Neutrino Moments
Supervisor: Jordy de Vries
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Neutrinos are electrically neutral in the Standard Model, but quantum loop effects give them tiny electromagnetic and electroweak form factors: an effective charge radius, magnetic and electric dipole moments, and an anapole moment. The pattern and size of these form factors depend sensitively on whether neutrinos are Dirac or Majorana particles. In the minimal Dirac case, the predicted magnetic moments are far below current experimental reach, whereas many beyond-Standard-Model scenarios can enhance them to potentially observable levels. This makes neutrino electromagnetic properties a clean and powerful probe of new physics and of the Dirac–Majorana nature of neutrino mass.

This 10-week project aims to (1) review the theoretical framework of neutrino electromagnetic and electroweak form factors for Dirac and Majorana neutrinos; (2) understand how these form factors affect observable processes such as neutrino–electron scattering and coherent elastic neutrino–nucleus scattering; and (3) quantify how current and near-future experiments compare to the Standard Model expectations and to typical beyond-Standard-Model benchmarks. You will derive or reproduce simplified cross-section expressions including a neutrino magnetic moment, collect and compare current experimental bounds and key astrophysical limits, and produce plots illustrating how many orders of magnitude away present experiments are from the minimal Standard Model predictions, and which experimental avenues offer the best prospects for a first detection.

Inelastic neutron scattering for quantum magnets
Supervisor: Jean-Sebastian Caux
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Inelastic neutron scattering is the preeminent method for investigating spin order and dynamics in magnetic materials. This project will teach the student how this method is theoretically described, and how to compute experimental predictions based on a number of simplified condensed matter models.

Tensor network simulations of the J1-J2 classical Ising model
Supervisor: Philippe Corboz
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The J1-J2 Ising model is one of the simplest models of frustrated magnetism, and its phase diagram is still not fully settled [1,2]. The goal of this project is to study this model using tensor network techniques, which are a powerful class of methods to study many-body problems. The idea is to represent the partition function of the model as a 2D network of

rank-4 tensors which can be efficiently evaluated using approximate contraction methods, such as the corner transfer renormalization group method [3] (a different approach was used in [2]). The accuracy of the contraction can be systematically controlled by the so-called bond dimension of the tensors. This approach will be used to study the thermodynamic properties and phase transitions of this model in a systematic way.

Requirements: knowledge in statistical physics and solid programming skills

References:
[1] A. A. Gangat, Weak first-order phase transitions in the frustrated square lattice J1 – J2 classical Ising model, Phys. Rev. B 109, 104419 (2024).
[2] H. Li and L.-P. Yang, Tensor network simulation for the frustrated J1-J2 Ising model on the square lattice, Phys. Rev. E 104, 024118 (2021).
[3] T. Nishino and K. Okunishi, Corner Transfer Matrix Renormalization Group Method, J. Phys. Soc. Jpn. 65, 891 (1996).

Lattice manipulation to optimise anionic diffusion
Supervisor: Emilia Olson
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Anionic diffusion can greatly affect the stability and properties of materials. Dependent on application area, anionic diffusion can be beneficial (for example for fuel cell applications), or detrimental (for example in transistors). Understanding and predicting anionic diffusion at the atomic scale can assist in designing the next generation high tech solutions.
In this project, you will identify a technology and material where anionic diffusion is either detrimental or beneficial. With the base in this application, you will computationally investigate anionic diffusion as a function of molecular structure and temperature. Using molecular dynamics and lattice dynamics you will first fit an interatomic force field for a multicomponent molecular system. You will then use your interatomic force field to investigate anionic diffusion in your chosen material and optimise it through lattice manipulation.

The effect of tensile and compressive stress on 2D materials properties
Supervisor: Emilia Olson
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Stress can be either a detriment or benefit for advanced materials. By mapping the effect of stress on model systems that you identify as important components in technological devices, you will guide the future research on these materials.
In this project, you will investigate the effect of tensile and compressive stress using lattice and molecular dynamics, or density functional theory. By computationally applying both tensile and compressive stress, you will predict the effect as a function of temperature and composition. Specifically, you will investigate how to model the interatomic interactions

using different interaction potentials, mapping how you can explore stress with each approximation.

Mechanics of compressed chains of hard spheres
Supervisor: Edan Lerner
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In this project we will employ a computational framework [1] that allows to compress "pearl necklaces" — long chains of hard spheres — until they jam and cannot be further compressed. We will study these "necklace packings" and their structural and mechanical properties. In particular, we will ask how these packings differ from "plain vanilla" packings of hard spheres, the latter are known to abide by the $d \to \infty$ mean-field theory [2].

This project requires some coding experience.

[1] Edan Lerner, Gustavo Düring, and Matthieu Wyart, Simulations of driven overdamped frictionless hard spheres, Comp. Phys. Comm. 184, 628 (2013).

[2] Patrick Charbonneau, Jorge Kurchan, Giorgio Parisi, Pierfrancesco Urbani & Francesco Zamponi, Fractal free energy landscapes in structural glasses, Nature Communications 5, 3725 (2014)

GPU-accelerated magnetohydrodynamics
Supervisors: Philipp Mösta, Sara Azizi
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This project will involve porting and profiling individual computation kernels for our GPU-GRMHD code GRaM-X. GRaM-X is a dynamical-spacetime general-relativistic magnetohydrodynamics code for simulation binary neutron-star mergers and supernova explosions. The project is flexible and can be focused on performance testing and optimization of existing modules of the code for specific GPU architectures or developing new physics modules (e.g. neutrinos, equation of state, magnetic fields). The former will give the student experience working with state-of-the-art GPU systems and gain insights into modern GPU programming while the latter also involves algorithm development for computational physics in astrophysical magnetohydrodynamic simulations.