Stars as laboratories for fundamental physics

Our current understanding of the standard paradigm of particles and forces in the Universe is strongly challenged by key observations. Probably, the most puzzling one is the mysterious “dark energy” problem which calls for new forces beyond the standard model of particles and General Relativity. New particles are expected to leave their imprints at different scales in the Universe: from cosmological scales to gravitational waves and stellar interiors.

This project aims to search for imprints of new forces using stars as laboratories. The end point will be to make predictions for the impact of new physics on the structure and pulsations of stars and confront with observations. The choices of stars to be employed is broad, ranging from the Sun to white dwarfs and red giants.

The student will familiarize with the concepts of state-of-the-art theories of dark energy or extensions of the standard model of particles (e.g. axions, dark matter theories), as well as with the physics of stellar evolution and asteroseismology. The project has a theoretical and numerical component. On the theoretical part the student will model the impact of new physics on stellar observables and test against observations. The numerical part will use state-of-the-art simulation codes for stellar evolution/asteroseismology to deliver accurate solutions of the equations.

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Challenging General Relativity with astrophysics

Various puzzling theoretical and observational hints suggest that General Relativity (GR) is not the ultimate theory of gravity. In particular, the need to explain the problem of dark energy at the current stage of the Universe, or to model the initial conditions of the Big Bang, has given rise to a multitude of extensions of Einstein's General Relativity.

This project can take various broad directions, either theoretical or numerical depending on the student's inclination. The common theme underlying the project will be the investigation of the consistency and predictions of general theories of gravity at astrophysical scales. In particular, the implications of new gravitational degrees of freedom for the structure and stability of relativistic compact objects such as neutron stars, the physics of gravitational waves from binary mergers, or the effects of fifth forces on the dynamics of galaxy clusters.

The student will first familiarize with the necessary theoretical tools depending on the particular physical system to be studied, such as the equations governing the dynamics of the astrophysical system and their solution, towards making observable predictions testable with current and future surveys (e.g. the LISA gravitational-wave interferometer). A component of this project may investigate the development of novel numerical methods based on machine learning for the analysis of gravitational waves or observations of stars.

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