PhD name: Sofia Contarini

PhD Cycle: 34°

Tutors: Lauro Moscardini, Federico Marulli

RESEARCH PROJECT: "Towards a full cosmological exploitation of cosmic voids"

Cosmic voids are large underdense structures filling most of the volume of the Universe. Analogously to galaxy clusters, their positive counterparts in the density field, voids' number counts and density profiles provide powerful cosmological probes. Thanks to their large typical sizes and their low-density interiors, voids are particularly suited to study dark energy and modified gravity theories, as well as massive neutrinos, primordial non-Gaussianity and physics beyond the standard model.

The number density of voids as a function of their radius, as known as void size function, has been modelled from first principles by Sheth & van de Weygaert (2004) with the subsequent contribution of Jennings et al. (2013). The latter model is commonly named Vdn model and its high accuracy in the prediction of the abundance of voids identified in the total matter distribution has been largely demonstrated, provided that the analysed sample of voids is modelled according to this theory. To this purpose, during the first year of the PhD, I improved an already existing algorithm for void cleaning, aimed at removing spurious underdensities and shaping voids following the prescriptions given by the theory. Moreover, I extended the applicability of the Vdn model to voids identified in the distribution of biased tracers, such as dark matter haloes, galaxy clusters and galaxies. In particular, I parametrised the model as a function of the large-scale bias, building an efficient methodology to predict the abundance of voids traced by any type of mass tracers.

During the second year of the PhD, I applied the methodology previously developed to study cosmic voids in alternative cosmological scenarios, characterised by modified gravity and massive neutrinos. To this purpose I analysed the DUSTGRAIN-*pathfinder*, a set of simulations specifically designed with the aim of investigating the degeneracies between cosmological models that simultaneously feature a modification of General Relativity – in the form of f(R) gravity – and the presence of massive neutrinos. I studied the cosmic void density profiles and abundances in the distribution of both dark matter particles and dark matter haloes, investigating the requirements to address in order to maximise the disentangling power of cosmic voids.

I found clear evidence of the enhancement of gravity in the void density profiles measured in f(R) cosmologies, especially at $z \sim 1$. However, any peculiar trend in the shape of void profiles has revealed to be almost completely overridden by the presence of massive neutrinos because of their thermal free-streaming. On the other hand, we find that the void size function at high redshifts and for large void radii is an effective probe to disentangle these degenerate cosmological scenarios, which is key in the perspective of the upcoming wide field redshift surveys.

In the third year of the PhD I mostly investigated the constraining power of different void statistics in the perspective of the future *Euclid* mission. In particular, I participated actively in the *EuclidVoids* group contributing to the study of the constraining power of void profiles and void-lensing cross-correlation, and leading a project focused on the exploitation of void number counts.

In this analysis I identified voids in the distribution of mock galaxies using the Flagship light-cone, which closely matches the features of the upcoming *Euclid* spectroscopic dataset. I found an excellent agreement between the predictions of the Vdn model and the measured mock void abundances, providing reliable void number estimates to serve as a basis for further forecasts of cosmological applications using voids. Then I computed the forecasts on the cosmological

constraints achievable on both the wCDM and w0waCDM scenarios, the latter characterised by the Chevallier-Polarski-Linder dark energy equation of state, including in the analysis the modelling of both geometrical and redshift-space distortions.
I showcased the impressive constraining power of the void size function on the main cosmological parameters, estimating the expected dark energy figure of merit and comparing the obtained confidence contours with those coming from different void statistics and different cosmological probes. Moreover we highlighted how the forecasted constraints derived from the void size function are in some cases almost independent and orthogonal to those obtained with standard probes (e.g. weak lensing and galaxy clustering), demonstrating the potential of the combination of these cosmological contours.
With a collateral project, I participated to the implementation of codes for probe combination, which will be exploited in the near future to explore the synergy between the studied void statistics and different *Euclid* probes.
As future developments of my work, I will apply the pipeline built during my PhD to real galaxy surveys, using in particular the final SDSS-III's Baryon Oscillation Spectroscopic Survey (BOSS) Data Release 12 (DR12) dataset and other state-of-the art catalogues. I will also test the possible dependencies of our methodology on the type of mass tracers, the void finding algorithm and the main cosmological parameters, assessing also the contribution of different observational effects, such as errors on the redshift of the tracers and survey mask effects.

WORKSHOPS, CONFERENCES & MEETINGS

3 – 7 February 2020, Paris – Virtual attendance to “Euclid joint meeting: WL+GC+CG SWG+OU-LE3”

10 – 12 February 2020, Bologna – Participation to Euclid Italy Meeting – Talk: “Cosmic void abundance as powerful additional probe for Euclid”

18 – 20 and 23 – 24 November 2020 - BeyondPlanck Release Conference and Tutorial

5 – 16 July 2021 Cosmology from Home – Contributed talk: “Tackling Universe’s fundamental questions with cosmic voids”

Monthly participation to telecons of the WP8: Voids, within the Galaxy Clustering Science Working Group of the Euclid collaboration, giving talks and updates on my project

PhD SCHOOLS

10 - 14 December 2018 Passo del Tonale, Italy – XII Tonale Winter School of Cosmology: “Theory for Observers & Observations for Theorists”

1 April - 5 June 2020 – School at the Institut Pascal “GOLD: The Golden Cosmological Surveys Decade” – canceled

15 - 26 June 2020 – Virtual attendance to “Advanced Euclid School: The science of future cosmological surveys”

28 June – 2 July 2021 - Como Lake school “Multi-Messenger Astrophysics”

INTERNAL COURSES

17 - 25 June 2019 Bologna, Italy – “Statistics for Astrophysics”

27 May - 22 July 2020 – “Virtual Seminar on Multimessenger Astronomy”

30 November - 2 December 2020: “The interstellar medium”

19 – 23 April 2021: “Gamma ray bursts: from observations to physical properties”

5-14 May 2021: “Writing, talking and presenting science”

ISA LECTURES

13 November 2018 - “A heart attack: can we re-wire the heart?” (by Damia Mawad)

7 May 2019 - “You have to be cool to go to Mars” (by Steven John Swoap)

12 November 2019 - “This Turbulent Turbulent World” (by Alexandre Lazarian)

15 December 2020 - “Translating texts which do not exist. Pseudo-originality, multistable figures, and Fortini's literary reception of Heine and Brecht" (by Irene Fantappiè)

19 November 2019 - “Rigour and aesthetics: Japanese traditional mathematics” (by Emanuele Delucchi)

19 January 2021 - "Extreme events: how to describe and predict them using mathematical theories" (by Sandro Vaienti)

RESEARCH PERIOD ABROAD

Marco Polo scholarship to Ludwig-Maximillian University (Munich) canceled for covid-19 pandemic

COMPETITIVE TELESCOPE/COMPUTER TIME ALLOCATIONS

Class C project IsC74 on MARCONI A2 and GALILEO on the CINECA HPC systems - 35000 h, 1024 Gb

Class C project IsC86 on GALILEO100 on the CINECA HPC systems - 64000 h, 1024 Gb

OTHER RELEVANT ACTIVITIES

Invited talk at Ludwig-Maximillian University “Cosmic voids in modified gravity models with massive neutrinos”

15 January 2020 , WPS meeting talk “Back-in-time Void Finder (BitVF): a code for the dynamical identification of cosmic voids”

6 April 2021 , WPS meeting talk “The constraining power of cosmic void counts”

Co-supervisor of the master’s thesis of Federico Zangrandi “A new free software package for painting galaxies into dark matter haloes”

Co-supervisor of the master’s thesis of Davide Pelliciari “Cosmology from probe combination: synergies between the number counts of galaxy clusters and cosmic voids”

Co-supervisor of the master’s thesis of Luca Stabellini, Simone Sartori, Elena Marcuzzo, Diego Bottoni – in progress

PUBLICATIONS

Cosmic voids uncovered – first-order statistics of depressions in the biased density field - T. Ronconi, **S. Contarini**, F. Marulli, M. Baldi, L. Moscardini (arXiv:1902.04585, MNRAS 488,5075)

Cosmological exploitation of the size function of cosmic voids identified in the distribution of biased tracers - S. Contarini, T. Ronconi, F. Marulli, L. Moscardini, A. Veropalumbo, M. Baldi (arXiv:1904.01022, MNRAS 488, 3526)

Cosmic voids in modified gravity models with massive neutrinos – **S. Contarini**, F. Marulli, L. Moscardini, A. Veropalumbo, C. Giocoli and M. Baldi (arXiv:2009.03309, MNRAS 504,5021)

AMICO galaxy clusters in KiDS-DR3. Cosmological constraints from large-scale stacked weak lensing profiles - C. Giocoli, F. Marulli, L. Moscardini, ..., **S. Contarini**, et al. (arxiv:2103.05653, A&A 653, A19)

AMICO galaxy clusters in KiDS-DR3: cosmological constraints from the galaxy cluster mass function - G. F. Lesci, F. Marulli, L. Moscardini, ..., **S. Contarini**, et al. (arXiv:2012.12273, submitted to A&A)

Euclid: Forecasts from redshift-space distortions and the Alcock–Paczynski test with cosmic voids - N. Hamaus, M. Aubert, A. Pisani, **S. Contarini**, et al. (arXiv:2108.10347, accepted by A&A)

Euclid: Forecasts from the void-lensing cross-correlation - M. Bonici, C. Carbone, S. Davini, ..., **S. Contarini**, ..., WP voids Collab, GCSWG Collab., Other Euclid members (ready to be submitted)

Euclid: cosmological forecasts from void abundance - **S. Contarini**, G. Verza, A. Pisani, N. Hamaus, M. Sahlén, ..., WP voids Collab, GCSWG Collab., Other Euclid members (ready to be submitted)

Cosmology from probe combination: synergies between the number counts of galaxy clusters and cosmic voids - D. Pelliciari, **S. Contarini**, F. Marulli, L. Moscardini (in preparation)