Candidature pour un début de contrat le 1er octobre 2025
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SPÉCIALITÉ / DEPARTMENT

☐ **Terre et Environnement** × **Physique de l'Univers**

TITRE et NUMERO du SUJET / TOPIC TITLE and NUMBER:
« Revealing the progenitors of GW mergers with neural networks »

Nom et e-mail de l'étudiant / Name and email of the candidate:

Directeur(trice) / Supervisor :
PR Sylvain CHATY, chaty@apc.in2p3.fr

Co-directeur (trice) / Co-encadrant(e) : Dr Eric Chassande-Mottin

Laboratoire et Equipe d'accueil / Host Laboratory and team: **APC** (Gravitation)

Financement (ou demi-financement) possible hors contrat doctoral / Possible funding or half-funding : Demi-financement de l'Académie Spatiale

Plus de renseignement sur : https://ed560.ed.univ-paris-diderot.fr/offres-de-these/
More information at: https://ed560.ed.univ-paris-diderot.fr/en/thesis-offers/

Développement du sujet et organisation du travail : (1 à 2 pages)

Context :

Accelerating stellar evolution models with neural networks, and application to the formation and evolution of astrophysical sources detected by LIGO/Virgo

Massive Stars Live in Pairs… Two major revolutions have transformed our understanding of stellar evolution. The first was the realization that most massive stars (over 75%) evolve within binary systems (Sana et al., 2012). This binarity has profound consequences on stellar evolution, significantly influenced by the presence of a companion, particularly through mass and angular momentum transfer (**Chaty, 2022**). The fate of these stellar pairs is dictated by the evolution of each component: the more massive star collapses first in a supernova explosion, giving birth to a neutron star or a black hole (Tauris et al., 2017). This process results in the formation of an accreting binary, where a compact object orbits its companion—one of the most fascinating objects in the Universe.

…and compact binaries eventually merge… The second revolution was the detection of gravitational waves by the LIGO-Virgo collaboration, originating from the merger of two black holes (first detected in September 2015) and later from two neutron stars (first detected in August 2017). These mergers occur at the final stage of binary evolution, depending on factors such as mass, orbital separation, and other key parameters (**García et al., 2021**). The merger of neutron stars is accompanied by electromagnetic radiation, producing a kilonova. Spectroscopic observations have, for the first time, unveiled the creation of heavy elements during such neutron star merger events, via the rapid nucleosynthesis process (r-process), confirming that it is a significant (even dominant?) source of galactic nucleosynthesis.

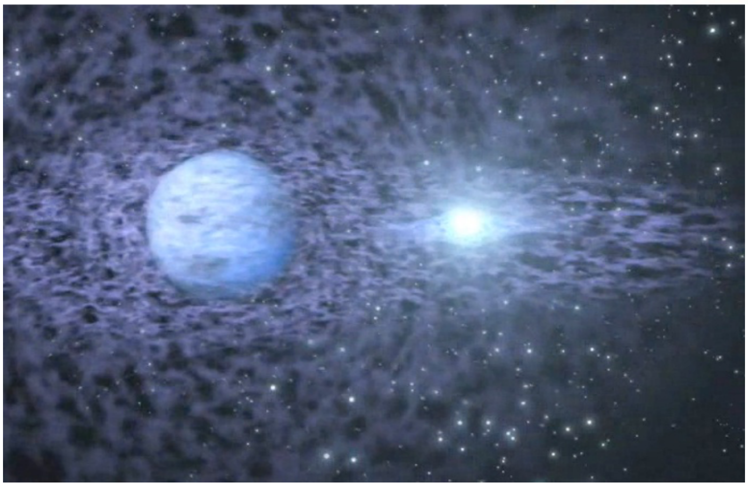
…impacting their environment. It is well established that the collapse of massive stars in supernovae plays a crucial role in enriching the interstellar medium—from heavy atoms to complex molecules—and triggering the formation of new stars. However, the long-term impact of massive stellar winds on their surroundings has long been overlooked. This ejected material disperses into the surrounding medium and may collide with dense interstellar clouds, potentially triggering the birth of new stars, as suggested by Herschel satellite observations (Chaty et al. 2012, Servillat et al. 2014).

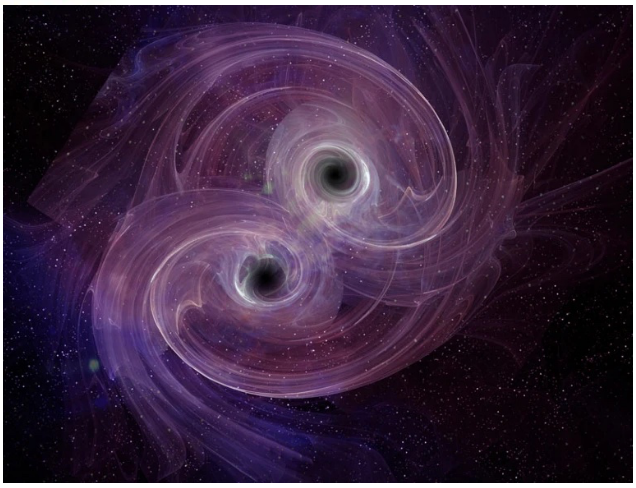
The **LIGO, Virgo, and KAGRA (LVK) gravitational-wave detectors** are currently conducting their fourth observing campaign (O4, [link]), which is expected to result in an enriched catalog containing several hundred compact binary sources (mainly binary black holes). The significant increase—by a factor of 3 to 5—in the number of detections enables a deeper statistical analysis of the physical properties of the detected sources. By identifying homogeneous source populations, these analyses will provide answers to fundamental questions regarding the origin, formation mechanisms, and evolution of compact binaries observed by LVK.

A more accurate understanding of the evolution of compact binary systems relies on physical models. The modeling of these populations is based on **stellar evolution simulations**, performed using tools such as the **MESA** code [https://docs.mesastar.org]. Tracking the evolution of binaries, from their formation to the production of black holes or neutron stars, allow us to model the complex processes that transform a stellar binary into a compact binary (either black hole or neutron star). However, the inherent complexity of these simulations is enhanced by various phases of stellar evolution, which are determined by different key-parameters: accreting phase with stable transfer, common envelope phase with unstable transfer, mass loss through stellar winds, etc. This complexity results in an extremely high computational cost, limiting the ability to fully explore the parameter space of observed compact binaries, and to reproduce detected GW events. This is precisely the purpose of the **POSYDON** project [https://posydon.org], developed to aggregate and interpolate thousands of simulations, aiming at describing entire populations of sources rather than individual binaries. However, POSYDON currently relies on a rudimentary interpolation method that does not fully capture the complexity of the interactions and physical processes involved in binary evolution.

The objective of this PhD project is to explore more advanced regression techniques, and in particular using neural networks, to enhance the accuracy and efficiency of POSYDON's population modeling.

This approach offers several advantages: on the one hand, increased precision thanks to the ability of neural networks to capture complex relationships; on the other hand, the development of a differentiable model that would facilitate the inference of initial binary properties from data observed by LVK. In this context, using **neural networks** to replace or enhance these interpolations appears to be a promising avenue. Neural networks can capture complex nonlinear relationships between stellar parameters, enabling more precise and generalizable modeling. Furthermore, a differentiable machine learning-based model would facilitate the inference of the initial conditions of binaries observed by LVK, thus improving our understanding of the formation channels of these sources. The application of artificial intelligence to the study of stellar evolution and compact binary evolution represents a major advancement, paving the way for faster and more precise analyses of future gravitational-wave detections by LVK, or even future GW detectors (ET, CE, etc).





Left : stellar binary hosting a compact object (neutron star or black hole); Right: binary black hole before merging

Thesis Objectives :

1. **Apply neural networks for interpolation and regression of stellar evolution simulations**, incorporating physical constraints into the learning framework ;
2. **Propose sampling strategies for the input parameter space**, for example, using adaptive learning techniques to obtain accurate neural networks with the smallest possible dataset ;
3. **Develop a Bayesian inversion approach** to reconstruct the initial conditions of stars (e.g., masses, spins) from observational data of detected GW events;
4. **Study the evolution of massive stars in binary systems**: Investigate the influence of mass, rotation, metallicity, and mass transfer and compare observations with stellar evolution models ;
5. **Improve the prediction of detected rates of mergers by LVK and LISA gravitational wave detectors, based on our simulations with the MESA-code, improved thanks to neural networks ;**
6. **Constrain the formation path of binary systems towards merging, by applying neural networks algorithms on various formation scenario, to be compared with actual GW event detections ;**
7. **Better understand the formation and evolution scenario of binary systems leading to merging, by a feedback on parameters constrained by comparing our simulations with detected GW events.**

At the crossroads of various fields in astrophysics—stellar evolution, interstellar medium, and galaxies—this PhD thesis aims to investigate the **evolution of massive stellar binaries**, whose role is pivotal in the matter cycle, as well as their environmental impact. Observations of massive stars, the majority of which form in **binary or even multiple systems**, indicate that they originate within **star-forming complexes** (Coleiro & Chaty 2013 ; Fortin et al. 2022a), influenced by the characteristics of their surrounding **interstellar medium** (density and composition), as well as the **mass and rotation** of the protostars. The evolution of massive stars in binaries is determined by several factors, such as **mass ratio, orbital separation, mass transfer, and angular momentum**. Since the publication of the previous catalogues, the number of identified **compact binaries** has significantly increased, allowing for a more precise census (Fortin et al. 2023, 2024). These new datasets enable comparisons between **observational constraints**—including spectral types, compositions, ages, asymmetric kicks, and migration distances—at various evolutionary stages and the predictions of stellar evolution models (Fortin et al. 2022b). The study of massive stellar pairs is particularly relevant as they represent among the best **candidates for mergers**, ultimately leading to the emission of **gravitational waves, in events detected by LVK**. In this PhD thesis we will study the evolution of stellar binaries mainly in the frame of the isolated scenario, but we will also explore the dynamical capture, and the Chemical Homogeneous Evolution, in order to distinguish which model preferentially leads to compact binaries with given parameters in term of mass ratio, orbital separation, spin, etc.

The study will use multi-messenger data, altogether with innovative simulations based on neural networks algorithms. During this PhD project, we will explore and adapt advanced data science and innovative machine learning tools, thereby strengthening technical skills while immersing in a dynamic and bright scientific environment. This project represents an opportunity to contribute to this research field at the interface between astrophysics, physical modeling, and artificial intelligence, while addressing fundamental questions about the global evolution of binary stellar systems and their detection via gravitational wave detectors. The work will involve developing suitable learning strategies, such as defining cost functions that explicitly incorporate the physical constraints of stellar evolution. The goal of this project is also to design adaptive predictive models capable of optimally guiding the production of new simulations with the MESA code, to achieve a target interpolation error. Finally, we aim at getting feedback from comparison between innovative simulations and GW event detections, to improve our understanding of overall stellar binary evolution.

While data from this project will rely primarily on gravitational wave events detected by LVK, when required we will complement the parameter dataset with observational data coming from ground-based and/or space telescopes covering the electromagnetic spectrum and astrometric data from ***Gaia***, for instance to obtain more accurate parameters of these binaries at earlier stages of their evolution (such as accreting phase, or common envelope phase), necessary to improve the learning phase of neural network algorithms. In our team we are used to obtain, retrieve and analyse data from various multi-wavelength observatories, both ground-based and on satellites.

Methodology and Proposed Work :

The student will work on an **existing dataset of simulations (more than 60 000 in total) obtained with the publicly available 1D-hydrodynamic stellar-evolution code MESA**. This code has been adapted by the supervising team during previous work, to include the black-hole formation and the unstable mass transfer developed during the common-envelope phase, as described in Garcia et al. 2021. We will likely integrate additional data, either coming from new MESA simulations produced in the frame of this project, or also including those from the POSYDON project. During the PhD thesis we will also explore innovative time series regression approaches to model the complete evolution of binary systems, including critical stellar evolution stages and dynamical regimes associated with mass transfer phases (both stable mass transfer in accreting phase, and unstable mass transfer in common envelope phase).

The PhD thesis will be structured around the following key steps:

- **WP1.1: Using neural networks for regression:** Designing models to predict the final properties of compact objects based on the initial conditions of binary systems (masses, orbital periods, metallicities…) ;
- **WP1.2: Applying physical constraints:** Developing a tailored loss function that directly incorporates physical laws, thereby improving the reliability of predictions ;
- **WP1.3: Active learning:** Implementing an adaptive method to optimize the structure of the training set. This technique will target areas of the parameter space where predictions are less reliable, dynamically refining the training dataset ;
- **WP2.1: Comparing various evolution scenario:** applying these adaptive methods on the three main models of compact binary evolution: 1. In the field (isolated evolution), 2. Dynamical capture (in nuclear cluster), and 3. Chemical homogeneous evolution (for massive stars), see Chaty 2022 for details on these evolution scenario ;
- **WP2.2: Comparing output of adaptive methods simulations, to GW database events detected by LVK, taking into account various astrophysical constraints, such as initial mass function, stellar formation rate, cosmological parameters, and final masses of compact objects ;**
- **WP2.3: Applying a feedback of these adaptive methods : using results obtained thanks to our simulations, to better constrain key parameters involved in various scenario of compact binary evolution.**

Supervision :

The PhD will be supervised by **Sylvain Chaty** (chaty@apc.in2p3.fr)and **Eric Chassande-Mottin (**ecm@apc.in2p3.fr**)**, at the **APC laboratory (Research group** : Gravitation**)**. **Doctoral training and** regular mentoring will ensure steady scientific and technical progress.

Required Skills

- Master's degree (M2) in Astronomy and Astrophysics ;
- Scientific programming (Python) ;
- Machine learning expertise ;
- Interest in astrophysics and stellar evolution

Developed Skills

- Scientific programming and modeling (including machine learning / neural networks algorithms) ;
- **Scientific Output:** Writing and publishing peer-reviewed articles ;
- Presentations at national and international conferences

Collaborations

- APC group of Virgo collaboration,
- ENGRAVE **(**gravitational wave observations linked to ESO**)**
- Institute of Astrophysics of La Plata (Argentina)
- University of Berkeley (USA)
- Purple Mountain Observatory (Nanjing, China)

Bibliography:

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- **Chaty, 2022, *Accreting Binaries, Accreting binaries*, AAS-IoP Publishing**
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- Fortin et al., 2022a, A&A, 665, A31 ; 2022b, A&A, 665, A69 ; 2023, A&A, 671, A149 ; 2024, A&A, 684, A124
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- Sana et al., 2012, *Science*, 337, 444
- Servillat, Coleiro, Chaty et al., 2014, ApJ, 797, 114
- Tauris et al. (incl. Chaty), 2017, ApJ, 846, 170