Giulia Campailla – Second year Ph.D. report

Supervisor: Prof. Marco Raveri

Research Activity Overview

During the second year of my Ph.D., I continued to build on the research directions initiated in my first year, focusing on the application of machine learning (ML) techniques to statistical inference problems in cosmology and astrophysics, within the broader context of multimessenger astrophysics. My research developed along two complementary lines: a personal project on the use of gravitational waves for cosmological studies, with particular attention to the phenomenon of strong gravitational lensing; and a collaborative effort within the Dark Energy Survey (DES), focused on the statistical analysis of survey data. These activities have been — and continue to be — carried out as part of my active involvement in both the LIGO–Virgo–KAGRA (LVK) and DES collaborations.

1 The main project of my Ph.D. focuses on identifying strongly lensed gravitational wave (GW) events using machine learning techniques. *Gravitational waves* are ripples in spacetime produced by the acceleration of massive objects, such as merging black holes or neutron stars. As they propagate through the universe, GWs can be deflected by the gravitational fields of massive structures like galaxies or galaxy clusters. In cases of *strong gravitational lensing*, this effect can generate multiple images of the same source, separated by time delays corresponding to different travel paths. While this phenomenon is well established for electromagnetic signals, in the case of GWs it would manifest as repeated detections of the same astrophysical event. In my work, I employed *normalizing flows*, a generative machine learning model, to represent the posterior distributions of GW events. This approach is particularly well suited for modeling high-dimensional and non-Gaussian data, as often encountered in GW analyses. By comparing pairs of detected GW events, I developed a strategy to identify those most consistent with the strong lensing hypothesis, selecting candidate pairs that may correspond to multiple images of the same source. The first results of this project were recently presented in a paper posted on the arXiv, which summarizes the progress of my first two years of Ph.D. research. I am currently preparing a revised version for submission to *Physical Review D*.

2 In parallel with my individual project, I contributed to the *Dark Energy Survey (DES)*, a large international collaboration aimed at exploring the nature of dark energy through detailed observations of the cosmos. DES collected deep and wide-field optical imaging data, enabling precise measurements of the large-scale structure of the universe and galaxy clusters. I specifically worked with the *Year 3 (Y3) and Year 5 (Y5) data releases*, covering about 5,000 square degrees of the southern sky, and I am currently involved in the statistical analysis of the final release, Y6, expected by the end of 2025. In this context, I apply ML techniques to study the consistency between weak lensing summary statistics and external datasets from other experiments, such as *Planck*, *SH0ES*, and *eBOSS*. Weak lensing refers to the subtle distortions of background galaxies caused by the gravitational influence of intervening mass, such as dark matter, along the line of sight. By studying weak lensing, it is possible to map the dark matter distribution and constrain key cosmological parameters, including the matter density and the properties of dark energy. Our study combined several weak lensing summary statistics to obtain *joint constraints* on cosmological parameters within different theoretical frameworks: the so-called Standard Cosmological Model, the Λ*CDM model* (where a cosmological constant Λ drives accelerated expansion, with Cold Dark Matter as the dominant dark matter component), and various *extension models*, such as Ω_KCDM (a model with non-zero curvature) or w_0w_aCDM (which allows for an evolving dark energy component). I also carried out *robustness tests* to evaluate the sensitivity of the DES results to possible systematic effects and to assess the reliability of the derived cosmological constraints. This analysis was published, providing insights into the consistency of the Y3 data with these models and into the agreement between weak lensing constraints and other cosmological probes. A follow-up work on the analysis of the upcoming Y6 data release is expected to be completed by the end of this year.

Courses and exams

1. **Computational Astrophysics and Cosmology** (MCs course) - Exam given
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 given

Schools and conferences

1. **Challenges and future perspectives in gravitational-wave astronomy: O4 and beyond** (Leiden, Lorentz center, October 14 - 18, 2024) During this workshop we had an interdisciplinary discussion about how ongoing and future observations of gravitational and electromagnetic waves can be used to shed light on the physics of compact-object formation and evolution.

2. **GraSP24-Gravity Shape Pisa 2024: Exploring New Sources of Gravitational Waves** (Physics Department E. Fermi of the University of Pisa, October 23 - 25, 2024) The conference focused on still undetected sources of gravitational waves and their study in current and future detectors. Presentations covered aspects of astrophysics, cosmology and fundamental physics. I gave a talk on my research project "Machine Learning Identification of Strongly Lensed Gravitational Waves Events".
3. **Visiting at Johns Hopkins University** (Baltimore, May 19, 2025) I visited JHU where I met Prof. Emanuele Berti and his research group. On this occasion I was given the opportunity to present my research project on Strong Gravitational Lensing of Gravitational Waves.
4. **Dark Energy Survey (DES) collaboration meeting** (University of Pennsylvania, May 20 - 23, 2025) I gave a talk presenting my work on "Data Combination and Joint Analysis with Normalizing Flows" to collaborators within DES.
5. **Advanced Statistical Methods for Astrophysics and Cosmology @ UniGe** (Genova, June 9 - 20, 2025) A two-week program consisting of lectures on advanced statistical methods for parametric models with applications to astrophysics and cosmology. The first week focused on theoretical foundations, covering topics such as Bayesian statistics, statistical tests for model comparison and dataset compatibility, empirical information geometry, and the geometry of multimodal distributions. The second week was dedicated to hands-on applications, where participants split into small groups to work on case studies in cosmology, gravitational waves, and related areas.
6. **26th SIGRAV Conference on General Relativity and Gravitation** (University of Milano-Bicocca, September 8 - 12, 2025) I presented the results from my project about the development of a new Machine Learning based method that aims to identify Strongly Lensed Gravitational Waves, based on a work I have recently submitted to the arXiv (*see Sec. Publications and Preprints*).
7. **Post-industrial Trispectrum** Quarterly meetings aimed at keeping the cosmology research groups from the universities of Genova, Milano, Torino, and Parma updated on each other's work.

Publications and Preprints

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*, Phys. Rev. D 111, 063504 – Published 3 March, 2025 (DOI: https://doi.org/10.1103/PhysRevD.111.063504, arXiv:2405.10881v1).
2. DES collaboration, *Dark Energy Survey: implications for cosmological expansion models from the final DES Baryon Acoustic Oscillation and Supernova data*, to be submitted to *Physical Review D*, arXiv:2503.06712 [astro-ph.CO]
3. **G. Campailla**, M. Raveri, W. Hu, and J. M. Ezquiaga, *Machine Learning Assisted Parameter-Space Searches for Lensed Gravitational Waves*, to be submitted to *Physical Review D*, arXiv:2509.06901 [gr-qc]

Other Activities

1. Organization of the *Astrophysics and Cosmology Journal Club*, including special sessions on DESI, ACT, and KM3NeT data releases (with Edoardo Maragliano) until March 2025 – I have been co-organizer since then.
2. Outreach activity at "Scuola Media Statale A. Cantore" in Genova, where I introduced various aspects of the profession of a researcher in astrophysics to middle school students.
3. Poster session presenting the research activities of the Astrophysics and Cosmology group to Master's students (Genova, May 30, 2025).
4. Teaching support activity as a teaching assistant for the Electromagnetism section of the FISICA GENERALE course (cod. 72360) for "Corso di Laurea in Ingegneria Elettrica a.a. 2024-2025", University of Genova.
5. Weekly online meetings of the LIGO–Virgo–KAGRA Lensing working group.
6. Weekly online meetings of the DES Y6–Extension Models working group.