	Thomas	Macquarie University, Australia
Weitz	Martin	University of Bonn, Germany
Wouters	Michiel	Universiteit Antwerpen, Belgium

List of Participants

Aiello	Gianluca	Universita' di Trento, Italy
Alvarez-Rodriguez	Unai	University of the Basque Country UPV/EHU
Andreakou	Peristera	LPN-CNRS, France
Baboux	Florent	LPN-CNRS, France
Bartolo	Nicola	Universite Paris 7, France
Benzoni	Claudio	Universita' di Trento, Italy
Bernard	Martino	Universita' di Trento, Italy
Biella	Alberto	Scuola normale superiore di Pisa, Italy
Biondi	Matteo	ETH Zuerich, Switzerland
Carusotto	Iacopo	INO-CNR BEC Center, Italy
Casteels	Wim	Universite Paris 7, France
Crippa	Lorenzo	Universita' di Trento, Italy
De Rosi	Giulia	Universita' di Trento, Italy
Degenfeld-Schonburg	Peter	TUM, Germany
del Valle-Inclan Redondo	Yago	University of Cambridge, UK
Fellows	Jonathan	University of Warwick, UK
Glorieux	Quentin	LKB-ENS, France
Karzig	Torsten	California Institute of Technology, USA
Kim	Hwan Mun	University of Maryland, USA
Kirton	Peter	University of St Andrews, UK
Larcher	Fabrizio	Universita' di Trento, Italy
Las Heras	Urtzi	University of the Basque Country, Spain
Lebreuilly	Jose	Universita di Trento, Italy
Lolli	Jared	Universite Paris Diderot – Paris7, France
Marsault	Felix	LPN-CNRS, France
Matuszewski	Michal	Institute of Physics, Polish Academy of Sciences, Poland
Menotti	Chiara	INO-CNR BEC Center
Milicevic	Marijana	LPN-CNRS, France

Minkov	Momchil	EPFL, Switzerland
Mordini	Carmelo	Scuola Normale Superiore, Italy
Noh	Changsuk	Center for Quantum Technologies, Singapore
Pieczarka	Maciej	Wroclaw University of Technology, Poland
Privitera	Lorenzo	SISSA, Italy
Pyrkov	Alexey	Institute of problems of chemical physics RAS, Russia
Rodriguez	Said Rahimzadeh-Kalaleh	LPN-CNRS, France
Rota	Riccardo	Universite Paris 7, France
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Sangouard	Nicolas	Laboratoire Kastler Brossel, France
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Sieberer	Lukas	University of Innsbruck, Austria
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Trenti	Alessandro	Universita' di Trento, Italy
Tylutki	Marek	INO-CNR BEC Center, Italy
Umucalilar	Onur	Koc University, Turkey
Van Regemortel	Mathias	Universiteit Antwerpen, Belgium
Vocke	David	Heriot Watt University, UK
Zamora Soto	Alejandro	University College London, UK
Zwerger	Wilhelm	TU Munich, Germany