UNIVERSITY OF CAMBRIDGE

KICC Annual Report 2021

Kavli Institute for Cosmology, Cambridge

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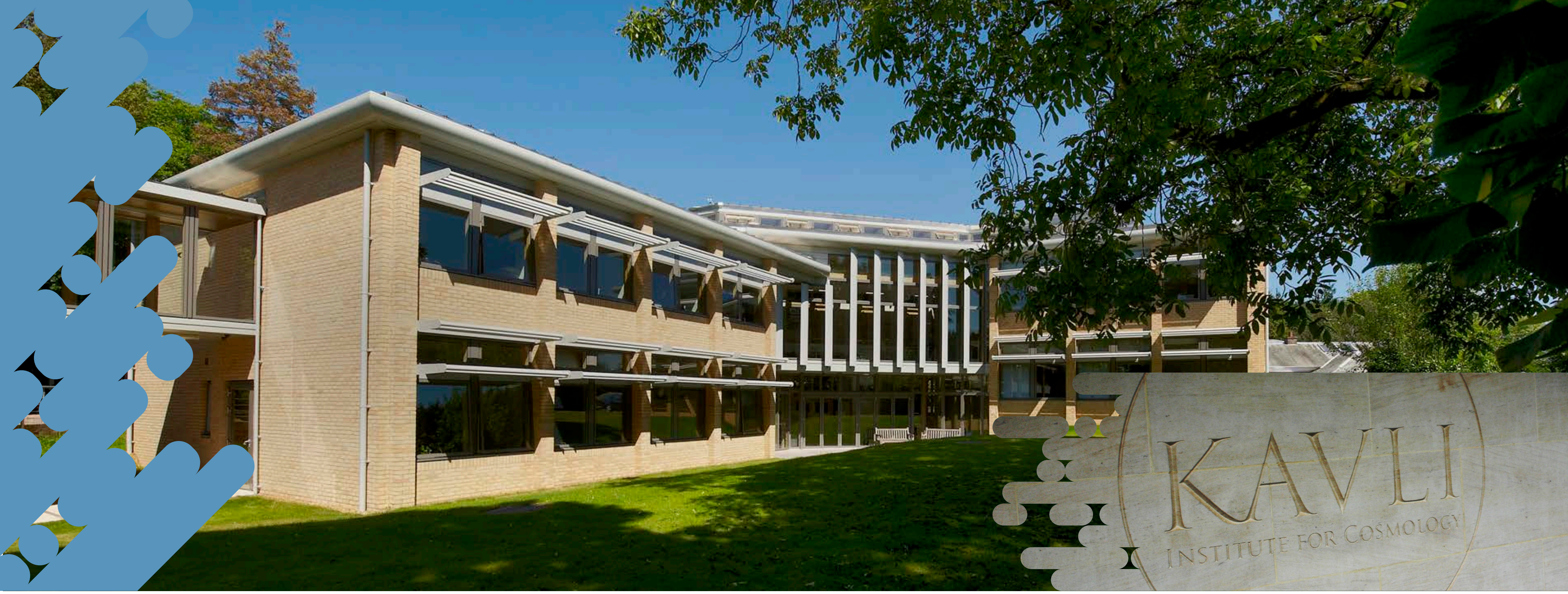
Message from the Director
Anthony Challinor



Welcome to the 2021 report from the Kavli Institute for Cosmology, Cambridge. It is my pleasure to write this introduction as the new Director, having had the honour to take over the role from Roberto Maiolino in September 2021. It is thanks to the energy and vision of Roberto and the founding Director, George Efstathiou, that the Kavli Institute is such a special place for its members and visitors.

Much of 2021 was, unfortunately, still blighted by the COVID-19 pandemic. The UK started the year in a further national lockdown, with the return of severely restricted social interactions, working from home for most and home-schooling. Unlike the first national lockdown in 2020, the Kavli Institute remained open but with very restricted access for its members. Despite the lack of in-person scientific interactions for a further several months, and often-difficult home-working arrangements, researchers from the Kavli Institute continued to produce world-leading research and to push forward major international projects through their leadership.

We hope that you enjoy reading about some of these research highlights in this report. Many of these have been written by our wonderful graduate students, postdoctoral researchers and research fellows, who are very much the lifeblood of astronomical research. Major advances and discoveries reported here include precise tests of the standard cosmological model with weak gravitational lensing measurements of over 100 million galaxies from three years of data from the Dark Energy Survey. Also on the dark Universe, we report on the intriguing possibility that anomalous signals seen recently in the XENON 1T direct dark matter detection experiment might be a signature of interactions of dark energy, not dark matter, with the detectors. At the high-redshift galaxy frontier, stellar-age estimates of galaxies observed as they were 13 billion years in the past suggest that cosmic dawn, when the Universe started to be bathed in starlight, occurred 250–350 million years after its beginning.

Relatedly, fervent preparations have continued at the Kavli Institute for the surveys that we will be conducting with the James Webb Space Telescope, in particular the JADES survey (led by Roberto Maiolino and new faculty member, Sandro Tacchella), which will be the most extensive survey to be conducted in the first few years of JWST operations. Following the relief of a successful launch on Christmas Day 2021, we are all excitedly looking forward to the first data, analyses and results expected in 2022. The science reach of Webb is phenomenal and will have a major impact on several of the research themes at the Kavli Institute, from the formation and evolution of galaxies and their supermassive black holes to the characterisation of exoplanets.

The start of my term as Director aligned well with the easing of COVID-related restrictions, with more people returning to work in-person at the Kavli Institute. An initial priority was to try and bring people together, safely of course, to promote scientific interactions and discussion. In late September we held a memorable Fellows' Science Day, when our Kavli Fellows updated us all on recent progress in their research. It is remarkable to think that this was the first significant in-person scientific meeting we had held for 18 months! Shortly after, we were delighted to welcome Roger Blandford (founding Director of the Kavli Institute for Particle Astrophysics and Cosmology at Stanford) as our twice-yearly Kavli Lectures returned to their usual, in-person format. The year ended with the first of our "Kavli Science Focus Meetings", in this case exploring feedback in and around galaxies. We hope this will become a regular series of one-day meetings for Cambridge Astrophysicists to explore cutting-edge topics in an interdisciplinary manner. We have, unfortunately, been unable to welcome many of our planned visitors for the past two years. However, many visits are now scheduled for 2022 and we look forward to the vibrancy that our visitors bring.

COVID-related restrictions curtailed most of our planned international workshops, with the organisers of two of these preferring to wait until large-scale in-person meetings are possible in 2022. However, "Distorted Astrophysical Discs" was run as an online, virtual event in May 2021, bringing together over 200 participants – way more than the 50 originally planned for an in-person event – working across the full spectrum of astrophysical-disc environments from those around supermassive black holes all the way down to planetary systems.

The work of our members has continued to be recognised with major national and international prizes, awards and honours, as described in a dedicated article in this report. It is particularly pleasing to see early-career researchers being recognised, including Gavin–Boyle Fellow, Mathias Nowak, who received the 2021 Olivier Chesneau Prize, and Newton–Kavli Fellow, Sunny Vagnozzi, who was awarded the "Alfredo di Braccio" Prize by the Accademia Nazionale dei Lincei (Lincean Academy). In addition, Roberto Maiolino started his prestigious Royal Society Research Professorship. Many congratulations to them all on their fantastic achievements!

In September 2021, Anthony Lasenby retired as Professor of Astrophysics and Cosmology in the Department of Physics. Anthony was a former Deputy Director of KICC and was instrumental in establishing the institute. We thank him for his many years of service to KICC and wish him a happy and productive retirement. We are delighted that Anthony will continue to be an active and valued emeritus member of the Kavli Institute.

December 2021 saw the announcement of the launch of two new Kavli Centres for Ethics, Science and the Public, one at UC Berkeley and one at the University of Cambridge. The Cambridge Centre is a collaboration between the University and Wellcome Connecting Science, with funding from the Kavli Foundation, and will be led by Professor Anna Middleton. Its mission is to create a programme of innovative research and public engagement on broad scientific domains, initially focusing on three rapidly changing fields: genome editing, artificial intelligence and big data. We wish Anna and colleagues every success as they launch the new Centre and look forward to collaborating with them on areas of common interest.

Further good news from our colleagues working on exoplanets came with the announcement of major funding from the Leverhulme Trust to support the new Leverhulme Centre for Life in the Universe. This Centre will bring together researchers from several of the University's departments to pursue inter-disciplinary research to tackle key questions such as how life emerged on Earth, whether the Universe is full of life, and what is the nature of life. The Centre will be led by our colleague Didier Queloz. We very much look forward to building on the synergies between the exoplanet programme at KICC and the work of the Leverhulme Centre.

I would like to end by thanking all those who help make the Kavli Institute thrive: 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. Particular thanks are due to the new Deputy Director, Debora Sijacki, who is a constant source of great ideas, and to the Kavli Institute Administrator, Steven Brereton, for his tireless work in supporting our members and visitors. Finally, I thank the Kavli Foundation for their continued financial and strategic support of the institute.

The James Webb Space Telescope Has Arrived At Its Destination And Delivered Its First Image

Sandro Tacchella & Roberto Maiolino


On Christmas Day 2021, the James Webb Space Telescope (JWST) was launched into space on an ESA Ariane 5 rocket (Fig. 1), starting its 29-day journey to the Sun–Earth second Lagrange point (L2) at a distance of 1.5 million km from Earth. Its launch and the two mid-course correction burns were so accurate that fuel could be saved and team engineers now estimate that JWST will have enough fuel to last well beyond its nominal 10-year mission lifetime.

JWST's deployment was a nail-biting undertaking. JWST is a large telescope: its primary mirror has a diameter of 6.5 m and its five-layer kite-shaped sunshield, which protects it from warming by the Sun, Earth, and Moon, is the size of a tennis court. Both the primary and secondary mirrors, as well as the sunshield, needed to be folded up in order to fit into the Ariane 5 rocket. JWST launched as a folded origami and then was unfolded in space (Fig. 2). JWST's sunshield assembly alone includes 140 release mechanisms, eight deployment motors and 90 cables totaling 400 m in length.

JWST was successfully deployed during the 29 days following the launch. Subsequently, the 18 segments of the primary mirror were aligned, so that they work together as one mirror. The mirrors were moved first in micrometer and then in nanometer increments to achieve alignment over several weeks. Figures 3 and 4 show images taken during the alignment process and on completion, respectively. During this period, the scientific instruments (cameras and spectrographs) continued to cool and their final commissioning and calibration is currently underway.

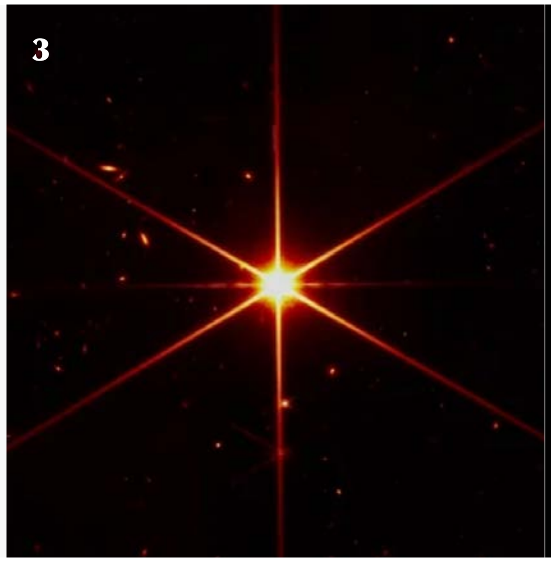
Fig 1: The James Webb Space Telescope (JWST) was launched on an Ariane 5 Launch Vehicle on December 25, 2021. Credit: NASA/Chris Gunn.

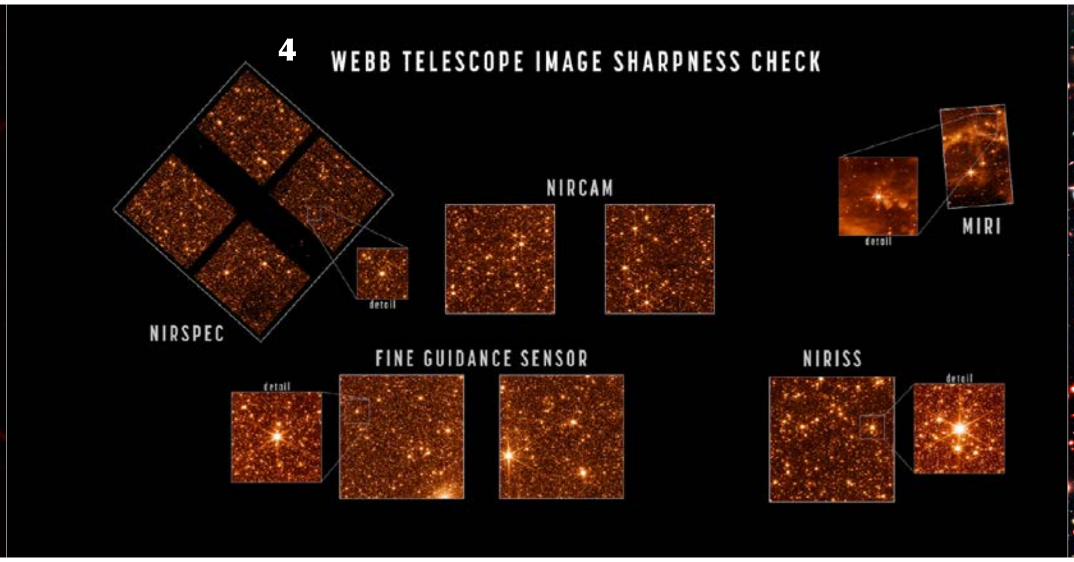
Fig. 2 (overleaf): For JWST to fit into the rocket, it had to be folded up. This image shows how it fitted into the rocket fairing. Image courtesy of ArianeSpace.com.

Fig. 3 (overleaf): Image of a star taken by the James Webb Space Telescope during its alignment process, with galaxies in the background. Credit: NASA/STScI.

Fig. 4 (overleaf): Engineering images from April 2022 of stars in the field of view of each instrument demonstrate that the telescope is fully aligned and in focus. JWST pointed at part of the Large Magellanic Cloud, a small satellite galaxy of the Milky Way. JWST's three imaging instruments are NIRCam (images shown here at a wavelength of 2 micron), NIRISS (image shown here at 1.5 micron), and MIRI (shown at 7.7 micron, a longer wavelength revealing emission from interstellar clouds as well as starlight). NIRSpec is a spectrograph rather than imager but can take images, such as the 1.1 micron image shown here, for calibrations and target acquisition. Lastly, JWST's Fine Guidance Sensor tracks guide stars to point the observatory accurately and precisely. Credit: NASA/STScI.

The James Webb Space Telescope - continued





The $10 billion JWST will revolutionize our understanding of the most distant and hard-to-see parts of the sky, helping with the search for exoplanets and with exploring the earliest days of the universe. Thanks to its operation in space, its large mirror and its sensitive infrared instruments, JWST allows us to undertake a giant leap in sensitivity from current instruments, comparable to going from Galileo Galilei's telescope to the 10 m Very Large Telescopes in Chile. JWST has four science instruments and one guide camera. The prime imager is the Near InfraRed Camera (NIRCam), which has a spectral coverage ranging from the edge of the visible through to the near infrared (wavelengths ranging from 0.6 to 5 micron). There are 10 sensors, each of four million pixels, for recording images and slitless spectroscopy. The Near InfraRed Spectrograph (NIRSpec) will perform spectroscopy over the same wavelength range. There are three primary observing modes: a multi-object mode, an integral field unit, and fixed slits. The Mid-InfraRed Instrument (MIRI) will measure light in the wavelength range from 5 to 27 micron with both a mid-infrared camera and an imaging spectrometer. Finally, The Near Infrared Imager and Slitless Spectrograph (NIRISS) module can perform imaging and slitless spectroscopy in the 0.8 to 5 micron wavelength range.

At the KICC, the extragalactic research group co-led by Roberto Maiolino and Sandro Tacchella is playing a crucial leadership role in this mission. Both are heavily involved in JWST's Guaranteed Time Observation (GTO) programme as well as other General Observation (GO) programmes. In particular, the NIRCam-NIRSpec joint GTO programme called JWST Advanced Deep Extragalactic Survey (JADES) will survey GOODS-North and GOODS-South extragalactic fields with a wide range of NIRCam, MIRI, and NIRSpec observations. With over 800 hours of observations, JADES is the most extensive JWST programme in the first few years; see Fig. 5 for a simulation of a zoomed in part of the survey.

There are two characteristic NIRCam exposure depths and survey areas for JADES wide-band imaging (deep imaging at magnitude m_{AB} = 29.8–30.4 over around 46 arcmin^2 and medium imaging at m_{AB} = 29.0–29.5 over 290 arcmin^2). The images will be taken in eight different filters with a wavelength coverage from 1 micron up to 5 micron. This imaging will be deeper, extend further into the infrared, and cover a wider area than the current imaging with the Hubble Space Telescope. NIRSpec observations are acquired with the prism, medium-resolution and high-resolution spectroscopy at 1–5 micron for thousands of galaxies – these infrared spectra will be the first taken from space at this resolution! These data will be taken over the next two years, starting from October 2022.

By combining imaging from NIRCam (led by Sandro) with spectroscopy from NIRSpec (led by Roberto), JADES will allow us to build unique synergies here at the KICC. For example, NIRCam images allow us to discover the earliest and most interesting objects in the Universe, while the follow-up with NIRSpec will help us to characterise their physical properties in great detail. Our scientific focus at the KICC will be on establishing a complete census of galaxy formation at the current redshift frontier (z = 8–10, a few hundred million years after the Big Bang), on studying the stellar and chemical enrichment of galaxies, learning about the production efficiency of ionizing photons and thereby find the sources that drive "cosmic reionization", the clearing of the primordial fog of neutral hydrogen in the early Universe.

Fig. 5: Zoomed region of a simulation of the JADES Deep imaging region in GOOD-S. Shown is a false-colour image created from synthetic data produced with the Guitarra (Willmer et al. 2020) image simulator and processed with the JADES mosaicing and analysis pipeline.

Let There Be Light!
An Observational Probe Of The Epoch When The First Stars Started To Shine

Nicolas Laporte

The first observational evidence that we are living in an expanding Universe was obtained by Edwin Hubble in 1929 when he demonstrated that more distant galaxies have larger velocities away from Earth. Thirty-five years later, Arno Penzias and Robert Wilson observed, for the first time, the cosmic microwave background (CMB) validating the model of the Big Bang. It is now widely accepted that the Universe was born 13.8 billion years ago and evolved from a very hot and dense phase to the current cold and low-density state. According to the current model of formation of our Universe, the CMB was released 380 000 years after the Big Bang when the temperature and density were sufficiently low to make the Universe transparent. After this, the Universe encountered a period known as the "dark ages", when no light was emitted. The density perturbations generated after the Big Bang continued to grow and eventually led to the formation of the first stars and galaxies. Nearly 50 years after the validation of this model, several questions remain unanswered: when did the first galaxies form in the early Universe, marking the end of the dark ages; what are the physical properties of the first generation of stars and galaxies; and how did they influence the properties of the early Universe.

Two independent methods can be used to determine observationally when the first stars and galaxies started to bathe the Universe in light: (i) observing absorption of the CMB in the 21 cm line of neutral hydrogen at very high-redshift; or (ii) observing directly the most distant galaxies. The first method is based on the coupling of the ultraviolet light emitted by the first generation of stars to the neutral hydrogen leading to an absorption in the 21 cm signal. The second approach aims to observe directly the first generation of galaxies and to measure the age of their stellar population via the detection of the 4000 Å break (Fig.1). This break is caused by the absorption of high-energy radiation from metals in stellar atmospheres and by a deficiency of hot, blue stars. The age-dependence arises because the more massive stars that contribute to this signal burn their nuclear fuel more rapidly and therefore die first. However, this method has two limitations: (i) before the arrival of the *James Webb* Space Telescope (JWST) this break can only be detected up to $z = 12$ between the two first IRAC/Spitzer channels (3.6 and 4.5 microns); and (ii) at $z < 9.1$ strong emission lines can mimic the presence of a stellar continuum (typically OIII and Hβ) and lead to wrong estimates of the age. In 2018, a first attempt was made on a magnified galaxy (MACS1149-JD1; $z = 9.11$) for which we measured an age of 250 million years, suggesting that this galaxy was formed around 250 million years after the Big Bang (*Hashimoto et al. 2018*). But how representative is this galaxy? What is the fraction of galaxies with an already evolved stellar population at high redshift?

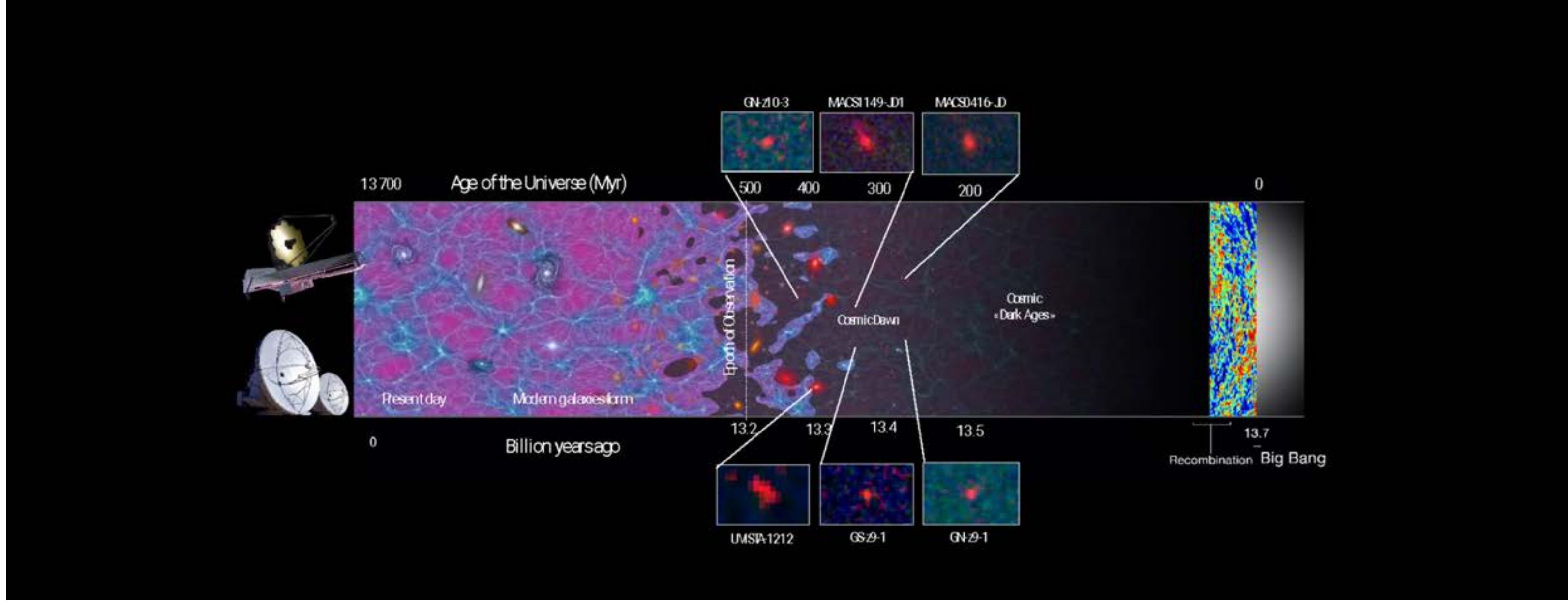
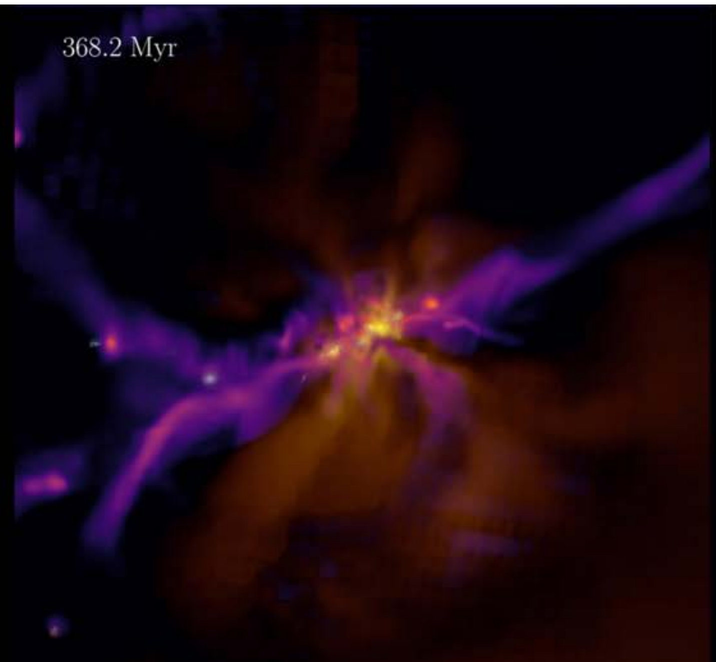


Fig. 1: Powerful telescopes such as ALMA probe to great distances, corresponding to "look-back" times of billions of years in the past. However, by measuring the ages of stars in the earliest galaxies, it is possible to probe even further back in time. Such galaxies may have first "switched on" when the Universe was only 250–350 million years old, and the birth of similar systems would be within the reach of JWST.

To try to answer these questions, our team performed a huge spectroscopic follow-up campaign combining data from the largest ground-based telescopes (the Very Large Telescope, Keck, ALMA and Gemini) totalling more than 70 hours of telescope time and measured the age of six galaxies at $z \geq 9$ selected in CANDELS fields and UltraVISTA. All of these galaxies were selected because of their prominent 4000 Å break, and four of them have been spectroscopically confirmed at $z \geq 9$ (*Laporte et al. 2021*). The first conclusion we can draw is that the fraction of detected Lyman-alpha radiation is higher than what is expected during the epoch of reionisation, where this emission line is likely absorbed by the neutral hydrogen surrounding galaxies. Therefore, we suggest that these galaxies are old enough and had time to ionise the neutral hydrogen making the Lyman-alpha line detectable. By analysing the spectral energy distributions of these galaxies, we also conclude that all of them formed less than 400 Myr after the Big Bang (i.e., at redshift $z > 12$), and they all formed more than 50% of their stellar mass before $z = 10$. Finally, by analysing their past star-formation history, we demonstrate that the progenitors of these galaxies will be easily detectable with the NIRCam instrument on JWST in less than 3 hours up to $z \geq 15$.

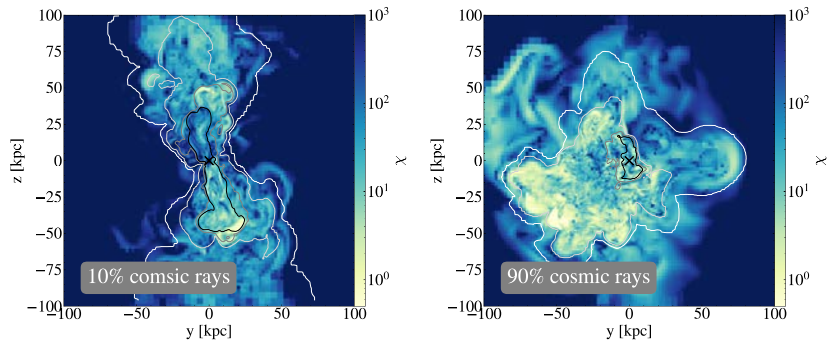
These results are based on *Laporte N., Meyer R. A., Ellis R. S., Robertson B. E., Chisholm J.* and *Roberts-Borsani G. W.*, MNRAS, 505, 3336 (2021) and *Hashimoto T., et al.*, Nature, 557, 392 (2018).

Fig. 2: Simulation of the formation and evolution of the first stars and galaxies. The age of the universe is shown in the upper left. Purple regions display the filamentary distribution of gas, composed mostly of hydrogen, white regions display starlight and the yellow regions depict energetic radiation from the most massive stars that is capable of ionising the surrounding hydrogen gas.



Cosmic Rays And Thermal Instability In Self-Regulating Cooling Flows Of Massive Galaxy Clusters

Ricarda Beckman



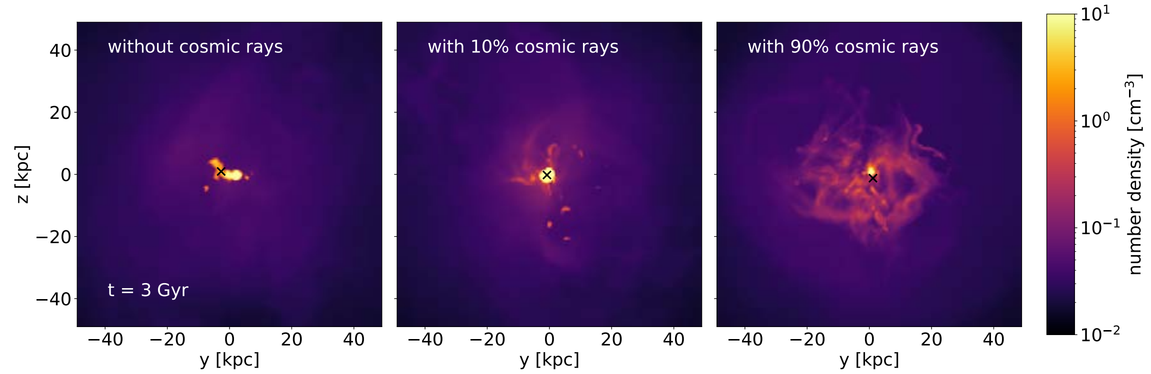
The space between galaxies in galaxy clusters is filled with hot, diffuse gas that is called the intracluster medium. This gas is strongly cooling, as can be seen by its X-ray emission. The cooling times we can infer from this emission are such that we would expect much of the gas in the cluster centre to have become sufficiently cold to be star-forming by now. However, this is not what we observe: galaxy clusters contain only a small amount of cold gas, and show little signs of active star formation. To maintain the gas as hot as we observe it to be, a heating source must be continuously offsetting some of the cooling and preventing the gas from cooling efficiently.

One likely source of energy re-injection are the jets driven by the supermassive black hole located in the cluster's central galaxy. Such black hole jets are known to carry sufficient energy to offset the cluster cooling. Extending far beyond their host galaxy, these jets inflate huge cavities in the hot intracluster medium, which continue to rise buoyantly like bubbles even once the jet that originally inflated them has turned off. However, how the energy is transferred from the jet and bubbles to the bulk of the hot intracluster medium, where most of the cooling occurs, remains an area of active research.

One recent idea is that the energy transfer might be mitigated by extremely high-energy particles, called cosmic rays. Cosmic rays are heavy charged particles, predominantly protons, moving at close to the speed of light. Each such particle carries a non-negligible amount of energy. Cosmic rays are closely coupled to the magnetic field that threads the hot intracluster medium. Through interactions with the magnetic field, and with the non-relativistic particles that make up the intracluster medium, energy originally carried in cosmic rays can be transferred to the intracluster medium, which gets reheated in the process. How efficient this reheating process is, and where in the cluster the energy is being transferred, strongly depends on the fraction of jet energy deposited in cosmic rays at injection, and on how these cosmic rays are redistributed within the cluster over time.

Fig 1 (below): Gas density in the cluster centre without cosmic rays (left), with 10 % cosmic rays (middle) and with 90 % cosmic rays (right). More yellow colours represent denser gas. The black cross marks the location of the central black hole.

Fig 2 (left): Jet structure with a small (left) and large fraction of cosmic rays (right). For high cosmic ray fractions, the jets become disrupted and lose their characteristic collimated shapes. The black cross marks the location of the central black hole.



To understand how cosmic rays change the long-term evolution of the cluster cooling cycle, we have performed a series of simulations of isolated galaxy clusters and the jets driven by their central black holes. Each simulation models an identical galaxy cluster but uses different parameters for the amount of cosmic rays injected in the jet, with fractions ranging from 0 % (no cosmic rays) to 90 % of total jet energy. By comparing and contrasting simulations, we were able to understand how the properties of the intracluster medium change with cosmic ray fractions, and to constrain the total allowed fraction of cosmic rays using observations of real galaxy clusters.

We found that if the jet energy budget is dominated by cosmic rays (i.e., in our case, if 90 % of the jet energy is injected in the form of cosmic rays) then the properties of the gas in the cluster centre change significantly. Rather than the expected distribution of hot gas, punctuated by a number of cold clumps and filaments, as observed, with a cosmic-ray-dominated jet the cluster center fills up with an extended warm, diffuse nebula (Fig. 1). As a result, the jets become disrupted and lose their characteristic structure (Fig. 2). Not only do we not observe such warm nebulae, but the gamma-ray emission we would expect from such an object is far higher than the observed upper limits on gamma rays from observations. We can therefore rule out high fractions of jet energy being injected in the form of cosmic rays. Interestingly, injecting only a small fraction of jet energy (10 % in our case) in the form of cosmic rays does not significantly change the appearance of the gas in the cluster center but does help to offset some of the cooling. Clusters with a small fraction of cosmic rays in the jet are far more thermally stable than those without any cosmic rays at all, and their predicted emission lies comfortably below observed upper limits. We therefore propose that a small fraction of cosmic rays injected by the jets driven by the central black hole could play an integral role in maintaining the thermal stability of a galaxy cluster over long periods of time.

These results have been submitted for publication as Beckmann R. S. et al. (2022), arXiv:2204.03629.

Active Galactic Nuclei Jets

Rosie Talbot & Debora Sijacki

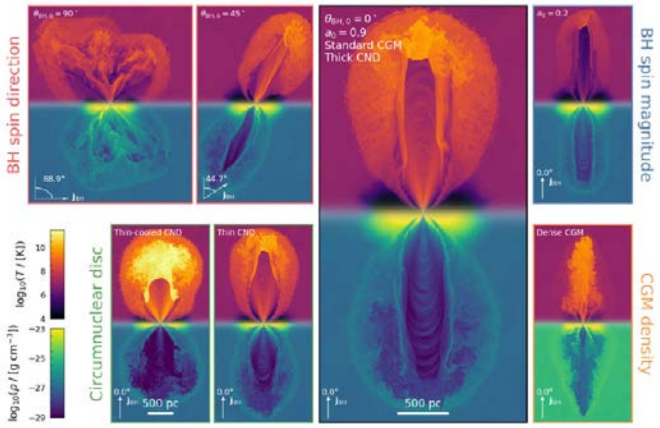


Fig. 1. Slices in the x–z plane of AGN jet simulations, where the top half of each panel shows the temperature field and the bottom half shows the density field. Each panel shows simulation results where we vary the initial spin direction and magnitude, the CGM density and the CND structure.

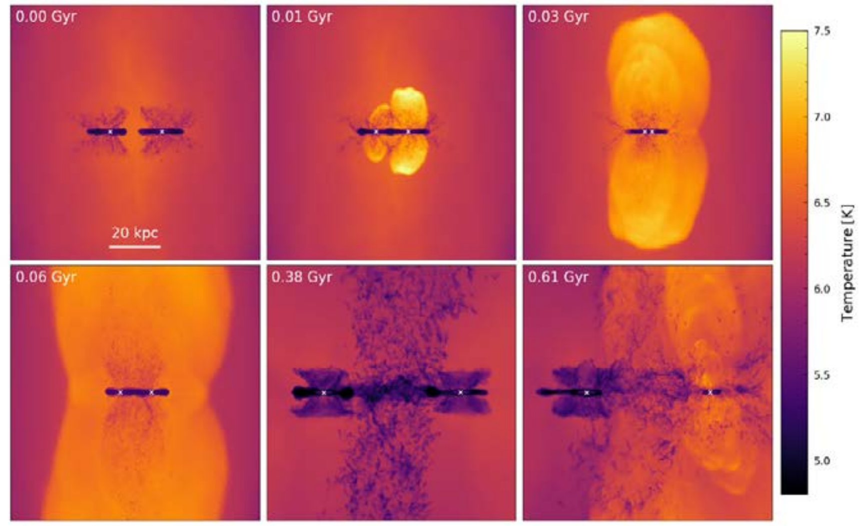


Figure 2. Time sequence of a major galaxy merger showing how "warm" supernovae-driven galactic outflows co-exist with the "hot" jet-driven outflows.

Galaxy formation is an inherently multi-physics, multi-scale problem and is, therefore, highly suited to exploration via numerical simulations. Since the evolution of supermassive black holes (SMBHs) and their host galaxies are so tightly coupled, it is of vital importance to explore active galactic nuclei (AGN) feedback in simulations that also follow the evolution of large-scale structure. But in these large simulations, the scales on which AGN jets are launched fall well below those that can be resolved and the resulting lack of *ab initio* jet formation means that the launching mechanisms are necessarily encoded in sub-grid models.

General-relativistic magneto-hydrodynamic (GRMHD) simulations of accreting, spinning black holes indicate that the Blandford–Znajek jet-launching mechanism is likely to be at play, wherein the jet energy is derived from the spin energy of the black hole. Most sub-grid jet models, however, do not track the evolution of the black hole spin and therefore cannot launch self-consistent Blandford–Znajek jets. Motivated by this, we have developed a novel sub-grid model for AGN accretion via a thin (warped) accretion disc and feedback in the form of a Blandford–Znajek jet and implemented the model into the moving-mesh code AREPO.

The spin-driven AGN jet model evolves the properties of the black hole on-the-fly during the simulation, is fully interfaced with the surrounding hydrodynamical simulation and accurately tracks the evolution of the black hole mass and spin. This information is then used, along with the properties of the accretion flow, to determine self-consistently the power and direction of the jet. Targeted refinement techniques ensure that the accretion flow, the injection of the jet and the subsequent inflation of the jet lobes are followed at sufficiently high resolution. Ultimately, this means that the jet feedback model is able to be employed in simulations ranging from studies of the very centres of radio galaxies to cosmological zoom simulations of galaxy clusters.

We carried out extensive benchmarking of our jet model using idealised simulations of the central regions of Seyfert galaxies and showed that the evolution of these self-regulated jets cannot be predicted using "fixed power and direction" jet models nor by analytic models. The jet power evolves significantly due to effective self-regulation by the black hole as it is fed by secularly-driven, intermittent mass flows.

We also carried out an extensive suite of simulations that varied the initial black hole spin magnitude and direction, the density of the circumgalactic medium (CGM) and the circumnuclear disk (CND) thermodynamics. Depending on their power and direction, we found that jets are able to drive a wide variety of large-scale outflows, ranging from light, hot and collimated structures to highly mass-loaded, multiphase, bipolar winds that can entrain significant amounts of cold CND material (see Fig. 1). While initially black holes are fed by coherent inflows from the CND, jet-launching cuts off this supply of gas and the properties of the accretion flow are then determined by the complex interplay between jet-driven outflows and backflows. We found that the mass outflow rates and kinetic powers of the warm outflow component in the simulations are in good agreement with recent observations for black holes with similar bolometric luminosities.

During the merger of two galaxies, significant quantities of gas may be funnelled towards the centre. The resulting rapid growth in the black hole merger remnant could then lead to the formation of a powerful relativistic jet. Indeed, AGN jets from the two black holes may also be present throughout the binary hardening and inspiral phases as well as post-merger. We are currently applying the spin-driven jet model to idealised simulations of SMBHs in gas-rich galaxy mergers at "cosmic noon" (see Fig. 2) with which we are exploring how the merger torques affect the jet directions both before and after the black holes coalesce and how the presence of accretion discs and jets alter the predictions for black hole growth during a major-merger. We are also considering how efficient gas fuelling impacts the mass-accretion rate through the accretion discs and the resulting jet powers.

With future observational facilities such as JWST, SKA and Athena, our understanding of AGN physics will expand greatly as we will be able to investigate black hole jet feedback at earlier times, lower luminosities and with higher spatial and spectral resolution. Additionally, LISA will expand the field of multi-messenger astronomy to the low-frequency range, detecting gravitational waves from the coalescence of SMBHs all the way back to cosmic dawn.

For numerical simulations to provide firm theoretical predictions with which to interpret accurately the wealth of data from these next-generation facilities, it is vital that physically motivated models of AGN feedback, such as the one we have developed, are applied in realistic galaxy formation scenarios.

Quenching Star Formation In Galaxies With Supermassive Black Holes

Joanna Piotrowska

The advent of large optical sky surveys made astronomers realise that galaxies in the observable Universe come in two main flavours: blue, star-forming; and red, quiescent. `Blue' galaxies owe their colour to hot, short-lived stars and have plenty of visible structure with gas, dust and, most importantly, active star formation. In contrast, quiescent galaxies are dominated by old stellar populations, have smooth light distributions and red optical colour indicative of low star-formation activity. When observed across cosmic time, these two populations are interpreted as an evolutionary sequence, in which blue, star-forming galaxies transition to become red in a process called `galaxy quenching'.

Understanding the physics responsible for the galactic transition to quiescence remains one of the biggest unsolved questions in the field of extragalactic astronomy. Decades of observations have shown that quenching correlates with a range of galactic properties. Quiescent galaxies are more massive, more elliptical in shape (as opposed to disk-like) and have larger supermassive black holes residing at their centres. These trends, however, are only an observable consequence of the underlying physical processes preventing galaxies from forming stars. As of today, a range of mechanisms was suggested to explain observed correlations, among which violent explosions of evolved stars (supernovae), shock-heating of gas around galaxies (halo shocks) and the influence of Active Galactic Nuclei (AGN; supermassive black holes surrounded by accretion disks) seem the most likely candidates. Until the present day, however, there has been no consensus on which of these mechanisms is a primary driver of quenching, due to the lack of irrefutable evidence in favour of any of these processes bringing star formation to a halt.

To address this issue, we set up a numerical experiment in which we obtain theoretical predictions from three state-of-the-art cosmological simulations: EAGLE, Illustris and IllustrisTNG and compare them with the observable Universe as seen by the Sloan Digital Sky Survey (SDSS). To identify which mechanism among supernovae, halo shocks and AGN is a primary driver of quenching, we harness the power of machine learning, allowing us to embrace the complexity associated with the galaxy transition to quiescence. More precisely, we train a random-forest algorithm to classify galaxies into star-forming and quenched categories, based on their estimated stellar, dark matter halo and black hole masses. We make use of random forests because they strike a perfect balance between sophistication and interpretability – we can both treat highly inter-correlated data and extract the relative importance of each input parameter for determining the classification. By finding out which amongst stellar, black hole and dark matter halo mass carries the highest importance within the algorithm, we can establish which among the corresponding processes – supernova explosions, AGN activity and halo shocks – is primarily responsible for quenching star formation in the local Universe.

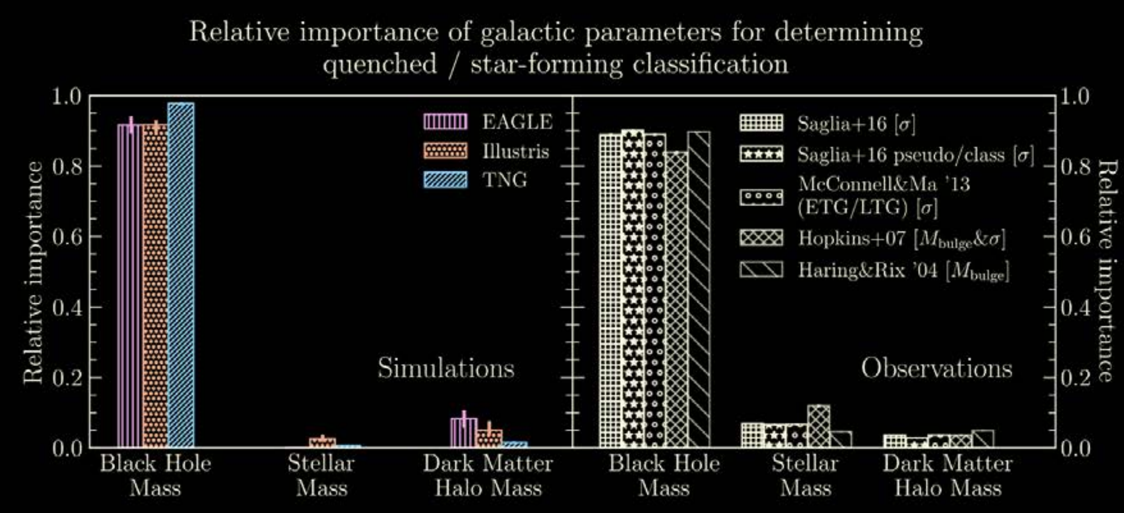
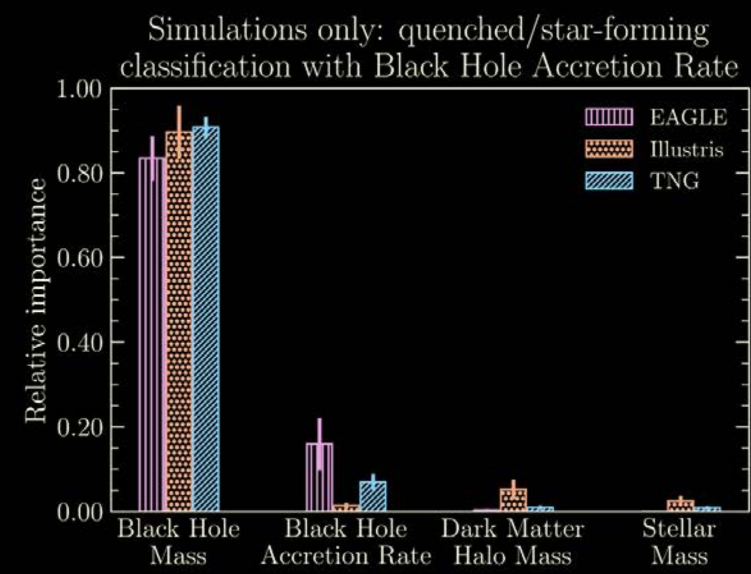


Fig.1 (above): Relative importance of galaxy parameters for determining star-forming/quenched classification using machine-learning algorithms (random forests). In simulations (left), black hole mass is clearly the most important input parameter, regardless of the exact model implementation. This result is an excellent match with the observations (right), where it is robust against the choice of method used to estimate black hole masses.

Fig. 2 (below): Relative importance of simulated galaxy parameters for determining star-forming/quenched classification with random forests with the parameter set extended by black hole accretion rate. The importance of black hole mass visibly dwarfs that of its accretion rate.



Quenching Star Formation In Galaxies With Supermassive Black Holes - continued

Figure 1 presents the relative importance of all three parameters in the quenched/star-forming classification in cosmological simulations (left) and observations (right). We find that all simulation suites unanimously predict black hole mass as the most important property discriminating between star-forming and quiescent galaxies, regardless of the differences in model implementation. Because the simulations rely on energy injected by AGN in and around galaxies to put the brakes on star formation, the left panel serves as a theoretical prediction for the observable consequences of AGN quenching. When we then repeat our machine-learning analysis in the SDSS, we find that this theoretical prediction is met overwhelmingly well in the observations, where the result is robust against our choice of method to estimate supermassive black hole mass. In simulations alone we then go a step further by including the instantaneous rate of growth of supermassive black holes among the input parameters. As shown in Fig. 2, we find that black hole accretion rate holds negligible importance for determining whether a simulated galaxy is star-forming or quenched in comparison with black hole mass.

Throughout this study we deliver first-of-a-kind evidence in favour of AGN driving galaxy quenching by showing an excellent agreement between cosmological simulations and the observable Universe. We also show that in order to study the influence of black holes in action in the future, we should focus on precise measurements of supermassive black hole masses, rather than their accretion rates. Following further investigation, we find that AGN most likely suppress star formation through a combination of gas heating around galaxies (e.g., via jets, illustrated in Fig. 3) and turbulence injection within galactic gas. These mechanisms together act to decrease gas reservoirs available for future star formation and the efficiency with which gas collapses to form new stars.

These results were published as Piotrowska J. M., Bluck A. F. L., Maiolino R. and Peng, Y., MNRAS 512, 1052 (2022).

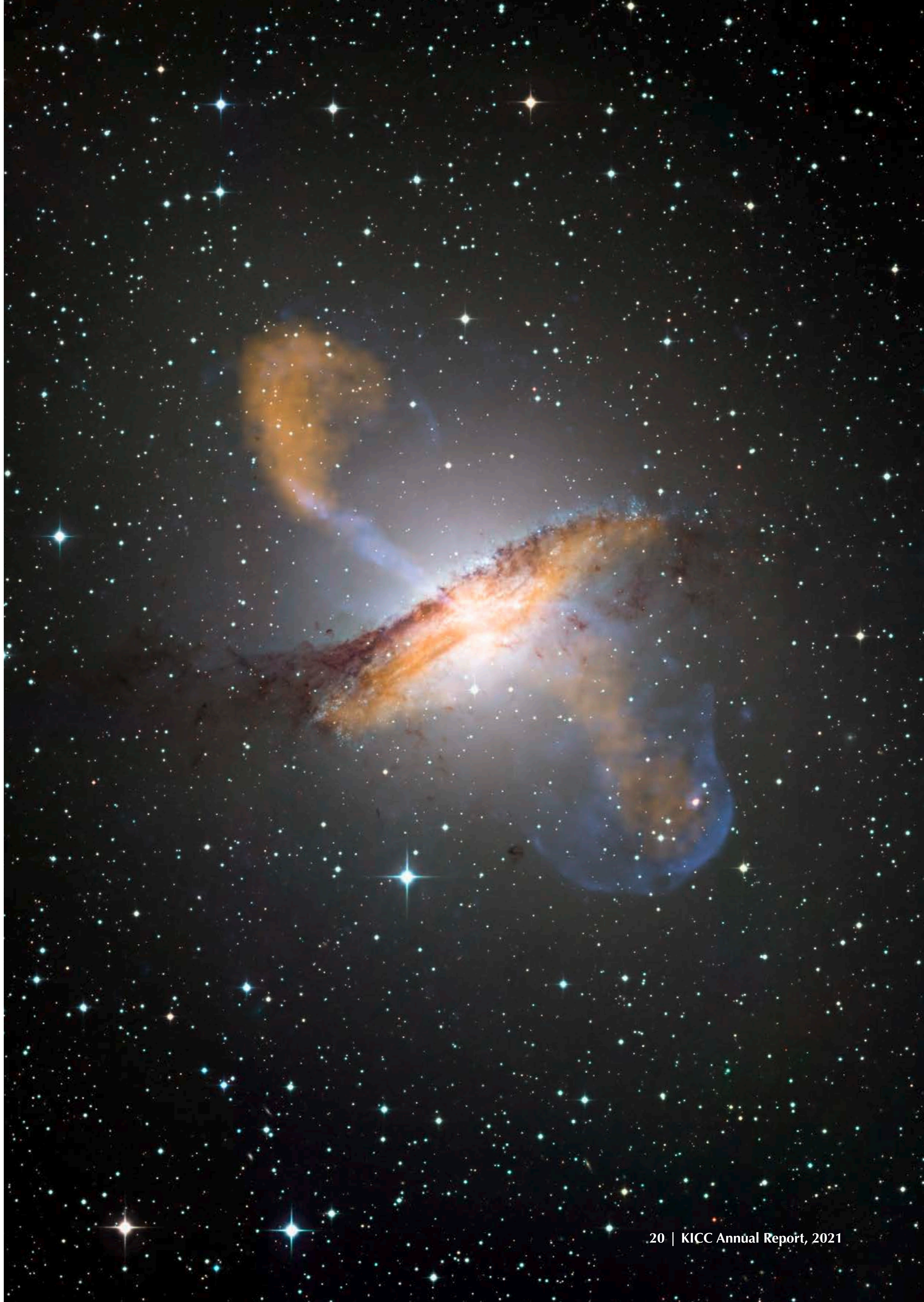


Fig. 3: Colour composite image of the Centaurus A galaxy, showing powerful AGN jets. The jets, observed at submillimetre wavelengths, extend to large distances away from the host galaxy seen edge-on in the image. Credit: ESO/WFI (Optical); MPIfR/ESO/APEX/A.*Weiss et al*. (Submillimetre); NASA/CXC/CfA/*R.Kraft et al*. (X-ray).

The Nature Of The Resolved Star Forming Main Sequence

William Baker & Roberto Maiolino

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Fig. 1: NGC 3583, an example of a local star forming galaxy. Credit: ESA/Hubble & NASA, *A. Riess et al.*

Star-forming galaxies are among the most beautiful extragalactic objects observed in the Universe. Most of them do not evolve chaotically, they follow a smooth, secular evolution during which the formation of stars is modulated by the availability of molecular gas (the fuel for star formation), the efficiency with which gas is transformed into stars, and the flow of gas to and from galaxies (gas accretion and gas ejection via outflows). Through this process, correlations ("scaling relations") are established between different galactic properties, which provides precious information on these various evolutionary processes. It is therefore important to understand the nature and origin of these relations.

The rate at which stars are formed in a particular region of a galaxy (the so-called surface density of Star Formation Rate, $\Sigma_{\rm SFR}$) is observed to strongly correlate with the amount of molecular gas contained within that region (surface density of molecular gas Σ_{H2}), which is described by the so-called resolved Schmidt-Kennicutt (rSK) relation. This relation describes, as already mentioned, how the gas provides the fuel for star formation, i.e. the more molecular gas the greater the rate of production of new stars which are then formed from this gas. The local star formation rate ($\Sigma_{\rm SFR}$) is also observed to strongly correlate with the mass of stars in that region (surface density of stellar mass, $\Sigma*$) which is called the resolved Star Forming Main Sequence relation or rSFMS. The Star Forming Main Sequence is often considered a fundamental property of galaxy populations, and has been widely used in both the local and distant universe to differentiate and characterise populations of galaxies. However, in addition to the two relations presented above, the amount of molecular gas in a particular region of the galaxy (Σ_{H2}) is linked to the mass of stars in that region ($\Sigma*$); this relation is likely tracing the effects of the local gravitational potential (atomic gas is more efficiently converted into molecular gas in regions of higher gas pressure associated with a stronger gravitational field). Therefore, we have three quantities that all appear correlated with one another - how can we determine which of these correlations are intrinsic (i.e. actually physically connected) and which may instead be a by-product of indirect correlations? As an example of the problem, suppose quantities *A* and *B* are uncorrelated, but both correlate with a third quantity C; then, if we explore A and B jointly, and separately from *C*, we will likely find a correlation between them, but only because we are not accounting for quantity *C*!

To tackle this problem we employ a hybrid approach using two different techniques, partial correlation coefficients and random forest regression. The first of these enables us to measure the correlation between two quantities whilst controlling for further quantities that may be correlated. For example, in our case, we can measure the partial correlation coefficient between star formation rate and stellar mass whilst controlling for the molecular gas mass. This means we can isolate the dependence of star formation rate and stellar mass at a given (fixed or "controlled") molecular gas mass, and uncover if an intrinsic correlation between these two quantities exists or not. We took partial correlation coefficients between each pair of the three quantities and found that (as can be seen in figure 1), once the dependence on molecular gas mass was factored out, the correlation between star formation rate and stellar mass was negligible – in other words almost totally caused by the strong correlation of both quantities with molecular gas mass!

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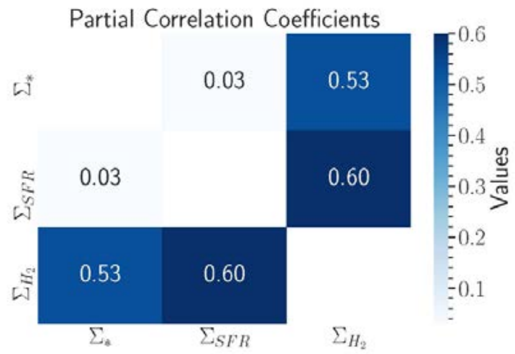

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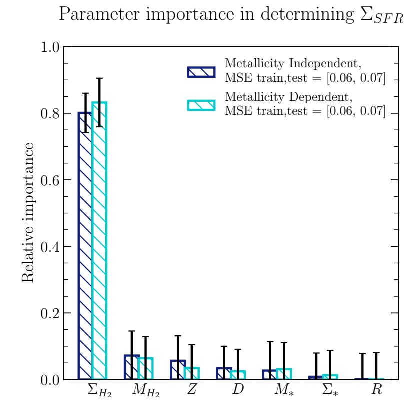


Fig. 2: Values for the partial correlation coefficients between each region's stellar mass ($\Sigma*$), star formation rate ($\Sigma_{\rm SFR}$), and molecular gas mass (Σ_{H2}), whilst keeping the third quantity constant. It is clear the partial correlation coefficient between $\Sigma*$ and $\Sigma_{\rm SFR}$ is the weakest.

Fig. 3: Bar-chart showing the random forest regression parameter importances in determining the star formation rate of each region ($\Sigma_{\rm SFR}$). The parameters evaluated are the region's molecular gas mass (Σ_{H2}), the total galaxy molecular gas mass $M_{\rm H2}$, the metallicity (*Z*), galactocentric distance (*D*), total stellar mass of the galaxy $M*$, the region's stellar mass ($\Sigma*$), and a uniform random variable as a comparison. The two different coloured bars correspond to different methods in determining Σ_{H2}; the result is the same regardless of which method is used. The bar-chart reveals that $\Sigma_{\rm SFR}$ is almost totally driven by Σ_{H2}.

The second technique we used, random forest regression, is a form of machine learning that uses many decision trees to predict the importances of a set of parameters in determining a particular quantity. It does this by splitting the data into a training and test sample enabling it to build a model based upon the training sample which it then applies to the test sample.We employed the random forest to find which of molecular gas mass or stellar mass are the most important in determining the star formation rate. This enabled us to test directly which of the rSK or rSFMS relations is more fundamental. Figure 2 shows the results of this random forest regression in a bar-chart, we see that the star formation rate is almost entirely determined by the molecular gas mass with negligible dependence on the stellar mass or any further quantity. This supports the findings with the partial correlation coefficients, i.e. the observed strong correlation between star formation rate and stellar mass is simply a by-product of the quantities own strong correlations with the molecular gas mass. *Therefore, the star forming main sequence is not a fundamental scaling relation! This result prompts for a reassessment of the widespread use of this relation to understand the properties of galaxies both in the local and distant universe.*

These results were published as *Baker W. M. et al.*, MNRAS 510, 3622 (2022).

What Drives The Scatter Of Local Star-Forming Galaxies In The BPT Diagrams?

Mirko Curti

Nebular emission lines from galaxy spectra provide a wealth of information about the physics that regulates the growth and evolution of galaxies. Their relative intensity is, in fact, reflective not only of the properties of the ionising radiation source, but also of the density, temperature, and chemical abundances of the surrounding ionised gas. Observationally, galaxies are often studied and classified based on their emission-line properties according to the location they occupy in a variety of different *diagnostic diagrams*, commonly referred to as the `BPT' diagrams. These diagrams, based on spectral lines emitted in the optical region of the spectrum (involving transitions from both hydrogen and heavier elements like oxygen, nitrogen and sulphur), are widely adopted to discriminate between the different excitation sources that power the emission in galaxies, in order to separate, for instance, systems ionised by stellar activity from those whose spectral properties are dominated by the presence of active galactic nuclei (AGNs) originating from the accretion of gas onto the central supermassive black hole.

More specifically, galaxies that are currently experiencing a significant level of star formation are observed to form a sequence in these diagrams, and the position along such sequence primarily reflects both the *metallicity* (i.e., the relative abundance of heavy elements compared to hydrogen) and the ionisation properties of their gas component. However, this sequence is characterised by a certain amount of dispersion, which is observed to correlate with different physical properties (Fig. 1). Therefore, from their relative position within these diagrams it is possible to constrain the physical conditions of gas and stars in different sub-populations of galaxies.

Interestingly, in the last decade several lines of evidence have also indicated that star-forming galaxies observed roughly 10 billion years ago (equivalent to a cosmological redshift between 1 and 3, i.e., the epoch where the star-formation activity of the Universe reached its peak) occupy a different location on the BPT diagrams compared to galaxies in the local Universe. Such difference is generally attributed to the combined effect of the evolution in both the stellar populations and in the physical properties of the interstellar medium (ISM). However, although such evolution in the emission-line properties of galaxies can be reproduced by many different theoretical models, it is often very challenging to disentangle the real contribution of each of the physical processes involved.

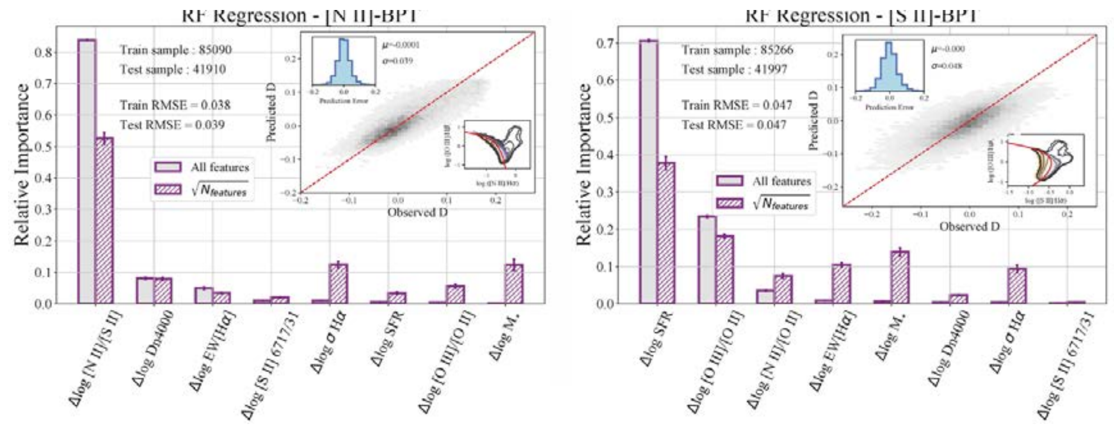
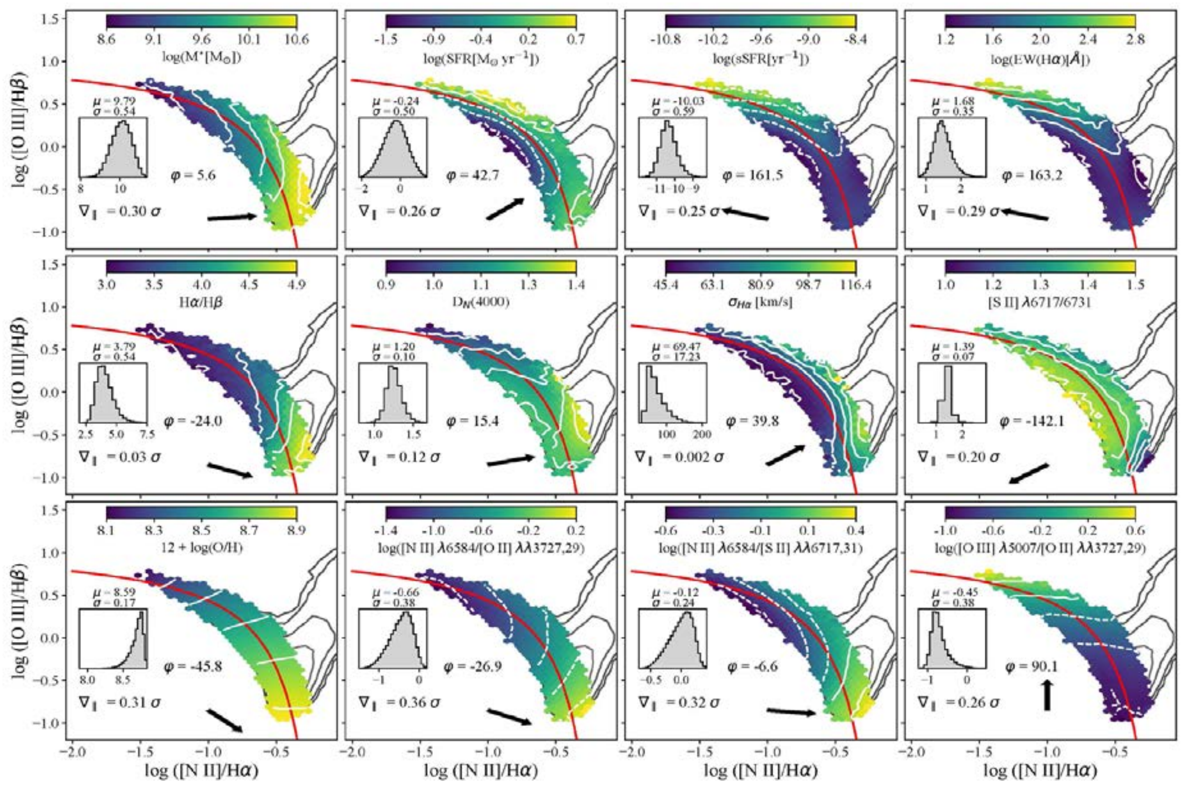


Fig. 1 (below): Distribution of star-forming galaxies from the SDSS in the [N II]-BPT diagram colour-coded according to different parameters, highlighting how the relative position of galaxies along and across the average sequence (indicated by the red line in each panel) correlates with a variety of physical properties.

Fig. 2 (above): Histograms reporting the relative contribution that each different physical parameter has in determining the offset from the average sequence in both the [N II]-BPT (left panel) and [S II]-BPT (right panel) diagrams, as inferred from a machine-learning analysis based on the Random Forest algorithm. Deviations in the nitrogen-over-oxygen abundance (here expressed in terms of the deviations in the [N II]/[S II] line ratio) dominate the relative contribution to the offset in the former case, whereas deviations in the star-formation rate dominate in the latter.



What Drives The Scatter Of Local Star-Forming Galaxies In The BPT Diagrams? - continued

We have recently explored a novel approach that leverages on the large statistics provided by the Sloan Digital Sky Survey (SDSS) and implements machine-learning techniques like Artificial Neural Networks and Random Forests to study the distribution of different galaxy physical properties within the BPT diagrams, linking relative variations in such properties to the offset from the average sequence of galaxies, and attempts to identify the most relevant physical parameter(s) responsible for the observed variation in the emission-line ratios. We have found that variations in the abundance of nitrogen at fixed metallicity are strongly correlated with the dispersion of galaxies around their average sequence in the [N II]-BPT diagram, with galaxies situated above the sequence prevalently more massive, older, and nitrogen-enriched than their closest *on-sequence* counterparts, and vice versa. The same analysis performed in the [S II]-BPT diagram revealed instead that variations in the star-formation activity of galaxies are tightly linked to the deviation from the average sequence in such a diagram. We interpret this as an observational consequence of the variation in the effective size of the emitting region of the doubly-ionised sulphur species in galaxies with different levels of current star formation, which has a direct impact on the [S II] emission lines (Fig. 2).

In ongoing research, we are trying to understand if the interplay of physical processes shaping the BPT diagrams in the local Universe is the same that drives the behaviour of high-redshift galaxies, or whether different physical mechanisms need to be considered. We are currently exploiting the data from the KMOS/KLEVER survey to test this scenario on a few tens of galaxies observed between redshifts 1 and 3. However, the advent of new, cutting-edge facilities like the near-infrared spectrographs MOONS on the VLT (Fig. 3) and NIRSpec on the JWST (both of which have significant involvement of KICC researchers) will allow us to perform this kind of analysis with unprecedented accuracy. The former will provide spectra of up to hundreds of thousands of galaxies from the epoch of the peak of the cosmic star-formation activity, matching the statistical power of the large surveys conducted in the local Universe, while NIRSpec will enable the investigation of the nebular diagnostic diagrams back into the era when the very first galaxies formed.

Some of these results were published in *Curti M. et al.*, MNRAS 512, 4136 (2022).

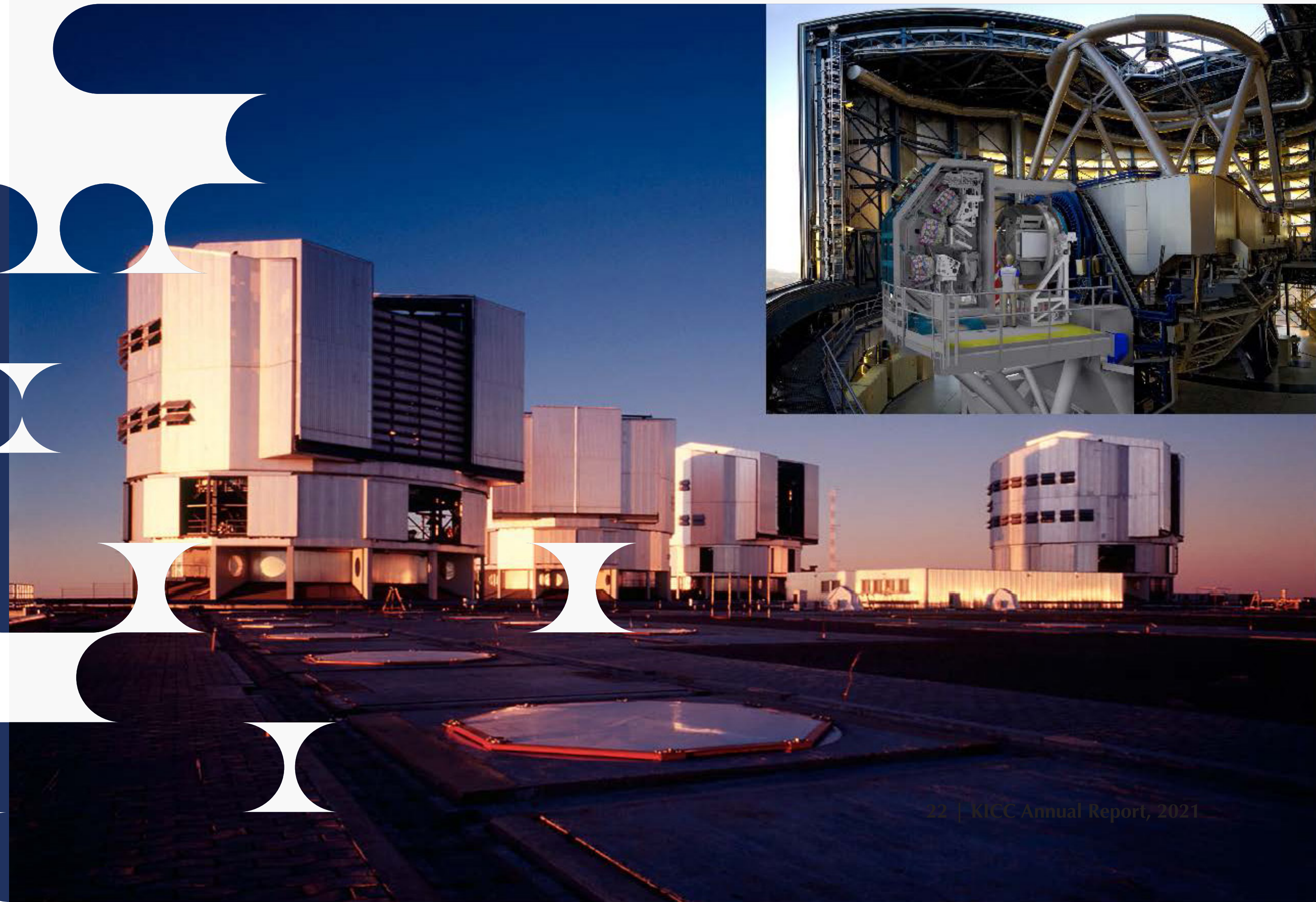
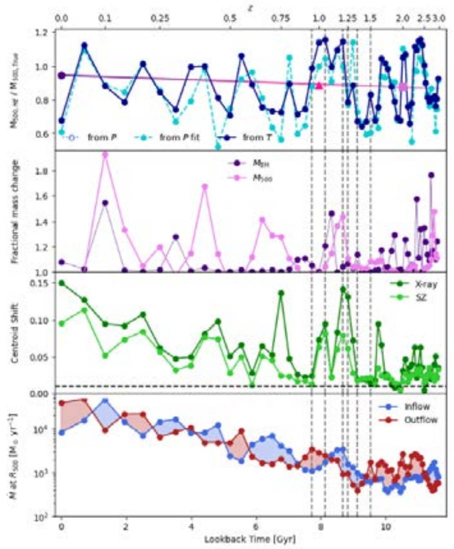


Fig. 3: The Very Large Telescope (VLT) at the Paranal Observatory in Chile. In the upper-right inset panel, an artistic impression of MOONS on the Nasmyth platform of the VLT. Image credits: ESO **https://www.eso.org/public/images/**; and *Cirasuolo et al.*, Msngr 180,10 (2020).

A Disturbing FABLE Of Mergers, Feedback, Turbulence, And Mass Biases

Jake Bennett & Debora Sijacki

Fig. 1 (below): From top to bottom, evolution of the hydrostatic mass bias, mass growth of the halo, centroid shift and mass flux, all considered at R_{500}.



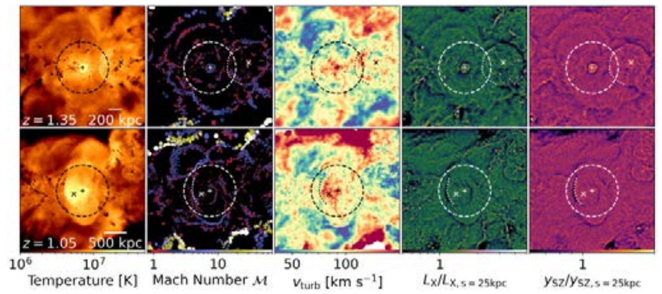
Galaxy clusters are the most massive virialised structures in our Universe, forming from the largest amplitude fluctuations in the primordial density field. The number of clusters in the Universe as a function of mass and redshift can therefore be used as a sensitive probe of cosmological parameters. For this, the total cluster mass is the key quantity that needs to be inferred from observations.

Clusters host a number of galaxies and a significant, hot atmosphere – the intracluster medium (ICM) – but their mass is dominated by dark matter. The total gravitating mass must therefore be estimated. The ICM itself can be used to do this; from X-ray observations we can measure a temperature and electron-density radial profile, while from measurements of the thermal Sunyaev–Zel'dovich (SZ) effect we can acquire a thermal pressure profile of the ICM. Then, by making the assumptions of spherical symmetry and hydrostatic equilibrium, the total mass profile of the halo can be estimated.

However, these assumptions do not always hold, biasing the obtained mass estimates. Galaxy clusters are dynamically young, and are actively accreting matter and merging even at late times. They are also host to a complex interaction of radiative cooling, star formation and feedback from supernovae and active galactic nuclei (AGN). All of these processes can lead to gas inhomogeneities, as well as driving bulk and turbulent motions in the ICM, which can affect the hydrostatic mass bias.

The level of ICM motions can vary dramatically as the cluster evolves, with major mergers providing the most significant dynamical perturbations. Merging haloes drive shocks that dissipate kinetic energy and heat up the ICM, produce turbulence, and disrupt the morphology of clusters. Black holes may also play a role in certain regions, as jets, strong shocks and outflows driven by AGN can have a similar effect on ICM gas, although the size of this effect is uncertain. Upcoming, high-quality observational data will transform our understanding of clusters and their use in cosmology. On the X-ray front, *XRISM* and *Athena* will provide deeper observations, along with dynamical information, of clusters and cluster progenitors out to high redshift.

SZ observations from the South Pole Telescope and the Atacama Cosmology Telescope, and the next generation of SZ telescopes such as the Simons Observatory and, eventually, CMB-S4, will also allow ICM and CGM properties to be probed to larger radii than with X-ray telescopes. Armed with these additional data, it will be possible for the first time to investigate observationally the redshift dependence of the hydrostatic mass bias, as well as the properties of clusters throughout their evolution. This motivates our recent theoretical work, which makes detailed predictions for this evolution from state-of-the-art cosmological simulations with the aim to uncover which physical processes are ultimately responsible for shaping the ICM properties.



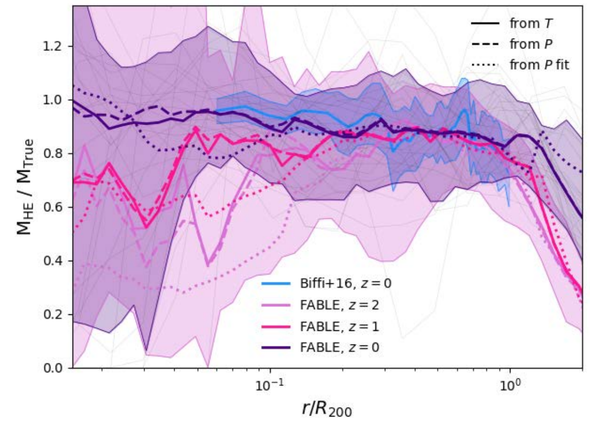


Fig. 2 (left): Maps showing the immediate pre-merger (top) and post-merger (bottom) stages of a major cluster merger, with bow/merger shocks highlighted with dotted lines. The right two columns show unsharp mask X-ray and SZ images, to highlight the shocks further.

Fig. 3 (right): Median radial profiles of the ratio of the hydrostatic to true mass at z = 0, 1 and 2, with solid lines showing our fiducial estimates.

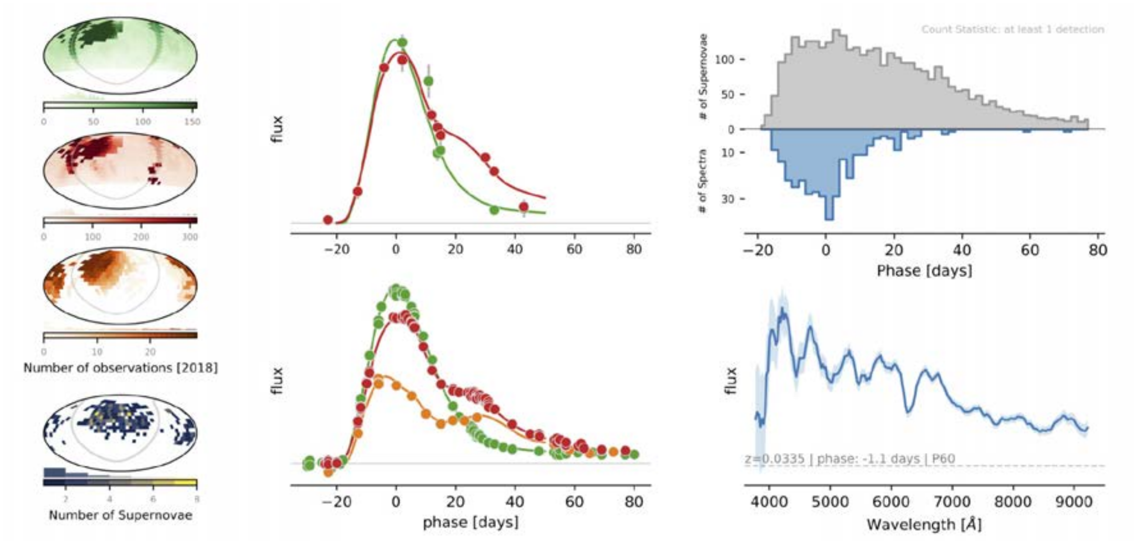
Following in detail a single, massive cluster from the FABLE simulation suite we found the bias varies significantly over cosmic time, rarely staying at the average value found at a particular epoch, as shown in Fig.1. Mergers (shown by peaks in the mass growth in the second panel), are generally preceded by an increase in mass bias followed by a rapid decrease. We find that variations of the bias at a given radius are contemporaneous with periods where outflows dominate the mass flux, either due to mergers or interestingly, at higher redshift, AGN feedback (visible in the maps of Fig. 2, which show a major merger progressing). The z = 0 ensemble median mass bias in FABLE is around 13 per cent at R_{500} (the radius inside which the average density is 500 times that of the cosmic matter density at the epoch) and around 15 per cent at the larger R_{200}, but with a large scatter in individual values. In halo central regions, we see an increase in temperature and a decrease in non-thermal pressure support with cosmic time as turbulence thermalises, leading to a reduction in the mass bias within 0.2 R_{200}, shown in Fig. 3.

When using an `analytic' pressure profile as commonly adopted in the literature, instead of the simulation data, to estimate the bias, we find there can be significant differences, particularly at larger radii and higher redshift. We therefore caution over the use of such fits in future work when comparing with the next generation of X-ray and SZ observations. Cosmological galaxy cluster simulations, like the ones presented here, will undoubtedly play a crucial role in interpreting these future observations and linking detailed ICM properties to the evolution of the hydrostatic mass bias.

Supernovae Cosmology With The Zwicky Transient Facility

Suhail Dhawan

Fig. 1 (below): Summary of the sky distribution of ZTF observations in three colours (green, red and orange; left) along with the brightness evolution of example supernovae (middle) and the spectrum of an example supernova splitting the light into constituent colours, an important observation to confirm that the supernova is of Type Ia (taken from *Dhawan et al.* 2022a).



Type Ia supernovae are a special class of bright cosmic explosions, acting as lighthouses to measure several key quantities defining our Universe. They are essential to measuring the current expansion of the Universe, known as the Hubble constant. The measurement of the Hubble constant from our nearby Universe is strongly inconsistent with the inference from the early Universe, using the fossilized heat from the big bang. This problem, termed as the Hubble tension, is one of the most important open questions in cosmology. Answering this question requires novel measurements of the expansion rate.

In the past year, I have led the first data release of Type Ia supernovae from the Zwicky Transient Facility (ZTF), a large survey of the night sky in optical wavelengths with a wide-field-of-view camera. ZTF is a unique survey of the optical sky that has already discovered and observed more than 3000 Type Ia supernovae, a factor 10 larger than the current best sample in the literature. My work centered on the dataset from the first year of operations, a total of 760 objects (a summary is presented in Fig. 1). This dataset was the first large sample of Type Ia supernovae where the discovery and detailed observations, in multiple colours, were derived from the same telescope. This feature allows us uniquely to study the dependence of the brightness of the supernovae on the environment of the galaxy it exploded in. Building upon this work, my collaborators and I published the first measurement of the Hubble constant using data from ZTF, combining it with high-precision data from the Hubble Space Telescope of the galaxy of a nearby Type Ia supernova. The Hubble data allow us to measure a precise distance to the supernova host galaxy using

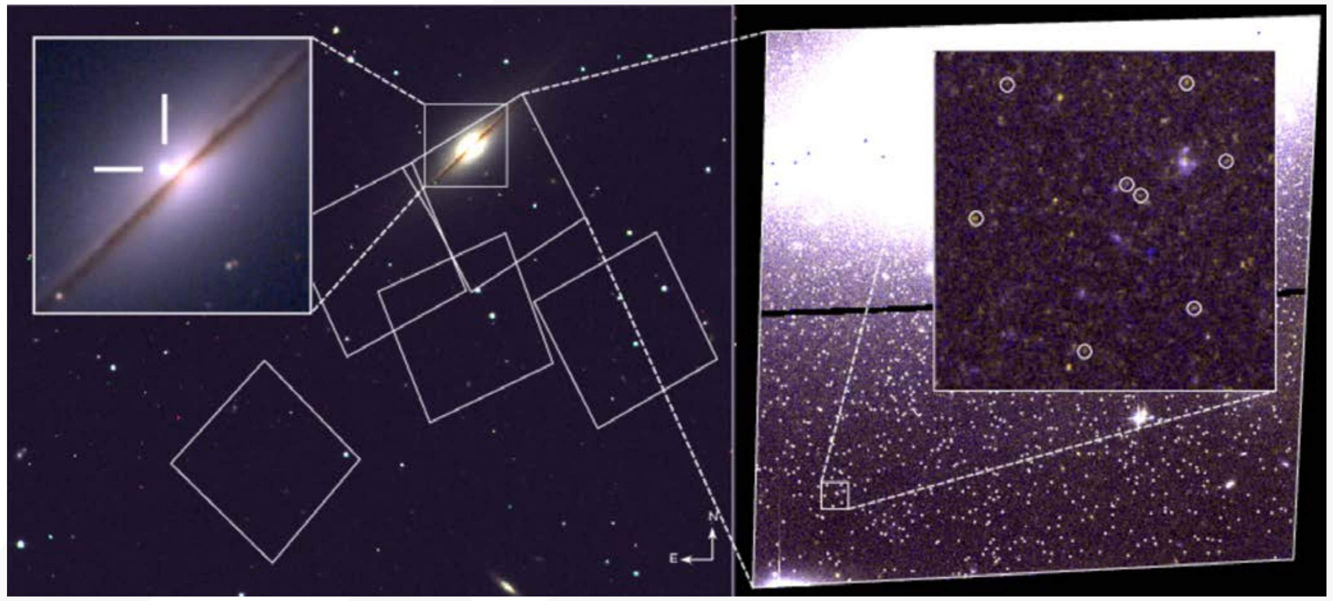


Fig. 2: Combined ZTF image of the supernova used for measuring the Hubble constant with the uniform-distance-ladder approach (taken from Dhawan et al. 2022b). *Right*: a zoom into the Hubble Space Telescope data used to identify the individual stars for the distance measurement to the galaxy.

old stars in the halo of the galaxy where there is a lot less contamination from effects of dust or crowded environments, both of which are roadblocks in conventional methods to measure the Hubble constant (see Fig. 2). Gearing up for the second data release of ZTF, which will contain more than 2500 Type Ia supernovae, we are now working to constrain the directional dependence of the expansion rate. This uses the most advanced data from the literature to determine whether the Hubble parameter is directionally dependent, using a framework of distance computation that is independent of the standard model assumptions in cosmology.

Type Ia supernovae are also key to measuring the curvature of the Universe. There has been a recent debate regarding whether the early-Universe data suggest the Universe is geometrically flat or closed. In collaboration with Newton–Kavli Fellow Sunny Vagnozzi, we used modern astrostatistics methods to show that Type Ia supernovae in combination with a series of Hubble parameter measurements suggest the universe is flat, although with less precision than inferences from the early Universe. We found, from forecasts, that these constraints, which are independent of the early Universe, can be improved by an order of magnitude with soon-to-be-online surveys of supernovae and Hubble parameter data.

These results are based on *Dhawan S., et al.*, MNRAS, 510, 2228 (2022), *Dhawan et al.* 2022, ApJ, 934, 185 and Dhawan S., Alsing, J., and Vagnozzi, S., MNRAS, 506, L1 (2021).

COSMOLOGY

Probing The 21-cm Signal From Cosmic Dawn With The REACH Experiment

Eloy de Lera Acedo

Fig, 1: First REACH antenna installed on site. It is a wideband hexagonal dipole operating at wavelengths compatible with the expected range at which a 21-cm signal that originated from hydrogen clouds surrounding the very first stars of the Universe should be detected. In the background one can see the dramatic landscape with high flat-top hills providing extra isolation from human-made radio interference.

How did the Universe transition from the simple, smooth state we observe in the cosmic microwave background radiation to a complex realm of stars, galaxies and other celestial objects? Critical epochs are believed to be “Cosmic Dawn”, when the first stars and galaxies formed, and the epoch of reionization, when energetic radiation from these first luminous sources ionized the intergalactic medium. 21-cm radio-cosmology is the field of research promising to unlock the secrets of these epochs for the infant Universe by studying radio signals from the most abundant element in the Universe: hydrogen.

Radio-interferometers have already placed upper limits on the power spectrum of 21-cm fluctuations, which probe the three-dimensional distribution of hydrogen. On the other hand, single-antenna experiments aim to measure the 21-cm signal averaged across all directions on the sky, which probes the evolution in time of the thermal properties and ionization state of hydrogen. Searches for these sky-averaged signals are promising the first breakthroughs.

The EDGES experiment shook the field in 2018, reporting a high-redshift sky-averaged cosmological signal twice as large as that expected. If real, this would likely require the introduction of some exotic physics. However, the EDGES measurements have been contested by several groups, who have raised concerns over aspects of the data analysis and the potential impact of systematic signals induced by the hardware. In particular, recent measurements from the SARAS3 experiment are incompatible with the EDGES findings. The contamination from instrumental systematic effects 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 birth to a second generation of experiments. The Radio Experiment for the Analysis of Cosmic Hydrogen (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 focusing on the detection and isolation of instrumental systematic signals. To this end, REACH will use a fully Bayesian data pipeline to fit jointly instrument models with models of the sky signals. The REACH team, with over 30 researchers in 10 countries, and led by KICC researchers, aims at a first confident detection and study of the sky-averaged 21-cm line.

Fig. 2: Some of the members of the REACH team during a recent trip to the site (February and March 2022) when the first radio antenna was installed. From left to right: Dr Eloy de Lera Acedo (KICC/Cavendish, PI), Prof Dirk de Villiers (Stellenbosch University, South Africa, Co-PI), Mr Dominic Anstey (KICC/Cavendish, PhD student), Ms Carla Pieterse (Stellenbosch University, South Africa, PhD student), Dr Saurabh Pegwal (Stellenbosch University, South Africa, PDRA) and Mr Wessel Croukamp (Stellenbosch University, South Africa, head technician).

Fig. 3: Aerial view of the Karoo radio reserve core showing the location of the future SKA1-MID core, the MEERKAT and HERA telescopes, and the location of REACH, approximately 20 km southwest from the other telescopes, and surrounded by a 4-km wide circus of flat-top hills (around 100–200 m in altitude) that provide extra shielding from human-made radio-frequency interference. Figure credit: GOOGLE.

During 2021 (and the first half of 2022), throughout the COVID pandemic, the REACH team has spent most of its time developing the complex machinery of Bayesian data analysis and calibration and cosmological numerical models that we are about to start using. Once the travel and access limitations due to the pandemic started to lift, the REACH team was able to go back to its site, in the radio-quiet reserve of the Karoo region, in Southern Africa, also the location of the future SKA1-MID telescope. The team has already installed the radio antenna and is currently working on installing the radio receiver, which should allow REACH to start its commissioning phase in the third quarter of 2022 closely followed by scientific observations. Figure 1 shows a picture of the first of two radio antennae planned for REACH Phase I, a wideband hexagonal dipole, chosen for its spectral smoothness. A second antenna, a conical log-spiral antenna, chosen for its very regular chromatic structure, will be installed following the start of observations with the first antenna. The use of two very different hardware front-ends is at the core of the novel experimental approach of REACH, since we expect that any instrument-induced features in the observed signal should be different between the two systems. Therefore, the fully Bayesian data pipeline featuring models of the instrument, sky foregrounds and the cosmological signal, should have a good chance to separate the aforementioned signal components.

Figure 2 shows the team that installed the first antenna, while Fig. 3 shows an aerial view of the Karoo radio reserve indicating the REACH site alongside the location of other radio telescopes.

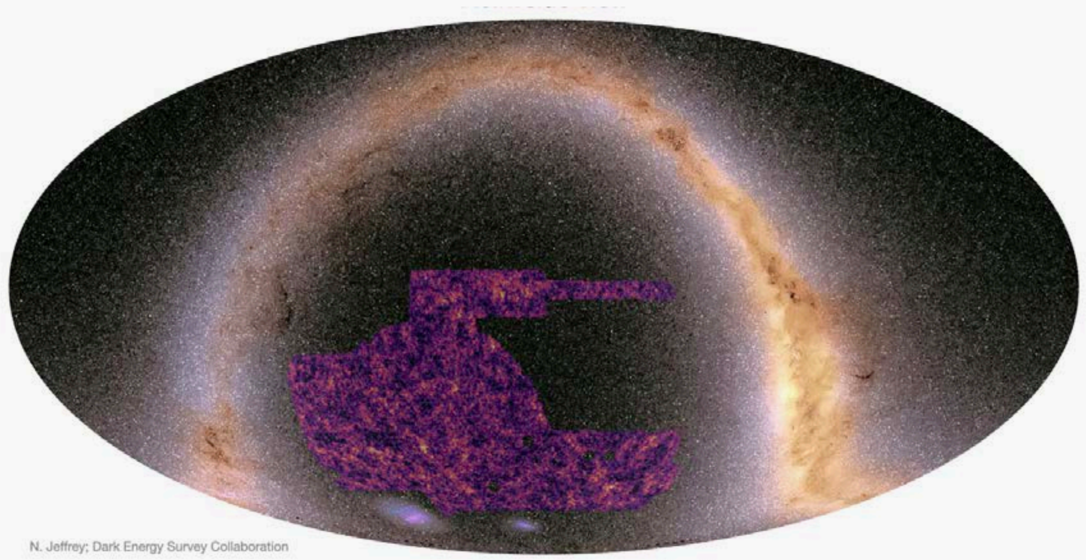
REACH[1] is partly funded by the Kavli Institute for Cosmology, Cambridge, the South African National Science Foundation and the Cambridge–Africa ALBORADA Trust fund.

Parts of this article are based on the REACH mission paper, recently published as de *Lera Acedo E. et al.*, Nature Astronomy (2022). DOI: 10.1038/s41550-022-01709-9.

COSMOLOGY

Shedding Light On The Dark Universe With The Dark Energy Survey

Alexandra Amon



When we observe a distant galaxy, we collect its light in our telescopes after it has journeyed for billions of years across the Universe. Do we see the galaxy as it really is? According to our theory of gravity, General Relativity, dark matter, like any massive structure, warps the space-time fabric of the Universe. As such, the path that the light travels along is altered and the image of the galaxy that we capture appears slightly distorted. This effect on the image we call *weak gravitational lensing* and it is one of the most powerful tools to study the nature of dark matter and dark energy. The gravity due to any dark matter along the line of sight has the effect of *lensing* the galaxy - making it appear more stretched in our images and inducing a coherent alignment among nearby galaxies. The stronger the average galaxy ellipticity in a patch of sky, the more dark matter there is in the intervening region of the Universe. Therefore, the induced distortion of the galaxies is a faint signature of dark matter inscribed throughout the Universe.

It is my immense privilege to play a leading role in the Dark Energy Survey (DES), an international team of over 400 scientists. From the vantage point nestled on a mountain top in Chile, we use the Blanco Telescope to scan our night sky and harness data from the cosmos (see Fig. 1). Over three years, we imaged 1/8th of our night sky and catalogued the positions, shapes and distances to more than 100 million galaxies. We measured their statistical alignments to extreme precision in order to map the matter lying between us and the distant galaxies (Fig. 2). This was the most rigorous analysis of its kind, and it allowed us to test against the predictions from the standard cosmological model.

This is no easy feat - while gravitational lensing is a powerful cosmological technique, it is extremely technologically challenging. The typical distortion induced by dark matter is less than a 1% alteration to the observed shape. As the lensing effect is weak, in order to detect it we need very large samples of galaxies. This data challenge necessitates rapid processing of petabytes of data. A scientific hurdle arises as the weak-lensing distortions are significantly smaller than the distortions that arise in the last moments of the light's journey. Due to the effect of the Earth's atmosphere, even in the exquisite conditions of the Coquimbo mountains, and our imperfect telescopes and detectors, our galaxies are not the picturesque spirals you might imagine, but instead appear as fuzzy blobs spanning only a few pixels. In order to isolate the dark matter signature, these nuisance distortions are mathematically modelled to high precision, allowing an accurate recovery of the cosmological signal.

With a new machine-learning technique, we infer galaxy distances - an effort that I led with my colleagues at Stanford University. Further complications arise due to the intrinsic properties of galaxies and their effect on the surrounding matter that needs to be modelled. To minimise our human bias, we do all this `blindly'- using intentionally tampered data throughout the years of testing, until we are convinced of our calibration and model choices and are ready to reveal what the Universe is really like.

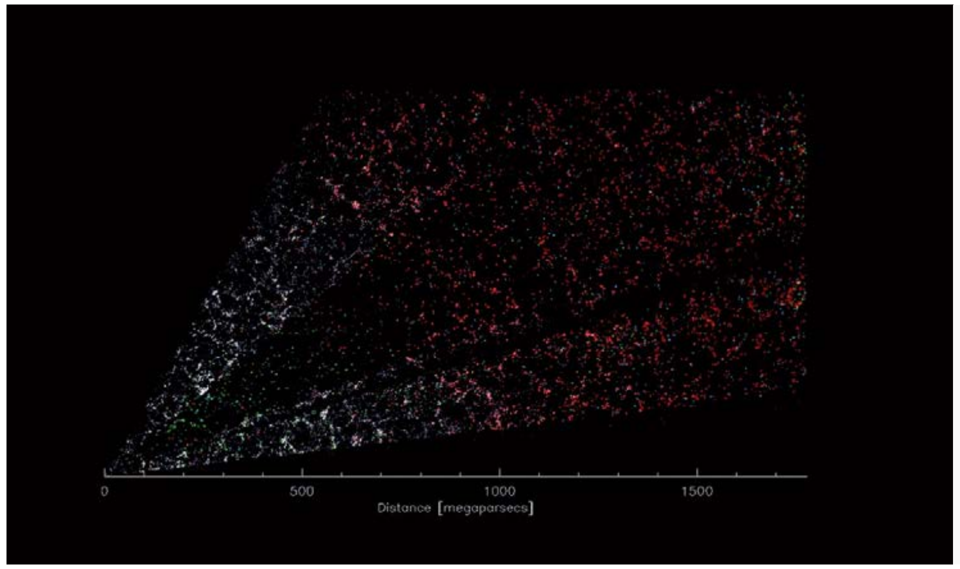
It is a particularly exciting time for cosmology. Let me set the scene: there are several competing teams performing weak-lensing measurements independently. We use much larger datasets than ever before, desperate to see if what we find is consistent with our model or, perhaps, if we find new cracks in the grand picture. Finally, we are starting to see hints of such cracks. Like our ESO Kilo-Degree Survey and Japanese Hyper Supreme Camera colleagues, DES found that weak lensing predicts a slightly less clumpy Universe than would be expected based on the prevailing model of cosmology. This suggests a need for either new physics, a new problem in the analysis to be solved, or perhaps just more data. It is exciting to think that it is time again for a new landmark moment - a call for some modification to our peculiar cosmological model. With my fingers crossed for new physics, I co-coordinate the weak-lensing science team and we are in the midst of analysing the remaining three years of DES data.

Our on-going experiments act as training grounds for an epic decade for cosmology: we are at the dawn of several major international projects that will survey the sky to greater depths and resolution than ever before. The Vera Rubin Observatory will image the entire Southern sky every few nights, building the deepest and largest map of our cosmos, and the Euclid satellite will survey the sky from a vantage point in space, eradicating the worry of Earth's atmosphere. There is an exceedingly bright future ahead, bringing us closer to fathoming our dark Universe.

This article is partly based on results published as *Amon A. et al.*, Phys. Rev. D 105, 023514 (2022); *Myles J. et al.*, MNRAS 505, 4249 (2022) and DES Collaboration, Phys. Rev. D 105, 023520 (2022).

Dark Energy Spectroscopic Instrument (DESI)

Roger de Belsunce & Vid Irsic



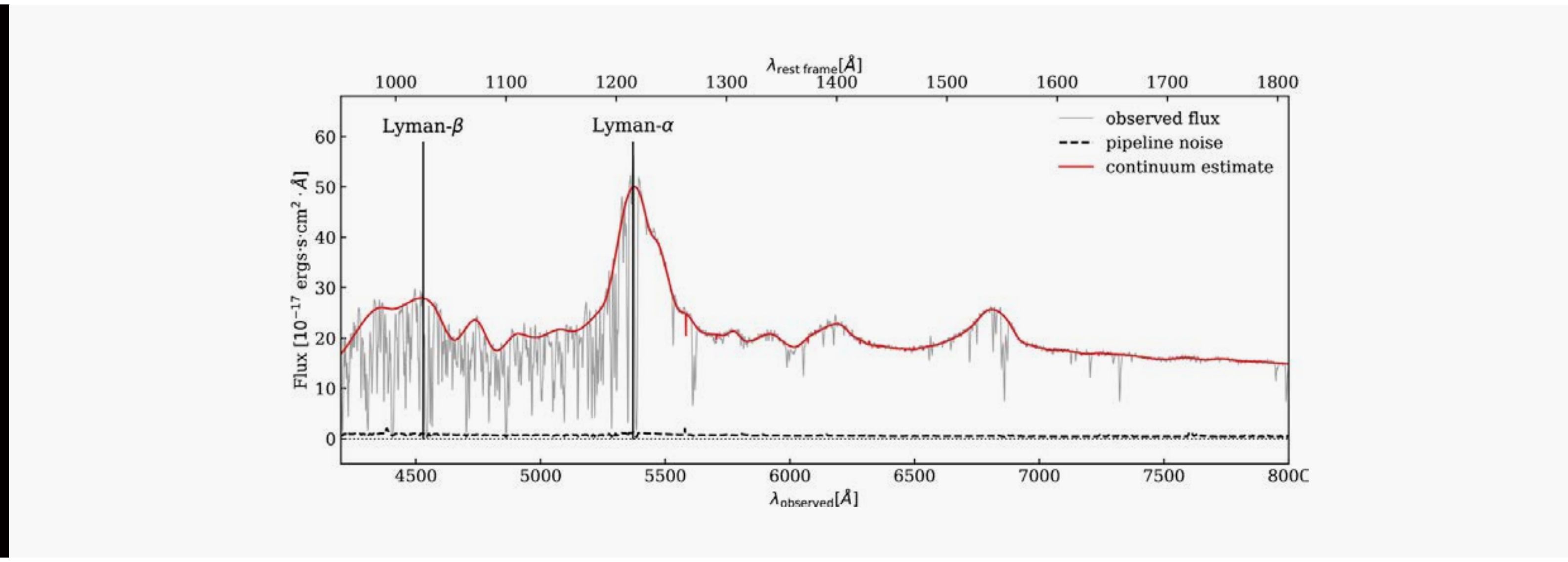


Fig. 1: 20-degree scan of the three-dimensional structure of the Universe revealed by the ongoing DESI survey. The Earth is in the lower left, looking out over 5 billion light years in the direction of the constellation Virgo. Each coloured point represents a galaxy, and gravity has pulled these galaxies into a cosmic web of structures consisting of dense clusters, filaments and voids. (Image credit: D. Schlegel/DESI Collaboration.)

Fig. 2: Spectrum of a distant quasar at redshift 3.2, observed by DESI during science verification, together with the over-plotted estimate of the quasar continuum obtained by the PCA method. The strongest emission line corresponds to the Lyman-alpha emission, and the absorption features at lower wavelengths correspond to the Lyman-alpha forest. (Image credit: R. de Belsunce.)

The Dark Energy Spectroscopic Instrument (DESI) is currently conducting the largest spectrographic survey of distant astronomical objects. Its main advantage over previous spectroscopic instruments is a focal plane containing 5,000 fibre-positioning robots fed by optical fibres to a bank of spectrographs. This allows for unprecedented speed of the data collection. The survey has so far broken all previous records, mapping the three-dimensional location of 100,000 galaxies and quasars in a single night during its first months of survey operations.

The DESI survey is a five-year redshift survey using the Dark Energy Spectroscopic Instrument, and is classified as one of the Stage-IV Dark Energy Experiments. The DESI Main Survey started on May 14, 2021, collecting data that will create the largest and most detailed 3D map of the Universe. Over its observation span it will cover 14,000 square degrees, and observe spectra of more than 35 million galaxies and quasars of which more than 6 million have already been observed in the first half a year of its operations (see Fig. 1). Once completed, that extremely detailed 3D map of the Universe will yield a more detailed understanding of dark energy, and thus further our understanding of the past, present and future evolution of the Universe.

Of the millions of spectra observed to date, there are over 2.8 million quasars above redshift 0.8, and of those over 300,000 are above redshift 2.1 tracing the evolution of the Universe beyond "Cosmic Noon" and the peak of the star-formation history. Quasars are the most luminous astrophysical objects, and can thus be observed to much larger distances, with some of the observed quasars stretching all the way to reionization and the formation of first galaxies. A unique feature of these high-redshift quasar spectra is a characteristic series of absorption lines – dubbed the Lyman-alpha forest – that trace the gas in intergalactic space (see Fig. 2). These absorption lines arise from scattering of the background quasar light by neutral hydrogen in the Universe.

Lyman-alpha scattering is a resonant process, which can only be triggered by photons with a wavelength corresponding to the energy transition between the ground and first-excited state of neutral hydrogen. However, as the Universe expands, the wavelengths of photons emitted by the quasar are stretched. This results in emitted photons with shorter wavelengths than the Lyman-alpha transition, and hence higher energies, scattering at some distance from the quasar. The higher the energy of the emitted photon, the further the photon will travel before scattering. The combination of the resonant scattering and the expansion of the Universe thus yields absorption features that correspond to scattering occurring at different redshifts between the quasar and us.

Since the scattering process depends on the density of the material (in this case neutral hydrogen), the Lyman-alpha forest makes for an excellent tracer of the distribution of the matter in the Universe at high redshift. However, to access this information accurately, one needs to estimate the number of photons with a given energy that are emitted by the quasar – the quasar continuum. The quasar continuum is relatively featureless, with a power-law tail towards higher wavelengths and several broad emission lines (Fig. 2).

The ions causing the emission lines are typically associated with the coronal emission around quasars, and they often come in a variety of outflows and ionization states. Unfortunately, it is impossible to observe quasar spectra at higher redshifts without the (contaminating) features in the Lyman-alpha forest, making the ultraviolet part of the continuum hard to estimate empirically. This makes modelling complex. To overcome this, we are adopting a more phenomenological approach. We have developed a principal-component-analysis-based (PCA) decomposition model that predicts the continuum of quasars within the Lyman-alpha forest based on the estimated continuum at higher wavelengths.

Direct Detection Of Dark Energy

Sunny Vagnozzi & Anne Davis

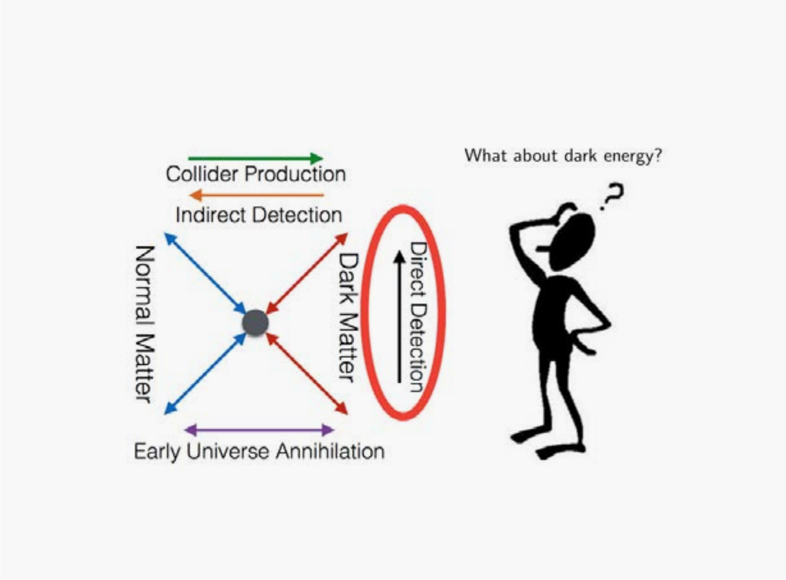


Fig. 1 (above): Three-pronged experimental approach for detecting dark matter, highlighting direct detection. What about dark energy?

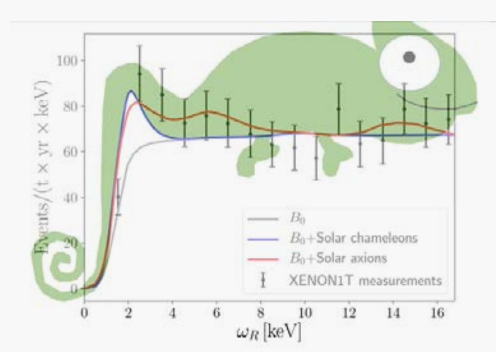


Fig. 2 (left): XENON1T detector.

Fig. 3 (right): Chameleon dark energy and axion signals, together with the XENON1T measurements.

When dark energy (DE), the mysterious component responsible for accelerating the expansion of our Universe, was first discovered in 1998, it was by means of its *gravitational* interactions: in other words, the effect of dark energy's gravity on the expansion of the Universe. Fast-forward to over 20 years later and, while our understanding of DE has significantly improved (though we are still extremely far from understanding its nature), one thing has essentially remained unchanged: the vast majority of the efforts in searching for DE are still focusing on its gravitational signatures, as probed both by the background expansion of the Universe, as well as the growth of cosmic structure. But is this the end of the story, or can we think of new ways of searching for DE *off the beaten track?*

Let us take a step aside and think about the other mysterious dark component: dark matter (DM), the glue that holds the Universe together on the largest scales. We first discovered DM in the 1920s through its gravitational effects, before convincingly re-discovering it in the 1970s, again through its gravitational signatures. However, now, in 2022, the state-of-the-art in searching for DM is instead all about determining its *non-gravitational* interactions with visible matter. This is mostly based on a three-pronged approach proceeding through complementary detection channels: direct detection, indirect detection, and collider searches (Fig.1). Direct-detection experiments search for signatures of DM recoiling ("scattering") off visible matter on Earth, using large detectors placed deep underground to avoid background contamination.

The question now is: can a similar experimental effort be carried out for DE as well? Although interactions between DE and visible matter are somewhat inevitable, they would equally inevitably lead to unwanted "fifth forces", which we do not observe. A way to get around this is to introduce "screening mechanisms", which dynamically hide the fifth force within dense environments. One well-known screening mechanism, which researchers at the University of Cambridge have been instrumental in developing, is the chameleon mechanism, which makes the fifth force very short-ranged in dense environments such as the local Universe. The proper way of phrasing the previous question is then whether an experimental effort parallel to that of DM can be carried out to search for non-gravitational interactions of *(chameleon-)screened* DE.

With former University of Cambridge researchers Philippe Brax and Jeremy Sakstein, and our collaborator Luca Visinelli, on a hot, stuffy afternoon in June 2020 we embarked on a journey to answer this ambitious question. We were motivated by the intriguing results of a DM direct detection experiment called XENON1T (placed under Gran Sasso in Italy; see Fig. 2), which found a potential signature of DM interacting with electrons in its detector. The trouble is, one of the leading DM explanations of these findings, based on hypothetical particles called axions produced in the Sun, runs into problems with stellar-evolution constraints: if the Sun is to produce enough axions to explain this puzzling signature, much denser stars would overproduce axions and live a much shorter life.

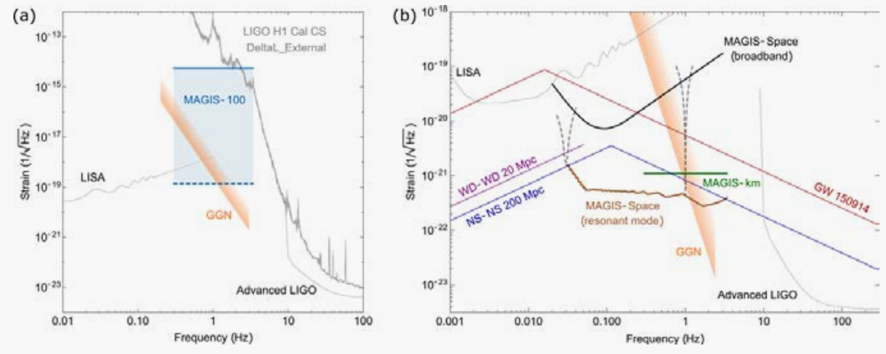
Together, we developed the formalism to calculate the spectrum of chameleon DE particles produced by the Sun, how they interact with detectors in direct-detection experiments, and finally what signal the latter should see. Much to our surprise, we found that DE could explain XENON1T's funny signal and, precisely because of the way chameleon screening works, we could bypass stellar-evolution constraints which kill the axion explanation (Fig. 3). As always in science, there are many caveats, ifs, and buts, but...if we are indeed right, XENON1T's results would constitute the first ever direct detection of non-gravitational signatures of DE, and would be nothing short of a breakthrough!

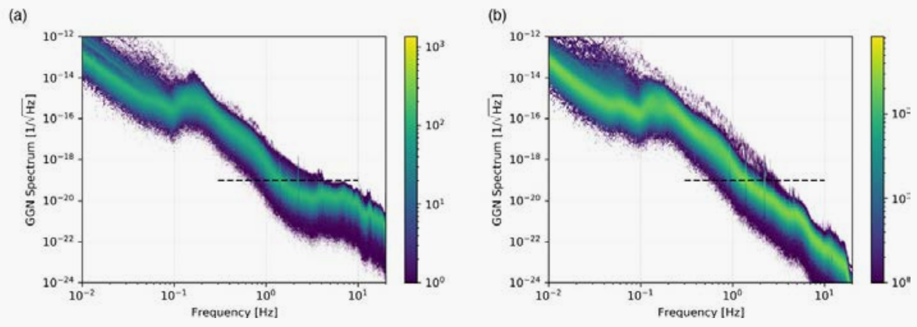
While the work in itself was a mathematical and physical tour-de-force, the fun we had working on it served as a reminder of why we do science. For our results, we also received the Buchalter Cosmology Prize, with the jury recognizing our work as "opening new, unforeseen vistas for the scientific scope of direct-detection dark matter experiments". Leaving aside the XENON1T results, which could also be due to a statistical fluctuation, the real legacy of our work is in its showing that there are promising ways to search for DE off-the-beaten-track that we can pursue at zero extra cost, using existing experiments searching for DM at the same time: two birds with one stone! Our hope is that a complementary approach combining cosmology and terrestrial searches for DE will bring us closer to understanding this mysterious component in the next decade.

These results were published as: S. Vagnozzi, L. Visinelli, P. Brax, A.-C. Davis & J. Sakstein, Phys. Rev. D 104, 063023 (2021).

Cold-Atom Interferometry For Fundamental Physics: AION And MAGIS Networking And Background Signals

Jeremiah Mitchell & Val Gibson





The Atom Interferometer Observatory and Network (AION) project in the UK and the Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS) in the US are novel experiments that aim to leverage cold atom interferometry technology to open a new window on fundamental physics. Both experiments are based on a multistage program with increasing baseline size of the detector platforms that enhance the sensitivity to the science signal linearly with baseline length (10 m, 100 m, 1 km, and space-based). A staged approach allows for testing and solving the technical challenges required for a network of atom interferometry observatories while unlocking increased potential to search for ultra-light dark matter candidates and gravitational waves in the frequency mid-band (0.1–10 Hz). Projected gravitational-wave sensitivities can be seen in Fig. 1.

The close collaboration between AION and the 100m atom interferometer MAGIS-100 at Fermi National Laboratory (FNAL), alongside other similar projects, will enhance the science programme for signal detection while operating in physically different environmental backgrounds. This enables comparison of different development approaches of the required ultra-cold atom systems underlying the atom interferometers. The feasibility of a kilometre-scale network of devices will require an international effort where the knowledge base is pooled together in a similar fashion to the LIGO and VIRGO experiments and other HEP detectors around the globe. Both collaborations are currently underway with MAGIS-100 about to begin civil engineering and AION assembling their first ultra-high vacuum systems.

Since 2019 both collaborations have made significant progress. Cambridge, with KICC committed resources, has developed the data acquisition, monitoring, and control systems for MAGIS-100 and provided design input for AION. Included in the data monitoring is the design of the data pipeline and networking to establish a robust method of moving and storing the measurement data and keeping track of crucial calibration and environmental effects and how best to handle the initial analysis. Location characterization of the environment for fully understanding the passive backgrounds at FNAL have also been carried out including measurement of the ambient temperatures, humidity and seismic and vibrational activity. Moreover, investigations for a potential future site location for AION with a 100 m baseline have been initiated. All this work provides support to the initial data-taking campaign, the optimization of the detector sensitivity, and effective long-term running of the atom interferometer.

A key terrestrial background that potentially limits sensitivity to ultra-light dark matter and gravitational waves for the longest baseline atom interferometers is Gravity Gradient Noise (GGN), which has been studied in detail for surface gravitational-wave detectors such as LIGO. This signal background can be sourced by various density perturbations, but most commonly is caused by seismic waves and atmospheric perturbations. Methods for establishing a baseline on the inferred strain noise from seismic motion were applied to seismometer measurements performed at the MAGIS-100 site at FNAL. Measurements of acceleration amplitude spectral densities, made above ground and 100 m below ground, were used to calculate displacement amplitude spectra that can be converted into what the inferred GGN strain on a long-baseline atom interferometer could be (Fig. 2). These models are currently being advanced and extended to account for the effects on ultra-light dark matter searches as well as how best to mitigate GGN through passive and active methods. From this work, an environmental-monitoring system has been in development to track systematic effects allowing for calibration of the datasets during analysis. The networking of MAGIS-100 and AION will also play a role in distinguishing between these environmental backgrounds across the Earth while also increasing sensitivity to other effects of fundamental physics.

We are eager for these experiments to continue development and are excited about the science potential they have for our fundamental questions about the Universe. The key contributions provided by Cambridge and KICC will enhance our ability to synchronize these detectors and provide the crucial control systems necessary for their effective operation.

This article is partly based on *Mitchell J. et al.*, J. Inst. 17 (01), P01007 (2022) and *Abe M. et al.*, Quantum Sci. Technol. 6 (4), 044003 (2021).

Fig.1 (left): (a) Projected gravitational-wave strain sensitivities for MAGIS-100 and follow-on detectors. The solid blue line shows initial performance using current state-of-the-art parameters. The dashed line assumes parameters improved to their physical limits. LIGO low-frequency calibration data (grey) is shown as an estimate for the state-of-the-art performance in the mid-band frequency range. An estimate of GGN at the Fermilab site is shown as an orange band. (b) Estimated sensitivity of a future km-scale terrestrial detector (MAGIS-km; green) and satellite-based detector (MAGIS-space; brown). The detector can be switched between both broadband (black, solid) and narrow resonant modes (black, dashed).

Fig. 2 (right): Inferred GGN strain amplitude spectral densities at the Fermilab site (a) above ground and (b) 100 m below ground. The colour-bars represent the number of counts per frequency bin. Dashed lines are future goal strain sensitivities for MAGIS-100.

Testing Massive Scalar-Tensor Gravity With Gravitational-Wave Observations

Michalis Agathos & Ulrich Sperhake

The Nobel-Prize winning detection of a gravitational-wave (GW) signal by LIGO in 2015 marks the dawn of a new era in observational astronomy. One of the most exciting prospects of GW observations is the direct access to some of the most extreme regions of the Universe: the merger or formation of black holes and neutron stars. This offers unprecedented opportunities to probe strong-gravity regions for signatures of new physics.

Einstein's theory of general relativity (GR) is an incredibly successful theory that has passed numerous tests and, together with the standard model of particle physics, forms the basis of modern theoretical physics. Notwithstanding this success, the enigmatic nature of dark matter and dark energy, required to reconcile cosmological and astrophysical observations with theoretical models, as well as the incompatibility of GR with quantum mechanics indicate that ultimately a modified theory of gravity will be required.

Up to 2015, tests of GR have largely been restricted to the regime of weak gravity, including the classic tests of measuring Mercury's perihelion precession, the deflection of light by the Sun and, more recently, the orbital motion of pulsars in binary systems. GWs, on the other hand, provide us with pristine information about the spacetime geometry in the neighbourhood of compact objects. The ground-based LIGO and Virgo detectors have so far observed close to 100 GW events, which have been used to search for possible deviations from the behaviour expected according to GR. These searches, however, are limited by our incomplete understanding of what types of deviations we need to search for. For future tests, it is imperative to predict theoretically "smoking-gun signatures" that will arise from modifications of GR.

One of the most dramatic signatures of this type arises from the *spontaneous scalarization* of compact objects, first discovered by Damour and Esposito-Farese in 1993 for neutron stars in scalar-tensor gravity. Here, GR is augmented by a single scalar field that results in a second branch of stationary neutron star models: besides the branch familiar from GR, there also exist strongly scalarized stars that are often energetically favoured over their GR counterparts. This has major consequences for the dynamics of neutron star binaries and for the GW emission from supernova core collapse. The spontaneous scalarization phenomenon has enabled us severely to constrain the parameter space for *massless* scalar-tensor gravity, but these constraints do not apply to theories involving a scalar field with *non-zero* mass. Motivated by this realization, we and our collaborators have started to investigate the GW emission of core-collapse events in *massive scalar-tensor gravity*.

Our work has uncovered highly characteristic features in the GW signal that we would expect to see in this theory, a long-lasting *inverse chirp*. This remarkable phenomenon can be understood in terms of the dispersive character of the wave propagation of massive fields. A star at the end of its nuclear burning life will gravitationally collapse into a neutron star or black hole. As the central region of the star reaches nuclear density, it rapidly evolves into the energetically favoured strongly scalarized configuration, leading to a sudden jump in the scalar field. This phase transition sources the emission of scalar GWs, known as the GW *breathing mode*. This signal consists of a wide spectrum of Fourier modes, each of them propagating with its own group velocity. Crucially, this group velocity is the same for all modes *if* the scalar field is massless, and the signal will travel across space unaltered in shape. For a massive scalar field, however, the group velocity is frequency dependent – the higher the frequency, the faster the mode travels and modes below a threshold set by the scalar mass do not propagate at all. An observer at large distance from the source would therefore observe at any given moment in time only one mode, namely that which has exactly the group velocity corresponding to the distance from the source and the elapsed time interval. Some time later, another mode with lower group velocity and frequency arrives and so on.

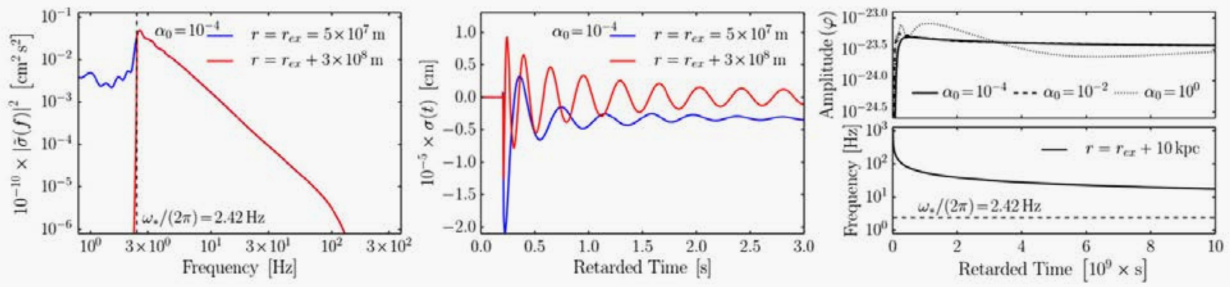


Fig. 1: Illustration of the dispersive effect of the propagation of a massive scalar field.

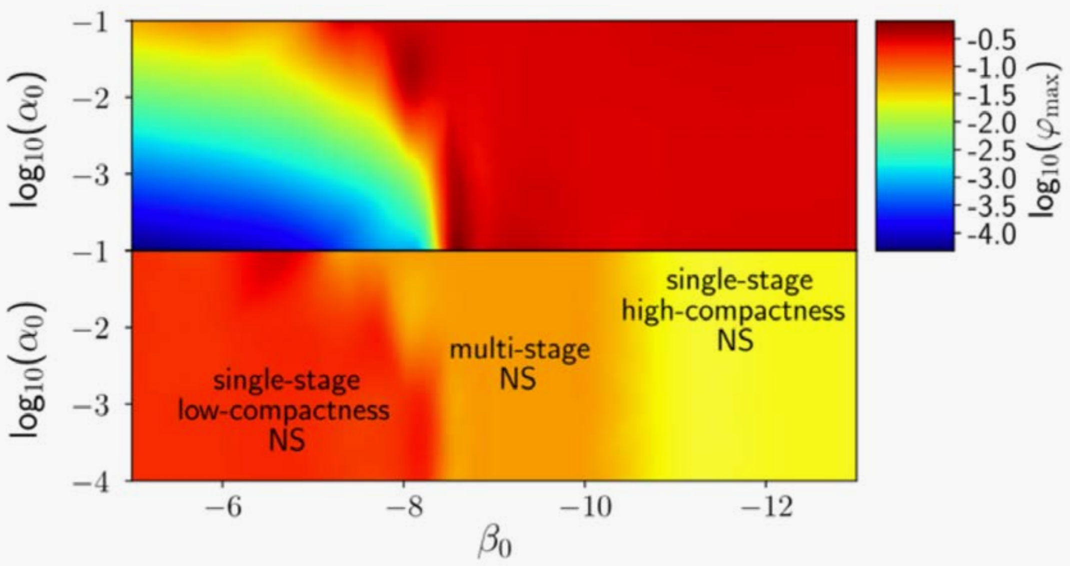
Testing Massive Scalar-Tensor Gravity With Gravitational-Wave Observations - continued

We illustrate this feature for a (fictitious) supernova event at 10 kpc distance in Fig. 1, where we plot the scalar GW signal σ as a function of time as observed at two different distances, 0.17 and 1 light-seconds. As the distance increases, the signal's power spectrum drops to zero below a threshold ω_* but remains unchanged above this frequency. Viewed as a function of time, the signal becomes increasingly oscillatory with a clear pattern of decreasing frequency. A detailed mathematical analysis shows that the observed frequency decreases in time as shown in the bottom-right panel of the figure while the amplitude remains approximately constant (upper-right panel). Remarkably, this "inverse chirp signal" can last for years or even centuries. As the sensitivity of ground-based GW detectors increases, searches for these quasi-monochromatic GW signals will enable us to constrain or, possibly, identify massive scalar-tensor gravity.

Furthermore, we have found that the corresponding core-collapse scenarios can be classified into five main scenarios, the formation of a black or a neutron star of high or low density in one or multiple collapse stages. This is illustrated in Fig. 2, where we colour-code the five scenarios (bottom) together with the resulting GW strength (upper panels). This classification enables us to compute in ongoing work the stochastic background signal that would result from the astrophysical population of supernova events in our cosmological neighbourhood.

Over the last few years, spontaneous scalarization has been identified as a very common feature in many types of modified theories of gravity. While our work has been performed for scalar-tensor gravity, the main effects, including the impact of the mass term, will hold in a similar way for this wide range of theories that we will thus be able to test observationally with the same degree of precision.

Parts of this work were published as *Rosca-Mead R. et al.*, PRD 102, 044010 (2020) and *Sperhake U. et al.*, PRL 119, 201103 (2017).



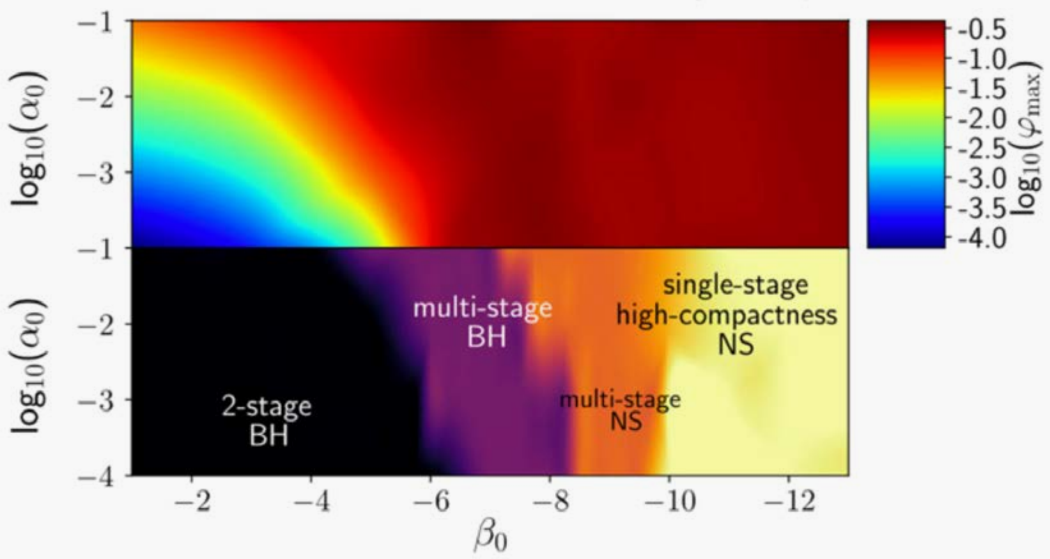
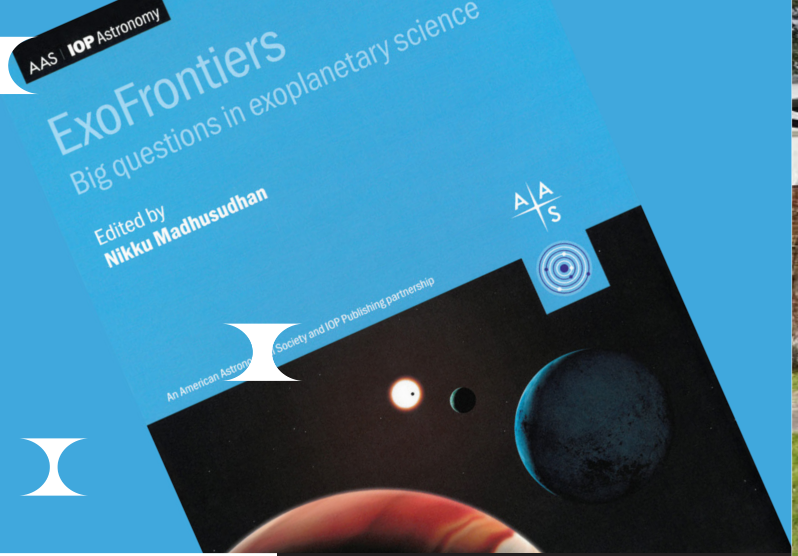


Fig. 2: (Pgs, 43 & 44) Classification of the core-collapse scenarios in scalar-tensor gravity (bottom) and the corresponding GW strength (upper panels). The left scenario applies to low-mass progenitors that cannot form black holes and the right applies to progenitor stars with high mass.

EXOPLANETS

Exoplanet-Related Activities At KICC

Nikku Madhusudhan, Annelies Mortier,
Mathias Nowak & Paul Rimmer



Cover of Exofrontiers: IOP ebooks


Group picture during the hybrid IPLU Science Day on 7 February 2022.

The exoplanet community at the University of Cambridge is one of the largest collections of exoplanet researchers in the world. As a result, a variety of exoplanet-related activities are held, bringing together researchers from across the University to discuss work related to exoplanets and, by extension, to planetary science and life in the Universe.

The Kavli Institute hosts the weekly exoplanet seminar, organised by Annelies Mortier (KICC and Department of Physics), Mathias Nowak (KICC and IoA) and Paul Rimmer (Department of Earth Sciences and Department of Physics). These seminars have been running in hybrid mode since September 2021, allowing a variety of speakers from across the world and a larger range of audience members. We cover topics across the full exoplanet field, going from detection over atmosphere characterisation to formation, debris discs, and the Solar System. Prior to the seminars, our researchers (and in-person speakers) meet to have lunch together, helping build cohesion amongst the Cambridge Exoplanet Group.

To further strengthen our interdepartmental connections, the new Cambridge Initiative for Planetary Science and Life in the Universe (IPLU) was launched in November 2021. This Leverhulme-funded initiative brings together researchers from several Cambridge departments and Laboratories beyond those conducting astronomy research, including Earth Sciences, Chemistry, Zoology, History and Philosophy of Science, Divinity, and Molecular Biology. The Initiative aims to enable cross-disciplinary research on the origin, nature and distribution of life in the Universe. An IPLU Science Day was held on 7th February 2022, organised by the exo-seminar organisers. The focus of the event was to bring together various groups from the University working towards one common goal: understanding exoplanets and the prevalence of life in the Universe. For the entire day, researchers and postgraduate students from across the University gathered in a hybrid format to share and discuss their work.

The event featured two invited talks, chosen to represent exoplanets as well as life. Matteo Brogi (University of Warwick) discussed the progress made over recent years in exoplanet atmosphere characterization with high-resolution spectroscopy and the main challenges to be addressed in the future. Secondly, Arik Kershenbaum (Department of Zoology) talked us through evolution by natural selection and the implications for predicting the nature of life in the universe.The rest of the day saw a series of talks and posters by our local students and postdoctoral researchers covering topics as diverse as planet formation, exoplanet detection, prebiotic chemistry, beyond-Earth modelling, and protoplanetary discs architecture and evolution. The programme assured that the topics kept changing between talks, with plenty of time for breaks, which fostered dialogue between disciplines. It was a great success, with many departments associated with IPLU represented.

The launch of the IPLU also kicked off the IPLU coffee meetings. These are informal gatherings, led by Paul Rimmer, on Thursday mornings at Trinity College, to discuss the wide range of topics connected to the origins, evolution and search of life in the Universe. The attendees range from undergraduate students to faculty, spanning a wide range of disciplines, including arts and humanities, astronomy, biology, chemistry, earth science, philosophy, physics, zoology and more. Therefore, discussions are kept open and at an accessible level, with lots of basic questions encouraged. We have held several meetings, with discussions lead by Dougal Ritson and Ziwei Liu (MRC Laboratory of Molecular Biology) on metabolism and origins of life; Laura Rogers (IoA), Sean Jordan (IoA) and William Bains (MIT) on aerial biospheres; Craig Walton (Earth Sciences) on phosphorus availability on prebiotic Earth; Donna Rodgers-Lee (Trinity College Dublin) on cosmic-ray chemistry; Filip Boskovic (Physics) on protocells; and Andrew Davison (Divinity) on connections between sciences and arts and humanities on the topic of the origins and search for life in the universe. Several new contacts have been made, and a couple of nascent collaborations have started at these meetings. They will continue, and new attendees with diverse points of view are always welcome to join in the conversation.

Finally, 2021 also saw the publication of the book "ExoFrontiers – Big Questions in Exoplanetary Science", edited by Nikku Madhusudhan (IoA) and published jointly by the American Astronomical Society and Institute of Physics Publishing. The book was motivated by the Kavli ExoFrontiers Symposium series at Cambridge that were held in 2016, 2017 and 2019 at the Kavli Institute and chaired by Madhusudhan. The book is a compendium of key scientific questions, challenges, and opportunities across different areas of the field of exoplanetary science, which is a major frontier of modern astronomy. Each chapter contains a short exposition in a specific area from the perspective of one or more leading experts in the area. The book aims to be a starting point for researchers, non-experts and experts alike, to obtain a quick overview of the forefront of exoplanetary science and a vision for the future of the field. The topics span the entire range from observational techniques, including various exoplanet detection and characterisation methods and state-of-the-art and future missions, to exoplanet theory and modelling including planet formation, planetary interiors, atmospheres, habitability and the search for life.

EXOPLANETS

Towards Detecting The Smallest Exoplanets With Reliable Radial-Velocity Measurements

Florian Lienhard & Annelies Mortier


Fig. 1: The Telescopio Nazionale Galileo at La Palma where HARPS-N is installed.

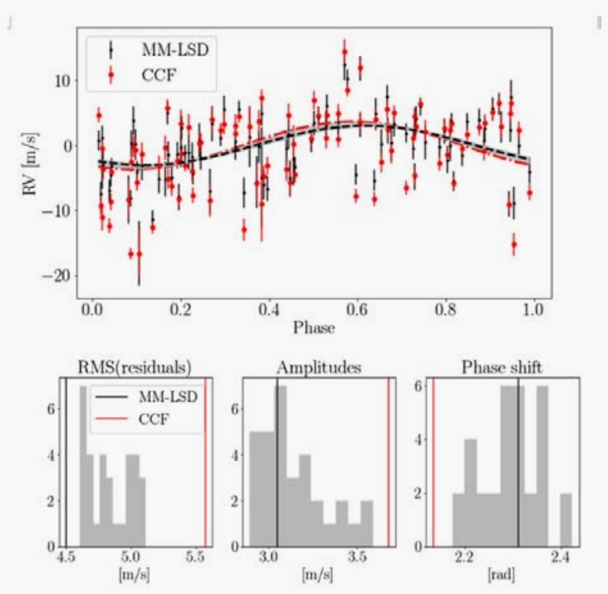


Fig. 2: Comparison of CCF and MM-LSD RVs (top) and fitted parameters (bottom) of known planet host Kepler-21. The grey histogram represents the results of each individual MM-LSD RV time series.

Less than 30 years ago, in 1995, the very first exoplanet orbiting a Solar-type star was found by Nobel Laureates Michel Mayor and Didier Queloz. This detection was made possible via the radial-velocity technique. A star's velocity measured along the line-of-sight (i.e., the radial velocity – RV) will periodically change over time due to the gravitational pull of an orbiting exoplanet on its host star. By monitoring a star's radial velocity over time, we can thus infer the presence of an exoplanet and measure its orbital period and eccentricity as well as its mass.

The changes in RV are mainly dependent on the mass of the planet as well as the host star and on the distance of the planet to the star. For reference, the detection of the first exoplanet, which was a hot Jupiter, had a semi-amplitude of about 50 $m\ s^{-1}$ while our own Jupiter in the Solar System exerts an effect of only 12 $m\ s^{-1}$ on the Sun. By going to smaller planets, the effect reduces, and our Earth has an effect on the Sun of only 9 $cm\ s^{-1}$.

RVs can be measured through the star's spectrum. Stellar absorption lines will be shifted from the rest-frame by the RV following the Doppler effect. Current high-resolution, high-stability spectrographs (such as HARPS-N in La Palma – see Fig.1) can resolve spectral lines very well and keep the wavelengths stable below the ms^{-1} level. However, spectral lines still have widths of about 7 $km\ s^{-1}$, where most of this broadening is due to the star itself rather than our instruments. Extracting RVs at the ms^{-1} precision level (or below), necessary for small planet detection and characterisation, is thus a very challenging task.

To accomplish this, advanced techniques are used to combine all the spectral lines across the optical wavelength range to form an average line profile from which a more precise RV can be measured. One historically used technique is the cross-correlation technique where the spectrum is correlated with a binary mask that was experimentally created from a series of high-signal-to-noise spectra. The resulting cross-correlation function (CCF) is then fitted with a Gaussian function to extract the RV.

Recently, we developed a more accurate technique based on least-squares deconvolution (LSD). The main breakthrough of this technique is the usage of a variety of different line masks rather than one fixed binary mask. This allows us to explore the multidimensional parameter space of key parameters that influence the final profile shape and extracted RV. Three parameters control the inclusion and exclusion of wavelengths, such as those contaminated by our own atmospheric absorption lines, those from very deep to saturated lines, and those from regions where the model fit deviates too much from the observation. Finally, the width of the final profile can be varied, influencing how we extract information from the wings of the absorption lines. We found that there is no single optimal parameter combination and so we extract RVs from many profiles across a multi-dimensional parameter grid. Our new technique is thus appropriately called the Multi-Mask LSD technique (MM-LSD).

In contrast with the CCF technique, our original line masks are theoretical and extracted from the Vienna Atomic Line Database 3, which provides spectral lines as calculated from theory and laboratory measurements. Having our line masks physics-based and star-specific further improves the model fits and results in near-perfect extraction of average profiles. We have shown that MM-LSD is more accurate with, on average, 12% lower RV scatter as compared to the more standard CCF technique. When analysing known planet hosts such as Kepler-21, we found that MM-LSD not only provided much lower residuals from a better fit overall of the data, but also different planet parameters (see Fig. 2). Having these more accurate extraction techniques is thus crucial to determine better the parameters of the smallest exoplanets.

In an extension of this project, we will include the effects of magnetic fields where each spectral line is differently sensitive to magnetic flux variations. This is another advantage over the CCF technique since our line masks are physics-driven. Magnetic fields form the basis of stellar surface variability. The latter is currently the biggest hindrance in extracting the small Earth-like planetary signals from data. Hence, extracting the RVs while simultaneously accounting for the magnetic field, will improve the accuracy of the RVs and allow us to pull out these smaller planetary signals.

These results have been published as *Lienhard F. et al.*, MNRAS 513, 5328 (2022).

Outreach Activities At KICC

Since the start of 2019, we have been running the flagship project "AstroEast", designed to extend our existing outreach efforts beyond the immediate Cambridge area. We are working with schools across Norfolk, Suffolk, and Peterborough to deliver a variety of astronomy teaching sessions, workshops and science clubs.

2021 remained a challenging year for schools. A combination of national lockdowns and uncertainty surrounding face-to-face contact resulted in schools being generally unwilling to host external visitors for much of the year. Fortunately, with the easing of restrictions over the summer, we were able to restart AstroEast teaching sessions in September.

In Autumn 2021 we began a partnership with the educational charity STEMPoint East, who are helping to expand the programme by connecting us to teacher networks across East Anglia. Several new schools have joined the AstroEast program as a result. We look forward to continuing and expanding the program throughout 2022 and beyond.

Working with Local Schools

A major part of our outreach programme involves working with local schools. This mainly takes the form of the Kavli Outreach Officer, Matt Bothwell, visiting schools to deliver astronomy teaching sessions (talks and Q&A sessions, designed around the school curriculum). In addition, we also host school visits at the Kavli Institute and Institute of Astronomy, where groups receive a talk followed by a range of activities (including telescope tours, library tours and demonstrations with our on-site heliostat).

Along with our AstroEast program, visits to local Cambridge schools began to restart in the Autumn term.

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). Throughout 2021, we continued to broadcast our weekly series of public lectures on our YouTube channel, resulting in a factor of four increase in viewership (compared to the 2019 in-person season of talks). Since the start of the 2020 lockdown, our videos have been viewed by more than 200,000 people.

Outreach Activities At KICC

Communicating Astronomy To Visually Impaired People

The Kavli Institute has partnered with Cam Sight, a Cambridgeshire charity that supports people with low vision and blindness. Over the past year we have provided a mix of workshops and lectures to visually impaired children and adults. We have hosted a number of children's groups and the Kavli 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 KICC research themes (such as exoplanets 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.

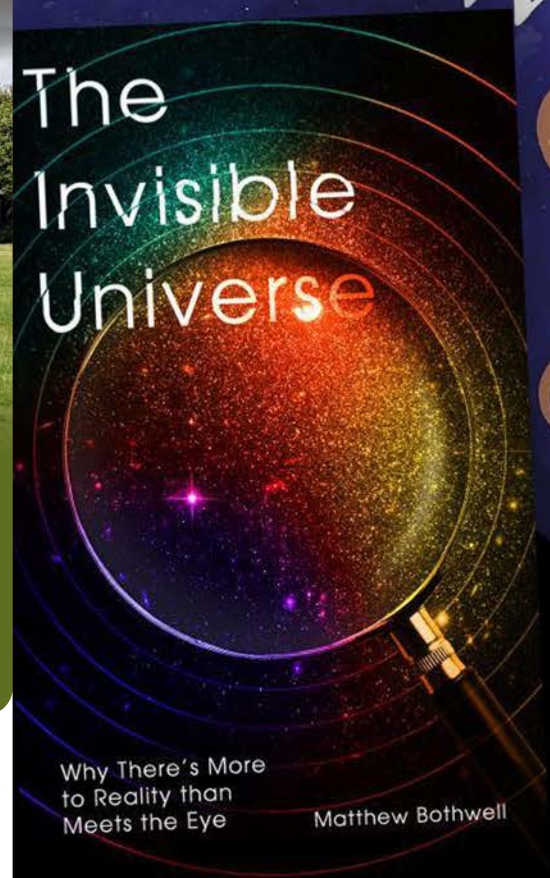
Cambridge Launchpad

The Kavli Institute (alongside the Institute of Astronomy) is a partner institution working with Cambridge LaunchPad (https://cambridge-launchpad.com/), a non-profit social enterprise that aims to inspire and enthuse young people about STEM and to address the significant gender gap that exists in STEM employment. As a Cambridge LaunchPad partner, we host groups of students aged 11–15 for single-day workshops. Partnering with Cambridge LaunchPad provides the advantage that many logistics – transport, computing, etc. – are provided by them; as such, schools with limited resources (such as for transport) face no barrier to entry. As these workshops will be 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 KICC research themes.

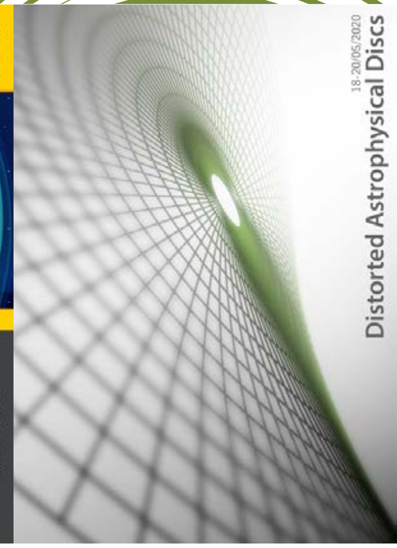
We were delighted to restart these workshops in late 2021, and will continue to run regular sessions throughout the coming year.

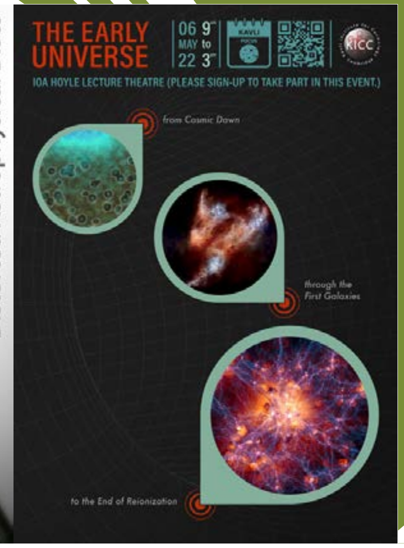
Books by KICC Members

In 2021 two members of KICC released books. Roberto Maiolino published "Stars And Waves" (2021, Clink Street Publishing), a scientific thriller set in the world of Cambridge University astronomy. Matt Bothwell published "The Invisible Universe: Why There's More to Reality than Meets the Eye" (2021, Oneworld Publications), a popular science book covering modern multi-wavelength astronomy.



KICC Workshops And Kavli Lectures





On 5th January 2021, a second major UK lockdown once again prevented in-person events at the Kavli Institute. Workshop organisers were therefore invited to review their plans and decide whether to postpone further or hold an online event instead.

The organisers of two of our scheduled workshops, “Charting the metallicity evolution history of the Universe” and “The Epoch of Galaxy Quenching”, opted to wait for an in-person meeting to become possible in 2022.

However, the local organising committee for the “Distorted Astrophysical Discs” workshop decided to make the event virtual, holding it online from 17–20 May 2021. As everything had originally been set up and ready to go for an in-person workshop in 2020, the workshop was effectively organised twice, the second time requiring everyone to “learn the ropes” in many respects for an online event.

Lead organiser Roman Rafikov reported it to be a very successful event hosting over 220 participants (thanks to its online nature), compared to the original plan of approximately 50, and at minimal cost. It brought together experts working in very diverse areas, from tidal-disruption events and supermassive black holes to protoplanetary and debris discs and planetary rings. Over four days there were 35 talks, 27 poster displays, and three very active discussion sessions on various hot topics.

It was a lively forum with researchers from different fields learning from each other and sharing their experience. This was facilitated by the use of Slack and a virtual Kavli social space using Wonder Room (in addition to Zoom), which enabled active interaction between the participants. Positive post-event comments and feedback confirmed it to be a successful Kavli workshop that helped raise the profile and international recognition of the Kavli Institute.

The Kavli Institute reopened on 5th May 2021. However, with limits on room occupancy and mask restrictions still in place, large-scale onsite events remained unfeasible.

Recognising the need to reboot in-person activities, many Kavli Fellows provided a series of talks on the morning of Thursday, 30 September. Billed as the “Kavli Fellows’ Science Day”, the weather was kind and those attending in-person were able to collaborate and socialise outside in the marquees in the grounds.

This enjoyable and informative event brought everyone up to speed on many of the exciting developments led by the Kavli Fellows over the past 18 months. It also provided an opportunity to celebrate Roberto Maiolino’s very successful term as Director of the Kavli Institute.

The talks were given in-person in the Hoyle Lecture Theatre at the IoA and live-streamed to the Ryle Meeting Room in the Kavli Building or for viewing from office or home.

Kavli Lectures this year again proved hugely popular and were provided by Jo Dunkley (Princeton) who presented on the “The Millimetre Sky from the Atacama Cosmology Telescope” and Roger Blandford (Stanford) on “Electromagnetic Surges”.

Jo’s lecture in May 2021 was still held remotely. However, we were delighted that with some return to normality in October, Roger was able to give his lecture in-person.

Continuing in the spirit of promoting in-person scientific activities at KICC, 2021 also saw the launch of “Kavli Science Focus Meetings”. We intend to hold one or two of these informal events each term, cycling through some of the science themes of the Kavli Institute, with interdisciplinary and cross-theme meetings also encouraged. The meetings are centred around a set of talks, with good representation from our students, postdoctoral researchers and fellows with the main aim of promoting discussion. Some external contributors are also welcomed.

The first of these Kavli Science Focus Meetings, “Feedback in and around galaxies” was held on 7th December 2021. It was split into two sessions, “Galaxy feedback and formation processes” and “Galaxy outflows and their connection with galaxy haloes”, which were followed by guided discussion, lunch and further informal discussion.

Kavli Fellows

Michalis Agathos

I am a Kavli Senior Fellow in Gravitational Waves at KICC and DAMTP. My research interests lie in gravitational physics, at the intersection between theory and experiment. I spend most of my time exploring the gravitational-wave phenomenology of neutron stars and black holes in General Relativity and alternative theories of gravity, developing methods for probing the nature of gravity and matter with gravitational-wave signals and applying them on real events detected by LIGO-Virgo.

After a PhD on gravitational waves at Nikhef Amsterdam, I spent two years as a Rubicon Fellow at DAMTP, Cambridge, then continued at TPI Jena for a year before returning to Cambridge as a Kavli Fellow in 2019. I have been a member of the LIGO-Virgo Collaboration since 2011, currently leading the working group on tests of General Relativity. Despite the hardships brought about by the pandemic, I am happy to see the gravitational-waves effort at Cambridge growing stronger and attracting young, talented researchers. Our group recently joined the scientific consortium for the Einstein Telescope with myself as the Cambridge PI.

Suhail Dhawan

I am a Newton–Kavli and Marie-Curie Fellow at KICC and the IoA. My main research interests are in cosmology and astrophysics with explosive transient phenomena. I have worked on measuring the Hubble constant with the local distance ladder calibrating the Type Ia supernova luminosity, most recently using the tip-of-the-red-giant-branch method, with the aim of extending the distance ladder to larger distances with NIRCam on JWST. I have been working on lensed supernovae, devising methods to infer time delays for the lensed SN Ia discovered and designing the search strategy for the Zwicky Transient Facility and LSST in the future. I have used the SNe Ia Hubble diagram to study line-of-sight effects like dust extinction and lensing to measure the amount of dark matter in compact objects. Previously, I have worked on dark energy inference with Bayesian model-selection techniques and am working on advanced astrostatistics methods for improving SN Ia distances.

Alexandra Amon

I am a Kavli Senior Fellow at KICC and IoA. My research focuses on cosmology and our understanding of the “dark” Universe, primarily using the tool of weak gravitational lensing. At present, I coordinate the lensing team for the Dark Energy Survey – a large international collaboration. At Cambridge, my focus is on combining lensing with other observables to understand better the impact of galaxy formation on our cosmological analyses. After growing up in Trinidad and Tobago, I studied at the University of Edinburgh, and my thesis working on the Kilo-Degree Survey was awarded the Royal Astronomical Society Michael Penston Thesis Prize. I moved to Stanford University as a Kavli Fellow at KIPAC. I’m grateful that my work there was recognised with the Tollestrup Award and the UK’s Caroline Herschel Lectureship. I enjoy devoting time to science communication and have featured in New Scientist, on Al Jazerra’s The Stream and on PBS “Ancient Skies”.

Mathias Nowak

After completing my PhD at the Paris Observatory in 2019, I joined the KICC and IoA as the first Gavin-Boyle Fellow in Exoplanet Science. My work here is centred on the observation and characterization of young, giant planets with the GRAVITY instrument on ESO’s Very Large Telescope Interferometer. I was directly involved in the very first interferometric detections of exoplanets, and I successfully obtained the first direct confirmation of a radial velocity planet by using GRAVITY to observe the recently detected beta Pictoris c. GRAVITY has proven to be an extremely powerful instrument to characterise young giant planets, and I am also involved in preparing its upgraded version with the GRAVITY+ consortium. Beyond my work with GRAVITY, I am also developing algorithms to improve the performance of direct-imaging instruments, and to allow for the detection of fainter planets.

Kavli Fellows

Matthew Auger

I have been a Kavli Senior Fellow since 2018, and prior to that I was an STFC Ernest-Rutherford Fellow at the IoA. I obtained my Ph.D. at UC Davis and followed this with a three-year postdoc at UCSB before leaving California and spending two years as a Postdoctoral Research Assistant at the IoA. I work with observational data -- often of galaxy-scale strong gravitational lenses -- to understand the structure and evolution of galaxies in the Universe. This includes trying to disentangle dark and luminous matter in massive galaxies as well as exploiting magnified views of objects at high redshifts to study star formation and the relationship between supermassive black holes and the galaxies in which they reside. I also work on developing new probes (primarily involving strong gravitational lenses) of the expansion history of the universe and therefore the dark energy that is driving the current accelerated expansion.

Steven Gratton

I am a theoretical cosmologist and have been a Kavli Senior Fellow at KICC and IoA since 2018. I did my PhD in Quantum Cosmology at the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge from 1997–2000. For the past 15 years, I have worked with colleagues in Cambridge analysing data from the Planck satellite to learn about the Universe. By looking at properties of the detailed pattern of cosmic microwave background fluctuations that Planck measured precisely, the Planck team were able to refine the standard ΛCDM cosmological model and rule out many extensions and alternatives. I am currently thinking about the implications of Planck's findings for inflationary models of the early Universe and am developing new general mathematical methods for accurately and efficiently comparing theories with data.

Vid Irsic

I am a Senior Kavli Fellow at the KICC and Department of Physics. I was born and raised in Ljubljana, Slovenia, where I pursued undergraduate and graduate studies at the University of Ljubljana, for which I received a B.S. in Physics in 2010 and a Ph.D. in Physics in 2013. From there, I took postdoctoral positions at the International Centre for Theoretical Physics in Trieste, and the University of Washington in Seattle. My research interests are in the fields of observational and theoretical astrophysics and cosmology. I am particularly interested in the epoch of reionization and numerical simulations and large observational survey data.

Nicolas Laporte

I am a Kavli Senior Fellow at the KICC and the Department of Physics. My main research interest is focused on understanding the formation and evolution of the first generation of stars and galaxies. As an observer, I am using data from the JWST, Hubble, ALMA, the VLT, Keck and the GTC. I am particularly interested in the role of AGN in the reionisation of the Universe and in constraining Cosmic Dawn, the period when the first galaxies were formed a few million years after the Big-Bang.

Zvonimir Vlah

I obtained my PhD in theoretical physics at the University of Zürich in Switzerland in 2014, after which I was a Research Fellow at the KIPAC at SLAC and Stanford University. In 2017, I became a Fellow in the Theory group at CERN in Genéva. Since 2020, I have held a Kavli Senior Fellowship at the KICC and Department of Applied Mathematics and Theoretical Physics; in 2021 I additionally became a Research Associate at IRB in Zagreb. I work primarily in the field of cosmology and galaxy clustering, with broad interests ranging from topics in theoretical physics to observational astrophysics. I am an expert in the formation of the structure of the Universe on large cosmological scales. My work consists mainly of cutting-edge analytic modelling and calculations in cosmological structure formation using field-theory methods.

Kavli Fellows

Sunny Vagnozzi

I am a Newton–Kavli Fellow at KICC and the IoA. I am a cosmologist and astroparticle physicist, and the goal of my research, broadly speaking, is to test fundamental physics using data collected from all corners of the (dark) Universe, and vice-versa to construct viable data-driven models of the Universe. Some of my most recent interests here at KICC include, but are not limited to, novel Earth-based searches of dark energy, using black hole shadows to test fundamental physics (including the existence of new ultralight particles), and model-agnostic tests of “new physics” beyond the ΛCDM model, but I am always on the lookout for new interesting ideas. I am originally from Italy and before moving to KICC I studied at the University of Trento for my Bachelor’s degree, at the University of Melbourne for my Master’s, and obtained my Ph.D. in theoretical physics at Stockholm University in 2019. At the end of 2022 I will be leaving KICC and returning to the University of Trento as a tenure-track Assistant Professor.

Hannah Ubler

I joined KICC and the IoA in May 2021 as a Newton–Kavli Fellow after a postdoc and Ph.D. at the MPE in Garching, Germany. I studied physics and philosophy in Munich, just a two-hour drive from my hometown, Forchheim in Upper Franconia. My observational work centres on kinematic studies and dynamical modelling of star-forming galaxies in the early Universe. With JWST we can now extend rest-frame optical studies previously limited to redshift $z = 3$ out to $z = 7$. This allows us to study the dynamics and physical conditions in galaxies less than 1 Gyr after the Big Bang, greatly advancing our understanding of galaxy evolution. I am thrilled to work on this with the NIRSpec GTO team, including many of my colleagues here at KICC.

Annelies Mortier

Originally from Belgium, I did my Ph.D. at the University of Porto in Portugal, under the supervision of Dr Nuno Santos, working on planet frequency as a function of stellar metallicity and the reliable measurement of stellar parameters for exoplanet hosts. I did a postdoc with Prof. Andrew Collier Cameron at the University of St Andrews getting more involved with exoplanet mass characterisation and the issue of stellar and Solar variability. Since 2018, I have been a Kavli Senior Fellow in Exoplanets at KICC and the Department of Physics but will become an Assistant Professor at the University of Birmingham in July 2022. As part of the HARPS-N and HARPS3 Science teams, I work on several projects related to exoplanets and their host stars, determining stellar parameters and chemical abundances, battling and understanding stellar activity, characterising planets via radial velocities, and studying the Sun-as-a-star. I love to play with the stars and go and observe them in Chile or La Palma.

Oliver Friedrich

I have spent three inspiring and delightful (except for the pandemic!) years as a Newton–Kavli Fellow at the KICC. Coming from a data-oriented branch of cosmology, the KICC’s synergistic approach to theory and observations helped me gain a better understanding of the open, foundational tasks of cosmology. As a result I focussed my research on questions that concern different manifestations of probability in cosmology: How do we accurately characterise uncertainties arising from cosmological data analyses? Which probability distribution describes the properties of today’s cosmic density field? And how does all of this connect to the quantum probabilities of the initial cosmic density fluctuations? I moved to the Munich University Observatory at the end of 2021 as a Karl-Schwarzschild Fellow, but am keeping close ties to Cambridge, particularly through my involvement in the coordination of the Cambridge-LMU Strategic Partnership.

Graduating Students

Many congratulations to the following graduate students at KICC who defended their Ph.D. theses in 2021.

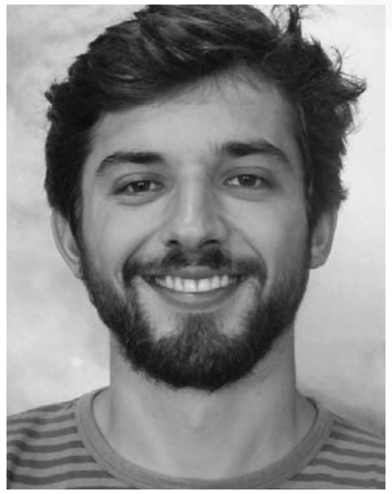
Fruzsina Agocs

Thesis title
Theoretical and computational methods or the evolution of primordial perturbations

Supervisors
Anthony Lasenby, Mike Hobson and Will Handley

Current position
Research Fellow at the Center for Computational Mathematics, Flatiron Institute, New York

https://fruzsinaagocs.github.io



Anton Baleato Lizancos

Thesis title
Polishing the lenses: refined modelling of lensing and delensing of the cosmic microwave background

Supervisors
Anthony Challinor and Blake Sherwin

Current position
BCCP Fellow at UC Berkeley and LBNL

https://abaleato.github.io/

Sim Brownson

Thesis title
Constraining the quenching mechanisms in galaxies

Supervisors
Roberto Maiolino

Current position
Associate Consultant at OC&C Strategy Consultants, London

William Barker

Thesis title
Gauge theories of gravity

Supervisors
Anthony Lasenby, Mike Hobson and Will Handley

Current position
Rosamund Chambers Junior Research Fellow in Astrophysics at Girton College, Cambridge

https://wevbarker.com

Lukas Hergt

Thesis title
Constraining the kinetically dominated Universe: Bayesian methods and primordial cosmology

Supervisors
Anthony Lasenby, Mike Hobson and Will Handley

Current position
Killam Postdoctoral Research Fellowship at UBC, Vancouver

https://phas.ubc.ca/users/lukas-hergt

Sophie Koudmani

Thesis title
Black Hole Feedback in New Regimes: Modelling Dwarf Galaxies with Active Galactic Nuclei

Supervisors
Debora Sijacki

Current position
Junior Research Fellow at St Catherine's College, Cambridge and Flatiron Research Fellow, CCA, New York

https://www.ast.cam.ac.uk/people/sophie.koudmani

Awards & Honours

Eloy de Lera Acedo (KICC and Department of Physics) has been awarded a prestigious STFC Ernest-Rutherford Fellowship to work on the project “Probing the Cosmic Dawn and the Epoch of Reionization with REACH”. Eloy leads the REACH international collaboration and experiment, which is aiming to measure the 21-cm radio signal from interaction of the cosmic microwave background with neutral hydrogen around the time the very first stars were born (see the dedicated article elsewhere in this report).

The Ernest-Rutherford Fellowships are awarded annually to around 10 promising researchers “with clear leadership potential to establish a strong, independent research programme” from all around the world to work in UK universities. The five-year Fellowships cover all of astronomy, Solar and planetary science, particle physics, particle astrophysics, cosmology, nuclear physics and accelerator science.

Sunny Vagnozzi (Newton–Kavli Fellow at KICC and IoA) has been awarded the “Alfredo di Braccio” Prize by the Accademia Nazionale dei Lincei (Lincean Academy) for “important contributions at the intersection of Cosmology, Astrophysics, and Particle Physics”.

Mathias Nowak (Gavin-Boyle Fellow in Exoplanet Science at KICC and IoA) has been awarded the 2021 Olivier Chesneau Prize for his doctoral work entitled “The 2017 conjunction of Beta Pictoris b: the Life and Death of PicSat, followed by a VLTI/GRAVITY observation of the re-emergence”. Dr Nowak conducted his doctoral research at the Observatoire de Paris. Undismayed by the loss of the PicSat satellite, which was to be the centrepiece of his planned doctoral work, Mathias started to work on the then newly commissioned GRAVITY instrument at the focus of ESO’s Very Large Telescope Interferometer. He rapidly made important technical contributions that led to improvements in the astrometric capability of GRAVITY and also joined the instrument’s exoplanet programme, where his data-processing skills contributed to the first GRAVITY observation of the exoplanet HR 8799e. The highlight of Mathias’s thesis work was the production of the first very high-quality spectrum of Beta Pictoris b, and ultimately, the first direct detection of Beta Pictoris c, a planet that had only been indirectly detected by the radial velocity technique. Overall, this work has had a major technical and scientific impact in both the interferometry and the exoplanet communities.

The Olivier Chesneau prize is awarded every two years to a Ph.D. student in the field of high-angular-resolution astronomy.

Awards & Honours

Ayngaran Thavanesan, a Ph.D. student at KICC has been awarded a prestigious grant from the Bell Burnell Graduate Scholarship Fund of the Institute of Physics. This is to enable Ayngaran to conduct his doctoral research in theoretical cosmology, studying the wavefunction of the Universe and cosmological correlators with supervisors. He is working with David Stefanyszyn and KICC members including Enrico Pajer, Anne Davis, Anthony Lasenby and Will Handley.

William Barker has been appointed as the Rosamund Chambers Research Fellow in Astrophysics at Girton College, Cambridge to work at KICC on theoretical cosmology. Will was also awarded the Abdus Salam Prize in Theoretical Physics for his work during his Ph.D. on the "Systematic study of background cosmology in unitary Poincaré gauge theories with application to emergent dark radiation and Hubble tension". The Abdus Salam Prize for Postgraduate Student Research has been donated to the Department of Physics at Cambridge. It is awarded annually to recognise outstanding work by Ph.D. students in the department, on the basis of a peer-reviewed paper reporting research undertaken by the student during their Ph.D.

Sunny Vagnozzi (Newton–Kavli Fellow at KICC and IoA) and **Anne Davis** (KICC and DAMTP) and collaborators have been awarded a Buchalter 2021 Cosmology Prize for their work entitled "Direct detection of dark energy: the XENON1T excess and future prospects", published in Physical Review D. The work was recognized by the judging panel for "opening new, unforeseen vistas for the scientific scope of direct-detection dark matter experiments, exploring the tantalizing prospect for terrestrial dark matter experiments to directly detect scalar particles, associated with the dark sector, produced in the strong magnetic field of the solar interior."

The Buchalter Cosmology Prize is an annual prize that seeks to stimulate ground-breaking theoretical, observational, or experimental work in cosmology that has the potential to produce a breakthrough advance in our understanding. It was created to support the development of new theories, observations, or methods that can help illuminate the puzzle of cosmic expansion from first principles.

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.**

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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.

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