Master in Photonics – “PHOTONICS BCN”
Master ERASMUS Mundus “EuroPhotonics”

MASTER THESIS PROPOSAL

Starting full time from April 2025
Presentation at the end of July or beginning of September 2025

Laboratory: Quantum Technologies Group, Institut de Ciències del Cosmos UB
Institution: Universitat de Barcelona
City, Country: Barcelona, Spain

Title of the master thesis: Neural Network Variational Approach to Ultra-cold Dipolar Bosons Trapped in Atomtronic Circuits

Name of the master thesis supervisor and co-supervisor: Maria Moreno and Montserrat Guilleumas
Email addresses: maria.moreno@fqa.ub.edu, muntsa@fqa.ub.edu,

Keywords: Dipolar Ultracold Quantum Gases, Neural Networks

Summary of the subject (maximum 1 page):

Ultra-cold atoms displaying strong magnetic moments (such as Dysprosium, Chromium, Erbium and Europium) enable long-range and anisotropic dipole-dipole interactions among them [1]. These strong interactions give rise to interesting quantum phases with domain fragmentation, as well as atom current persistence and vortex emergence, among other phenomena, which could be useful to exploit for quantum applications. Using optical potentials it is possible to experimentally trap these gases forming atomtronic circuits of different geometries, which strongly determine the properties of the system. Here we will be interested in the geometry of fully connected wells, starting with three sites forming a triangle, and more generally, forming a ring-like shape. This particular geometry is appealing from the theoretical point of view due to its high symmetry, but it also enhances the formation of vortices in the superfluid phase [2,3].

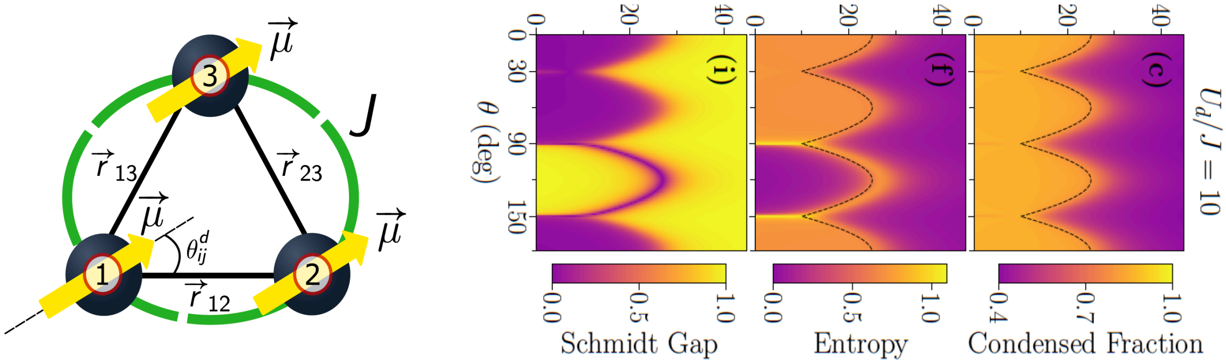

Figure: Schematics of a three-well potential configuration with dipolar bosons and emerging quantum properties and phase diagram (extracted from [3]).

However, as it is well known, the theoretical description of quantum many-body systems faces in general the scalability problem (the Hilbert space increases exponentially with the number of constituents). Therefore, it is very desirable to find new methods to circumvent this problem, which can efficiently encode the information of the quantum state in a smaller number of parameters (for example, that scale polynomially with the system size instead of exponentially). In this sense, neural network architectures are emerging as a new variational method to describe the wave function of the system. The simplest approach is based on Restricted Boltzmann machines and it has already been applied to a model with short-range spin exchange Hamiltonians of the Ising or Heisenberg type (interactions restricted to first neighbors), providing very promising results [4].

In this project we will combine different many-body techniques to describe the ground-state phases emerging in a dipolar ultra-cold gas confined in connected discrete well potentials forming a ring-shaped geometry. The main goal of the project is the **generalization, and analysis of the performance and efficiency of a neural-network description to capture long-range anisotropic interactions emerging in this system.**
We will start analytically solving the problem in the limiting regimes (e.g. no interactions or very large tunneling), and continue with exact diagonalization of the system for an arbitrary value of the interaction. We will then implement a neural network algorithm based on Restricted Boltzmann to describe the ground state of the system, and we will benchmark the results with those obtained previously with exact diagonalization. Finally, we will analyse the scalability and performance of the method when increasing the system size.

[1] L. Chomaz, et al., "Dipolar physics: a review of experiments with magnetic quantum gases", Reports on Progress in Physics, 86, 026401 (2023).

[2] A. Gallemí, M. Guilleumas, R. Mayol, and A. Sanpera, "Role of anisotropy in dipolar bosons in triple-well potentials", Phys. Rev. A 88, 063645 (2013).

[3] M. Rovirola, H. Briongos-Merino, B. Julià-Díaz, M. Guilleumas, "Ultracold dipolar bosons trapped in atomtronic circuits", Phys. Rev. A 109, 63331 (2024).

[4] G. Carleo, and M. Troyer, "Solving the quantum many-body problem with artificial neural networks", Science 355, 602 (2017).

Objectives:

- Understand the theoretical formalism to describe dipolar ultracold quantum gases.
- Implement exact diagonalization to solve the problem at arbitrary value of the interactions, and understand the emerging ground state phase diagram.
- Construct a neural network algorithm (based on previous work) to efficiently describe the system and analyse its performance when increasing system size.

Additional information (if needed):
* Required skills: Quantum many-body physics, Ultracold Quantum Gases (desirable), Neural Network approaches (desirable), Programming skills (Python, Fortran, Matlab, Julia or similar)
* Miscellaneous: