Axions in cosmology and astrophysics

Summary

Axions constitute one of the prime candidates for dark matter. This PhD project explores the role of axions and axion-like particles in cosmology and astrophysics. The first goal of this project is to study axion formation in the early universe, focusing on the novel effects of cosmological phase transitions and domain walls. These effects can change the power spectrum of axions, consequently affecting the axion dark matter structures. This connects the first part of the project to the second one, where the goal is to study astrophysical probes of axion dark matter. In particular, the second part of the project will include studies of the galaxy evolution, the reionisation history and the formation and evolution of supermassive black holes.

Research field:	Applied physics and mathematics
Supervisor:	Ville Vaskonen
Availability:	This position is available.
Offered by:	School of Science National Institute Of Chemical Physics And Biophysics
Application deadline:	Applications are accepted between June 01, 2025 00:00 and June 30, 2025 23:59 (Europe/Zurich)

Description

The nature of dark matter (DM) is among the major unresolved problems in physics. The existence of DM is widely recognised, and it constitutes a crucial component of the Universe, being the primary driver of cosmological structure formation. Despite extensive experimental efforts, our understanding of DM remains limited, particularly regarding its fundamental nature and potential non-gravitational interactions. A large variety of DM candidates have been proposed, ranging from ultralight axion-like particles to heavy primordial black holes. Remarkably, many of the alternatives to the cold DM paradigm predict different amounts and types of structures at small scales. Probes of DM structures, therefore, offer crucial insights into the fundamental properties of DM.

This project focuses on studies of axions and axion-like particles as DM candidates. The project includes studies of their formation in the early Universe as well as their astrophysical signatures. This research is timely due to the recent JWST observations of the reionisation era, pulsar timing array observations of supermassive black holes, and the upcoming data from 21-cm experiments. The project is divided into two parts:

1. **Numerical studies of axion dynamics in the early universe:** The axion dynamics will be studied with numerical lattice simulations. The novel aspect of this research is to consider in detail the effects of cosmological phase transitions and domain wall networks on the dynamics. These effects can enhance the axion production and modify the axion DM power spectrum.
2. **Analysis of axion DM signatures in astrophysics:** The modifications in axion DM models compared to the cold DM model will be quantified and analysed against data from JWST and pulsar timing arrays. This includes the effects of modified small-scale structures on the formation and evolution of galaxies and supermassive black holes. In addition, prospects for the near future 21-cm observations will be derived.

Responsibilities and foreseen tasks

- Development of accurate estimates of axion production in the early universe in phase transitions and in the decay of domain walls.
- Development of accurate estimates of the axion dark matter structures.
- Analysis of galaxy formation in axion DM models against JWST data.
- Analysis of supermassive black hole formation and evolution in axion DM models against pulsar timing array data.
- Analysis of axion DM effects on the 21-cm signal from the cosmic dawn.
- Active participation in scientific seminars and discussions at the research institute.
- Presenting the results of the project at conferences and workshops.

Applicants should fulfil the following requirements:

- a master’s degree in physics
- a clear interest in the topic of the project
- excellent command of English
- strong and demonstrable writing and analytical skills
- capacity to work both as an independent researcher and as part of an international team

The candidate should submit a research plan for the topic. The candidate can expand on the listed research questions and tasks.

We offer:

- a 4-year PhD position
- a chance to do high-level research
- opportunities for research visits and networking, and to attend conferences and workshops

About the department

The Laboratory of High Energy and Computational Physics (HEPC) of the National Institute of Chemical Physics and Biophysics (NICPB) provides an active international atmosphere with over 20 researchers from different countries. It is a member of the CERN CMS experiment and the ESA LISA consortium and has ongoing collaborations with researchers from several other European universities. HEPC has competence in theoretical and experimental particle physics, cosmology, gravitational wave phenomenology and high-performance computing, and aims to carry out systematic interdisciplinary research on dark matter, dark energy, cosmic inflation, gravity and the interplay of those physical phenomena.

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