Ph.D. name: Nicola Borghi
PhD Cycle: 36 (first year)
Tutor: Dott. Michele Moresco

RESEARCH PROJECT:

Title: Cosmology with gravitational waves and combination with other probes

In this Ph.D. project, I am exploring cosmological probes beyond the standard ones to maximize their scientific yield and ultimately use new observational data to obtain independent constraints on the expansion history of the Universe. In this first year, I studied the so-called cosmic chronometer (CC) approach, which relies on the differential dating of massive and passively evolving stellar populations to derive direct measurements of the Hubble parameter H(z) (Jimenez & Loeb 2002). In particular, I investigated the stellar population properties of 140 individual passive galaxies at $0.6 < z < 0.9$ obtained from the LEGA-C spectroscopic survey (Straatman et al. 2018) and used an optimized set of optical absorption (Lick) indices to derive stellar ages, metallicities [Z/H], and α-enhancements [α/Fe] (Borghi et al. 2021a). This work provides the first extensive CC analysis with the well-established method of Lick indices. From the age-redshift relation of these galaxies, I obtained a new determination of the Hubble parameter H(z) (Borghi et al. 2021b, *to be submitted*). Much effort was put into the study of the effects that could bias the age-redshift slope, and ultimately, H(z): I repeated the analysis assuming several index sets and binning schemes, and two different sets of models with two different star formation histories (single-burst and exponentially decreasing). Considering all these effects, I derived a new measurement of the Hubble parameter, $H(z=0.75) = 98.8+34.3-24.8$ km/s/Mpc. This result expands the CC approach joining the detailed study of the stellar populations of individual passive galaxies with their underlying cosmology. I presented this work at two international meetings, and contributed to develop PyLick, a Python tool to measure spectral line indices on galaxy spectra that we made available for the community (see refs.). Finally, I worked on two side projects: (1) analysis of a different dataset (SDSS/BOSS) with the same method (Alexandre et al., *in prep*); (2) analysis of the same dataset with a different method, i.e. full spectral fitting (Kang et al., *in prep*).

In the near future, gravitational waves (GW) could potentially be another key probe to study the expansion history of the Universe. Observationally, GW produced from compact binaries can be thought of as standard 'echoes' from which we can derive the luminosity distance of the source itself without additional calibration rungs. To complement this information, the source redshift must be known, either directly from an electromagnetic counterpart ("bright sirens", Holz & Hughes 2005), or inferred through a statistical approach ("dark sirens", e.g. Schutz 1986). Currently, only one bright siren measurement has been performed (GW170817), leading to a new independent determination of the Hubble parameter at z~0, H0=70+12-8 km/s/Mpc. In the next main phase of my Ph.D., I aim to set up a comprehensive framework to explore how GW events and - possibly - their electromagnetic counterparts can be used to study H(z). First of all, I will compare and optimize already available pipelines using the publicly available data from LIGO-Virgo-KAGRA observing runs O1/O2/O3, in preparation for the fourth observing run O4 (scheduled for the second half of 2022). I will also explore synergies with ongoing and upcoming EM telescopes (e.g. SDSS/BOSS, DES, DESI, Nancy Grace Roman Space, Euclid). In particular with Euclid, which will be measuring about 1.5 billion galaxies over a large sky area (15000 sq. deg.) in the redshift range $z=0.8-2$. The spatial distribution of these galaxies can be cross-correlated with GW detections to obtain constraints on H(z) through a statistical

approach (e.g. Mukherjee et al. 2021). Finally, I will study how the combination of GW, CC, and other cosmological probes can be used to break parameter degeneracies and improve our understanding of the expansion history of the Universe and the associated cosmological parameters. This year I attended the ISAPP Summer School on Gravitational Waves and started to build the theoretical framework, learn the data analysis techniques, and study the currently available literature.

Refs.

Borghi N. et al., 2021, «Towards a Better Understanding of Cosmic Chronometers. I. Stellar Population Properties of Passive Galaxies at Intermediate Redshift», *under review* (arXiv:2106.14894)

Borghi N. et al., 2021, «Towards a Better Understanding of Cosmic Chronometers. II. A new measurement of H(z) at z ~ 0.7», *to be submitted*

Farr et al. 2019, «A Future Percent-level Measurement of the Hubble Expansion at Redshift 0.8 with Advanced LIGO», ApJL, 883, L42 (arXiv:1908.09084)

Holz D. E., Hughes S. A., 2005, «Using Gravitational-Wave Standard Sirens» ApJ, 629, 15 (arXiv:astro-ph/0504616)

Jimenez R., Loeb A., 2002, «Constraining Cosmological Parameters Based on Relative Galaxy Ages» ApJ, 573, 37 (arXiv:astro-ph/0106145)

Mukherjee, S. et al. 2021, «Accurate precision cosmology with redshift unknown gravitational wave sources», PhRvD, 103, 4 (arXiv:2007.02943)

PyLick code: https://gitlab.com/mmoresco/pylick

Schutz B. F., 1986, «Determining the Hubble constant from gravitational wave observations» Nature, 323, 310

Straatman C. M. S. et al. 2018, «The Large Early Galaxy Astrophysics Census (LEGA-C) Data Release 2: Dynamical and Stellar Population Properties of z=1 Galaxies in the COSMOS Field» ApJS, 239, 27 (arXiv:1809.08236)

WORKSHOPS, CONFERENCES & MEETING

❖ Nov 2020 - June 2021   **INAF-OAS seminars**

❖ 3 Dec 2020   **11th Einstein Telescope Symposium**

❖ 2 Feb - 14 Dec 2021   **Quid Ultra? Frontiers and controversies in Astrophysics**

❖ 12-16 April 2021   **Extragalactic Spectroscopic Surveys [...] (GALSPEC21)**

❖ 21-23 June 2021   **Massively Parallel Large Area Spectroscopy from Space**

    ➢ Contributed talk: "Robust constraints on the physical properties of individual passive galaxies from Lick indices in the LEGA-C survey

❖ 5-10 July 2021   **Sixteenth Marcel Grossmann Meeting - MG16**

    ➢ Contributed talk: "A new measurement of the expansion history of the Universe from cosmic chronometers in the LEGA-C survey"

❖ 21-22 September 2021   **Kick Off Workshop of the ET Observational Science Board**

PhD SCHOOLS

❖ 7-17 June 2021   **ISAPP Summer School on Gravitational Waves 2021 (remote)**

    ➢ Poster: " Measuring the expansion history of the Universe from cosmic chronometers in the LEGA-C survey" (awarded)

    ➢ Awarded for the data analysis project

❖ 14-18 September 2021 **ONSCI Officina di Narrazione della Scienza (DIFA, Unibo)**

INTERNAL COURSES

❖ 30 Nov - 2 Dec 2020   **The Interstellar Medium**

❖ 29 Jan - 5, 12 Feb 2021 **How to give a scientific presentation and write a scientific paper?**

❖ 19-23 April 2021   **Gamma Ray Bursts: from observations to physical properties**

❖ 5-14 May 2021   **Writing, talking, and presenting Science**

ISA LECTURES

❖ 19/01/2021   "Extreme events: how to describe and predict them using mathematical theories"

❖ 26/01/2021   "RNA: Biological Functions and Therapeutic Potential"

OTHER RELEVANT ACTIVITIES

- ❖ 2020-2021 **Astroversi Podcast (DIFA, Unibo)**
  https://www.spreaker.com/show/dottorato-et-al - role: pre & post-production

- ❖ 14-24 June 2021 **Officina-Laboratorio (DIFA, Unibo)**
  Summer school for high school students, part of the 'Piano Lauree Scientifiche' - Astronomy module: Measurement of the summer solstice [with Prof. M. Gitti e Dott. R. Serra]

- ❖ Nov 2020, Sept 2021 **Notte dei Ricercatori 2020 e 2021 (DIFA, Unibo)**
  [with Dott. R. Serra]

PUBLICATIONS

- ❖ Borghi et al. 2021 - Towards a Better Understanding of Cosmic Chronometers. I. Stellar Population Properties of Passive Galaxies at Intermediate Redshift [under review]
  https://arxiv.org/abs/2106.14894

- ❖ Borghi et al. 2021 - Towards a Better Understanding of Cosmic Chronometers. II. A new measurement of H(z) at z~0.7 [to be submitted]

- ❖ Alexandre et al. (*in prep*)

- ❖ Kang et al. (*in prep)*

Author contributions: CRediT taxonomy*	Borghi21a	Borghi21b
1) Conceptualization		
2) Methodology		✕
3) Software	✕	
4) Validation	✕	✕
5) Formal analysis	✕	✕
6) Investigation	✕	✕
7) Resources		
8) Data curation	✕	✕
9) Writing – original draft	✕	✕
10) Writing – review & editing		
11) Visualization	✕	✕
12) Supervision	✕	✕
13) Project administration		
14) Funding acquisition		

* Url: https://journals.biologists.com/dev/pages/author-contributions