Giulia Campailla – First year Ph.D. report

Supervisor: Prof. Marco Raveri

Research Overview

During my first year of the PhD, I have focused on the application of machine learning algorithms for statistical inference across cosmology and astrophysics, within the context of multimessenger astrophysics. In particular, I decided to concentrate on two main projects: one personal project focused on doing cosmology with gravitational waves and studying a specific phenomenon known as strong gravitational lensing, and another project related to analyzing weak lensing statistics as part of my work with the Dark Energy Survey (DES) collaboration.

Project 1: Strongly Lensed Gravitational Wave Events Using Machine Learning Methods

My first research project focuses on identifying strongly lensed gravitational wave (GW) events using machine learning-based techniques. *Gravitational waves* are ripples in spacetime caused by the acceleration of massive objects, such as merging black holes or neutron stars. As these waves propagate through the universe, they may encounter massive structures like galaxies or galaxy clusters, whose gravitational fields bend the waves' path: a phenomenon known as *strong gravitational lensing*. In electromagnetic waves, this lensing typically produces multiple images of the same source. Similarly, strong lensing of GWs can result in multiple detections of the same event, separated by distinct time delays due to the varying travel paths of the lensed signals. In my work, I employed *normalizing flows*, a powerful generative machine learning model, to model the posterior distributions of GW events. This approach allows for flexible, high-dimensional modeling of complex data, making it especially well-suited to GW signal analysis. By comparing pairs of detected GW events, I aimed to identify those that exhibit the greatest consistency with the strong lensing hypothesis. This methodology enables us to pinpoint event pairs that may be lensed versions of the same underlying source. Currently, I am finalizing a paper that outlines the results of this analysis, with the goal of publishing by the end of this year.

Project 2: Weak Lensing Analysis in the Dark Energy Survey (DES)

In my second project, I contributed to the *Dark Energy Survey (DES)*, a large international collaboration designed to explore the nature of dark energy through detailed observations of the cosmos. DES has collected deep and wide-field optical imaging data, which allows for precise measurements of the large-scale structure of the universe and galaxy clusters. I specifically worked with the *Year 3 (Y3) data release*, which covers approximately 5,000 square degrees of the southern sky. In this project, I applied machine learning techniques to assess the consistency between weak lensing summary statistics and external datasets from other experiments, such as *Planck*, *SHOES*, and *eBOSS*. Weak lensing refers to the subtle distortion of background galaxies caused by the gravitational influence of intervening mass, such as dark matter, along the line of sight. By studying weak lensing, we can map the dark matter distribution and infer key cosmological parameters, including the matter density and the nature of dark energy. Our study combined various weak lensing summary statistics to derive *joint constraints* on cosmological parameters within two theoretical frameworks: the Λ*CDM model* (which posits a cosmological constant, Λ, as the driver of the universe's accelerated expansion, with Cold Dark Matter as the dominant dark matter component) and the *wCDM model* (which allows for a time-varying equation of state for dark energy, denoted by 'w'). This analysis was published, offering insights into the consistency of the Y3 data with these models and the compatibility of weak lensing constraints with other cosmological probes.

Courses and exams

1. **Computational Astrophysics and Cosmology** (MCs course) - Exam not given yet
2. **Gravitational Waves, theoretical and experimental aspects** (MSc course) - Exam not given yet
3. **The Double Trouble of the Missing Matter in the Universe** (PhD course) - Exam not given yet

Schools and conferences

1. **Machine and Deep Learning @ INAF-IASF** (Milano, January 15 - 19, 2024) "Machine and Deep Learning" was a series of lessons designed for both researchers and students which covered a wide range of topics relevant to Machine and Deep Learning, beginning with an introduction to the mathematical tools necessary for implementing algorithms and extending to applications in the field of astrophysics. These lessons have been conducted by Dr. Umberto Michelucci. The program consisted of morning theoretical lessons and afternoon hands-on practical exercises using Python.
2. **Nordic Winter School on Multimessenger Astrophysics** (Skeikampen, January 28 - February 2, 2024) I gave a talk on my research projects "Looking for Strongly Lensed Gravitational Waves".
3. **Dark Energy Survey (DES) collaboration meeting** (S'Agarò, May 26 - 31, 2024) I gave a short talk to present my research activity to collaborators within DES.
4. **Fundamental Physics and Gravitational Wave detectors** (Pollica, September 8 - 14, 2024) I participated giving a talk about my research activity and in particular I presented my project about Strong Gravitational Lensing of Gravitational Waves.
5. **Understanding the Galaxy/Matter Connection in the Era of Large Surveys** (Sestri Levante, September 16 - 17, 2024)
6. **CASTLE - Cosmological and Astrophysical Synergies: Tactics for the Latest Era** (Tagliolo Monferrato, September 17 - 20, 2024) I gave a talk about Machine Learning techniques for Strongly Lensed Gravitational Waves identification.
7. **Post-industrial Trispectrum** Quarterly meetings aimed at keeping the Cosmology research groups from the departments of Genova, Milano, Torino and Parma updated. In February 2024 we hosted the event in Genova and I gave a talk about my research project "Searching for Strongly Lensed Gravitational Waves with Machine Learning techniques".

Publications

1. M.Gatti, **G. Campailla** et al., *Dark Energy Survey Year 3 results: simulation-based cosmological inference with wavelet harmonics, scattering transforms, and moments of weak lensing mass maps II. Cosmological results*, to be submitted to *Physical Review D*, arXiv:2405.10881v1 [astro-ph.CO]

Other Activities

1. Organizer of the *Astrophysics and Cosmology Journal Club* for the Cosmology research group at University of Genova, Department of Physics.