SFT-2024
Lectures on Statistical Field Theories
Galileo Galilei Institute
Florence, 5-16 February 2024

Program of lectures

Dmitry Abanin (Princeton University)
Non-equilibrium quantum matter through the prism of quantum entanglement (2+8h)

The remarkable experimental advances led to the creation of quantum simulation platforms, including systems of ultracold atoms, and of quantum processors, in particular based on superconducting qubits. These systems proved to be uniquely suited for probing nonequilibrium behavior of interacting quantum systems. From statistical mechanics, we expect that a non-equilibrium system will thermalize, settling to a state of thermodynamic equilibrium. Remarkably, there are classes of systems which do not follow this expectation, and breakdown of thermalization opens the door to fundamentally new out-of-equilibrium quantum phenomena.

In this course, we will start by discussing the eigenstate thermalization hypothesis (ETH) — the mechanism of thermalization in isolated quantum many-body systems. Furthermore, we will discuss examples of systems which avoid thermalization, thanks to disorderinduced many-body localization (MBL). While thermalization leads to scrambling of quantum information, its absence due to MBL protects local quantum coherence. This enables non-equilibrium states of matter not envisioned within the framework of statistical mechanics. We will introduce the recent theoretical insights into the remarkable physical properties of such states, based on the underlying patterns of quantum entanglement.

Next, we will discuss qualitatively different kinds of non-thermalizing dynamics, including quantum many-body scars, as well as prethermalization — a general route to drastically slowing down thermalization. Finally, we will discuss the state of the art in probing these and other non-equilibrium quantum phenomena with quantum simulators and quantum processors.

<u>Recommended reading:</u>

- D. A. Abanin, E. Altman, I. Bloch, M. Serbyn, *Many-body localization, thermalization, and entanglement,* Rev. Mod. Phys. 91, 021001 (2019), arXiv:1804.11065v2
- R. Nandkishore, D. Huse, *Many-body localization and thermalization in quantum statistical mechanics,* Annual Reviews in Condensed Matter Physics 6, 15 (2015), arXiv:1404.0686.
- A. Daley et al., *Practical quantum advantage in quantum simulation,* Nature 607, 667 (2022).

Andrea Cappelli (INFN, Florence)
Quantum field theory anomalies in condensed matter physics (10h)

The course will closely follow the review I wrote on this topic, see arXiv:2204.02158 (SciPost Phys. Lect. Notes 62 (2022)). I will present the initial part on anomalies in 1+1 dimension and their application to the Fractional Quantum Hall Effect, including topics like the Chern-Simons topological theory and the bosonization of fermions. If time permits, I will briefly discuss:

- the anomalies of 3+1 dimensional fermions and the application to Weyl semimetals;

- the classification of topological states of matter and the interplay with anomalies.

Prerequisites:
Basic knowledge of many-body quantum theory, quantum field theory and the Dirac theory of relativistic fermions. Basic accounts can be found in the beginning of the books:

- E. C. Marino, *Quantum Field Theory Approach to Condensed Matter Physics*, Cambridge University Press (2017);
- E. Fradkin, *Quantum Field Theory: An Integrated Approach*, Princeton University Press (2021); (see YouTube presentation if you wish);

The domain is `quantum field theory' and `condensed matter': if you google these keywords you will find plenty of books, overviews and Wikipedia accounts. Solid books on many aspects of this field are:

- A. M. Tsvelik, *Quantum Field Theory in Condensed Matter Physics*, 2nd ed. Cambridge University Press (2010);
- E. Fradkin, *Field Theories of Condensed Matter Physics*, Cambridge University Press (2013);
- G. Mussardo, *Statistical Field Theory: An Introduction to Exactly Solved Models in Statistical Physics*, 2nd ed. Oxford Univ. Press (2020).

Cristiane de Morais-Smith (Utrecht University)
Dissipation in quantum systems (6h)

In this course, we will treat dissipative quantum systems. Usual quantum mechanics is based on canonical quantization, which requires energy conservation. The so-called Caldeira-Leggett model was proposed in the 80's to describe quantum open systems.
This model couples the system of interest to a reservoir and leads to an effective description after integrating out the bath degrees of freedom. It is based on a path-integral approach, since it involves N+1 degrees of freedom. We will start by discussing Josephson junctions and SQUIDs, which are the paradigmatic examples that led to the Caldeira-Leggett formulation. Then, we will introduce the Caldeira-Leggett model and show that it reproduces a Langevin equation, characteristic of Brownian motion, in the semiclassical limit. Finally, we will perform the full path integral calculation to derive the dynamical reduced density operator, and the one in equilibrium. The last lecture will be about applications of the Caldeira-Legget model, including the more general case involving fractional derivatives, which leads to the concept of a time-glass.

Bibliography:

- A. O. Caldeira, *An Introduction to Macroscopic Quantum Phenomena and Quantum Dissipation*, Cambridge University Press (2014);
- R. C. Verstraten, R. F. Ozela, and C. Morais Smith, *Time glass: a fractional calculus approach*, Phys. Rev. B 103, L180301 (2021);

Gregory Schehr (LPTHE, Sorbonne Université, Paris)
Random matrices and statistical physics (6h)

The course will focus on the following three main topics:
i) Introduction to random matrix theory (RMT): I will present the different classical ensembles of RMT together with their main macroscopic properties, with a special emphasis on the Coulomb gas formulation, à la Dyson.
ii) Universal local statistics in RMT: I will discuss both the bulk and the (soft) edge scaling limits and show how the latter (in particular the Tracy-Widom distribution) is related to the large time be-

havior of one-dimensional fluctuating interfaces in the Kardar-Parisi-Zhang (KPZ) universality class.
iii) RMT and one-dimensional trapped fermions: I will discuss the deep and wide connections between the classical ensembles of RMT and the ground state properties of fermions in a one-dimensional external trap, both with and without interactions. Finally, I will discuss the precise relation between fermions at finite temperature and the KPZ equation at finite time.

Peter Zoller (ITP and IQOQI, Innsbruck)
Quantum Simulation with Quantum Optical Systems (6h)

Quantum optical systems of atoms and ions provide one of the most promising ways to implement quantum information processing, and quantum simulation in particular. In this course we provide an introduction to the foundations and techniques of theoretical quantum optics. The course starts with lectures on Hamiltonian and quantum gate engineering, illustrated in context of laser-controlled trapped ion systems. This is followed by lectures on open quantum systems from a quantum optics perspective. In the second half of the course this quantum optical toolset is applied and illustrated in context of quantum simulation of quantum many-body systems with atoms and ions. Topics of interest include: the randomized measurement toolbox to explore large scale entanglement in quantum simulation, open many-body systems and reservoir engineering, and quantum metrology.

Reading material:

- Cristian Gardiner, and Peter Zoller, *The Quantum World of Ultra-Cold Atoms and Light Book II: The Physics of Quantum-Optical Devices,* World Scientific (2015);
- C. Monroe, W. C. Campbell, L.-M. Duan, Z.-X. Gong, A. V. Gorshkov, P. Hess, R. Islam, K. Kim, N. Linke, G. Pagano, P. Richerme, C. Senko, N. Y. Yao, *Programmable Quantum Simulations of Spin Systems with Trapped Ions,* Rev. Mod. Phys. 93, 25001 (2021);
- AJ Daley, I Bloch, C Kokail, S Flannigan, N Pearson, M Troyer, P Zoller, *Practical quantum advantage in quantum simulation,* Nature 607 (7920), 667 (2022);
- Andreas Elben, Steven T Flammia, Hsin-Yuan Huang, Richard Kueng, John Preskill, Benoît Vermersch, Peter Zoller, *The randomized measurement toolbox,* Nature Reviews Physics 5 (1), 9-24 (2023);
- M. Dalmonte, V. Eisler, M. Falconi, B. Vermersch, *Entanglement Hamiltonians: from field theory, to lattice models and experiments,* Vol 534, 11, 2200064 (2022) ;
- Christian Kokail, Rick van Bijnen, Andreas Elben, Benoît Vermersch, and Peter Zoller, *Entanglement Hamiltonian tomography in quantum simulation,* Nature Physics volume 17, 936 (2021);
- Manoj K. Joshi, Christian Kokail, Rick van Bijnen, Florian Kranzl, Torsten V. Zache, Rainer Blatt, Christian F. Roos, Peter Zoller, *Exploring Large-Scale Entanglement in Quantum Simulation,* arXiv:2306.00057 ;
- Christian D Marciniak, Thomas Feldker, Ivan Pogorelov, Raphael Kaubruegger, Denis V Vasilyev, Rick van Bijnen, Philipp Schindler, Peter Zoller, Rainer Blatt, Thomas Monz, *Optimal metrology with programmable quantum sensors,* Nature 603 (7902), 604 (2022).