

Topic for M2 internship / PhD — AY 2025-2026

Proto-Neutron Star Dynamics : A Stepping Stone to Beyond-Standard-Model Physics

Core-collapse supernovae mark the final stages of massive stars ($\geq 8 M_{\odot}$), releasing enormous amounts of energy. At their center forms a proto-neutron star (PNS) — an ultra-dense object, hotter than ~ 50 MeV, that cools primarily via neutrino emission before either stabilizing as a neutron star or collapsing into a black hole.

Understanding PNS dynamics is a **highly interdisciplinary challenge**, at the crossroads of observational astrophysics, nuclear physics, condensed-matter physics, and quantum field theory at finite temperature. Crucially, **NSs serve as laboratories for new physics**: any exotic cooling mechanism — such as the emission of axions or particles from hidden sectors — could significantly alter their cooling history and leave detectable multimessenger imprints.

The novelty of this project lies in its integrated approach: combining a rigorous beyond-Standard-Model theoretical framework, grounded in effective field theories, see our recent Ref. [1], with state-of-the-art numerical simulations of hydrodynamics and neutrino transport using one of the leading PNS evolution codes, see Ref. [2]. This synergy will enable quantitatively robust predictions of how exotic physics could distort neutrino and gravitational-wave signals.

The project revolves around two main objectives:

(1) Theoretical modeling of exotic cooling processes. We will identify the most prominent and reliably calculable channels for exotic particle emission, focusing on the well-motivated QCD axion. This will rely on the predictive framework of Chiral Perturbation Theory to describe the interactions among the lightest hadrons at finite temperature and density.

(2) Numerical simulation of PNS evolution with extended microphysics. We will extend the PNS evolution code [2] to incorporate additional degrees of freedom, including muons, pions, hyperons, and axions. Refinements will also target the hydrodynamic treatment, such as improved modeling of turbulence and transport processes, to achieve unprecedented realism.

The project combines analytical and computational work, ensuring a **balanced and comprehensive training** in effective field theory, nuclear astrophysics, and numerical modeling. The thesis will be co-supervised by UniStra for the numerical and astrophysical aspects and LAPTh Annecy for the effective-field-theory component.

We are looking for a candidate with a strong background in theoretical or astrophysics, ideally with exposure in quantum field theory or numerical simulations, and a motivation to work at the frontier between fundamental physics and astrophysical applications. An M2 internship in spring-summer 2026 is strongly encouraged. Depending on the candidate's preferences, this period may be spent in one of the two participating labs. Please contact diego.guadagnoli@lapth.cnrs.fr and micaela.oertel@astro.unistra.fr on this or any other related matters.

[1] M.Cavan-Piton et al., Phys. Rev. Lett. 133 (2024) no.12, 121002

[2] A. Pascal et al., Mon. Not. R. Astron. Soc. 511 (2022) 356