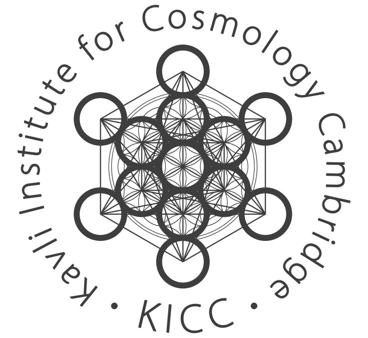
KICC ANNUAL REPORT 2023

KAVLI INSTITUTE FOR COSMOLOGY, CAMBRIDGE


Kavli Institute for Cosmology Cambridge
KICC

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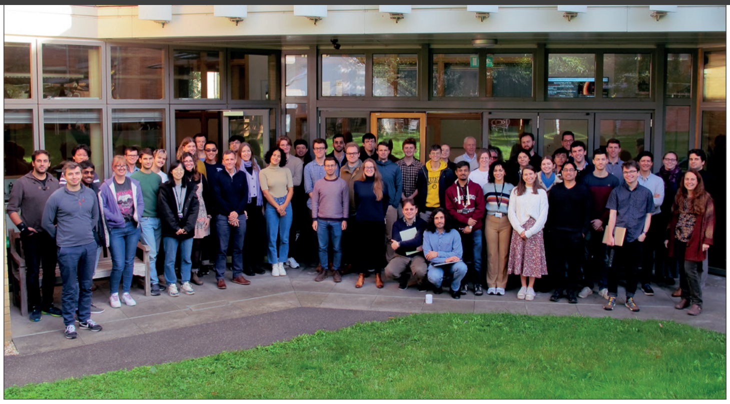


I am thrilled to introduce the 2023 report from the Kavli Institute for Cosmology, Cambridge. I hope that you will enjoy reading about some of the exciting research conducted by our members and the many activities that we have held during the year.

Many of the articles report on the amazing discoveries made with the James Webb Space Telescope (JWST). Particularly prominent are the first results from the JWST Advanced Deep Extragalactic Survey (JADES) – one of the largest programmes in the first year of JWST observations – which are revolutionising our ideas about the growth and evolution of galaxies in the first billion years of cosmic history. Researchers based at the Kavli Institute have led work suggesting unexpectedly rapid development of these first galaxies, as revealed by intense star formation, efficient production of carbon-rich dust grains (possibly diamond-like), and the earliest supermassive black holes ever observed. To celebrate and discuss the remarkable results from JWST, the Kavli Institute hosted a major international workshop in March 2023: "*A new era in extragalactic astronomy: early results from the James Webb Space Telescope*".

The excitement has not been limited to galaxy formation and evolution though. Other highlights you can read about include new lensing maps from the Atacama Cosmology Telescope, revealing in projection the distribution of dark matter across the entire observable Universe and providing tight constraints on the growth of cosmic large-scale structures across time. New limits on the mass of dark matter particles have been obtained by constraining their impact on the small-scale clustering of matter as revealed by the absorption of light from distant quasars by intergalactic hydrogen gas. Furthermore, the first measurements with early DESI data of the correlations in this Lyman-alpha absorption showcase the remarkable promise of this ongoing spectroscopic survey. Finally, the discovery of the unusual, highly magnified and multiply imaged supernova "*SN Zwicky*" – by a team involving Kavli Institute researchers – ushers in new opportunities to learn about the properties of distant supernova explosions, the inner cores of lens galaxies, and the expansion of the Universe.

2023 marks the 15-year anniversary of the appointment of our first Kavli Institute Fellows. These independent research fellowships allow us to bring talented early-career scientists from around the world to Cambridge for stays of up to five years. Many of the past holders of these fellowships have gone on to become leading researchers in their fields, often as faculty members at prestigious institutions, and are now nurturing the next generation of talented students and postdoctoral researchers. In 2023, five of our Kavli Institute Fellows moved on to new positions – you can read about their destinations and reflections on their time at the Kavli Institute in a dedicated article. We were delighted to welcome Harry Bevins and William Coulton as new Kavli Institute Fellows in October.

The work of members of the Kavli Institute has continued to be recognised with prizes and awards. Alex Amon, Kavli Institute Senior Fellow, was awarded the Winton Award by the Royal Astronomical Society and a British Science Association Lecture. Roberto Maiolino was appointed to the honorary position of Blaauw Professor at the University of Groningen. In addition, three of our members received prestigious, major research grants from the European Research Council: Suhail Dhawan, Marie-Curie and Kavli Institute Fellow, was awarded a Starting Grant; Eloy de Lera Acedo received a Consolidator Grant; and Roberto Maiolino an Advanced Grant (his second!). Congratulations to them all on these fantastic achievements.

We were delighted to welcome four new faculty members to the Kavli Institute this year. Miles Cranmer, a leading figure in applications of machine learning in astronomy, and Chris Moore, an expert in gravitational waves, were appointed to Assistant Professorships in Data Intensive Science jointly between the Institute of Astronomy (IoA) and the Department of Applied Mathematics (DAMTP) and Theoretical Physics. These appointments are in support of a new Master's degree launched by the Department of Physics, DAMTP and IoA (see below). Our colleague Eloy de Lera Acedo, a leading researcher in experimental radio cosmology, was appointed to an Associate Professorship in the Department of Physics, where he previously held an Ernest Rutherford Fellowship. Finally, Hiranya Peiris joined the IoA as the Professor of Astrophysics (1909). Hiranya is a world leader in survey cosmology and the connection between observational cosmology and fundamental physics. Her appointment opens many new interdisciplinary research directions for Cambridge, including quantum condensed-matter analogues of the physics of the early universe and laboratory searches for the QCD axion, a prime dark matter candidate.

The Department of Physics, IoA and DAMTP – the three parent departments of the Kavli Institute – launched a new M.Phil. in Data Intensive Science for the academic year 2023/24. This aims to take science graduates and prepare them for data-intensive research careers by providing advanced training in statistical analysis, machine learning and research computing, and their application to current research frontiers. The course proved extremely popular, with nearly 400 applicants; the first cohort of 62 students started in October 2023. Many Kavli Institute members are contributing through lectures and project work, including former Kavli Institute Senior Fellow Steven Gratton, who has been appointed to the position of Assistant Teaching Professor in DAMTP from October 2024.

It has been another busy year hosting international workshops and other events. As well as the JWST workshop, we hosted "*Gambit at the KICC*" in July 2023, a workshop by the inter-disciplinary Gambit Collaboration, which develops a global-fitting code for constraining theories beyond the Standard Model of particle physics with a variety of particle physics and astrophysical data. Our popular "*Focus Meetings*" continued, bringing together cosmologists across Cambridge (plus, usually, a few external participants) to discuss topics such as The Milky Way and its high-redshift progenitors in theory and observations; astro-statistics and astro-machine learning; a multi-scale view of the epoch of reionization; and next-generation surveys in the Rubin–LSST era. Such is the excitement about the first results from JWST that we welcomed two outstanding Kavli Lecturers, Daniel Eisenstein and Marcia Rieke, to speak on different aspects of these findings. Astronomers from across Cambridge gathered twice termly for our Kavli-hosted "*New Frontiers talks*", with subjects ranging from what substructures in protoplanetary discs can tell us about planet formation, by Roman Rafikov (DAMTP), to a new theory of the Universe, by Neil Turok (Edinburgh). We hosted nearly 100 academic visitors who came to work with our staff and students. If you are interested in visiting, please do get in touch with us.

Many of our members communicate their science to a variety of audiences through public-engagement activities. Enthusing the next generation to consider careers in STEM is a major focus of this work under the leadership of Kavli Outreach Officer, Matt Bothwell, and new appointee Dr Hannah Strathern. Hannah's new position of cross-departmental Outreach Facilitator provides project management support for astronomy public-engagement activities across DAMTP, IoA and Physics, and capacity to grow the flagship AstroEast programme and associated initiatives in exciting new directions. You can read more about their work in the dedicated article in this report.

The Kavli Institute could not function without the support of our fantastic administrative team, Steven Brereton and Alison Wilson, and the professional-services staff in the parent departments who help with events, recruitment, IT and much more. Many thanks to you all! I am lucky to be working alongside Debora Sijacki, the Deputy Director, who has again been a great source of ideas, energy and support. 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.

Shikhar Asthana & Martin Haehnelt

Studying The Cosmic Dawn with JWST And Supercomputer Simulations

As discussed in previous annual reports, Christmas Day 2021 saw the launch of the James Webb Space Telescope (JWST), our most advanced space observatory. JWST is designed to peer back to the earliest epochs of the Universe, capturing light from galaxies formed shortly after the Big Bang. Among its many discoveries, JWST has observed galaxies at a time when the Universe was only 400 million years old. Before the first galaxies formed, the intergalactic gas had cooled sufficiently for hydrogen and helium to become neutral. Many of the earliest galaxies detected by JWST nevertheless shine brightly in the Lyman-alpha line, indicative of newly formed stars. In its neutral state, hydrogen, the most abundant element in the intergalactic gas, absorbs this light, preventing it from reaching us. So, why can JWST nevertheless detect Lyman-alpha emission and what does this reveal about an early phase of the Universe aptly termed the cosmic dawn?

To answer this, we have run supercomputer simulations of the cosmic dawn. During cosmic dawn, newly formed stars in the first galaxies emitted intense ultraviolet radiation, gradually (re-)ionizing the hydrogen in the surrounding intergalactic gas. The resulting bubbles of ionized hydrogen grew in time and eventually overlapped to encompass the entire Universe.

Prior observations and simulations suggested that this epoch concluded roughly 1 billion years after the Big Bang, with rapid reionization of hydrogen starting around 600 million years after the Big Bang. This led to the prediction that observed galaxies shining brightly in the Lyman-alpha line should be exceedingly rare at earlier times, as ubiquitous neutral hydrogen effectively obscures any Lyman-alpha light. Contrary to these predictions, JWST has observed numerous galaxies shining brightly in Lyman-alpha before the Universe was 600 million years old. This suggests the presence of sizable ionized bubbles early on in the history of the Universe allowing the Lyman-alpha light from the first galaxies to evade obscuration by too much neutral hydrogen in the surrounding intergalactic gas.

In response to JWST's findings, we adapted our super-computer simulations to consider earlier and more varied onsets of the reionization of hydrogen. Figure 1 illustrates three of our simulations. Blue areas denote regions where hydrogen is mostly ionized, while red areas denote regions where hydrogen is mostly neutral. As more and more galaxies form, more and more of the neutral hydrogen becomes ionized. The simulations show how small bubbles of ionized hydrogen around the first galaxies grow in size and eventually overlap. Despite differences in the timing of the onset of the growth of ionized

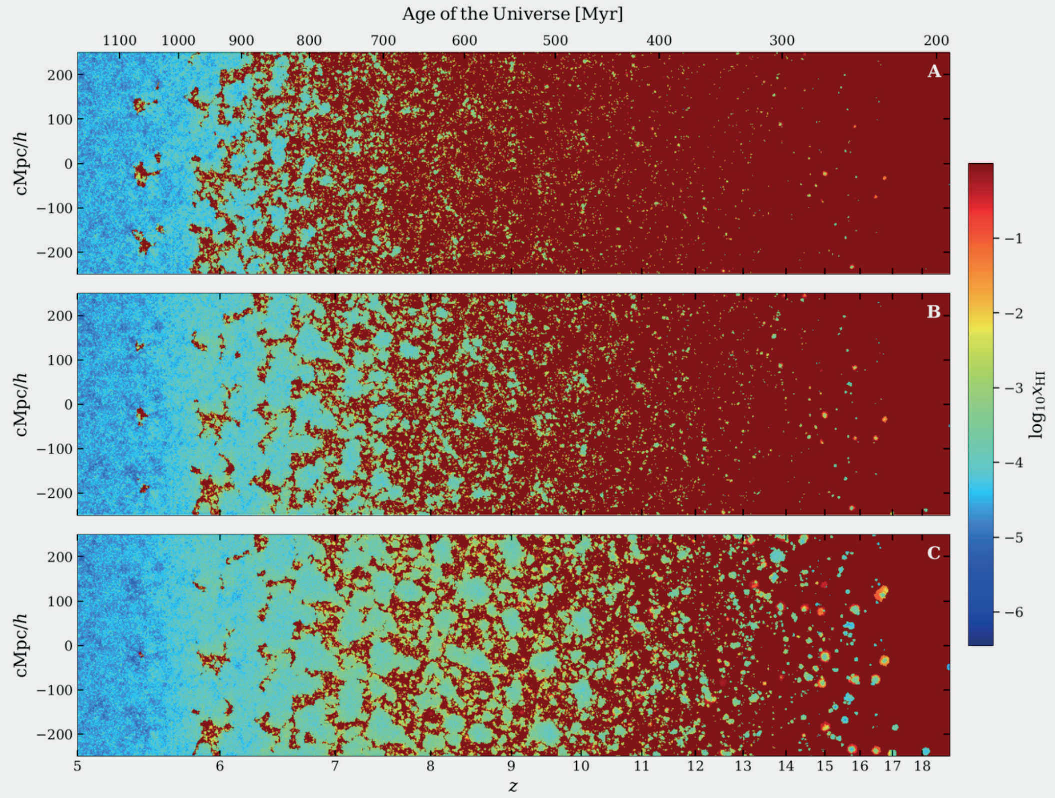


Figure 1. Timeline of the reionization of hydrogen by the first galaxies in different supercomputer simulations of cosmic dawn. The neutral fraction of hydrogen is shown, as indicated by the colour bar. Panel B shows the model that appears to agree best with current observations.

regions, all models converge by the end of reionization, consistent with observational data. Our simulations suggest that large ionized regions could indeed exist earlier than previously thought, allowing the Lyman-alpha light from the stars in the first galaxies to reach us. Our simulations also explain why the visibility of the Lyman-alpha light from brighter galaxies remains consistent over time, unlike that of fainter galaxies. The brighter galaxies are preferentially located within early-formed ionized bubbles, and thus remain consistently observable throughout cosmic dawn. Conversely, visibility of fainter galaxies, which ionize their surroundings more gradually, depends on the time required to create a sufficiently large ionized bubble around them.

Observations made with JWST combined with our advanced supercomputer simulations have refined our understanding of the timeline of hydrogen reionization suggesting a more protracted reionization process than previously envisioned. Yet, JWST continues to make new observations. Ionizing radiation has been found to be emitted not only by newly formed stars in galaxies, but also by numerous accreting massive black holes. Our understanding of how hydrogen is reionized during cosmic dawn may thus have to shift once again.

This article is based on results submitted to MNRAS as Asthana S. et al., arXiv:2404.06548.

William Coulton and the Atacama Cosmology Telescope Collaboration

New Views Of The Universe From Atacama Cosmology Telescope Data

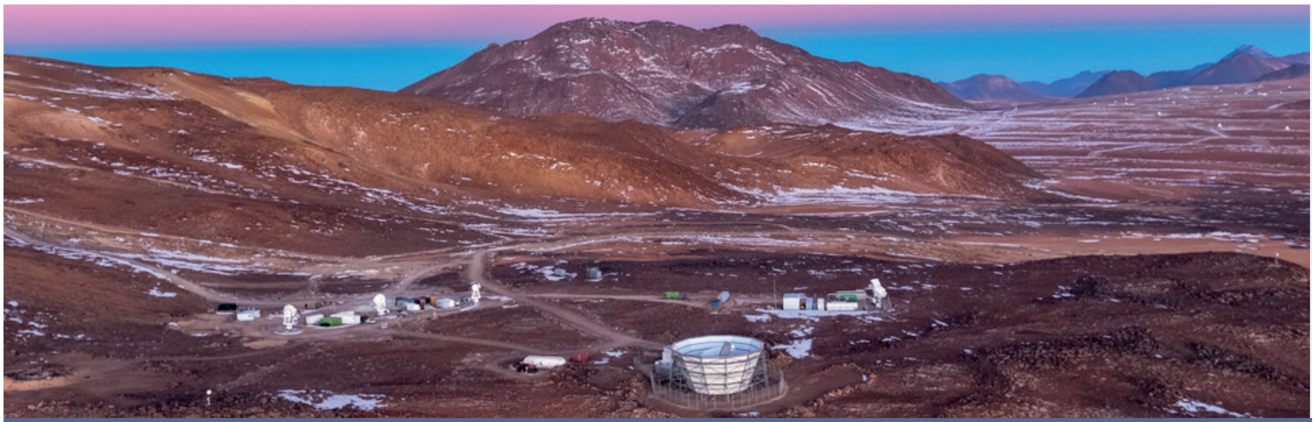


Figure 1. The Atacama Cosmology Telescope in the foreground, sited in the Atacama Desert in northern Chile at an altitude of 5,200 metres. Image credit: Debra Kellner.

In the past decade many telescopes have been built to observe the sky at microwave frequencies (millimetre wavelengths). A key goal of these telescopes is to study the cosmic microwave background, light produced in the Universe's youth almost 13.8 billion years ago! Studying this snapshot of the young Universe is one of the most powerful observables that cosmologists can use to learn about the history and properties of our Universe.

Whilst the cosmic microwave background is the brightest signal in the microwave sky, it is not the only signal. In fact there is a profusion of signals produced across almost the entire history of the Universe! This includes signals from the solar system, such as emission from asteroids and planets – including potentially a new planet, "*planet 9*"; from within the Milky Way, such as emission from small grains of cosmic "*dust*" or accelerating electrons spiralling the Galactic magnetic field; and from hot gas residing within the most massive objects in the Universe, galaxy clusters. For studies of the cosmic microwave background, these are a contaminant that can obscure the information on the early Universe. However, they can also be considered a new means of learning about the Universe and the processes within it.

Each of these sky signals can be characterised by its observational properties: how the strength of the signal varies with the observation frequency and with the location on the sky, or by its statistical properties. For example, signals produced within our Galaxy mostly lie within the plane of our Galaxy (the band of light across the sky that is visible in the absence of light-pollution), whilst signals from beyond are typically uniformly distributed over the sky. This variety in observational properties is a gift as it provides a way for us to separate the different contributions, a process known as component separation. Separating the sky contributions allows each signal to be studied without contamination from other signals and could enable the discovery of new small signals that are otherwise swamped.

The Atacama Cosmology Telescope (ACT) was a 6-metre telescope located in the Atacama desert in Chile (Fig. 1). It observed almost one-third of the microwave sky over the course of 14 years. The telescope measured the properties of the sky at five frequencies ranging from 30 GHz to 220 GHz. Just over a year ago, the experiment recorded its last observations and it is now being dismantled and removed from

Figure 2. Map of the cosmic microwave background isolated from ACT observations.

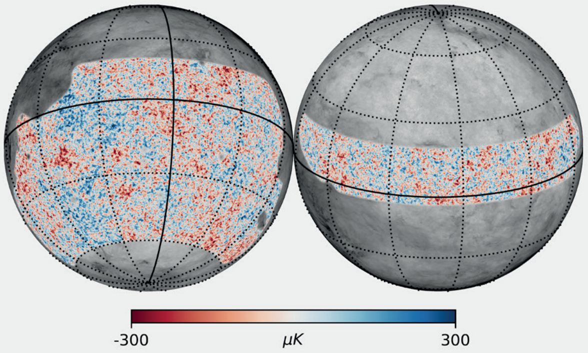
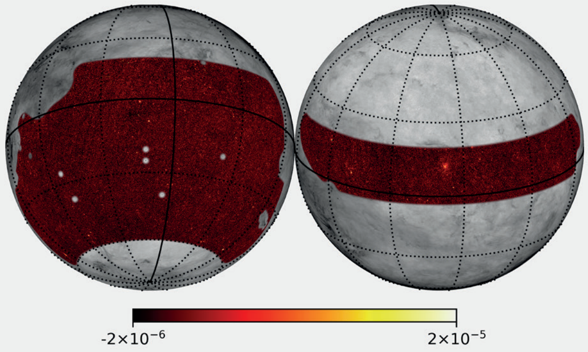


Figure 3. The highest precision map of hot gas throughout the universe. Each bright dot denotes the sky location of massive groups of galaxies.



the mountain – leaving the site as it was found is an important duty to preserve these idyllic, and often sacred, locations. Researchers within the ACT collaboration are now working intensely to analyse the final data-sets.

Through the application of state-of-the-art component separation techniques, ACT researchers have isolated numerous interesting signals from the ACT dataset. In Fig. 2, we show a map of the cosmic microwave background anisotropies. This is the clearest image to date of the Universe when it was only 380,000 years old. The blue and red spots correspond to regions of the early Universe where the radiation was hotter or colder than average. The specific distribution in number and size of these spots encodes information of the processes that happened at the beginning of the Universe.

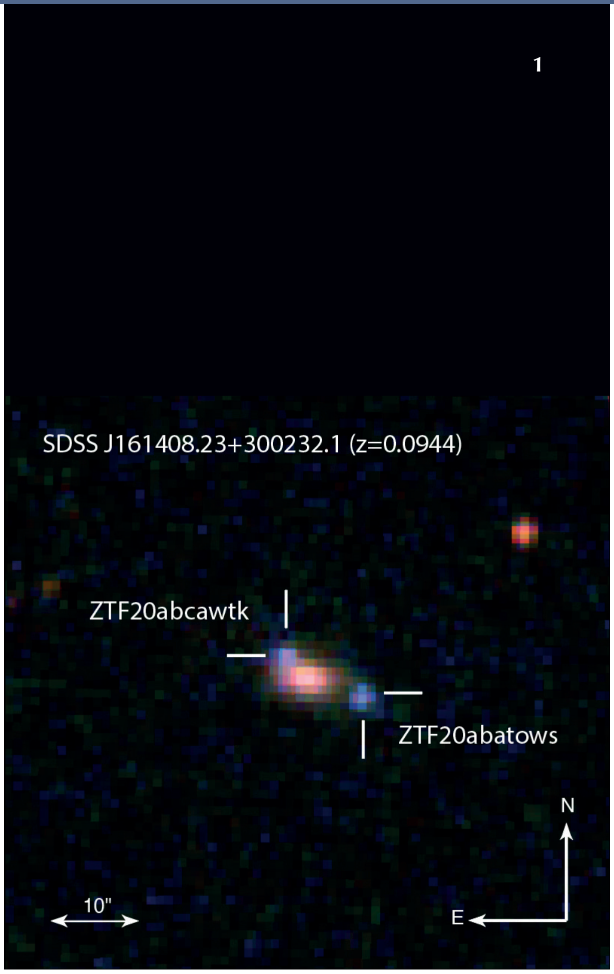
In Fig. 3 we show a map of a second interesting signal. This map traces out the distribution of hot dense gas throughout the Universe. A wealth of information is contained in this map as the detailed properties depend upon the balance of cosmic processes, such as the gravitational pull from the most massive objects in the Universe, with highly energetic astrophysical processes, such as hot gas accreting onto supermassive black holes. Each of the bright dots in Fig. 3 is a galaxy cluster. Galaxy clusters contain hundreds to thousands of galaxies bound together and filling the space between these galaxies is a hot dense gas. It is this gas that is imaged by ACT.

These maps are far from the final step in the analysis of these datasets. On-going analyses of the statistics of the data in Fig. 2 will allow us to learn about the age, composition and potential fate of the Universe. Similarly analyses of the data shown in Fig. 3 will tell us about the intense processes that heat the gas in galaxy clusters and about how clumpy the Universe is. As cosmologists work to tease out information from these maps, perhaps even some unexpected signals will be found!

This article is partly based on results published as Coulton W. et al., Phys. Rev. D 109, 063530 (2024).

Suhail Dhawan

New Frontiers In Supernova Cosmology From Wide-Field Surveys And JWST



Cosmology with Type Ia supernovae is at an exciting stage. In the past year, we have seen the culmination of analyses of large datasets addressing key science questions such as *"what is the physical mechanism driving accelerated expansion?"* and *"what is the present day value of the expansion rate of the universe?"*.

Wide-field surveys in multiple optical filters are crucial to answer these questions. At present, the constraints on dark energy from supernovae are limited by systematic not statistical uncertainties. Using Type Ia supernovae for cosmology requires correcting – or *"standardising"* – their peak brightness for their lightcurve shape and colour. One of the important open questions is whether these standardisation relations used in cosmological analyses with Type Ia supernovae are valid. An exciting route to constrain these relations without any dependence on cosmology, is via supernova siblings, i.e., two or more supernovae in the same parent galaxy. With the advent of surveys like the Zwicky Transient Facility (ZTF), which has monitored the entire Northern sky in two optical filters once every 2–3 days, it has been possible to assemble a large sample of supernova siblings, crucially with both objects observed with the same telescope and instrument (see Fig. 1 for one example).

With ZTF, we analysed a sample of 25 sibling pairs to test the width–luminosity and colour–luminosity relations. Since both supernovae are at the same distance any impact of cosmology cancels out. Moreover, this measurement is independent of any dependence on global host-galaxy properties, which is important since the origin of a correlation observed between host-galaxy properties and Hubble residuals (the difference between the inferred distance modulus to the supernova, inferred from its apparent luminosity after standardisation, and the expected value at the redshift of the host galaxy) is highly debated. From the ZTF sample, we find that the colour–luminosity relation – which is the dominant correction for cosmology – is consistent with the estimate from cosmological analyses. However, the width–luminosity relation has a steeper slope than in cosmological analyses, largely driven by the faster-declining supernovae. This result could be indicating that those supernovae are from a different, possibly older, progenitor population.

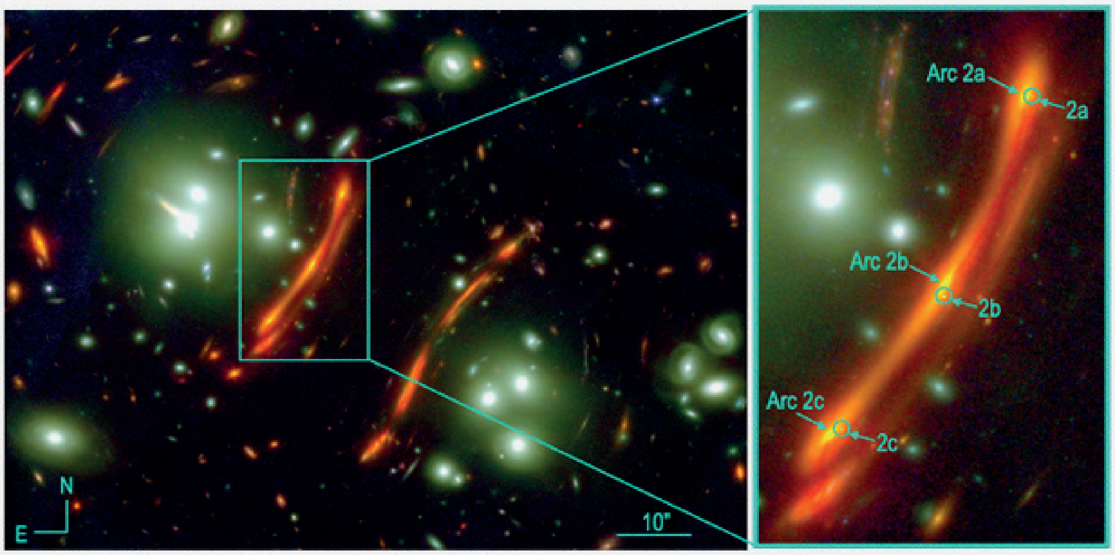


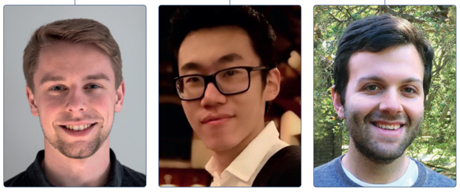
Figure 1. Example pair of Type Ia supernova siblings from ZTF. Both supernovae were above ZTF's detection threshold at the same time and their lightcurve and spectroscopic properties were consistent with normal Type Ia supernovae allowing this novel test of supernova standardisation.

Figure 2. SN H0pe, a Type Ia supernova at redshift z = 1.78, lensed by a foreground galaxy cluster. The close-up to the right shows the individual images of the system.

An independent channel to measure cosmological parameters from supernovae is via strong gravitational lensing. Such systems are important since they measure time-delay distances as opposed to the local distance ladder, which measures luminosity distances. While the idea has been posited for more than half a century, the first lensed supernova was only discovered a few years ago and only a handful of objects have been discovered since. Last year, ZTF published the analysis of a strongly lensed Type Ia supernova, SN Zwicky, which was the most compact lensing system known to date – having an Einstein radius less 2 arcsec (Fig. 2). Due to the lensing magnification, we studied the lightcurve features in detail and found that SN Zwicky looks extremely similar to nearby Type Ia supernovae. From modelling the lens galaxy, we found that the isothermal ellipsoid works well to describe the mass distribution in the deflector. Ongoing work on the spectroscopy of SN Zwicky finds further consistency with low-redshift Type Ia supernovae, making it robust to use Type Ia supernovae for inferences about dark energy. We also demonstrated that with future surveys, e.g., the Rubin Observatory's legacy survey of space and time (LSST), we can expect to find around 20 lensed supernovae, with the potential for precisely measuring the Hubble Constant with only a few years of LSST operations.

With the LensWatch Collaboration, we also serendipitously discovered a Type Ia supernova, SN H0pe, lensed by a foreground cluster of galaxies. While galaxy clusters are more difficult to model than single field galaxies, cluster-lensed supernovae have longer time-delays making it easier to make an accurate time-delay estimate with only a few observations. The analysis led to the first precise estimate of the Hubble constant (H0) from a lensed Type Ia supernova, 75.4 + 8.1 - 5.5 km s^{-1} Mpc^{-1}, demonstrating that the time-delay cosmography method works effectively. In the coming year, we will be analysing the photometric and spectroscopic data of a new lensed Type Ia supernova discovered in November 2023, to begin to build a sample and improve the precision on the Hubble constant.

This article is based on results published as Dhawan S. et al., A&A submitted (2024); Goobar A. et al., NatAs 7, 1098 (2023); and Pierel J. D. R. et al., ApJ accepted (arxiv:2403.18954).



Gerrit Farren, Frank Qu & Blake Sherwin

Tracing Cosmic Structure With CMB Lensing And Cross-Correlations With Galaxy Surveys

The cosmic microwave background (CMB) appears to us as a nearly uniform glow with small temperature fluctuations across the sky. These fluctuations can be used to learn about the early Universe when the CMB was released, but also encode information about the whole cosmic history as the CMB photons are affected by the intervening matter on their 13.8-billion-year journey to our telescopes. It is interesting to measure the growth of cosmic structure as it not only provides a powerful way to probe for new physics, but also because recently there have been claims that the growth of structure is not as expected for our standard cosmological model.

Dark matter accounts for almost all of the Universe's mass (about 85%) and dominates the way it evolves and structure grows within it. However, detecting dark matter has proven difficult because it does not emit or absorb light and can only be indirectly observed through its gravitational effects. As the CMB photons travel across the universe towards our telescopes, they are slightly deflected or "*lensed*" by the gravity of the large-scale mass distribution they pass through, similar to the way a magnifying glass bends light. By measuring the new correlations that lensing produces in the CMB maps, one can work backwards to reconstruct the lenses that created these distortions and hence map the projected distribution of dark matter between us and the CMB.

This warping effect produced by the dark matter "*lenses*" is very small, inducing deflections of only fractions of a degree. However, leveraging high-resolution measurements of the CMB made by the Atacama Cosmology Telescope (ACT), we are able to use statistical techniques to extract this lensing signal and produce the dark matter map shown in Fig. 1, which covers over a quarter of the sky. To extract quantitative information from the lensing map, we compress its information into the lensing power spectrum. The lensing power spectrum, as measured by ACT, is shown in Fig 2. It shows how much lensing there is as a function of angular scale. The agreement between our measurements and the theory line in black shows that structure growth is exactly as predicted by our cosmological model tuned to fit the early-time information from the CMB.

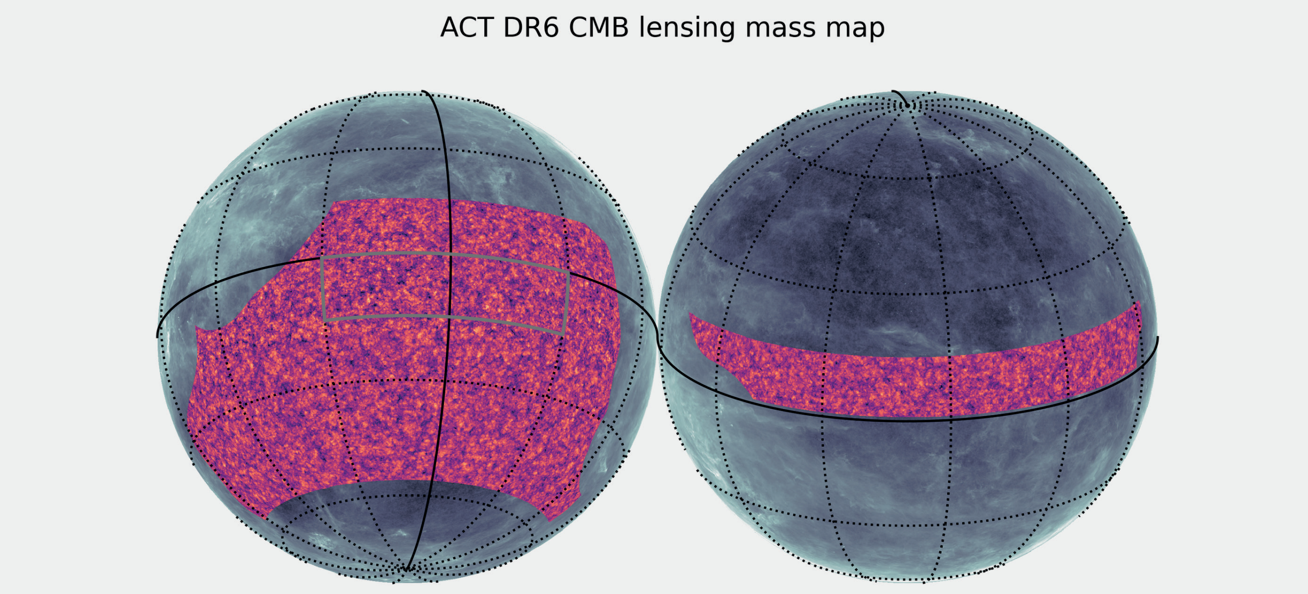


Figure 1. ACT CMB lensing map covering over a quarter of the sky. It provides one of the most detailed accounts of the matter in the Universe currently available.

It is sometimes desirable to be able to probe cosmic structure formation at different epochs. Galaxy surveys offer this possibility by dividing the observed galaxies into several redshift bins. However, the ability to learn about cosmology from the galaxies alone is hampered by the fact that the exact relationship between galaxies and the underlying dark matter structures is difficult to predict from first principles. By additionally measuring the correlation between the gravitational lensing signal and the galaxy distribution one can jointly infer the underlying matter structure and the matter–galaxy relationship. Such cross-correlations also allow us to examine only certain “slices” of the CMB lensing reconstruction and probe cosmic structure formation epoch-by-epoch.

In recent work, we combined the ACT lensing reconstruction shown in Fig. 1 with galaxy observation from the Wide-field Infrared Survey Explorer (WISE). WISE covers the full sky and provides high densities of galaxies out to large distances. The high-significance measurements of the correlation between CMB lensing and galaxies (shown in Fig. 3) allow percent-level constraints on cosmic structure. In contrast to the finding of some other late-time measurements, our results are consistent with model predictions from fits to the CMB.

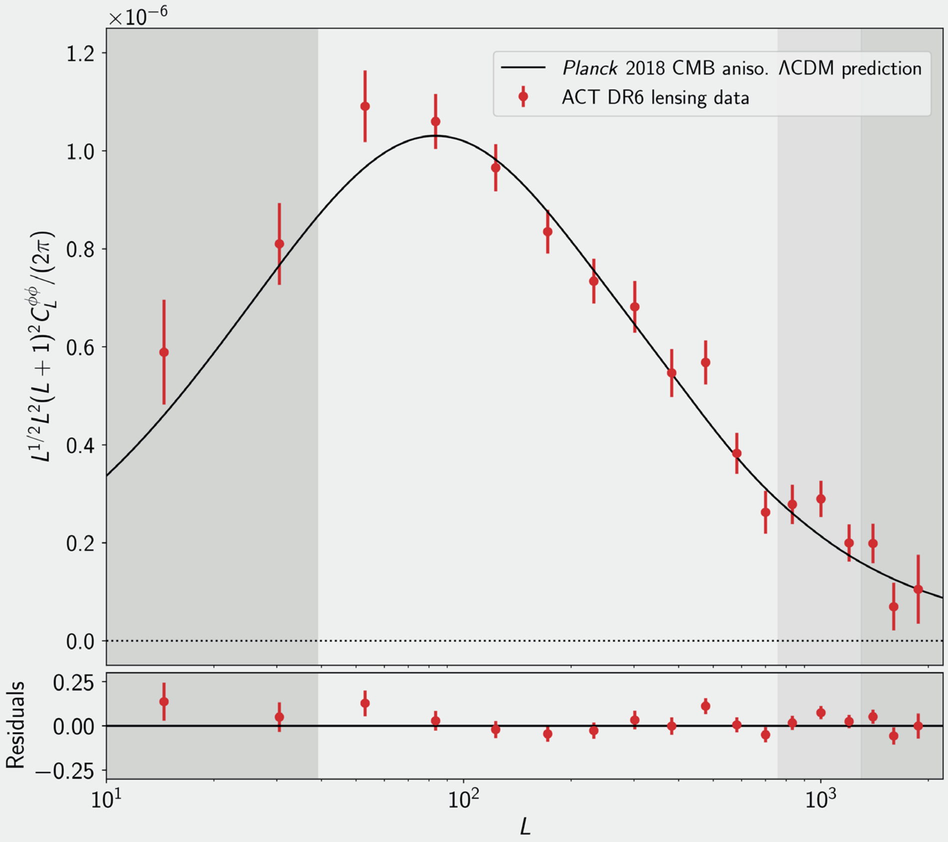


Figure 2. To learn about the cosmic structure we compress the lensing map into a power spectrum and compare it to theory predictions. We can see that our measurement (red) is in excellent agreement with the amount of structure expected within the standard cosmological model fit to the primary CMB fluctuations.

In work currently in preparation, we are further combining the measurements of the lensing auto- and cross-correlations to probe structure growth over an even larger range of redshifts and further improve our understanding of the fundamental physics of the Universe. We will provide insight into the accelerated expansion of the Universe, the spatial geometry, possible modification to Einstein's theory of gravity, as well as into the mass of the neutrinos.

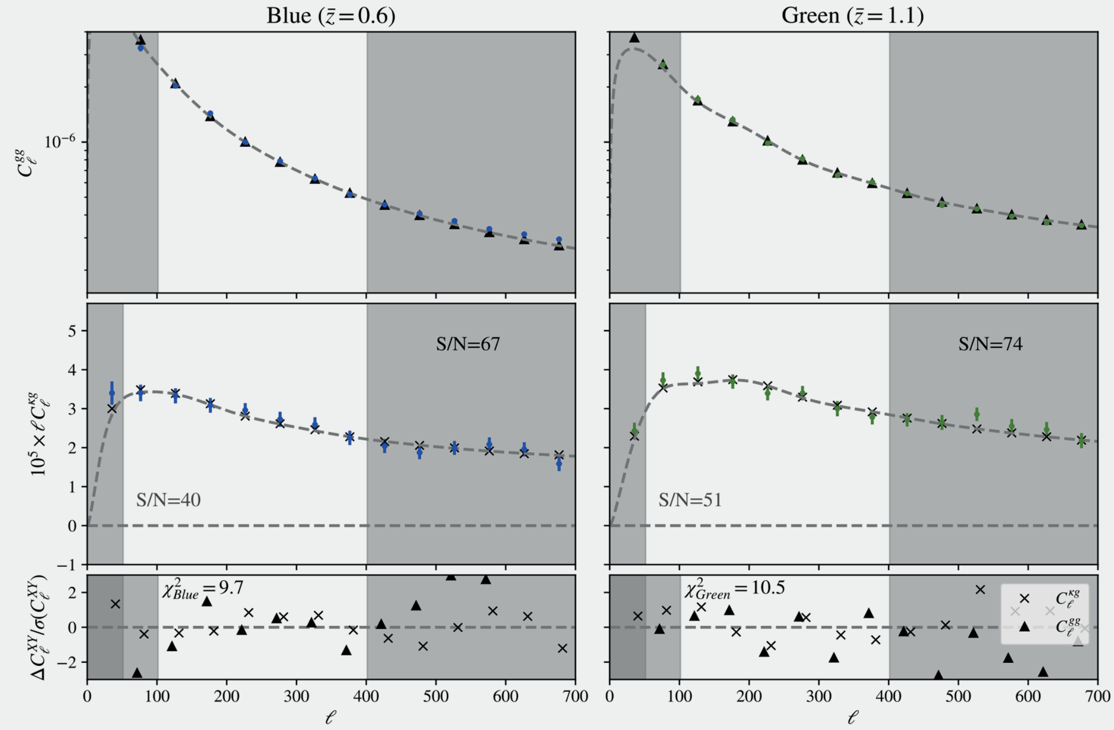


Figure 3. Correlations between the galaxy distribution and CMB lensing is detected at high significance (second row) enabling tight constraints on cosmological parameters when combining with galaxy auto-correlations (top row).

Looking further ahead, we will turn our attention towards the next generation of CMB and large-scale structure surveys including Simons Observatory, CMB-S4, the Dark Energy Spectroscopic Instrument (DESI), Euclid and the Vera Rubin Observatory's Legacy Survey of Space and Time. Data from these future observatories will probe our Universe to even higher precision and help us cast light on the fundamental physics that underpins the formation and evolution of cosmic structures.

This article is partly based on results published as Qu F. J. et al., ApJ 962, 112 (2024); Madhavacheril M. et al., ApJ 962, 113 (2024); MacCrann N. et al., ApJ accepted (arXiv:2304.05196); and Farren G. et al., ApJ accepted (arXiv:2309.05659).

Matthew Grayling & Kaisey Mandel

Unveiling Intrinsic Differences Across The Type Ia Supernova Population

Type Ia supernovae (SNe Ia) are excellent distance indicators and have played a key role in the history of cosmology, first demonstrating the accelerating expansion of the Universe. To this day, they play a central role in constraining the properties of dark energy, the mysterious agent thought to be driving the acceleration.

Despite this, there remains much that we do not understand about the physical nature of these explosive events. Although we can apply empirical relations to "*standardise*" SNe Ia and measure distances, there are some effects that we know are not captured in this standardisation procedure. For example, post-standardisation we have consistently observed that SNe Ia located in high-mass galaxies are brighter than those in low-mass galaxies; this effect is referred to as the "*mass-step*".

One persistent challenge when analysing supernovae, and astrophysical sources in general, is disentangling the intrinsic light emitted by an object from the effect of dust along the line-of-sight, which absorbs this light causing it to appear dimmer and redder. Some have suggested that this explains the mass step; differences in dust properties as a function of stellar mass may cause apparent differences in the SN Ia population. Others suggest there are intrinsic, environment-dependent variations across the population of SNe Ia, something that would have large astrophysical implications. In either case, it is vital that such effects are handled correctly within cosmological analyses; treatment of dust was a major source of uncertainty in the recent cosmological analysis of SNe Ia from the Dark Energy Survey's five-year dataset.

Typically, models that capture the full emission of SNe Ia at different wavelengths – their spectral energy distribution (SED) – have not attempted to distinguish between the intrinsic emission of these objects and the effect of dust. However, we have developed a model, called BayeSN, which leverages the full time and wavelength-dependent variation of SNe Ia to constrain these two effects separately. BayeSN is able to constrain separately the variation in dust properties and intrinsic properties across the population of SNe Ia, through the use of an approach known as hierarchical Bayesian modelling.

Motivated by the ongoing debate about the exact cause of the mass-step, we applied BayeSN to a sample of 475 SNe Ia. We performed the first analysis of a sample of SNe Ia that separately constrained both the intrinsic SED and the effect of dust on either side of the mass step. Our results support the existence of intrinsic differences between these two populations; we find that SNe Ia in high-mass galaxies are brighter and bluer around peak brightness than their low-mass counterparts (Fig. 1). These intrinsic differences become more significant at later times in longer-wavelength filters.

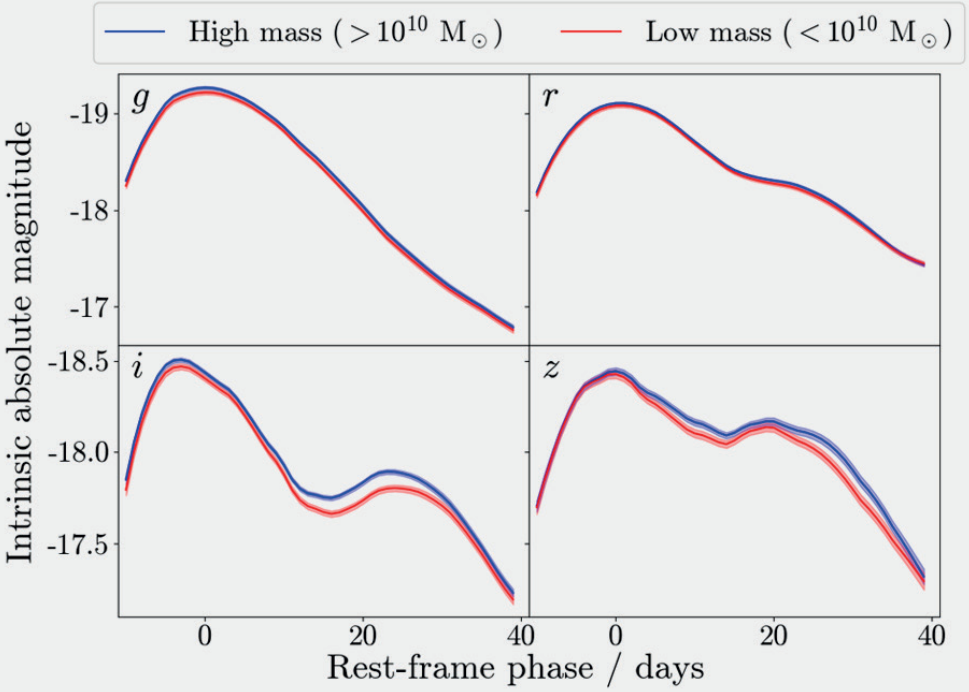


Figure 1. Mean intrinsic light curves of type Ia supernovae in high- and low-mass galaxies, independent of variations with decline rate and dust. Results are shown in four wavelength filters. Our analysis demonstrates that there are intrinsic physical differences between type Ia supernovae in different environments.

Our findings demonstrate the need to consider what might cause this environmental effect on the intrinsic properties of SNe Ia. For example, much remains unknown about the nature of their progenitor systems. These explosions may occur in systems composed of a white dwarf star and massive companion star, or alternatively are the result of the interaction between two white dwarf stars in a binary system; in reality, both of these scenarios may occur. This former scenario can occur for younger progenitors, whereas the latter picture requires more time to have passed to form two white dwarfs and is therefore associated with older environments. It may be the case that older, high-mass galaxies contain SNe Ia from different progenitor systems with differing intrinsic properties when compared with young, low-mass galaxies.

We must also consider how we might incorporate this effect within our models to obtain more precise distance measurements and cosmological constraints. In future, we plan to incorporate the continuous variation of the intrinsic SED of SNe Ia with environmental properties such as host galaxy stellar mass within the BayeSN model. This will ensure that all astrophysical variations across the population are taken into account when constraining distance and, ultimately, cosmology.

This article is partly based on results published as Grayling M. et al., MNRAS 531, 953 (2024).

Vid Irsic

DESI Early Data Release

The Dark Energy Spectroscopic Instrument (DESI) released its first batch of data in 2023, marking a significant milestone in cosmological research. This dataset, obtained during the experiment's survey-validation phase, comprises almost 2 million galaxies and quasars, including a quasar dating back approximately 12 billion years. Led by a collaboration of over 1000 scientists worldwide, DESI aims to map over 40 million galaxies to deepen our understanding of dark energy and the Universe's evolution.

DESI's primary objective is to produce a detailed cosmic map, surpassing previous ground-based surveys in both depth and detail. By pinpointing the locations of millions of galaxies and quasars, DESI seeks to track the evolution of dark energy over the Universe's history. This ambitious endeavour relies on robotic technology to position light-collecting fibres precisely, enabling spectroscopic observations of targeted regions in the sky. These spectral measurements provide crucial information about the classification of observed objects and their distances from Earth.

The successful operation of DESI's robotic technology has exceeded expectations, ensuring the preservation of every photon captured by the telescope. The released dataset, comprising over 80 terabytes of information, underwent rigorous validation tests to confirm the accuracy and reliability of the measurements. Notably, the One-Percent Survey, conducted at a higher resolution, provided detailed insights into galaxy formation over 12 billion years (see Fig. 1).

DESI's capacity to observe over 100,000 galaxies in a single night represents a remarkable technical achievement, and will enable unprecedented insights into dark energy and cosmic evolution. By measuring redshifts, DESI can track the expansion of the Universe and unravel mysteries surrounding the properties of dark energy.

While the released data present a treasure trove for researchers, the collaboration emphasises that cosmological results derived from DESI's main survey data are still forthcoming. With the project in its third year of a planned five-year run, ongoing data processing is essential before drawing cosmological conclusions. Despite this, the significance of the first data release cannot be overstated, heralding a new era in cosmological research.

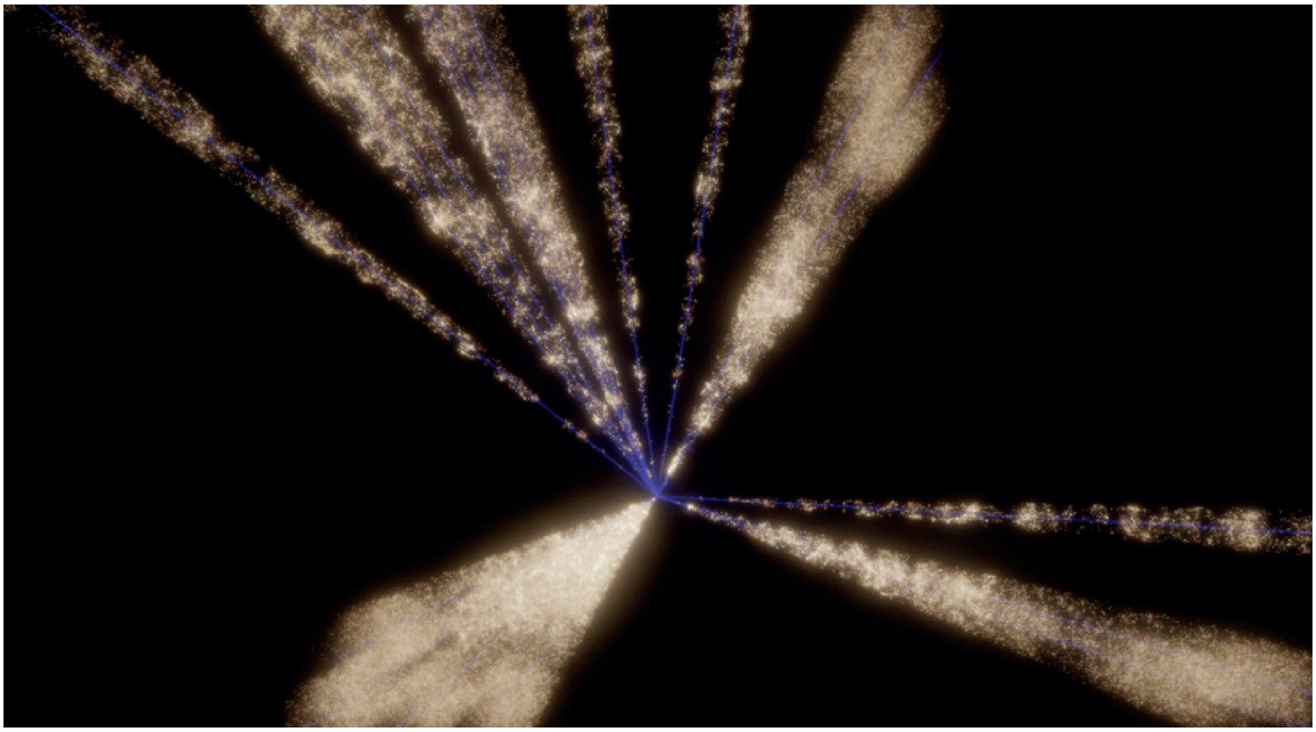


Fig. 1: As part of the Early Data Release, DESI observed 1% of the full survey's targeted region along multiple beams through the Universe. (Image credit: D. Kirkby/DESI Collaboration.)

Cambridge participates in the DESI collaboration through the UK Regional Participation Group, and has been leading the efforts to map out the expansion history of the Universe in its earliest epochs from the time of the first galaxies to the peak of star-formation history around 2 billion years after the Big Bang.

The observations of high-redshift quasars show a series of absorption lines due to intervening neutral hydrogen in the Universe. This spectral feature is called the Lyman-alpha forest, and provides a high-redshift anchor on the expansion history, complementing low redshift galaxies.

Within the Early Data Release, the DESI Collaboration published measurements of Lyman-alpha clustering covering a vast range of environments, underlining the capability of DESI to provide answers to questions beyond the expansion history of the Universe.

As DESI continues its survey, adding millions of redshift measurements each month, the project's impact on cosmology and astrophysics is poised to grow. The wealth of data produced by DESI promises to unlock new insights into the Universe's structure, evolution, and the enigmatic dark sector.

This article is partly based on results published as DESI Collaboration, arXiv/2306.06308 (2023); Ravoux C. et al., MNRAS 526, 5118 (2023); Karacayli N. G. et al., MNRAS 528, 3941 (2023); and Gordon C. et al., JCAP 2023, 045 (2023).

Vid Irsic & Martin Haehnelt

The Nature Of Dark Matter With The Lyman-Alpha Forest

The Universe's composition is the subject of intense study, revealing that about 80% of its matter exists in the form of dark matter. Understanding the properties and the emergence of dark matter within the standard model of particle physics are pivotal questions in cosmology and astroparticle physics.

A crucial property of dark matter is its "*coldness*". It is an open question whether dark matter is made of heavy, slowly moving particles or light, fast-moving particles. Attempts to answer this question at Cambridge rely on studying the abundance of small satellite galaxies in the Milky Way and the spatial distribution of intergalactic gas.

Utilising observations of distant quasar spectra from the VLT/UVES and Keck/HIRES spectroscopic instruments, our recent study has mapped the intergalactic gas in the Universe when it was only a billion years old. The "*coldness*" of dark matter influences the formation and evolution of filamentary structures in the early Universe. We sought to understand how the imprint on quasar spectra of these structures in intergalactic gas, in the form of a series of absorption features called the Lyman-alpha forest, allows us to measure the "coldness" of dark matter. We found that heavy, slowly moving dark matter particles result in more numerous small filaments and sharper absorption lines; light, fast-moving particles lead to the formation of larger filaments and smoother features in the Lyman-alpha forest.

To compare observations with theoretical predictions, many numerical simulations of the Universe's evolution were conducted, varying dark matter models and physical properties of the intergalactic gas. The filamentary structure of the cosmic web in one of our simulations is shown in Fig. 1. The figure represents slices of simulated universes, 96 million light-years across, showing the intergalactic gas distribution for different dark matter models. The lower the dark matter particle mass the smoother the gas density. The results are shown at a time when the simulated universes had an age of 1.4 billion years, roughly 10 percent of the Universe's current age. For the first time, predictions accounting for the non-uniform illumination of the intergalactic gas during the epoch of reionization were included in our study. Our results support the suggestion of the intergalactic gas being embedded in a sea of very "cold" dark matter particles, while being ionised and heated by early galaxies.

Our findings offer compelling evidence against dark matter being composed of light particles. Particle masses in the range of 3 keV or lower are excluded at a significance level of 5 sigma. Additionally, our results support previous studies characterising the evolution of the temperature of intergalactic gas, suggesting the presence of a reservoir of cold gas fueling future star formation.

Our study utilised, for the first time, the full resolution of the spectrographs with which the quasar spectra were obtained, enabling more precise measurements. Our much-improved simulations account for spatial variations in ionising radiation from galaxies and have enhanced our confidence in ruling out light, fast-moving particles as the primary constituent of dark matter.

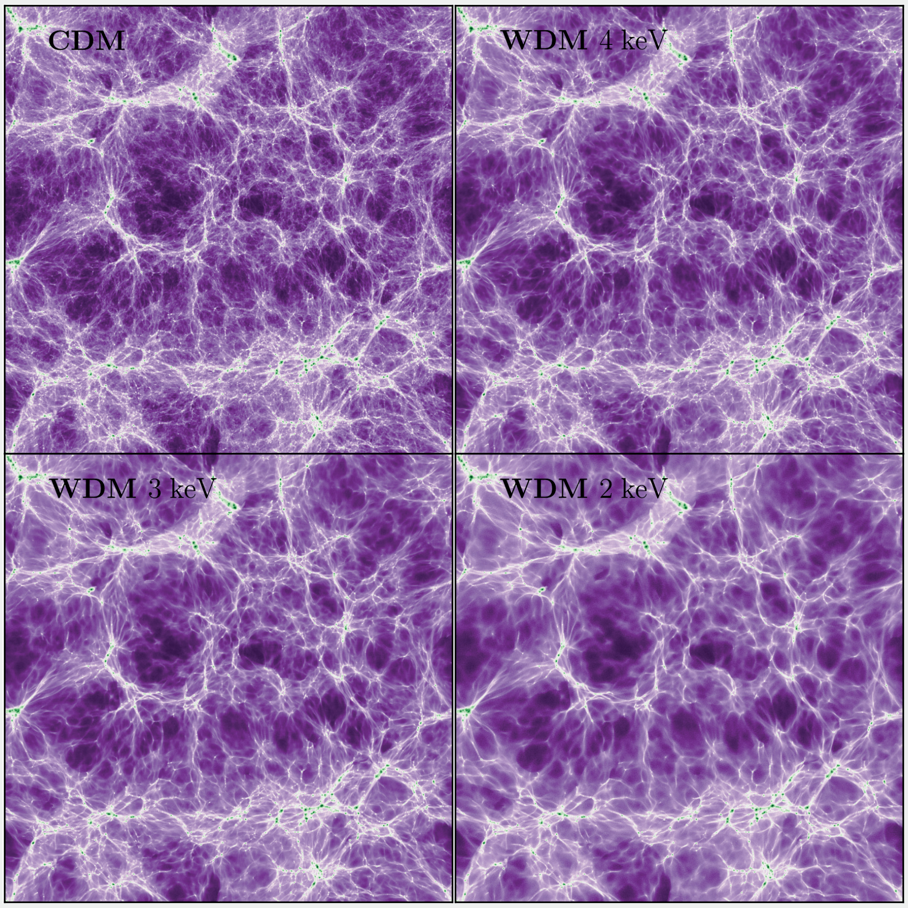


Figure 1. The gas density distribution in the simulations of the Universe, comparing a "cold" dark matter model (top left), and several "warm" dark matter models varying the particle mass from 4 to 2 keV.

Our results have significant implications for galaxy formation, ruling out light dark matter particles as the primary explanation for the "*missing satellite galaxies*" problem. They also strongly disfavour suggestions that characteristic line emission from the Perseus cluster at X-ray wavelengths is due to annihilation of warm dark matter particles into photons.

Surprisingly, our study highlighted the importance of the hydrodynamic response of the intergalactic gas to the heating during reionization, a previously overlooked physical effect. The ability to quantify the velocity of filaments expanding due to the hydrodynamic response represents a notable advancement.

The excitement of our research lies in its contribution to unravelling one of the Universe's greatest mysteries, the nature of dark matter. In future we will focus on acquiring more high-quality spectra from distant quasars and refining our modelling techniques, aiming to illuminate further the nature of dark matter and its impact on the evolution of structure in the Universe.

This article is partly based on results published as Irsic V. et al., Phys. Rev. D 109, 043511 (2024).

Calvin Preston, Alexandra Amon & George Efstathiou

A Non-Linear Solution To The S_8 Tension

The subtle distortions of the shapes of distant galaxies due to gravitational lensing by the large-scale structure of the Universe is known as weak gravitational lensing. Measurements of this effect are used by cosmologists to help learn about the age and matter distribution of the Universe.

Weak gravitational lensing is not the only tool that cosmologists can use to learn about the Universe. The cosmic microwave background (CMB) provides a window to the universe when it was only 380,000 years old. Temperature fluctuations in this relic of the Big Bang appear correlated. Understanding the correlations in temperature fluctuations and the polarisation of the CMB has led to some of the most precise cosmological constraints to date.

Measurements of weak lensing with galaxy surveys have consistently pointed towards a lower amplitude for the matter fluctuation spectrum, as measured by the S_8 parameter, than expected in the cosmology favoured by the CMB experiment Planck. This discrepancy ranges in statistical significance from 2–3 sigma depending on dataset and is consistent between experiments performed over the last decade. This persistent trend of lensing measurements lying low compared to CMB results has become known as the "*S_8 tension*".

In our work, we proposed a solution to this tension. Whilst other solutions in the literature have proposed a change to physics over cosmic time, we instead proposed a scale-dependent solution that requires no new physics, but rather a detailed investigation of small cosmological scales.

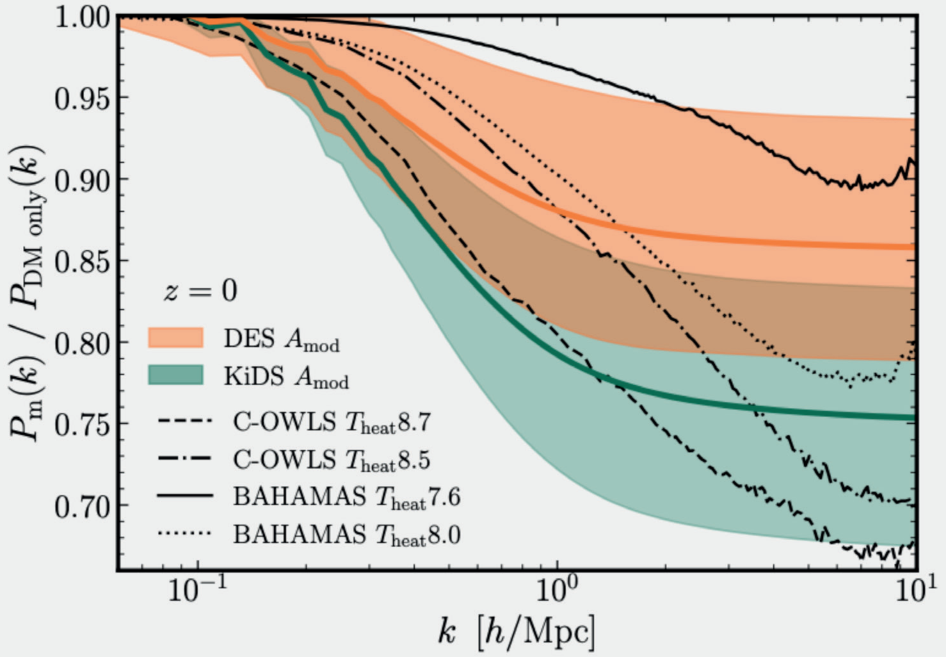


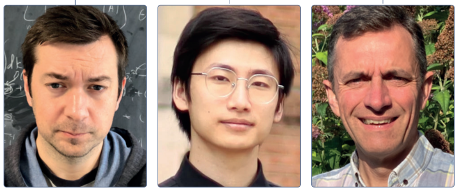
Figure 1. Suppression of the matter power spectrum required to solve the S_8 tension assuming the Planck cosmology for two weak lensing surveys: the Kilo Degree Survey in green; the Dark Energy Survey in orange. The black lines show the power suppression predictions from a range of cosmological hydrodynamical simulations.

We proposed that the cosmology inferred from Planck CMB is correct on linear scales. In order to reconcile weak lensing measurements with this cosmology, the small-scale matter power spectrum must be suppressed compared to the dark matter-only prediction. The required suppression for weak lensing datasets is shown in Fig. 1.

A suppression of the matter power spectrum is predicted by large-scale cosmological hydrodynamical simulations, with active galactic nuclei ejecting gas to cosmological scales. However, the spatial extent and amplitude of such suppression is not accurately understood. Our reported suppression is extreme compared to most simulations, but not unphysical. Alternative dark matter models, such as ultralight axions, may also act as a source of such a suppression.

In the future, new surveys will help to understand further the source of the S_8 tension and evaluate our hypothesis, whilst we continue our present work assessing the best way to use new galaxy weak-lensing data.

This article is partly based on results published as Preston C., Amon A. & Efstathiou G., MNRAS 525, 5554 (2023) and Amon A. & Efstathiou G., MNRAS 516, 5355 (2022).



Zvonimir Vlah, Zucheng Gao & Anthony Challinor

Understanding Cosmological Correlators In The Sky

The standard model of cosmology encapsulates our most comprehensive understanding of the Universe and the underlying physical processes governing its development. This model is predominantly supported by precise measurements of the cosmic microwave background (CMB) and the distributions of galaxies, via the baryon-acoustic-oscillation (BAO) scale. As our observations improve further and we gather more data from galaxy surveys such as DESI and EUCLID, we can scrutinise our cosmological model's accuracy with greater finesse. This presents an exciting opportunity to delve into the earliest stages of our Universe, explore the properties of dark energy and dark matter, understand the gravitational dynamics on the largest cosmological scales, and investigate various other physical phenomena in the cosmos.

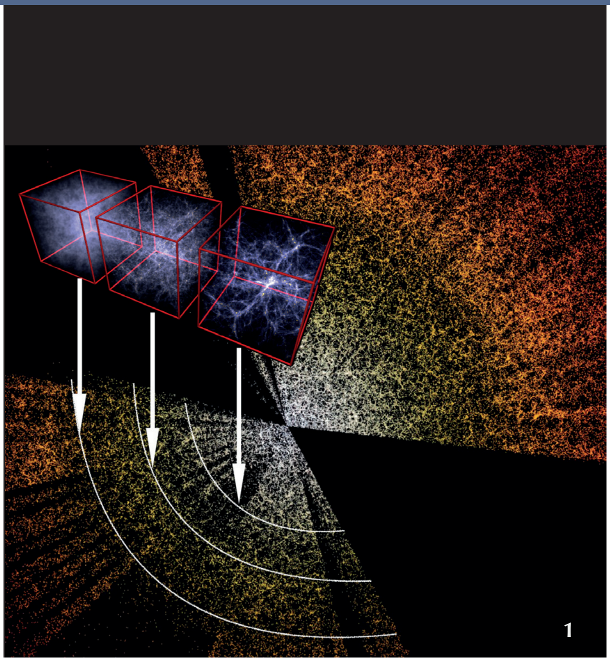
However, to extract information of interest from our data, it is essential to make a robust connection between the observed data and our theoretical models and predictions, which predominantly rely on understanding the correlations between the number and distributions of galaxies in the sky. The most straightforward and valuable correlations are those between the two points, indicating the excess probability of finding galaxies beyond the random scatter. The standard ways of determining and estimating these correlations from the data and connecting them to the theory need to be revised and, importantly, could cause misinterpretations of our measurements.

On the other hand, given the complexity and abundance of the data and the challenges in the analysis driven by the need to explore vast parameter spaces in search of an optimal fit describing our universe, we need to be very mindful of efficiency and computational feasibility.

To address these modern-day challenges, at KICC, we have developed novel approaches to describe and connect the theory and observations, establishing a robust link between the theoretical predictions and galaxy observations. As shown in Fig. 1, as we look deeper into the sky, we see the Universe at earlier epochs, indicated by white lines. The issue arises when we compare our dynamical models at different epochs (indicated by the red boxes) with the data projected to a single sheet in the sky.

In our recent studies, we have successfully implemented these projection effects (also called unequal-time effects) in the observable correlators for the first time. It was essential to obtain these corrections as the missing signal might be misinterpreted as a specific deviation from Einstein's theory of general relativity on large cosmological scales, or alternatively, we might have mistakenly favoured some specific (*"non-Gaussian"*) models describing the initial conditions in the early Universe.

Moreover, computing these theoretical predictions and projections in full detail remains chall-



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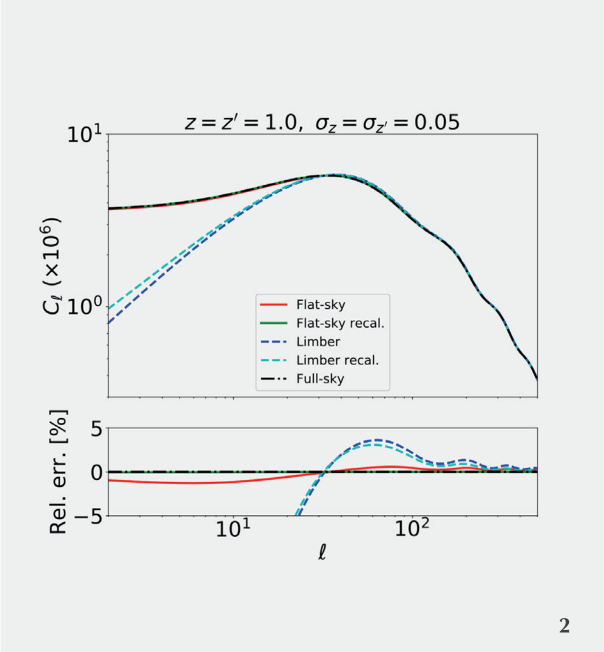

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enging and computationally demanding. To resolve these issues, we have developed a new approximate but extremely accurate (asymptotic) approach for robust and efficient computation of these observables. Figure 2 compares this full and computationally prohibitive approach (black line) with our efficient and fast result in the green (and red) line, showing excellent agreement and indicating high accuracy on all scales of the sky.

With these valuable results, we can now embark on a journey of analysing the forthcoming and future data from cosmological surveys. This endeavour promises to scrutinise the physical principles that govern the early stages of our Universe and the nature of gravity on large cosmological scales.

This article is based on results published as Z. Gao et al., JCAP 02, 003 (2024) , Z. Gao et al., Phys. Rev. D 108, 4 (2023) & A. Raccanelli et al., Phys. Rev. D 108, 4 (2023).

Figure 1. Galaxy distribution map from the DESI survey, indicating the distributions of the galaxies from the origin (observer position). Overlaid are results from N-body simulations of the universe (red boxes) at different epochs of its evolution. Credits: for three cosmological simulations, V. Springel (MPA), while for the DESI galaxy survey image, D. Schlegel (LBNL) and M. Zamani (NSF's NOIRLab).

Figure 2. Cosmological two-point correlation function (angular power spectrum) as a function of scales (the multipole ℓ can be interpreted as the inverse angular scale). The black line indicates the complete, expensive approach, while our new fast results are shown as green and red lines. Previous approximation attempts are shown in blue and cyan dashed lines. The bottom panel shows the relative error.

Íñigo Zubeldia

Constraining Cosmological Models With Galaxy Clusters

Galaxy clusters, the largest gravitationally bound objects in the Universe, offer a wealth of insights into our Universe. Amongst other things, their abundance as a function of mass and redshift depends on general properties of the Universe such as the mean density of matter, the degree to which matter clumps on large scales, the behaviour of dark energy across cosmic time, and the sum of the neutrino masses. By comparing observed cluster counts from cosmological surveys with theoretical predictions, we can effectively constrain these cosmic properties.

As a postdoctoral researcher at the KICC, I am working on several aspects of cluster cosmology. I have developed SZiFi, a new millimetre-wavelength cluster finder that exploits the imprint that clusters leave on the cosmic microwave background (CMB), known as the thermal Sunyaev–Zel'dovich (SZ) effect in order to detect them (see Fig. 1). I have applied SZiFi to existing millimetre data from the Planck satellite, obtaining an improved cluster catalogue that addresses issues such as contamination from dust emission from the cluster-member galaxies. Together with collaborators in Cambridge, Manchester, Paris and Munich, I am currently using this catalogue for cosmological inference, in combination with crucial information about the cluster masses from optical lensing observations from the Dark Energy Survey (DES) and CMB lensing measurements from Planck.

In addition, in collaboration with Boris Bolliet (DAMTP/KICC), I have developed a very general and flexible framework for extracting cosmological constraints from cluster catalogues (more technically, to compute the catalogue likelihood). This framework, called cosmocnc, is being used in the cosmological analysis of my new Planck cluster catalogue, where its ability to combine consistently several cluster observables (e.g., SZ signal and lensing masses) is being exploited. cosmocnc has also been extensively tested in the context of the upcoming Simons Observatory (SO), which is expected to detect an order of magnitude more clusters than current surveys (about 16,000–20,000 of them), thus providing unprecedented cosmological constraining potential. Using simulated SO-like observations, I have shown that cosmocnc will be accurate enough to deliver unbiased cosmological constraints from the SO clusters. With this validation, I hope that cosmocnc will become a key tool for analysing the forthcoming SO cluster data.

Other research interests to which I intend to devote more time in the coming year include the role of clustering of galaxy clusters in the modelling of cluster catalogues (currently ignored in cosmocnc and our simulated observations), the cosmological information content in cluster catalogues relative to other low-redshift probes such as optical weak lensing, and the contribution to the SZ signal of clusters by non-thermal pressure in the intra-cluster medium.

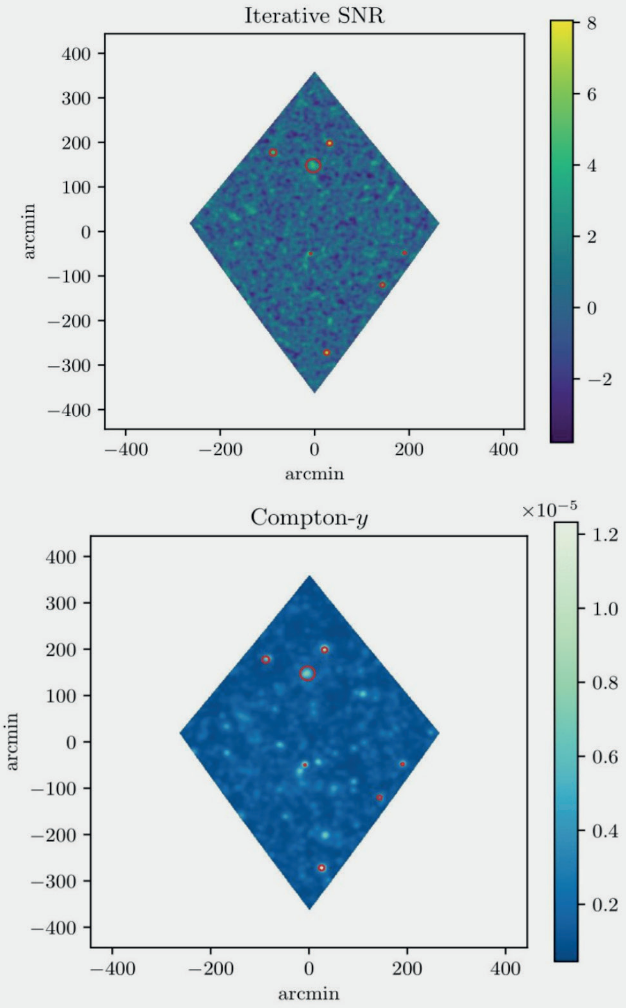

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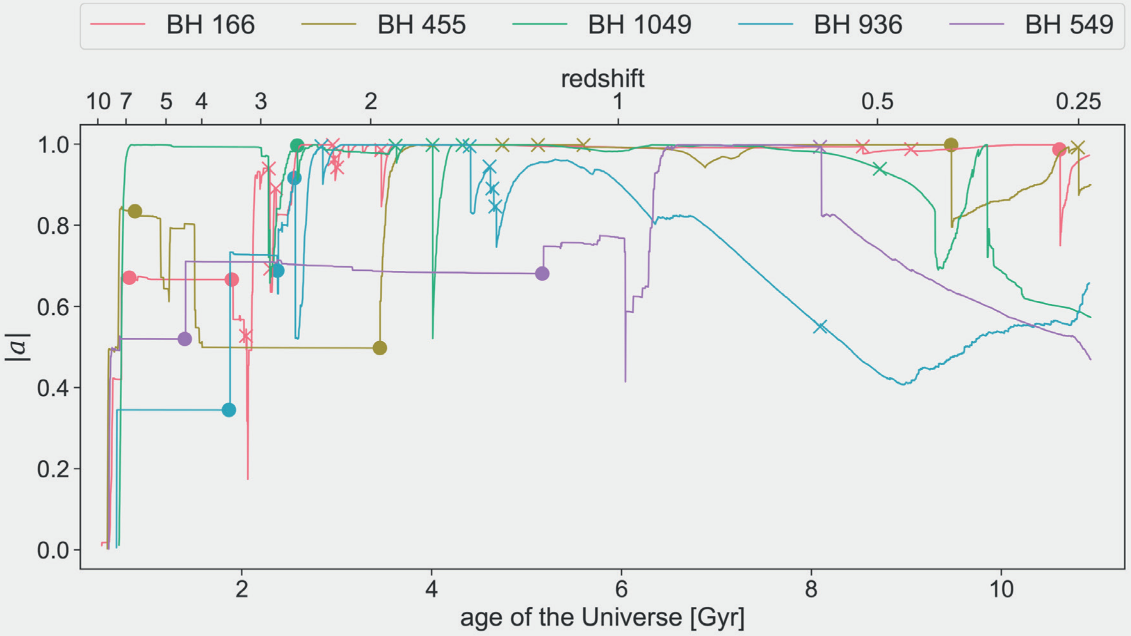
Figure 1. Upper panel – cluster detection signal-to-noise map produced by SZiFi for simulated Planck-like observations for a small patch of the sky. Significant detections are shown as the red circles. Lower panel – input simulated signal. As is apparent, the detections do correspond to real clusters in the simulation.

This article is partly based on results presented as Zubeldia I. & Bolliet B., arXiv:2403.09589, Zubeldia I. et al., MNRAS 522, 5123 (2023) & Zubeldia I. et al., MNRAS 522, 4766 (2023).

Ricarda Beckmann

The Spin Evolution Of Massive Black Holes From The NewHorizon Simulation

1



Any massive astrophysical black hole can be described by only two fundamental properties: its mass and its spin. Mass is the simpler of the two, accumulating through gas accretion and mergers with compact objects such as other black holes or neutron stars over time. Spin is more complex. As well as being a vector, with both direction and magnitude evolving over time, black hole spin can both increase and decrease throughout a black hole's life-time through gas accretion, mergers with other compact objects, and feedback.

Whether a given process spins a black hole up or down depends on the current spin of the black hole and its environment. For example, for gas accretion, black holes are spun up if the angular momentum of the accreted gas aligns with the black hole spin, but spun down if they counter-align. As a consequence, black holes will preferentially spin up if they find themselves in an environment where gas flows are coherent over long timescales. If instead a black hole finds itself in a galaxy where gas inflows onto the black hole change randomly on short timescales, black hole spin will decrease or remain low, as spinning down black holes is more efficient than spinning them up. Similarly, mergers preferentially spin up low-spinning black holes, but decrease the spin of highly spinning ones. The impact of mergers on a given black hole's spin depends therefore on how the other black holes in its vicinity have evolved. Finally, some of the observed powerful jets driven by black holes are powered by rotational energy extracted from the black hole, spinning it down if it is growing efficiently in mass.

While the first supermassive black hole mass measurements have been available for decades, observational measurements of black hole spin have only recently become available. This is because measuring spin requires powerful telescopes that are able to study emission coming from a region very close to the black hole, which has only recently become possible. So far, the insights are intriguing: all observed black holes have at least intermediate to high spin, with (so far) no evidence for slowly spinning or non-spinning black holes. To understand why supermassive black holes tend to be spinning rapidly today, and what the distribution of spins might look like for a much wider population of black holes than we can currently observe, we need to turn to simulations.

Figure 1. Simulated spin evolution over time for the five most massive black holes in NewHorizon. Each black hole is shown in a different colour. Mergers with other black holes are marked by round markers and lead to jumps in the black hole's spin. Gas accretion and the impact of feedback changes black hole spin more continuously.

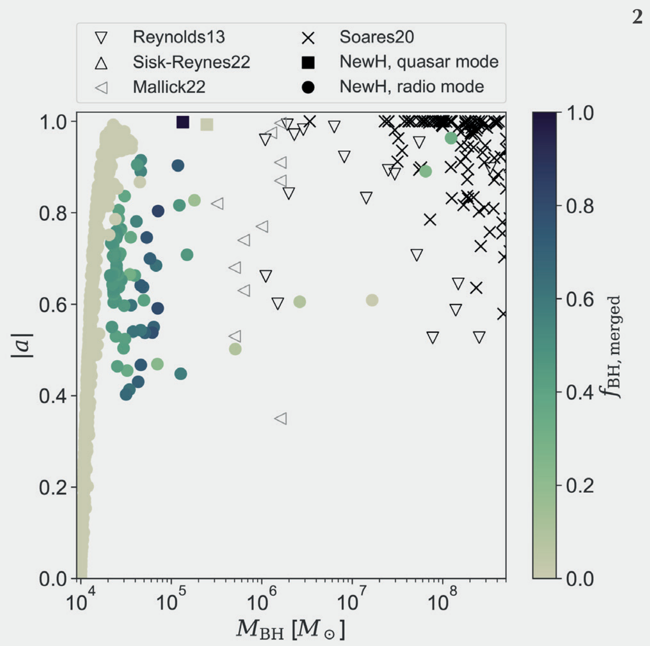
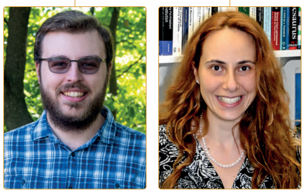


Figure 2. Distribution of black hole spins for all massive black holes in NewHorizon today (filled, colourful markers) in comparison to observations (open markers). Our simulated massive black holes are in good agreement with observed black holes.

I recently studied the evolution of black hole spin for a simulated population of massive black holes using the NewHorizon simulation. NewHorizon is a cosmological galaxy evolution simulation that evolves the gas flows in and around thousands of galaxies from cosmic dawn to today, and tracks the mass and spin evolution of a large sample of massive black holes. Using this unique dataset, I found that black hole spin evolves in three phases (Fig. 1). First, newly born black holes are rapidly spun up through coherent gas accretion in their gas-rich formation locations. As this early accretion spike tails off, the evolution of black hole spin is dominated by mergers with other, usually also highly spinning, infant black holes of similar masses. Such mergers on average decrease the black hole spin of the remnant black hole, creating a much wider distribution of possible black spin values in the total population of black holes. Over time, as the host galaxy of the black hole becomes more massive, gas flows settle down and black holes can grow to high spins again through maximum accretion. However, during this late period, for some black holes the extraction of rotational energy through powerful jets can become very efficient. This slowly decreases the black hole's spin over long timescales. Our simulation reports a range of possible spin values for massive black holes in the local Universe, from intermediate spins (those spun down by jets) to highly spinning black holes (those growing more efficiently). This is in good agreement with observations (Fig. 2), and gives key insights into why supermassive black holes have the spin values we observe them to have today.

This article is partly based on results submitted to MNRAS as Beckmann R. et al.



Jake Bennett & Debora Sijacki

The Rise Of Gargantuan Black Holes At Cosmic Dawn

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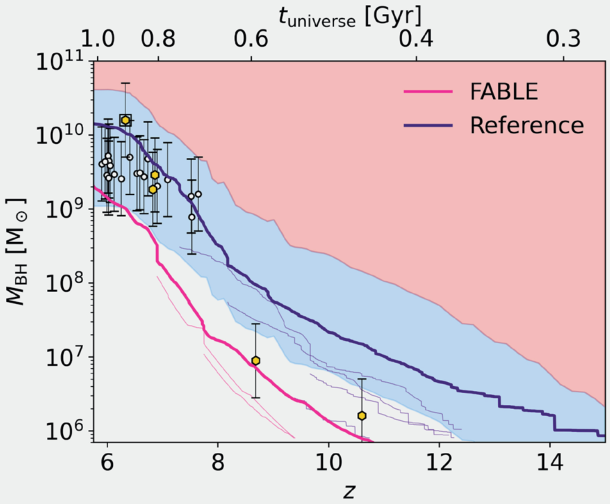

High-redshift surveys have so far discovered over a hundred quasars above redshift six. This number will likely increase significantly in the coming years, due to ongoing and planned deep, wide-field surveys, such as eROSITA in X-rays, the Vera Rubin Observatory at optical wavelengths, as well as recently launched Euclid in infrared. Already a revolution is underway in the field of high-redshift black holes thanks to JWST, with many luminous black hole candidates discovered at record redshifts (including $z > 10$!).

Focusing on the most extreme examples, supermassive black holes in excess of a billion solar masses have been detected above $z = 7$, challenging theoretical models of the growth of such objects. The current record holders in terms of luminosity, and so likely in black hole mass, are J0529-4351 and J0100+2802, with inferred masses exceeding 10^{10} solar masses at $z = 4$ and $z = 6.3$, respectively. While there have been a number of theoretical studies of these objects, they still struggle to form some of the most massive observed black holes.

Motivated by these considerations, we have investigated the most promising scenarios for building up the most massive known supermassive black holes in the early Universe. Allowing for mildly super-Eddington accretion and earlier seeding redshift, which is still entirely compatible with the widely used direct-collapse seeding model, we have found that it is possible to assemble a 10^{10} solar mass black hole by $z = 6$.

As shown in Fig. 1, the mass growth of our simulated black hole is consistent with observations, including the latest JWST data. The simulated luminosities and Eddington fractions we get in our new model are much more consistent with observed values than our Eddington-limited models, hinting that episodic super-Eddington accretion may be required in the early Universe to grow the most extreme-mass black holes within a billion years of cosmic time. Importantly we found that the feedback impact of this black hole is very significant.

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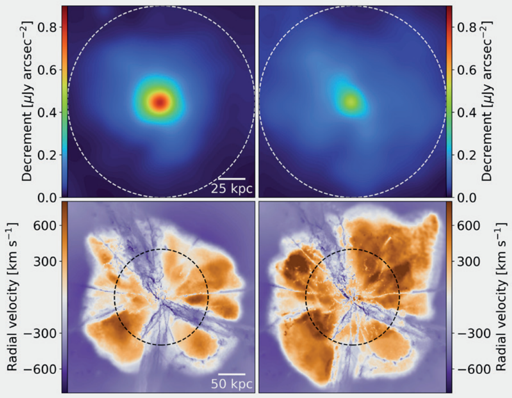

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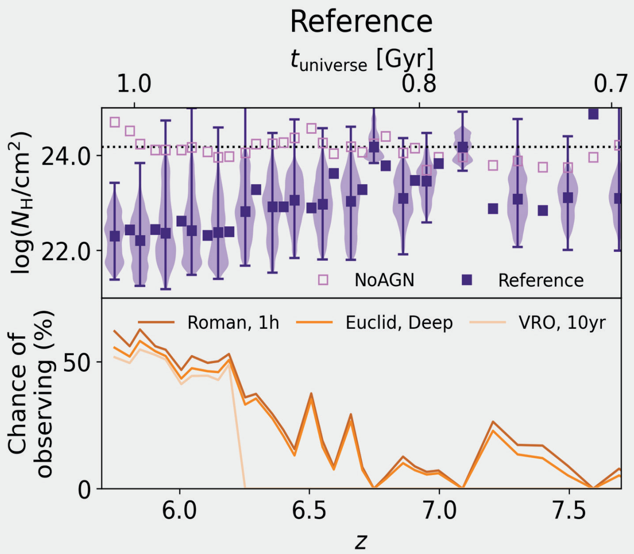


Figure 1. Black hole mass growth for our two simulation models (purple/pink lines), compared to the latest observational data (white circles/gold hexagons). Shaded regions show a comparison to the black hole mass-stellar mass relations found at low redshift.

Figure 2. Maps of the SZ decrement (top) and radial velocity (bottom) of our two simulation models. Gas is ejected from the halo centre due to the powerful black hole feedback at high velocities, which decreases the SZ signal for the model with early black hole growth (right).

Figure 3. Evolution of gas column density in sightlines from the galaxy centre (top) comparing runs with (solid markers) and without (open markers) black holes, and how this translates into the observing probability along a given sightline in the rest-frame UV.

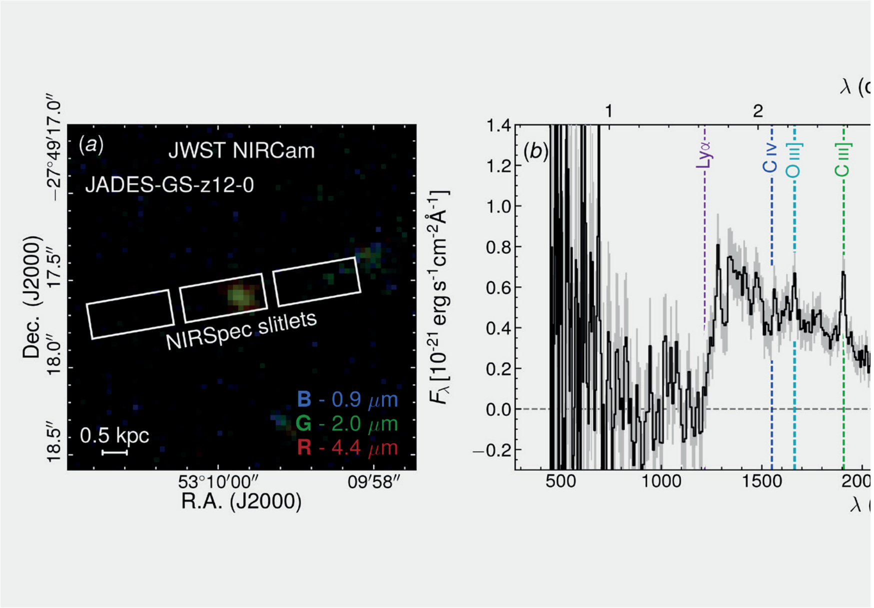
The impact of feedback is shown in Fig. 2. There, we plot the combined thermal and kinetic Sunyaev–Zel'dovich (SZ) decrement (due to Compton scattering of the cosmic microwave background off hot gas in bulk motion; top panel) and gas radial velocity (bottom) for the original model that harbours a factor of 10 less massive black hole (left) and our new simulation with a gargantuan black hole (right). Hot, fast outflows are pushing gas way beyond the virial radius, diminishing the SZ signal on small scales and enhancing it on large scales. Moreover, by studying the redshift evolution of the simulated hot halo we have made detailed predictions for mock maps, from sub-millimetre to X-rays, that should help us disentangle how mass is accumulated onto these gargantuan black holes over cosmic time, e.g., scenarios with early (sustained) growth and feedback versus late, rapid growth and feedback.

We also found that for much of the history of these objects, they are shrouded by a huge amount of incoming material, even with powerful feedback, as shown by the many high-column-density sightlines in the top panel of Fig. 3. This material could then block detection of the quasar along many sightlines in the rest-frame UV, shown in the bottom panel of Fig. 3. Given these results are for such a gargantuan black hole, and that even the powerful feedback of such an object cannot completely clear its surroundings, this further suggests that the high-redshift black holes currently detected by JWST may be just the tip of the iceberg.

This article is based on results published as Bennett J. et al., MNRAS 527, 1033 (2024).

Francesco D'Eugenio & Roberto Maiolino

JADES: Carbon Enrichment 350 Myr After The Big Bang



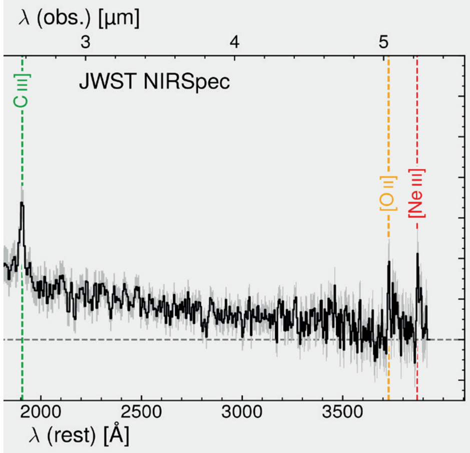
All chemical elements heavier than hydrogen and helium – "metals" – were not present in the primordial Universe (except for traces of lithium), they were produced by nuclear fusion inside stars and are dispersed in the interstellar medium as stars evolve and die.

Stars of different initial mass and chemical composition have different metal "yields", i.e., they eject chemically enriched gas with different relative abundances of the various elements. In addition to metal production, the chemical content of galaxies is also affected by metal removal due to (generally metal-rich) galactic winds, and metal dilution, due to accretion of (generally metal-poor) gas from the cosmic web. This complicated balance makes it difficult to read the chemical-evolution history of external galaxies. However, by looking at the earliest galaxies, we can bypass billions of years of complicated processes, to get a glimpse of how the elements that are essential to our very life came to be.

Using the deepest JWST programme yet, we discovered the most-distant evidence of metals to date. Galaxy GS-z12 is observed at redshift z = 12.48, only 350 Myr after the Big Bang, when the Universe was a mere three percent of its current age. This galaxy is very compact, at least twenty times smaller than the Milky Way (Fig. 1a). Its interstellar gas displays unequivocal evidence of line emission at 2.6 μm (Fig. 1b). From the location of the Lyman-α drop at 1.6 μm, we know that this is the carbon line C III].

Interpreting the spectral energy distribution of GS-z12 in the framework of normal galaxies, we can estimate a stellar mass of just 50 million solar masses, and yet a star-formation rate of 1.6 solar masses per year, almost twice as much as our own galaxy. We find a mismatch between the wavelengths of the Lyman-α drop and the carbon doublet, due to a high column density of neutral hydrogen atoms of 10^{22} cm^{-2} in the vicinity of this galaxy. This extra absorption, if common, may bias our distance estimations based off the Lyman-α drop.

Together with bright C III], lines from other chemical elements, like oxygen and neon, are comparatively weaker. Since GS-z12 is observed at such an early epoch, we can rule out some of the most common carbon-production mechanisms that are viable at later epochs, such as intermediate-mass stars, which require long timescales to evolve and enrich the interstellar medium. Due to the intensity of star formation in the early Universe, and due to the short available time, the carbon we see in GS-z12 must have been produced in core-collapse supernovae.



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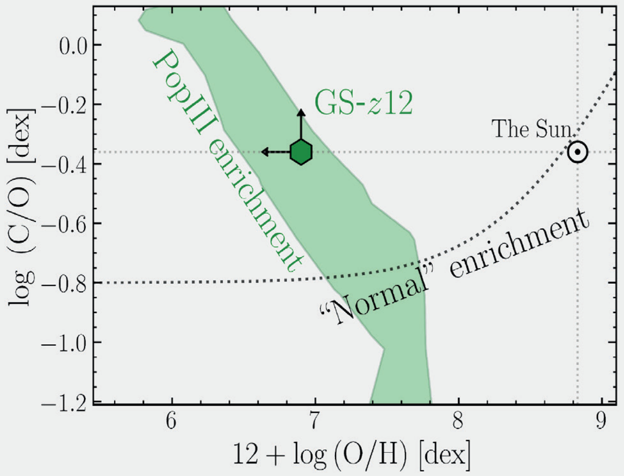

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Figure 1a. JWST/NIRCam image of GS-z12, with the NIRSpec slits overlaid. Figure 1b. The spectrum, with the C III] and other possible features marked. Unmarked features are due to noise.

Figure 2 . GS-z12 displays a peculiar chemical abundance, with low metallicity (x-axis) but high C/O, equal to or higher than the solar value (horizontal dotted line). These peculiar chemical abundances lie off the "normal" enrichment pattern of later galaxies, but could potentially be explained by some PopIII models.

Yet, the ratio between the carbon line and the oxygen line implies that this galaxy has a carbon-to-oxygen abundance ratio, C/O, similar to or even higher than the Sun (Fig. 2). This is extremely surprising, because supernovae are expected to yield much lower C/O than seen in GS-z12. Such high carbon-to-oxygen ratios are not seen again until much later in the history of the Universe, when intermediate-mass stars begin to evolve off the main sequence and start to contribute to the production of elements, increasing C/O (dashed line in Fig. 2) up to values equal or higher than in our Sun. However, this increase in C/O arises from the very intermediate-mass stars that we can definitely rule out at the early epoch of GS-z12.

There is no clear explanation why such a high ratio is observed so early in the Universe. An intriguing possibility is that this abundance ratio may be the signature of the first generation of stars. Being made only of primordial elements, these stars may have had very different properties than normal stars. According to models, these stars can give rise to relatively low-energy supernova explosions, which are able to unbind the carbon-rich stellar layers, but leave relatively more oxygen and neon "locked" inside the stellar remnant, leading to higher C/O than in more-metal-rich supernovae. This may be in agreement with the observations of high C/O in low-mass galaxies seen in absorption, which have already been thought to indicate peculiar chemical enrichment from the first stars. GS-z12 may be the missing link between these low-mass systems and the general galaxy population at high redshift. This discovery may indicate that such exotic and yet-to-be-confirmed stars had an important role in bootstrapping the chemical evolutionary history of the Universe.

This article is based on results to be published as D'Eugenio F. et al., A&A (2024) in press [arXiv: 231109908]

Tibor Dome, Sandro Tacchella & Anastasia Fialkov

Mini-Quenching of High-Redshift Galaxies by Bursty Star Formation

A Gateway to Understanding Galaxy Evolution

In the vast expanse of the cosmos, galaxies stand as celestial beacons, each telling a unique tale of their evolution through time. In the high-redshift Universe, galaxies are more fragile, the star formation in their shallow potential wells easily snuffed out by feedback-driven winds triggered by secular or merger-driven starbursts. Such temporary periods of quiescence interlace strong bursts of star formation and constitute a peculiar phenomenon which we call "*mini-quenching*". These episodes defy conventional classification based on photometric colour cuts like the UVJ diagram, posing intriguing questions about the underlying mechanisms driving galactic evolution.

Recently, JWST has pushed the frontier of known mini-quenched systems out to very high redshift. Notably, in 2023 Looser (based at KICC) and coworkers reported the discovery of a low-mass quiescent galaxy (JADES-GS-z7-01-QU) at redshift z = 7.3, when the Universe was only 700 Myr old. The NIRSpec spectrograph has confirmed that the galaxy experienced a short and intense burst of star formation followed by rapid quenching. To explain this phenomenon, we draw upon the insights gleaned from four distinct galaxy formation models – a periodic-box simulation (IllustrisTNG) and two zoom-in simulations (FirstLight and VELA), alongside an Empirical Halo Model (EHM) – which show remarkable consistency in their predictions of (mini-)quenched galaxy fractions. This population first appears below around redshift 8 in the typical mini-quenching mass range of 10^7–10^9 solar masses, after which their fraction increases with cosmic time, from around 0.5–1.0 per cent at z = 7 to around 2–4 per cent at z = 4. Our analysis reveals that while feedback-driven winds triggered by starbursts are the primary cause for mini-quenching, a considerable fraction of these starbursts are tidally driven. Even in the absence of full mergers, gravitational dances with other galactic companions can herald episodes of mini-quenching.

Delving deeper into the temporal dynamics of mini-quenching, we turn our attention to the aforementioned zoom-in simulation suites (FirstLight and VELA) which offer unprecedented insights into the timescales of galactic dormancy. In Fig. 1, we show some typical trajectories of FirstLight galaxies around the star-forming main sequence (the tight relation between stellar mass and star-formation rate). By tracking such star-formation histories, we discern a characteristic mini-quenching timescale, peaking around 20–40 Myr across redshifts z = 4–8. This timescale, akin to the local free-fall time of the inner halo, provides crucial clues to the underlying mechanisms driving mini-quenching events.

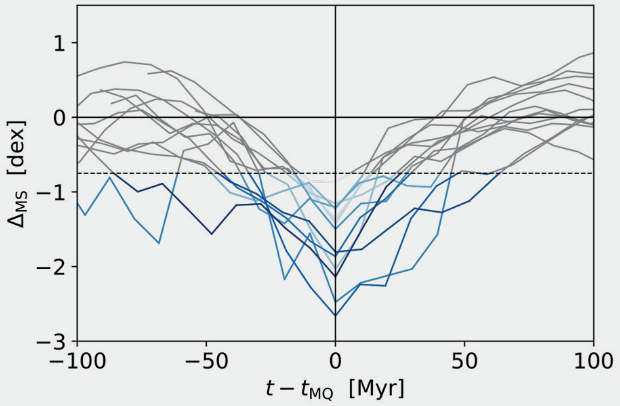

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Figure 1: Bursty star-formation histories of FirstLight galaxies around 12 selected mini-quenching events in the redshift range z = 4–8. Each trajectory shows the deviation from the main sequence from 100 Myr before until 100 Myr after the mini-quenching event. Mini-quenching time-scales are obtained by summing up the time spent below this threshold.

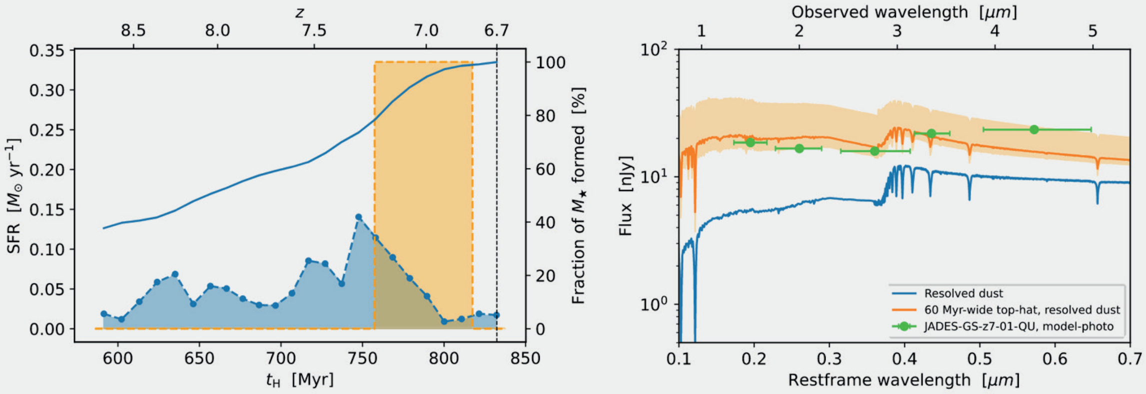

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Figure 2: Original and modified star-formation histories of the VELA galaxy V5 at z > 6.6 (left panel) and corresponding spectral-energy distributions compared to JADES-GS-z7-01-QU (right panel). The level of burstiness inferred from VELA on short time-scales of around 40 Myr is lower than what is observed.

However, a discrepancy arises when attempting to reproduce observed mini-quenched galaxies, particularly the recently reported intermediate-mass quenched galaxy at z = 7.3. Our comparison with JADES-GS-z7-01-QU reveals a notable discrepancy in flux density,, challenging our ability to replicate observed spectra accurately within our simulations. The disparity is only resolved when artificially altering the star-formation histories of mock galaxies and rendering them more bursty on time-scales of around 40 Myr. This is illustrated in Fig. 2, where we compare the original and modified star-formation histories of the VELA galaxy V5. The discrepancy with JADES-GS-z7-01-QU underscores the urgent need for refined sub-grid models governing galaxy formation, particularly at high redshifts. On-the-fly radiative transfer and non-equilibrium chemical networks are more suitable prescriptions in the epoch of reionization, but might prove insufficient as recent results show. As we navigate these challenges, the promise of reconciling observation with simulation beckons, guiding our quest for a deeper understanding of galaxy evolution.

This article is based on results published as Dome T. et al., MNRAS 527, 2139 (2024).

Sophie Koudmani, Debora Sijacki & Martin Bourne

A Novel Model For Simulating Supermassive Black Holes In The Multi-Messenger Era

Large galaxies, like our own Milky Way, commonly harbour supermassive black holes at their centres. These cosmic giants emit powerful radiation and jets while devouring surrounding gas. This black hole activity plays a pivotal role in galaxy evolution, serving as the primary force regulating the transformation of gas into stars in galaxies across cosmic time. However, accurately modelling black hole feedback poses a formidable challenge due to the vast range of spatial scales involved, from the black hole's accretion disc (around 10 light-days) to the cosmic web feeding gas to galaxies (around 1 billion light-years). Prior cosmological simulations have relied on 'ad-hoc' treatments of black hole feeding and feedback, significantly limiting their predictive capabilities.

Recent observational breakthroughs have challenged these ad-hoc models, as the newly launched James Webb Space Telescope has discovered many more active black holes in the early Universe than predicted. This exposes a fundamental gap in our theoretical understanding of black hole activity. Moreover, radio telescopes around the world have detected a distinctive hum consistent with supermassive black hole mergers, marking the first hint of gravitational waves in the supermassive regime. Existing simulations lack the complexity for self-consistent predictions for both electromagnetic and gravitational-wave ("*multi-messenger*") tracers, necessitating more sophisticated galaxy-formation models.

We have developed a novel model of supermassive black holes suitable for galaxy-formation simulations, based on the latest small-scale, general-relativistic, magneto-hydrodynamical simulations, which tracks the state of the accretion disc around the black hole and evolves the black hole's mass, spin and luminosity accordingly (see Fig. 1 for a schematic of our model). We then used our novel model to perform an extensive suite of simulations of supermassive black hole binaries, with a special focus on multi-messenger predictions. In addition to exploring variations of our model for the accretion disc, we also investigated different binary configurations (see Fig. 2, top panel). Notably, we find that the assumed model for the accretion disc significantly affects observable luminosities, and we predict markedly different electromagnetic counterparts in supermassive black hole binaries. We forecast that future searches with next-generation radio telescopes such SKA and the ngVLA should significantly increase the known samples of wide supermassive black hole binaries. Importantly, the assumed disc model shapes the spin magnitudes and orientations of the supermassive black holes (see Fig. 2, bottom panel), parameters that gravitational-wave observatories like LISA and IPTA are poised to constrain.

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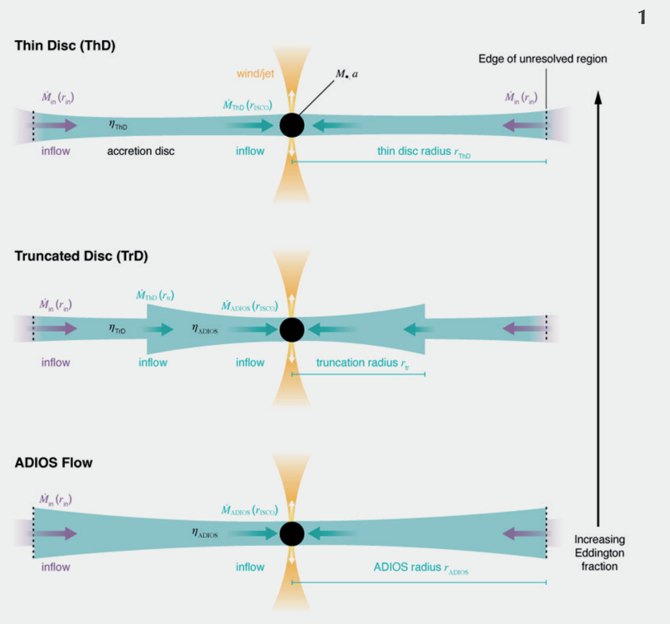

Figure 1. Schematic overview of our unified accretion disc model for supermassive black holes in galaxy-formation simulations. We track the state of the accretion disc according to the resolved inflow properties from the simulation.

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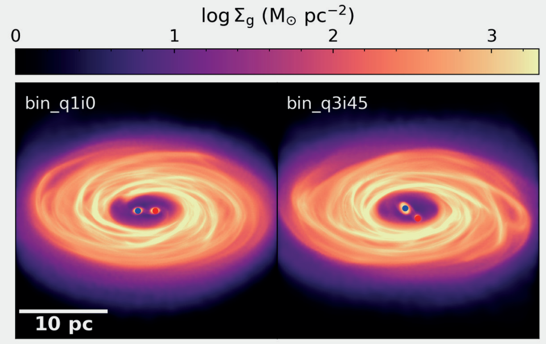

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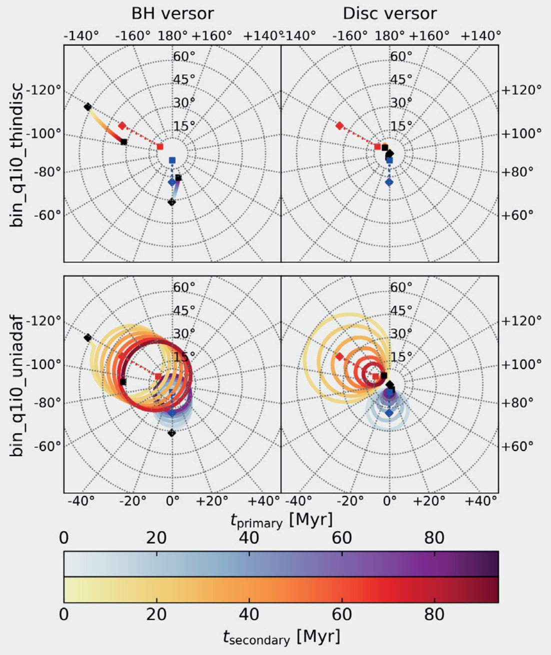


Figure 2. Top: Gas density projections of our binary simulations. We explore different mass ratios and inclination angles. Bottom: Spin evolution for the traditional thin-disc model (top row) and our unified disc model (bottom row).

Our new model provides a crucial advancement in the modelling of gas accretion flows around supermassive black holes, and there are numerous promising avenues for extensions, including radiative and jet feedback. In the near future, next-generation cosmological simulations, incorporating these types of advanced models, will provide unprecedented insights into the complex interplay of supermassive black holes and their host galaxies, and provide the scientific community with much-needed robust predictions for the era of multi-messenger science.

This article is based on results submitted to MNRAS as Koudmani S. et al., arXiv:2312.08428.

Tobias Looser, Francesco D'Eugenio & Roberto Maiolino

A Recently Quenched Galaxy 700 Million Years After The Big Bang

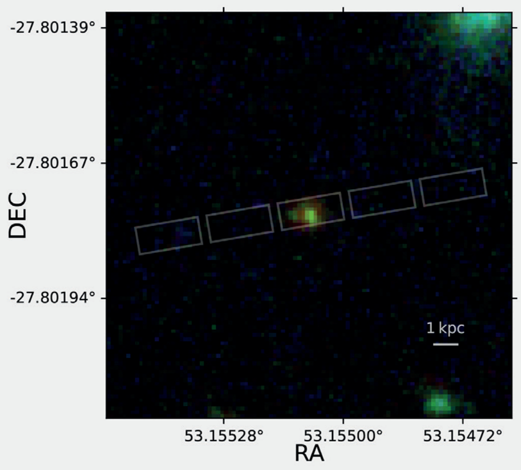
Local and low-redshift ($z<3$) galaxies are known broadly to follow a bimodal distribution: actively star-forming galaxies with relatively stable star-formation rates, and passive systems. These two populations are connected by galaxies in relatively slow transition. In contrast, theory predicts that star formation was stochastic at early cosmic times and in low-mass systems: these galaxies transitioned rapidly between starburst episodes and phases of suppressed star formation, potentially even causing temporary quiescence – known as mini-quenching events. However, the regime of star-formation burstiness is observationally highly unconstrained. Directly observing mini-quenched galaxies in the primordial universe is therefore of utmost importance to constrain models of galaxy formation and transformation.

Early quenched galaxies have been identified out to redshift $z < 5$, and these are all found to be massive (with stellar masses greater than 10 billion solar masses) and relatively old. However, using the James Webb Space Telescope (JWST), we have discovered a mini-quenched galaxy at redshift $z=7.3$ when the Universe was just 700 million years old; the oldest such galaxy ever observed. See Fig. 1 for a JWST/NIRCam image of the galaxy. Its JWST/NIRSpec spectrum (Fig. 2) is very blue, but exhibits: (i) a Balmer break, indicating matured stellar populations; and (ii) no nebular emission lines, indicating no recent star formation on timescales of at least 3–10 Myr (million years).

In addition to the oldest, this galaxy is also relatively low mass – about the same as the Small Magellanic Cloud (SMC), a dwarf galaxy near the Milky Way, although the SMC is still forming new stars. Other quenched galaxies in the early Universe have been far more massive, but Webb's improved sensitivity allows smaller and fainter galaxies to be observed and analysed.

Four different spectral-fitting codes, designed to infer star-formation histories of galaxies by modelling their spectra, namely pPXF, Bagpipes, Beagle and Prospector, agree that this system experienced a short starburst followed by rapid quenching; see Fig. 3. The stellar-age–metallicity grid inferred by pPXF indicates predominantly metal-poor stellar populations forming from around 150 to 50 Myr prior to observation (left subplot). The star-formation histories, i.e., the star-formation rate as a function of look-back time, inferred by Bagpipes, Beagle and Prospector agree that the galaxy formed around 150–200 Myr and quenched 50–20 Myr prior to observation (right subplot).

Star formation in galaxies can be slowed or stopped by different factors, all of which will starve a galaxy of the gas it needs to form new stars. Internal factors, such as a supermassive black hole or feedback from star formation, can push gas out of the galaxy, causing star formation to stop rapidly. Alternatively, gas can be consumed quickly by star formation, without being promptly replenished by fresh gas from the surroundings of the galaxy, resulting in galaxy starvation.



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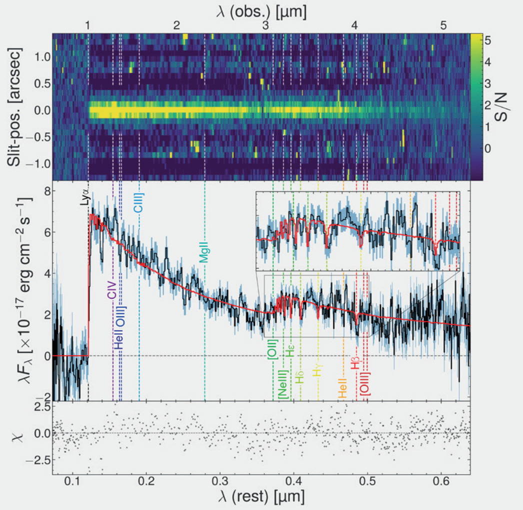

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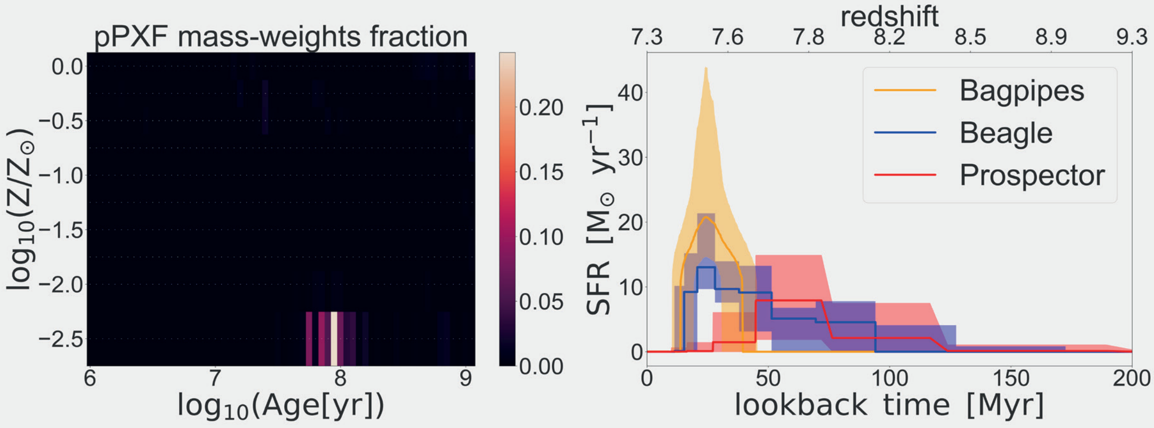

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Figure 1. JWST /NIRCam image covering JADES-GS-z7-01-QU and its nearby projected environment. The five NIRSpec micro-shutter positions used for this target are overlaid in white.

Figure 2. NIRSpec spectrum of JADES-GS-z7-01-QU. The absence of emission lines, together with the Balmer break (rest-frame wavelength 365 micrometres), reveals that this is – temporarily or permanently – a (mini-)quenched galaxy.

Figure 3. The galaxy's star-formation history as inferred by four different full spectral fitting codes. All codes confirm that the galaxy is quenched at the epoch of observation and reconstruct comparable histories.

Given the very short inferred duration of the star-formation history and the rapidity of the transition to quiescence, it seems reasonable to speculate that the galaxy may have experienced a powerful outflow, driven either by star-formation feedback or by accretion on a primaeval supermassive black hole, which rapidly ejected most of the star-forming gas. However, to date it is not entirely clear what caused the galaxy to stop forming new stars and whether this galaxy's "quenched" state is temporary or permanent.

We conclude by emphasising that this is just the starting point for investigating stochastic star formation and mini-quenched systems in the early Universe. We will be looking for other galaxies like this one with our recently awarded 73-hour JWST Cycle 3 program OASIS, which will help us place constraints on how galaxies in the early Universe evolve and why they stop forming new stars.

This article is based on results published as Looser T. J. et al., Nature 629, 53 (2024).

Gabriel Maheson, Roberto Maiolino & Sandro Tacchella

The Nature of Dust in Galaxies

Dust, produced in the atmospheres of some stars, can affect the way stars form, evolve, and die. Some methods by which star formation is shut down rely on how the gas cools in the galaxy, which is affected by the dust content.

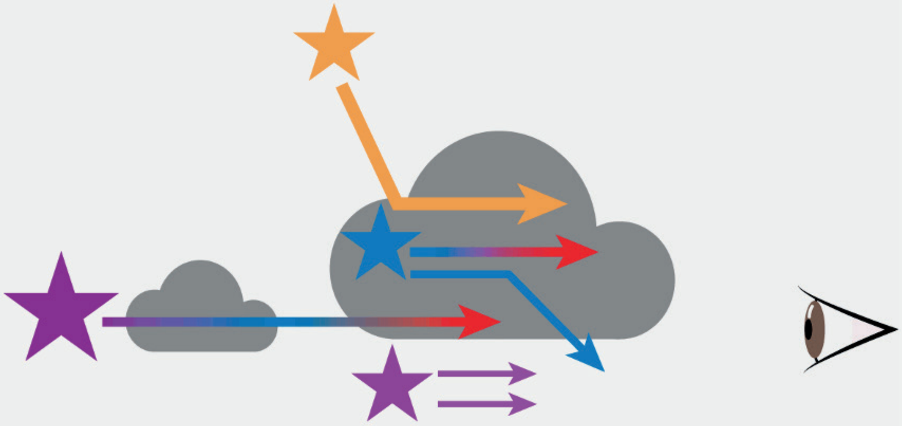
The light emitted from the stars and ionised regions in galaxies at different wavelengths holds information on the ages and compositions of the stars, temperatures of the gas and the overall shape and geometry of the galaxy. When this light interacts with dust, it can be scattered or absorbed, warming the dust and then being re-emitted in a random direction at a longer/redder wavelength. This net effect is known as dust attenuation, and the effect on the spectra from the galaxies is to reduce the shorter wavelength flux and increase the flux in the longer wavelengths, leading to an overall reddening effect. This effect is demonstrated in the cartoon schematic in Fig. 1 and depends on the overall amount of dust present between the source of light and the observer, as well as the type of dust and how it is distributed around stars and ionised regions.

Understanding how the amount of dust present in a galaxy relates to other physical properties of a galaxy, such as the mass of its stars, how quickly the stars are forming and how many metals are present, can help us better study how dust forms in galaxies. We studied this by looking at the dust attenuation of a sample of *"local"* galaxies, whose light has taken roughly 5 billion years to reach us, and used the Balmer decrement – a ratio of the H-alpha and H-beta emission lines in the Balmer series of hydrogen – as a proxy for the dust attenuation.

Many of the galaxy parameters thought to affect the amount of dust we see in a galaxy are all correlated with each other in different ways. This makes it difficult to work out which is the primary parameter correlated with the dust, due to that parameter being involved in the mechanism of dust production, and which parameters are correlated with that primary parameter due to other processes in the galaxy. Any correlation we see with the dust and these other parameters is a secondary, indirect correlation.

To disentangle these different parameters, we implemented two advanced statistical tools: random forest regression (RF) and partial correlation-coefficient analysis (PCC). RF is a machine learning tool that tells us the importance of each galaxy parameter in determining the Balmer decrement using decision trees. It considers all the parameters and so can control for cross-correlations between the parameters. PCC calculates the correlation between two parameters whilst controlling for all other parameters.

These methods produced very similar results, finding that the stellar mass is in fact the most important parameter in determining the amount of dust attenuation observed. The metallicity and the velocity dispersion of the nebular regions in the galaxy show a significant importance in determining the dust attenuation, whereas the star-formation rate shows surprisingly small importance. These results from the RF analysis are shown in Fig. 2. The green bars with stars are for a sample cut on inclination. Results for the full sample are in blue with circles, showing the



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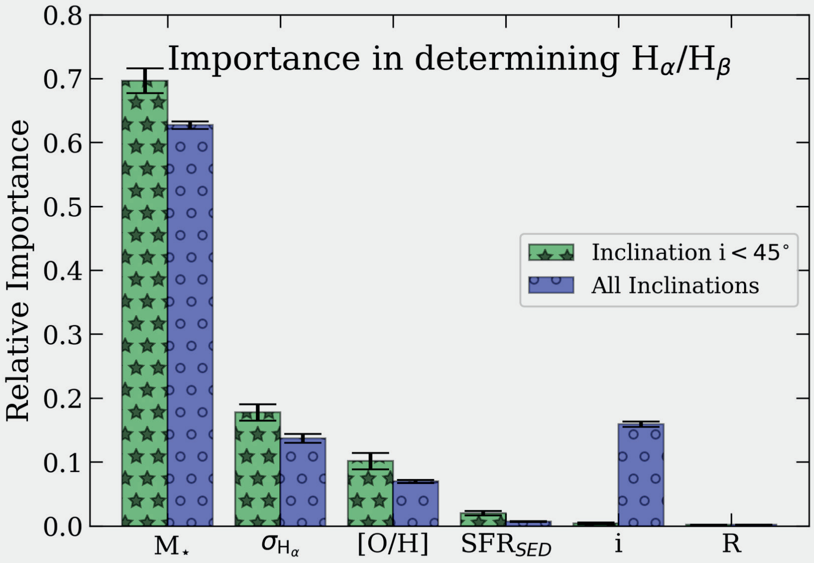

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Figure 1. Cartoon demonstrating the effect of dust on a collection of stars mixed with the dust. Some starlight is scattered into the line of sight, some out of the line of sight, and others are reddened.

Figure 2. Relative importance of (from left to right) stellar mass, velocity dispersion, metallicity, star-formation rate, inclination, and a random control variable, in determining the Balmer decrement (H-alpha/H-beta).

effect of the inclination: a more edge-on galaxy will have more dust attenuation as the light must pass through more dust, hence this parameter was controlled for.

These results can be physically understood by considering that more massive galaxies will have built up a larger reservoir of dust, since dust forms in the atmosphere of stars. A galaxy with more metals will also have more dust, since metals are typically stored in dust grains, and a galaxy with a higher velocity dispersion implies the galaxy has a larger gravitational potential, leading it to retain its gas better and preventing dust from being blown out of the galaxy by radiation pressure, winds and gas outflows. Here we suggest this stellar-mass route is dominant.

This article is partly based on results published as G. Maheson et al., MNRAS 527, 3 (2024).

Jan Scholtz, Roberto Maiolino & Sandro Tacchella

GN-z11: The Most Distant Black Hole Observed In The Universe

Figure 1. JWST image of the JADES GOODS-N imaging with zoom-in on GN-z11. We highlighted all galaxies in the vicinity of GN-z11 with similar redshifts (from Tacchella et al., 2023).

Figure 2. Spectrum of GN-z11 from JWST/NIRSpec observations. We detected a large amount of emission lines, rarely seen in low-redshift galaxies.

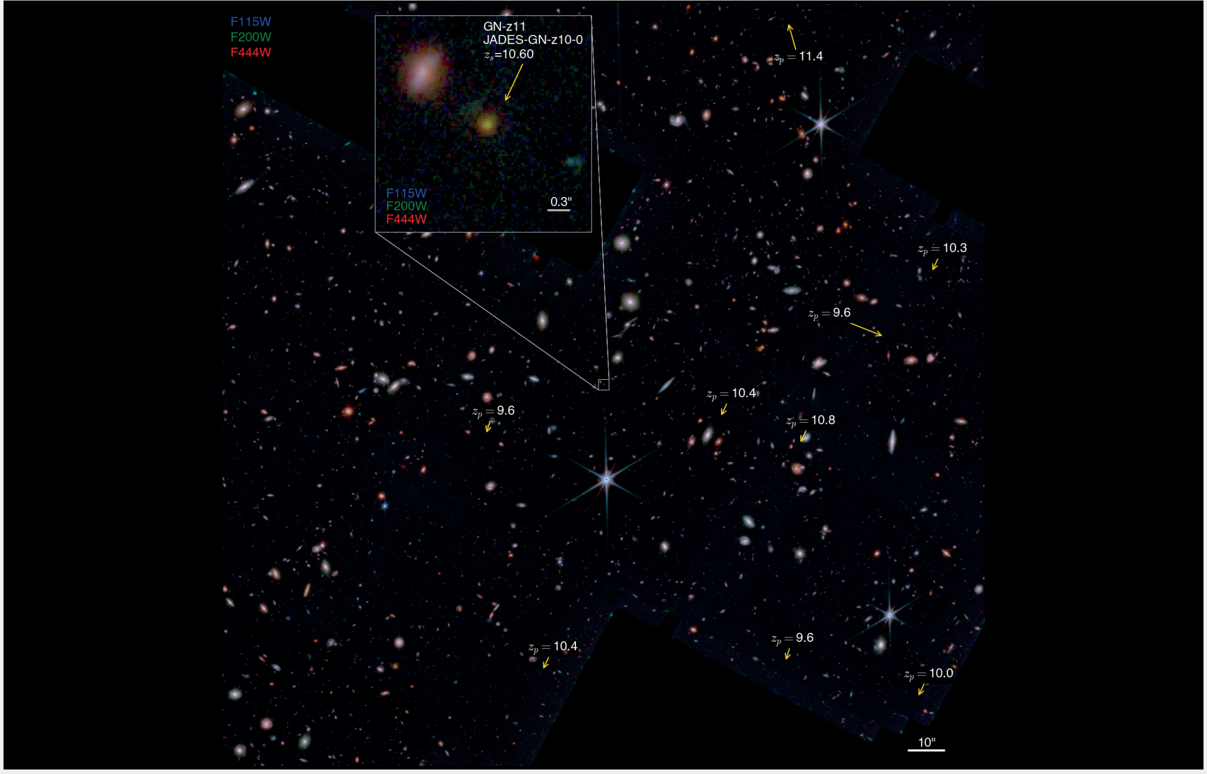
One of the main questions of modern astronomy is the detection and study of the first galaxies and black holes in the Universe: the search for cosmic dawn. The launch of the James Webb Space Telescope (JWST), with its exquisite resolution and sensitivity at near-infrared wavelengths, allows astronomers to detect and study these early galaxies in great detail.

GN-z11, the most distant galaxy confirmed by the Hubble Space Telescope, has been a great puzzle for astronomers. It is incredibly bright for a galaxy from such an early epoch of the Universe (at a redshift of 10.6, just 440 million years after the Big Bang). The JWST has observed the galaxy with two instruments, NIRCam imaging and NIRSpec spectroscopy, as part of the JWST Advanced Deep Extra Galactic Survey (JADES), in which astronomers at the Kavli Institute are heavily involved.

These new observations surprised the entire team and the community with their sheer beauty but also the new scientific puzzles they raised. The morphology (shape) of the galaxy turned out to be more complex than anticipated for a high-redshift galaxy. The galaxy comprises multiple components: an extremely compact unresolved component in the middle, an extended disc, and a small companion "*Haze*" on the side. Moreover, an investigation of the surroundings of GN-z11 found multiple galaxies at similar redshifts, suggesting that GN-z11 is at the centre of a growing cluster of galaxies (see Fig.1).

The spectroscopic data has revealed that this galaxy contains the most distant supermassive black hole yet observed. The unusually bright emission lines show harsh ionising radiation and an unusual nitrogen enrichment. Combining careful modelling of the emission lines detected by NIRSpec with bespoke theoretical models, we showed that the nitrogen emission lines are coming from an incredibly dense region in the galaxy (with number densities exceeding 10^{10} cm^{-3}). This is most easily explained by dense gas clumps orbiting close to the supermassive black hole, also called the broad-line region. This explanation is also supported by the detection of high ionisation lines, such as HeII, [NeIV] and a fluorescent CII* line, indicating a growing supermassive black hole with a mass two-million times the mass of our Sun. Linking this finding to the NIRCam imaging data, the unresolved compact component is actually the accretion disk surrounding the supermassive black hole.

Despite this breakthrough, GN-z11 has still produced more surprises. Our team noticed a potential HeII emission from the "*Haze*" companion in the NIRCam imaging, with no other emission lines. This hints at the presence of Population III stars, a rare type of stars from the early Universe containing only hydrogen and helium. Excitingly, our special 'Director Discretionary Time' (DDT) JWST observations, using the spatially resolved spectroscopy mode, confirmed the presence of the HeII emission with no other metals, making this one of the strongest candidates for confirmed Population III stars so far.



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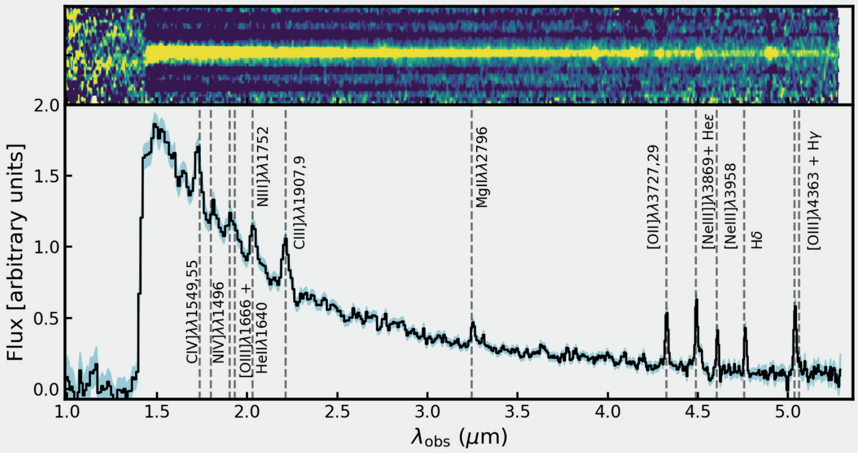

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GN-z11 is also challenging our ideas about re-ionisation of the Universe. The DDT spatially resolved spectroscopy also allowed us to map an ionised gas hydrogen halo around the galaxy. Although this is common at later epochs, GN-z11 appears to have this "*ionised bubble*" 400 million years before it becomes a common phenomenon.

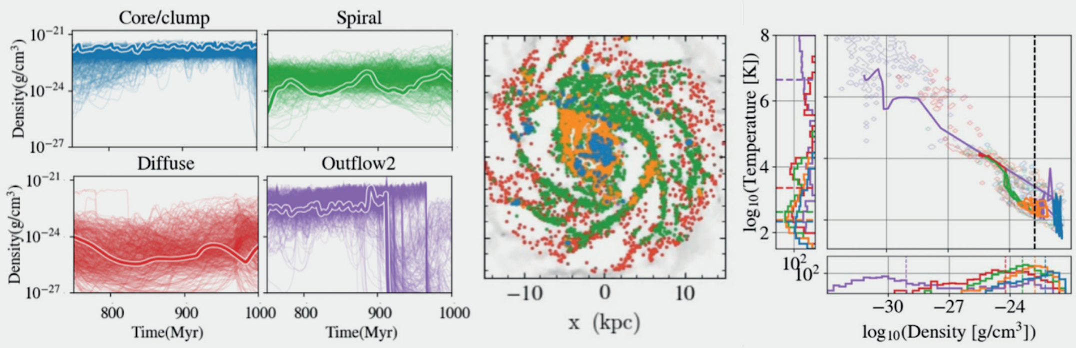
As work continues on investigating this galaxy, the focus of our team's attention is on answering three key questions: What is the exact mass of the black hole in GN-z11? What is the mass of the Population III star cluster and can we confirm it at high statistical significance? Is the galaxy orderly rotating around its centre or is it highly disturbed?

To answer these questions, astronomers at the Kavli Institute have secured a further 70 hours of JWST observing time to devote to uncovering the secrets of this unique high-redshift galaxy.

This article is partly based on results published or submitted as Tacchella S. et al., ApJ 952, id.74 (2023); Maiolino R. et al., arXiv:2306.00953; Maiolino R. et al., Nature, 627, 59 (2024); Scholtz J. et al., arXiv:2306.09142.

Eun-jin Shin & Sandro Tacchella

Star Formation Variability As A Probe For The Baryon Cycle Within Galaxies



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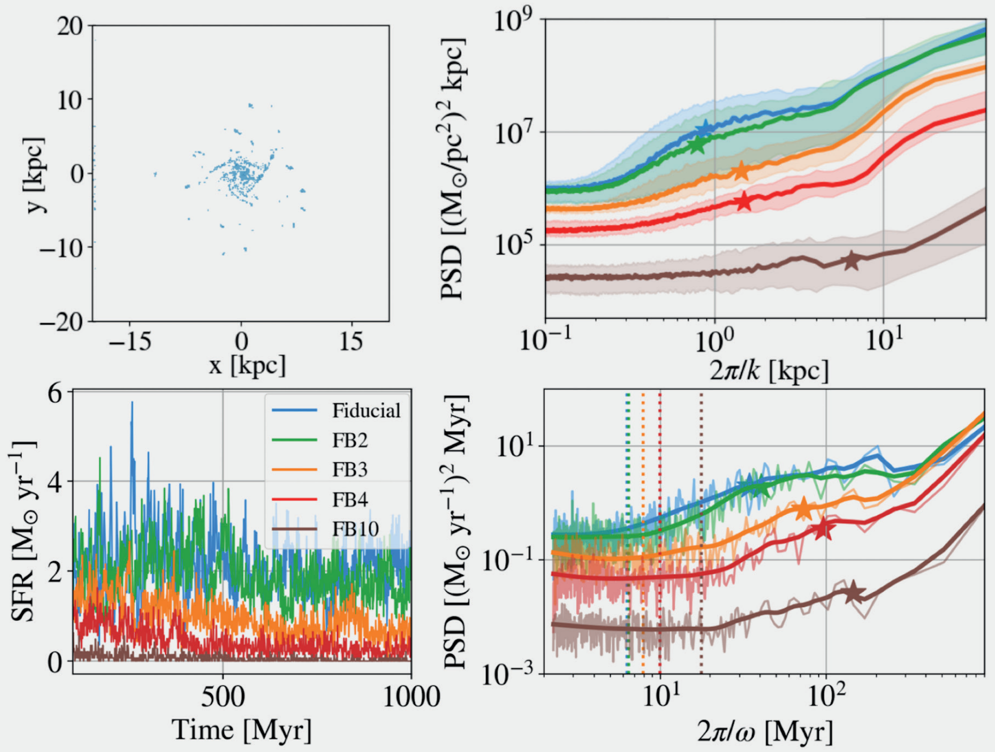
Star-forming galaxies are dynamic ecosystems in which gas cycles in and out of the galactic disk. They are governed by a wide range of physical processes that act on a stellar to cosmological scale: the growth of the large-scale structure, the cooling and heating of the interstellar medium (ISM), and the formation of stars and central black holes and their associated feedback processes. The "regulator model" offers a holistic perspective on the baryon cycle, connecting this wide range of processes through the fundamental continuity equation of the gas content in galaxies. Based on the balancing between the rates of gas inflows, outflows, star formation and the recycling of gas, this model describes the baryon cycle within the galaxy and can reproduce global scaling relations for the overall baryon content of galaxies (such as the mass–metallicity relation).

An important insight from this model is that star formation plays a pivotal role in the baryon cycle. This implies the necessity of comprehending the star-formation history (SFH) in galaxies, a temporal and spatial record of the various physical processes related to star formation. Considering the stochasticity of gas inflow and the formation of giant molecular clouds (GMCs), the extended regulator model constructs a more comprehensive model of galaxy evolution. It shows the star-formation variability in galaxies can be explained with the characteristic timescales for gas inflow, equilibrium, and GMC lifetimes, suggesting the significance of observing the process coupled with these characteristic timescales.

Motivated by the analytical study of star-formation variability, we investigated the SFH and the baryon cycle in idealised numerical simulations of Milky Way-mass galaxies. Leveraging the advantages of particle-based simulations, we traced the time evolution of individual gas parcels. We categorised different gas density histories and analysed the movement and oscillation of gas between various phases of the ISM, establishing connections with star-formation dynamics (see Fig. 1). We examined how physical processes, such as stellar feedback, and morphological properties impact the baryon cycle and the characteristic timescale of star-formation variability. Our simulations elucidate various evolutionary timescales of gas, showing their relation to movement through spiral arms and their dependence on location within galaxies.

Figure 1. Gas density histories (left four panels) over 250 Myr; gas projection (middle); and phase trajectories (right) for the selected gas particles. The highlighted lines in the left panels are the history functions for the selected gas parcels presented in the right panel.

Figure 2. Top: example of projection of young stars (less than 10Myr; left) and the corresponding spatial power spectral densities (PSDs; right) with varying stellar-feedback strengths. Bottom: star-formation histories (left) and the corresponding temporal PSD (right). Star markers in the right-hand panels are at the spectral breakpoints.



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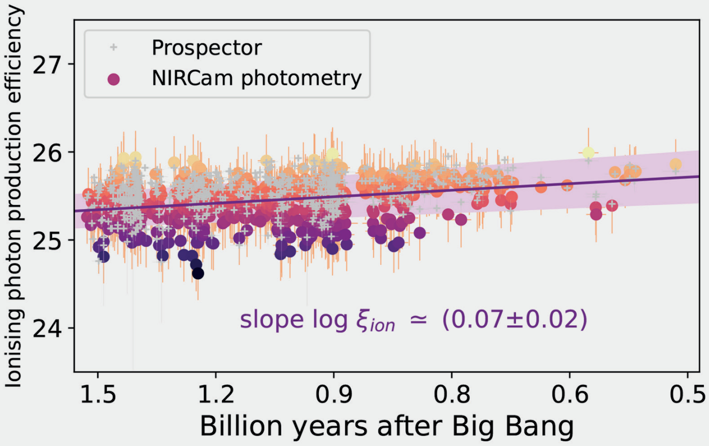
The spatial and temporal fluctuations of the SFH in simulated galaxies follow the predictions of the extended regulator model. Our findings reveal that the breakpoints of the spatial and temporal power spectral densities (PSDs; see Fig. 2), indicative of scales of SFH correlation, shift to larger scales for both spatial and temporal PSDs with stronger feedback. Star formation occurs in dense molecular gas, and the SFH follows the mass history of these dense molecular gas clouds, which is related to the formation and destruction of the GMCs in the galaxy. Dense molecular clouds form stars, and a few million years later the stellar feedback from newly born stars injects thermal energy into the ISM, dispersing the dense gas and rendering it non-star-forming. The correlation time of SFH is associated with the residence time in the non-star-forming state or the formation time of dense gaseous clumps. Therefore, the stronger the feedback, the longer the break timescale of the SFH PSD.

Our study demonstrates an interesting connection between global star formation in galaxies and the temporal evolution of gas in the ISM. We find that the location of the break in the temporal around 10–100 Myr is associated with the lifetime of gas in the diffuse phase, which depends on the stellar feedback strength. This suggests that observational estimates of the PSD can be used to constrain the strength of stellar feedback and may serve as a probe of the thermodynamic structure of the ISM in galaxies.

This article is mainly based on results published as E. Shin et al., ApJ 947, 61 (2023).

Charlotte Simmonds & Sandro Tacchella

Unveiling The Galaxies That Lit Up The Universe With JWST

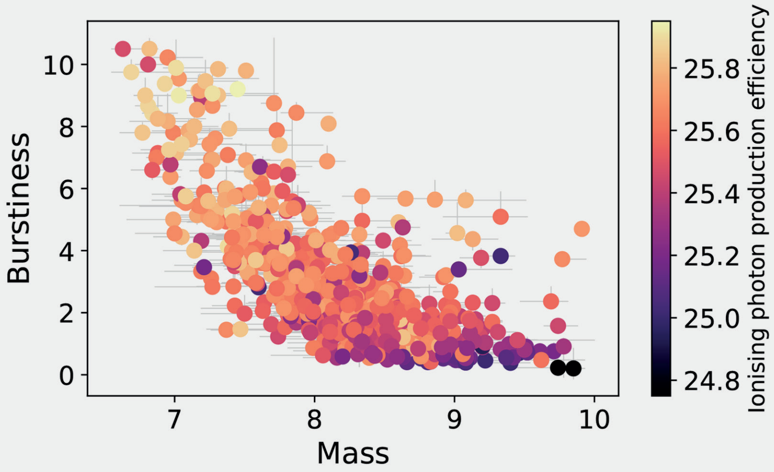


The Universe has gone through several phase changes in its history. In particular, about 100 million years after the Big Bang, as the Universe cooled down enough for matter to collapse due to gravity, the first stars started to form. Their light – and the light of the galaxies that formed some time after – shined through the dark intergalactic medium, eventually leading the Universe to transition from being completely dark to the one we know today, full of light. This transition takes place during a time we call the epoch of reionisation (EoR). One of the greatest challenges in current cosmology is to understand which kind of galaxies are the main responsible culprits for lighting up the Universe.

The advent of the James Webb Space Telescope (JWST), launched in December 2021, has given scientists an unprecedented view of the distant Universe. Its infrared sensors and large primary mirror are particularly well suited to observe faint galaxies in the very early Universe, whose light has travelled more than 13 billion years before reaching us. The scientific community has greatly benefited from this outstanding instrument, and this work has been produced through one of the largest collaborations centred around this telescope: the JWST Advanced Deep Extragalactic Survey (JADES).

In order to study galaxies at the EoR, we exploited synergies between NIRCam, onboard JWST, and other facilities, specifically the Hubble Space Telescope and MUSE, which is an instrument on the Very Large Telescope, in Chile. This combination allowed us to constrain the distance to these galaxies, and to create relevant samples. The first step was to construct a sample of Lyman-alpha emitters (LAEs), whose light was produced approximately 1 billion years after the Big Bang and that had been observed from Earth with MUSE, resulting in 30 LAEs. We selected these kinds of galaxies because their massive young stars produce copious amounts of ionising radiation (i.e., photons with enough energy to remove an electron from a hydrogen atom). We see the evidence of their ionising radiation through a specific signature in their hydrogen emission called Lyman-alpha, which explains their name. We

Left: Ionising photon production efficiency as a function of the age of the Universe, measured with NIRCam and the software Prospector. Right: Burstiness of star formation versus galaxy mass.

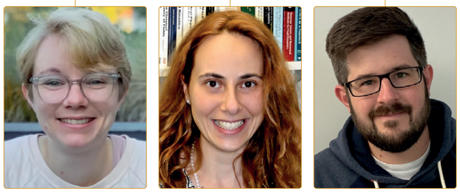


found that, as expected, LAEs are very efficient in producing ionising photons. In fact, efficient enough that they might be the main agents responsible for lighting up the Universe.

In a follow-up study, we went deeper into the early Universe, observing light from galaxies that was emitted about 0.5 billion years after the Big Bang. This time we did not restrict ourselves to LAEs, but extended the sample to contain galaxies with evidence of star formation in general, which allowed us to build a sample of 677 galaxies, the largest one to date covering the EoR (around 0.5–1.5 billion years after the Big Bang). We used Prospector, a powerful piece of software, to analyse the properties of these galaxies, especially to understand how efficient they are in producing ionising radiation and why. Our main findings are that the further we go back in time, the more efficient galaxies are at producing ionising photons (see Fig. 1, left panel). Furthermore, we find that the main driver of this behaviour is their mass. Stars are born in groups, and depending on the conditions of the medium, some of them will be massive enough that they will end their lives as supernova explosions. These explosions might not be very disruptive in massive galaxies, such as our own, but in low-mass galaxies have a significant effect (Fig. 1, right panel). Basically, they heat and expel the gas around them temporarily halting star formation, which can later be triggered to start again once the gas cools down sufficiently. This bursty on-and-off star formation favours an efficient production of ionising photons.

Although the results have been promising, we are far from having a full understanding of which galaxies lit up the Universe. In the future we aim to study an even larger sample of galaxies, in order to paint a full picture of the galactic population at the EoR. We look forward to further unveiling the mysteries of the EoR with JWST.

This article is partly based on results published as C. Simmonds et al., MNRAS 423, 5468 (2023) and C. Simmonds et al., MNRAS 527, 6139 (2024).



Rosie Talbot, Debora Sijacki & Martin Bourne

Powering Supermassive Black Hole Jets In Galaxy Collisions

It has now been widely established that supermassive black holes are present in the cores of many galaxies and that feedback processes from these central black holes can affect not only the innermost regions of galaxies, but also influence galaxy-wide properties leading to morphological transformations and ultimately the establishment of the famous Hubble sequence.

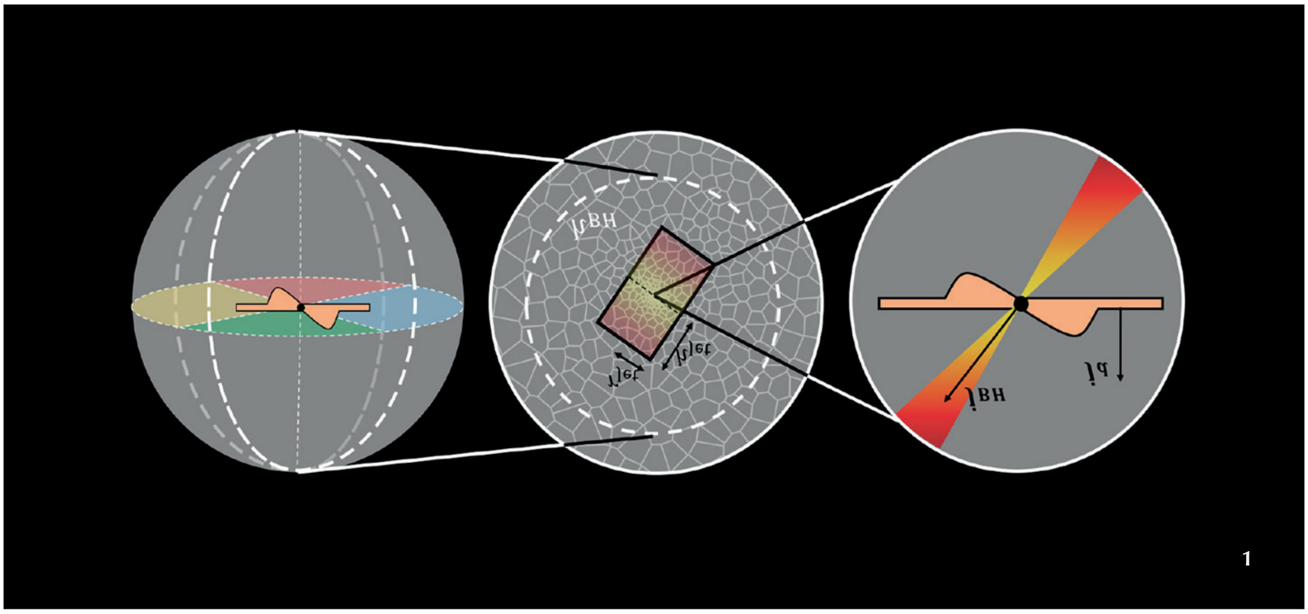
There is strong observational evidence that jets launched by accreting black holes lead to effective thermal regulation of the intracluster medium of galaxy clusters, solving the long-standing "*overcooling*" problem. Furthermore, thanks to ongoing observational programmes with, e.g., MUSE, ALMA, VLA, and LOFAR, a novel picture is emerging where jets may well be ubiquitous across the whole range of black hole masses, from X-ray binaries, to radio jets in dwarf galaxies, to classical radio-loud Seyferts in spirals and finally FRI and FRII sources in massive ellipticals.

This calls for a detailed investigation of the role of jet feedback in galaxy-formation simulations. However, state-of-the-art simulations are still rudimentary in this respect due to the physical and numerical modelling difficulties: black hole mergers, feeding and feedback occur on sub-parsec scales, while jets are known to propagate to kpc and even Mpc scales. Major theoretical improvements in modelling jet feedback in a realistic galaxy-formation context are urgently needed.

To tackle this issue, over the last six years our group in Cambridge has developed self-consistent and physically well-posed black hole accretion and feedback models. In these, we can track gas inflows onto the black holes through a realistic accretion disc (see also the article by Sophie Koudmani elsewhere in this report), and jets are modelled based on the latest simulations including general-relativistic effects, hydrodynamics and magnetic fields, in accord with the Blandford–Znajek mechanism (for a schematic representation, see Fig. 1). Importantly, our model contains all ingredients to link reliably predictions in the electromagnetic spectrum to ones in gravitational waves (i.e., caused by black hole mergers that the space-based interferometer LISA and the International Pulsar Timing Array will observe) opening the way to the emerging field of multi-messenger science.

Therefore, one important avenue of research here is simulations of galaxy mergers that track the formation of binary black holes, as these are especially suitable to predict possible multi-messenger signatures of black hole mergers. To be able to tackle this problem we have recently optimised our code to do the first ultra-high-resolution simulation of galaxy mergers with jets over one billion years of cosmic time.

We found that the jets launched by black holes at the centre of galaxies that are undergoing a merger are capable of driving large-scale, multiphase outflows with peak velocities of up to 5000 km s^{-1}, whose kinematics are complex and in agreement with the ALMA and MUSE observational data. Interestingly, the gas in the outflows can, eventually, decelerate, cool and fall back down towards the orbital plane of the galaxies. This inflowing, cool gas provides a rich source of fuel for the black holes, ultimately resulting in further episodes of intense jet activity, especially as the galaxy cores coalesce and a jetted black hole binary is formed (see Fig. 2).



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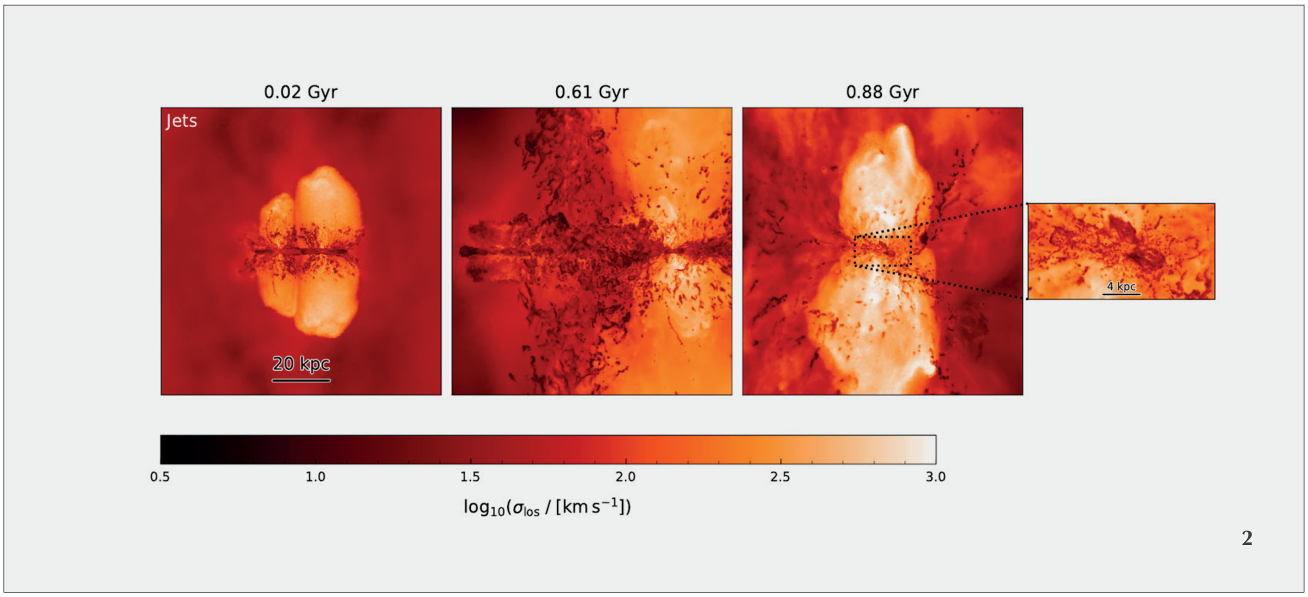

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Figure 1. A schematic overview of our Blandford–Znajek jet model. The circle on the right shows the angular momenta of the black hole and warped accretion disc and how these correspond to the jet direction.

Figure 2. Emission-weighted line-of-sight velocity dispersion maps with galaxies during a merger viewed edge-on, illustrating a prominent high-velocity jet, multi-phase outflows as well as perturbed galaxy kinematics.

Moving forward, it will be possible to perform full cosmological zoom-in simulations of such merging systems, as well as follow the cosmological evolution of present-day spiral and elliptical galaxies, spanning the Hubble fork diagram, with the ultimate goal of self-consistently predicting the gravitational wave background from merging black holes and unlocking the potential to probe cosmology and gravity in the strong-field regime.

This article is based on results published as R. Talbot, D. Sijacki & M. A. Bourne, MNRAS 528, 5432 (2024).

Hannah Übler & Roberto Maiolino

An Offset Active Galactic Nucleus 740 Million Years After The Big Bang

Supermassive black holes with masses in excess of millions to billions of solar masses are observed in the centres of all massive galaxies in the nearby Universe, including in our own galaxy, the Milky Way. All theoretical models of galaxy evolution agree that these supermassive black holes have had a major impact on the evolution of the galaxies they reside in, and this is also supported by observations. However, we do not understand how these black holes managed to grow so massive over the lifetime of the Universe. Even more puzzling has been the discovery of supermassive black holes that existed already during the first billion years of cosmic history, when the Universe was less than 10 percent of its current age. These findings suggest that the growth of some of these black holes must have been extremely rapid, shortly after the Big Bang.

Thanks to the unprecedented capabilities of the James Webb Space Telescope (JWST) to detect faint emission from the dawn of time, we are now in a position to study this epoch in much more detail and to scrutinise early black hole populations. And indeed, first results from JWST already show us that there are many more active black holes in the early Universe than previously expected. We call black holes *"active"*, or *"active galactic nuclei"* (AGN), when we observe them during intense growth phases, while they swallow large amounts of gas or even stars, leading them to release enormous amounts of energy. By pushing observations of massive active black holes to earlier times, we can slowly start to constrain some of the theoretically proposed formation scenarios and growth channels of massive black holes, and at the same time study the impact that they have on their host galaxies.

In this context, our recent discovery of an ongoing merger of two galaxies and most likely also of two massive black holes only 740 million years after the Big Bang is particularly exciting: it shows that merging may have been a viable pathway for black hole growth in the distant Universe. We could identify one of the black holes through ionised gas clouds swirling around it with high velocities (the *"broad-line region"*; see Fig. 1), finding that it already weighed about 50 million times the mass of the sun. The second black hole was revealed through its powerful radiation, ionising and heating the surrounding gas in its host galaxy to high temperatures.

Considering the projected distance and velocity difference of the two massive black holes, we estimated that it would take them only a few 100 million years more to get close enough together so that they would eventually merge, resulting in an even more massive black hole. When black holes merge, they release energy in the form of gravitational waves. Such gravitational wave signals from mergers of supermassive black holes in the early Universe will be detectable with future space missions like LISA.

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 partly based on results presented in H. Übler et al., MNRAS 531, 355 (2024).

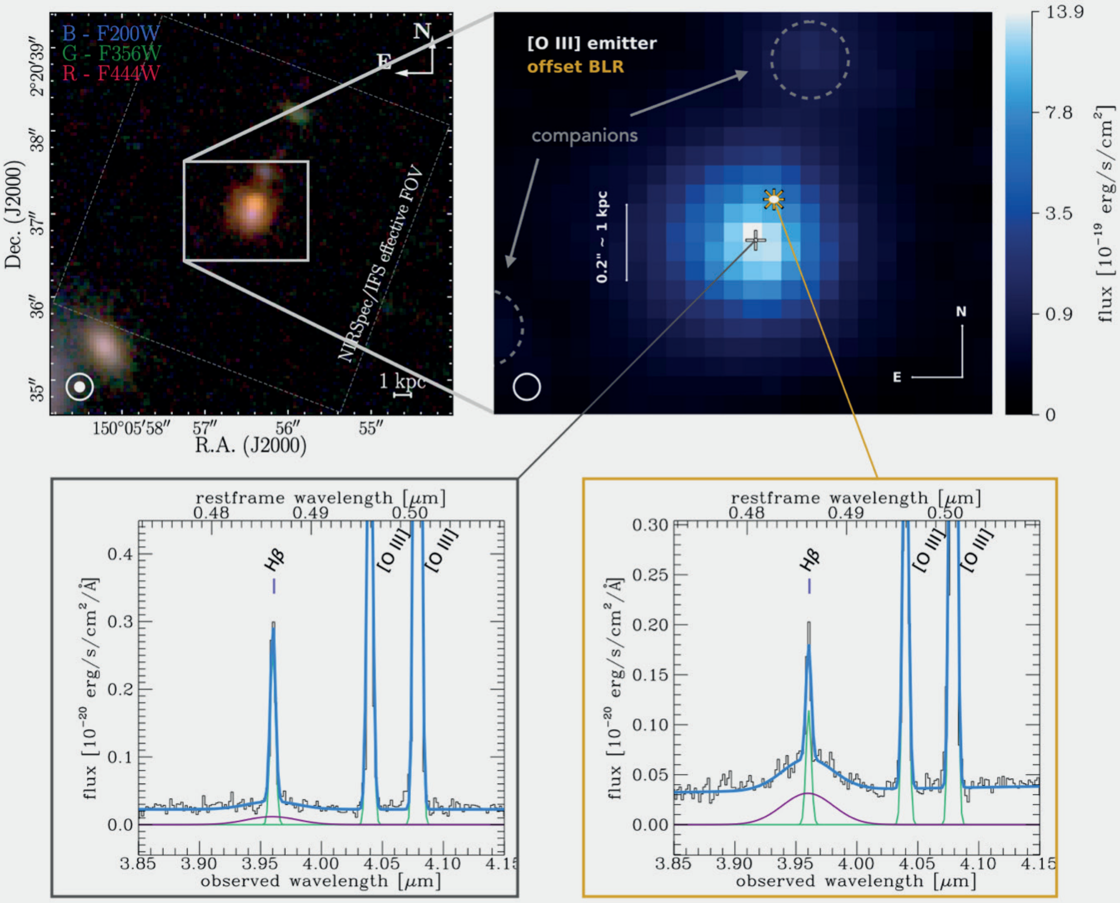

Figure 1. Top: image (left) and oxygen map (right) of the merging system at redshift z=7.15. We detect the broad-line region of an active black hole (bottom right) at a projected separation of 620 pc from the centre of another galaxy that is bright in oxygen (bottom left).

Joris Witstok, Roberto Maiolino & the JADES collaboration

Carbonaceous Dust Grains Seen In The First Billion Years Of Cosmic Time

Galaxies are not only made up of stars and dark matter, but contain large amounts of gas and small solid particles referred to as astrophysical dust. These dust grains, which have a variety of sizes and compositions, are thought to form mainly during the violent later stages of stellar evolution, including in the dense gaseous material ejected in supernova events. Dust is crucial to the evolution of galaxies, as the grains play an important role in the formation of new stars and planets. However, by causing strong absorption of stellar light mainly around those sites of star formation, they also complicate astronomical observations by obscuring our view of these stellar nurseries. Knowing the composition of these dust grains is important to understand the exact pattern of absorption, which also allows us to learn about how dust grains form and grow.

For instance, carbon-rich dust grains can be particularly efficient at absorbing ultraviolet light with a wavelength around 217.5 nanometres (nm). This 217.5-nm absorption, known as the “UV bump”, features prominently in the spectra of individual stars within the Milky Way and other nearby galaxies, where it is attributed to polycyclic aromatic hydrocarbons (PAHs) or nano-sized graphitic grains. PAHs are complex molecules, and models predict that their formation requires very specific conditions only found in the outflowing material of stars that have reached the evolutionary phase known as the asymptotic giant branch (AGB), several hundreds of millions of years after their formation. Looking at more distant galaxies, which are seen at a time when the Universe and everything within it was increasingly younger, the expectation had therefore been that the UV bump gradually would become weaker.

Observing some of the most distant and earliest galaxies has now become possible thanks to JWST and the unparalleled sensitivity improvement provided by its Near-Infrared Spectrograph (NIRSpec). The increase in sensitivity is equivalent, at visible wavelengths, to instantaneously upgrading Galileo’s 37-millimetre telescope to the 8-metre Very Large Telescope, one of the most powerful modern optical telescopes. Currently, the largest survey aiming to discover and characterise faint, distant galaxies is the JWST Advanced Deep Extragalactic Survey, or JADES (Fig. 1), in which many KICC researchers are closely involved. For the first time, we have now directly observed the UV-bump feature in the spectra of very early galaxies, seen less than a billion years after the Big Bang or at a redshift of $z = 6.7$ (Fig. 2).

The newly discovered feature was observed at a wavelength of 226.3 nm in the rest-frame of the galaxy, a slight shift with respect to the canonical 217.5 nm that may be explained by measurement error or, more interestingly, could indicate a difference in the composition of dust in the very early Universe. Such a different mix of carbonaceous grains could potentially point towards a different production mechanism that acts on short timescales, for example Wolf–Rayet stars or supernovae.

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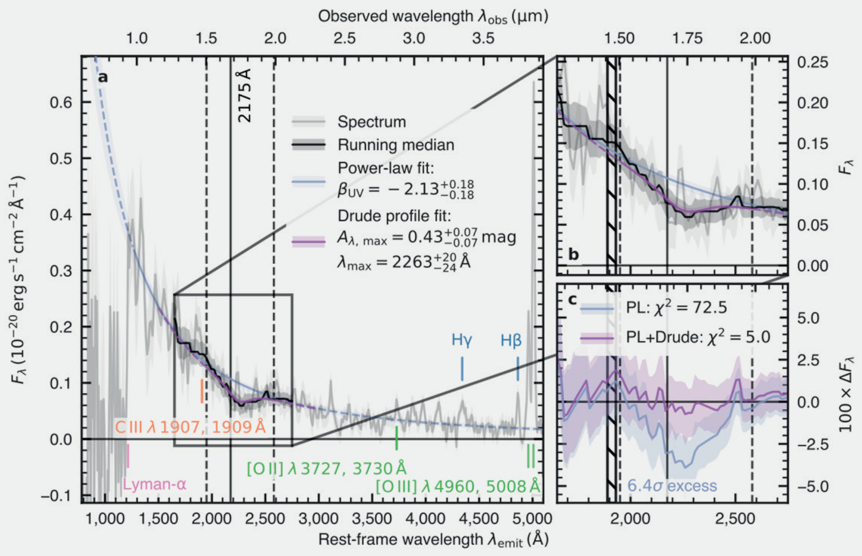

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Figure 1. JWST imaging obtained by JADES in the GOODS-South field, highlighting the location of JADES-GS-z6. Credit: ESA/Webb, NASA, ESA, CSA, B. Robertson, B. Johnson, S. Tacchella, M. Rieke, D. Eisenstein, A. Pagan, J. Witstok.

Figure 2. Spectrum of JADES-GS-z6-0 taken by JWST/NIRSpec. The panel on the left highlights several spectral features used to confirm the spectroscopic redshift of the galaxy. A zoom-in of the UV-bump region is shown in the panels to the right.

This discovery implies that infant galaxies in the early Universe developed much faster than anticipated, revealing a complexity of the earliest birth-places of stars (and planets) that models are yet to explain. Intriguingly, this pattern has been repeatedly seen in observations by JWST, perhaps most strikingly through the uncovering of a population of galaxies and supermassive black holes in the very early Universe that is much larger than previously expected.

This article is partly based on results published as J. Witstok et al., Nature 621, 267 (2023) and the accompanying ESA press release.

Callum Witten, Nicolas Laporte, Sergio Martin-Alvarez,
Debora Sijacki, Martin Haehnelt & Yuxuan Yuan

JWST Reveals Galaxy Collisions Are The Key To Solving An Early Universe Conundrum

Over the last decade, one of the most intriguing unknowns about primaeval galaxies was why some galaxies show a specific form of hydrogen emission (i.e., the Lyman-α emission) whilst others do not. According to our best model of the Universe, ΛCDM, some 380,000 years after the Big Bang, the temperature and density of the Universe facilitated the binding of electrons and protons to form neutral hydrogen, while it took another 70–100 million years for the very first stars to appear, marking the start of the Cosmic Dawn.

These first stars are expected to be extremely massive and to emit a huge amount of ultraviolet photons, leading to the production of Lyman-α emission. However, the primaeval galaxies in the early Universe are surrounded by copious amounts of neutral hydrogen which absorbs Lyman-α emission. Therefore, this emission is not expected to be seen from galaxies emitting light within the first billion years of the Universe. Surprisingly, ground-based spectroscopic observations of galaxies at these earliest epochs revealed that some, but not all, show this Lyman-α emission.

Many hypotheses had been proposed to explain this unexpected detection of Lyman-α emission, such as the presence of extremely active supermassive black holes in the very early Universe, but no consensus had been reached. Our team made use of the exquisite resolution and sensitivity of JWST's imaging instrument (NIRCam) to study the morphology of these Lyman-α emitting galaxies. Unexpectedly, all of the galaxies that show Lyman-α emission were in fact found to be in pairs or even triplets of interacting galaxies on collision courses with each other (see Fig. 1). This complex dynamical interaction was previously unseen by the Hubble Space Telescope due to the comparably low resolution and sensitivity of its camera.

To understand how interactions between galaxies can explain the detection of this unexpected Lyman-α emission, our team employed novel on-the-fly radiative transfer magneto-hydrodynamical simulations with cosmic-ray feedback, which have proven to be an excellent match to our observations (see Fig. 2). These simulations have demonstrated that these violent interactions between galaxies promote the formation of many new stars. These young stars in turn produce copious amounts of Lyman-α emission. Moreover, these interactions also disturb the neutral hydrogen that we know absorbs Lyman-α emission, moving it away from the stellar nurseries towards the outskirts of galaxies. This is caused by strong winds produced by these young stars and by gravitational forces produced as the two galaxies interact and finally merge. The combination of the increased production of Lyman-α emission and the removal of neutral hydrogen that ordinarily absorbs Lyman-alpha facilitates the emission and escape of Lyman-α where it was previously believed to be impossible (see **this video - https://www.youtube.com/watch?v=O5eqIJqEpB8** showing the drastic effects of interactions on the gas distribution of merging galaxies).

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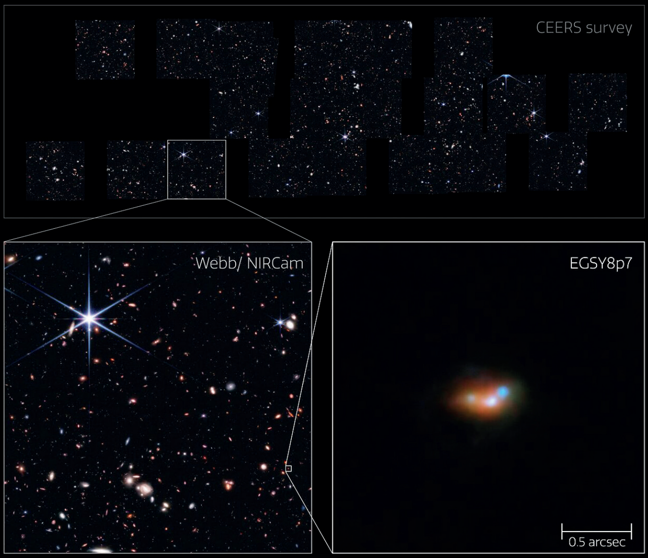

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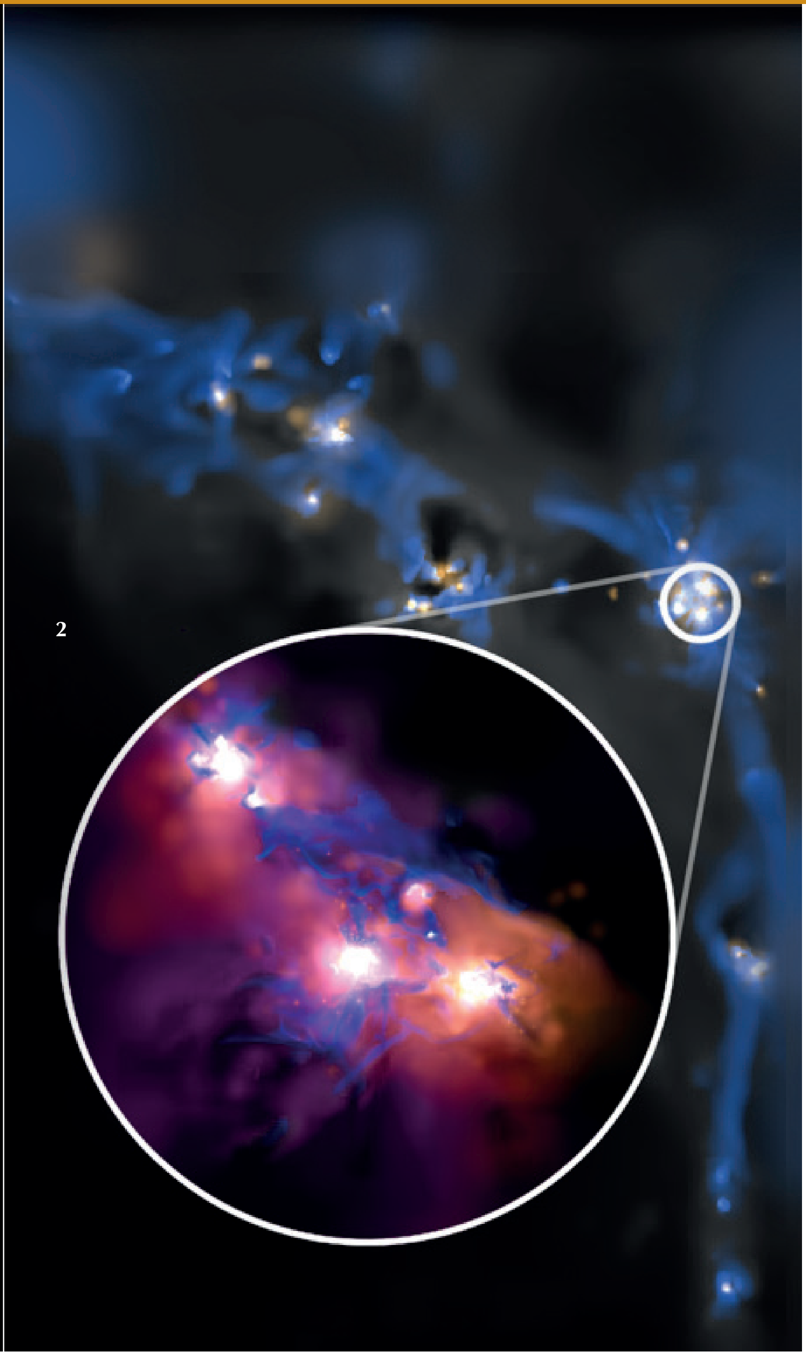
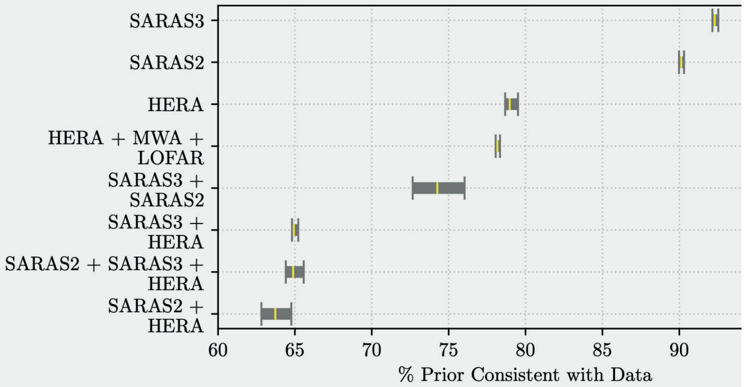


Figure 1. Example of a Lyman-α emitter in the very early Universe surrounded by two companion galaxies in the EGS field. Image credit: ESA/Webb, NASA & CSA, S. Finkelstein (UT Austin), M. Bagley (UT Austin), R. Larson (UT Austin), A. Pagan (STScI), C. Witten, M. Zamani (ESA/Webb).

Figure 2. The view of the state-of-the-art simulation Azahar. A triple galaxy system is in the process of merging. The yellow-white colours indicate ultraviolet emission from these galaxies, while blue traces the neutral gas, which is displaced from the centres of these galaxies due to a violent galaxy encounter.

Our results show the power of high-resolution JWST images in conjunction with state-of-the-art cosmological simulations to understand the properties of galaxies in the very early Universe, which allowed us to solve the long-standing Lyman-α emission conundrum.

This article is based on results published as C. Witten et al., Nature Astronomy 8, 384 (2024).



Harry Bevins & Will Handley

Getting The Most Out Of Our Inference Products With Machine Learning

The KICC has a long history of pioneering work on data analysis techniques for cosmology. In particular, researchers in Cambridge have led the development and use of Bayesian-inference tools in the study of the cosmic microwave background, galaxy evolution and the 21-cm line from the cosmic dawn. The data-driven paradigm of Bayesian inference, the cost of cutting-edge experiments and the fact that we only have one Universe to observe, together incentivise cosmologists to extract as much information from their analysis products as is feasible. This is particularly true in the field of 21-cm cosmology, where we are attempting to observe the impact of the first stars on the evolution of the early Universe through the 21-cm line from neutral hydrogen using radio telescopes. Cosmologists in this field have to calibrate their data to one part in one-hundred thousand and members of KICC have led the development of robust Bayesian methods to deal with this daunting challenge.

Now, a new generation of machine learning tools are allowing researchers in the field of 21-cm cosmology and across KICC to push the boundaries of what we can learn from our data. Motivated by the challenges of 21-cm cosmology, we are working hard to understand how we can effectively integrate these cutting-edge tools into our Bayesian pipelines to better interrogate our data and extract all the information in our inference products about the first stars.

Cosmologists have developed novel methods that utilise existing analysis products to help perform efficient joint analysis of results from different experiments, inform future experimental efforts, enhance inference algorithms and develop more complete forecasting tools.

We attempt to probe the 21-cm signal through different observables with different experimental setups that use individual telescopes, like the Cambridge-led REACH, or arrays of telescopes, known as interferometers, like HERA. We often want to know whether different experiments are in agreement, which experimental setups give us the most information, and how our understanding changes when we combine different observations.

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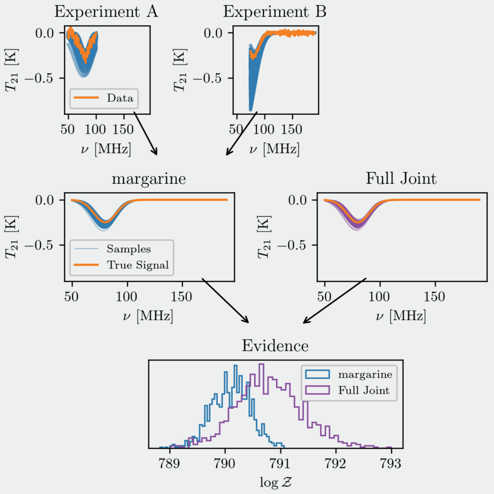

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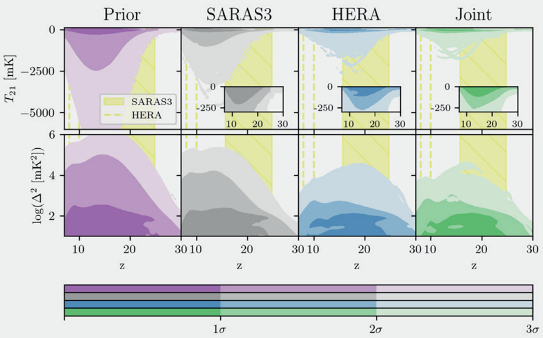


Figure 1. Researchers at the KICC have developed novel methods that allow analysts to identify which experimental techniques provide more information about fundamental physics while marginalising over the specific nuances of each instrument. This example is for various 21-cm cosmology experiments. Instrument combinations further to the left are more constraining.

Figure 2. Machine learning-enhanced Bayesian workflows, such as margarine, being developed by researchers at KICC for 21-cm cosmology, allow one to analyse multiple experimental datasets more efficiently than previous methods by marginalising over the experimental nuances without sacrificing accuracy. In this example, consistent Bayesian evidence estimates are recovered by the traditional and novel machine learning-enhanced methods, as can be seen in the bottom panel.

Figure 3. Members of KICC used the new machine learning tools to analyse jointly data from the HERA and SARAS3 instruments and put constraints on the magnitude of the 21-cm signal. In this work, we disfavoured large portions of the parameter space and put limits on the star-formation rate and mass of the first stars.

It is often hard to answer these questions effectively because of experiment-specific nuances that prevent direct comparisons. However, members of the KICC have developed a novel machine learning method to marginalise out the impact of these nuances from our inference products. This allows us to compare the constraining power of different experimental approaches and promote the development of the most-informative methods. This tool was first demonstrated by researchers in Cambridge on an analysis of data from various experiments targeting the 21-cm signal, including the interferometer HERA in South Africa and the SARAS instruments in India (see Fig. 1).

The new tools being developed at KICC also allow cosmologists to combine more efficiently the constraining power of different experiments to improve our understanding of the Universe. Taking advantage of existing inference products, we are now able to constrain the fundamental physics probed by multiple experiments without having to reanalyse complex instrumental effects and without sacrificing the accuracy of the results (see Figs 2 and 3). This reduces the financial and environmental cost of computationally expensive cosmological analysis pipelines and allows researchers to focus on interpreting the key science results.

The current advances in machine learning are revolutionising how we are analysing our data. The KICC is at the forefront of this advance and is bringing unparalleled expertise and experience to the playing field.

This article is partly based on results published as Bevins H. et al., MNRAS 526, 4613 (2023), Bevins H. et al., MNRAS 527, 813 (2024) and Bevins H. et al., Phys. Sci. Forum, 5(1), 1 (2022).

Mathias Nowak

Verdict Pending: The Unfolding Case of HD 142527

Figure 1.
Orbital dance of HD 142527 B, showing the best fit of the orbit (purple lines) and the multi-instrument orbital monitoring (various symbols). The system is at 160 parsecs, so 10 mas is equal to 1.6 au.

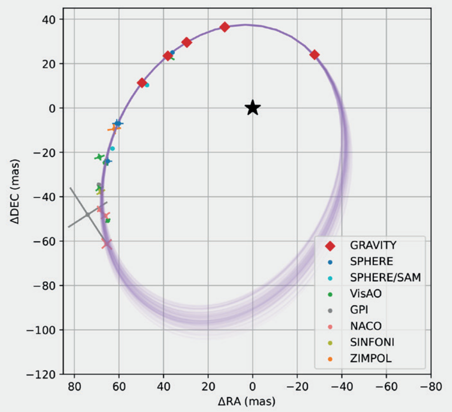
Figure 2.
Hydrodynamical simulations of the disc in the presence of the binary, on its previously determined orbit (left panel), and on our updated orbit (middle and right panels).

HD 142527 — a star barely out of its stellar infancy at 5 million years old — resides 160 parsecs away from us. Classified as a Herbig Ae/Be star, it has always stood out in the cosmic crowd with its large and elaborate surrounding disc, a rich tapestry of features including multiple spiral arms, a pronounced horseshoe-shaped region of dust emission, and a distinctive set of shadows cast by the inner disc on the outer disc. The centrepiece, however, is the vast cavity stretching from 30–130 au from the star, suggesting that the disc has been the scene of enigmatic astronomical events.

For years, the investigation into these celestial events moved at a glacial pace. However, a significant breakthrough came in 2012, when observations made with the NACO instrument on the Very Large Telescope (VLT), revealed that HD 142527, previously thought to be flying solo, was one half of a binary system. Its partner, HD 142527 B, is a low-mass star with just over one-tenth the mass of the primary, HD 142527 A. Further observations accumulated along the years slowly revealed that the companion was following an eccentric orbit extending up to 30–50 au from the star. With this revelation came the key allegation: was HD 142527 B the instigator behind the disc's striking characteristics?

Fast forward to 2018, where hydrodynamical simulations informed by six years of tracking of its orbital trajectory confirmed HD 142527 B as the architect of the central cavity and other disc features. Subsequent data gathered over the following years further solidified this theory. The story seemed set: the disc was circumbinary, not transitional. Case closed.

But every good mystery deserves a twist. Enter the GRAVITY instrument, and our four-year long monitoring of the system, covering the period from 2017 to 2021. Because it combines the four telescopes of the VLT into a single interferometer, GRAVITY is able to break the limit sets by the eight-metre size of the individual VLT telescopes, resulting in a drastic improvement of the astrometric precision. What our



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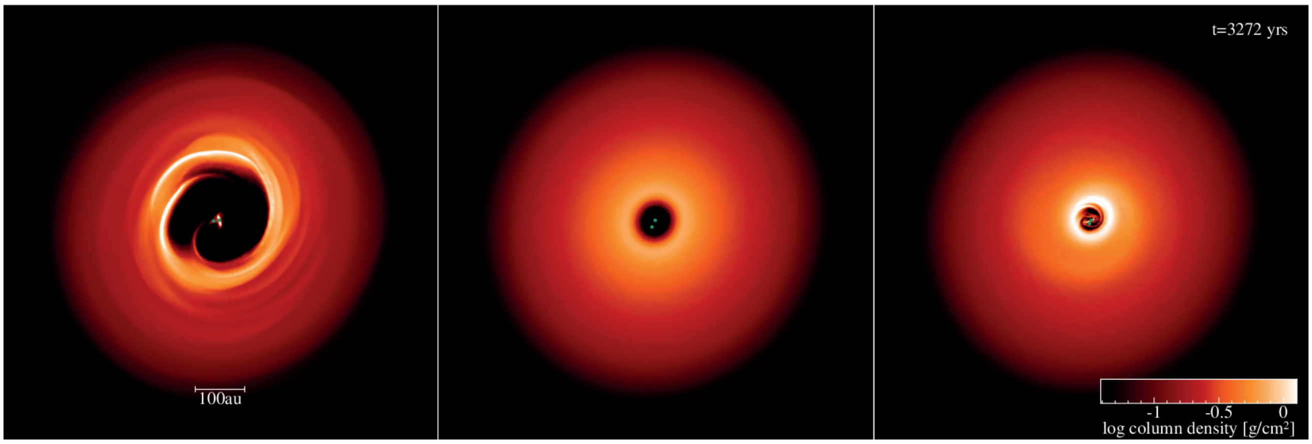


observations revealed was startling: HD 142527 B actually follows a moderately eccentric orbit with a much more moderate semi-major axis of just 10.80 au (Fig. 1) — far smaller than the disc's central cavity.

This pivotal finding forced us to reconsider the suspect's role. We hit the simulation labs again with our new orbital insights in hand. After ensuring that our 3D hydrodynamical simulations could replicate earlier "*convictions*" with previous orbital data, we started to explore new scenarios based on our latest findings. The verdict? While HD 142527 B could stir up some inner-disc turmoil — carving gaps and spiralling arms — it could not have crafted the expansive cavity on its own (Fig. 2).

With this new evidence, there was no alternative: the case had to be re-opened. The HD142527 disc might not solely be circumbinary, after all. This revelation prompts for a wider investigation: could other, subtler astronomical entities such as planets be influencing the disc's structure? Or maybe unseen material is lurking within the cavity, eluding our current detection capabilities? Of course, there is always the possibility that some of our earlier "*verdicts*" in the cosmic courtroom were based on flawed hydrodynamical assumptions, requiring a fresh re-examination of the evidence with a more critical eye.

The only certainty is that this investigation into HD 142527 is not over. Each new finding unravels more mysteries, compelling us to refine our models and assumptions. The court of cosmic inquiry remains in session.

This article is based on results published as Nowak M. et al., A&A 683, A6 (2024); Price D. et al., MNRAS 477, 1270 (2018); Biller B. et al., ApJ 753, L38 (2012).

KICC 2023

Events and Lectures

Workshops

JWST 2023: A new era in extragalactic astronomy: early results from the James Webb Space Telescope
Date: 20–24 March 2023
Event Location:
Kavli Institute for Cosmology, Cambridge

Gambit at the KICC
Date: 10–14 July 2023
Event location:
Kavli Institute for Cosmology, Cambridge

Kavli-Villum Summer School on Gravitational Waves
Date: 25–30 September 2023
Event location:
Corfu, Greece

JWST 2023

Since July 2022, the first data from JWST has been providing exciting scientific results on a wide range of topics in astrophysics.

The first KICC conference of 2023, "A new era in extragalactic astronomy: early results from the James Webb Space Telescope", provided an opportunity to share and discuss first results and discoveries obtained with JWST in the field of extragalactic astronomy, with a focus on high-redshift galaxies.

Held at KICC and IoA from 20–24 March, with over 80 delegates attending, it covered the key themes of first galaxies, reionisation, galaxy evolution, active galactic nuclei and quasars, kinematics and outflows, and interstellar-medium conditions.

Taking advantage of Dr Jane Rigby's kind offer of the "Use me up astronomy!" approach to travel ("If I'm going to go all that way, I want to be of use") the workshop also included an excellent public talk, "The Webb Telescope's New Era in Astronomy" as part of the IoA public open evenings. **https://www.youtube.com/watch?v=SZ-rOTav3DOM**

We also seized the opportunity to invite another attendee, Prof. Marcia Rieke (The University of Arizona) to give a Kavli Lecture whilst she was here.

GAMBIT at the KICC

GAMBIT at the KICC was a week-long workshop combining the annual GAMBIT collaboration meeting with a series of introductory lectures on the GAMBIT software and a series of talks on the latest results from the GAMBIT community. The workshop was attended by 20 members of the GAMBIT community, an additional 10 local members attending the whole week, and a further 20 attending intermittently. Visitors came from Australia, Canada, China, Europe and Japan, and even the Cambridge high-energy physics groups!

Highlights of the week included an introductory talk "*What is GAMBIT?*" (a community and software framework for combining data from particle physics accelerators with cosmology telescopes and terrestrial experiments), a discussion of the recent NanoGrav pulsar-timing results on the stochastic gravitational-wave background and how this would link into the GAMBIT framework, as well as incorporating the latest statistical developments into GAMBIT. Alongside this were Cambridge-based social events facilitated by the KICC such as a reception after the introductory talk, a formal dinner, pub trips, croquet and punting.

An unprecedented five new members joined that week (the global community is about 80 people, although with 20–30 people working actively at any one time), from both astrophysics and particle physics backgrounds.

Top: *JWST* Conference Photograph, taken in front of the IoA Observatory. Below: *GAMBIT at the KICC* participants - Kavli Institute for Cosmology, Cambridge.

A new interdisciplinary project was initiated that combines data on direct detection of dark matter, cosmological likelihoods and *"low-energy"* particle physics experiments.

The GAMBIT community were enormously grateful to the KICC for supporting the event, and very impressed at how well-organised the logistics were and how well-suited the venue was to their event, from the remote-linked lecture theatre and breakout rooms, to the nearby accommodation and lunches at Robinson and Churchill Colleges.

Kavli-Villum Summer School

In the last week of September 2023, together with NBI Copenhagen and AEI Potsdam, the Kavli-Villum Summer School on Gravitational Waves was held, co-funded by the Kavli Foundation and Villum Fonden, and hosted at the Corfu Summer Institute in the historical site of Mon Repos in Corfu, Greece.

The school's programme was filled with lectures and hands-on tutorials on some of the most exciting topics in gravitational wave (GW) physics, from the foundations of GW theory and black-hole physics, to numerical-relativity simulations of compact binaries and the bleeding-edge of machine learning techniques used in GW data analysis. About 70 participants attended the school in person and a few more joined remotely. Lectures and tutorials were delivered by early-career researchers with world-leading expertise in their respective fields. Together with the students and organisers, they contributed to a vibrant and inspiring atmosphere, with engaging discussions extending to the coffee breaks and lunches.

To complement the academic workings of the school, a number of activities were organised, including a reception dinner in the gardens of the old palace at Mon Repos (the birthplace of HRH Prince Philip), a poster session where the students exhibited their work in the foyer of the Municipal Theatre of Corfu, a day-trip to the west coast of the island and a conference dinner at one of the most historical tavernas of Corfu.

Participants at Kavli Science Focus meeting - *Introduction to KICC*

Kavli Lectures

16 March 2023
Marcia Rieke (The University of Arizona)
The Webb Telescope's First Year:
A Treasure Trove of Results

08 June 2023
Daniel Eisenstein (Harvard)
Looking into the First Billion Years with JWST

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

We hold two invited Kavli Lectures per academic year. We were delighted to be joined in-person by Marcia Rieke and Daniel Eisenstein, who surveyed different aspects of the remarkable results emerging from early JWST data.

KICC 2023 LECTURES

THURSDAY 16 MARCH, from 4pm in the HOYLE LECTURE THEATRE, INSTITUTE OF ASTRONOMY

PRESENTED BY THE KAVLI INSTITUTE FOR COSMOLOGY, CAMBRIDGE & THE UNIVERSITY OF CAMBRIDGE

Marcia Rieke - The University of Arizona
The Webb Telescope's First Year: A Treasure Trove of Results

The launch of the James Webb Space Telescope followed by the successful deployment of its sun shield and optics has ushered in a new era in astronomy. The six-month commissioning period revealed a telescope and set of instruments that outperform the pre-launch predictions. The image quality of the telescope is spectacular which in turn enhances the science return. The sensitivity stemming from the great image quality means that observing programs will yield better signal to noise, and deep surveys will see further back in time. The first programs are yielding new insights into areas of astronomy ranging from the first galaxies to form after the Big Bang to the composition and climates of planets orbiting other stars.

Image: NASA, ESA, Ann Feild (STScI).

KICC 2023 LECTURES

THURSDAY 8 JUNE, from 4pm in the HOYLE LECTURE THEATRE, INSTITUTE OF ASTRONOMY

PRESENTED BY THE KAVLI INSTITUTE FOR COSMOLOGY, CAMBRIDGE & THE UNIVERSITY OF CAMBRIDGE

Daniel Eisenstein - Harvard University
Looking into the First Billion Years with JWST

The James Webb Space Telescope is giving us an unprecedented view into the early phases of galaxy formation. I will review the motivations for why a large cold infrared-optimized telescope in space has been the dream of high-redshift astronomers for 25 years and give a tour of some of the data. I'll then describe the JWST Advanced Deep Extragalactic Survey, which is performing very deep imaging and multi-object spectroscopy in the regions in and around the Hubble Deep Field and Ultra Deep Field, focusing on some of the early highlights from the survey, extending to z~13.

Image: JADES/GOODS-S, SWST/CIRCam

Image: Pablo Carlos Budassi

New Frontiers in Astrophysics: a KICC perspective
11:30, Friday 21 July 2023, in the Kavli - Martin Ryle Seminar room and online via Zoom. For more information visit: https://www.kicc.cam.ac.uk/events

Roman Rafikov (DAMTP)
Spirals, gaps, arcs and rings: substructures in protoplanetary discs shedding light on planet formation

Recent observations of multiple protoplanetary discs with ALMA and direct imaging in the near-IR revealed a richness of intricate substructures - gaps and rings, spirals, arcs, eccentric offsets, etc. A number of ideas have been proposed to explain the emergence of these structures, with the most exciting possibility being that their origin is related to the presence of the young planets in these discs. Indeed, it has been known for more than four decades that the gravitational coupling of an embedded planet and its protoplanetary disc has a strong effect on the orbital evolution of the planet and on the disc structure. I will cover some recent progress in our understanding of the disc-planet interaction, showing in particular that planets can indeed be the culprit behind the various substructures that we observe in the protoplanetary discs. I will also illustrate how these substructures can be used to constrain the properties of (yet unseen) planets causing them.

Image: Pablo Carlos Budassi

New Frontiers in Astrophysics: a KICC perspective
Friday 24 November 2023 at 11:30, in the Hoyle Lecture Theatre, IoA
(In-person/Streamed)

Miles Cranmer (IOA)
Effective Use of Machine Learning in Astrophysics

The field of machine learning (ML) offers a powerful set of frameworks for addressing complex problems in astrophysics, ranging from emulating expensive simulations to performing anomaly detection in large datasets. This talk explores a diverse range of ML applications within astrophysics, highlighting the role of these methods in extracting insights from multidimensional and multimodal datasets. I will also discuss the major challenges of ML, such as model robustness, interpretability, uncertainty estimation, and incorporation of physical priors. In all, this presentation will provide astronomers with a pragmatic overview of machine learning's capabilities and limitations, and how these techniques will continue to shape astrophysical discovery.

FRIDAY, 12 MAY 2023
A MULTI-SCALE VIEW OF
THE EPOCH OF REIONISATION

GALAXIES • AAYUSH SAXENA • UNIVERSITY OF OXFORD
IGM • LAURA KEATING • UNIVERSITY OF EDINBURGH
SIMULATIONS • HARLEY KATZ • UNIVERSITY OF OXFORD

KAVLI FOCUS

KAVLI FOCUS

4th & 5th December 2023
in the Hoyle Lecture Theatre, Institute of Astronomy
Day 1, 13:30-17:30 & Day 2, 09:30-17:00

The Milky Way and its high-redshift progenitors in theory and observations

Invited speakers:
Freeke van de Voort (Cardiff University), Ricardo Schiavon (Liverpool John Moores University), Robert Grand (Liverpool John Moores University), Hannah Übler (KICC)

(Please sign-up to take part in this event)

New Frontiers in Astrophysics: A KICC Perspective

Friday 03 March 2023 - *A New Theory of the Universe* - Neil Turok, University of Edinburgh

Friday 26 May 2023 - *Unveiling the Cosmic Dawn and the Epoch of Reionization with Radio Observations* - Eloy de Lera Acedo and Anastasia Fialkov (both University of Cambridge)

21 July 2023 - *Spirals, Gaps, Arcs and Rings: Substructures in Protoplanetary Discs Shedding Light on Planet Formation* - Roman Rafikov (University of Cambridge)

24th November 2023 - *Effective Use of Machine Learning in Astrophysics* - Miles Cranmer (University of Cambridge)

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

The *"New Frontiers in Astrophysics: A KICC Perspective"* talk series, in which (usually) local experts survey topics at the research frontiers of astrophysics and cosmology, continued into its second year with four exciting talks.

Kavli Science Focus Meetings

27 & 28 March 2023 - *Next Generation Surveys in the Rubin-LSST Era*

12 May 2023 - *A Multi-Scale View of the Epoch of Reionisation*

1 & 2 June 2023 - *Astrostatistics and Astro-Machine Learning*

4 & 5 December 2023 - *The Milky Way and its High-Redshift Progenitors in Theory and Observations*

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

The popular interdepartmental collaboration and networking series of *"Science Focus meetings"* continued with a wide variety of topics covered. The series also includes an *"Introduction to KICC"* meeting, which helps orient new arrivals and gives the opportunity for current KICC members to present and share their work with our members.

KICC 2023
Awards & Honours

Suhail Dhawan

ERC Starting Grant

Dr Suhail Dhawan, a Marie-Curie Postdoctoral Fellow and Kavli Institute Fellow, has been awarded a prestigious Starting Grant.

His ERC project is aimed at developing new methods to measure the present-day expansion rate of the universe – the Hubble constant – and its potential dependence on direction to search for new fundamental physics beyond the standard cosmological model.

The project will use two independent methods, the lensing of light from faraway supernovae and halo stars in nearby galaxies, to measure the Hubble constant with next-generation observatories like the Vera C. Rubin Observatory and JWST. The current prediction for the Hubble constant within the standard cosmological model, from the cosmic microwave background, disagrees with local-Universe measurements from pulsating stars.

Suhail's project will develop new methods to test whether this is a sign of exotic new cosmology, or unknown systematics with current measurements.

https://www.ast.cam.ac.uk/news/ioa-researcher-awarded-erc-starting-grant

Roberto Maiolino

ERC Advanced Grant

Professor Roberto Maiolino, former Director of the Kavli Institute, was awarded a second consecutive prestigious Advanced Grant from the European Research Council (ERC). Worth more than £2M, it will be used to pursue his research project 'RISEandFALL'. The first part (the 'Rise') is aimed at investigating the nature and properties of galaxies during their infancy, as well as their black hole seeds, in the early Universe. Particular emphasis will be given to the formation of the first stars, first black holes and the early chemical enrichment. The second part (the 'Fall') will explore the physical processes driving the subsequent galaxy evolution and transformation across the cosmic epochs, with focus on understanding the mechanisms responsible for the suppression of star formation.

To achieve these goals, Professor Maiolino will use new data coming from the revolutionary James Webb Space Telescope, and from MOONS, the next-generation multi-object near-infrared spectrograph for the Very Large Telescope. The information coming from these facilities will also be combined with data coming from the Atacama Large Millimetre Telescope (ALMA), the largest telescope operating in the (sub-)millimetre band.

The project will be developed between 2023 and 2028, and the funds will be primarily used to support postdoctoral researchers and students working on the project at the Department of Physics and at the Kavli Institute.

https://www.kicc.cam.ac.uk/news/professor-roberto-maiolino-awarded-his-second-erc-advanced-grant

Eloy de Lera Acedo

ERC Consolidator Grant

Dr Eloy De Lera Acedo, an Associate Professor in the Department of Physics and the Kavli Institute, has been awarded an ERC Consolidator grant for his project REACH_21: Probing the Cosmic Dawn and Epoch of Re-ionization with the REACH experiment.

De Lera Acedo said "*REACH_21 aims at unveiling the mysteries of the infant Universe, when the cosmos evolved from dark and simple after the Big Bang to the complex and luminous realm of celestial objects we can see today from Earth. How did this happen? This unknown missing piece in the puzzle of the history of the Universe is now closer to being understood thanks to a new experimental approach attempting to observe extremely faint radio signals emitted nearly 13.5 billion years ago by the most abundant element at the time: neutral hydrogen.*"

He went on to note that "*This funding is amazing news for the REACH Collaboration. We have been working for over five years designing our experiment, currently awaiting start of scientific observations in South Africa, and this ERC grant is now going to allow us to use the REACH telescope, analyse its data, and hopefully access a whole new world of information about the early evolution of the cosmos.*"

https://www.cam.ac.uk/news/cambridge-researchers-awarded-european-research-council-consolidator-grants

KICC 2023
Awards & Honours

Alexandra Amon

2023 Royal Astronomical Society Winton Award and British Science Association Award 2023

Dr Alexandra Amon, Kavli Institute Senior Fellow, has been awarded the 2023 RAS Winton Award *"for her leadership, mentorship, and wide-ranging scientific contributions"* in the field of weak gravitational lensing.

This early-career award for early achievement in astronomy is for research by an individual in a UK institution whose career has shown the most promising development within five years of completing their PhD (including emerging areas).

Alex is also one of seven winners of the prestigious British Science Association (BSA) Award Lecture series for 2023. In her Physical Sciences and Mathematics Award Lecture, she explained why dark matter is important, and how we peer deep into the Universe to learn more.

In September 2023, Alex moved to Princeton University as an Assistant Professor.

https://ras.ac.uk/news-and-press/news/royal-astronomical-society-unveils-2023-award-winners

https://www.britishscienceassociation.org/News/award-lectures-british-science-festival-2023

Roberto Maiolino

Blaauw Professor
at the
University of Groningen

In December 2023, Roberto Maiolino was appointed Blaauw Professor for 2024 at the University of Groningen. This is an honorary professorship in the field of Astronomy and Astrophysics at the Kapteyn Astronomical Institute in the Netherlands.

This appointment will foster collaborations between the Kavli Institute and the Kapteyn Institute in multiple areas of common interest and, in particular, the exploration of galaxy formation and their interplay with the growth of black holes across cosmic time. In the Blaauw Lecture, which will be held Tuesday 12 November 2024, Professor Maiolino will give an overview of Webb's exciting findings in the first two years of operations, from the characterisation of the atmospheres of planets in other solar systems to the discovery of the first galaxies and black holes in the primaeval universe.

https://www.rug.nl/research/kapteyn/blaauw/blaauw-lecture-2024

George Efstathiou

Biermann
Lecture
2023

In July 2023, founding KICC Director Professor George Efstathiou gave the 2023 Biermann Lectures at the Max Planck Institute for Astrophysics. With the overall title *"Do we have a standard model of cosmology?"* he gave three lectures focusing on "*'The ΛCDM cosmology*", "*Tensions in cosmology?*" and "*Cosmology in crisis*". George explained how ΛCDM cosmology became the standard model for cosmology, its limitations, and how it might evolve in the future

In the 1980s, Simon White, Carlos Frenk and Marc Davis teamed up with George to find an explanation for the large-scale structures observed in the galaxy distribution – establishing *"cold dark matter"* as the standard model of cosmology. Even though inflation and dark energy had to be incorporated in later years, the basic framework still stands.

https://www.mpa-garching.mpg.de/1074837/biermann-2023

KICC 2023

Graduating Students

Many congratulations to the following graduate students at KICC who successfully defended their Master's or PhD theses in 2023.

Erik Rosenberg
PhD Thesis Title:
CMB Analysis with ACT and Planck

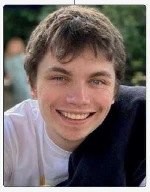
Supervisor:
Steven Gratton
Current position:
Postdoctoral research associate, University of Manchester.

Jenny Wan
Master's Thesis Title:
Decoding the Variability in Galaxy Star-Formation Histories

Supervisor:
Sandro Tacchella
Current position:
PhD student, Stanford University.

Danielle Dineen
Master's Thesis Title:
Cosmological Matching Conditions for Primordial Perturbations

Supervisor:
Will Handley
Current position:
PhD student, University of Toronto with the Canadian Institute for Theoretical Astrophysics (CITA).

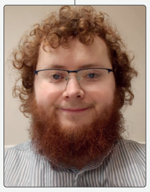


Harry Bevins

PhD Thesis Title:

A Machine Learning- Enhanced Toolbox for Bayesian 21-cm Data Analysis and Constraints on the Astrophysics of the Early Universe

Supervisor:
Eloy De Lera Acedo, Will Handley, Anastasia Fialkov
Current position:
Kavli Institute Fellow, KICC.



Dominic Anstey

PhD Thesis Title:

Data Analysis in Global 21 cm Experiments: Physically Motivated Bayesian Modelling Techniques

Supervisor:
Eloy De Lera Acedo and Will Handley
Current position:
Postdoctoral Research Associate, University of Cambridge.

John Cumner

PhD Thesis Title:

Numerical Modelling and Design of Wideband Electromagnetic Structures at Radio Frequencies: Applications in Cosmology and Digital Communications

Supervisor:
Eloy De Lera Acedo
Current position:
Postdoctoral Research Associate, University of Cambridge.

Frank J. Qu

PhD Thesis Title:

The Universe Through a Magnifying Glass: Precision Cosmology with CMB Lensing

Supervisor:
Blake Sherwin
Current position:
Postdoctoral Fellow, University of Cambridge (KIPAC Fellow, Stanford University, from autumn 2024).

KAVLI FELLOWS : 2023 LEAVERS

During 2023 we said goodbye to five Kavli Fellows as they moved onto the exciting next stages of their careers. We wish them every success and are delighted to be continuing to collaborate with many of them in their new positions.

> “I spent four years at KICC, and I consider myself fortunate to have been there when the first images and spectra from the James Webb Space Telescope were released on July 14, 2022. Following that date, all conversations near the (excellent) coffee machine were around JWST discoveries. I have no doubt that being part of KICC has significantly influenced my career and played a crucial role in securing the position in the South of France that I had been pursuing for nearly a decade.”

Nicolas Laporte
Current position:
Assistant Astronomer (faculty), Laboratoire d’Astrophysique de Marseille of the Aix-Marseille University.

Michalis Agathos
Current position:
Lecturer of Mathematics, Queen Mary University of London.

Alexandra Amon
Current position:
Assistant Professor of Astrophysical Sciences, Princeton University.

“I became a Kavli Fellow in 2018. Previously I was a postdoc, based in KICC since its opening, working as part of the Cambridge Planck team. My fellowship enabled me to complete my decade-long work learning about the Universe with Planck, both on large angular scales through the development of my “momento” likelihood, and on small angular scales working with Prof. George Efstathiou, also based in KICC, on the “CamSpec” likelihood. The award allowed me to take on my first PhD student as primary supervisor. My computing, research and graduate-level teaching experience as a Kavli Fellow qualified me in April 2023 to become a Senior Teaching Associate for the new MPhil. in Data Intensive Science course at the University of Cambridge, which took its first students in October 2023. Albeit now based in DAMTP, I retain strong links with KICC, visiting regularly throughout the week for seminars, talks and research discussions with my friends and colleagues.”

“My time as a Kavli Fellow at KICC was very rewarding, and I particularly valued the interactions that KICC fostered between students, postdocs, and staff. I learned a lot from my Cavendish and DAMTP colleagues, and also had loads of opportunities to share my work with them.”

Steven Gratton
Current position:
Senior Teaching
Associate and Industry
Training Coordinator,
DAMTP, University
of Cambridge.

Matt Auger-Williams
Current position:
Software Engineer,
Observatory
Sciences, Ltd.

Matthew Bothwell &
Hannah Strathern

KICC 2023
Public Outreach

New Outreach Facilitator

In 2023, we were joined by Hannah Strathern, the new cross-departmental Outreach Facilitator who will be supporting public-engagement activities across KICC and the Institute of Astronomy, as well as DAMTP and Cavendish Astrophysics. Hannah's role is to provide administrative support and project management for all astronomy outreach activities run from these departments.

Hannah is helping us expand our existing outreach efforts, working with schools across East Anglia to spread the reach of our AstroEast program, as well as designing exciting new initiatives (which in 2024 will include a residential Space Camp in Cambridge, run in collaboration with the National Space Academy).

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 2023, we have run astronomy education sessions for more than 1500 pupils.

Cambridge Festival

Across the two weeks of the Cambridge Festival, the University engages with the public showcasing a wide range of cutting-edge research happening at Cambridge. In 2023 we saw the full return of the indoor and outdoor KICC+IoA Open Day, as it was before COVID. We ran a range of drop-in activities designed to entertain and educate the public about our astronomical research. As always our Open Day was enormously popular, with around 1000 members of the public visiting over the course of the afternoon.

CAMBRIDGE
FESTIVAL

Cambridge LaunchPad

The KICC (alongside the Institute of Astronomy) is a partner institution working with Cambridge LaunchPad (**https://cambridge-launchpad.com**), a non-profit social enterprise that aims to inspire and enthuse young people about STEM and to address the significant gender gap that exists in STEM employment.

As a Cambridge LaunchPad partner, we host groups of students for single-day workshops. Partnering with Cambridge LaunchPad provides the advantage that many logistics – transport, computing, etc. – are provided by Cambridge LaunchPad; as such, schools with limited resources (such as for transport) face no barrier to entry. As these workshops are more extended than our normal school visits, we have worked with Cambridge LaunchPad to design a suitable curriculum, consisting of taught material and hands-on activities, designed to promote Kavli research themes. During 2023, we hosted six primary-school workshops, delivering a day of activities related to exoplanetary research to 180 children (aged 9–11).

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 2023 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