PhD position, 2025

Weak gravitational lensing of galaxy clusters with artificial intelligence

Context
Galaxy clusters are one of the key cosmological probes in modern astronomical surveys from microwave to X-ray wavelengths, e.g. [1, 2, 3]. Measurements of their abundance, i.e., the number of clusters as a function of mass and redshift, can provide strong constraints on dark energy and the growth of structure [4]. In particular, cluster observations can shed light on the tension on the amplitude of matter fluctuations, σ_8, between early- and late-time measurements, and to confirm (or refute) recent claims of a time-varying dark energy [5]. The European space satellite Euclid [6], and the Vera C. Rubin telescope with the Legacy Survey of Space and Time (LSST; [7]) will measure those and other cosmological parameters to unprecedented accuracy [8], with galaxy clusters being one of the main ingredients.

To use clusters for modern cosmology, their masses must be measured to great precision. Weak gravitational lensing [9] is a formidable method to measure those masses. Weak lensing is the distortion, or shear, of images of distant galaxies by matter along the line of sight. Lensing probes the dark+baryonic matter in the Universe, and provides thus a measure of the total cluster mass. These measurements have been shown to be very precise [10], and do not need to rely on incomplete knowledge of their content or dynamical state that plagues other methods using baryonic tracers as mass proxies.

However, challenges remain in measuring weak-lensing cluster masses for the systematics-limited datasets from Euclid and LSST:

1. Significant biases can arise due to errors in shear estimates of background galaxies. Special care needs to be taken to calibrate such measurements in the cluster regime where lensing is no longer very weak, and where crowding biases measured shapes.
2. Model biases arise when making simplified assumptions about the cluster profile, neglecting substructure and baryonic effects.

Both of these systematic biases are strong and not well understood towards the cluster center, which must then be cut from the analysis. However, removing the entirety of these regions will result in a significant loss of signal-to-noise, limiting the precision of upcoming cosmological measurements.

State-of-the-art statistical and, in particular, machine learning (ML) and artificial intelligence (AI) methods promise a way to account for those limitations:

1. Shape measurement and calibration is significantly improved with automatic differentiation: Non-linear effects, important in high-density central cluster regions, such as reduced shear, flexion, and a second-order shear response can be modelled accurately and efficiently.

   Biases due to complexities in observed galaxy images from crowding and blending can be handled with forward simulations in combination with generative AI models to create realistic galaxy models.
2. Non-trivial cluster mass distributions need to be modelled in a non-parametric and less time-consuming way than full N-body simulations. Fast forward-simulations in combination with neural likelihood or posterior estimation can be used for efficient and flexible inference of cluster properties such as its mass.

This PhD thesis

The goal of this PhD is to develop novel methods of ML and generative AI models to provide accurate measurements of galaxy cluster masses using weak gravitational lensing. This work aims to push lensing measurements to smaller cluster-centric distances. This will significantly increase the accuracy and precision of weak-lensing derived masses, and help our understanding of baryonic effects on dark matter in the poorly known inner cluster regions.

Outline of the project

The tasks and objectives of the internship are as follows.

1. Get familiar with weak-lensing measurements of galaxy clusters, the analysis of those data, and calibration methods.

2. Implement the metacalibration method in Jax for automatic differentiation support. A working prototype code is available. Metacalibration has been used within our group in past work, e.g. [11, 12].

3. Create models of background galaxies in cluster fields with generative AI models and forward model the cluster profile.

4. Implement likelihood-free inference methods using the above-developed forward model and infer cluster masses of simulated and real data.

Observational constraints will be obtained using multi-band imaging data from Euclid, and from Rubin (estimated to be available in 2026). Large samples of clusters selected in various wavelengths are available on the footprint of those surveys.

Scientific environment

The PhD will be carried out in the CosmoStat laboratory at the Département d'Astrophysique at CEA Saclay, under the supervision of Martin Kilbinger and Franç Lanusse. CosmoStat hosts a multidisciplinary team whose research includes statistics, signal processing, ML, AI, and cosmology. The group is strongly involved in the weak-lensing analysis of data from surveys including Euclid and LSST.

Requirements

The candidate should have a master 2 (or equivalent) degree with a background in either physics/astrophysics or applied mathematics/signal processing/data science. The application deadline is 15/04/2025. The starting date is October 2025.

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References

[1] Planck Collaboration, Ade, P. A. R., Aghanim, N., et al., *A&A*, 594:A13, 2016.

[2] Bocquet, S., Dietrich, J. P., Schrabback, T., et al., *ApJ*, 878(1):55, 2019.

[3] Lesci, G. F., Marulli, F., Moscardini, L., et al., *A&A*, 659:A88, 2022.

[4] Dodelson, S., Heitmann, K., Hirata, C., et al., *arXiv e-prints*, page arXiv:1604.07626, 2016.

[5] Collaboration, D., Adame, A. G., Aguilar, J., et al. DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations, 2024.

[6] Euclid Collaboration, Mellier, Y., Abdurro'uf, et al., *arXiv e-prints*, page arXiv:2405.13491, 2024.

[7] Ivezić, Ž., Kahn, S. M., Tyson, J. A., et al., *ApJ*, 873(2):111, 2019.

[8] Euclid Collaboration, Blanchard, A., Camera, S., et al., *A&A*, 642:A191, 2020.

[9] Kilbinger, M., *Reports on Progress in Physics*, 78(8):086901, 2015.

[10] Herbonnet, R., Sifón, C., Hoekstra, H., et al., *MNRAS*, 497(4):4684–4703, 2020.

[11] Pujol, A., Kilbinger, M., Sureau, F., & Bobin, J., *A&A*, 621:A21, 2019.

[12] Guinot, A., Kilbinger, M., Farrens, S., et al., *A&A*, 666:A162, 2022.