PhD thesis, 2021 – 2023

Weak-gravitational lensing mass maps for cosmology and gravitational wave astronomy

Context

Weak gravitational lensing, the distortion of the images of high-redshift galaxies due to foreground matter structures on large scales, is one of the most promising tools of cosmology to probe the dark sector of the Universe [1]. Patterns of lensing distortions derived from galaxy shapes allows us to create maps of the projected dark matter on large scales. With additional redshift information of the lensing galaxies we can trace the evolution of the dark-matter distribution over cosmic time. This provides us with valuable information about the accelerated expansion of the cosmos, and we can measure the properties of dark energy and the validity of the laws of gravity on cosmic scales.

In addition, weak-gravitational lensing mass maps contribute to the analysis of gravitational wave (GW) events. GW signals contain a wealth of information, from the luminosity distance to the merger to the masses of the merging objects. This allows us on the one hand to place constraints on the Hubble constant H_0, and properties of dark energy. On the other hand, we can gain unprecedented insights into the populations of compact objects and their progenitors, and probe General Relativity in the strong-field regime.

Gravitational lensing magnification of gravitational waves is one of the main systematic uncertainty on the luminostiy distance at redshifts $z > 0.25$ [2]. This magnification caused by intervening structures on the line of sight can be estimated from weak-gravitational lensing mass maps. Deep photometric surveys with excellent image quality required for weak-lensing analyses will be of crucial importance for future GW experiments such as LISA, which will detect thousands of GW events at $z > 1$.

Methodology

To create weak-lensing mass maps from galaxy image distortions, the student will measure galaxy shapes, and, from multi-band images, they will infer photometric redshifts. To carry out these measurements to a high precision is very challenging, since typical lensed galaxies are small, faint, detected with low signal-to-noise ratio, and suffer from instrumental distortions induced by the optical imaging system.

The student will develop and apply state-of-the art calibration methods for both galaxy shapes and redshifts, including machine-learning techniques [3, 4] that have been developed in CosmoStat. A project on joint galaxy shape and redshift calibration has been started recently by M. Kilbinger and W. Luo. The student will assess and quantify the influence of systematic errors on weak-lensing mass maps.

The student will work on wide-field imaging data from the Ultraviolet Near-Infrared Optical Northern Sky survey (UNIONS)/Canada-France Imaging Survey (CFIS)[1]. This is an ongoing large imaging survey that will cover 5,000 deg^2 in the Northern hemisphere in multiple optical bands. First results on lensing distortions of galaxies on around half of that area have been measured in our group (Guinot, Kilbinger et al. in prep).

UNIONS data will serve as test bed for the upcoming Wide-Field Survey Telescope (WFST)

[1]http://www.cfht.hawaii.edu/Science/CFIS/

[5]. This new 2.5m optical telescope with a field of view of 6.55 $\deg^2$ will observe the entire Northern sky ($20,000$ $\deg^2$) in 5 bands. The short 30-second exposures, and each sky area being observed every 3 days makes WFST ideally suited for time-domain science, including GW observations. The projected excellent image quality, with median seeing of 0.7 arcsec, together with deep imaging (total exposure time of 50 min.) complements the time domain with a superb data set for weak gravitational lensing.

Objectives

The tasks and objectives of the thesis are as follows.

1. To develop the methodology to create accurate mass maps using weak gravitational lensing data from wide-field optical galaxy surveys. This includes calibration of galaxy shapes and redshifts to an accuracy such that (1) reliable cosmological constraints on dark matter and dark energy can be extracted from the maps; and (2) the lensing magnification of GW events can be estimated.

2. Weak-lensing mass maps will be obtained from the state-of-the art multi-band UNIONS/CFIS survey, over an area of up to $4,800$ $\deg^2$ in the Northern sky.

3. The methodoloy will be further developed for the upcoming WFST. The student will contribute to the preparation of this survey, and provide important work for the analysis of weak lensing with WFST for cosmology and gravitational-wave scisnce.

Scientific environment

The PhD will be carried out in the CosmoStat[2] laboratory at the Département d'Astrophysique[3] (DAp) at CEA Saclay, under the supervision of Martin Kilbinger. CosmoStat hosts a multidisciplinary team whose research includes statistics, signal processing, machine learning, and cosmology. Kilbinger is the co-lead of the Weak-Lensing Science Working Group in the Esa space mission Euclid (launch in 2022), and leads the UNIONS weak-lensing analyis.

This project will be carried out in collaboration with Wentao Luo (USTC Hefei/China and IPMU University of Tokyo/Japan). Luo is leading the weak-lensing analysis of WFST. Luo is working on data quality control for the HSC-SSP survey, and the connection between galaxies and dark matter in HSC-SSP and SDSS DR7 [6, 7].

[2] http://www.cosmostat.org
[3] http://irfu.cea.fr/Sap/

References

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

[2] Bonvin, C., Durrer, R., & Gasparini, M. A., *Phys. Rev. D*, 73(2):023523, 2006.

[3] Pujol, A., Bobin, J., Sureau, F., Guinot, A., & Kilbinger, M., *A&Ain press, also arXiv:2006.07011*, 2020.

[4] Frontera-Pons, J., Sureau, F., Moraes, B., et al. Dictionary Learning for Photometric Redshift Estimation. In *2018 26th European Signal Processing Conference (EUSIPCO)*, pages 1740–1744. IEEE, 2018.

[5] Lou, Z., Liang, M., Yao, D., et al. Optical design study of the Wide Field Survey Telescope (WFST). In *SPIE Conference Series*, page 101542A, 2016.

[6] Luo, W., Yang, X., Zhang, J., et al., *ApJ*, 836(1):38, 2017.

[7] Luo, W., Yang, X., Lu, T., et al., *ApJ*, 862(1):4, 2018.

Contact

Martin Kilbinger
✉ martin.kilbinger@cea.fr
⌂ http://cosmostat.org/kilbinger
CEA/Irfu/Sap
Laboratoire AIM, Bât 709
F-91191 Gif-sur-Yvette