Highlights of Spanish Astrophysics XII, Proceedings of the XVI Scientific Meeting of the Spanish Astronomical Society held on July 15 - 19, 2024, in Granada, Spain. M. Manteiga, F. González Galindo, A. Labiano Ortega, M. Martínez González, N. Rea, M. Romero Gómez, A. Ulla Miguel, G. Yepes, C. Rodríguez López, A. Gómez García and C. Dafonte (eds.), 2025

Exploring Galaxies in Cosmic Voids: CAVITY and its First Public Data Release (DR1)

I. Pérez[1,2], S. Verley[1,2], L. Sánchez-Menguiano[1,2], T. Ruiz-Lara[1,2], R. García-Benito[3], S. Duarte Puertas[1,2,4], A. Jiménez[1], J. Domínguez-Gómez[1], D. Espada[1,2], R. F. Peletier[5], J. Román[6], M. I. Rodríguez[1], M. Argudo-Fernández[1,2], G. Torres-Ríos[1], B. Bidaran[1], M. Alcázar-Laynez[1], R. van de Weygaert[5], S.F. Sánchez[7], U. Lisenfeld[1,2], A. Zurita[1,2], E. Florido[1,2], J. M. van der Hulst[5], G. Blázquez-Calero[3], P. Villalba-González[8], I. del Moral-Castro[9], P. Sánchez Alarcón[10], A. Lugo-Aranda[11], M. Canossa[5], A. Conrado[3], S.B. De Daniloff[1,18], R. González Delgado[3], J. Falcón-Barroso[10,12], A. Ferré-Mateu[10,12], M. Hernández-Sánchez[13], P. Awad[5,14], K. Kreckel[15], H. Courtois[16], L. Galbany[17], P. Sánchez-Blázquez[6], E. Pérez-Montero[3], M. Sánchez-Portal[18], A. Bongiovanni[18] , S. Planelles[13], V. Quilis[13], P. Vasquez-Bustos[1], A. Weijmans[19], M. A. Raj[5], M. A. Aragón-Calvo[7], J.F. Agüí-Fernández[20], M. Blažek[20], G. Bergond[20], A. Fernández-Martín[20], J. Flores[20], S. Góngora[20], A. Guijarro[20], I. Hermelo[20],V. Pinter[20], J. I. Vico Linares[20]

[1] Universidad de Granada, Departamento de Física Teórica y del Cosmos, Campus Fuentenueva, Edificio Mecenas, E-18071, Granada, Spain (e-mail: isa@ugr.es)
[2] Instituto Carlos I de Física Teórica y Computacional, Facultad de Ciencias, E-18071 Granada, Spain
[3] Instituto de Astrofísica de Andalucía - CSIC, Glorieta de la Astronomía s.n., 18008 Granada, Spain
[4] Départment de Physique, de Génie Physique et d'Optique, Université Laval, and Centre de Recherche en Astrophysique du Québec (CRAQ), Québec, QC, G1V 0A6, Canada
[5] Kapteyn Astronomical Institute, University of Groningen, Landleven 12, 9747 AD Groningen, The Netherlands
[6] Departamento de Física de la Tierra y Astrofísica & IPARCOS, Universidad Complutense de Madrid, E-28040, Madrid, Spain
[7] Universidad Nacional Autónoma de México, Instituto de Astronomía, AP 106, Ensenada 22800, BC, México
[8] Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada
[9] Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile
[10] Instituto de Astrofísica de Canarias, Vía Láctea s/n, 38205 La Laguna, Tenerife, Spain

[11] Instituto de Astronomía, Universidad Nacional Autónoma de México, A. P. 70-264, 04510, México, D.F., Mexico
[12] Departamento de Astrofísica, Universidad de La Laguna, 38200 La Laguna, Tenerife, Spain
[13] Departament d'Astronomia i Astrofísica, Universitat de València, E-46100 Burjassot (València), Spain
[14] Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, University of Groningen, 9700 AK, Groningen, The Netherlands
[15] Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, 69120 Heidelberg, Germany
[16] Université Claude Bernard Lyon 1, IUF, IP2I Lyon, 4 rue Enrico Fermi, Villeurbanne, 69622, France
[17] ICE-CSIC, Carrer de Can Magrans, 08193 Cerdanyola del Vallés, Barcelona, Spain
[18] Institut de Radioastronomie Millimétrique (IRAM), Av. Divina Pastora 7, Local 20, 18012 Granada, Spain
[19] School of Physics and Astronomy, Univ. of St Andrews, North Haugh, St Andrews, KY16 9SS, UK
[20] Centro Astronómico Hispano en Andalucía, Observatorio de Calar Alto, Sierra de los Filabres, 04550 Gérgal, Almería, Spain

Abstract

This contribution presents a summary of the Calar Alto Void Integral-field Treasury surveY (CAVITY) project, focusing on the first public Data Release 1 (DR1). The CAVITY project is a Calar Alto Legacy project at the 3.5 m telescope using the PMAS integral field spectrograph (IFS). The aim is to investigate the properties of a final sample of around 300 galaxies inhabinting cosmic voids, with the goal of understanding galaxy formation and evolution in low-density environments. Complementary follow-up projects, including deep optical imaging, integrated as well as resolved CO data, and integrated HI spectra, have joined the PMAS/PPak observations and naturally complete the scientific aim of CAVITY. The DR1 offers, already fully available to the public, PMAS IFS datacubes for 100 galaxies, key to reveal structural, chemical, and dynamical properties of void galaxies, enriching our understanding of how these isolated systems compare to galaxies in denser regions.

1 Introduction

The CAVITY project is a large-scale observational effort, one of the Legacy projects of the Calar Alto Observatory, dedicated to studying galaxies within cosmic voids[7]. These low-density regions comprise about 70% of the universe's volume but contain only around 10% of its mass [5]. Galaxies in voids provide a natural laboratory for studying isolated galaxy evolution, as they are relatively unaffected by interactions with neighboring galaxies.

Using the PMAS/PPak spectrograph on the 3.5m telescope at the Calar Alto Observatory, the CAVITY project aims to provide high-quality integral field spectrograph (IFS) data for around 300 galaxies to understand the unique properties of void galaxies.

Data Release 1, DR1 [4], is the first publicly available dataset from CAVITY, containing IFS observations of 100 void galaxies that can be easily accessed from the dedicated database[1]. This release marks a significant milestone, offering researchers a new resource to study galaxy formation, star formation histories, and dark matter distribution in low-density environments.

2 CAVITY project

The CAVITY project is driven by several key scientific questions:

- How does the large-scale void environment impact the mass assembly and chemical evolution of galaxies?
- What are the specific star formation histories (SFHs) and stellar population properties of void galaxies?
- How do void galaxies differ in their dark matter content compared to galaxies in denser environments?

2.1 Sample selection

In the CAVITY project, galaxies located in cosmic voids were identified from a catalogue based on Sloan Digital Sky Survey data[6], based on data from the Sloan Digital Sky Survey (SDSS). This initial selection was refined to focus on voids fully enclosed within the SDSS footprint and in a redshift range of 0.005 to 0.050. To ensure representativeness, only voids with at least 20 galaxies were included, resulting in a subset of 42 voids containing 8,690 galaxies. Further narrowing down identified 15 key voids that cover a broad range of properties, such as effective radius, galaxy density, and color distributions, making the final sample suitable for observation from the Calar Alto Observatory.

The final sample for the CAVITY project, known as the 'CAVITY parent sample', contains 4866 galaxies after removing those in close association with dense clusters. An additional refinement based on void centre distance was applied, including only galaxies within 0.8 times the effective radius of each void to capture those most centrally located within these underdense regions. Careful verification of each galaxy's observability further reduced the sample to 1115 galaxies, accounting for factors like surface brightness and observational suitability. This selection ensures that the sample is representative of void environments, enabling detailed investigation of galaxy evolution in these isolated, low-density cosmic regions (see [7, 4] for a more detailed explanation on the sample selection).

[1] https://cavity.caha.es/

2.2 Observations, data reduction, and DR1

Observations for the CAVITY project are conducted with the PMAS spectrograph in PPak mode, which provides integral field spectroscopy (IFS) data over a 74"x64" field of view (FoV) with 60% coverage. This configuration utilises 331 fibers to observe the target region, along with six independent bundles of six fibers each positioned 72" from the center to sample the sky background. Our primary observational setup employs the V500 grating, covering wavelengths from 3745 to 7300 Å with a resolution of approximately 6 Å. Additionally, we plan to use the V1200 grating in upcoming observations to target brighter galaxies, covering 3400–4750 Å with a higher resolution of 2.7 Å. To achieve complete coverage, we apply a three-point dithering pattern, with total exposure times between 1.5 and 3 hours depending on the galaxy's brightness. Data are collected at airmasses below 1.4 to ensure optimal observation conditions.

The CAVITY pipeline follows a similar reduction process to that of the CALIFA survey [7, 4]. This process involves merging raw data from the 4k x 4k detector, correcting cosmic rays and bad pixels, and applying wavelength and flux calibrations. Sky subtraction is performed using sky fibers, and the data are resampled and spatially reconstructed into a 3D datacube with a 1"/pixel scale. Further processing includes correcting for differential atmospheric refraction, as well as Galactic extinction. Final datacubes are thus optimized for scientific analysis, with anticipated future improvements in flux calibration linked to SDSS DR16. This setup provides the scientific community with high-quality spatially resolved data of galaxies in cosmic voids, enabling detailed studies of their unique properties.

Data Release 1 (DR1) comprises IFS data for 100 void galaxies, covering the stellar mass - optical colour space of galaxies in voids. Fig. 1 displays the distribution of CAVITY and DR1 galaxies in the colour-magnitud diagram. See [4]for further details on the DR1 characteristics.

3 CAVITY+ Expansion

The CAVITY+ project extends the capabilities of CAVITY by incorporating additional data types, providing a multi-wavelength perspective on void galaxies. Key additions include:

- **CO Observations**: Molecular gas data to provide insights into the cold gas reservoirs in void galaxies. Single dish CO spectroscopic survey was carried out on a sample of 106 CAVITY galaxies. Interferometric CO(1-0) data have been secured from the Atacama Large Millimeter/submillimeter Array (ALMA) for a sub-sample of 41 galaxies at similar resolution than the IFS data (less than 1 kpc).
- **HI Spectroscopy**: Neutral hydrogen (HI) data complementing the IFS and CO database. A dedicated observing campaign of 146 hours has been executed with the Green Bank Telescope to observe 78 CAVITY galaxies with CO information from IRAM 30m and for which no HI spectra was available from the literature.
- **Deep Optical Imaging**: The deep optical imaging to support detailed morphological studies of void galaxies. We have carried out dedicated extensive observational cam-

paigns with the 2.54-m *Isaac Newton* Telescope to provide deep imaging of the CAVITY galaxies. We use the Wide Field Camera (WFC). We use the SDSS g and r filters.

These complementary datasets enhance the insights from the IFS data, allowing for a more comprehensive examination of star formation potential, structural characteristics, and gas dynamics in void galaxies, Fig. 2 shows the potential of the CAVITY and project extension data.

4 Status of the project and Future Directions

To date, 240 galaxy data cubes have been generated, 100 of which were made available to the scientific community in the first CAVITY data release (DR1[4]) on July 15, 2024. The data are ready for immediate use and can be downloaded from the project database[2]. In the second public data release, scheduled for July 2026, an expanded sample of 300 void galaxy cubes is expected to be shared with the community, along with detailed maps of their properties.

The IFS database for the 300 galaxies in the CAVITY study, along with all additional information from the expanded CAVITY+ project, will offer a unique opportunity to explore the properties of galaxies residing in cosmic voids. This will allow the scientific community to address a wide range of astrophysical questions. Within the CAVITY team's expertise, there is a particular interest in investigating aspects such as baryonic mass assembly, the impact of large-scale environments on gas accretion, specific star formation rates, and the molecular and atomic gas content in void galaxies. Additionally, the team is particularly interested in tracing galaxy merger and accretion histories through light distribution in the outer regions of galaxies, as well as studying the influence of local versus large-scale environments on general galaxy properties. Another active area of research is characterising the effects of large-scale structure on the prevalence of AGNs and their role in the cessation or enhancement of star formation in void galaxies. Finally, the properties and formation of dwarf galaxies in these environments are one of the collaboration's key projects.

In previous studies by the CAVITY team [2, 3], using 1D integrated SDSS spectra, it was concluded that stellar mass assembly in void galaxies occurs more slowly than in filament and wall galaxies, and much more slowly than in clusters, suggesting that different physical factors drive galaxy evolution depending on the large-scale environment. Additionally, an analysis of the relationship between stellar mass and metallicity in the same sample revealed that enrichment processes vary by environment.

We recently published the first papers showcasing the potential of CAVITY's spatially resolved data, presenting the stellar properties of void galaxies using data cubes from CAVITY galaxies [1, 9]. These works found that spiral galaxies in voids tend to have lower surface mass densities and younger stellar ages than galaxies in denser environments, suggesting the presence of less-evolved disks in cosmic voids. Additionally, in a recent study on the molecular content of void galaxies, Rodríguez et al (2024)[8] demonstrated that the total molecular gas

[2]https://cavity.caha.es/

content of CAVITY galaxies is similar to that of galaxies located in denser environments. With the release of data cubes for the first 100 CAVITY galaxies, the development of the CAVITY+ database, and ongoing scientific analyses, the exploitation of CAVITY data is now set to yield its most significant scientific results. This data will provide new insights into how the cosmic environment affects galaxy evolution, contributing significantly to our understanding of the universe.

Acknowledgments

Based on observations collected at the Centro Astronómico Hispano en Andalucía (CAHA) at Calar Alto, operated jointly by Junta de Andalucía and Consejo Superior de Investigaciones Científicas (IAA-CSIC). We acknowledge financial support by the research projects AYA2017-84897-P, PID2020-113689GB-I00, and PID2020-114414GB-I00, financed by MCIN/AEI/10.13039/501100011033, the project A-FQM-510-UGR20 financed from FEDER/Junta de Andalucía-Consejería de Transformación Económica, Industria, Conocimiento y Universidades/Proyecto and by the grants P20-00334 and FQM108, financed by the Junta de Andalucía (Spain). TRL acknowledges support from Juan de la Cierva fellowship (IJC2020-043742-I) LSM acknowledges support from Juan de la Cierva fellowship (IJC2019-041527-I). DE acknowledges support from a Beatriz Galindo senior fellowship (BG20/00224) from the Spanish Ministry of Science and Innovation. RGD, RGB, and AC acknowledge financial support from the State Agency for Research of the Spanish MCIU through 'Center of Excellence Severo Ochoa' award to the Instituto de Astrofísica de Andalucía, CEX2021-001131-S, funded by MCIN/AEI/10.13039/501100011033, and to financial support from the projects PID-2019-109067-GB100 and PID2022-141755NB-I00. HC also acknowledges support from the Institut Universitaire de France and from the CNES. JF-B acknowledges support from the PID2022-140869NB-I00 grant from the Spanish Ministry of Science and Innovation. VQ,SP, and MH acknowledge that this work has been supported by the Agencia Estatal de Investigación Española (AEI; grant PID2022-138855NB-C33), by the Ministerio de Ciencia e Innovación (MCIN) within the Plan de Recuperación, Transformación y Resiliencia del Gobierno de España through the project ASFAE/2022/001, with funding from European Union NextGenerationEU (PRTR-C17.I1), and by the Generalitat Valenciana (grant PROMETEO CIPROM/2022/49). PSB acknowledges financial support from the from the Spanish Ministry of Science under the projects with references: PID2019-107427GB-C31 and PID2022-138855NB-C31. PVG acknowledges that the project that gave rise to these results received the support of a fellowship from "la Caixa" Foundation (ID 100010434). The fellowship code is B005800. AFM acknowledges support from RYC2021-031099-I and PID2021-123313NA-I00 of MICIN/AEI/10.13039/501100011033/FEDER, UE, NextGenerationEU/PRT. IMC acknowledges support from ANID programme FONDECYT Postdoctorado 3230653 and ANID, BASAL, FB210003 M.A-F. and P.V-B acknowledges support from the Emergia program (EMERGIA20-38888) from Consejería de Universidad, Investigación e Innovación de la Junta de Andalucía. JR acknowledges funding from University of La Laguna through the Margarita Salas Program from the Spanish Ministry of Universities ref. UNI/551/2021-May 26, and under the EU Next Generation. GTR acknowledges financial support from the research project PRE2021-098736, funded by MCIN/AEI/10.13039/501100011033 and FSE+.

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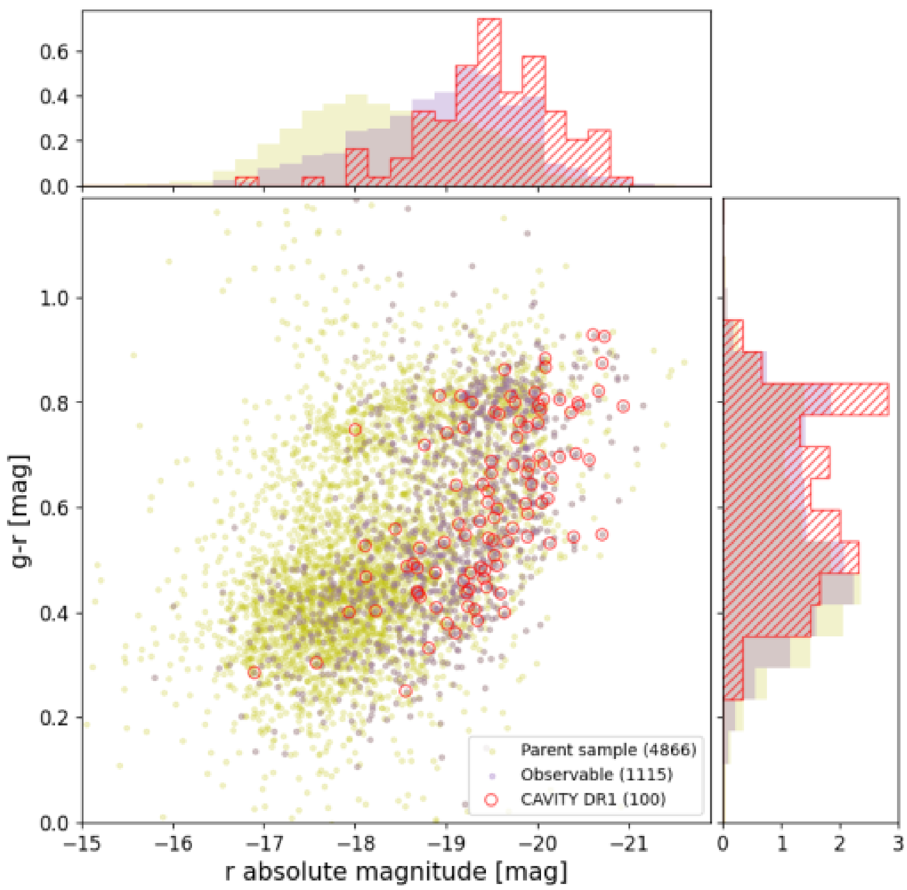

Figure 1: Colour-magnitude diagram of the CAVITY galaxies in the SDSS. Yellow dots (and histograms) represent galaxies in the CAVITY parent sample (4,886 galaxies), while violet and red indicate galaxies in the observable subsample (1115) and the final CAVITY DR1 sample (100), respectively. The top and side panels display the color and absolute magnitude distributions for each group.

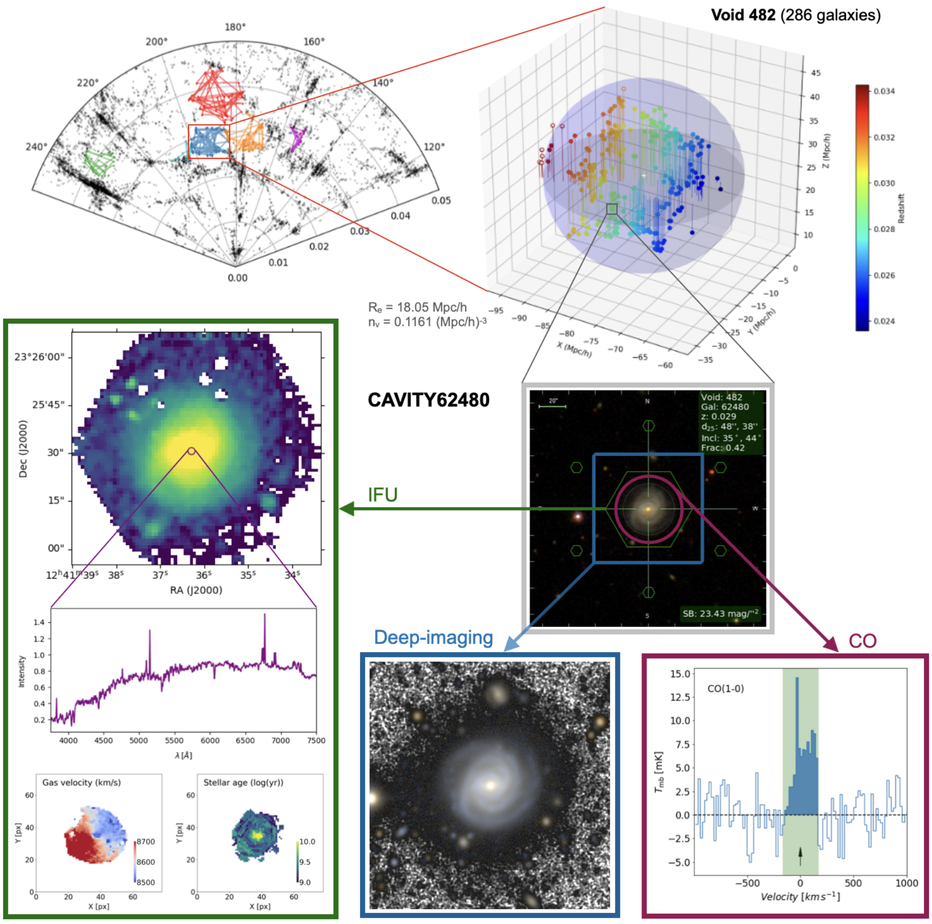

Figure 2: Summary figure of CAVITY and project extension. The middle right panel (framed by a grey square) zooms in on CAVITY62480, an example galaxy contained in void 482, showing its SDSS colour image with the PMAS footprint (green hexagon), INT cutout (blue square), and IRAM beam (purple circle) on top of it. The next main section (framed by the green rectangle) is devoted to illustrate the IFS data. We represent the integrated light of the galaxy within the covered wavelength range of the instrument (on top), the spectrum of the central spaxel (in the middle), and the gas velocity and stellar age maps (at the bottom) as examples of the potential of IFS data in deriving spatially resolved distributions of the galaxy properties. We show a coloured image using the INT g- and r-band deep imaging (framed by the blue rectangle, bottom middle panel) and the integrated CO(1-0) spectrum from the IRAM observations purple rectangle, bottom right panel) for CAVITY62480.