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Mapping the universe with galaxies: astronomy, cosmology, and artificial intelligence (Invited contribution)

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Abstract

This text discusses the cosmic web as a tool to enhance our understanding of galaxy evolution and refine our knowledge of cosmological parameters. It explores recent advances at the intersection of astronomy, cosmology, and artificial intelligence, aiming to extract valuable insights from the cosmic web. As an illustrative example, I showcase the Dark Energy Spectroscopic Instrument (DESI), a Stage-IV spectroscopic survey constructing the most comprehensive 3D map of the universe. Emphasis is placed on how machine learning techniques have been crucial to DESI's scientific mission.

Resumen

Este texto analiza la red cósmica como una herramienta para mejorar nuestra comprensión de la evolución de las galaxias y perfeccionar nuestro conocimiento de los parámetros cosmológicos. Explora los avances recientes en la intersección de la astronomía, la cosmología y la inteligencia artificial, con el objetivo de extraer conocimientos valiosos de la red cósmica. Como ejemplo ilustrativo, menciono el Instrumento Espectroscópico de Energía Oscura (DESI), un estudio espectroscópico de Etapa IV que construye el mapa 3D más completo del universo. Se hace hincapié en cómo las técnicas de aprendizaje automático han sido cruciales para la misión científica de DESI.

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1. Astronomical Achievements

By November 2023, the Dark Energy Spectroscopic Instrument (DESI) collaboration had gathered approximately 27 million galaxy spectra since it started taking science data in May 2021 (DESI Collaboration et al., 2024). This singular number serves as an indicator of the exponential growth in the capabilities for gathering extragalactic spectra since the early eighties of the past century (Schlegel et al., 2022).

DESI was meticulously designed with the ambitious goal of creating the largest and most detailed three-dimensional map of the Universe to date (DESI Collaboration et al., 2022). Its primary objective is to characterize the filamentary structure of matter distribution on the largest scales, known as the cosmic web, with unprecedented detail (DESI Collaboration et al., 2016).

The 3D map created with DESI will serve as the foundation for constraining cosmological parameters, including the time evolution of the dark energy component, aimed at elucidating the accelerated expansion of our Universe. The primary mathematical tool for this purpose is the isotropic two-point correlation function, pioneered by Jim Peebles and refined by observers, theorists, and simulators studying the universe's large-scale structure (Peebles, 2001).

However, a distinctive feature of the cosmic web is its anisotropy, leading to the emergence of new methodologies to quantify anisotropic effects within the cosmic web, enabling new constraints on cosmological parameters (Li et al., 2014).

Furthermore, as cosmic web studies have matured, the traditional cosmic web elements (peaks, sheets, filaments, and voids) have evolved into valuable tools for constraining cosmological parameters. Recent advancements suggest that all cosmic web types are valuable for these constraints (Paillas et al., 2024)

2. Cosmology with the Cosmic Web

At a conceptual level, the current spatial distribution of galaxies relies on two factors: the initial conditions in the universe and the physical laws governing its evolution. Cosmic web science aims to use observed patterns for inferences about these initial conditions and evolutionary laws. For instance, pioneering work in the early eighties demonstrated that the observed galaxy distribution pattern required cold dark matter in the universe's initial conditions (Davis et al., 1985).

In the first decade of the 21st century, cosmic web studies primarily focused on simulations, leading to diverse algorithms classifying the cosmic web into four types: peaks, filaments, sheets, and voids. In the second decade, some algorithms were applied to observational datasets, mainly focusing on identifying voids or filaments. For a comprehensive overview of cosmic web finders, refer to the paper "Tracing the Cosmic Web" (Libeskind et al., 2018).

The cosmic web has found application in various scientific cases, including:

- Determining the position of the Local Group in the cosmic web and assessing the extent of its configuration's commonality in the standard cosmological model (Forero-Romero & González, 2015).
- Quantifying the alignment of dark matter halo shapes, their angular momentum, and peculiar velocities with the cosmic web (Forero-Romero et al., 2014).
- Constraining cosmological parameters by leveraging the anisotropy of the filamentary structure of the cosmic web (Li et al., 2014).

3. Artificial Intelligence in Cosmic Web Science

Due to the significant increase in data volumes compared to previous surveys, Artificial Intelligence (AI) plays a crucial role within DESI across survey design, operations, and data interpretation.

For instance, in the design phase, Machine Learning (ML) and Deep Learning (DL) techniques assist in target selection, defining low-contamination galaxy samples (Darragh-Ford et al., 2023).

In survey operations, ML has been used to identify outliers in spectroscopic data, often stemming from instrument glitches. Addressing these issues involves hardware/software corrections, challenging through visual inspection alone given the vast data quantities (Suárez-Pérez & Forero-Romero, 2022).

On the interpretation front, novel analysis techniques utilize DL algorithms trained on simulated universes to predict cosmological parameters from data similar to DESI's observed 3D map (Villanueva-Domingo & Villaescusa-Navarro, 2022). Convolutional Neural Networks could also be used to estimate cosmological parameters provided that a dark matter reconstruction could be built with DESI data (Pan et al., 2020).

4. Summary

In summary, here are my three key takeaways:

- DESI is a novel experiment, mapping the galaxies in the Universe with unprecedented detail.
- The cosmic web provides sufficient anisotropic information to help constrain cosmological parameters.
- AI plays a crucial role within DESI, impacting survey preparation, operation, data processing, and interpretation.

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