UNIVERSITY OF CAMBRIDGE

KICC ANNUAL REPORT, 2022

KAVLI INSTITUTE FOR COSMOLOGY, CAMBRIDGE

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COSMOLOGY
GALAXIES
ASTROSTATISTICS
EXOPLANETS
GRAVITATIONAL WAVES

Prof. Anthony Challinor

Message from the Director

Welcome to the 2022 report from the Kavli Institute for Cosmology, Cambridge. I hope you will enjoy reading about some of the many research highlights from our members and the activities that we have supported in the past year.

There has been a real buzz around the Institute this year. A full 12 months with no COVID-related restrictions meant most people were back working in their offices and greatly enjoying in-person scientific interactions, many visitors were welcomed through our doors once again, and seminars and workshops returned to their regular format. Adding to the buzz has been the huge excitement around the early data from the James Webb Space Telescope, following the successful launch in December 2021 and the first release of its spectacular images in July 2022. Our large group of researchers working on the formation and evolution of galaxies has already made major discoveries with these data, including spectroscopically confirming the most distant galaxies observed in the Universe, which date back to less than 350 million years after the Big Bang. Our understanding of the properties of the first galaxies will continue to be transformed through the JADES survey. This is the most extensive survey to be conducted in the first few years of JWST operations and is co-led by former KICC Director, Roberto Maiolino. You can read more about progress and plans for the JADES survey, and other remarkable discoveries with JWST data, in dedicated articles in this report.

The work of our members has continued to be recognised with prizes and awards. At the start of the year, George Efstathiou was named as the recipient of the Royal Astronomical Society's Gold Medal, the highest honour awarded by the Society. In further great news, Roberto Maiolino was elected Fellow of the Royal Society. In addition, Kavli Institute Senior Fellow Alex Amon received the Tollestrup Award for Postdoctoral Research for her work on weak gravitational lensing with the Dark Energy Survey, and was also awarded the 2022 Caroline Herschel Prize Lectureship from the Royal Astronomical Society. Many congratulations to them all on these fantastic achievements.

We were delighted to welcome Dr Sandro Tacchella to the Kavli Institute in April 2022 as a new Assistant Professor in the Department of Physics. Sandro is a well-known expert in galaxy evolution and has made key contributions to understanding the mechanisms and physical processes driving the formation, evolution, and transformation of galaxies across cosmic epochs. At the end of September, George Efstathiou retired from his University position as Professor of Astrophysics (1909) at the Institute of Astronomy. George played a pivotal role in the establishment of the Kavli Institute and served as its founding Director from 2008–2016. Throughout his very distinguished career, George has made profound contributions to an unusually wide range of topics in extragalactic astrophysics and cosmology. We all wish George a long and happy "retirement", although, judging from the first few months, he may be busier and more in demand than ever!

Tempering the highs of the year, we were all shocked and saddened by the news in June that our colleague, Professor Richard Hills, had passed away aged 76. Richard, who was emeritus Professor of Radio Astronomy in the Department of Physics, was a great friend and supporter of the Kavli Institute. You can read more about his exceptional career in experimental and observational sub-mm astronomy in the short obituary that appears in this report. Members of the Kavli Institute are planning a conference in Richard's honour, "Raising the veil on star formation near and far", to be held in April 2024.

The Kavli Institute hosted, or supported, a wide variety of events in 2022. International workshops included "The epoch of galaxy quenching" held at KICC and "Key challenges in galaxy and CMB lensing" held in DAMTP and co-supported by the Centre for Theoretical Cosmology. We started a new "Frontiers" talk-and-lunch series aimed at bringing together astrophysicists from across Cambridge to share exciting developments at the frontiers of research and explore future directions. Topics ranged from "Decoding the origin of the elements", by visitor David Weinberg, to "Do we have a standard model of cosmology?" by George Efstathiou. Our successful Kavli Focus Events continued to attract much interest. These are, typically, day-long internal meetings, proposed by our members, focussed on a specific interdisciplinary research topic; in 2022 these included "Observational and theoretical 21-cm cosmology" and "Baryons and cosmology".

In-person public-engagement activities ramped up again under the leadership of Dr Matt Bothwell, our Kavli Outreach Officer. These included an expansion of the flagship "AstroEast" programme, the return of the annual IoA/KICC public open day, and innovative ways of communicating the magic of astronomy to the visually impaired. See Matt's article in this report for further details. Finally, we were delighted to welcome over 80 academic visitors throughout the year to work with our students and staff.

Let me close by thanking all those who help make the Kavli Institute such a special place to work or visit: the professional-services staff at the Institute of Astronomy and Departments of Physics and of Applied Mathematics and Theoretical Physics, our graduate students, postdoctoral researchers and research fellows, and faculty members. I am particularly grateful to be working alongside Debora Sijacki, the Deputy Director, and Steven Brereton and Alison Wilson, our wonderful team of Kavli Institute Administrators. I gratefully acknowledge the continued financial and strategic support provided by the Kavli Foundation. For several years, Dr Chris Martin has been our main point of contact with the Kavli Foundation in his role as Director of Physical Sciences. As Chris has now moved on to pursue new ventures, we thank him for all his support and guidance and wish him success for the next stage of his career.

Enrico Pajer

A Timeless History of Time

It is a remarkable fact about our Universe that the spatial distribution of radiation and matter across the cosmos was determined during the first fraction of a second of the big bang. For the past 40 years, scientists have been trying to predict this distribution by postulating a phase of extremely fast and accelerated expansion in the very early Universe known as inflation. Whatever substance was responsible for inflation is called an "inflaton". It is the inflaton's distribution in space that eventually provides the seed for the distribution of radiation and matter that we observe today. A host of models of inflation have been proposed and many are compatible with all current cosmological data.

But there is a catch: no one was around during inflation to monitor what the inflaton was actually doing. We can only observe the state of the Universe at the end of inflation. Any two different models that agree on the final state of the Universe at the end of inflation are indistinguishable to us. Moreover, even assuming a concrete model, we face a serious computational challenge when trying to determine the precise distribution of the inflaton that it generates. Even a crude estimate requires performing a series of nested integrals in time of special functions with intricate properties. Last, but not least, even when we do come up with an answer, it is not straightforward to extract general lessons from it that generalise to other models.

In the past few years, we have been developing an alternative approach, known as the cosmological bootstrap, to overcome the above difficulties and derive new and more general predictions to be tested in cosmological surveys. The main idea is to tackle the following hard question: how do we know if a given set of predictions is compatible with general principles of physics? A few examples shed light on how we have made progress on this front.

Probabilities must land between 0 and 1, with the probabilities of all possible events always summing to one. This very simple observation has profound consequences in any quantum theory. This is because quantum theories derive probabilistic predictions from quantum "amplitudes", which are complex as opposed to real numbers. Demanding that quantum amplitudes combine to give meaningful classical probabilities leads to powerful constraints. For example, in particle physics these constraints have been known since the 1960s and have played a key role in pretty much all developments in the field. Because inflation relies on quantum theories, many expected similar restrictions, but nobody was able to derive them. In 2020, however, our group made a breakthrough on this problem by deriving an infinite set of relations on the final distribution of radiation and matter, which must be satisfied by a consistent quantum theory (Fig. 1). This has been the starting point of much further progress on the theoretical and observational side. We were able to show that these constraints have very concrete implications. For example, they predict that, under certain reasonable assumptions, the distribution of galaxies must be statistically indistinguishable from its mirror image.

Fig. 1: An artistic AI rendering (DALL-E) of how the quantum conservation of probability restricts the possible spatial distribution of light and matter across the cosmos.

Another cherished principle of physics, known as causality, simply states that we cannot affect the past. The way a causal system reacts to a perturbation is highly restricted. In mathematical terms, one discovers that only a very restricted class of functions, known as analytic functions, are allowed to describe the behaviour of the system. Remarkably, we recently proved that this powerful connection operates in the very early Universe as well. Only analytic functions can appear as predictions for the distribution of radiation and matter. This rigidity goes a long way. For example, it tells us that even if we are not able to observe certain properties of the distribution of radiation and matter, we can nevertheless determine them from other data we have collected.

While much progress has taken place in just a few years, we cannot help feeling that this is just the tip of a cosmological iceberg. General properties of the predictions of inflation are yet to be revealed but can be discovered following the trail of general principles of physics. This new understanding leads directly to new signals to be searched for in the sky, and to new ways to extract information from cosmological data.

Roger de Belsunce, George Efstathiou & Steven Gratton

Learning more about the Galaxy and the Universe with an Advanced Analysis of Planck Satellite Data

The Planck satellite was launched in May 2009 and scanned the sky over a period of years to build up maps of the emission of our Galaxy, other galaxies and the early Universe at multiple frequencies in the microwave band of the electromagnetic spectrum. Planck measured both the intensity and the polarization of this incoming radiation, with the main target being the cosmic microwave background (CMB).

The Planck collaboration, which included several members of KICC, presented their increasing understanding of these data and their science implications through a series of releases over the following decade. A small French team, however, continued working on improving the quality of the sky maps made from the Planck data even after the formal end of the Planck collaboration, and made their "SRoll2" products publicly available in 2019 for the community to use.

Also, over the past few years we at KICC have developed a theory of how best to "disentangle" observed maps efficiently back into their constituent physical components. Compared to some previous approaches, the main time saving of this "component-separation" method comes from focussing on finding the "best-fit" decomposition first and then calculating uncertainties around that best-fit, rather than trying to deduce a full distribution of possibilities in one go. This is not only faster but much less computationally demanding.

Using both the new maps and the new component-separation method it has thus been possible to refine our knowledge about the Galaxy and the Universe.

On the Galactic side, we have found evidence for spectral index variations in the polarization of the synchrotron emission from our Galaxy. Synchrotron radiation is one of the main sources of signal from the Galaxy, emitted from electrons spiralling in the Galaxy's magnetic field. Such spirals have a direction, so the light from electrons in a particular region is preferentially emitted in a particular polarization state, giving a relatively highly polarized signal. Synchrotron emission also varies with wavelength, being brighter at lower frequencies. Just how much brighter is described by the spectral index parameter. This parameter does not necessarily have to be the same looking through different parts of the Galaxy, reflecting the potentially different physical conditions there.

In looking for such variations, one needs to start with a "prior" on what sorts of variations are plausible, and the speed of our method allowed us to check the robustness of our results with respect to the assumptions made. We were thus able to see that priors previously used in the literature were rather restrictive and actually prevented some analyses from ever seeing such effects. In our synchrotron spectral-index variation maps (see Fig. 1) we were able to pick out ring-like structures that correlate with the loops seen in low-frequency radio surveys of the Galaxy, coming from remnants of nearby supernovae.

On the Universe side, we have been able to provide reasonable constraints on primordial "B-modes". B-modes are particular patterns in the sky polarization signal. They are of particular interest because the main known way of generating them on large scales is from a period of high-energy "inflation" (accelerated expansion) in the early Universe. Bounding the size of the B-modes, therefore, puts constraints on theories of inflation.

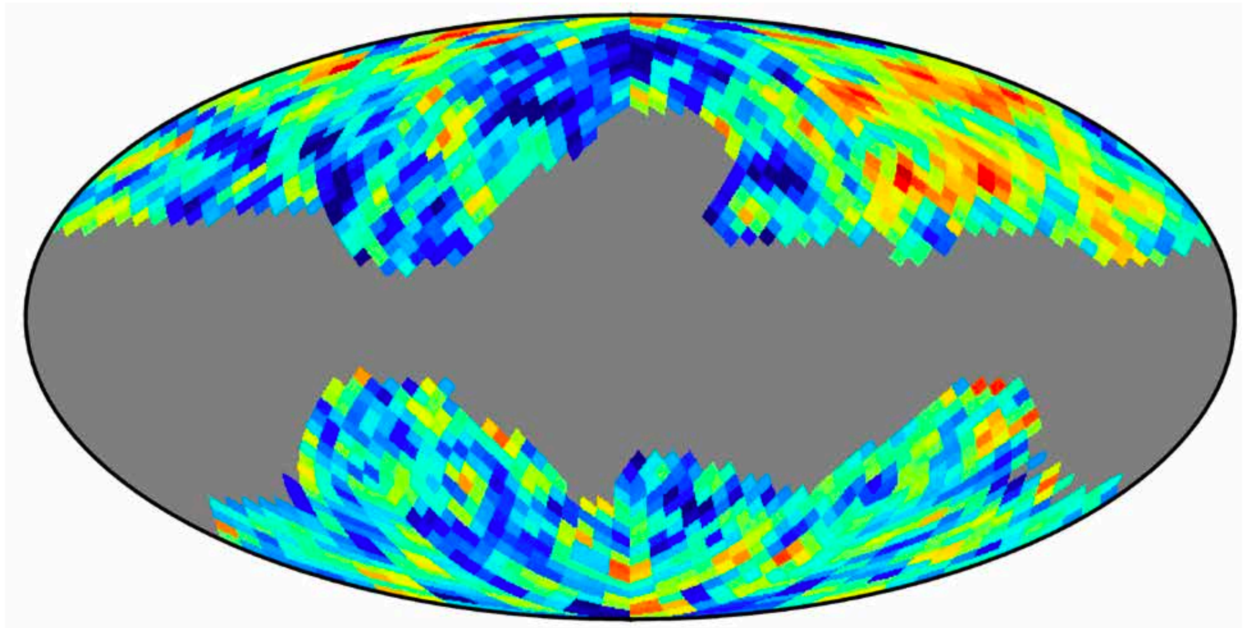


Fig. 1: Sky map of the spectral index of the polarized synchrotron emission found with SRoll2 maps using the authors' component-separation method.

As well as the foreground components, our component separation procedure also delivered CMB polarization maps suitable for use in constraining inflation. In addition, the procedure generated the uncertainties in the maps, with contributions both from instrument noise but also from ambiguities in the separation itself.

Our constraints on inflationary models turned out to be significantly weaker than some that have been claimed in the literature from Planck data. They are, however, what one might expect from estimates of noise levels in the Planck data.

With the publication of these results the baton for the analysis of the microwave sky is now passed on from Planck to the next generation of telescopes, including the BICEP Array at the South Pole and the Simons Observatory in the Atacama desert in Chile, and the Litebird satellite mission of the Japanese Space Agency JAXA.

This article is partly based on results published as De Belsunce R., Gratton S. and Efstathiou G., MNRAS 517, 2855 (2022) and De Belsunce R., Gratton S. and Efstathiou G., MNRAS 518, 3675 (2023).


Anthony Challinor & Blake Sherwin

Searching for Our Cosmic Origins with the Simons Observatory

The cosmic microwave background (CMB) is the thermal relic radiation from the very early universe. The small fluctuations in its temperature and its linear polarization provide a snapshot of conditions when the universe was only 400,000 years old and less than one-thousandth of its current size. Being established at such early times, these primary anisotropies provide our cleanest probe of the early universe and our most direct connection to the primordial perturbations, widely thought to be generated in a period of cosmic inflation. In addition, in passing through all the large-scale structures in the visible universe, further fluctuations are imprinted in the CMB due to gravitational and scattering processes. With these secondary anisotropies, we can probe the more recent universe with CMB observations, allowing us, for example, to track the growth of structure across cosmic time.

Measurements by the Planck satellite (for which KICC researchers played a leading role in their interpretation) exhausted the information in the temperature fluctuations on primordial cosmology. However, there is still much to learn from more sensitive measurements of the polarization of the CMB on all angular scales and of the temperature secondary anisotropies on arcminute scales, which were not resolved by Planck. In particular, if inflation happened at sufficiently high energy, quantum fluctuations in the metric of spacetime should be stretched and amplified resulting in a stochastic background of primordial gravitational waves that would leave an observable imprint through a curl-like, or B-mode, component of the CMB polarization. Such B-modes of primordial origin are yet to be detected, although upper limits from the BICEP family of telescopes operating from the South Pole have already ruled out many simple models of inflation.

The Simons Observatory (SO) is a new US-led CMB observatory being deployed in the Atacama Desert in Chile, at an altitude of more than 5000 metres. SO builds on the rich heritage of CMB experiments that have operated at this site, including the Atacama Cosmology Telescope (ACT) and POLARBEAR. The new observatory comprises three small-aperture telescopes (SATs) targeting degree-scale measurements of primordial B-mode polarization, and one six-metre large-aperture telescope (LAT) that will conduct a survey of half of the sky at arcminute resolution to measure temperature and polarization on smaller scales. This wide survey will address a range of unsolved questions including the nature of neutrinos and other relativistic species, and the physics giving rise to the observed accelerated expansion of the Universe. As of Spring 2023, the LAT and its giant cryogenic receiver have arrived on site (the telescope mirror will follow later in the year), the three platforms for the SATs have been installed (see Fig. 1) and the first SAT is being shipped to site. First observations from two of the SATs, both operating at 90 and 150 GHz, should commence in Autumn 2023, with full operations of the observatory starting in early 2024.

A major addition to the nominal Simons Observatory has recently been funded in the UK by UKRI and STFC. SO:UK, a consortium of six UK universities including the University of Cambridge, will deliver two further SATs, providing a significant increase in sensitivity to primordial B-mode polarization, and lead major components of the data management and data processing. Our colleagues in Japan have also been successful in securing funding for a further SAT, making six in total. The UK SATs are expected to be deployed in a phased manner over the next three years.

Fig. 1: Two of the three SATs, and their associated ground screens, on site in Chile. SO:UK will add a further two SATs and Japanese colleagues will provide a further one, totalling six.

KICC researchers play a major role in SO, particularly leading analysis activities in CMB lensing science, making precise measurements of the gravitational deflections of the CMB light as it passes through large-scale structures, and Sunyaev–Zel'dovich science, exploiting scattering of the CMB from ionized gas in galaxy clusters and from bulk flows. Within SO:UK, Cambridge's role is to assess the quality of maps from the LAT for reconstructing the subtle effects of gravitational lensing in the CMB and to contribute to the simulation effort needed to interpret these maps. We will develop tools for lensing quality assurance, making extensive use of the redundancy of the SO LAT data to perform suites of null-tests that characterise potential residual systematic effects that might affect the lensing measurements. Indeed, many such tools under development for SO are currently being applied to ACT data, as its most recent wide survey closely mimics the forthcoming SO LAT survey, albeit with lower sensitivity. Exciting new CMB lensing science results and data products from ACT will be released in 2023. The map in Fig. 2 is an example, showing (in projection) the distribution of all of the matter in the universe out to distances of billions of light years, as revealed by CMB lensing.

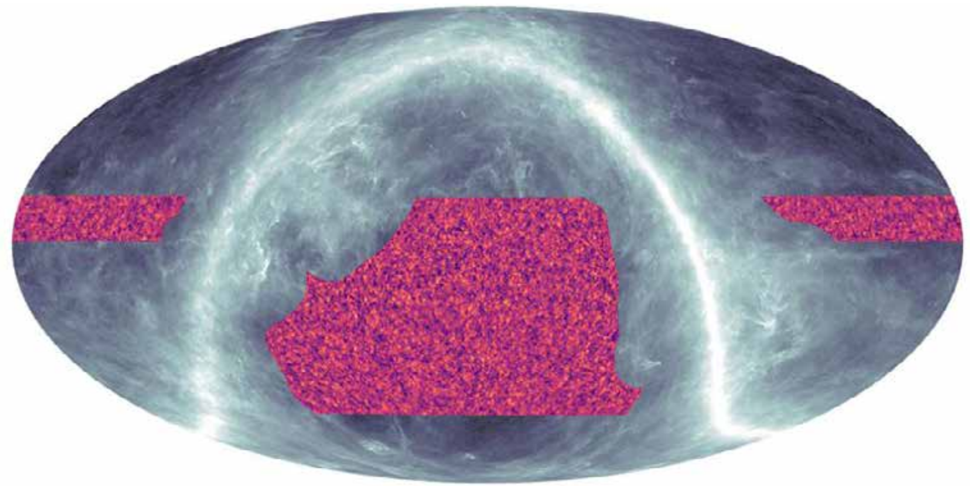


Fig. 2: New map of the projected matter distribution as traced by CMB lensing extracted from ACT data. Orange regions correspond to over-densities, purple to under-densities. The greyscale background shows dust emission from the Galaxy, as measured by Planck. Credit: ACT Collaboration.


Anastasia Fialkov & Eloy de Lera Acedo

21-cm Cosmolgy

KICC is very active in theoretical and observational 21-cm cosmology: we are developing state-of-the-art models of the 21-cm signal from cosmic dawn and the epoch of reionization, considering some of the subtle effects for the first time. Cambridge is also leading in several radio telescopes including the current HERA and the future SKA interferometers, and the home-grown REACH radiometer. We are also leading the field developing new Bayesian-based data analysis techniques.

Properties of the very first stars (Population III stars), such as their masses, are poorly constrained by existing observations, such as stellar archeology, with the cosmic dawn 21-cm signal of neutral hydrogen predicted to be a unique and new probe of the early stellar physics. We have recently studied the impact of the masses of the first stars on the 21-cm signal. More specifically, we looked at different possible distributions of stellar masses (the initial mass function, or IMF, of stars) for the first population of stars formed a few tens of millions of years after the Big Bang. The cosmological 21-cm signal is predicted to be sensitive to Lyman-band photons produced by these stars, thus providing a unique way to probe the first stellar population. We calculate the emission spectra (Fig. 1) of star-forming halos for different possible IMFs by integrating over individual metal-free stellar spectra, computed from a set of stellar-evolution histories and stellar atmospheres, and taking into account variability of the spectra with stellar age. Exploring a variety of possible IMFs, we show that variations in the 21-cm signal are driven by stars lighter than 20 Solar masses. For the models explored, we find maximum relative differences of approximately a hundred percent in the cosmic dawn signals. This effect is expected to grow once the impact of the IMF on X-ray sources is included (ongoing work). Although this impact is modest, precise modelling of the first stars and their evolution is necessary for accurate prediction and interpretation of the 21-cm signal.

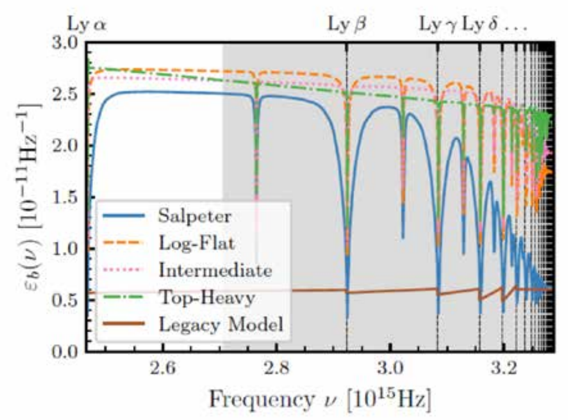


Fig. 1

Fig.1: Photon-number emissivity per stellar baryon in the Lyman band for our example IMFs compared to a model widely used in the literature (labelled as Legacy model). Figure from Gessey-Jones et al. (2022).

Fig.2: Comparison of the constraints from the SARAS2 analysis (Bevins et al. 2022b) and the SARAS3 analysis (Bevins et al. 2022a). The Kullback–Leibler divergence in the bottom panel shows that the SARAS3 data provide tighter constraints on these astrophysical models with an additional radio background at redshift $z > 10$ and the SARAS2 data at $z < 10$. Figure from Bevins et al. (2022a).

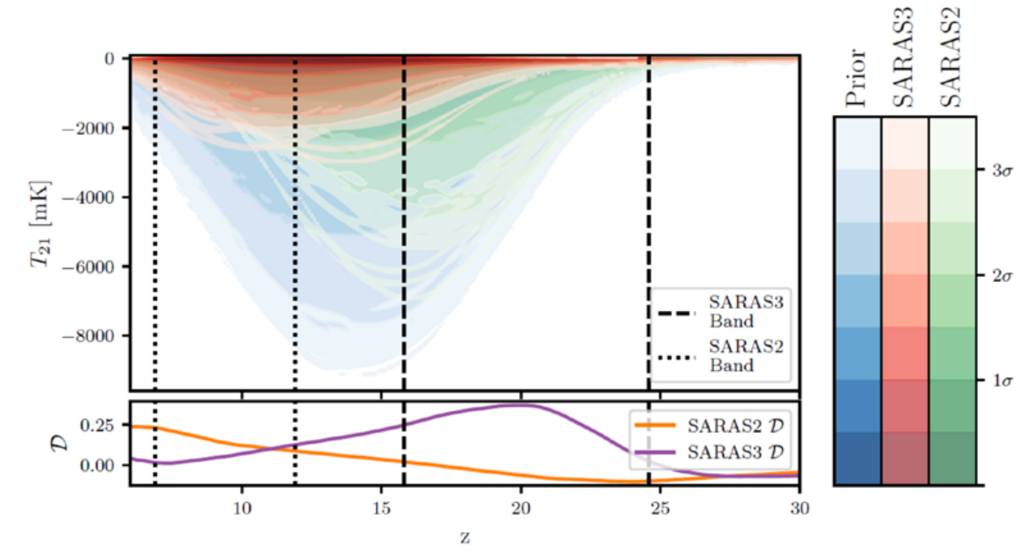


Fig. 2

The existing upper limits on the 21-cm signal coming from the HERA, LOFAR, LWA, SARAS and EDGES radio telescopes, although still very weak, can already improve our understanding of the early Universe. In a series of papers, we explored the power of these limits by considering models with an extra radio background in addition to the cosmic microwave background (CMB). Such a radio background can be produced either by astrophysical sources at early times or by exotic processes (e.g., decay of dark matter) and increases the intensity of the 21-cm signal (compared to the CMB-only case).

We used the data recently collected by the SARAS3 and HERA radio telescopes to constrain star formation and X-ray heating mechanisms at cosmic dawn. From the first analysis of SARAS3 data (Fig. 2), we constrain a population of radio-luminous galaxies approximately 200 million years after the Big Bang. We find, using Bayesian data analysis, that the data disfavours (at 68% confidence) radio-luminous galaxies in dark matter halos with masses between 4.4×10^5 Solar masses and 1.1×10^7 Solar masses and galaxies in which more than 5% of the gas is converted into stars. The data disfavour galaxies a thousand times brighter than today in radio, and, separately, a synchrotron radio background in excess of the CMB by more than 6% at 1.42 GHz. Constraints on the global high-redshift 21-cm signal in these models from analysing the SARAS3 (and the earlier SARAS2) data are shown in Fig. 2.

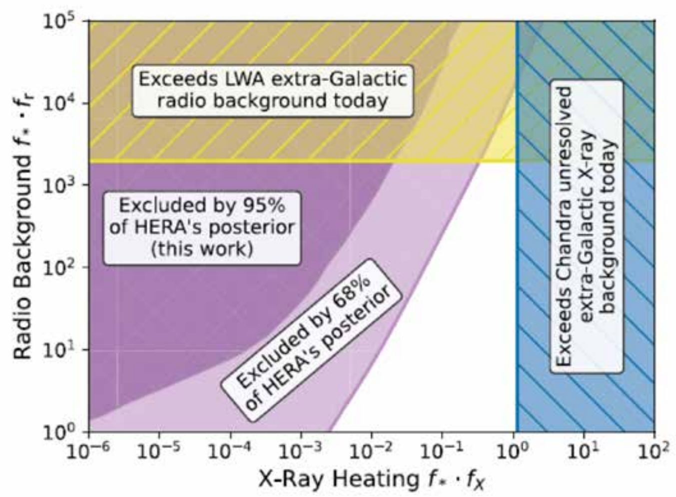


Fig. 3

Fig.3: Constraints on the model parameters associated with radio background and X-ray heating for models with excess high-redshift radio background. We show the constraints derived from the upper limits on the 21-cm power spectrum by HERA (purple) and compare them to the limits on the radio background directly measured by the LWA (blue) and X-ray background measurements by the Chandra X-ray satellite (yellow). Via its limit on the 21-cm signal, HERA provides complementary constraints on the amount of heating and radio background. Figure from HERA Collaboration (2023).

continued

21-cm Cosmolgy

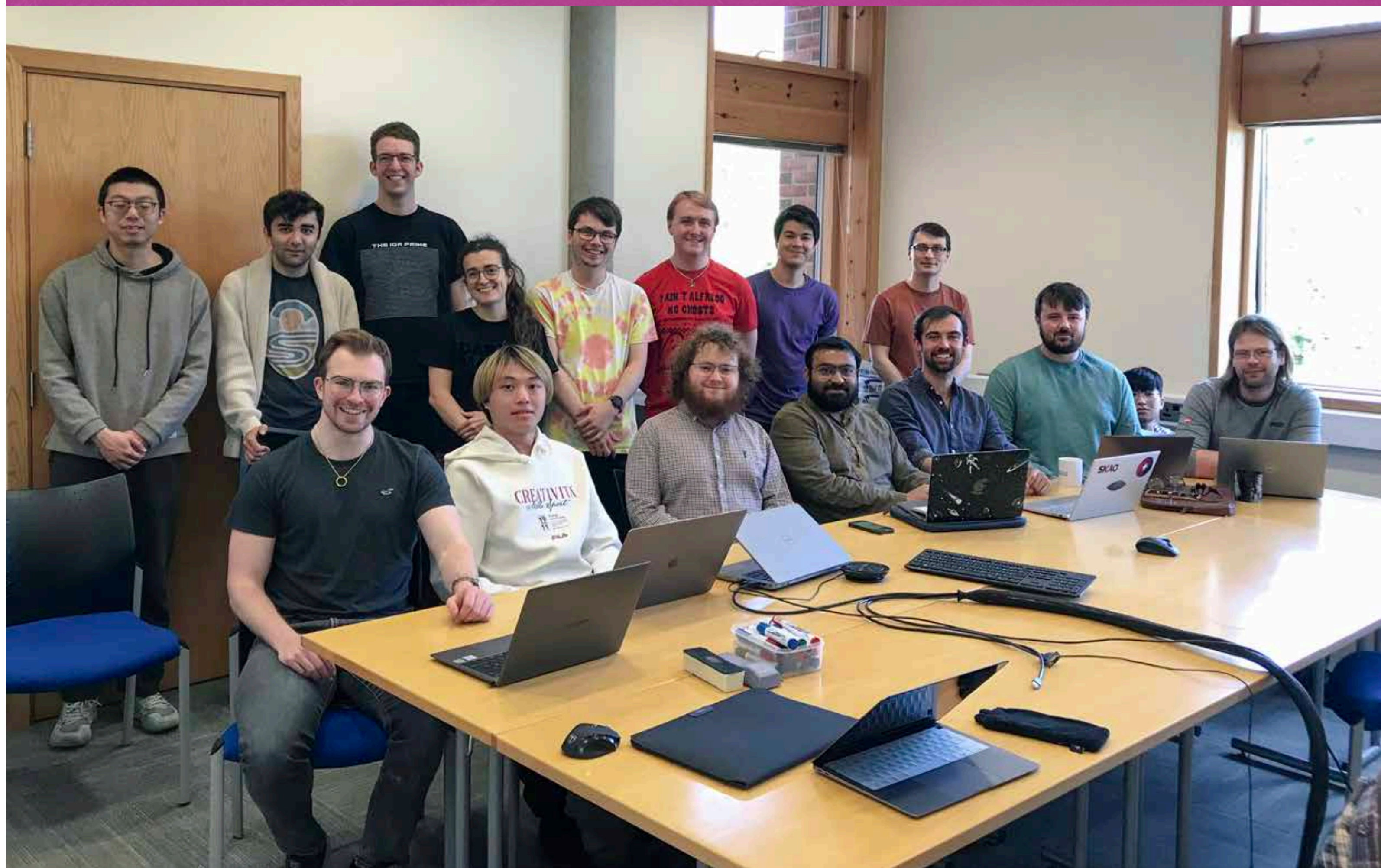
HERA is a radio interferometer measuring fluctuations in the 21-cm signal, and, thus, provides constraints complementary to those of SARAS2 and SARAS3, which are measuring the sky-averaged power. In our recent papers we considered implications of HERA upper limits on the 21-cm fluctuation power spectrum. Models with excess high-redshift radio background can produce much larger power spectra than the standard scenario where the 21-cm brightness temperature is seen in contrast to the CMB. However, such models without accompanying X-ray heating of the intergalactic medium are excluded by HERA. In Fig. 3 we show the region of parameter space disfavoured by the HERA upper limits, as well as regions inconsistent with either the radio background measurements by the Long Wavelength Array (LWA) telescope or Chandra's X-ray background measurements. Between the constraints by HERA and Chandra, models where the extragalactic radio background observed by the LWA is entirely explained by emission at redshift $z > 8$ are disfavoured but not entirely excluded.

In the summer of 2023 we will start observations with the home-grown REACH (Radiometer for the Analysis of Cosmic Hydrogen; see Fig. 4) experiment, partially funded by KICC. REACH, from its location in the Karoo radio reserve (South Africa), aims at a first confident detection of the sky-averaged 21-cm signal from the cosmic dawn. The EDGES experiment shook the field in 2018, reporting a cosmological signal twice as deep as expected and which would require exotic physics to be explained. This has been contested by several groups amid concerns on the data analysis and potential impact of hardware systematic signals, including recent measurements from the SARAS3 experiment incompatible with the EDGES findings. The contamination from instrument systematics is the main bottleneck for these first-generation 21-cm radio telescopes. Aiming to resolve these concerns, a new experimental approach has emerged over the last five years giving rise to a second generation of experiments. REACH is a sky-averaged experiment leading this new wave of instruments, where the focus has shifted to a data-driven hardware and algorithm design emphasising the detection and isolation of instrumental systematic signals. To this end, REACH uses a fully Bayesian data pipeline to fit jointly instrument models with models of the sky signals. REACH has participation from 17 institutions worldwide, including over 20 researchers in Cambridge. In early 2023, an *ERC Consolidator Grant* was awarded to *de Lera Acedo* (REACH PI). This will fund the observation and scientific exploitation phase of the project as well as enhancing the instrumentation (to five antennas observing the entire sky simultaneously).

This article is partly based on results published as Gessey-Jones T. et al., MNRAS 516, 841 (2022); Bevins H. et al., Nature Astronomy 6, 1473 (2022a); Bevins H. et al., MNRAS 513, 4507 (2022b); HERA Collaboration, ApJ 945, 2 (2023); de Lera Acedo E. et al., Nature Astronomy 6, 1332 (2022).

Opposite: Group picture of students and post-docs who have contributed to this work, supervised by Eloy de Lera Acedo, Anastasia Fialkov and Will Handley.
Back row (Left – Right): Jiacong Zhu, Kaan Artuc, Stefan Heimersheim, Irene Abril Cabezas, Harry Bevins, Christian Kirkham, Simon Pochinda, Thomas Gessey-Jones.
Front row (Left – Right):Joe Pattison, Yuchen Liu, Dominic Anstey, Jiten Dhandha, Oscar Sage David O'Hara, Sam Leeney, Emma Shen, John Cumner

Fig.4 . REACH dipole antenna at the Karoo radio reserve, South Africa, a site ideally suited for radio astronomy and future location of the SKA-MID telescope. The antenna is placed over a 20x20 m elevated metallic mesh in order to shield the antenna from soil emission. Credit: Christian Kirkham.




Vid Irsic & Martin Haehnelt

Relics of Inhomogeneous Reionization

The first stars and galaxies in the Universe produce ionising UV radiation that transforms the surrounding intergalactic gas from its neutral state during the "Dark Ages" to the highly ionised Universe we observe today. The ionisation fronts sweeping through the Universe thereby photo-heat the gas through dissociation of hydrogen atoms, from a few Kelvin to around 10,000 Kelvin. As this process of cosmic reionization progresses, the ionised regions grow and eventually overlap, leading to an almost fully ionised state of the intergalactic gas.

The photo-heating due to cosmic reionization also increases the gas pressure, which causes the gas to respond hydrodynamically and expand. While gravity still dominates the structure formation of baryons on large scales, the small-scale structure of the intergalactic gas is drastically affected by the dynamical response to the photo-heating. Over-pressurized regions expand, erasing much of the small-scale structure. This effect is important for the formation of galaxies as well as the intergalactic gas during and after reionization.

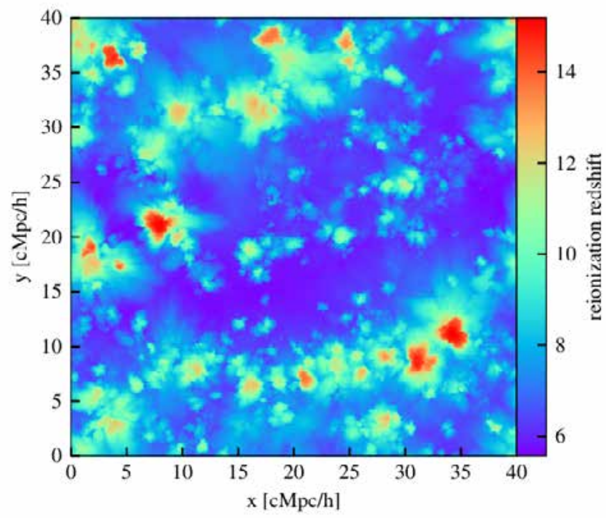
While the flux of ionising radiation in the low-redshift Universe is almost entirely homogeneous, this was not the case during cosmic reionization. The spatial inhomogeneities in the flux of ionising radiation can be large until the end of the reionization process, and decay away slowly after the average state of the gas has reached highly ionised levels. We used a novel, hybrid approach to capture this effect in cosmological simulations, combining evolution of the ionising radiation field and hydrodynamical simulations to capture the inhomogeneous state of the ionisation and temperature fields of the intergalactic gas, as well as self-consistently model the dynamic response of the gas due to photo-heating.

Typically high-density regions contain many sources of ionisation, and are therefore the first to ionise, while regions further away in cosmic voids ionise last. Figure 1 shows a slice through one of our simulations, colour-coded by the redshift at which different regions in the Universe become ionised. The map of redshifts at which different regions become ionised is then propagated forward in time to calculate the ionisation and temperature state of the intergalactic gas at later times.

For an observer at a time when the reionization process has already started, the regions that became ionised earlier have had longer to cool, and would appear colder, than regions that have become ionised more recently. This is shown in Fig. 2, where we compare slices through two of our simulations after cosmic reionization has finished. The top panels show a simulation of a homogeneous-reionization model, while the bottom panels show a simulation with inhomogeneity in the flux of ionising radiation. The left panels of the figure show the distribution of the neutral-hydrogen fraction of the gas, showing that if the inhomogeneous nature of reionization is taken into account, the gas remains neutral only in the most dense regions, while the filamentary structures surrounding those regions are highly ionised. The right panels of the figure show the temperature of the gas, indicating that the gas between galaxies is hotter in lower-density regions because they have ionised later compared to a model with a homogeneous ionisation background.

This article is partly based on results published as Molaro M. et al., MNRAS 509, 6119 (2022) and Puchwein E. et al., MNRAS 519, 6162 (2022).

Fig. 1: Slice through a simulated Universe with inhomogeneous sources of cosmic reionization. The colour-coding illustrates the redshift at which different regions enter the process of reionization. Highly dense regions contain more sources and are typically the first to ionise, with a correspondingly higher redshift of reionization.



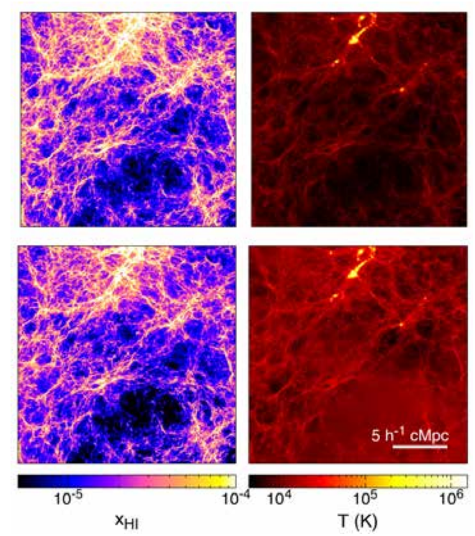


Fig. 2: Effects of homogeneous (top row) and inhomogeneous (bottom row) cosmic reionization on the neutral-hydrogen fraction (left) and gas temperature (right). The underdense regions become ionised later and exhibit higher temperatures in the model of inhomogeneous reionization. The neutral fractions of the gas are also lower in the filamentary structures of the cosmic web as the flux of ionising radiation is greater in higher-density regions hosting more sources of ionising radiation from the first galaxies and stars.

Vid Irsic

Weighing Cosmic Structure

The standard model of cosmology, which was established over two decades ago, has seen consistent confirmation with the exquisite measurements of the cosmic microwave background (CMB), and the baryon acoustic oscillation (BAO) scale – the typical scale of the baryon–photon oscillations in the primordial plasma of the Universe – imprinted into the distribution of galaxies in the later Universe.

Nevertheless, the standard model of cosmology has been under intense scrutiny over the last decade. Much like in particle physics, there are hints that the concordance model of cosmology is not yet complete (e.g., the unknown nature of dark matter and dark energy), and many observational surveys focus on finding the breaking point of the model that might hint at new physics. One promising lead is the evolution and formation of structure in the Universe. The temperature and polarization anisotropies in the CMB measure the amount of fluctuations in the matter distribution in the early Universe – often quantified as a power spectrum, or variance of the fluctuations, as a function of scale. Within the standard cosmological model, the measured power spectrum can be extrapolated forward in time, making precise predictions for the fluctuation power expected in probes of the matter distribution at lower redshift, such as galaxy clustering or weak gravitational lensing.

Among all the probes of the matter distribution, galaxy clusters and the intergalactic gas are of particular interest to cosmology due to their complementarity in environment and redshift of origin. At lower redshifts, galaxy clusters represent the largest cosmic fluctuations that evolved in the non-linear structure formation and reached virialization. On the other hand, intergalactic gas is mostly studied at higher redshifts in only mildly over-dense filamentary structures within the cosmic web. The cosmic web is shown in Fig. 1.

The number counts of galaxy clusters can be used to study cosmology by comparing the observed and expected number of galaxy clusters of a given mass and at a given time. The galaxy cluster mass is not directly observed, but rather inferred using scaling relations from measurements of, for example, X-ray emission or the thermal Sunyaev-Zel'dovich effect due to Compton scattering of the CMB off free electrons in the intracluster gas. These 'weighing' methods are sensitive to the hot – around 50 million Kelvin – component of the gas in the galaxy clusters.

Similarly, the main cosmological measure of the intergalactic gas is in the form of the Lyman-alpha forest – a series of absorption lines in quasar spectra that are a result of scattering of light on the neutral hydrogen atoms in the line-of-sight towards a quasar. These absorption features are an excellent tracer of the amount of cold – around 10,000 Kelvin – neutral hydrogen in the intergalactic gas. The cosmological analyses rely on large hydrodynamical simulations to model the effects of the thermal state of the gas on the absorption properties, alongside effects of cosmological parameters.

Both galaxy clusters and the intergalactic gas can be used to infer the amplitude of matter density fluctuations at late times. Compared to the predictions from the CMB, the amplitude of the fluctuations is found to be slightly high in the intergalactic gas, and a little low when inferred from counts of galaxy clusters.

There are several possible solutions to this conundrum. The least exciting possibility is that there are unresolved systematic effects in one or both of the analyses that would shift the value of the amplitude of the matter fluctuations. In our analysis, we showed that it is infeasible to reconcile the two measurements by adjusting the modelling of, for example, the thermal state of the intergalactic gas or scaling relations for galaxy clusters to match the observations. However, the positive side of this argument is that future and better data will resolve this issue with time, if systematic effects are driving the results.A more exciting possibility is that the tension between the two sets of measurements persists with more data, and points to new physics. One possible solution could be a modified dark matter model, where dark matter self-interactions reduce the amplitude of fluctuations in very dense environments such as galaxy clusters.

The last possibility to reconcile the measurements from intergalactic gas and galaxy clusters, however, is that the results are driven by differences in the response of small-scale baryonic physics on the matter fluctuations in varied environments. Both measurements trace the distribution of the gas component of matter, but while the intergalactic gas traces low-density regions, galaxy clusters are more affected by complicated galaxy-formation dynamics.

This article is partly based on results published as Esposito, E. et al., MNRAS 515, 857 (2022).

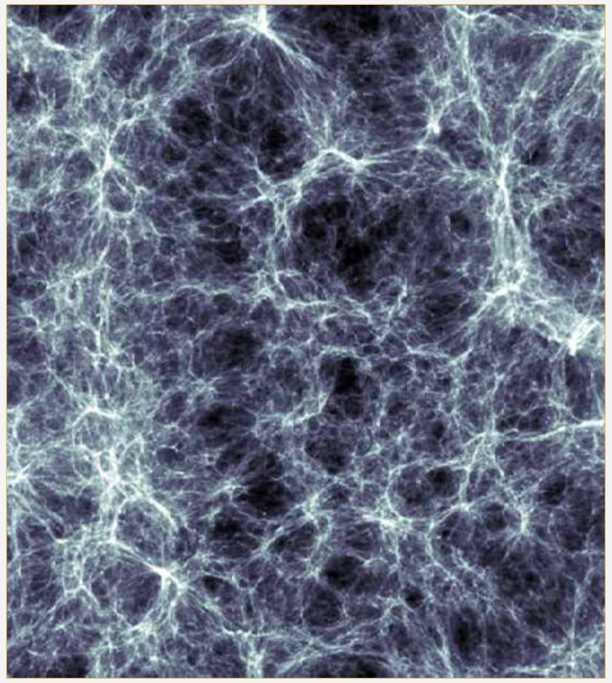


Fig. 1: A simulation of the cosmic web. The brighter regions are where the most massive objects in the Universe are forming,and the darker filamentary structure is the intergalactic gas.

Tibor Dome & Anastasia Fialkov

Fuzzy or Not: Cosmic Web Studies at High Redshift

Swiss astronomer Fritz Zwicky was the first to suggest the existence of dark matter when he noticed that the observed mass of galaxy clusters was not enough to explain the gravitational forces needed to hold them together. Since the 1930s, numerous observations have provided evidence for the existence of dark matter, including the rotation curves of galaxies, gravitational lensing, and the cosmic microwave background radiation. Despite these observations, the precise nature and composition of dark matter remain unknown, making it one of the greatest mysteries in modern physics.

The observed clumpiness of large-scale structure suggests that the bulk of dark matter is cold (CDM). However, traditional CDM candidates, such as weakly interacting massive particles (WIMPs), have not yet been found despite decades of searches. One well-studied candidate in both theoretical and experimental particle physics is the axion, an extremely light and highly diffuse particle that may constitute some of the dark matter. In fact, the axion is unique in that it behaves more like a wave than a particle, giving rise to the terms "wave dark matter" or "fuzzy dark matter" (FDM).

Advancing our theoretical understanding of dark matter has become more important recently. This is in part due to the tremendous statistical power of the next generation of weak-lensing and galaxy-redshift surveys, such as the Vera Rubin Observatory, Euclid and the Nancy Grace Roman Telescope, which places great demands on the accuracy of theoretical modelling of the signals they seek. For example, if intrinsic alignments of nearby halos and galaxies – the tendency for their projected shapes to align with each other due to their common local tidal field – are poorly understood theoretically, this will compromise the ability to extract the weak-lensing signals and associated science from an 800-million-dollar telescope such as Euclid. To this end, we have investigated the internal properties of dark matter halos and large-scale cosmic environments and their dependence on dark matter models. Using cosmological N-body simulations, we have evolved model universes in CDM and FDM from high redshift ($z = 127$). One of our key findings is that not only halo density profiles, but also shapes and relative shape alignments are sensitive to the dark matter model. To illustrate this, in Fig. 1 we show shape profiles as a function of halocentric radius of the intermediate-to-major (q) and minor-to-major (s, for sphericity) axis ratios, and a measure of triaxiality (T), in various dark matter models at redshift 4.4. In CDM, monotonicity relations are observed for both q and s; they increase towards larger halocentric radii. However, these monotonicity relations can be disrupted not only by the effects of baryonic physics such as supernovae, active galactic nuclei, and other radiative feedback processes, but also by alternative dark matter models, including FDM as we demonstrate in the figure. In particular, FDM halos (especially at low masses) are highly aspherical (small s) and highly elongated (T close to unity) around the virial radius.

While the distribution of halo shapes is interesting in its own right, how halos align with one another and with the cosmic web is equally important for galaxy formation. The cosmic web is a vast network of filaments and voids that make up the structure of the Universe. Simplistic geometric shape-shape and shape-position measures indicate that nearby FDM halos are more aligned than CDM halos, as we find.

However, what is of greater importance to weak-lensing surveys are intrinsic-alignment models, i.e., models that relate the shape of halos/galaxies to the strength and orientation of nearby tidal fields. One theoretical framework for describing such alignments is the linear alignment model (LAM), which suggests that the orientations of halos/galaxies are not random but instead are arranged in a quasi-linear pattern along the major axes of the cosmic web. This correlation between halo shapes and nearby tidal fields is illustrated in Fig. 2, with the strength of the LAM correlation given by the slope of the linear regression. Compared to CDM, we see that FDM intrinsic alignments are up to 50% stronger at redshift 4.4. These results suggest that the internal properties of dark matter halos and large-scale cosmic environments may offer powerful constraints on FDM and other alternative dark matter models.

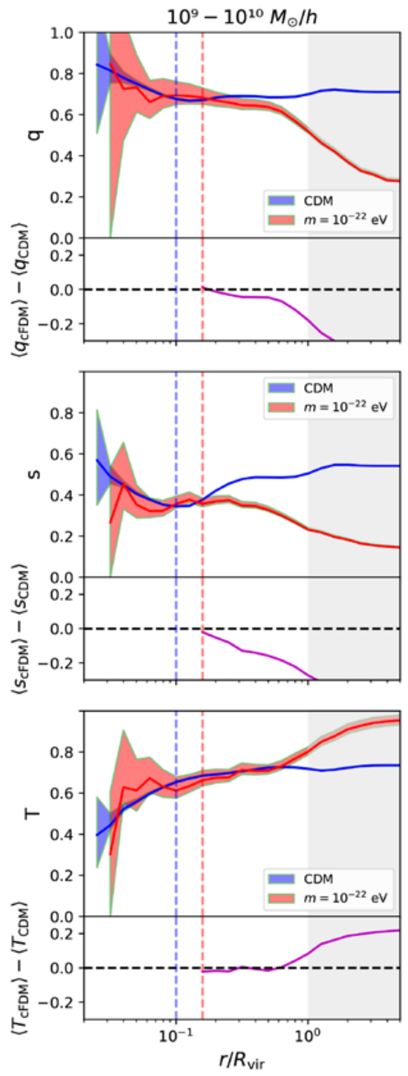
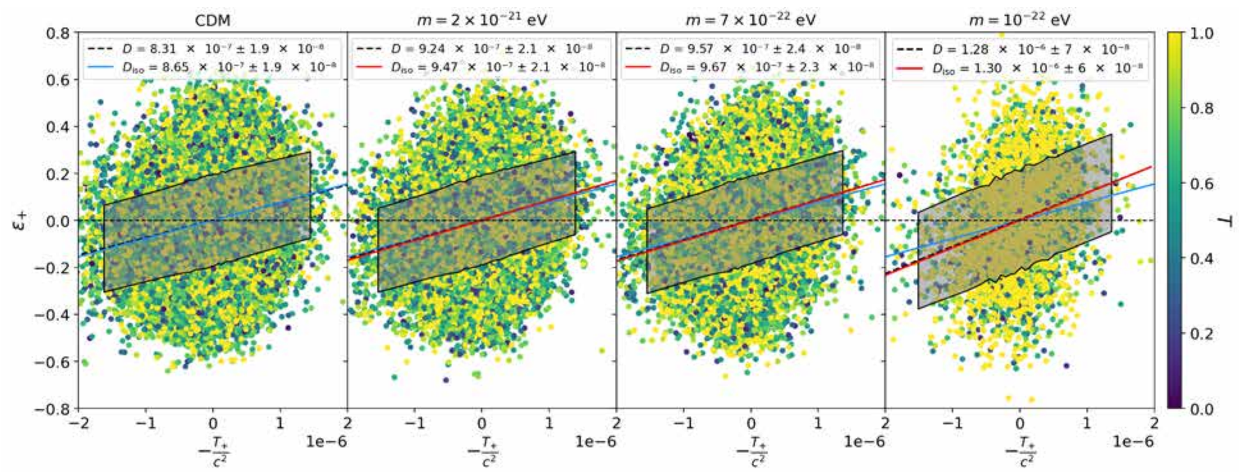


Fig. 1: Shape profiles in halocentric radius of intermediate-to-major (q), minor-to-major (s) axis ratios and triaxiality (T) in CDM and a selected FDM model at redshift 4.4.

Fig. 2: Intrinsic-alignment strengths in different cosmologies. We show the correlation of one component (ϵ_+) of the halo ellipticity with the respective tidal field component (T_+) at redshift 4.4. Each dot represents one halo colour-coded by its triaxiality T.



This article is based on results published as Dome T. et al., MNRAS 525, 348 (2023).

Ricarda Beckmann

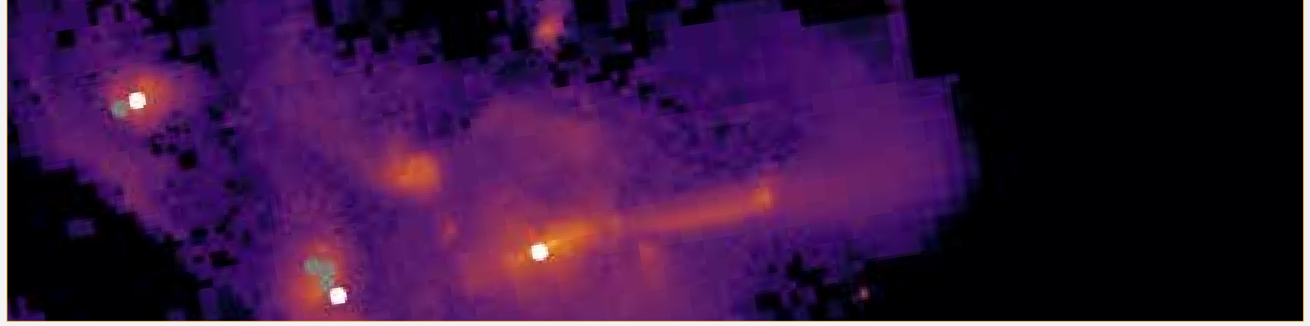
Intermediate-Mass Black Holes as a Sensitive Probe of Black Hole and Galaxy Coevolution

It is well known that properties of supermassive black holes correlate with their host galaxy: every massive galaxy in the local Universe contains a central supermassive black hole, whose mass is tightly correlated with the properties of its host galaxy such as the distribution of stellar velocities and the total stellar mass. This correlation is thought to arise because the feedback energy released by black holes as they grow and evolve regulates the star formation in the galaxy over timescales of billions of years.

For a long time, it was unknown if lower-mass galaxies, known as dwarf galaxies, which have a stellar mass of up to 5 x 10^9 Solar masses or less, also host and coevolve with central black holes. Extrapolating from the correlations at higher masses, black holes in dwarf galaxies would have to be in the intermediate mass range, from 10^4 to 10^6 Solar masses in black hole mass. This makes them very difficult to detect observationally, as their lower mass means they have both fainter emission and a much smaller region where they dynamically influence the stars in their galaxy. It is only in recent years that powerful telescopes have been able to detect such intermediate-mass black holes and confirm that at least some dwarf galaxies do indeed seem to coevolve with black holes. As observations remain challenging, much work remains to be done to build an understanding of the whole population of black holes from the few we can observe.

One powerful way to do so is to use cosmological simulations, which simulate the evolution of a large sample of galaxies and all their constituents (including stars and black holes) from cosmic dawn to today. We have recently used the NewHorizon simulation, which was specifically designed to include a large sample of dwarf galaxies, to understand if and how intermediate-mass black holes and dwarf galaxies evolve. An image showing stellar maps and black holes for a small sample of the NewHorizon simulation is shown in Fig. 1. Using a sample of more than 600 such galaxies, we determined that intermediate-mass black holes and dwarf galaxies can indeed coevolve, particularly for galaxies at the upper end of the dwarf galaxy mass range. However, unlike for massive galaxies, the coevolution process is easily disrupted and much more sensitive to our model for black hole formation, dynamics and growth.

For example, we would expect that almost every massive galaxy contains a supermassive black hole, as massive galaxies undergo many galaxy mergers. If only one of those many galaxies merging together contains a black hole to start with, the final galaxy will have a central black hole. Dwarf galaxies undergo far fewer mergers, so the number of dwarf galaxies that do or do not contain a black hole today is much more sensitive to when and how black holes formed in the early Universe.



Similarly, our work with NewHorizon showed that the dynamics of black holes play a key role in regulating coevolution with their host galaxy. Massive galaxies host massive black holes which stay easily attached to the centres of galaxies where coevolution can occur. Black holes in dwarf galaxies are less massive, which makes them more easily dislodged from galactic centres. Once wandering through their host galaxy, it can take a long time for intermediate-mass black holes to settle back in the galactic centre, which disrupts coevolution. This is also relevant to massive galaxies, which had much smaller masses in the distant past.

By testing different models in simulations, for example for when and how black holes are formed in the early Universe and how they move within their host galaxy over time, and comparing the predictions from such simulations to observations from the real Universe, we will be able to place firm constraints on the relevant black-hole physics. As dwarf galaxies and their intermediate-mass black holes are much more sensitive to model details, they make an ideal testing ground to understand the physical processes that underlie black hole and galaxy coevolution.

This article is partly based on results submitted as Beckmann R.S., Dubois Y., Volonteri M., Dong-Paez C.A., Trebitsch M., Devriendt J., Kaviraj S., Kimm T. and Peirani S., submitted to MNRAS, arXiv:2211.13301.

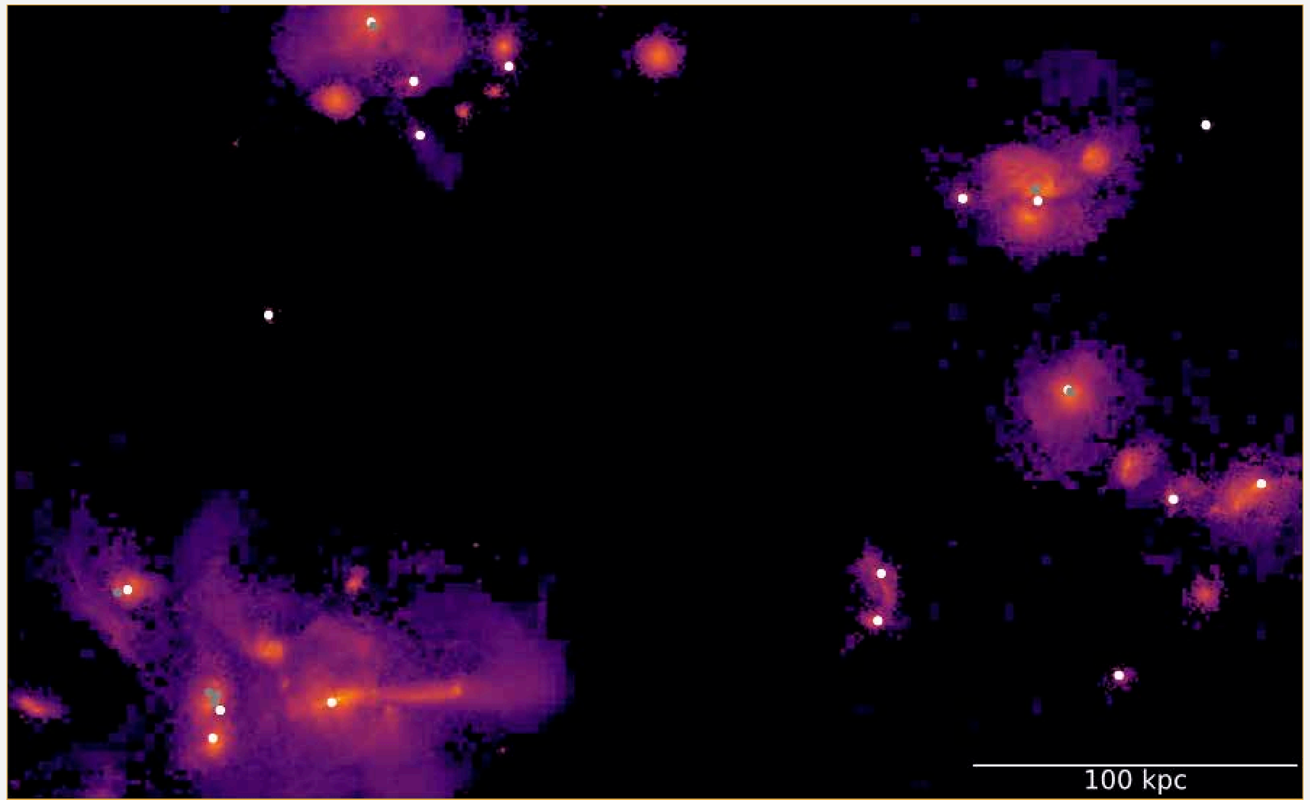


Fig. 1: Image of a small sample of galaxies from the NewHorizon simulation. The colormap shows the stellar density, while white and grey dots denote the locations of central and secondary intermediate-mass black holes, respectively.

Sergio Martin-Alvarez, Debora Sijacki & Martin Haehnelt

The Pandora project: The Impact of Radiation and Cosmic Rays on Baryonic and Dark Matter Properties of Dwarf Galaxies

Amongst many different galaxy types, dwarf galaxies are certainly some of the most mysterious and intriguing systems. They lie at the heart of multiple unanswered questions in galaxy formation and have fuelled a number of controversies, related to `small-scale' challenges to our standard ΛCDM cosmological model. These challenges concern, for example: a large disparity between the number of observed dwarf galaxies with respect to the predicted number of dark matter haloes that may be hosting these systems; observed density profiles with central cores rather than the cuspy profiles predicted by CDM haloes; and too few massive observed satellite galaxies.

These problems have prompted prolific and intense research in the field of near-field cosmology and were motivation for state-of-the-art observational efforts with facilities such as DES, VISTA, GAIA and LSST, which aim to give us a more complete and unbiased census of the dwarf properties of our Local Group of galaxies.

In fact, a large body of theoretical work has identified two important processes that may fundamentally affect properties of dwarf galaxies and largely alleviate, if not solve, all of the aforementioned discrepancies, indicating no departures from ΛCDM are necessarily needed. The first regards energetic feedback by supernovae, which can dramatically affect the baryon fraction, star formation and even the dark matter distribution especially in low-mass haloes. The second concerns the reionization of the Universe, where energetic photons emitted by high-redshift sources can photo-heat the gas suppressing the infall into low-mass galaxies thus drastically reducing the number of luminous low-mass haloes.

Motivated by this, we have performed the first simulations where realistic supernova feedback is included, along with state-of-the-art, on-the-fly radiative transfer, constrained-transport magnetohydrodynamics and cosmic ray feedback accounting for both their streaming and diffusion processes. Our simulations demonstrate that all these physical processes acting together are needed to reproduce realistic dwarf galaxies. Additionally, we are now able to predict self-consistently the neutral hydrogen component of these systems and to generate detailed synthetic observations of radio synchrotron emission for next-generation radio facilities such as SKA (see Fig. 1).

This work serves as a pathfinder for our upcoming suite of simulations featuring larger cosmological zoom-in volumes that will explore the role played by cosmic rays, radiative transfer and magnetic fields in the formation of galaxies across cosmic time.

This article is partly based on results submitted as Martin-Alvarez S. et al., MNRAS, 525, 3806 (2023).

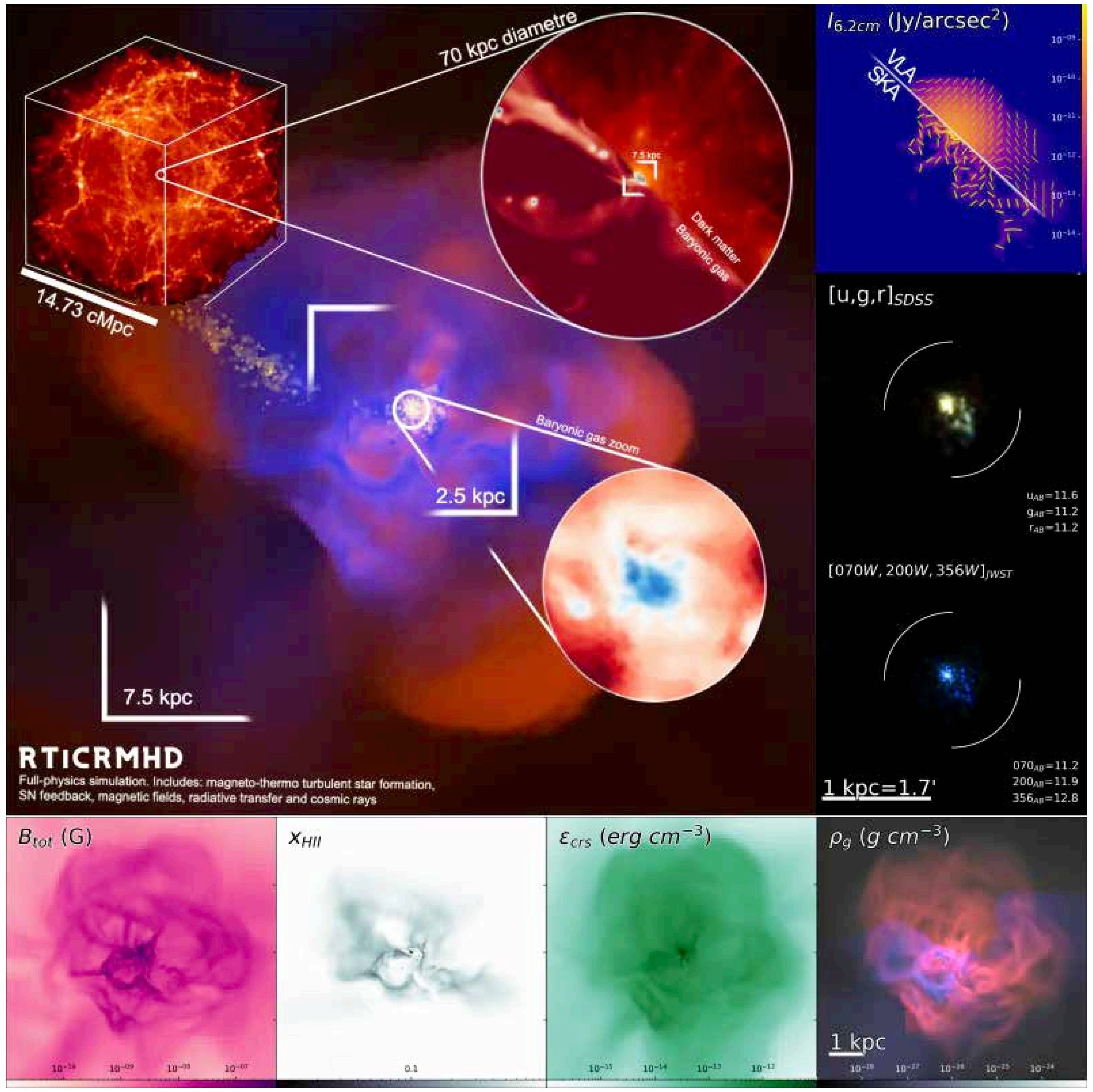


Fig. 1: Projections of our full-physics simulated dwarf galaxy, displaying various physical properties as labelled, as well as synthetic observations as would be seen by VLA, SKA, SDSS and JWST.


Sophie Koudmani & Debora Sijacki

Massive Black Holes in Dwarf Galaxies: from AGN Feedback to Multimessenger Signatures

Contrary to the standard lore, there is mounting observational evidence that feedback from active galactic nuclei (AGN) may also play a role at the low-mass end of the galaxy population in addition to supernovae explosions and photo-heating from energetic sources. We have explored this intriguing possibility with a novel series of high-resolution zoom-in simulations of dwarf galaxies, varying the AGN prescription and supernova energetics.

We find that with the commonly employed model for black hole growth in cosmological simulations, black hole accretion in dwarf galaxies is completely degenerate with the black hole seed mass. This motivated us to develop an alternative black hole accretion model that is directly tied to the gas availability in the immediate surroundings of the black hole and does not artificially suppress the growth of low-mass seeds. We find that this "supply-limited" accretion model leads to efficient accretion onto low-mass black hole seeds in our simulated dwarf system. In fact, there are sufficient amounts of gas even to power brief, Eddington-limited accretion episodes in dwarf galaxies.

These episodes have a profound effect on the large-scale outflows, increasing outflow temperatures and velocities, which could be probed by future observations with JWST NIRSpec. The AGN-boosted outflows heat the circumgalactic medium and regulate star formation via `maintenance'-mode feedback, i.e., keeping the gas around the galaxy hot, with the most significant impact at high redshifts, where supernova feedback alone cannot suppress cosmic inflows efficiently (see Fig. 1).

Interestingly, even moderate AGN outflows can be as efficient as the strong supernova feedback commonly employed, leading to star-formation regulation and neutral hydrogen gas masses in agreement with observations of field dwarf galaxies. All our models with efficient AGN heating are associated with over-massive black holes compared to the (heavily extrapolated) observed scaling relations between black hole mass and stellar mass, with future direct observational constraints in this mass regime being crucially needed. However, most efficient AGN activity is restricted to high redshifts, with hot, accelerated outflows and high X-ray luminosities being the clearest tell-tale signs for future observational campaigns.

Finally, we investigated possible `multi-messenger' signatures of black hole mergers, where the same merger event can be probed both via gravitational waves and electromagnetic observations. The dwarf galaxy used for our zoom-in simulations resides in a relatively quiet environment, however, it experiences a high-redshift minor merger at redshift $z = 4$ that delivers significant amounts of fresh gas. For reasonable assumptions on the secondary black hole mass, we would expect this merger event to be observable by the LISA gravitational wave space mission with a signal-to-noise ratio greater than 10. Crucially, this merger event would also result in a bright electromagnetic counterpart, with the AGN X-ray luminosities for the majority of simulation set-ups explored peaking just after the merger at $z = 4$, which may be observable by future X-ray missions such as AXIS or Lynx.

This article is based on results published as Koudmani S., Sijacki D. and Smith M. C., MNRAS 516, 2112 (2022).

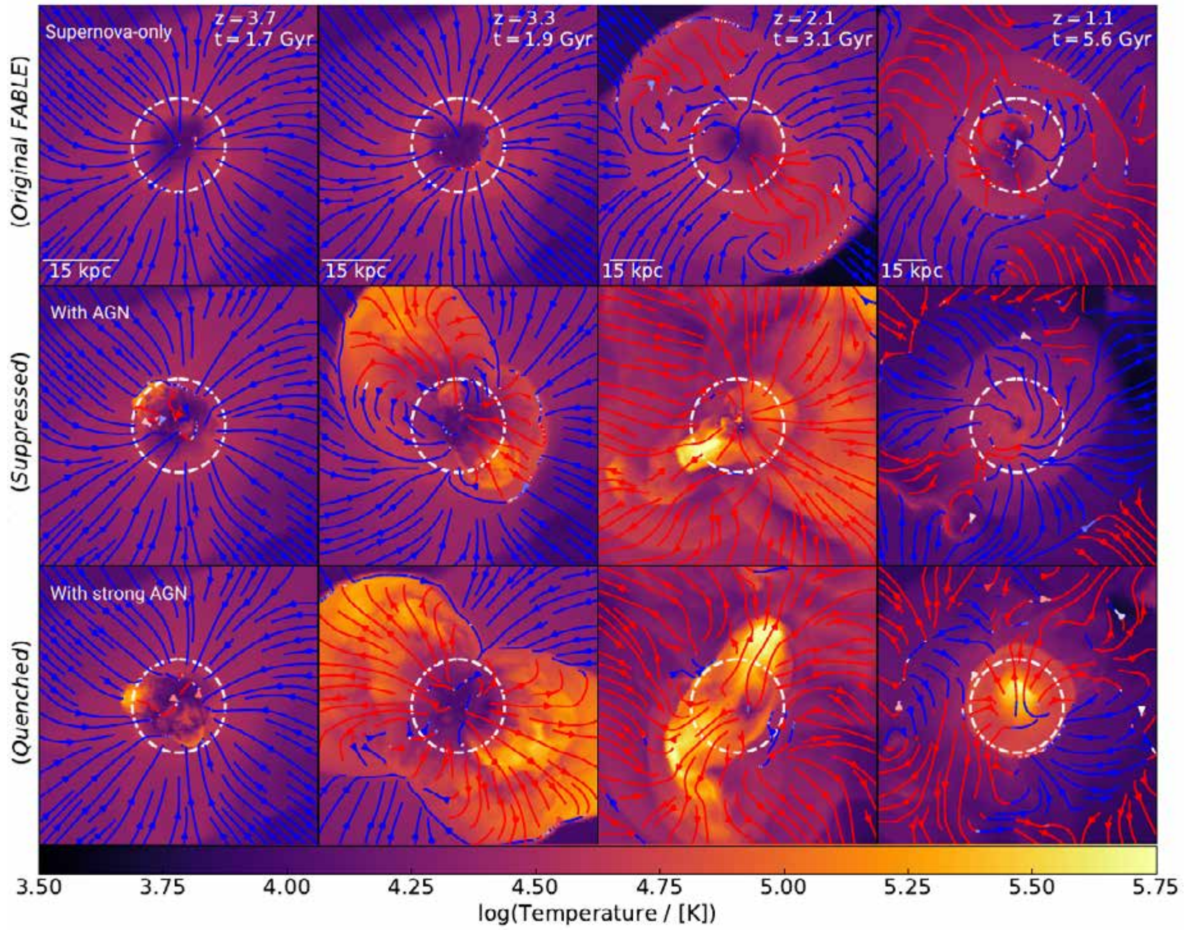
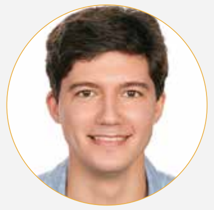


Fig. 1: Gas temperature maps with streamlines for selected cosmological zoom-in simulations. The AGN activity can suppress the cosmic inflows at much higher redshifts and keep the dwarf galaxy in a `quenched' state, suppressing all star formation.

GALAXIES




Sandro Tacchella & Roberto Maiolino

JADES Survey: Building the Deepest Extragalactic Survey with JWST

The James Webb Space Telescope (JWST) was launched into space by ESA on an Ariane 5 rocket on Christmas Day 2021. After a flawless deployment, the commissioning of the telescope and its instruments were successfully completed in the following months. On 12th July 2022, the first full-colour images and spectroscopic data from JWST were released during a televised broadcast, including an image of galaxy cluster SMACS 0723 ("Webb's First Deep Field"), which – at that time – was the deepest and sharpest infrared image of the distant universe. This showed that JWST was working better than expected.

Since July 2022, JWST has been taking and delivering new observational data every day. The extragalactic research group at the KICC, co-led by Roberto Maiolino and Sandro Tacchella, has led several of the very first analyses of these data. For example, using the above-mentioned observations of Webb's First Deep Field, Mirko Curti used the Near InfraRed Spectrograph (NIRSpec) to measure gas-phase metallicity of galaxies in the first billion years after the Big Bang (see the article by Mirko Curti), while Sandro Tacchella combined these NIRSpec measurements with images from the Near InfraRed Camera (NIRCam) to shed light on the driver of both star formation and early metal enrichment of galaxies. After a few weeks, medium-band imaging data for JEMS (JWST Extragalactic Medium-band Survey; co-PI Sandro Tacchella) were collected and group member Charlotte Simmonds used those data to measure the ionizing-photon production efficiency of galaxies during the epoch of reionization.

In Autumn 2022, the deepest extragalactic survey with JWST started. Both Roberto Maiolino and Sandro Tacchella are playing a crucial leadership role in this survey, which is a Guaranteed Time Observation (GTO) programme. In particular, the NIRCam–NIRSpec joint GTO programme called JWST Advanced Deep Extragalactic Survey (JADES) will survey the GOODS-North and GOODS-South extragalactic fields with a wide range of NIRCam and NIRSpec observations. With over 800 hours of observations, JADES is the most extensive JWST programme in the first few years. There are two characteristic NIRCam exposure depths and survey areas for JADES wide-band imaging (deep imaging over around 46 arcmin^2 and medium imaging over around 290 arcmin^2). The images are taken in eight different filters with a wavelength coverage from 1 micron up to 5 micron. This imaging is deeper, extends further into the infrared, and covers a wider area than any previous imaging with the Hubble Space Telescope. NIRSpec observations are obtained with the prism and with the medium- and high-resolution gratings, covering the full 1–5 micron band for thousands of galaxies – these infrared spectra are the first taken from space at this resolution!

The key aim of JADES is to combine imaging with spectroscopy: we will use the new NIRCam images to discover new galaxies that can then be characterised in detail with NIRSpec. We were able to show that this approach works already in the first week of our observation campaign: we unambiguously confirmed four galaxies dating to when the Universe was around 300–400 million years old, presenting these results in two papers in Nature Astronomy.

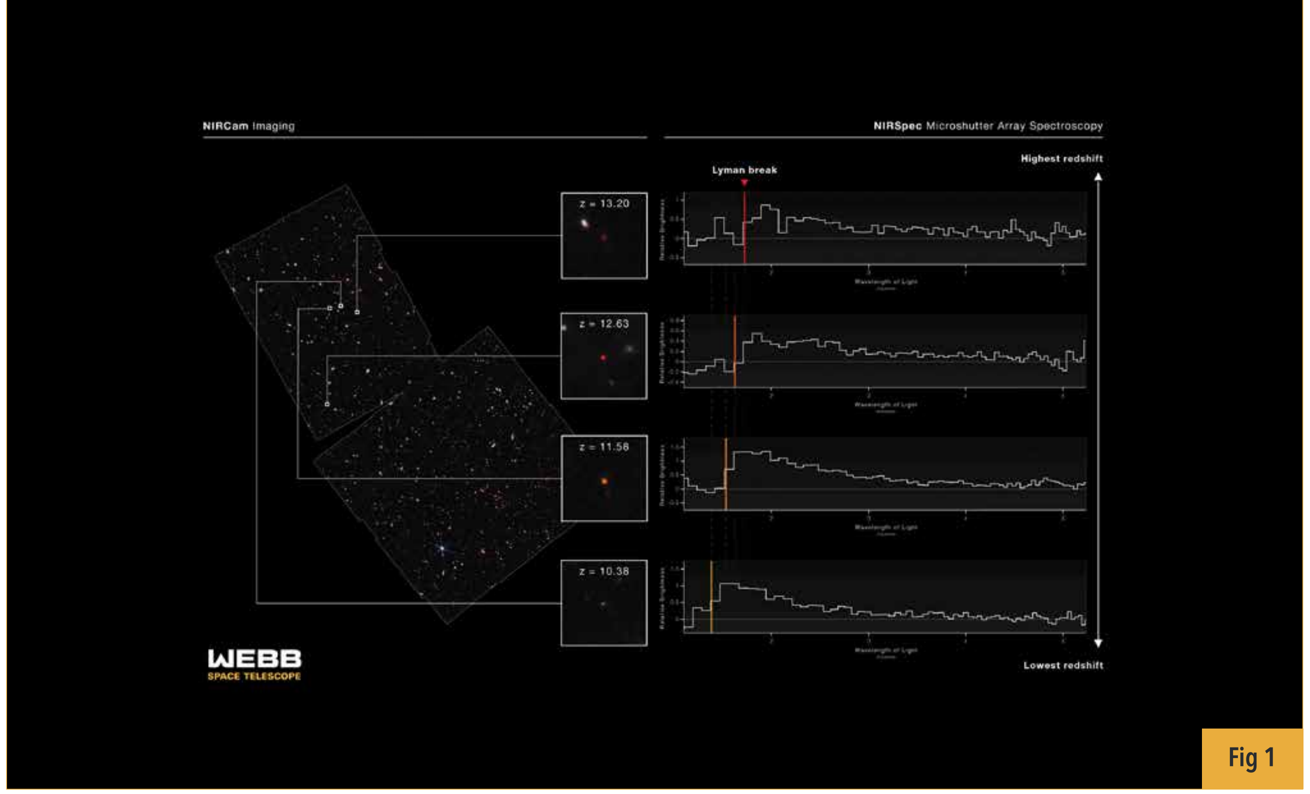


Fig 1

Fig. 1: Webb's Advanced Deep Extragalactic Survey (JADES) focused on the area in and around the Hubble Space Telescope's Ultra Deep Field. Using Webb's NIRCam instrument, we observed the field in nine different infrared wavelength ranges. From these images (shown at left), we searched for faint galaxies that are visible in the infrared but whose spectra abruptly cut off at a critical wavelength known as the Lyman break. Webb's NIRSpec instrument then yielded a precise measurement of each galaxy's redshift (shown at right). Four of the galaxies studied are particularly special, as they were revealed to be at an unprecedentedly early epoch. These galaxies date back to less than 400 million years after the Big Bang, when the Universe was only 2% of its current age. Image Credit: NASA, ESA, CSA, and STScI, M. Zamani (ESA/Webb), L. Hustak (STScI). Science: B. Robertson (UCSC), S. Tacchella (Cambridge), E. Curtis-Lake (Hertfordshire), S. Carniani (Scuola Normale Superiore), and the JADES Collaboration.

Specifically, we identified four galaxies (JADES-GS-z10-0, JADES-GS-z11-0, JADES-GS-z12-0, JADES-GS-z13-0) using NIRCam images in the redshift range 10.3–13.2. (Redshift is a measure of the recession speed of a galaxy and allows us to infer its distance.) JADES-GS-10-0 and JADES-GS-11-0 were known previously from Hubble imaging, while JADES-GS-z12-0 and JADES-GS-z13-0 were newly discovered. However, the NIRCam data alone only give us a rough estimate of their redshifts and we need spectroscopy to confirm these via spectral features such as emission lines or strong spectral breaks. In the NIRSpec follow-up, we indeed confirmed their large redshifts and, hence, distances (see Fig. 1). Interestingly, the spectra do not show fingerprints of complex elements like carbon, oxygen and nitrogen, indicating that the stars in these galaxies have not yet processed the pristine hydrogen and helium left over from the Big Bang to produce large stores of these heavier elements. Furthermore, we determined their star-formation rates, sizes and other properties indicating that each galaxy could contain 100 million Solar masses in stars, in stellar populations that are less than 100 million years old based on their cosmic age. The moderate levels of star formation and their compact size indicate high star-formation rate surface densities, which suggests that these galaxies formed rapidly with intense internal radiation fields.

After this initial success of JADES, our team at the KICC is currently working on a range of different topics using JADES data, from the current redshift frontier to studying the stellar and chemical enrichment of galaxies. You will be able to read more about this in next year's KICC report!

This article is partly based on results published as Robertson B. E. et al., Nature Astronomy 7, 611 (2023) and Curtis-Lake E. et al., Nature Astronomy 7, 622 (2023).

Nicolas Laporte

New Insight on Galaxy Formation in the Early Universe

JWST Probes Distant Protoclusters of Galaxies

One of the most fascinating unresolved questions in modern extragalactic astronomy pertains to the emergence and progression of the earliest galaxies. Thanks to more than three decades of investigation, the Hubble Space Telescope (HST) has offered a clearer perspective of the early Universe. Presently, the demography of galaxies at redshift $z < 7$ is well established, with sound constraints on the ultraviolet luminosity function (giving the number density of galaxies per luminosity interval). Recently, the epoch of formation of the first galaxies, known as "Cosmic Dawn", has been estimated with the detection of a few galaxies at redshift around 11, and evidence indicating that star formation was already ongoing at $z > 15$. However, HST's capabilities in detecting and analysing sources at $z > 7$ are restricted to the brightest ones, despite magnification due to gravitational lensing by foreground objects in some cases. Consequently, a highly debated question is the evolution of galaxies at $z > 8$, with two possible scenarios: a rapid decrease in galaxy density or a gradual decline. Presently, neither of these scenarios can be constrained by existing theoretical models, and novel observational tools are urgently required. Despite the extensive hours spent by HST observing deep and blank fields to identify $z > 8$ galaxies, only a few dozen have been discovered at $z = 8$, and less than ten at around $z = 10$, making the conclusions on this subject tentative.

In the last year, the HST's limitations in studying the remote Universe were overtaken by the advent of the James Webb Space Telescope (JWST). JWST has already transformed our perspective and comprehension of the first few hundred million years of the Universe's history. In just a few weeks of observation, the Early Release Observations and Early Release Science programs identified several tens of galaxy candidates with $z > 10$. While most of these candidates require spectroscopic verification, JWST has already extended the current observational frontier from around $z = 11$ to $z > 15$.

Notably, the initial observations of deep fields with JWST reveal that several luminous, high-redshift galaxies previously detected with HST are situated in young protoclusters. Although contemporary models of galaxy formation predicted this outcome, HST only recognised a handful of such structures. Our research group analysed one of these galaxies behind the SMACS0723 gravitational-lensing cluster, one of the first JWST fields observed. We discovered eight galaxies with matching colours (indicative of similar redshift) in a small region of the field (40 arcsec by 40 arcsec), including two spectroscopically confirmed at $z = 7.66$; see Fig. 1. The physical features of all protocluster constituents correspond well with what has been observed at lower redshifts, including the star-formation main sequence and protocluster size. This detection supplements the very few protoclusters currently known in the first billion years of the Universe. Using multiple techniques, we calculated the dark-matter halo mass of this protocluster to be around 3.3×10^{11} Solar masses, accounting for gravitational lensing magnification, in accordance with various forecasts. We also demonstrated that this high-redshift protocluster possesses a total dark matter-halo mass that places it on an evolutionary track that leads to a Coma-like cluster by $z = 0$ (i.e., a mass greater than 10^{15} Solar masses); see Fig. 2. These massive clusters have substantial effects not only on the development of individual galaxies within them but also allow us to probe the cosmic web, where protoclusters are preferentially located along filaments.

This article is partly based on results published as Laporte N. et al., A&A 667, 3 (2022).

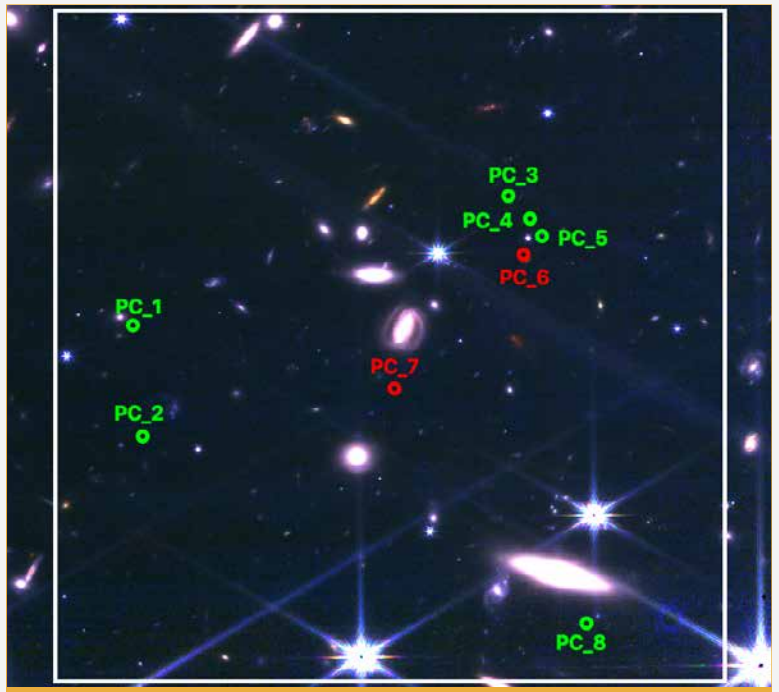


Fig. 1: Positions of all the protocluster's members within a 40 arcsec by 40 arcsec region (white square). Green circles indicate the positions of galaxies with similar colours, while red circles show galaxies with measured redshifts of $z = 7.66$.

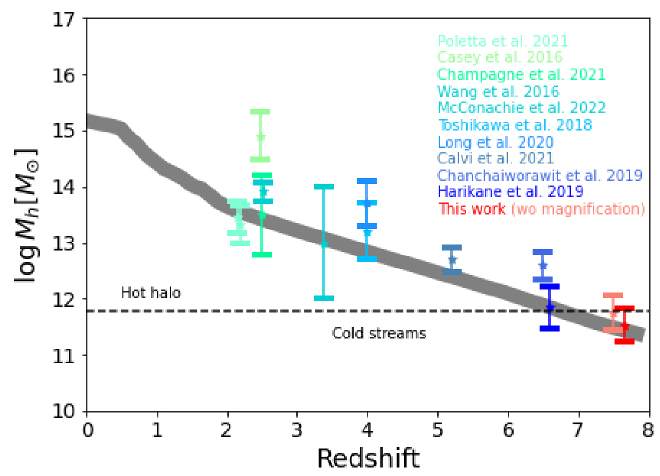


Fig. 2: Evolution of the dark-matter halo mass, which leads to a Coma-like cluster by $z = 0$. The red and pink points are for the protocluster identified behind SMACS J0723-7327, accounting for magnification and without lensing magnification, respectively.

GALAXIES

Mirko Curti

A New Frontier for Studying the Chemical Evolution of Galaxies

The abundance of heavy elements ("metallicity") in the interstellar medium (ISM) provides important information on the physical processes that regulate the cycle of baryons in and out of galaxies, being a sensitive probe to both star-formation and gas flows. Their constant interplay is indeed manifest in the existence of scaling relations between some of the main galaxy properties and their metal content: among these is the relationship between stellar mass and metallicity in galaxies, i.e., the mass–metallicity relation (MZR). Such tight relations reflect the connection between the build-up of mass and the chemical enrichment in galaxies and represents one of the most critical observational features to be matched by models for galaxy formation and evolution.

In the previous decades, the cosmic evolution in the metallicity properties of galaxies have been studied exploiting large spectroscopic surveys from ground-based telescopes observing in the near-infrared (NIR). However, these programmes were intrinsically limited to observe galaxies only up to a cosmological redshift of around $z = 3.3$ (equivalent to an age of the Universe of 2 Gyr), when the key optical spectral features are still shifted within the NIR bands observable from Earth. However, this field has been completely revolutionised by the advent of the James Webb Space Telescope (JWST), ever since the very first observations released in July 2022. In particular, the spectrograph NIRSpec on the JWST is now capable of obtaining spectra in the NIR (up to 5.3 micron) for hundreds of galaxies simultaneously, with a sensitivity much higher than any other current facility.

The first JWST/NIRSpec spectra have been released in the context of the Early Release Observations Programme (ERO), targeting sources behind the galaxy cluster SMACS J0723.3- 7327 and hence leveraging the gravitational lensing magnification effect induced by the cluster itself. The quality of these spectra exceeded all expectations: not only were all of the most prominent rest-frame optical emission lines observed up to cosmic redshifts of $z = 8$, but even much fainter features were detected. Among these, the emission line from doubly-ionised oxygen at 4363 Angstrom (rest-frame), i.e., [O III]4363, is of particular relevance for studying the metallicity properties of galaxies. In fact, this emission line is a sensitive temperature diagnostic, and an accurate determination of gas temperature is critical to obtain a more physically motivated estimate of the chemical abundances of the ISM.

In one of the first studies published from JWST data, we leveraged the spectral properties and, in particular, the detection of the [O III]4363 auroral line in three galaxies around redshift $z = 8$ to probe their metal content at the epoch when the Universe was only 600 million years old. The spectra revealed some of the most extreme conditions ever observed in the ISM of galaxies at any cosmic time, associated with high-temperature and low-metallicity gas; see Fig. 1. One of the galaxies in particular, at a cosmological redshift of $z = 8.5$, was found to be extremely metal poor, with an abundance of oxygen only approximately 2% that of our Sun. This galaxy, therefore, not only deviates from the mass–metallicity relation observed at lower redshifts (i.e., around z = 3), but its very low metallicity cannot be explained even by accounting for the current rate of star-formation, in what is referred to as the fundamental metallicity relation (FMR); see Fig. 2.

These findings suggest that galaxies in the early Universe might be experiencing rapid evolutionary paths placing them off the scaling relations observed in the local Universe, which are instead the results of smooth evolutionary processes and reflect long-timescale interactions between gas flows, star-formation, and chemical enrichment.

This article is based on results published as Curti M. et al., MNRAS 518, 425 (2023).

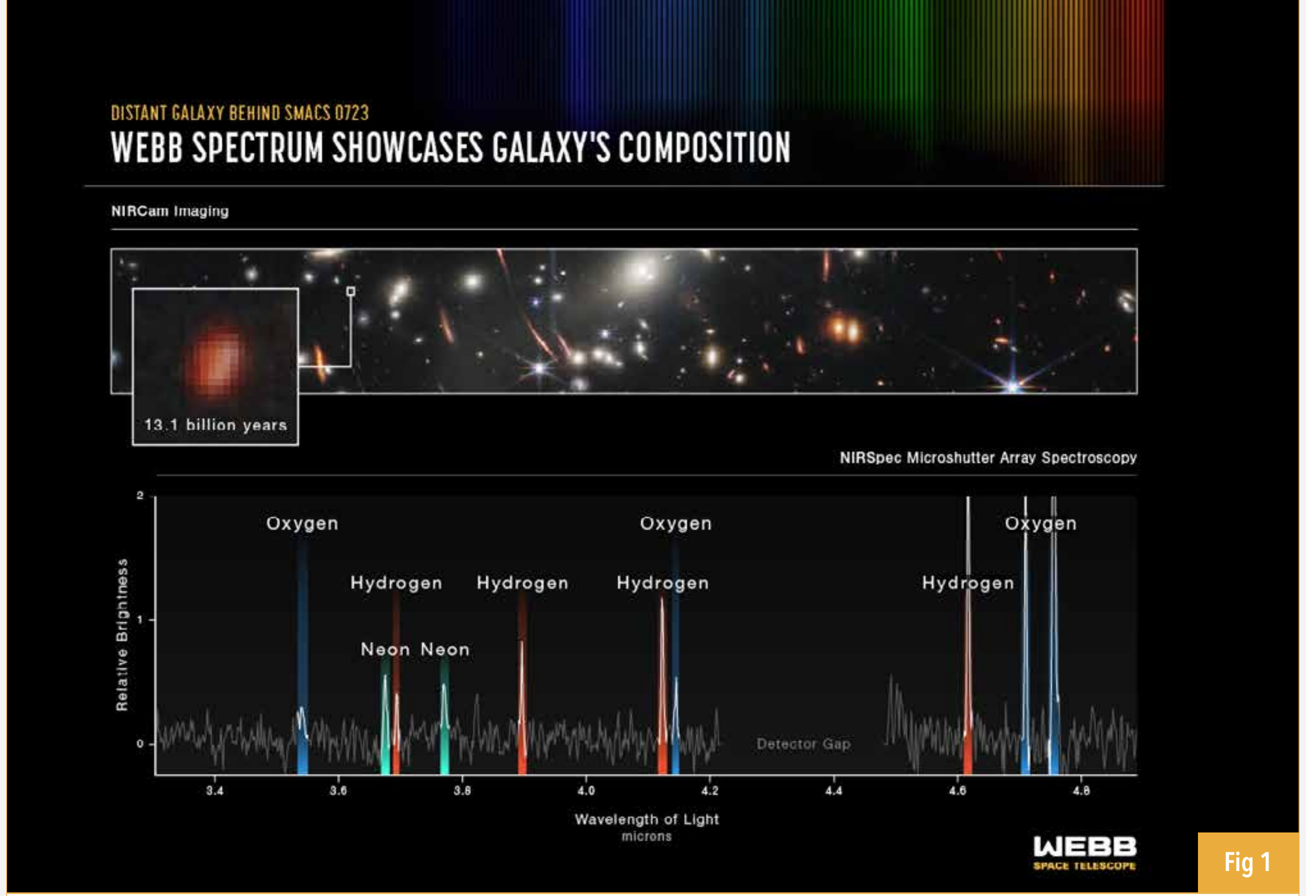


Fig 1

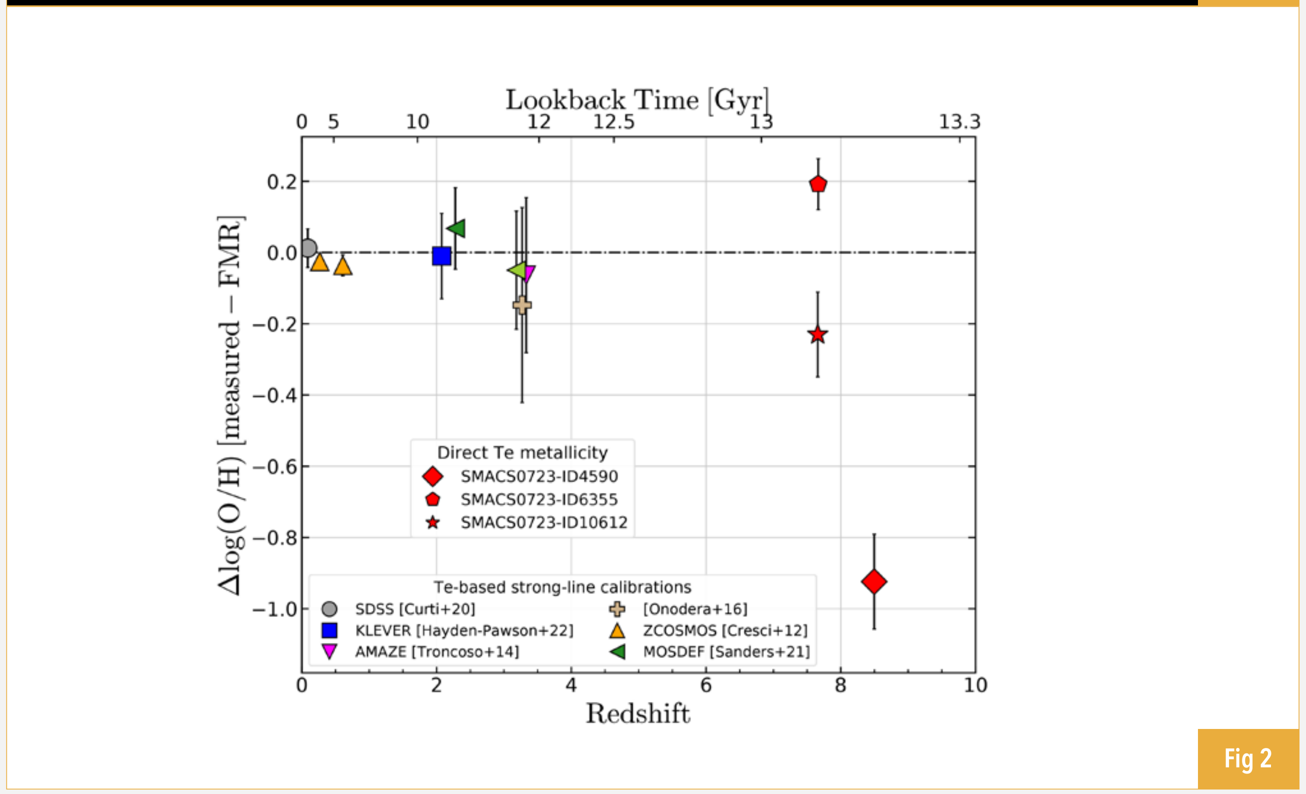


Fig 2

Fig. 1: Spectrum of the galaxy at redshift $z = 8.5$ observed by JWST in the SMACS 0723 field, revealing prominent emission lines of different elements, including the [O III]4363 auroral line (here shifted to a wavelength of 4.14 micron). Credit: NASA, ESA, CSA, STScI.

Fig. 2: Deviation of galaxies at different redshift from the predictions of the scaling relations between stellar mass, star-formation rate, and metallicity (known as the fundamental metallicity relation, FMR) as observed in the local Universe. Galaxies up to $z = 3$ are in good agreement with the FMR, whereas JWST galaxies around $z = 8$ are more offset, with the source at $z = 8.5$ being significantly less enriched than similar galaxies in the local Universe.

Joris Witstok

Dual Constraints with ALMA: New Emission-Line and Dust-Continuum Observations Reveal the Interstellar Medium Conditions of Luminous High-Redshift Galaxies

Cosmological models predict the first chapter of cosmic history concluded with the emergence of the first stars, a few hundred million years after the Big Bang. The subsequent rise of the first galaxies at the centres of dark-matter accumulations drastically altered the Universe that had thus far been filled with a dark, homogeneous, neutral primordial gas made up of hydrogen and helium. Newly formed stellar populations produced energetic photons, setting in motion the reionization of the intergalactic medium (IGM). At the same time, the most massive stars ended in supernova (SN) explosions in which the first heavier elements (metals) were synthesised and blown away in violent shock waves.

Over the past few decades, the Hubble Space Telescope (HST) has been pushing the frontiers of the observable Universe. Ever-more-distant galaxy candidates have been identified in deep, broadband HST imaging by exploiting absorption of the bluest ultraviolet (UV) light by intervening neutral intergalactic hydrogen before reionization is fully complete. However, with imaging alone we are greatly limited in learning about the physical properties of these galaxies. A critical question that cannot be conclusively answered, for example, is whether a given source is truly a distant galaxy. Precisely establishing the distance of a galaxy can be accomplished by measuring the wavelength shift of one or more spectral features, usually emission lines, which results in a *spectroscopic redshift*. Such spectral features are furthermore crucial tools in characterising these galaxies, for example in terms of their metal enrichment, which gives an indication of how many stars have been formed and strongly influences the process of forming new stars.

Before the advent of the James Webb Space Telescope (JWST), there were a limited number of telescopes capable of achieving this for the most distant galaxies, at redshifts $z > 5$. One of these facilities is the powerful Atacama Large Millimeter/submillimeter Array (ALMA), operating in a transparent atmospheric window located between near-infrared and radio wavelengths. In this work, we used ALMA to observe the [O III] 88 μm emission line in five bright galaxies around redshift $z = 7$, which had previously been spectroscopically confirmed by ALMA through the [C II] 158 μm line. With HST, we obtained new images of the rest-frame ultraviolet, revealing their young, star-forming regions at Hubble's trademark ultra-high resolution. The [O III] 88 μm emission generally traces these regions well, though not always perfectly, while we found [C II] to be more extended (Fig. 1).

Having observed multiple emission lines, we can furthermore study the physical conditions of the interstellar medium (ISM) that characterise star formation at these early epochs. A non-detection of [N II] 205 μm in one source shows (via the [C II]/[N II] ratio) that for typical physical conditions, the [C II] emission can likely be traced to a neutral medium, such as the gas in photodissociation or X-ray dominated regions. The [O III]/[C II] ratio – seemingly elevated in the most distant galaxies – has been hotly debated in recent years. Surprisingly, when we start to look at the [O III] luminosity in detail, theoretical models struggle to reproduce its strength, unless we assume a near-Solar nebular oxygen abundance.

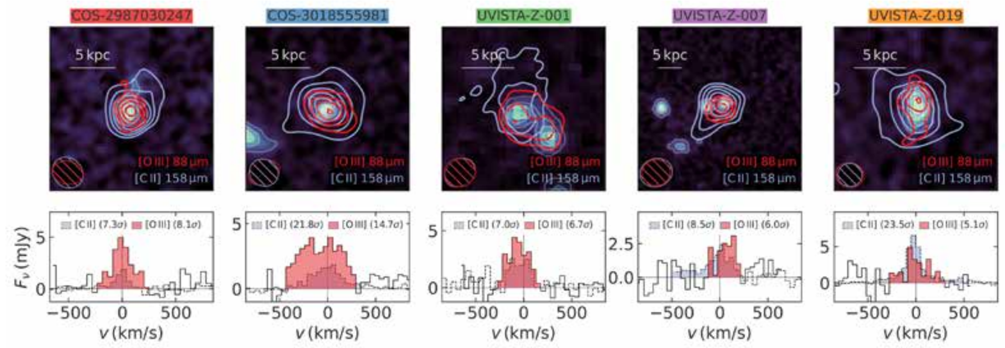


Fig. 1: Detections of the [C II] 158 μm and [O III] 88 μm lines. Top row: contour images of the [C II] and [O III] lines overlaid on a background of HST rest-frame UV images. Bottom row: line spectra. Figure from Witstok et al. (2022).

Fig 1

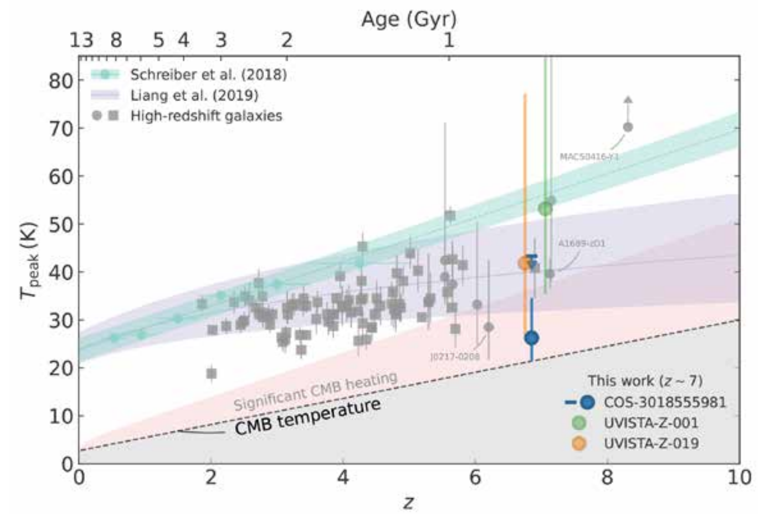


Fig. 2: Dust peak temperature, T_{peak}, as a function of cosmic time or redshift. Sources studied in this work are shown in colour, one of which has a notably low temperature. Figure from Witstok et al. (2022).

Fig 2

There are more surprises when we look at the thermal radiation emitted by dust, a collective term for small interstellar particles predominantly made up of silicon, carbon, and iron. Constraints at both 90 μm and 160 μm allow us to study (currently poorly understood) dust properties such as the temperature of these dust grains. To do so, we applied a newly developed far-infrared spectral-energy-distribution fitting routine, MERCURIUS. This indicates the presence of exceptionally cold dust in one system (Fig. 2), implying a large dust mass that again would require a high yield of metals and efficient subsequent conversion into dust grains. Currently, we eagerly await new JWST measurements on this specific system that will reveal more details on the hot ionised gas and stars in this galaxy. This will tell us whether our theoretical models need refining, or that we are truly seeing a remarkably mature system that has built up a considerable amount of metals and dust.

This article is based on results published as Witstok J. et al., MNRAS 515, 1751 (2022).


Hannah Übler & Roberto Maiolino

A Massive Black Hole in a Low-Metallicity Active Galactic Nucleus at $z = 5.55$

Black holes are some of the most fascinating objects in the Universe. Celestial bodies with a gravity so strong that even light cannot escape them were first conceptualised in the late 1800s. Theoretically founded within General Relativity about 100 years ago, observing black holes is still challenging because we can only infer them from their surroundings – for instance through the motions of stars and gas in their vicinity. Today we believe that most massive galaxies harbour a supermassive black hole in their centre with millions to billions of Solar masses. Not only do they impact their immediate surroundings through gravity, but there is growing evidence that they play a decisive role in the evolution of their host galaxies, extending their reach over more than 10 orders of magnitude.

Finding and characterising massive black holes and their host galaxies in the early Universe is therefore a powerful path to constrain theoretical models of galaxy evolution. Black holes are easiest to catch when they are "active", that is when material is accreting onto the black hole, and we call it an "active galactic nucleus" (AGN). During this time, and under the right viewing angle, the properties of the light-emitting hot plasma close to the black hole, specifically the "Broad Line Region", give us a means to measure its mass (Figs 1 and 2). The earlier in the Universe's history we find massive black holes, the stronger the constraints these observations can place on theory. But for accurate measurements we need well-understood emission lines in the optical wavelength range.

A game changer has been the launch of the James Webb Space Telescope (JWST) in late 2021, because its instrumental capabilities enable us to observe optical line emission from very distant galaxies, when the Universe was only a small fraction of its current age. These light waves have been stretched through the expansion of the Universe while travelling towards us, and we can now collect this "redshifted" light with the near- and mid-infrared instruments on board JWST. Through Guaranteed Time Observations (GTO) with the NIRSpec instrument we can now, under the right conditions, observe the hot gas around high-redshift AGN and measure their black hole masses.

And we were lucky right away: in one of our first observations of a distant galaxy at redshift $z = 5.55$, that is one billion years after the Big Bang, we found an active black hole that was previously unobserved. Through the velocity and luminosity of the hot plasma around it, we could measure a black hole mass of about 10^8 Solar masses. It is considered overly massive compared to its host galaxy, which amounts to only $10^{9.5}$ Solar masses (Fig. 3). Our high-quality observations allowed us to constrain many other physical properties in this young galaxy, for instance its gas-phase metallicity, which is only about 20 per cent Solar – this is because massive stars had little time to enrich the interstellar and intergalactic medium with metals. Through this knowledge, we could empirically demonstrate that diagnostics commonly used in the local Universe to identify AGN cannot be applied to low-metallicity galaxies in the early Universe.

We expect JWST to reveal many more AGN in the young Universe. In fact, from our Guaranteed Time Observing program we have already published data from another three luminous AGN – and we cannot wait to look for the most massive, the least massive, and the most distant black holes in our upcoming data.

This article is partly based on results presented in Übler H. et al., A&A 677, 145 (2023).

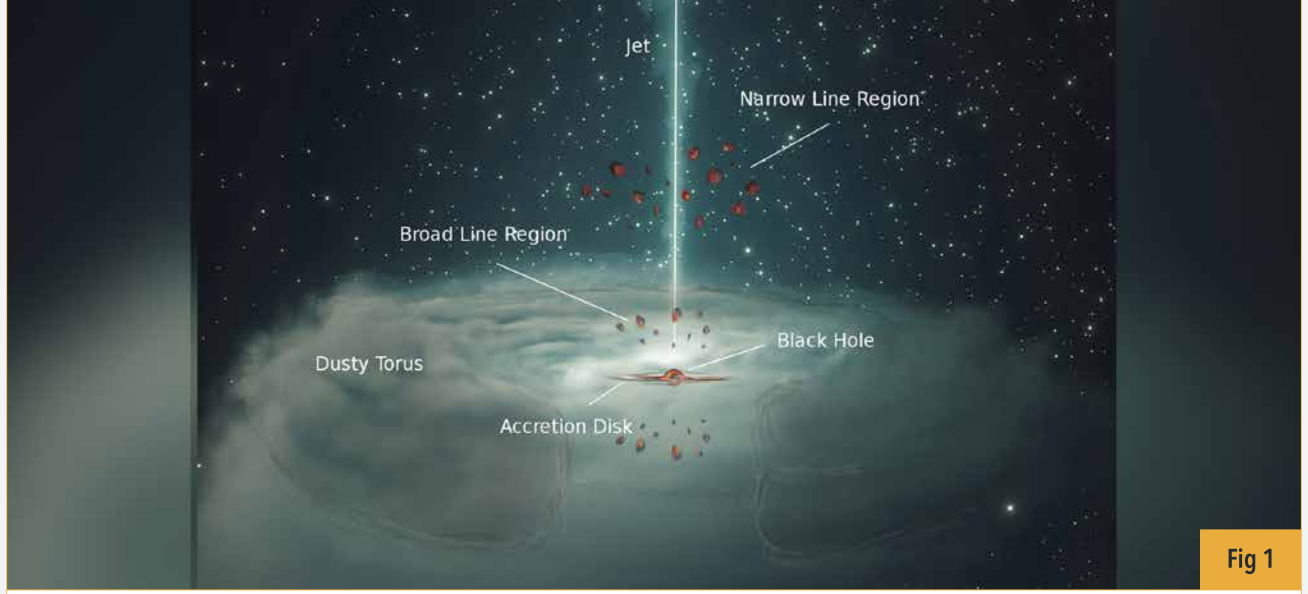


Fig 1

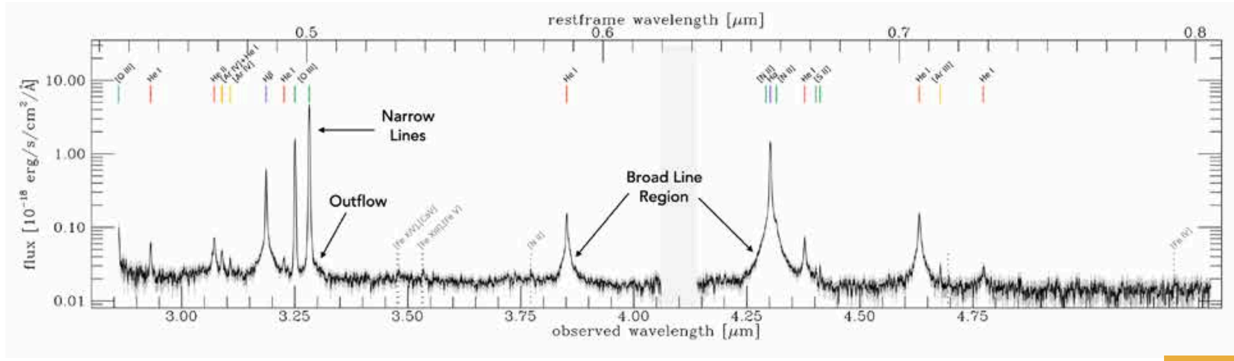


Fig 2

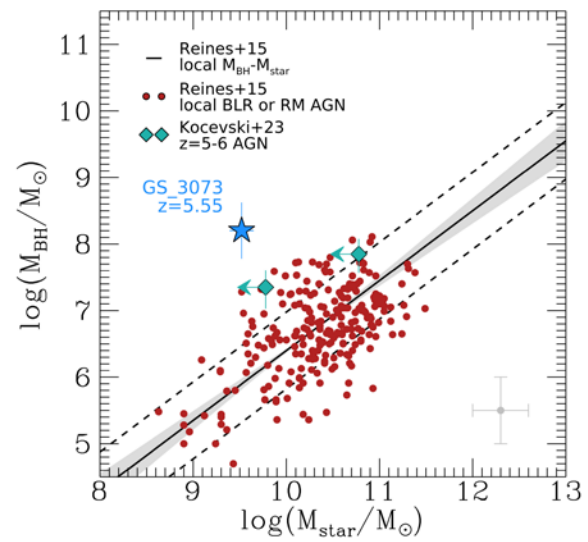
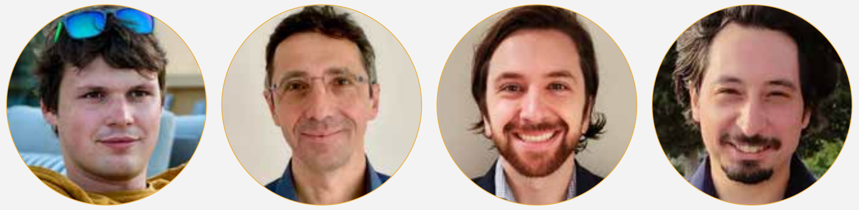


Fig 3

Fig. 1: Sketch of an Active Galactic Nucleus – we measure the black hole mass through our observations of the Broad Line Region. (Credit: Heike Prokoph and DESY/Science Communication Lab.)

Fig. 2: Spectrum of our GTO/NIRSpec data – in addition to the Broad Line Region in the permitted hydrogen (Hα, Hβ) and helium lines (He I, He II), we see an outflow and narrow line emission from the host galaxy and/or the AGN.

Fig. 3: The black hole (left axis) in the galaxy GS_3073 (blue star) is more massive compared to its host galaxy (bottom axis) than local AGN (red points) or some other black holes at similar redshift (green diamonds).



Jan Scholtz, Roberto Maiolino, Gareth Jones & Stefano Carniani

Cold-Gas Halos Around Extreme Red Quasars at Cosmic Noon

It is now widely accepted that every galaxy contains a super massive black hole (SMBH) at its centre with a mass around 1% of the total mass of the host galaxy. As these SMBHs grow by accreting gas they become visible to us, either as active galactic nuclei (AGN) or, if very luminous, as quasars. During their growth, the SMBHs release more than 100 times the binding energy of a galaxy. This means that SMBHs have the potential to rip their host galaxies apart. While this destructive potential does not become a reality, intriguing evidence exists that through this release of energy SMBHs could be playing an influential role in shaping how galaxies develop.

However, despite decades of research into the role of AGN and SMBHs in galaxy evolution, we still lack convincing observational evidence for AGN 'feedback' – the processes caused by the AGN releasing energy – influencing galaxy evolution. Indeed, our current best evidence for this effect comes from numerical simulations. Every cosmological simulation requires SMBHs and feedback from AGNs to reproduce our Universe. Without them heating the gas inside the galaxy and expelling gas from the galaxy, the growth of galaxies – the rate at which stars are formed – is too great to model our Universe accurately.

The search for observational proof of AGN feedback is a hot topic in extragalactic astronomy. We know that AGN can influence the gas surrounding the galaxy – the circumgalactic medium (CGM). The CGM is a mixture of cold pristine gas (meaning it does not contain elements heavier than helium) accreting from the intergalactic medium, and metal-enriched gas that was pushed out of the galaxy by AGN-driven outflows (see Fig. 1).

In our work we focused on the detection of cold metal-enriched gas in the CGM regions surrounding the host galaxies of 15 extremely red quasars at redshift $z = 2.1–2.5$, corresponding to the epoch of the Universe called "Cosmic Noon". These quasars are a subcategory of very luminous, yet dust-obscured, accreting SMBHs. We used state-of-the-art ALMA (Fig. 2) archival data tracing the dust emission and emission lines tracing cold gas of various temperatures in the range 40–200 K (atomic carbon [CI], CO(6-5) and H_2O). In our analysis we stacked all of these tracers to create even deeper stacked maps.

Fig 1

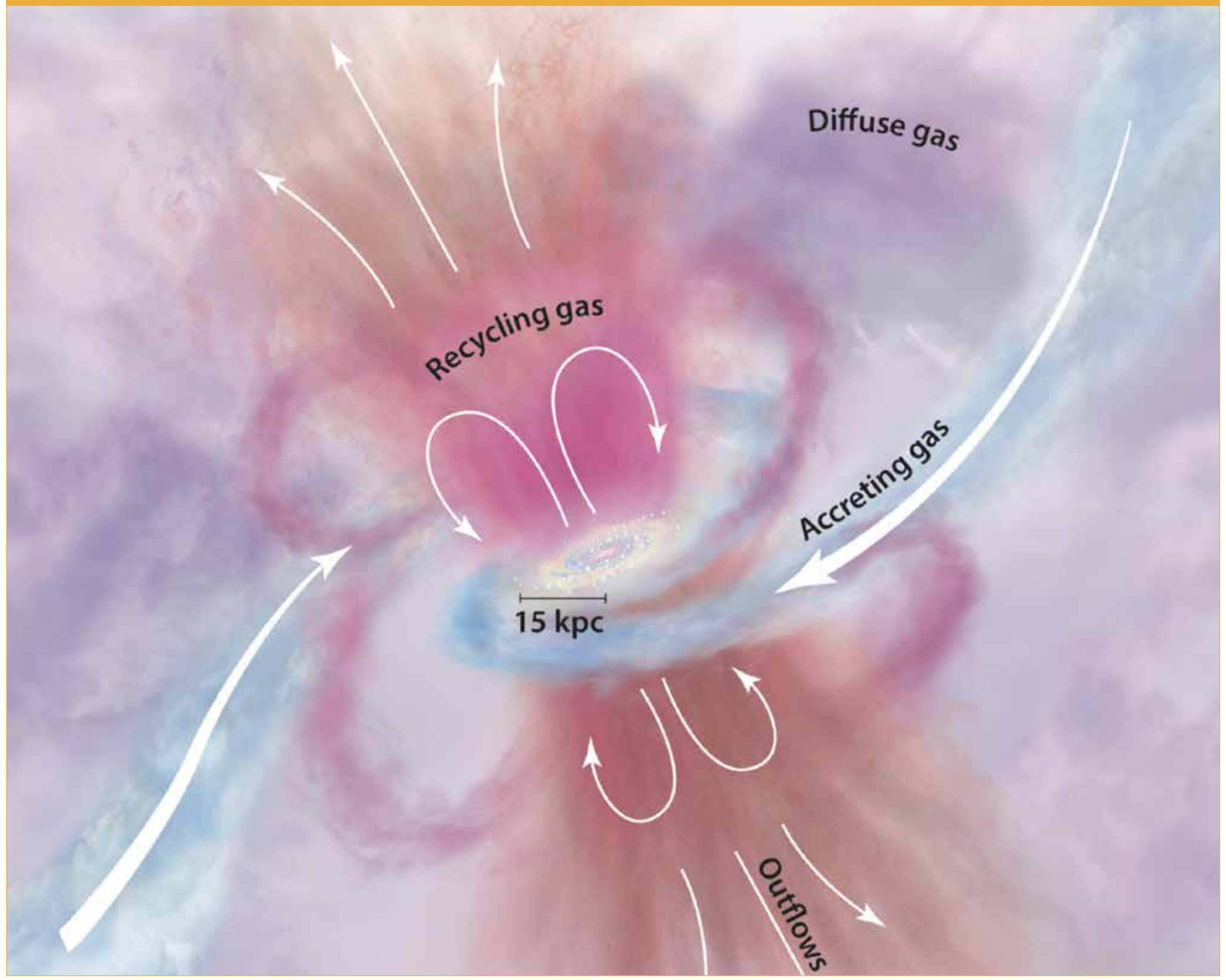


Fig. 1: Schematic of the CGM from Tumlinson et al. (2017). The cold pristine gas from the intergalactic medium is accreting onto the galaxy. Warm metal-enriched gas is pushed out of the galaxy by AGN-driven outflows.

Once we created the maps of the dust, [CI], CO and H_2O, we extracted the radial surface brightness profiles. We created these profiles by measuring the median flux in increasing ring apertures on the image (see Fig. 3). The radial profiles are larger than the beam of the observations, suggesting that the emission is resolved. In order to determine the extent of the emission of each tracer we created mock images of the quasar host galaxy (using a 2D Gaussian model), extracted mock radial profiles and compared them to our data using a Markov-chain Monte-Carlo algorithm to determine the size of the emission region. We also ran additional fitting with two components, a quasar-host galaxy and an extended halo.

continued

Cold-Gas Halos Around Extreme Red Quasars at the Cosmic Noon

Using this analysis, we detected extended halos in dust, [CI] and CO(6-5), indicating a large cold-gas and dust supply around these quasars. The halos have a size of around 14 kpc, twice the size of a typical galaxy at these redshifts. Interestingly, the measured cold gas and dust masses in these halos are $10^{10.6}$ and $10^{7.6}$ Solar masses, which is around 20% of the galaxies' total gas supply.

So how does this fit with galaxy evolution? Is this the smoking gun we have been seeking – observational evidence of AGN-driven outflows pushing gas out of the galaxies? Using typical outflow velocities in these powerful quasars, we estimated it took between 5 and 30 million years for the gas to get to these distances. Since the average quasar episode lasts only 1–5 million years, the gas halos we observe may not have been created by the current quasar episode. This could be evidence that previous AGN and star-formation episodes created these halos. We also theorised that the powerful obscured quasar could be present because of the gas-rich halo supplying this quasar's activity. Either way, we now need follow-up observations to detect these halos in individual objects, rather than stacks.

This article is partly based on results published as Scholtz J. et al., MNRAS 519, 5246 (2023).

Fig. 2: ALMA telescope in the Atacama desert in Chile. ALMA consists of 66 antennas linked together to act as a single telescope. Credit: ESO/José Francisco Salgado (josefrancisco.org).

Fig 2

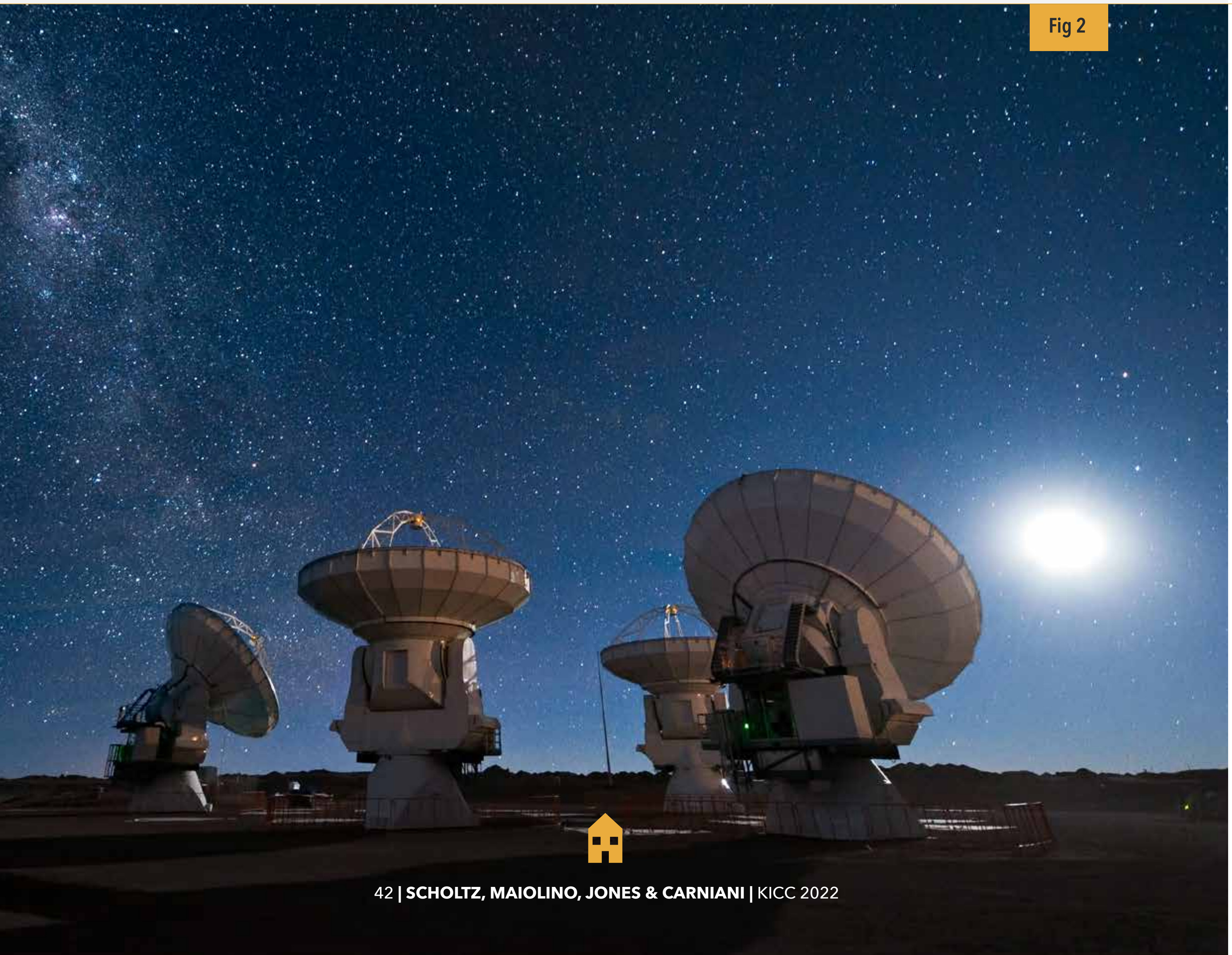
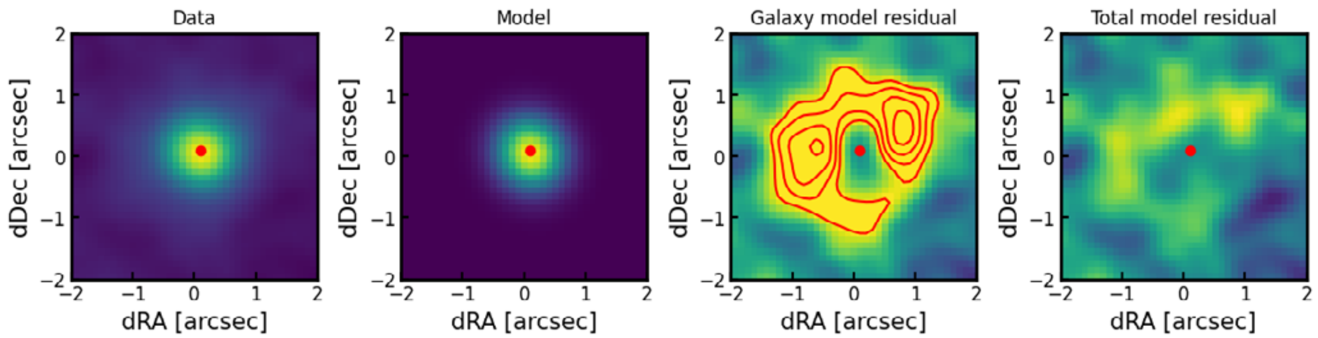


Fig. 3: Our results for the [CI] emission line. From left to right: Stacked data, our model, data after subtraction of the galaxy component, residuals of our total model. We can clearly see extended emission after subtraction of the galaxy model.

Fig 3

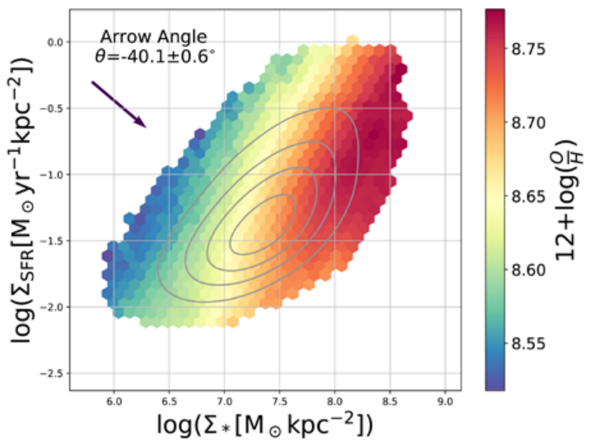


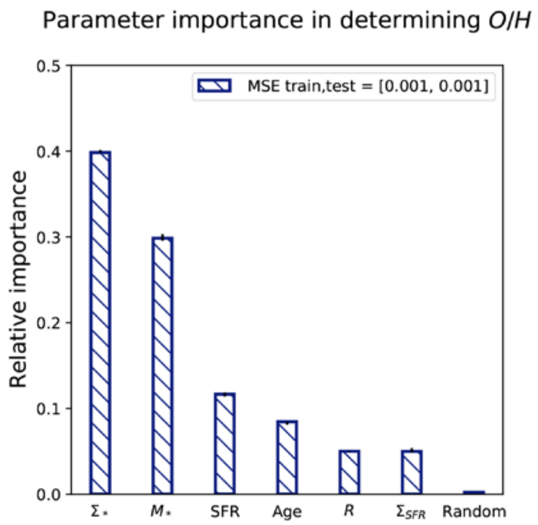
William Baker & Roberto Maiolino

Metallicity's Fundamental Dependence on both Local and Global Galactic Quantities

Elements heavier than helium (`metals' in astrophysics) are produced in stars, then released into the interstellar medium via supernova explosions and stellar winds. The chemical enrichment of galaxies therefore provides information on their star formation history, but also about processes that are key to the formation and evolution of galaxies, such as galactic outflows (which preferentially remove metals) and inflows of (near-)pristine gas (which dilute the amount of metals).

Fig 1





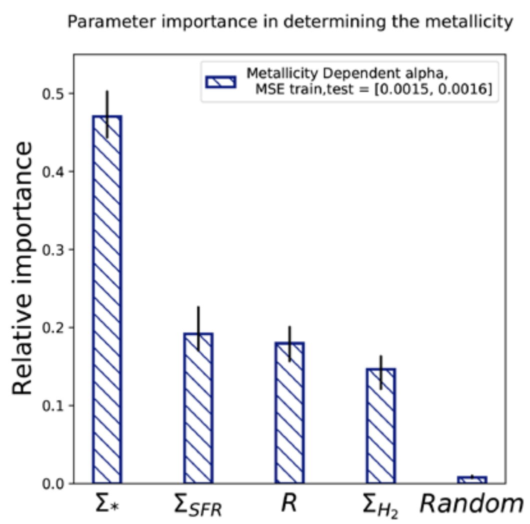


Fig 2

Fig 3

To provide constraints on these evolutionary mechanisms, it is particularly important to investigate the scaling relations between metallicity and galaxy properties. We investigated these using MaNGA, an extensive survey providing spatially resolved spectroscopy of about 10,000 nearby galaxies.

On galaxy-wide scales it is known that stellar mass (i.e., the mass of stars in the galaxy), metallicity and star-formation rate (SFR, the mass of stars produced in a year) follow a three-dimensional relationship called the Fundamental Metallicity Relation, where metallicity correlates with stellar mass and anticorrelates with SFR. The dependence on stellar mass is likely tracing the integral of metals produced, while the dependence on the SFR was thought to result from gas accretion, which both boosts star formation and dilutes the metallicity. The question is whether the Fundamental Metallicity Relation holds also on resolved scales.

Figure 1 shows the resolved star-formation rate (surface density of SFR, Σ_{SFR}) versus resolved stellar mass (stellar-mass surface density, Σ_*), colour coded by average metallicity for over 1.2 million star-forming regions. The colour-shading and the arrow, which points in the direction of the greatest increasing gradient of the colour-coded quantity (i.e., metallicity), indicate that the metallicity depends both on Σ_* and on Σ_{SFR}, i.e., it reveals the existence of a spatially resolved version of the Fundamental Metallicity Relation. Does this mean that the global Fundamental Metallicity Relation stems from its spatially resolved version?

We investigate this by exploring whether the resolved metallicity depends also on global galaxy properties, such as total stellar mass M_* and SFR, and on other properties, such as age of the stars, or the distance from the centre of the galaxy (R). Figure 2 shows the relative importance of these properties in determining the local metallicity of galaxies based on a supervised machine-learning algorithm called a `Random Forest', which is powerful in uncovering many hidden relationships. The result is shown in Fig. 2 and illustrates that the metallicity depends primarily on both resolved (Σ_*) and global (M_*) stellar mass with a secondary dependence on SFR. This means that the metallicity of individual star-forming regions of a galaxy depends on both the properties of that region and on global properties of the entire galaxy. In particular, the Fundamental Metallicity Relation does not simply stem from its local version.

The next stage is to investigate whether the molecular gas mass (Σ_{H2}) of a star-forming region contributes to the observed metallicity. Indeed, according to the scenario discussed above to interpret the FMR, the metallicity dependence on SFR (or Σ_{SFR}) is resulting from the accretion of (near-)pristine gas diluting the metallicity and the strong dependence of Σ_{SFR} on Σ_{H2} (as the molecular gas is the fuel for star-formation). To probe this, we utilise the ALMaQUEST survey of 46 local galaxies, containing measurements of molecular gas masses for over 10,000 star-forming regions. We again use random forest regression to explore which of the resolved quantities is most important in determining the metallicity, this time with the addition of Σ_{H2}. Figure 3 shows the resulting parameters' importance. We can immediately see that the metallicity is again driven by Σ_* with a secondary dependence on Σ_{SFR} (and R) whilst a weaker dependence is found on Σ_{H2}. This tells us that the dependence on Σ_{SFR} is a direct relation and not simply a by-product of a more fundamental dependence on Σ_{H2}. Hence, gas inflows cannot fully account for the Fundamental Metallicity Relation.

This article is based on results published as Baker W. M. et al., MNRAS 519, 1149 (2023).

Fig. 1: Star-formation rate surface density versus stellar-mass surface density colour coded by the average metallicity [12+log(O/H)] in each bin. The arrow angle gives the direction of the steepest gradient across the entire distribution. The colour shading and arrow show the dependence of metallicity upon Σ_*, with a secondary inverse dependence on Σ_{SFR}, revealing the existence of a resolved Fundamental Metallicity Relation.

Fig. 2: The importance of global and local galactic parameters for determining the local metallicity of the star forming regions in galaxies, based on Random Forest (RF) regression. The RF clearly indicates that both resolved (Σ_*) and global (M_*) stellar mass play the most important role.

Fig. 3: The importance of local parameters in determining the resolved metallicity of the star-forming regions in 46 local galaxies with resolved molecular gas mass measurements (Σ_{H2}).

David Yallup & Will Handley

Bringing Astrostatistics Back to Earth

The field of cosmology has generated, and solved, complex data science questions for longer than data science has even been a widely recognised term. When we have only one run of the grand experiment – our observable universe – physicists have to develop methods that squeeze every last drop of information out of the observations we can make. This dictates how we approach data science, and advocates for an approach that maximises the information gain given our input knowledge – the maximum-evidence viewpoint. The group led by Will Handley at KICC, and its predecessors across Cambridge astrophysics, have been at the frontier of developing techniques that embody these ideas. The Kavli Institute has supported the group with an environment that encourages a broad interdisciplinary viewpoint, and provides a platform for broader engagement across Cambridge with data science questions in many areas of fundamental physics. This has formed one of the group's recent research themes, seeking to engage with fundamental physics beyond the traditional borders of cosmology and astrophysics, forging new research connections between the KICC and an array of collaborators on a wide range of topics.

The core technology the group works on is creating tools for precise Bayesian inference, developing tools and algorithms to allow precise comparison between models of observed data. This strikes at the heart of one of the central conflicts in data science – the tradeoff between bias and variance in a proposed model – capturing this conflict by calculating the Bayesian evidence. Historically, calculating the evidence has always been desirable but has been too difficult to calculate accurately in many practical settings. Our group is world-leading in developing algorithms to perform these calculations, and by battle-testing them on precision-cosmology problems has developed a unique angle on data science that is now being pushed beyond borders.

Aside from exploring the utility of the Bayesian inference paradigm enabled by an "evidence-first" approach, it is worth investigating what the novel algorithmic techniques can do beyond probabilistic modelling, and this is an area where the group has expanded its interests in recent years. In calculating the Bayesian evidence we are evaluating a high-dimensional integral, developing techniques to perform calculations that may have been previously considered intractable and potentially opening up whole new possibilities in fundamental physics. Recent work of the group has dived into the world of calculations in quantum field theory (QFT). QFT is the theoretical framework through which almost all of the high-energy, and hence small-scale, particle interactions are understood. At particle colliders such as the Large Hadron Collider (LHC), these interactions are well understood in terms of perturbative calculations, generating a series of increasingly complex integrals that rely on numerical tools to estimate the solutions. In a recent collaboration with high-energy physicists, the group developed a novel numerical technique, powered by the algorithms developed in cosmology, to explore the kinematic structures of LHC collisions. An example of mapping out the kinematic variables of complex high-energy collisions is shown in Fig. 1. At the other end of the scale in particle physics, the same QFT equations are probed in a non-perturbative regime. This requires discretization on a lattice to solve, which again generates high-dimensional integrals to be solved, a discipline known as Lattice Field Theory. The group has recently proposed a new method to integrate field equations on a lattice, demonstrating a route to access the full thermal history of a lattice that has previously been unexploited (captured in Fig. 2). Attacking numerical problems at both ends of the theory space of QFT is a challenging program, one that pushes beyond the traditional realm of the KICC and into new territory in fundamental physics.

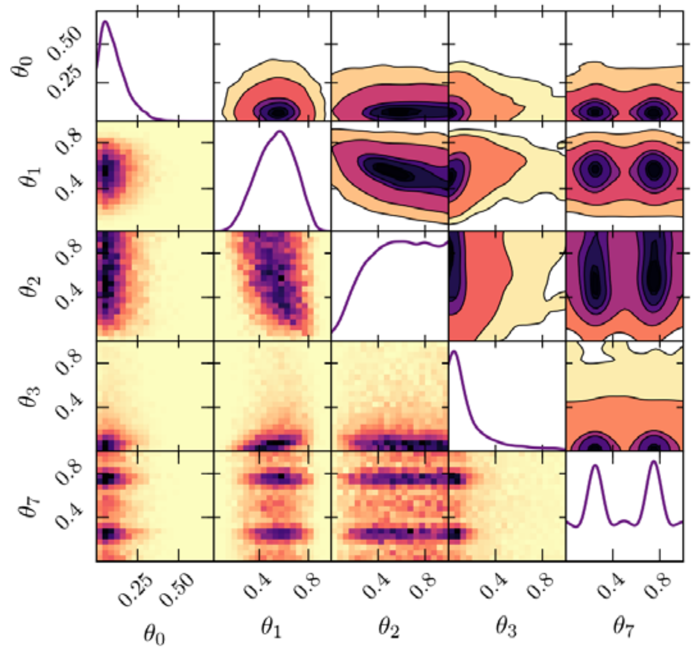
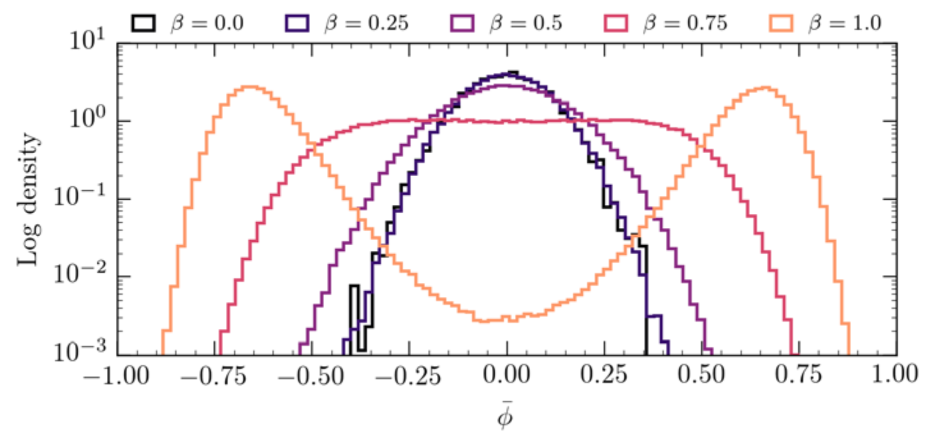


Fig. 1: Learning the kinematic structure of particle collision events at the Large Hadron Collider. The variables, Θ, govern the kinematics in gluon scattering processes at the LHC.

This article is partly based on results published as Yallup. D. et al., European Physical Journal C 82, no. 8 (2022).

Fig. 2: Uncovering the thermodynamic structure of solutions to Lattice Field Theory equations for scalar field theory with a symmetry-broken phase emerging as the temperature decreases (β increasing).



Annelies Mortier

The Link Between the Chemical Composition of Stars and Their Orbiting Planets

Exoplanets are planets orbiting stars other than the Sun. In merely 30 years we went from having just the Solar System planets to knowing over 5000 exoplanets. They are most commonly detected via two methods. The radial-velocity method, credited with the first discovery of a planet orbiting a Solar-type star, relies on the gravitational effect of a planet on its host star. An orbiting planet makes its host star wobble slightly and by monitoring a star's velocity along the line-of-sight (its radial velocity), we can measure the planet's orbital period and mass. The transit method is conceptually even simpler and relies on monitoring a star's brightness. When a planet passes between its host star and our line-of-sight, the brightness will momentarily dip, allowing us to measure the exoplanet's radius and orbital period.

The first exoplanets to be discovered were all massive planets orbiting close to their star, appropriately called hot Jupiters. Very early on after these first discoveries of these new exotic worlds, it became obvious that there was a relation between stellar metallicity (a measure of the chemical composition of the stellar atmosphere) and the existence of a massive exoplanet. The more metal-rich a star was, the more common a massive planet was found in their system. This exciting link between stellar composition and the existence of a massive planet was the basis of my Ph.D. (ten years back) and I have been interested ever since in what that could possibly mean for smaller, more Earth-like planets.

The Kepler space telescope, launched in 2010 by NASA, has revolutionised the exoplanet field, finding thousands of small exoplanets via the transit method. After careful investigation, it was found that in contrast with the giant planets, small planets are not more or less common around stars with different chemical compositions. While small planets are thus equally common around all these stars, it is easy to imagine that their interior structure may be different and possibly related to the chemical composition of their host star (Fig. 1). After all, both the host star and their orbiting planets were formed from the same gas and dust cloud.

The Earth, in its simplest interior structure model, consists of a heavy iron core, a rock-like silicate mantle, and a tiny water layer and atmosphere on top of that. Unfortunately, we cannot directly probe this interior structure of exoplanets. We can, however, measure an exoplanet's bulk density. We use the term "bulk density" because planet densities are not uniform. Each of the layers in the Earth have vastly different densities. The exoplanet's bulk density comes from combining the two detection methods mentioned above. Together they measure both a planet's mass and radius, effectively providing a bulk density of the exoplanet.

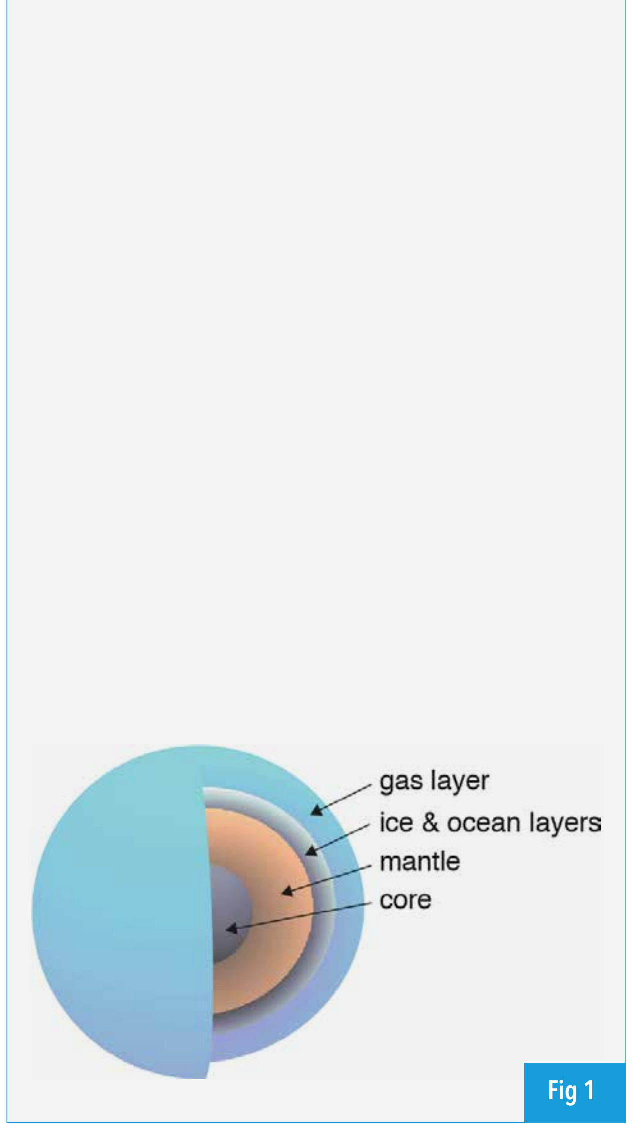


Fig 1

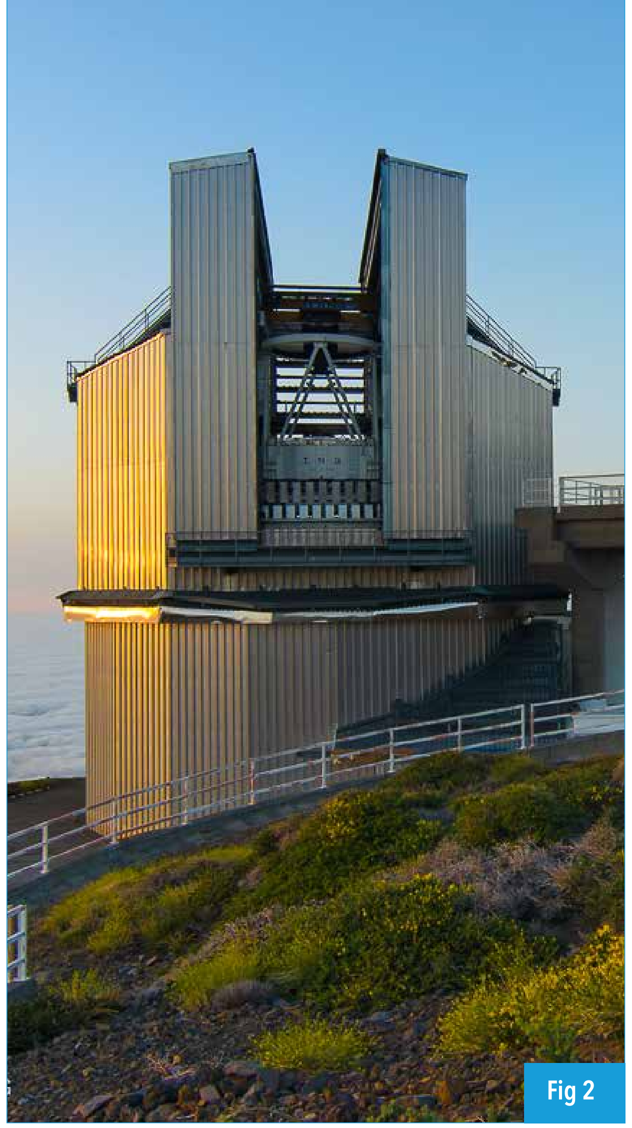


Fig 2

Building a sample of small planets with precise bulk densities is a slow process as it is observationally expensive and pushing technology to its limits, but early results show that a small planet's bulk density decreases with a star's iron mass fraction. In other words, if a star has less iron than it has silicon and magnesium, then early evidence indicates that its orbiting Earth-like planets would have much smaller iron cores and significantly larger mantles than the Earth. It is crucial for this research that we focus on stars with a different chemical composition than the Sun in order to discriminate between different regimes. Only two small planets have been well characterised so far where their host star is chemically significantly different from the Sun. I have led the first study of such a planet (named K2-111b) and heavily contributed to the second one (TOI-561b), both using radial-velocity data from HARPS-N (Fig. 2). The search continues for these small planets orbiting chemically different stars and will lead to a better understanding of the rich diversity of small exoplanets in the Universe.

Fig. 1: Schematic of a general exoplanet interior (from Dorn et al. 2017).

Fig. 2: The Telescopio Nazionale Galileo, housing the HARPS-N spectrograph.

Mathias Nowak

A Deuterium-Burning Planet?

28 August 2021: this was our second attempt to use the GRAVITY instrument, on the Very Large Telescope Interferometer, to confirm the presence of a planet suggested by radial-velocity measurements. The first time was just a year earlier, in 2020, when we pointed the fibre of the instrument towards the beta Pictoris system, at a slight offset from the central star, to confirm the presence of beta Pictoris c. This time, our target system was HD 206893, already known to harbour a brown-dwarf of about 26 Jupiter masses, but in which a second, less-massive, companion was suggested from radial-velocity measurements.

And so, during two consecutive nights, we searched for the presence of HD 206893 c, trusting the data accumulated over several years with the HARPS spectrograph, the Gaia astrometric measurements, and our own orbital estimates to predict the on-sky position of the planet. It had to be here, somewhere! Or at least, it was very likely to be here. But it did not seem to be. We had spent 2.5 hours with the four 8-metre telescopes of the VLT, but the only thing we had found was random noise.

But during a very careful re-examination of all the data acquired on these two nights, we later noticed something. Just on the edge of one of the fields probed by GRAVITY, a little spot, barely visible, hard to trust, and certainly not publishable. But could it be it? Could it be our missing planet? One month later, a repeat observation at this particular location confirmed that it was: HD 206893 c, a massive (10–13 Jupiter masses) planet whose existence had only been hinted at by radial-velocity data. A clear, direct, and beautiful confirmation of the hybrid nature of the HD 206893 system, where one giant plant cohabits with a brown-dwarf.

But more than just an observational feat, this observation also drastically improved our estimates of the orbits of the two companions, and made it possible to determine the luminosity and the mass of the planet, and to improve the estimates we already had for its sister brown-dwarf. And to our surprise, we found that the planet was actually very bright, only fainter than its sister brown dwarf by 50%. This was certainly unexpected, and, considering that the two companions must be of similar age since they were born in the same system, hard to explain with the available models. These models could explain the luminosity of planet c if the system was relatively young, but this would have left the brown-dwarf B weirdly under-luminous for its age. Alternatively, the models could explain the luminosity of B if the system was older, but in this case, planet c would be utterly over-luminous for its age.

When the models do not fit the data very well, we tend to love it: this is usually a clear sign that something rather unique and interesting is going on. In this case, the answer probably lies in the fact that the giant planet HD 206893 c is very close to the deuterium-burning limit, which is the minimum mass that a planet must have to be able to fuse deuterium in its core. So some deuterium fusion must be going on in the core of HD 206893 c. This gives a boost in luminosity to the planet, and, with a relatively old age of 155 Myr for the system, this explains the luminosity of both companions.

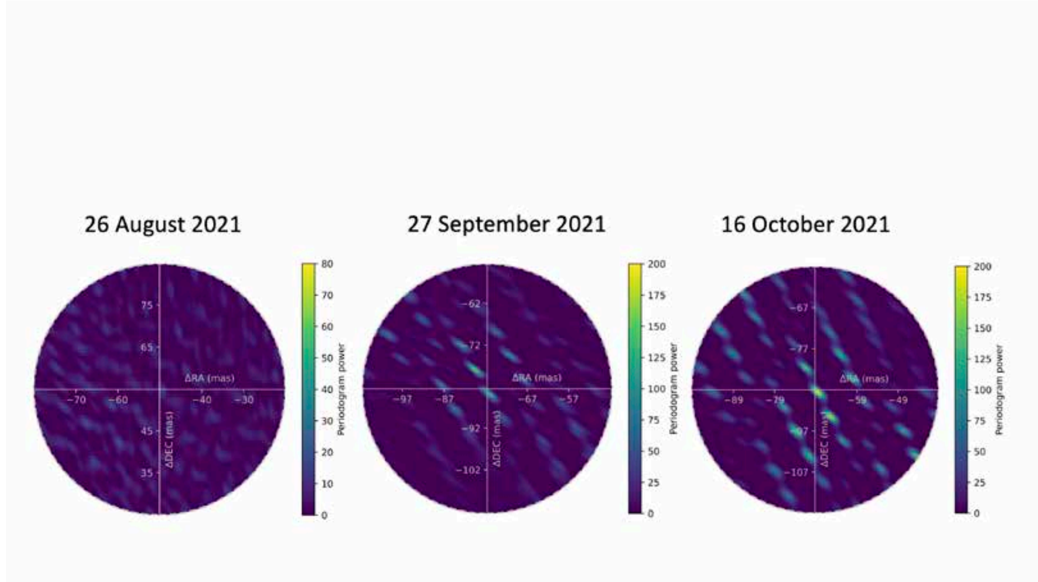


Fig. 1: Interferometric observations of HD 206893 c. Each plot represents the periodogram power in the limited field-of-view of GRAVITY. Nothing was detected in August, but a clear detection is visible in September and October.

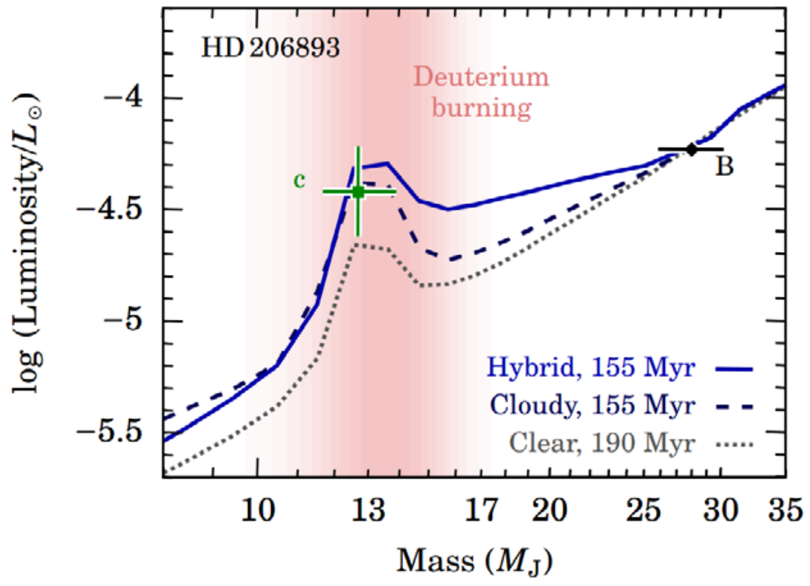


Fig. 2: Position of the planet HD206893 c and brown-dwarf HD 206893 B in the mass-luminosity diagram. Planet c falls exactly on the luminosity bump of deuterium burning.

There is no doubt that this system will become a very interesting laboratory to study planet formation and evolution processes, and in particular to understand better the differences between giant planets and brown-dwarfs.

This research was published in: Hinley, S. et al., A&A 671, L5 (2023).

Michalis Agathos

Gravitational Waves Beyond Einstein's Relativity

Together with the Standard Model of particle physics, Einstein's theory of General Relativity (GR) is one of the most successful theories in modern physics: it has accurately explained all gravitational phenomena observed to date, and predicted the existence of gravitational waves (GWs) 100 years before their detection by the LIGO-Virgo Collaboration in 2015. From a mathematical viewpoint, GR is furthermore a unique theory in the spirit of Lovelock's theorem: a geometric theory of gravity satisfying a specific set of plausible requirements must be GR. In spite of its elegance and success, it is widely acknowledged that GR will eventually have to be superseded by a quantum theory of gravity. This knowledge gives us sufficient motivation to analyse observed data, carefully looking for signs of GR being violated, particularly from astrophysical systems as extreme and violent as black holes or neutron stars colliding at close to the speed of light.

But in what manner could GR be violated? Are there examples of viable alternatives or are we searching in the dark? By dropping one requirement in Lovelock's theorem, we can allow for additional fundamental fields to contribute to the gravitational interaction. Two fellow researchers at Cambridge, A. Kovacs and H. Reall, recently proved the well-posedness of a large class of such theories, known as Horndeski theories, where a scalar field is added to the dynamics of gravity. Apart from providing a simple extension of GR at a fundamental level, gravitational scalar fields arise naturally in approaches to quantum gravity such as string theory. They also seem to act like magic wands in resolving observational puzzles in modern cosmology, such as the flatness problem or the nature of dark matter. By modelling astrophysical systems in these theories and searching for their "smoking gun" signatures, we can then test their predictions against GR, in the light of new observations.

In GR, gravitational waves are described as "tensorial" or "spin-2" fields propagating on a background spacetime, and have two associated degrees of freedom (known as the "+" and the "x" polarisations). The addition of a "scalar" or "spin-0" field in extensions of GR results in an extra component in the GW signal that interacts differently with our detectors than the standard GR waves (Fig. 1).

There are two ways such a field can manifest itself in signals from binary mergers: during the inspiral and ringdown phases. The longest part of the signal comes from the inspiral stage, during which the two objects are on a slowly evolving circular orbit around their centre of mass, gradually getting closer as they lose energy in GWs. We only get a glimpse of the final few to few thousand cycles of this stage, but this is the most interesting bit as it can reveal crucial details about the dynamics of spacetime where gravity is strong and where massive objects interact at relativistic speeds. Tamanna Jain, a PhD student at DAMTP, calculated to high precision how the presence of the scalar field would modify the orbital dynamics and how its signature would show up in our detectors. Having seen no such anomaly in the data, we can set observational constraints to the coupling constants of the theory.

Fig 1

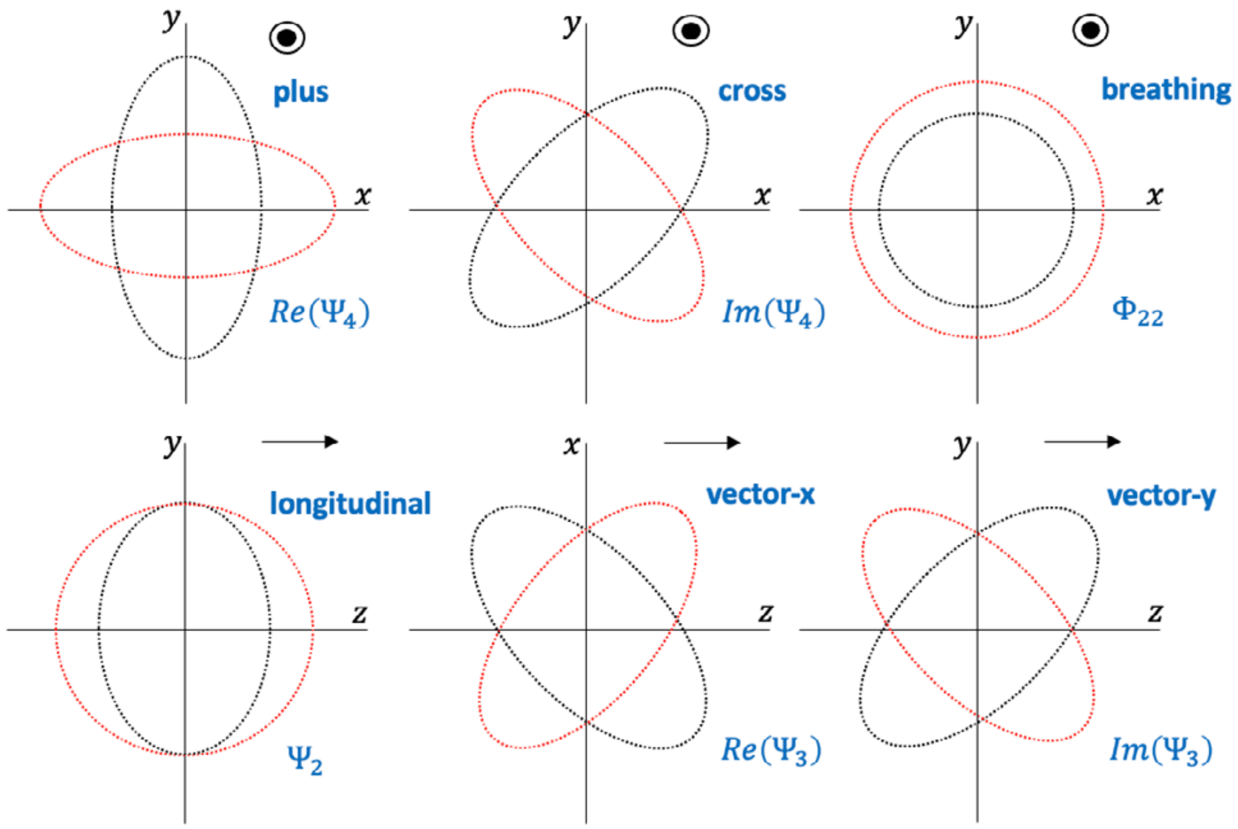


Fig. 1: Ways that different polarisations of a GW propagating along the z-axis affect a circular array of test particles. In GR, only the plus and cross polarisations exist.

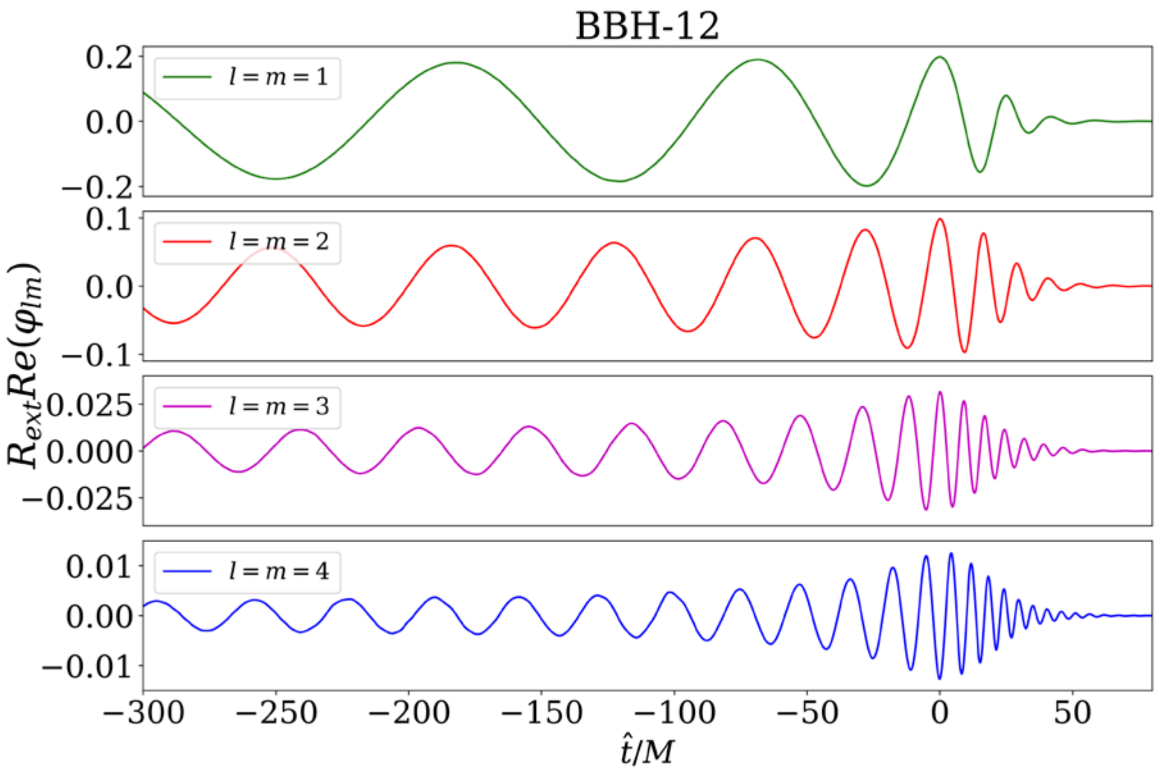


Fig 2

Fig. 2: Mode decomposition of a scalar GW signal from two black holes merging in Einstein-scalar-Gauss-Bonnet gravity. The merger takes place at t = 0, followed by the ringdown.

Eventually the two objects merge into a highly perturbed final black hole that wobbles around for a fraction of a second and quickly rings away its asymmetry in the form of GWs. That ringdown signal can be broken down into a discrete spectrum of frequencies. The merger–ringdown process cannot be solved analytically, so we resort to numerical simulations. With PhD student Tamara Evstafyeva and postdoctoral researcher Justin Ripley, we simulated black-hole mergers in a particular Horndeski theory, known as Einstein-scalar-Gauss-Bonnet. We identified a ringdown spectrum for the scalar waves, in addition to (but much weaker than) the standard tensorial GW signal (Fig. 2). We can now envision a generic form of "black-hole spectroscopy", where we can directly search GW data for the presence of the characteristic scalar spectrum; a smoking gun for modified gravity.

In some theories, the scalar field can be "massless" (so that scalar waves propagate at the speed of light), while in others it can be "massive", in which case higher-frequency waves will travel faster than lower-frequency waves. This dispersion feature can turn a burst-like GW emission into a long-lived signal, from the viewpoint of a distant observer.

A "cosmic symphony" of such overlapping scalar waves can result from the population of supernovae exploding across the Universe. With Prof. Ulrich Sperhake (DAMTP) and former Cambridge colleagues Roxana Rosca-Mead (Jena) and Chris Moore (Birmingham), we numerically reproduced this "stochastic background" of scalar GWs and showed that for part of the theory's parameter space, this type of signal can be detectable in the near future. Meanwhile, incoming PhD student Jack Kwok devised a method that searches for continuous scalar signals coming from nearby historical supernovae such as Cassiopeia A.

As the fourth observing run of the LIGO, Virgo and KAGRA detectors is unfolding, hundreds more binary-merger events are expected to be added to our collection. With the prospect of further upgrades to our detector network as well as the development of next-generation detectors (Einstein Telescope and Cosmic Explorer), we will eventually be searching for signs of Einstein's theory breaking, in every nook and cranny of extreme spacetime across the entire observable Universe!

This article is partly based on results published as Jain T. et al., Phys. Rev. D 107, 084017 (2023); Evstafyeva T. et al., Phys. Rev. D 107 124010 (2023); and Rosca-Mead R. et al., Phys. Rev. D 107, 124040 (2023)

Public Engagement Work at KICC Matt Bothwell

Fig. 1: A group of visually-impaired adults and children attending a sonified and tactile astronomy evening.

Fig. 2 & 3: Members of the public enjoying children's crafting activities and telescope tours at the 2022 KICC & IoA Open Day.

Project AstroEast

Since the start of 2019 we have been running the 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. AstroEast picked up during 2022, with a number of schools returning to a level of pre-COVID normality.

Our partnership with STEMPoint East has resulted in four new schools across the region joining the program, for a total of nine schools in low social-capital areas. During 2022, we delivered a range of workshops, careers assemblies, after-school science clubs, and stargazing evenings for these schools.

Looking ahead to 2023, we are intending to create an additional public-engagement position, partly to provide administrative support and project management to AstroEast, with the aim of significantly growing the number of schools in the program.

Working with local schools

A major part of our outreach program involves working with local 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).

Visits to schools picked up significantly in 2022, with 2–3 school visits in a typical term-time week. In total, during calendar year 2022 there were 55 school visits, delivering outreach to approximately 1500 children.

Online outreach activities

The virtual venue for many of our outreach activities over the past year has been our YouTube channel, "Cambridge University Astronomy" (so named because it functions as a joint channel for both KICC and Institute of Astronomy public engagement). During 2022, we have adopted a hybrid approach, holding our public lectures in-person and simultaneously broadcasting to YouTube. In the 2022–23 season, approximately 13,000 people watched our online lectures (in addition to around 3500 in-person attendees).

Communicating astronomy to visually impaired people

The KICC has partnered with Cam Sight, a Cambridgeshire charity that supports people with low vision and blindness. Throughout 2022, we have continued to provide a mix of workshops and lectures to visually impaired children and adults. We have hosted a number of children's groups, and the KICC outreach officer has travelled out to deliver workshops at rural community groups that serve people with mobility issues.

These workshops and lectures, all relating to Kavli research themes (such as exoplanetary science and the formation of galaxies), combine our 3D printed models with multi-sensory information, such as data sonification, in order to communicate effectively the excitement of astronomy in a fully accessible way to the visually impaired community.

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 which 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 aged between 11 and 15 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 2022, we hosted six primary-school workshops, delivering a day of activities related to exoplanetary research to 175 children (aged 9–11).

Cambridge Festival

In 2022 we saw the return of the in-person Cambridge Festival, for the first time since 2019. Across the two weeks of the Festival, the University engages with the public showcasing a wide range of cutting-edge research happening at Cambridge. The KICC and the Institute of Astronomy ran an Open Day, with a range of drop-in activities designed to entertain and educate the public about our astronomical research. All activities were run outside to ensure COVID safety. Our Open Day was enormously popular, with around 1000 members of the public visiting over the course of the afternoon.

Professor Richard Hills FRS
1945 – 2022

Malcolm Longair

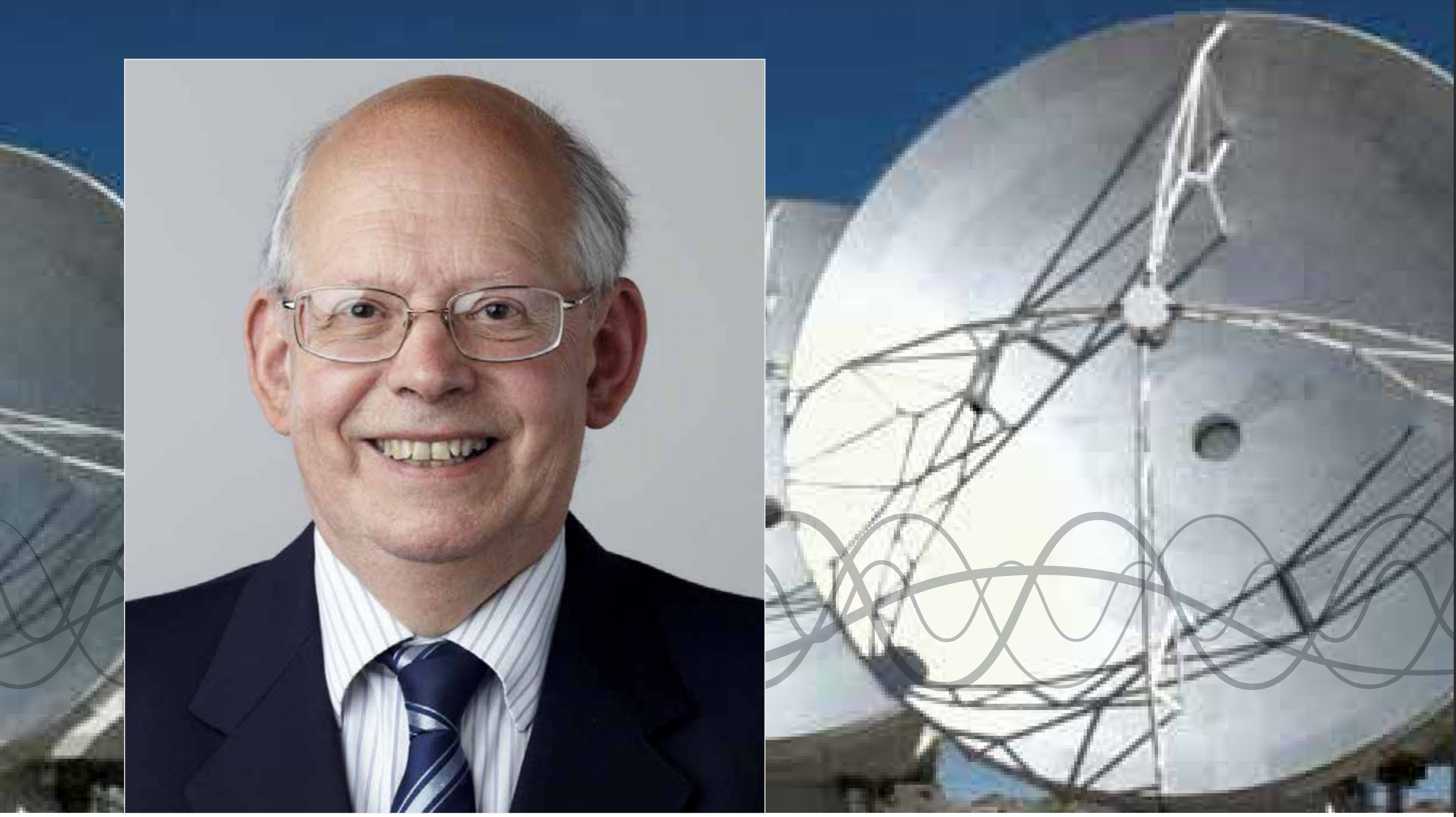


Photo credit: Debbie Rowe, released under a CC BY-SA 3.0 license.

Readers will be saddened to learn of the untimely death of Richard Hills.

Richard was a world-leading millimetre astronomer with extraordinary gifts as an instrument designer and builder, telescope and instrument specialist, observer and astrophysicist. His technical expertise was unparalleled. For his Ph.D. at the University of California, Berkeley, he built the world's first millimetre interferometer. During a postdoctoral position at Bonn, he made successful application of innovative techniques for setting the surface of the Effelsberg 100-metre radio telescope to enable observations in the centimetre waveband. On his return to Cambridge, he performed outstandingly in his roles as project scientist for the James Clerk Maxwell Telescope (JCMT) in Hawaii. While the JCMT was being developed he built up expertise in the Cavendish Astrophysics Group in millimetre-wave observing using other telescopes and also built a receiver for sub-millimetre observing with the UK Infra-Red Telescope (UKIRT) in Hawaii. He was subsequently appointed project scientist in Chile for the Atacama Large Millimetre Array (ALMA) on the high-altitude Atacama Desert. All these projects have been outstanding successes for the benefit of the whole UK and world community of astronomers.

Richard was a brilliant observer. Among his achievements were observations of the Sag B2 source in the Galactic Centre for which he and his students developed the technique of making measurements 'on-the-fly' – simultaneously performing a two-dimensional scanning motion with the antenna while 'switching' the beam rapidly between two positions with the sub-reflector to remove the effects of atmospheric emission. The paper on Solar observations provided an early indication of what structures could be seen on the Sun at millimetre wavelengths with the angular resolution provided by the JCMT. The paper on CO observations at sub-millimetre wavelengths was one of his first efforts at observations in the 600–700 GHz band. The paper on 'fast outflows' in Orion is an example of how the angular resolution and sensitivity of the JCMT enabled him to extract the physical parameters of the high-velocity flows of gas that had been found to be associated with the process of forming new stars. One piece of work of particular importance was sub-millimetre observations of high-redshift objects. This was the first time that emission at these wavelengths had been seen from anything more distant than 'local' galaxies and paved the way for extragalactic astrophysics with the ALMA telescope array.

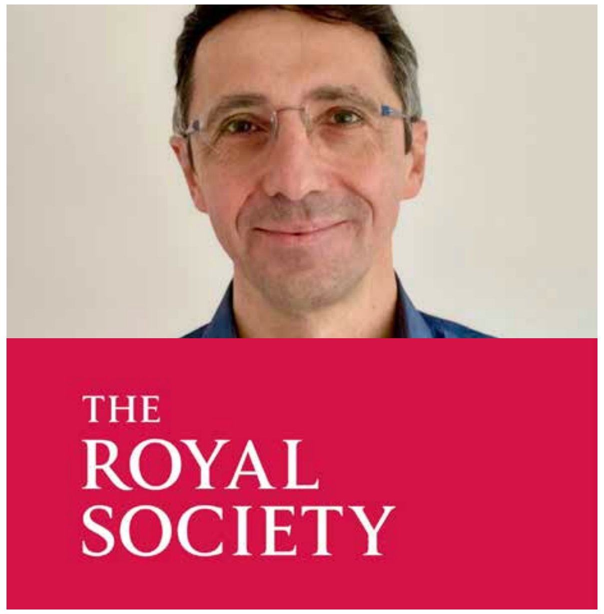
Richard was always a great friend and supporter of the Kavli Institute. He was generous with his time and served on several of our Fellowship selection panels. Scientifically, Richard's observations of galaxies and active galaxies at large redshifts were of special interest to members of the Kavli community, as was his deep involvement in star and planet formation which paralleled the expansion of the Kavli programme in these areas. His most direct contribution to the cosmological work at the Kavli Institute was his analysis in 2018 of claims that evidence had been found in data from the EDGES experiment for a global 21-cm (rest-frame) signal due to absorption of the cosmic microwave background against hydrogen gas around redshift 17, when light from the first stars is thought to have lowered the spin temperature of hydrogen. The claimed absorption signal has twice the amplitude expected and an unusual flat-bottomed profile. In a paper in Nature, Richard and his colleagues (including two Kavli Institute Fellows) showed that the signal was almost certainly due to instrumental effects. This area of astrophysical cosmology remains one of the great observational challenges – it is being pursued by several new global 21-cm experiments including REACH, led by KICC researchers.

For his major contributions to the JCMT project, Richard was awarded the Jackson–Gwilt Medal of the Royal Astronomical Society in 1989 as well as the MacRobert Award of the Fellowship of Engineers in 1990. He was elected Professor of Radio Astronomy (1970) in the Cavendish in 1990, the chair created by the University for his colleague and Nobel Prize winner, Antony Hewish. Richard was elected as a Fellow of the Royal Society for his many astronomical and technical achievements in 2014.

We pass on our sincere condolences to Richard's wife Beverly and their sons Alex and Chris. Richard will be sorely missed by all of us as a brilliant physicist and astronomer and a splendid friend and colleague. A workshop in his honour is being organised at KICC in Spring 2024.

A comprehensive Memoir of Richard Hills' life and work may be found in *Biographical Memoirs of Fellows of the Royal Society*, 74, 237 (2023).

Awards & Honours In 2022



Roberto Maiolino

Elected as a Fellow of the Royal Society

Professor Roberto Maiolino, a previous Director of the Kavli Institute for Cosmology, Cambridge and Professor of Experimental Astrophysics and Royal Society Research Professor in the Department of Physics has been elected as a Fellow of The Royal Society.

Professor Maiolino studies the formation of galaxies using observations collected at some of the largest ground-based and space telescopes. He has obtained key results on the interplay between the evolution of galaxies and the supermassive black holes at their centres. He has also investigated the enrichment of chemical elements across the cosmic epochs, as well as the origin and nature of dust particles in the early Universe.

He said: *"I am truly honoured by such a prestigious appointment. Being a Fellow of the Royal Society will certainly foster my research activities and will allow me to further promote exciting, cutting-edge projects."*

https://tinyurl.com/RSMaiolino

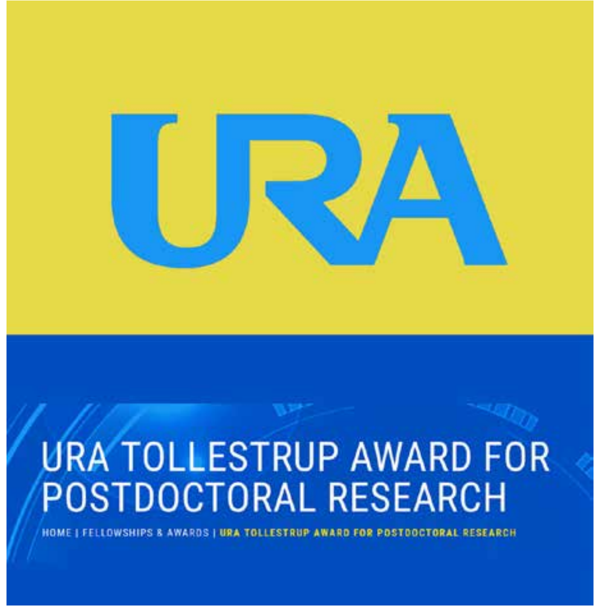
George Efstathiou

Royal Astronomical Society Gold medal for Astronomy

The Royal Astronomical Society's 2022 Gold Medal for Astronomy has been awarded to Professor George Efstathiou, founding Director of the Kavli Institute. This is the Society's highest honour which can be awarded for any reason but usually recognises lifetime achievement. Past winners include Albert Einstein, Edwin Hubble, Arthur Eddington and Stephen Hawking.

As his citation highlights, "He is amongst the most distinguished cosmologists of his generation, one of the architects of the standard model of cosmology, Lambda cold dark matter (LCDM). Prof. Efstathiou has made transformational contributions in computer simulations of the formation of structure in the universe, galaxy surveys and the analysis of the cosmic microwave background (CMB) radiation, faint background radiation lingering from the early stages of the Universe. He was one of the first to use computer simulations to calculate the non-linear evolution of the primordial perturbations (density variations in the early universe) from which cosmic structure grows."

https://tinyurl.com/RAS2022Winners



Dr Alexandra Amon

Royal Astronomical Society 2022 Caroline Herschel Prize Lectureship & Tollestrup Award for Postdoctoral Research

Dr Alexandra Amon, Kavli Institute Senior Fellow and a Senior Postdoctoral Researcher at Trinity College Cambridge has been awarded the Royal Astronomical Society's 2022 Caroline Herschel Prize Lectureship.

The Caroline Herschel Prize Lectureship was established in 2018 by what is now the Herschel Society, in association with the Royal Astronomical Society, to celebrate Caroline's memory by supporting promising women astronomers early in their careers. The Caroline Herschel Prize Lecture is hosted by University of Bath in November in cooperation with the Society as part of the University's public lecture series.

Dr Amon is co-coordinator of the Weak Lensing group of the worldwide collaboration "The Dark Energy Survey", including over 100 members. She uses observational data for over 100 million galaxies and the technique of gravitational lensing in order to test the standard cosmological model.

The intriguing results she and her collaborators find hint at cracks in the currently accepted model for our Universe, which is mostly dark, with over 95 percent of it in the form of dark energy and dark matter, whose natures are the biggest mysteries in modern physics.

Dr Amon has also been awarded the 2022 Alvin Tollestrup award for Outstanding Postdoctoral Research for her leadership, mentorship and wide-ranging scientific contributions to solving the novel challenges presented in the world-leading Dark Energy Survey weak-lensing analysis.

https://tinyurl.com/RASAmon
https://tinyurl.com/TollestrupAward

Graduating Students

Many congratulations to the following graduate students at KICC who defended their Ph.D. theses in 2022.

Roger de Belsunce

Thesis Title:
Cosmology from the CMB and Lyman-a forest
Supervisors:
George Efstathiou and Steven Gratton
Current Position:
Postdoctoral Researcher, Lawrence Berkeley National Laboratory (LBNL)

Jake Bennett

Thesis Title:
On the Evolution of Gaseous Haloes in Cosmological Simulations of Galaxy Formation
Supervisors:
Debora Sijacki
Current Position:
Research Fellow, Harvard University

Joanna Piotrowska-Karpov

Thesis Title:
Quenching of Star Formation in the Local Universe: a Comparison of Hydrodynamical Simulations with Spectroscopic Observations
Supervisors:
Roberto Maiolino and Asa Bluck
Current Position:
Postdoctoral Research Scholar, Caltech

Rosie Talbot

Thesis Title:
The complex interplay between AGN jet feedback and galaxy evolution
Supervisors:
Debora Sijacki, Martin Bourne and Christopher Reynolds
Current Position:
Postdoctoral Researcher, Max Planck Institute for Astrophysics, Garching

Connor Hayden-Pawson

Thesis Title:
The chemical evolution of galaxies explored through multi-object integral field spectroscopy
Supervisors:
Roberto Maiolino
Current Position:
Data Scientist, EG Group

Joris Witstok

Thesis Title:
Spectroscopic studies of star-forming galaxies and the intergalactic medium in the early Universe
Supervisors:
Renske Smit and Roberto Maiolino
Current Position:
Postdoctoral Researcher, KICC

2022 KICC Events & Lectures

Workshops:

1. Key Challenges in Galaxy & CMB Lensing
Workshop on Weak Gravitational Lensing
Date: Monday, 4 July 2022 to Friday, 8 July 2022
Event location: DAMTP, University of Cambridge

2. Epoch of Galaxy Quenching
Date: Monday, 5 September 2022 to Friday, 9 September 2022
Event location: Kavli Institute for Cosmology, Cambridge

3. Charting the Metallicity Evolution History of the Universe
Date: Monday, 19 September 2022 to Friday, 23 September 2022
Event location: Museo Diocesano, Catania, Italy

We were delighted that in 2022 we were once again able to hold in-person workshops, talks and meetings after two years of pandemic disruptions and lockdowns. A busy programme of Kavli-supported events took place, not only at KICC but at other venues locally and internationally.

The first workshop of the year, 'Key Challenges in Galaxy & CMB Lensing' took place in the Department of Applied Mathematics and Theoretical Physics (DAMTP), which is one of the three parent departments of KICC. Alex Amon, Kavli Institute Senior Fellow and one of the lead organisers, reported: "The weak-lensing conference was met with great delight in the community, attracting over 70 scientists across both galaxy lensing and CMB lensing. For the meeting we tried a new format that received excellent feedback: each half day dedicated to a systematic effect in the field and included an expert review by a duo of a senior and early-career researcher, technical talks, discussions in groups to tackle key questions in smaller settings that encouraged all to participate, and finally a discussion panel. We reflected on the immense progress of the field, yet on the other hand the significant challenges ahead – in the era of the Rubin, Euclid and Roman optical surveys and the Simons Observatory and CMB-S4 CMB surveys – across both data calibration and modelling. As one of the first post-pandemic meetings of our field, it was especially fantastic to gather experts from each of the disparate collaborations to Cambridge, where we play leading roles in the Dark Energy Survey and the Atacama Cosmology Telescope and Simons Observatory Collaborations."

The 'Epoch of Galaxy Quenching' workshop was an in-person follow-up to a virtual event in 2020. According to Francesco D'Eugenio, a postdoctoral researcher at KICC and one of the lead organisers, "the workshop raised a lot of interest in the community, with almost 200 abstracts submitted for 60 talks. The workshop summarised the observational evidence for galaxy quenching mechanisms across environments and cosmic time, and combined observers and theorists in almost equal proportions. Many of the problems that were highlighted could not be overcome with the data available at the time – highlighting the need for JWST and MOONS data, two key projects where the Kavli Institute has a central role."

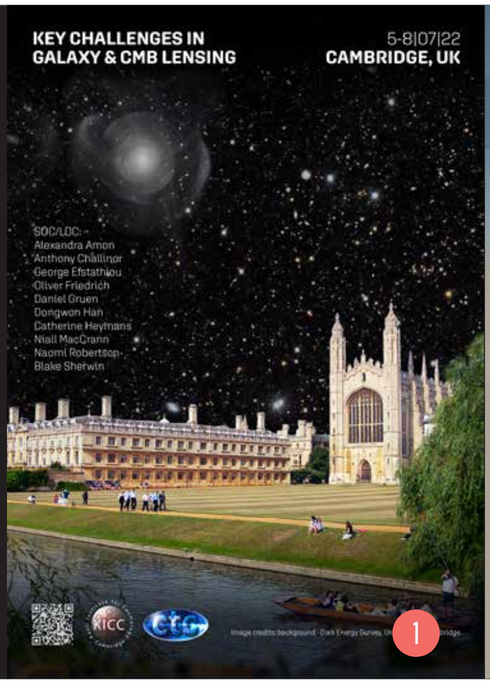
A summary of the conference was published in Nature Astronomy in February 2023 (Nature Astronomy 7, 247, 2023, titled '*The epoch of galaxy quenching*'). https://www.nature.com/articles/s41550-023-01911-3

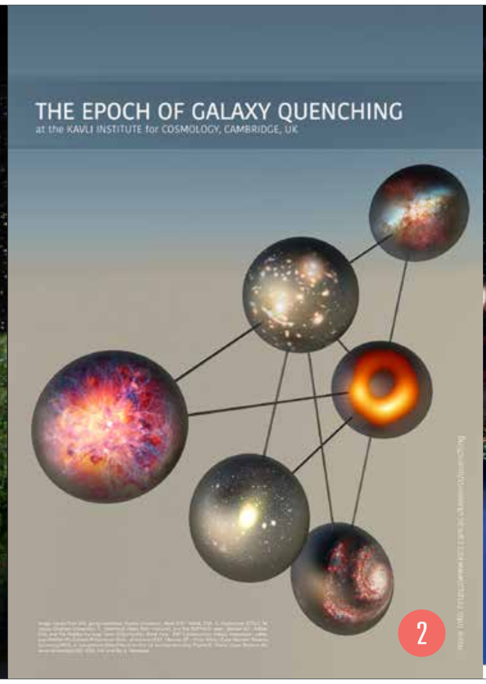
'Charting the metallicity evolution history of the Universe' was the first recent event that KICC had supported overseas and the first example of a KICC workshop organised and funded by a joint collaboration of institutes across the UK and Italy, including the KICC itself, the Italian National Institute for Astrophysics (INAF), the University of Florence (UniFi), and the Scuola Normale Superiore Pisa (SNS).

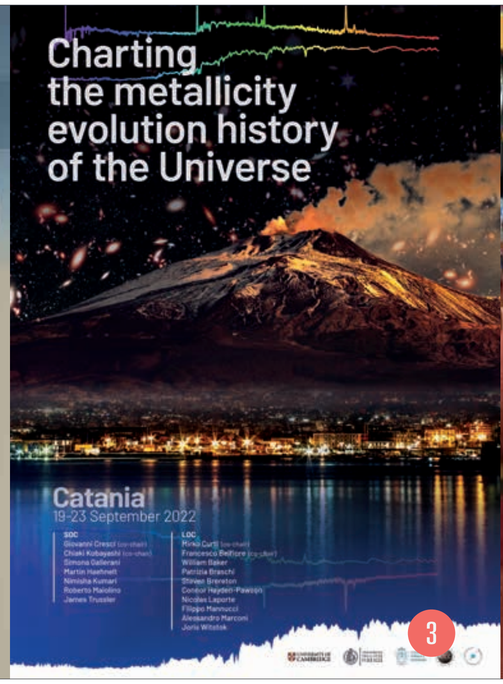
During the week of 19–23 September 2022, about 70 scientists from all over the world gathered in the Sicilian town of Catania, in the beautiful setting of the Diocesan Museum, to discuss chemical enrichment processes in galaxies and to try to draw a coherent picture of their evolution across the entire history of the Universe.

One of the organisers, Mirko Curti (a former postdoctoral researcher at KICC), reported that the meeting triggered significant interest in the scientific community, with more than 150 abstracts received out of which 61 talks were allocated. These covered different topics (from stellar metallicity to the properties of the interstellar medium, from the enrichment of the circumgalactic medium to the production of dust in the early Universe) that were addressed from both observational and theoretical points of view. The meeting was particularly timely allowing participants to discuss the first results and forthcoming perspectives from the newly operational (since July 2022) James Webb Space Telescope (JWST) which is set to revolutionise the field in the coming years.

The conference also hosted a very successful public talk on the JWST by Prof. Roberto Maiolino from KICC, with local community attendance beyond the expectations of the organisers.







2022 KICC Events & Lectures

Kavli Lectures

26 May - Vicky Kalogera - Gravitational-Wave Astrophysics: Progress and Puzzles

New Frontiers in Astrophysics: A KICC Perspective
(image credit opposite, universe illustration - Pablo Carlos Budassi)
25 February - George Efstathiou - Do We Have a Standard Model of Cosmology?
20 May - Sunny Vagnozzi and Anne Davies - Direct Detection of Dark Energy
4 October - David Weinberg - Decoding the Origin of the Elements
25 November - Roberto Maiolino - A First Glimpse of Webb's Revolution for our Understanding of Galaxy Formation

Kavli Science Focus Meetings
11–13 April 2022 - Observational and Theoretical 21-cm Cosmology
6 May 2022 - The Early Universe
17–18 May 2022 - Baryons and Cosmology

Our 2022 Kavli Lecture was given remotely by Vicky Kalogera from Northwestern University, Evanston IL on the topic of Gravitational-Wave Astrophysics: Progress and Puzzles.

New in 2022 was the introduction of the appropriately titled series of talks 'New Frontiers in Astrophysics: A KICC Perspective'. The first speaker was the founding Director of KICC, George Efstathiou, who asked the question "Do We Have a Standard Model of Cosmology?". Subsequent talks covered a wide variety of areas at the research frontiers in Cosmology and Astrophysics.

In addition, in the spirit of fostering collaboration amongst researchers from the three University departments associated with KICC, particularly in interdisciplinary areas, a series of 'Science Focus meetings' was also introduced in 2022. One or two meetings per term cycle through some of the science themes of the Kavli Institute and also include cross-themed meetings. These popular informal events, typically over one or two days and including networking lunches, successfully promote discussion on cutting-edge topics within our community and often include a few external contributors from across the UK attending in-person.

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

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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.

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