ANNUAL REPORT - KAVLI INSTITUTE FOR COSMOLOGY, CAMBRIDGE

2018

UNIVERSITY OF CAMBRIDGE

Kavli Institute for Cosmology Cambridge

KICC

01 Message From The Director
03 Research Overview

Early Universe and Precision Cosmology
05 PLANCK 2018: final data release and legacy
07 Cosmic microwave background science with ground-based telescopes
09 In pursuit of the largest scales in our Universe
11 Understanding the relation between galaxies and matter

First Light and Epoch of Reionisation
13 Constraining reionisation through Lyα fluctuations
15 Astrophysical modeling of the 21-cm signal
17 Doubts about the claimed detection of "Cosmic Dawn"
19 Preparing for JWST

Formation of galaxies and black holes
21 Order in the Chaos of the early Universe
23 A "KLEVER" look at primeval galaxies
25 The hunt for distant quasars with big sky surveys
27 Tracing dark matter with gravitational lensing
29 The FABLE simulations of galaxies, groups and clusters
31 Fast and energetic AGN-driven outflows in simulated dwarf galaxies
33 Regulating properties of dwarf galaxies with supernova feedback

Gravitational Waves
35 Gravitational wave physics
37 Using the Gaia satellite to detect low frequency gravitational waves

Exoplanets
39 Weighing exoplanets
41 Exploring the conditions for life

Astronomical Instrumentation and Big Data
43 MOONS: the next generation multi-object spectrograph for the Very Large Telescope
45 ELT-HIRES: the high resolution spectrograph for the Extremely Large Telescope
47 REACH: the Radio Experiment for the Analysis of Cosmic Hydrogen
49 Deep Learning for RAPID classification of the transient Universe

51 Outreach activities
53 Events and meetings
55 Fellowships
57 Awards
59 Donald Lynden-Bell
61 Stephen Hawking
63 Further Information & Acknowledgements

The Kavli Institute for Cosmology, Cambridge (KICC)

Message from the Director

Roberto Maiolino

KICC is a truly special institute, unique in many aspects. It is a centre of excellence gathering the expertise of leading scientists from three world-famous Cambridge Departments, namely, the Institute of Astronomy (IoA), the Cavendish Laboratory (Department of Physics) and the Department of Applied Mathematics and Theoretical Physics (DAMTP), which hosts the Stephen Hawking Centre for Theoretical Cosmology (CTC). KICC is therefore a fantastic platform where scientists can fully exploit their potential by leveraging mutual synergies, optimally exploiting existing projects with international partners, and developing new ideas and projects in Cosmology as well as in other areas of Astrophysics.

Within the context of such a broad and ambitious mission, 2018 has been a particularly successful year for KICC. Major progress and breakthroughs have been achieved in multiple areas of research. The last major data release of the Planck satellite, which has mapped the cosmic microwave background delivering an unprecedented amount of information, and the associated set of papers have set the state of the art for understanding the early Universe and its components. Advanced cosmological simulations, exploiting clusters of hyper-computers, have enabled us to solve long-standing conundrums on how galaxies and black holes emerged out of the dark ages, how they evolved and how they cleaned the primeval fog of hydrogen pervading the intergalactic space.

Observations with cutting-edge observing facilities, such as the Atacama Large Millimetre Array (ALMA) and the Very Large Telescope (VLT), have enabled us to test these theories by tracing the multiple components of distant galaxies, but they have also revealed new, unexpected phenomena associated with galaxy formation and evolution. Indeed, as we further our understanding of the cosmos and its constituents, new fascinating puzzles open up. To face these new challenges we are gearing up to exploit the next generation of observing facilities with which we are heavily involved, including the James Webb Space Telescope, the next generation of instruments for the Very Large Telescope and for the Extremely Large Telescope, Simons Observatory and the Square Kilometre Array.

KICC has expanded its scope to support research in areas beyond Cosmology, such as Gravitational Waves and Exoplanets, yielding major new results in these areas too. KICC is also involved in the development of new instrumentation, such as MOONS, the next-generation multi-object spectrograph for the Very Large Telescope, and ELT-HIRES, the high-resolution spectrograph for the Extremely Large Telescope. In 2018 we have also started the development of REACH, a new experiment to trace the evolution of hydrogen in the primeval universe.

Rather than providing an extensive, detailed description of all results and research carried out at KICC, in this report we have decided to include only a few highlights and short stories representative of the various areas of activity. However, it should be clear that the achievements and results obtained by scientists affiliated and linked to KICC are much broader than reported here and involve many more people. A more extensive description and list of people active in the various areas can be found at our website (www.kicc.cam.ac.uk), which also gives access to a list of our scientific publications.

KICC supports strategic research in the various areas discussed above primarily by investing in researchers at the early stage of their career. The Kavli Fellowship at KICC is a well-recognised, high-profile and highly competitive, coveted position, which we have been advertising with success every year since the foundation of the institute. The Kavli Fellowship keeps attracting some of the best minds and rising stars in Cosmology and Extragalactic Astrophysics. Thanks to a joint donation from the Isaac Newton Trust and the Kavli Foundation, in 2018 we started the programme of Newton–Kavli Junior Fellowships, more focussed on strategic areas of research, and we are glad that the first two Junior Fellows have started in 2018.

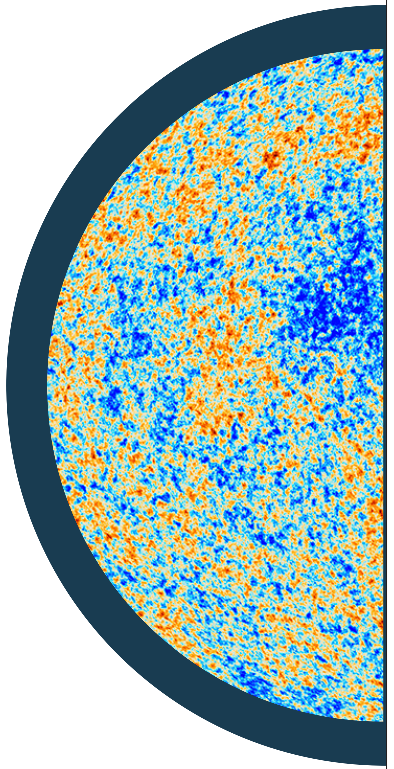
Thanks to an additional donation by the Kavli Foundation, we have also started a Senior Fellowship in Gravitational Waves and we aim at making this strategic fellowship a long-term commitment of KICC. We have also successfully supported a new fellowship in Exoplanets. Finally, thanks to the generous donation of Gavin Boyle, matched by the Kavli Foundation, in 2018 we have also permanently established the Gavin Boyle Fellowship in Cosmology and Exoplanetary Science, which holds the promise of attracting outstanding candidates from all over the world in these disciplines and whose first recipient will start in 2019.

While 2018 has been a year of major progress, of new developments and new ideas on multiple fronts, it has also been a sad year in which Cambridge, and the whole scientific community, has had two major losses: Donald Lynden-Bell and Stephen Hawking. Their contribution to science has been invaluable, and we have been lucky enough to interact with them, and get their insightful thoughts on a vast range of scientific topics, on a nearly daily basis. Their spirit and approach to science has always been inspirational to us all and will continue to be so for generations to come. We will greatly miss them.

In the same spirit as Donald's and Stephen's tireless work in promoting science beyond the academic community, and especially in engaging with the next generations, in 2018 we have started a new outreach programme aimed at reaching a broader audience. In particular, thanks to a donation by the Kavli Foundation we have started a new range of outreach activities aimed at exciting the youth audience both through new material for media, in collaboration with the Discovery Channel, and by reaching a wider range of schools in the east of England.

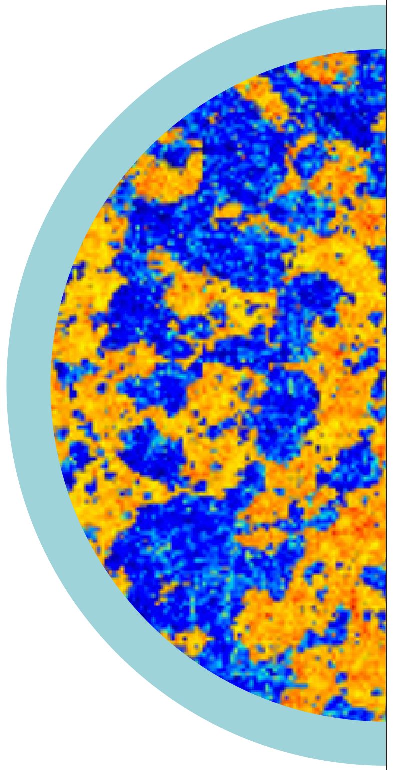
Overall, 2018 has been an amazing year for KICC, both in terms of scientific achievements and the breadth of its activities, which have been greatly expanded. I am sure this is just part of a long-term positive pattern that we will see continue and flourish further in the years to come.

RESEARCH THEMES - OVERVIEW



EARLY UNIVERSE AND PRECISION COSMOLOGY

The understanding of the primeval Universe and its constituents has been at the core of KICC's research since its foundation, both through the extensive analysis of observational data and through detailed modelling. KICC has been one of the leading institutes in the Planck space mission, which has delivered the most extensive multi-frequency map of the Cosmic Microwave Background (CMB) available so far. KICC is now heavily involved in groundbased CMB experiments, such as the Atacama Cosmology Telescope and the Simons Observatory, which will probe with unprecedented detail and sensitivity the polarization of the CMB. We are also involved in large galaxy surveys that are probing Large Scale Structures in the Universe, which will enable us to provide additional constraints on the cosmological parameters.

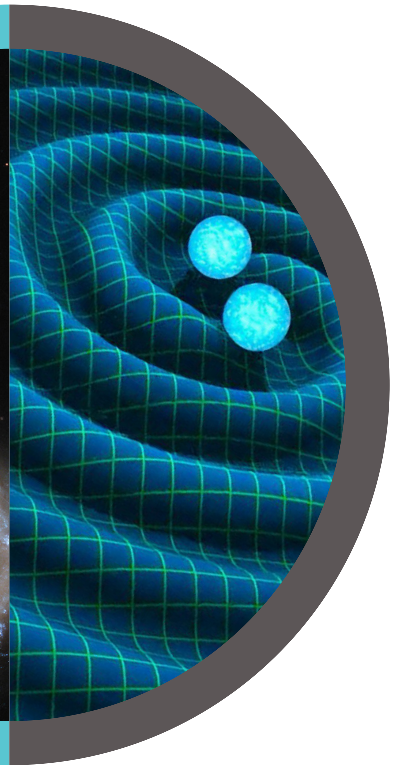


FIRST LIGHT AND EPOCH OF REIONISATION

Characterising the nature of the first sources of light in the Universe (stars and accreting black holes) and investigating how they have reionised the primeval fog of neutral hydrogen are some of the most exciting challenges of modern astrophysics. Scientists at KICC are using super-computer cosmological simulations to investigate how the reionization might have occurred. We are particularly active in modelling the observational signatures resulting from this process. We are involved in multiple experiments, such as HERA, SKA and REACH, that will attempt to directly detect and characterise the re-ionisation era. We are also heavily involved in the James Webb Space Telescope; we will exploit its leap in sensitivity with respect to current facility to identify and characterise the first population of stars and black holes formed in the early Universe.

FORMATION AND EVOLUTION OF GALAXIES AND BLACK HOLES

Scientists at KICC are using various observing facilities to understand the physical mechanisms that have been responsible for the formation and evolution of galaxies. These facilities include ALMA, VLT, JVLA, and HST. Data from these facilities are used to constrain the relative content of stars, dark matter and gas in galaxies, their evolutionary stage, their chemical enrichment and to reveal processes, such as outflows and galaxy merging, that may have been responsible for galaxy transformation. These observations are compared against detailed super-computer simulations obtained by KICC scientists that can trace in detail the expected evolution of galaxies from their early formation to the present day. KICC is heavily involved in various future observing facilities, such as JWST, MOONS@VLT, HIRES@ELT, and SKA, which will enable a major leap forward in our understanding of the formation and evolution of galaxies and of the supermassive black holes hosted at their centres.

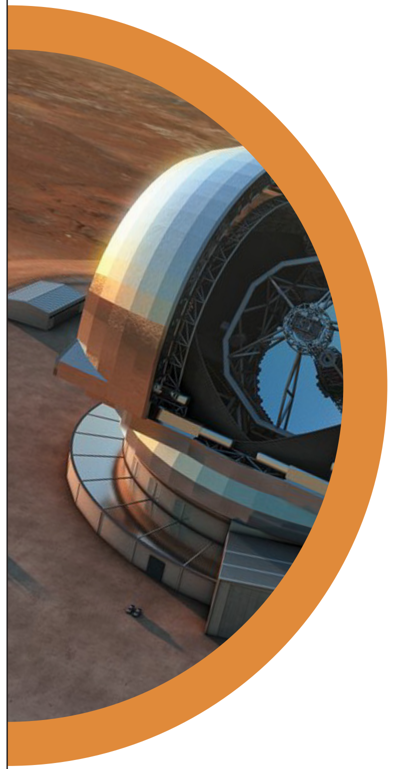


GRAVITATIONAL WAVES

Modelling the sources of gravitational waves and their specific signal has traditionally been one of Cambridge's strengths, leveraging on Stephen Hawking's legacy. KICC's exploration of gravitational waves ranges from those produced by the Big Bang, by merging supermassive black holes, neutron stars and stellar-type black holes, as well as by supernovae. We are part of the LIGO-Virgo collaboration, in which we have played a role not only in the theoretical modelling but also in the data analysis. ATC and the Simons Observatory, in which we are involved, will be facilities that are expected to constrain or detect the B-mode polarization of the CMB, which embeds information on the primordial gravitational waves. We are also exploring methods to detect low frequency gravitational waves associated with supermassive black holes in merging galaxies, by using the Pulsar Timing Array or precision astrometry of large samples of stars with the Gaia satellite.

EXOPLANETS

Exoplanetary science has grown significantly in Cambridge in the last few years and KICC has been contributing to this area both through new fellowships and through its activities in planning new observing facilities that will be pivotal in this area, such as JWST and the HIRES instrument for the ELT. Specific research has been undertaken at KICC is related to the determination of the mass of exoplanets with known size, hence for which the composition can be inferred, the understanding of the conditions required for the emerging of life and the detection of bio-signatures in exoplanets.



ASTRONOMICAL INSTRUMENTATION AND BIG DATA

By leveraging the expertise in optical and infrared instrumentation, Cambridge, including KICC, is one of the major players in the development of next generation, cutting edge astronomical instruments. These include MOONS, the next generation multi-object optical and near-infrared spectrograph for the Very Large Telescope, and HIRES, the high resolution spectrograph for the Extremely Large Telescope. KICC is also the prime partner of REACH, a new experiment for detecting the signature of the epoch of re-ionisation of the Universe by tracing its global signature through the 21cm transition of hydrogen in the primeval universe. These and many other facilities in which Cambridge is involved (e.g. CMB surveys, ZTF, Gaia, SKA, LSST) will produce huge amount of data that pose serious challenges for their processing and exploitation. We are leading the development of advanced Artificial Intelligence and machine learning techniques to face these new astronomical Big Data challenges.

1 page 5
2 page 13
3 page 21
4 page 35
5 page 39
6 page 43

PLANCK 2018: FINAL DATA RELEASE AND LEGACY

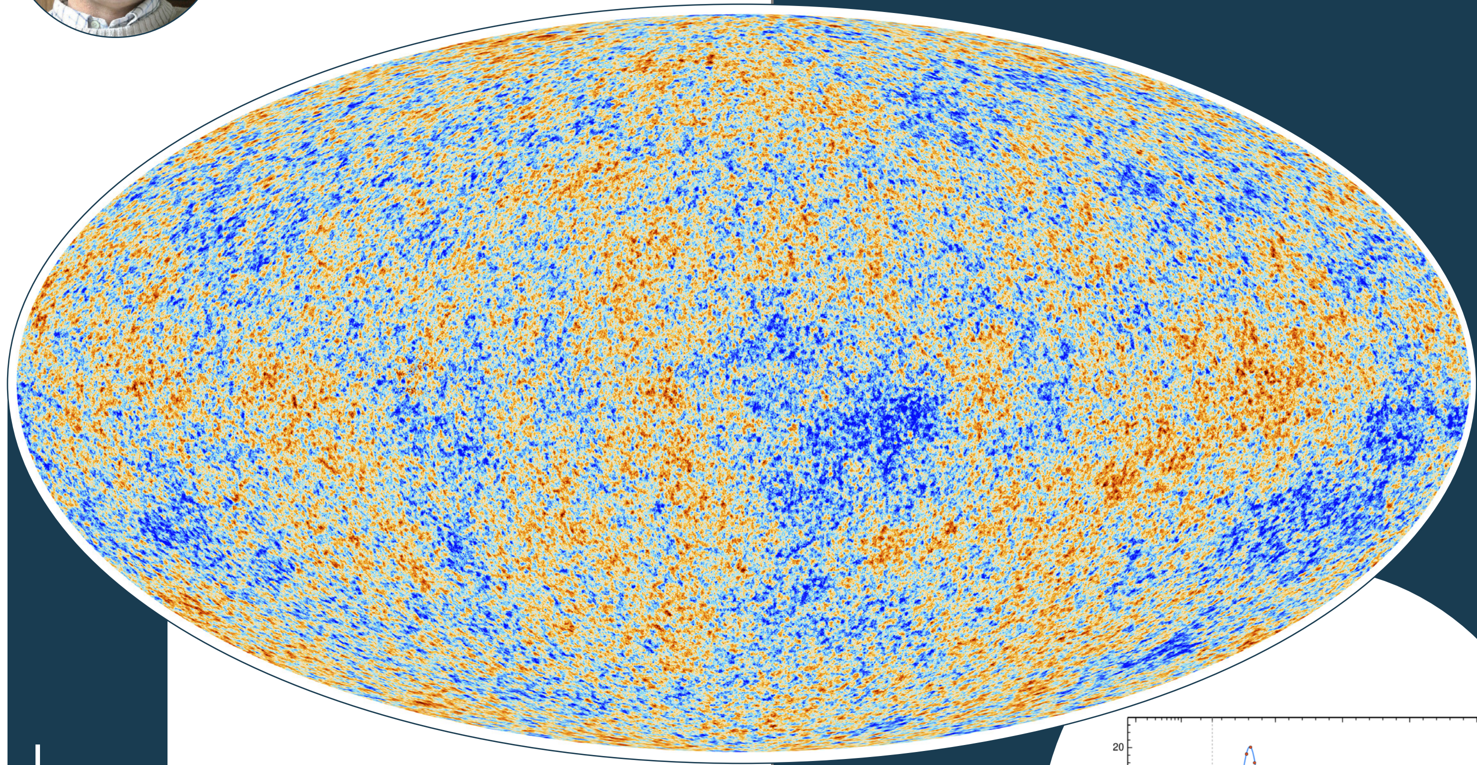

Steven Gratton &
George Efstathiou

The European Space Agency's Planck satellite was launched on 14 May 2009. Also that year the KICC building was completed! In the intervening decade almost twenty scientists from KICC, in concert with hundreds of colleagues across the world, have worked hard on analysing the data from Planck, using it to learn about our Universe.

In a special orbit, being dragged by the Earth around the Sun, Planck scanned ring after ring of the sky in order to build up pictures of the sky in various microwave frequencies or "colour bands", measuring small variations in the light from direction to direction. Part of each image comes from light emitted far away when the Universe was only about 380,000 years old (a tiny fraction of its present age of about 14 billion years) and very smooth, hot and simple. However, there is also "light pollution" from radiation emitted closer to home at much later times, from both our Galaxy and different ones.

Planck's very sensitive detectors relied on an active cooling system that worked for 2½ years. Many of the detectors measured the light's polarisation as well as its intensity. The initial results from Planck, reported in 2013, were based on the first 14 months of data and only considered the intensity maps. A more complete analysis was presented in 2015, based on the full amount of data and including a preliminary analysis of the polarisation maps along with the intensity ones. Kavli members Ashdown, Carvalho, Harrison and Sutton contributed greatly to the two "Planck Catalogue of Compact Sources", indexes of bright sources in the various maps, associated with these releases. July 2018 saw the appearance of the Legacy papers, based on a mature analysis of both intensity and polarization, with an accompanying data release being imminent.

By combining information from these pictures, Efstathiou, Gratton, Migliaccio and colleagues have been able to extract the signal from the early Universe to form "likelihood functions" that can be used to compare cosmological models to the data. These likelihoods will form part of the Planck Legacy data release and be a valuable resource for the community for years to come.



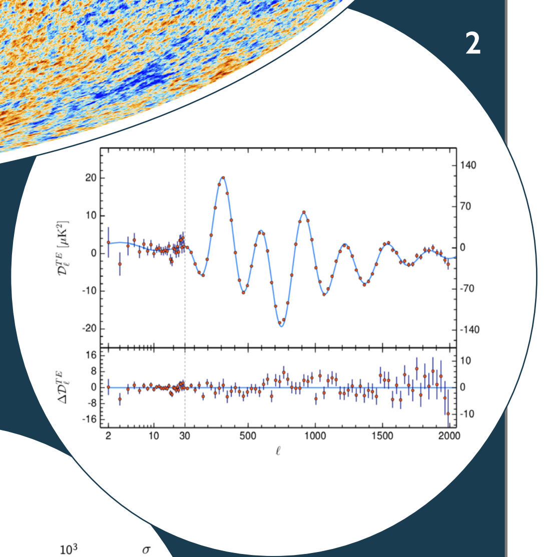
1

Data processing and analysis procedure improvements came with the 2018 release. A much-improved "map-making" algorithm was employed, mitigating uncertainties in our understanding of precisely how the instrumentation in the satellite converted the sky signal into digital data ready to send back to earth. To better understand noise properties of our maps, the NERSC supercomputer in California was used to make 300 very realistic simulations, with Ashdown contributing to the effort. Comparing these to the data helped us to understand the correlations Planck saw in the large-scale polarisation data enough to tightly constrain the "optical depth to reionisation" in our Universe. This is a measure of the number of free electrons along a line of sight from us back to the big bang, and the value inferred by Planck is on the low side but consistent with constraints from the spectra of high-redshift quasars. Bounds on other aspects of models of the Universe were also refined, and Efstathiou co-led the comprehensive 2018 "Cosmological Parameters" paper which gives a definitive say on the state of cosmology in the light of Planck. The simple "Lambda-Cold-Dark-Matter" model of the Universe based on general relativity continues to provide a compelling fit to the data.

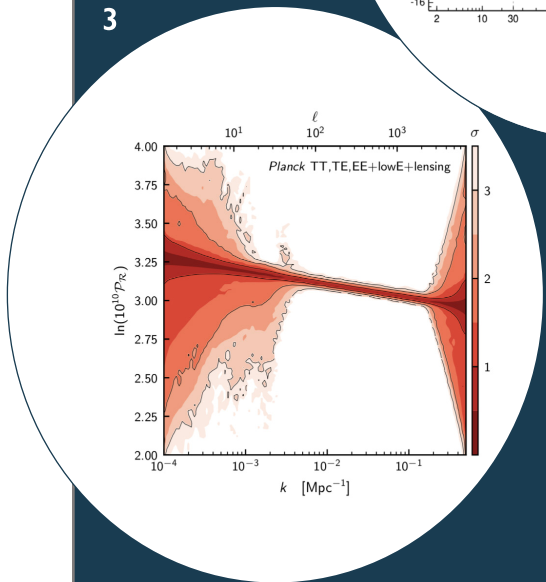
1. Planck's view of the Cosmic Microwave Background. (Image Credit: ESA)

2. Plot illustrating how well the Planck data (red dots, in this case coming from a combination of the temperature and polarisation data) fits the Lambda-Cold-Dark- Matter model of the Universe (blue line). (Image Credit: ESA)

2



3



3. Figure illustrating Handley and Lasenby's investigation into how inflation might have changed with time – the good agreement of the allowed region in red with a straight line suggesting that inflation proceeded smoothly. (Image Credit: ESA)

One of the key goals for Planck was to add to our understanding of the early Universe. A leading hypothesis is that some form of "inflation", or accelerated expansion, occurred, before the Universe became radiation-dominated as in a standard hot big bang. Handley and Lasenby developed and applied advanced analysis techniques to the Planck data, reported in the 2018 Inflation paper. They looked for hints of a sudden change in the nature of inflation as it may have proceeded by looking for sudden deviations in the fluctuations of the cosmic microwave background as one scans from larger to smaller scales. No convincing features were found however, suggesting that inflation, if it did occur, proceeded relatively smoothly.

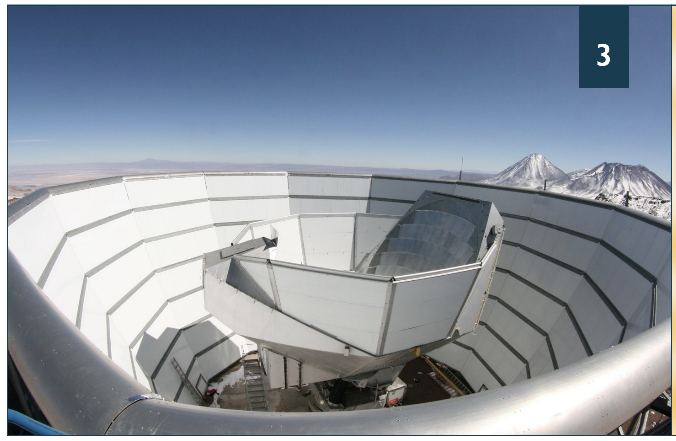
Another hint of the Universe being more complicated than as envisaged in the simplest models of inflation could come from a detection of "primordial nongaussianity", a subtle complication in the pattern of the fluctuations of the light from the early Universe. Fergusson and Shellard developed and applied a test for this in all of the Planck releases, finding no significant effect, and coding improvements in conjunction with the new simulations are enabling them to refine their limits in the forthcoming Planck paper on this topic.

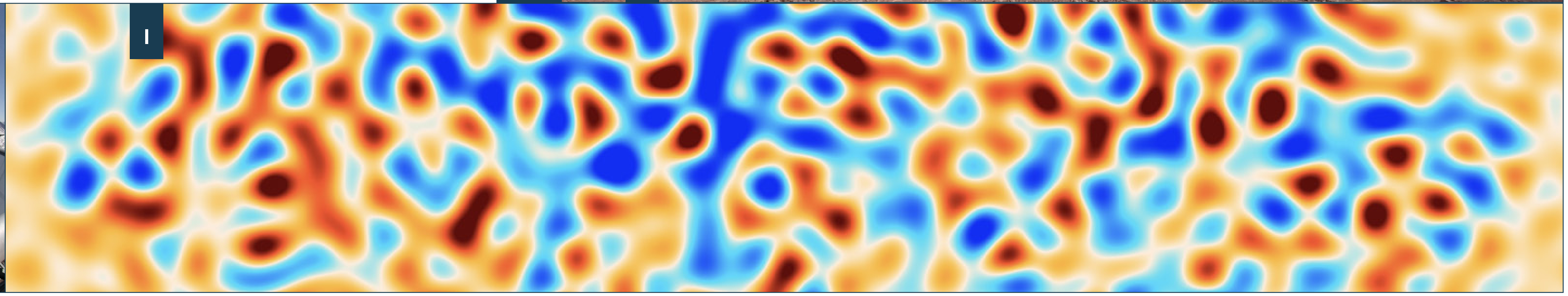
A final key cosmological success of Planck has been its emphatic detection of gravitational lensing, the slight distortion of the light from the early Universe as it passes through the gravitational field of intervening clumped matter, in which Challinor has played a leading role. The 2013 lensing analysis used the intensity maps alone, with the 2015 one bringing in the polarized ones also. The main improvements for the 2018 release came through the incorporation of insights from extensive numerical simulations and improved analysis techniques. In addition, the team were able to combine information from the distortions with that from direct observations of the light from distant galaxies in order to better estimate the lensing effect.

So, 10 years after Planck's launch, what is the future for Cosmic Microwave Background research at KICC? Challinor, Coulton, Meerburg and Sherwin are already hard at work, preparing for data from the forthcoming ground-based "Simons Observatory" being built in Chile. This telescope will provide a stunning view of the microwave sky at much lower noise and down to much finer scales than Planck achieved. Building on the legacy of Planck, in 10 more years we will surely know much more about whether the Universe is really as simple as it seems to us today.

COSMIC MICROWAVE BACKGROUND SCIENCE WITH GROUND-BASED TELESCOPES

Anthony Challinor & Blake Sherwin





1. Preliminary map of the CMB gravitational lensing signal made by ACTPol. The color indicates the strength of lensing and hence the density of matter projected across the Universe.

2. Image of the current CMB experiments sited in the Chajnantor Science Preserve high in the Atacama Desert in Northern Chile. The Atacama Cosmology Telescope is the left-most telescope The new Simons Observatory telescopes will be installed in the foreground.

3. An image of the Atacama Cosmology Telescope.

The cosmic microwave background (CMB), the afterglow radiation from the hot, infant Universe, provides us with our earliest view of the primordial density fluctuations out of which all cosmic structures grow. Analysis of the statistical properties of the fluctuations in the temperature and linear polarisation of the CMB has given precise answers to key questions, such as “what is the composition of the Universe?” and “what are the Universe’s large-scale geometric properties?”. Furthermore, the CMB has played a pivotal role in developing our understanding of the origin of primordial fluctuations, now thought to result from the stretching of quantum fluctuations from microscopic to cosmic scales during a brief period of cosmic inflation, an exponential primordial cosmic expansion. Given that the CMB originates from such early times, it also shines a backlight on all large-scale structures in the observable Universe. These can leave imprints in the CMB on small scales through gravitational lensing and scattering processes, which we are using to learn about the properties of the intervening structures.

The data from the Planck satellite have been instrumental in the efforts described above, and analysing and interpreting Planck data has been a major focus of CMB research at KICC since its opening in 2009 (the year that Planck launched). The measurements from Planck are close to exhausting the primordial cosmological information that can be extracted from the CMB temperature fluctuations. However, there is much more that can be learned with sensitive CMB observations on smaller scales inaccessible to Planck, and, particularly, with better measurements of the CMB polarisation.

The next decade of CMB observations will be dominated by measurements from ground-based telescopes, building on the rich legacy of experiments currently operating at the South Pole (the BICEP programme and the South Pole Telescope) and in Chile (e.g., the Atacama Cosmology Telescope, ACT, and POLARBEAR). Researchers at KICC are playing leading roles in the analysis of ACT data and we are very excited to be a part of the Simons Observatory, a new experiment now under construction in Chile that will see first light in the early 2020s.

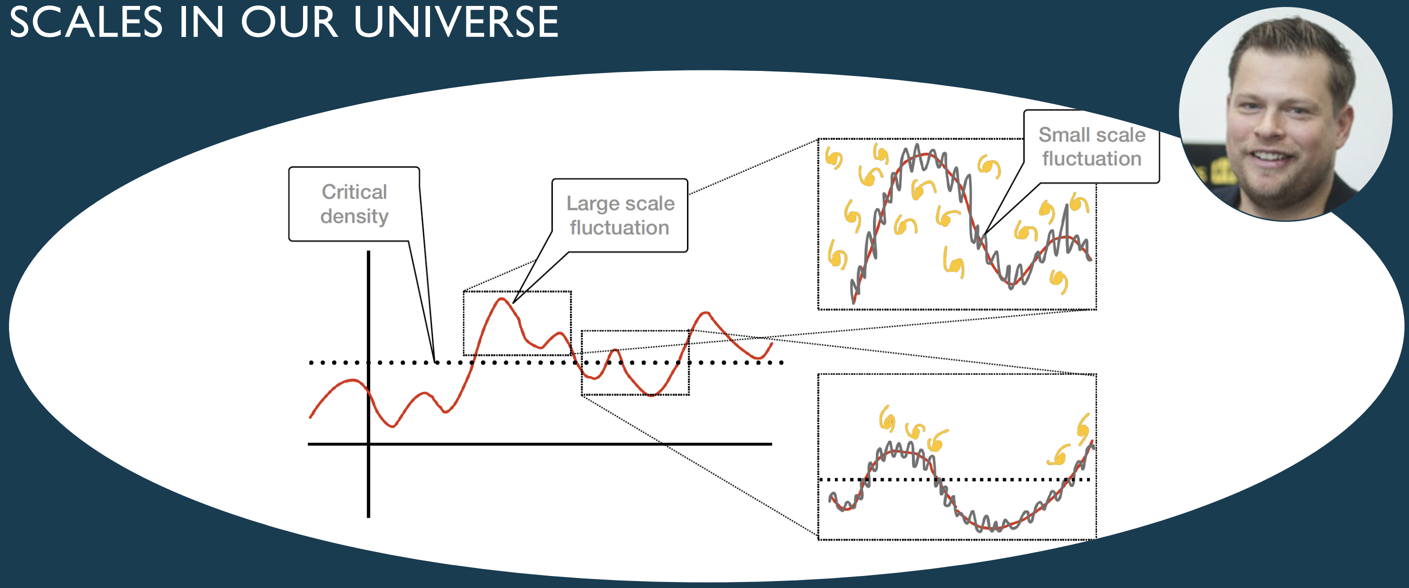
The Atacama Cosmology Telescope is a 6m CMB telescope located at more than 5000 meters altitude in the Atacama Desert in Chile. In its first incarnation, ACT began observing in 2007; it was subsequently upgraded with a polarisation-sensitive “ACTPol” camera in 2013 and with the latest, high sensitivity, multi-frequency “AdvancedACT” detector arrays in 2016. ACT has already made a number of key scientfic contributions, including tight constraints on new light particles and the first detection of a signal from the bulk motion of electrons in galaxies.

One area where ACT has made particularly significant advances is the study of CMB gravitational lensing: as the CMB propagates through the large-scale distribution of matter in the Universe, it is gravitationally deflected. Just as a glass lens can bend light, focusing or spreading the rays, large gravitational masses can similarly distort the path of the CMB. This lensing effect leaves subtle imprints in the temperature and polarisation fluctuations, which can be used to reconstruct a map of the lensing effects and hence the integrated distribution of dark matter (see Fig. 1). KICC researchers played a key role in some of the first demonstrations of lensing science with ACT; as part of the Planck team, they subsequently led the remarkable advance of CMB lensing science to a mature field of cosmology. With AdvancedACT operating until 2021, KICC scientists will lead the mapping of the cosmic mass distribution to unprecedented precision; this will allow us to measure the unknown mass of the neutrino, a poorly-understood particle, and will allow us to test whether dark energy is constant or dynamical by tracking the growth of structure with time.

KICC researchers are also playing a leading role in next-generation ground-based CMB experiments. From 2021–2025, the Simons Observatory (SO) will operate in the Atacama Desert site next to ACT (Fig. 2). Observing the sky at many different frequencies and at unprecedented depth with one large-aperture and three smallaperture telescopes, SO observations will provide new insights into the universe at the earliest times. In particular, SO will search for a characteristic signal, the CMB Bmode polarisation, which is produced by primordial gravitational waves originating from the earliest times and the highest energies. By strengthening constraints on primordial B-modes by more than an order of magnitude beyond current bounds – potentially detecting primordial B-mode for the first time – SO will contribute to new and powerful insights into the very early Universe. KICC researchers are playing a major role in this hunt for primordial gravitational waves, providing the primary expertise for the critical step of removing B-modes from lensing, which can be confused with primordial signals. Beyond B-modes, SO will also make major contributions to the search for new light particles, the understanding of neutrino physics, the scientific exploitation of galaxy clusters, and many other research areas in cosmology and astrophysics. Furthermore, KICC work on Simons Observatory will pave the way for CMB-S4, the ultimate ground-based CMB experiment, which will begin operations on multiple sites during the late 2020s.

IN PURSUIT OF THE LARGEST SCALES IN OUR UNIVERSE

Daan Meerburg



Sketch illustrating the concept of galaxy formation in overdense regions.

The most powerful observable that teaches us about the large structure and evolutions of the Universe is the so-called power spectrum. Technically, the power spectrum measures the variance of a field as a function of (physical) scale. Practically, in cosmology, we measure the variance of, for example, the number density of galaxies as a function of the separation between the galaxies. Likewise, in the cosmic microwave background (CMB) we measure tiny fluctuations in the temperature field and their variance as a function of their angular separation on the sky. Pioneering work in the 70s showed that the shape of the power spectrum provides information about the constituents of the universe, its topology and its initial conditions.

Observationally we have made tremendous progress in measuring the power spectrum. With the help of the Planck satellite (with significant contributions from members at Kavli) we have been able to measure the power spectrum all the way from scales the size of the current observable Universe, down to scales of large galaxy clusters (10 Mpc). In the future, the Simons Observatory will further improve the measurements of the smallest scales (see Challinor and Blake's piece on page 7).

Since the power spectrum is a statistical observable, it is limited in cosmology by what is known as cosmic or sample variance. This variance is introduced because a statistical measurement in our Universe is based on just one Universe (ours!), where the initial conditions are assumed to have been drawn from a statistical ensemble. At a given physical scale then, to obtain a constraint on the variance or power on that scale, we take the ensemble average over all realisations of that same scale within the observable Universe (since we lack the possibility to average over other universes). As a consequence, this sample variance on the largest scales is very large, because there only so many that fit in the entire observable Universe. On small scales, sample variance is small, because there are many copies of such scales which we can observe and average over. When we say that Planck has measured the power spectrum down to Mpc scales, we actually mean that on those scales thermal noise (coming from the limitations of the experiment) will become more important then sample variance.

Because sample variance is so important on large scales, even in the far future, it will be very challenging to learn more about the largest physical scales. Unfortunately, from a fundamental point of view, these largest scales are sometime more interesting then those on very small scales. For example, in the CMB we know that the largest scales on the sky are the 'cleanest', in the sense that they just appeared on our horizon and have gone through minimal processing. In the context of inflation, these scales are also the scales that would provide us with information about the early Universe that dates furthest back. Several interesting theoretical ideas, such as so-called kinetic inflation (currently pioneered by members at Kavli Will Handley and Anthony Lasenby) predict interesting effects on the largest scales which could indicate new physics. In large scale structure, the physics that determines where galaxies from inside dark matter haloes, is sensitive to deviations from Gaussianity in the initial conditions. This effect, know as galaxy bias, is best measured on the largest scales. There again, we are hindered by cosmic sample variance, fundamentally limiting how well can measure this effect in the data.

Besides sample variance, observationally it also a challenge to observe the largest scales in the Universe. Measuring such scales in for example a galaxy survey would require a very good calibration because large scale structure surveys would never be able to observe the entire sky at once.

Fortunately, there might be a way to measure the power on these largest scales after all. As alluded before, if the fluctuations in a field are Gaussian, then the only relevant measure is its variance. However, we know at least one very familiar process that can turn a Gaussian field into a non-Gaussian field: gravity. Gravity is a non-linear effect and this automatically generates deviations from Gaussianity. It produces stars, galaxies and galaxy clusters from what appear to be random Gaussian initial conditions. As a result, the field will not longer be described by the power spectrum but also by higher order moments (i.e. beyond the variance) such as the skewness (bispectrum) or kurtosis (trispecrum). Eventually, non-linearities will become too large, and it will not longer be possible to describe the field in terms of small fluctuations. However, in the limit of weak non-Gaussinity, a 'perurbative' description is still valid, which generally allows us to perform analytical computations.

One aspect of the higher order moments is that they describe how fluctuations couple on different scales; for a Gaussian field, only fluctuations on the same scale can be correlated. However when gravity plays a role, such scales can become coupled. For example, a very well studied effect is gravitational lensing of the CMB. While the primary CMB is Gaussian, as photons travel between the CMB surface and our telescopes, gravity can deflect their path as they pass through the large scale gravitational potential of the Universe. The measured power on small scales in the CMB is thus modified or coupled by a large scale fluctuation of the gravitational field. The coupling of scales is intuitively easier to understand if you think about the formation of galaxies. Imagine the Universe filled with a matter field. On large separation you can imagine that you can either be in a large scale under density (where the density is lower then the average) or over density (where it is larger). If you find yourself in an overdensity, small scale fluctuations around this point tend to form galaxies much easier then if your would find yourself in a large scale minimum, simply because the average local density is higher (similar to the probability of seeing a large mountain in Austria compared to seeing one in say, the Netherlands). If you would locally measure the variance of the galaxy field, you would find that it is correlated with the fluctuations of the large scale density field, i.e. there is a coupling between large scale fluctuations (in the matter field) and small scale power.

The effect of lensing has been well studied and a measurement of lensing relies on this coupling. In recent years however it has also been suggested that one could actually do the reverse: if you can reliably measure small scales power, you can infer what the local large scale fluctuation must have been. In other words, by measuring small scales power, gravity provides a translation between the fluctuations of this small scale power on large scales.

In a series of studies, we have considered this reverse engineering of the large scale CMB fluctuations, using small scale power. By accurately measuring the lensed CMB on small scales, we showed that it is possible to reconstruct the large scales mode. We showed how you can use the lensed temperature fluctuations to measure the cosmological dipole. This dipole is hard to measure on the sky, because of the earth motion through the galaxy generating a much larger dipole than that predicted by cosmology. However, using the reconstruction technique, it is possible to avoid the large foreground dipole.

In recent work we also showed that at late times, similar techniques can be used to reconstruct the largest scales in large scale structure. This can be used to investigate primordial deviations from Gaussianity. For a better understanding of the physics behind the generation of the initial conditions, non-Gaussianity is comparable to the detection of primordial gravitational waves. Cambridge has played a leading role for the search of primordial non-Gaussianity in the Planck data. So far, all measurements are consistent with Gaussian initial conditions. Improved measurements from future CMB missions (such as SO) as well as newly developed techniques proposed here, could eventually lead to a monumental discovery.

UNDERSTANDING THE RELATION BETWEEN GALAXIES AND MATTER

Oliver Friedrich

1. Illustration of the Kaiser bias model. Halos (i.e. collapsed, small scale peaks in the density field; see upper panel) are more likely to cross a particular threshold in mass if they are located in large scale overdensities. The relative density fluctuations of galaxies that form in these halos will hence differ from the relative fluctuations in total matter density (lower panel).

2. Illustration of gravitational lensing of extended background light sources (e.g. distant galaxies) by a foreground mass distribution. The images of the light sources will appear tangentially stretched around overdensities in the foreground (upper panel; so called positive tangential shear). In contrast, they will appear radially stretched into the direction of underdensities in the foreground (lower panel; negative tangential shear). The strength of the stretch is a direct measure of the foreground matter density profile.

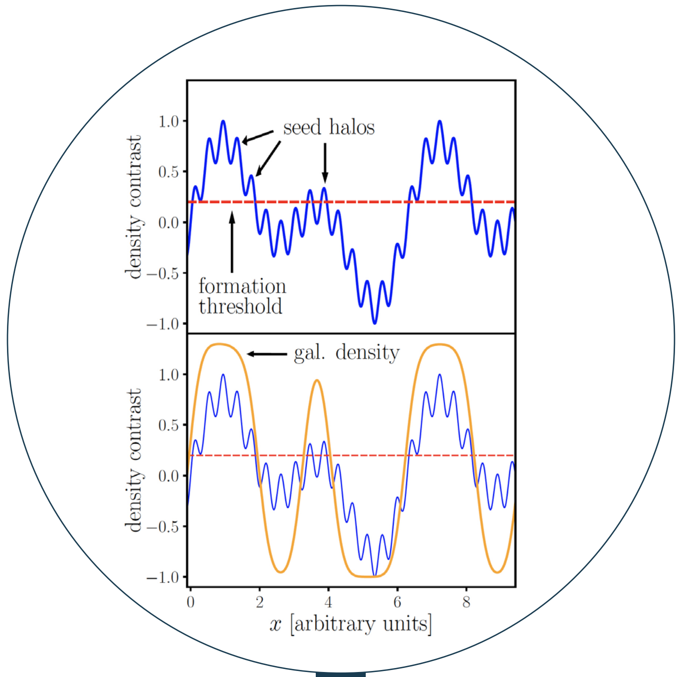
The matter that is filling our Universe today is not homogeneously distributed but rather organises itself in a variety of structures, in and around galaxy groups and clusters or in the matter and galaxy filaments connecting clusters and groups. This is in stark contrast to the time of the last scattering of the cosmic microwave background (CMB; redshift = 1100, about 14 billion years ago) where the average fluctuations of matter density were only about 0.1% of the average density in the Universe. The structures we observe today resulted from gravitational collapse of these small initial fluctuations. Observations of how those structures grow over time hence provide a test of the laws of gravity on cosmological scales. Especially, the late time growth of structure is a sensible probe of how quickly dark energy accelerates the expansion of the Universe.

There are two rather distinct views of the large scale structure (LSS) of our Universe. One in which it is described as a density field that is smoothly varying in space (or two density fields if we distinguish between the densities of dark matter and ordinary matter). The other view reduces this density field to its collapsed high density peaks, i.e. describes the LSS as a collection of collapsed halos of different mass, concentration, ellipticity etc. Connecting these two views is essential for the success of LSS cosmology for the following reason: cosmological theory primarily predicts statistical properties of the smooth density field, such as the so called power spectrum, which measures how the amplitude of density fluctuations varies with scale (see Daan Meerburg's piece). But our primary observables of the cosmic density field are the positions of galaxies, which form in small scale, collapsed halos.

Translating the halo description of the large scale structure and the smooth description amounts to understanding the so called halo bias – the stochastic relation between fluctuations in halo and total matter density. In figure 1 we describe a simplified picture of this relation: halos are more likely to cross a certain threshold in mass, if they are located in a large scale overdensity. Depending on this threshold the resulting relative density fluctuations of halos can either be enhanced or diminished with respect to the smooth density field. In addition, there will be stochasticity between halo and matter density, i.e. the two will not perfectly correlate with each other.

The 2-point correlation function of the galaxy density field (which like the power spectrum measures information about the scale dependence of the amplitude of density fluctuations) is an integral part of a recent cosmological analysis of the growth of structure which we carried out with data from the Dark Energy Survey (DES). Our limited understanding of halo bias (and even more so of galaxy bias, which in addition requires an understanding of which types of galaxies form in which types of halos) has been a major restriction for this analysis since it determines the minimal scale to which we can accurately interpret the clustering of galaxies as well as the gravitational lensing signal around galaxies. Moreover, our limited knowledge of the redshift dependence of galaxy bias forced us to treat it as an independent nuisance in all redshift bins considered in the past. This significantly reduced our ability to detect any possible redshift evolution of dark energy density.

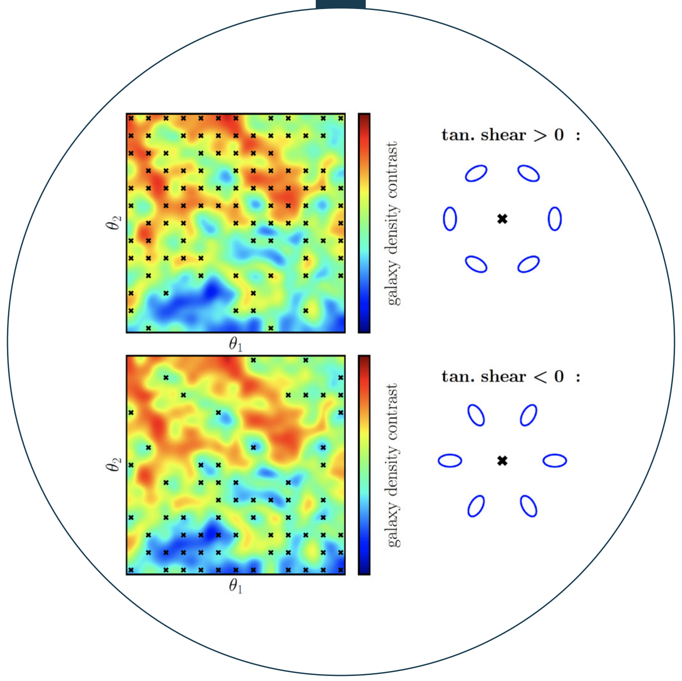
In future analyses, we will lift these restrictions with a new technique called Density Split Statistics (DSS). DSS was first devised and successfully applied to data in a series of papers by Gruen et al. (2016, MNRAS 455, 3367), Friedrich et al. (2018, PhRvD 98b, 3508) and Gruen et al. (2018, PhRvD 98b, 3507). It uses the gravitational lensing effect to directly translate galaxy density into dark matter density (Figure 2). This requires two galaxy samples: one foreground sample (the sample whose bias relation is to be determined) and a background sample at higher redshifts, which acts as a source for the gravitational lensing effect. This effect causes the images of the background galaxies to appear radially stretched into underdense regions of the foreground sample. Similarly, they will appear tangentially stretched around overdense regions of the foreground sample. Since the strength of gravitational lensing depends directly on the total matter density in the foreground, this allows us to directly recover the relation between matter and galaxy density.



1

While we previously used this technique in a standalone cosmological analysis, we will now combine it with DES 2-point function measurements. This will recover the small scales of galaxy clustering for the DES main analysis and also provide unprecedented information about the scale and redshift dependence of the relation between galaxies and the underlying matter density field. The framework we create in this process will significantly impact the analyses of future missions such as Euclid and DESI. The latter will measure the growth of density fluctuations with excellent precision along the redshift dimension and will require an equally excellent understanding of the relation between galaxies and total matter density. Our work on density split statistics will pave the way towards that goal.

2



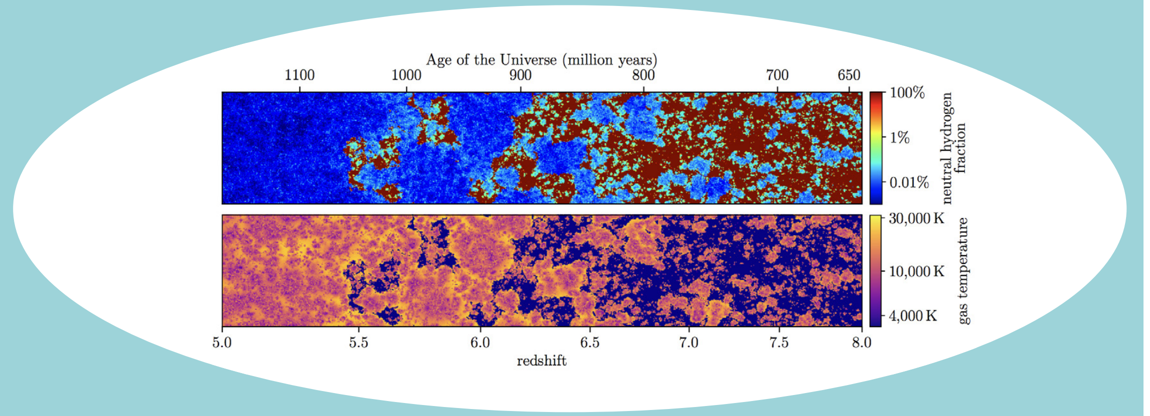
CONSTRAINING REIONISATION WITH Lyα FLUCTUATIONS

Girish Kulkarni & Martin Haehnelt

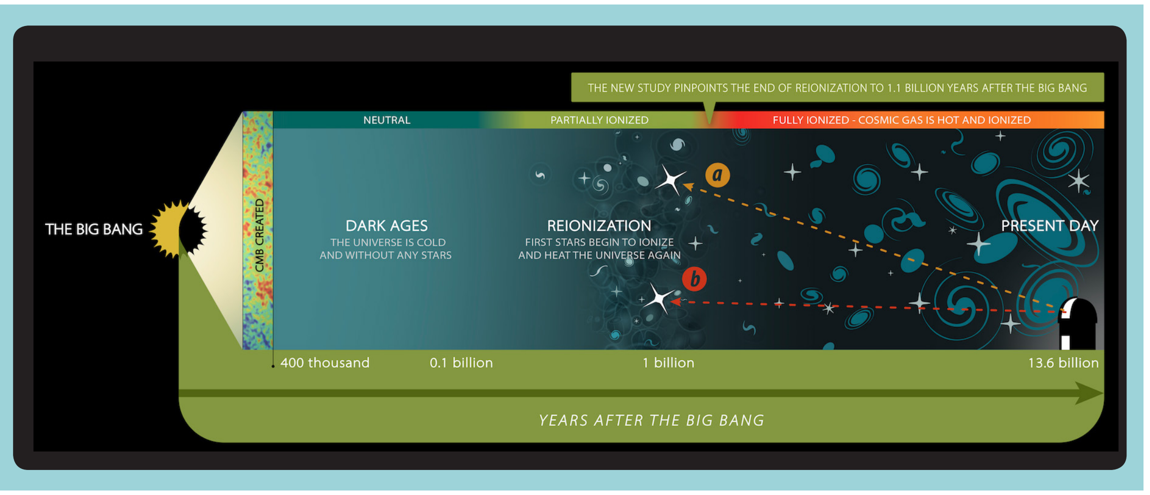
In the Big Bang model of cosmology, the Universe began evolving 13.6 billion years ago. Fifty million years after the Big Bang, the Universe was cold and dark. It contained gas with temperature only a few degrees higher than absolute zero, and no luminous stars and galaxies. But today, about 13.6 billion years later, the universe is bathed in light from stars in a variety of galaxies, and the gas is a thousand times hotter. Most of this gas is located outside galaxies in what is known as the intergalactic medium, and it typically has temperatures of around 10,000 kelvin. An important goal of cosmological research in the last two decades has been to understand the phase of cosmic evolution in which the Universe transitioned from the state of cold, cosmic "dark ages" to a state in which most of the cosmic gas is hot and the Universe itself is full of galaxies. This period in cosmic history is termed the epoch of reionisation, as the heating of the cosmic gas is accompanied by the ionisation of its hydrogen content (most of the cosmic gas mass, about 76%, is in hydrogen). The two governing questions in this area of research are (a) when did reionisation happen? and (b) what caused reionisation? The technique of observing the so-called "Lyman-α forest" has been the pre-eminent method for constraining the cosmic time at which the epoch of reionisation ended. Small amounts of residual neutral hydrogen in the post-reionisation Universe leave a dense forest-like distribution of Lyman-α absorption lines in the spectra of bright, distant objects such as quasars. Such lines have been observed in quasar spectra since the 1970s and they were shown to have an intergalactic origin in the 1980s.

Since these early detections, quasars at higher and higher redshifts (increasingly earlier in cosmic time) have been discovered and targeted for their Lyman-α forest spectra. These measurements have revealed that more than 99 per cent of the intergalactic hydrogen volume is ionised at least out to redshift of about 5 (when the age of the Universe was about 1.1 billion years). It has been difficult to probe the ionisation state of the intergalactic medium at redshift beyond 5 using the Lyman-α forest technique. One reason behind this is that the number of quasars seen at this early time in cosmic history is small. While close to hundred thousand quasars are known with redshifts less than 5, quasars with redshift higher than this number only about a few hundred. A second hurdle in pushing the redshift limit of the Lyman-α forest approach is the intergalactic medium itself. It has been noted since the early 2000s that the Lyman-α forest absorption appears enhanced as one goes to higher redshifts. At redshift of about 5.5, several Lyman-α forest spectra show complete absorption. That is, none of the emission from the quasar is seen in the given part of its spectrum. When this happens, the Lyman-α absorption is said to be saturated. Saturated Lyman-α absorption can no longer be used to infer the temperature and the neutral fraction of the intergalactic gas, because as long as the neutral hydrogen fraction is greater than 0.01 per cent, any value of it can produce saturated absorption.

Evolution of the neutral hydrogen fraction (top) and gas temperature (bottom) in our reionisation model. The vertical extent of each of the panels is 236 megaparsecs (770 million light years). Credit: Kulkarni et al. 2019, Monthly Notices of the Royal Astronomical Society, 485, L24.



Sketch illustrating some of the main features of cosmic reionisation and cosmic evolution.



We have approached this problem by performing computational simulations of reionisation caused by star-forming galaxies. These simulations resolve scales down to about 100 kiloparsecs (about 330,000 light years) and up to 450 megaparsecs (about 1.5 billion light years). This makes them ideal to study the problem of spatial fluctuations in the Lyman-alpha forest. Using these simulations, we developed a reionisation model that explains not just the CMB optical depth and the mean Lyman-α transmission but also the extent of the fluctuations in the Lyman-α transmission. This significant breakthrough - perhaps the most important theoretical result in this field in the last decade - allows us to pin down an epoch of reionisation that ends at $z = 5.3$ with the middle of reionisation at $z = 7$, much later than in previous models. Our model has revealed other interesting properties of the cosmic thermal evolution. For example, we find that there are ubiquitous and large-scale spatial fluctuations in gas temperature, coherent on scales of hundreds of megaparsecs, down to redshifts as low as 5.

Our findings suggest that reionisation occured much later than previously thought. This is good news for upcoming experiments that aim to observe the epoch of reionisation using the 21 cm spectral line of hydrogen. Indeed, a late reionisation scenario would mean that the features that these experiments are after will appear at higher frequencies, where observing conditions are better. A global effort is underway to detect this 21-cm signal using the largest of radio observatories (such as LOFAR, SKA, and HERA). This is also the beginning of the era of thirty-metre-class telescopes (such as ELT, GMT, and TMT) and observatories like Euclid that will transform our view of the universe by increasing the number of observed high- redshift galaxies and quasars by orders of magnitude. Over the longer term, observations of 21-cm and new quasars will hopefully not only confirm our reionisation model but lead us towards understanding the whole of the epoch of cosmic reionisation.

ASTROPHYSICAL MODELING OF THE 21-CM SIGNAL

Anastasia Fialkov

After the Big Bang protons and electrons recombined to form the first neutral atoms. The primeval Universe was filled with neutral hydrogen and neutral helium, which steadily cooled for the first few hundred million years. This fog of neutral gas was then slowly heated and reionised by the development of the first cosmic structures and, specifically, by stars and accreting black holes forming inside them. This process can potentially be traced through a transition emitted by hydrogen atoms at the wavelength of 21cm, i.e. at radio frequencies. The shape and the features of the sky-averaged (or global) signal of the 21cm transition (Fig. 1) are indeed tied to major events in cosmic history, such as formation of first stars and black holes. Ultraviolet (Lyman-α) radiation produced by first stars couples the 21-cm signal to the thermal state of the gas, which is cooled by the expansion of the Universe and heated by X-ray radiation of first black holes. In addition, radiation produced by stars at energies above 13.6 eV ionises neutral hydrogen in the intergalactic medium. These processes are responsible for the expected deep absorption trough (centered at the frequency of about 60 MHz) and the emission peak (at 100 MHz) shown in Figure 1.

Astrophysical processes that regulate the primordial star and black hole formation are poorly constrained by observations, which results in a large uncertainty in the expected global radio signal. Figure 2 shows variety of potential signals obtained by varying the underlying astrophysical properties in the widest range allowed by existing observations. The colors correspond to the relative strength of the Lyman-α coupling to the X-ray heating rate.

1. Sketch illustrating the variation of the 21cm signal across the cosmic times.

2. The global 21-cm signals as a function of frequency/redshift for 194 different astrophysical models. The colors indicate the ratio between the Lyα intensity and the X-ray heating rate. Adapted from Cohen et al. (2017, Monthly Notices of the Royal Astronomical Society 472, 1915).

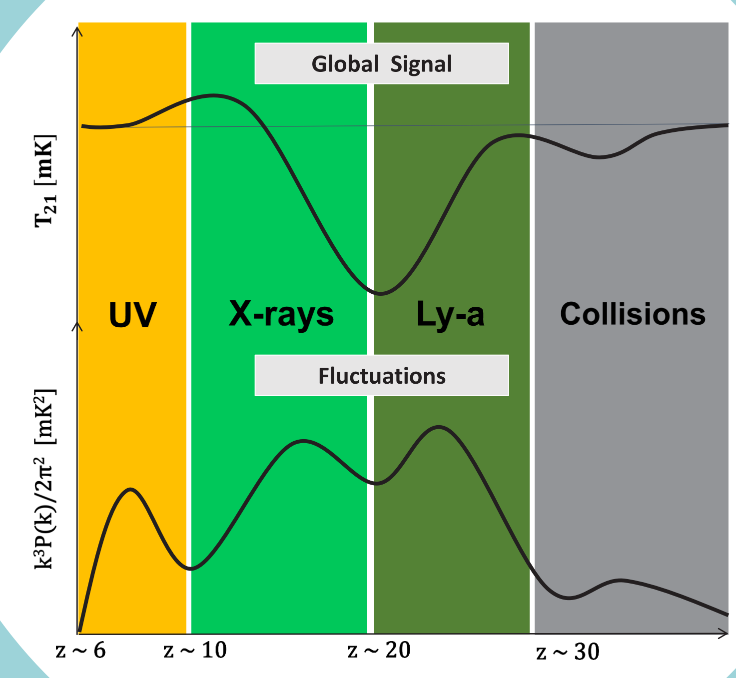
Owing to the patchiness of primordial star formation and the finite distance from each source out to which the photons can propagate before being absorbed or scattered, the radiative backgrounds (Lyman-α, X-ray, ionising) are not uniform across the sky. These fluctuations result in variability of the 21-cm across the sky.

Summarising, in order to reliably model the 21-cm signal, we need to include star formation which happens locally (on characteristic scales of few astronomical units, AU, the distance between the Earth and the Sun), capture the cosmic distribution of stars and black holes which varies on Mega parsec scales (Mpc, more than one hundred billion times larger than an AU), and account for characteristic scales on which radiation affects the gas (few hundreds Mpc). In full glory, such analysis is prohibitively computationally expensive.

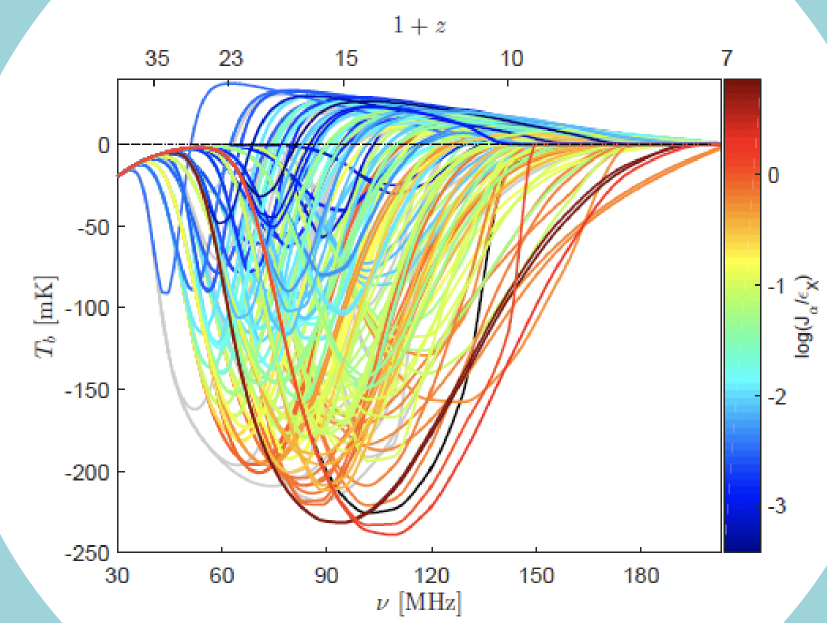
We have developed a hybrid computational method which allows us to predict the 21-cm signal on scales of few hundreds Mpc, and, simultaneously, incorporates high-redshift star and black hole formation. The code is based on a fusion of numerical simulations and analytical calculations and incorporates processes such star formation, heating and ionsation. The method is fast and flexible enabling efficient exploration of the astrophysical signatures.

Using this code we explored a large set of plausible astrophysical scenarios and derived first observational constraints on cosmic heating and ionisation using data from two pioneering independent global signal experiments: SARAS2 (Singh et al. 2017, 2018) and EDGES High Band (Monsalve et al., 2019). For the latter study, almost 10 million models were produced using Artificial Neural Networks, which were trained and tested on a set of nearly 30000 models (e.g. Fig.2).

1



2



DOUBTS ABOUT THE CLAIMED DETECTION OF "COSMIC DAWN"

Richard Hills, Girish Kulkarni,
Dan Meerburg & Ewald Puchwein

There was a great deal of interest in the astronomical community in a paper announcing the detection of "An absorption profile centred at 78 megahertz in the sky-averaged spectrum" (Bowman et al. Nature, 555, 67, 2018). This was a finding by the EDGES experiment of an apparent feature in the radio emission coming from all parts of the sky which could be the signature of "Cosmic Dawn" – the moment, early in the history of the Universe, when the first stars came into being. As explained in the Anastasia Fialkov's article (P.15), it had previously been predicted that, when the light from these first stars penetrated into the surrounding clouds of hydrogen gas, it would have disturbed the equilibrium between the hydrogen atoms and the surrounding radiation – the Cosmic Microwave Background (CMB). The prediction was that this disturbance would produce an absorption feature, and that if the first stars were created about 200 million years after the Big Bang (i.e. at a redshift of ~18) this be found at about the frequency of the reported profile. The feature observed was however much deeper than that predicted and its flat-bottomed shape was also unexpected. Figure 1 shows the observed feature and the predictions for a wide range of models based on our current understanding of the conditions at this stage in the evolution of the universe.

This result is particularly important because we have very little in the way of direct observations of this period. By contrast we can make detailed observations of the CMB, which tells us about the conditions at much earlier times, and we can of course observe the stars and galaxies at later times and so we believe that our models for those periods are good. For the absorption feature to be as large as that observed would mean that there is something important that has been missed – some new physics or perhaps a previously unseen constituent of the Universe. Following the publication of the EDGES result, a large number of theoretical papers have been published trying to explain the observations along these lines.

It should be appreciated that this is a very difficult observation because the sky is very bright at these low frequencies: the cold (3-degrees) CMB radiation is tiny compared to the several thousand degrees "foreground" emission produced by the energetic particles in our own Galaxy. In addition, there are the emissions from other radio sources and significant absorption and emission by the electrons in the Earth's ionosphere. These unwanted signals all need to be removed before the apparent absorption profile can be seen.

We have examined in detail the way in which EDGES data had been analysed in order to subtract off the unwanted signals and noticed some anomalies. We found that the proposed absorption profile can only be extracted from the data if the processes producing the foreground emission are assumed to have unphysical properties, for example a negative temperature for the electrons in the ionosphere. If the parameters describing the properties of the foregrounds are restricted to physically reasonable values, then the remaining profile has a completely different shape from that shown in the EDGES paper. This is shown in Figure 2.

This suggested to us that there must be some remaining systematic errors in the measurements of the sky brightness. After discussions with the EDGES team they agreed that there may indeed be some residual effects arising in the instrument or in the way in which the calibration was done.

The problem then is that it is not clear what is the correct model to use to account for these effects. Although it is true that if one chooses to use the particular model adopted by the EDGES team, then one does recover the profile that they published, we found that simply by making changes to the assumptions about the foregrounds and/or the form of the profile we obtained very different results. Figure 3 shows some examples of this.

Therefore, these findings call into question the interpretation of the EDGES data as an unambiguous detection of the cosmological 21-cm absorption signature and that it seems premature to suppose that new physical theories are needed to explain it.

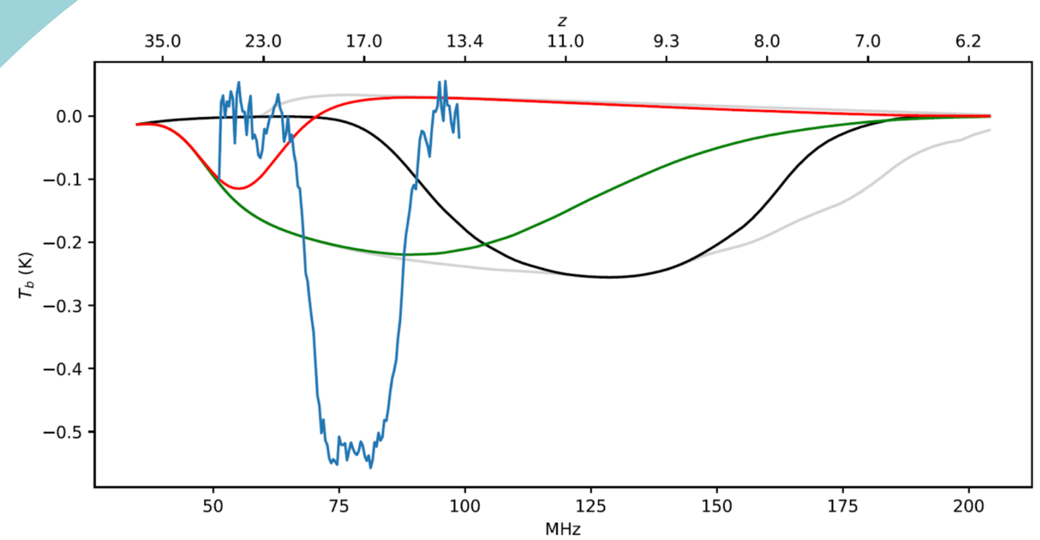
These results were published in the paper "Concerns about modelling of the EDGES data" is by Richard Hills, Girish Kulkarni, P. Daniel Meerburg and Ewald Puchwein. Nature 564: E32–E34, 2018

1. The signal published by the EDGES team (blue) compared with a wide range of physically plausible models among those shown by Anastasia Fialkov on page 16. The black, green and red curves show the cases which make the strongest features with the "dawn" occurring at various different times, and the grey curves show the envelope of the highest and lowest values seen in a total of over 9000 models.

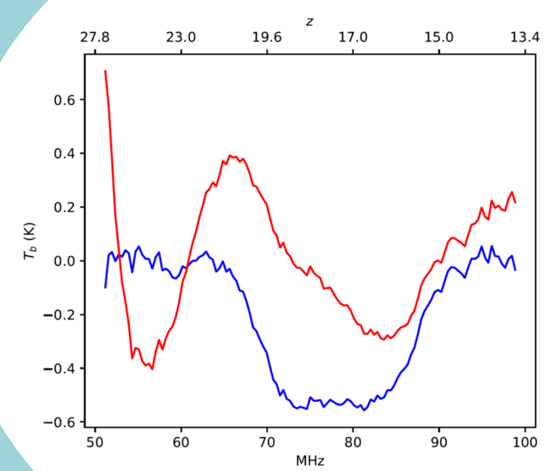
2. This shows, in blue, the signal after subtraction of foreground emission as modelled by the EDGES team and, in red, the same signal when the parameters of the model are constrained to have physically plausible values.

3. Alternative models fitted to the EDGES data. Case 1: the profile found by the EDGES team. Case 2: using the same formula for the profile but with a different model for the foreground. Case 3: using the original model for the foreground but a different formula for the profile. Case 4: with changes to both the foreground model and the profile formula. All these cases have the same number of free parameters – nine – and leave a similar level of residuals between the data and the fitted model. (The lines have been shifted vertically for clarity.)

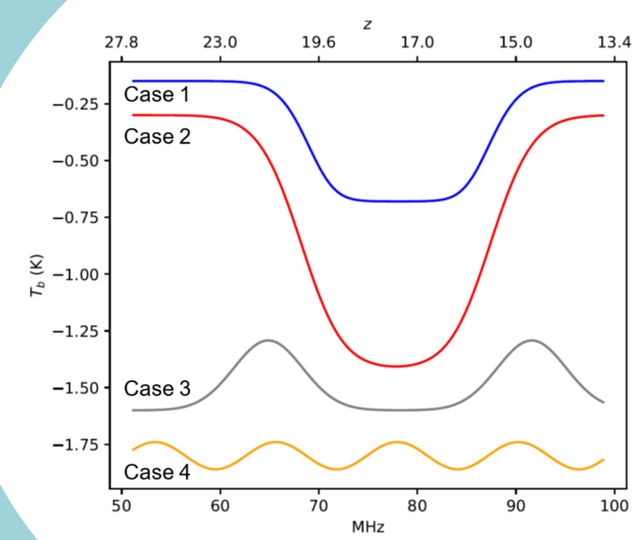
1



2

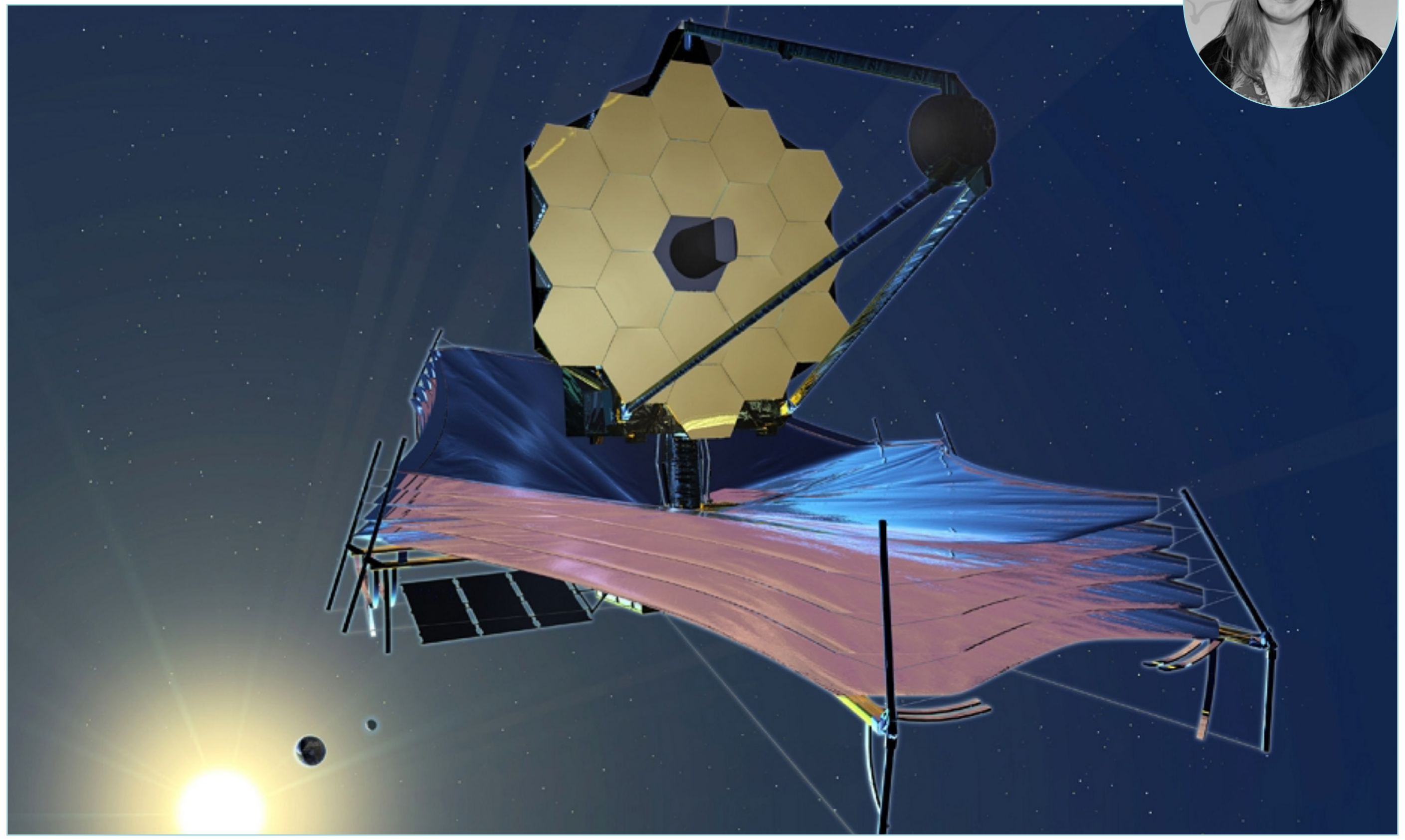


3



PREPARING FOR JWST

Emma Curtis Lake



The Hubble Space Telescope has become a household name. Being placed above the Earth's atmosphere, it has allowed us to peer into the far reaches of the Universe, where blue light from young, hot stars has been red-shifted into the near-infrared. Thanks to Hubble, we have discovered thousands of galaxies with z >3.5, i.e. less than 2 billion years after the Big Bang, and our current redshift frontier is z ~11.

But we have only scratched the surface.

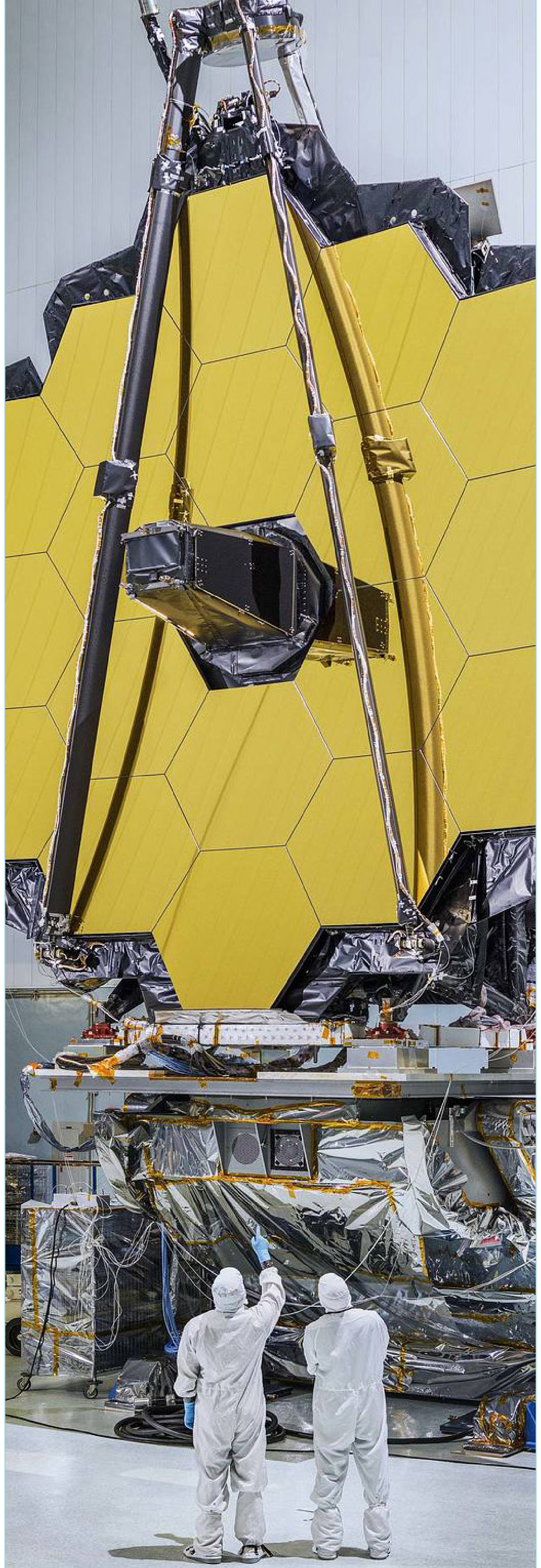
With its small mirror and an orbit which keeps it close to the heat radiated by the Earth, Hubble has observed these galaxies by staring at small patches of sky for hundreds of hours. With the James Webb Space Telescope (JWST) we will be able to observe to these depths in tens of hours. This is thanks to the largest mirror yet launched into space, measuring 6.5 m in diameter. In fact, this mirror is made up of 18 hexagonal mirror segments that will allow it to un-fold once released from its cramped transit into space (we have to fit it into an Ariane 5 rocket after all).

Added to that, it will be in an orbit far from the warm Earth (four times the distance of the Moon) and shielded from the sun by an incredibly efficient solar shield made up of sheets of a thin metallic film, allowing us to observe further into the infrared, and to discover even more distant objects than ever before.

But JWST will not only be a discovery telescope. It will be equipped with spectroscopic capabilities that allow us to measure galaxy spectra that we simply cannot measure from the ground. One instrument in particular, the Near-Infrared Spectrograph (NIRSpec), will provide spectra of hundreds of objects simultaneously, as well as detailed spatially-resolved spectra for individual objects. These spectra will allow us to trace the formation of different metals, search for strong outflows in primeval galaxies that might allow for the escape of radiation that could have re-ionised the Universe, address questions of how star formation is triggered and quenched in primordial galaxies, and detected the signature of the first generations of stars and black holes and how these have interacted with their host galaxies.

1. An artist's impression of JWST in orbit.
Image credit: Northrop Grumman.

2. JWST's mirror is made out of 18 hexagonal segments.
Image credit: NASA/Chris Gunn.



At the KICC, we are involved in the Near-infrared spectrograph (NIRSpec) guaranteed time observations (GTO) team, who has access to ~ 900 hours of observing time on JWST once it launches. A significant fraction of this time will be dedicated to observing the distant Universe, and we have been working with our colleagues in the NIRCam GTO team to coordinate with their observations.

To be able to design our survey, we really needed to be able to predict what we are going to be able to see with JWST, especially what kinds of objects we haven't yet observed with Hubble. This was no easy task, as the amount of information we have about galaxies decreases drastically with increasing redshift, and we wanted a catalogue that spanned a large fraction of the history of Universe, from 2.5 billion years ago to just 200 million years after the Big Bang. We had to marry together very different sets of observations and build a model that could be extrapolated to fainter objects, and higher redshifts than we've currently observed. Additionally, we needed to assign a simulated spectrum associated with each galaxy so that we could predict what it would look like with JWST. This was a truly collaborative project, requiring expertise on statistical modelling, observations of galaxy populations spanning most of the history of the Universe, expertise on galaxy spectral modelling, and two years of collaborative work between the NIRSpec and NIRCam teams. This was the first time a semi-empirical catalogue spanning such a wide range of the history of the Universe was produced and, realising it's usefulness, we released it for the entire community to use.

Equipped with this catalogue we are now hammering out the details of how we will select our target galaxies for follow-up spectroscopy. More than that, the two teams are preparing for our tight turn-around time between NIRCam observations and follow-up with NIRSpec. We will be practicing the whole process to make sure we are ready for it. With our mock Universe, we can produce simulated raw images from NIRCam ready to process, identify objects and measure key properties that we will use to determine which ones we will select for follow-up with NIRSpec. With a limited lifetime of 5 to perhaps 10 years, every second of observing time counts, and we are working to ensure that we prioritise the most distant and rarest sources, which will reveal the properties of the first generation of galaxies and black holes, while at the same time building up a large, statistical sample of objects. In brief, a survey that will allow for major new discoveries as well as indepth, multi-faceted analysis for years to come, not only by the GTO teams but by all future astronomers researching galaxy evolution in the young Universe.

ORDER IN THE CHAOS OF THE EARLY UNIVERSE

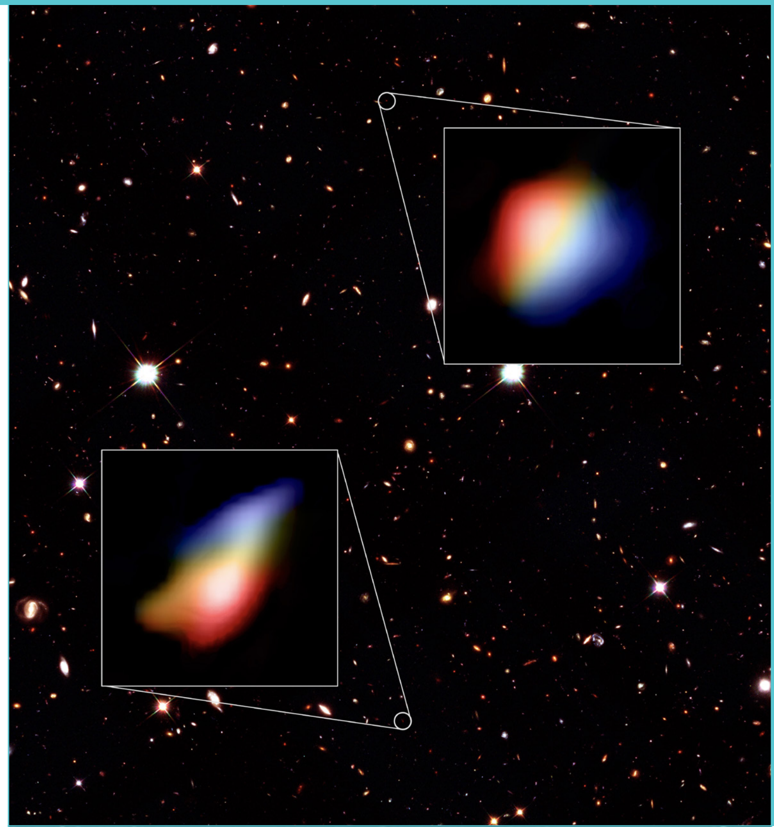
Renske Smit

Ever since Edwin Hubble uncovered the nature of spiral galaxies, astronomers have been fascinated by the organised spiral structure and disk rotation of these 'Island Universes'.

With the continuous improvement of astronomical instrumentation, optical 8- to 10-meter class telescopes have been able to make studies of earlier generations of star-forming galaxies up to about 10 billion years back in time, spanning roughly 70% of the history of the Universe. The further we look back in time, clear changes in the appearance of these galaxies are observed. These starforming galaxies observed billions of years ago already rotated in thick, 'puffedup' disks but their spiral-arm morphology had not yet developed The increased turbulence in the gas of these galaxy disks has suggested that the rapid inflow of gas in the dense early Universe is important in determining the structures of these galaxies.

These results pose many questions about the earliest generations of galaxies during the first three billion years of cosmic time. When did the first disk-like starforming galaxies, distant cousins of our own Milky Way, appear in the history of the Universe? Does the highly turbulent environment in which galaxies form just after the Big Bang prevent the formation of ordered disk rotation? New research with the Atacama Large Millimetre Array carried out by our team (led by Renske Smit and including Stefano Carniani and Roberto Maiolino) suggests that we are on the brink of answering some of these very fundamental questions.

In our current understanding of the early Universe, the first stars formed a few hundred million years after the Big Bang from essentially pristine hydrogen gas. The first stars are thought to be supermassive and explode as supernovae on very short timescales. The first supernovae pollute their environments with elements such as carbon and oxygen which are synthesised in these explosions and these elements enable the gas to cool rapidly to form the new populations of stars that make up the first galaxies.



1. Two galaxies 800 million years after the Big Bang (6% of the current age of the Universe) as seen by ALMA (inset panels). The color gradient in the sources shows the motion of the gas detected by ALMA, indicative of rotation. credit: Hubble (NASA/ESA), ALMA (ESO/NAOJ/NRAO), P. Oesch (University of Geneva) and R. Smit (University of Cambridge).

2. A few of the ALMA antennas.

These results were published in the paper "Rotation in [C II]-emitting gas in two galaxies at a redshift of 6.8" 2018, Nature, 553, 178.

With modern-day telescopes we are able to look back in time and search for galaxies that formed in the first billion years of cosmic time, often referred to as "cosmic dawn". While the light from these galaxies travels to the Earth, the expansion of the Universe stretches the wavelengths of all the emitted electromagnetic radiation. This reddening, or 'redshift' of radiation from the early Universe, has proven to be both a blessing and a curse. On the one hand, the exact determination of redshift is a remarkably effective and precise means of determining the cosmic epoch at which the light was emitted. On the other hand, the starlight from the most distant objects in the Universe that reaches our ground-based telescopes is shifted out of the optical 'window' of the Earth's atmosphere, where transmission of radiation is high, into the more challenging infrared wavelength regime.

In order to determine the redshift of light, and thereby determine the distance and look-back time of the most distant galaxies, we need a sharp feature, preferably a narrow emission line, in the spectra of the objects we are studying. For galaxies close to home, we find a wealth of emission lines in the spectra of starforming galaxies in the optical spectrum. For the most distant galaxies, however, these lines are redshifted into that part of the electromagnetic spectrum where light barely penetrates the atmosphere and out of the wavelength range of current-day space-based spectrographs. Observers of the distant Universe have therefore shifted their focus towards the long wavelength regime of the (sub)millimetre sky. At these low frequencies, at the edge of the hightransmission radio window of the atmosphere, we are now seeing the signatures of cool gas and dust of some of the most distant galaxies in the Universe.

New discoveries in this wavelength regime have grown exponentially once the Atacama Large Millimetre Array (ALMA) become fully operational in 2013. ALMA is the largest sub-millimetre telescope array in the world consisting of 66 millimetre/submillimetre antennae on a high plane in the Atacama desert in Chile.

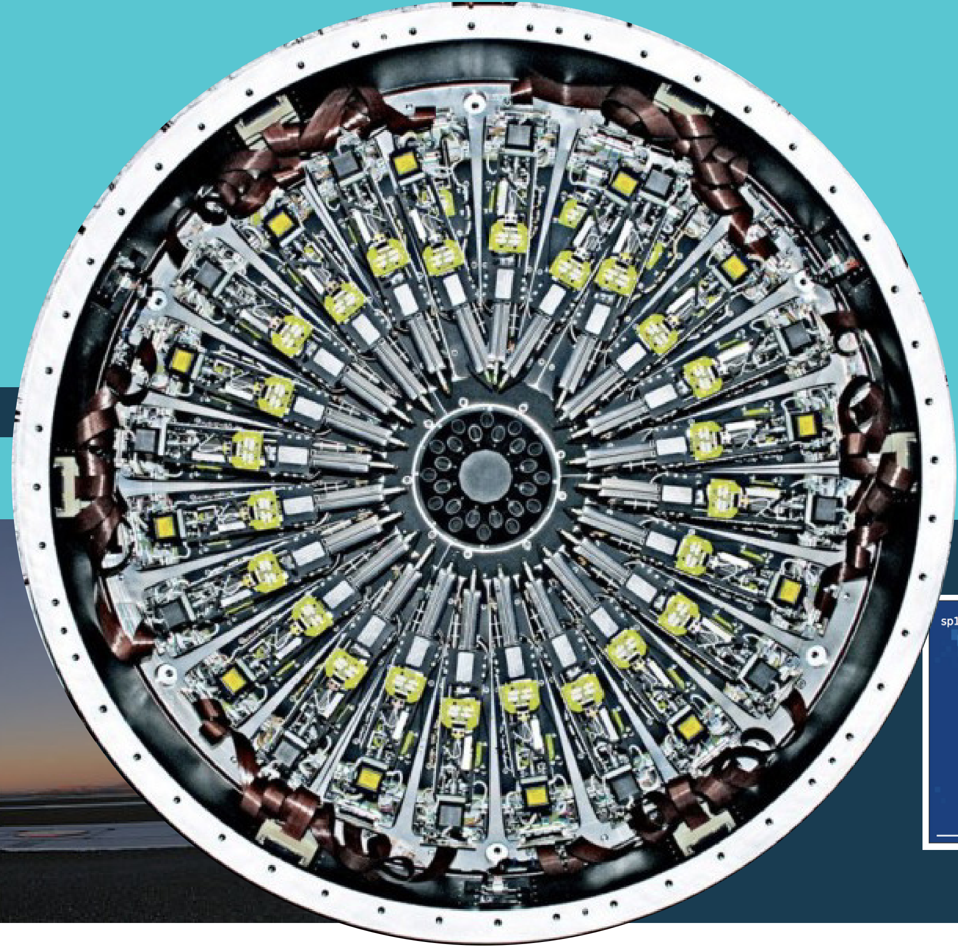
We recently used ALMA to obtain precision measurements of the redshifts of two galaxy candidates during the first billion years of cosmic time, the first time such a measurement has been carried with a sub-millimetre telescope. These galaxies were selected from images obtained from both the Hubble and Spitzer Space telescopes, but these telescopes did not have spectroscopic facilities to confirm their extreme distance. A short frequency 'scan' of both sources by ALMA revealed a transition of ionised carbon - typically the brightest collisional excited fine-structure line emerging from star-forming galaxies - and confirmed a lookback time of almost 12.9 billion years, 94% of the age of the Universe.

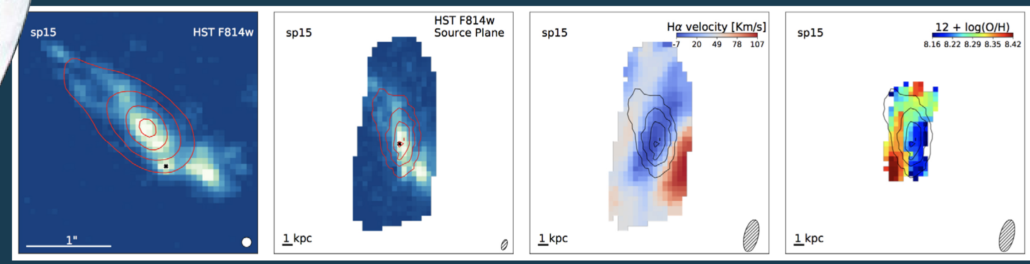
While the success of the redshift determinations was an important proof of concept for ALMA's role in early Universe research, the observations yielded another unexpected result. The relatively bright carbon lines were remarkably spatially extended and, despite the low-angular resolution of the observations, the velocity structure within such galaxies was revealed for the first time by mapping the variations in the Doppler shift of the lines.

The smooth gradient in the velocity of the gas is highly suggestive of the rotation of disk-like galaxies, similar to those seen three billion years later in cosmic time, during the peak epoch of star-formation in the Universe. Despite the turbulent environments in which these early galaxies are located, they seem to be able to 'mature' early and settle down into relatively regular systems. Some theoretical models and cosmological numerical simulations had recently highlighted the possibility that galactic disks formed very early in the primeval Universe and the new ALMA observations have nicely confirmed this scenario. New observations with ALMA at higher angular resolution are underway and will provide us with even more physical insight into the kinematics of galaxies during this crucial first epoch of galaxy formation.

A "KLEVER" LOOK AT PRIMEVAL GALAXIES

Mirko Curti





Several lines of evidence have indicated that primeval galaxies were characterised by more extreme physical conditions than their descendants observed in the local Universe. Extensive observational efforts have been devoted in the last decades to the analysis of primordial galaxies and to the understanding of the mechanisms that have transformed them across the cosmic times. In particular, the epoch comprised between 9.5 and 11.5 billion years ago is of great interest for astronomers. In fact, at that time the Universe was undergoing a period of great transformations, as the result of the incessant interplay between gas accretion from the cosmic web, the formation of stars, the presence of powerful winds expelling the gas, as well as close galaxy encounters that ended up in dramatic merging events. It was the time of the highest activity in the history of the Universe, and the intense star formation that took place contributed to build-up the majority of the stars that we see today in local galaxies. This epoch, which is sometimes referred to as the "cosmic noon", represents therefore one of the most privileged temporal windows from which we can have a direct look at the processes responsible for the evolution of galaxies.

One of the most fruitful ways in which astronomers can do that is to look at the bright emission lines visible in the spectra of these distant objects. These lines, emitted primarily by Hydrogen atoms and several metal species (like Oxygen, Nitrogen and Sulfur) present in the warm interstellar gas within galaxies, can be used as powerful diagnostics of their physical conditions. Most of the strongest lines are emitted in the optical region of the spectrum. However, due to the cosmological expansion of the Universe, their wavelength is stretched and shifted into the near-infrared, in a region where fortunately the atmospheric transmittance still guarantees their observability from ground. Although large samples of distant galaxies have been observed through near-infrared spectroscopy, the majority of past studies either lacked spatial information or targeted only a few emission lines, hence inadequate to properly characterise the physical properties of these systems.

1. The Very Large Telescope

2. The 24 arms of KMOS positioning the 24 integral field units on the focal plane of one of the VLT telescopes.

3. One of the several gravitationally lensed galaxies observed with KMOS in the KLEVER programme. from left to right: grabitationally lensed image, reconstructed (de-lensed) image, velocity field, metallicity map.

To get a step forward in this direction, an international team led by scientists of the KICC is now carrying out a project exploiting the near-infrared multi-object spectrograph KMOS, mounted on the Very Large Telescope (VLT) on top of Mount Paranal (Chile) and operated by the European Southern Observatory (ESO). KMOS is constituted by 24 individual integral field spectrographs, capable of providing both spatial and spectral information at the same time for each of the 24 sources observed simultaneously. The strategy behind this project, which is an ESO Large Programme denominated KLEVER (Kmos LEnsed Velocity and Emission line Review), is to observe about 150 galaxies in the three main infrared bands (J, H and K), to get simultaneous access to multiple emission lines and map them spatially thanks to the integral-field spectroscopy provided by KMOS. Using the data from KLEVER we are attempting to obtain a full, spatially resolved picture of the physical conditions of the interstellar gas in these galaxies by simultaneously mapping gas density, ionisation state, excitation mechanism and chemical abundances, along with kinematic information on galaxy rotation and presence of outflows.

Nearly half of the KLEVER galaxies are magnified by the gravitational lensing effect provided by giant, massive galaxy clusters located between them and us. This cluster's mass distribution acts like a lens, deflecting, stretching and magnifying the incoming light from the very distant objects behind it and allowing us to achieve a level of spatial resolution otherwise unreachable even by the largest ground-based telescopes. Combining this technique with the wealth of diagnostics provided by our observing strategy, we are obtaining insights on the distribution of the heavy elements within our galaxies with an accuracy and with a statistics that has not been possible in previous surveys. The analysis of the first available observations in the program revealed that the majority of the sources are characterised by an apparent homogeneous distribution of metals, as pointed out by the absence of prominent radial gradients in the chemical abundances. However, a closer look to the metallicity maps reveals more complex morphologies, probably indicative of a more turbulent history of chemical enrichment. This information is important to shed light on the processes driving the assembly of galaxies over cosmic time. In fact, the lack of metallicity gradients at these epochs implies either that the buildup of stars, and therefore the subsequent metal enrichment, has occurred on similar timescales throughout the galaxy or, assuming a faster growth of the inner regions (the so called 'inside-out' scenario, predicted by the majority of galaxy evolution models), that powerful outflows must have been active at that time redistributing the gas across galaxies, a possibility often explored also by many numerical simulations. On the other side, the presence of irregular patterns in the metallicity maps may be indicative that star formation in these galaxies is a more stochastic process taking place in compact clumps, as suggested by some other observations.

THE HUNT FOR DISTANT QUASARS WITH BIG SKY SURVEYS

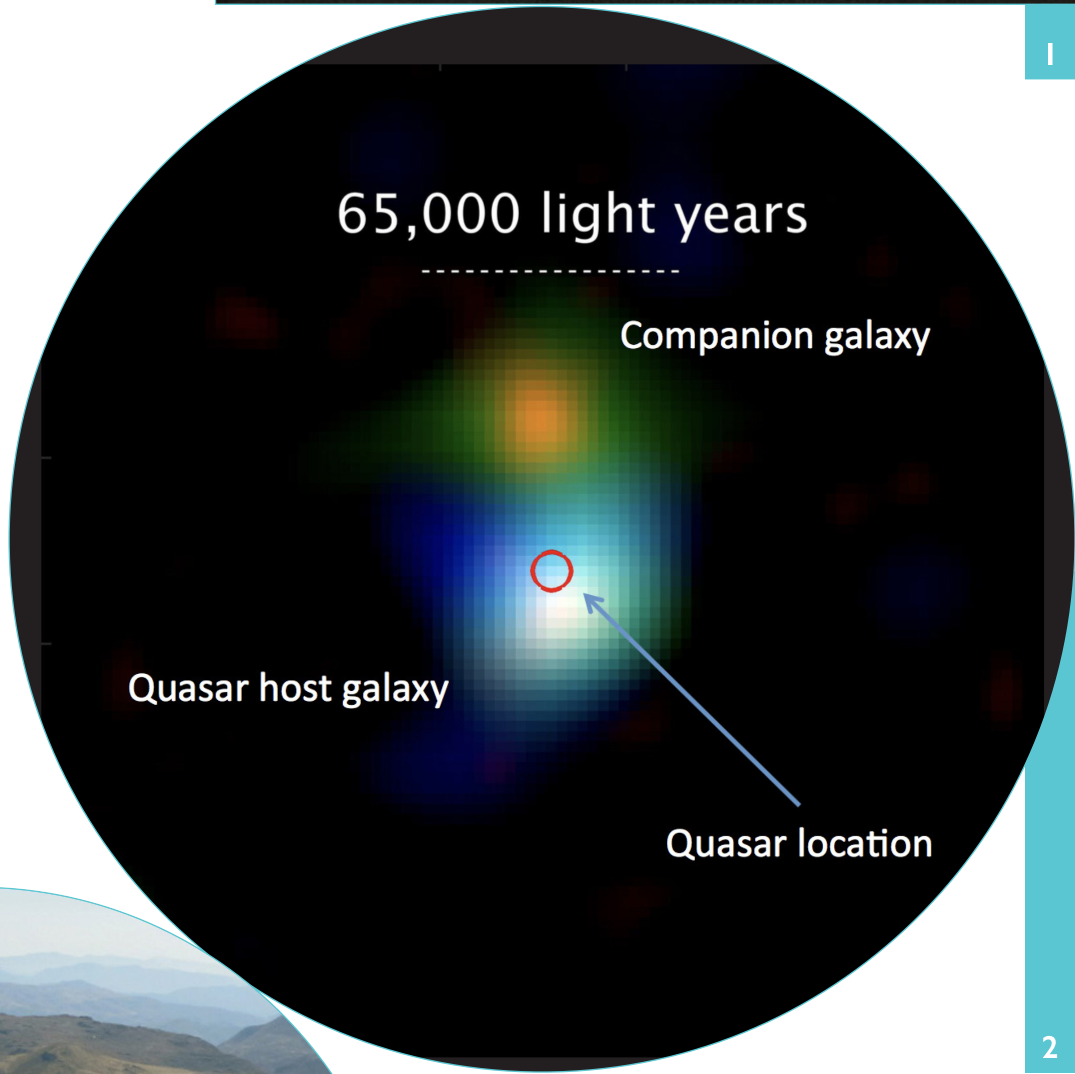
Manda Banerji

Quasars are among the most exotic and enigmatic objects in our Universe. Powered by feeding supermassive black-holes that inhabit the centers of almost all galaxies, the brightest quasars can emit the equivalent amount of energy to several trillion Suns. As a consequence, these quasars can be seen out at vast cosmic distances and light from the most distant quasars can take several billion years to reach us on Earth today.

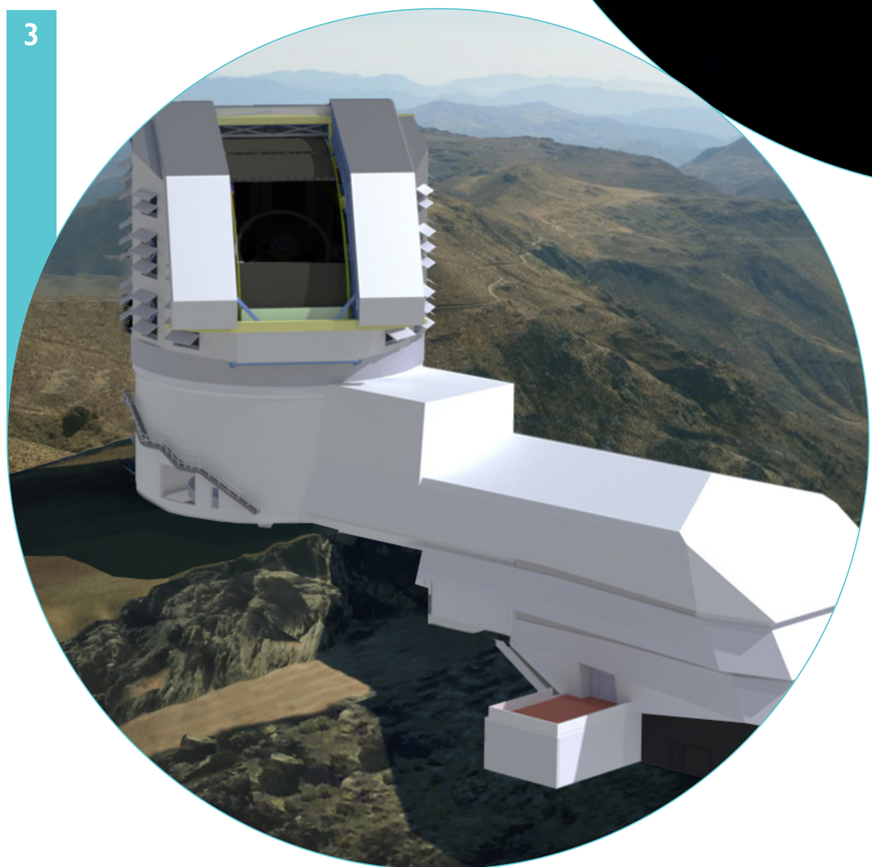
Studying quasars helps astronomers to understand the formation and evolution of supermassive black holes in the Universe and how their growth shapes the galaxies in which they reside. However, distant quasars are rare objects, greatly outnumbered by stars and galaxies, which are the most abundant sources of light in our Universe. Finding distant quasars is therefore comparable to looking for a needle in a haystack.

In recent years the search for these quasars has been greatly aided by the development of sensitive digital cameras that can be mounted on some of the largest telescopes in the world to effectively scan large swathes of the observable sky. We have been heavily involved in the Dark Energy Survey (DES), which is making use of a 570 Megapixel camera mounted on the Blanco telescope in Chile to image about one-eighth of the southern sky. The DES data can be used in conjunction with data from VISTA telescope to locate the most distant quasars and separate them from the more numerous stars and galaxies. While DES images the sky in visible light, the VISTA telescope is providing a complementary view of the Universe in infrared light. For the most distant quasars the expansion of space-time means that light emitted by the quasar is redshifted from the visible to the infrared wavelengths and this signature can be utilised to locate the quasar. Recently astronomers at KICC have been involved in the discovery of four new quasars seen less than 800 million years after the Big Bang using these surveys.

1. The VISTA infrared telescope.



2. Distribution of gas mass associated with a distant quasar host galaxy and a companion in the process of merging revealed by ALMA. Colors indicate different velocities.



3. Illustration of the LSST dome at the planned location in Chile.

The DES and VISTA data can also be used to locate another class of quasars, those that are heavily enshrouded by dust. In this case the dust absorbs the visible light allowing the quasars to shine brightly only in the infrared. We have led the discovery of this new population of quasars, which were hidden from our view before infrared sky surveys became operational. Large sky surveys have again been instrumental in the search for these rare objects.

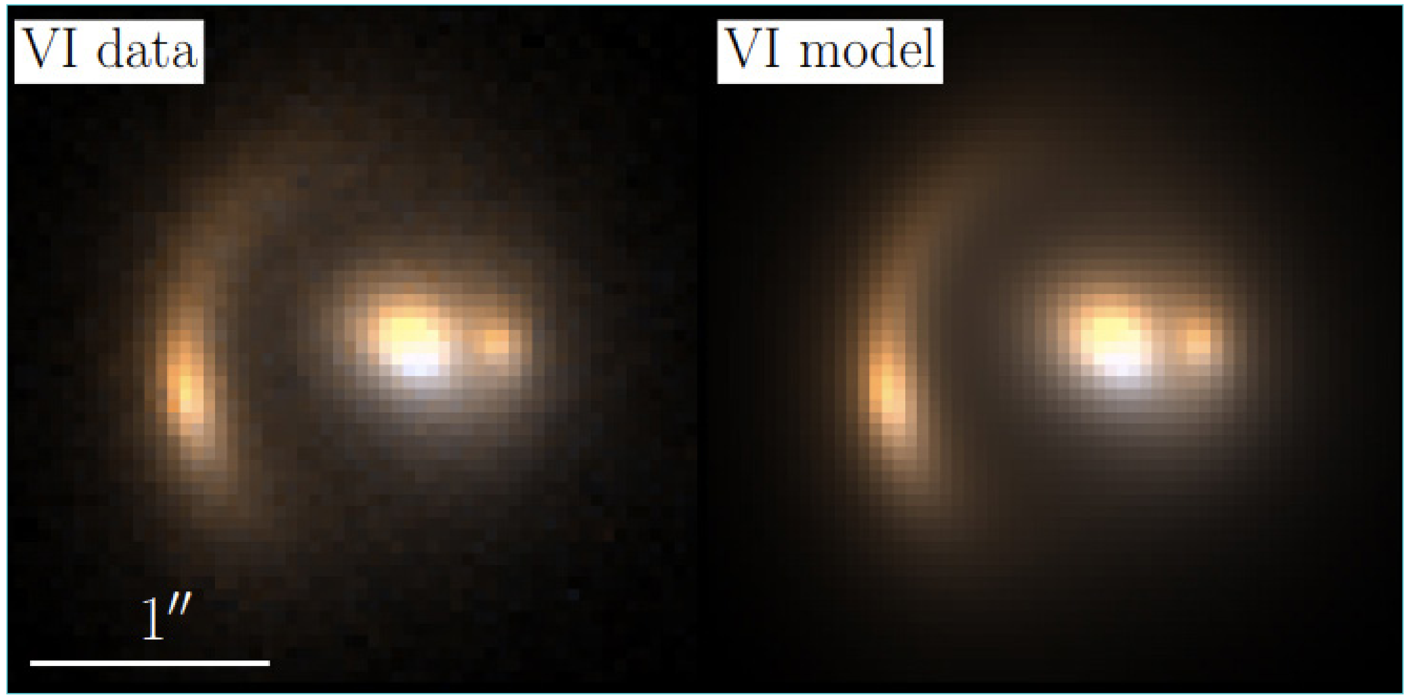
Once discovered, observations from the Atacama Large Millimeter Array (ALMA) are used to image these systems in microwave radiation, which picks up gas and dust in the quasar host galaxy. The gas will eventually serve as the fuel on which the black-hole feeds thus growing in size and energetic output. Fig. 2 illustrates one such quasar system where the gas and dust distribution imaged with ALMA reveals two galaxies less than 100,000 light years apart that are in the process of crashing into one another. This kind of galaxy merger is almost certainly responsible for triggering the feeding onto the supermassive black hole, which as a consequence shines brightly as a quasar.

Looking into the future, the hunt for more distant and enigmatic populations of quasars will be further revolutionized by the Large Synoptic Survey Telescope (LSST, Fig.3). In 2022 the 3.2 Gigapixel camera on board this brand new telescope will start gathering vast amounts of data. The resulting data volumes will dwarf current sky surveys – 15 trillion bytes of data per night, which will provide astronomers with an ever-changing view of all kinds of objects in the Universe from near Earth asteroids to the most distant galaxies and quasars. We are heavily involved in this major enterprise and looking forward to the deluge of data over the next decade and beyond that will enable ever-increasing numbers of rare objects such as distant quasars to be discovered. These discoveries will in turn lead to new insights into how supermassive black-holes shape the formation and evolution of their host galaxies.

TRACING DARK MATTER WITH GRAVITATIONAL LENSING

Matt Auger

Left: image of a galaxy (arc) that is gravitationally lensed by the mass of a foreground galaxy (located near at the arc centre). Right: Model of the gravitationally lensed arc image obtained by reconstructing the dark Matter mass distribution in the foreground galaxy.



Since the identification of galaxies as `island universes' external to the Milky Way, astronomy has tried to address the fundamental question: What are galaxies made of? They shine brightly, considering their vast distances from the Earth, and so it would seem that they are composed of millions or even billions of stars. However, Fritz Zwicky in the early 20th century noticed that stars often move too fast in groups of galaxies -- at least too fast if their motions are only affected by the gravitational pull of other stars within the galaxy, and theorised a significant missing mass component must be present. We know that our own galaxy, the Milky Way, also has planets and moons and lots of gas and dust, but this still doesn't come close to balancing the mass budget required by Zwicky. In the late 1970's, Vera Rubin's observations of how gas rotates around galaxies at large distances finally provided very strong evidence that there was a fundamental ingredient missing; this has now been termed `dark matter' and is thought to make up nearly 90 per cent of the mass of galaxies.

One of the primary focusses of my research is trying to `see' dark matter by observing the gravitational effect it has on objects, either by causing stars and gas to move more rapidly or `strong gravitational lensing' -- the bending of light rays due to the presence of a massive object. We endeavour to phenomenologically describe how dark matter is distributed in and around galaxies. Similar to how we use conventional telescopes to see the structure of the stars in galaxies by observing their light, we observe the gravitational effects of dark matter on stars and light rays to create a model of the dark matter distribution. Computer simulations suggest that the dark matter should have a fundamentally different shape than the starlight, and our observations confirm this. However, our data also differ from simulations in describing the central dark matter distribution. Indeed, we have found that the dark matter components of galaxies are as diverse as the stars, with some galaxies having an excess of dark matter in the central regions whilst others show a clear paucity of dark matter. Why does this diversity exist?

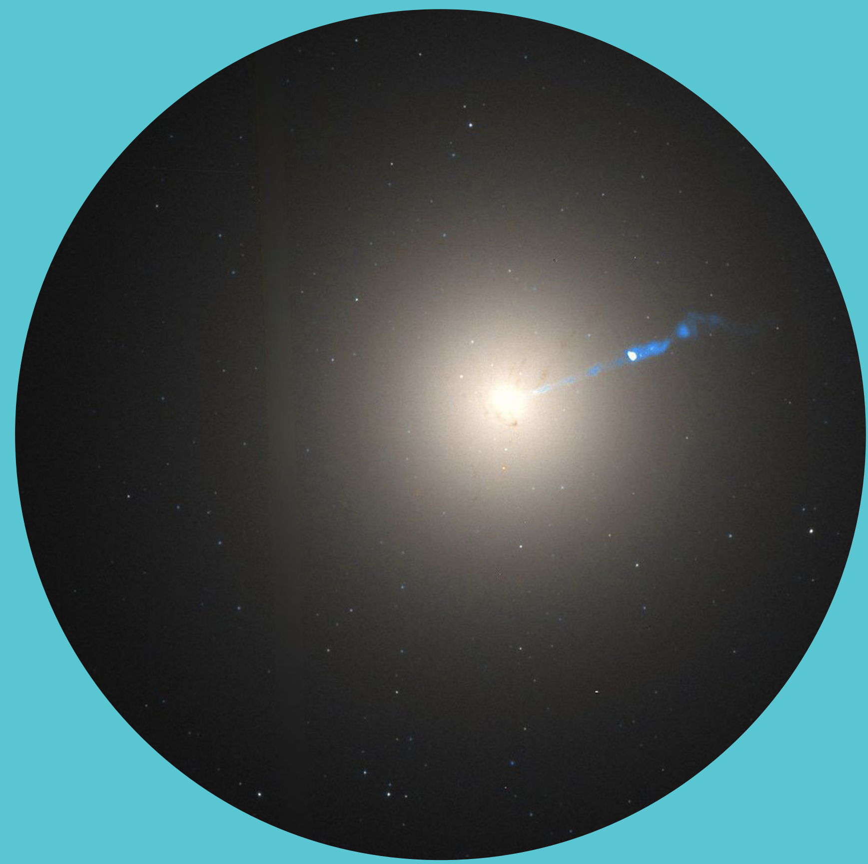


Image of the massive galaxy M87, hosting a supermassive black hole whose accretion produces a jet (seen as blue light in this image).

One object that shows an absence of central dark matter -- a dark matter `core' -- is M87, the 87th Messier object, which is a huge galaxy (nearly one hundred times more massive than the Milky Way) approximately 60 million light years from Earth. Two clues might hint at why this massive galaxy seems to be missing dark matter in its central region. Curiously, M87 has an enormous number of globular clusters, perhaps one thousand times as many as the Milky Way, suggesting a violent formation history via mergers. M87 also hosts an accreting central supermassive black hole, approximately 1 billion times the mass of the Sun, that is producing an enormous amount of power as an active galactic nucleus, or AGN. Both the merger and AGN history of a galaxy can reshape the central dark matter distribution, and moving forward my goal is to make even more precise measurements to distinguish between these mechanisms.

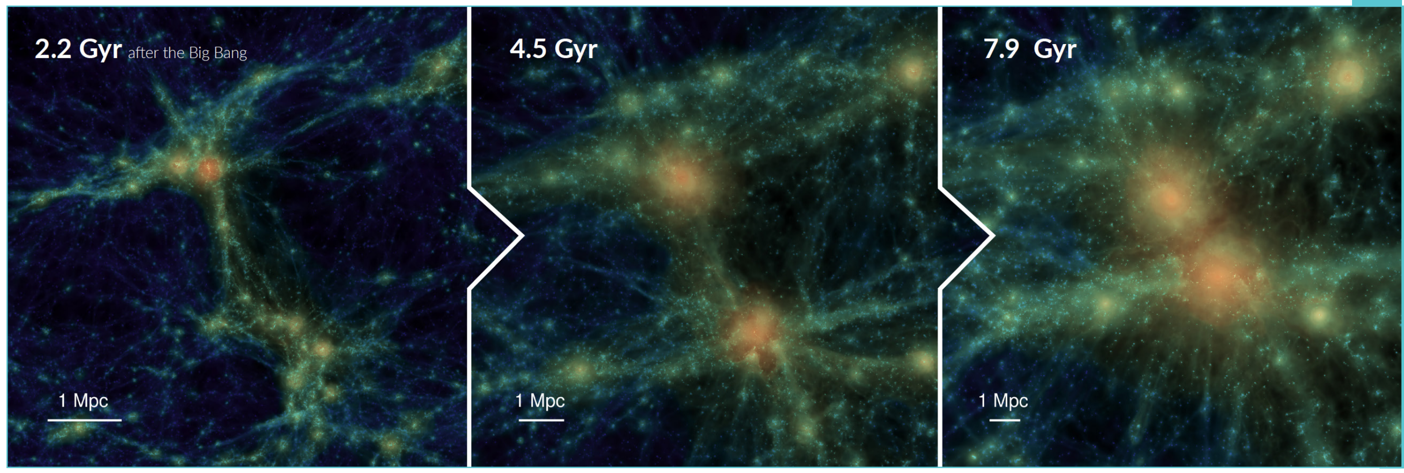
The most significant challenge to inferring the central dark matter distribution is in simultaneously modelling the gravitational impact of the stars in a galaxy; we observe the light from these stars but don't directly know their masses. We can compare their light to that of the Milky Way and then use a conversion factor, the stellar mass-to-light ratio M/L, to determine the mass, but this is quite uncertain. In particular, M/L depends on something called the `stellar initial mass function,' or IMF, that dictates how many stars of a given mass are created in a galaxy. The IMF is often assumed to be the same everywhere, but this doesn't need to be true. For example, babies born Earth also have a distribution of masses, but this distribution depends on many things including genetic and socio-economic factors. My recent study of two sets of gravitational lenses suggests a similar result: stars born in different environments appear to have different IMFs. There is still much work to be done to understand this result, but what is clear is that galaxies are much more diverse than we previously thought!

THE FABLE SIMULATIONS OF GALAXIES, GROUPS AND CLUSTERS



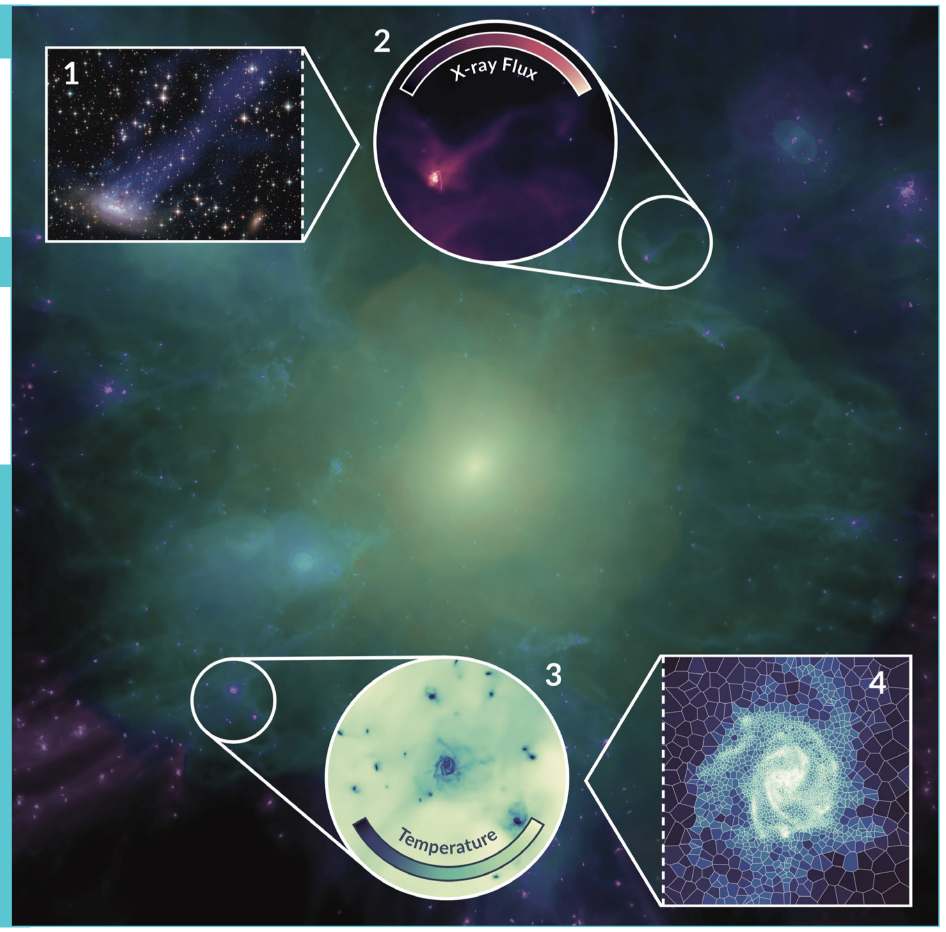
Nick Henden, Debora Sijacki
& Ewald Puchwein

1



1. The evolution of the FABLE cluster shown in figure 2, starting from just 2.2 billion years after the Big Bang (left) through to the onset of a major merger between two smaller clusters 5.7 billion years later (right) that will eventually form one of the largest possible gravitationally-bound objects in the simulated (and real) Universe.

2



Clusters of galaxies collapse from the densest regions of the early Universe to become the largest objects in existence by the present day. Their unparalleled sizes make them powerful tools to probe the growth of large-scale structure and further our understanding of cosmology. At the same time, clusters represent unique astrophysical playgrounds in which galaxies interact with each other and with the intracluster gas, which itself is churned up by the powerful energy output of supermassive black holes. This process, known as AGN feedback, stems from black holes at the centres of galaxies swallowing gas, converting it into outflows of energy and impacting not only their galaxy, but also the surrounding intracluster medium millions of light-years away.

The inclusion of AGN feedback in cosmological hydrodynamical simulations of galaxy formation has proven to be a key ingredient for producing realistic galaxies in a representative region of the Universe. Projects such as the Illustris simulation have met with great success in this area and thus have made great strides in our understanding of galaxy formation and evolution, as well as guiding observations. Yet whilst this model matches a wide range of observed galaxy properties, it struggles to reproduce other important properties of galaxy clusters and groups such as the contents of the intracluster medium.

With the FABLE project we have built upon the success of Illustris by improving the models for feedback from AGN and stars so that we can simultaneously produce realistic galaxies, groups and clusters, thereby completing our picture of the Universe across this vast range of scales. Consisting of high-resolution simulations of more than thirty groups and clusters performed with the state-of-the-art moving-mesh code AREPO, FABLE reproduces a number of important observables such as the buildup of stars in galaxies and the thermodynamic properties of the intracluster medium.

FABLE further reproduces a range of integrated cluster properties and their interdependencies as represented via the studied cluster scaling relations. These relations are vital for the cosmological interpretation of observed cluster data, the availability of which is set to be greatly expanded by numerous ongoing and future surveys, for example with observations of the Sunyaev-Zel' dovich effect via SPT-3G and ACTpol or in X-rays with the eROSITA and Athena observatories. Yet, as larger cluster surveys beat down the statistical uncertainties, we are increasingly limited by our incomplete understanding of cluster physics and its impact on the cluster scaling relations, which are required to link cluster observables to their fundamental masses.

Cosmological hydrodynamical simulations are in a unique position to quantify these effects and thereby facilitate the use of clusters as precise cosmological probes. Indeed, careful comparison of our results with observed scaling relations hints towards a non-negligible bias in observational studies that attempt to measure the masses of clusters from their X-ray emission under simplifying assumptions about the clusters' dynamical state.

Furthermore, the increased size and depth of future surveys means that many new clusters will lie at vast distances from which their detectable emission may have taken many billions of years to reach us. This means it is vital to understand how the cluster scaling relations change over time so that they can be applied reliably to the most distant objects in upcoming datasets. While current observations are severely limited in their ability to constrain such evolution, simulations allow us to study the scaling relations for a well-defined sample of objects over the whole history of the Universe. Upcoming results from FABLE demonstrate a significant departure of the evolution of the relations from the simple model typically assumed in observational studies, which has important implications for interpreting the incoming wealth of new cluster data.

2. The main panel shows the gas distribution of one of the largest FABLE clusters, revealing an array of interconnecting filaments and infalling galaxies and groups. Panel 1 shows an observed spiral galaxy with an enormous tail of gas shining in X-rays and panel 2 shows a similar view for one of our simulated galaxies. This gas has been stripped from the galaxy as it falls into the dense cluster environment. Panel 3 highlights a smaller group of galaxies of various shapes and sizes, while panel 4 shows the structure of AREPO's moving hydrodynamical mesh through a slice of the central galaxy.

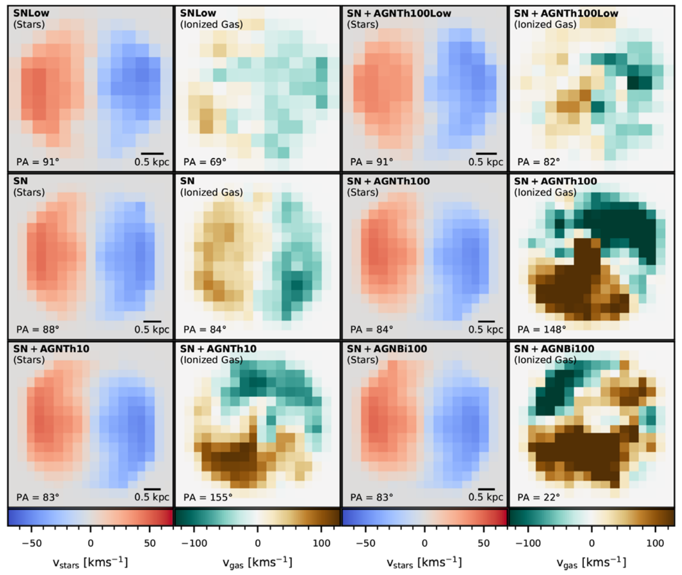
FAST AND ENERGETIC AGN-DRIVEN OUTFLOWS IN SIMULATED DWARF GALAXIES



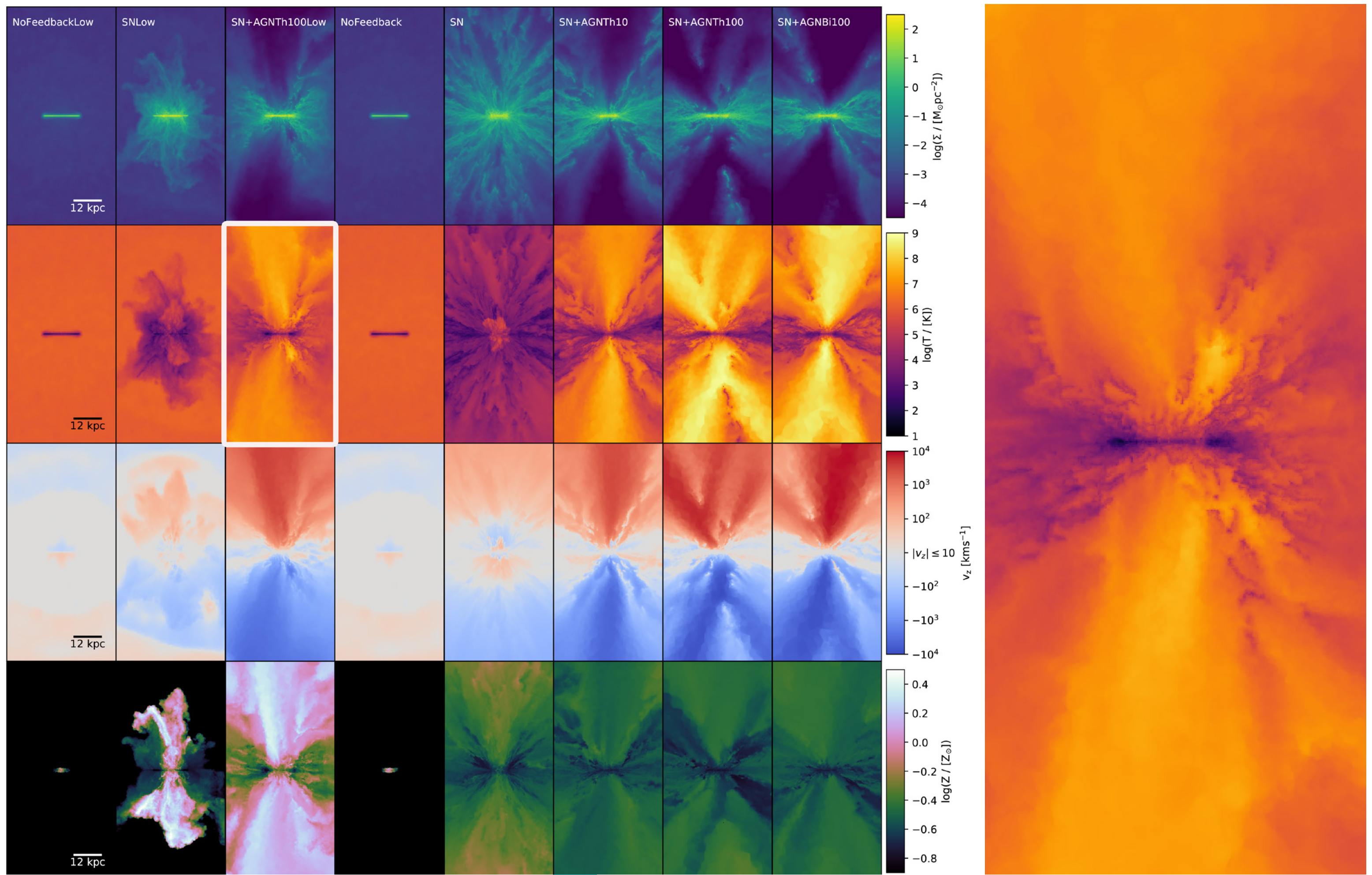

Sophie Koudmani, Debora Sijacki, Martin Bourne & Matthew Smith

Dwarf galaxies, the least massive galaxies in the Universe, are the smallest building blocks of the cosmic structure formation process. They are interesting cosmological probes, as there are a number of apparent discrepancies when comparing observations of dwarf galaxies with the predictions of structure formation models. For example, the large disparity in the number of observed dwarfs with respect to the predicted number of dark matter haloes that may be hosting these systems (the missing satellite problem) or the lack of observed massive dwarf galaxies (the too-big-to-fail problem). Some have suggested that these issues could be resolved by changing our models of dark matter, which provides the skeleton for cosmic structure formation. Others argue that the focus should be on improving our models of the luminous, 'baryonic' matter that we can observe directly.

One of the most important baryonic processes, reionisation, stems from the radiation produced by the first galaxies in the Universe. This radiation shuts down star formation in the low-mass dwarf galaxies rendering them undetectable. For the more massive dwarf galaxies it has been suggested that violent stellar explosions - supernovae (SNe) - could shut down star formation, however this remains controversial. Most simulations indicate that another ingredient would be needed for the theoretical models to explain the sparsity of massive dwarf galaxies in our Universe. Recently, it has been proposed that active galactic nuclei (AGN) - actively-accreting massive black holes - might be this missing ingredient. Previously, theorists did not include AGN in their simulations of dwarf galaxies as these were only observed in more massive galaxies. However, the systematic analysis of optical surveys has revealed a population of dwarf galaxies hosting AGN, which have been confirmed by X-ray follow-up observations.



2. Comparison between the line-of-sight velocity maps for stars and ionised gas at t = 150 Myr. The spatial resolution is matched to the MaNGA resolution at the mean redshift of the primary sample. For the AGN runs, the ionized gas is visibly offset from the stellar component, just like in the observed MaNGA galaxies. Credit for figures 1 and 2: Koudmani et al. 2019, Monthly Notices of the Royal Astronomical Society, 484, 2047.



1. Edge-on projections of all the simulation runs at t = 300 Myr. The first row shows surface densities, the second row shows temperatures, the third row shows vertical velocities, and the fourth row shows metallicities. The runs with low star formation efficiency are depicted on the left hand side, and the high star formation efficiency runs on the right hand side. With only SN feedback, the outflows are slow, warm, and high-density. With additional AGN feedback, the outflows have an additional hot, low-density component moving at high velocities.

All of these AGN are extremely luminous relative to their black hole mass and are likely only the tip of the iceberg. There has also been some first evidence of direct AGN feedback from the MaNGA survey, which identified six dwarf galaxies that appear to have an AGN that is preventing on-going star formation. These observational results are very exciting as they suggest that AGN may be able to solve the too big-to-fail problem.

It is therefore timely to study the physical properties of dwarf galaxies, in particular whether the presence of an AGN can affect their evolution. Using the moving mesh code AREPO, we have investigated different models of AGN activity, ranging from simple energy-driven spherical winds to collimated, mass-loaded, bipolar outflows in high resolution simulations of isolated dwarf galaxies hosting an active black hole. Our simulations also include a novel implementation of star formation and mechanical SN feedback.

Figure 1 shows the visuals of our simulation suite. Here, edge-on projections of surface density, temperature, vertical velocity and metallicity at an age of 300 Myr are plotted. The control runs with neither SN nor AGN feedback ('NoFeedback' runs) do not produce any outflows. With added SN feedback, we obtain relatively cold and slow- moving outflows. When we also include AGN activity in our simulations, the outflows are much faster as well as much more energetic, reaching temperatures of up to 10^9 K.

These results provide tantalizing evidence that the observed large kinematic offsets between gas motions and stellar motions in dwarf galaxies with AGNs may be due to high-velocity AGN-driven outflows. In our simulations, the effect is seen only when AGN-driven gas outflows are present, as they are fast enough to alter the velocity patterns set by the rotational motion of the galaxy (Figure 2).

We also investigated the effects of these AGN-driven outflows on star formation and found that AGN activity has a small but systematic effect on the central star formation rates (SFRs) for all set-ups explored, while substantial effects on the global SFR are only obtained with strong SNe and a sustained high-luminosity AGN with an isotropic wind. Our findings from the isolated galaxy set-up therefore indicate that AGN are unlikely to directly affect global dwarf SFRs. However, in realistic cosmological environments inflows are known to be important especially for high-redshift dwarfs. It is hence possible that AGN boosted outflows may prevent some of this cosmic 'pristine' gas reaching the dwarfs in the first place, providing a mechanism for indirect star formation regulation. This possibility will be addressed in a follow-up study using cosmological zoom-in simulations.

REGULATING PROPERTIES OF DWARF GALAXIES WITH SUPERNOVA FEEDBACK

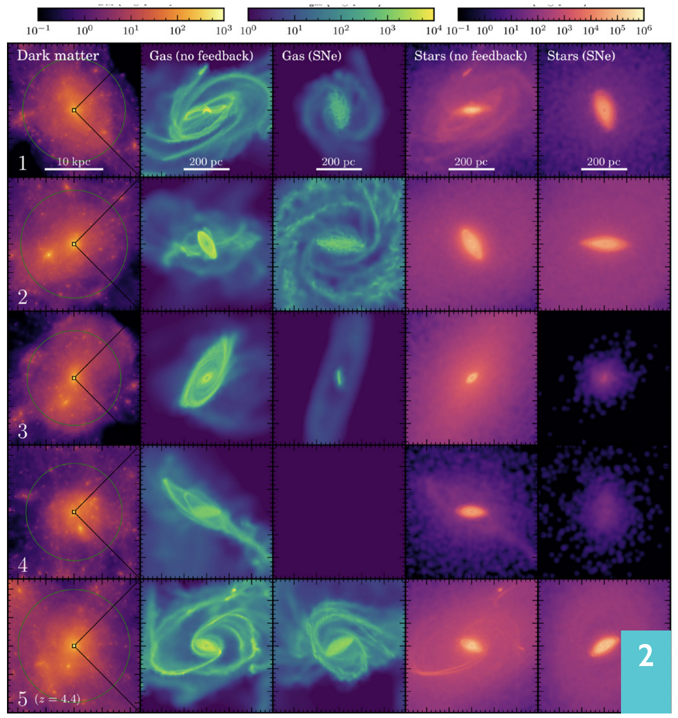

Matthew Smith
& Debora Sijacki

One of the most important classes of baryonic physics impacting galaxy evolution are feedback processes. This label covers a broad range of phenomena in which gas in and around galaxies are influenced by stars or active galactic nuclei (AGN), typically through the injection of mass, energy, momentum, metals (elements heavier than helium) or ionising radiation. Such processes are labeled as "feedback" because the stars and supermassive blackholes (the 'engines' of AGN) are themselves formed from the gas which they regulate, having radiatively cooled and flowed into the galaxy's host dark matter halo under the influence of gravity. Thus, the feedback sources can naively be thought to operate much like a thermostat to regulate galaxy properties: large amounts of cold gas in a galaxy leads to a larger magnitude of feedback sources, which in turn remove the cold gas either by heating and/or ejecting it from the galaxy. Without feedback processes, hydrodynamic simulations predict that galaxies should form many more stars than is observed in the real universe. As well as controlling the total mass of stars formed, feedback also regulates other galaxy properties, such as their structure, morphology, kinematics and chemistry. Outside of the galaxy, feedback processes have a large impact on the surrounding circumgalactic medium (CGM) by driving galactic outflows of gas, enriching it with metals, and ionising neutral gas.

The impact of feedback on galaxy properties is heavily dependent on the mass of the galaxy in question. Galaxies living in dark matter haloes similar in mass to our own are the most efficient at forming stars, while as halo mass increases the relative efficiency of star formation drops. This phenomena is usually ascribed to the role of AGN. On the other end of the mass scale, the ability of galaxies to form stars also drops with decreasing halo mass in haloes lower in mass than our own. This is usually thought to be caused by stellar feedback, particular in the form of supernovae (SNe) (although see piece from Sophie Koudmani on the role of AGN in dwarf galaxies). Stars more massive than ~8$M_\odot$ (i.e. 8 times the mass of our sun) end their lives in extremely powerful explosions, depositing energy into the surrounding gas, disrupting the dense gas of stellar nurseries and ejecting mass out of the galaxy. It is easier to expel gas from lower mass dark matter haloes because they have a shallower gravitational potential well. This is believed to be one of the primary reasons why dwarf galaxies are less efficient at forming stars than Milky Way mass galaxies.

The relevant length scales on which the SN explosion initially evolves (and below) are many orders of magnitude smaller than the size of the galaxy in which they occur (kiloparsecs and above). The resulting dynamic range required makes accurate modelling of SNe in simulations of galaxies an extremely challenging computational problem, requiring the adoption of sophisticated numerical schemes. Fig. 1 shows the application of our novel "mechanical" SN feedback scheme to an isolated simulation of dwarf galaxy, using the AREPO code. The SNe regulate the properties of the galactic disc of gas (shown in blue) and stars (not shown) while also efficiently driving an outflow of gas at a wide range of temperatures ("multiphase"), in agreement with observations.

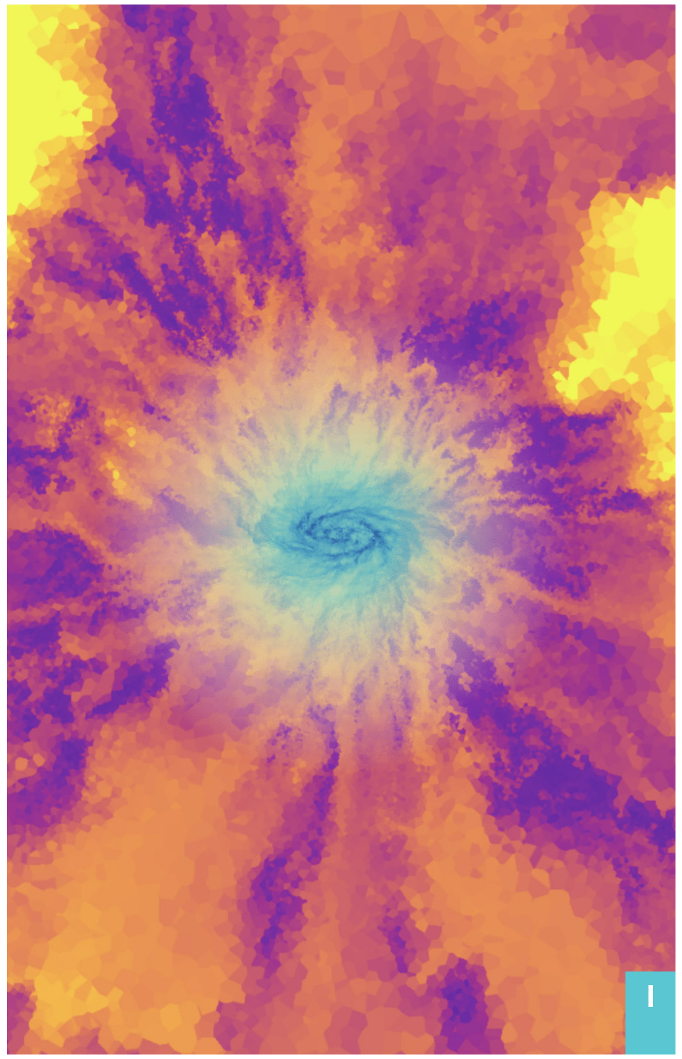
However, while SN feedback is often shown to be efficient at regulating the properties of low mass galaxies in isolated simulations (a simplified setup in which a galactic disc of gas is initially put in by hand), the picture is not so clear when the galaxies are allowed to grow realistically in a simulation that includes the full cosmological context, including build up of mass via inflows of gas and mergers of smaller galaxies. We carried out an in-depth suite of cosmological simulations of dwarf galaxies (using the "zoom-in" technique to focus computational power on the region of interest) with our state-of-the-art models of star formation and SN feedback, evolving them until z = 4 (approximately 1.5 billion years after the Big Bang). If the simulations were continued until the present day, these galaxies would have reached a total mass of about 10^{10} $M_\odot$. These represent some of the highest



2. Density projection of dark matter (left), gas (centre) and stars (left) from a suite of cosmological zoom-in simulations of dwarfs. In the majority of cases, SN feedback has little impact on galaxy properties, resulting in extremely compact and overmassive stellar discs. Only in dwarf 4 is the feedback efficient, due to its unique merger history, expelling gas from the galaxy and forming a low mass stellar spheroid. Credit: Smith et al. 2019, Monthly Notices of the Royal Astronomical Society, 485, 3317.

resolution cosmological galaxy simulations carried out to date. Fig. 2 shows the gas and stars of the resulting galaxies (as well as their dark matter haloes) for simulations run both with and without the inclusion of SN feedback. Without SNe, the resulting galaxies are extremely compact and contain a large mass of stars. For 4 out of the 5 galaxies, the addition of SN feedback has little to no impact on the results.

The cause appears to be the manner in which the gas assembles in the galaxies. Unlike in the isolated simulation in which the galaxy was created artificially, these galaxies are much more compact as they accrete gas at early times. The initially low volume density of SNe are unable to expel the first inflows of gas, leading to a dense core. Once the gas density becomes high, SN feedback becomes extremely inefficient, despite the large number occurring, as their energy is rapidly radiated away. This effect is exacerbated by the delay between the stars being formed and their eventual explosion as SNe (after ~3-10 Myr). This leads to unregulated cooling and collapse of the gas to even higher densities, resulting in several orders of magnitude greater star formation than that given by observational constraints.



1. A hydrodynamic simulation (using an isolated setup) of a dwarf galaxy using a novel implementation of SN feedback. The galaxy has a total mass of 1010 $M_\odot$. A density projection of the gas disc is superimposed onto a slice showing the temperature of the surrounding gas. Gas is ejected from the galaxy in the form of a multiphase (~ 100 − 10^7 K) outflow. The image is 12 kpc in width.

Our conclusions, therefore, are that in contrast to naive expectations, SNe on their own are unable to regulate galaxy properties in galaxies of this mass. Instead, the efficiency of SNe must be boosted by some (or several) other physical processes. Radiation from the SN progenitor stars could help prevent the build up of dense gas by heating, ionisation or radiation pressure. More detailed models of the manner in which star formation proceeds (very much an unsolved problem) could produce more clustered SNe, allowing them to work together more efficiently. Alternatively, stellar dynamics could lead to SN progenitors "running away" into lower density regions. The dense gas could be pressurized by as yet unresolved turbulent support. Finally, more radically different forms of feedback, such as cosmic rays or AGN from intermediate mass black holes, may be responsible. We continue to explore these ideas in our ongoing research.

GRAVITATIONAL WAVE PHYSICS

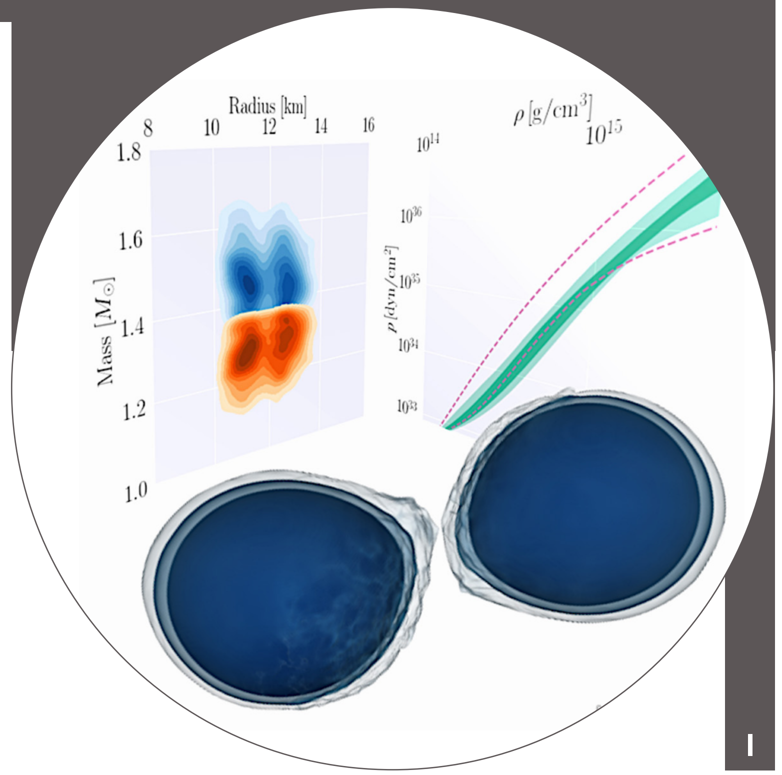
Ulrich Sperhake

The LIGO and Virgo gravitational-wave detectors have detected 10 binary black hole (BBH) coalescences and one binary neutron star (BNS) coalescence, with the first detection, GW150914, in 2015. The Cambridge group, including various KICC researchers (Michalis Agathos, Nathan Johnson-McDaniel, Chris Moore, Anthony Lasenby, Ulrich Sperhake), has made a number of contributions to the analyses of these events, whose properties are summarised in the first LIGO-Virgo gravitational wave transient catalogue GWTC-1.

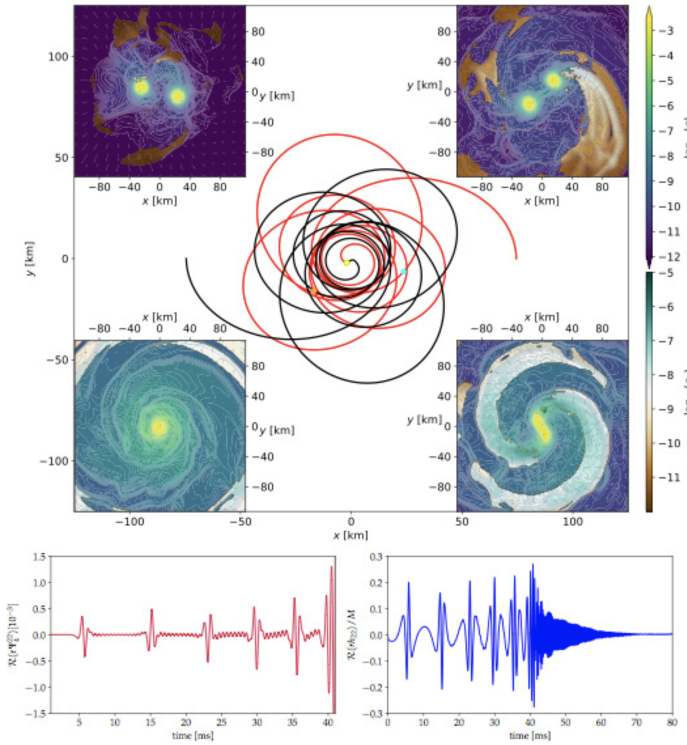
Cambridge researchers made major contributions to the paper presenting tests of general relativity (GR) on all the BBHs in GWTC-1 as members of the writing team, by developing analysis codes (simplified versions of which are published as online tutorials), by interpreting the analysis and generating plots. The combined results in this paper give the most sensitive tests of GR with BBH gravitational wave signals to date. We also contributed to the development of an automated script for the computation of the mass and spin of the post-merger black hole, which was used for all the BBH events in GWTC-1.

The Cambridge group is also active in exploratory R&D projects, such as developing methods for identifying potential "echoes" that may be emitted after the main gravitational wave signal. It is believed that the presence of such a characteristic feature in the data would signify that the source is a more exotic compact object (e.g. a wormhole), rather than a black hole.

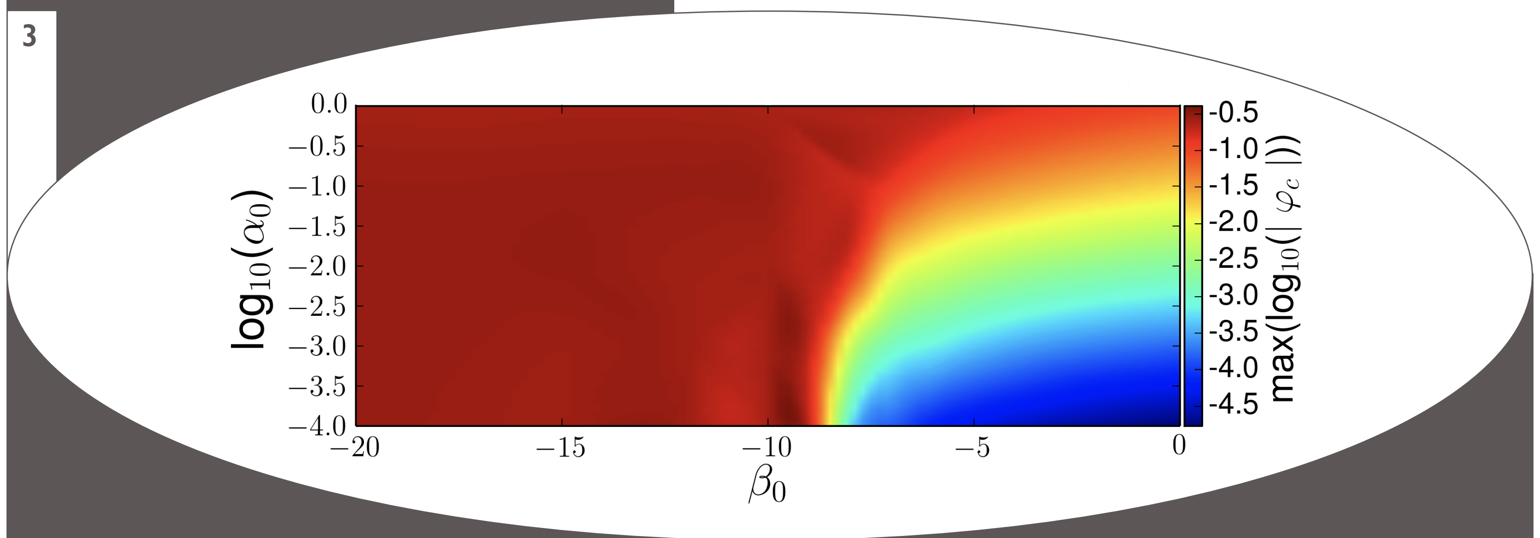
The first gravitational-wave detection of a BNS, GW170817, provided an excellent opportunity to probe the cold dense matter inside the neutron star interior and measure its physical properties, one of the unresolved mysteries of modern astrophysics and nuclear physics. We led the modeling of the effects of matter on the emitted gravitational-wave signal, and we were able to constraint the equation of state and the radii of the coalescing neutron stars to unprecedented levels (Fig.1).



1



2



3

1. The tidal deformation of neutron stars close to merger (bottom) and its impact on the gravitational wave signal allow us to constrain the mass and radius and the density profile of the neutron stars (upper panels). This, in turn, constrains the equation of state at super-nuclear densities. (Credit Virgo Collaboration and CoRe Collaboration).

2. Numerical model of the coalescence of highly eccentric neutron stars binaries.

3. Each point in this plane represents a particular theory. The color shows whether the theory in question would lead to a strong gravitational wave (red) or not (blue).

We also contributed to the development of a fast, accurate and complete waveform model, which will set a new benchmark for the analysis of GW signals from compact binaries. We have also worked on waveform modeling, giving the first frequencydomain model for waveforms from BBH coalescences that includes a subtle feature in the ringdown portion of the signal, where the merged black hole is settling down to its final state.

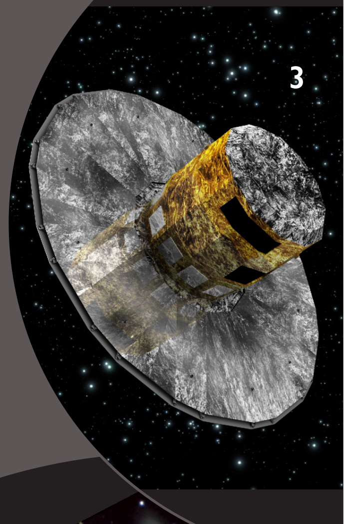
Our group also worked on analysing numerical simulations of coalescences of highly eccentric neutron star binaries. These systems are potential sources for future, even more sensitive GW detectors. The neutron stars in these systems oscillate due to the strong tidal perturbations the stars experience during their close approaches (see Fig.2). We derived a method for making an accurate estimate of the energy stored in those oscillations and found that close to merger it can be as large as the energy released in a supernova.

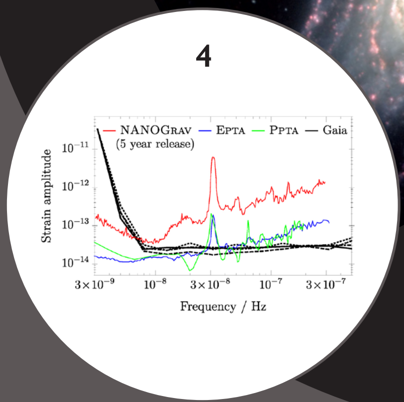
We have also explored the exploitation of Gravitational Waves to test alternative theories of gravity. Scalar-tensor theory of gravity is one of the most popular candidates to extend Einstein's theory of general relativity in attempts to come closer to an understanding of the enigmatic behavior observed in galactic rotation curves, the cosmic microwave background and the expansion of the universe at large, as well as in reconciling relativity with quantum theory. We identified a smoking gun effect in the collapse of stellar cores in massive scalar tensor theory. The signal is stretched out over years while remaining above the sensitivity threshold of current gravitational wave detectors and oscillates with a gradually decreasing frequency. This inverse chirp character of the signal is a robust and characteristic prediction for this class of theories. An amazing consequence of this phenomenon is that we can direct gravitational wave observations at historic supernovae such as Kepler's 1604 or SN1987A and search for this gravitational-wave afterglow.

This scalar-tensor theory of gravity is described by two parameters α_0 and β_0 which mark the horizontal and vertical axis in Fig.3. Each point in this plane therefore describes a specific theory of gravity with Einstein's relativity located on the far right bottom. The color indicates whether the stellar collapse generates a strong inverse chirp signal (red) or not (blue). Depending on whether LIGO and Virgo observe the gravitational wave afterglow of an historic supernova, we can tell which theory, i.e. which parameter values α_0 and β_0, give the best description of gravity in our Universe.

USING THE GAIA SATELLITE TO DETECT LOW FREQUENCY GRAVITATIONAL WAVES

Anthony Lasenby





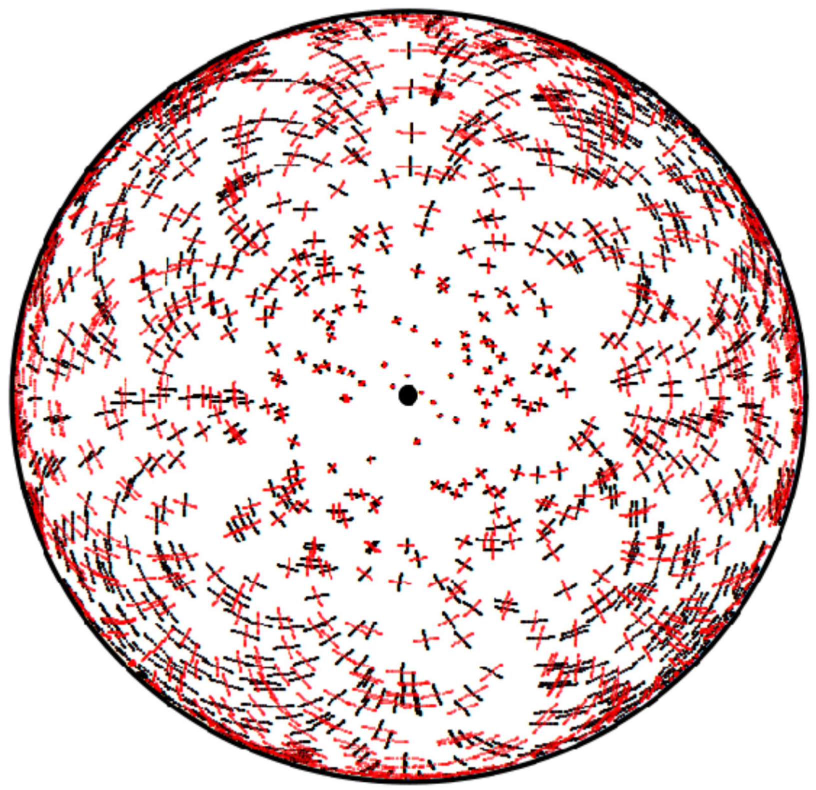
1 . The colliding galaxy pair NGC 5426 and NGC 5427, jointly known as Arp 271. It is thought the Milky Way will collide with our own nearest large neighbour, the Andromeda Galaxy, in about 4 billion years time. (Credit: Gemini Observatory)

3. Artist's impression of the Gaia spacecraft. (Credit: European Space Agency)

4. The black curves show the strain sensitivity of the final Gaia data release using different time samplings. The coloured lines show 95% upper limits from various current PTAs.

When the Advanced LIGO Observatory made the first detection of gravitational waves in September 2015, they observed the signal from the final stages of the coalescence of two black holes, each of mass about 30 times that of our sun. It was not previously known that black holes existed in this mass range and this was, in a sense, a 'double first' for this remarkable discovery. We know, however, that in the nuclei of galaxies, much larger black holes exist, with that at the centre of our own Milky Way galaxy known to have a mass of about four million times the mass of the Sun. This is a relatively modest black hole compared with the supermassive black holes in the centres of massive galaxies, which span the range up to about ten billion times the mass of the sun. Mergers and collisions between galaxies are quite frequent (Fig. 1), and when they occur the black holes in their centres may end up in orbit about each other, forming a supermassive binary pair. These will gradually lose energy by gravitational radiation, very much like a scaled up, and slowed down, version of the binary pair of black holes that led to the first detection. However, we don't have to wait until they finally merge in order to have a chance of detecting such pairs. The frequency of gravitational waves emitted before the final stages is likely to be in the range 10^{-9} to 10^{-6} Hz, for which there is no chance of detection from the ground (bear in mind that 10^{-8} Hz corresponds to a period of about 3 years). However, our team has identified a promising method that involves looking for changes in the apparent positions of celestial objects. According to general relativity, a gravitational wave is responsible for changing the proper distance between objects as it passes by. For a given polarisation of the wave, distances in one direction are compressed, whilst distances in the orthogonal direction are expanded, and then vice versa as the wave progresses. A gravitational wave also changes the directions that light waves appear to come from. If the star lies at several gravitational wavelengths from the Earth, all objects in a given direction in the sky will appear to execute a sinusoidal motion, back and forth along a line tangential to the sky. This effect is illustrated in Fig. 2, in which a gravitational wave travels from one pole of the celestial sphere - the black and red lines indicate the induced apparent motions of the stars within a hemisphere, exaggerated by a large factor to make them visible, and corresponding to the two possible polarisations of the wave.

We need an instrument which can give us exquisite sensitivity to changes in apparent stellar positions, for a large number of stars, covering the whole sky, and which ideally can make many repeated measurements for a given star over a timescale of a few years. The Gaia satellite (Fig.3), launched in 2013, is ideal for this purpose.



2. A projection of the Northern hemisphere of the sky in which a GW is coming from the North pole (marked with a black dot) and the black and red lines show the apparent stellar motions.

It will take up to 70 measurements of the position of a star over a period of up to 10 years, for at least 1 billion stars in the Galaxy, as well as of order ½ million quasars. The measurement accuracy per star, in terms of how well its position can be determined, is very impressive, amounting to the angle subtended by a human hair at a distance of about 1000 km for the brightest stars, but this is orders of magnitude greater than the values needed to detect a plausible gravitational wave. We can make this factor up, however, by the fact that Gaia is able to carry out this measurement for at least a billion stars around the sky. This brings its own problems in terms of data fitting to a sinusoidal component for so many objects, and one of the main features of the work in our paper is to show how the enormous dataset can be compressed by a large factor. This is accomplished by a tessellation of the celestial sphere, in each cell of which the coherent motions over the cell means that results for individual stars can be represented by a single 'virtual star' at the cell centre. We then look for sinusoidal 'wobbles' in position, with a coherent spatial pattern in the sky at a given frequency in time. Using these methods, Fig. 4 shows the projected sensitivity of Gaia for the detection of very low frequency gravitational waves. It can be seen that Gaia's full mission sensitivity is comparable to that from other methods, such as current and near-future pulsar timing arrays, and improves slightly on these at frequencies greater than about 10^{-7} Hz. A further interesting possibility is provided by the fact that within modified gravity theories, the possible polarisation states of a gravitational wave can depart from those in general relativity. These polarisation states can be quite difficult to detect via laboratory-based detectors, but they give rise to quite different patterns on the sky compared with those shown in Fig. 2, and thus to the possibility of quite stringent tests of alternative gravity theories. This has now been explored in a further work which has also introduced the notion, for the first time, of joint searches using both Gaia and Pulsar Timing Arrays in which correlations between the two signals could be detected, thereby helping to beat down possible systematic effects. It will be exciting, in future work, to see what level of realistic constraint can be set on alternative gravity theories via these techniques.

These results have been presented in two papers: Moore, C.J., Mihaylov, D., Lasenby, A. & Gilmore, G., Phys. Rev. Lett., 119, 261102 (2017), which was selected as Editor's Choice and featured on the front cover of the December 2017 issue, and Mihaylov, D.P., Moore, C.J., Gair, J.R., Lasenby, A. & Gilmore, G., Phys. Rev. D, 97, 124058 (2018)

WEIGHING EXOPLANETS

Annelies Mortier

Ever since the discovery of the first exoplanet in the 1990s, the hot Jupiter 51 Peg b, we have witnessed an exponential rise in the number of known exoplanets with close to 4000 exoplanets discovered so far. These discoveries have shown us that many different types of planets exist at all possible orbits around their star or even stars. The existence of all these exotic new worlds challenges planet formation and evolution theories and certainly opens up many more roads towards the evolution of life on these planets. Essential in gaining more insight into the details of planet formation, evolution, and even habitability, is the full characterisation of these exoplanets and their host stars.

Space missions such as CoRoT, Kepler, and currently TESS have detected thousands of extrasolar planets, precisely measuring their orbital period and radius via the transit technique. To shed light on the possible compositions of these planets, it is essential that their mass is measured as well. This can be done by modelling a star's radial velocity over time since an orbiting planet exerts a gravitational pull on its host star, changing the radial velocity in a periodic manner.

The HARPS-N Collaboration aims to characterise terrestrial planets via radial velocity measurements. HARPS-N is a high-resolution optical spectrograph, installed at the Telescopio Nazionale Galileo in La Palma (Figure 1). The instrument is precise and stable at the metre per second level, a necessary feature to detect the small variations induced by orbiting Earth-like exoplanets (note that the Earth only induces a variation of 9 centimetre per second on our Sun). The HARPS-N Science Team is the most effective team at precisely measuring planet masses of small stars, having contributed to the majority of precise mass measurements of planets smaller than four Earth radii.

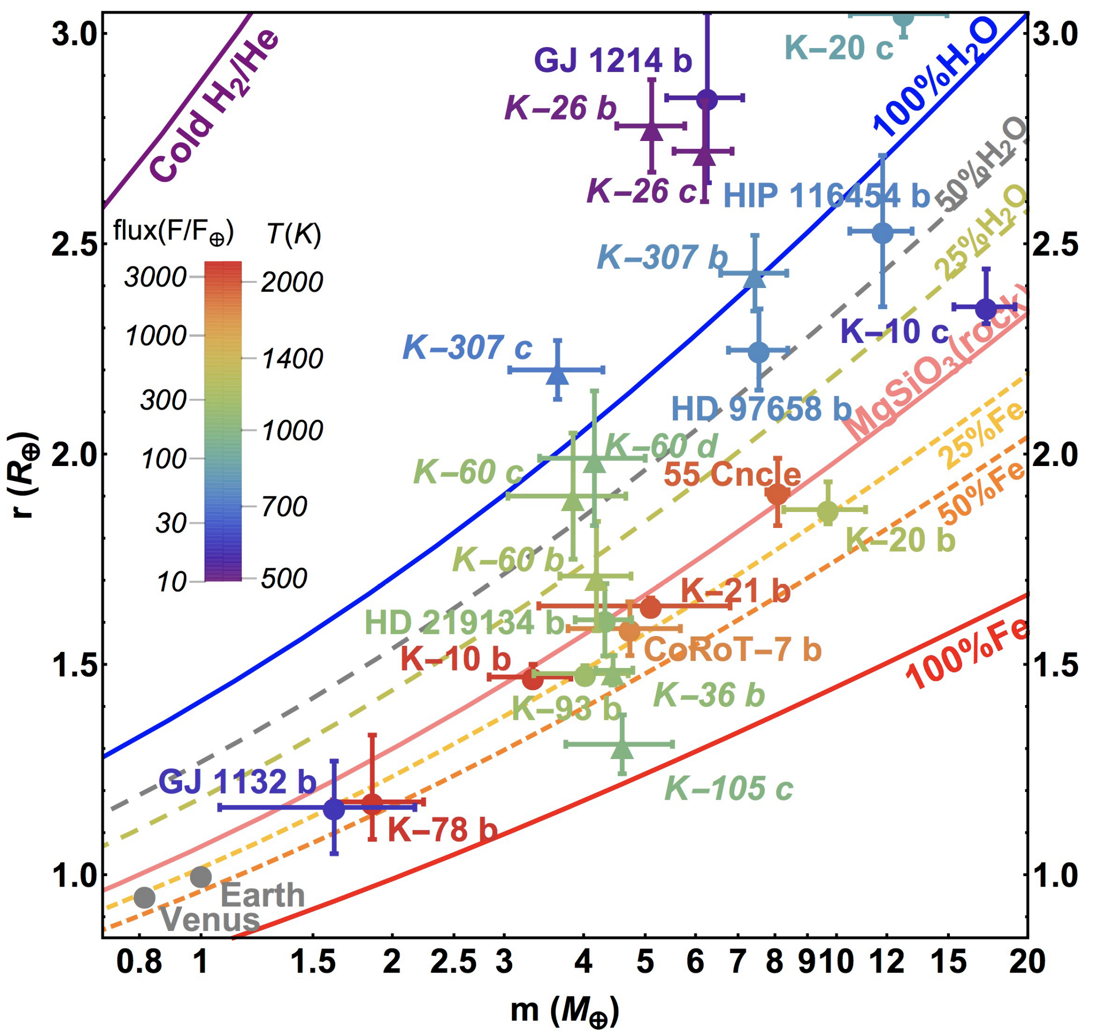
1. The Telescopio Nazionale Galileo (TNG) on La Palma.
2. Mass-radius diagram showing the distribution of exoplanets for which both quantities are known. Credit: Zeng, Sasselov and Jacobsen 2016, Astrophysical Journal.

However, despite having extremely precise and stable measurements, extracting the signature of the exoplanet is a tricky task. The main barrier is the star itself, generating signals intrinsic to their surface features that can drown out or even mimic the signals of genuine exoplanets. Handling these signatures of stellar activity properly is essential to obtain an accurate and precise planet mass. We have developed a statistical tool, the stacked Bayesian General Lomb-Scargle periodogram, that aims to quantify and visualise the long term stability of a periodic feature in time-series data. If a feature is unstable over time, it is unlikely to have been produced by an orbiting planet but rather be an effect of the star itself.

Combining stellar as well as planetary effects in the radial velocity model further helps to extract the small periodic signals related to the planet, ensuring a precise as well as accurate planet mass. Combined with the planet radius extracted from the light curve, the planet can then be placed in a mass-radius diagram (Figure 2). Assuming specific planet interior compositions, based on iron, silicates, and water, conclusions can be drawn on the types of planets found in the Universe.

Detailed knowledge on the host star is important for two main reasons. First, as we are not observing the exoplanets directly, all our measurements of the planet are relative to the star. Knowing the star, especially its mass and radius, is thus crucial to convert our measurements to planetary parameters. Second, specific elemental abundances present in the photosphere of these stars can further narrow down the possible interior compositions of its orbiting planets, as both the stars and its planets are assumed to be formed from the same material. The high-resolution spectra, used to measure the precise radial velocities, can easily be used for the purpose of characterising the star, making use of the thousands of spectral lines formed from different chemical elements. This way we maximise the information available through us, using it for the double purpose of characterising both the star and the planet.

2

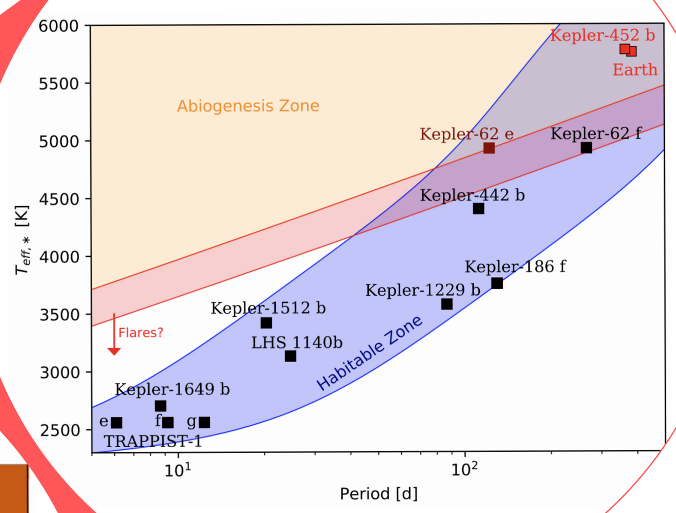


1

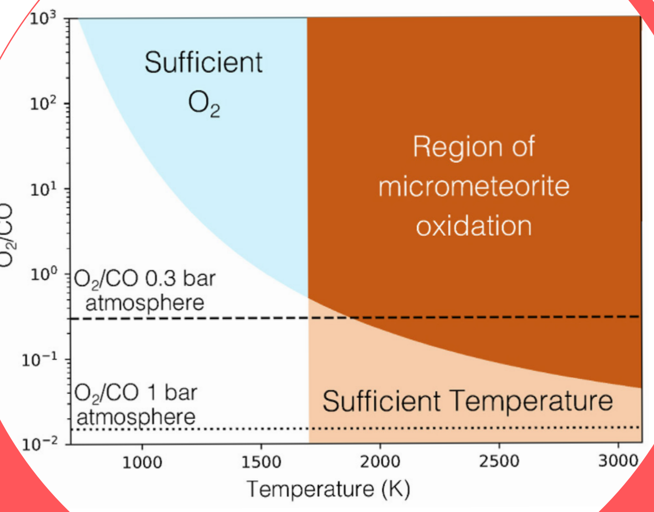
A handful of planets have been discovered with a very similar mean density as the Earth, despite being twice as large and in various orbits. This is reassuring in the hunt for an actual Earth twin. The University of Cambridge is leading the efforts to find an actual Earth twin via the Terra Hunting Experiment, that will be conducted with HARPS3, an improved close-copy of the current HARPS and HARPS-N, that is currently being built at the Cavendish Laboratory. This experiment will aim to observe a handful of nearby stars for ten years with a close-to-optimal cadence for a ground-based observatory, aiming to extract for the first time the tiny signal of an actual Earth twin.

EXPLORING CONDITIONS FOR LIFE

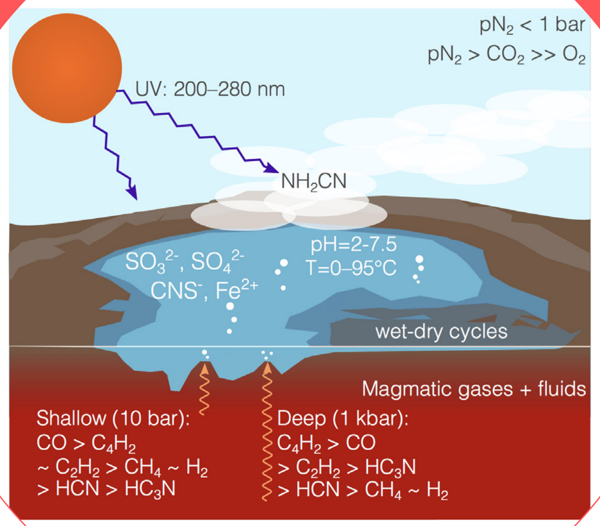
1



2



3



Paul Rimmer

1.The abiogenesis zone (outside of which life's building blocks cannot be generated via photochemistry), and liquid water habitable zone (outside of which liquid water is not stable on the surface of a planet), as a function of a planet's orbital period (days) and effective temperature of its host star (Kelvin). (Credit Rimmer et al. 2018 (Credit: Rimmer et al. 2018, Science advances, 4, 8, eaar3302.).

2. Figure showing that micrometeorite oxidation can be explained by a low pressure (0.3 bar) atmosphere (Credit: Rimmer et al. 2019, Geochemical Perspectives Letters, 9, 38.).

3. Surface hydrothermal vent scenario for early Earth (Credit: Rimmer & Shorttle 2019, Life, 9, 1, 12).

We humans are fascinated by questions of origins. How did the universe originate? How does matter become distributed throughout spacetime? How do galaxies, stars and planets form? How did life begin? What is the origin of consciousness? These origins questions are often as difficult to answer as they are important, and these questions are far more difficult when we only have one example to work with. Much has been discovered about galaxy formation, stellar evolution and planet formation, because we have many examples of galaxies, stars, protoplanetary disks, and exoplanets. For the origin of the universe, however, we will probably only ever have a samplesize of one, and that makes finding an answer, and knowing whether that answer is correct, much more difficult.

In this regard, the origin of life finds itself in the same place as the origin of the universe. We have only one example that we know about. This may not always remain the case, now that dozens of planets have been discovered that likely have the right surface temperature for liquid water to persist on their surfaces. How many of these planets are likely to harbor life? This question also cannot really be answered from our sample size of one, without a better idea about how life originated. Origin of life research this past decade has seen a series of major experimental breakthroughs toward solving the problem. For the first time, there is a network of reactions that, driven by UV light, when fed by certain simple 'feed-stock' molecules, result in high and selective yields of amino acids, nucleotides and lipids, the three essential building blocks of life as we know it, as well as mechanisms to join them together toward protocellular life.

Over the past two years, we have used these new discoveries to inform the search for life on exoplanets. The ultraviolet flux from the mercury lamps used in the lab can be compared to the stellar ultraviolet flux, to find out which stars produce enough light to set off the prebiotic chemistry. We use this criterion to delineate an abiogenesis zone, outside of which the building blocks of life cannot arise photochemically (Fig. 1). This zone can be used in the future to identify which exoplanets are most likely to harbor life, in order to focus limited observational time on the most likely candidates. Our next project is to construct a stellar simulator, to simulate the starlight accurately, and simulate flares that may be able to drive prebiotic photochemistry on exoplanets like TRAPPIST-1e, whose star is otherwise too faint.

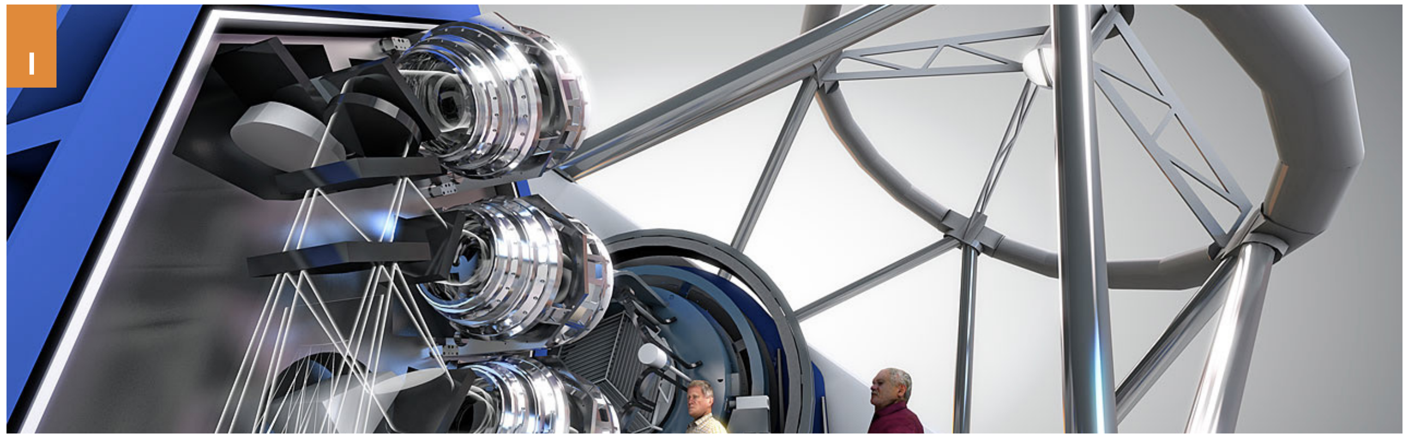
These investigations have surprisingly informed the chemistry as much as the astronomy. Investigations into sulfur dioxide, SO_2, as a more plausible sulfur-containing atmospheric species, have shown that the presence of its dissolved form, bisulfite (SO_3^{2-}), enhances the UV chemistry by more than a hundredfold. The need for a molecule with a very energetic triple bond, HCN, has initially suggested scenarios where comets or volatile-rich meteorites either deliver HCN or generate it upon impact. We have also explored alternative energetic chemical scenarios for the generation of HCN. All of these scenarios would also generate nitrogen oxides (NOx's), which participate out as nitrites, depleting the amount of N_2 in the atmosphere. These nitrites drive chemistry that connects the building blocks of life. Investigation into the consequences of lower N_2 in the atmosphere of early Earth lead us to a novel explanation of micrometeorite oxidation in the Archaean, the oxidation of meteoritic iron in the upper atmosphere happens if the surface pressure of the early Earth, and therefore its nitrogen content, were lower in the past (Fig. 2).

The sequestration of nitrogen into nitrites and ammonium salts on the surface has further implications for origin of life scenarios. Surface hydrothermal vents, ponds fed by volcanic gases, are thought to have been present on early Earth. These vents would be naturally anoxic, phosphate rich, iron rich, with both SO_2 and H_2S bubbling up through their surfaces. On the early Earth, where the crust was more reducing, and nitrogen-rich, the volcanic chemistry could produce HCN and HC_3N, providing a "buffet lunch" for the prebiotic chemistry (Fig. 3). This scenario will need to be tested both experimentally and by seeking out geological tracers of such environments on early Earth. The scenario itself has implications for the search for life on exoplanets. The search for biosignatures on exoplanets could concentrate on exoplanets like those in the TRAPPIST system, thought to experience high rates of impacts, or planets on which plate tectonics, and therefore active volcanism required for hydrothermal systems, is more likely. At the same time, if signs of life were found on water-world exoplanets, this would suggest life could have started another way.

The work we have undertaken these past two years, supported generously by the Kavli Foundation, has allowed for new laboratory simulations of the conditions of early Earth and other planets, that have already led to insights about what early Earth was like, and what physical conditions exoplanets need to have for the photochemical origin of life's building blocks. Future simulations will allow us to make serious strides toward finally answering one of the central origins questions that has captivated humanity. Prebiotic chemistry research is on the cusp of discovering the "Big Bang" theory for life. This theory will tell us where to look for other instances of life. Newly discovered life may be the only way to test this future theory.

MOONS: THE NEXT GENERATION MULTI-OBJECT SPECTROGRAPH FOR THE VERY LARGE TELESCOPE

Roberto Maiolino



MOONS is the next generation multi-object optical and near-infrared spectrograph for the Very Large Telescope (VLT) of the European Southern Observatory (ESO), located in the Atacama Desert in Chile. MOONS will enable us to obtain spectra (hence velocity, detailed position in space, chemical composition, and multiple physical properties) for millions of stars in the Milky Way and millions of galaxies across the cosmic times. By probing near-infrared wavelengths MOONS will be able to pierce in the obscured regions of the Milky Way (e.g. the inner bulge and disc). By accessing near-infrared wavelengths MOONS will also enable us to access diagnostics of galaxy evolution in distant galaxies that have been shifted into the near-infrared because of the expansion of the Universe. More specifically, MOONS is expected to deliver a survey similar to the successful Sloan Digitalized Sky Survey (SDSS, which focussed on the characterisation of millions of local or low-redshift galaxies), but primarily at redshift between 1 and 3 (when the age of the Universe was between 2 and 6 billion years, i.e. between 15% and 40% of its current age); this is a crucial epoch in the history of the Universe when both the formation of new stars and of supermassive black holes reached their maximum (the so-called "cosmic noon"). MOONS will therefore enable us to investigate with unprecedented detail the formation and evolution of galaxies, as well as of our own Galaxy.

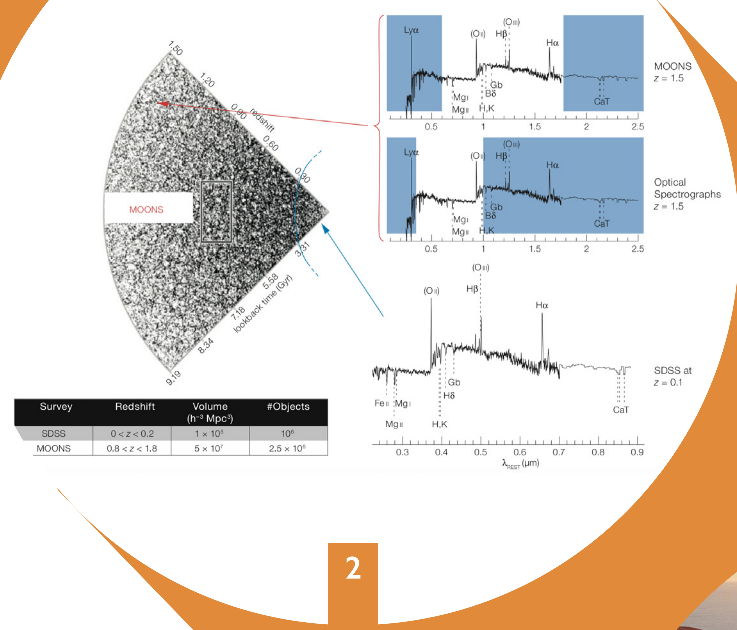
1. Artist's view of MOONS mounted at the Very Large Telescope.

2. Sketch illustrating the capability of MOONS of delivering a SDSS-like survey at in the distant Universe.

MOONS will use 1,000 fibres that will be positioned on the focal plane of the VLT thanks to an array of motorised positioners, developed specifically for this project. The fibres will guide the light of the targeted objects to two twin large spectrographs (the size of a van) that will obtain spectra of all individual objects. This will enable astronomers to take high-sensitivity spectra, in the wavelength range from 6,400 Å to 1.8μm, simultaneously of 1,000 astronomical objects.

KICC, the Cavendish Laboratory and the Institute of Astronomy (David Sun, Martin Fisher, Ian Parry, George Hawker, Mirko Curti, Roberto Maiolino), are heavily involved in the development of MOONS. We have been in charge of designing the optomechanics of the six large optical cameras hosted in the spectrograph, of assembling them, aligning them, testing them for resilience to shocks from earthquakes (which are unfortunately not rare in the Atacama desert) and checking their alignment at cryogenic temperatures (the spectrograph will be cooled to about -150ºC). Cambridge also has scientific leadership of the project by hosting MOONS' Project Scientist (Roberto Maiolino).

The project is making good progress. The first of the six cameras has been assembled and is being tested in our clean room. We have also been very busy in planning the strategy for the Guarantee Observing Time (as a reward for delivering the instrument, ESO has awarded 300 nights of observations at the VLT). MOONS is planned for first light at VLT in 2021 and we are all thrilled to obtain the first set of data with this new, cutting edge instrument.



Survey	Redshift	Volume (h^{-3} Mpc^3)	#Objects
SDSS	$0 < z < 0.2$	1×10^8	10^6
MOONS	$0.8 < z < 1.8$	5×10^7	2.5×10^6

3. The Very Large Telescope.

4. The first of the six optical cameras of the spectrograph assembled in the clean room
Left to right: Philippa Downing, David Sun (the engineer who designed and assembled the camera optomechanics) and Steve Brereton.

ELT-HIRES: THE HIGH RESOLUTION SPECTROGRAPH FOR THE EXTREMELY LARGE TELESCOPE

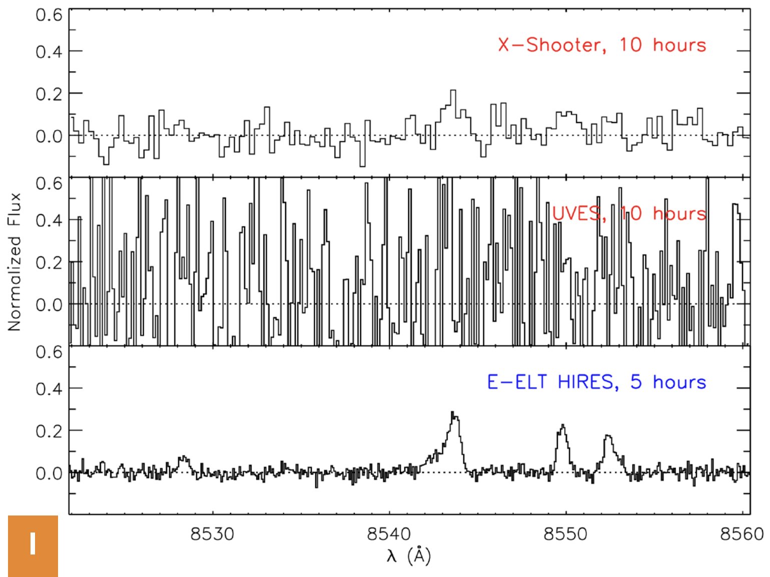
Martin Haehnelt

One of the future flagship facilities that will shape astronomical research for decades to come are the next generation of 30-40m class optical telescopes. Construction of the European Extremely Large Telescope (ELT) by the European Southern Observatory (ESO), with a diameter of 39m, in the extremely dry Atacama mountain desert in the Chilean Andes, close to ESO's very successful Paranal Observatory, is well under way.

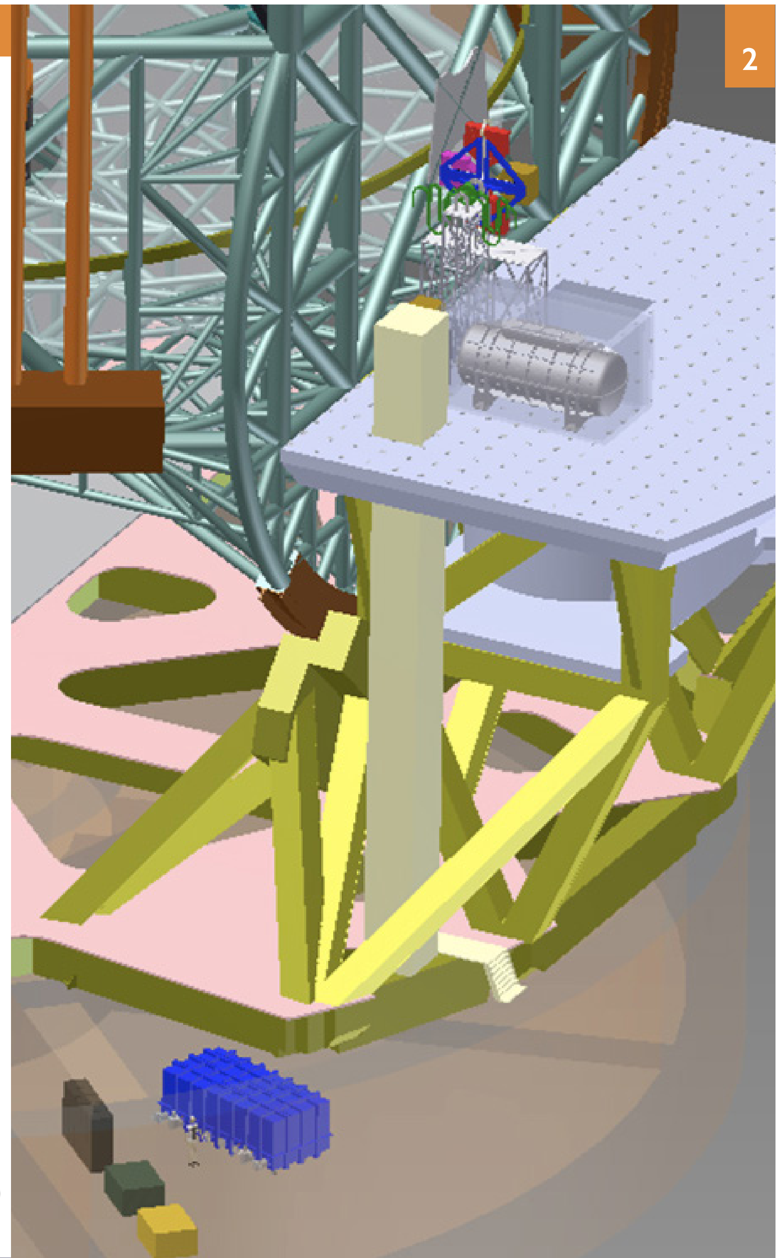
At first light in 2025, the ELT will be the largest ground-based telescope at visible and infrared wavelengths. Flagship science cases supporting the successful ELT construction proposal were the detection of life signatures in Earth-like exoplanets and the direct detection of the re-acceleration of the cosmic expansion of the Universe.

As UK-PI and Project Scientist the KICCs Martin Haehnelt and Roberto Maiolino have key roles in the consortium proposing to build the ELT's optical/near-IR high-resolution spectrograph ELT-HIRES that will enable these nobel-prize calibre science cases. KICC and the Cavendish Laboratory are also heavily involved on the technical front, by leading the challenging work packages associated with the gratings mosaicing (required to obtain the combined large grating 1.2m in size) and the cameras of the spectrometer.

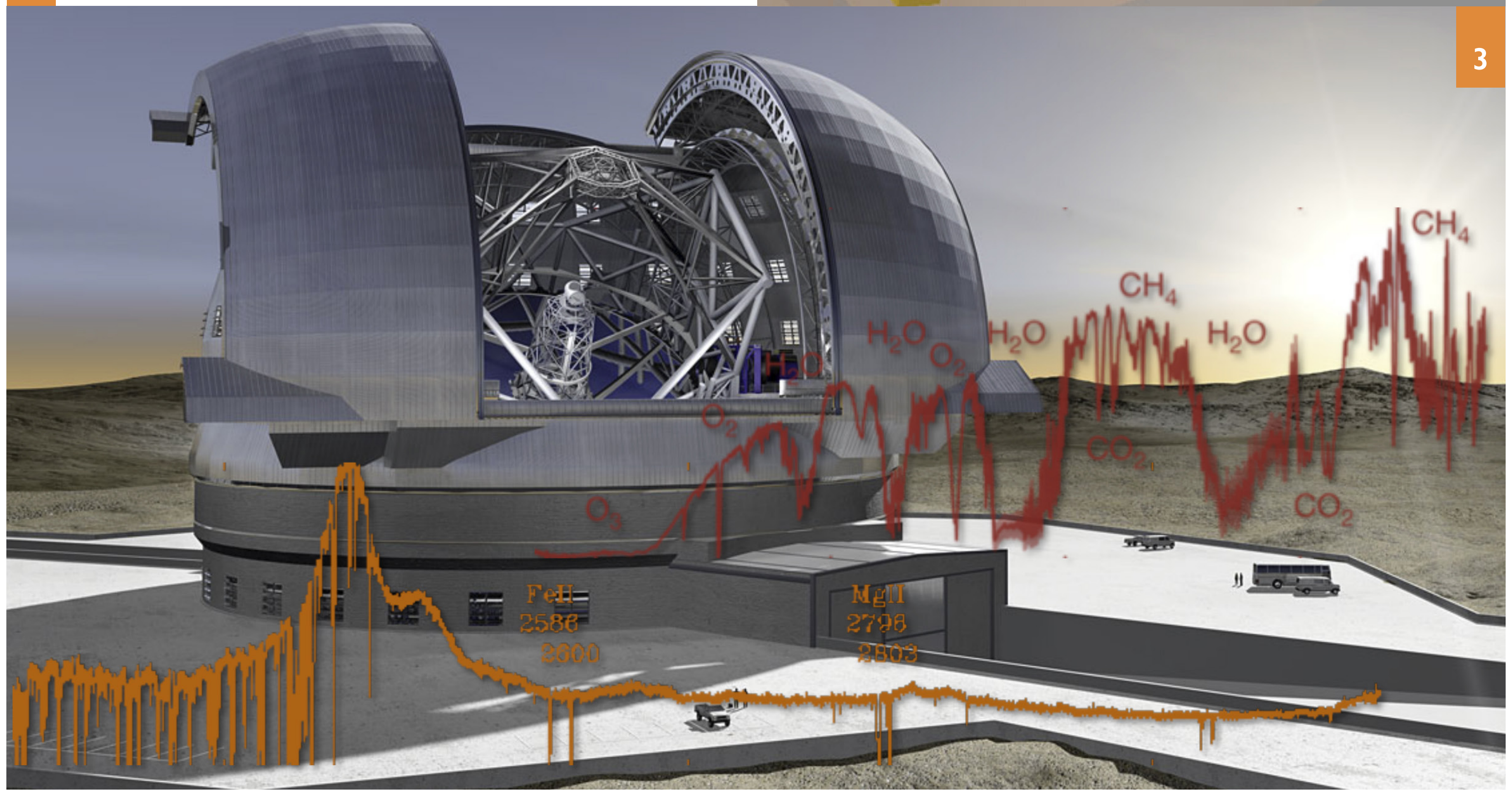
The surface area of the ELT's primary mirror is about a factor fifteen larger than that of the largest existing optical telescopes. Building ELT-instruments provides thus unprecedented challenges and the ELT-HIRES consortium will combine high-resolution spectroscopy expertise from many partners. ELT-HIRES has successfully passed the initial planning phase in 2018, and the ELT-HIRES consortium hopes to sign a construction agreement with ESO in late 2019/early 2020.



1



2



3

1. Simulated observations of a section of the Lyman-α forest at z ~ 6 as it would look if observed with ELT-HIRES compared to what is achievable with currently available high-resolution spectrographs.

2. The near-IR module of the proposed ELT-HIRES underneath the ELT is shown in blue and the vacuum vessel that will host the optical module on the Nasmysth platform at the side of the ELT is shown in grey.

3. Artist's impression of the European Large Telescope (ELT). The red graph shows a model spectrum of an exo-planet atmosphere exhibiting signatures of life. The orange graph is an observed QSO absorption spectrum probing the thermal and ionisation state of the intergalactic medium.

ELT-HIRES will enable the pursuit of a very broad science case ranging from exoplanets and circumstellar discs, stars and stellar populations, galaxies and the intergalactic medium to cosmology and fundamental physics. Science supported by ELT-HIRES is thus not only very well aligned with research at KICC but will lead to major breakthroughs in many other areas of astronomical research in which Cambridge researchers have a leading role.

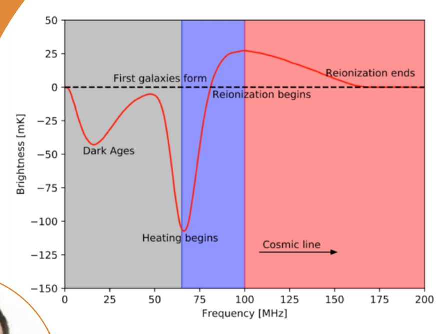
Studying galaxies and the intergalactic medium at high redshift during the epoch of reionisation is the ELT-HIRES flagship science case that is probably of most immediate interest for researchers at KICC. The figure on the right illustrates the remarkable improvement that can be expected from ELT-HIRES spectra of high-redshift QSOs, an invaluable tool for studying the evolution of the thermal and ionisation state of the intergalactic medium during and after the epoch of reionisation (see article on page 13). Spectra of this unprecedented quality will also enable major breakthroughs in our understanding of the chemical composition of the first generation of stars in the Universe, providing important synergies with work that will be performed at KICC with data from the next generation space telescope JWST (see article on page 19).

Most exciting about ELT-HIRES is, however, the spectrograph's capability to characterise the atmospheres of hopefully soon detected Earth-like exo-planets with sufficient fidelity to detect possible signatures of life outside our own solar system, a capability eagerly awaited by the lively Kavli-supported community of exo-planet hunters in Cambridge (see articles on page 39).

REACH: RADIO EXPERIMENT FOR THE ANALYSIS OF COSMIC HYDROGEN

"When were the first luminous objects in the Cosmos born?"
"How did they shape the Universe?"

1



Eloy de Lera Acedo

These are 2 fundamental questions in modern cosmology that REACH will try to answer in the coming years.

The Big Bang model for the origin and initial evolution of the Universe is by now a familiar and well-studied research field. The subsequent, late time, evolution of stars and other celestial objects over billions of years is perhaps even better understood. Less is known, however, about the time between these periods (from about 0.2 to 1 billion years after the Big Bang). During this time the Universe transitioned from being a vast volume filled with a cooling neutral gas to become the realm of cosmic objects that we can now observe from Earth.

At the beginning the Universe was filled with a hot, dense fog of ionized gas until the continued expansion and cooling allowed electrons and protons to combine and form the first neutral atoms, such as hydrogen. Eventually, the neutral matter clumped together under the effects of gravity, providing the conditions for nuclear fusion to occur, leading to the birth of the first stars and galaxies, a period known as the Cosmic Dawn. Subsequently, the radiation emitted by these objects heated and re-ionised the surrounding hydrogen in the Universe during the so-called Epoch of Re-ionisation.

Neutral hydrogen emits radiation in the radio domain, specifically at a rest wavelength of 21 cm. By observing at low radio frequencies we can study directly its red-shifted (due to the expansion of the Universe) emission (and absorption) from the gas clouds that were the raw material that formed the first luminous cosmic structures at these early epochs. This is considered to be one of the prime tools to study these epochs.

The REACH experiment will open a window to these early epochs of the Universe by observing radio signals naturally emitted by hydrogen. We will in essence be looking at these first stars through their interaction with the hydrogen clouds in the same way one would infer a landscape by looking at the shadows in the fog embedding it.

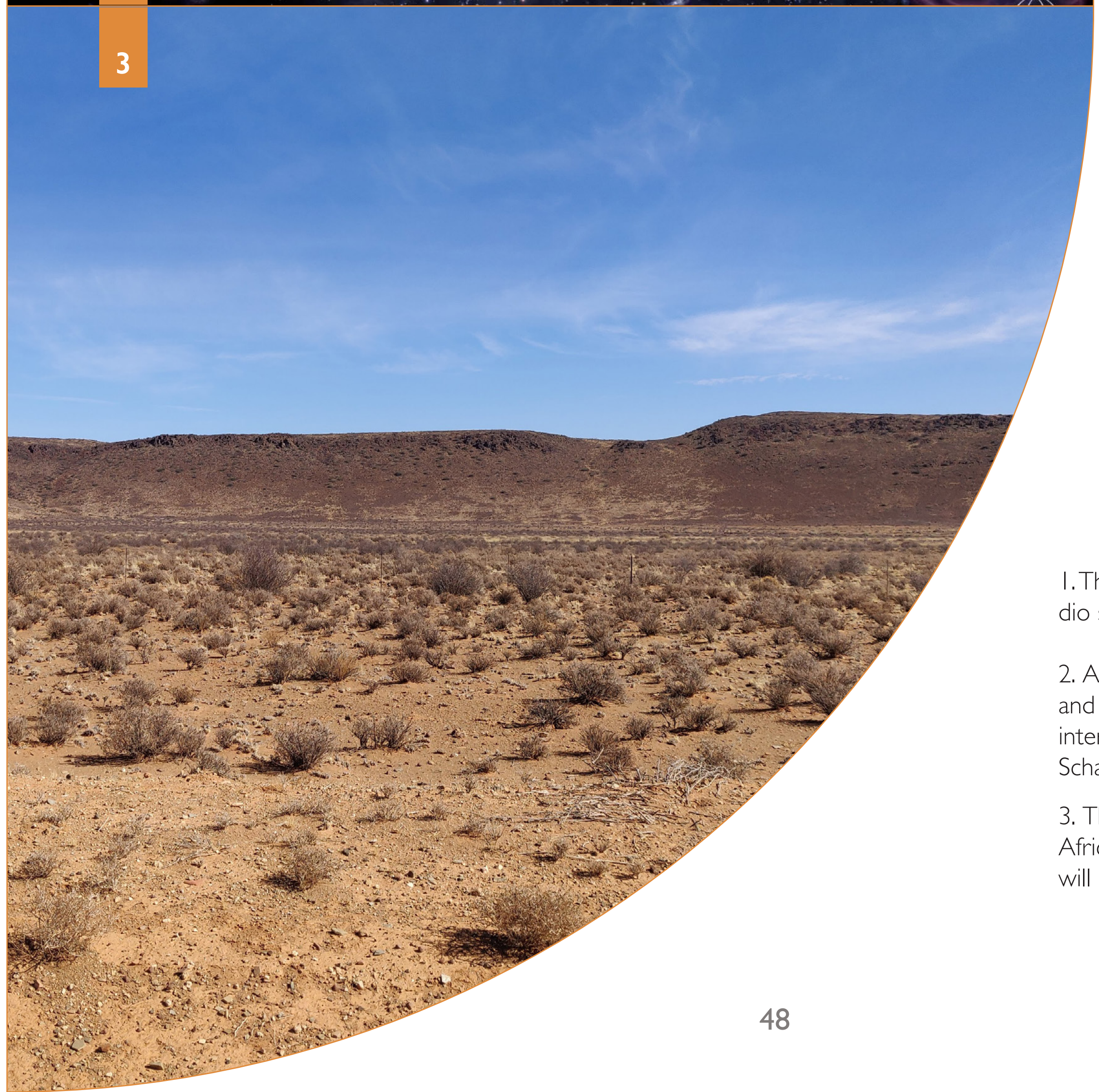
REACH is a joint project between the University of Cambridge and Stellenbosch University in South Africa. With primary funding from the KICC, REACH will be deployed in the semi-deserted land of the Karoo radio reserve in South Africa, a unique location with no radio interference from human settlements (a "Radio Frequency Interference quiet" site) also home of the future Square Kilometer Array telescope.

The instrument will operate at frequencies between 50 and 200 MHz in order to explore both the Cosmic Dawn and the Epoch of Reionization. REACH is a wideband radiometer using state of the art ultra smooth wideband radio antenna designs aiming at reducing the sources of contamination of the cosmic signal. REACH is furthermore making use of advanced Bayesian data analysis tools as well as physics rooted models of the instrument, the 21-cm signal and the foreground signals under which the cosmic signal is buried. Precisely these foregrounds (~100,000 times brighter than the cosmic signal) are the main reason why this detection has not been made yet.

A detection and posterior analysis of this signal will represent a giant leap in modern Cosmology, finding one of the missing pieces in the puzzle of the history of the Universe.

2

3



1. Theoretical model of the cosmic radio signal REACH aims to detect.

2. Artist's impression of the first stars and of their reionisation effect on the intergalactic medium (credit Adolf Schaller, STScI).

3. The Karoo radio reserve in South Africa, where the REACH experiment will be deployed.

DEEP LEARNING FOR RAPID CLASSIFICATION OF THE TRANSIENT UNIVERSE


Daniel Muthukrishna & Kaisey S. Mandel

Observational astronomy has entered a new era of *Big Data*, as automated surveys are collecting more data at a greater rate than humans can possibly process and analyse themselves. Artificial intelligence and machine learning techniques are key drivers in tackling these new large-scale astronomical data challenges. To deal with the large data volumes of modern time-domain astronomy, we have recently applied deep neural networks to the problem of classifying astronomical transient phenomena in survey data streams.

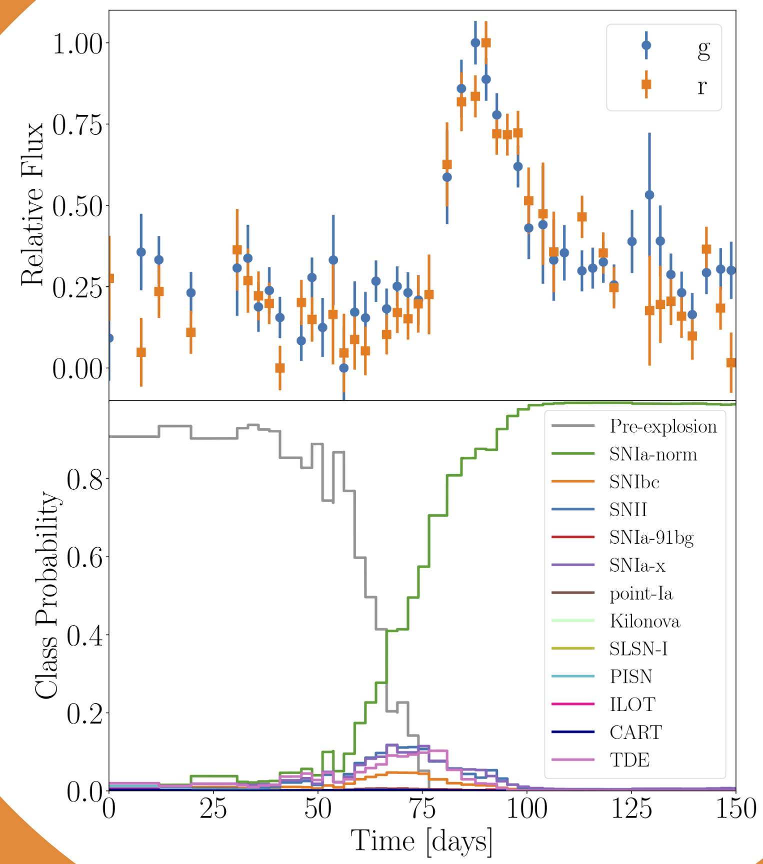
Astronomical *transients* are stellar objects that become temporarily brighter on various timescales and have led to some of the most significant discoveries in astrophysics and cosmology. Some of these transients are exploding stars called supernovae, which are critical for measuring the expansion and composition of the universe. Kilonovae, a newly discovered class of transients, are the visible-light signatures of gravitational-wave sources caused by neutron star mergers, responsible for creating most of the universe's heavy elements. With new surveys, astronomers are discovering rare, exotic, or entirely new kinds of stellar explosions, which teach us about the diverse pathways of stellar evolution and death.

New wide-field telescope surveys, such as the current Zwicky Transient Facility (ZTF), are producing hundreds of thousands of transient alerts per night, and the upcoming Large Synoptic Survey Telescope (LSST) is expected to observe tens of millions of transients, recording in excess of 20 Terabytes of images each night. To meet this demand, we have developed a novel machine learning approach, RAPID (Real-time Automated Photometric IDentification), that uses deep recurrent neural networks (RNNs) to automatically classify transients as a function of time. Variants of RNNs have achieved state-of-the-art performance in several time-series applications. In particular, they revolutionised speech recognition, outperforming traditional methods, and have very recently been used in the trigger word detection algorithms popularised by *Apple's Siri, Amazon's Echo, Google's voice assistant, and Microsoft's Cortana.* Interestingly, the recording of different frequencies of sound waves as someone says "Okay Google" to their Google Home device, looks extraordinarily similar to the early part of a supernova exploding as we record it in different frequencies of light waves. The success of RNNs in trigger word detection algorithms inspired us to apply them to classifying different types of transients. We adapted this technique to deal with noisy, multi-channel, sparse, astronomical time-series data. RAPID is the first method designed to quickly classify transient data streams in real-time, and identifies 12 different astrophysical types. An example of a supernova explosion's brightness as a function of time is shown in the top panel of Figure 1, and the classification accuracies from our RNN-based algorithm are plotted in the bottom panel.

Our strategy is well-suited to classifying these events very shortly after their explosion. This early classification allows us to alert the global astronomical community to follow up interesting transients with more detailed measurements to probe their underlying physics, before they fade away.

We are deploying RAPID to classify the real-time ZTF data stream, and it is currently classifying over 5000 extragalactic transients each night. It is enabling astronomers to make best use of their precious telescope time by prioritising the most interesting events to follow up with further observations. This will allow us to better understand the physical mechanisms driving these diverse and puzzling explosions, and to build up large samples for cosmological analyses to precisely determine the history and composition of the Universe.

1



2

1. Artist's impression of the LSST dome .

2. The brightness of a transient measured in two different frequencies (g and r) is shown in the top panel. The classification probabilities of 12 different transient types as predicted by our RNN-based algorithm are plotted in the bottom panel. The correct transient type is predicted as the most probable type within just a few days of the explosion. The confidence in this prediction improves as more data is taken.

OUTREACH

Matthew Bothwell

Working with local schools

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

Project 'Astro-East'

In 2018 the Kavli Outreach Officer has taken responsibility for setting up the flagship project 'Astro-East'. This program is designed to extend the existing outreach efforts beyond the Cambridge area, to regions that are not usually covered by the University's outreach programmes. Importantly, this new initiative is designed to be proactive rather than reactive – explicitly approaching schools across this new target area, rather than responding to local demand. An initial 'pilot' sample of 30 schools were approached across Norfolk, Suffolk, and Peterborough.

One challenge of this programme is that each individual school has different needs, and requires the teaching sessions to fit around their curriculum and timetable. The Kavli Outreach Officer has to coordinate with the science teachers to design bespoke visits, including setting up after-school science clubs, giving lunchtime talks, and hosting assemblies promoting science careers.

Cambridge Science Festival and Open Afternoon

On the last weekend of the Cambridge Science Festival KICC and the Institute of Astronomy (IoA) open their doors to the public at our annual Open Afternoon.

We run between 2-6pm on a Saturday afternoon. We provide talks, displays, demonstrations, activities, arts workshops with a keen amateur/general public/young family audience in mind. These are staffed by volunteers among the researchers and students at KICC and IoA. The brief given to volunteers is to present entertaining and educational activities that highlight the research done at KICC and IoA.

The day is completely free, and these events are well attended with more than 1500 people typically coming through the doors.

Cambridge Launchpad

Starting in 2018, KICC (alongside the IoA) has become a partner institution with Cambridge LaunchPad (https://cambridge-launchpad.com/), a non-profit social enterprise which aims to inspire and enthuse young people about STEM and to address the significant gender gap which exists in STEM employment. Cambridge LaunchPad is an established organisation, and KICC/IoA will be the first non-corporate partner (other partners include Marshall, ARM, and Microsoft).

As a Cambridge LaunchPad partner, we are hosting groups of students aged between 11 and 15 years of age for single-day workshops. Cambridge LaunchPad provides many logistics, such as transport, computing, etc, so that schools with limited resources (such as for transport) face no barrier to entry.

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

Astronomy on Tap

In 2018, Cambridge astronomy (including the KICC and IoA) became a satellite location for 'Astronomy on Tap', a series of events featuring astronomy talks, games, and activities in pubs. Cambridge's first Astronomy on Tap evening was held in June 2018 at the Maypole pub.

These events will run either monthly or bi-monthly during the summer season (April through September), while our public open evenings are on summer break. The Maypole have agreed to host the evenings on a regular basis, and research groups at the Kavli have expressed interest in participating in future events.

Discovery Channel

In 2018 KICC has started a partnership with the Millennium Project (DAMTP) and the Discovery Channel to produce KICC multimedia streams for social media websites specifically targeting the youth audience and with the goal of enthusing them about astrophysics. The resulting material will be first released in 2019.

EVENTS AND MEETINGS

The Kavli Institute has hosted and supported a wide variety of events and meetings during 2018.

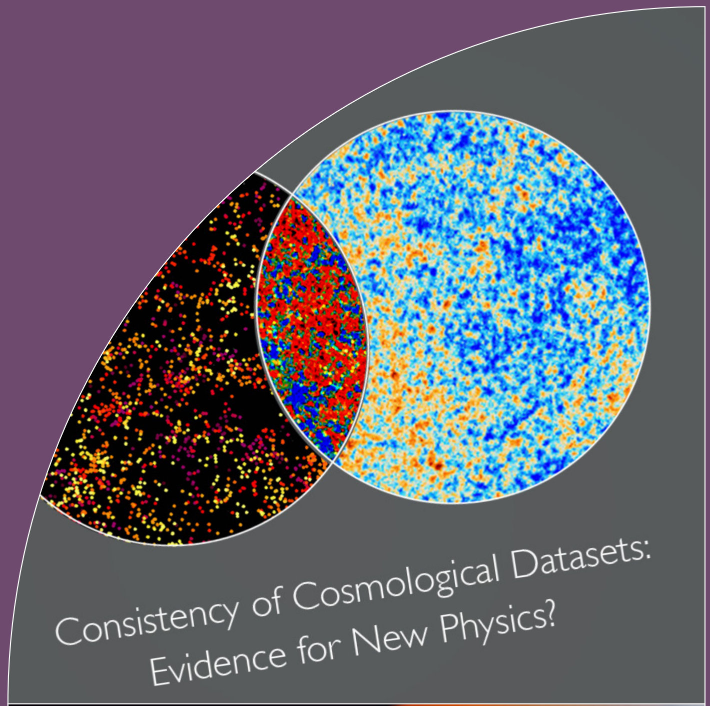
From 28th May to 1st June 2018, in connection with the last Planck data release, we hosted the workshop *"Consistency of Cosmological Datasets: Evidence for New Physics?"* in which major experts in different areas of precision cosmology compared constraints on cosmological parameters obtained with different techniques. Interesting tensions between different datasets were highlighted, which may either be due to observational effects or potentially hinting at new physics. This very successful workshop was the last of a series jointly supported by Kavli Foundation and by the Templeton Foundation held by Professor Martin Rees.

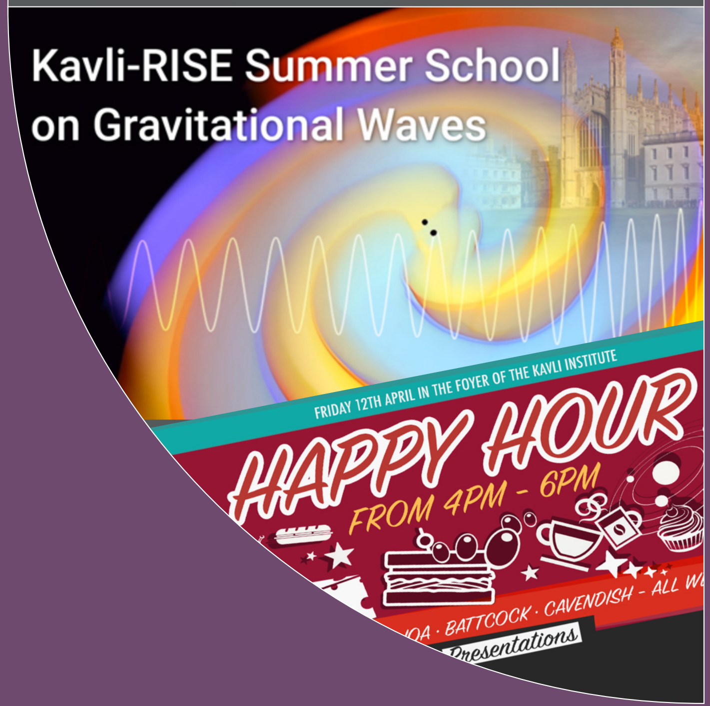
We plan to continue to regularly support and host workshops in the coming years. Two are scheduled for 2019: *AstroHackWeek'19* and *Rocky Worlds: from the Solar System to Exoplanets.*

Furthermore, thanks to a donation by the Kavli Foundation and funding from the European Community, we have started the organisation of a series of summer schools in Gravitational Waves, which will take place in Cambridge every two years. The first of them will be in September 2019.

The Kavli Instute also hosts numerous, regular weekly seminars, such as the talks organised by the Centre for Doctoral Training in Data Intensive Science and numerous other specialist talks.

The Kavli Institute also hosts social events such as the monthly Kavli Happy Hour, which offers an opportunity for the broad astronomical community in Cambridge to know each other better in an informal and friendly setting.





THE KAVLI FELLOWSHIPS

Steven Gratton

Ewald Puchwein

Daan Meerburg

Anastasia Fialkov

Oliver Friedrich

Renske Smit

Matt Auger

Annelies Mortier

The Kavli Fellowships, which are advertised regularly every year, have established themselves as high profile, coveted positions for scientists in the early stages of their career.

In 2018 three new Kavli Fellows have started at KICC: **Anastasia Fialkov** (21cm cosmology), **Matt Auger** (strong lensing and dark matter) and **Steven Gratton** (CMB and precision cosmology).

Kavli Fellow **Ewald Puchwein** has left KICC to take a faculty position at the Leibniz-Institut für Astrophysik in Potsdam. We are proud of this appointment and we are glad that Ewald is maintaining tight collaborations with many of us and visits KICC on a regular basis.

We have also appointed three additional Kavli Fellows who will start in late 2019: **Eric Baxter** (LSS, CMB lensing, SZ), **Nicolas Laporte** (primeval galaxies) and **Vid Irsic** (IGM and reionization).

Thanks to a donation from the **Isaac Newton Trust**, matched by the **Kavli Foundation**, we have started a new programme of **Newton-Kavli Junior Fellowships in Cosmology and Astrophysics**. The first two Newton-Kavli Fellows, who started in 2018, are **Oliver Friedrich** (LSS and dark matter) and **Renske Smit** (primeval galaxies).

The Newton-Kavli Junior Fellowship for 2019 has been awarded to **Sunny Vagnozzi** (CMB, LSS, dark matter and dark energy), who will start in autumn 2019.

We are also supporting a Fellowship in exoplanets, together with the School of the Physical Sciences and with the three departments (IoA, Physics and DAMTP), which has been awarded to **Annelies Mortier** (radial velocity detection and mass measurements of exoplanets), who started in 2018.

Thanks to the donation of **Mr Gavin Boyle**, which has been matched by the Kavli Foundation, we have endowed the **Gavin Boyle Fellowship in Cosmology and Exoplanetary Science at the Kavli Institute**. This fellowship scheme will run in perpetuity. The first of such fellowships has been advertised in the area of exoplanets and awarded to **Mathias Nowack** (interferometry and high contrast imaging), who will start in autumn 2019. This fellowship has been combined with a College Fellowship at **Selwyn College**, thanks to an additional donation by Gavin Boyle.

Thanks to a donation of the Kavli Foundation we have advertised a **Senior Kavli Fellowship in Gravitational Waves**, which has been awarded to **Michail Agathos** (active member of the LIGO-Virgo collaboration) who will start in late 2019. We plan to make this fellowship in gravitational waves a long term commitment of the Kavli Institute.

Finally, in 2018, KICC joined the **Stephen Hawking Programme** that will permanently fund two Hawking-Kavli Fellowships in areas that are of common interest of KICC and DAMTP. These are linked with Stephen Hawking's legacy, such as Gravitational Physics, Black Holes, Gravitational Waves and Cosmology.

Photograph: the opening of the Stephen Hawking programme on 29th November 2018 at the Science Museum in London.

The **Planck satellite team** has been awarded the **2018 Gruber Cosmology Prize** for collecting data from the Cosmic Microwave Background at an unprecedented level of accuracy, which have provided virtually irrefutable evidence in support of the standard model of the Universe on the smallest to the largest scales.

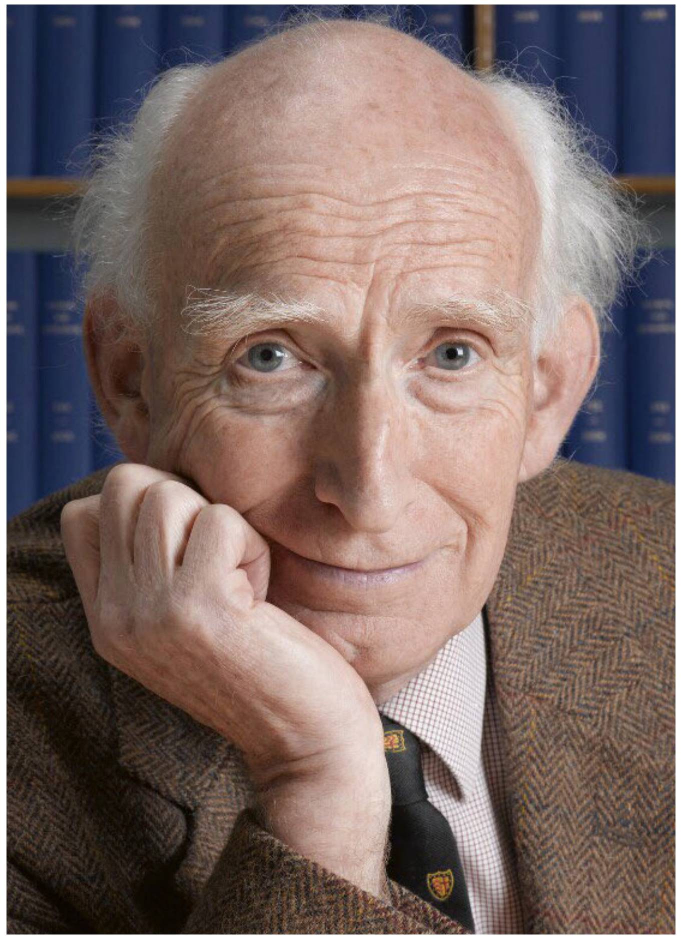
Renske Smit has been awarded the **2018 Merac Prize** for the best PhD thesis in Observational Astrophysics. The award was given by the European Astronomical Society during the European Week of Astronomy and Space Science in Liverpool.

Roberto Maiolino has been **knighted** by the Italian President in the Order of the Star of Italy. The knighthood was given in recognition of his achievements in various areas of astrophysics and for promoting collaborations between Italian researchers and the British and international scientific communities.

Donald Lynden-Bell, 1935 – 2018

By George Efstathiou and Roberto Maiolino

Donald Lynden-Bell (centre) and Maarten Schmidt (left) receiving the inaugural Kavli Prize for Astrophysics in 2008.



We were all very saddened when Professor Donald Lynden-Bell passed away on the 5th February 2018.

Donald Lynden-Bell was Professor of Astrophysics at the Institute of Astronomy from 1972-1997 and served several terms as Director.

He was a pioneering figure in several areas of astrophysics. One of his major achievements was (in 1969) the theoretical understanding of the nature of quasars, extremely luminous sources that, at that time, had been recently discovered. He illustrated that the engine powering such extraordinary sources could be plausibly explained in terms of matter accreting onto a supermassive black hole. More specifically, he showed that the extremely huge luminosities emitted by quasars could be ascribed to the frictional heating of matter rotating around a supermassive black hole. He also speculated that this mechanism implied the existence of fossil supermassive black holes at the centres of many galaxies. He suggested that such dormant black holes could be detected through their gravitational effect on the orbits of the stars in the central region of galaxies, a prediction that has been subsequently confirmed observationally.

His studies in galactic dynamics have been pivotal, providing the statistical mechanics fundaments for understanding the distribution of stellar orbits in elliptical galaxies and also providing key concepts for our understanding of the spiral structure in disc galaxies.

His studies were not confined only to these areas. He explored more broadly the formation and chemical evolution of our Galaxy, the large scale streaming motions in the Universe, relativistic jets and broad problems in General Relativity.

He won many awards throughout his career, including the Gold Medal of the Royal Astronomical Society and the first Kavli Prize for Astrophysics awarded jointly with Maarten Schmidt in 2008. Donald was elected a Fellow of the Royal Society in 1978 and was made a CBE in 2000.

Donald was a pivotal figure in Cambridge Astronomy. A scientist and a friend who, even when retired, was continuously and lively contributing to discussions and to scientific debates with his own insightful perspective.

We will all miss his joyous character, his contagious enthusiasm and widespread interest in all areas of astronomy.

Stephen Hawking, 1942-2018

By Paul Shellard

On the 14th March 2018, Professor Stephen Hawking died at the age of 76. He was one of the truly great figures of twentieth century theoretical physics and cosmology and, more than this, he succeeded in reaching outside his academic discipline to inspire millions. His life was a beacon characterised by unparalleled intellectual achievement and tremendous courage in the face of many challenges. The sadness of his passing was felt around the world, but especially keenly in Cambridge by those who knew him personally as a mentor, colleague and friend. Stephen had supported the Kavli Institute for Cosmology here and participated in the fund-raising effort for its foundation. Although most of his career was spent in the Department of Applied Mathematics and Theoretical Physics (DAMTP), for several years he had also been a postdoctoral researcher at the Institute of Theoretical Astronomy (now the IoA), so he recognized the complementary scientific strengths of the three sister departments and the value of combining these into a world-leading centre, the KICC.

Stephen Hawking was a living demonstration that there should be no boundary to human endeavour, as we had seen daily though his courage and perseverance in the face of grave disability; as a PhD student in 1963 he was diagnosed with motor neurone disease, beginning a battle that lasted over half a century. He said at the opening of the 2012 London Paralympics games: "There is no such thing as a standard run-of-the mill human being. And however difficult life may seem, there is always something you can do, and succeed at." Stephen identified what he could do well – in fact, exceptionally well – and he just got on with his life and work with immense determination and his legendary good humour.

Those who had the privilege to observe Stephen's work at first hand are deeply indebted for the example he set and can appreciate the foundations for his success; he struck at the heart of a problem using his incisive physical intuition and, out of complex mathematics, he distilled the essential geometric concepts. Stephen's laser focus was always on tackling the really Big Questions about our Universe; those for which there are now answers because of his foundational contributions include:

- Did the Universe have a beginning in time? Yes. Stephen's cosmological singularity theorems 1965-8, some obtained before the cosmic microwave background radiation discovery, established mathematically that general relativity required that there must have been a Big Bang singularity in the past.
- Are black holes unique? Yes. In 1971 Stephen made a pivotal contribution to the famous black hole uniqueness theorems by proving that a stationary black hole must possess a simple axis of symmetry around which it rotates.
- Do we know what happens when black holes collide? Yes. Stephen introduced the concept of the black hole event horizon (defining the region from which light and matter cannot escape). His horizon area theorems from 1971-2 also set an upper limit on the gravitational waves produced when black holes merge, and should soon be tested by the LIGO/Virgo experiment.
- Do black holes live forever? No. His 1974 discovery of quantum emission from the black hole horizon – known as Hawking radiation – brought together for the first time the two great revolutions of 20th century physics, quantum mechanics and general relativity; it remains the touchstone in the quest to unify physics through a theory of quantum gravity.
- Can we explain where all the galaxies in the Universe come from? Yes. In early 1982 Stephen proposed that, during a period of inflation (rapid expansion in the early universe), quantum effects could create the primordial seeds required for galaxy formation; this is Hawking radiation from the cosmological horizon. The paradigm, developed along with others, has been confirmed in successive decades by the COBE, WMAP and Planck satellites surveying the cosmic microwave sky.
- Can we understand the origin of the Universe? Maybe. Stephen's most daring intellectual project was his ambitious 1981 proposal that the Universe has no boundary. This theory of quantum cosmology remains a work in progress and one on which he kept shining a bright light even into his last years.

With such a pantheon of scientific achievements, Stephen became the recipient of many awards and honours, including the Adams Prize, Pius XI Medal, Albert Einstein Award, RAS Gold Medal, Wolfe Prize, Copley Medal, the Breakthrough Prize in Fundamental Physics and the BBVA Foundation Frontiers of Knowledge Award. His foray into science outreach, starting in 1988 with his first book, A Brief History of Time, brought him instant worldwide fame. Many popular books and regular media appearances followed, with a particular highlight being the 2015 film of his life, The Theory of Everything, for which Eddie Redmayne, playing Stephen, received an Academy Award. His achievements were recognized far beyond the academic domain with a CBE in 1982, the Companion of Honour in 1989 (while also declining a knighthood), and the US Presidential Medal of Freedom in 2008. His Memorial Service in Westminster Abbey saw moving and fitting tributes to his greatness, with his ashes interred between the graves of Isaac Newton and Charles Darwin.

Stephen Hawking, together with Roberto Maiolino and members of the Kavli Foundation Board of Directors and Staff during their visit in November 2017.

The passing of such a singular individual is a sad loss, but the time has come to build on his amazing legacy and to ensure that future generations are also encouraged by his positive vision. In Cambridge, Stephen had even embarked on this process himself, when in 2007 he founded the DAMTP Centre for Theoretical Cosmology (CTC), thanks to a generous endowment from Denis and Sally Avery. This was a complementary development that coincided with the founding of KICC; the purpose of CTC was, in his own words, "to develop theories of the Universe that are both mathematically consistent and observationally testable." In November 2017, Stephen met with Kavli Foundation Board Members, delivering a speech in which he noted that "by combining together their renowned cosmology groups through the Kavli Institute, Cambridge now has very few equals globally." In November 2018, the Vice-Chancellor launched the Stephen Hawking Programme at the Science Museum in London. The purpose is to celebrate and memorialise Stephen's life and achievements in perpetuity through establishing prestigious PhD studentships, postdoctoral fellowships and faculty positions that will attract the very best candidates from around the world. Long may Stephen's unique contributions continue to inspire us all.

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/publications

Acknowledgements

The numerous activities of KICC are made possible by the tireless administrative and logistical work of 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 Physics Department and the Department of Applied Mathematics and Theoretical Physics, and by the School of Physical Sciences.

The artwork and layout of this report were produced by Amanda Smith, who has produced numerous other artworks associated with KICC.

The activties of KICC are made possible by the generous donations by the Kavli Foundation, in combination with the University of Cambridge and its Departments. We would also like to thank Gavin Boyle and the Isaac Newton Trust for their support of our fellowships programme (see page 55).

Kavli Institute for Cosmology, Cambridge • University of Cambridge • 2019