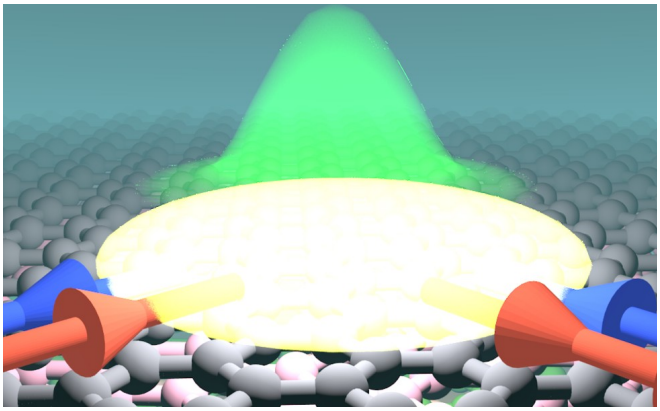
About the Correlated Quantum Materials (CQM) group



The Correlated Quantum Materials group, led by Prof. Jose Lado, focuses on ttheoretical design and engineering of new quantum materials with exotic properties that are hard to find in natural compounds. Specifically, we are working on designing quantum materials featuring exotic quantum phenomena, including unconventional superconductivity, symmetry-broken states, topological states, unconventional magnetic order, and fractional emergent quantum excitations. For this purpose, we combine theoretical methodologies from condensed matter physics, quantum many-body physics, quantum chemistry, machine learning, and materials science. More information can be found here.

The group has three research lines:

[1] Theory of van der Waals quantum materials: Van der Waals heterostructures provide an outstanding platform to engineer elusive quantum phenomena, by exploiting materials engineering, twist engineering and proximity effects. We are interested in developing new theoretical routes to exploit the flexibility of these materials to create exotic physics not accessible in conventional compounds. We are currently focusing on correlated emergent states in twisted van der Waals heterostructures, unconventional van der Waals superconductors, artificial heavy fermion systems, and artificial van der Waals multiferroic phases.

[2] Emergence in quantum many-body physics: Interactions in strongly correlated materials are capable of creating exotic behaviors not existent in conventional compounds, including unconventional superconducting states, strongly correlated topological states, and fractionalized particles. We are focusing on exploring new forms of quantum matter that can emerge in systems featuring quasiperiodicity, strong many-body interactions, and coupling to an environment. We develop quantum many-body models that allows us to solve interacting quantum models and simulate noisy quantum computers.

[3] Machine learning quantum materials: A variety of problems in quantum materials remain greatly challenging with conventional methods. We are focusing on how to use generative machine learning to design quantum materials, how to solve interacting two-dimensional quantum many-body problems with neural network solvers, and how to infer Hamiltonians from experimentally available measurements with machine learning. We are developing generative machine learning algorithms to explore complex behavior in quantum materials, allowing the incorporation of interactions, disorder, and hidden variables. Hamiltonian learning is an inverse problem of critical importance for quantum materials that cannot be solved using conventional methods in condensed matter physics. Ultimately, we aim to combine generative models and Hamiltonian learning, bringing together experimental data and theoretical models.

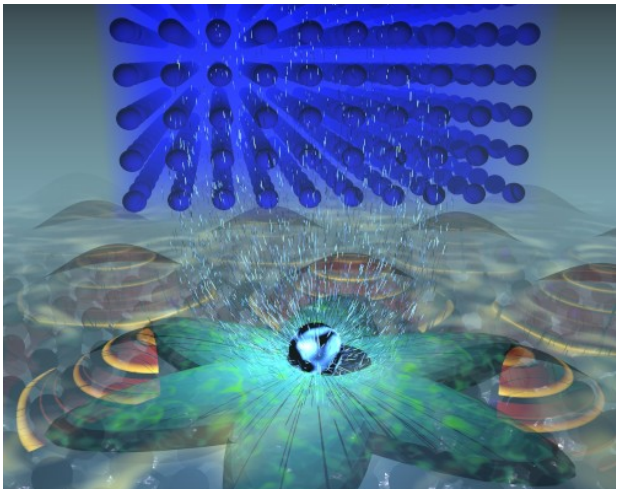
The group offers two summer trainee projects, whose relation with the research lines is shown in **[]**:

- *Project #1:* ***Hamiltonian learning van der Waals moire quantum matter*** **[1,3]**
- *Project #2:* ***Machine learning fractional quantum magnets*** **[2,3]**

A detailed description of each project can be found below.

Summer trainee project 2024, Department of Applied Physics:

Hamiltonian learning van der Waals moire quantum matter



Summary

This is a project in theoretical quantum materials, in particular in the field of machine learning for van der Waals quantum materials. This project can be suitable as a bachelor's thesis, a special assignment, or a master's thesis, and its difficulty can be adjusted to your level. The project will be carried out in the Correlated Quantum Materials group led by Prof. Jose Lado,.

Background

Twisted van der Waals materials represent one of the cornerstones of modern quantum materials, leading to the realization of a variety of exotic correlated states. Twisted van der Waals materials allow the realization of very different states in the very same compound, thanks to the possibility of controlling the electronic structure with proximity, gates, and twist engineering. This flexibility, however, comes at a price, which is that a specific material can show very different phenomena when undesired perturbations are present in the system. Assessing in which correlated phase a twisted material represents an open problem, and so far, it has been tackled on a case-by-case basis, and in many instances, it is not possible to uniquely identify its state. Machine learning provides a powerful framework for tackling complex, non-trivial problems in the presence of incomplete, noisy, or even faulty information. Specifically, the task of learning the underlying Hamiltonian and ground state of a twisted van der Waals material represents a paradigmatic complex problem where machine learning can overcome the limitations of conventional theoretical methods.

Task

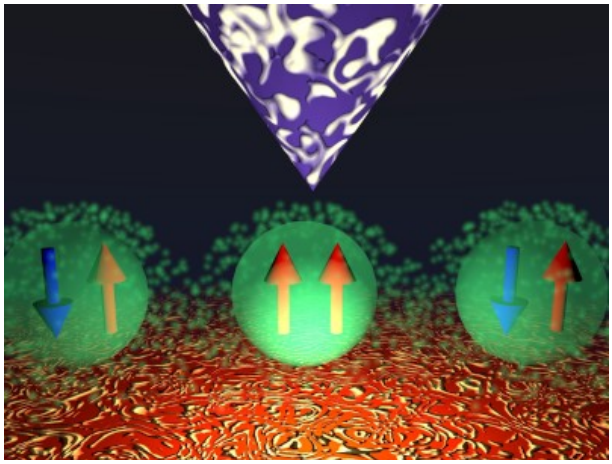
In this project, you will create a machine-learning algorithm that allows you to identify the correlated state of a twisted van der Waals material directly from its spectroscopic data. You will show that a machine learning methodology trained on simulated correlated moire materials allows inferring the symmetry breaking of the ground state and extracting the effective Hamiltonian of the system. For this project, you will combine quantum many-body solvers for moire systems, together with a deep learning architecture you will develop. Ultimately, the algorithm you will develop during this project could potentially be deployed with experimental data to infer the correlated state of a real device.

For more details, contact Prof. Jose Lado (jose.lado@aalto.fi).

Summary of Applied Physics:

Machine learning fractional quantum magnets

Summary
This is a project in theoretical condensed matter physics, in particular in the field of machine learning for fractional quantum magnetism. The project can be suitable for a bachelor's thesis, a special assignment, or a master's thesis, and its difficulty can be adjusted to your level. The project will be carried out in the Correlated Quantum Materials group led by Prof. Jose Lado.



Background
Quantum many-body systems give rise to exotic phases of matter that cannot occur in a classical framework. In particular, in the field of magnetic materials, quantum spin liquids represent a paradigmatic example of such exotic phases, featuring fractional excitations and lacking magnetic order even at zero temperature. Despite strong theoretical efforts, the experimental characterization of quantum spin liquids has remained a critical open problem in quantum matter. Interestingly, techniques based on inelastic spectroscopy allow us to probe excitations in quantum magnets with both frequency and spatial resolution, establishing a promising strategy to reveal fractional excitations in these materials. Machine learning has raised in the last years as a compelling framework for tackling highly-non trivial problems in the presence of incomplete, noisy or even faulty information. Identifying fractional modes has been an open challenge in quantum materials, one that machine learning methodologies have shown potential to allow us to solve.

Task
In this project, you will develop a machine-learning algorithm to detect fractional quantum excitations in a quantum many-body model for a quantum spin liquid. You will show that a machine learning methodology allows inferring entangled modes directly from dynamical spectroscopy. This will be performed by solving the many-body Hamiltonian with an exact computational many-body formalism and combined with a deep neural network architecture. You will show how fractional excitations can be directly inferred from experimental measurements.

For more details, contact Prof. Jose Lado (jose.lado@aalto.fi).