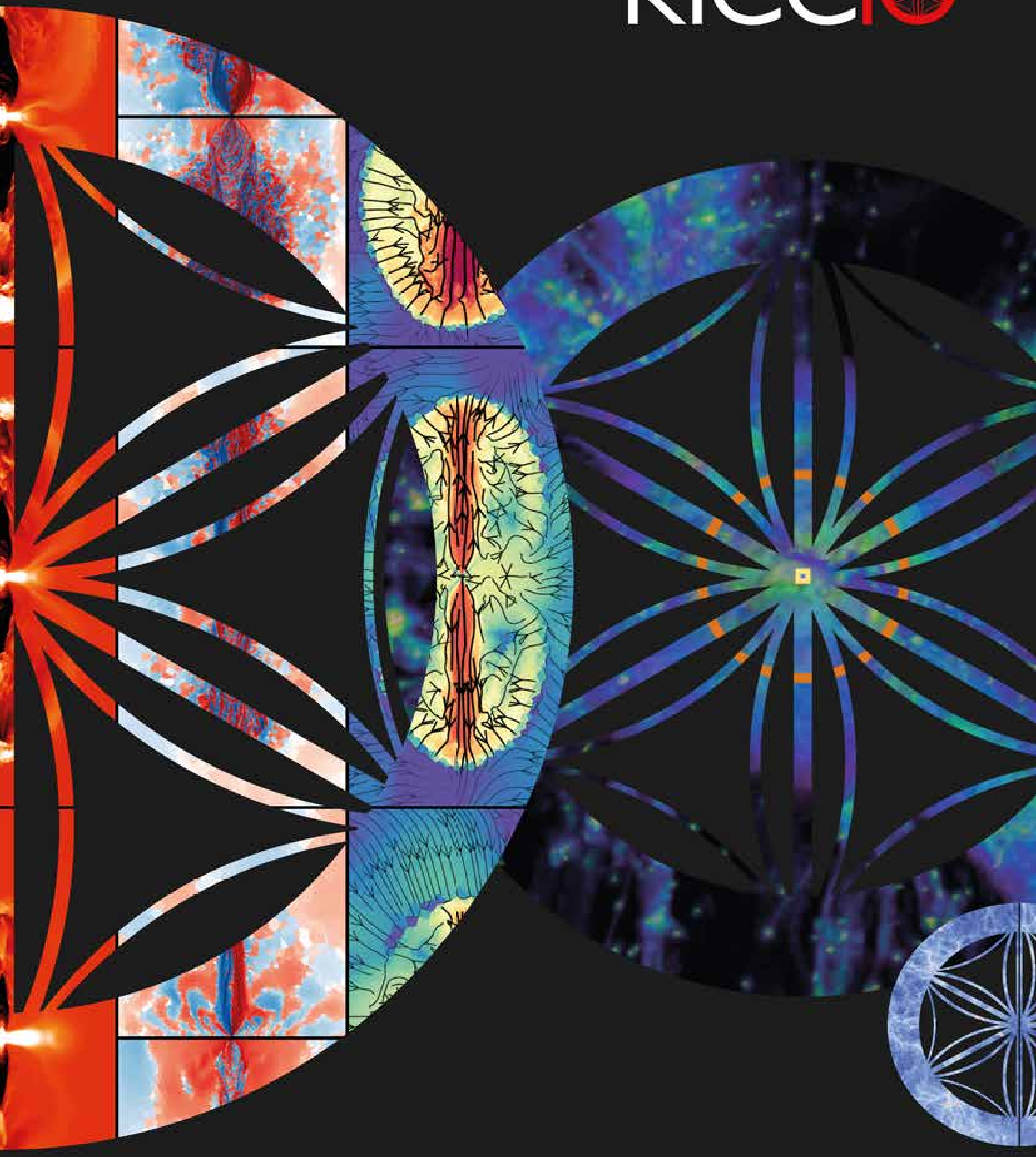
KICC10



Annual Report • 2019

Kavli Institute for Cosmology, Cambridge

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MESSAGE FROM THE DIRECTOR

Roberto Maiolino

2019 has been a special year for KICC on several fronts. Indeed, we have celebrated ten years of excellence since the opening of the institute in 2009. This has been an occasion for us to reflect on our achievements and to look with inspiration to the exciting challenges ahead of us. We were delighted that more than two hundred colleagues and authorities from all over the world joined our celebrations during events organized by KICC.

More broadly, 2019 has been a remarkable year for astronomy in Cambridge with the award of the Nobel Prize in Physics to Didier Queloz for his seminal work on exoplanets. During the last few years, KICC has expanded its scope to support this area of research and we are very glad to have supported Didier's team with our Exoplanet Fellowships, through our visitors and workshops schemes, and we are looking forward to supporting more ventures in this flourishing field.

In 2019 KICC has also further consolidated and expanded its activities in the area of gravitational wave astronomy, and in the exploration of the nature of dark matter by joining the AION project, a cutting edge programme using cold-atom interferometry to detect gravitational waves in the mid-frequency range and to search for ultra-light dark matter. Of course, KICC has continued to thrive in those research fields that have been more traditionally areas of excellence for the institute since its foundation, that is, Cosmology in its broad meaning. Our researchers have been producing a wide spectrum of fantastic results in areas ranging from the exploration of the primeval Universe to the formation and evolution of galaxies, both by using many of the major observing facilities around the world and in space and by developing some of the most detailed numerical simulations and theoretical models. In addition, activities have been ramping up in preparation for the forthcoming cutting-edge facilities and projects in which KICC is heavily involved, such as JWST, VLT-MOONS, the Simons Observatory, REACH, HARPS3, 4MOST, DESI, the next generation of cosmological numerical simulations and, in the longer term, ELT-HIRES.

In 2019 we have also greatly expanded our outreach efforts. Among a wide range of activities, we have enthused thousands of pupils about astronomy by reaching a broader range of schools in the surroundings of Cambridge through our flagship project 'Astro-East'. In collaboration with the Discovery Channel, more than thirty episodes were filmed in which KICC researchers explain the big themes of Cosmology to the general public. These will be released in 2020 on various media worldwide. We have also started the programme 'TOUCH ASTRO'; consisting in the production of tactile material of various astronomy and space subjects, by using a new dedicated 3D printer, and with the goal of making these themes accessible to visually-impaired children through visits to specific schools. Only a fraction of these research and outreach activities are illustrated in this report. Indeed, we retain the philosophy of our past reports, avoiding a lengthy list of the many activities and achievements in the past year. Rather, we simply provide a selection of a few representative highlights, particularly focusing on those led by our junior scientists. A more extensive overview of our activities and scientific results can be found at our website, **www.kicc.cam.ac.uk**.

CELEBRATING THE 10TH ANNIVERSARY OF KICC

Anthony Challinor, Debora Sijacki & Roberto Maiolino

Several events took place in 2019 to celebrate the 10th anniversary of the opening of KICC, the highlights being a celebration day in July and a major Symposium in September.

The celebration day was attended by delegates from the Kavli Foundation, the University Vice-Chancellor, Head of School, Heads of Departments and Directors of other Kavli Astrophysics Institutes, who joined over a hundred people from KICC and from the three host departments (Institute of Astronomy, Cavendish Laboratory and Department of Applied Mathematics and Theoretical Physics). It was a chance to review the past, discuss current research and look forward to the future.

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Fig 1. Vice-Chancellor Stephen Toope opens the day of celebration.
Fig 2. Kavli atrium with the gathering of the participants.
Fig 3. Public talks evening.

The Vice -Chancellor of the University of Cambridge, Professor Stephen Toope, opened the event by praising KICC as a model that highlights the benefits of collaboration not only between individuals, but also between departments and Universities. He took the opportunity to endorse the ethos of the Kavli Foundation's founder, Fred Kavli, of needing to be 'willing to fund science without knowledge of the benefits'.

George Efstathiou, founder and first Director of the Kavli Institute, and Roberto Maiolino, the current Director, gave overviews of the achievements of the institute during the first 10 years and the prospects for the future. Their presentations spanned from developments in our understanding of the early universe with cosmic microwave background (CMB) data obtained with the Planck satellite, to pioneering advances in cosmological simulations, to breakthroughs in the understanding of the evolution of galaxies and black holes, to the involvement and leadership in the next generation of cutting-edge projects, such as the James Webb Space Telescope, the MOONS spectrograph for the Very Large Telescope, the wide-scale spectroscopic surveys 4MOST, WEAVE and DESI, the Atacama Cosmology Telescope, the Simons Observatory, the Square Kilometre Array, the REACH experiment, and the HIRES spectrograph for the Extremely Large Telescope.

Students and postdoctoral researchers illustrated a broad range of achievements and exciting results in the several areas covered by KICC, from precision cosmology, to the epoch of reionization, galaxy formation, astroarcheology, gravitational waves and exoplanets. In addition, the Kavli Outreach Officer, Matt Bothwell, discussed our ongoing programmes to promote our work to a wider audience.

The Directors from other Kavli Institutes around the world illustrated their activities and shared their research interests in common with KICC, as well as their active collaborations with us and the prospects for new joint initiatives.

Rockell Hankin, Chair of the Board of Directors of the Kavli Foundation, and Kevin Moses, Vice President (Science Programs) of the Kavli Foundation, praised the achievements and success of KICC and confirmed the commitment of the Kavli Foundation to support cutting-edge scientific research. Representatives of the Kavli Foundation also visited the clean room facilities where astronomical instruments are being developed and tested.

The day was a great success, not only in celebrating 10 years of very significant achievements, but also in making everyone aware of the multiple ways the Kavli Institute supports joint research across departments in Cambridge and with institutes around the world.

The KICC 10th Anniversary Symposium in September brought together more than 150 scientists from all over the world (and we regret that we had to decline many more registrations due to the limited capacity of the theatre). It was an impressive gathering of many of the leading researchers in all areas covered by KICC. Entitled 'Cosmology: the end of the beginning. Future prospects in cosmology, large scale structure and galaxy formation' (borrowing from Winston Churchill's wartime quote), the Symposium was an opportunity to reflect on achievements and ponder open questions in these entangled areas of astrophysics. Indeed, the 10th Anniversary of KICC happens at an interesting time when observing facilities and theoretical developments have established a 'standard model' of cosmology, but also a time when big open questions remain unsolved and that will be the focus of the next decade.

As KICC has been a platform for bringing together experts from all areas of cosmology in Cambridge, the Symposium as a fantastic platform where many of the experts worldwide in these fields could jointly discuss the successes and issues of different cosmological scenarios and jointly look at the challenges in the future ahead of us.

The Symposium included a fantastic evening of public talks by three highly-distinguished astrophysicists, Roger Blandford, Martin Rees and David Spergel. They addressed some of the biggest outstanding questions in our field in front of an audience of more than 460 members of the general public.

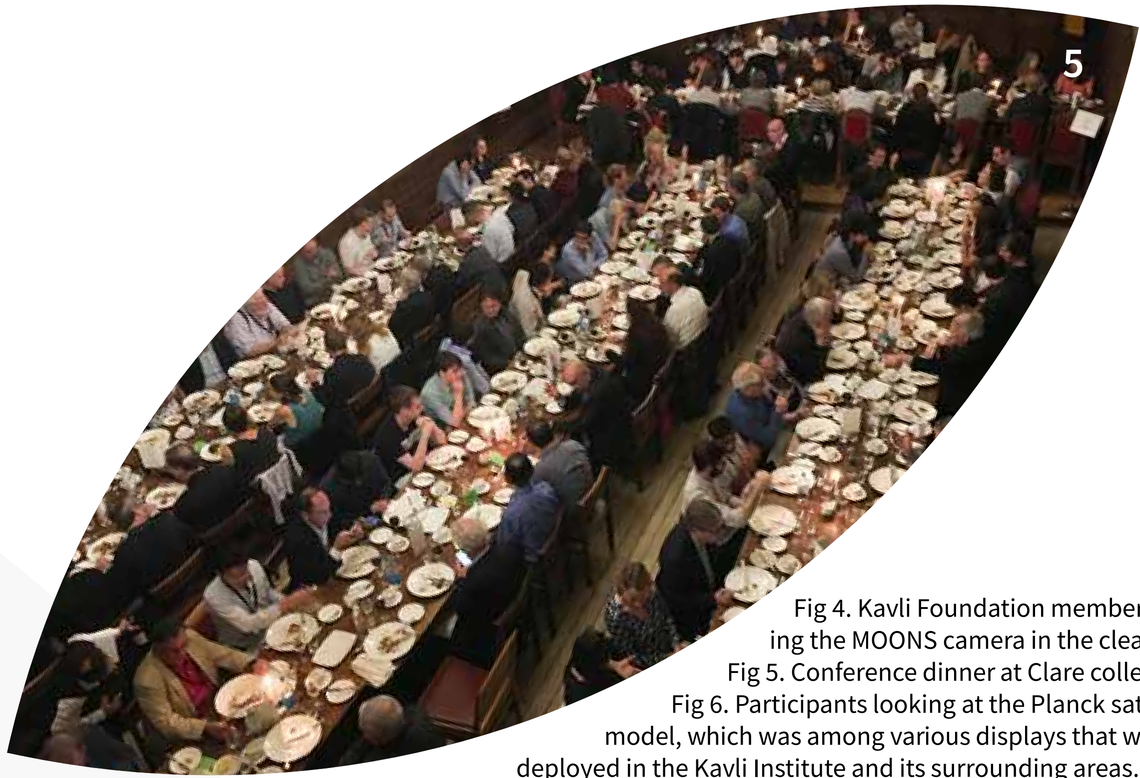


Fig 4. Kavli Foundation members viewing the MOONS camera in the clean room.
Fig 5. Conference dinner at Clare college.
Fig 6. Participants looking at the Planck satellite model, which was among various displays that were deployed in the Kavli Institute and its surrounding areas.
Fig 7. Final discussion session of the Symposium.

The Symposium was an intense week of reviews and highlight talks, with ample time for discussion and exchange of ideas. In addition, a large number of early-career researchers gave flash-talks highlighting their latest work. The Symposium was regarded by all participants as an important and memorable event. Given the strong resonance with the community, the journal Nature asked for a summary of the meeting from the chairs of the final, concluding session: Roger Blandford, Jo Dunkley, Carlos Frenk, Ofer Lahav and Alice Shapley. We believe that the following extract from the final paragraph of their Nature article summarizes well the spirit and the outcome of the Symposium:

"..., cosmology has much to celebrate right now with the definition of its robust, standard model whose birth dates back to the early 1980s. However, cosmologists must also confess their ignorance. They do not know the identity of dark matter, they cannot explain why a tiny fraction of baryons should survive the early universe, they do not understand the mechanics of inflation and they cannot account for the cosmological constant. Fortunately, as emphasized in a panel discussion at the end of the meeting, many audacious ideas are in play and complementary, new observatories should address these questions as well as advance our understanding of neutrinos and elucidate the complex interplay of stars, massive black holes and intergalactic gas in promoting and regulating galaxy formation and evolution..."

PROBING THE EPOCH OF RE-IONIZATION USING THE WIDTH OF TRANSMISSION SPIKES IN THE LYMAN-ALPHA FOREST AS A COSMIC THERMOMETER

Prakash Gaikwad & Martin Haehnelt

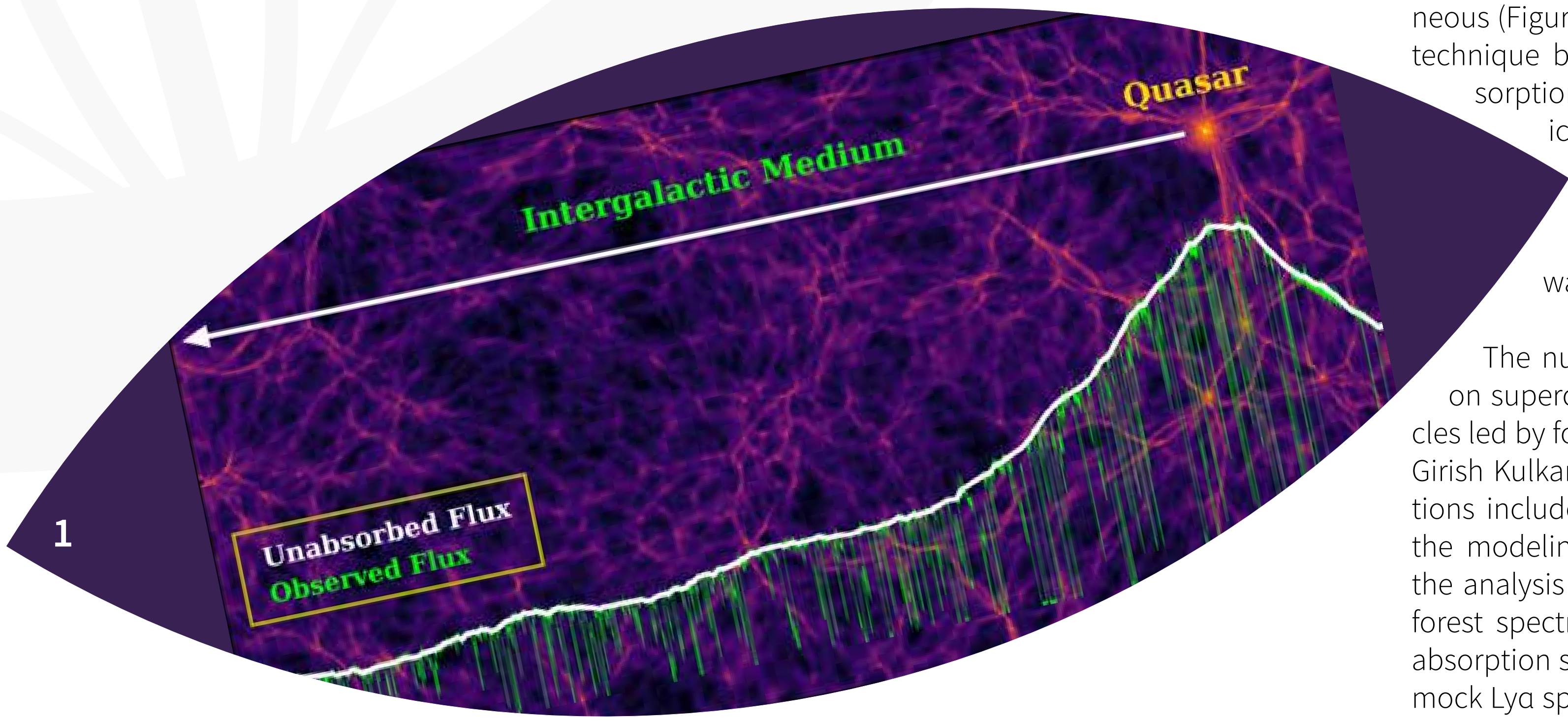
Early on the Universe was extremely hot and dense and consisted of dark matter and a soup of elementary particles tightly coupled to photons via frequent collisions. As the Universe expanded, its density and temperature dropped and collisions became less frequent. The interaction between elementary particles lead to the formation of many of the chemical elements we know. Most ordinary matter is in the form of hydrogen and helium since then. Hydrogen and helium transitioned from being ionized to neutral when the temperature of the Universe had fallen to a few thousand degree. At this stage the Universe entered the so called "dark ages", a phase that only ended when the first sources of light powered by black holes and stars in the first galaxies formed from density fluctuations growing by gravitational instability. Photons emitted by these first sources of light once more ionized hydrogen during an epoch commonly referred to as the epoch of *re-ionization*. The research described here pertains to the effect of the re-ionization of hydrogen on the thermal state of the Intergalactic Medium (IGM), the all-pervading gas between galaxies.

Hydrogen re-ionization is believed to start around redshift $z \sim 20 - 30$. In last year's annual report, KICC researchers have discussed their finding that hydrogen re-ionization likely ends later than previously thought at $z \sim 5.2 - 5.3$. Our current understanding suggests that the first generation of stars were massive, short lived and copiously emitted ultra-violet (UV) photons. The UV photons from these stars are expected to have ionized the surrounding neutral hydrogen, creating ionized bubbles around them. As time progresses, these bubbles have grown and eventually overlapped with each other to fill the entire IGM. When hydrogen is ionized by photons, the temperature of the IGM is expected to increase to ~ 10000 -15000 K as the energy of the ionizing photons is typically somewhat larger than necessary to ionize hydrogen. The temperature at locations where hydrogen becomes once more ionized is then set by the balance between atomic cooling, adiabatic cooling due to Hubble expansion and photo-heating. As a result, re-ionized regions of the Universe then gradually cool again to ~ 7000 K.

The Lyα forest, prominent absorption features in the spectra of distant quasars due to the intervening neutral hydrogen along the line of sight, is a sensitive probe of the ionization and thermal state of the IGM (Figure 1). The smoothness of the absorption features increases with increasing temperature and can therefore be used as a cosmic thermometer. Together with Carnegie Observatories astronomer Michael Rauch, we have obtained and analysed a new sample of five high redshift, high quality quasar absorption spectra obtained with the Magellan II telescope and the Keck I telescope. The Lyα opacity in quasar absorption spectra increases rapidly with redshift, with the occurrence of only few transmission spikes indicating that the re-ionization process is indeed inhomogeneous (Figure 2). The team has developed a novel technique based on comparison with mock absorption spectra from state-of-the art numerical simulations that uses the shape of the transmission spikes to measure the temperature of the IGM at $5<z<6$, i.e. at significantly earlier times than was previously possible.

The numerical simulations were performed on supercomputers with up to 16 billion particles led by former KICC researchers Laura Keating, Girish Kulkarni and Ewald Puchwein. The simulations include the physical processes relevant for the modeling of the epoch of re-ionization. For the analysis we have created 2 million mock Lyα forest spectra that closely mimick the observed absorption spectra. The overall appearance of the mock Lyα spectra in the middle and right panel of Figure 2 is indeed remarkably similar to that of the observed spectrum shown in the left panel. Comparison of the middle and the right panel demonstrates nicely how the absorption features in the mock absorption spectra from the simulations get smoother with increasing temperature.

Numerical simulations for different thermal evolutionary histories allowed our team to figure out how exactly the widths of the transmission spikes depend on the temperature of the IGM. To quantify their width we have thereby fitted the transmission spikes in the 2 million mock spectra and in the observed spectra using our automated VoIgt profile Parameter Estimation Routine (VIPER). By comparing the spike width distribution from observations with that from the mock spectra, we have then measured the average IGM temperature to be 12000 K at $z \sim 5.5$. Our results confirm the suggestion that re-ionization ends late, with islands of neutral gas still persisting at $z \sim 5.5$ and consistent with the latest results from the CMB experiment PLANCK. Our results will guide ongoing and future epoch of re-ionization experiments (SKA, LOFAR, HERA, REACH) utilising the more difficult to detect 21cm absorption/emission to probe the earlier stages of re-ionization. Our results and simulations will also inform the interpretation of studies of the nature of the sources of the ionizing photons responsible for the re-ionization of hydrogen with the space mission JWST that are planned with major involvement from KICC.



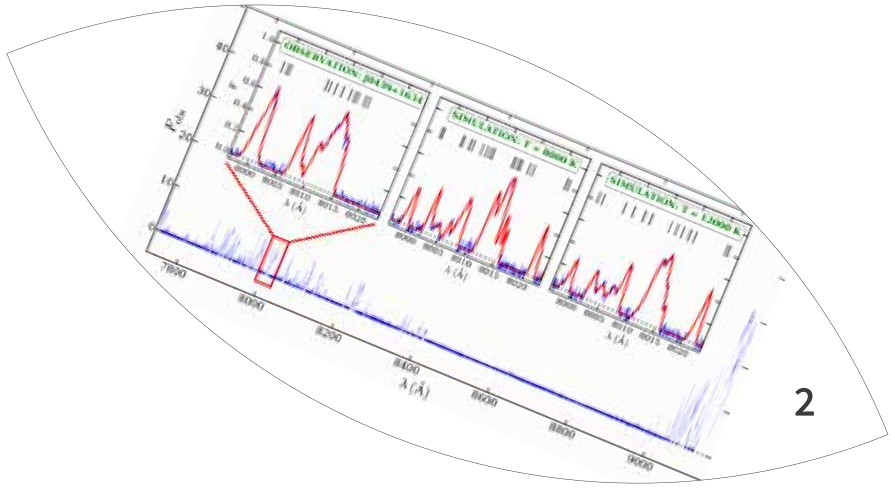
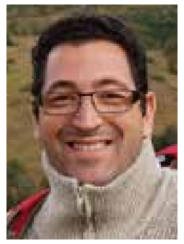
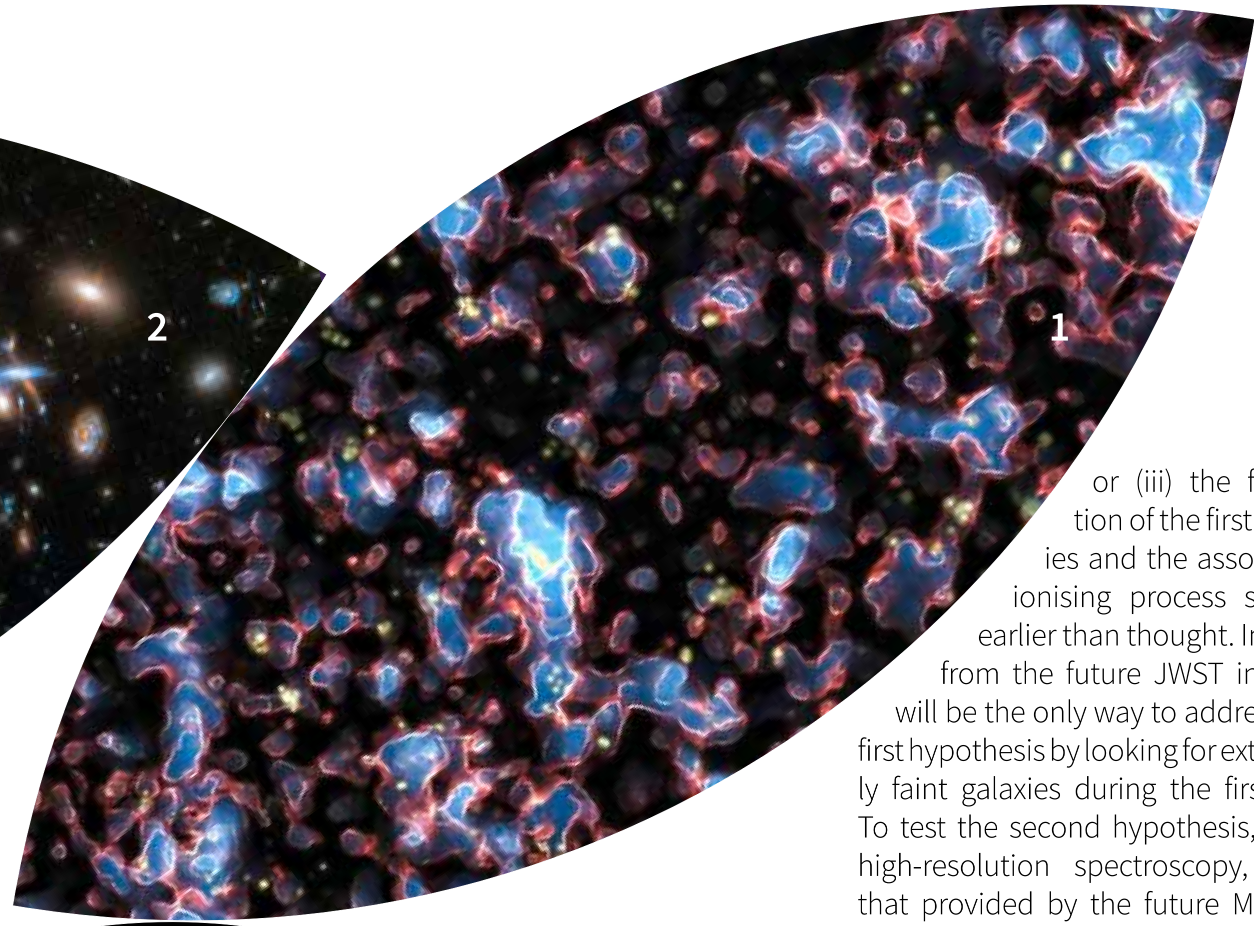


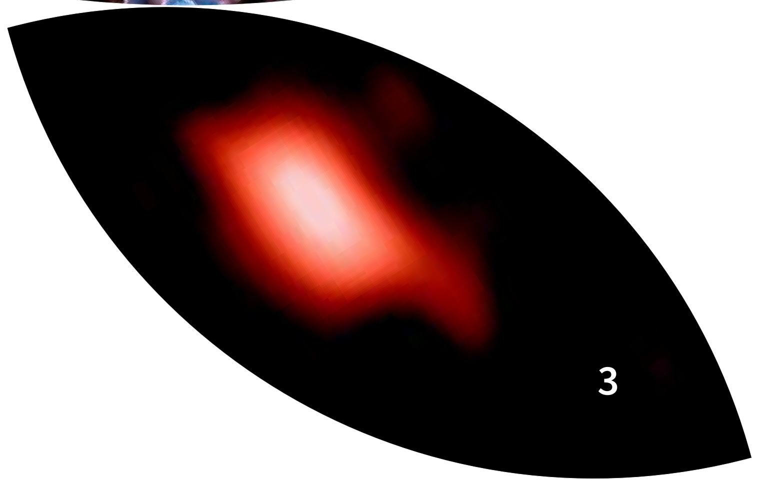
Fig 1. The Lyman alpha forest: imprint of the Intergalactic Medium in a quasar absorption spectrum. The white curve shows the unabsorbed flux from the quasar as it would look if the IGM is not present. The absorption features in the green curve are the characteristic so called Lyman-alpha forest and are due to the neutral hydrogen in the Intergalactic Medium (IGM) along the line-of-sight to the quasar.

Fig 2. An example of an observed spectrum from the analysed sample is shown in blue. The left panel of the inset shows an enlarged version of the red region in the observed spectrum. The middle and right panels show simulated absorption spectra with IGM temperature 8000 K (smaller spike width) and 10000 K (larger spike width).

PROBING COSMIC DAWN WITH THE FIRST GALAXIES







Nicolas Laporte

One of the most exciting challenges of modern extragalactic astronomy is to pinpoint the birth of the first stars and galaxies, or in other words to determine when the Universe became bathed by starlight (aka the `Cosmic Dawn'). According to recent simulations, dark matter haloes massive enough to sustain the formation of stars may exist as early as 150 million years after the Big-Bang (z~20). The first stars are expected to be massive and to produce a huge amount of UV photons, which start to ionise the neutral hydrogen formed after the Big-Bang. This process, also known as Reionisation, was first a local phenomenon, where each star ionised the neutral hydrogen in its surroundings, creating bubble of ionised hydrogen, and then became a global process when these bubbles increased in size and merged (Figure 1). Observational evidence has shown that 1 Gyr after the Big-Bang (z~6) hydrogen intergalactic medium is mainly ionised, marking the end of the Epoch of Reionisation. This time constraint is a boon: it demonstrates that galaxies formed during the first Gyr years of the Universe have emitted enough UV photons to ionise the bulk of neutral hydrogen in the intergalactic medium.

The logical way to prove that galaxies are responsible for the reionisation of the Universe is to count the number of galaxies emitting light during the first billion years of the Universe. In this framework, many deep imaging surveys with the largest ground-based and space telescopes have been conducted, such as the Hubble Ultra Deep Field, CANDELS or UltraVISTA. These surveys can only observe the brightest galaxies in the early Universe. However, according to recent hydrodynamical simulations, faint sources in the early Universe are more numerous than the bright galaxies and may therefore play a key role in re-ionising the Universe. To go beyond the capabilities of current telescopes, and reach faintest galaxies, we can use “natural telescopes” with a technique called “gravitational lensing”. The gravitational field of massive galaxy clusters (Figure 2) amplify the light coming from background galaxies, making them brighter and therefore detectable by the current facilities. Many deep surveys have been designed to exploit this natural effect to identify the faintest galaxies in the early Universe and explore their properties. By combining results from deep surveys as well as lensing fields, we can obtain a better picture of the distribution in luminosity of galaxies, and therefore on their contribution to the ionising photons budget. The conclusion is clear: assuming that galaxies we observed in the early Universe have properties similar to the galaxies observed locally, they have not produced enough photons during the first billion year of the Universe to explain its reionisation.

To explain this observed deficit in ionising photons, three main hypothesis can be considered : (i) there are more faint galaxies with a luminosity well below the limits of current telescopes, (ii) the properties of primeval galaxies in terms of ionising photons emission is different than what is observed in the local Universe or (iii) the formation of the first galaxies and the associated ionising process started earlier than thought. Images from the future JWST in 2021 will be the only way to address the first hypothesis by looking for extremely faint galaxies during the first Gyr. To test the second hypothesis, deep high-resolution spectroscopy, such that provided by the future MOONS instrument on the VLT (in which the KICC is strongly involved), is needed to resolve either the most prominent emission line from hydrogen (the so-called Lyman-α) or absorption lines from other elements (such as carbon, silicon, etc...). The last hypothesis can be addressed by determining the age of the most distant galaxies by modelling their Spectral Energy Distribution or by measuring the amount of dust produced by supernovae along the lifetime of the galaxy. Researchers from the KICC are part of a leading team aiming to estimate the age of the most distant galaxies by combining data coming from Hubble, Spitzer, the VLT, Keck, the GTC and ALMA. Preliminary results show that galaxies may already exist only 250 million years after the Big-Bang (Figure 3), which is earlier than expected by current simulations. Further observations of similar galaxies will be done in 2020 to confirm this conclusion and therefore probe Cosmic Dawn.

THE ALPINE SURVEY

Gareth Jones

Galaxies in the early Universe (i.e., within the first two billion years after the Big Bang) existed in a markedly different environment than the one in which we currently reside. Studies have shown that this epoch featured a rapid increase in the amount of star formation activity, as primordial galaxies formed out of infalling gas. With current instruments, it is now possible to observe these sources, allowing us to determine the initial conditions of galactic evolution.

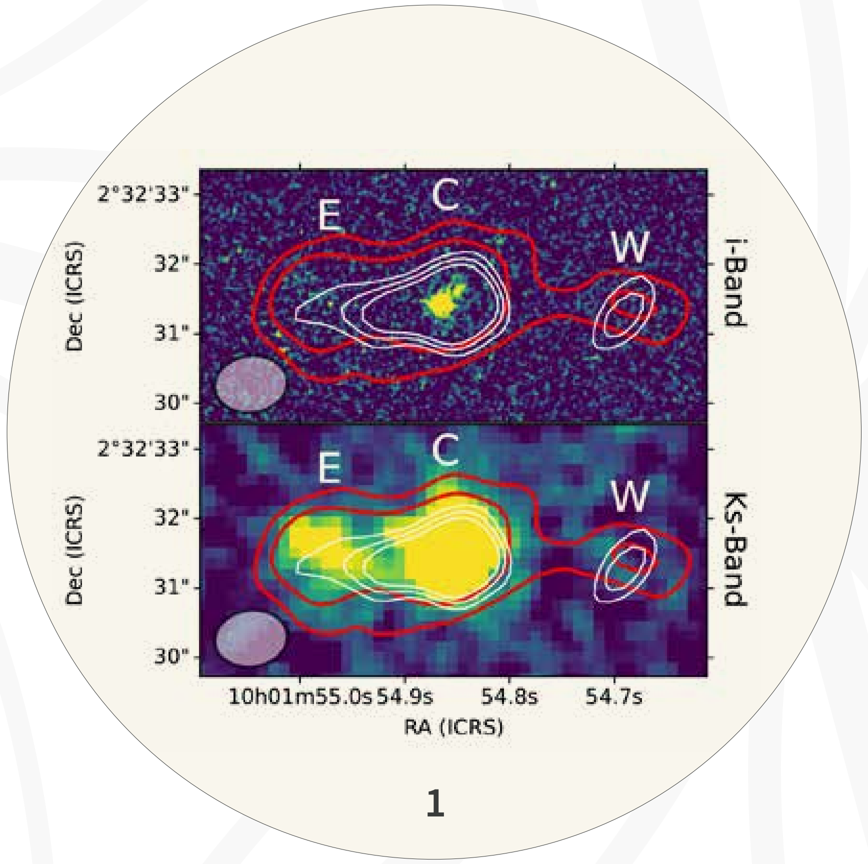
Until relatively recently, most of the observations of galaxies in the early universe have focused on the brightest sources. However, they are not representative of the fainter population of normal galaxies in this epoch. In order to fill this observational void, the ALMA Large Program to Investigate [CII] in Early galaxies (ALPINE) observed both warm dust emission and a strong emission line tracing recent star formation in over a hundred normal galaxies within the first 1.5 billion years of the Universe, increasing the number of such observations by an order of magnitude.

ALPINE (led by Olivier Le Fèvre) is a large international collaboration, including Gareth Jones and Roberto Maiolino at the KICC. By combining these new ALMA observations with a rich archive of multiwavelength data, we are in a unique position to characterize this set of early galaxies. As the first sample in this epoch that is large enough to be statistically significant, ALPINE allows us to make inferences on the properties of the overall galaxy population when the Universe was less than 10% its current age.

We have focused on the kinematics of each source, including determining how many galaxies in this sample are in the process of merging, and how others deviate from disk-like ordered rotation.

As a first step, each galaxy was individually classified into one of four categories: rotating, merging, spatially extended dispersion dominated, and spatially compact dispersion dominated. Of the 63 galaxies whose line emission was bright enough to allow classification, 9 (14%) were classified as rotators, 31 (49%) as mergers, 15 (24%) as extended dispersion-dominated, and 8 (13%) as compact dispersion-dominated. This kinematic diversity suggests that galaxies in this early epoch were not a homogeneous group but had already undergone various evolutionary routes.

In the course of this investigation, we find interesting behaviour within individual galaxies. Perhaps the most visually striking galaxy in the sample is DEIMOS COSMOS 818760. This system features three separate, extended components in line emission: two bright, closely separated sources, and one weaker, more distant component. Using the line emission intensities, we find that this system is forming stars at a rate hundreds times higher than that of the Milky Way. Despite this high star formation activity, the two weaker components were undetected in an archival optical HST observation, indicating a large amount of dust obscuring the light. By examining the kinematics of the system, and comparing it to simulations of galaxy evolution, we conclude that the three-component morphology represents an ongoing major merger, with a third minor source that will merge later, resulting in a massive system within the next billion years.



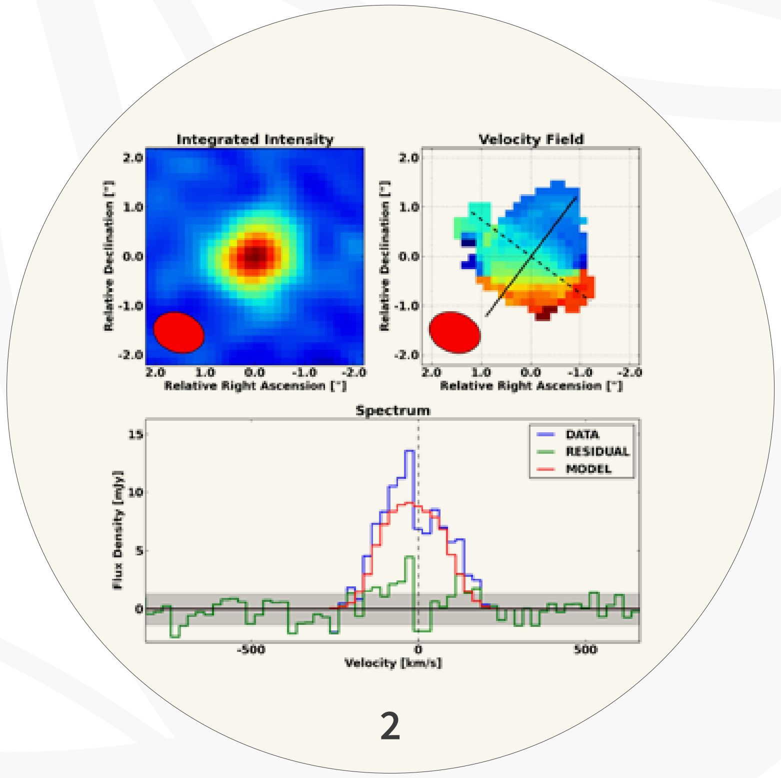


Fig 1. Optical (color), star formation-tracing line emission (red contours), and dust emission (white contours) of DEIMOS COSMOS 818760. The three components are here denoted by the letters C (center), E (east), and W (west).

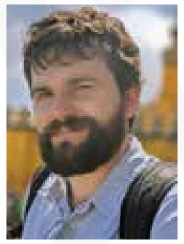
Fig 2. Example of integrated line emission (top left), velocity field (top right), and spectrum of an ALPINE source. The original data (blue), best-fit dynamical model (red), and the difference between them (green) is presented.

Currently, we are applying a well-tested dynamical model fitting code (^{3D}Barolo) to the sample. These models calculate how well a simple rotating disk model fits the observed kinematics of each galaxy. Preliminary results show that few galaxies are spatially extended and strong enough to be well fit, but the residuals between the data and model hint at the existence of minor mergers or possibly outflows.

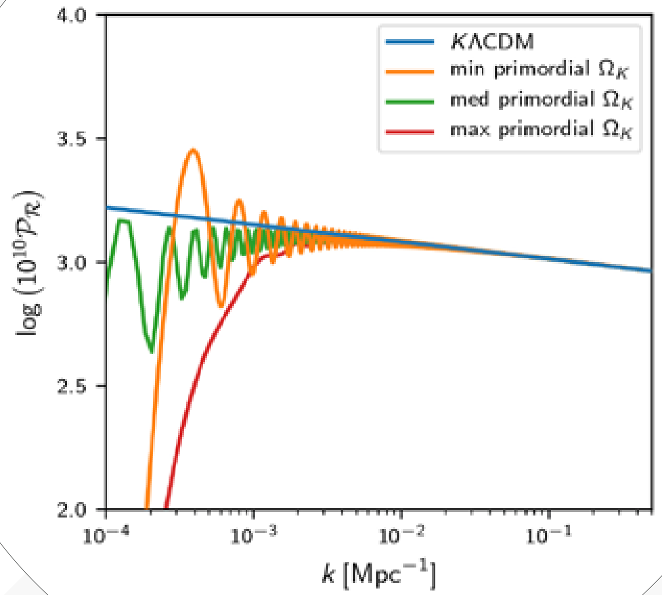
ALPINE is an ongoing work, so there is much more analysis to be performed. Additionally, follow up observations with ALMA and other observatories (e.g, VLT, JWST) will enable us to characterize these early galaxies further, providing key information to simulations and galaxy evolution models.

These results were partially published in:
"The ALPINE-ALMA [C II] survey: a triple merger at z ~ 4.56" Jones, G. C.; Béthermin, M.; Fudamoto, Y., et al. 2020, MNRAS, 491, L18 and "The ALPINE-ALMA [CII] survey: Survey strategy, observations and sample properties of 118 star-forming galaxies at 4<z<6" Le Fèvre, O., Béthermin, M., Faisst, A., et al. 2019, arXiv e-prints,arXiv:1910.09517

COMPROMISE-FREE BAYESIAN COSMOLOGY



Will Handley



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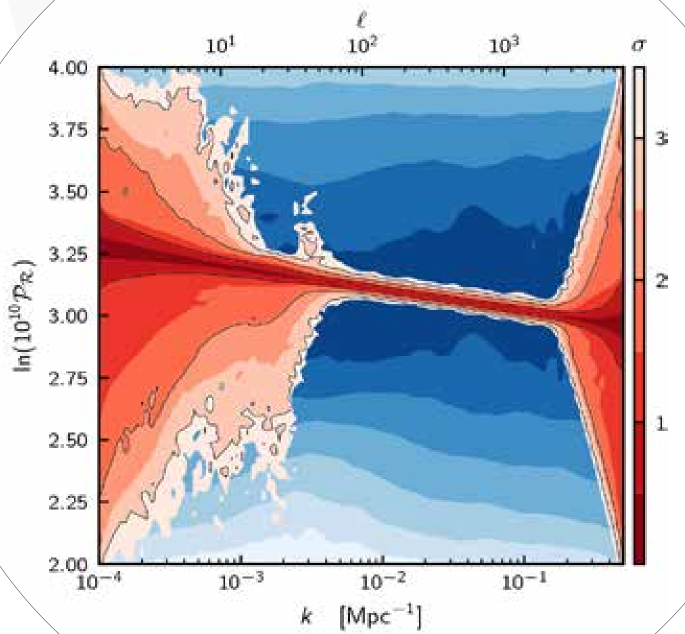

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Fig 1.
Reconstruction of our earliest observational window onto the primordial universe performed as part of the Planck collaboration.

Fig 2.
Predictions of the same quantity by theories investigated at the KICC.

In 2019 a significant fraction of our research focussed around the theoretical and observational exploration of our primordial universe using the cutting edge of Bayesian machine learning techniques. This is characterised by what we term a 'compromise-free' approach, where one solves cosmological inference problems in the fullest generality without recourse to approximation. This methodology allows one to forecast how such analyses will scale now and in the future (with more time, money or compute), whilst also enabling us to assess and improve current widely-used approximation schemes.

In light of the ever-increasing cosmological tensions between modern datasets, research early in the year focussed on developing novel statistical inference approaches (such as the 'suspiciousness statistic') to quantify the level of hidden discrepancy between datasets in a principled Bayesian fashion.

Different cosmological datasets (such as the cosmic microwave background, weak lensing or supernovae data) may only be combined if they produce consistent predictions. As the datasets and modelling increase in their volume and complexity, methodologies for determining their consistency will prove critical for guiding current and future data analyses. Our approaches are now being used by next-generation collaborations to quantify cosmological parameter tensions. This work was performed together with former KICC student Pablo Lemos, in a collaboration forged as a direct result of a KICC meeting symposium. The research in 2019 culminated in a controversially titled publication quantifying the internal parameter tensions between Planck likelihoods in the context of models of our Universe which include spatial curvature.

In order to perform such research we require the use of advanced Bayesian algorithms such as nested sampling, a Cambridge incepted technology developed at KICC.

A second application of nested sampling was published in a 'tour-de-force' of the reconstruction work performed at the KICC, together with Anthony Lasenby, as part of the Planck collaboration. In this paper, we reconstruct the primordial universe three ways. The results of this work (Figure 1) represent our observational knowledge of the earliest phase of the universe (mere fractions of a second 'after the big bang') using the Planck satellite data.

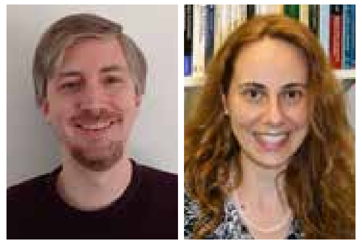
Nested sampling is also widely used to perform compromise-free Bayesian model comparison. Ongoing work at the Kavli with PhD student Lukas Hergt involves confronting theories of the primordial universe with and without curvature using the latest cosmological data. This observational work was supplemented by theoretical work building novel mathematical power series techniques for analysing this period, as well as deriving the equations governing the generation of the primordial power spectrum for curved universes (Figure 2). Alongside KICC student Will Barker we also continue to investigate novel theories of modified gravity and their potential for parameter tension resolution.

Another compromise-free element of our research involves the development of novel numerical techniques for solving ordinary differential equations with oscillatory solutions. Such equations sit at the heart of cosmological computational codes, and any improvement in the efficiency of solution will result in an increase in the scope of cosmology theories that we can test against data, and a reduction in the time and energy spent running them on supercomputers. This research was conducted with PhD student Fruzsina Agocs and Masters student Jamie Bamber.

The compromise-free approach has applications far beyond cosmology, with researchers at the Kavli such as Kamran Javid applying it to cutting-edge machine learning problems such as Bayesian Neural networks . By exploring compromise-free Bayesian inference in the context of cosmology and beyond, the KICC pushes the boundary of what is possible with modern-day computational resources and acts as a pioneer of next-generation machine learning techniques.

The work and results outlined in this article are presented in a series of scientific papers that can be found on arXiv at:
1902.04029, 1903.06682, 1910.07820, 1908.09139, 1905.04768, 1908.00906, 1809.07737, [1901.07540], [1907.08524], [1811.09844], [1906.01421], [2004.12211], 1907.11638]

BLACK HOLES SEEDS AND MERGING ACROSS THE COSMIC EPOCH



Colin DeGraf & Debora Sijacki

It is generally understood that massive galaxies host supermassive black holes at their centre and that the black hole and galaxies masses are correlated. This suggests a causal link between the black hole and its host galaxy's evolution and making them a crucial aspect to understand galaxy formation. However, despite their ubiquitousness throughout the Universe, the process by which these supermassive black holes form remains an open question, with three commonly proposed 'seed' mechanisms: at low-masses from the collapsed remnants of the first generation of stars, at intermediate masses from runaway stellar collisions in dense nuclear star clusters, or at high masses by direct collapse of massive, pristine gas clouds in the early Universe.

Given the uncertainty between formation pathways, a common approach in cosmological simulations is to simply neglect the seed formation and only incorporate black holes into more massive halos, with the intent of remaining broadly consistent with any of the suggested models. While this avoids the extreme computational cost of running a full set of cosmological simulations to probe each formation scenario, it neglects the impact that the different seed masses and conditions may have on black hole populations, which may play an important role on both black hole growth and their co-evolution with host galaxies.

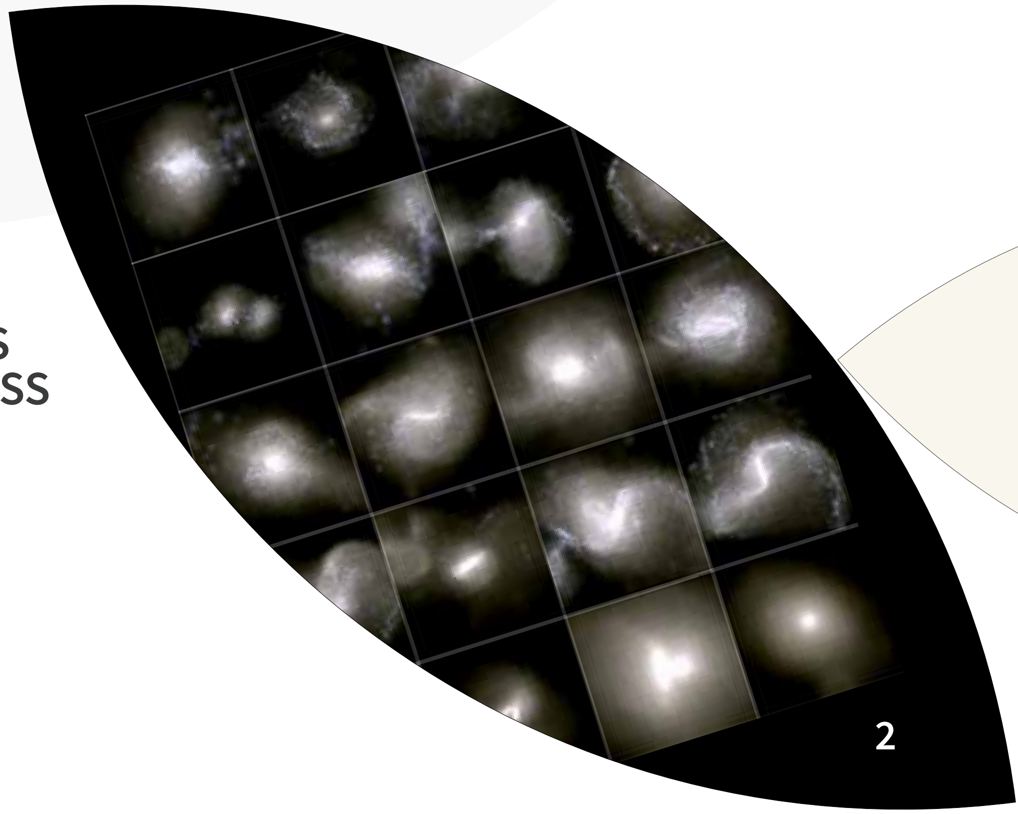


Fig 2. A montage of redshift z = 0.5 galaxies which have hosted a high-mass major black hole merger in the prior 300 Myr, showing a tendency toward disturbed morphologies indicative of a recent galaxy merger.

To investigate this, we developed a novel post-processing method which can be applied to previously-run simulations, here specifically the Illustris simulation, to estimate how changing the seed model would impact black hole populations across cosmic time, from low mass black holes in the early periods, shortly after formation, to late times and the most massive black holes in the Universe. By using a post-processing approach, the minimal computational cost lets us test a variety of models, and keeping everything else fixed lets us determine the importance of the black hole formation pathway itself.

We primarily focus here on the Direct Collapse Black Hole (DCBH) seed model, and find that simulations with DCBH only are in broad agreement with present observational constraints for black hole populations. However, we find significant differences in the black hole number densities and halo occupation fractions especially at low masses and luminosities, which are currently observationally unconstrained. In particular, the seeding efficiency of DCBHs decreases with cosmic time, producing fewer low-mass, faint black holes at low redshifts compared to the original Illustris simulation, suggesting that future observational surveys may be able to differentiate between seed formation models based on observed black hole populations.

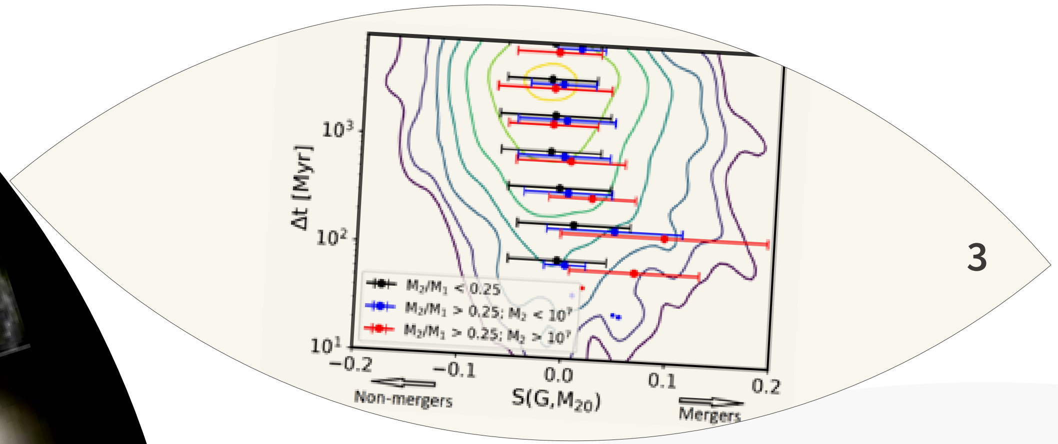


Fig 3. The correlation between merger statistic S and the time since the most recent black hole merger within the galaxy. Recent black hole mergers, especially between high-mass black holes, are much more likely to have a high merger statistic (S > 0), suggesting a recent merger involving the host galaxy which leaves significant imprint on galaxy morphology.

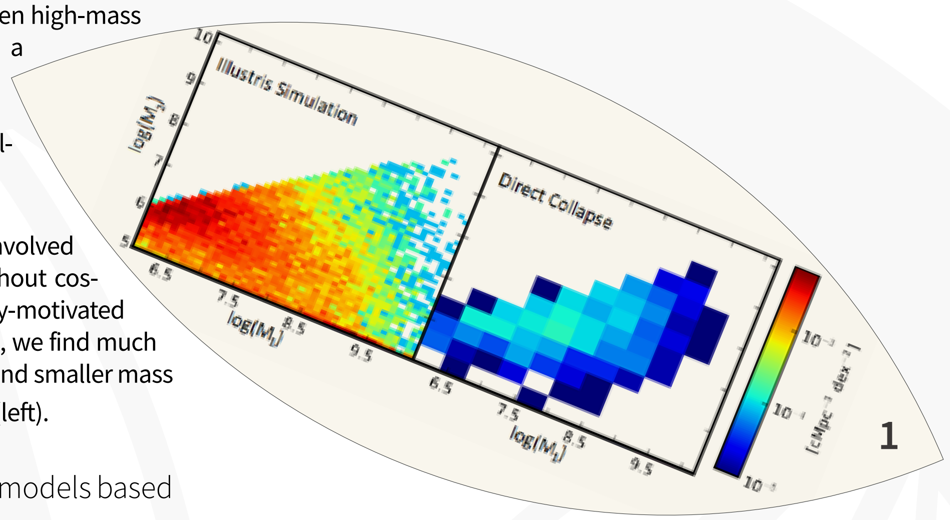


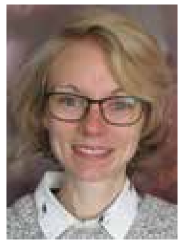
Fig 1. Frequency distribution of the masses involved in supermassive black hole mergers throughout cosmic time. When implementing a physically-motivated direct collapse black hole seed model (right), we find much fewer mergers with typically higher masses and smaller mass ratios than in the original Illustris simulation (left).

However, we find that the impact that seed formation has on black hole mergers is more significant than that on the overall black hole populations. More specifically, the merger rate for DCBHs may be as much as an order of magnitude lower than the rate in the original simulation. Furthermore, the decreasing formation efficiency for DCBH with cosmic time means that late-time mergers would be expected to have higher masses, and mergers are more likely to be between comparable-mass black holes, as shown in Figure 1. Both the decrease in expected merger rates and the change in expected merger masses have significant implications for gravitational wave (GW) detections from projects like LISA and Pulsar Timing Arrays, as it impacts the expected number of detections and also provides a means by which GW-detectors could differentiate between models for black hole seed formation.

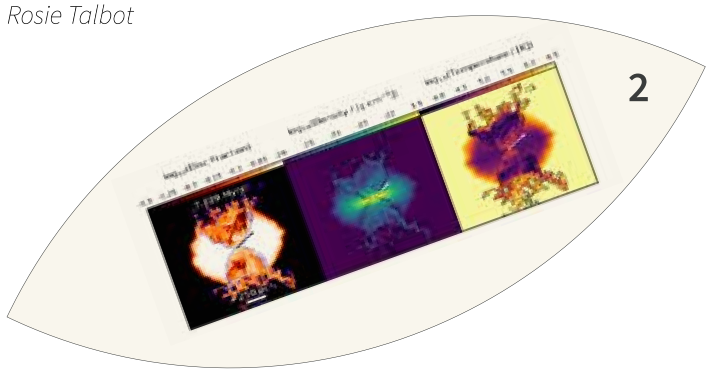
Given their importance both for our understanding of the theory of galaxy formation as well as their upcoming detections from GW projects, we have further investigated the mergers of supermassive black holes and their host galaxies, with a particular focus on the correlation between the black hole merger and the host galaxy morphology. Using the Illustris simulation, we look at the galaxies which host black hole mergers, and find that the typical host galaxies show a range of disturbed morphologies, consistent with what we expect following a recent galaxy merger (see Figure 2).

By characterizing the morphology with a merger statistic (S), we quantify the connection between black hole mergers and the morphological evidence for a galaxy merger across a range of masses and times. This is shown in Figure 3, demonstrating that host galaxies remain morphologically disturbed (S>0) for ~300-500 million years after the black hole form a binary, with the strongest effect found in mergers between high-mass black holes with comparable masses. While initially promising for multi-messenger astronomy, this timescale of several hundred million years is comparable to the expected time between black hole binary formation and the final coalescence and emission of GWs, suggesting that electromagnetic follow-ups to GW detections may not be capable of observing merging morphologies of the host galaxies. However, both this timescale and the expected black hole growth during the merger itself are poorly constrained by current cosmological simulations, and will be addressed in several planned cosmological and zoom-in simulations.

THE NATURE AND ROLE OF RELATIVISTIC JETS



Rosie Talbot



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One component that plays a significant role in the evolution of the most massive galaxies stems from the existence of supermassive black holes (SMBHs) in their centres. There is growing evidence that these SMBHs are not just passive observers, lying dormant while the galaxy evolves around them. Rather, we are seeing clear evidence that, despite being extremely compact they are able to shape global galaxy properties through powerful, large-scale outflows.

A significant fraction of growing SMBHs, the so-called active galactic nuclei (AGN), show a radio-jet that is often relativistic and will pierce the surrounding medium leading to the deposition of energy into the circum-galactic and intra-cluster medium (ICM).

With significant advances in observational techniques in recent years and the prospects offered by forthcoming observing facilities, it is particularly important to understand how these jets are launched and how they interact with their surroundings.

Since some observations of AGN jets seem to imply that more energy is being extracted than available from the accretion flow, a particularly promising jet launching mechanism is that of the Blandford-Znajek (BZ) process whereby the spin-energy of a rotating black hole (BH) is extracted via magnetic fields that thread its horizon.

The complex interplay between the individual processes that come together to shape galaxy formation make numerical simulations an invaluable tool. We have seen significant progress in the speed and accuracy of General Relativistic Magneto-hydrodynamic codes, which probe the smallest scales of jet launching. However, to follow the evolution of large scale structure on cosmic timescales where, crucially, jets interact with the circumgalactic environment, the scales on which jet is launched become unresolvable. The physical processes occurring on these unresolvable scales then need to be encoded in "subgrid" models rather than followed from first principles.

Most "subgrid" models of BH accretion make use of the spherically symmetric Bondi-Hoyle-like prescription. However, theoretical and observational evidence indicates the existence of accretion discs around BHs. We have therefore developed an entirely novel "subgrid" model for BH accretion and feedback in the form of a BZ jet, which accurately tracks the evolution of the system from the accretion disc all the way to the BH.

As a first test, we place a SMBH at the centre of an isolated circumnuclear disc embedded within a stellar bulge and surrounded by a uniform ICM, neglecting any wider effects of the surrounding galaxy for now. Before fully implementing the BZ model we first consider jets with a fixed direction and power, allowing us to isolate the environmental effects on the jet evolution from those due to the BZ mechanism. Fig 1. shows various physical properties for three different fixed jet powers 1 Myr after the jet launches. Overall, we find that the high power jets are broader, hotter and able to propagate further in a given time compared to the low power

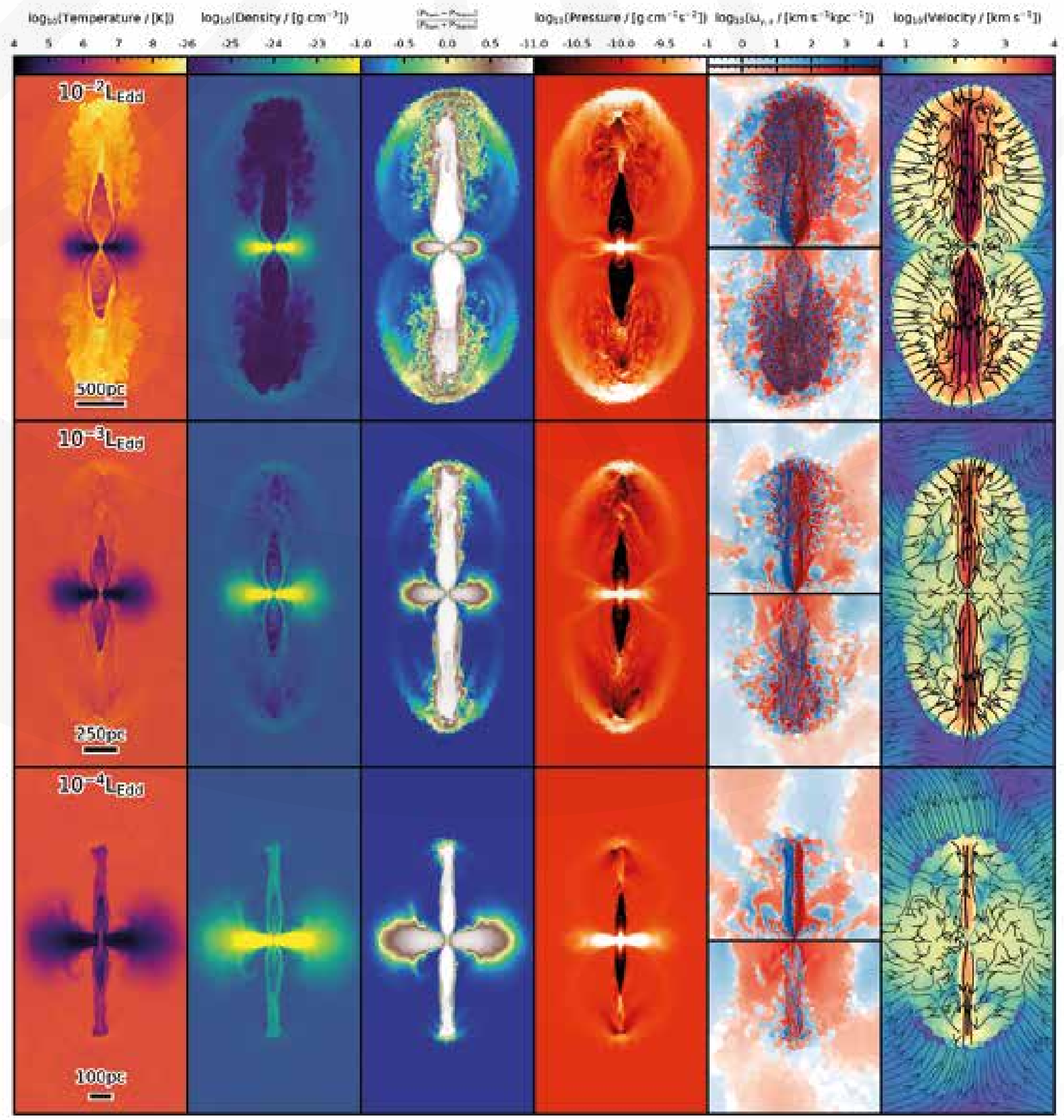

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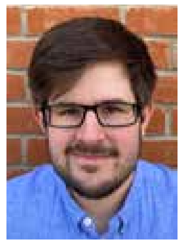
Fig 1. Slices of various diagnostic quantities taken 1 Myr after the jet turns on for three different jet powers.

Fig 2. Disc tracer, density and temperature slices for a jet with BH spin direction initially in the perpendicular to the plane of the disc. The dotted contours outline the region defined as the jet and the arrow indicates the BH spin direction.

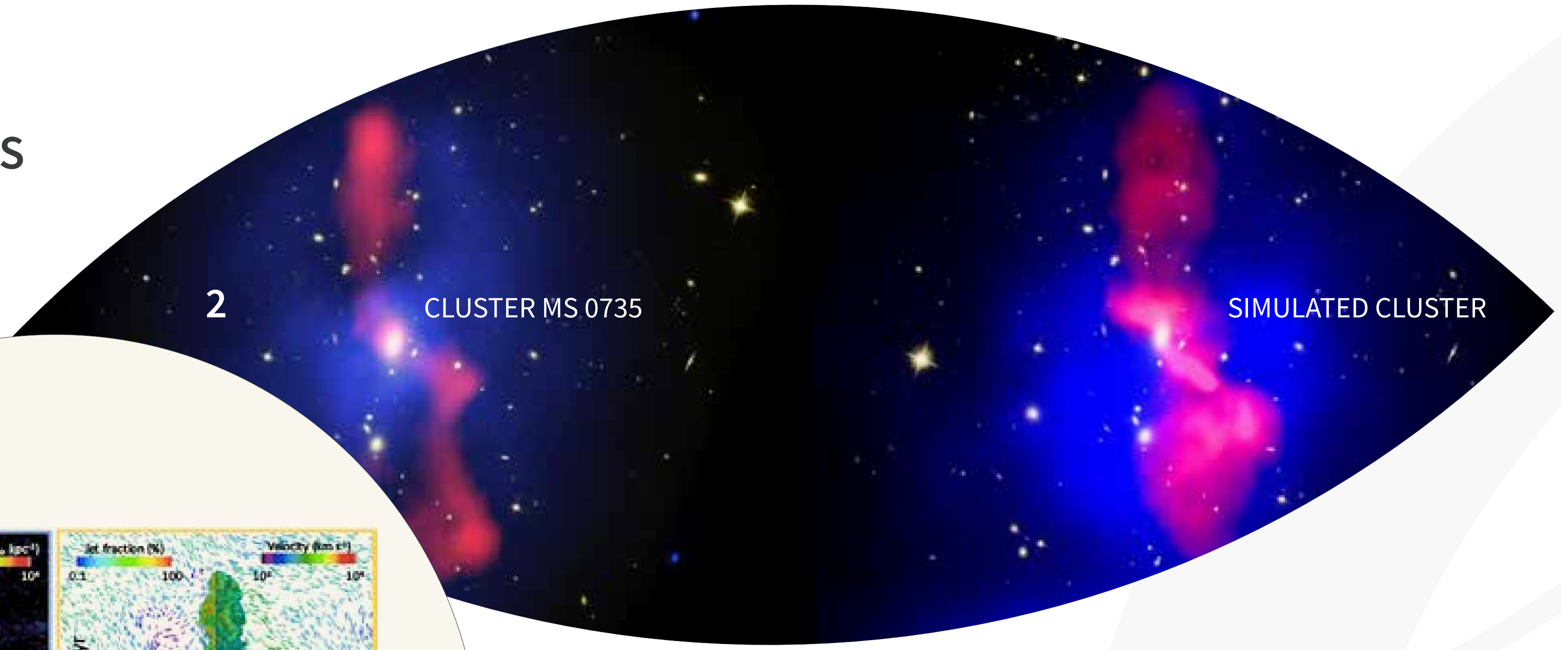
jets that are colder, slower and more collimated. Moreover, there are strong shocks at the poles of the jet where the jet material thermalises and a hotspot forms. The thermal pressure then drives the expansion of the cocoon of shocked material which we see is outlined by a weak bow shock. For all jet powers examined, jets transition from the state of kinetic to thermal energy dominance which makes them an excellent source of ICM heating. Now, implementing the full BZ model, as an extreme example we consider jets where the BH spin is initialised at 90 degrees to that of the circumnuclear disc.

Naively, it would be expected that, with jets directed straight into the disc, the outflow would be stunted by the disc. We find, however, that the jet is promptly torqued back towards alignment with the disc by inflowing gas and, while the jet is realigning, a largely perpendicular and extended outflow develops. This permits the BH to continue accreting from the disc which sustains the large-scale outflow. Such outflow is multi-phase, with temperatures spanning four orders of magnitude, which could lead to the formation of isolated sites of star formation embedded in the hot outflow.

SUPERMASSIVE BLACK HOLE JETS STIR OLD COSMIC PUZZLES



Martin Bourne



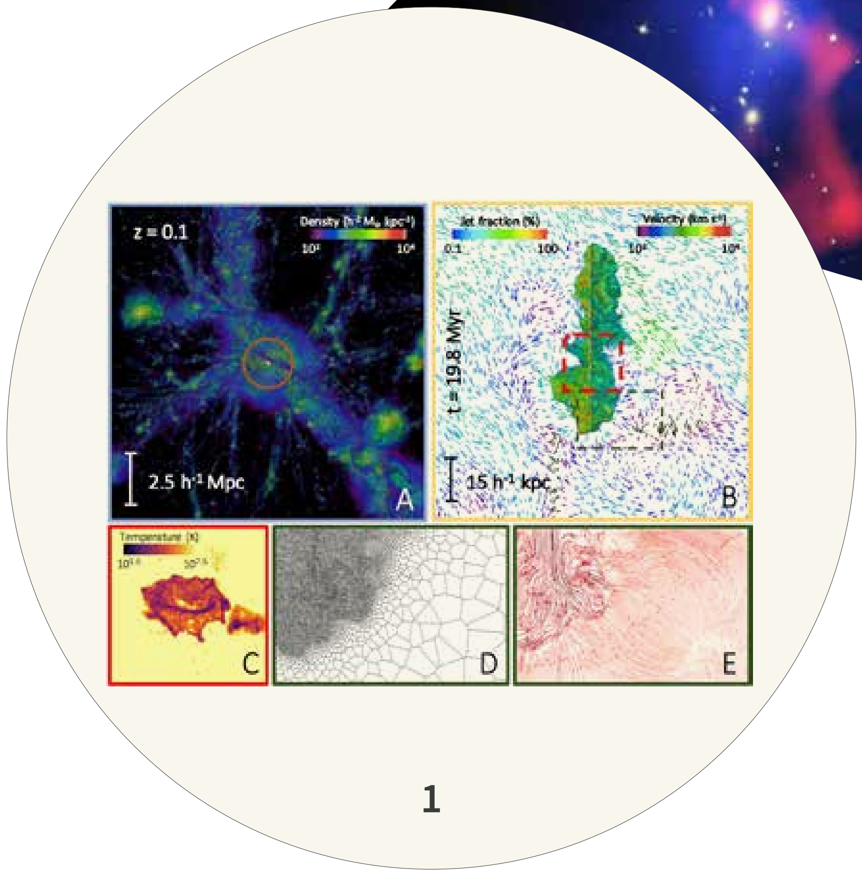


Fig 1. Panel A shows a volume-rendered image of a galaxy cluster and panel B shows the volume-rendered jet material as well as the gas velocity field (arrow vectors) in the cluster centre. Panel C shows a cold disc structure which surrounds the SMBH. Finally, panels D and E show a 2D reconstruction of the Voronoi grid used and a velocity streamline map of the lower-right lobe-ICM interface, respectively. (Credit: Bourne et al. 2020, MNRAS).

Fig 2. This shows a mock observation made from the simulation on the right and actual observations of the galaxy cluster MS 0735.6+7421 on the left. Both images show cavities excavated by the lobe inflation surround by X-ray bright rims of dense gas (blue), which are filled by distorted jet material (pink). Credit: Hubble and Chandra Image: NASA, ESA, CXC, STScI, and B. McNamara (University of Waterloo); Very Large Array Telescope Image: NRAO, and L. Birzan and team (Ohio University). Simulated Cluster Image credit: Hubble and Chandra Image (background): NASA, ESA, and B. McNamara (University of Waterloo); Simulated Observation Data: M. A. Bourne (University of Cambridge).

Galaxy clusters assembling at the intersection of the cosmic filaments are the most massive gravitationally bound systems and encode unique information on the composition of our Universe. They comprise of a massive dark matter halo and up to a few thousand rapidly moving galaxies enveloped by a very hot X-ray emitting plasma, known as the intracluster medium (ICM).

The properties of the ICM are determined by a number of factors – from the cosmology of our Universe that dictates the build-up of large-scale structure, through to outflows launched by supermassive black holes lurking in their cores acting on "macro" scales, and down to complex plasma physics processes acting on "micro" scales within the ICM itself. Of particular importance for regulating the heating and cooling of the ICM, the decades-long "cooling flow" problem, are the relativistic jets produced by supermassive black holes with masses in excess of a billion solar masses. Notwithstanding massive theoretical and observational effort, a major puzzle left to crack is how the energy from these powerful jets is transferred to the ICM to stop the catastrophic cooling.

Using the moving-mesh code AREPO, we performed state-of-the-art simulations with the highest-resolution jets to-date within a large scale, fully cosmological cluster environment to shed light on this issue. The simulations make use of a novel refinement technique that not only allows high resolution close to the central black hole but also within the jet lobes themselves. While the previous article used a similar approach to investigate the launching physics of the jet and its effect on the host galaxy, here we focus on the larger scale effect on the CGM and ICM. Figure 1 gives an overview of the simulation, illustrating the range of scales captured from the Mpc scales of the galaxy cluster down to 10s of parsecs in the cold dense disc of the brightest cluster galaxy (BCG). Thanks to self-consistently capturing the build-up of the galaxy cluster over cosmic time and hence the development of a realistic cluster environment, we have been able to investigate with unprecedented realism how the jets, and hot plasma lobes they inflate, interact with a dynamic ICM. We found that the mock X-ray observations of the simulated cluster revealed the so-called "X-ray cavities" and "X-ray bright rims" generated by supermassive black hole-driven jet, which itself is distorted by motions in the cluster remarkably resemble those found in observations of real galaxy clusters (see Figure 2).

While it is well accepted that the vast amount of energy injected into the jet lobes (which would be enough to meet the Earth's power usage for more than 10^{31} years) is sufficient to offset the cooling losses within the intracluster medium and prevent the formation of a cooling flow, how this energy is effectively and isotopically communicated to the ICM is still an open debate. Our simulations showed that the ICM motions or "weather" are crucial to solving this problem. Through the cluster weather action, the jet lobes can be significantly moved and deformed, stirring them around the cluster, which ultimately leads to jet lobe disruption and effective energy transfer to the ICM which could be the long-sought-after solution to combat the "cooling flow" puzzle.

This work has been published in the Monthly Notices of the Royal Astronomical Society: "AGN jet feedback on a moving mesh: lobe energetics and X-ray properties in a realistic cluster environment" by Martin A. Bourne, Debora Sijacki and Ewald Puchwein. Royal Astronomical Society press release: "Stormy cluster weather could unleash black hole power and explain lack of cosmic cooling", 14 October, 2019.

COSMIC ACCRETION THROUGH MASSIVE HALOES

Jake Bennett

During the hierarchical gravitational collapse of primordial dark matter overdensities, the baryonic content of haloes grows by accreting gas and stars from the intergalactic medium (IGM). This gas is what then feeds the formation of a galaxy at the halo's centre. The mechanism by which this feeding occurs is not fully understood, as it involves a complex interplay between cooling, shock heating, and feedback from a variety of physical processes in the galaxy itself. All of these processes act in concert in the circumgalactic medium (CGM), which thus plays host to the baryon cycle that regulates the process of galaxy formation.

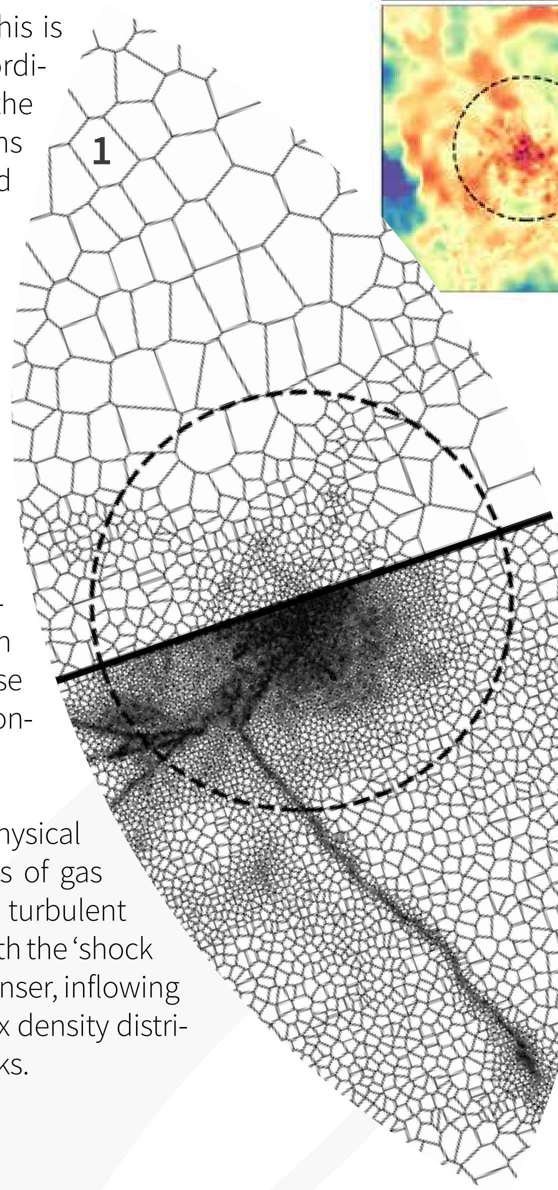
In the 'classical' analytic model of accretion onto massive dark matter haloes gas shock heats as it infalls, forming a hot atmosphere. Recently however, a significant amount of observational evidence points to a more complex, multi-phase CGM with a substantial cold component across a wide variety of galaxy masses.

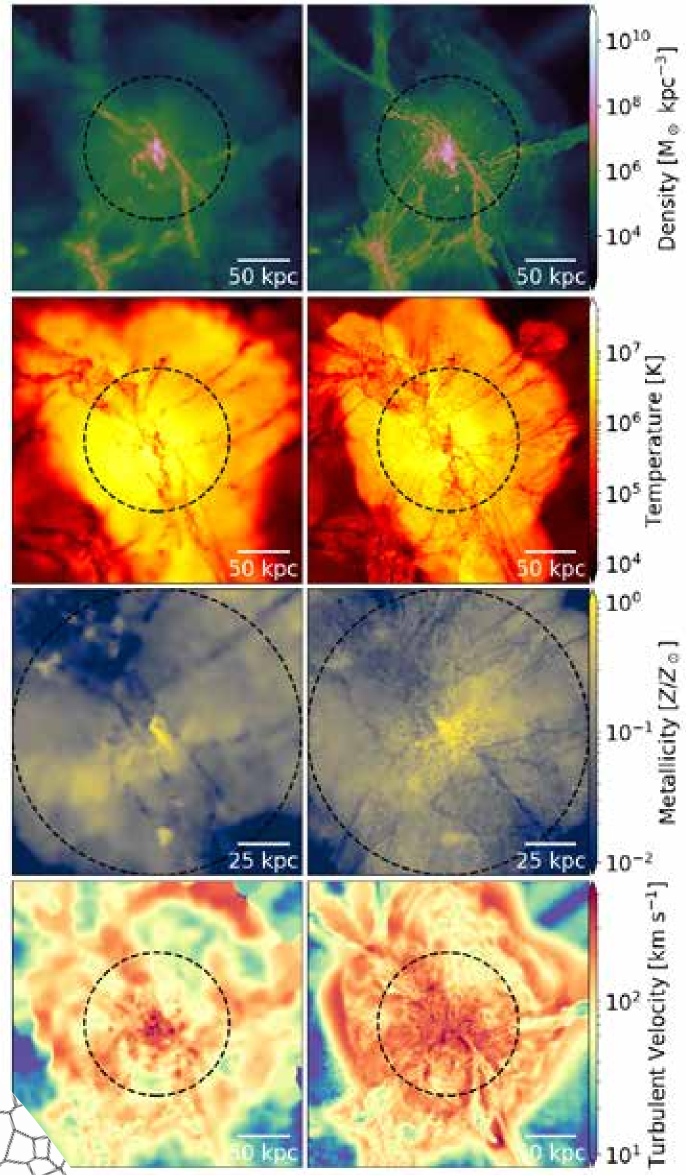
In massive haloes, cold gas is thought to bypass accretion shocks and penetrate deep into haloes via filaments that deliver cold gas through the CGM. Numerically this is difficult to model, as the CGM is primarily made up of multi-phase gas that cosmological simulations do not focus resolution on. Accretion shocks themselves are also numerically broadened in simulations which may affect gas shock heating and energy dissipation at the shocks. These effects can potentially lead to inaccurately modelled properties of CGM gas.

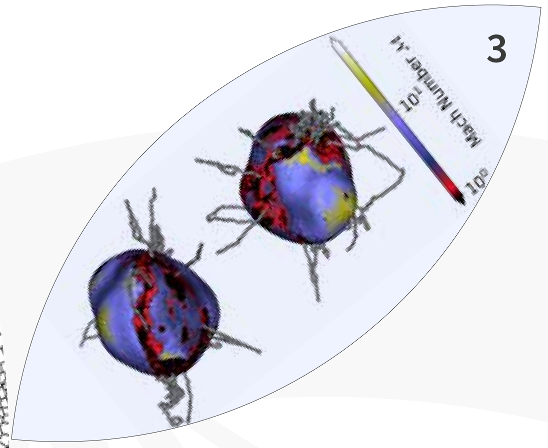
We have introduced a novel computational technique that automatically and on-the-fly boosts numerical resolution around shocks during the simulation. This allows us to better resolve the accretion shocks at the boundary of the CGM and IGM in massive haloes. This is the region that determines if primordial gas filaments can penetrate into the hot halo, and how turbulent motions are generated in the wake of curved shocks.

To do this, we resimulate a massive (10^{12} $M_{\odot}$), high-redshift (z ~ 6) galaxy cluster progenitor with the successful physical model employed in the FABLE suite of simulations using the moving-mesh code AREPO. Figure 1 shows how our 'shock refinement' scheme boosts resolution significantly in and around cosmic filaments and at the accretion shocks, compared with AREPO's 'base refinement' scheme which is commonly adopted in the literature.

Figure 2 demonstrates clearly the physical effect of our novel method in maps of gas density, temperature, metallicity and turbulent velocity. The top panels show that with the 'shock refinement' scheme active we see denser, inflowing filaments of gas and a more complex density distribution in the wake of accretion shocks.







The second row illustrates how the amount of cold gas penetrating into the hot halo is increased with 'shock refinement', leading to a much more multi-phase CGM more in line with observations. These cold gas filaments are shown to also have a low metallicity in the third row, indicating how our 'shock refinement' scheme allows primordial gas to more easily penetrate deep within the virial radius of the halo. Finally we see that higher numerical resolution and better defined curved accretion shocks lead to a significant boost in turbulent velocities in the halo, which is important when comparing models to the next-generation of X-ray observations from eROSITA and Athena.

Having a well-resolved accretion shock also allows us to create a 3D shock surface, as shown in Figure 3. Here we colour the surface with the Mach number, indicating that a significant amount of the surface area has no associated accretion shock at all. To explain this we also plot the positions of inflowing gas filaments in grey (identified with DisPerSE), whose points of intersection with the halo correspond very well with the unshocked regions of the shock surface. This visually demonstrates the filamentary feeding of galaxy growth, and how even in massive dark matter haloes with a hot gaseous atmosphere, cold, primordial gas can be delivered directly to the central galaxy.

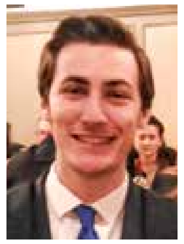
Improved physical models and a better understanding of the CGM and the feeding of galaxies are important for a wide variety of current and upcoming observations, including those by MUSE and the Keck Cosmic Web Imager and enhanced Sunyaev-Zel'dovich observations from SPT and ACTpol.

Fig 1. Representation of the AREPO Voronoi mesh shown for the 'base refinement' (top) and 'shock refinement' (bottom) runs.

Fig 2. From top to bottom: Maps of average gas density, temperature, metallicity and turbulent velocity in the halo. The left column shows the 'base refinement' run and the right column shows the 'shock refinement' run. The black dashed line indicates the virial radius.

Fig 3. 3D surface showing accretion shocks from two different orientations, coloured by Mach number. Cosmic filaments identified with DisPerSE are shown in grey.

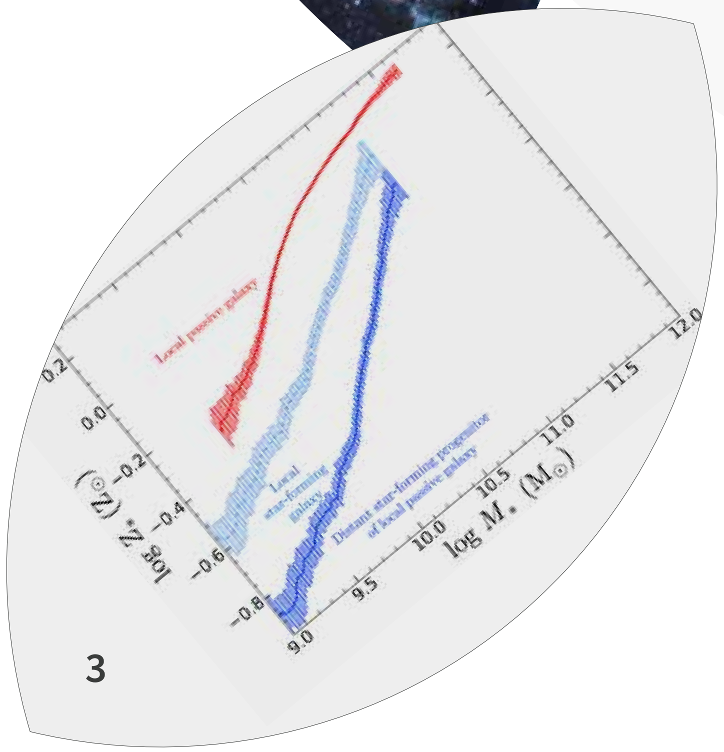
WHY DO GALAXIES DIE?



James Trussler

Galaxies, despite their plethora of properties, can be broadly divided into two categories: galaxies that are alive and galaxies that are dead. Although every galaxy has a unique history and a special story to tell, it is only through large galaxy surveys that we have begun to understand the common thread tying all living galaxies and all dead galaxies together.

Living galaxies actively form stars. Like our very own Milky Way, these star-forming galaxies (Fig.1) tend to be disc-like, with spiral arms filled with sites of active star formation: stellar nurseries housing young, bright blue stars embedded in red-glowing nebulae like the Orion Nebula in our Galaxy. In contrast, dead galaxies are passive and no longer form any stars. Like M87, the most massive galaxy in the nearby Virgo Cluster (Fig.2) whose central, supermassive black hole was imaged in 2019, dead galaxies tend to be rather featureless, spheroidal, with mostly old, yellow-red stars and no star-forming nebulae. Although the general properties of living and dead galaxies are now well understood, it is still not clear what drives the difference between these two populations of galaxies and, specifically, what are the processes taking (or not taking) place during the transition from living to dead, that is, from star-forming to passive. Understanding why galaxies stop forming stars, a process known as galaxy quenching, has been and continues to be a major focus for researchers at the KICC.



Since stars form out of clouds of cold, dense gas which collapse under their own gravity, any physical process that either removes gas from the galaxy (known as galactic outflows), prevents accretion of fresh, cold gas onto the galaxy (known as starvation) or stabilises the gas against gravitational collapse can reduce the amount of star formation in the galaxy. For example, supernova explosions, the death throes of stars, as well as massive black holes during their accretion phase, are phenomena that are known to be effective in ejecting gas out of galaxies. The formation of hot haloes around a galaxy (for instance through injection of energy from the supermassive black hole through jets or winds) can impede the delivery of fresh, new gas. Thus there are a multitude of mechanisms that can quench star formation in a galaxy. But which of these mechanisms is the most important? How does this depend on the internal properties of the galaxy and external factors (i.e. nature vs nurture)? Does the quenching of star formation change over the history of the Universe?

In order to determine the primary quenching mechanism in the Universe, that is, the leading cause of galaxy death, researchers at the KICC have been leveraging on the statistical power of the Sloan Digital Sky Survey, a spectroscopic survey of one million galaxies in the nearby (up to one billion light years away) Universe. Since the spectrum of a galaxy contains a wealth of information, with tell-tale troughs and peaks that serve as a chemical fingerprint, astronomers can determine the abundance of various elements (such as iron, oxygen and magnesium) in the galaxy, that is, the level of chemical enrichment.

By building on a powerful and innovative new method for studying galaxy quenching that was developed at the KICC, we studied the relative level of chemical enrichment in star-forming and passive galaxies to unveil why galaxies die. The key principle behind this technique is that the more star formation that takes place during the quenching process, the greater should be the difference in chemical enrichment between star-forming and passive galaxies, as each star that forms will fuse and subsequently release heavier, more chemically enriched elements into the surrounding gas. Therefore, it is possible to distinguish between abrupt quenching (driven by sudden gas ejection) and slow quenching (driven by starvation, i.e. lack of gas supply).

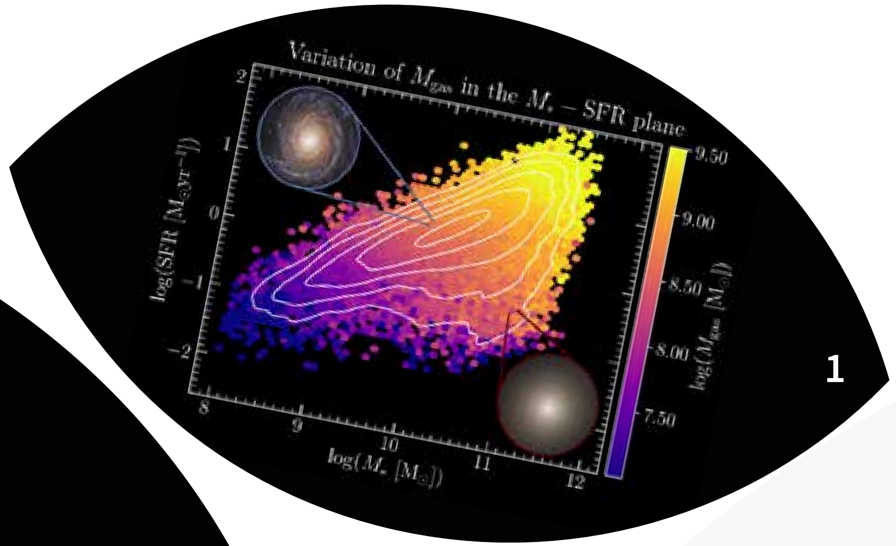
We find that passive galaxies in the nearby Universe are significantly more chemically enriched than their star-forming counterparts of the same mass, indicating that galaxies typically undergo significant chemical enrichment during the quenching phase (Fig.3). Furthermore, this gap in enrichment widens even further when comparing against distant star-forming galaxies, which, given the finite speed of light and the sheer scale of the Universe, are the true progenitors of local passive galaxies, as we see these distant galaxies directly as they were at an earlier epoch in cosmic history. Using models for chemical evolution, we find that the significant difference in enrichment implies that for galaxies at all masses, quenching must have involved an extended phase of starvation. We further find that the ejection of gas from galaxies becomes relatively less important for more massive galaxies. Thus, despite the direct observational evidence for powerful galactic winds in massive galaxies, both in the nearby and distant, early Universe, these ejection events must either be short-lived and/or most of the ejected gas does not escape the galaxy and is instead recycled at a later time.

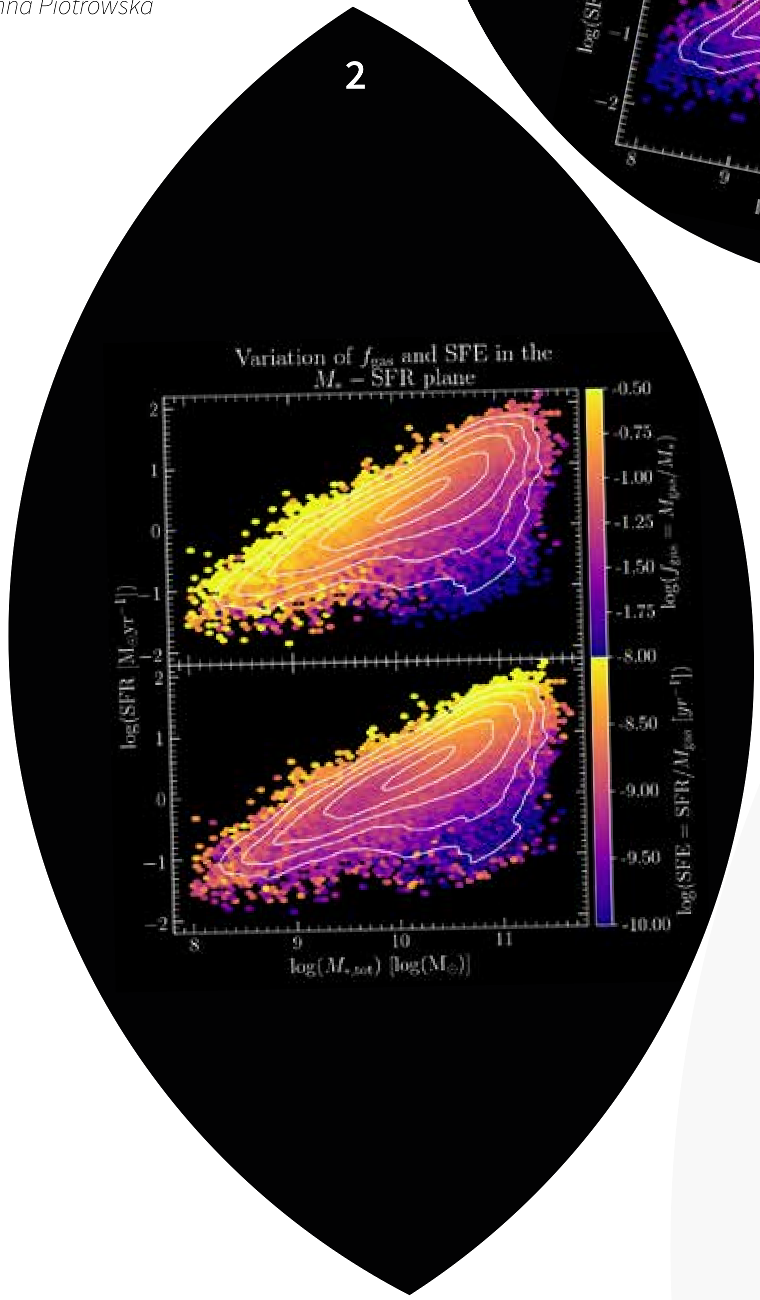
The results presented in this paper have been published in *"Both starvation and outflows drive galaxy quenching"* 2020, MNRAS, 491, 5406

Fig 1. The star-forming galaxy M101.
Fig 2. The passive galaxy M87.
Fig 3. The level of chemical enrichment (as measured by the stellar metallicity) against stellarmass, for local passive galaxies (red), local star-forming galaxies (blue) and the distant star-forming progenitors of local passive galaxies (dark blue).

HALTING STAR FORMATION: TWO TALES

Joanna Piotrowska





As already discussed in the previous article by James, most galaxies in the observable Universe can be classified into two broad categories, based on their colour and star formation activity. Thanks to the arrival of large sky surveys we can now differentiate between the blue, star-forming and the red, passive populations both locally and at higher redshifts. When observed across cosmic time, these two groups are interpreted as an evolutionary sequence in which actively star-forming galaxies transition to become quiescent in a process called “quenching”, in analogy to quenching a fire. Over the past 10 billion years, star formation activity in our Universe has been slowing down and thus understanding the physical processes responsible for its cessation is one of the most important questions in astrophysics.

Until present, quenching was shown to correlate well with the stellar mass of galaxies, their environment and morphology and a broad range of phenomena was suggested as potential origin of these observed relations. In order to differentiate among the plausible mechanisms, we need to access their key physical parameter – the cold molecular gas content of galaxies. It is challenging, because, unlike its ionized form, molecular hydrogen does not produce strong electromagnetic signature (at the typical temperatures of molecular clouds) and one can only infer its presence indirectly. State-of-the-art approaches include observing CO transitions, or far-infrared dust emission, and using empirically calibrated conversion factors to obtain hydrogen masses. These observations require long exposure times on prime facilities and hence the currently available sample sizes are of the order of a few hundred, insufficient for pinning down the physics at play.

Hence, we use a more indirect method to estimate the cold gas content of 60 000 Sloan Digital Sky Survey (SDSS) galaxies. This way we achieve a hundred-fold increase in sample size, greatly improving statistical power at the cost of individual measurement accuracy. We use an empirical relation between the amount of dust (small solid particles in the inter-stellar medium) and neutral gas. Dust grains absorb light preferentially at shorter wavelengths, causing “reddening” of the observed light, which affects the emission line flux ratios. We determine the strength of this effect, and hence the amount of gas, by comparing the observed ratios with their theoretical values set by atomic physics. With this method, we obtain the cold gas masses shown in Fig. 1, presented as a colour map in the stellar mass ($M_\odot$) – star formation rate (SFR) plane. The two circular inserts show an example of a star-forming (blue frame) and a passive galaxy (red frame), indicating the location of both sequences in the graph.

In order to understand the mechanism of quenching, we calculate two relevant quantities: gas fraction (f_{gas}) – the mass of gas divided by stellar mass, and star formation efficiency (SFE) – SFR divided by gas mass. Ultimately, one can imagine two scenarios in which galaxies cease to form news stars: the lack of fuel (the scenario explored by James in the previous article), where passive galaxies would be devoid of gas, i.e. have very low gas fractions; or plenty of fuel prevented from collapsing to form new stars, where passive galaxies would have low SFEs. Fig. 2 presents the variation in both quantities as function of their position in the $M_\odot$- SFR plane. It is apparent that as galaxies transition towards quiescence, both their f_{gas} and SFE decrease significantly. Moreover, the magnitude of change is comparable for both quantities, suggesting that both variations contribute equally during quenching.

This result indicates that, during transition to quiescence, galaxies not only decrease their available gas reservoirs, but also decrease the efficiency with which these reservoirs get turned into new stars. Our findings indicate that the commonly invoked scenarios of gas removal via outflows and heating of the galactic halos are not enough to quench galaxies as these would result in decreased gas fractions only. Moreover, our work also shows that neither of the processes is dominant, prompting further theoretical search for processes which would act to reduce the SFE, which have not received much attention in the literature as of yet.

Fig 1. Gas mass inferred for 60 000 SDSS galaxies in the $M_\odot$ SFR plane. The circular inserts show a typical active (blue) and passive (red) galaxy pointing to their location in the plane. Image credit: NASA/ESA.

Fig 2. Gas fraction f_{gas} and star formation efficiency (SFE) calculated for galaxies within our sample. Both gas quantities show a significant decrease during their transition towards quiescence.

MOLECULAR GALACTIC WINDS IN THE LOCAL UNIVERSE

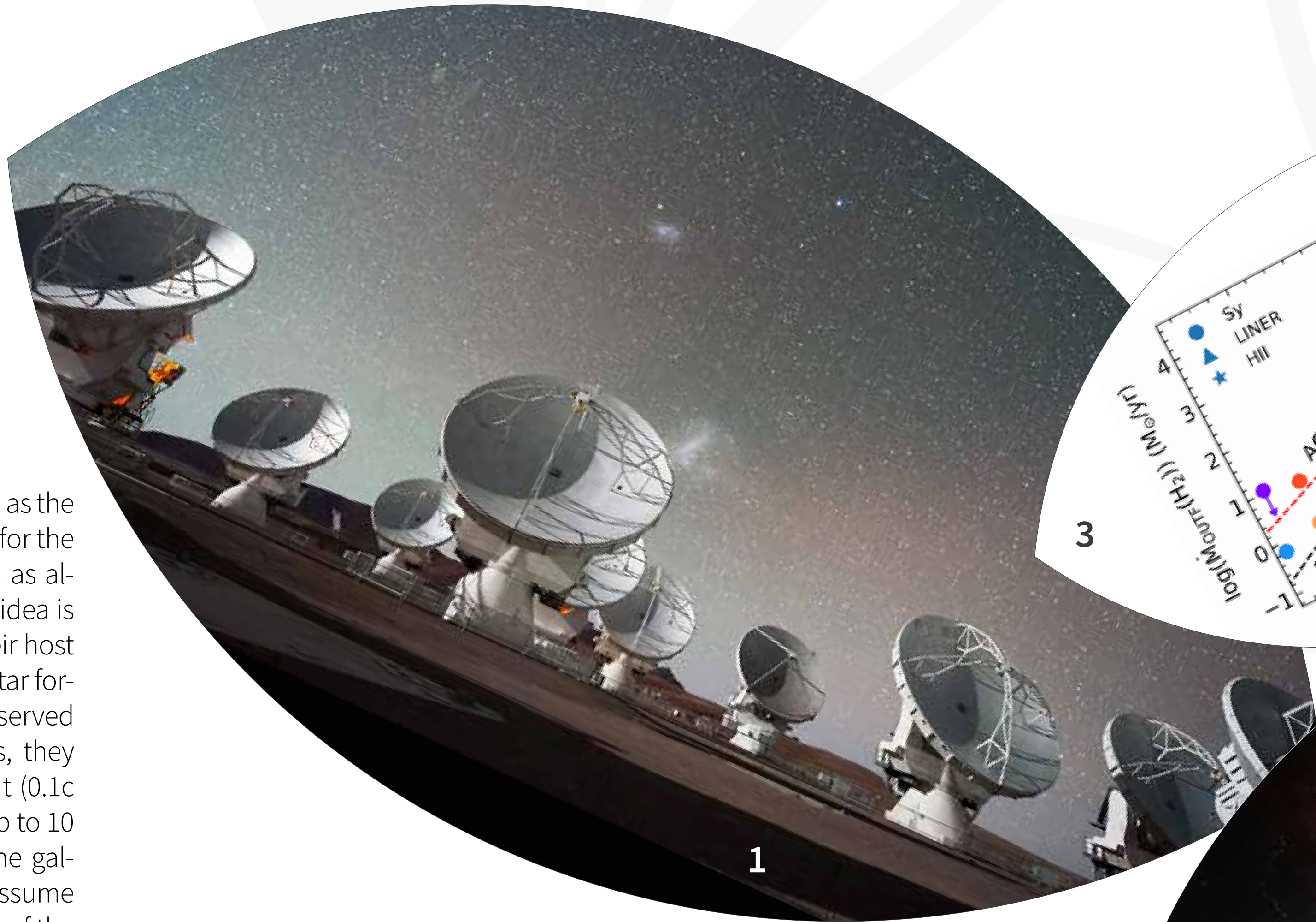
Andrin Fluetsch

Galactic winds or outflows have been invoked as the main feedback processes which can account for the rapid cessation of star formation in galaxies, as already discussed in the previous articles. The idea is that they eject large amounts of gas from their host galaxies and thus remove the fuel for future star formation. Galactic winds have indeed been observed in several different phases. In some phases, they reach velocities about 10% the speed of light (0.1c = 30'000 km/s) and they push material out, up to 10 kiloparsecs (33'000 light years) away from the galaxy's centre. Hence it seems reasonable to assume that they could affect the interstellar medium of the host galaxy profoundly.

We have focused on the molecular phase of outflows, which if of particular interest in this context, as stars form out of dense molecular clouds. Most molecular gas is in the form of molecular hydrogen, H_2, but this is difficult to observe. Instead, astronomers use emission lines of carbon monoxide, CO, at millimetre wavelengths, as a tracer of molecular gas mass.

With the Atacama Large Millimeter Array (ALMA) in Chile (Fig.2) molecular gas can now be studied with unprecedented sensitivity and spatial resolution. Our team (Andrin Fluetsch, Roberto Maiolino, Stefano Carniani, Martin Bourne and other international collaborators) used ALMA to investigate molecular outflows in about 50 galaxies. This is the largest study of molecular outflows to date, more than twice as large as previous ones. Many of these galaxies display powerful and massive outflows (with masses up to 1 billion times the mass of the Sun), in which the molecular phase generally dominates the mass budget. The observed outflows are driven by supermassive black holes or processes associated with star formation, such as supernovae explosions.

We find that both outflows driven by star formation and those driven by accreting supermassive black holes (i.e. Active Galactic Nuclei), with the latter boosting the mass outflow rate sometimes by a large factor (Fig.3). However, both of them fall below the expectations of theoretical models in terms of their capability of cleaning galaxies of their gas content. Moreover, we find that most of the material (> 95%) entrained in the wind does not escape the galaxy's gravitational potential. These findings suggest that galactic winds may not be able to suppress star formation as easily as commonly thought but rather in a delayed manner.



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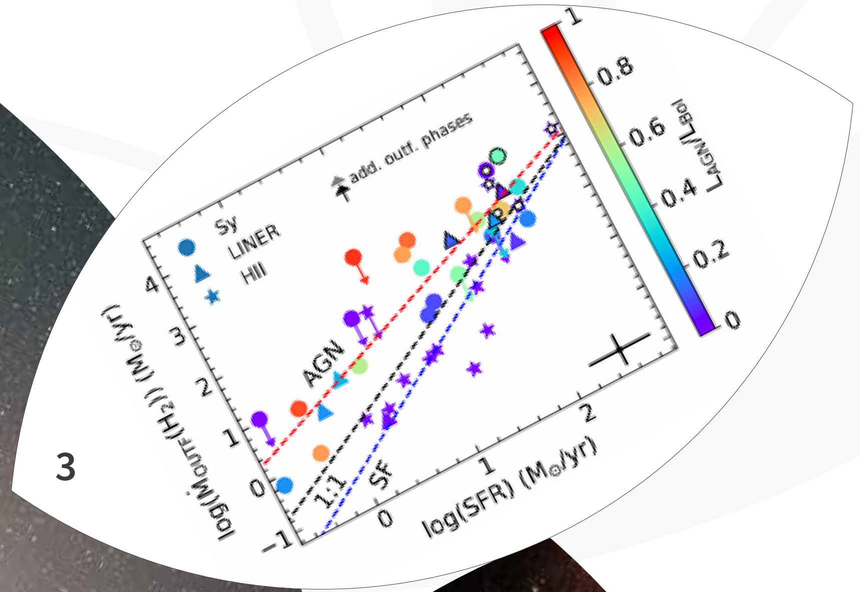

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In our study, we made another interesting and puzzling discovery. Some galaxies do not seem to agree with any known physical model. Specifically, they show strong outflows but the source of these outflows cannot easily be identified. The most likely explanation for these objects is that they are "fossil outflows", meaning that the source of these outflows, likely an accreting supermassive black hole, has faded and is no longer visible, but the outflow remains observable.

Our findings support the findings obtained by James and Joanna in the previous articles, that the ejective mode of galactic outflows is little effective in quenching star formation in galaxies. However, although outflows might not instantaneously stop star formation, they could have a more delayed feedback effect, for instance by heating the galaxy's surrounding. Furthermore, these galactic winds are possibly even more powerful at higher redshifts (i.e. when the Universe was younger). Future studies, some of them at the KICC, are now also studying galactic winds in galaxies tens of billions of light years away.

These results are published in *"Cold molecular outflows in the local Universe and their feedback effect on galaxies",* 2019 MNRAS, 483. 4586.

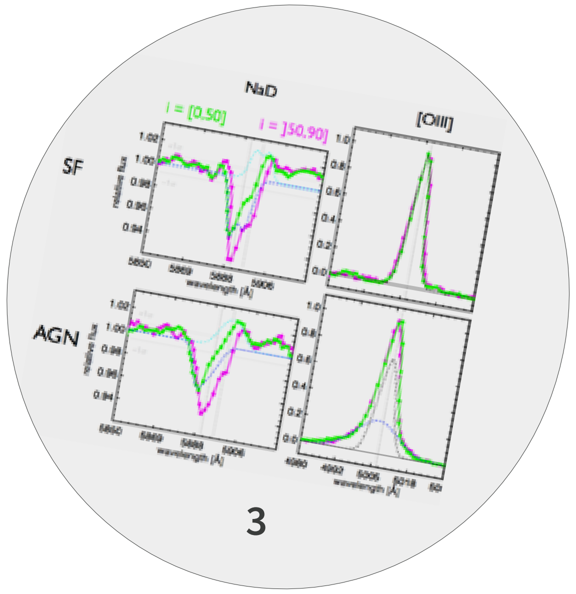
Fig 1. An artist's impression of a galactic wind driven by the black hole at the centre of the galaxy.

Fig 2. The Atacama Large Millimeter Array in Chile.

Fig 3. Molecular gas outflows rate versus star formation rate, where galaxies are color-coded by the dominance of Active Galactic Nuclei relative to star formation.

THE TWO FACES OF GALACTIC WINDS

Alice Concas



Galaxies are complex ecosystems whose growth and evolution through cosmic time is governed by the intricate exchange of gas flows with their surrounding environment.

While gas accretion is required to support their star formation activity, gas expulsion is another crucial phenomenon that regulates star formation and prevents galaxies from overgrowing, as already discussed in the previous article by Andrin.

Gas can be expelled through two main mechanisms. During the last phases of their life, massive stars can generate winds and supernova explosions of great magnitude whose cumulative effect can drive strong gas flows out of the galaxy. In addition, the accretion of material onto the SuperMassive Black Holes (SMBH) at the centre of galaxies, resulting into the so called active galactic nuclei (AGN), can release a huge amount of energy and radiation providing a further effective ejective mechanism via strong outflows. Such processes, usually referred to as star-forming (SF) and AGN ejective feedback, can remove gas from galaxies causing a drastic reduction of the fuel needed for the formation of new stars. Such ejective feedback is currently believed to be one of the causes responsible for the formation of "passive" galaxies, galaxies in which the star formation rate is very low or totally quenched.

While Andrin in his previous article has focussed on the molecular phase of galactic outflows, we have focussed on the warm (ionized) phase (traced by nebular emission lines in the optical band) and on the cold, atomic neutral phase (that can be traced by a transition of sodium, also in the optical band). We have investigated this effect by using spectra of several thousands galaxies, with a broad range of properties.

We have found that warm (ionized) outflows are far more common and more prominent among AGNs, while barely seen in star forming galaxies that do not harbour an accreting black hole. The cold, neutral atomic outflow appears instead to be primarily driven by the ejective phenomena associated with star formation, with an unnoticeable effect seen when an AGN is present (Fig. 2). Apparently, cold, neutral outflows are ubiquitously associated with star formation, while a significant warm, ionized component requires the presence of the powerful radiation field produced by an accreting supermassive black hole.

These findings have important implications to understand how galaxies evolve and co-evolve with their supermassive black hole, and in particular how these "double-faced" outflows affect the formation of stars in galaxies.

It is however important to investigate these properties in the distant universe, at the cosmic epoch when we know that galaxies were forming and transforming at a much higher rate than locally.

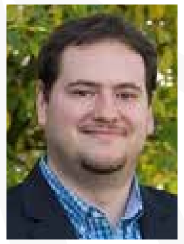
At KICC we are currently carrying out a project that exploits observations obtained with the K-band Multi-Object Spectrograph (KMOS) infrared spectrograph installed at the Very Large Telescope (Fig. 3) of the European Southern Observatory (Chile). Thanks to these observations we will be able to quantify the dynamics of warm/ionized and cold/neutral gas by revealing and mapping the final fate of these galactic gas flows for more than one hundred galaxies, at an epoch when the Universe was only 3 billion years (about 20% of it current age). In the longer term, we will investigate these properties for several hundred thousand distant galaxies by using the next generation multi-objects spectrograph MOONS for the Very Large Telescope, in which KICC has a major role.

Fig 1. The galactic outflow in the nearby starburst galaxy M82.

Fig 2. Left: The sodium line tracing cold, neutral atomic outflows which does not show significant differences between star forming galaxies (SF, top) and active galactic nuclei (AGN, i.e. supermassive accreting black holes, bottom). Right: The transition of ionized oxygen, trancing the presence of high velocity warm, ionized gas (broad component) only in the case of AGNs (bottom).

Fig 3. The Very Large Telescope of the European Southern Observatory.

WHO IS THE CULPRIT?



Asa Bluck

In the past few articles we have discussed the possible routes through which star formation in galaxies may be quenched: gas removal (through winds), starvation (lack of fresh gas supply) or suppression of the star formation efficiency. We have also explored what might be relative role between these processes. However, although conclusive results were obtained, those studies do not provide information about the primary culprit responsible for each of these processes, i.e. the culprit responsible for the death of galaxies.

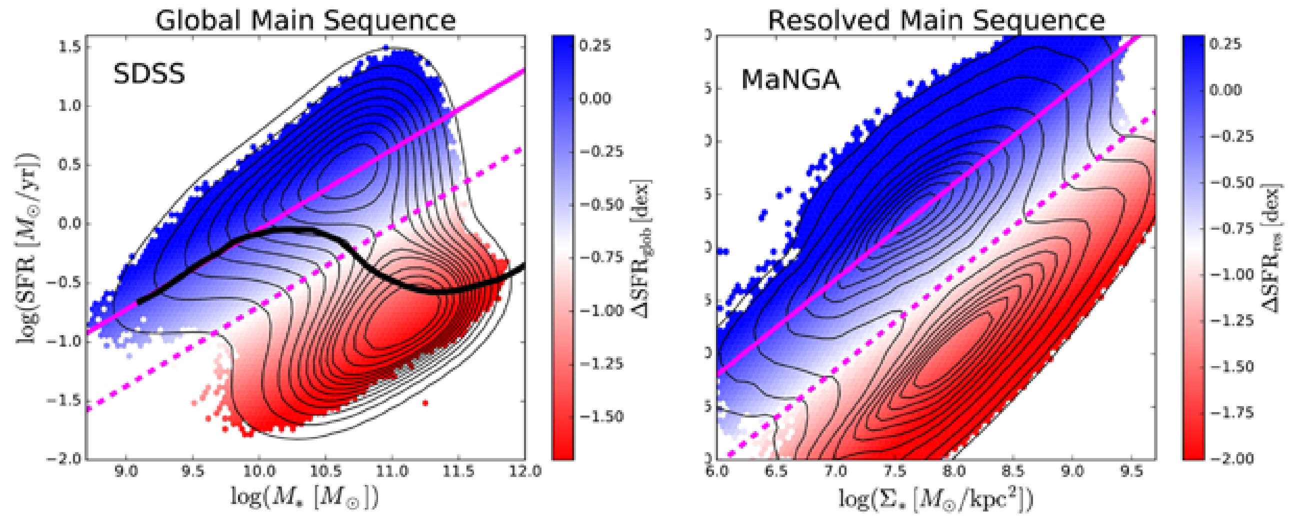
To answer this question, it is first important to recall that the environment in which galaxies live is not really devoid of gas that could be used as fuel for star formation. On the contrary, the vast majority of hydrogen gas in the Universe never makes it into stars (~90%) and instead tends to reside in a hot (ionised) halo around massive galaxies. Understanding why these hot gaseous haloes do not cool rapidly, leading to dramatic rejuvenation of star formation in massive galaxies, is a deeply challenging problem at the very heart of understanding galaxy evolution.

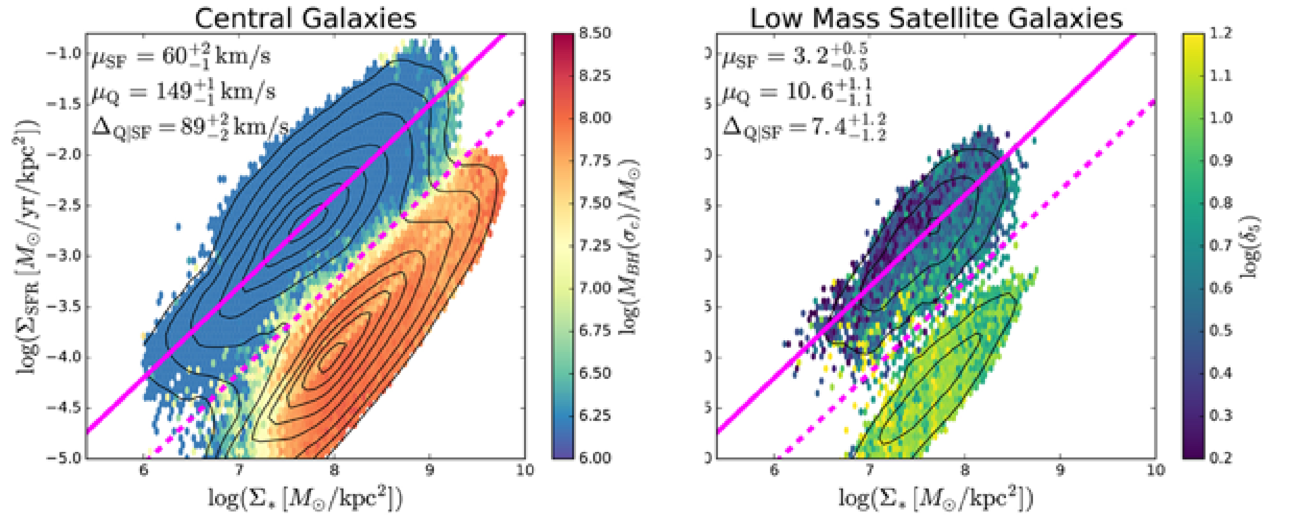
Over the past decade the two primary methods of optical astronomy (photometry and spectroscopy) have been combined in a revolutionary synthesis with Integral Field Spectroscopy (IFS). One can think about IFS in two ways - thousands of images of galaxies at very narrow wavelength ranges, or equivalently, thousands of spectra of galaxies at each spatial location. The largest IFS project to date is the Mapping Nearby Galaxies at Apache Point Observatory survey (MaNGA, Bundy et al. 2015). MaNGA is in the process of observing over 10,000 local Universe galaxies, spanning a wide variety of galaxy types - from blue spirals to red ellipticals. As such, MaNGA offers unprecedented insight into the inner-workings of both star forming and quenched galaxies, and hence what mechanisms may be responsible for quenching.

First, we established that the regions within galaxies also exhibit a clear separation between star forming and quenched (Fig. 1). Using a sophisticated suite of modern machine learning techniques (from artificial neural networks to random forests) we established that the quenching process is global - i.e. it acts in such a way as to impact entire galaxies, over relatively short time periods. For central galaxies (the most massive galaxy in their group or cluster), we found that the speed with which stars move in their cores (the central velocity dispersion, σ_c) is by far the most predictive parameter of quenching (Fig. 2). This result is particularly interesting because σ_c is well known to correlate strongly with supermassive black hole mass in galaxies, which offers a plausible mechanism for central galaxy quenching via energetic feedback from accretion, the so called active galactic nucleus feedback, i.e. the scenario in which the halo is heated by the energy deposited by jet or winds launched by the accreting black hole.

On the other hand, satellite galaxies (galaxies in orbit around their centrals) are found to have strong environmental dependence on their quenching (Figs. 2 & 3). At low supermassive black hole masses, satellite galaxies are more likely quenched than centrals, and satellites in clusters are the most frequently quenched systems. Strong interactions between galaxies, and stripping of gas via interactions with the cluster medium, are likely to be responsible for these enhancements in quenching of satellites. However, at high supermassive black hole masses, all populations of galaxies (centrals, satellites & cluster satellites) are found to be quenched.

In ongoing research, we are comparing the predictions from cutting-edge cosmological simulations to these new observational constraints, expanding our understanding of why galaxies stop forming stars.

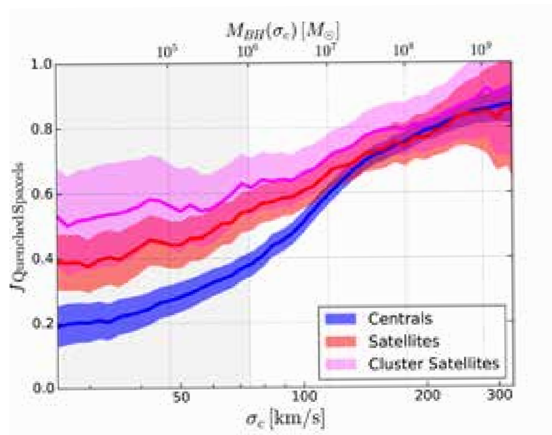




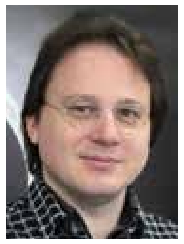
Panel 1a & 1b. Comparison of the galaxy (1a) and spatially resolved (1b) main sequence relationships, depicting the dependence of star formation rate on extant stellar mass. Each panel is colour coded by the distance to the star formation main sequence ridge line, shown as a magenta line. Note how both galaxies as a whole, and regions within galaxies, separate out into a star forming (upper contours, blue) and quenched (lower contours, red) population, divided by a dashed magenta line located at the minimum of the density contours. [Bluck et al. 2020]

Panel 2a & 2b. The resolved star forming main sequence for central galaxies, colour coded by the mean supermassive black hole mass within each hexagonal bin (inferred from the empirical $M_{BH} - \sigma_c$ relation). This is the parameter most predictive of quenching in both centrals and high mass satellites. Panel 2b: The resolved star forming main sequence for low mass satellite galaxies, colour coded by the density of galaxies surrounding the satellite. This is the parameter most predictive of quenching in low mass satellites. [Bluck et al. 2020]

Fig 3. The fraction of quenched spaxels plot as a function of the central velocity dispersion (σ_c) of the host galaxy. This figure shows the results for centrals, satellites and cluster satellites (in blue, red and magenta, respectively). Additionally, the supermassive black hole mass associated with each central velocity dispersion is shown as an additional upper x-axis. At low black hole masses, satellites are more quenched than centrals, with cluster satellites being the most quenched population. However, at high black hole masses, all types of galaxies are quenched.



UNRAVELLING THE NATURE OF DARK MATTER WITH INTERGALACTIC HYDROGEN GAS



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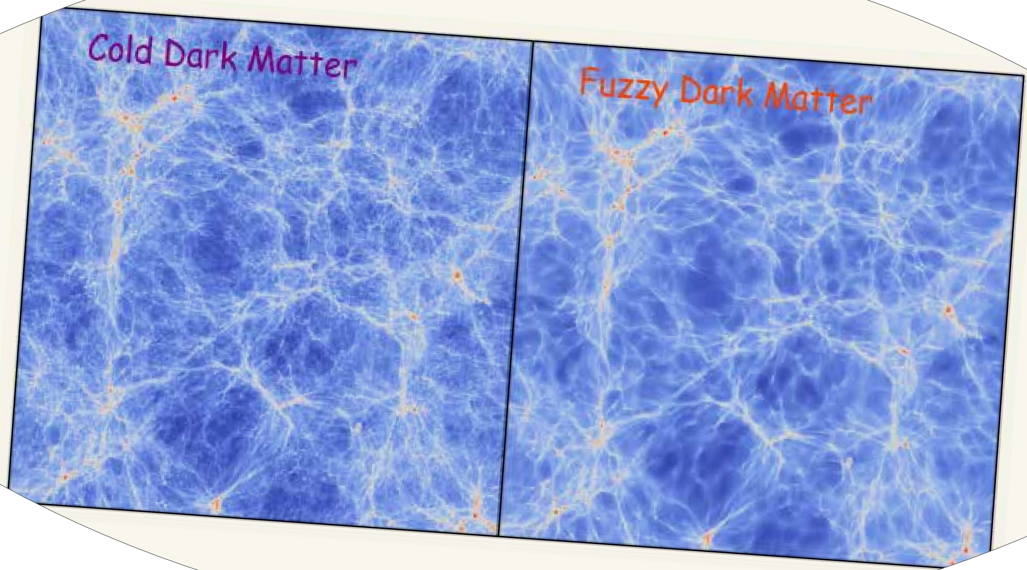

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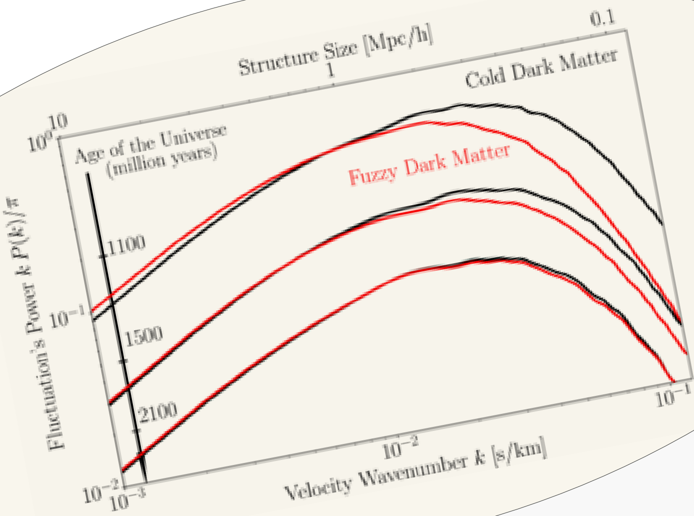

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It has been nearly 50 years since the realisation that dark matter exists, and that it is different from the baryonic matter that makes up protons and atoms. Astrophysical observations tell us that it is much more ubiquitous than the baryonic matter, constituting more than 85% of the matter in the Universe. The most natural explanation is that the dark matter is made up of massive, weakly interactive particles. This has become known as the Cold Dark Matter, and works excellently when explaining galaxy clustering or cosmic microwave background. The exact mass of such particles however, remains unknown.

One of the simplest scenarios suggests that the dark matter particles were produced in the early Universe such that they were in thermal equilibrium with the baryonic matter. However, due to their weak interactions they decoupled and have acted as dark matter particles since. If the average velocity due to the thermal motion of the particles at the time of decoupling is much smaller than the rest mass of the particle, this leads to the limit of the Cold Dark Matter. On the other hand, if the average velocity at the time of decoupling is much larger than the mass of the particles, these particles are able to free stream and erase the gravitational wells that would later seed galactic structures.

The largest size of the erased structures depends on the time it takes the particles to become non-relativistic, which in turn depends on the mass of the particles, with smaller masses resulting in longer time for the particles to become non-relativistic. These models are sometimes collectively called the Warm Dark Matter models.

Another alternative scenario are axions, or axion-like particles. The axion is a very light (~ 10^{-6} eV) boson proposed to solve the parity and charge conjugation problems in the strong sector of the standard model of particle physics. The production of such light scalar particles is also predicted in abundance in string theories. The axion-like particles behave very similarly to the axion, but have a range of possible masses and can be much lighter than the axion. If the axion-like particle masses fall in the 10^{-22}-10^{-20}eV mass range, their de Broglie wavelength reaches galactic scales. The uncertainty principle prevents localization of the wave front below the particles de Brogile wavelength, as the increase in the momentum is opposed by any attempts to confine the particle further. This leads to natural suppression of galactic structures on scales smaller than de Brogile wavelength. However, unlike the free streaming of the Warm Dark Matter model, this is present in the very seeds of the gravitational wells already. Such models are collectively referred to as Fuzzy Dark Matter models.

Although Warm and Fuzzy Dark Matter models are wildly different, they have very similar effect on the formation and evolution of structure in the cosmic web: both of them suppress the structures on small scales, and the scale is set by the mass of the particles. This signature would appear in the distribution of matter – both dark and baryonic – in the Universe, as shown in Fig. 1. The cosmic web in a Cold Dark Matter simulation (left panel of Fig. 1) is showing smaller and sharper structures compared to the same simulation but with a Fuzzy Dark Matter model (right panel of Fig. 1). To look for the amount of structure we used a statistical measure -- the fluctuation's power spectrum. The fluctuation's power spectrum is a clustering measurement of the intergalactic hydrogen gas, obtained by looking at the transmission spikes tracing the matter density along the lines of sights to distant quasars. The difference between a Cold and Fuzzy Dark Matter model is at short distances, and at early times (as shown in Fig. 2).

We have combined data obtained at the ESO Very Large Telescope and at the Keck Observatory, with a new suite of state-of-the-art hydrodynamical simulations including Cold, Warm and Fuzzy Dark Matter models. The analysis put the tightest lower limits on the particle masses allowed by the current data, ruling out masses below 5.3 keV for Warm Dark Matter, and below 2 x 10^{-21} eV for Fuzzy Dark Matter models.

Fig 1. A slice through state-of-the-art hydrodynamical simulation with a width of 20 Mpc/h. Left: Simulation ran with the standard Cold Dark Matter model. Right: Simulation ran with the Fuzzy Dark Matter model. In this case the structure seen in the Cold Dark Matter model is washed out and erased.

Fig 2. A sketch of the flux power spectrum as measured in the quasar spectra data. The flux power spectrum measures the amount of structure of a given size. Compared to a Cold model, Warm and Fuzzy Dark Matter models show additional suppression of structures below 1 Mpc/h scale, with the suppression being more apparent earlier in the Universes history..

GALAXY FORMATION IN FUZZY DARK MATTER COSMOLOGY

Anastasia Fialkov (together with P. Mocz - Princeton University)

Shortly after the Big Bang, dark matter particles would have clumped together forming gravitational 'halos' in which gas could accumulate, cool down and condense into stars. Therefore, dark matter is the starting ingredient for brewing up the very first galaxies in the Universe. Without dark matter there would have been no galaxies, no life, no humans. Although dark matter is considered to be the backbone of the cosmic structures in the Universe, we know very little about its nature, as the particles have so far evaded detection. Understanding the nature of dark matter is one of the fundamental questions science aims to answer.

While dark matter has yet to be directly detected, the cold dark matter (CDM) hypothesis has proven to be quite successful at describing the large-scale structure of the observable Universe. As a result, most models of galaxy formation are based on the assumption that dark matter is cold, made up of slow-moving particles that, aside from gravitational, have no interactions. However, direct searches failed to detect CDM particles, shifting the interest of the scientific community to alternative theories including warm and fuzzy dark matter scenarios. Warm dark matter (WDM) is thought to be a slightly lighter and faster version of CDM. Fuzzy dark matter, the main focus of our research, is something entirely different, consisting of ultralight particles. Evolution of such particles is subject to quantum effects leading to unique characteristic patters in cosmic web and the structure of first galaxies. These particles act in a quantum, wave-like fashion, rather than as individual particles.

With colleagues at Princeton University, MIT and elsewhere, we have conducted a series of first-of-the-kind simulations to compare the buildup of first galaxies in CDM, WDM and FDM. In our simulations, we found that (on relatively small scales) cosmic web would have looked very different in the three scenarios (Fig. 1) with galaxies forming first in extended filaments in FDM and WDM rather than in spherical halos, as it happens in CDM. Furthermore, the size, shape, and fragmentation of these filaments have distinct differences between FDM, WDM and CDM.

In all three scenarios, galaxies formed wherever there were over-densities, or large concentrations of gravitationally collapsed dark matter. The pattern of this dark matter, however, was different, depending on whether it was cold, warm, or fuzzy (Fig. 1). In a scenario of cold dark matter, galaxies formed in spherical halos, as well as smaller subhalos (Fig. 2). Warm dark matter produced more filamentary-like first galaxies, and no subhalos. This is due to warm dark matter's lighter, faster nature, making particles less likely to stick around in smaller, clumps. In a similar way to warm dark matter, fuzzy dark matter formed stars along filaments (Fig. 3). But then quantum wave effects took over in shaping the galaxies. The dark matter cosmic filaments are unstable, and where gravity is strong enough, the overdensities form stable spherical structures, called solitons, in the filament. These solitons are unique to FDM. Their characteristic features are imprinted in the distribution of gas and stars and are potentially observable.

Even though in the late Universe these different dark matter scenarios are designed to predict similar shapes for galaxies, the look of the first galaxies formed at the dawn of star formation in the early Universe would be strikingly different. Therefore, modelling and observing the first galaxies may illuminate what type of dark matter we have today. As new telescopes such as the James Webb Space Telescope (in which KICC is heavily involved) are coming online, with their ability to see further back into the early Universe, scientists may be able to deduce, from the pattern of early galaxies, whether the nature of dark matter is fuzzy as opposed to cold or warm. In our work, for the first time, we have simulated what early galaxy formation would have looked like if dark matter were "fuzzy," rather than cold or warm.

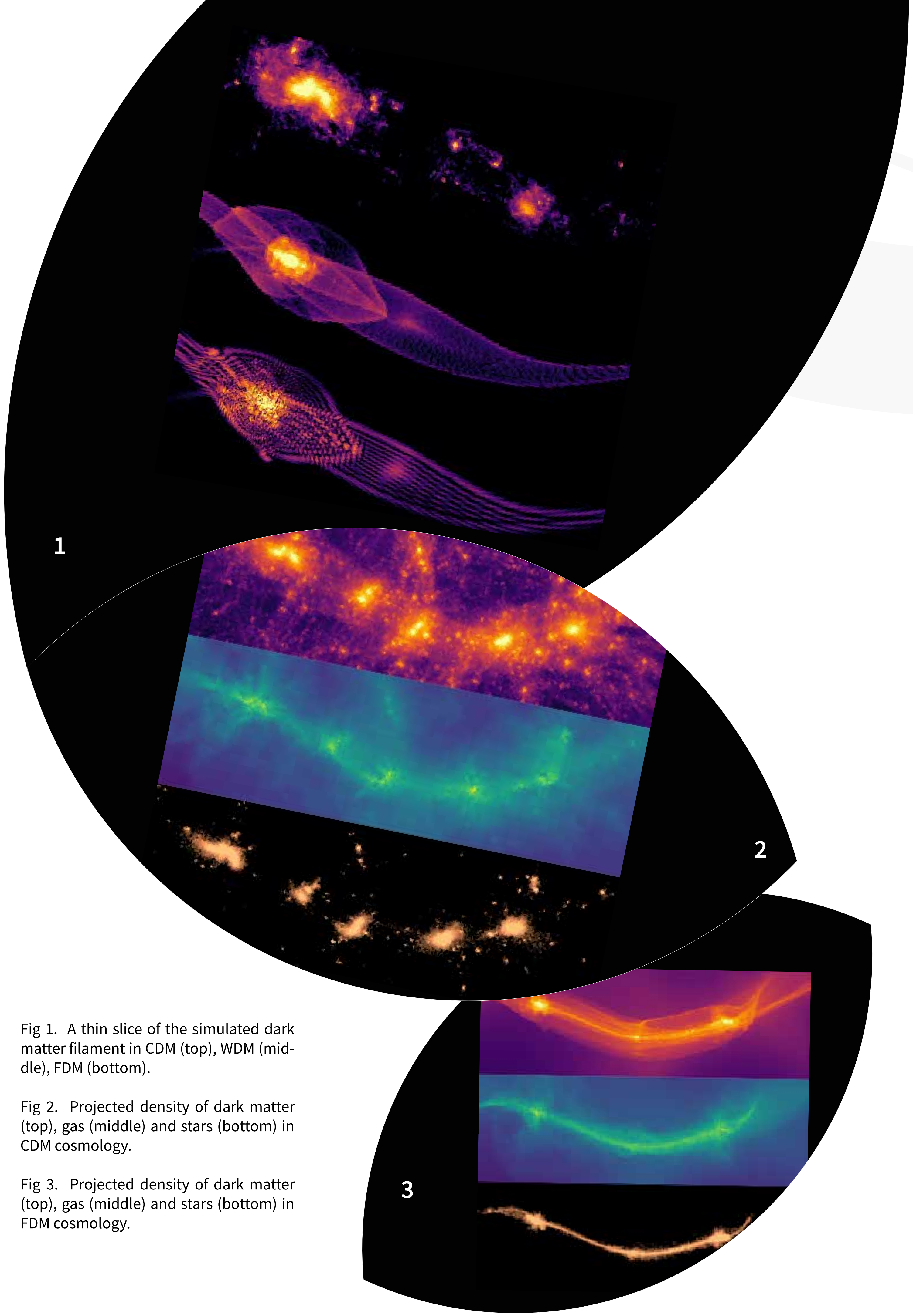
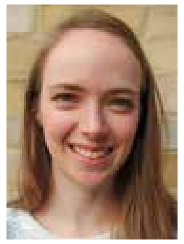


Fig 1. A thin slice of the simulated dark matter filament in CDM (top), WDM (middle), FDM (bottom).

Fig 2. Projected density of dark matter (top), gas (middle) and stars (bottom) in CDM cosmology.

Fig 3. Projected density of dark matter (top), gas (middle) and stars (bottom) in FDM cosmology.

OBSERVING FILAMENTS WITH WEAK LENSING



Naomi Robertson

It is now well established that the matter we observe – galaxies, dust and gas is not uniformly distributed throughout the Universe. We see instead that visible matter follows a web-like structure, that we believe was created through a process of hierarchical structure formation. The same distribution of matter is seen in N-body simulation and from this combination of observation and simulation we think that this 'cosmic web' traces an underlying dark matter skeleton. The cosmic web can be loosely described by four environments: voids, sheets, filaments and clusters. Voids are large regions that contain few galaxies and are enclosed within sheet and filament structures (anisotropically collapsed surface and line structures). Where filaments and sheets intersect, the densest isotropic regions are formed which we recognise as massive halos. This web structure is evident across many scales so that these halos contain massive galaxies up to groups of galaxies and clusters. From the Zel'dovich approximation and simulation we expect that nearly half of the mass in the Universe is contained within filaments. However, observing filaments comes with a variety of difficulties primarily due to filaments having a low density contrast.

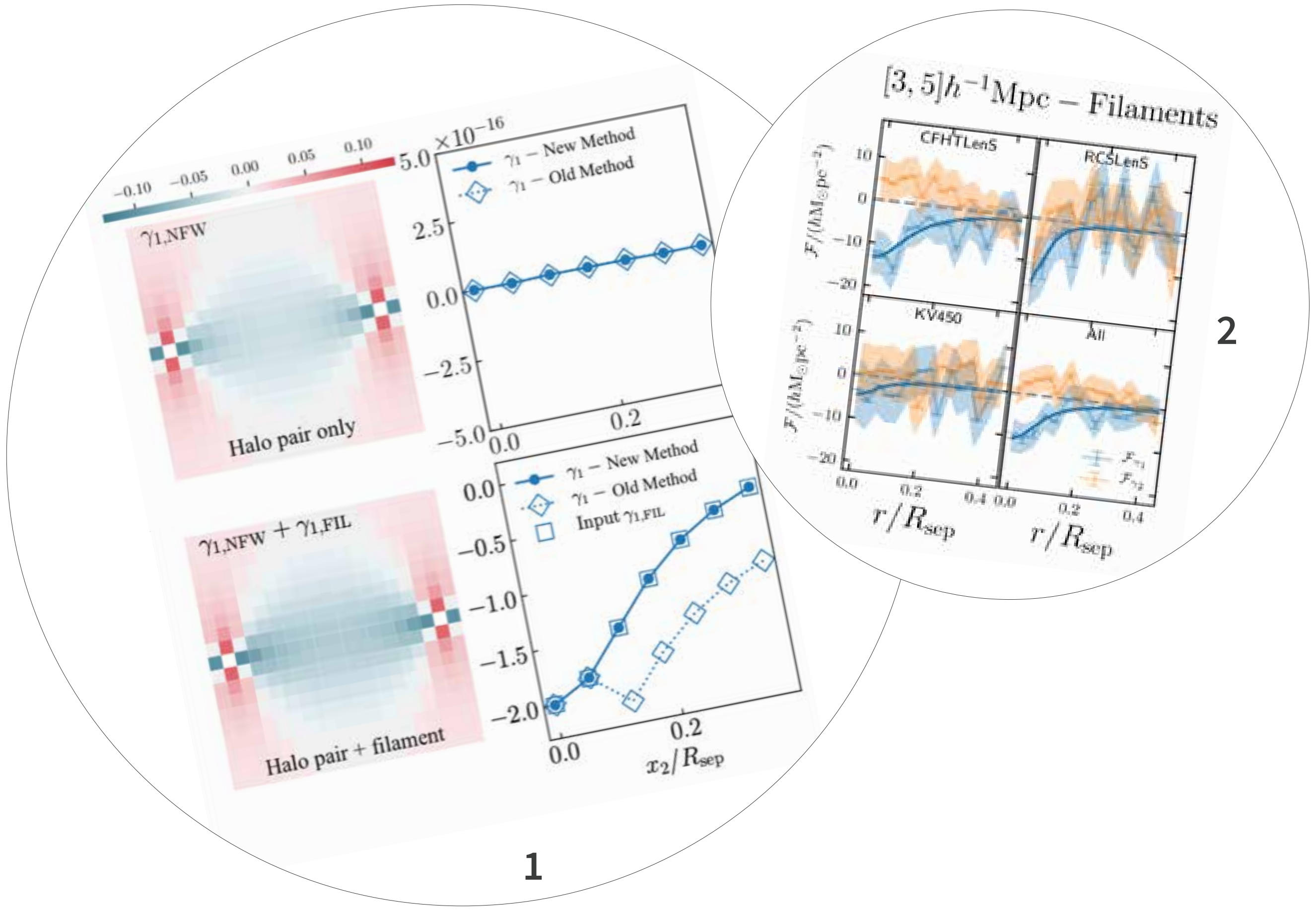


Fig 1. In the two left plots, the lensing shear component is shown in the case of a pair a halos (top) and a pair of halos with a connecting filament (bottom). The right plots show the nulling method applied to each case. It can be seen that in the new method the filament signal is exactly recovered.

Fig 2. The nulled lensing signal is shown on the y-axis as a function of distance from the filament axis. The signal is shown in blue with a systematics test shown in orange.

Weak gravitational lensing provides a potential method for filament studies as a well established probe of halo objects. The lensing effect exists due to structures changing the path light travels. In practice we observe this as the distortion of distant galaxies around foreground structures, most notably around massive galaxy clusters. Therefore, this distortion effect contains information about the mass of structures and is sensitive to both dark and baryonic components. Previous studies have considered single filaments connecting massive clusters. However, this approach cannot detect most filamentary structures as their signal would be too low to detect. Alternatively, we can consider stacked measurements analogous to halo-lensing, which is already a well developed field. Since we expect halos that are closely separated to be connected by a filament, pairs of galaxies can be used as positions to measure the lensing effect around. The halos themselves produce a lensing signal which dominates the measurement, implying that the presence of a filament cannot be easily disentangled. However, we have constructed methods that effectively remove the circularly symmetric contribution from a pair of halos, which we refer to as a 'nulling' technique.

Fig. 1 shows an improved nulling technique, which in theory recovers the exact filament profile and removes all contamination from the halo tracers. This approach can be understood as a three-point galaxy-galaxy-shear correlation function, conditioned on specific intervals of separation between lensing galaxies.

The approach described above is applicable to wide field spectroscopic galaxy surveys that cover the same sky observed by an optical weak lensing survey. We have used the Luminous Red Galaxy (LRG) sample from the BOSS survey, to trace potential filaments by selecting pairs of galaxies which have a small separation in three dimensions (hence the importance of having a spectroscopic galaxy sample). To be able to measure a stacked lensing signal, the pairs of galaxies are rotated and rescaled. BOSS has an area overlapping with weak lensing datasets from the KV-450, CFHTLenS and RCSLenS surveys. The area overlap corresponds to about 11,000 filament candidates. With these datasets we find that we can detect an anisotropic lensing signal, although at low significance, (Fig. 2). This is in line with expectations from simulations, which found that LRGs with a small separation are all connected. Considering a filament density model motivated by simulations of large scale structures, we can also estimate the average density at the centre of these filaments, which we find to be around 15 times the critical density. This measurement is intrinsically noisy because of blurring by large scale structures. We expect major improvements from the reduced systematics and increase in sky-area observed with upcoming the DESI and Euclid surveys.

These results were published in Xia, Robertson et al. (2020, A&A 633, A89).

GRAVITATIONAL WAVES WITH LIGO AND VIRGO

Michalis Agathos

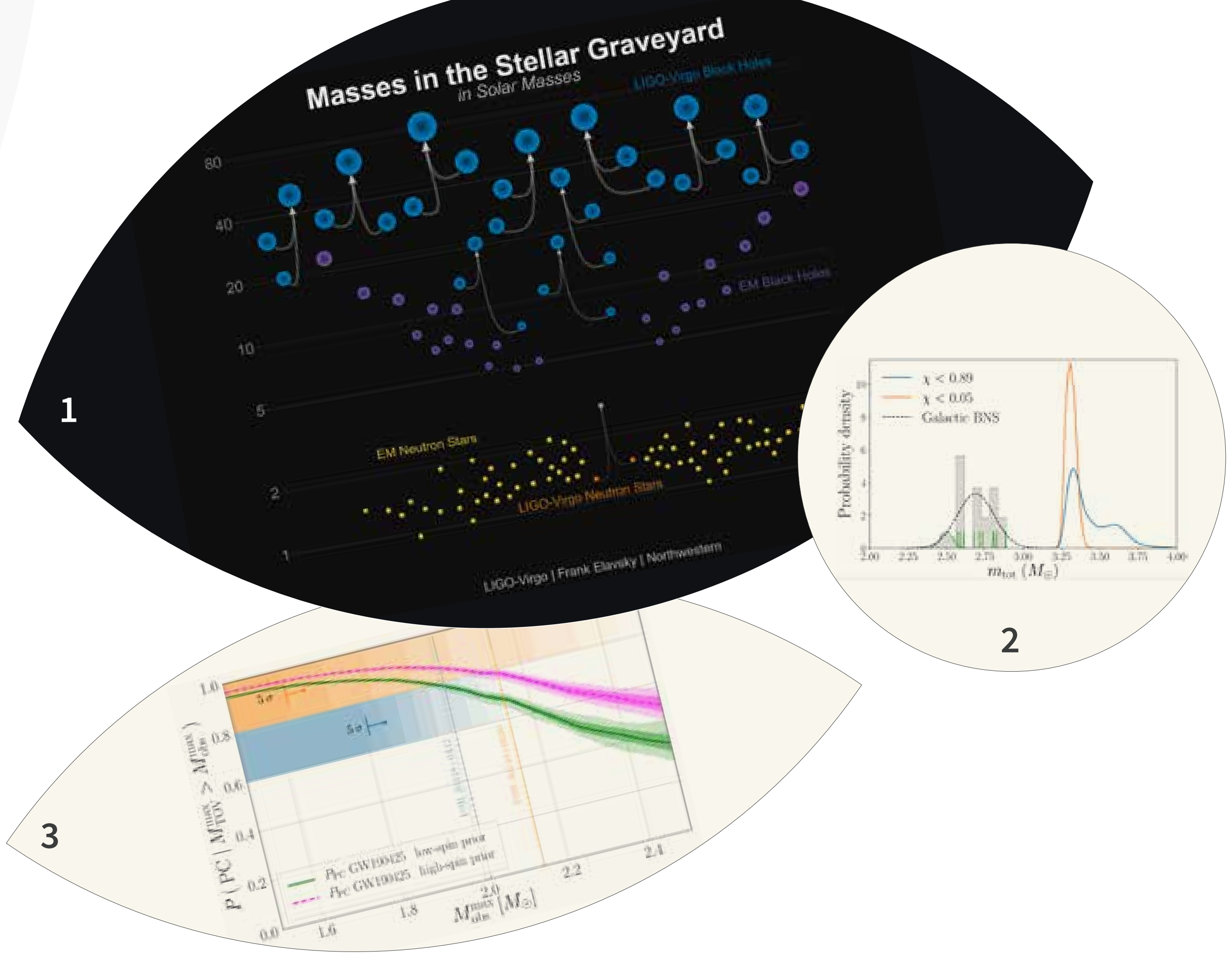
One of the major scientific developments of the 21st century that radically changed the landscape of gravitational physics and astrophysics was the detection of gravitational waves (GW) by the LIGO and Virgo observatories. With this achievement, human kind has activated a new sense for observing the Universe, with an entire new spectrum waiting to be explored. The Cambridge LIGO group mainly consists of KICC researchers (Nathan Johnson-McDaniel, Ulrich Sperhake, Anthony Lasenby, Michalis Agathos), who have made numerous contributions to the analyses and scientific results based on LIGO/Virgo data, and have developed methods that use GW observations to address long-standing questions in fundamental physics. Most crucially, we aim at probing the nature of spacetime, gravity and matter in extreme conditions by observing some of the most violent events in the history of the Universe, such as mergers of black-hole and neutron-star binaries, or the death of stars in Supernova explosions. We are investigating alternative theories of gravity, most notably massive scalar-tensor gravity that serves as a well motivated alternative to Einstein's General Relativity, as well as more exotic objects, such as boson stars, "hairy" black holes, wormholes, cosmic strings and black holes in higher-dimensional spacetimes. By modelling the theories' GW phenomenology we can compare their predictions against the observed data.

Fig 1. Masses of binary black- hole (blue) and neutron-star (orange) mergers detected by LIGO/Virgo up until the end of the second observing run, O2. Credits: LIGO/VIrgo/ Northwestern Univ./Frank Elavsky.

Fig 2. Probability distribution of the total mass of the neutron-star binary system whose coalescence produced the GW event in 2019, compared with Galactic pulsar binary systems. The two curves are obtained assuming a realistic or agnostic upper limit on the rotation rate.

Fig 3. The probability (vertical axis) that the remnant of the GW190425 binary merger promptly collapsed to a black hole, plotted as a function of the heaviest observed neutron star mass (horizontal axis, annotated with the two heaviest pulsar measurements to date). The two curves assume the rotation rate limits of Fig.2. In either case, the remnant is likely massive enough to promptly collapse to a black hole after merger.

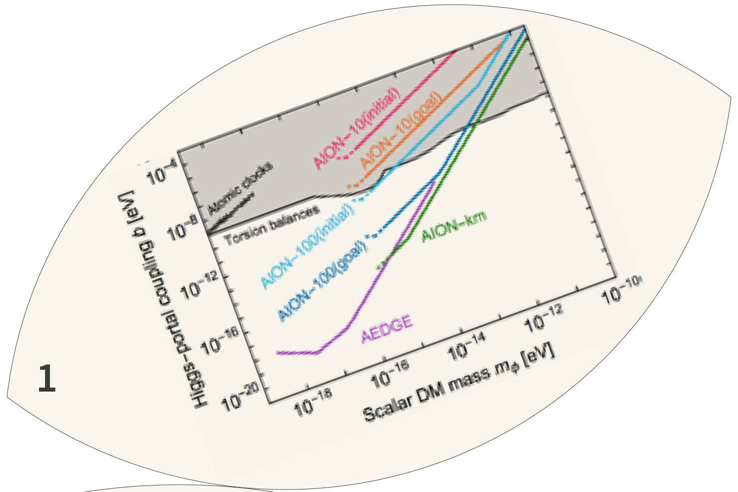
Since the first detection in September 2015 (GW150914), the two LIGO detectors in Hanford and Livingston (USA) and the Virgo detector in Cascina (Italy) have undergone significant instrumental upgrades. As the sensitivity improves and the instrumental noise is being meticulously pushed to unprecedented lows, the "horizon" of our network of observatories reaches ever-increasing distances.
Consequently, the rate of detections, being proportional to the volume of accessible universe, has very quickly gone up by more than an order of magnitude. Within 4 years, the task of detecting GWs has been transformed from nonexistent to a weekly business! So far, the LIGO/Virgo network has recorded more than 12 verified GW detections, all related to coalescing compact binaries, while more than 50 candidate triggers in total are being thoroughly followed up, many of which will soon be added to the list of confirmed GW events. Researchers at KICC have led a series of investigations that have shown consistency of the thus far confirmed GW signals with the predictions of General Relativity.



In 2017 came the first detection of GWs emitted by two neutron stars spiralling into each other (GW170817). Neutron stars are the most dense astrophysical objects known to date, reaching densities larger than those of atomic nuclei. These compact objects are the last frontier separating dense matter from complete gravitational collapse into a black hole. While our knowledge on the properties of neutron-star matter has remained uncertain for decades, the copious emission of GWs by coalescing neutron stars makes them the perfect natural laboratory that may yield such information. As a result of finite-size effects — most notably tidal deformations that the gravitational field of each star induces on its companion — the spacetime geometry, the orbital dynamics and, in turn, the emitted gravitational waveform, undergo a subtle, yet measurable modification. With the analysis of data from GW170817, we thus managed to constrain the *equation of state* of neutron-star matter and the two neutron stars' radii to unprecedented levels. On the 25th of April 2019, a second GW signal from a neutron-star binary was detected. This time the system was exceptionally heavy, at least as far as neutron star binaries go. Their total mass, estimated at 3.4+0.3 $M_\odot$, is far larger than the typical values seen in Galactic pulsar binaries (Fig. 2). This raises some very intriguing questions regarding the nature of this binary and, more importantly, may challenge our current understanding of the mass range for neutron stars and black holes. But what was the fate of this merger, what type of remnant did it leave behind? To answer this we made use of information on the properties of neutron-star matter, that we had gained from the first event back in 2017. After tuning and validating two different methods using a large number of state-of-the-art Numerical Relativity simulations, we infer that the binary of this second event was massive enough to promptly collapse upon merger, forming a black hole (Fig.3). Hence (unlike the case of GW170817), we did not expect a strong electromagnetic afterglow.

DETECTING DARK MATTER AND GRAVITATIONAL WAVES WITH AION

Val Gibson & Roberto Maiolino



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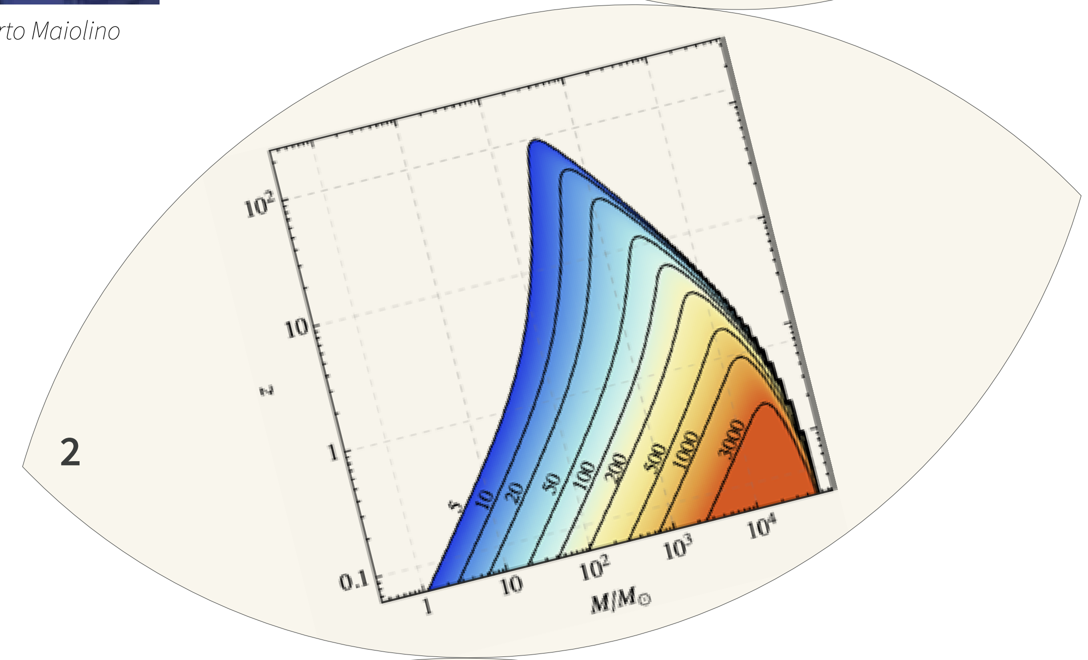

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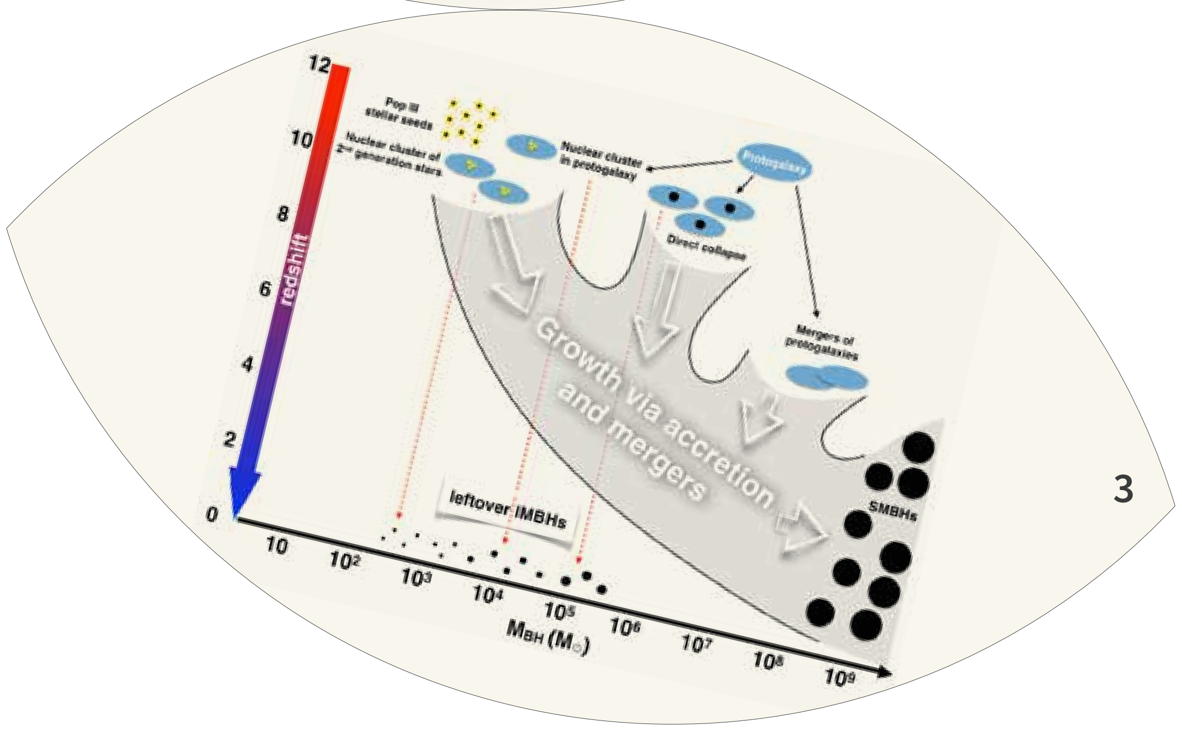

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In 2019 KICC committed significant resources that have enabled Cambridge to play a prominent role in AION (Atom Interferometer Observatory and Network) and its counterpart, MAGIS, based at the Fermi National Laboratory in the USA. AION is a new UK-based experimental programme exploiting a novel concept based on several atom interferometers using cold atoms in free fall. The system will be sensitive to a frequency range that makes it optimal to detect putative time-varying signals from various phenomena in a domain that cannot be explored by other current or future facilities, enabling potentially ground- breaking results, as discussed in the following.

The AION programme will be developed in four stages, by constructing gradually longer vertical detectors, spanning from an initial length of 10m, up to 100m and to km-scale and, finally, satellite-based ('AEDGE' reaching thousands of kilometres scale). Moreover, AION will be combined in a network with MAGIS in the USA, as well as with other interferometers, to further expand its capabilities.

The frequency range (~0.01 H_Z to 10 H_Z) in which AION will be highly sensitive will make it the optimal experiment to search for signals caused by ultra-light bosons. The discovery of these particles would be a breakthrough and could reveal the nature of Dark Matter. There are several such candidate ultra-light bosons - including dilatons, relaxions, moduli, axions and vector bosons - that are able to produce a signal in the frequency range of AION. Such hidden-sector particles could play a crucial role in particle physics beyond the Standard Model. The early stages of AION will already have the potential to search for ultra-light dark matter candidates in a large mass range from ~ 10^{-12} to ~ 10^{-17} eV with unprecedented sensitivity (Fig.1).

AION will also be a fantastic experiment for the detection of gravitational waves in the mid-frequency range, where currently operating and planned GW detectors are relatively insensitive. In this frequency range it will be possible to detect the merging of Intermediate Mass Black Holes (IMBH), with masses in the range from 100 to 10,000 solar masses, up to high redshift (Figs.2-3). These IMBH are expected from various theories as the result of the first generation of stars and from the direct collapse of pristine clouds in the early Universe, and are thought to be the building blocks (through merging and accretion) of the super-massive black holes found at the centres of galaxies (Fig.4). Additional fascinating sources of gravitational waves in the frequency band of AION are first-order phase transitions in the early Universe and cosmic strings.

By leveraging on our expertise in control electronics and cold atoms systems, Cambridge will provide an essential contribution to various key technical aspects of the AION project and will also contribute to the parallel MAGIS project. Obviously, Cambridge is also contributing to develop the science cases of AION and MAGIS and, by being involved in these projects in their early phases, we will be on the front line for their scientific exploitation when they become operational.

[This article is partly based on the White Paper *Badurina et al. 'AION: An Atom Interferometer Observatory and Network' arXiv:1911.11755v2]*

Fig.1. Sensitivities of different AION scenarios to scalar DM interactions with the Higgs portal. The grey regions show parameter space that has already been excluded through previous experiments.

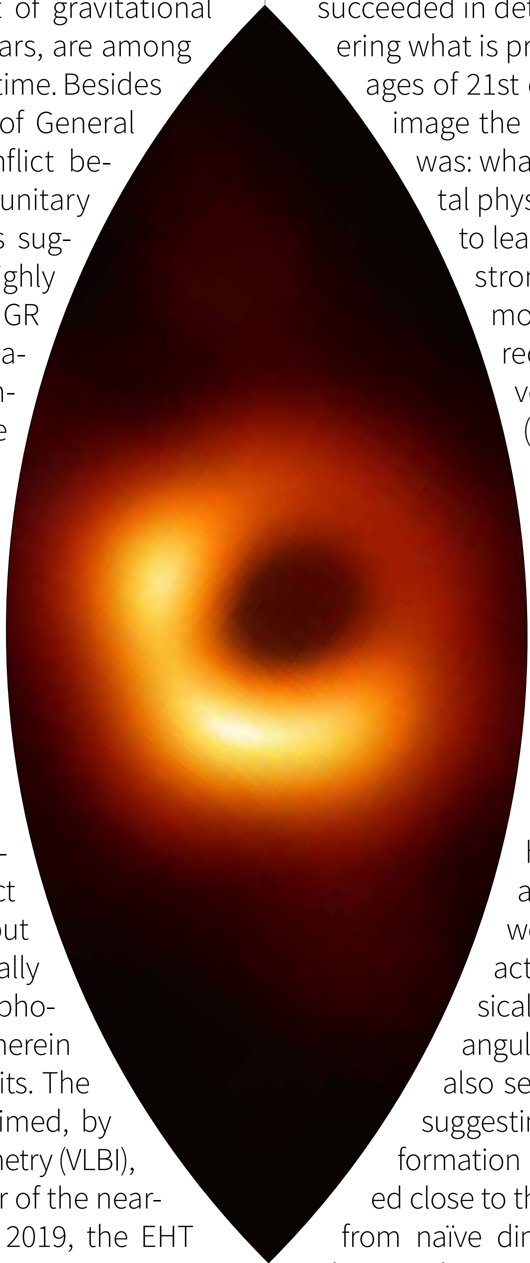
Fig.2. Sensitivity of AION (1km) o the mergers of IMBHs with the contours showing the signal-to-noise ratio.

Fig.3. Possible pathways for the formation of Supermassive Black Holes (SMBHs), several of which pass through the formation and mergers of Intermediate-Mass Black Holes (IMBHs), with some IMBHs left over at low redshifts (courtesy of Woods et al. arXiv:1910.06346).

BLACK HOLE SHADOWS AS WINDOWS ONTO FUNDAMENTAL PHYSICS

Sunny Vagnozzi

Fig 1. the image of the black hole M87* delivered by the Event Horizon Telescope. The dark central region is the black hole shadow. Credits: Event Horizon Telescope collaboration.

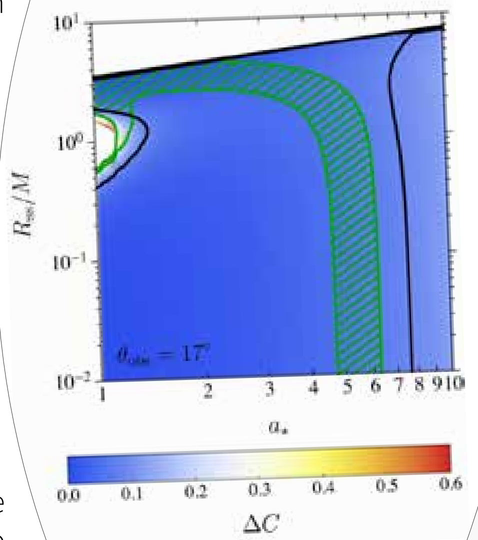


Black holes (BHs), the end point of gravitational collapse of sufficiently massive stars, are among the most bizarre regions of space-time. Besides being a fundamental prediction of General Relativity (GR), the apparent conflict between Hawking BH radiation and unitary evolution in quantum mechanics suggests that BHs likely hold the highly coveted key for the unification of GR and quantum mechanics. Observations of BHs can therefore, in principle, provide powerful tests of the laws of gravity in the strong-field regime, and possibly of the structure of space-time itself.

What would we "see", were we to image a BH? To a distant observer, an accreting BH surrounded by a geometrically thick optically thin emission region would appear as a dark central region (the BH shadow) surrounded by a bright emission ring. The shadow is not a direct image of the BH event horizon, but is approximately the gravitationally lensed image of the interior of the photon sphere, the region of space wherein photons travel along unstable orbits. The Event Horizon Telescope (EHT) aimed, by using very-long-basline- interferometry (VLBI), to image M87*, the BH at the center of the nearby elliptical galaxy M87. In April 2019, the EHT successfully succeeded in detecting the shadow of M87*, delivering what is probably one of the most iconic images of 21st century physics. Upon seeing this image the first question we asked ourselves was: what can it teach us about fundamental physics? While it is virtually impossible to learn anything from the ring given its strong dependence on the (hard to model) details of the accretion flow, recent work has shown that for advection dominated accretion flow (ADAF) the morphology of the dark shadow is instead relatively insensitive to these details. We therefore started to explore how to use details of the geometry of the dark shadow to extract relatively robust information about the underlying theory of gravity and the structure of space-time.

One promising use is to test the no-hair theorem, the conjecture that all BH solutions of the Einstein-Maxwell equations are completely characterized by three observable classical parameters: mass, charge, and angular momentum. Recent years have also seen mounting theoretical evidence suggesting that, in order to solve the BH information paradox, new physics is not needed close to the singularity (as one would expect from naïve dimensional arguments), but rather closer to the BH event horizon scale.

Fig 2. hatched in green is the superspinar parameter space (scale at which quantum gravity effects enter, in units of mass, versus dimensionless spin) allowed by the shadow of M87*. The colour coding indicates the deviation from circularity of the resulting shadow.



Exotic near-horizon new physics can naturally be tested using BH shadows. Finally, string theory has proven exceptionally good at resolving space-time geometries with timelike singularities, which suggests that it might be possible to test observational aspects of string theory through VLBI shadow imaging.

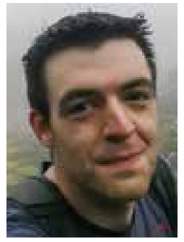
In the past year, we explored tests of all these aspects using the image of M87*. Aiming to obtain maximum freedom at minimum cost, we have tried to understand what is the most efficient way of compressing the shadow image information into image statistics to enable tests of fundamental physics, including deviations from GR. We have found that the deviation from circularity of the shadow is a particularly constraining diagnostic of new physics.

One interesting scenario we have tested envisages the string theory-motivated possibility of violating the Kerr bound, which sets an upper limit to the BH spin. In these so-called superspinars, which would naturally address the information paradox, quantum gravity effects come into play to cover the otherwise naked singularity. We have used the image of M87* to set limits on both the superspinar spin and the scale at which quantum gravity effects kick in. It exciting that for the first time we have been able to confront this class of string theory-motivated objects against real data. We have further used the shadow of M87* to test other new physics scenarios, partially motivated by string theory. These include Randall-Sundrum extra dimensional models, and non-linear corrections to the Dirac-Maxwell electrodynamics Lagrangian. In the near future, we plan to further explore probes of light bosons (such as axions) from BH shadows. Other future plans include exploring the possible synergies between cosmology, gravitational waves, and BH shadows as probes of fundamental physics, in particular deviations from GR. Our general goal is to understand how to constrain new physics in a relatively model-independent way.

The use of BH shadows as windows onto fundamental physics is in its very infancy. Upgrades to the EHT, as well as future VLBI programs, suggest that this will develop into a hot and more mature field, with the ambitious goal of testing gravity in the strong-field regime and possibly shedding light on the underlying structure of space-time itself. Our works will contribute to paving the way towards these goals.

These results were published in the papers: Bambi, Freese, Vagnozzi, & Visinelli, Phys. Rev. D 100 (2019) 044057; Vagnozzi & Visinelli, Phys. Rev. D 100 (2019) 024020; Allahyari, Khodadi, Vagnozzi, & Mota, JCAP 2002 (2020) 003; Vagnozzi, Bambi, & Visinelli, to appear in Class. Quant. Grav. (2020, doi:10.1088/1361-6382/ab7965).

DIRECT DETECTION OF GIANT PLANETS WITH LONG-BASELINE INTERFEROMETRY



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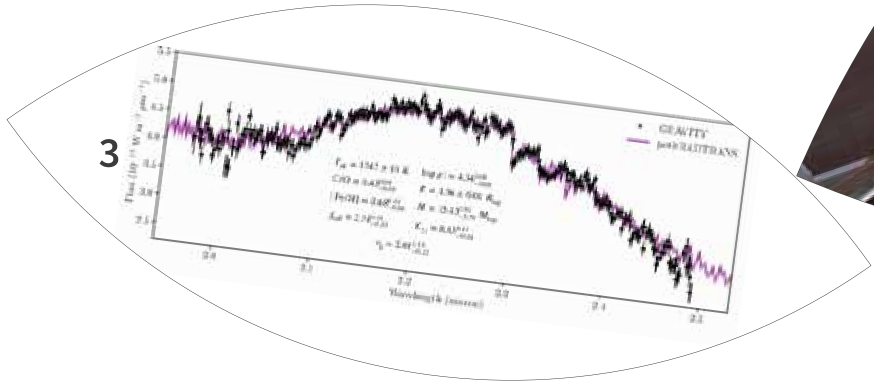

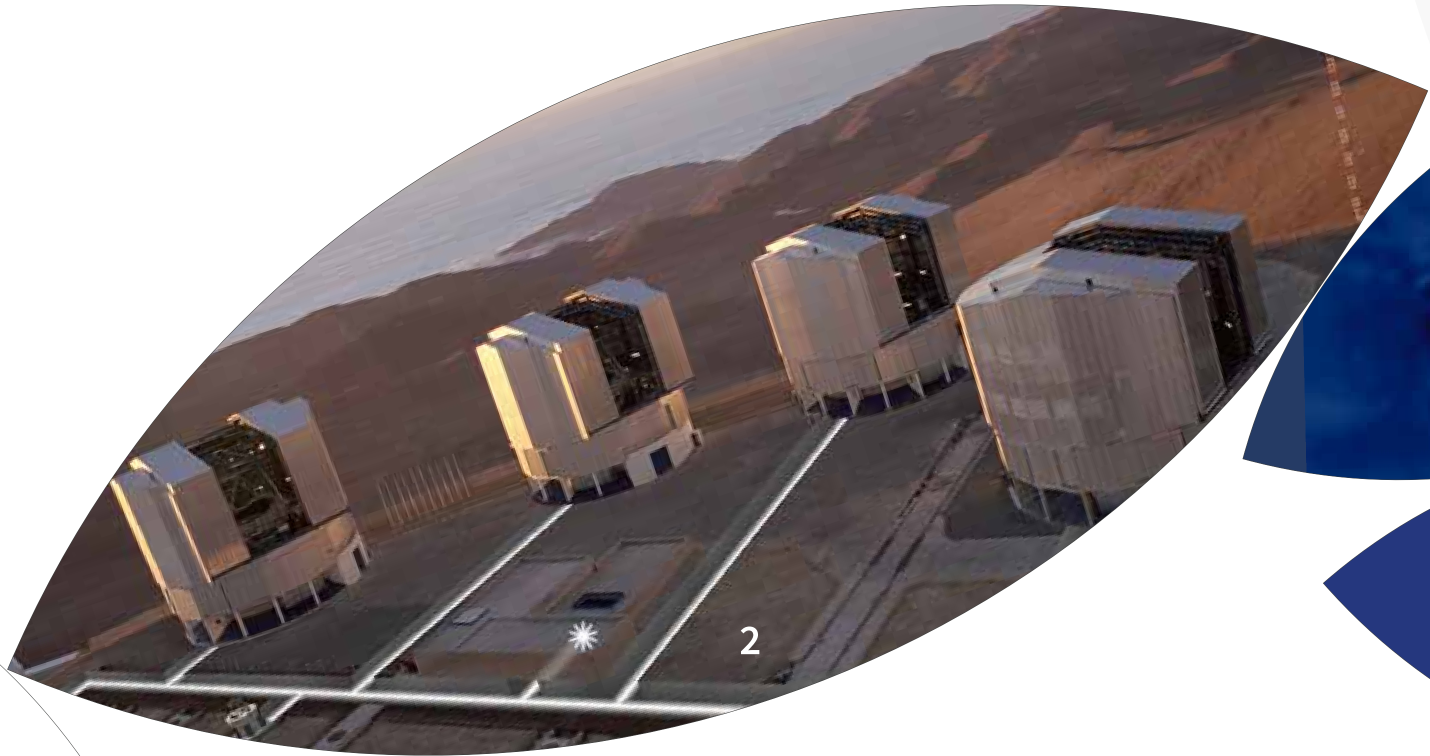

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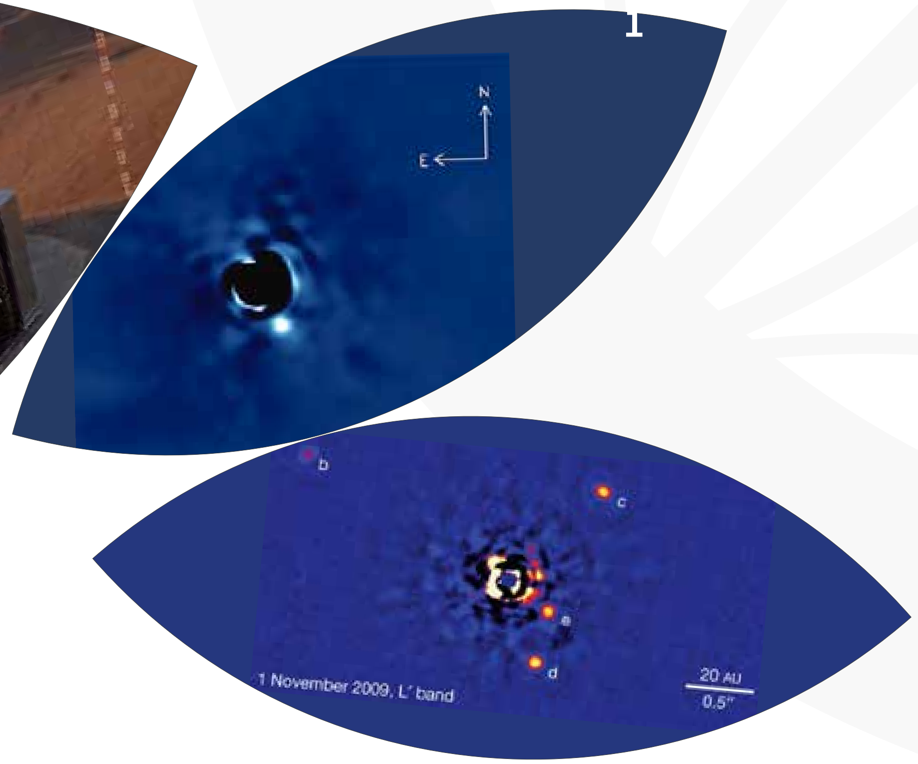


The emergence of high-contrast imaging instruments over the past 10 years has made possible to directly observe some of the most massive planets that we know of, such as the four planets of the HR 8799 system, or the giant beta Pictoris b.

These planets are typically 5 to 10 times more massive than Jupiter, and orbit at a few astro- nomical units from their host stars. They are also very young (a few tens of million years, at most), and haven't had enough time to dissipate the energy accumulated during their formation. As such, they retain some information about the mechanisms and processes that led to their creation.

Two plausible theories, known as "disk instability" and "core-accretion", have been proposed to explain the formation of these giant planets. The first one is a rapid mechanism, somewhat similar to the mechanism of star formation, in which a fraction of a circumstellar disk becomes dense and cool enough to collapse under its own weight.

In this scenario, it takes only a few thousand years to create a planet which can be several times more massive than Jupiter. In the second scenario, the giant planet is formed from the slow and steady accretion of small bodies, continuously colliding to form bigger ones. This progressively creates a planetary core, which later-on can capture a giant gaseous envelope. In this scenario, the formation of a giant planet can take millions of years.

But even though some of these "super Jupiters" are bright enough to be observed directly, and young enough to retain some information about their formation history, it turns out to be extremely difficult to find a way to distinguish between the two scenarios, as they can both lead to very similar planets, in terms of temperature, radius, etc. One interesting avenue of investigation which has been pushed forward recently is to measure the relative abundances of atomic elements, such as carbon and oxgen, in the atmosphere of these planets. The core-accretion scenario, in which giant planets are formed

Fig 1. Top panel: The four planets of the HR 8799 system, as observed with the Keck II telescope (Marois et al. 2010). Bottom panel: the giant planet beta Pictoris b, oberved with NaCo, on the Very Large Telescope (Lagrange et al. 2010). In both images, the central star is masked to reveal the much fainter planetary companions.

Fig 2. The four 8.2 meter telescopes of the Very Large Telescope Interferometer (Credits: ESO).

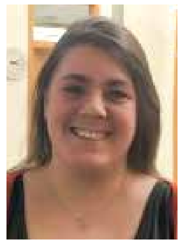
Fig 3. Infrared spectrum of the giant planet beta Pictoris b obtain with GRAVITY, with the atmospheric model overlayed (Credit: GRAVITY Collaboration et al. 2020.

from the bottom-up, tends to trap most of the solid dust particles from the initial circumstellar disk into the core of the planet. Because these dust particles are rich in oxygen (mainly from water ice), most of the oxygen ends up trapped in the core, and is undetectable in the atmosphere.

But measuring something like the carbon to oxygen abundance ratio in the atmosphere of an exoplanet is extremely challenging. It requires the ability to obtain high-quality atmospheric spectra, in order to be able to detect and measure the abundance of at least some of the main carriers of carbon and oxygen: water (H2O), carbon monoxyde (CO), and methane (CH4), for example. Unfortunately, the high-contrast imagers offer only low spectroscopic resolution observations, from which it is difficult to estimate these abundances.

Combining the light from four 8 meter telescopes comes with its own challenges: the optical path length from each telescopes to the instrument need to be carefully adjusted and monitored with a dedicated laser system, the fibers collecting the light need to be perfectly pointed, etc. But 1 these new observations in the near-infrared carry with them the promise of excellent atmospheric spectroscopic data, which in turn can be used in conjunction with advanced modelling techniques to estimate temperatures, surface gravities, and most importantly abundance ratios. This opens up the possibility to really start peering into the formation history of giant planets.

PROF. DIDIER QUELOZ AWARDED THE NOBEL PRIZE IN PHYSICS: THE PAST AND FUTURE OF DETECTING EXOPLANETS



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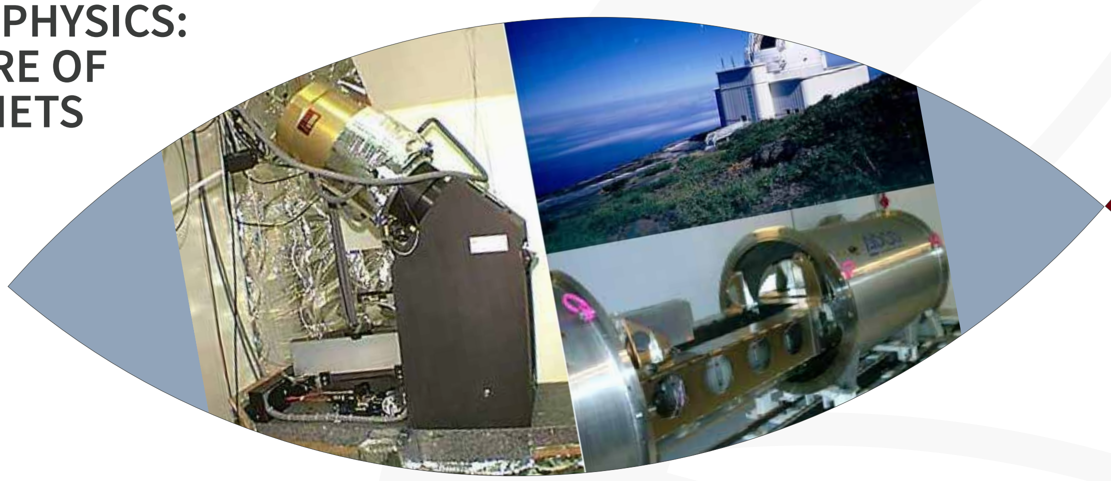


Fig 2. Left: The ELODIE spectrograph with which 51 Peg b was detected. Upper right: The Isaac Newton Telescope. Lower right: The HARPS spectrograph. Credits: CNRS / OHP / ESO /ING.

Fig 1. The Cambridge planet detection and characterisation group at the Cavendish Laboratory and Kavli Institute, led by Prof Didier Queloz, when we celebrated his Nobel Prize.

8th October 2019. That is the day me and many people working in exoplanet research are unlikely to forget. It was the day on which University of Cambridge Professor Didier Queloz was jointly awarded the Nobel Prize in Physics for contributions to our understanding of Earth's place in the cosmos. More specifically, Prof. Queloz received this recognition for the first discovery of a planet orbiting a solar-type star outside our Solar System, the hot Jupiter 51 Peg b.

Didier was a PhD student when he discovered 51 Peg b in 1995. His PhD project centered around calibrating and testing a new stable spectrograph, ELODIE (see Figure 2), that would be capable of measuring precise and stable stellar radial velocities. It would thus allow to find exoplanets, if these existed, by the gravitational wobble they induce on their host star. When starting observations with this new purposely-built instrument, Didier pointed the telescope to 51 Pegasi, a bright solar-like star. Rather than the expected steady and constant behaviour, the data showed large variations on a short timescale. Prof Queloz was convinced he must have done something wrong in calibrating the instrument or analysing the data.

Having a curious mind, Didier was keen to understand the nature of these variations and refused to give up till he could explain them. After ruling out many alternative explanations, he came to the conclusion and eventually managed to convince his supervisor, Prof Michel Mayor, he found an exoplanet. What made the discovery even more intriguing was that 51 Peg b, a planet with half the mass of Jupiter but on a 4-day orbit, wasn't deemed possible according to planet formation theories back then. The path towards the confidence to make such an extraordinary claim, was one of scientific rigour and persistence, hard work, but above all one of open-mindedness, both by a young PhD student and by their supportive supervisor.

Now, 25 years later, planet formation theories have been adapted to try and explain all the discovered exoplanets as well as the Solar System planets. Perhaps more importantly, though, the discovery of 51 Peg b started a revolution in exoplanetary research. Not only have we since witnessed an exponential growth in discovered exoplanets, with over 4000 exoplanets so far, but also in the researchers working in this field. In just a couple of decades, large-scale observational exoplanet meetings have gone from non-existent to fully booked with hundreds of participants. Here in Cambridge, exoplanet research is pursued in four different departments and the Kavli Institute for Cosmology now supports exoplanet research through Kavli Institute Fellowships in its dedication to advance science and pursue excellence.

As one of those Exoplanet Kavli Fellows, I am part of the large exoplanet detection and characterisation group, led by Didier Queloz at the Cavendish Laboratory (see Figure 1). With the group, we are striving towards a better understanding of the exoplanet population, how they form and evolve, what they are made of, and ultimately what this means for habitability and potential life outside the Solar System. We are involved in various observational programmes and are even designing several experiments and instruments necessary to achieve this.

Many of our projects focus on the photometric transit method, where exoplanets are discovered through the dip in stellar light they cause if they transit between their host star and us, the observers. Team members are involved in NGTS, the Next Generation Transit Survey that discovered the shallowest transit as seen from the ground; SPECULOOS, the Search for habitable Planets EClipsing ULtra-cOOl Stars that probes a parameter space complimentary to solar-type stars; CHEOPS, the CHaracterizing ExOPlanet Satellite which is the first mission dedicated to search for transits on bright stars already known to host planets; Kepler, K2 and TESS, the US-led space missions that advanced our statistical knowledge of the close-in exoplanet population.

Didier, however, did not forget his roots. In the 1990s, he helped to build ELODIE, that led to the discovery of 51 Peg b and thus his Nobel Prize. In the present, at the University of Cambridge, he is leading the project to build HARPS3, an improved close-copy of HARPS(-N) which themselves were upgrades from CORALIE and ELODIE (see Figure 2). This new and improved spectrograph will be installed at the Isaac Newton Telescope in La Palma and will be used to perform the Terra Hunting Experiment (www.terrahunting.org). Together with various institutes around the world, Didier, myself, and others, will perform this ten-year experiment, the most intensive search ever attempted for Earth-like planets around the nearest Sun-like stars.

Thousands of exoplanets have been discovered since 51 Peg b, but what we are still missing is a Solar System analogue, or even a true Earth analogue. Being led by a Nobel laureate, the Terra Hunting Experiment aims to change that and extract, for the very first time ever, the tiny signal of an actual Earth twin.

KICC OUTREACH OVERVIEW

Matthew Bothwell
Outreach Officer

In 2019 the outreach activities of the Kavli Institute have flourished and expanded further, by leveraging on a donation by the Kavli Foundation and by also coordinating with other departments. In the following we provide an overview of some of these activities, while in the next two articles we discuss more in detail the outreach **programme for visually impaired children, 'Touch Astro'**, and the production of video episodes for the **Discovery programme 'Universe Unravelled'**.

Project 'Astro-East'

During 2019, we have been successfully running the flagship project 'AstroEast'. This program is designed to extend the existing outreach efforts beyond the Cambridge area, to regions of across Norfolk, Suffolk, and Peterborough, which are generally less exposed to other outreach activities. Importantly, this new initiative is designed to be pro-active rather than reactive – explicitly approaching under-served schools across this new target area, rather than responding to local demand.

Throughout 2019 we have been working with a pilot sample of nine schools, running a range of activities including after-school science clubs, giving lunchtime talks, and hosting assemblies promoting science careers. Working with a relatively small number of schools has allowed for substantial engagement with each one over an extended period – for example, in one school we successfully ran an after-school astronomy club every week for several months. Going forward to 2020 and beyond, we will be increasing the number of schools in our program. To do this, we will be working with Ormiston Academies Trust (an educational charitable trust which aims to support and improve schools) which sponsors a further 17 schools in the region.

KICC Podcast

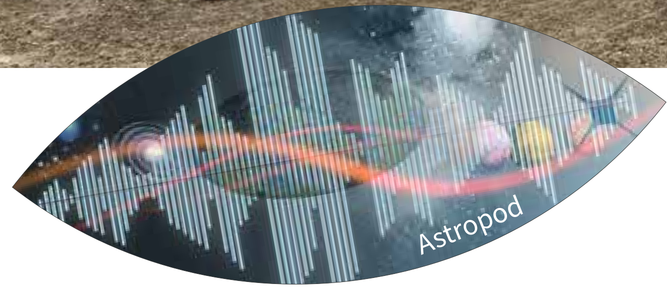
Towards the end of 2019 we were pleased to launch 'The Astropod', a monthly space science podcast run jointly by the Kavli Institute of Cosmology and the Institute of Astronomy. Going forward, The Astropod will showcase KICC research highlights by conducting interviews with KICC staff and students.

Cambridge Science Festival and Open Afternoon

On the last weekend of the Cambridge Science Festival KICC opened the doors to the public at our annual Open Afternoon.

We ran between 2-6pm on Saturday 23rd March, and provided talks, displays, demonstrations, activities, arts workshops designed to highlight the research done at the Kavli (and IoA). These were staffed by volunteers among the researchers and students at the Kavli and IoA.

The day was well attended with approximately 1300 people coming through the doors.



Cambridge Launchpad

Throughout 2019, KICC hosted a number of workshops in collaboration with Cambridge LaunchPad (https://cambridge-launchpad.com/). Cambridge LaunchPad is a movement led by Cambridge science, technology and engineering companies, investing their talent and resources to inspire young people into STEM careers. It is aimed at providing support, experiences and opportunities in STEM to students in Cambridgeshire schools, aged 8 to 18. Specifically, it was designed to address the significant gender gap which exists in STEM employment.

As a Cambridge LaunchPad partner, we have been hosting groups of students aged between 11 and 15 years of age for single-day workshops. Partnering with Cambridge LaunchPad provides the advantage that many logistics – transport, computing, etc – can be provided either by Cambridge LaunchPad or by the other partners. As such, schools with limited resources (such as for transport) will face no barrier to entry.

As these workshops are more in depth than our normal school visits, we have worked with Cambridge LaunchPad to design a suitable curriculum, consisting of taught material and hands-on activities designed to promote Kavli research themes.

TOUCH ASTRO : ACTIVITIES FOR VISUALLY IMPAIRED CHILDREN

Nicolas Laporte, Colin DeGraf & Matt Bothwell

Astronomy outreach is commonly presented through visual media, with many results and concepts being communicated to the general public via images from our space and ground-based telescopes. As such, people with visual impairments are generally underserved by traditional astronomy outreach programs.

In order to improve the accessibility of our outreach program, The KICC has acquired a 3D printer, and we are in the process of designing a range of activities for young people which will utilise 3D models. We are currently designing a series of classroom sessions relating to Kavli research themes (ranging from our own solar system, the search for life in the Universe, to the formation of galaxies and the structure of the cosmos), which will combine our 3D printed models with multi-sensory information, such as data sonification, in order to effectively communicate the excitement of astronomy in a fully accessible way to the visually impaired community.

For the youngest children (less than 8 years old), we are planning a touchable Solar System in two parts : (i) printed models of telluric planets and satellites to allow children to feel the difference between for exemple Mars and the Earth, the two faces of the Moon or between Venus and Europa; (ii) a scaled version of the Solar System where all planets will be connected by a wire to let the children experience the distance between the eight planets of our solar system. We will also take advantage of the huge amount of sounds from the Solar System (either a sound translation of the radio emission from a planet or a direct record from the ground of the planet) to offer another way to understand the difference between each planet.

To show areas of active research, using a process developed by the Tactile Universe project we have begun printing a set of tactile images: for these we convert pixel brightness from an image into height in a 3D model, so that the information conveyed can be interpreted by touch alone. In addition to the galaxies provided by the Tactile Universe project (in both red and blue bands to show young vs. old stars), we are printing a collection of tactile images of key discoveries and aspects of astronomy (e.g. the CMB and the cosmic web), as well as recent results from KICC members. Furthermore, for those best suited to it, we are printing full 3D representations of astrophysical phenomena, both from large collaborative projects (e.g. the Tycho supernova remnant from the Chandra X-ray Observatory) and from ongoing work by KICC members (e.g. a full 3D rendering of the gaseous jet from an Active Galactic Nucleus). In addition to the models themselves, we are compiling a set of instructions so that any Institute member can easily produce a model of their current work.

We are planning to release all models and sounds we create and use on a public website to allow schools across the country to develop their own activities.

Fig 1. (From Left to Right) The Moon, The Earth, The Rosetta Spacecraft and the 67P Tchourioumov- Guérassimenko comet.

Fig 2. Tactile images of the Cosmic Web, the Cosmic Microwave background, an AGN jet and the Moon surfaces.

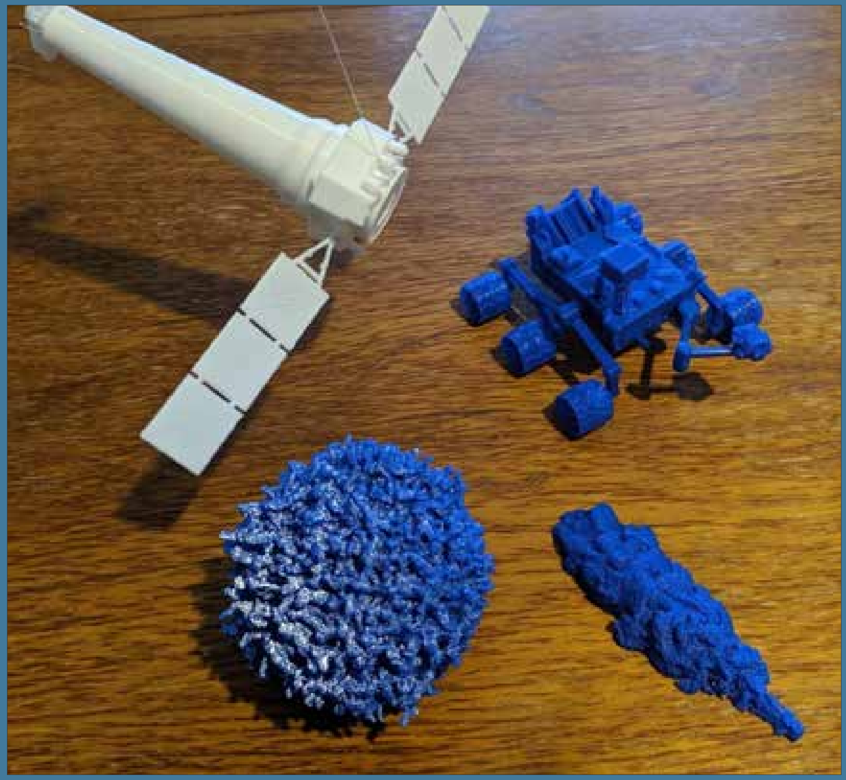


Fig 3. Printed models of the Chandra X-Ray Observatory, the Curiosity Mars Rover, a SN remnant and an AGN Jet.

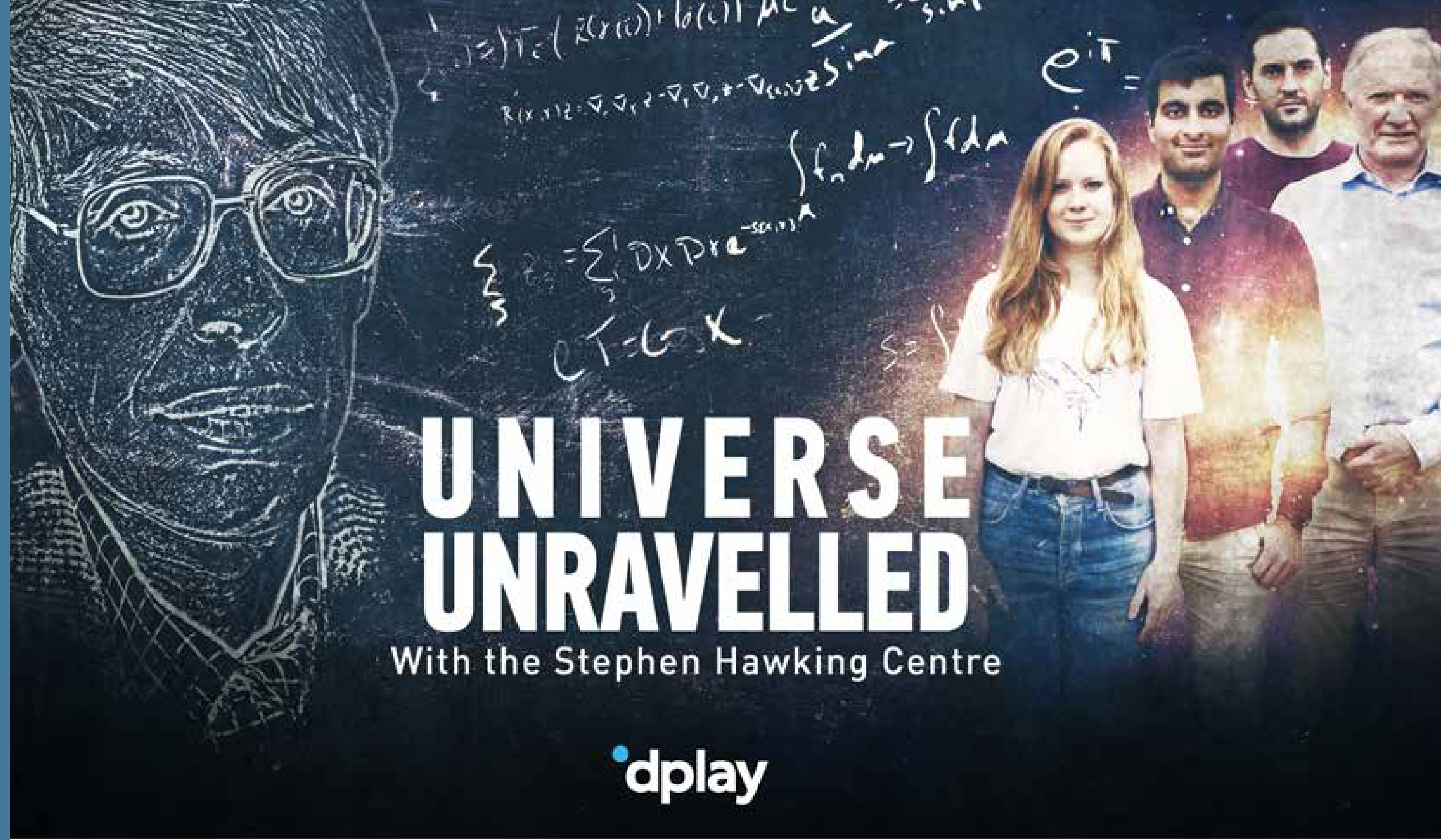
UNIVERSE UNRAVELLED WITH DISCOVERY

Ulrich Sperhake and Paul Shellard

Universe Unravelled is an extended scientific outreach programme produced by Discovery, Navada Studios, the Centre for Theoretical Cosmology (CTC), at the University of Cambridge, and KICC. This high impact project has been made possible by the Kavli Foundation with funding for science editorial support. The Universe Unravelled series takes the form of a documentary arranged in 25 short video episodes, each of about 7 to 10 minutes duration, which focus from the outset on Einstein's theory of General Relativity and, in particular, the research topics inspired by Stephen Hawking's work and ideas: Black holes, Cosmology and Gravitational Waves.

The fundamental goal of this series is twofold. First, to present the foundational concepts and ideas of General Relativity and Cosmology to the public in a manner that does not require mathematical training and yet conveys their deep meaning and paradigm-shifting character in the way we think about the Universe. Secondly, to elucidate the main questions in contemporary research and the tools scientists are employing in their quest for answers. To this end, each episode is dedicated to the self-contained explanation of one specific topic, while the sequence merges together into a comprehensive history of the fabric of our Universe and how we came to understand it.

The production of this programme proceeded in several stages. In the beginning, members of the CTC and KICC drafted scientific scripts for the major topics to be covered in this series, with expert guidance and help from our science editors, Marianne Freiberger and Rachel Thomas (at the Millennium Mathematics Project). A prominent role in the development of the series has also been taken by Michalis Agathos, the new KICC Fellow in Gravitational Waves. Besides the immediate scientific content, these scripts inspired a wide range of methods to convey the ideas in a comprehensible way; these included graphical animations, familiar analogies from daily life, and historical footage such as the Apollo moon landings. Based on these scripts, Navada with Discovery developed a first, tentative, schedule for the episodes together with a concrete plan for those questions to be explored in head-to-head interviews with the Cambridge researchers. These interviews were filmed over the course of several visits by the Navada team to the Centre for Mathematical Sciences, the Kavli Institute and the Institute of Astronomy in summer and autumn 2019. We were pleased that it was possible to film some footage of the KICC 10th Anniversary Symposium. The interviews, along with computer animations from CTC's collaboration with Intel Corporation, and graphics Navada have generated themselves, formed the basis for the creation of the individual episodes.



The sequence of episodes follows a natural development, starting with the fundamental features of Einstein's relativity and proceeding to increasingly complex features of the theory and the major goals of present-day research by groups in Cambridge and the wider community. For each episode, Navada with Discovery first created a storyboard on the basis of the edited scripts, outlining the minute-by-minute sequence of interview excerpts, voice-over, graphics and additional footage. Following revision by the CTC's outreach and research team, these detailed scripts were converted into a fine cut film of each episode.

These were then reviewed and further refined iteratively by the Cambridge researchers and Navada, with constant editorial oversight by the Discovery producers ensuring high production standards and the Discovery style. The intimate involvement of researchers in this feedback process has also ensured high levels of scientific accuracy, offering an excellent model for future outreach collaborations. As Unai Iparragirre, Executive Producer for Discovery, has stated: "One of the key goals for Discovery is to give back to the world and to make it a better place, offering viewers programming that inspires and educates. And this was fully aligned with the project that we started discussing and developing in late 2018: Universe Unravelled."

Over half of the eventual number of episodes are now completed at the time of writing and the review process is continuing, even in the present difficult circumstances affected by COVID-19. However, there have been delays to finalising the audio voiceover because sound editing studios in London and many worldwide have not been able to operate (the series will be dubbed into several languages). Discovery's initial launch date for its digital platforms in May 2020 has had to be delayed. Now anticipated to start in September, look out for "Universe Unravelled" airing on a weekly basis for several months.

Image courtesy of Discovery Inc, used by permission.

WORKSHOPS, SCHOOLS & KAVLI LECTURES

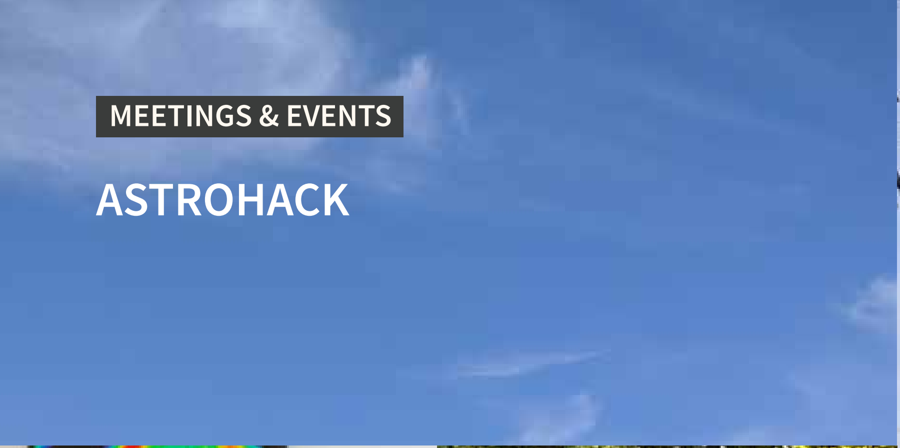
In addition to the large Symposium in Cosmology organized for the 10th Anniversary, KICC has organized and supported other conferences, workshops, schools and various events, bringing scientists from all over the world to discuss exciting areas of research and to share intriguing new results.

In July 2019 KICC supported the Kavli ExoFrontiers 2019 Symposium, the last one of a very successful series focused on addressing pressing questions in forefront areas of exoplanetary science. In 2019 the theme was "Future Observational Landscape of Exoplanetary Science". The meeting brought together twenty-two major experts from diverse areas of Exoplanetary Science to discuss some of the most pressing open questions and to identify the new challenges in this rapidly growing field. A major topic of discussion has been the development of new cutting edge techniques and astronomical facilities, both groundbased and in space, which will be used to tackle these various aspects.

In August we hosted the Astro Hack Week 2019. This is an innovative format that combines a summer school with a "unconference", which every year (in a different location) gathers people from all over the world an informal and very effective environment, where participants form and reform in collaborative groups with a focus on solving research problems using the state of the art techniques (neural networks, Bayesian statistics, etc...). The selected participants (48 in total) were encouraged to bring along hack ideas from their current research and interests to work on with others during the week. Not surprisingly, the Hacks spanned a broad range of topics, both in terms of astrophysical phenomena and in terms of methodologies. A more extensive report of this successful event is provided in the next article.

KICC also made it possible the first Kavli-RISE (Research and Innovation Staff Exchange) Summer School on Gravitational Waves, in September 2019. This was the first summer school of a new series supported by a donation of the Kavli Foundation. The School attracted an impressive cohort of junior scientists from across the globe, which have been introduced to a wide range of topics at the foundation of the new exciting research field of gravitational wave astronomy, such as: Black Holes and Neutron Stars, Numerical Relativity, Post-Newtonian Theory, Electromagnetic Counterparts, Cosmological Sources of Gravitational Waves, Dark Matter Candidates, Exotic Compact Objects. These and many other topics were taught by some of the best experts in these areas.

On the occasion of the 10th Anniversary of KICC we have also started a series of Kavli Lectures. These are colloquia given by high profile scientists, who provide a broad overview of some of the areas of research at the frontiers of Astrophysics. The first inaugural lecture was given by Sylvain Veilleux (with an overview on galactic winds) and followed by Jean-Michel Desert (exoplanets' atmospheres), Sara Ellison (galaxy collisions) and Lars Hernquist (cosmological simulations).



MEETINGS & EVENTS

ASTROHACK








For those unfamiliar with the concept, "AstroHackWeek is a week-long workshop that combines summer school and unconference" [1,2]. Participants with a wide range of abilities attend interactive lectures and workshops in the morning given by the world experts in their respective fields. The afternoon then facilitates an unstructured "hacking" environment, where participants form and reform collaborative groups with a focus on solving research problems using the state of the art techniques discussed in the morning. "Breakout sessions" are encouraged, whereby participants and lecturers give spontaneous tutorials on topics that people agree require further discussion.

At the KICC AstroHackWeek there were 48 official participants from a wide variety of institutions from countries across the world ranging from India and Taiwan through most of Europe and the US to Brazil and Chile, as well as local participants from across the University. In keeping with previous AstroHackWeeks hosted at other institutions, participants with a range of abilities were chosen by an algorithm designed to draw a wide and unbiased selection from an applicant pool. The selected participants were encouraged to bring along hack ideas from their current research and interests to work on with others during the week.

The lectures this year covered a wide variety of key tools in a cosmologist's toolbox, ranging from Bayesian statistics and neural networks to how to create clear and attention-grabbing figures using the latest research in visual communication and perception. Alongside theoretical concepts, participants were instructed and encouraged to make use of the cutting edge in data science and collaborative software tools such as tensorflow, numerical Python, GitHub, Overleaf, IPython notebooks, colab, google drive and google slides.

As expected, the Hacks covered a wide variety of topics with many of them resulting in research outputs that continue to be used and developed beyond the week. The astronomical hacks included topics such as: manifold learning for M-dwarf classification, applying genetic algorithms to model- independent reconstruction from supernovae data and comparing techniques for emulating the large scale structure of the universe using autoencoders, adversarial neural networks and principle component analysis.

There were also outreach projects, such as producing a functioning python package for "returning the state of the universe" for use in planetarium presentations to get everything from the current tally of exoplanets to the location of constellations in the sky tonight and the which historical astronomers have birthdays today [3].

On the visualisation side, participants created a software tool for designing themed colour schemes for beautiful and accurate scientific plots with the now publicly available colormapize python package [4].

There were also many more parenthetical projects such as correlating participant concentration with CO_2 levels measured by fitbits in the lecture theatre, and the construction of end-to-end tutorials for astronomical deep learning.

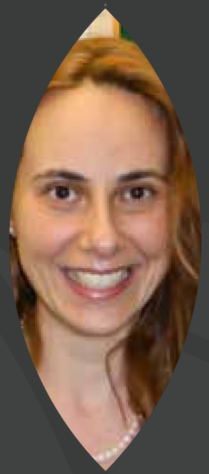
The KICC and Cambridge as a whole formed an ideal venue for AstroHackWeek. The lecture theatre was able to be reconfigured for working with laptops during the interactive lectures (incidentally setting an important precedent for future events such as the KICC 10 year anniversary), and the open surroundings of the KICC foyer were well-suited for hacking. High-quality lunches were hosted at the nearby Møller centre, and the workshop dinner in the gardens of Gonville and Caius College, which helped facilitate more open-ended discussion and networking away from computers between participants and organisers alike. In the middle of the week was a "Community hack" where the participants visited the nearby British Antarctic Survey institute to apply machine learning methods to a variety of problems such as sea ice prediction [5].

It was rated by participants and organisers to be an immensely enjoyable and productive week, with many projects created, concepts learnt and collaborations joined.

Alongside the Kavli Foundation, AstroHackWeek was supported in part by the University of Cambridge, the Alfred P. Sloane Foundation, the Moore Foundation, the eScience Institute and Google.

[1] astrohackweek.org/2019
[2] github.com/AstroHackWeek/AstroHackWeek2020/wiki/Hacking-Central
[3] github.com/ojhall94/stateoftheuniverse
[4] github.com/astrofrog/colormapize
[5] github.com/fruzsinaagocs/sea-ice

AWARDS AND HONOURS

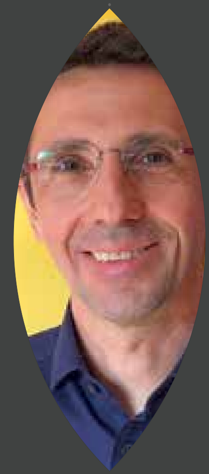


Debora Sijacki has won the PRACE Ada Lovelace Award for HPC 2019. This prestigious prize is awarded annually to a female scientist in recognition of their outstanding impact on HPC research and computational science at a global level and for being a role model for young women beginning their careers in HPC.

Oliver Friedrich (Newton-Kavli Fellow) has been awarded the annual PhD thesis award by the German astronomical society for his outstanding contributions studying the large scale structure of the Universe. In his thesis titled “Statistical Properties of the Cosmic Density Field beyond 2-point Statistics” he developed new methodologies to explore different cosmological scenarios.

Anne Davis has been awarded the Richard Glazebrook Medal and Prize for her outstanding support and leadership in physics, particularly for women and those from non-traditional backgrounds, for her leadership of the UK particle cosmology community, and her gender championship roles.

Sunny Vagnozzi (Newton-Kavli Fellow) has been awarded the “Pio Picchi” prize from the Italian Physical Society. Every year this prize is awarded to a young talented researcher. Sunny has also received the “Springer Thesis Award” from Springer Nature. This award selects the very best PhD theses in physical sciences from across the world. This will mean that his thesis will be published in the Springer Theses series. Finally, Sunny has received the Outstanding Reviewer Award for the journal Classical and Quantum Gravity from IOP Publishing.



Roberto Maiolino has been appointed Honorary Professor at University College London. This appointment will provide the opportunity of strengthening the collaborations between KICC and the Astrophysics Group at UCL in several areas of research of common interest and on a number of cutting edge scientific projects.

Further Information

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

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

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

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

Acknowledgements

The numerous activities of KICC during 2019 were made possible by administrative and logistical support provided by Steve Brereton and Philippa Downing.

KICC also receives extensive support from the administrative IT and logistics staff of the Institute of Astronomy, as well as by the Physics Department, the Department of Applied Mathematics and Theoretical Physics and by the School of the Physical Sciences.

The artwork and layout of this report were produced by Amanda Smith, who has also produced numerous other artworks associated with KICC, especially for its 10th anniversary events. Furthermore the production of this report was made possible with the help of Maria Lopez-Celi, who has joined the Kavli administrative staff in 2020.

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

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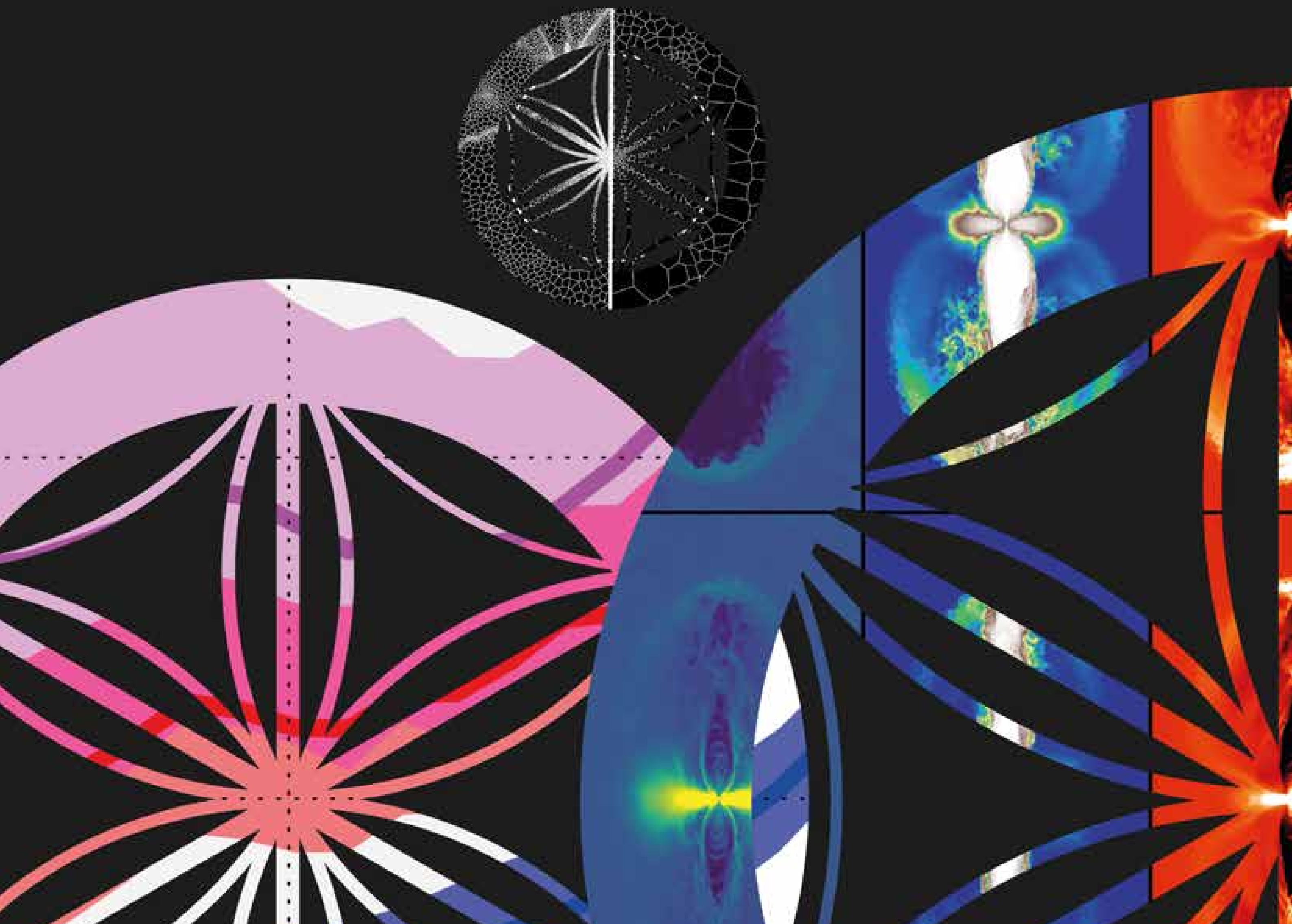

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