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PhD Cycle: 36th
Tutor: Federico Marulli, Lauro Moscardini

RESEARCH PROJECT:

Cosmological constraints from galaxy cluster statistics in KiDS and Euclid

From observations, we know that we live in an expanding universe with a flat geometry, described by the ΛCDM model. Here, Λ outlines the presence of a dark energy, contributing to about 68% of the matter-energy content of the universe, explaining the accelerated expansion of the universe. On the other hand, CDM stands for Cold Dark Matter and its presence is necessary to describe the dynamics of the structures in the universe and the angular power spectrum of the CMB. The cold dark matter is the first matter component which is able to collapse due to gravitational instability, and from such collapses, in a bottom-up growth scenario, the large scale structure of the universe has formed.

In this framework, galaxy clusters play a crucial role. Such objects lie in correspondence of the nodes of the cosmic web and, reaching masses up to 10^{15} $M_{\odot}$ and radii up to 5 Mpc, they trace the deepest virialized potential wells of dark matter. In fact, galaxy clusters mark the transition between the linear and the nonlinear regime of the gravitational perturbations, so that their formation and evolution can be theoretically described with excellent accuracy. Since the dark matter component is dominant in galaxy clusters, it is accurate enough, given the current observational uncertainties, to model the cluster formation and evolution through N-body dark matter simulations. Such simulations allow calibrating the mass function of galaxy cluster haloes, as well as finding a functional form describing the cluster dark matter profiles.

With a calibrated cluster halo mass function at hand, it is possible to model the observed counts of galaxy clusters in order to derive strong constraints on fundamental cosmological parameters. Indeed cluster counts are among the most powerful cosmological probes, providing exceptional constraints on Ω_m and σ_8, respectively the density parameter of matter and the square root of the mass variance on scales of 8 Mpc/*h* at redshift z = 0, and are a key tool for constraining the parameters of the dark energy equation of state. In turn, it is necessary to predict the cluster matter profiles in order to derive the cluster masses from weak-lensing data, since the knowledge of the masses is required to carry out such cosmological analyses.

During the first year of PhD I developed a joint analysis of cluster counts and cluster weak-lensing in the Third Data Release of the Kilo Degree Survey (KiDS-DR3), described in Lesci et al. (under review by A&A, arXiv:2012.12273). The catalogue of galaxy clusters has been built up through the use of the AMICO algorithm, which will be used also in Euclid. The analysis included about 3700 galaxy clusters over the redshift range $z \in [0.1, 0.6]$ and in an effective area of 377 deg^2. In particular, I measured the differential surface density profiles of galaxy clusters, which are proportional to the tangential shear profiles, by performing a stacked weak-lensing analysis in bins of redshift and cluster richness. Then I modelled such profiles, deriving the mean cluster masses in the aforementioned redshift and richness bins, in order to constrain the mass-richness scaling relation. In particular, I developed a joint analysis of mass-richness relation and cluster counts as a function of richness, deriving exquisite constraints on the fundamental cosmological parameters Ω_m and σ_8. Indeed, I derived a constraint for the cluster normalisation parameter, $S_8 \equiv \sigma_8 (\Omega_m/0.3)^{0.5} = 0.80 \pm 0.04$, which is consistent with Planck results and is among the most relevant results, in terms of uncertainties, obtained from observations of the late universe (see Fig. 1 in this document).

I also started analysing the AMICO cluster catalogue derived from KiDS-DR4, which will lead to two papers: one on the weak-lensing analysis and the other on the cosmological analysis. Given the extraordinary constraints obtained on Ω_m and σ_8 in KiDS-DR3, I expect a dramatic improvement of the results in DR4. The reason is twofold: first, I will combine the analyses of cluster weak-lensing, counts and clustering. In addition, the KiDS-DR4 sample of AMICO clusters contains more than triple the number of objects present in the previous data release, providing outstanding data up to redshift 0.8, with a huge improvement of the photometric redshifts thanks to five additional near-infrared bands. Since galaxy clusters reach higher redshifts in this Data Release, I am developing a new colour selection of the background galaxies for the weak-lensing analysis. In addition, I developed a method through which it is possible to directly perform joint analyses of cluster counts and cluster density profiles. In particular, with this method one retrieves the mass-richness relation directly from the stacked profiles, without the need of deriving the mean masses first. Consequently, I will account for the cosmological dependence of cluster profiles in the analysis, and I will also model the 2-halo term of the profiles describing the correlated matter around clusters.

Lastly, I am a developer of the Euclid Python software CLOE (Cosmology Likelihood for Observables in Euclid), implementing in particular the module for cosmological analyses based on galaxy cluster observations. Specifically, I am one of the main contributors to the implementation of the halo mass function and to its validation through the use of benchmark datasets.

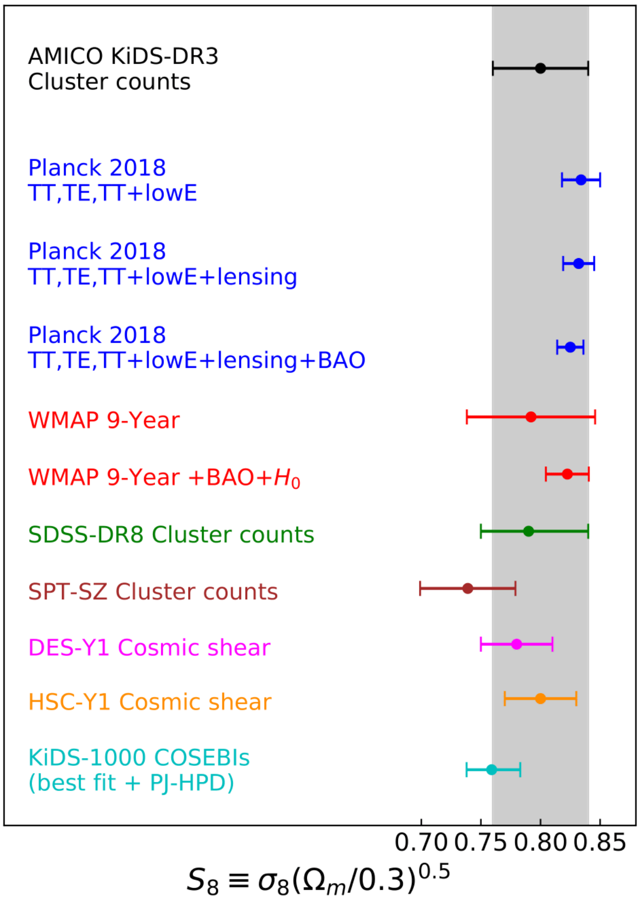

Figure 1: Comparison of the constraints on $S_8 \equiv \sigma_8\ (\Omega_m/0.3)^{0.5}$ obtained, from top to bottom, from the joint analysis of cluster counts and weak-lensing in the AMICO KiDS-DR3 catalogue (black dot), from the results obtained by Planck Collaboration et al. (2020) (blue dots), Hinshaw et al. (2013) (red dots), Costanzi et al. (2019) (green dot), Bocquet et al. (2019) (brown dot), Troxel et al. (2018) (magenta dot), Hikageet al. (2019) (orange dot), Asgari et al. (2021) (cyan dot). Median, 16-th and 84-th percentiles are shown.

WORKSHOPS, CONFERENCES & MEETINGS

Attended conferences/meetings (entirely online):

- November 18-20, 2020: Beyond Planck conference
- November 23-27, 2020: KiDS busy week

- May 25-28, 2021: Euclid Consortium meeting
- June 6th, 2021: OAS spring lecture: what's the universe made of? A strong gravitational lensing perspective
- June 14-28, 2021: Gravitational waves from theory to experiments: the birth of a new astronomy (Università di Napoli Federico II and Scuola Superiore Meridionale)
- June 21-25, 2021: KiDS busy week
- September 6-9, 2021: A multi-wavelength view of galaxy clusters: deriving masses in the era of wide-field surveys (ESA/ESAC)
- Weekly meetings of the KiDS consortium
- Euclid: general telecons of IST:L and of the Clusters of Galaxies Science Working Group

Held talks (entirely online):

- June 23rd, 2021: KiDS busy week ("AMICO KiDS working group: an overview on the cosmological results from KiDS-DR3, and perspectives for the DR4 cluster catalogue")
- September 6th: A multi-wavelength view of galaxy clusters: deriving masses in the era of wide-field surveys (ESA/ESAC) ("AMICO galaxy clusters: cosmological analyses and mass-observable relations")
- Several talks during the weekly KiDS meetings
- Several talks during the Euclid meetings, including a talk where I described the Euclid software CLOE to the Clusters of Galaxies Science Working Group

PhD SCHOOLS

June 28th - July 2nd, 2021: Lake Como School on "Multi-Messenger in Astrophysics" (attended online)

INTERNAL COURSES

- November 30th - December 2nd, 2020: "The interstellar medium"
- April 19-23, 2021: "Gamma ray bursts: from observations to physical properties"
- May 5-14, 2021: "Writing, talking and presenting science"

ISA LECTURES

- December 15th, 2020: "Translating texts which do not exist. Pseudo-originality, multistable figures, and Fortini's literary reception of Heine and Brecht"
- July 6th, 2021: "How positive pedagogy can address mental health and wellbeing of students?"

RESEARCH PERIOD ABROAD

I submitted a project for a Marco Polo scholarship at Heidelberg University, for the period April-July 2022

COMPETITIVE TELESCOPE/COMPUTER TIME ALLOCATIONS

N.A.

OTHER RELEVANT ACTIVITIES

My PhD project is funded by an **OPH fellowship:**

- I have been leveraging my enhanced CPU allocation time on the HPC DIFA cluster "Blade/Matrix", in order to perform cosmological analyses through the use of MCMC
- I wrote an article for the OPH newsletter, which will be published in the next few months, where I describe the impact of my OPH fellowship on my research

Euclid:

- From November 2020: Member of the Euclid Consortium
- February 2021: I participated in a challenge within the Clusters of Galaxies Science Working Group for the implementation and validation of likelihood codes for counts of galaxy clusters.
- From February 2021: I am the contact point between Clusters of Galaxies SWG (Science Working Group) and IST:L (Inter-SWG Taskforce - Likelihood)
- From April 2021: I am a developer of the galaxy cluster likelihood module in the Euclid software CLOE
- I have been selected as the coordinator of the Euclid paper “Constraints from the AMICO HSC Cluster Catalogs with the Euclid Cluster Cosmology Pipeline” (pre-launch paper, KP-CL-1)

Mentoring:

- Co-supervisor for the bachelor thesis of Daniele Pinelli “Validazione del codice per l'analisi cosmologica della missione Euclid” (degree in Physics)

Referee activity:

- My reviews for MNRAS can be found at my publons web page: https://publons.com/researcher/4618550/giorgio-francesco-lesci/metrics/

Main **implementations in the CosmoBolognaLib**, our C++/Python libraries for cosmological investigations:

- CombinedPosterior: class originally created by D. Pelliciari and S. Contarini, where I added the possibility to combine any number of statistically-dependent probes (i.e. described by the same covariance matrix), allowing also to manage the posteriors of the parameters shared (or not) by the probes
- CombinedModelling: class for the combination of Modelling objects, based on CombinedPosterior
- NumberCounts1D_MassProxy & Modelling_NumberCounts1D_MassProxy: classes for measuring and modelling, respectively, cluster counts as a function of a mass proxy
- StackedDensityProfile: class for measuring differential surface density profiles of galaxy clusters from weak-lensing data
- Modelling_DensityProfile: class for the modelling of cluster density profiles
- Modelling_MassObservableRelation: class for the modelling of the cluster mass-mass proxy relation
- SuperSampleCovariance: class computing the super-sample covariance terms, generalised in order to be adapted to any cosmological probe (e.g. cluster counts, cosmic shear, galaxy/cluster clustering)

PUBLICATIONS

AMICO galaxy clusters in KiDS-DR3: cosmological constraints from galaxy cluster counts and stacked weak-lensing, **G. F. Lesci**, F. Marulli, L. Moscardini, M. Sereno, A. Veropalumbo, M. Maturi, M. Radovich, F. Bellagamba, M. Roncarelli, C. Giocoli, S. Contarini, L. Nanni, S. Bardelli, E. Puddu, G. Covone, L. Ingoglia (submitted to A&A)

CoMaLit – VI. Intrinsic scatter in stacked relations. The weak lensing AMICO galaxy clusters in KiDS-DR3, M. Sereno, S. Ettori, **G. F. Lesci**, F. Marulli, M. Maturi, L. Moscardini, M. Radovich, F. Bellagamba, M. Roncarelli, 2020, MNRAS, 497, 894

AMICO-KiDS DR3: Cosmological constraints from large scale stacked weak lensing profiles, C. Giocoli, F. Marulli, L. Moscardini, M. Sereno, A. Veropalumbo, L. Gigante, M. Maturi, M. Radovich, F. Bellagamba, M. Roncarelli, S. Bardelli, S. Contarini, G. Covone, J. Harnois-Déraps, L. Ingoglia, **G. F. Lesci**, L. Nanni, E. Puddu, 2021, A&A, 653, A19

AMICO galaxy clusters in KiDS-DR3: Measurement of the halo bias and power spectrum normalization from a stacked weak lensing analysis, L. Ingoglia, G. Covone, M. Sereno, C. Giocoli, S. Joudaki, S. Bardelli, F. Bellagamba, G. Castignani, H. Hildebrandt, E. Jullo, **G. F. Lesci**, F. Marulli, M. Maturi, L. Moscardini, E. Puddu, M. Radovich, F. Sapio, C. Schimd, D. Lanzieri, L. Nanni, M. Roncarelli, (submitted to MNRAS)

AMICO galaxy clusters in KiDS-DR3: constraints on the mass-richness relation and cosmological parameters from the clustering of galaxy clusters, L. Nanni et al. (to be submitted)