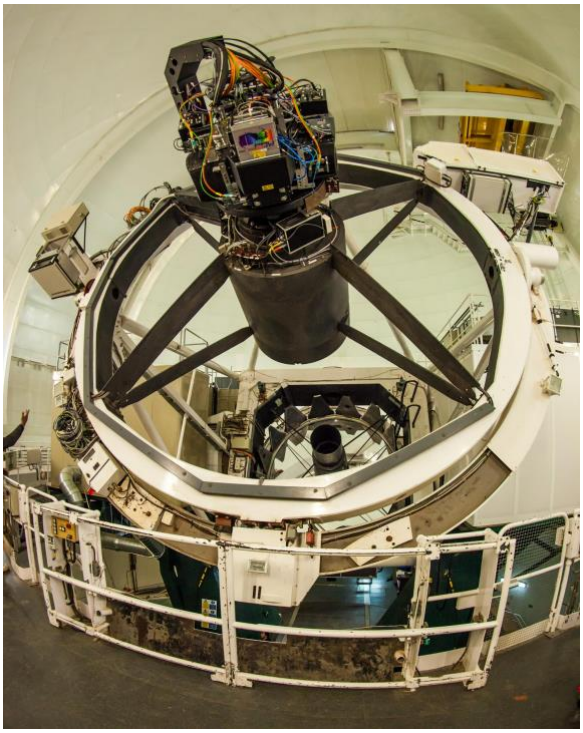
Instituto de Física Teórica UAM-CSIC

The PAUS survey releases a new cosmic distance catalogue to unlock the mysteries of the Universe formation

- **The catalogue collects data for over 1.8 million objects gathered over 200 nights between 2015 and 2019, using the 4.2-meter WHT telescope in La Palma, Spain.**

- **The released information will help astronomers to understand the formation of cosmic structures influenced by dark matter and dark energy.**

- **IFT-UAM/CSIC has contributed to the study along with six other Spanish institutions. ICE-CSIC has led the PAUS survey, coordinated the observations and the scientific exploitation, in close collaboration with IFAE, IEEC, PIC, CIEMAT, Durham University, Ruhr-Universität Bochum, University College London, ETH Zurich, Leiden Observatory, the University of Portsmouth and Tsinghua University.**



La cámara PAUcam instalada en el foco primario del telescopio William Herschel (WHT) en La Palma, España. Créditos: PAUS.

Madrid, September 17, 2024.- The Physics of the Accelerating Universe Survey (PAUS), an international collaboration led by the Institute of Space Sciences (ICE-CSIC), dependent on the Ministry of Science, Innovation and Universities (MICIU), involving 14 institutions across six countries, releases a groundbreaking catalogue of cosmic distances. Collected over 200 nights between 2015 and 2019 using the PAUCam camera on the William Herschel Telescope (WHT) in La Palma, this catalogue is now available on the PAUS website and the CosmoHub web portal. The release is detailed in two articles published today in the *Monthly Notices of the Royal Astronomical Society (MNRAS):* one measuring distances and another one on calibration of the PAUS data.

This new catalogue provides information on millions of distant galaxies, determining their distances with unprecedented precision over a field of view and depth never before explored. Covering a vast sky area of 50 square degrees, similar to an area of approximately 250 full moons, it includes data for 1.8 million astronomical objects. These insights will enable astronomers to create more accurate maps to understand how structure forms in the Universe and to study dark matter and dark energy.

The PAUCam camera was specially designed to accurately measure galaxy distances, enabling the study of the Universe's expansion under the influence of dark matter and dark energy. The project builds on existing deep images from the Canada-France-Hawaii Telescope Lensing Survey (CFHTLenS), carried out with the Canada-France-Hawaii Telescope in Hawaii, and the Kilo-Degree Survey (KiDS) carried out with the European Southern Observatory's VLT Survey Telescope in Chile. By combining these datasets, PAUS has achieved highly accurate distance and time information for deep space objects.

The work of theoretical physicists, such as **IFT cosmologist Juan García-Bellido**, has contributed both to the construction of the PAUCam camera and to the interpretation of the data obtained. "This PAUS mapping was made possible thanks to the collaboration of the six Spanish groups, who installed the camera on the William Herschel telescope," says García-Bellido. "Unlike other projects such as the Dark Energy Survey (DES) or the Legacy Survey of Space and Time (LSST), which use only five filter bands, **PAUS also has 40 narrow-band filters. This allows us to significantly improve the precision of galaxy measurements**, achieving a redshift position resolution of about one part in a thousand, compared to about one part in a hundred in other experiments. This advantage enables us to measure many aspects of the universe that we couldn't before, **providing an unprecedented window into the evolution and structure of the cosmos**," the cosmologist emphasizes.

The accelerated expansion of the Universe is attributed to dark energy, which constitutes about 70% of the Universe, yet its nature remains a mystery. The PAUS survey offers new insights into this enigma, providing an accurate and comprehensive characterisation of millions of galaxies up to distances of more than 10 billion light years. This catalogue is a valuable resource for the astronomical community, aiding in the scientific analysis and calibration of other cosmological surveys.

"The PAU Survey offers a groundbreaking approach to creating cosmic maps, made possible through the design and development of a novel instrument and a dedicated survey to collect and analyse data in ways never done before. It has been a privilege to collaborate with such a talented and dependable group," says Enrique Gaztañaga, Director of the PAUS Survey, which started in 2015, and currently a Professor at the Institute of Cosmology and Gravitation at the University of Portsmouth, on leave from ICE-CSIC and the Institute of Space Studies of Catalonia (IEEC).

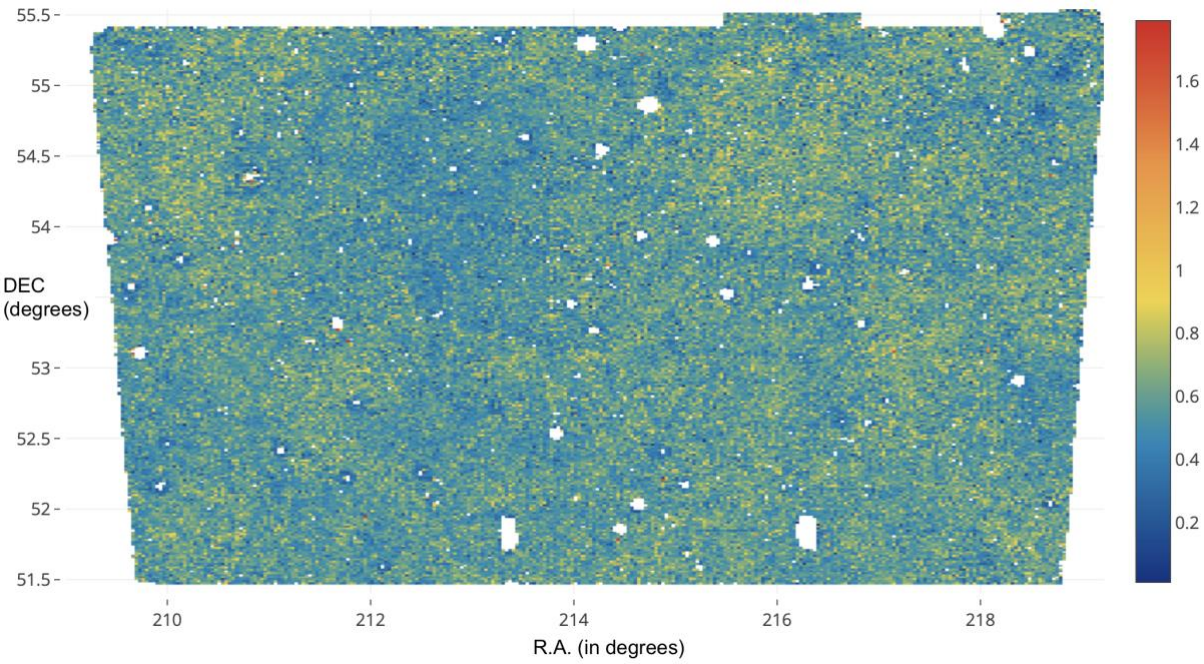
A Milestone in Cosmic Research

This catalogue represents a significant advancement in cosmic research with its extensive catalogue offering photometric redshift measurements that determine the distances of galaxies as they appeared billions of years ago. To achieve these measurements, the PAU camera employs 40 filters across different colours, representing narrow bands in the optical spectrum. This technique involves photographing the same field multiple times through various colour filters. As objects move away from us, the light they emit experiences a redshift, shifting towards the red end of the spectrum. In astronomy, redshift is crucial for calculating the distance of an object from Earth.

While ongoing and future state-of-the-art spectroscopic cosmic surveys are equipped with large focal planes that enable simultaneous measurement of redshifts for thousands of preselected galaxies—acquiring several hundred galaxy redshifts per square degree in a single observation (out of a total of approximately 30,000 galaxies at the desired depth limit)—the PAUS survey takes a different approach. PAUS does not require preselecting target galaxies. Instead, it utilises its 40 filters to measure the redshifts of all 30,000 galaxies within the field of view at once, albeit with lower spectral resolution.

"The precision in measuring galaxy distances depends on the number of filters you use, as each filter provides different information about the galaxy. The great advantage of PAUS is that it combines information of 40 different filters, allowing for highly accurate distance measurements. This level of precision is crucial for the study of the structure of the universe, which in turn requires data from a large number of galaxies" says David Navarro-Gironés, PhD student at ICE-CSIC and first author of the paper published today.

The PAUS survey provides complete, flux-limited, and highly accurate redshift and spectral energy distribution information for millions of galaxies and stars, reaching a depth and coverage previously unexplored. This is accomplished without the need for specific target selection, offering a powerful tool to better understand sample selection and completeness in astronomical surveys.



This map shows the sky positions of approximately 750,000 galaxies in one of the four PAUS fields (W3 CFHT-Lens). The colours represent the mean redshift (z) of galaxies in each pixel, with z indicating both cosmic distance and time. For instance, z ≈ 0.9 (yellow) indicates light emitted about 7.4 billion years ago, when the universe was 1.9 times smaller than it is today. Empty regions correspond to bright foreground objects (bright stars or galaxies) that obscure more distant galaxies. This map provides valuable insights into the large-scale structure of the universe, supporting studies of galaxy evolution, dark matter and dark energy. Credits: CosmoHub.com

International contribution to the PAUS survey

An extensive international collaboration involving contributions from Spain, the United Kingdom, the Netherlands, Switzerland, Germany and China has made the PAUS survey possible. The scientific exploitation of PAUS survey data—including observations, data reduction and calibration, simulations, photometric redshift, and clustering analysis—has been spearheaded by ICE-CSIC alongside the Institut de Física d'Altes Energies (IFAE) and other Spanish institutions such as the Port of Scientific Information (PIC, a joint venture between IFAE and CIEMAT), the Institute of Space Studies of Catalonia (IEEC), the Instituto de

Física Teórica (IFT-UAM/CSIC), and the Research Centre for Energy, Environment and Technology (CIEMAT).

The construction and integration of PAUCam was entirely carried out in-house in Barcelona, led by IFAE in partnership with ICE-CSIC, PIC, IEEC, CIEMAT, and IFT-UAM/CSIC. Besides helping in the camera design, optical bench and construction, the ICE-CSIC also played a pivotal role in data reduction, calibration, automated analysis pipelines, and data distribution, working closely with PIC, which serves as the PAUS data centre, alongside the broader PAUS team.

CIEMAT was responsible, together with IFAE, for the design, production, testing and installation of the full PAUCam electronics. CIEMAT was also responsible for the testing and validation of the filters and the production and installation of several mechanical parts of the camera.

The commissioning and first light of PAUCam on the 4.2m WHT Telescope were achieved by these Spanish groups in 2015, with invaluable assistance from the WHT engineers of the Isaac Newton Group of Telescopes (ING) in La Palma. Following this milestone, an international collaboration was formed in 2015, including Durham University (the United Kingdom), Leiden Observatory (the Netherlands), Ruhr-Universität Bochum (Germany), University College London (UCL, the United Kingdom), ETH Zurich (Switzerland), the Institute of Cosmology and Gravitation at the University of Portsmouth (the United Kingdom), and Tsinghua University (China). These institutions contributed external funding, human resources and expertise, playing a crucial role in the successful execution and exploitation of the PAUS survey.

The teams from Leiden, the UK, and Spain, as members of the ING Group, also secured observing time by successfully competing in 10 different international time allocation competition calls between 2015 and 2019. Additionally, external groups have had the opportunity to use PAUCam as a visitor instrument for various observational campaigns.

Scientific exploitation

The foundations of the PAUS project were laid around 2007 as part of the Consolider Ingenio 2010 initiative, funded by the Spanish government. The Spanish groups mentioned above continued the project, building PAUCam for its use at the WHT telescope and forming the PAUS Collaboration, which prepared for the analysis of the data now being released.

"Starting a collaboration of several Spanish groups and continuing it with a very ambitious instrument, despite rather limited material and human resources, was not without risks. However, the fact is that the camera worked correctly almost from first light. Equally remarkable is that six European and one Chinese group joined PAUS for data analysis, contributing with their own resources," says Enrique Fernández, from IFAE and UAB

(Universitat Autònoma de Barcelona), who led the PAU Consolider Project and the PAUS Collaboration during its initial years.

Nine years after its first light in 2015, the PAUS survey has reached a remarkable milestone, measuring the distances of numerous distant galaxies with a relative precision of 0.3%. The team is currently utilising this data to enhance the calibration of existing cosmological surveys. For instance, PAUS data is being used to improve weak lensing analyses and simulations for dark energy missions such as ESA's Euclid mission and the Rubin Observatory's Legacy Survey of Space and Time (LSST).

Additionally, these samples can refine the redshift distributions for such missions, as has already been done for the scientific collaborations Kilo-Degree Survey (KiDS) and the Dark Energy Survey (DES).

"In addition to high-precision redshifts, the 40 narrow band filters of PAUS offer a unique window into the evolution and environment of galaxies. With PAUS, we can directly observe strong emission lines and spectral breaks. usually reserved to slower and more expensive spectroscopic surveys. These observations allow us to better constrain the age and composition of galaxies, identify quasars with high accuracy, and may even provide a window into the diffuse gas clouds around and between galaxies", says Pablo Renard, a postdoctoral fellow at Tsinghua University and currently Data Manager of PAUS.

In the coming months, the team will also present an ongoing study on galaxy clustering and intrinsic galaxy shape alignments, contributing to a deeper understanding of how our universe formed and evolved.

More information

- D. Navarro, E. Gaztanaga, M. Crocce, A. Wittje et al, The PAU Survey: Photometric redshift estimation in deep wide fields. Monthly Notices of the Royal Astronomical Society. DOI: 10.1093/mnras/stae1686

- F. Castander, S. Serrano, M. Eriksen, E. Gaztanaga et al, The PAU survey: photometric calibration of narrow band images. Monthly Notices of the Royal Astronomical Society. DOI: 10.1093/mnras/stae1507

- PAUS data available here: https://pausurvey.org/public-data-release/.

- More details about PAUS: https://pausurvey.org. Other publications by PAUS: https://pausurvey.org/pausurvey/publications/

IFT

The Institute for Theoretical Physics (IFT) UAM-CSIC was officially created in 2003 as a joint research center belonging to the Spanish National Research Council (CSIC) and the Autonomous University of Madrid (UAM). It is the only Spanish center dedicated entirely to research in Theoretical Physics. The IFT members develop research in the frontiers of Elementary Particle Physics, Astroparticles and Cosmology, in order to understand the fundamental keys of Nature and the Universe. They are also leading many research projects, both at the national and international level. The IFT is part of the strategic line `Theoretical Physics and Mathematics´ of the Campus of International Excellence (CEI) UAM+CSIC established in 2009. Since 2012, it is credited as Severo Ochoa Centre of Excellence. Besides purely scientific activity, in the IFT is also conducted intensive training tasks of young researchers and professionals through the graduate program in Theoretical Physics with mention of excellence from the CEI and the Ministry of Education. In addition, the Institute carries out the important task of transferring knowledge to society through several outreach programs.

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