Project title: New Physics in the Intergalactic Medium

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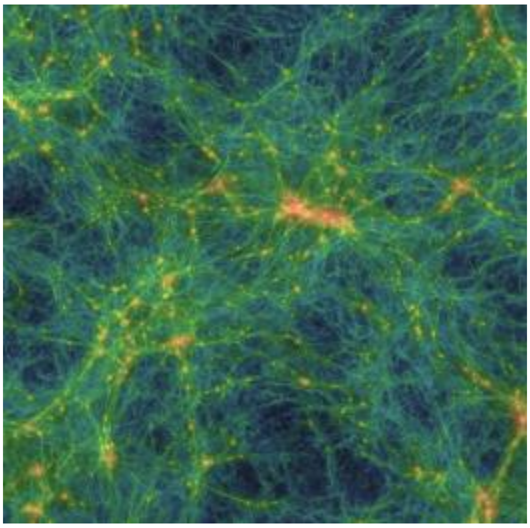
The history of the Universe is recorded in the all-pervading intergalactic medium (IGM), which at high redshift is believed to contain most of the baryons. Throughout the epoch of structure formation, the IGM became clumpy and acquired peculiar motions under the influence of gravity. It acted as a reservoir for the gas that is accreted, cools and forms stars within galaxies and as a sink for the metal-enriched material, energy and radiation that they eject. We can study the spatial distribution, motions, chemical enrichment as well as ionization and thermal histories of gaseous structures from redshifts beyond 7 until the present through the analysis of the absorption features along the line of sight of a distant luminous source such as a QSO, a gamma-ray burst, a galaxy. In this way, it is possible to deduce a surprising number of important properties of our Universe, especially when we link the information provided by absorption lines with the complementary information derived from the Cosmic Microwave Background (CMB) and the evolutionary properties of luminous galactic structures. In the last two decades, the understanding of the IGM has greatly improved. Advances have taken place both in observations (thanks to the availability of new spectroscopic facilities e.g. Keck and VLT) and simulations (e.g. the Sherwood, EAGLE and Illustris projects: Bolton et al. 2017 MNRAS 464, 897; Schaye et al., 2015 MNRAS 446, 521; Vogelsberger et al. 2014 MNRAS 444, 1518). A fairly comprehensive view of the IGM over 14 billion years of cosmic history has been developed (e.g. McQuinn 2016 ARAA, 54, 313). *In the Fig. the simulated cosmic web from the Sherwood relics simulation can be appreciated [see https://www.nottingham.ac.uk/astronomy/sherwood-relics/].*



The study of the IGM impacts in a synergic way on three different key areas: Cosmology, Galaxy Formation & Evolution and Fundamental Physics.
In cosmology the IGM is relevant because it can be used to test our models of structure formation on the smallest comoving scales and upto intermediate-high redshifts (Viel et al. 2005 PhRvD 71, 3534), induces anisotropies in the cosmic microwave background (Hu 2000 ApJ 529, 12), the astrophysical processes that shape the IGM can bias cosmological parameter inferences from galaxy clustering (Wyithe & Dijkstra 2011 MNRAS 415, 3929).
The CMB data have set tight constraints on the matter distribution at large scales at z~1100 and the galaxy clustering and gravitational lensing mapped it at lower redshift, allowing us to enter the era of precision cosmology. The IGM provides unique information at **small scales and intermediate-high redshifts** (e.g. Iršič et al., 2017 MNRAS 466, 4332 and PRD, 96, 2), a range in which cosmic density fluctuations are more linear and thereby the observed flux power spectrum (PS) could better probe primordial features (like those induced by warm dark matter, WDM). The Lyman-α forest has also been used for measuring the Baryon Acoustic Oscillation (BAO) scale at redshift z~2.35 (Blomqvist et al., 2019 A&A 629, A86). In particular, more high-resolution (hi-res), high signal-to-noise-ratio (SNR), high-fidelity spectra are needed, possibly up to z~7, as well as large sets of simulations covering

the cosmological and astrophysical parameter space (varying amplitude, slope, curvature of the linear DM PS and also the thermal history of the IGM).

The goal of the proposed research is to constrain cosmological models in standard and non-standard scenarios by analyzing a database of high resolution and high SNR quasar spectra and comparing the results with simulated lines of sight extracted from hydrodynamic simulations. In order to reach this goal, it will be necessary to improve the knowledge of the astrophysical parameters, thus obtaining information on the thermal evolution of the IGM, reionization redshift, astrophysical modeling of radiative transfer (UV/temperature fluctuations/imprints of reionization).

State of the art achievements will be obtained by exploiting new data and new simulations.

DATA USED: New brighter cosmic beacons are obtained from the QUBRICS survey (Calderone et al. 2019, ApJ, 887, 268; Boutsia et al. 2020, ApJS, 250, 26; Guarneri et al. 2021, MNRAS, 506, 2471); New high-fidelity high-resolution high-SNR spectra are obtained with the ESPRESSO spectrograph, taking advantage of GTO and GO observing time. These spectra will extend the best data obtained with the UVES and HIRES spectrographs (cf. the SQUAD and KODIAQ databases); New high-SNR intermediate resolution spectra, extending to the IR domain will be obtained with the X-Shooter@VLT, MagE and FIRE@Magellan spectrographs, extending the XQ-100 database.

THEORETICAL SETUP

- New physical models for the IGM simulations and new mock data sets will be used. A set of cosmological parameters will be defined in the standard LCDM scenarios and in alternative cosmological models: warm DM (WDM), mixed cold and warm DM models (CWDM) models with an arbitrary suppression of power at small scales able to capture different small scales departure (Murgia et al. 2017, JCAP, 2017, 046; Iršič et al., 2017). The resolution and box sizes will be tailored to address the scientific goals. Where possible, we will use simulations already developed and available to us (Sherwood simulation suite - Bolton et al., 2017; Relics simulation suite - Puchwein et al., 2019). Otherwise, the simulations will be run in dedicated supercomputing machines like the Ulysses supercomputer at SISSA by M. Viel and collaborators.
- Generating a full set of mock QSO spectra as extracted from high-resolution simulations in LCDM and beyond LCDM cosmologies. These spectra will be post-processed in order to provide realistic mock data at the desired resolution and signal to noise to be compared with the data, taking advantage of an analysis pipeline to extract quantitative information from QSO spectra: Bayesian MCMC analysis of transmitted flux power, flux pdf etc.
- New tools for the comparative analysis of the observed and simulated spectra will be used in the framework of the Astrocook environment (Cupani et al., 2020, ASPC, 522, 187) and higher order statistics as new methods to extract information.

The focus of the present PhD project is thus to infer fundamental physical properties of the universe (dark matter, neutrinos, new particles) by the **modelling of IGM**. The aim is to study not only the large scale physics pertaining to the cosmology and background thermal and ionization state of the IGM, but also small scale physics related to alternative DM models, galactic feedback, etc. with improved precision. An analysis pipeline will be used to extract quantitative information from QSO spectra. Bayesian Monte Carlo Markov chains analysis will be performed.