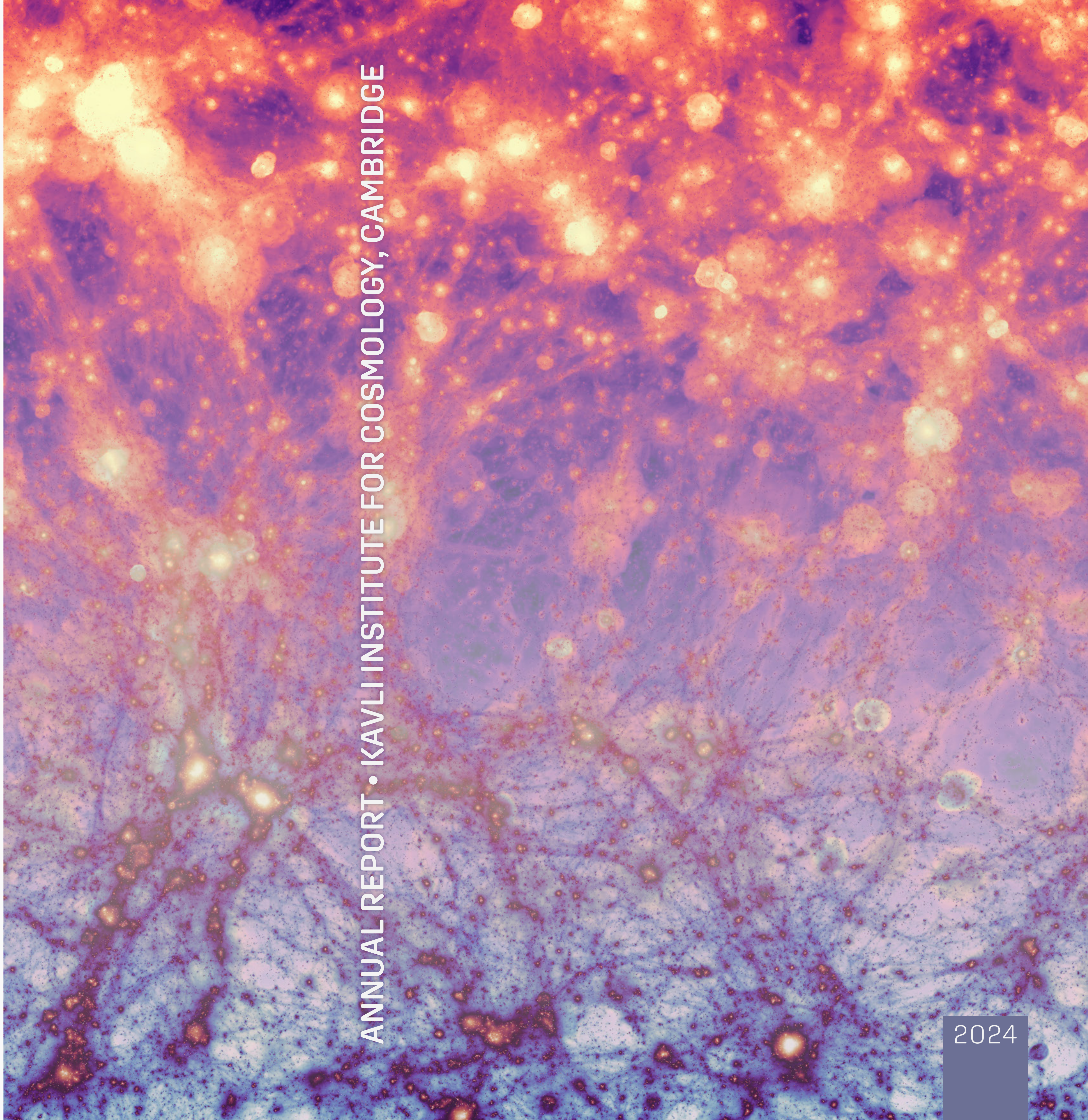
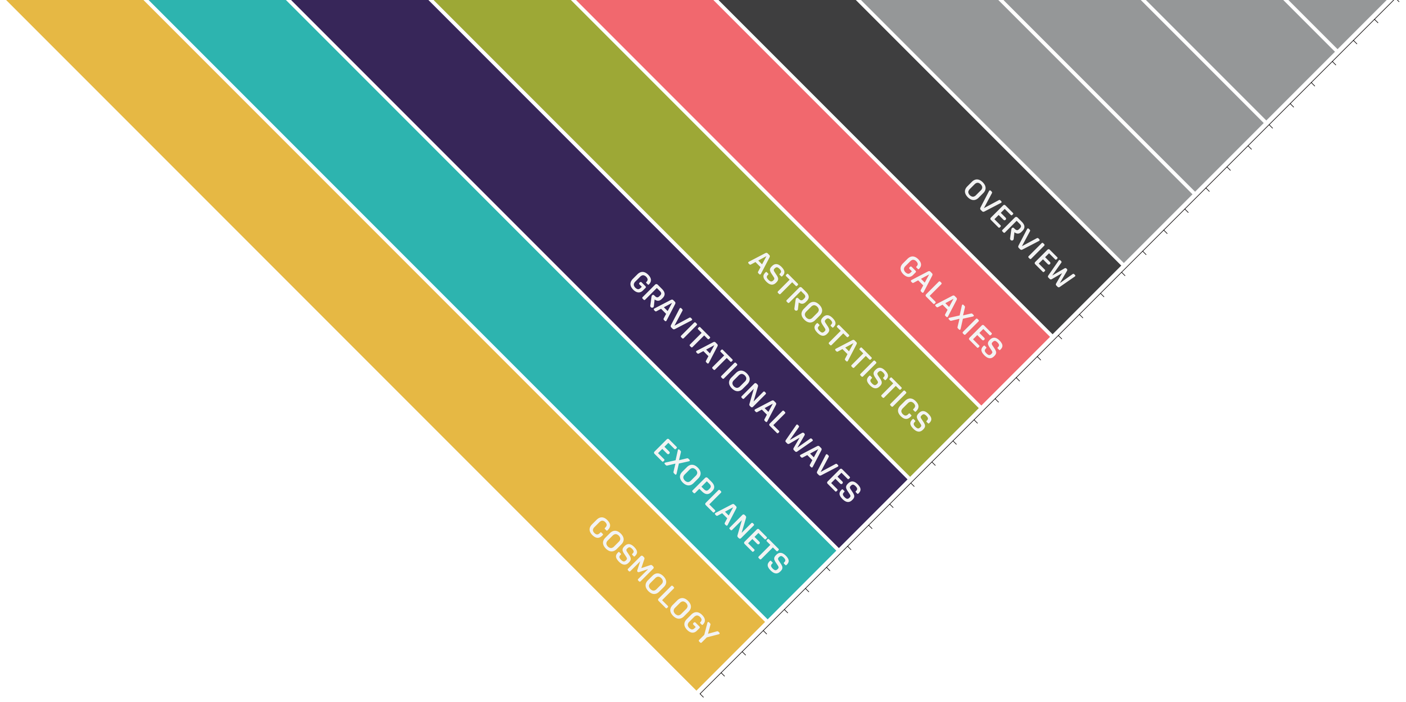
Cover Image: Projection visualising the blend of the gas surface density and mass-weighted temperature of our new AGN feedback model XFABLE (from Bigwood et al. 2025, MNRAS submitted. Pg. 38)

Kavli Institute for Cosmology, Cambridge, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom. www.kicc.cam.ac.uk



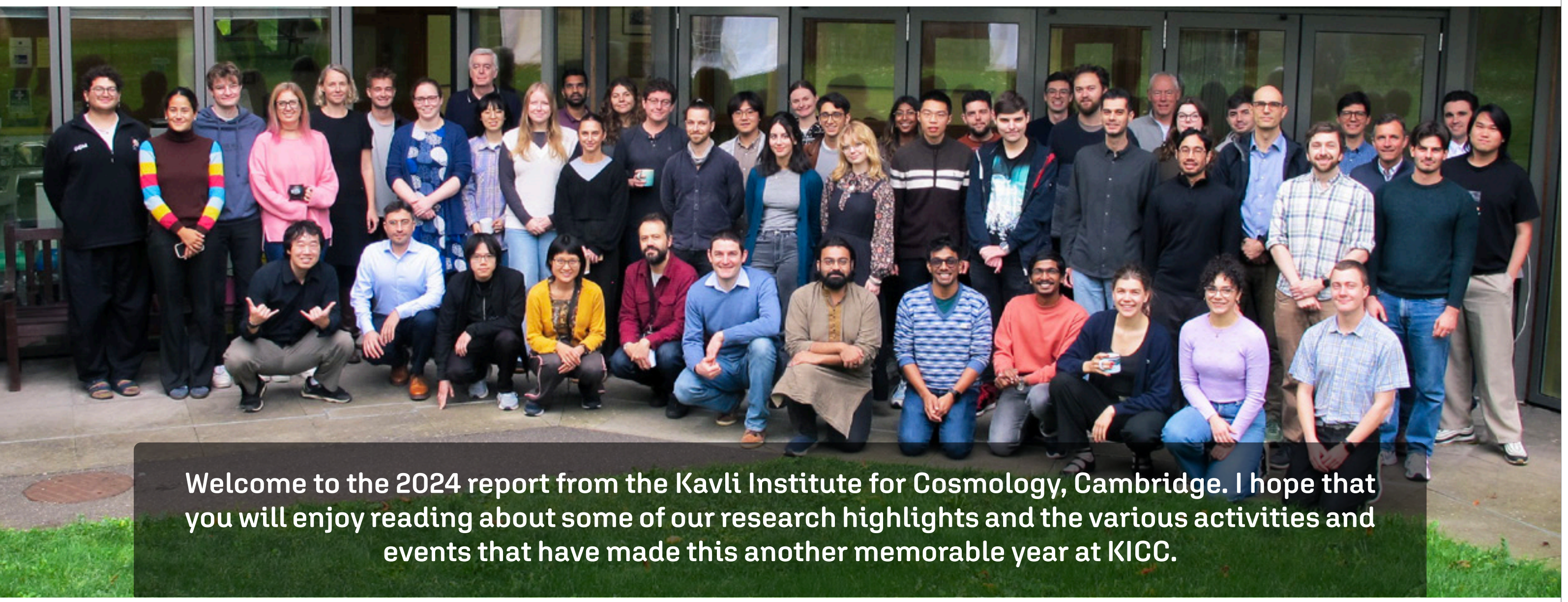
KICC ANNUAL REPORT

KAVLI INSTITUTE FOR COSMOLOGY, CAMBRIDGE


OVERVIEW
GALAXIES
ASTROSTATISTICS
GRAVITATIONAL WAVES
EXOPLANETS
COSMOLOGY

Professor Anthony Challinor

Message from the Director



Welcome to the 2024 report from the Kavli Institute for Cosmology, Cambridge. I hope that you will enjoy reading about some of our research highlights and the various activities and events that have made this another memorable year at KICC.

Progress in modern cosmology and astrophysics often requires huge surveys conducted with cutting-edge international facilities. This decade is particularly remarkable from this perspective, with transformative new facilities coming online across a range of wavebands. The year 2024 saw several major milestones reached on facilities that will be critical for our future science programmes at KICC. These include: the Simons Observatory cosmic microwave background experiment beginning its search for primordial gravitational waves from the early Universe; the installation of the 3200-megapixel camera at the Vera Rubin Observatory, which will start its transformative 10-year Legacy Survey of Space and Time in 2025; the Euclid satellite showcased its fantastic imaging with its Early Release Observations, marking the start of its Wide Survey to explore the nature of dark energy; and first-year results were released from the Dark Energy Spectroscopic Instrument, which has produced the largest 3D map of the Universe ever made and used this to measure the expansion history of the Universe over 11 billion years of cosmic history, revealing enticing hints of troubles for our standard cosmological model when combined with other cosmological observables. Not all observational progress requires projects at this scale, though. Our home-grown REACH experiment, which aims to measure the global 21-cm signal from neutral hydrogen interacting with the cosmic microwave background in the early Universe, also achieved first light in South Africa. We eagerly await its first science results!

It was another bumper year for exciting discoveries from the James Webb Space Telescope (JWST), particularly the Advanced Deep Extragalactic Survey co-led by KICC researchers. This survey is revolutionising our understanding of the formation of galaxies and their supermassive black holes in the early Universe. These findings, many of which made headlines in the press, include detection of the oldest black hole ever observed, when the Universe was only 400 million years old. How such a massive black hole could have grown so quickly in the early Universe is currently unknown. The JWST discovery of the most distant merger of two massive black holes sheds new light on this mystery, suggesting that merging may play a major role in early black hole growth. You can read about these, and many more, JWST discoveries in this report.

One of the most significant legacies of KICC is our community of Kavli Institute Fellows. Most of our endowment income is used to fund three- and five-year independent research fellowships. We have appointed over 30 fellows over the past 16 years, many of whom are now faculty at top universities, have become leaders in their fields and are now training the next generation. In 2024, we said farewell to several fellows – Hannah Übler, Mathias Nowack, Suhail Dhawan and Vid Irsic – but were delighted to welcome new fellows Alex Jenkins, James Alvey and James Rogers.

It is wonderful that several members of KICC were awarded prizes and other honours during the year. George Efstathiou was awarded the Albert Einstein Medal, from the Albert Einstein Society in Bern, and an Honorary Doctor of Science from Durham University, his alma mater. Anne-Christine Davies was appointed OBE in the King's Birthday Honours 2024 for "services to Higher Education and Scientific Research". Newton-Kavli Fellow, Hannah Übler, was awarded a prestigious ERC Starting Grant, which she has taken to the Max Planck Institute for Extraterrestrial Physics in Garching (MPE). Postdoctoral researchers Martin Bourne and Giulio Fabbian were awarded a Stephen Hawking Fellowship and Ernest Rutherford Fellowship, respectively, from UKRI. Finally, 10 Master's and PhD students graduated in 2024. Many congratulations to them all on these fantastic achievements.

Two new faculty members joined us at KICC this year. Will Handley was appointed as an Associate Professor and Boryana Hadzhiyska as an Assistant Professor, both in the Institute of Astronomy. These appointments significantly strengthen our faculty expertise in data-intensive science and AI, cosmological survey science and numerical simulations. Such interdisciplinary expertise and conceptual agility – a hallmark of KICC's approach – is essential for progress in modern cosmology and astrophysics. We wish Boryana and Will every success in their new positions.

It was a pleasure for KICC to host two major international workshops in 2024. "Raising the veil on star formation near and far" was held in April 2024 in honour of the late Prof. Richard Hills, a pioneering, world-leading millimetre-wave astronomer (see the KICC 2022 Annual Report for an obituary). The delegates discussed star formation on all scales, from pre-stellar and protoplanetary cores, astrochemistry, star formation in stellar nurseries to star formation in local and distant galaxies; many of their findings would not have been possible without the technical innovations introduced by Richard. In September 2024, "New physics from old light: illuminating the Universe with CMB secondaries" surveyed the rapidly developing field that uses the cosmic microwave background as a backlight to probe the growth of large-scale structure and the astrophysics of galaxy evolution. We were also delighted to host two Kavli Lecturers: Prof. Eve Ostriker from Princeton University, who spoke on star formation, feedback and cosmic evolution; and Prof. Reinhard Genzel from MPE, a recipient of the Nobel in Physics 2020, on experimental studies of black holes. Combined with our internal programmes of "New-Frontiers" talks and "Focus Meetings", it was another packed year of science events at KICC. In addition, we welcomed around 100 academic visitors, 14 of whom were supported through our twice-yearly calls for Official Kavli Visitors. It was a particular pleasure to have Prof. Jo Dunkley, from Princeton University, join us in September 20204 for a sabbatical year as a Royal Society Wolfson Visiting Fellow and Institute of Astronomy Distinguished Visitor. If you are interested in visiting KICC, please do get in touch with one of our members.

Finally, let me acknowledge the fantastic administrative support that the Kavli Institute receives from Steven Brereton and Dr Alison Wilson, and the professional-services staff in the parent departments who help with events, recruitment, IT, graphics and much more. Many thanks to you all! Thanks also to Debora Sijacki, the Deputy Director, who continued to devote enormous time and energy to KICC despite being on sabbatical leave for some of the year. Finally, I gratefully acknowledge the continued financial and strategic support from the Kavli Foundation and financial support from Mr Gavin Boyle and the Isaac Newton Trust.

William Coulton

Simulating Signatures of the Primordial Universe in the Cosmos

How did it all begin? This question has motivated scientists and philosophers for thousands of years. Whilst we are still unable to shed light on the physics of the very beginning, cosmologists are getting tantalizingly close. Increasing observational evidence suggests that in the first fractions of the Universe's history (around 10^{-30} seconds!) the Universe underwent a process called "inflation". During inflation, cosmologists think that the Universe underwent a dramatic expansion that stretched microscopic quantum scales to cosmological scales. This theory has made a range of tested predictions; however, we are still searching for smoking-gun signatures from the era. Furthermore, there are actually many microphysical processes that could cause inflation, and cosmologists are searching for new signals that could distinguish between these options.

In the past few years, a range of powerful new telescopes, such as the Dark Energy Spectroscopic Instrument and Euclid, have started precisely mapping the 3D positions of galaxies in the Universe. Hidden in the distribution of galaxies in the sky are small, statistical signatures from the early Universe, and hopefully the sought after signals from inflation. Unfortunately, the physics relating our observations of galaxies to the early Universe is complex and difficult to solve completely with analytical methods. To address these challenges, my colleagues in the *Quijote-PNG* collaboration and I have been using suites of numerical simulations to explore how we can use observations of galaxies to probe the physics of inflation.

The *Quijote-PNG* collaboration has now publicly released a large suite of simulated possible universes with a range of different models for the physics of inflation. The goal of this project is to be a sandbox for developing new methods of robustly and efficiently extracting primordial information from galaxy distributions. The different models of the early universe contain unique statistical signatures that would tell us something new about primordial physics.

As an example, in Fig. 1 we compare two of our simulated universes that differ only by whether the primordial physics preserves parity symmetry or not. Parity symmetry can be thought of as a generalization of mirror symmetry. A violation of this symmetry would mean that physics acts differently between an object and its parity-inverted (mirror) image. A simple example would be that we may observe different numbers of galaxies rotating clockwise or anticlockwise. These simulations allow us to test these ideas on a cosmic scale.

The *Quijote-PNG* collaboration has used these simulations to pioneer new analysis methods for extracting the primordial information from observations. These include deriving new analytical-inspired methods and machine learning methods, which leverage the large data volume to train an algorithm to isolate the key features. A particularly exciting result is the identification of two statistical features that arise only from primordial physics and are distinct from the uncertain physics that describes the formation and evolution of galaxies. The next step is to search for these signals in real observations; perhaps these methods will provide us with a way of detecting the elusive primordial signatures.

This article is partly based on results of the *Qujote-PNG* collaboration and a discussion of the results published in Coulton W. et al., Phys. Rev. D 109, 023531 (2024).

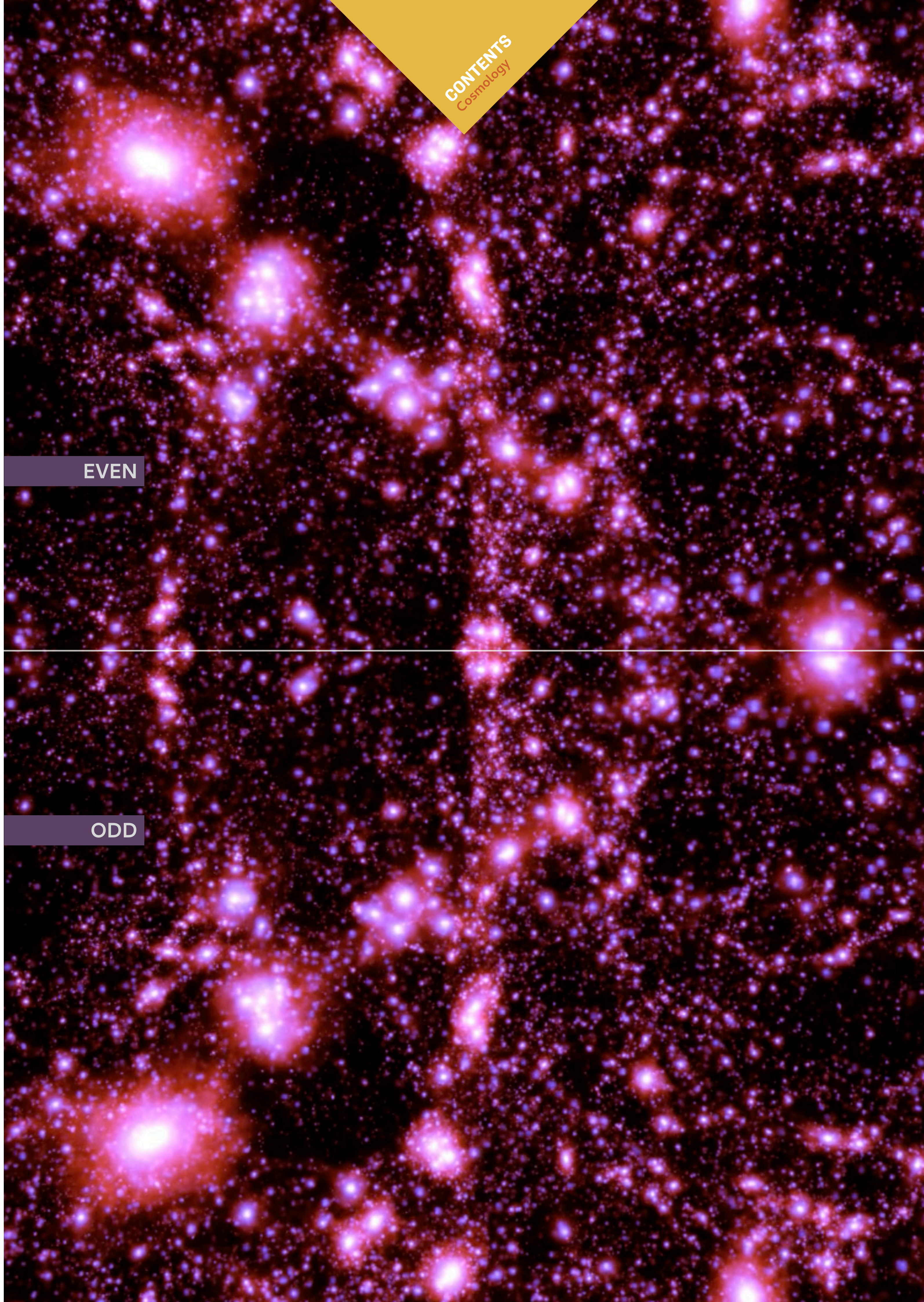


Fig 1. What does a parity-violating Universe look like? We compare two almost identical, simulated universes; the only difference is that the bottom universe (inverted to aid comparisons) contains a small amount of parity-violating primordial physics.

Alex Jenkins

The Universe on a Table-Top: Simulating Cosmic Bubble Nucleation with Ultra-Cold Atoms

One of the fundamental challenges of cosmology is that it is an observational science, not an experimental one: as cosmologists, we cannot control the system we are studying (the Universe), and can only access a single version of it (the one we live in). This problem is particularly acute when investigating the very early stages of the Universe's evolution, for which observational data are scarce and the underlying physics is poorly understood. These challenges have driven a recent surge of interest in simulating the early Universe in the laboratory using purpose-built *analogue experiments*, enabling controllable and reproducible tests of cosmological theories.

One particularly compelling application of this approach is to *cosmological phase transitions*. Much like how liquid water forms gas bubbles when heated on the stove, conditions in the early Universe can cause quantum fields to transition from one state to another by nucleating "bubbles" of a new phase. Unlike in water, however, the extreme energies associated with these bubbles make them grow at almost the speed of light, eventually undergoing violent collisions with each other that generate gravitational waves and possibly even black holes. Transitions like this could explain the long-standing puzzle of why the Universe contains so much more matter than antimatter, and might even describe the formation of our entire Universe, with everything we observe contained in just one bubble within a vast "multiverse" of bubbles.

Thanks to recent developments in quantum technologies, we are now on the verge of testing these ideas in the laboratory using tabletop experiments with ultra-cold atoms (see Fig. 1). By cooling clouds of atoms down to less than a millionth of a degree above absolute zero, these experiments are able to probe the strange behaviour of matter deep in the quantum regime. Remarkably, by appropriately tuning the parameters of the experiment, it is possible to make these atomic systems mimic the behaviour of fundamental fields in the early Universe, including cosmic bubble nucleation. However, unlike in the early Universe, we can repeat this process many times and directly image the system to capture pictures of quantum bubbles as they are being born.

My collaborators and I, including KICC members Emilie Hertig and Hiranya Peiris, are working closely with the experimental group led by Zoran Hadzibabic in the Cavendish Laboratory to bring these analogues to fruition. These efforts are now at an advanced stage (see Fig. 2), and we are eagerly awaiting the first experimental data. In the meantime, we are working actively to develop our theoretical understanding of these systems, so that we are prepared to analyse these data and extract cosmological insights from them. Our main tools in this theoretical work are numerical simulations like the one shown in Fig. 3, which give a detailed picture of bubble formation in these atomic systems and allow us to test the limits of the cosmological analogy.

Our work has already led to significant progress: we have shown that these cold-atom systems mimic the early Universe in terms of their *quantum* properties and not just their classical behaviour, which is crucial for faithfully capturing bubble nucleation. We have also solved some of the main experimental obstacles initially facing this programme, for example, by showing that the analogy holds in a much broader range of atomic systems than previously recognised.

Looking forward, we continue to work towards the first experimental tests of cosmic bubble nucleation. These experiments could have transformative implications for our understanding of the Universe's beginnings, and of the fundamental laws governing its evolution.

This article is partly based on results published as Jenkins A. C. et al., Phys. Rev. A 110, L031301 (2024) and Jenkins A. C. et al., Phys. Rev. D 109, 023506 (2024).

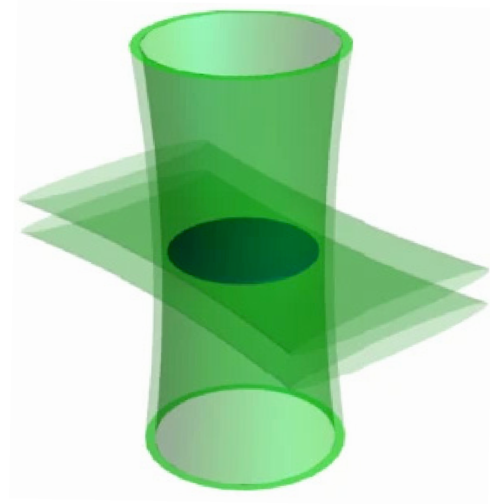


Fig 1. The planned experiment uses a "box trap" made of laser light to confine ultra-cold atoms into a 2D plane. Image from Navon N. et al., Nat. Phys. 17, 1334–1341 (2021).

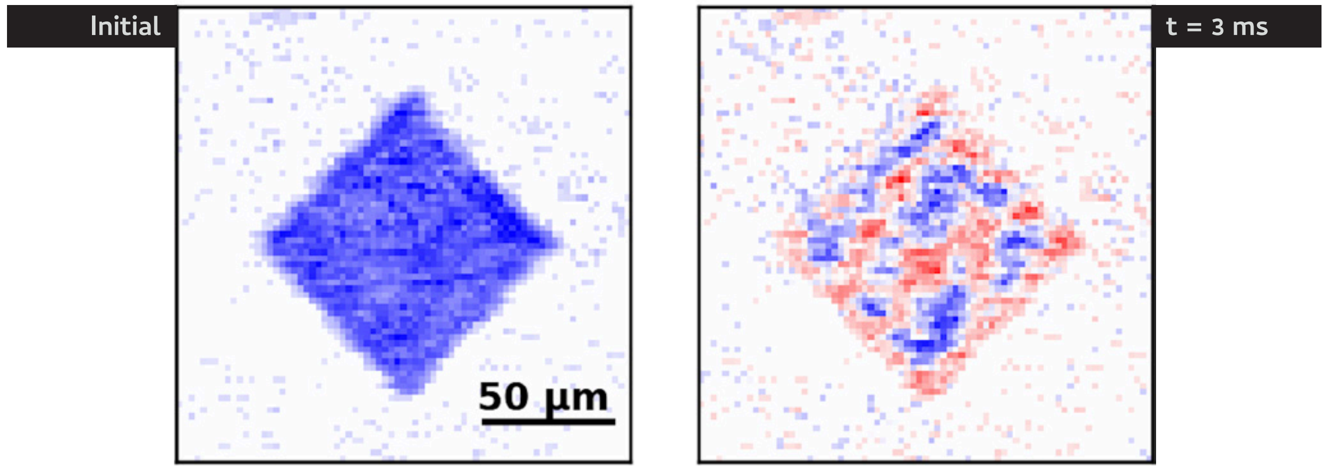


Fig 2. Early results from the Cavendish group, demonstrating high-resolution imaging of the 2D experimental setup. Image provided by Paul Wong.

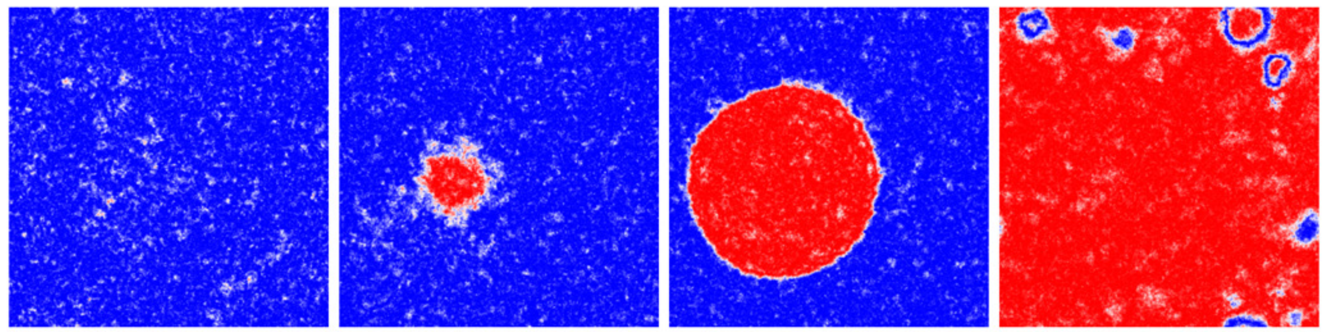


Fig 3. Numerical simulation of bubble nucleation in a 2D analogue experiment, with time increasing from left to right. The system starts in a "false vacuum" state (blue), and nucleates a bubble of "true vacuum" (red) that rapidly expands to fill the volume.

Anastasia Fialkov & Eloy de Lera Acedo

Unlocking the Secrets of the Early Universe with 21-cm Cosmology

The first few hundred million years after the Big Bang were a time of darkness, literally and figuratively. During this period, known as the cosmic dark ages, the Universe was filled with neutral hydrogen gas, shrouding the birth of the first stars and galaxies. Although we cannot observe this epoch directly with visible light, radio signals at the 21-cm wavelength offer a promising window into this hidden era. By studying these signals, scientists hope to uncover the structure of the early Universe, constrain the nature of dark matter, and probe the first galaxies.

The first stars and galaxies: shedding light on Population III stars

While experiments such as the JWST are pushing the redshift limit of direct observations, measurements in the low-frequency radio band promise to probe early star and black-hole formation via observations of the hydrogen 21-cm line. One of the most interesting questions that 21-cm cosmology can answer is to determine the role of the first stars and galaxies. Our group have explored synergies between 21-cm data from the HERA and SARAS 3 experiments and observations of the unresolved radio and X-ray backgrounds to constrain properties of Population III stars as well as early X-ray and radio sources. These stars were massive, short-lived, and played a crucial role in shaping the early Universe. Understanding these objects is essential, as they created the first heavy elements and influenced the formation of later generations of stars and galaxies. Although our constraints are weak due to the poor constraining power of the currently available data, our multi-wavelength Bayesian analysis revealed a 68 percentile disfavouring of Population III star-formation efficiencies larger than 5.7%. We also showed how the 21-cm and the X-ray background data synergistically constrain the X-ray efficiency of X-ray binaries (Fig. 1).

In this study, we found that early galaxies were likely 0.3 to 318 times as X-ray efficient as present-day starburst galaxies. The constraints are expected to become stronger as new 21-cm experiments are coming online, including the under-construction Square Kilometer Array.

Partly based on results published as Pochinda S. et al., MNRAS 531, 1113 (2024).

Superconducting cosmic strings: a mysterious possibility

One intriguing hypothesis is the existence of superconducting cosmic strings — thin, high-energy filaments stretching across the Universe. Constraints on the potential properties of superconducting cosmic strings would provide an indirect probe of physics beyond the Standard Model of particle physics at energies inaccessible to terrestrial particle colliders. Our group performed the first joint Bayesian analysis to extract constraints on superconducting cosmic strings from current 21-cm signal measurements while accounting rigorously for the uncertainties in foregrounds and high-redshift astrophysics. We included the latest publicly available 21-cm power spectrum upper limits from HERA, 21-cm global signal data from SARAS 3, and the synergistic probe of the unresolved X-ray background in our final analysis. In contrast to previous works, we found no strong constraints can be placed on superconducting cosmic strings from current 21-cm measurements owing to the uncertainties in the X-ray emission efficiency of the first galaxies. However, effects not included in this study, such as the recently proposed soft photon heating, could help to improve the constraints due to their potential to break degeneracies.

Partly based on results published as Gessey-Jones T. et al., MNRAS 529, 519 (2024).

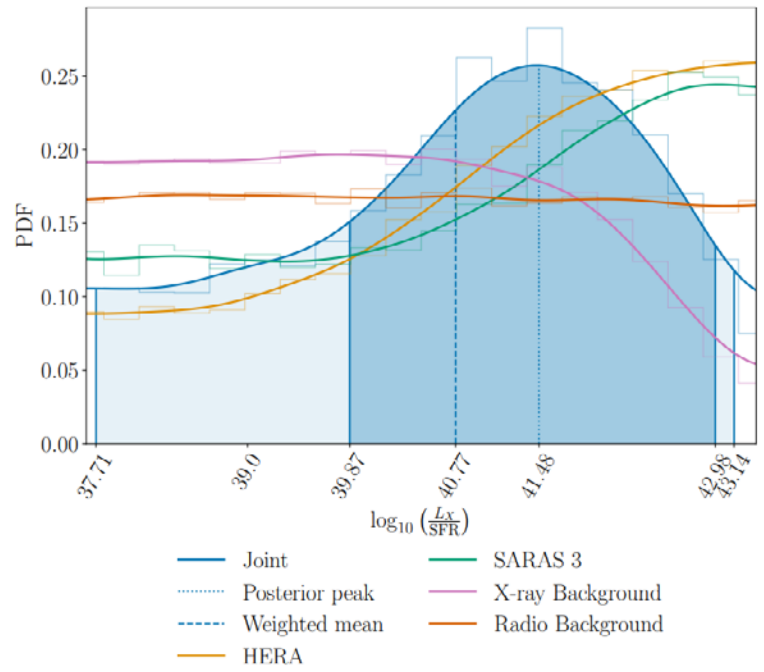


Fig 1. Probability density for the X-ray efficiency parameter. The peak appears due to the X-ray data (magenta) and 21-cm data (HERA in orange and SARAS 3 in green) weakly constraining opposite ends of the parameter range. The X-ray efficiency is unconstrained by radio background data (red). The joint fit (blue) reveals a distinct posterior peak (dotted vertical line) in the log X-ray luminosity per star formation rate of high-redshift X-ray binaries.

A new tool to decode ancient radio signals: the FlexKnot model

Extracting meaningful information from radio data about the cosmological 21-cm signal is notoriously tricky due to contaminants such as the foreground emission by our own galaxy, radio-frequency interference and instrumental noise. To tackle this, our group have used the FlexKnot model — a flexible way to model these signals without assuming an astrophysics-based theory. FlexKnot is a function parameterised by freely moving knots stringed together by splines. Unlike the astrophysical scenarios, FlexKnot can adapt to a wide range of possible signal shapes, making it easier to identify true cosmic signals buried in the noise if they differ from the canonical models. We tested the FlexKnot model in the framework of the realistic data-analysis pipeline of the REACH global signal experiment using simulated antenna temperature data. We demonstrate that the FlexKnot model performs better than, e.g., a simple phenomenological Gaussian signal model at reconstructing the shape of the true signals present in the simulated REACH data, especially for injected signals with complex structures. This model will be used as part of the REACH data-analysis and signal-interpretation pipeline.

Partly based on results published as Shen E. et al., MNRAS 529, 1642 (2024).

Conclusion: a bright future for 21-cm cosmology

These advances in 21-cm cosmology are opening up new ways to study the early Universe. While challenges remain — particularly in dealing with foreground contamination and model uncertainties — the future looks promising. As more sensitive instruments come online, and as techniques like the FlexKnot model are refined, we are poised to make unprecedented discoveries about the first billion years of cosmic history. These efforts represent a thrilling frontier in our quest to understand the cosmos.

Eloy de Lera Acedo

Pushing the Frontiers of Radio Astronomy:
Instrumentation Advances at the KICC/Cavendish

Within the Cavendish Astrophysics Radio Cosmology group, our team has spent the past year pushing the boundaries of radio astronomy — a field that uses radio waves to explore the cosmos. Our focus has been on developing cutting-edge technology for projects like the Square Kilometre Array (SKA), the Radio Experiment for the Analysis of Cosmic Hydrogen (REACH), and CosmoCube. These initiatives aim to answer some of the most profound questions about the Universe's origins and evolution.

The SKA Telescope: Listening to the Early Universe

The SKA will soon be the world's largest radio telescope, capable of detecting faint signals from billions of years ago. However, achieving this vision comes with challenges. One major hurdle is the interference caused by radio waves from stars and galaxies, which can obscure the faint whispers from the early Universe.

To tackle this, our team has been developing new techniques to filter out these unwanted signals. For instance, we have explored the impact of mutual coupling — a phenomenon where antennas interfere with each other, complicating signal detection — and proposed solutions to mitigate its effects. By designing better ways to capture and process radio waves, we can help the SKA focus on the signals that matter most. This progress is vital for uncovering how the first stars and galaxies formed.

In addition to our efforts in developing instrumentation for the SKA, we are also leading the construction of the Science Data Processor (the brain of the telescope) and advancing the development of the UK Square Kilometre Array Regional Centre (UKSRC).

REACH: Searching for the Universe's First Light

Our REACH experiment is designed to detect one of the oldest signals in the Universe — faint radio waves produced by hydrogen from a period known as the cosmic dawn, when the first stars were born.

Detecting this signal is like finding a whisper in a storm. Radio waves from our own galaxy and even from REACH's own equipment can drown out the ancient hydrogen signal we seek. To overcome this, we have developed advanced computer algorithms that act like high-tech sieves, filtering out unwanted noise and allowing the ancient signal to shine through. Early results suggest that these techniques can significantly improve the accuracy of our observations. These advances bring us closer to understanding how light first emerged in the Universe.

CosmoCube: Exploring the Dark Ages from the Moon

While REACH focuses on the first stars, our CosmoCube project aims to explore an even earlier time, known as the dark ages, before any stars or galaxies existed. The idea is to place a small satellite in orbit around the Moon, far from Earth's radio interference, to search for signals from this mysterious era.

Our team has developed an innovative, compact and powerful radio receiver capable of detecting these faint signals. This receiver has been rigorously tested to ensure reliable performance in the harsh conditions of space. If successful, CosmoCube could provide a new way to explore the Universe's beginnings, helping us understand the first steps in the formation of everything we see today.

A Future Full of Discovery

The next few years promise to be incredibly exciting for radio astronomy. As the SKA, REACH, and CosmoCube projects advance, each will offer new insights into the Universe's earliest moments. With continued support and collaboration, we are eager to turn these projects into powerful tools for discovery.

This article is partly based on results published as Gueuning Q. et al., IEEE Transactions on Antennas and Propagation PP. 1-1. 10.1109 (2025); O'Hara O. et al., MNRAS 538, 31 (2025); Anstey D. et al., MNRAS 520, 850 (2023); Leeney S. et al., Phys. Rev. D 108, 062006 (2023); Cumner J. et al., MNRAS 531, 4734 (2024); Kirkham C. et al., MNRAS 527, 8305 (2024); Kirkham C. et al., MNRAS submitted (arXiv:2412.14023); Shen E. et al., MNRAS 529, 1642 (2024); Pattison J. et al., MNRAS 527, 2412 (2024); Pattison J. et al., MNRAS 538, 1301 (2025); Mittal S. et al., MNRAS 534, 1317 (2024); Artuc K. & de Lera Acedo. E., RAS Techniques and Instruments 4, id.rzae061 (2025); Zhu J. et al., RAS Techniques and Instruments 4, id.rzae064 (2025).

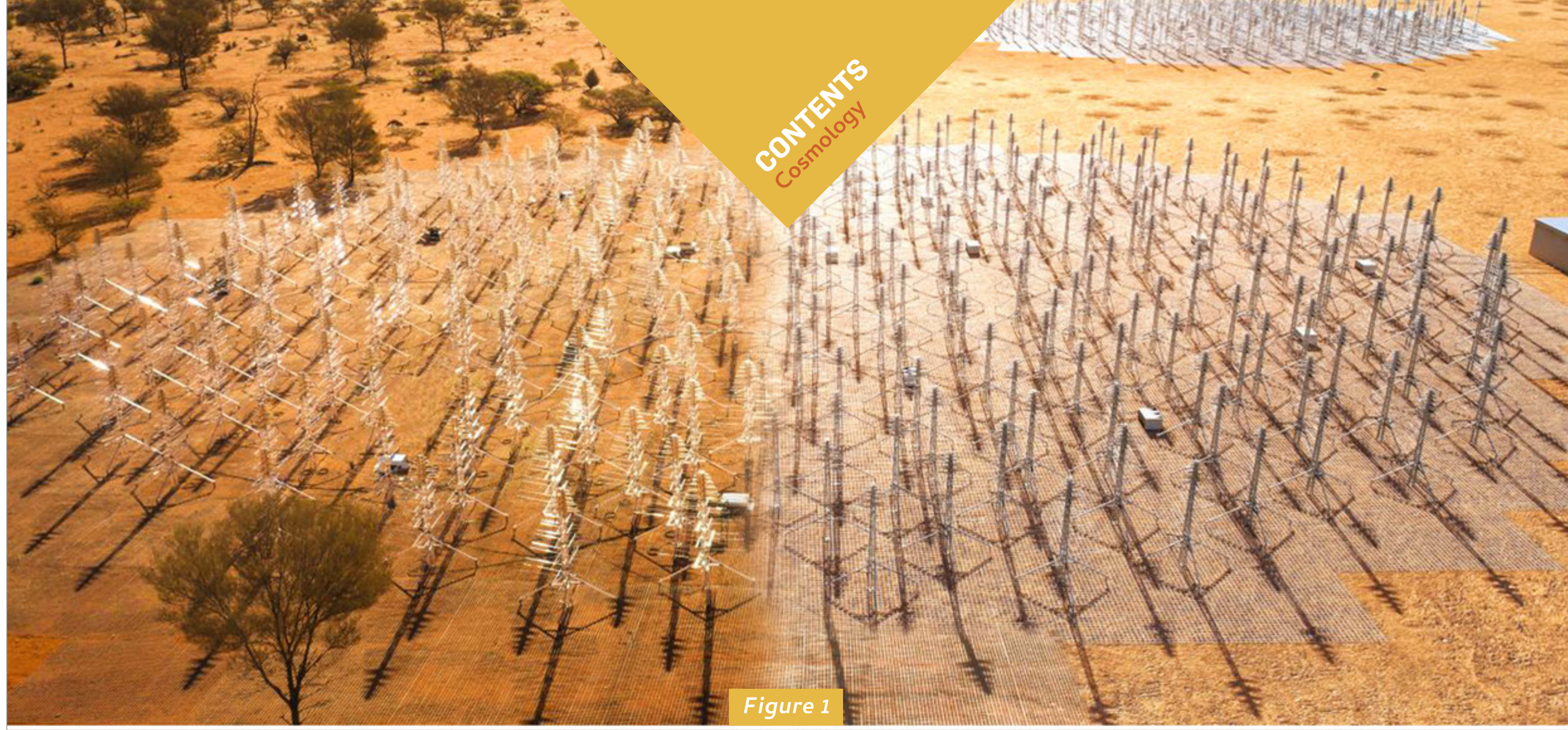


Figure 1

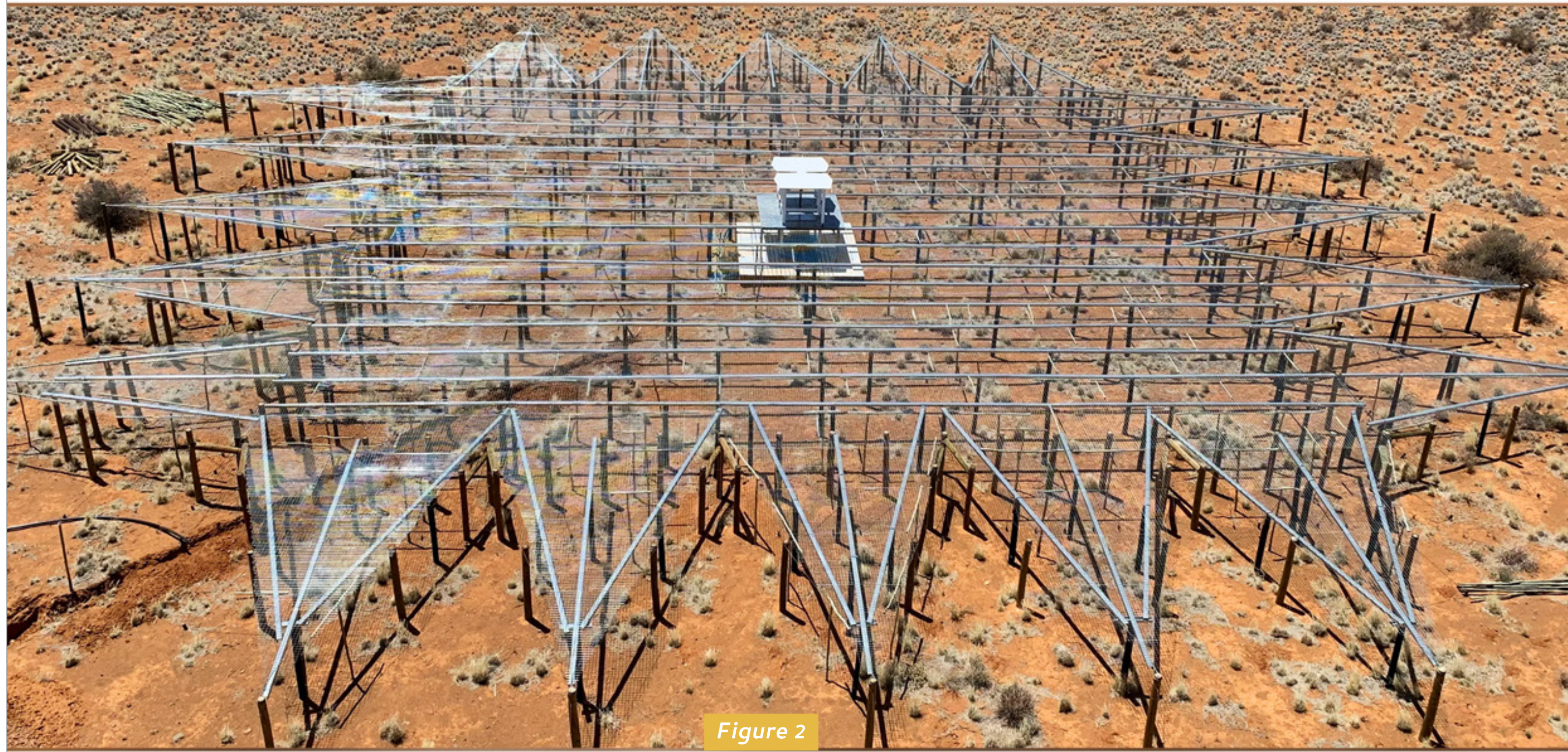


Figure 2

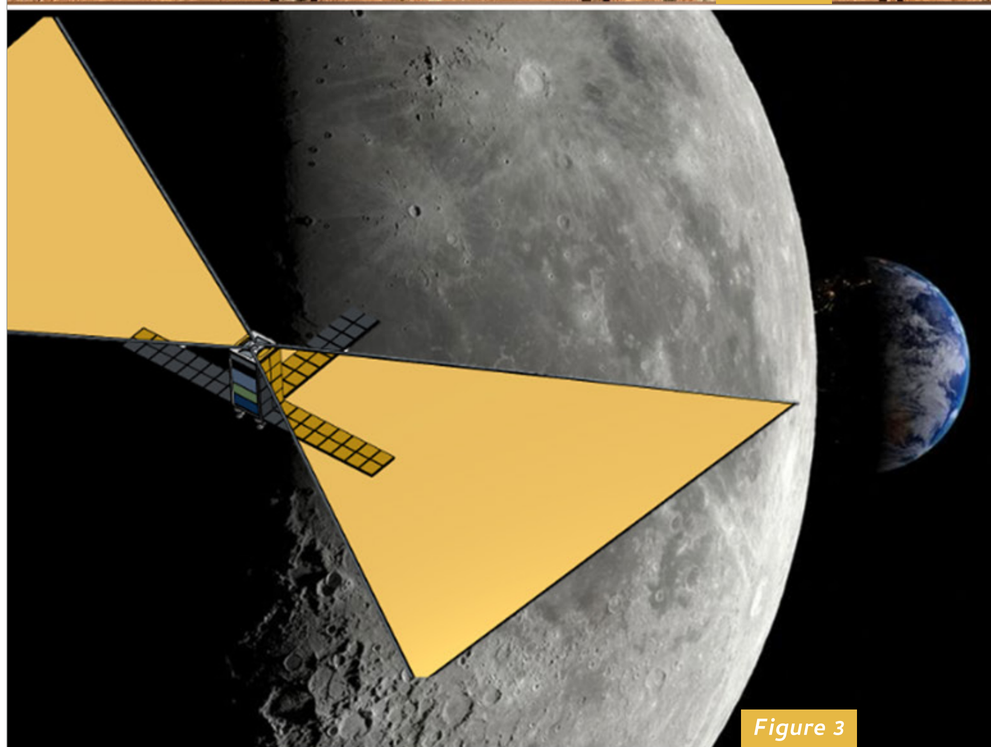


Figure 3

Fig 1. SKA-LOW instrument in Western Australia. Real instrumentation on the ground is shown on the left, while an artist's impression of the full array is shown on the right. Credit: SKAO.

Fig 2. REACH telescope in the Karoo radio reserve in South Africa.

Fig 3. CosmoCube mission in orbit around the Moon (artist's impression).

Giulio Fabbian

Euclid: First Year Surveying the Sky and Counting

2024 has been an extraordinary year for Euclid, the latest space mission led by the European Space Agency (ESA), and for the over 2,000 scientists and engineers involved in the project.

Euclid's ultimate goal is ambitious: shedding light on the physics of the mysterious dark energy, which makes up 70% of the energy content in the Universe and drives its current phase of accelerated expansion. Understanding dark energy is crucial not only for comprehending the evolution of our Universe, but also for advancing our knowledge of fundamental physics, as its presence may signal the need for a new theory of gravity.

Euclid will achieve this goal by mapping the distribution of matter in the Universe, as traced by luminous galaxies, as a function of distance from us (and thus time). Using statistical techniques, Euclid's scientists will convert the images captured by the spacecraft's instruments into insights about dark energy itself. Examples of such techniques include calculating the likelihood of finding galaxies at specific distances from each other (galaxy clustering) and studying how the presence of matter — and by extension, gravitational forces — distorts the shape of distant galaxies through the phenomenon of gravitational lensing. While similar measurements have been conducted in the past decade by several astronomical surveys on Earth, operating from space allows Euclid to conduct these observations on an unprecedented scale, with far greater detail and accuracy.

By the end of its nominal six-year mission, Euclid will have surveyed the entire sky, excluding regions obscured by the Milky Way or our solar system's light, at a quality comparable to the images produced by the Hubble Space Telescope. It will do so using multiple wavelengths (visible and infrared) and complementary technologies (photometry and spectroscopy) to ensure the robustness of its findings.

After its launch in July 2023, and a month-long journey to its final orbit alongside the James Webb Space Telescope, 2024 marked the completion of Euclid's initial commissioning and the start of its Wide Survey on February 14th.

Since then, Euclid has been relentlessly imaging the sky, covering an area equivalent to the size of the Moon as seen from Earth with each pointing. Within a month, Euclid had covered the same sky area that the Hubble Space Telescope had observed over more than 30 years! However, challenges soon arose. The humidity brought from Earth and trapped in some of the satellite's components had accumulated as ice on Euclid's mirrors, causing its view to become hazy. A first decontamination attempt, which involved warming the mirrors up, successfully recovered the light loss, but the ice reappeared faster than expected and worsened the transmission issue. A second warming attempt ended the unwanted "ice age" and, since May 2024, Euclid's sight has been as sharp as expected.

In addition to this, Euclid had to deal with energetic protons and X-rays from the Milky Way and the Sun, which is currently at the peak of its activity. Fortunately, these did not affect the data beyond manageable levels.

The scientific potential of Euclid was showcased in the Early Release Observations and associated papers in May 2024 (Fig. 1). Since then, data from the first pass on the deepest 60 deg^2 that the mission will observe (Q1) were delivered to scientists in November 2024. Several science projects using the Q1 dataset have already been completed, with results and data becoming public on March 19, 2025.

As I write this, Euclid's data processing pipelines are being adapted and refined to handle the challenges presented by real data. The first major data release (DR1), covering around 2,000 deg^2, will be made available to Euclid scientists in autumn 2025, and to the public in 2026. It will include results ranging from studies of globular star clusters in the Milky Way to the combination of Euclid data with maps of the oldest light in the Universe — the cosmic microwave background. With all of this ahead, next year promises to be an incredibly busy and exciting one. I can't wait to see the outcomes!

Additional materials on the results covered in this piece are available on the ***ESA*** and ***Euclid Consortium*** websites.

** ESA:* ***https://www.esa.int/Science_Exploration/Space_Science/Euclid*** *& Euclid:* ***https://www.euclid-ec.org/***

Fig 1. Five Euclid Early Release Observations images published in May 2024 and available on ESA Sky (credits: ESA/Euclid/Euclid Consortium/ NASA, processing by J.-C. Cuillandre, G. Anselmi).

Zvonimir Vlah

Going Beyond One-Loop in Perturbative Large-Scale Structure Formation

Understanding how galaxies are distributed throughout the Universe is one of the central challenges in modern cosmology. Cosmologists thus rely on vast astronomical surveys that measure the positions of billions of galaxies. The patterns in this distribution contain valuable information about the fundamental laws of physics, the nature of dark matter and dark energy, and even the earliest moments after the Big Bang. However, testing theoretical models against observations from galaxy surveys involves complex calculations, called perturbative corrections, that traditionally require significant computational resources. This becomes particularly challenging when scientists need to compare millions of slightly different theoretical scenarios with observational data.

Together with our collaborators from Utrecht University, we have developed an innovative computational framework that dramatically speeds up such calculations of how matter is distributed throughout our Universe. The new method, called COBRA (Cosmology with Optimally factorized Bases for Rapid Approximation), allows cosmologists to perform thousands of complex calculations per second with extraordinary precision. Separating the dependence on scale from the dependence on cosmological parameters allows researchers to pre-compute the most time-consuming parts of the calculations just once.

Instead of recalculating everything from scratch, COBRA relies on factorisation to simplify the most complex elements of these calculations. It separates the influence of cosmological parameters (such as the overall density of dark matter or the properties of dark energy) from the way structures form in the Universe. COBRA can reproduce calculations that would normally require specialised software with better than 0.1% precision (Fig. 1) and it does this thousands of times faster than conventional methods. We applied our framework to calculate how galaxies appear to cluster when observed from Earth.

This clustering pattern is affected not only by the actual distribution of galaxies in space but also by their motion relative to us, which creates distortions in the observed pattern. COBRA can perform about 4,000 such calculations per second on a single computer processor – a remarkable improvement over existing methods.

What makes COBRA particularly valuable is its versatility. It applies to any statistical measurement of the Universe's structure, no matter how complex. With existing methods, only next-to-leading order corrections (involving one-loop Feynman diagrams) are computationally feasible and can be applied in data analysis, and then only for the simplest statistic, the two-point correlation function. COBRA's dramatic computational improvements make it possible to include higher-order perturbative corrections (involving higher-loop Feynman diagrams) and higher-order correlators, all while requiring far fewer computational resources (Fig. 2). Analysis of survey data that previously demanded large supercomputers can now be performed on personal laptops. This remarkable reduction in required computing power effectively creates a new paradigm of resource-efficient *green cosmology*.

This breakthrough comes at a critical time, as ongoing galaxy surveys with the Euclid satellite and the Dark Energy Spectroscopic Instrument are collecting unprecedented amounts of data about the Universe's structure. Computational methods like COBRA will be essential for extracting fundamental insights about our Universe from this wealth of observational data, ensuring that scientists can analyse this data efficiently, testing new models of the Universe without the computational bottlenecks that previously existed. Moreover, COBRA is publicly available as open-source software, meaning researchers worldwide can integrate it into their work, pushing the boundaries of cosmology even further.

This article is partly based on results submitted to Phys. Rev. Lett. as Bakx T. et al., arXiv:2407.04660.

Figure 1

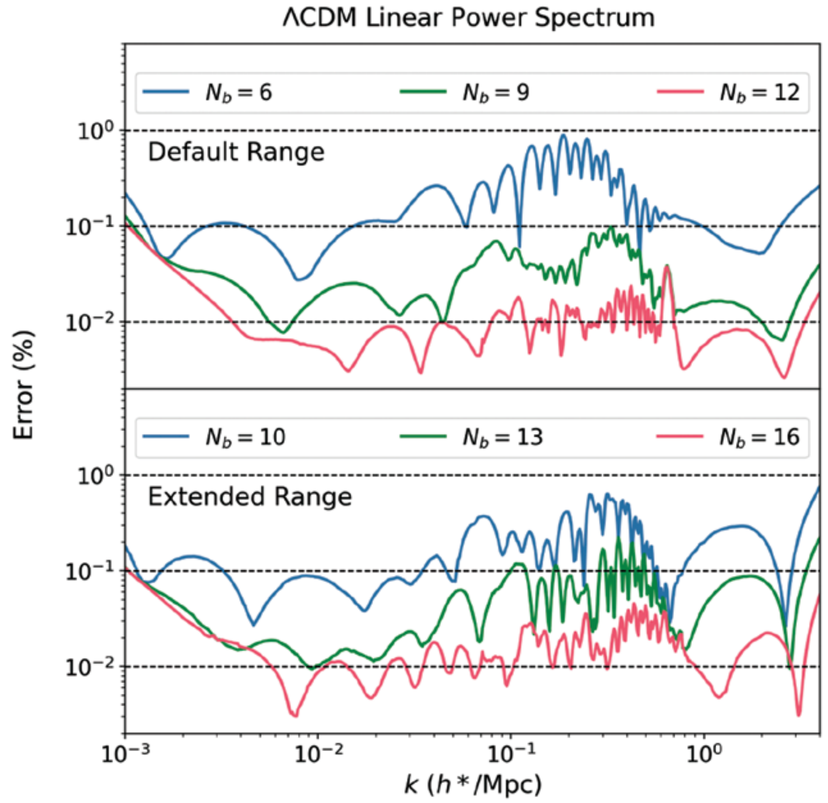


Figure 2

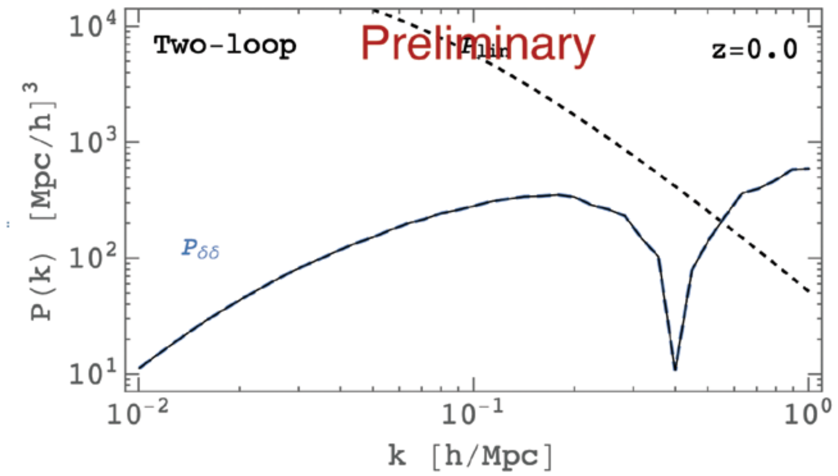


Fig 1. Error on the two-point correlation function in Fourier space as a function of scale in the standard cosmological model for several choices of the COBRA setup (number of basis functions N_b). The upper panel corresponds to a smaller cosmological parameter range, while the lower panel corresponds to an extended range. Dashed lines indicate 0.01%, 0.1% and 1% errors.

Fig 2. Preliminary results of using the COBRA framework for higher-order (two-loop) corrections in the two-point correlation function. Black and blue-dashed lines show excellent agreement between the current slow method of computation and the new fast method.

Vid Irsic

Amplitude of Large-Scale Matter Clustering
at Redshift 2.5 with eBOSS and DESI

With the rapid advancement of observational tools and theoretical models, we are entering a golden era of cosmology. High-precision measurements of the Universe's expansion and the formation of large-scale structures are placing increasingly stringent demands on the standard cosmological model. At the same time, these observations are revealing intriguing tensions between different methods of measuring cosmic evolution, hinting at the possibility of new physics.

One of the key areas where these tensions appear is in the comparison of different measurements of cosmic expansion. Observations of Type Ia supernovae and baryon acoustic oscillations (BAO) in the clustering of galaxies suggest that the late-time expansion of the Universe does not perfectly align with predictions from the cosmic microwave background (CMB), the afterglow of the Big Bang. Similarly, measurements of how cosmic structures grow over time, using galaxy distributions and weak-gravitational lensing, suggest that these structures are evolving at a slower pace than expected based on CMB predictions. This mismatch has led to significant interest in testing the standard cosmological model, known as ΛCDM, at earlier epochs in cosmic history.

One powerful tool for these tests is the Lyman-alpha forest, a pattern of absorption lines in the light from distant quasars. These absorption features arise as the quasar's light passes through vast cosmic structures filled with neutral hydrogen gas. The Lyman-alpha forest allows us to probe the distribution of matter at high redshifts ($2 < z < 6$), far beyond the reach of traditional galaxy surveys. Unlike galaxy clustering, which relies on detecting individual galaxies, the Lyman-alpha forest provides a continuous tracer of matter across enormous cosmological volumes, offering a unique window into the Universe's early structure.

Recent advancements in observational techniques have enabled the first precise measurements of the three-dimensional clustering of Lyman-alpha absorption in Fourier space. These 3D flux-power-spectrum measurements provide new insights into the statistical properties of the matter distribution at high redshifts (see Fig. 1). Analyzing these patterns allows researchers to study how cosmic structures evolved and test fundamental assumptions of cosmological models. Additionally, the Lyman-alpha forest's sensitivity to small-scale physics makes it a key tool for probing the nature of dark matter.

The Dark Energy Spectroscopic Instrument (DESI) is playing a crucial role in these efforts. Cambridge is actively involved in the DESI Collaboration, contributing to mapping the expansion history of the Universe from the first galaxies to later epochs of cosmic evolution. DESI's Data Release 1, published in 2024, delivered groundbreaking results on both BAO and redshift-space distortion measurements. These results provide new constraints on the expansion history of the Universe and the growth of cosmic structures.

New techniques in full-shape clustering analysis of the Lyman-alpha forest in Fourier space now allow for measurements of cosmological parameters analogous to those in galaxy clustering studies (e.g., using DESI data). This advancement facilitates seamless inference of theoretical models over more than 10 billion years of the Universe's history (see Fig. 2). High-precision measurements of full-shape Lyman-alpha clustering will provide critical constraints on expansion rates and structure growth, helping to resolve cosmological tensions in the intermediate redshift range between galaxy surveys and the CMB.

Beyond precision cosmology, these clustering measurements have broader implications for high-redshift galaxy formation, multi-messenger astronomy, and astro-particle physics. The interpretation of these measurements will yield state-of-the-art constraints on dynamic interactions within the dark sector, such as potential interactions between dark matter and dark energy or evolving dark energy models.

This article is partly based on results published as de Belsunce R. et al., MNRAS 533, 3756 (2024) and DESI Collaboration, JCAP 2025, 70 (2025).

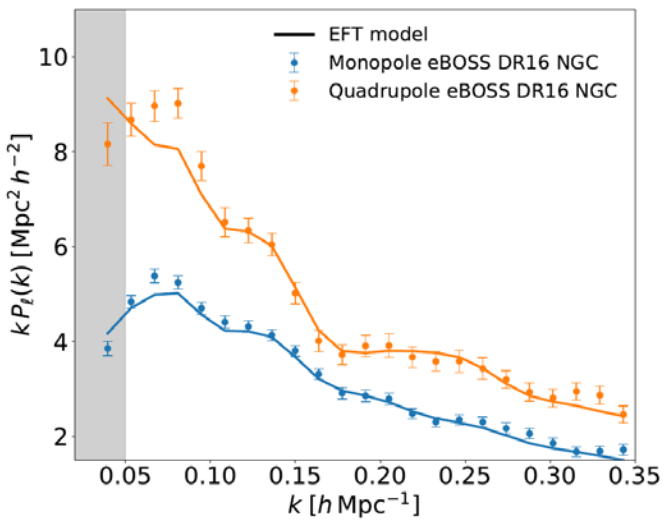


Figure 1

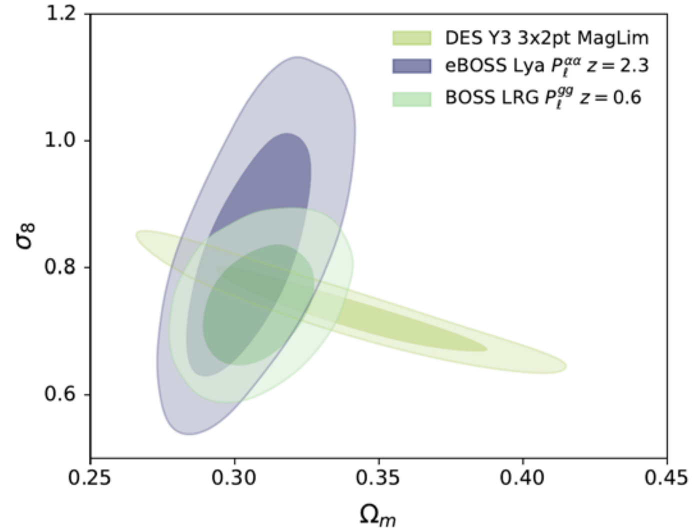


Figure 2

Fig 1. Measurements of the 3D clustering of the Lyman-alpha absorption as measured by the extended Baryon Oscillation Spectroscopic Survey (eBOSS) Data Release 16. Effective field theory models describe the data well, despite the models being developed for low-redshift galaxy clustering.

Fig 2. Constraints on the present-day amplitude of matter clustering (y-axis) and the relative energy density of matter in the Universe (x-axis) inferred from data over a range of cosmic epochs: from nearby galaxy clustering ($z = 0.6$) and weak gravitational lensing of background galaxies ($z = 1$) to Lyman-alpha forest ($z = 2.3$). The figure highlights the agreement of the cosmological parameters over 10 billion years of cosmic expansion.

Suhail Dhawan

Strongly Gravitationally Lensed Supernovae:
A View from Ground-Based Surveys and JWST

The value of the Hubble constant, the current rate of expansion of the Universe, has been a matter of heated debate over the last decade. The global inference predicted from standard cosmology, using the relic light from the Big Bang, i.e., the cosmic microwave background, is lower than the direct measurement from supernovae calibrated with pulsating stars. If it can be ruled out that this discrepancy — dubbed the "Hubble tension" — is due to unknown systematic effects, we are looking at the strongest sign of new cosmological physics.

Strongly gravitationally lensed supernovae are extremely powerful probes of cosmology. For cases when a lensed supernova has multiple images, distances are measured via the difference in arrival times of the individual images. This method is completely independent of any calibration from local stars and is insensitive to the cosmological model, therefore, providing a new pathway to understanding the cause of the Hubble tension. Moreover, the magnification from strong lensing boosts the flux of light from the background supernovae allowing us to study them in detail. This is very important in light of recent results on dark energy — the agent introduced to explain the observed accelerated expansion of the Universe — from the combination of supernovae with baryon acoustic oscillations in the clustering of galaxies and the cosmic microwave background, which suggest that dark energy may be evolving with time.

Currently, there are only a handful of lensed supernova discoveries. For the first time, a lensed supernova, SN Encore, was discovered in the same galaxy as a previous discovery of a lensed supernova, SN Requiem. SN Encore is an excellent laboratory both to measure the Hubble constant (work ongoing) and the cosmic evolution of Type Ia supernova properties. We analysed the spectra of SN Encore taken with NIRSpec on the James Webb Telescope at two separate epochs and compared to an ensemble of low-redshift Type Ia supernovae (Fig. 1) and found no differences. SN Encore is at redshift $z = 2$, so occurred around 10.5 billion years ago. The remarkable similarity with local Type Ia supernovae is very interesting for the use of high-redshift supernovae for dark energy measurements. Moreover, we used the spectra to measure the age of the supernova, independently of any photometric information. Different methods for spectroscopic aging of the SN all agreed and this was the first high-redshift spectral analysis of a Type Ia supernova at one month after maximum brightness. We compared the spectral line velocities at these late phases to local supernovae and found no signs of evolution with redshift. Future studies, e.g., with the sample using the Vera C. Rubin Observatory, will be necessary to build large statistics and confirm or refute whether this is true for the entire population at high redshift.

The spectroscopic phasing of SN Encore is an important prior in the arrival-time measurement. This work is part of a series of studies on modelling the foreground lens (a galaxy cluster) and measuring the Hubble constant from SN Encore. We also explored how efficient current ground-based surveys are at finding lensed supernovae. Detailed simulations of the observing strategy of the Zwicky Transient Facility found that the survey would have discovered around five objects down to its photometric limit, however, with realistic spectroscopic selection criteria, which is a shallower limit, this number is consistent with the discovery of only one object, SN Zwicky in 2022. A complete archival data search of the survey led to the possible suggestion that two objects in the data stream were consistent with lensed supernova lightcurves; having spectra in real-time could have confirmed or refuted this classification. The biggest roadblock for future searches was found to be spectroscopy of the supernova host galaxy to get an accurate redshift and a real-time classification spectrum.

In a complementary study we explored how systematics — both astrophysical and instrumental — in the supernova Hubble diagram can impact constraints on the properties of dark energy. We found that a calibration difference of 0.05 magnitude and a change in the galactic dust law can cause a shift in the cosmology that is consistent with the dynamical dark energy parameters inferred from recent observations (Fig. 2). This calibration difference could arise from instrumental shift — e.g., filter functions or zeropoint — or due to evolution of dust properties around supernova or the intrinsic properties of the supernovae themselves at high redshift. The latter can be tested using lensed supernovae from next-generation missions.

This article is partly based on results published/submitted as Dhawan S. et al., MNRAS 535, 2939 (2024); Townsend A. et al., A&A 694, A146 (2024); Sagues-Carracedo A. et al., A&A submitted (arXiv:2406.00052); Dhawan S., Popovic B. & Goobar A., MNRAS submitted (arxiv: 2409.18668).

Figure 1

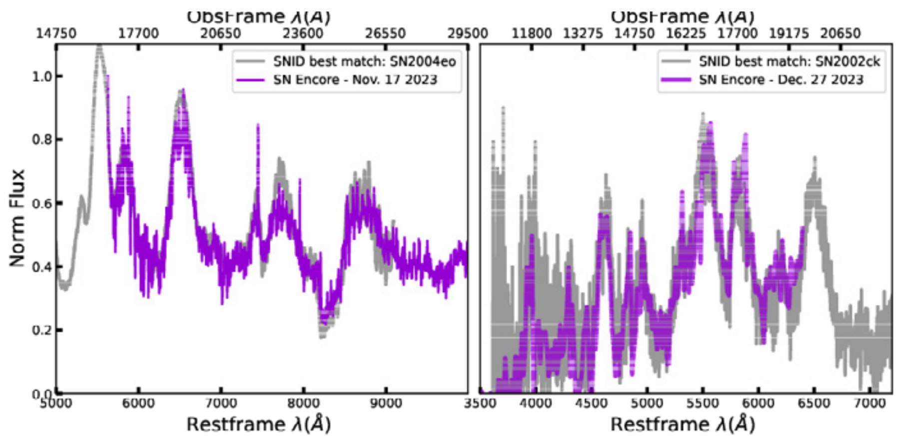


Figure 2

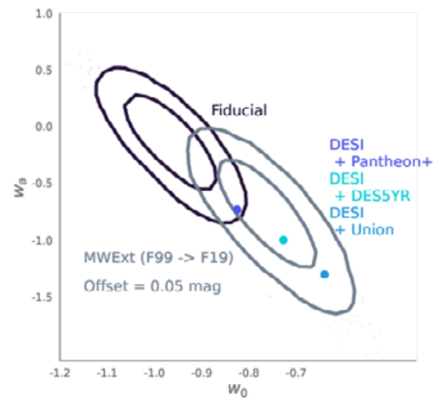


Fig 1. Comparison of spectra of a low-redshift Type Ia supernova (gray) and SN Encore (violet). The spectra look very similar showing no strong signs of cosmic evolution.

Fig 2. Inferred values of the parameters of a dynamical dark energy model when the true model is non-dynamical (w_0 = -1 and w_a = 0) and there are additional systematics of 0.05 mag and a different galactic dust law (grey contours). similar showing no strong signs of cosmic evolution.

James Rogers

Exoplanets and the Road to the Radius Valley

In the past two decades, our knowledge of the abundance and diversity of planetary systems has been revolutionised by space telescopes such as NASA's *Kepler* and *TESS* observatories (see Fig. 1). To date, we have detected over 5500 extra-solar planets, referred to as "exoplanets", which are planets that orbit other stars in our Galaxy, rather than the Sun. We have discovered that over 50% of Sun-like stars host at least one planet, with many likely hosting more than five planets. Simply put, the Milky Way has more planets than stars.

One of the most intriguing discoveries in the past decade is the characterisation of two classes of planets referred to as super-Earths and sub-Neptunes. These planets have typical sizes between that of Earth and Neptune, but orbit very close to their host stars, typically 10–30 times closer than Earth is to the Sun. Perhaps even more intriguing is that the size distribution of super-Earths and sub-Neptunes is bimodal. In other words, there are very few planets with sizes around 1.8 times the size of Earth. This lack of planets is referred to as the "radius valley", with super-Earths defined as those with sizes smaller than the valley, and sub-Neptunes as those larger than the valley (see Fig. 2).

Two leading theories aim to explain the emergence of the radius valley. The first, referred to as the "gas dwarf hypothesis", posits that most close-in exoplanets began life with a rocky interior (similar to the composition of Earth), surrounded by a thick hydrogen-rich atmosphere. The presence of this atmosphere can significantly increase the planet's size, much like the gas giants in our own Solar System. As such, we refer to these planets as "gas dwarfs". However, hydrogen is a very light element and is thus vulnerable to atmospheric escape driven by extreme irradiation from its host star. Planets closer to their host stars and smaller in mass tend to lose their hydrogen-rich atmosphere completely, leaving behind a naked rocky planetary core. The "gas dwarf" hypothesis states that planets that retain their atmospheres stay larger and form the population of sub-Neptunes, while the planets that lost their atmospheres shrink and create the population of super-Earths. Relatively few planets exist in between, which causes the formation of the radius valley.

The alternative theory is the "water world hypothesis", which states that super-Earths and sub-Neptunes formed through very different mechanisms. Super-Earths formed very water-poor (much like Earth, which is made up of less than 1% water), while sub-Neptunes formed water-rich, with up to 50% water, similar to some of the icy moons of Jupiter and Saturn. Super-Earths and sub-Neptunes thus have very different densities and sizes due to their differing compositions, which causes the emergence of the valley.

To date, there has been no clear way of determining which of these two hypotheses is correct. In a new study, we have shown that insight can be found by looking at young exoplanets. We have shown that when planets are young, their sizes are directly controlled by the composition of their atmospheres. Gas dwarfs have hydrogen-rich atmospheres, which is a light element, causing the planet to be very inflated when young. As shown in Fig. 3, gas dwarfs eventually shrink to become smaller than Neptune. Water worlds, on the other hand, have steam-rich atmospheres. Water is nearly 10 times heavier than molecular hydrogen, meaning such atmospheres are never puffy, even when young.

Detecting young exoplanets less than 100 million years old is notoriously difficult. However, a handful have been found in the *TESS* survey. We have shown that these detections are more consistent with the gas dwarf scenario, with inflated sizes approximately 2–3 times larger than old sub-Neptunes. Our study encourages the future detection of more young sub-Neptunes to increase the statistical significance of this result. Upcoming space telescopes, such as *PLATO* and *Nancy Grace Roman*, offer an exciting future for this avenue of research.

This article is partly based on results submitted to MNRAS as Rogers J., arXiv:2503.17364.

Figure 1

Fig 1. The Transiting Exoplanet Survey Satellite (TESS) launched in 2018 and has detected some of the youngest exoplanets to date. (Image credit: NASA/MIT.)

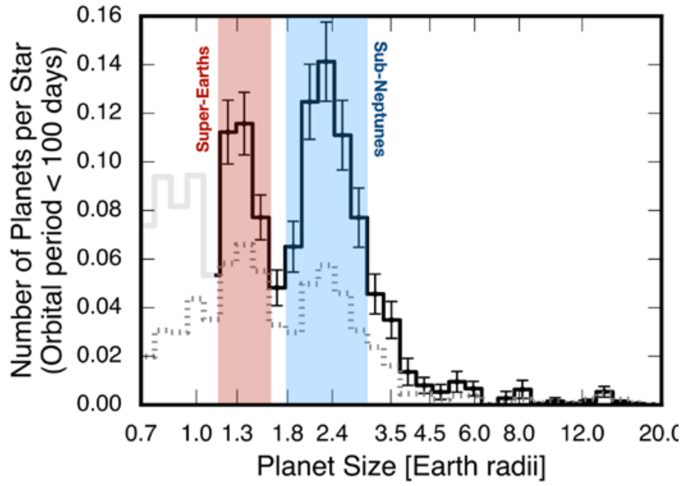


Figure 2

Fig 2. The "radius valley" describes the bimodal distribution of small exoplanet radii. Planets in the smaller population are called the super-Earths, while planets in the larger population are called sub-Neptunes.

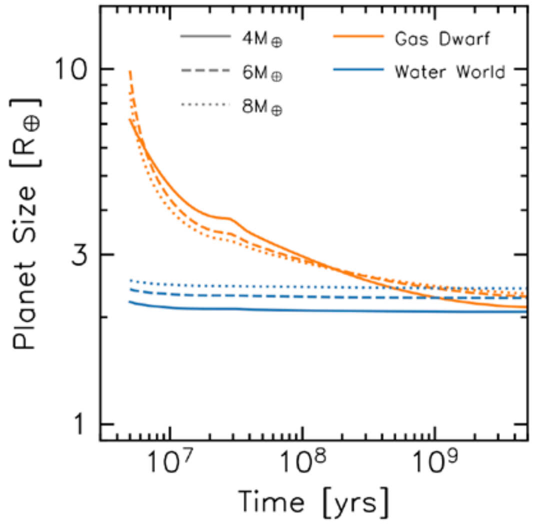
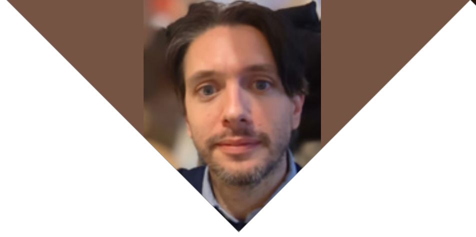


Figure 3

Fig 3. Gas dwarfs (orange) and water worlds (blue) have very different sizes when young (less than 100 million years old).



Fabio Antonini, Isobel Romero-Shaw & Thomas Callister

Evidence from Gravitational-Wave Data for a Population of Merging Binary Black Holes Originating in Star Clusters

The most recent catalogue of the LIGO–Virgo–KAGRA Collaboration reports 69 confident detections of gravitational waves from binary black holes inspiralling and colliding. Despite this wealth of observations, there is a mystery pervading every detection: the mechanisms by which these systems evolved into binaries that merged within the age of the Universe are unknown.

Binaries like this may evolve in isolation, with two stars born into a binary undergoing the specific processes of mass transfer that can keep them closely bound throughout their various expansions and explosions until they collide as compact stellar remnants. Alternatively, such binaries can become bound *dynamically*. Dynamical formation occurs in densely populated environments, like globular star clusters, where compact objects sink to the core via dynamical friction, and there undergo sequences of gravitationally-driven interactions that can lead to tightly-bound binaries that merge.

The different evolutionary pathways give rise to a range of different binary black hole properties. In isolation, there is expected to be an upper limit to the mass of a black hole that can form via supernovae, between 40–75 solar masses. Meanwhile, dynamically formed binaries can contain more massive black holes that are themselves remnants of previous mergers. In isolation, black holes are expected to have spins that are aligned with each other due to tidal effects during stellar evolution, if they are spinning at all. In comparison, dynamically formed binaries in clusters can have spins tilted at any angle, and may have higher spins if they contain merger remnants.

There is a correlation here for dynamically formed binaries in clusters: when at least one of the binary components has a mass above the theoretical limit, binaries should have a wider spin distribution. This distribution has an analytical form that fits well to simulations of binary black hole mergers in clusters. Using this analytical model, we performed hierarchical Bayesian inference on the LIGO–Virgo–KAGRA population of binary black holes, looking for the black hole mass at which a transition from a narrow to wide spin distribution was observed. Strikingly, we found a very strong transition at 45 solar masses. Below this mass, spins were small and mostly aligned; above this mass, spins became suddenly much more broadly distributed.

The low-spin population at low masses is likely a combination of isolated and dynamical mergers, while the broad-spin population at high masses is likely to be dynamical in origin. Using relative rate arguments, we predict that overall, if these high-mass binaries formed in star clusters, around 20% of the binary black holes observed by LIGO–Virgo–KAGRA formed dynamically.

This article is based on results published as Antonini F. et al., Phys. Rev. Lett. 134, 011401 (2025).

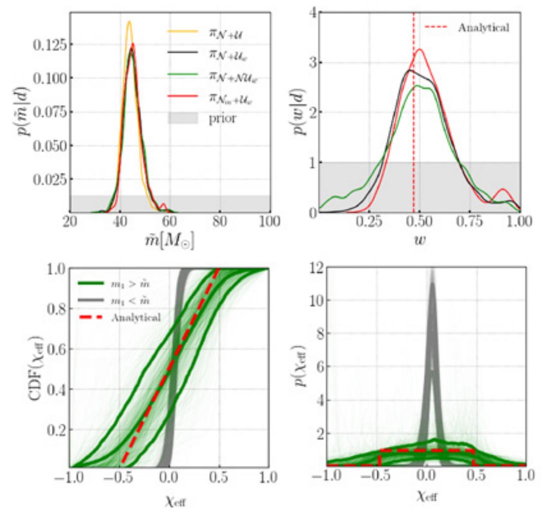


Figure 1

Fig 1. AI-generated image of a star cluster with black holes inside. Credit: Fabio Antonini.

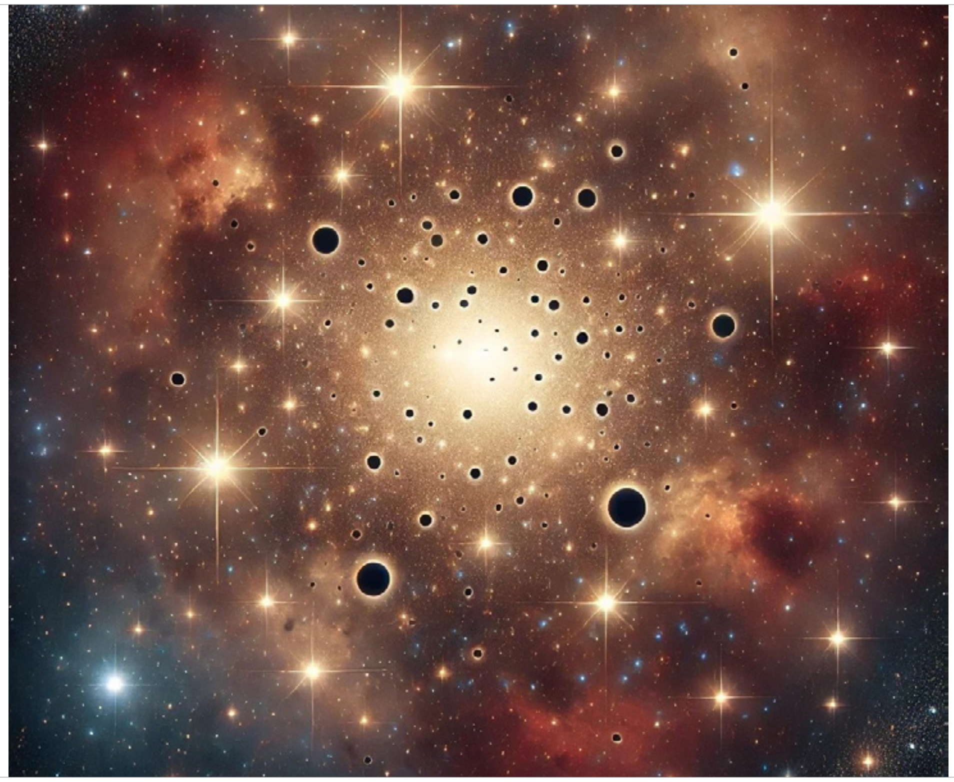


Figure 2

Fig 2. Plots showing: the constrained transition mass between small spins and broad spins under four different models, compared to the prior (top left); the inferred width of the broad spin distribution in the three models in which this varies, which matches well with the analytic prediction shown with a red dashed line (top right); the cumulative distribution of effective spins for low-mass (grey) and high-mass (green), in comparison to the analytic prediction for the broad spins of the high-mass population (bottom left); and the population posterior reconstruction of the effective spin distribution compared to the analytic prediction for broad spins of the high-mass population (bottom right).

Isobel Romero-Shaw, Samir Goorachurn, Magdalena Siwek & Christopher Moore

Eccentricities of Stellar-Mass Binary Black Holes with Circumbinary Disks in LISA

The future space-based gravitational-wave detector LISA will detect, amongst many other things, the gravitational-wave emission from stellar-mass binary black holes that are inspiraling towards merger: the kind of gravitational-wave events that have so far been observed with the LIGO–Virgo–KAGRA detectors. However, due to its lower-frequency sensitivity, LISA will observe these stellar-mass binary black holes at much earlier stages of their lives — many years before they merge.

At earlier stages in their lives, black hole binaries are not as thoroughly decoupled from their environments as they are in the few seconds before merger that can be detected by LIGO–Virgo–KAGRA. This means that LISA has a better chance of detecting telltale signs of perturbing influences on the orbit, like tertiary masses, or — as is the focus of this study — circumbinary disks.

Circumbinary disks can exist around binary black holes if they form in gaseous environments, like the disks of active galactic nuclei; if they accrete matter from a stellar tertiary; or if the binary evolved through common-envelope evolution. Identifying the presence of a circumbinary disk around an inspiralling binary black hole can indicate that this binary could produce an electromagnetic counterpart when it merges — something that has not yet confidently been detected for a binary black hole merger.

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One of the authors, Magdalena Siwek, had previously produced hydrodynamical simulations of binary black holes in circumbinary disks (shown in Fig. 1), and found the orbit-averaged evolution of the binary's separation and eccentricity due to the disk's influence. Her simulations showed that the binary would be pushed towards an equilibrium eccentricity between around 0.2 and 0.5, the value of which directly correlated with the binary's mass ratio. The results of these simulations were scalable to black holes of any mass, and had already been applied to supermassive black hole binaries. However, after seeing these simulation results, Isobel Romero-Shaw was interested in how this would affect binaries of the type seen by LIGO–Virgo–KAGRA: stellar-mass binary black holes that merge.

Romero-Shaw combined Siwek's results with the effects of gravitational-wave-driven binary evolution, with interesting results. The authors found that the presence of a circumbinary disk can be identified by measuring the eccentricity of the binary when its gravitational-wave emission becomes detectable in LISA, at a frequency around 0.01 Hz (shown in Fig. 2). Even though the binary has decoupled from the disk at this point, the earlier driving of the binary to its equilibrium eccentricity leaves an echo: a detectable eccentricity in LISA. While the expected eccentricity induced by circumbinary disks is within the range expected to arise also in binaries that form through dynamical interactions, the authors show that there can be a characteristic correlation between eccentricity and mass ratio that would be a smoking-gun for identifying the influence of a circumbinary disk.

This article is based on results published as Romero-Shaw I. et al., MNRAS Lett. 534, L58 (2024).

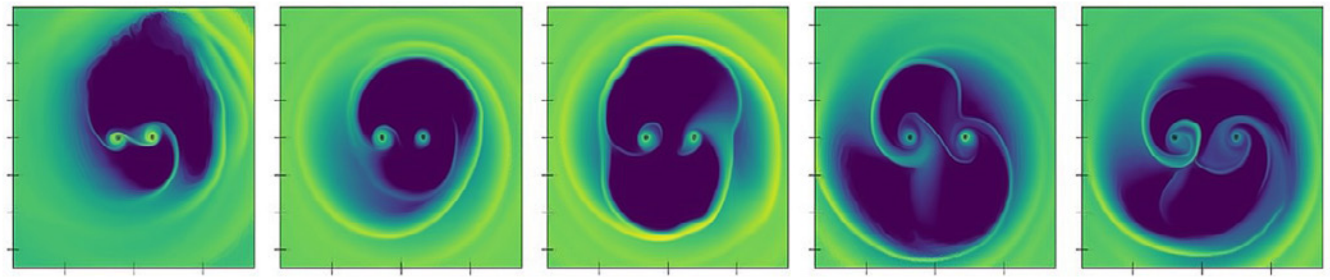

Fig 1. Snapshots of the hydrodynamical simulations produced by Siwek and collaborators.

Figure 1

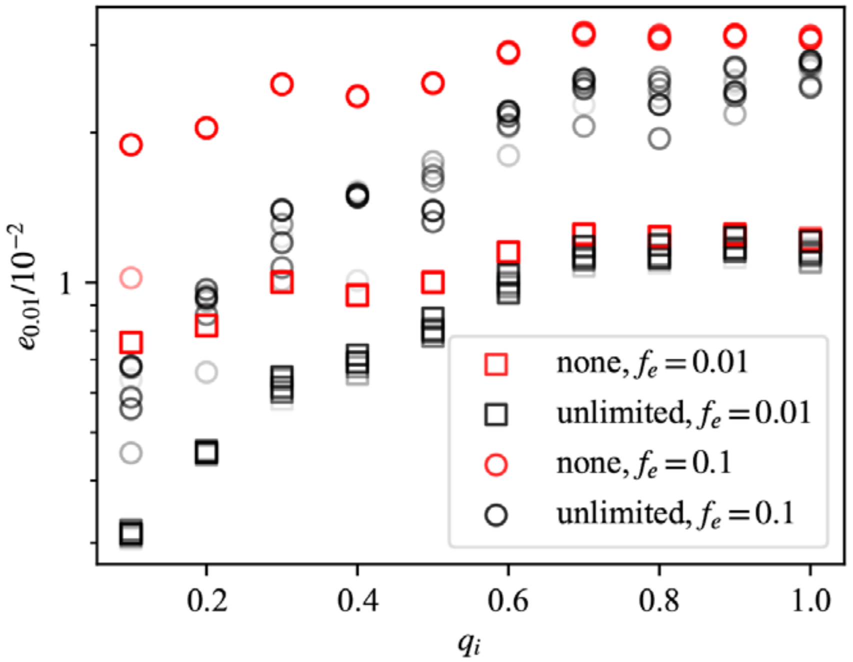

Fig 2. Orbital eccentricity at 0.01 Hz for systems with long-lived circumbinary disks, which have a primary mass of 30 solar masses and initial mass ratios denoted by qi (the ratio of the secondary to the primary mass). There is a clear correlation between initial mass ratio and measured eccentricity. Red (black) colours correspond to systems with no accretion (unlimited accretion). Square (circular) points correspond to the assumption of Eddington accretion fraction 0.01 (0.1). The opacity of points corresponds to initial eccentricity, which has little influence on the final measured eccentricity; initial mass ratio is the most valuable predictor of measured eccentricity in LISA.

Figure 2

James Alvey

Decades to Days – A Simulation-Based Future for Gravitational Wave Astronomy?

Since the first detection in September 2015, our observations of *gravitational waves* (GWs) continue to reshape astrophysics and cosmology. Through the LIGO-Virgo-Kagra Collaboration, we have directly "heard" numerous mergers of black holes and neutron stars. Last year, there was also the exciting data release from worldwide pulsar timing array collaborations that presented the tentative detection of a stochastic background. The current leading theory suggests that this stochastic signal is a symphony of numerous gravitational wave sources originating from the mergers of supermassive black holes in massive galaxies. Next-generation facilities such as the (ground-based) Einstein Telescope and Cosmic Explorer, and the (space-based) LISA mission promise further breakthroughs in general relativity, neutron-star astrophysics, and black hole formation across cosmic time.

All of these achievements to date rely on *statistical inference*. Traditional GW parameter estimation is framed as a Bayesian inference problem: given detector data, what are the most likely parameter values (e.g., black hole masses or sky locations) as quantified by the posterior distribution? The goal of any Bayesian inference algorithm (Markov-Chain Monte-Carlo, nested sampling, etc.) is to construct and/or sample from this posterior. Classically this is achieved by evaluating a likelihood function that quantifies how well a model fits the data, following Bayes' theorem.

Why might we need an alternative to these classical methods though? To give a glimpse as to where the problems lie, imagine someone hands you a few years worth of data from LIGO and asks you to analyse it. Like any good computational physicist, before we boot up the computing cluster, we should estimate the possible costs. Suppose there are N events, each requiring K parameter/likelihood evaluations, with each sample taking T seconds to compute. The total inference cost is then $C = N \times K \times T$. With (very) conservative estimates of K = 1 billion and T = 1 ms, this scales as C = (3 hrs) x N. This is manageable today with 100s of events (on the week's timescale) but stretches into *decades* of computing time for next-generation detectors observing 100s of thousands of mergers.

So, is there another way? Simulation-based inference (SBI) is a new class of techniques that use machine learning to solve the Bayesian inference problem. There are some technical differences between the various algorithms (e.g., neural ratio estimation and neural posterior estimation), but broadly they all rely on the following setup. Given a forward simulator that maps parameters to simulated data, SBI constructs machine learning-based estimators of the posterior, likelihood, or posterior-to-prior ratio. Originally, SBI's main advantage was avoiding an explicit likelihood function, which indeed may be important for GW science moving forwards as detectors get more complex and, for example, noise may break assumptions about Gaussianity or stationarity. More importantly here, SBI has the potential to mitigate the scaling problem. Our recent work applied SBI to binary black hole mergers and showed that the required number of samples could be reduced by *two orders of magnitude*. This means that even with more than 100,000 events, computational time could remain within the weeks-to-months time frame, leaving lots more time to do exciting GW science! Our SBI algorithm is illustrated in Fig. 1.

SBI is not without issues though. Model mis-specification remains critical – if training simulations fail to capture astrophysical or instrumental effects, inference and scientific outcomes may be biased. Another of our recent works explored machine learning-driven approaches to assess model fit across various mis-modeling scenarios. We applied the pipeline to GW150914, the first detection by LIGO (see Fig. 2).

Since 2015, GW detection capabilities and analysis techniques have advanced greatly. With this, the next-generation detectors bring new opportunities but also large computational challenges. We believe that simulation-based inference could be an extremely promising avenue to free up resources for cutting-edge GW science.

This article is partly based on results published as Bhardwaj U., Alvey J. et al., Phys. Rev. D 108, 042004 (2023) and Anau Montel N., Alvey J. et al., Phys. Rev. D accepted (arxiv:2412.15100).

Figure 1

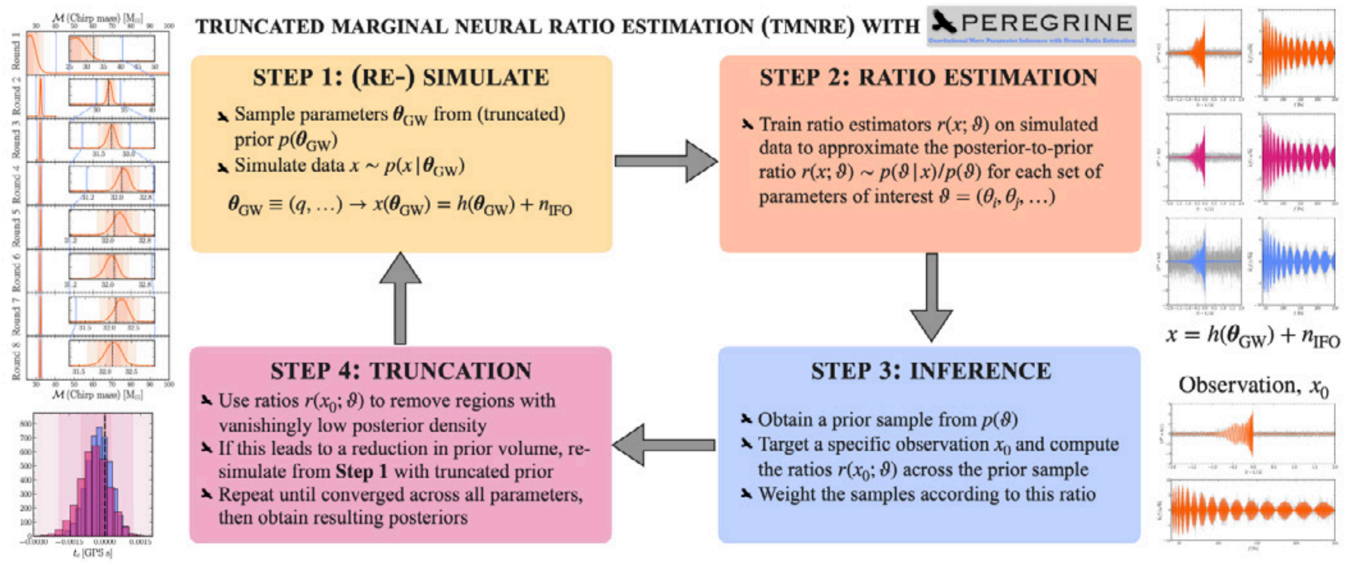

Figure 2

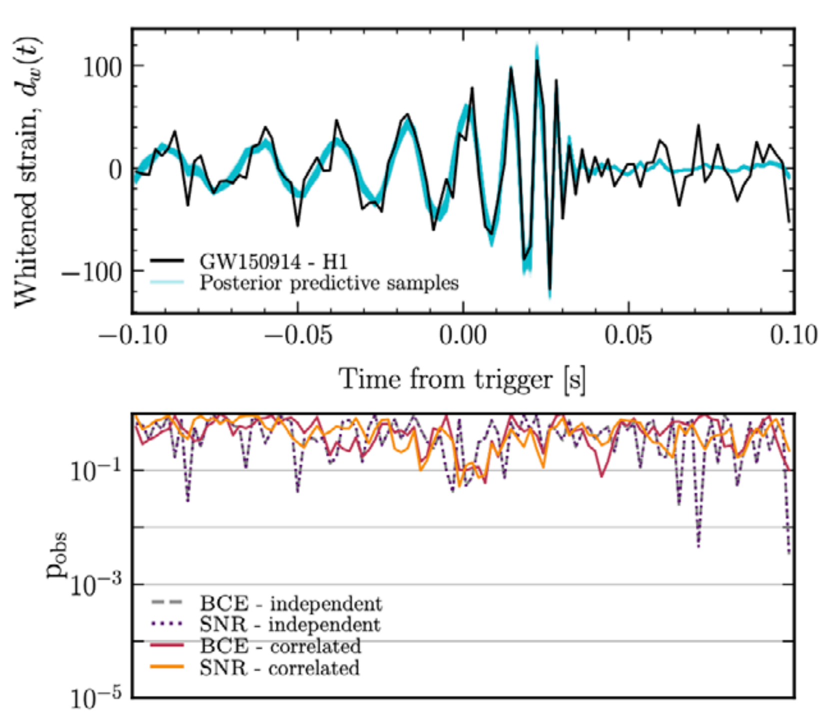

Fig 1. Schematic representation of the SBI inference algorithm for analysing binary black hole mergers at LIGO.

Fig 2. Testing for modelling errors in the first gravitational wave detection, GW150914 – fortunately none were found!

Harry Bevins

Calibrating Tensions with Machine Learning Tools

In the quest to understand our Universe, scientists often rely on multiple experiments to measure the same cosmological parameters. Ideally, these independent measurements should align, reinforcing our confidence in the cosmological models we use. However, discrepancies, or “tensions”, sometimes arise between datasets, prompting questions about potential new physics or unrecognised systematic errors.

Cosmologists have spent the last decade pondering several tensions, including the Hubble tension and the σ_8 tension. The Hubble tension concerns measurements of the expansion rate of the Universe from observations of the cosmic microwave background (CMB), primarily from the Planck instrument, and supernova light curves from the SH0ES project. The weaker σ_8 tension concerns measurements of the amplitude of matter fluctuations on the scale of 8 megaparsecs, with CMB measurements suggesting higher values than those derived from large-scale structure surveys probing weak gravitational lensing and clustering of galaxies.

Historically, scientists have employed various statistical tools to assess the significance of these tensions. An important metric for measuring tension is the statistic *R*. This statistic effectively quantifies how our confidence in one experiment improves when we look at data from another. It is rooted in Bayesian statistics, but its value is dependent on assumptions made by researchers about the models used for the two data sets in question, and it has no absolute scale. This makes interpreting its value and comparing the relative tension between different combinations of data very difficult. Current methods to calibrate the tension statistic are often computationally expensive and incomplete in their assessments.

While these cosmological tensions have intensified, researchers have been developing novel ways to perform inference on their data sets. Advances in machine learning and computing power have led to a surge in popularity of simulation-based inference (SBI) techniques. In SBI, machine learning tools are trained using simulations to infer which values of the simulation parameters are most likely given an observation. A commonly used technique is neural ratio estimation (NRE) which, when trained properly, can tell you how probable it is that an observation came from a particular parameter set.

Researchers at KICC identified a connection between NRE and the tension statistic *R*. By training a classifier on simulations from two experiments, we can rapidly predict all possible values of *R* for observations from experiments constraining the same parameters. This allows researchers to calibrate for their model assumptions and better understand the relative tension between different data sets.

We demonstrated this approach using hypothetical observations of the 21-cm signal from Cosmic Dawn that given the noise in the data could all potentially be in agreement (see Fig. 1). We modelled observations from two fictional experiments with different capabilities and trained our “tensionnet” algorithm on simulations to predict the expected distribution of *R* values for in-concordance observations within the models for the data sets. By calibrating the true *R* values for the observed data sets, obtained with more traditional methods like Nested Sampling, against this distribution, we correctly identify that the two measurements from the second experiment that are in tension with the first are indeed very unlikely given the modelling assumptions.

To test this on a real cosmological example, we evaluated the tension between measurements of baryon acoustic oscillations (BAO) from the Sloan Digital Sky Survey (SDSS) and the Dark Energy Spectroscopic Instrument (DESI). We trained the neural network shown in Fig. 2 on simulated observations from the two surveys and used the network to calibrate the tension between the observed data sets. Given the modelling choices made for each data set, we were able to conclude that there is very little tension between the observations.

Our new approach provides cosmologists with a powerful tool to interpret tensions between datasets better. By calibrating the *R* statistic through machine learning, we can more reliably quantify tension and calibrate for our modelling choices.

This article is based on results submitted as Bevins H., Handley W. & Gessey-Jones T., arXiv:2407.15478.

Figure 1

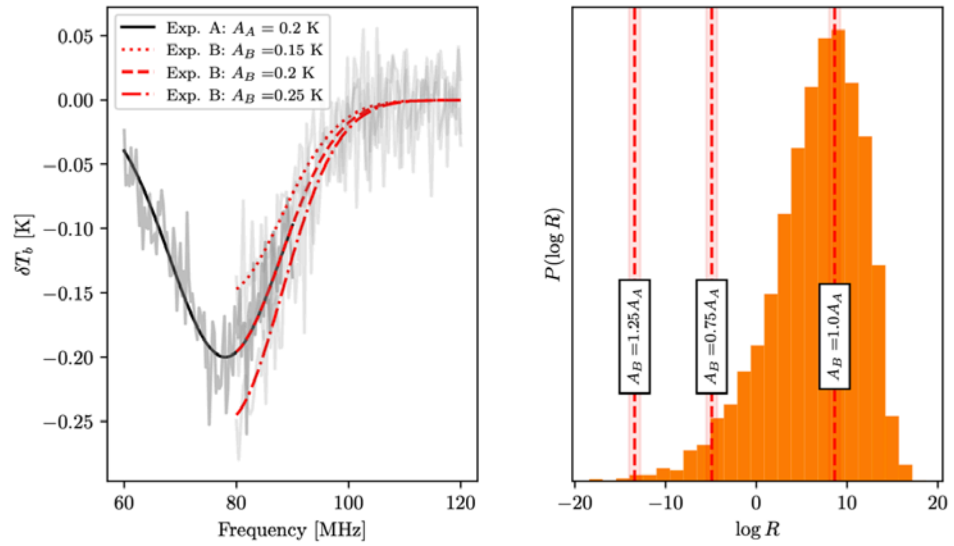

Figure 2

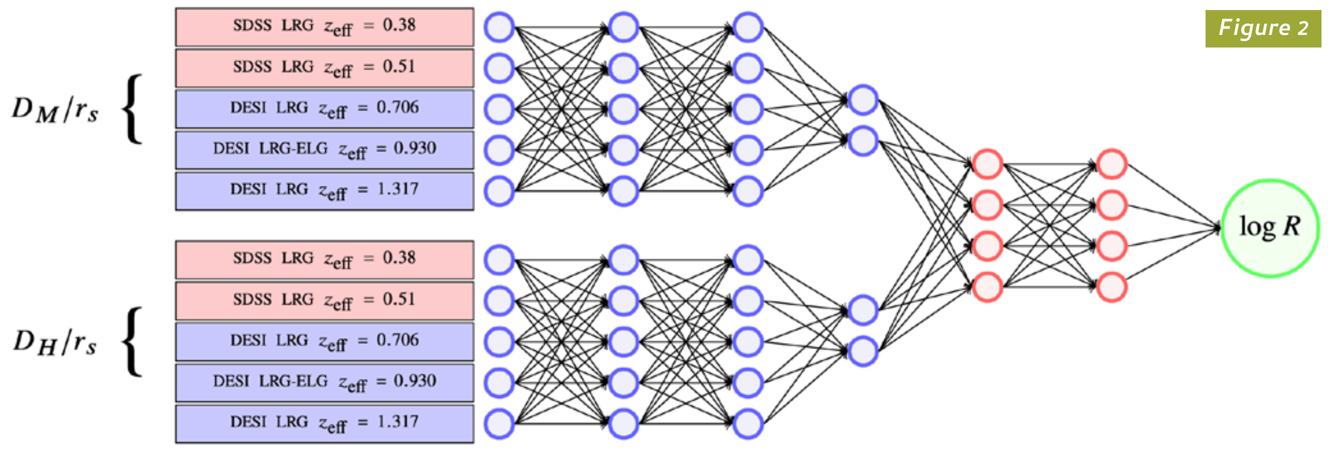

Fig 1. Left: Hypothetical 21-cm signals from two experiments with different bandwidths. Right: The expected distribution of the tension metric R given our modelling assumptions and the measured values of R for different combinations of the data sets in the left panel.

Fig 2. Diagram showing the neural network used to calibrate the tension between measurements of the BAO signal with SDSS and DESI.

Boris Bolliet & Íñigo Zubeldia

Towards Self-Driving Cosmological Laboratories

Modern cosmology (and, in general, science) is increasingly driven by vast and complex datasets. Analysing these datasets in order to infer fundamental information about the Universe has traditionally involved complex pipelines requiring sophisticated software and significant computational power. Developing and implementing these demanding analysis pipelines typically represents a major bottleneck, consuming substantial researcher time and slowing the pace of discovery.

With the goal of addressing this bottleneck, we have developed CMBAGENT, an AI-driven multi-agent system for quantitative research. CMBAGENT is based on Large-Language-Model (LLM) agents operating under a plan designed to answer the user's prompt. The plan, created by a "planner" agent following a planning and control strategy, is a key element in the system, as it devises the workflow and breaks down large research tasks into smaller, manageable steps. These steps are carried out by specialised agents with distinct functions: one may retrieve relevant information from scientific literature using an approach known as Retrieval Augmented Generation (akin to an AI doing an open-book search), another one may generate computer code using specialised tools, and another one may execute the code locally and plot the results. In a remarkable initial test, CMBAGENT successfully reproduced a state-of-the-art cosmological analysis, the cosmic microwave background (CMB) lensing analysis of the Atacama Cosmology Telescope (ACT), delivering constraints on cosmological parameters that matched the published ones for the same dataset.

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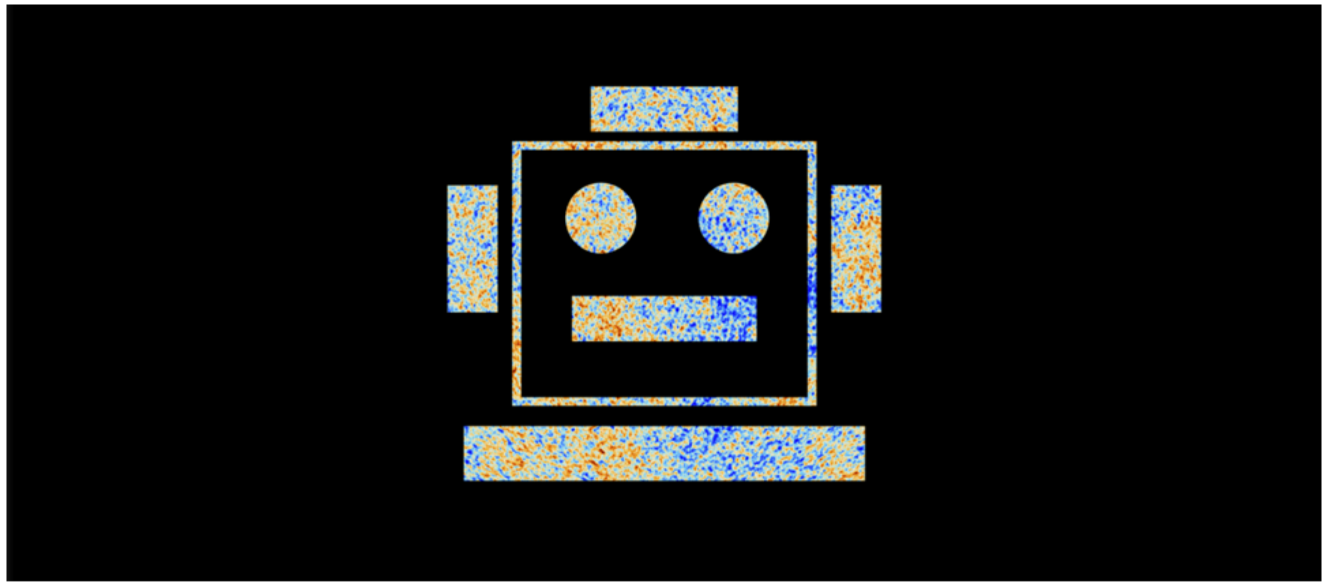
A significant recent advancement is that CMBAGENT now operates fully autonomously, without a "human-in-the-loop". Previous versions required researcher oversight, but the system can now execute complex analysis pipelines from start to finish independently. This removal of the human from the loop constitutes, we hope, a small but significant step towards realising the vision of "self-driving laboratories" in fundamental science. In this vision, AI agents partner with human researchers by handling tedious and complex computational tasks, allowing human researchers to focus more on higher-level thinking, interpretation, and question formulation, ultimately accelerating the discovery process.

While CMBAGENT is primarily designed for cosmology, its planning and control strategy has demonstrated remarkable versatility. As shown in a recent demo video released on YouTube, the same methodology has been successfully applied to data analysis challenges in diverse fields such as education, economics, and undergraduate physics. This broad applicability may mark the beginning of an answer to the compelling question: "Can AI do Science?".

The CMBAGENT team includes Boris Bolliet, Miles Cranmer, Sven Krippendorf, Andrew Laverick, Julien Lesgourgues, Antony Lewis, Blake Sherwin, Kristen Surrao, Francisco Villaescusa-Navarro, Licong Xu, and Íñigo Zubeldia. Their work is supported by the *Accelerate Programme for Scientific Discovery* at the University of Cambridge. By automating complex data analysis, CMBAGENT promises not only to accelerate progress in cosmology but also to pioneer more efficient and robust research methodologies across many scientific disciplines.

This article is partly based on results submitted as Laverick A. et al., arXiv:2412.00431v2 (2024). Further information about CMBAGENT can be found at **https://github.com/CMBAgents/cmbagent** and **https://www.youtube.com/@cmbagent**.



multi-agent systems for autonomous discovery

Tibor Dome, Sergio Martin-Alvarez, Sandro Tacchella, Yuxuan Yuan & Debora Sijacki

AZAHAR Cosmological Simulations Unveil the Origin of Bursty Star Formation in High-Redshift Galaxies

The James Webb Space Telescope (JWST) is revolutionizing our understanding of the properties of galaxies all the way back to the very early Universe, with a leap in sensitivity, especially in measuring spectra, of more than three orders of magnitude. JWST observations have led to numerous surprising results and have enabled new avenues of research in galaxy formation. One salient example is the inference of bursty star formation in high-redshift galaxies, whereby galaxies likely go through cycles of intense star formation followed by periods of virtually no star formation, i.e., quiescence.

These first quiescent galaxies forming in the early Universe offer a unique probe into the physical mechanisms behind the cessation of star formation, as the cosmic time of their assembly is particularly short. Specifically, spectroscopic JWST studies suggest a fast build-up of stellar mass within the first one or two billion years of the Universe, followed by rapid suppression of star formation, also known as `quenching', within a few tens of millions of years, which is challenging our current understanding of galaxy formation.

While the majority of early quiescent galaxies identified to date are massive systems, JWST is opening a new window on the first generations of quiescent low-mass galaxies populating the high-redshift Universe. A recently observed quiescent galaxy, JADES-GS-z7-01-QU, has a remarkably low stellar mass at a redshift z = 7.3. To understand the likely physical mechanisms at play that led to the formation of objects like JADES-GS-z7-01-QU, we took advantage of novel galaxy formation simulations from the Azahar suite (see Fig. 1). These simulations, performed with the adaptive-mesh-refinement RAMSES code, include galaxy formation models ranging from magneto-hydrodynamics with a magneto-thermo-turbulent prescription for star formation to more sophisticated setups incorporating full on-the-fly radiative transfer and cosmic-ray physics.

We analyzed a sample of 10 simulated galaxies at very high resolution in the early Universe and found that the inclusion of cosmic rays and radiative transfer leads to much burstier star-formation histories, as well as a greater variety of star-formation burst intensities. We generated a forward-modeled mock spectrum during a `mini-quenching' event at redshift z = 7.5 and compared it with observational data for the high-redshift quiescent galaxy JADES-GS-z7-01-QU, showing very good agreement (see Fig. 2).

This study underscores the critical role of incorporating comprehensive physical processes, such as cosmic rays and radiative transfer, into hydrodynamical simulations to capture more accurately the burstiness of star formation in high-redshift galaxies. By quantifying the burstiness of galaxies in Azahar using observable metrics, such as detailed mock spectra, we are able to bridge the gap between simulations and observations, aiding the physical interpretation of JWST findings. Refining our understanding of galaxy formation models through such detailed comparisons with JWST data will ultimately shed light on the puzzling early stages of galaxy formation.

This article is based on results published as Dome T. et al., MNRAS 537, 629 (2025).

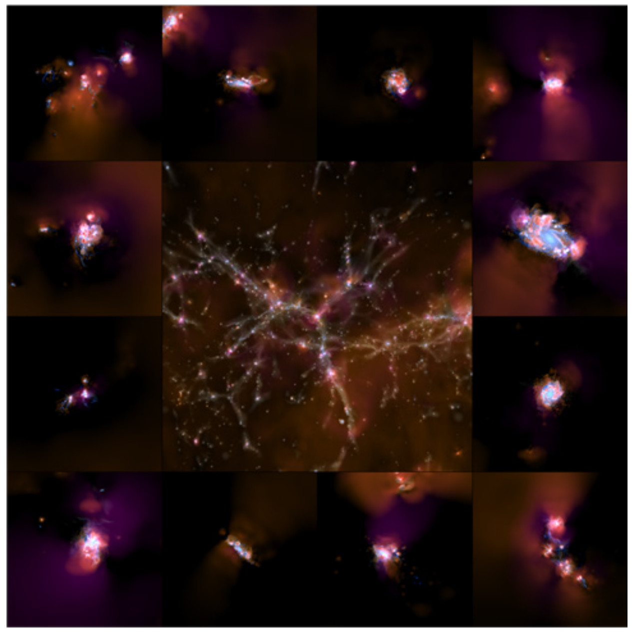


Figure 1

Fig 1. Central panel: Large-scale view of the Azahar simulation capturing galaxy formation in the very early Universe. Galaxies (bright white compact regions) form at the intersection of cosmic filaments. Surrounding panels: Zoom-in views into a varied collection of galaxies from the Azahar simulation, ranging from massive spiral systems to complex galaxy mergers. Colours show neutral hydrogen (blue), ionized hydrogen (gray), JWST stellar emission (white), and emanating radiation in pink-orange hues.

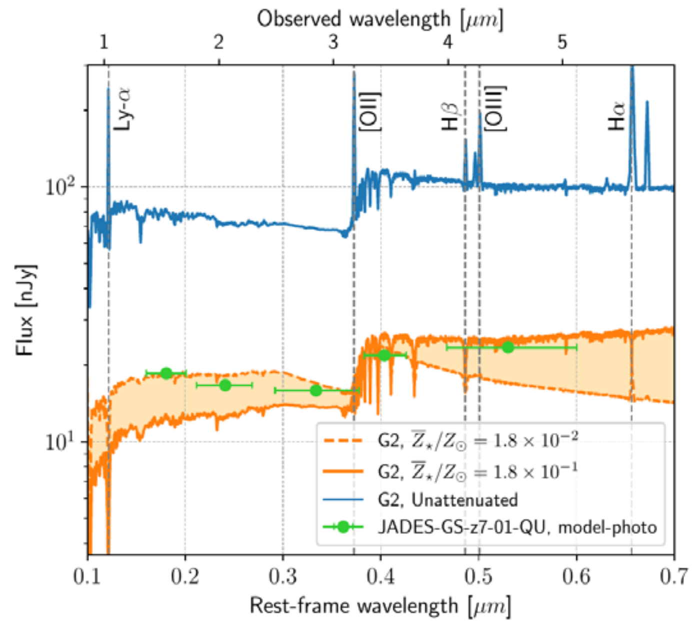


Figure 2

Fig 2. Unattenuated mock spectrum of our simulated galaxy (blue) and the dust-attenuated spectrum (orange; for two choices of stellar metallicity) compared to the observed JWST photometry (green) for the JADES-GS-z7-01-QU galaxy.

Leah Bigwood, Martin Bourne, Vid Irsic, Alex Amon & Debora Sijacki

The Case for Large-Scale AGN Feedback in Galaxy Formation Simulations

Our standard cosmological model, ΛCDM, assumes the Universe comprises three main components: dark energy in the form of a cosmological constant (Λ), which drives an accelerated expansion of the Universe, cold dark matter (CDM), which interacts only gravitationally, and the ordinary baryonic matter, which is, in principle, observable. The ΛCDM model has proven extremely successful when stress-tested against observations over a remarkable span of the Universe's cosmic history.

However, a number of "tensions" in measuring key ΛCDM cosmological parameters through different approaches have been highlighted in recent years, with one salient example being the measurement that probes the distribution of matter in the Universe (the "S_8 tension"). In this case, *Planck's* measurements of fluctuations in the cosmic microwave background in the early Universe, when extrapolated forward in time, appear to be systematically at variance with estimates coming from "late-universe" probes, such as weak galaxy lensing surveys. However, weak lensing is sensitive to spatial scales on which baryonic matter may have a significant impact and for which theoretical modelling is uncertain.

While it has been hypothesized that the likely solution to this "tension" may stem from "baryonic feedback" – an umbrella term referring to complex physical processes, such as star and black hole formation, and their associated feedback – rather than requiring modifications to our standard model of cosmology, state-of-the-art cosmological simulations have not yet provided a consensus view on the overall level at which baryonic feedback impacts the matter distribution. Moreover, these simulations have struggled to reproduce the matter distribution in agreement with the latest weak galaxy lensing measurements, and with measurements of the gas distribution in the outskirts of groups of galaxies as probed by kinetic Sunyaev-Zel'dovich (kSZ) measurements.

To address this issue, we have performed a large suite of high-resolution cosmological galaxy formation simulations on DIRAC high-performance computing facilities, comprising more than 40 cosmological boxes. In these simulations, we systematically varied baryonic feedback implementations, based on the FABLE simulation project, but going beyond standard modelling approaches. We have particularly focused on the role of feedback stemming from actively accreting supermassive black holes powering active galactic nuclei (AGN), which are among the most energetic objects in the Universe, able to heat and eject large amounts of gas from their host galaxies.

Importantly, we found that a novel AGN feedback model, XFABLE (see Fig. 1), is able to produce a distribution of matter that aligns with weak galaxy lensing and kSZ estimates (see Fig. 2), while simultaneously maintaining very good agreement with all key stellar and gas observables, such as the amount of baryons present in galaxies of different sizes. Our simulations demonstrate that there is a physically plausible galaxy formation model within the ΛCDM universe, which is consistent with all current observational constraints from this diverse range of datasets, without the need to invoke alternative cosmological models.

The future observational landscape for unraveling how baryonic feedback operates is very promising. Soon, we will gather multi-wavelength, next-generation observational datasets, ranging from X-rays (eROSITA and Athena) to optical and near-infrared (Rubin Observatory and *Euclid*), and extending to the radio regime (Simons Observatory, LOFAR, and SKA). Together with the rapid advancement in realistic galaxy formation simulations, our ability to constrain baryonic physics for precision cosmology will soon be within reach.

This article is based on results submitted to MNRAS as Bigwood L. et al., arXiv:2501.16983." -> "This article is based on results published in Bigwood et al., MNRAS, 2025, doi:10.1093/mnras/staf1435.

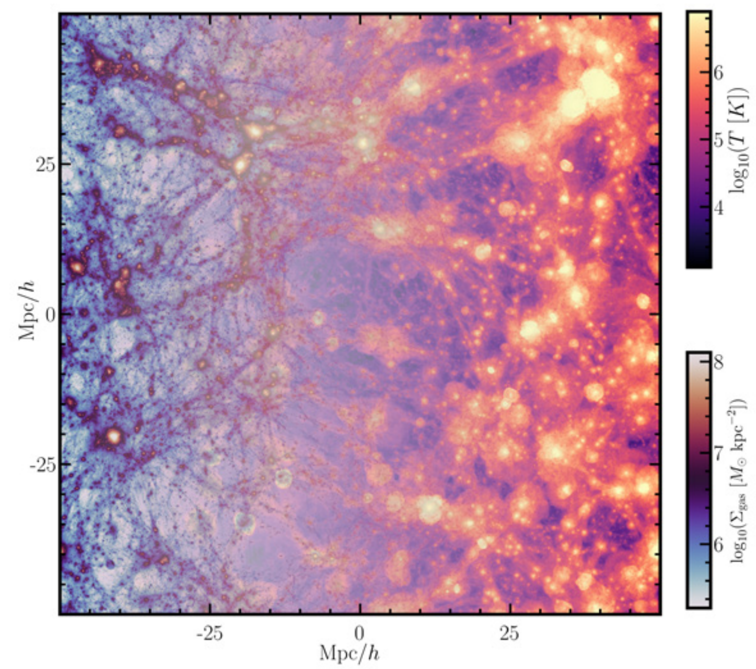


Figure 1

Fig 1. Projection visualising the blend of the gas surface density and mass-weighted temperature of our new AGN feedback model XFABLE.

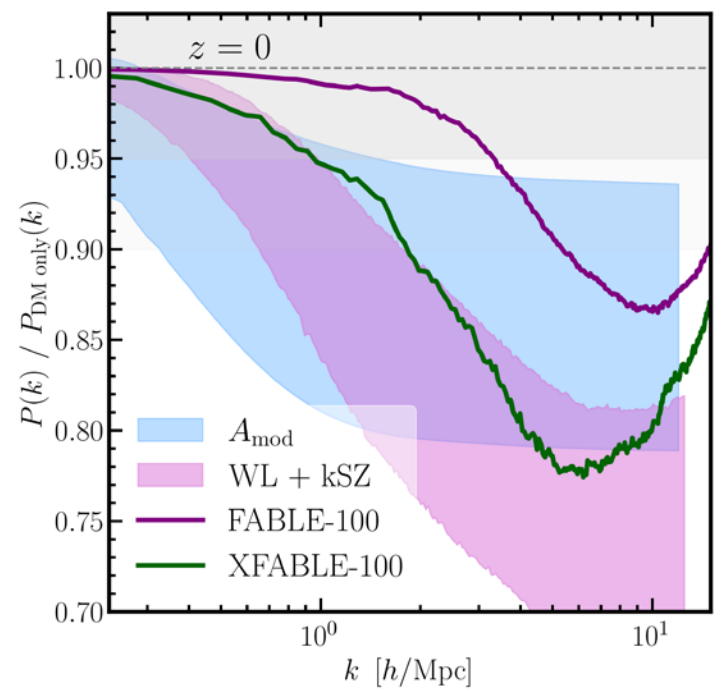


Figure 2

Fig 2. With respect to our default FABLE simulations (purple curve), our new XFABLE simulations (green curve) produce a distribution of matter that aligns with weak galaxy lensing and kSZ estimates (purple band), and with the constraints required to resolve the S_8 tension (blue band).

Yuxuan Yuan, Sergio Martin-Alvarez, Martin G. Haehnelt & Debora Sijacki

The Effect of Dust and Extended Red Wings on the Visibility of Reionization-Epoch Lyman-α Emitting Galaxies

The early-universe galaxy population that emits Lyman-α (Lyα) light is an important probe of how and when the hydrogen in the Universe became reionized by the first galaxies. How easily we can see early Lyα-emitting galaxies depends on how much of their light escapes at slightly longer and thus redder wavelengths than the central Lyα wavelength. This is because most of the light at shorter wavelengths is absorbed by neutral hydrogen gas between galaxies, known as the intergalactic medium. We have used computer simulations from the Azahar and Sherwood-Relics simulation suites to study how Lyα emitters and their visibility evolve during the epoch of reionization when the Universe transitions from hydrogen being predominantly neutral to highly ionized. We have examined in particular, how dust and galaxy collisions affect the brightness and visibility of Lyα emitting galaxies.

The evolution of a simulated reionization-epoch galaxy as it undergoes a sequence of mergers with other galaxies is shown in Fig. 1. The different rows of the figure show the emitted and observed Lyα light for different assumptions about the amount of what astronomers call dust. In Fig. 2, we show that the observed properties of Lyα-emitting galaxies recently discovered with the James Webb Space Telescope (JWST) appear to suggest that very little dust is present in reionization-epoch galaxies emitting Lyα light.

Our simulations also allow us to create realistic mock spectra of the Lyα light. The bright red peaks in the spectra that are caused by the light scattering within galaxies, are often modelled as a simple symmetrical peak shape (a Gaussian). Our simulated Lyα spectra exhibit more extended red wings than predicted assuming simple Gaussian peak shapes. As shown in Fig. 3, the more extended red wings greatly enhance the visibility of the Lyα light emitted by our simulated galaxy. This likely goes a long way to explaining why JWST is finding many more Lyα-emitting galaxies than had been expected.

We further have confirmed the previous finding by KICC researcher Callum Witten of galaxy mergers as the frequent origin of early bright Lyα-emitting galaxies. JWST is allowing us to see Lyα light from reionization-epoch galaxies at greater distances than ever before, helping us understand how and when the first galaxies lit up the Universe. By studying these distant galaxies, we uncover clues about the cosmic dawn and how early galaxies evolved.

This article is partly based on results submitted as Yuan Y. et al., MNRAS submitted (arxiv:2412.07970)." -> "This article is partly based on results published in Yuan et al., 2025, MNRAS, 542, 762..

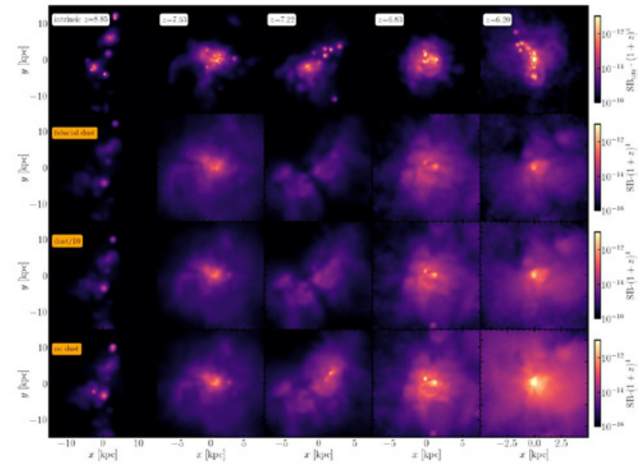


Figure 1

Fig 1. Impact of dust content on the Lyα light emitted by a simulated reionization-epoch galaxy as it undergoes a sequence of mergers with other galaxies. The first row shows maps of the intrinsic Lyα emission while the second to fourth rows show the emission assuming different amounts of dust. In the first row, we mark redshift on the top left of each panel, with cosmic time increasing to the right.

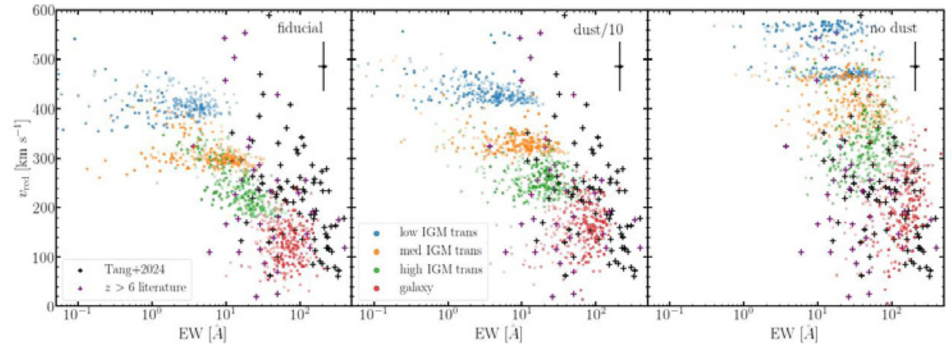


Figure 2

Fig 2. Coloured markers show the position of the red peak of the Lyα light (given as velocity v_{red}) versus the strength of the Lyα line (given as an equivalent width; EW) for different amounts of dust in the simulated spectra of reionization-epoch galaxies. The different colours of the markers represent different ionization levels of the intergalactic medium. Higher opacities of markers represent higher redshift and thus earlier times. For comparison to observations, we also overplot literature data of redshift z = 5–6 Lyα-emitting galaxies as black crosses (with a representative error bar in the top right corner), and z > 6 galaxies as purple crosses.

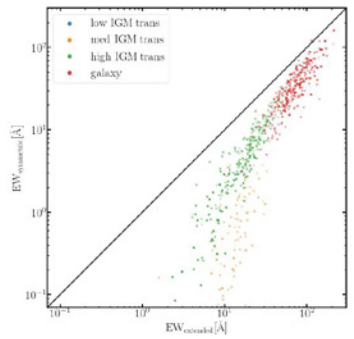


Figure 3

Fig 3. Testing the effect of the assumptions for the shape of the red peak in the Lyα spectra. We compare the equivalent width (EW) calculated assuming a widely used symmetric (Gaussian) shape to that calculated with shapes that have extended red wings, as suggested by our simulation of a reionization-epoch galaxy. Extended red wings can greatly enhance the visibility of the abundant early Lyα-emitting galaxies discovered by JWST.



Shikhar Asthana, Martin G. Haehnelt & Girish Kulkarni

The Impact of Faint AGN on Reionization

The James Webb Space Telescope (JWST), our most powerful eye on the cosmos, has begun to unveil the Universe's earliest moments. One of its most intriguing discoveries is the detection of unexpectedly large numbers of faint quasars (QSO) — compact active galactic nuclei (AGN) powered by feeding black holes — appearing just 500 million years after the Big Bang. These objects were not expected to exist so early, and their detection has opened up new questions about how the early Universe evolved.

AGN are more than just astrophysical curiosities. They are potent sources of ultraviolet (UV) radiation — so energetic that it can strip electrons from hydrogen atoms. This kind of radiation is central to one of the great transitions in cosmic history: the epoch of reionization. In this period, the Universe shifted from a dark, neutral state to the bright, transparent cosmos we see today. The first stars and galaxies began to shine, and their radiation gradually ionized the intergalactic hydrogen. For years, scientists debated which sources were chiefly responsible — early massive stars in galaxies, AGN powered by feeding black holes, or both.

Before JWST, the consensus leaned toward massive stars in galaxies. AGN were considered too rare in the early Universe to make a meaningful impact. But with JWST revealing up to a hundred times more faint AGN than expected, this view has been challenged. Could these newly discovered AGN have contributed significantly to reionizing the Universe?

To investigate this possibility, we ran a series of advanced computer simulations, incorporating AGN into early galaxy environments. We tested three scenarios: one where galaxies alone drive reionization; one where AGN contribute about 20% of the ionizing light; and one where AGN are the sole contributors. The main differences between these models come down to the number of sources and the types of photons they emit. AGN, while fewer in number, emit harder and more energetic radiation than stars.

The results are striking. Our visualizations, seen in Fig. 1, show the distribution of the ionized and neutral hydrogen in the top row, and the temperature in the bottom row. The black dots represent the galaxies, while the white dots represent AGN. The sizes of the dots represent the number of photons emitted by the sources. The presence of AGN changes both the timing and morphology of reionization. When galaxies dominate, reionization unfolds in a gradual, widespread fashion. When AGN contribute moderately, some regions become hotter and more highly ionized as seen around the cluster of sources in the bottom of the slices. However, in the QSO-only model, reionization happens more unevenly and finishes later, with fewer, brighter sources creating smaller bubbles with highly ionized gas. Looking into other observables with these simulations, we found that a universe driven entirely by AGN would not match observations — such as the temperature of intergalactic gas or the distribution of hydrogen seen in the late stages of reionization.

What our study shows is that a mixed model, where galaxies are the main drivers of reionization, but AGN provide a modest but meaningful contribution, best matches both JWST data and other astronomical observations. It is a revised, more nuanced, picture of how the Universe lit up after its dark ages. And as JWST continues to push the cosmic frontier, hinting at galaxies as early as 200 million years after the Big Bang, our understanding of this epoch may shift again. The early Universe remains full of surprises, and with each new discovery, we come a step closer to understanding our cosmic origins.

This article is based on results submitted as Asthana S., Haehnelt M., Kulkarni G. et al., MNRAS submitted (arXiv:2409.15453).

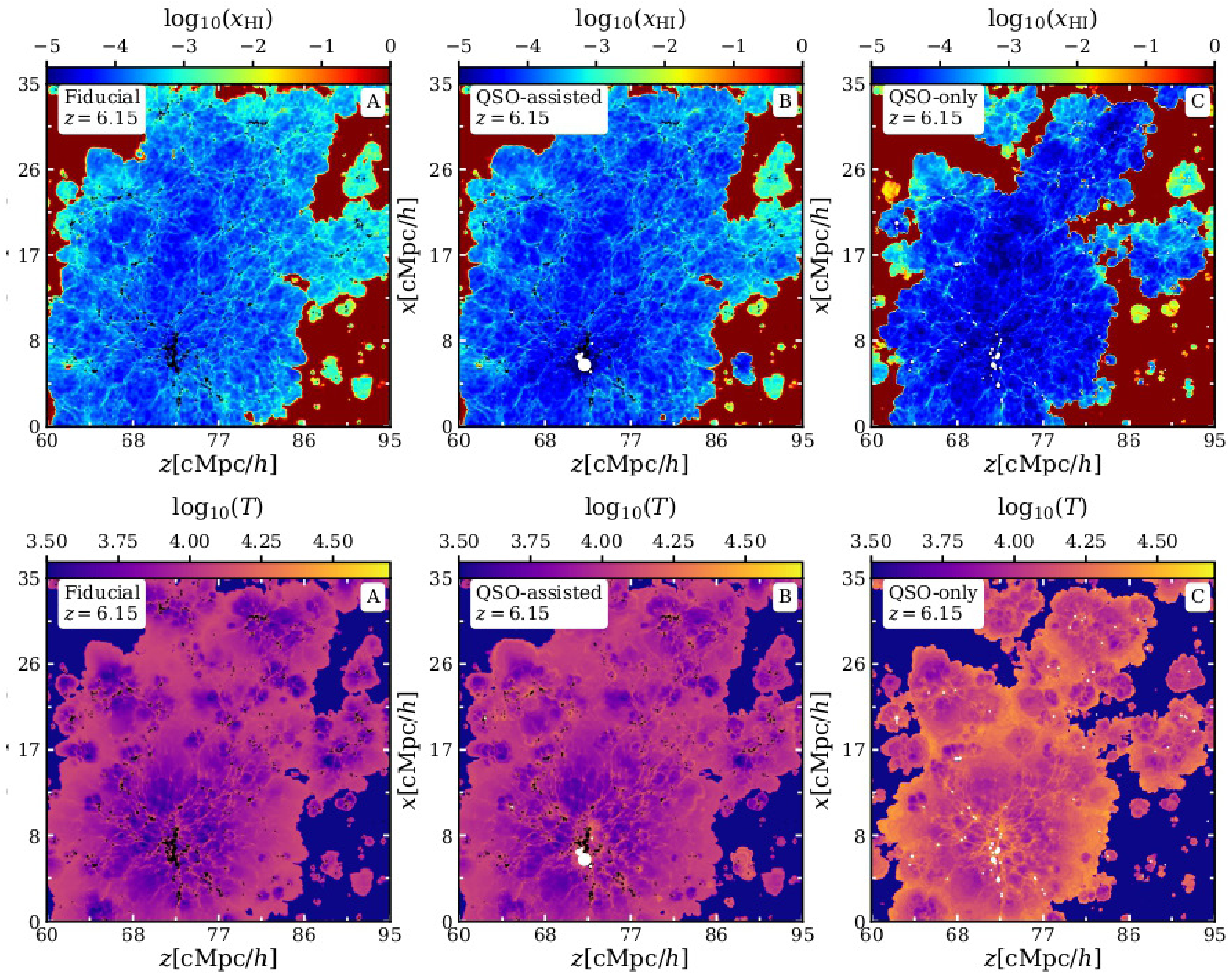


Fig 1. Spatial distribution of the neutral hydrogen fraction (top) and gas temperature (bottom) in three simulations of reionization at redshift z = 6.15, around 1 billion years after the Big Bang. Black markers represent stars in galaxies, while white markers represent AGN/QSO.



Seughwan Lim, Sandro Tacchella & Roberto Maiolino

Simulation View of Galaxy Protoclusters in the First Billion Years: Are There Too Many from JWST?

Protoclusters, identified as overdensities of galaxies in the early Universe, represent the first cosmic structures and the sites where the earliest galaxies emerged, playing a pivotal role in the epoch of reionization. As the progenitors of present-day galaxy clusters, protoclusters are of fundamental importance for understanding the environmental evolution of galaxies. They are also believed to contribute more than 20 percent of the cosmic star formation at redshifts $z > 2$.

Despite their significance, studying protoclusters presents numerous challenges. By definition, protoclusters are considered the progenitors of galaxy clusters, but establishing this link directly from observational data is difficult. Observations provide snapshots of different objects at various epochs rather than tracking the same systems across cosmic time. Additionally, the diverse techniques and methods used to identify protoclusters make it challenging to compare their populations systematically. Comparisons with theoretical models are also complicated by the rarity of these systems; even state-of-the-art cosmological simulations contain only a few tens of such structures at best.

Recent observations with the James Webb Space Telescope (JWST) have extended the exploration of protoclusters to higher redshifts, identifying more than a dozen protocluster candidates between $z = 5$ and 9 from the JADES and FRESCO surveys. Analyzing these observations within a theoretical framework can provide insights into the formation of early galaxies and large-scale structures, as well as shed light on cosmology and the epoch of reionization.

In our recent work, we addressed these challenges by investigating protocluster samples from the FLAMINGO simulations at high redshifts and comparing them with JWST candidates. FLAMINGO is a large-volume cosmological simulation spanning 2.8 Gpc on each side. Given the observed number density of protoclusters (approximately tens to hundreds per 1 Gpc cube), FLAMINGO is one of the first simulations to provide a sufficiently large sample for robust statistical analysis and comparison.

Using an observationally motivated approach to identify and select protoclusters in FLAMINGO, we found that more than 50 percent of cosmic star formation at $z > 4$ occurs within protoclusters, consistent with previous studies. Notably, the simulation results suggest that star formation during the epoch of reionization is dominated almost entirely by the progenitors of Coma-like clusters.

We also investigated the impact of varying aperture sizes used in the literature to identify and define protoclusters in observations. We found that these differences can introduce significant biases, potentially overestimating the total mass of protoclusters by up to a factor of 10 around $z = 4$. This bias can also affect assessments of their evolutionary pathways, including the sizes of the systems they evolve into and their connection to present-day clusters. A notable discrepancy arises in the number density of protoclusters between JWST observations and FLAMINGO predictions, with the data suggesting an order-of-magnitude more systems — a 3σ discrepancy (see Fig. 1). However, we demonstrate that this apparent disagreement is largely due to the heterogeneous apertures used in JWST protocluster discoveries. Once aperture effects are accounted for, the observed number density aligns with theoretical predictions. Our results indicate that many protocluster candidates reported in the literature have their masses — both observed and projected future masses — significantly overestimated (Fig. 2).

Finally, we find that FLAMINGO predicts the total star formation rates of high-redshift protoclusters in agreement with observations for the first time, unlike previous models that have consistently underpredicted these rates.

This article is partly based on results published in Lim S. et al., MNRAS 532, 4551 (2024).

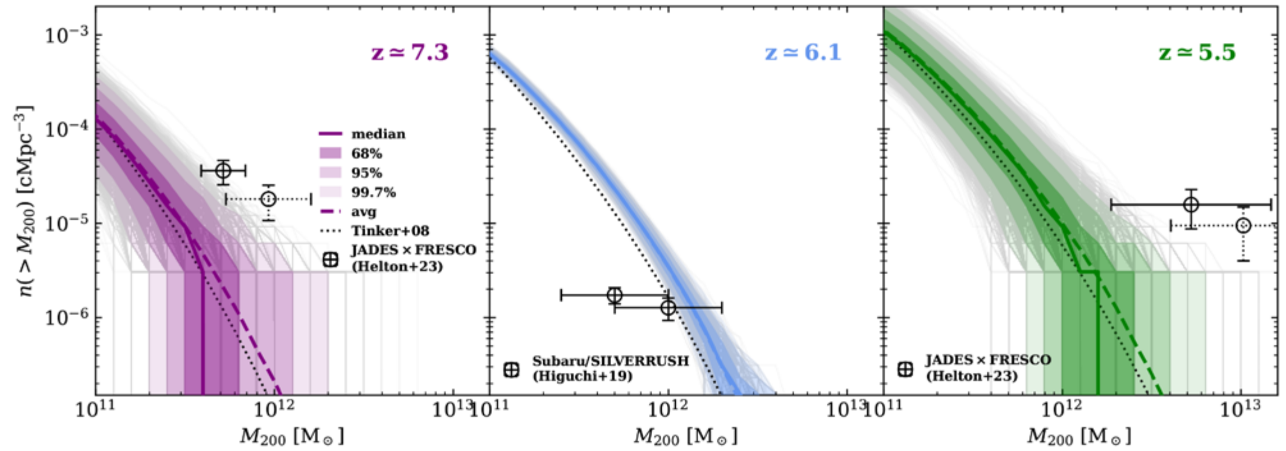


Figure 1

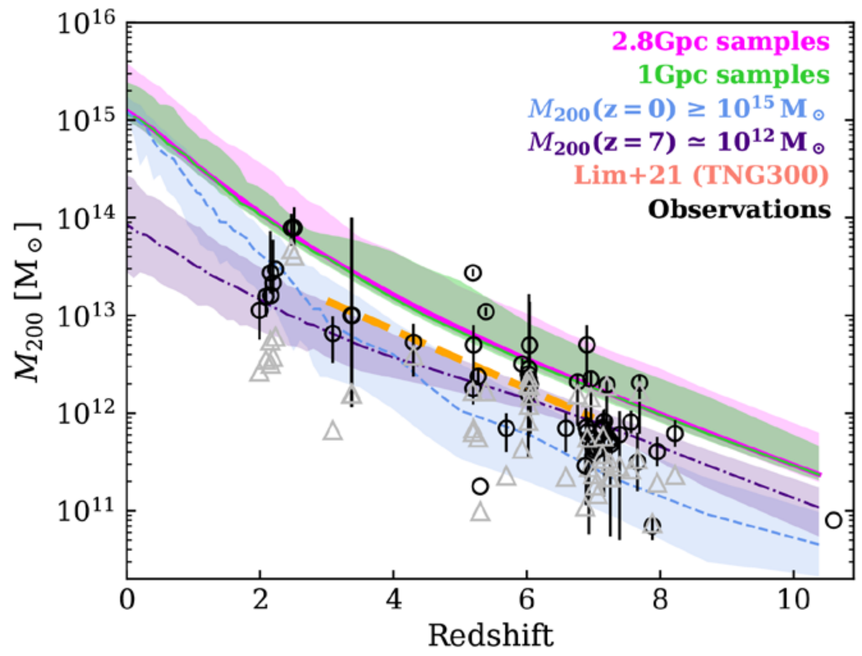


Figure 2

Fig 1. The number density of protoclusters from observations (circles with error bars; JWST results in the left and right panels), in comparison with theoretical predictions from the FLAMINGO simulation (lines and bands).

Fig 2. Mass evolution of protoclusters from FLAMINGO (lines), in comparison with observations (circles with error bars). The mass after the aperture correction (triangles) is generally much smaller.

William McClymont & Sandro Tacchella

The Temper Tantrums of Teenage Stars

Star-forming galaxies are vibrant ecosystems where new stars ignite within enormous clouds of gas and dust. While the dazzling glow from newly formed star clusters and nebulae often steals the limelight, a subtler component quietly fills these galaxies: the diffuse ionized gas.

The diffuse ionized gas comprises faint, expansive clouds of ionized gas distinct from the compact, brilliantly glowing regions known as nebulae or HII regions, where stars are actively born. Figure 1 shows how the Milky Way appears in hydrogen emission (Balmer-alpha emission). Despite its faintness, the diffuse ionized gas surprisingly can account for over half of the glowing hydrogen emission observed in star-forming galaxies, such as the Milky Way. Because of this, understanding how diffuse ionized gas forms and evolves is crucial for interpreting observations of distant galaxies, ultimately shaping our understanding of how galaxies evolve through cosmic time.

Until recently, the source of the faint glow from diffuse ionized gas remained puzzling. Young, massive stars (younger than 5 million years) emit huge numbers of ionizing photons capable of stripping electrons from gas atoms, but nearly all of these photons are quickly absorbed by dense gas clouds surrounding the stars. Previously, astronomers suspected that small leaks of this radiation from stellar birth clouds might be responsible for creating the diffuse ionized gas. Yet, when researchers examined emission lines from the diffuse ionized gas closely, they realized the source had to be more intense and energetic than the youngest stars could provide.

In our recent research, we tackled this mystery by turning to computer simulations. We modelled a galaxy resembling our own Milky Way, harnessing advanced simulation techniques known as Monte-Carlo radiative transfer. These methods allow us to track realistically how photons emitted by stars interact with gas and dust across an entire galaxy, offering insights inaccessible through direct observations alone. Figure 2 shows our simulated galaxy as seen with different wavelengths of light.

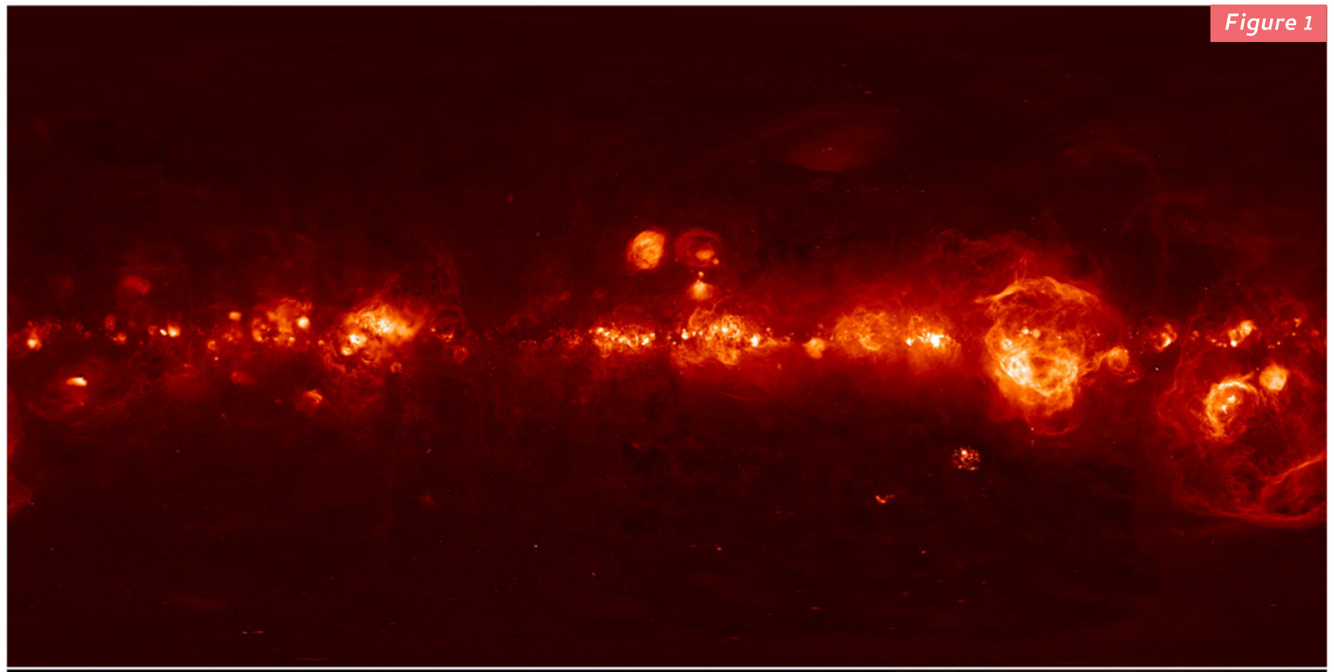
Through these simulations, we uncovered an exciting revelation: the diffuse ionized gas is mainly ionized not by the youngest stars, but by their slightly older siblings — those between 5 and 25 million years old. We dubbed these stars "teenage" because they are old enough to have emerged from their dense birth clouds, thanks to the explosive supernovae of neighbouring massive stars. Once freed, these teenage stars illuminate surrounding regions of lower-density gas, creating the extensive, diffuse glow that defines the diffuse ionized gas.

Importantly, teenage stars produce a harsher radiation spectrum — especially influenced by interactions between pairs of stars known as binaries and stellar winds — which neatly explains the unique emission signatures previously measured in the diffuse ionized gas. Our simulations closely match observations from state-of-the-art telescopes, confirming our interpretation and showing that these teenage stars, rather than freshly formed stellar nurseries, predominantly shape the emission features of the diffuse ionized gas.

Understanding the diffuse ionized gas has broad implications. Because it can account for over half the ionized hydrogen emission in galaxies, the diffuse ionized gas significantly impacts how galaxies appear to us and influences their evolution. Accurately identifying the origin and nature of the diffuse ionized gas thus enhances our understanding of stellar lifecycles, galaxy ecosystems, and the visible universe.

These results were published as McClymont W. et al., MNRAS 532, 2016 (2024).

Figure 1



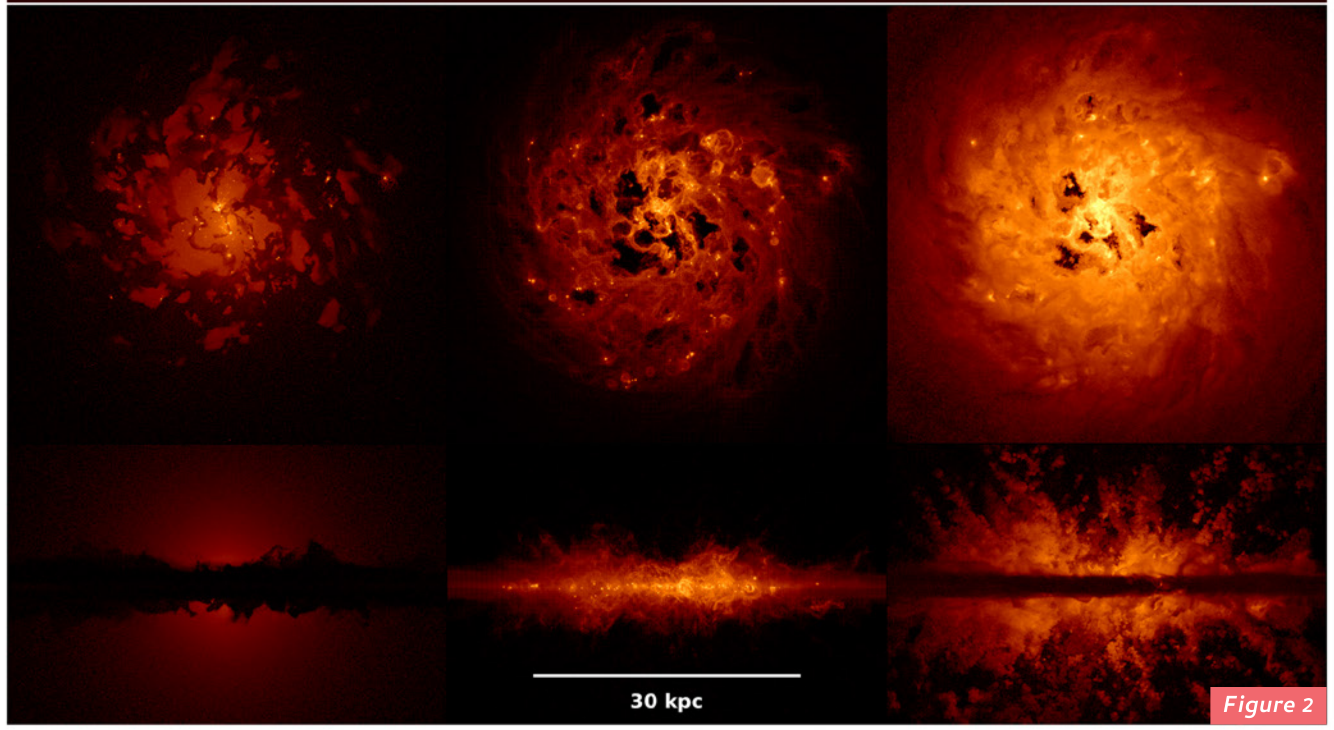


Figure 2

Fig 1. The Milky Way galaxy as seen in hydrogen emission. The brightest regions are generally areas where young stars have recently been formed. The diffuse ionized gas is seen as the fainter, wispy structures. Image credit: D. P. Finkbeiner. (2003).

Fig 2. Face-on (top) and edge-on (bottom) maps of our simulated galaxy with different wavelengths of light. The central panel shows hydrogen emission comparable to the map of the real Milky Way shown in Fig. 1.



Sandro Tacchella, Francesco D'Eugenio & Roberto Maiolino

The JWST Advanced Deep Extragalactic Survey (JADES): A Visionary Leap in Understanding the Early Universe

The James Webb Space Telescope (JWST), launched in December 2021, enabled a leap forward in our understanding of the Universe. One of its flagship projects, the JWST Advanced Deep Extragalactic Survey (JADES), has quickly emerged as a transformative programme in the quest to probe the early stages of galaxy formation. Through JADES, we are reaching back in time to observe the formation and evolution of galaxies in the first billion years after the Big Bang — an era that has long been shrouded in mystery. By studying galaxies at high redshifts ($z > 10$), JADES promises to provide insights into the very mechanisms that led to the assembly of the first structures in the Universe.

JADES is an ambitious survey, with groundbreaking scientific objectives, in which KICC scientists have played a leading role. Indeed, researchers at KICC have been at the forefront of the JADES survey, driving critical aspects of its design, execution, data reduction, and scientific analysis. In collaboration with other partner institutions, the survey is already delivering remarkable results, providing unprecedented views into the formation of the earliest galaxies and the conditions of the Universe during the epoch of reionization (EoR) and beyond.

The JADES Survey: A Pioneering Effort in Extragalactic Astronomy

The JADES survey, conducted by JWST's Near-Infrared Camera (NIRCam) and Near-Infrared Spectrograph (NIRSpec) instrument teams, represents, with over 1000 hours of observations, one of the most extensive observational campaigns targeting the early Universe to date. It aims to answer some of the most profound questions in cosmology: How did the first galaxies form? What role did black holes and dark matter play in shaping these galaxies? And how did the Universe evolve from the simple primordial gas of the Big Bang to the complex cosmic structures we observe today?

One of the key features of JADES is its deep, high-resolution imaging and spectroscopic capabilities, which allow researchers to examine galaxies at redshifts as high as z = 13–14, i.e., less than 300 million years after the Big Bang. JWST's infrared sensitivity enables it to detect faint galaxies and their emission lines, providing a detailed view of their physical properties such as mass, size, star-formation rates and chemical enrichment. This is a significant leap from earlier surveys, which, limited by the capabilities of telescopes like Hubble and Spitzer, were unable to penetrate the obscuring dust and gas of high-redshift galaxies or to detect such distant sources. The JADES survey targets two main fields: GOODS-South (Fig. 1) and GOODS-North. With their deep coverage in previous surveys, these regions contain an extraordinary wealth of data, making them ideal for probing the Universe at high redshifts.

KICC's Leadership and Recent Exciting Results from JADES

The leadership role of Cambridge has been instrumental in shaping the JADES survey. As world-renowned experts in extragalactic astrophysics and galaxy formation, the extragalactic research group at the KICC/Cavendish Astrophysics have guided the scientific direction of the survey and have contributed to its design, development of the observational strategy, and the scientific analysis of the resulting data (D'Eugenio et al. 2025). The most recent results from JADES have already begun to reshape our understanding of galaxy formation in the early Universe. The survey has provided several groundbreaking discoveries that highlight the power of JWST and the unique capabilities of the JADES survey.

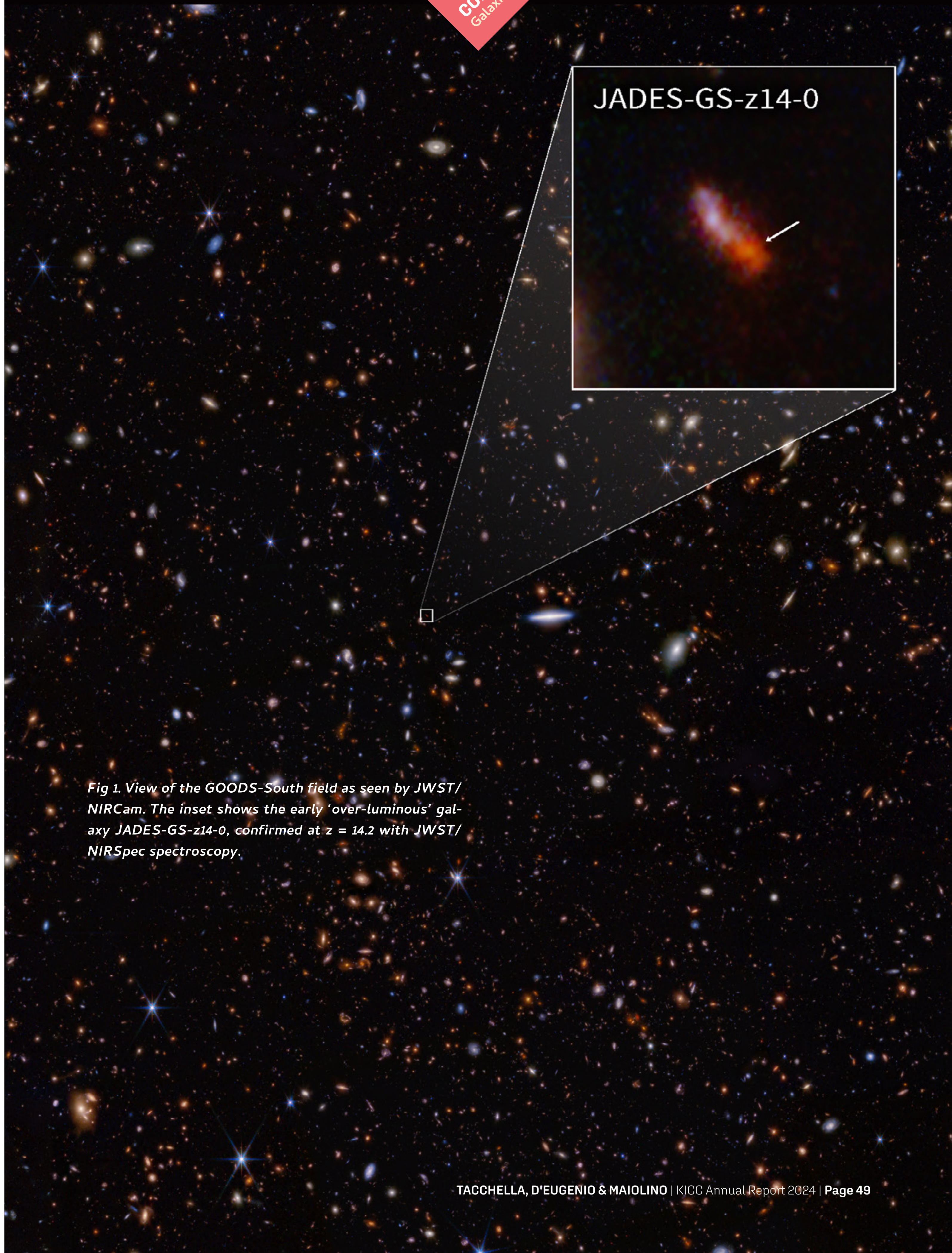


Fig 1. View of the GOODS-South field as seen by JWST/NIRCam. The inset shows the early 'over-luminous' galaxy JADES-GS-z14-0, confirmed at z = 14.2 with JWST/NIRSpec spectroscopy.

continued...

The JWST Advanced Deep Extragalactic Survey (JADES):
A Visionary Leap in Understanding the Early Universe

One of the most exciting findings was the discovery of the most-distant known galaxy at the time, JADES-GS-z14-0 (Carniani et al., 2024). The spectrum reveals the ultraviolet continuum with prominent Lyman-α break, placing this galaxy unequivocally at redshift z = 14, i.e., only 300 million years after the Big Bang, thus pushing the boundaries of our knowledge about the early Universe. However, what truly sets this galaxy apart is not merely its redshift record, but its extraordinary and unexpected luminosity. Moreover, the imaging data indicates that this galaxy is spatially resolved with a radius of 260 pc (Fig. 1), showing that the excess of luminous galaxies in the early Universe cannot be entirely explained by accretion onto black holes. This system challenges galaxy formation models, which will need to address the existence of such large and luminous galaxies so early in cosmic history.

The JADES survey also opened up a new angle in mapping the growth of supermassive black holes in the early universe. The discovery of high-redshift quasars and the detection of ionized gas surrounding these black holes provide critical clues about the role of feedback from black hole accretion in regulating galaxy growth and star formation. We have discovered a million-solar-mass black hole in GN-z11, a galaxy at redshift z = 10.6, only 400 million years after the Big Bang (Maiolino et al. 2024). GN-z11 exhibits both an extended component and a compact, unresolved source (Tacchella et al. 2023), with the unresolved emission consistent with the presence of an accreting black hole. Another surprising discovery is that early galaxies host overly massive black holes, with systems reaching a black hole-to-host galaxy stellar mass ratio of 0.4 — that is, about 1000 times above the local relation (Juodžbalis et al 2024a; Fig. 2). These findings suggest that supermassive black holes may have formed and grown much earlier than previously thought, influencing the evolution of their host galaxies in profound ways.

The exquisite imaging data from JADES allows us to assess the morphological properties of galaxies in the first billion years after the Big Bang. The physical processes that establish the morphological evolution and the structural diversity of galaxies are key unknowns in extragalactic astrophysics. The discovery of a mature galaxy, within the first 700 million years of the Universe's history, is a surprise (Baker et al. 2025). This star-forming galaxy with a stellar mass of 400 million solar masses consists of three components: a highly compact core with a half-light radius of less than 100 pc, an actively star-forming disc with a radius of about 400 pc and a star-forming clump, all of which show distinctive star-formation histories. The central stellar mass density of this galaxy is within a factor of two of the most massive present-day ellipticals, while being globally 1,000 times less massive. The radial profile of the specific star-formation rate is rising towards the outskirts. This evidence suggests a detection of the inside-out growth of a galaxy as a proto-bulge and a star-forming disc in the epoch of reionization. You can find more details on these findings in the dedicated article by William Baker and Sandro Tacchella elsewhere in this report.

Finally, JADES has had a central role in uncovering the early stages of chemical enrichment in the universe. The systematic deviation from local metallicity relations (Curti et al. 2024), the discovery of unexpected abundance ratios (D'Eugenio et al. 2024) and their potential connection to active galactic nuclei (AGN; Isobe et al. 2025), and the discovery of dense-gas absorbers around the broad-line region of AGN (Juodžbalis et al. 2024b), all point to a fundamental breakdown of the chemical relations observed at later epochs. Together, these findings reveal the onset of "chemical chaos" — a hallmark of the transition from the epoch of "galaxy evolution" to that of true "galaxy formation".

The Future of JADES and Its Impact on Cosmology

Looking ahead, JADES is poised to make even more transformative contributions to our understanding of galaxy formation and the early Universe. With the continued observations from JWST and the planned follow-up observations in the coming years, JADES will provide a more detailed picture of galaxy evolution during the epoch of reionization and beyond.

The survey will continue to explore the physical properties of high-redshift galaxies, focusing on their star-formation rates, metallicities, gas content, and the role of feedback mechanisms in shaping their growth. We will also investigate the influence of large-scale structures on galaxy evolution, shedding light on the interplay between galaxies and their environments. A theme that we will also push forward with the upcoming MOONS spectrograph at the Very Large Telescope in Chile.

This article is partly based on results published as: Baker W. et al., Nature Astronomy 9,141 (2025); Carniani S. et al., Nature 633, 318 (2024); Curti M. et al., A&A 684, 75 (2024); D'Eugenio F. et al., ApJS 277, 4 (2025); D'Eugenio F. et al., A&A 689, 152 (2024); Isobe Y. et al., MNRAS in press (arXiv:2502.12091); Juodžbalis I. et al., Nature 636, 594 (2024a); Juodžbalis I. et al., MNRAS 535, 853 (2024b); Maiolino R. et al., Nature 627, 59 (2024); Tacchella S. et al., ApJ 952, 74 (2023).

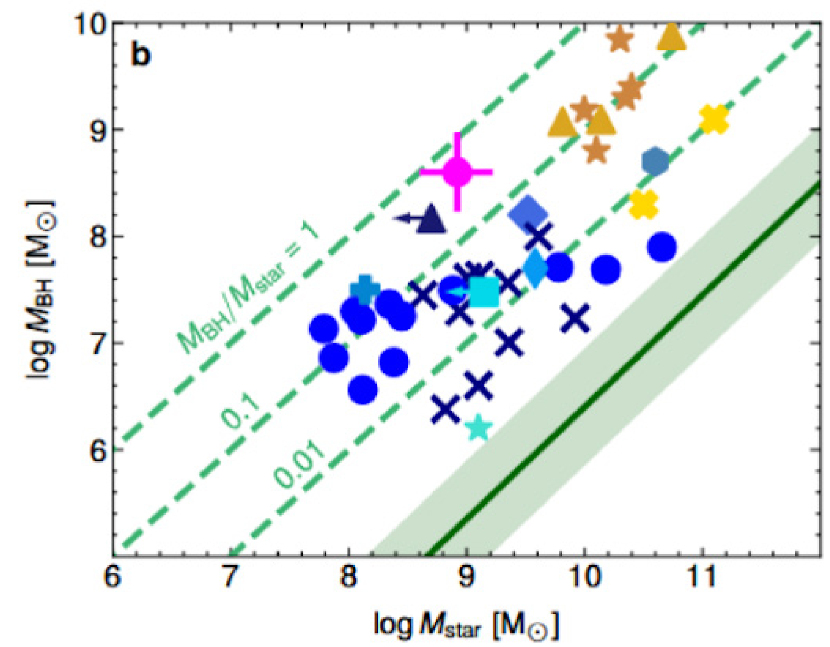


Fig 2. A galaxy with a 'dormant' black hole discovered by JADES, enabling an accurate measurement of both the mass of the black hole and the galaxy's stellar mass (magenta circle with error bars). This system has been crucial for confirming the existence of galaxies with 'over-massive' black holes, i.e., with high black hole-to-stellar mass ratio compared to the local scaling relation (solid green line). Figure from Juodžbalis et al. (2024a).

Xihan Ji, Hannah Übler & Roberto Maiolino

Extreme Nitrogen Enrichment in a Galaxy Hosting an Active Black Hole One Billion Years After the Big Bang

As galaxies evolve, they leave chemical imprints in the interstellar medium (ISM) through stellar winds and supernova explosions. The chemical abundances of the ISM are thus tightly related to the star-formation history. In observations, chemical abundances of the ISM can be measured through strong nebular emission lines. With the advent of the James Webb Space Telescope (JWST), measurements of the ISM abundances have been pushed back to the first billion years (Gyr) of the Universe.

Amongst all the elements heavier than helium, oxygen and nitrogen are usually the easiest to measure in observations due to their strong transitions in the rest-frame UV and optical wavelengths. These two elements are also useful tracers of chemical evolution. This is because the enrichment of oxygen is dominated by core-collapse supernovae of massive stars and occurs within the first few tens of millions years of star formation, whereas the enrichment of nitrogen is dominated by winds from intermediate-mass asymptotic giant branch (AGB) stars with a typical delay time of 0.1–1 Gyr. Consequently, one expects that the abundance ratio, N/O, is sub-solar at sub-solar O/H.

Interestingly, the first two years of observations with JWST have revealed a population of galaxies showing bright UV emission lines of nitrogen at redshift $z > 5$. These galaxies, while being clearly metal-poor with significantly sub-solar O/H, show super-solar N/O in their ISM, challenging our understanding of the chemical evolution of galaxies established in the local Universe. The cause of the extreme nitrogen enhancement remains debated and more observational evidence is needed.

In this study, we provide a new piece of evidence for solving the mysterious nitrogen enhancement by analyzing observations from JWST and and the Very Large Telescope (VLT) of a bright galaxy at $z = 5.55$, whose image is shown in Figure 1. This galaxy was previously found to host an unobscured black hole through detection of broad emission lines in the rest-frame optical. Figure 2 shows the rest-frame UV spectrum of this galaxy, GS_3073, where key transitions are marked. Through nebular diagnostics, we inferred an unprecedentedly high N/O that is 19 times above the solar value, with O/H being only 20% of the solar value. Figure 3 compares the abundance patterns of GS_3073 with those of local galaxies as well as several nitrogen-enhanced systems at high redshift. An even more intriguing discovery in this system is the inhomogeneous chemical enrichment. Based on the previous VLT observations, we found the UV emission lines are produced in a region where the gas density is significantly higher than that of the optical-line-emitting region. Meanwhile, only the dense-gas region probed by UV lines show the abnormally high N/O, whereas the optical-line emitting region has a clearly sub-solar N/O. The abundance patterns of the two regions in GS_3073 are indicated by the same symbols in Figure 3. Notably, such a chemical inhomogeneity has also been observed in the Sunburst Arc galaxy at $z = 2.37$ and the blue compact dwarf Mrk 996 in the local Universe, where bright super star clusters and/or large HII associations are present.

Combining the above evidence, we speculate that the extreme chemical enrichment in GS_3073 is confined to dense cluster environments, where atypical enrichment channels through very massive stars become possible. Meanwhile, normal chemical evolution occurs outside the dense star clusters. At early times of galaxy evolution, most star formation occurs in dense clusters, which might lead to the ubiquity of nitrogen enhancement. The formation of dense nuclear star clusters might also help to seed and feed the supermassive black hole observed in GS_3073, explaining the rapid build-up of black hole masses revealed by JWST.

This article is partly based on results published as Ji X. et al., MNRAS 535, 881 (2024) and Übler H. et al., A&A 677, A145 (2023).

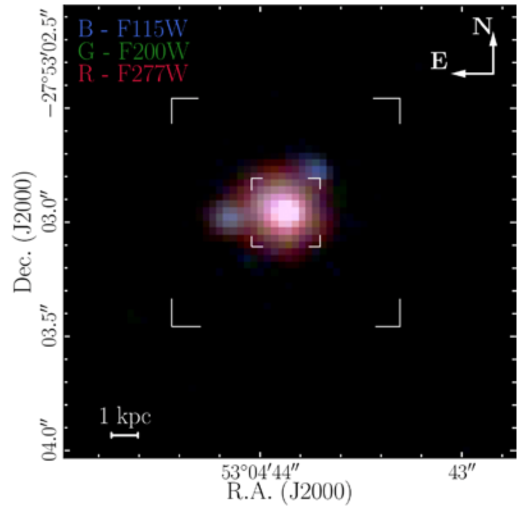


Figure 1

Fig 1. JWST/NIRCam color-composite image of GS_3073. The smaller and larger squares correspond to the extraction aperture of the JWST spectrum and the VLT spectrum, respectively.

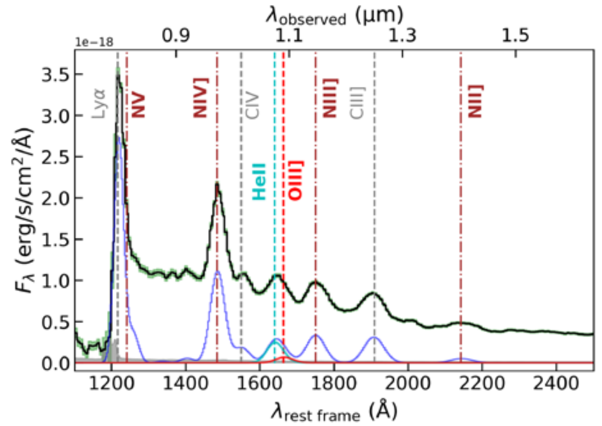


Figure 2

Fig 2. JWST/NIRSpec low-resolution spectrum covering the rest-frame UV of GS_3073. The spectral noise is plotted as the shaded green region. Detected UV emission lines are labeled and their best-fit profiles are shown below the observed spectrum.

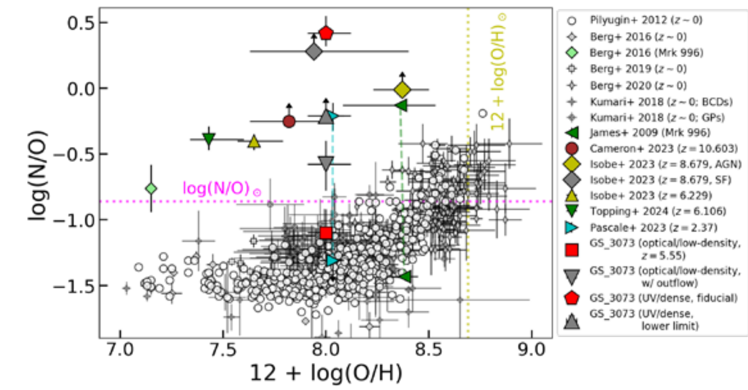


Figure 3

Fig 3. N/O versus O/H for local and high-redshift galaxies. The open symbols are local galaxies, which form a tight sequence. Colored symbols (except for Mrk 996) are high-redshift galaxies showing enhanced N/O. Among these sources, GS_3073 not only exhibits the highest N/O, but also shows a striking chemical inhomogeneity indicated by the red pentagon and square.

William M. Baker & Sandro Tacchella

Evidence for Inside-Out Growth in the Early Universe:
A Core in a Vigorously Star-Forming Disc

How galaxies grow represents one of the big open questions in extragalactic astronomy. We see a variety of galaxy shapes and morphologies in the galaxy population today, but we cannot observe how any individual galaxy is changing with time. Fortunately, we can look back in time by looking at more distant galaxies: the further away a galaxy is from us, the longer it takes for light from it to reach us, and the further we look back in time. From this, we must piece together how these more distant galaxies turn into those we see around us today (i.e., in the local Universe). Galaxies can grow in multiple ways, although in practice this can be simplified to growth from the inside-out or outside-in, and this tells us crucial information about the physical processes involved. Commonly, local galaxies contain bulges, a concentrated light distribution in their centre, which is correlated with many other galaxy properties and linked to an inside-out growth mechanism. The question is at what stage of the Universe can galaxies form these bulges and what are their properties? To investigate this, we utilised the NIRCam instrument on the James Webb Space Telescope (JWST) to look for one of the earliest examples of a galaxy with spatially resolved structure.

Figure 1 (left) shows a RGB (red-green-blue) image of JADES-GS+53.18343-27.79097, a redshift 7.43 galaxy (i.e., existing over 13 billion years ago) that shows clear signs of a multi-component morphology. We model this structure as a core (a kind of early bulge), a disc, and the addition of a small off-centre clump. By modelling the components and their light, we can infer their masses and their star-formation histories (shown on the right in Fig. 1). We find that the core (red) is decreasing in star formation whilst the disc (blue) is undergoing a recent burst in star formation.

We find that the core is massive (around 240 million times the mass of the Sun) and compact (with a half-light radius of less than 100 pc), making it extremely dense, whilst the disc is less massive (around 95 million solar masses) and more extended (half-light radius of 400 pc). Combined with the decrease in star-formation rate of the core and increase for the disc this implies that the galaxy is growing from the inside out! The current star-formation is taking place within the disc and at larger radii, whilst the previous star-formation has taken place within the dense core.

A big question, considering we observe this galaxy as it was 13 billion years ago, is how it would evolve over time. Figure 2 shows two models (orange and green) for how it could grow both in size and stellar mass compared to more local non-star-forming galaxies (grey dashed line) and star-forming galaxies (grey dotted line). We see that as time increases (i.e., left to right, denoted by decreasing redshift) the galaxy becomes consistent with the quiescent galaxy population (i.e., those extremely massive galaxies that are no longer actively forming new stars), showing that this core-disc galaxy is a natural progenitor of these kinds of galaxy, so we catch a glimpse of what they might have looked like 13 billion years ago!

In summary, the galaxy JADES-GS+53.18343-27.79097 provides a compelling example of how the most massive galaxies we see locally may have built up their structure and mass via inside-out growth in the form of a massive central core with a surrounding star-forming disc.

This article is partly based on results published as Baker W. M. et al., Nature Astronomy 9, 141 (2025).

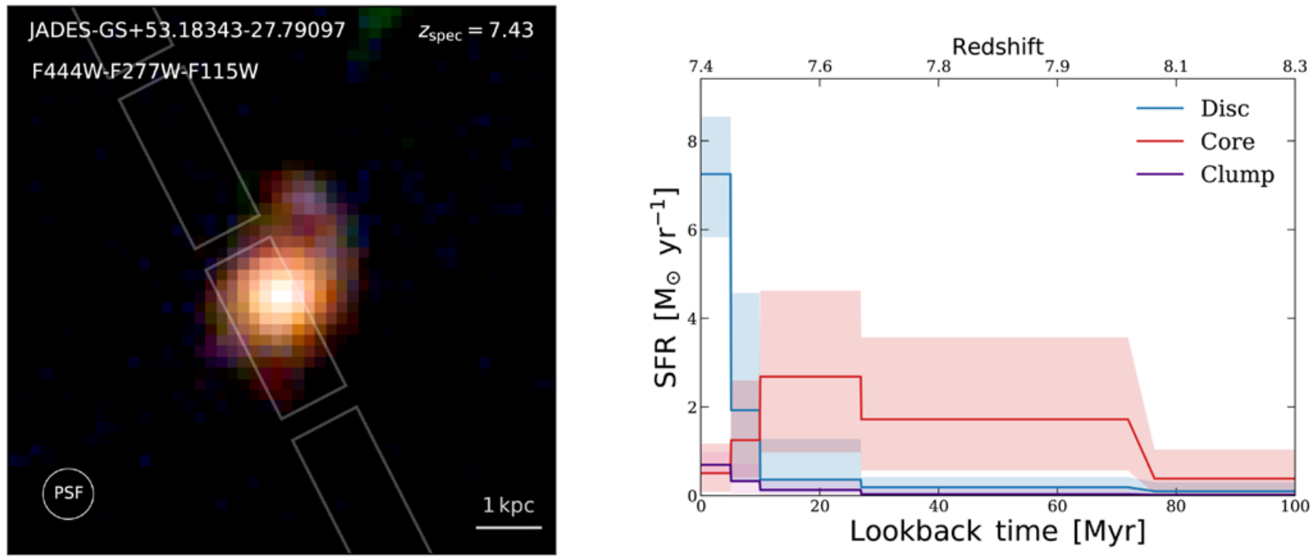


Figure 1

Fig 1. Left: JWST image of the galaxy JADES-GS+53.18343-27.79097 showing its multi-component morphology. Right: The inferred star-formation histories of the three morphological components.

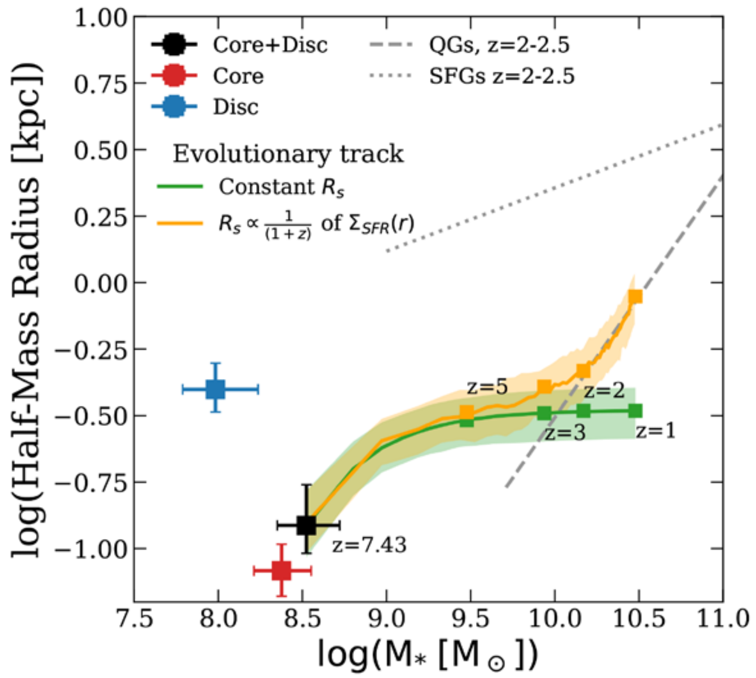


Figure 2

Fig 2. The half-mass radius versus stellar mass for the galaxy JADES-GS+53.18343-27.79097 (black), modelled growth in time (green and orange) and more local galaxies (dashed and dotted line).

Hannah Übler

GA-NIFS Reveals an Active Black Hole in an Enigmatic Galaxy at $z = 4$

Imagine you want to build a galaxy. What does it contain? Of course there are the stars, like the Sun and like those we can observe every night within our own galaxy. Then there is gas, which partly fills the space between the stars, known as the 'interstellar medium'. Dust is typically in the mix as a by-product of stellar evolution. A massive black hole may be found in the galaxy centre, easiest to spot when it is actively growing through gas accretion. Furthermore, the dynamics of galaxies teach us about the existence of an additional, invisible component, fittingly labelled dark matter. We believe that the dark matter is extended on larger scales, while the visible components – stars, gas and dust – are fairly homogeneously distributed in smaller, disk-like or spheroidal components.

With this simple picture in mind, you may understand the surprise of astronomers when a distant galaxy was detected about 20 years ago, dubbed GN20, consisting of a large disk of molecular gas with some dust in the centre, but the only stars that could be seen were gathered in a small patch in the Western outskirts of the system. Being located in such a distant part of the Universe that ground-based telescopes were unable to map emission from the optical range of the wavelength spectrum, this system remained an enigma for almost two decades.

Last year, this galaxy finally revealed its secrets to us (or at least some of them). Using novel data from the James Webb Space Telescope (JWST), we could map the extended emission in the rest-frame ultra-violet to near-infrared wavelength range (Fig. 1), revealing a beautiful rotation pattern in the ionised-gas kinematics, largely compatible with the previously known molecular-gas kinematics. Yet, we encountered two surprises. Firstly, we found evidence for deviations from regular rotation in the interstellar medium (Fig. 2, left). These deviations are indicative of gas flowing towards the centre of the galaxy, a process rarely observed in distant galaxies. The inflows may be fed from faint gas clouds, which we discovered in the outskirts of the system. We even discovered a neighbouring galaxy that may have interacted with GN20 in the past (green object in the top right corner of Fig. 1). Secondly, right at the galaxy centre we uncovered a previously concealed active massive black hole (Fig. 2, middle). We could identify this black hole through ionized hydrogen emission with high velocities, which we were able to measure for the very first time with our observations.

While some of the inflowing gas may accrete onto the black hole and therefore fuel its activity, we could show that radiation from the central engine is in turn able to photoionize the interstellar medium throughout GN20 (Fig. 2, right). Therefore, in this single system we are witnessing some of the key processes in the evolution of massive galaxies and their central black holes: accretion of gas onto the galaxy and subsequent transport to the centre, increasing the mass of both the galaxy and the black hole; and, as a consequence, the impact of the active black hole on the interstellar medium through ionizing radiation. Combining our data with additional information on the smooth stellar structure, also newly revealed through JWST observations, we could construct a dynamical model of the galaxy. This enabled us to constrain the fraction of dark matter on galactic scales to about 10–30 percent, thus providing us with the final ingredient for our galaxy construction set.

These observations were performed as part of the Guaranteed Time Observations (GTO) with the NIRSpec Integral Field Spectrograph on board JWST, within the programme "Galaxy assembly with NIRSpec IFS" (GA-NIFS).

This article is based on results published as Übler H. et al., MNRAS 533, 4287 (2024).

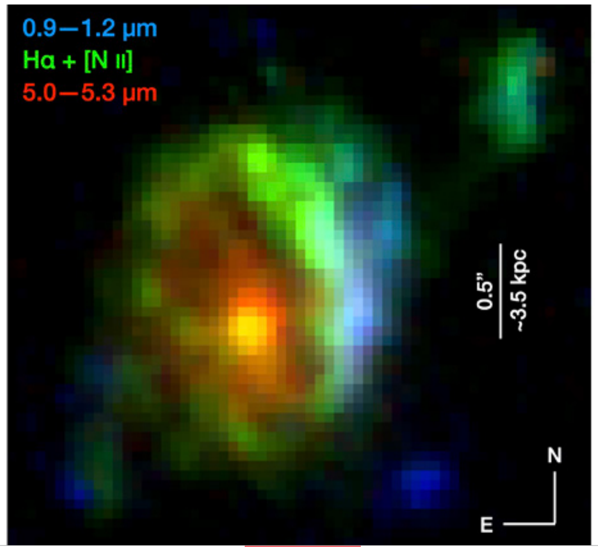


Figure 1

Fig 1. Colour-composite of the galaxy GN20 from our novel JWST observations. Blue shows unobscured light from young stars, red shows the smooth distribution of dust-obscured stars and green highlights ionised gas in the optical wavelength range.

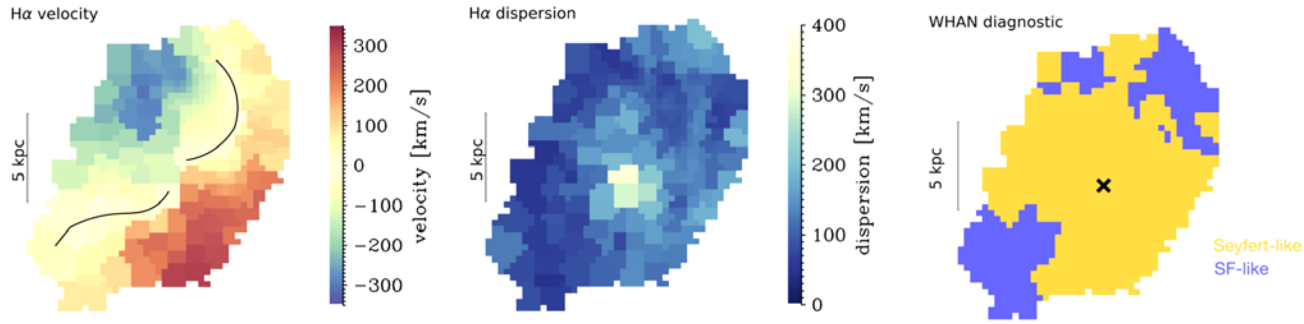


Figure 2

Fig 2. Left to right: deviations from rotation in the gas kinematics (twisted black lines); the active black hole revealed through gas with high velocity dispersion in the centre; and a line-ratio analysis shows the impact of the black hole throughout GN20 ('Seyfert-like').

Francesco D'Eugenio, Jan Scholtz & Roberto Maiolino

How Supermassive Black Holes Quench Star Formation

In the local Universe, the majority of massive central galaxies (stellar masses greater than 3×10^{11} times the mass of the Sun) are quiescent, i.e., have not formed stars for billions of years. Because stellar or supernova feedback alone do not have the energy required to permanently halt star formation in these systems, we expect that they are quenched and then kept quiescent by feedback from accreting supermassive black holes (SMBH), via episodes when they act as Active Galactic Nuclei (AGN).

Two main forms of feedback have been invoked: SMBHs may either remove star-forming gas already present in the disc ('ejective feedback') or, alternatively, they could stop the cosmic accretion of new gas onto the galaxy ('preventative feedback'). In this case, star formation would continue until the galaxy runs out of fuel.

Since local massive quiescent galaxies are all very old, they were quenched at high redshifts, and studying AGN feedback at high redshift means investigating this phenomenon near to its cosmic peak. In the past decades, we have learned much from studying ionized gas outflows at and before this cosmic noon, thanks to emission-line studies in the near infrared (IR). However, we were unable to connect feedback directly to the star-formation history (SFH) of galaxies, which can only be studied accurately with continuum spectroscopy. What is worse, bright emission lines accessible from the ground trace only warm ionized gas (10,000 K), which provides a biased view of the multiphase gas content of galaxies.

JWST transformed our ability to study AGN quenching, allowing us — for the first time — to observe AGN feedback and its impact on SFHs directly, during the epoch when most of this activity occurred. In addition to simultaneous observation of feedback and SFHs, observing at high redshift means bypassing the need for reconstructing long SFHs (since the age of the Universe was shorter), and overcoming the issue of billions of years of passive evolution, which can alter the distinctive traces of different quenching mechanisms.

This paradigm shift is demonstrated by our study of the massive, quiescent galaxy GS-10578 at redshift z = 3. This system was known to host a heavily obscured AGN, observed from X-rays, mid-IR and radio, but deep JWST spectroscopy with the NIRSpec integral field unit revolutionized our understanding of AGN-driven quenching.

With the accuracy afforded by continuum spectroscopy, we determined that this galaxy started to quench 500 million years before the time of observation. The AGN is powering fast ionized gas outflows comparable to those seen in bright quasars, yet this ionized gas has negligible mass outflow rate — in agreement with ground-based observations. However, thanks to JWST, we discovered fast neutral-gas outflows traced by sodium absorption — with a mass rate of 60 solar masses per year, capable of halting star formation (Fig. 1, left). Moreover, spatially resolved stellar kinematics (a record at z = 3) display ordered rotation, indicating that quenching was dynamically gentle (Fig. 1, right).

Does this mean that ejective feedback quenched this galaxy? It is not so simple: the SFH tells us that the galaxy started quenching 500 million years prior to the time of the observations, while the outflow cannot be much older than a few million years.

We followed up this object for seven hours with ALMA, targeting molecular gas, the fuel of star formation. Despite the presence of neutral gas, no molecular gas was detected, with an upper limit on the molecular gas mass fraction below 3%. This makes GS-10578 the earliest-known galaxy that is completely gas depleted. By combining the gas fraction from ALMA to the SFH from JWST, we can reconstruct the gas-consumption history of this system (Fig. 2). The red line shows how the gas fraction of GS-10578 decreased over time, assuming no outflows. We reconstruct this history up to the point in time when the galaxy doubled its mass (earlier phases of the SFH are highly uncertain). At this point, the galaxy would have had a gas fraction very close to that of typical star-forming galaxies (black line).

This coincidence is significant: theoretically, the red line could have ended up below the black line (if there were significant outflows), or even above it (if substantial inflows occurred). Physically, this coincidence could be due to preventive feedback, which interrupted the accretion of gas, so that the galaxy continued forming stars until it ran out of fuel. Alternatively, some self-regulating mechanism could have removed any accreted gas that was not converted into stars — after all, we see that this galaxy is experiencing efficient ejective feedback right now. Distinguishing these two scenarios — and assessing if our conclusions can be generalized — requires expanding this pioneering work to a sample study, something that is already ongoing, thanks to an already approved ALMA programme.

These findings mark a shift of paradigm in the study of AGN feedback: from the pre-JWST focus on ionized outflows towards less visible but more impactful gas phases, and from systems where AGN are most luminous, towards galaxies where time-integrated AGN feedback has already had a measurable impact on the SFH.

This article is partly based on results published as D'Eugenio F. et al., Nature Astronomy 8, 1443 (2024) and submitted to Nature Astronomy as Scholtz J. et al., arXiv:2405.19401.

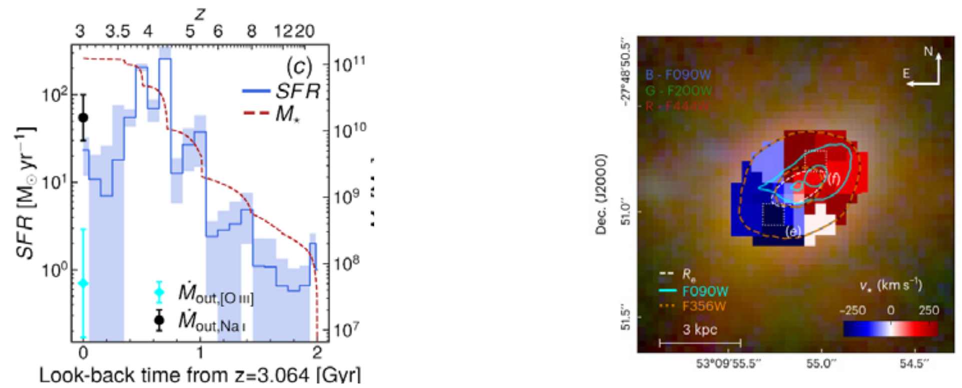


Figure 1

Fig 1. Left: SFH of GS-10578, from JWST spectroscopy. The SFR declined since z = 4.5. The cyan and black measurements are the mass-outflow rates in the ionized and neutral gas, respectively, showing that most of the mass is in the neutral phase — which was completely inaccessible to observers before JWST. Right: Velocity map of the stars in GS-10578, showing clear rotation.

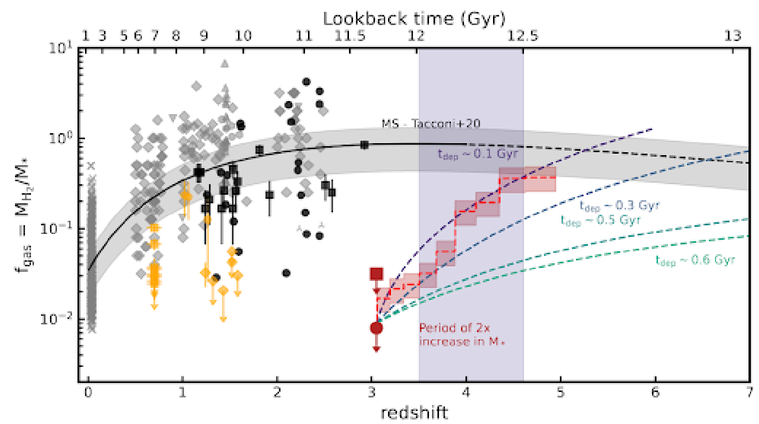


Figure 2

Fig 2. Gas-consumption history of GS-10578 (red), reconstructed by combining ALMA and JWST observations. This kind of analysis provides new constraints on quenching models (dashed lines). The black line shows the gas fraction of typical star-forming galaxies.



Jan Scholtz, Francesco D'Eugenio & Roberto Maiolino

Unveiling the Physics of a Dusty Galaxy Merger, Billion Years After the Big Bang

Before the launch of the James Webb Space Telescope (JWST), one of the primary means to study the properties of galaxies at the epoch of reionisation (i.e., around 1 billion years after the Big Bang) has been using the ALMA observatory in Chile, through observations of doubly ionised oxygen ([OIII]) 88 μm and ionised carbon ([CII]) 158 μm emission lines and the continuum emission originating from the cold dust in these galaxies. These observations identified a large number of extremely bright dusty galaxies. One of the most famous examples is COS-3018, a UV-luminous galaxy with a rich history, written here at KICC. Former Kavli Institute Fellow, Dr. Renske Smit identified this as the most distant settled disk in the Universe in 2018, while Dr. Joris Witstok revealed in 2022 a massive cold dust reservoir, challenging the theoretical models of dust production by supernovae and asymptotic giant branch (AGB) stars.

Given these properties, this galaxy was observed with JWST as part of the Galaxy Assembly with NIRSpec-IFS (GA-NIFS) survey to study this galaxy in detail using the rest-frame optical emission lines via spatially resolved spectroscopy. Using the rest-frame optical light, JWST allows us, for the first time, to study the ionised interstellar medium (the gas between stars) and stellar populations. Furthermore, the integral field spectroscopy (IFS) mode of the NIRSpec instrument not only gives the combined spectrum from the whole system, but also a full spectrum for each pixel in our image.

Combining deep NIRCam imaging (see left panel of Fig. 1) with the spectroscopy (right panel of Fig. 1) revealed a complex system with at least three clumps that we refer to as Main, North and East clumps, with the Main and North clumps having similar size and mass, while the East component is a low-mass satellite. These findings are in tension with the original conclusions that this is a dynamically cold rotating disk, but more likely a merger of multiple components (see left map of Fig. 2).

Also, the detailed analysis of the emission line profile of doubly ionised oxygen ([OIII], tracing hot gas with temperature around 20,000 K) shows a high-velocity outflow with velocities of up to 1200 $km s^{-1}$, driven either by the extreme merger-driven starburst or accretion onto a supermassive black hole.

The high-velocity outflow, UV luminosity and luminous [OIII] compared to the continuum raises the question of what is powering this galaxy: star-formation or accretion onto a supermassive black hole (an active galactic nucleus; AGN). However, the low metal content in this galaxy makes it extremely challenging to distinguish between the different powering scenarios. Using state-of-the-art photoionisation modelling from the literature, we performed multiple tests and found no strong evidence that rules out star formation as the main driver of this galaxy. However, AGN activity is not ruled out either, showcasing the challenges at high redshift.

The spatially resolved spectroscopy has also allowed us to find a small group of star clusters, west of the North component, with very high nitrogen content compared to the rest of the galaxy and the typical galaxy population. This region also shows a high gas density, similar to other nitrogen-rich galaxies in the early Universe. This indicates that the enrichment of galaxies with nitrogen and other elements is coming from smaller regions and then scattered throughout the galaxy.

The spectacular JWST data demonstrate the immense capabilities of JWST in studying galaxies at the beginning of the Universe. The integral field spectroscopy, although requiring a large amount of time, can achieve multiple science goals, diving deep into the physical mechanisms of galaxy evolution.

This article is partly based on results published as Scholtz J. et al., MNRAS staf518 (2025).

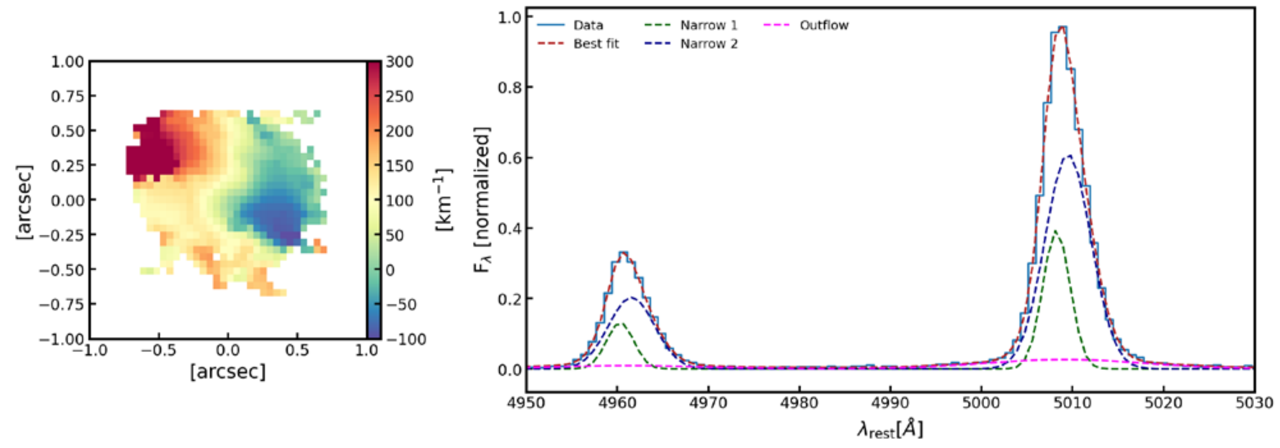


Figure 1

Fig 2. Map of the orbital velocity of gas in COS-3018 (left). Although the map resembles a rotating galaxy, the spectrum of [OIII] emission lines (right) shows a complex line profile and an outflow (magenta).

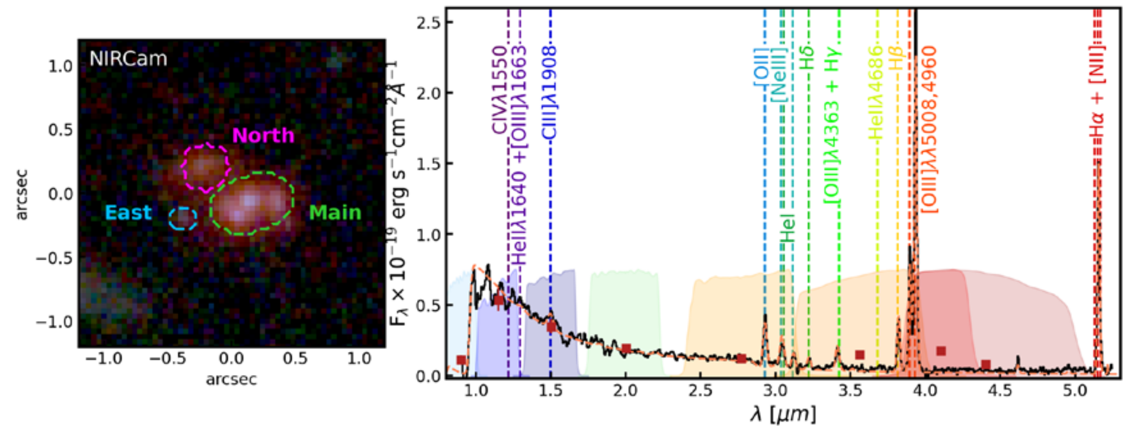


Figure 1

Fig 1. Imaging from NIRCam (left) and the spectrum from NIRSpec (right) of the COS-3018 system. Our target comprises multiple merging luminous components. Excellent detection of emission lines allows us a detailed study of the ISM.

Charlotte Simmonds & Sandro Tacchella

Unveiling the Properties of the Galaxies that Ionised the Universe with JWST NIRCam

Ever since the Big Bang, our Universe has been expanding. This has led to changes in its temperature, which, in turn, give rise to different phases. Soon after the Big Bang, the Universe was akin to a hot soup, where electrons and protons were moving at such speeds that they could not combine to form hydrogen atoms. As the Universe expanded and cooled down, however, these free particles were able to join and form neutral hydrogen. At this point in our cosmic history, there were no stars or galaxies, so the Universe was completely dark. As time went on and the Universe continued cooling down, eventually matter started to collapse due to gravity, giving rise to the first stars and galaxies. As these stars and galaxies started to shine, they produced radiation with enough energy to ionise (i.e., to remove an electron from a neutral hydrogen atom) the regions around them, creating ionised bubbles in an otherwise neutral medium. As more galaxies formed, these bubbles overlapped until finally, about one billion years after the Big Bang, the Universe settled into what we know today, full of light. This transition between a dark and neutral Universe to an ionised one is called the epoch of reionisation (EoR). Understanding the sources responsible for this transition is one of the biggest outstanding problems in observational cosmology.

With the advent of the James Webb Space Telescope (JWST), scientists now have unprecedented access to the EoR and the sources responsible for it. This work has been performed using the Near Infrared Camera (NIRCam) onboard JWST, through the JWST Advanced Extragalactic Survey (JADES) collaboration. This survey has imaged tens of thousands of galaxies at this epoch, allowing us — for the first time — to build statistical samples of galaxies to answer the question: which types of galaxies were the main ionising agents of the Universe? Within this context, one of the key questions to address is whether a large amount of faint low-mass galaxies or rather, just a few massive bright ones, dominated the process of reionisation. Moreover, JWST has reignited the debate regarding the importance of accreting supermassive black holes in the early Universe.

In order to unveil the properties of the galaxies that ionised the Universe, we constructed a sample of galaxies whose light was emitted between about 0.5 and 2 billion years after the Big Bang. We first focused on 677 galaxies that had strong evidence of ionising radiation production, especially through signatures left in hydrogen and oxygen (Fig. 1, white circles). These signatures allowed us to measure directly their ionising photon production efficiencies, and compare these to the values inferred by Prospector, powerful software that analyses observations of galaxies to constrain their physical properties. Promisingly, we found good agreement between both methods, and concluded that faint-low mass galaxies are likely the main sources responsible for ionising the Universe. Furthermore, we found that galaxies in the early Universe are more efficient in producing ionising radiation. However, there is an important caveat to this work. Since we focused only on galaxies with strong signatures of ionising radiation, we were looking at a biased sample. To overcome this issue — and taking the success of Prospector in measuring galaxy properties as motivation — we built a sample of around 15,000 galaxies (shown as blue circles in Fig. 1) . Not only is this sample the largest one ever studied at the EoR, but it also has a very special property: it is complete in stellar mass, meaning that we are potentially studying all types of galaxies, and are not restricted to the ones with obvious evidence of production of ionising photons.

With a stellar-mass-complete sample, we confirmed our previous findings, concluding that faint low-mass galaxies are the main sources responsible for ionising the Universe. However, we noted that the increased efficiency in ionising photon production towards the early Universe is much less significant when considering a less-biased sample. Although this work has meant an important step towards understanding the EoR, future work disentangling the importance of accreting black holes will help unveil the mysteries of this epoch.

Studies such as ours highlight the importance of analysing statistical samples when making conclusions about the evolution of the Universe. Thanks to JWST and other future missions, constructing such samples is now a reality. We look forward to what the next years will bring!

This article is partly based on results published as Simmonds C. et al., MNRAS 527, 6139 (2024) and Simmonds C. et al., MNRAS 535, 2298 (2024).

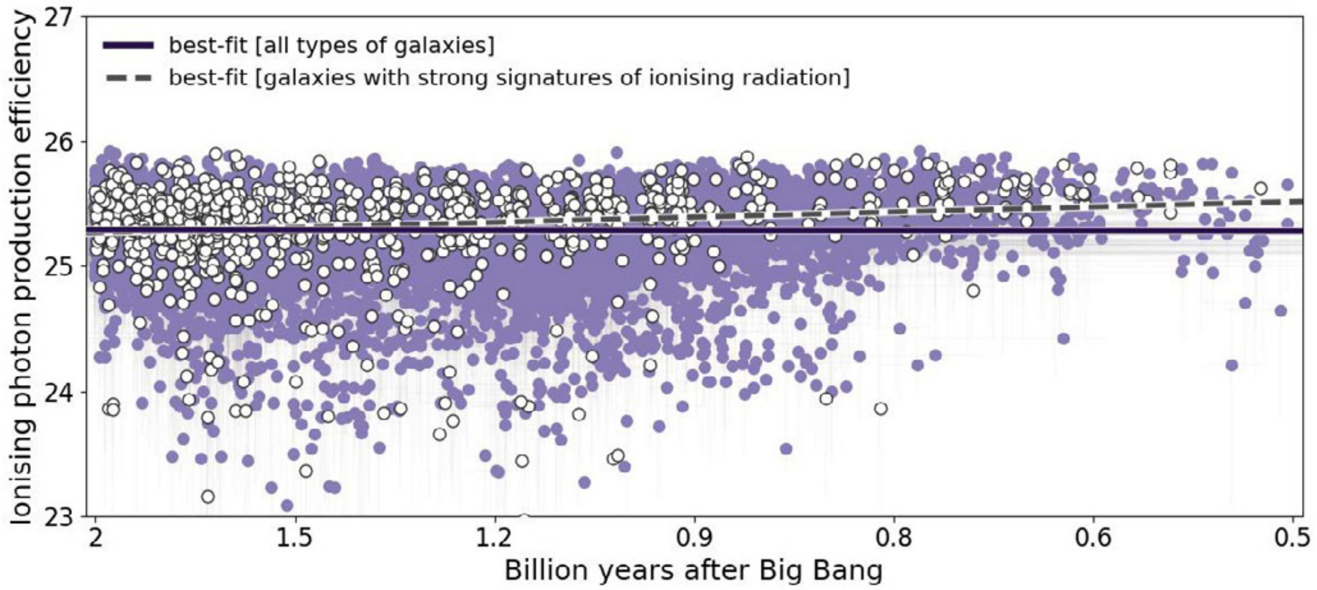


Figure 1

Fig 1. Ionising photon production efficiency as a function of the age of the Universe. The white circles show galaxies with strong evidence of ionising radiation, while the blue ones potentially show all galaxy types.


Matthew Bothwell & Hannah Strathern
KICC 2024 Public Outreach

Working with Schools

A major part of our outreach program involves working with schools. This mainly takes the form of the Kavli Outreach Officer visiting schools to deliver astronomy teaching sessions (talks and Q&A sessions designed around the school curriculum). In addition, we also host school visits to the Institute, where groups receive a talk followed by a range of activities (including telescope tours, library tours, and demonstrations with our on-site heliostat). We also visit schools as part of our flagship project "AstroEast", designed to extend our existing outreach efforts beyond the Cambridge area. We are working with schools across Norfolk, Suffolk, and Peterborough to deliver a variety of astronomy teaching sessions, workshops, and science clubs. Across all our school visits in 2024, we have run astronomy education sessions for more than 1500 pupils.

Space Camp

In July 2024 we hosted a week-long Space Camp for Year 11 pupils, in collaboration with the UK Space Agency and the National Space Academy. The pupils, all of whom came from communities with low science capital, visited departments around the university, had talks on everything from solar weather to JWST, and a practical session with virtual reality and underwater astronaut training.

Throughout the week, students had spent time each day working on a project to produce an information broadcast or leaflet regarding a specific threat to the Earth. They then had to pick an alternative exoplanet to colonise, detailing what we would need to take, and how we would get there. Each group gave their presentations on Friday afternoon, which was a wonderful way to finish off, seeing how much they had learnt and how wonderfully they'd performed in teams to achieve their goals!

We had a fantastic week with a great set of curious and enthusiastic students, and we can't thank our speakers and collaborators enough for the excitement and passion they brought to every aspect of the camp!

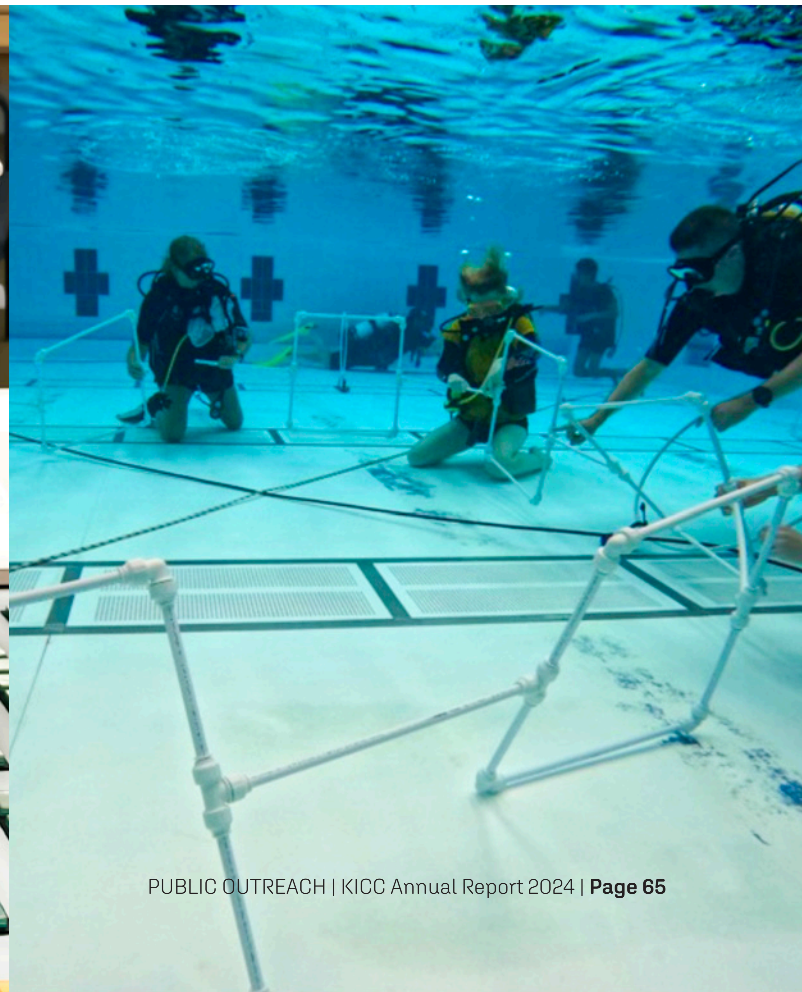
KICC + IoA Open Day

As always, KICC and the IoA opened their doors in March 2024 for our annual Open Day, part of the Cambridge Festival. The day was one of the busiest ever, with around 1500 visitors coming through our doors over the course of the afternoon.

Many Kavli researchers staffed the day and showcased their research to the public, with activities including JWST face painting, experiments with spectra and gravitational lensing, images of galaxies, and exploring the CMB.

https://nationalspaceacademy.org/about-us/news/space-to-learn-making-a-splash-at-our-cambridge-camp/



Raising the Veil on Star Formation Near and Far: A Conference in Honour of Richard Hills
Date: 22–26 April 2024
Event Location: Kavli Institute for Cosmology, Cambridge

Galaxy Formation and Evolution in a Cosmological Context - 5th Summer School
Date: 16–23 June 2024
Event location: Spetses, Greece

New Physics from Old Light: Illuminating the Universe with CMB Secondaries
Date: 16–20 September 2024
Event location: Kavli Institute for Cosmology, Cambridge

Raising the Veil on Star Formation Near and Far: A Conference in Honour of Richard Hills
During the third week of April, KICC hosted a week-long hybrid conference in honour of the late Richard Hills, Emeritus Professor of Radio Astronomy in the Department of Physics and a pioneering, world-leading millimetre-wave astronomer. He guided the development of instrumentation for far-infrared and submm observatories as a key person in the James Clark Maxwell Telescope in Hawaii and ALMA in Chile. His key technical innovation helped astronomers study the cold and dusty side of galaxy evolution and star formation in galaxies.

Below: Raising the Veil Conference Photograph, taken in front of the IoA Observatory.

The conference attendees studied star formation on all scales, from pre-stellar and protoplanetary cores, astrochemistry, star formation in stellar nurseries to star formation in local and distant galaxies. Most of the results presented at the conference would have not been possible without the new state-of-the-art concepts conceived by Richard Hills. A special session during the conference celebrated Richard's legacy as a scientist, mentor, and friend.

Galaxy Formation and Evolution in a Cosmological Context - 5th Summer School
KICC was delighted to support the 5th "Galaxy Formation and Evolution in a Cosmological Context" Summer School, which took place in June in Spetses, Greece. KICC faculty, Sandro Tacchella, was a co-organiser and lecturer.

New Physics from Old Light: Illuminating the Universe with CMB Secondaries
In September, the KICC and IoA hosted the New Physics from Old Light workshop. This workshop brought together over 40 visiting scientists to discuss cosmic microwave background (CMB) secondary anisotropies. In the last decade, the topic of CMB secondaries – the gravitational and scattering interactions of CMB photons with cosmic structures after recombination – has attracted great interest as a promising way of studying astrophysical processes across the Universe and for testing fundamental properties of the Universe. This workshop synthesized past progress, highlighted key challenges and explored new ways of testing our understanding of our cosmological model. Hopefully it also seeded many new collaborations and inspired new research projects.

Below: New Physics from Old Light: Illuminating the Universe with CMB Secondaries workshop photograph, taken on the Hoyle Lawn at the IoA.

KICC 2024 • Events, Lectures & Visitors

Kavli Lecture Series

12 March 2024
Eve Ostriker (Princeton University)
Star Formation, Feedback, and Cosmic Evolution: A Modern Primer

2 May 2024
Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics)
Experimental Studies of Black Holes: Status & Prospects

We were delighted to host Eve Ostriker and Reinhard Genzel as our Kavli lecturers this year. The Kavli Lectures are biannual prize lectures given by distinguished astronomers and astrophysicists from outside Cambridge.

https://www.kicc.cam.ac.uk/events/kavli-lectures

New Frontiers in Astrophysics: A KICC Perspective

23 February 2024
Isobel Romero-Shaw (DAMTP)
Decoding the Gravitational-Wave Biographies of Binary Black Holes

25 June 2024
Blake Sherwin (DAMTP)
Do we understand cosmic structure growth? Insights from new CMB lensing measurements with the Atacama Cosmology Telescope

22 November 2024
Jo Dunkley (Princeton)
The start of the Simons Observatory

The "New Frontiers in Astrophysics: A KICC perspective" series continued this year with three exciting talks by local experts, Isobel Romero-Shaw and Blake Sherwin, and Royal Society Wolfson Visiting Fellow and joint Kavli medium-term and IoA distinguished visitor, Jo Dunkley. These talks survey topics at the research frontiers of astrophysics and cosmology.

https://www.kicc.cam.ac.uk/kicc-new-frontiers

Kavli Science Focus Meetings

6 & 7 February 2024 - Science with the 21-cm line
16 & 17 May 2024 - Confronting tSZ simulations and observations
21 June 2024 - Dark matter in astrophysical laboratories
20 November 2024 - Cosmological Inference in High Dimension
5 December 2024 - Tackling the CMB component separation problem with new methods

Kavli Science Focus Meetings are primarily internal meetings encouraging interdepartmental networking and collaboration across the science themes of the KICC, occasionally including external speakers. This series continued to be a success during 2024 with five meetings across a wide range of topics as well as our annual "Introduction to KICC" meeting in October. This introductory event welcomes and orients new members at the start of the academic year and provides an opportunity for current members to showcase the variety of research taking place at KICC.

https://www.kicc.cam.ac.uk/events/kavli-science-themed-meetings

Kavli Visitors

KICC has a large and vibrant visitor programme that encourages broad scientific interactions, fostering existing collaborations and generating new ones. Official Kavli Visitors are selected from nominations by Cambridge astronomy researchers across DAMTP, Cavendish Astrophysics and the Institute of Astronomy. In 2024, we were delighted to support 11 short-term and 3 medium-term Kavli visitors through this programme:

Short-term Kavli visitors

Roger de Belsunce (Lawrence Berkeley National Laboratory)
Riccardo Buscicchio (University of Milano-Bicocca)
Erin Kara (Massachusetts Institute of Technology)
Evan Kirby (University of Notre Dame)
Martin Laming (Space Science Division, Naval Research Laboratory)
Sergio Martin-Alvarez (Stanford University)
Tsevi Mazeh (Tel Aviv University)
Matthew McQuinn (University of Washington)
Nikhil Sarin (Stockholm University)
Saurabh Singh (Raman Research Institute)
Francisco Villaescusa-Navarro (Simons Foundation)

Medium-term Kavli visitors

Jo Dunkley (Princeton University) - joint Kavli medium-term visitor and Institute of Astronomy distinguished visitor; Royal Society Wolfson Visiting Fellow
Trevor Mendel (Australian National University)
Emily Wisnioski (Australian National University)

Image: "Introduction to KICC" meeting, taken outside the Kavli Institute for Cosmology, Cambridge

CONTENTS
Overview

Hannah Übler

ERC Starting Grant

Newton–Kavli Fellow, Dr Hannah Übler, was awarded an ERC Starting Grant to investigate "Active galactic nuclei and Population III stars in early galaxies". In September 2024, Hannah moved to the Max Planck Institute for Extraterrestrial Physics to continue her research as an ERC research group leader.

https://www.mpe.mpg.de/8040789/news20241105

George Efstathiou

Honorary Doctor of Science degree from Durham University
Albert Einstein Medal 2024

Professor George Efstathiou, founding Director of KICC, received an honorary Doctor of Science degree from Durham University. George said: "I started my PhD in Durham in 1976 and immediately fell in love with the town, the people, the magnificent cathedral and the University. I joined a new Cosmology group led by Richard Ellis which was small, very enthusiastic and unhindered by orthodox thinking. This is where I learned how to do research. Durham played a critical role in my life and I am especially honored to receive this recognition, which I much appreciate."

https://www.durham.ac.uk/about-us/professional-services/ceremonies/honorary-degrees/#d.en.2104623

Professor Efstathiou was also awarded the Albert Einstein Medal 2024. The medal is awarded to deserving individuals for outstanding scientific findings, works, or publications related to Albert Einstein.

https://www.einstein-bern.ch/en

Martin Bourne

Stephen Hawking Fellowship

Dr Martin Bourne, Research Associate at KICC, was awarded a three-year EPSRC/STFC Stephen Hawking Fellowship to research "How supermassive black holes shape the Universe: at the interface of galaxy formation, cosmology and multi-messenger astronomy". He says "The main aim of the research is to make use of state-of-the-art simulations across a range of scales to study the evolution of supermassive black holes over cosmic time, how they impact their environment and the implications for galaxy formation, cosmology, gravitational waves and multimessenger astronomy. The hope is not only to provide theoretical insights but also to generate observational comparisons and predictions for current (e.g., JWST) and future (e.g., SKAO, Athena and LISA) observing missions." In October 2024, Martin moved to the University of Hertfordshire as a Senior Lecturer. He remains heavily involved at KICC as a collaborator and regular visitor.

https://gtr.ukri.org/projects?ref=EP%2FX04257X%2F1#/tabOverview

Anne-Christine Davis

OBE

Professor Anne-Christine Davis, Professor of Mathematical Physics and member of the KICC Faculty, received an OBE in 2024 in recognition of her services to Higher Education and to Scientific Research. She said: "I am amazed and overwhelmed to receive this honour. I could not have done it alone and wish to thank my wonderful students and collaborators over the years. I would like to dedicate this honour to those women in STEMM who came before me and did not receive the recognition they deserved."

https://www.maths.cam.ac.uk/features/professor-anne-christine-davis-awarded-obe

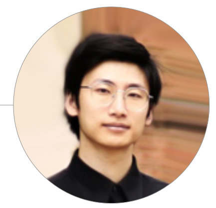
Many congratulations to the following graduate students at KICC who successfully defended their Master's or PhD theses in 2024.

William Baker
PhD Thesis Title: *New Insights on the Evolutionary Mechanisms of Local and Distant Galaxies*
Supervisor: Roberto Maiolino
Current position: DARK Postdoctoral fellow, Niels Bohr Institute, University of Copenhagen

Tibor Dome
PhD Thesis Title: *Modelling Astrophysical and Large-Scale Structure Signatures in Axion Cosmologies (Subtitle is: Navigating Ultralight and Ultracold Frontiers)*
Supervisor: Anastasia Fialkov, Debora Sijacki
Current position: Software engineer, GMV

Gerrit Farren
PhD Thesis title: *Tracing the Cosmos: Probing Cosmology with the Large Scale Structure of the Universe*
Supervisor: Blake Sherwin
Current position: Postdoctoral fellow, Berkeley National Laboratory

Zucheng Gao
PhD Thesis title: *Projected Angular Statistics for Large-scale Structure Cosmology*
Supervisor: Anthony Challinor, Zvonimir Vlah
Current position: Postdoctoral researcher, Laboratoire d'Annecy-le-Vieux de Physique Théorique



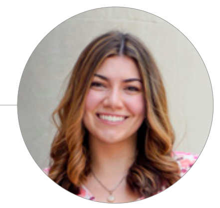
Thomas Gessey-Jones
PhD Thesis title: *Probing the First Stars with the 21-cm Signal: Theory, Methods, and Forecasts*
Supervisor: Eloy De Lera Acedo, Anastasia Fialkov, Will Handley
Current position: Research Data scientist, PhysicsX

Brian Jiang
Master's Thesis Title: *Super-Eddington black hole accretion in the early universe: insights from cosmological galaxy formation simulations and JWST*
Supervisor: Debora Sijacki, Sandro Tacchella
Current position: PhD student, Massachusetts Institute of Technology

Tobias Looser
PhD Thesis Title: *Regulating and Quenching Star Formation across the Cosmic Epochs*
Supervisor: Roberto Maiolino
Current position: Postdoctoral fellow, Harvard University

Lester Sandles
PhD Thesis Title: *Star-forming Galaxies and Quenched Systems throughout Cosmic Time*
Supervisor: Roberto Maiolino
Current position: Site Reliability Engineer, Vodafone

Natalia Villanueva
Master's Thesis Title: *The size growth of star formation in the early Universe*
Supervisor: Sandro Tacchella
Current position: PhD student, University of Texas at Austin



Callum Witten
PhD Thesis Title: *New Insights into Primeval Galaxies in the Era of JWST*
Supervisor: Debora Sijacki, Nicolas Laporte
Current position: Postdoctoral researcher, University of Geneva

KICC 2024 • KAVLI Fellows & Leavers

Hannah Übler
Current job title: ERC research group leader,
Max Planck Institute for Extraterrestrial Physics

"During my 3.5 years at KICC I was fortunate to have had the opportunity not only to work with the first spatially resolved JWST data of distant galaxies, but to enjoy a community of wonderful colleagues across the departments. There is no doubt that the Kavli Fellowship was a significant propellant for my career."

Suhail Dhawan
Current job title: Assistant Professor of Physics and Astronomy and 125th Anniversary Fellow, University of Birmingham

"My time at the KICC was a very enriching experience. The discussions with institute members of all career stages were very dynamic and fruitful. I hope to keep these connections for the entirety of my career."

Vid Iršič
Current job title: Senior Lecturer, University of Hertfordshire

"I joined KICC in 2019 and have spent five extraordinary years there, enriching not only my own research but also enhancing my research career. The welcoming atmosphere, the wealth of activities and seminars, the inspiring colleagues and visitors who have sparked countless scientific discussions, and the unwavering support of the administrative team have all come together to make this an unforgettable experience. My time at KICC has profoundly influenced both the direction of my career, and the way I approach research as a whole."

Mathias Nowak
Gavin Boyle Fellow

Current job title: Chargé de Recherche, CNRS

Acknowledgements

Further Information and Acknowledgements

This report is a summary of the KICC activities and is not a comprehensive review. There are more extensive descriptions of KICC and its activities by researchers, postdocs and students at **https://www.kicc.cam.ac.uk**.

The full list of people working at or associated with KICC is available at **https://www.kicc.cam.ac.uk/directory**.

The full list of research projects is available at **https://www.kicc.cam.ac.uk/projects**.

The full list of scientific publications is available at **https://www.kicc.cam.ac.uk/aboutus/scientific-publications**.

Acknowledgements

The numerous activities of KICC during 2024 were made possible by the extensive administrative and logistical support provided by the administrative, IT and logistics staff of the Institute of Astronomy, Departments of Physics and of Applied Mathematics and Theoretical Physics and the School of Physical Sciences.

The artwork and layout of this report were produced by Amanda Smith, who has also produced numerous other artworks for our various KICC events.

The activities of KICC are facilitated by the generous donations by the Kavli Foundation, in combination with the University of Cambridge and its Departments. We would also like to thank Gavin Boyle and the Isaac Newton Trust for their additional support of our fellowship programmes.

Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA