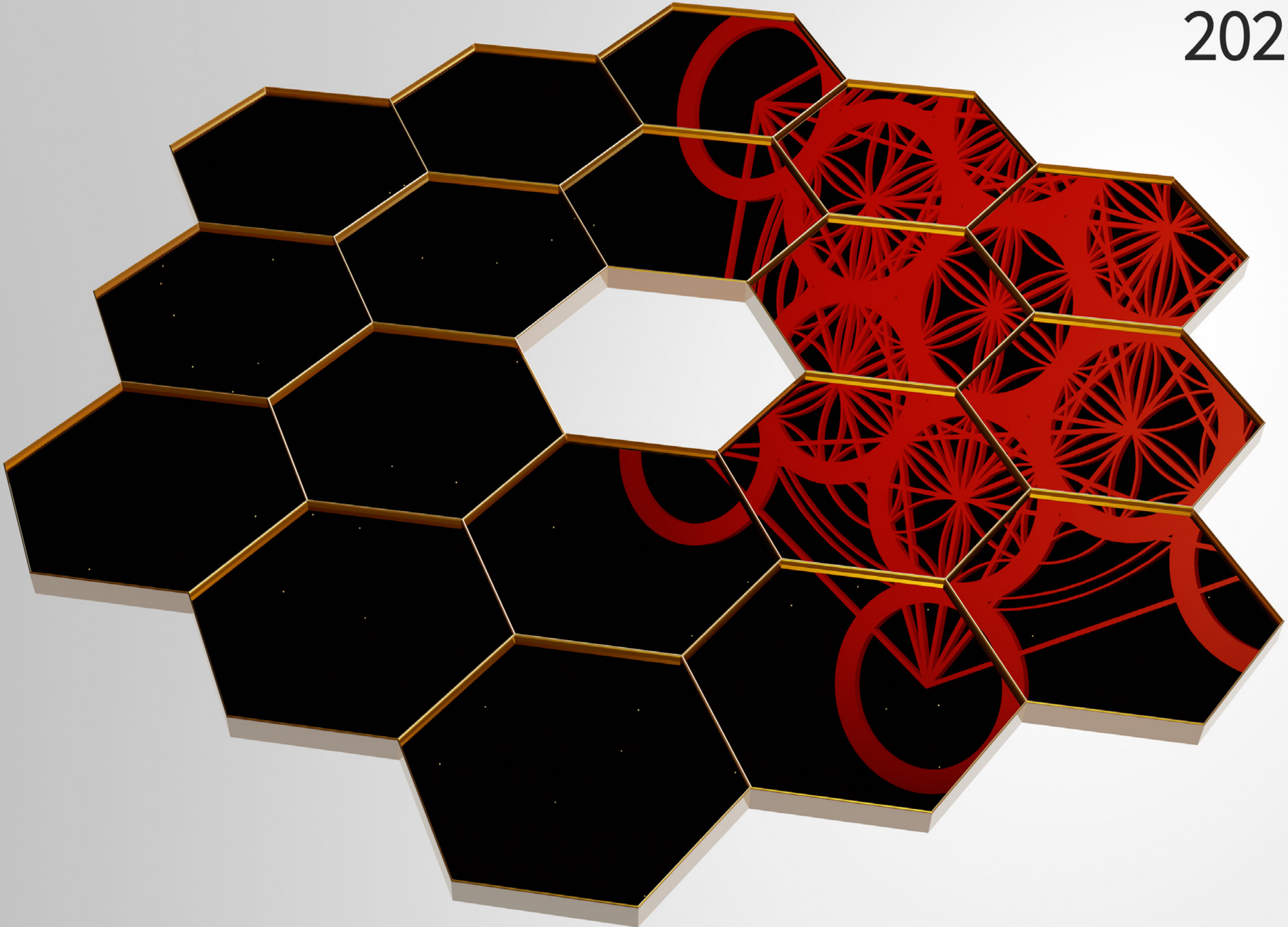

# 2020

# KICC - ANNUAL REPORT

KAVLI INSTITUTE FOR COSMOLOGY, CAMBRIDGE

UNIVERSITY OF CAMBRIDGE

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## Message from the Director • Roberto Maiolino

Resilient and creative. That is how I would describe the scientific community, and in particular the astronomical community, as they had to face the difficulties and challenges resulting from the global pandemic in 2020. Scientists have rapidly adapted to the changing situation by finding new ways to minimise disruption, to advance their research projects efficiently, and to foster and expand their collaborations.

These considerations certainly also apply to the Kavli Institute. It would be foolish to claim that we have not suffered from the strenuous circumstances in 2020, but we have managed to maintain cutting-edge research, with fantastic new results, some of which are presented in this report.

Although COVID-19 has undoubtedly created some delays to the development of several of our forthcoming, new projects, we have nevertheless mitigated the issues and achieved major progress in many areas. Activities have been ramping up in preparation for the extensive surveys to probe the early Universe that we will be undertaking with the James Webb Space Telescope, which will be launched towards the end of 2021. We have delivered the first optical cameras for MOONS, the next generation multi-object spectrograph for the Very Large Telescope. Major progress has also been made in prototyping some optical elements and in defining the technical and scientific specifications for HIRES, the high-resolution spectrograph for the Extremely Large Telescope, which is under construction in Chile. Activities have also been fervent in preparation of the new CMB experiments, such as the Simons Observatory, and new massive cosmological surveys, such as DESI. Numerical hydrodynamical simulations developed at our institute have reached new, unprecedented levels of sophistication and detail.

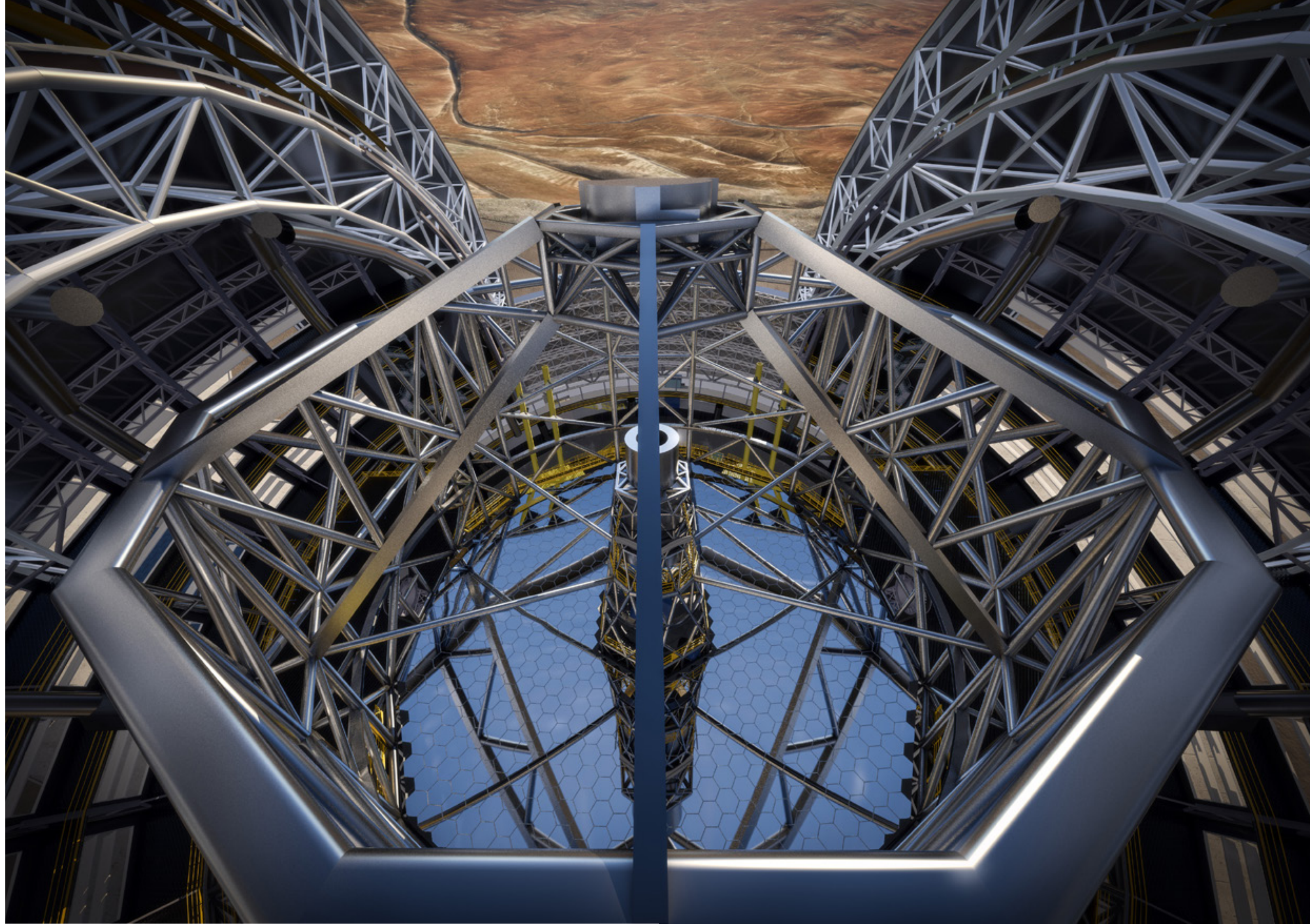
The Kavli Institute has maintained its commitment to excellence also by continuing, uninterrupted, its prestigious fellowships programme. For this, as well as for many other activities, such as workshops and public outreach (although online), we also have to thank the generous support from the Kavli Foundation.

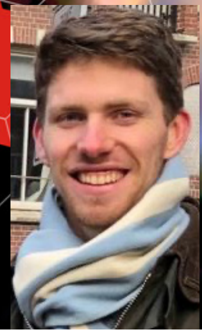
In 2020, we have been thrilled by the announcement of the award of the Kavli Prize in Astrophysics to Professor Andy Fabian. We are immensely proud of Andy's outstanding contributions to X-ray astronomy, and this award is yet another recognition of Cambridge's excellence in astronomy and astrophysics.

Sadly, in 2020, Cambridge and the whole scientific community also lost one of its most prominent, inspiring and energetic figures, Professor John Barrow, who has left a huge void among us, but also an immense scientific legacy.

I look at 2020 as a year of achievements. Despite all the challenges and difficulties, we, as an institute, but also as a community, have emerged strengthened and with the energy to face the challenges and endeavours in the years to come.

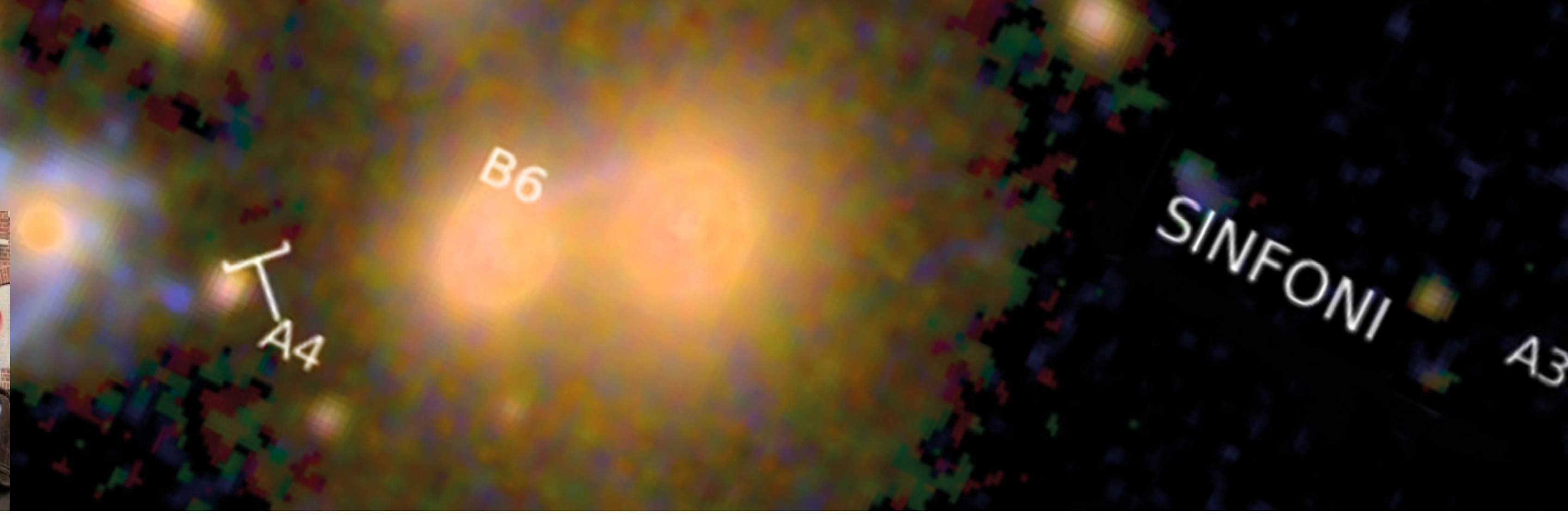
2021 will be my last year as Director of the Kavli Institute. My time as Director has been a fantastic experience and I wish to thank all of my colleagues and students who have contributed to making the Institute thrive. In particular, my deepest gratitude goes to Steven Brereton, who has been a superb aide. I am sure that the Institute will continue to flourish under the guidance of the next Director, Anthony Challinor – I cannot think of a better person to lead the institute in the coming years. I wish him all the best for a successful Directorship.



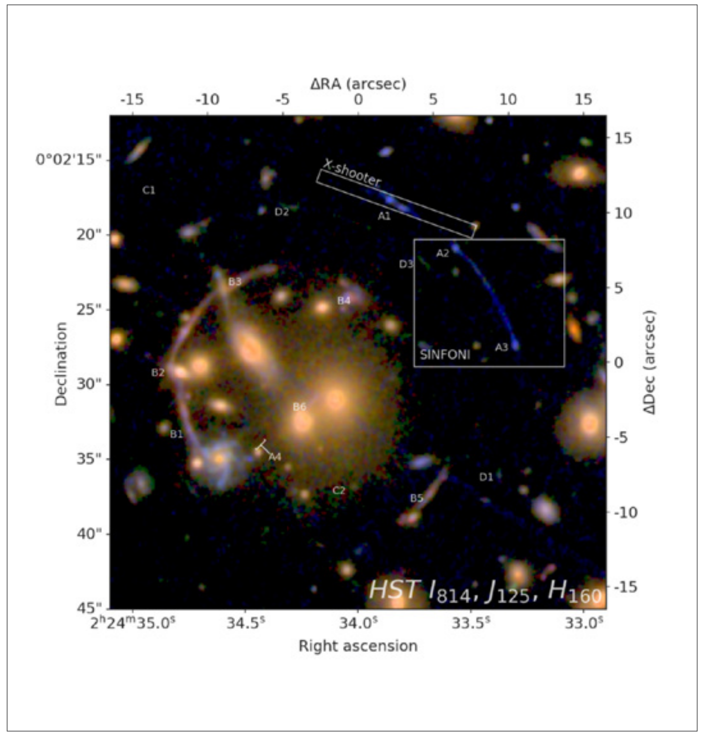



# Preparing for the Sources Behind Reionisation: a Case Study of a Strongly Lensed Galaxy at Redshift 5

Joris Witstok




One of the main challenges faced in modern astrophysics is explaining the major phase transition that transformed the very early neutral Universe into an (almost) completely ionised state. This process, referred to as reionization, was set in motion with the formation of the first stars and galaxies, around 150 million years after the Big Bang (around redshift 20), and was completed in under a billion years later (redshift around 6). The current hypothesis is that low-mass galaxies were the main culprit behind Reionisation: at that point in time, pristine gas – largely composed of hydrogen and helium, not yet enriched with heavier elements like carbon and oxygen – abundantly flowed into these galaxies and was rapidly converted into stars. Therefore, a significant fraction of the resulting stellar populations were likely metal-poor, massive (O- and B-type) stars, whose spectra are much 'harder' than stars like the Sun: they produce copious amounts of photons with sufficiently high energy to ionize neutral atoms.

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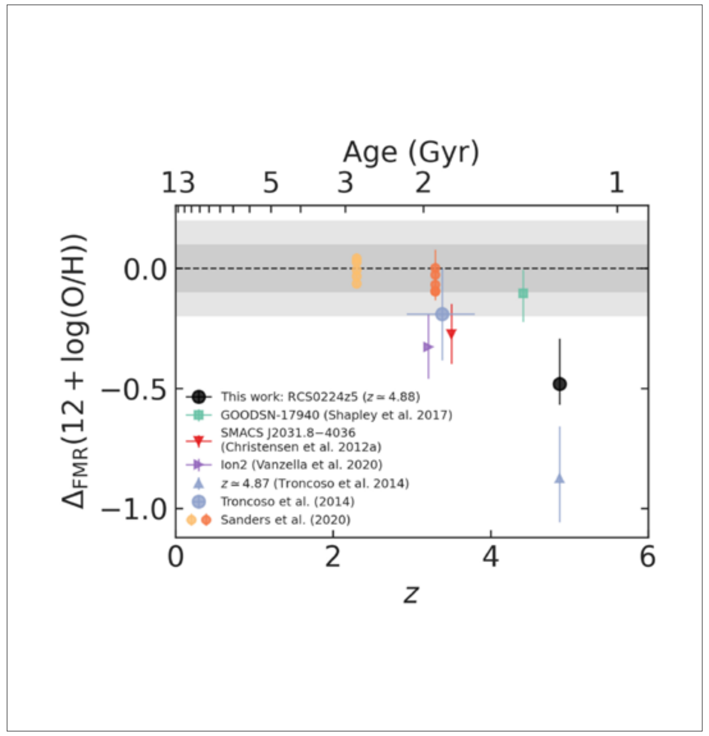


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The challenge of confirming this hypothesis lies in the fact that as a result of their low stellar mass, these galaxies are necessarily faint, and thus hard to detect. To constrain their contribution to reionisation, an accurate measurement of two quantities is required. Firstly, observations need to reveal their occurrence rate, which can, in principle, be established relatively easily by number counts in deep surveys – this will certainly be achieved by the much-anticipated James Webb Space Telescope (JWST). Secondly, however, there is the slightly more complex question of their average ionising ability: did these systems produce enough ionising photons, and critically, could these escape the galaxy? This measurement is hindered by the very fact the Universe was in a neutral state initially, since intervening neutral gas (which absorbs all ionizing photons) precludes us from directly observing the process of reionization. (Moreover, Lyman-alpha – the principal emission line of hydrogen and hence one of the main ways to identify high-redshift galaxies via their spectra – is also absorbed.)

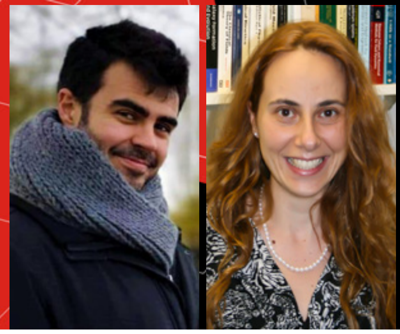
Fig 1. False-colour image of the foreground cluster and the two arcs (A1–A3) of the background galaxy RCS0224z5 observed with X-shooter and SINFONI.

Fig 2. Offset in metal enrichment (the ratio of oxygen to hydrogen, O/H) relative to the prediction of the Fundamental Metallicity Relation (FMR) as a function of redshift or, equivalently, the age of the Universe.

Characterising sources that are 'leaking' ionising radiation is therefore crucial to aid JWST in finding the sources responsible for reionisation. To this end, we obtained new VLT/Xshooter spectroscopic observations (PI: former KICC Fellow, Renske Smit) of a unique gravitationally lensed galaxy at redshift 5 (Fig. 1). A massive foreground cluster (RCS 0224–0002) serendipitously magnifies the background galaxy, named RCS0224z5, by a factor of about 30; only two other known sources at such high redshift have a comparably high magnification. Through measurements of rest-frame energetic ultraviolet emission lines, we found the radiation field to be predominantly stellar in origin. Further analysis of previous observations taken with VLT/SINFONI allowed a measurement of neon and oxygen emission lines, which revealed a high number of ionising photons relative to the gas density inside the galaxy, far exceeding what is typically seen in local galaxies and indeed similar to nearby 'leakers', a class of extremely rare galaxies from which a significant fraction of ionising photons escapes. Furthermore, these lines are an indicator for the enrichment of heavy elements, which shows a tentative departure from the Fundamental Metallicity Relation (Fig. 2). Finally, we detected a magnesium emission line that has been shown to correlate with the same class of leakers. Independently, we also indirectly inferred that RCS0224z5 has a significant ionizing photon escape fraction. Being the most distant galaxy for which this magnesium line has been reported, this demonstrates for the first time its potential as an indirect tracer of ionizing photon leakage at high redshift.

# Unravelling the Origin of Magnetic Fields in Galaxies

Sergio Martin-Alvarez • Debora Sijacki



Primordial magnetic fields are one of the least understood components of our Universe. In particular, we do not know how strong these primordial magnetic fields were by the epoch of recombination, when the cosmic microwave background (CMB) was emitted. The topic is complicated by the fact that we have no direct measurements of cosmic magnetic fields. Rather, our current understanding of magnetic fields on scales larger than galaxies is limited to constraints based on their apparent lack of impact on, e.g., the CMB.

Nonetheless, magnetic fields have been detected in most astrophysical objects at and below the scale of galaxies. In fact, the contribution of magnetic energy in galaxies is comparable with their thermal and turbulent energies, making magnetic fields an important component in our study of galaxy evolution. However, even with a myriad of magnetic field observations in galaxies, the origin of magnetic fields remains unclear. Current limits on the strength of primordial magnetic fields allows them directly to magnetise galaxies, and even affect their properties, such as the star formation rates and galaxy sizes. Consequently, while there are various mechanisms that could generate magnetic fields within galaxies once these have formed, we cannot rule out a primordial origin. As these in-galaxy, astrophysical channels are likely to be at play, it has been presumed that all information regarding primordial magnetic fields is quickly erased.

However, the two types of mechanism have very different cosmological evolution, and would source magnetic fields with intrinsically different properties. To unravel this question, cosmological galaxy formation simulations provide an ideal tool and allow us to perform controlled physical experiments. Specifically, we run various realistic cosmological simulations of a spiral galaxy, magnetising it through either a solely astrophysical or primordial mechanism, or combinations of both.

By considering how magnetic fields evolve in the galaxy under each magnetisation scenario, we explore whether primordial magnetic fields are erased by their astrophysical counterpart, and whether they are distinguishable. Our simulated galaxies are shown in Fig. 1, where columns present from left to right an SDSS-like optical mock view, various physical quantities, and the decomposition of magnetic energy into its origins, respectively. These rightmost panels divide the two types of magnetic energy as astrophysical (in red) and primordial (in green).

Even when combined with astrophysical sources, primordial magnetic fields survive and remain important in the galaxy and its outskirts. This provides an exciting prospect to further our understanding of primordial magnetic fields, as it confirms that strong enough primordial magnetic fields are not ‘erased’ by astrophysical sources. Nonetheless, spatial mixing of the two fields occurs but their differentiation is possible. Primordial fields are mostly found and dominate the magnetic energy budget of the warm, unprocessed, metal-poor gas. Interestingly, different magnetisation channels concentrate fields at different scales. Primordial magnetic fields dominate on large galactic scales (greater than a few kpc), whereas the astrophysical ones dominate on the small scales.

While the survival of strong primordial fields and their differentiation based on their intrinsic properties is a novel result, it is not that surprising: primordial magnetic fields are generated early in the history of our Universe, and thus are associated with cold, pristine gas distributed at large cosmological scales. On the other hand,



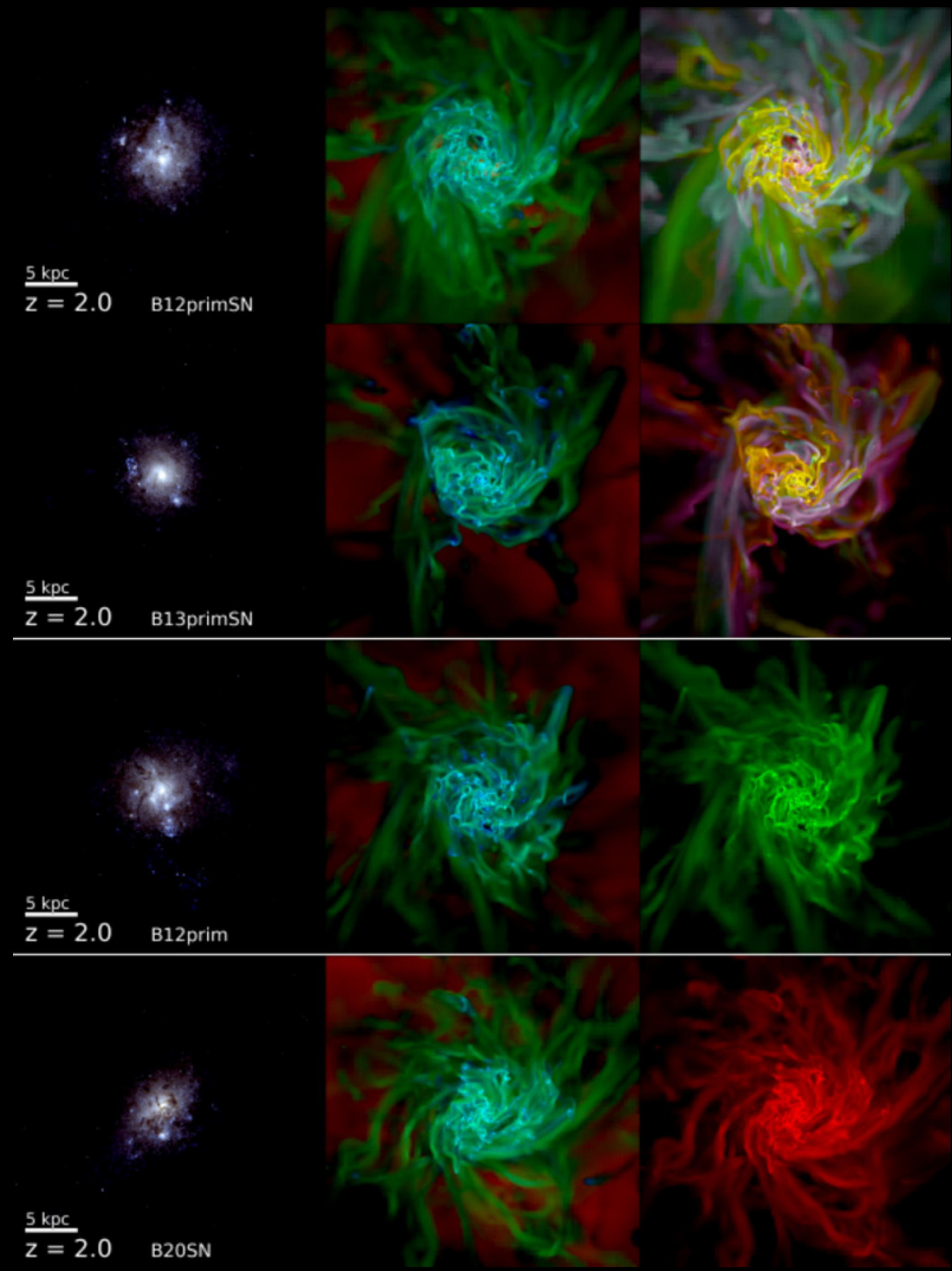
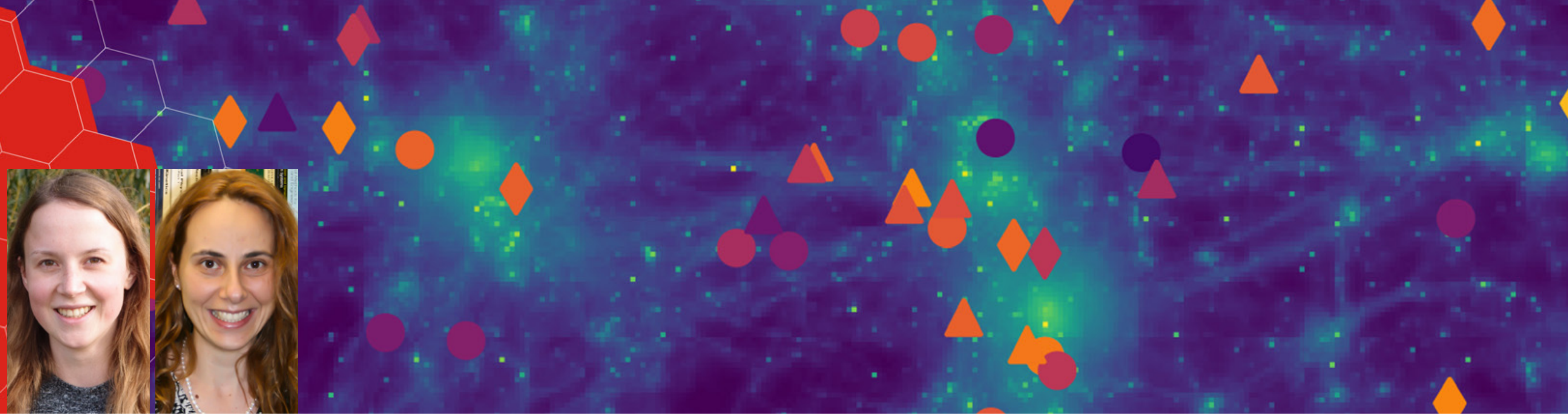



Fig 1. Simulations of a spiral galaxy at redshift 2, with each row employing different magnetisation mechanisms. From top to bottom, simulations correspond to primordial and astrophysical magnetisation, weak primordial and astrophysical, exclusively primordial and exclusively astrophysical, respectively. The leftmost column shows a synthetic optical SDSS-like observation of the galaxy. The central column corresponds to a combination of gas density (cyan), temperature (orange) and magnetic energy (green). The rightmost column separates the magnetic energy into the parts originating from the primordial field (green), generated astrophysically (red), or emerging through the interaction of both (blue).

astrophysical fields are generated inside (or around) galaxies, which are enriched with metals and bustling with activity.

This work opens the door for studies of primordial magnetism in galaxies. If galaxies are able to provide us with information about primordial magnetic fields, they may become our new window to the primordial magnetic Universe, and help us determine whether primordial magnetic fields were strong enough to magnetise our Universe.

These results were published as Martin-Alvarez S. et al., MNRAS 504, 2517 (2021).



# Black Hole Feedback in New Regimes

Sophie Koudmani • Debora Sijacki

Virtually all large galaxies, like our own galaxy the Milky Way, harbour massive black holes at their centres. Some black holes are 'active', i.e., they are growing by devouring gas, releasing massive amounts of energy as the gas spirals inwards. Improved technology has recently enabled astronomers also to detect active black holes in small galaxies (known as dwarf galaxies). This has prompted a paradigm shift as black holes had previously been completely neglected in dwarf-galaxy models. There are several long-standing 'dwarf-galaxy anomalies', concerning a stark mismatch between observations and theoretical predictions, which we may finally be able to solve by including active black holes in our dwarf-galaxy models.

The interaction between black holes and their host galaxies is a highly complex process, necessitating massively-parallel simulations on high-performance computing clusters. We have modelled the impact of active black holes on dwarf galaxies using a variety of cosmological simulations. The aim of this research is to determine whether active black holes could shut down the metamorphosis of gas into stars in dwarf galaxies since a 'feedback mechanism' is needed to prevent excessive star formation and match observations. Previously, supernovae had been assumed to be the main feedback mechanism in dwarfs, though whether supernova feedback alone can be effective enough is still controversial.

Firstly, we analysed black hole activity in a statistical sample of dwarf galaxies using the cosmological simulation suite FABLE (see Fig. 1). We found that active black holes drive hotter and faster outflows in the FABLE dwarf galaxies. These outflows lead to a reduced gas reservoir and suppress star formation in the early Universe. Note that, like most large-scale cosmological simulations, FABLE employs (artificially) strong supernova feedback to regulate star formation in dwarfs. This strong supernova feedback ejects gas from the central region of the galaxy and stunts black hole growth. Therefore, black hole activity levels in FABLE are somewhat reduced for low-mass galaxies – in contrast with observations from X-ray telescopes, which have identified highly-active black holes in dwarfs.

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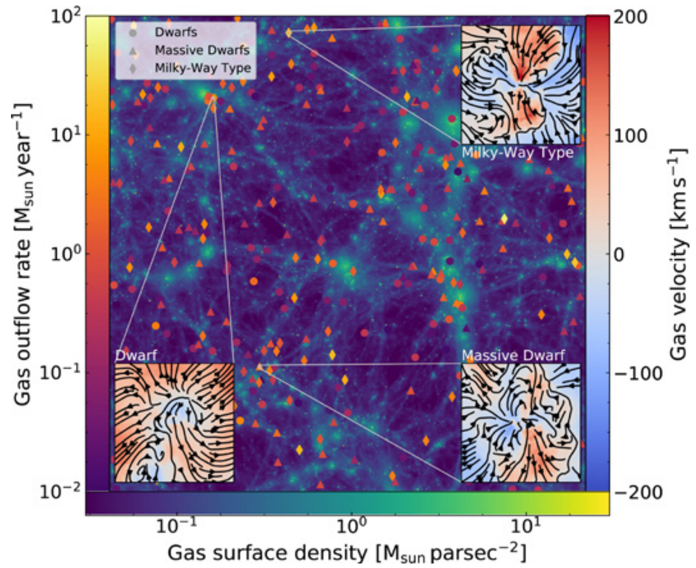


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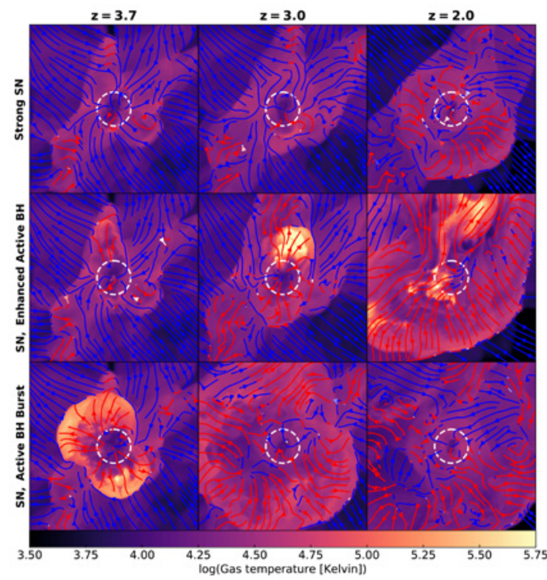



Fig 1. Gas density projection of the FABLE cosmological simulation box. Each tiny green dot is a galaxy. The markers indicate the locations of active black holes hosted by different types of low-mass galaxies and their outflow rates. The zoomed-in insets show example outflow structures.

Fig 2. Gas temperature projections of the circumgalactic medium in dwarf galaxy zoom-in simulations at different redshifts and with different feedback mechanisms. The gas outflow and inflow structures are indicated by red and blue streamlines, respectively. Active black holes (BHs) can be significantly more efficient at suppressing inflows than supernova (SN) feedback.

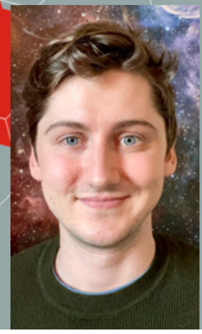
Next, we investigated whether black hole activity in tandem with more realistic supernova feedback could have the same quenching success as the strong supernova feedback assumed in FABLE, using cosmological zoom-in simulations of dwarf galaxies. Zoom-in simulations model representative regions of the Universe, but significantly increase the resolution of the region around the galaxy of interest. The evolution of this galaxy can then be studied in detail whilst also following the interaction with the large-scale environment, allowing for different feedback mechanisms to be tested systematically. We found that with a more realistic supernova feedback parametrization, there is enough gas available for the black hole to accrete efficiently and drive powerful outflows. These boosted outflows can suppress fresh gas inflows from the cosmological environment and shut down star formation by depleting the gas reservoir of the host galaxy (see Fig. 2).

However, note that the efficiency of active black holes in dwarf galaxies crucially depends on the assumed gas accretion model, supernova feedback strength and black hole seeding mechanism(s). Next-generation galaxy formation models combined with future deep electromagnetic surveys (e.g., JWST, RST, Athena, Lynx and SKA) and gravitational-wave observatories (e.g., LISA, pulsar timing arrays and AION) will allow us to break these degeneracies and elucidate the role of active black holes in dwarf glaxies.

These results were partially published in: Koudmani S., Henden N. A. and Sijacki D., MNRAS 503, 3568 (2021).

# The Chemical Evolution of Galaxies

Connor Hayden-Pawson



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The evolution of galaxies is strongly influenced by the interplay between several different key mechanisms. Galaxies can accrete fresh supplies of gas, which then cools and fuels the formation of new stars. As these stars die, they can enrich the surrounding interstellar medium (ISM) with the products of their stellar nucleosynthesis, "*metals*". Furthermore, the death of these stars through explosive supernovae, coupled with other phenomena such as stellar winds and radiation pressure, can cause outflows that drive the gas out of the galaxy, suppressing star formation. Numerous models and cosmological simulations have studied how these mechanisms can reproduce properties of galaxies across cosmic time, but a detailed observational understanding remains elusive, mainly due to the difficulties in directly observing inflows and outflows, especially in fainter, more distant galaxies. Studying the abundances of different metals within galaxies therefore represents a useful way to probe indirectly many of the processes that drive galaxy evolution.

Since different chemical elements are produced by different stellar populations that enrich the ISM on different timescales, the relative abundance between different elements can provide unique constraints on the evolutionary history of a galaxy. Most gas is in the form of hydrogen, however the most abundant heavy element by mass is generally oxygen. As such, we trace the amount of metals within the galaxy, "*metallicity*", through the ratio of oxygen to hydrogen (O/H). Oxygen is mainly produced by massive, short-lived stars that enrich the ISM after they die as core-collapse supernovae, and is simple in that it is a primary nucleosynthetic product, meaning its production is independent from the amount of metals already present in the galaxy. However, the production of other elements, such as nitrogen, is more complex. Unlike oxygen, nitrogen is mainly produced in low- and intermediate-mass stars, which have much longer lifetimes and enrich the ISM as strong stellar winds strip metals from the star towards the end of its life.

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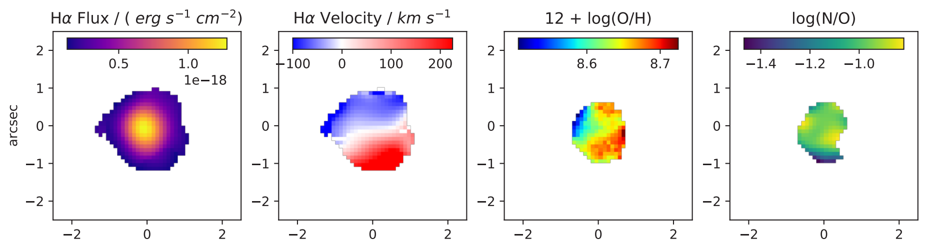


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Moreover, nitrogen can be a secondary nucleosynthetic product, meaning that as the galaxy becomes more metal-rich, it begins to produce more nitrogen. Studying the ratio of nitrogen to oxygen (N/O) therefore allows us to probe the star formation history of a galaxy. We can gain further insight by comparing N/O to other galactic properties. For example, a galaxy with higher than expected N/O at a low O/H may have recently accreted gas (if it has a high star-formation rate) or may have strong oxygen-loaded outflows (if it has a low star-formation rate).

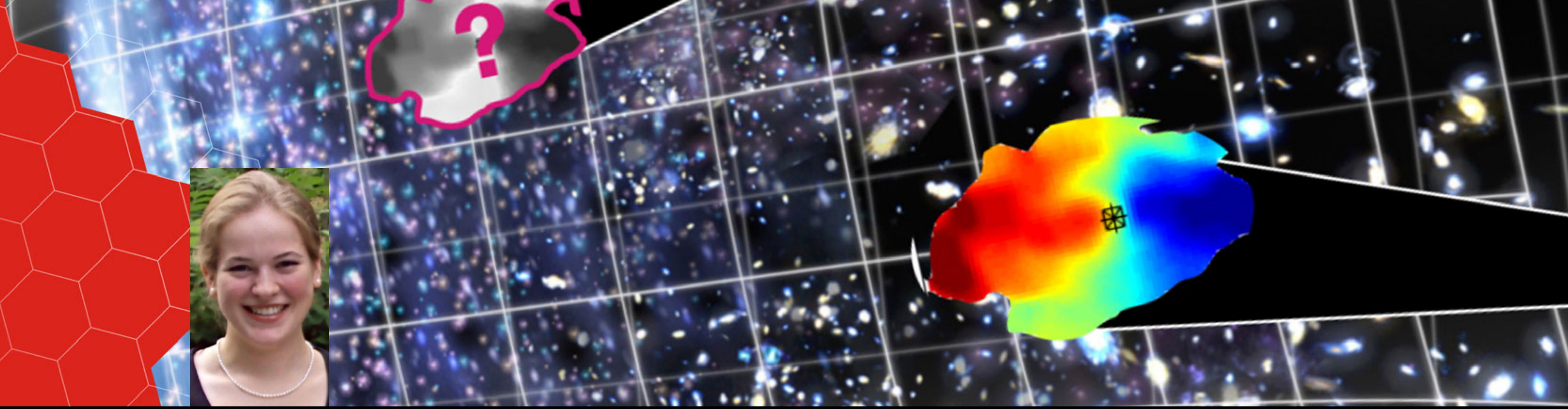
Of particular interest are the chemical abundances in galaxies between 9.5 and 11.5 billion years ago. It is during this time that cosmic star formation density peaked, and galaxies were at their most active. Elements such as hydrogen, oxygen and nitrogen within the ISM of these galaxies all emit light in the optical region of the spectrum when ionised by the young, massive stars within the galaxy. However, once this light has reached the Earth, it has been stretched by the cosmological expansion of the Universe, meaning we observe it in the near-infrared. Instruments such as KMOS, a near-infrared multi-object spectrograph (Fig. 1) mounted on the Very Large Telescope in Chile (Fig. 2), can then be utilized to investigate these galaxies. At the KICC, we have been studying the chemical abundances within galaxies that are roughly 10 billion years old through the KLEVER (KMOS Lensed Velocity and Emission line Review) project. KLEVER is a European Southern Observatory (ESO) Large Programme that observed roughly 200 galaxies in three main infrared bands (J, H and K). Observing simultaneously in three different wavelength bands ensured multiple different emission lines could be observed, allowing us to obtain independent estimations of the metallicity and nitrogen abundance.

Initial analysis of the full KLEVER sample (see Fig. 3 for an example) shows that galaxies around 10 billion years ago had, on average, lower nitrogen abundances than galaxies observed today, when compared at a fixed stellar mass. This suggests that galaxies at cosmic noon were significantly more efficient at converting their gas into stars, allowing them to produce many stars rapidly, and hence reach high stellar masses before secondary nitrogen production could begin and boost the nitrogen abundance. Furthermore, we find no evidence for excessive inflows or outflows of gas within the KLEVER galaxies, suggesting that the equilibrium between these processes is fundamental across cosmic time.

Fig 1. (above) The K-band Multi Object Spectrograph (KMOS). *(Image credit: ESO https://www.eso.org/public/images/.)*

Fig 2. The Very Large Telescope array (VLT) at the Paranal Observatory in Chile. *(Image credit: ESO https://www.eso.org/public/images/.)*

Fig 3. One of the galaxies observed in the KLEVER programme. From right to left: map of flux in the Hα line; velocity field; metallicity map; and nitrogen abundance map.



# Galaxy Dynamics in the Early Universe

Hannah Übler

Nothing is truly at rest in the Universe. We experience this by the Earth's rotation around its own axis, leading to our day and night rhythm. We perceive it by the Earth's revolution around the sun that structures the year. And we see it when observing the night sky, where the positions of the Moon, stars, or planets change with respect to Earth. But there is much more going on: our solar system whirls at almost 600,000 mph around the centre of our Galaxy. In fact, all hundreds of billions of stars in our Galaxy, all gas and dust, together referred to as "baryons", move according to the Galaxy's gravitational potential.

For disc galaxies like our Milky Way, this galactic rotation can be measured via the Doppler shift of characteristic spectral lines. These lines are like beacons sent out by baryons in the galaxy. From our perspective, some of the baryons are moving towards us, and others are moving away from us. From their relative motion we can construct a velocity field or a rotation curve of the galaxy – this tells us the average speed of baryons at a certain distance from the galaxy's centre.

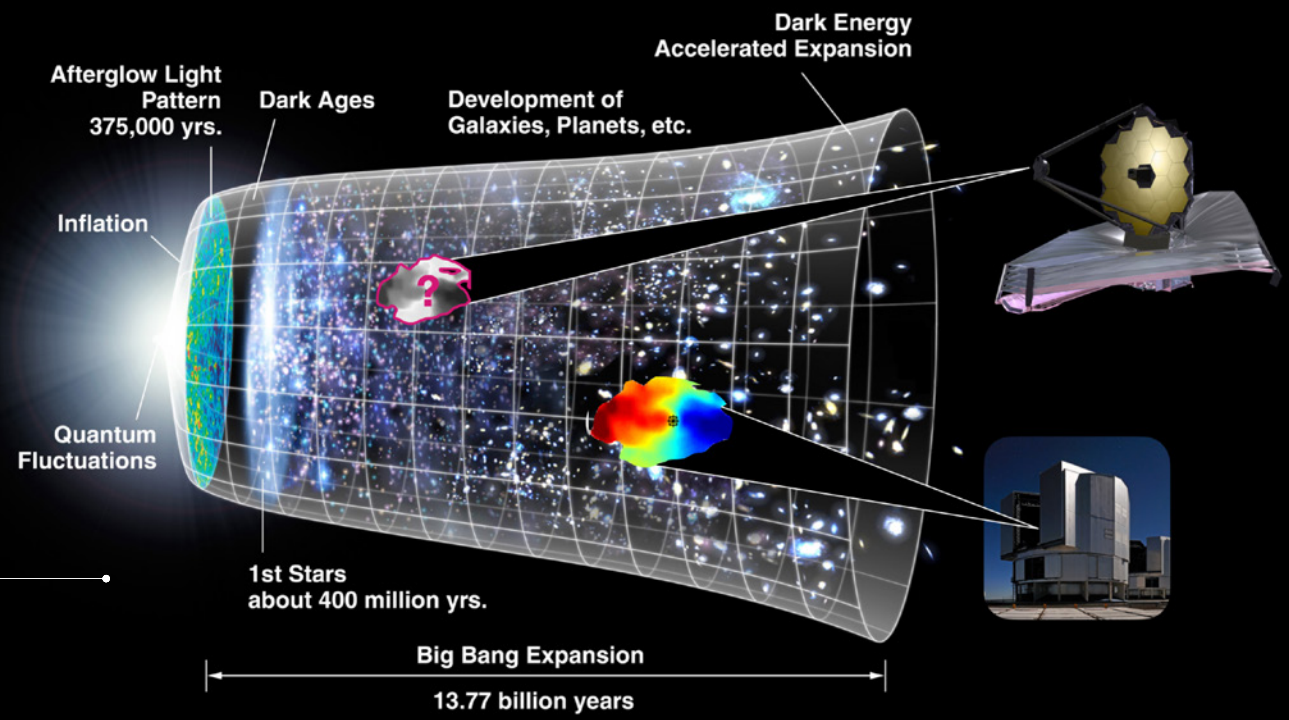



Fig 1. When did the first disc galaxies form? What was the role of dark matter for their dynamics? With JWST/NIRSpec we will push observations of galaxy kinematics with key spectral lines into the first billion years of cosmic history to tackle these questions.

But galaxy dynamics can tell us even more: if we know a galaxy's rotation curve, we can calculate the enclosed mass. This principle applied to nearby galaxies led to the introduction of one of the major puzzles of modern astronomy: dark matter. Galactic rotation curves as well as the motions of galaxies in clusters could not be explained by visible matter alone and it was inferred that substantial amounts of "*dark*" mass were required.

Today, the majority of astronomers believe that dark matter is the dominant mass component in the Universe. This is largely based on the success of the favoured theoretical model, ΛCDM, in describing our earliest data about the Universe, and its evolution, resulting in the large-scale structures we observe today. However, no direct detection of dark matter has yet been achieved.

One way of advancing our knowledge about this missing mass component is by studying its contribution on galactic scales in a cosmological context, i.e., at different times in the Universe's history. By identifying changes in the mass contributions of baryons and dark matter, we can learn about the assembly history of galaxies, and about the interaction of dark matter with "*normal*" matter like stars and gas. Such studies have particular potential when targeting phases in cosmic history, when the baryons we have a much better understanding of, were more "*active*". A peak epoch of such activity was 10 billion years ago at "*cosmic noon*", when stars were forming and gas was being accreted at much higher rates than today.

Recent observations facilitated by modern instruments on 8- to 10-meter class ground-based telescopes have demonstrated, both through population studies and based on detailed analyses of individual systems, that galaxies during cosmic noon have lower dark matter fractions than nearby disc galaxies. These results are interesting because the inferred dark matter fractions of the youngest and most massive galaxies are, at face value, in tension with predictions from cosmological hydrodynamical simulations.

As observations of distant galaxies are subject to several cosmological and instrumental effects, it is important to approximate observations of the real Universe with mock-observations of the simulated universe. Through a careful comparison of state-of-the-art simulations and observation, we could show that a proper consideration of observational effects indeed reduces the apparent tension between theory and observations for dark matter fractions. However simulated galaxies still have comparably too much dark matter in their centres.

This discrepancy in the central dark matter fraction points toward physical processes that are spatially and/or temporarily unresolved even in modern simulations, and which are likely related to interactions between baryons and dark matter via, e.g., outflows. However, the true origin of the remaining tension is still unclear.

We expect to take the next step in our quest of understanding the interplay of baryons and dark matter through upcoming observations with the James Webb Space Telescope (JWST). In particular, the NIRSpec instrument, which researchers at KICC are heavily involved in, will provide us with the opportunity to push observations of key spectral lines for kinematic classification to even earlier times in cosmic history. With JWST, we should be able to witness the occurrence of the first disc galaxies and measure their dark matter content. Because the nature of dark matter and its interplay with baryons will have dictated how early disc galaxies formed, and what they look like, these upcoming observations and analyses will provide crucial benchmarks for theoretical models and our understanding of dark matter.

# Towards Dissecting the Main Sequence in the High-Redshift Universe

Lester Sandles • Emma Curtis-Lake

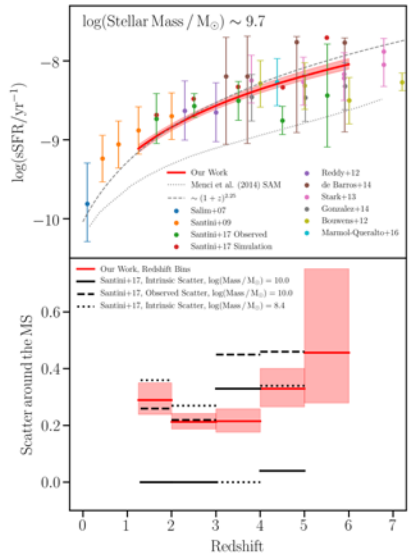
Galaxies in the local Universe can be split into two broad categories: those that are forming stars and those that have stopped. Gas is the fuel for star formation, while we suspect that interactions between supermassive black holes and their host galaxies are one of the driving forces behind its cessation. Interestingly, those galaxies that are forming stars generally sit on a neatly formed 'sequence' that we call the main sequence of star-forming galaxies, or main sequence for short. Higher-mass galaxies are forming more stars than lower mass galaxies. Some very energetic starburst galaxies sit above the relation, and those that are shutting down or quiescent sit below it.

As we probe higher redshifts, we might expect the physical conditions of star formation to change, since there was much more gas available in the early Universe and black holes had less time to build up their mass. Indeed, we see the position of the main sequence evolving with 'normal' galaxies inhabiting regions occupied by the most energetic starbursts in the local Universe. We might also expect there to be different physical mechanisms regulating star formation at high and low stellar mass. At low stellar mass, the energy injected from supernovae can overcome the gravitational potential, temporarily clearing the galaxy of gas, and shutting off star formation. This might change the slope or scatter about the relation at the lowest stellar masses. And finally, although previous studies have taught us a lot about the main sequence and how it evolves, we still do not know why galaxies follow this relation. Do galaxies evolve along the main sequence, oscillating about it to produce the scatter we see? Or could it be that we view the population as a snapshot at different redshifts, with their position on the main sequence encoding information about their past lives, such as when they started forming and how they accreted gas over time? To start to answer these questions we would like to dissect the scatter about the sequence, but constraining the scatter is complicated by measurement errors.

We have developed a Bayesian hierarchical model to take account of complex uncertainties self-consistently, as well as the possibility that objects sit off the relation, to gain constraints on the evolution of the main sequence and the form of its intrinsic scatter. The *Hubble* Frontier Fields uses massive galaxy clusters (one of them is shown in Fig. 1) as nature's magnifying glasses to image fainter galaxies than can be viewed in blank fields. Applying our model to this data set, we have also taken account of the full variation in galaxies when deriving our masses and star-formation rates (SFRs) by using complex models of stellar and nebular light (light emitted from stellar birth clouds).

From our analysis we have constrained the main sequence over 5 Gyrs, from just 900 Myrs after the Big Bang (redshift 6.0) to an epoch just less than half the present age of the Universe (redshift 1.0). We show the evolution in the main sequence throughout cosmic time using the specific star-formation rate (sSFR): the ratio of current to past integrated star formation (SFR/stellar mass; Fig. 2, top panel). This is analogous to the normalisation of the star-forming main sequence, and we show good agreement with previous results in the literature. In the bottom panel of Fig. 2, we show the measured intrinsic scatter. The uncertainties are large and the measurement sensitive to which objects are considered to be on the relation. We see no strong evidence for redshift evolution in the intrinsic scatter.

Fig 1. (above) *Hubble* Space Telescope image of Abell 2744, the first Frontier Field strong-lensing cluster. (Figure credit: Lotz et al., ApJ 837, 97, 2017.)

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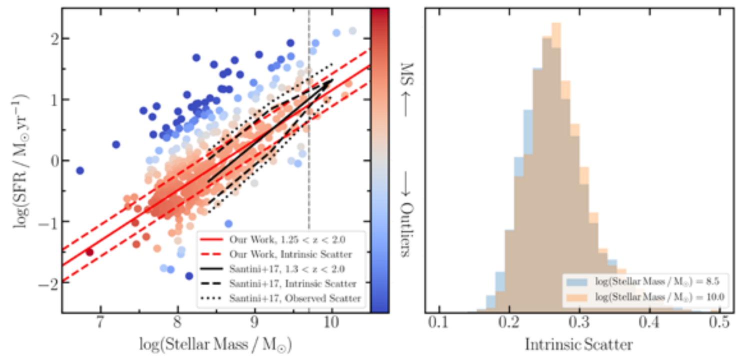


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We adapted our model to allow for a linear dependence of intrinsic scatter with stellar mass and focussed on the well-constrained lowest-redshift bin (spanning the redshift range 1.25–2.0). Our results provide no evidence for an increase in the scatter at low stellar mass, contrary to a previous study (both shown in Fig. 3). However, an overriding theme throughout our analysis was that across all redshifts, the values of stellar mass, star-formation rate and redshift were often not well constrained at lower stellar masses. The soon-to-launch James Webb Space Telescope will provide us with considerably improved constraints, enabling us to overcome these difficulties and continue to investigate the evolutionary paths of galaxies across cosmic time.

# What Drives Galaxy Quenching?

Simcha Brownson

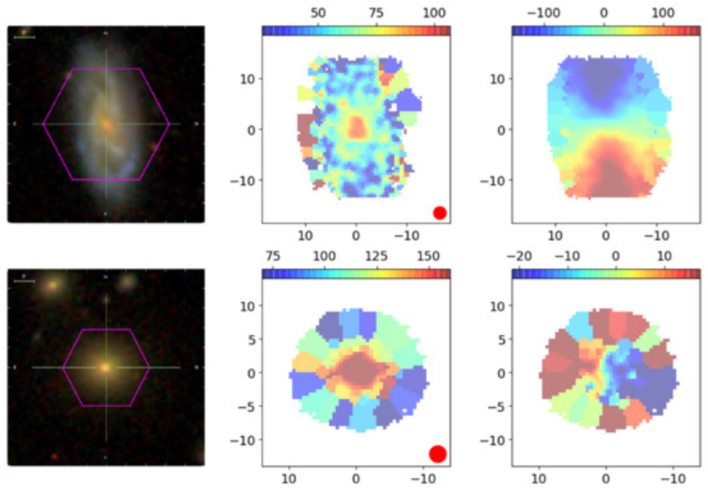
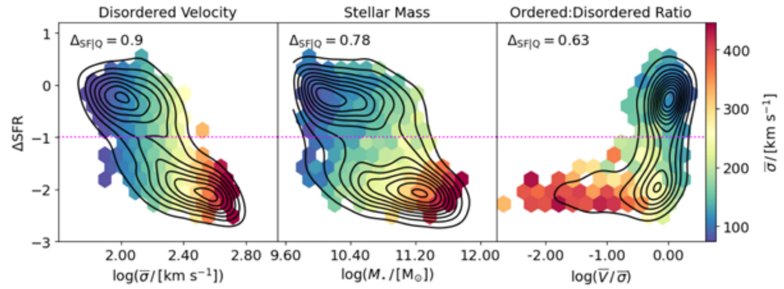


Fig 2. Morphology and kinematics of a star-forming (top row) and quenched (bottom row) galaxy. In the first column we show the optical map, where blue colours reflect the presence of young stars and red colours reflect the presence of old stars. In the second column we show maps of the disordered, chaotic motion in each galaxy, and we see that the random motions are more significant for the quenched galaxy. In the final column we show maps of the ordered rotation of the stars. The star-forming galaxy shows the ordered structure typical of a rotating galaxy, whilst the quenched galaxy does not appear to be rotating.

Fig 1. (above) The blue star-forming galaxy M101 (left) and red quenched galaxy M87 (right).

Fig 3. Star-forming state (ΔSFR) of MaNGA galaxies as a function of the absolute level of the disordered motion (left panel), the stellar mass (middle panel) and the relative levels of the ordered and disordered motion (right panel). Galaxies with ΔSFR > -1 dex are star forming, whilst galaxies with ΔSFR < -1 dex are quenched. The disordered velocity is the best parameter at separating the star-forming and quenched populations.




The observed population of galaxies can be divided into two broad categories: star-forming galaxies and quenched galaxies. Star-forming galaxies are typically blue, which reflects the presence of hot, recently formed stars, whilst quenched galaxies are red, which indicates that they have little or no ongoing star formation and that their stars are mostly old (Fig. 1). We know that the quenched galaxies observed in the local Universe must have been star forming in the past, but it is not clear why they stopped forming stars and 'quenched'. This remains one of the most important outstanding questions in the field of galaxy evolution.

It is natural to suggest that galaxies quench because they lack the gas necessary for star formation. However, galaxies live within massive halos that contain dark matter and vast reservoirs of hot gas. This hot gas is expected to cool and fall into the galaxy, feeding it with the gas required for further star formation. The existence of quenched galaxies is thus a major theoretical challenge known as the cooling catastrophe, and any viable quenching mechanism must be effective at preventing the cooling of the hot gas in the halo.

One avenue for understanding quenching lies in the structural and kinematic differences between star-forming and quenched galaxies, commonly referred to as the 'morphology–colour' relation. Star-forming galaxies tend to be disc-like, and their stars follow ordered, circular orbits around the centre of the galaxy. Quenched galaxies, on the other hand, tend to be spheroidal, and their stellar orbits are highly disordered and chaotic. We show an example of both galaxy types in Fig. 2. The 'morphology–colour' relation suggests a deep connection between galaxy structure/kinematics and star formation, and it is tempting to look for mechanisms that are simultaneously capable of quenching star formation and transitioning galaxies from having ordered stellar orbits to disordered ones.

The Mapping Nearby Galaxies at Apache Point Observatory survey (MaNGA) provides astronomers with thousands of images of galaxies, each sensitive to light at different wavelengths. Together, these images form a 3D 'data cube' that can be used to constrain the properties of the stars and gas within local galaxies. We use this data to model the ordered and disordered velocity of the stars, and to identify the kinematic properties of galaxies that are most fundamentally connected to galaxy quenching.

In Fig. 3 we show the star-forming state of galaxies (i.e., quenched or star forming) as a function of the following three parameters: the absolute level of the disordered motion; the relative levels of ordered and disordered motions; and the stellar mass. In each panel, the black contours show the density of galaxies, where the upper density peak represents star-forming galaxies and the lower density peak represents quenched galaxies. We find that the disordered component of the stellar orbits is the parameter that differs most significantly between the star-forming and quenched populations. We complement the analysis in Fig. 3 with a machine-learning approach and find that many correlations between galaxy properties (such as the stellar mass) and quenching are incidental. In fact, the fundamental parameter is the absolute level of the disordered motion.

The success of the disordered motion in predicting quenching may be explained by the strong empirical correlation between the disordered motion and the mass of the supermassive black hole at the centre of a galaxy. Considering this relationship, our results show that galaxies with large black holes are generally quenched, whilst galaxies with small black holes are generally star forming. This is consistent with recent theoretical models where feedback from the black hole injects energy into the halo, prevents the hot gas from cooling and shuts off the galaxy's gas supply.

# Star Formation Inside Galactic Winds

Federica Loiacono • Roberto Maiolino

Galactic winds are a phenomenon commonly associated with galaxies experiencing bursts of star formation or hosting accreting supermassive black holes. In either case, the energy released by supernova explosions or by the accretion disc surrounding the black holes can eject large amounts of gas out of the galaxies. As gas is the fuel for forming new stars in galaxies, galactic winds are often considered one of the main mechanisms responsible for regulating or even quenching star formation in galaxies.

However, galactic winds are observed to have large amounts of molecular, very dense and clumpy gas, which are the optimal conditions in which stars can form. Indeed, various recent models and hydrodynamical simulations have suggested that stars can potentially form inside galactic outflows, which would be a totally new mode of star formation in galaxies, overlooked in the past (Fig.1 shows an artistic impression of this new scenario). We also note that one of the very first models predicting this phenomenon was proposed by Andy Fabian, Kavli Laureate in 2020, and his team.

Indications for star formation in a number of galactic winds have been found in the past by scientists at KICC and also by other international teams. However, these studies have focused on indirect evidence, by investigating the properties of ionised gas in galactic outflows and inferring that this must be excited by young stars formed in-situ, i.e. inside the outflow. However, it would be important to directly confirm the presence of such young stars in galactic outflows.

We have used ultraviolet spectra of several tens of active galaxies obtained with the COS spectrograph on the Hubble Space Telescope, with the goal of tracing the kinematics of very young, hot stars, which dominate the emission at these wavelengths. By targeting specific features of this class of stars (and in particular the CIII line at 1176 Å), we found a significant number of galaxies for which the young stellar population is characterized by motions towards us (Fig.2). This is exactly what is expected for stars formed in galactic outflows, whereby we preferentially see stars formed in the gas ejected on the approaching side of galactic wind, while the receding side is mostly obscured by dust in the galactic disc.

Our finding directly confirms the scenario in which star formation does occur in galactic winds and according to models, might contribute significantly to the formation and evolution of the spheroidal component of galaxies (bulge, halo, or even elliptical galaxies), as stars formed in galactic winds would have highly radial orbits.

Fig 1. Artist's impression of stars born in a galactic wind (credit: European Southern Observatory).

Fig 2. Distribution of the velocities of young stars in the sample of galaxies observed with the COS spectrograph on the Hubble Space Telescope. Negative velocities correspond to stars approaching us, while positive velocities correspond to receding stars. The green histogram corresponds to the population of stars that have a star formation rate higher than 30 solar masses per year.



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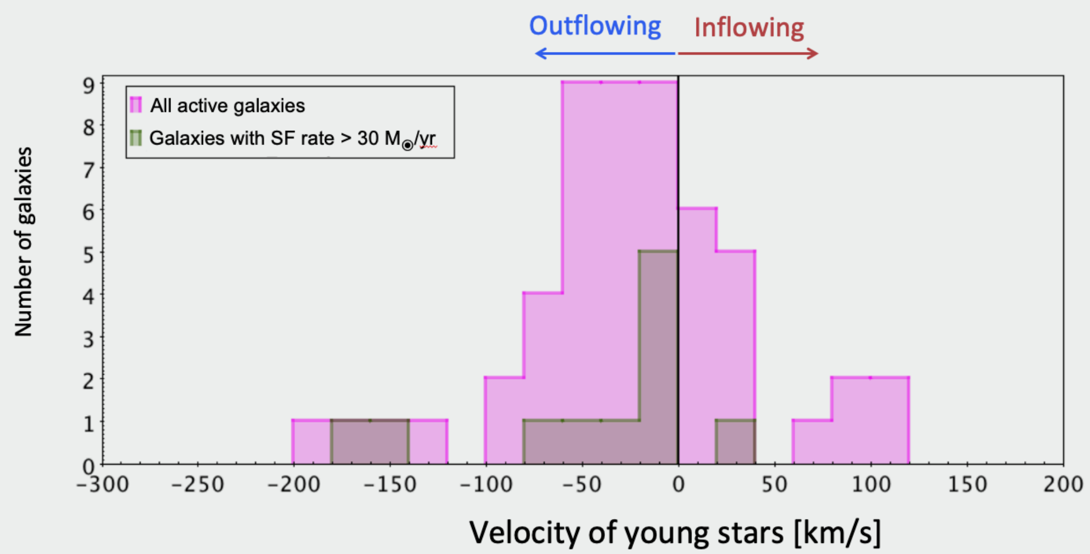
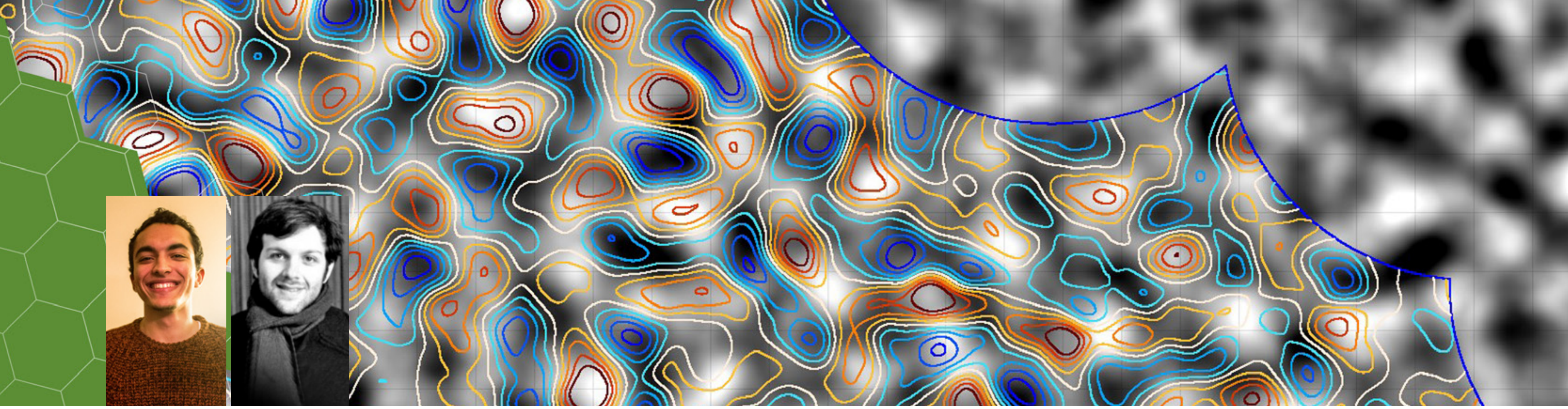


# Mapping Dark Matter with CMB Lensing

Omar Darwish • Blake Sherwin



From high up in Chile's Atacama Desert, cosmologists working on the Atacama Cosmology Telescope (ACT) experiment have taken high-resolution pictures of the oldest light in the Universe, the cosmic microwave background or CMB, which was emitted roughly 13.8 billion years ago.

If the Universe were devoid of structure, CMB light emitted from far away would just travel in a straight line. But the matter in our Universe is, of course, not uniformly distributed. Rather, it is organised in a rich cosmic web of large-scale structure, as traced, for example, by the positions of galaxies.

As the CMB light travels towards our telescopes, it is deflected by this intervening large-scale structure, which consists primarily of invisible dark matter. These deflections imprint tiny distortions on the image of the CMB. This phenomenon, known as gravitational lensing, is analogous to observing through textured glass, where the image we see appears magnified, squeezed, and stretched.

By studying the magnification and stretching patterns in the observed CMB light, it is possible to infer the gravitational lensing signal and hence map the (projected) distribution of the dark matter. These CMB lensing dark matter maps contain a wealth of information about key questions in cosmology, such as: What are the properties of poorly understood phenomena such as dark-matter and dark energy? What are the unknown masses of neutrinos? Did the universe begin in a phase of inflation?

However, the real Universe is a messy place, full of effects such as scattering of the CMB by hot gas in galaxy clusters that can contaminate the lensing measurement. This can lead to incorrect conclusions when trying to map the mass distribution and understand the Universe via the lensing effect. To mitigate this problem, in 2020 the ACT team, led by KICC researchers Omar Darwish and Blake Sherwin, produced CMB lensing maps using a new technique that significantly reduces contamination from scattering in galaxy clusters.

Figure 1 shows the ACT CMB lensing map of cosmic mass in grey. Most of the mass (80%) seen in this image is invisible dark matter.

The fidelity of this CMB lensing mass map is such that we can use it to illustrate a basic principle in cosmology. Luminous objects such as galaxies do not form at random locations in space but instead, driven by gravity, form within a cosmic scaffolding (the cosmic web) of dark matter. We therefore expect the distribution of luminous galaxies to show a strong correlation with the distribution of dark matter probed by lensing.

This is exactly what we see in Fig. 1. The coloured contours show an overlay of the infrared light emitted from distant, dusty galaxies. The fact that galaxies closely trace the underlying dark matter distribution can be seen by the fact that the coloured contours, representing galaxy emission, clearly overlap with grey peaks and troughs of the lensing mass map.



This strong correlation of lensing and galaxies will be a powerful cosmological tool going forward. First, this correlation will allow us to understand in detail how galaxies trace the underlying dark matter, which will give new insights into the complexities of astrophysics and galaxy formation at early times. Second, while lensing maps only tell us about the projected mass distribution, correlations with galaxies whose distance is well known will allow us to probe the cosmic mass distribution in full 3D. This detailed, 3D picture of cosmic mass distribution will allow us to understand how cosmic structure formed over time and hence test for new physics such as nonstandard models of dark energy.

CMB lensing correlations with galaxies therefore will provide an exciting window to probe the Universe. While early results such as Fig. 1 from ACT are exciting, this field is only just beginning. Going forward, the ACT team will measure cross-correlations between lensing and galaxies at unprecedented precision over nearly half of the sky. These future measurements promise a wealth of new insights into dark matter, dark energy and galaxies and will allow us to test the limits of the standard cosmological model.

These results were published as Darwish O. et al., MNRAS 500, 2250 (2021).

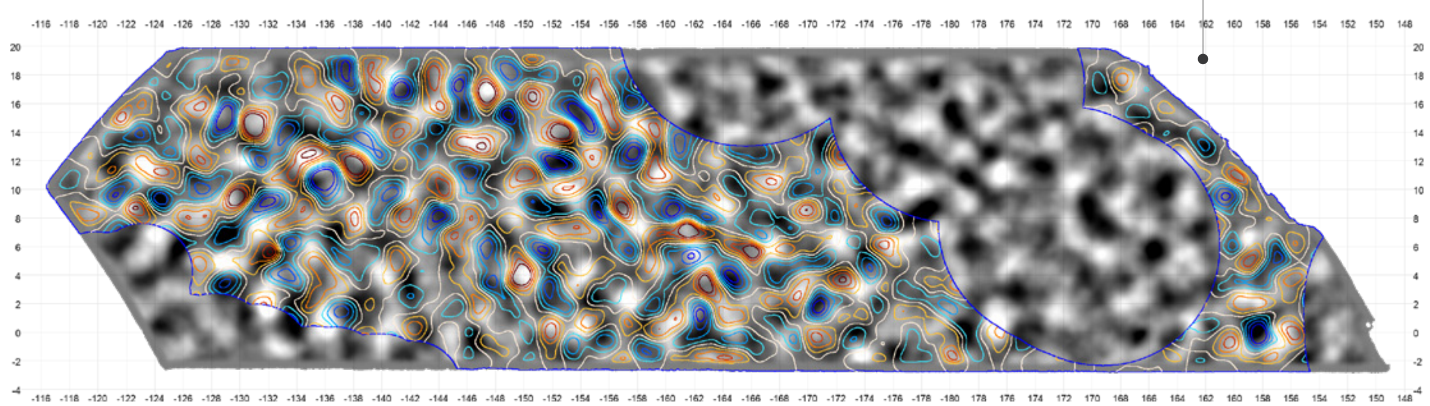
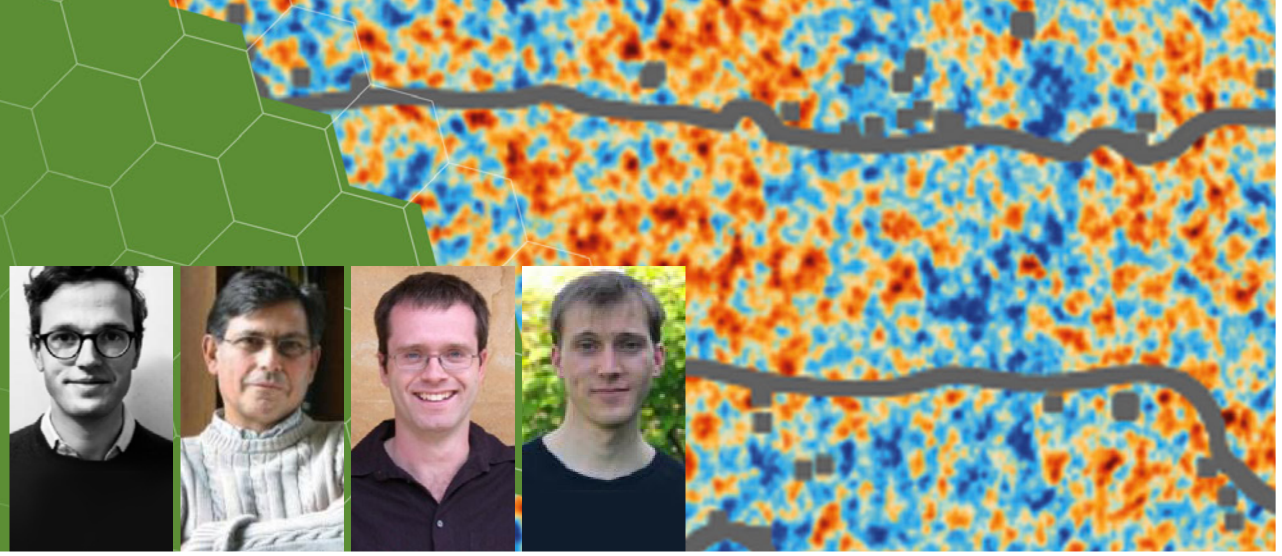


Fig 1. In grey, a reconstructed map of the projected matter distribution, including dark matter, in a small region of the sky near the celestial equator, probed by the ACT experiment. We also show contours of light emitted by dusty galaxies: the overlap between the coloured and grey peaks show that matter and galaxies are highly correlated on large scales. (Due to contamination from our Galaxy, some contours are excised from the plot.)

# Cosmology from Planck Revisited and Cosmic Tensions

Roger de Belsunce • George Efstathiou
Steven Gratton • Erik Rosenberg



In the past decade, exquisite measurements of the cosmic microwave background (CMB) from the Planck satellite, as illustrated in Fig. 1, have led the way into a period of precision cosmology. Even as new surveys of the large-scale structure and ground-based CMB experiments extend our knowledge of cosmology ever further, Planck continues to play a central role. Researchers at KICC have worked to maximise the information extracted from Planck through reanalysis of the Planck data and have gone on to use it to address some of the most pressing problems in modern cosmology.

## Cosmic Microwave Background

Following the final data release from the Planck satellite, Efstathiou and Gratton completed a thorough reanalysis of the Planck power spectra – the main statistics used to compare CMB fluctuations with theoretical models – by extending the usable sky area. One of the principal aims of this study was to investigate whether internal “tensions” in the Planck CMB data became better or worse as the sky area was increased. In fact, this study showed that the fit to the standard six-parameter cosmological model improved with increasing sky area and the internal tensions identified in the final, official data release were consistent with moderate statistical fluctuations. These results did not support some recent claims for non-zero spatial curvature in the Universe.

[See Efstathiou G. and Gratton S., arXiv:1910.00483 and Efstathiou G. and Gratton S., MNRAS 496, L91 (2020).]

In July 2020, the Planck Collaboration released a new set of maps of the microwave sky from Planck data, created using a new analysis pipeline known as *NPIPE*. These new maps use a substantially different analysis framework compared to the previous data release in 2018, with many systematic effects dealt with in a new way. To understand the effects that these new analysis choices have on science conclusions, we have calculated CMB angular power spectra using these new maps and created a likelihood with which to constrain cosmology.

We find good consistency between *NPIPE* and the 2018 results, indicating that conclusions about cosmology drawn from the Planck data are robust to differing data analysis choices and differing methods of dealing with systematic errors.

In cosmological data analysis, an accurate representation of the likelihood function is crucial in order to make reliable statistical inferences. However, exact likelihoods are often either unknown or prohibitively expensive to compute. Limited knowledge of noise and systematic effects renders the problem even more difficult. This is particularly acute for the determination of the reionisation optical depth from the large-angle polarization measurements from Planck. The optical depth provides a measure of the time at which the intergalactic medium was reionized by light produced by early generations of stars and galaxies and thus offers an important and instructive test of simulation-based likelihood techniques. We therefore developed flexible likelihood-approximation techniques to measure signals affected by systematic effects, which we tested against each other (see Fig. 2) and against the Planck data. One of these methods used neural networks and machine learning whilst another took a new mathematical approach, and both techniques can be applied to other statistical inference problems involving data with complex noise properties.

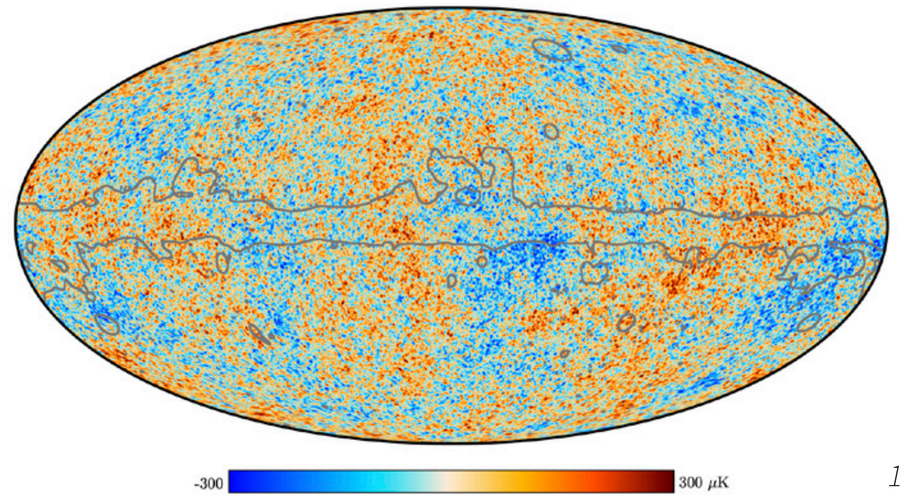
[See de Belsunce R., Gratton S., Coulton W., and Efstathiou G. (2021), arXiv:2103.14378.]

## Hubble Tension

One of the biggest puzzles in cosmology concerns the discrepancy between the determination of the Hubble parameter by the Planck satellite and the distance-ladder value determined from Cepheid-calibrated Type Ia supernovae. These values differ by nearly 10% (or 4.2 standard deviations), a discrepancy that has become known as the Hubble tension, as shown in Fig. 3. The Planck value assumes the standard six-parameter LCDM cosmology, so if the distance-ladder measurements are correct the Hubble tension requires new physics.

Many authors have suggested that the distance-ladder measurement requires an unusual phantom-like dark energy at late times. In a recent paper, Efstathiou has shown that this conclusion is driven by an incorrect interpretation of the distance-ladder measurements. Using an inverse distance ladder, he was able to demonstrate that no modification of the late-time expansion history can explain the Hubble tension. In a similar vein, fellow KICC researcher Sunny Vagnozzi showed that the CMB anisotropies place strong constraints on “*early dark energy*”, thereby testing another class of models that have been proposed to explain the Hubble tension. Thus, it appears that wide classes of early- and late-time solutions to the Hubble tension are not viable. Ages of astrophysical systems may potentially shed some light on this problem as noted by Vagnozzi and collaborators.

[See Efstathiou G. (2021), arXiv:2103.08723; Vagnozzi S. (2021), arXiv:2105.10425; and Vagnozzi S., Pacucci F., and Loeb A. (2021), arXiv: 2105.10421.]

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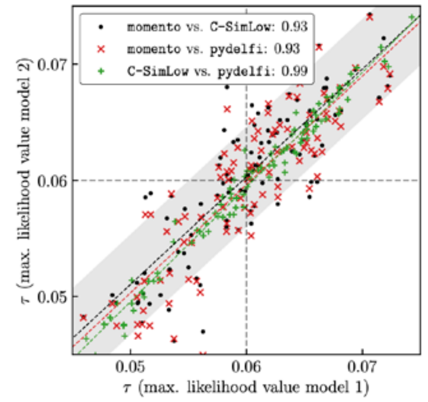


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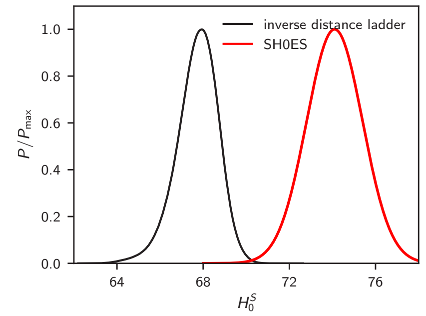


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Fig 1. Cosmic microwave background temperature fluctuations extracted from the multi-frequency Planck data. (Credit: ESA and the Planck Collaboration.)

Fig 2. Scatter plot between the maximum-likelihood values of the reionization optical depth obtained with different likelihood approximations applied to simulated Planck polarization data. There is a high degree of correlation between the methods.

Fig 3. Comparison of the current-day Hubble parameter as measured with Cepheid-calibrated Type Ia supernovae (SH0ES) and the inverse-distance ladder, illustrating the discrepancy between these approaches.

# Perturbative Approach to Understanding the Large-Scale Structure of the Universe

Zvonimir Vlah

The large-scale structure of our Universe consists of galaxies, gas, and matter distributed over the largest observable scales, much larger than the scale of individual galaxies. Correlated patterns in this structure tell us the story of our Universe's origin, constitution, and evolution. They encode a plethora of physical phenomena ranging from the exotic components like dark matter and dark energy to the well-known, but still elusive, neutrinos and to the experimentally unapproachable mechanisms driving the beginnings of our Universe like inflation and string cosmology.

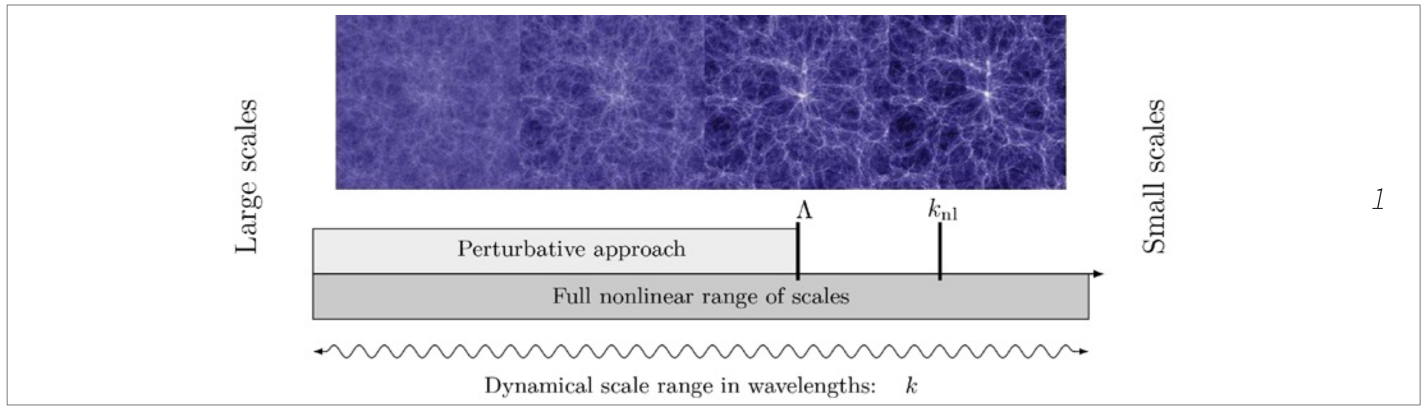
In recent decades, primarily relying on data from cosmic microwave background and galaxy surveys, the standard cosmological model (called ΛCDM) has gradually arisen as the canonical framework describing the components and evolution of our Universe. However, many aspects of this model are poorly understood and have opened new and exciting questions:

- *How did our Universe begin, and what is the actual (inflationary) mechanism governing it?*
- *What is the nature and dynamical properties of dark energy?*
- *What is the nature of dark matter? What is its mass range and its coupling to other fundamental forces?*
- *What are the masses and the role of neutrinos and other light particles in the formation of our Universe?*
- *What is the value of the Hubble parameter, and how can one reconcile various current measurements?*

These questions can now be addressed because of many cosmological and astrophysical surveys and experiments, either already in operation or planned to come online in the near future. Amongst these, galaxy imaging and spectroscopic surveys, such as Euclid, DES, DESI and LSST, will play a leading role in the next decade in providing new data and information about the Universe on cosmological scales. Such vigorous observational activity guarantees an abundance of upcoming data of unprecedented quality, thus opening a new window of opportunity for answering some of the key questions listed above. However, to analyze this data and extract the physical and cosmological information, it is critical to have a robust theoretical framework that provides us with accurate models and predictions that match the high-quality standards needed to analyze this pristine data.

Using the most current theoretical methods, we have developed the analytic framework to describe correlators of the galaxy distributions on the sky. Focusing on the description of large observable scales, we utilized perturbative methods initially developed in particle physics (effective field theory) to describe systematically the non-linear gravitational evolution of dark matter. We then meticulously linked this evolution to the distribution of galaxies in the sky. This is schematically indicated in Fig. 1, where we show how our perturbative approach is constrained to scales larger than some scale Λ (not to be confused with the cosmological constant, also denoted by Λ) while most of the highly non-linear evolution happens on smaller scales around kNL. In this way, we are able to focus on the large scales while parametrically taming the small-scale non-linearities. This enables us to develop a rigorous and highly accurate theoretical description of the fluctuation correlations, leading to the most precise constraints on cosmological parameters like dark matter and dark energy abundances, the Hubble parameter, and others.

Figure 2 shows the accuracy of our theoretical models, which have been scrutinized in a 'blind challenge' against high-accuracy, N-body simulations. Contours on the left show how accurately we are able to recover the cosmological parameters using our perturbative models.

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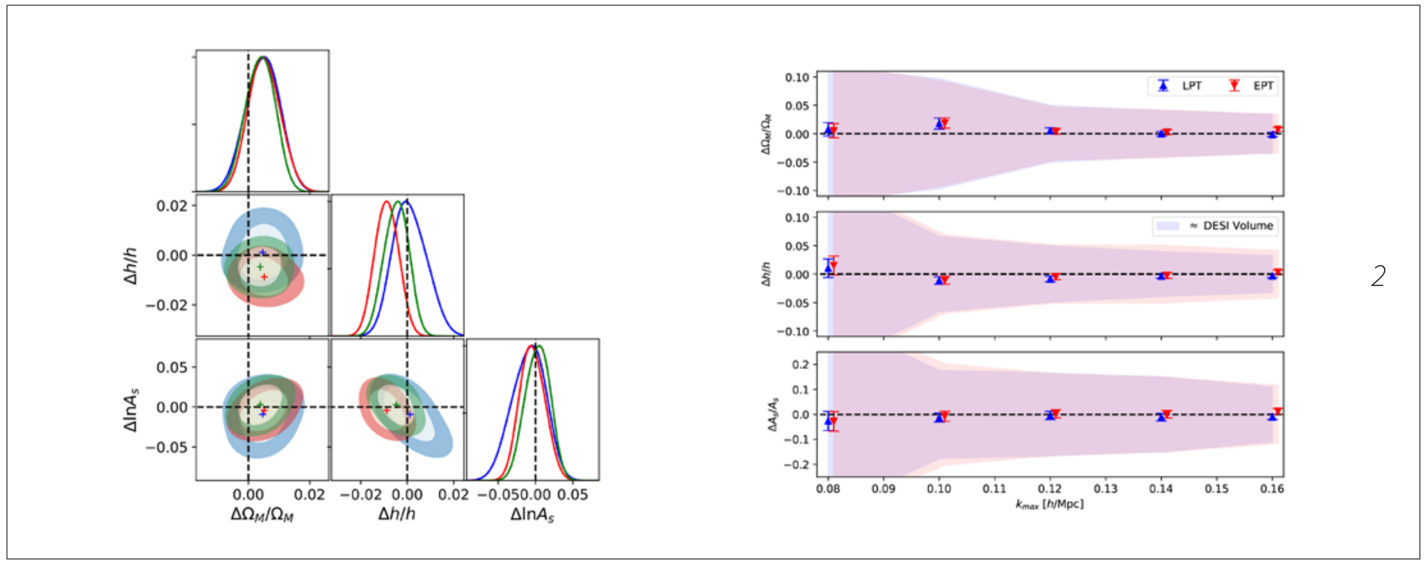


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Fig 1. Wavelength scales of structure formation. Perturbation theory describes large scales (long wavelengths) where non-linear effects are small and under theoretical control.

Fig 2. Left: Parameter constraints obtained from simulations of large cosmological volumes analysed with several of our analytic models. Right: Estimates of the bias in parameters due to inaccuracies in our theoretical models (data points) compared to the expected statistical precision for the upcoming (DESI) galaxy survey (shaded bands) as a function of the smallest scale retained in the analysis. We see that the performance of the models is well within the expected statistical precision of the data.

On the right, we compare estimates of the theoretical errors in inferences of the cosmological parameters due to inaccuracies in our modelling, as a function of the smallest scale included in the analysis, with the statistical precision expected for one of the upcoming galaxy surveys. These results guarantee that our theoretical framework is up to the task and ready to analyze the wealth of data anticipated from upcoming surveys.

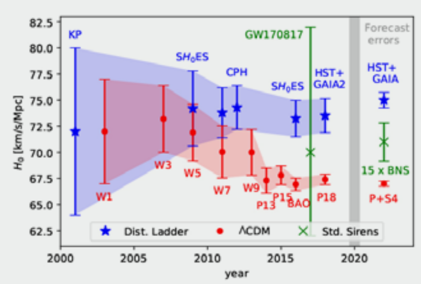
Some of these results were published as Chen, S.F. et al., JCAP 03, id.100 (2021).

# Constructing an Alternative to General Relativity: Torsion and Curvature Squared?

Will Barker • Will Handley
Mike Hobson • Anthony Lasenby

More than one hundred years after its initial formulation, Einstein's *General Relativity* (GR) remains the preferred effective theory of gravity. GR stipulates that gravity is actually spacetime *curvature*. This curvature is generated by matter, while simultaneously dictating how that matter moves (or *falls*) through spacetime. Myriad astrophysical observations support the predictions of Einstein's gravity; from the orbital precession of Mercury and solar bending of starlight, to recent gravitational wave detections and the imaging of a supermassive black hole "shadow". The theory also excels on larger, cosmological scales, and underpins our phenomenological "best-fit" Λ-*Cold Dark Matter* (LCDM) model of cosmology.

Despite this, Einstein's gravity does not explain the *origin* of CDM, or of the *cosmological constant* Λ. Particularly, Λ must be added to Einstein's equations by hand to account for *dark energy*, which is presumed to accelerate the expansion of our Universe.



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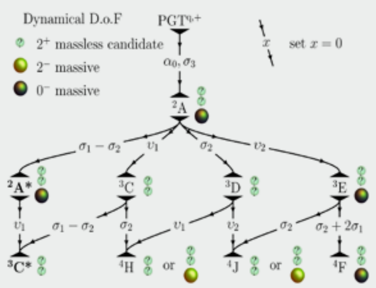

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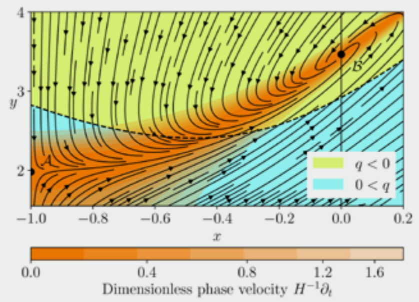

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Fig 1. Cepheid-calibrated observations of the late Universe (e.g. SH0ES survey, Hubble and GAIA space telescopes) suggest fast expansion today, or higher $H_0$. According to the LCDM model, observations of the microwave background from the early Universe suggest lower $H_0$ (e.g. 2018 Planck data). J. Mara and M. Zumalacarregui Front. Astron. Space Sci. 5:44 2018.

Fig 3. In addition to the massless graviton required for gravitational waves, our theory ($^2$A) contains a massive torsion particle which acts as dark energy.

Fig 4. Torsion acts as emergent dark energy, our Universe inexorably flows towards a state of accelerated expansion (yellow).

In recent years the cosmological phenomenology of the theory has prompted some yet-unexplained questions. Principally, an alleged *Hubble tension* has grown between semi-direct observations of our Universe's current expansion rate $H_0$ and indirect $H_0$ inferences based on LCDM (Fig 1).

In a separate conundrum, Einstein's is a classical theory of gravity that, alone among the four fundamental forces, has stubbornly resisted all attempts at quantum reformulation. The quantum regime of gravity is associated with an energy scale known as the Planck mass $m_p$, which is far heavier than the fundamental particles accessible to modern colliders ($m_p$ is around $10^{-8}$ kg, comparable to the mass of a mosquito egg), thus frustrating quantum gravity experimentation.



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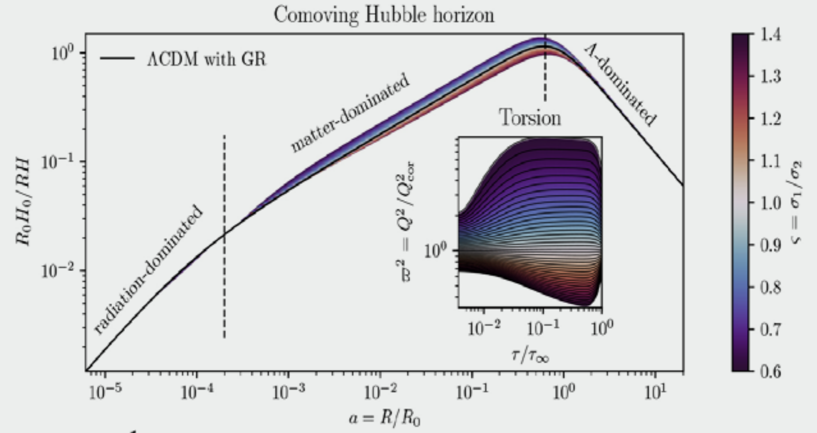



Fig 2. Expansion rate vs size of our Universe: our theory matches Einstein's when its dimensionless couplings are numerically natural. Also shown for comparison are the two theories' *Lagrangia*: mathematical expressions which completely encode their physics. Einstein's gravity is linear in curvature, ours is quadratic in torsion and curvature.

$$L_{\text{Einstein}} = -\frac{1}{2}m_p^2\mathcal{R} - m_p^2\Lambda$$

$$L_{\text{NewGrav}} = -\frac{4}{9}m_p^2\mathcal{T}^2 + \Lambda\mathcal{T}_{ijk}\left(\mathcal{T}^{ijk} - 2\mathcal{T}^{jik}\right) - \mathcal{R}_{ijkl}\left(2\mathcal{R}^{ijkl} - 8\mathcal{R}^{ikjl} - 7\mathcal{R}^{klij}\right) - \mathcal{R}_{ij}\left(\mathcal{R}^{ij} - \mathcal{R}^{ji}\right) - 3\mathcal{R}^2$$

$\mathcal{R}$ is curvature
$\mathcal{T}$ is torsion
$m_p$ is Planck mass
$\Lambda$ is cosmological const.

## Our approach

We have sought to construct a theory of gravity with viable quantum mechanics by introducing spacetime *torsion*, a geometric property complementary to curvature. Our starting point was a catalogue of parameters obtained by Yun-Cherng Lin (KICC) that, for weak gravitational fields, suggest a set of possibly viable quantum theories. We next showed that an expanding Universe reacts to cosmic torsion just as if Einstein's theory had been replaced by another theory of gravity known as *Horndeski theory*. By combining the quantum catalogue with the Horndeski analogue we obtained a novel theory of gravity that can produce the same Universe expansion history as LCDM (Fig. 2).

Despite being theoretically grounded, our theory appears to address certain questions surrounding Einsteinian phenomenology. Firstly, any initial deviation from this expansion history at the (still poorly-understood) Big Bang would be indistinguishable from adding *dark radiation* to a Universe in which gravity were described by Einstein's theory. Dark radiation would have slightly boosted the expansion rate of the young Einsteinian Universe: its addition to the LCDM model is a well-known candidate solution to the Hubble tension, though in the past this was done "by hand".

Secondly, in addition to the massless graviton (Einstein's curvature particle, necessary for gravitational waves just as the photon is necessary for light), our theory also predicts a massive torsion particle (Fig. 3). This particle freezes out into *emergent dark energy*, effectively explaining the origin of Λ through its own mass (Fig. 4). Rather than adding the cosmological constant manually, our mechanism portrays Λ as a second energy scale that emerges out of gravity itself, just like $m_p$. The key unresolved question now lies in the *smallness* of this scale: the *cosmological constant problem* presented by the unnatural ratio $\Lambda \sim 10^{-121}\, m_p^2$. Such "energy hierarchies" are thought to signal that a physical theory is incomplete. Among the various extensions, we are exploring the possibility that our theory might also be *scale-invariant*. Rather like certain fractal patterns, scale-invariant laws of physics would not change between length-scales, which are associated inversely with energy-scales. In some sense, the smallness of the cosmological constant would then reflect the vastness of cosmological scales. Scale-invariance is also very attractive theoretically, as it is fundamentally associated with predictive quantum mechanics.

It is encouraging that principled quantum gravity considerations can produce such attractive classical phenomenology – though a great deal of comparison with the existing Einsteinian predictions is still needed. We are further pursuing this "theory-first" approach by assessing nonlinear corrections to our theory that prevent causality breakdown in strong gravity.

This work has been published as Barker W. E. V., Lasenby A. N., Hobson M. P., and Handley W. J., Phys. Rev. D. 102, 102, 084002 (2020) and Phys. Rev. D. 102, 102, 024048 (2020). It builds on earlier work published as Lin Y. C., Hobson M. P., and Lasenby A. N., Phys. Rev. D 101, 064038 (2020) and Phys. Rev. D 99, 064001 (2020).

# Strong Lensing and the Hubble Conststant: Demonstrating the Importance of Model Assumptions

Matthew Auger

How old is the Universe? This is a straightforward question to ask, but obtaining a precise answer has proven to be remarkably difficult. The best current model for the Universe describes its evolution starting from the Big Bang, moving through the cosmic 'dark ages' and the dawn of stars and galaxies, and evolving into the dark-energy-driven accelerated expansion that we observe today. The age of the Universe is determined by rewinding the model of this evolution, but calculating the age in practice requires knowledge of the current expansion rate of the Universe and this, in turn, depends on the Hubble Constant $H_0$.

$H_0$ describes how rapidly galaxies are moving away from observers on Earth as the Universe expands, with the speed depending on how far away these galaxies are. The value of $H_0$ can be determined by using redshifts to infer the recession velocities of galaxies and comparing these with the distances to the galaxies, which are obtained using standard candles, such as Type Ia supernovae. $H_0$ can also be inferred indirectly from measurements of the fluctuations in the cosmic microwave background (CMB), and this is why the age of the Universe is not well known: the value of $H_0$ derived from galaxies in the local Universe does not agree with the value derived from the CMB!

A separate method to determine $H_0$ relies on observing objects that have been multiply imaged by galaxies in the foreground due to strong gravitational lensing. To develop an intuitive idea of this phenomenon, consider two rays of light emerging in slightly different directions from a very distant bright source. Initially these light rays slowly move apart, diverging from each other as they move away from their source. However, eventually these light rays may pass either side of a massive galaxy, at which point they will experience a gravitational pull towards the galaxy and will therefore be deflected inwards and begin converging again. If the distant source, the galaxy and the Earth are well-aligned, observers will see both light rays as individual objects in the sky on either side of the lensing galaxy. These two light rays will have taken slightly different paths through the Universe to reach our telescopes, and in general one path will be longer than the other. If the emitting object suddenly gets brighter, we will notice the brightening in one image before the other since that image will travel a shorter path and arrive in our telescopes first. By comparing the 'time delay' between first observing the brightening of one image and then the other we can measure the differential distance the light rays have travelled – which itself depends on $H_0$.

Observations of time delays between the multiple images of strongly lensed quasars can therefore also be used to infer $H_0$, but doing so requires accurately understanding the lensing effect of the intervening galaxy. As a member of **TDCOSMO**, an international consortium of astronomers working to use strong gravitational lens time delays to discover more about the Universe, I have been part of several experiments over the past decade that have made inferences on $H_0$. These results have broadly agreed with the value of $H_0$ determined from galaxies in the local Universe, although our analyses relied on several assumptions about the masses of galaxies. In an updated study undertaken during the summer of 2020, we revised these assumptions in two ways: first, we made our galaxy mass models significantly more flexible, and second we used data from a different set of galaxies to help better constrain these models.

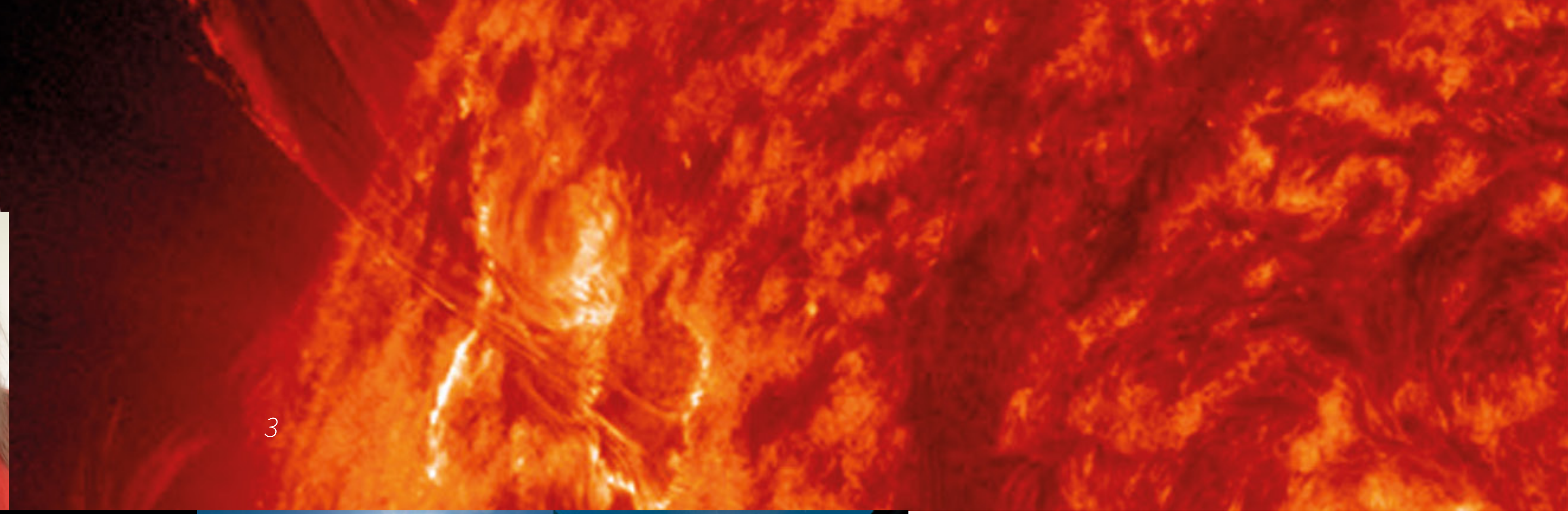
Fig 1. A three-colour image from the Hubble Space Telescope of the gravitational lens system RXJ1131-1231, one of the seven lenses used by **TDCOSMO** to infer the Hubble Constant.

The result of the first change was unsurprising: by allowing significantly more flexible models for the lensing galaxy, we obtain an inference on the value of $H_0$ that is three times more uncertain than our previous result but is nevertheless still centred on the same value (and is therefore still consistent with $H_0$ obtained from local galaxies). However, the second change – including additional data from a separate set of galaxies that do not have measured time delays – shifts our inference on $H_0$ to be consistent with the value obtained from the CMB! The conclusion is that the strong lens time delay inference on $H_0$ strongly depends on assumptions, and more data and analysis investigating the mass structure of galaxies is required to understand better the age of the Universe from time-delay lenses.

These results were published as Birrer S. et al., A&A 643, id.A165 (2020).

# Observing our Sun to Help Detect the Smallest Exoplanets

Annelies Mortier



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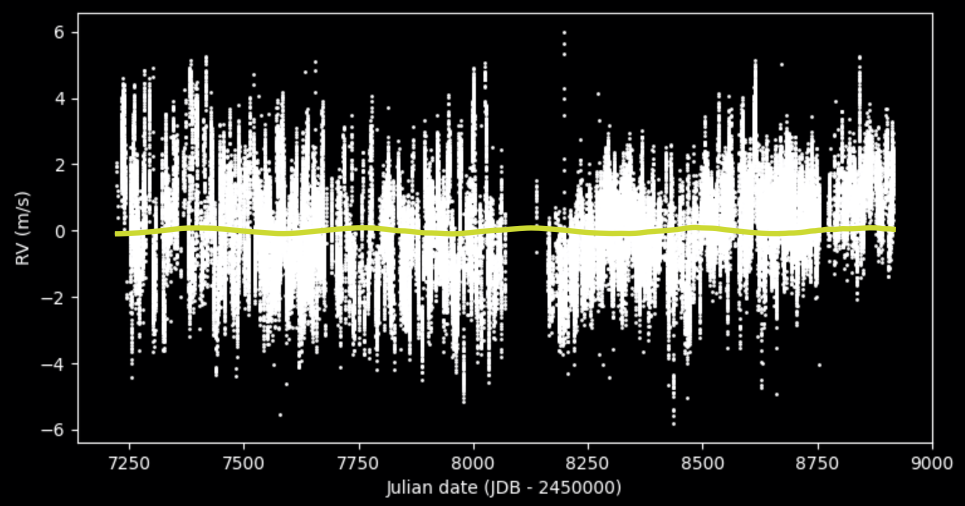


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Fig 1. The small Solar Telescope (left) and the Telescopio Nazionale Galileo (right) both feeding into HARPS-N.

Fig 2. The HARPS-N radial-velocity data in white (with the Solar System planets removed). On the same scale, the yellow curve represents the radial-velocity variation due to our Earth.

Fig 3. A real image, courtesy of NASA/SDO, showing the surface behaviour of the Sun.

Exoplanets are planets orbiting a star other than the Sun. Detecting these other worlds is the first step in understanding how common or unique our Solar System is and how prevalent other life in the Universe may be. Since the first discoveries of exoplanets in the 1990s, there has been an exponential rise in detected exoplanets and we have now found thousands of exoplanets.

Most stars are orders of magnitude brighter than their closely orbiting exoplanets. This makes the direct detection of exoplanets still mainly beyond our capabilities. Note, however, that the direct-imaging technology and techniques are constantly improving (see, for example, the work of KICC Fellow Dr Mathias Nowak). The majority of exoplanets are detected via the transit and/or radial-velocity technique. The former measures a planet's radius by modelling the periodic dip in a star's brightness when a planet passes between its star and our line-of-sight. The latter measures a planet's mass by modelling the periodic wobble of a star's velocity due to the gravitational pull of its orbiting planets. Having measurements of both allows for further investigation of the planet, such as its interior composition and the existence of an atmosphere.

Technology is being pushed to its limits to provide the data required to detect the smallest exoplanets. Space missions such as Kepler and TESS have revolutionised the field, detecting thousands of distant worlds via the transit technique. Similarly, high-stability spectrographs, such as HARPS-N (see Figure 1) and ESPRESSO, are delivering radial velocities with a precision better than 1 m $s^{-1}$ and long-term stability. However, despite having these extremely precise and stable measurements, extracting the signature of the exoplanet in radial-velocity data remains a tricky task. A planet like the Earth orbiting the Sun shows a radial velocity signature of only 9 cm $s^{-1}$. This is technically within reach of current and near-future instrumentation. Unfortunately, the main barrier is the star itself.

Stellar activity and in particular its surface features, such as spots and plages, can generate signals in radial-velocity data that can drown out or even mimic the signals of genuine exoplanets. A moderately active star, such as the Sun, can induce radial-velocity variations with amplitudes of about 3 m $s^{-1}$, on average, which is 30 times larger than the signals of small planets in the habitable zone of their stars. It is thus crucial that we understand and can handle these signatures of stellar activity properly to obtain an accurate and precise planet mass.

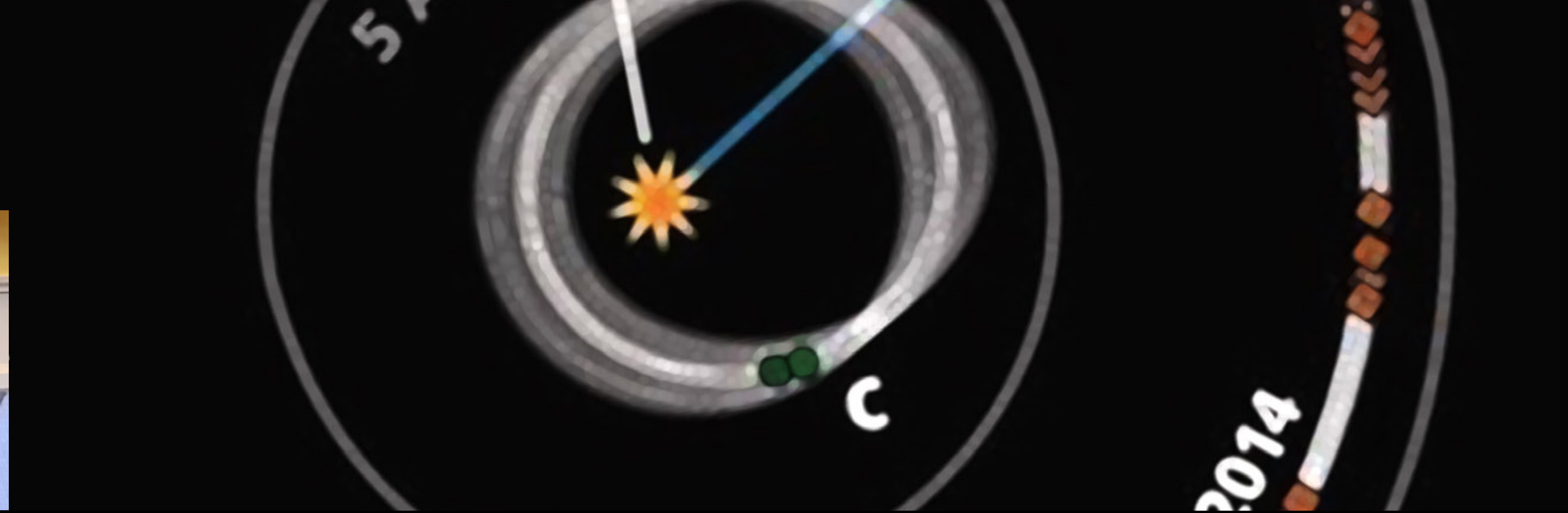
For this purpose, the HARPS-N Science Team (of which I am an active member) has been observing the Sun as a star, daily (on clear days) since July 2015, with the same spectrograph used during the night for weighing transiting exoplanets. By removing the known effects of the Solar System planets, we are left with a truly unique data set (see Figure 2). It gives us the only long-term data set with stable and precise radial velocities of a star where we are certain no planetary signals are present. We have already used this data set to improve our data pipeline, ensuring instrumental systematic effects are kept to a minimum.

The main study of this data set obviously revolves around the understanding of stellar variability. Since we can resolve the Sun, we know, thanks to space missions such as NASA's Solar Dynamics Observatory (SDO), where the active regions are located and how strong they are (see Figure 3 for an example image). This information can then be compared with our radial velocities that were measured by scrambling the Solar light, treating it as any other star. We have already found that the effects of spots, large bright regions, and smaller networks all have a different effect on the inferred radial velocity. We can successfully reduce the scatter in our data set from 1.7 m $s^{-1}$ to below 1 m $s^{-1}$, but some additional variability remains that we are still studying.

Understanding the stars in extreme detail, with the help of our own Sun, is the only way to find the smallest planets like the inner-Solar-System planets. It will be key for the upcoming Terra Hunting Experiment, led by the University of Cambridge, which aims to find a true Earth twin for the first time ever.

# The First Direct Detection of a Young Radial-Velocity Planet

Mathias Nowak




Two quantities are of prime interest in the study of giant planets: planet masses and luminosities. For young planets (less than 100 Myr), which are still hot due to the energy released during their formation, the general rule of thumb is: the more massive, the more luminous.

The exact relationship between the mass and the luminosity is thought to be an imprint of the formation mechanisms, and motivates my work to measure both quantities simultaneously. It may sound easy, but it is not. Planetary masses are measured mainly using a technique known as radial-velocity, in which we look at the wobble of a star due to the gravitational influence of a planet. This is an indirect method of observing exoplanets, in which the planet itself is never actually "seen". But to measure the luminosity of a planet, we really need to detect its light. We need to "see" it.

And there lies the problem – when a planet is far enough from its star to be seen with our telescopes, its influence on the star is usually too small to be detected. And, when this influence can be detected, the planet is usually too close to be seen in the dazzling halo of its parent star.

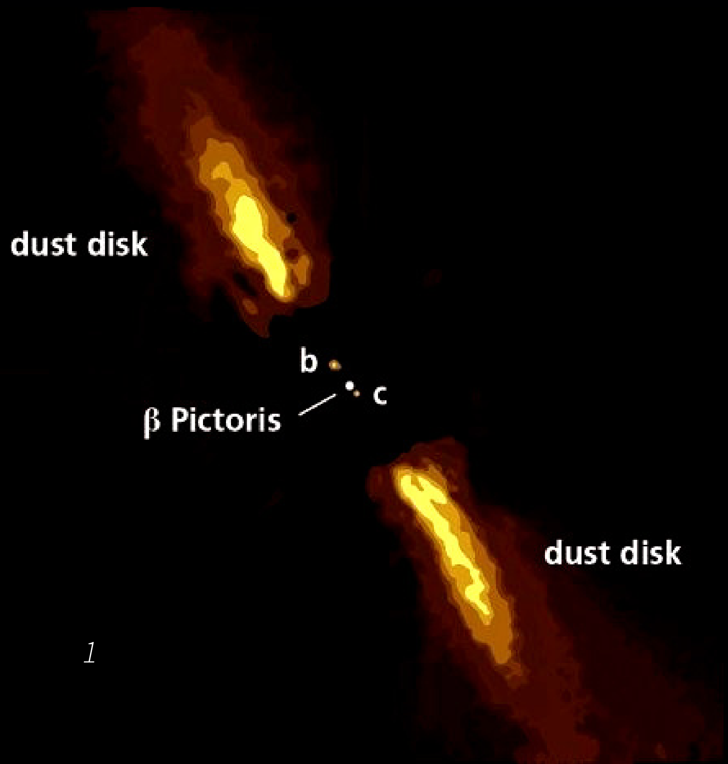



Fig 1 Artist's view of the Beta Pictoris system, with its two young giant planets embedded in the dust disc (based in part on actual observations). Credit: GRAVITY Collaboration / Axel M. Quetz, MPIA Graphics Department


Fig 2. Illustration of results from an almost two-decade observational campaign on the Beta Pictoris system. The diagram shows the orbits of the two planets (white lines, with shaded area representing the uncertainties), and the positions of the planets when they were directly observed with the different methods. Credit: GRAVITY Collaboration / Axel M. Quetz, MPIA Graphics Department.

The situation is not hopeless though. In 2020, we were able, for the very first time, to "see" a planet, Beta Pictoris c, that we knew only indirectly from radial-velocity measurements.

The Beta Pictoris system has been extensively observed and studied over the past few decades, and we have known of the existence of the giant planet Beta Pictoris b (10 times more massive than Jupiter) for more than 10 years. But what we did not know until very recently is that Beta Pictoris b has a sister planet, Beta Pictoris c, with a mass nine times larger than Jupiter. How could such a massive planet escape detection for so long? Mainly because it is orbiting in a region extremely difficult to probe. Separated by 2.7 AU, the planet appears very close to its star, Beta Pictoris, and is very challenging to separate from the stellar halo. And with an orbital period of about three years, the star needs to be regularly monitored over at least several years for the wobble induced by the planet to be visible. This is a tedious and difficult task, but was undertaken by Lagrange et al., who presented the detection of the planet with radial-velocity in 2019.

With this indirect detection of the planet, which also gave a measurement of its mass, the rewards of a direct detection were high: this had the potential to be the first combined mass/luminosity measurement of a young giant, and a first point in a diagram that will undoubtedly become extremely valuable in the future.

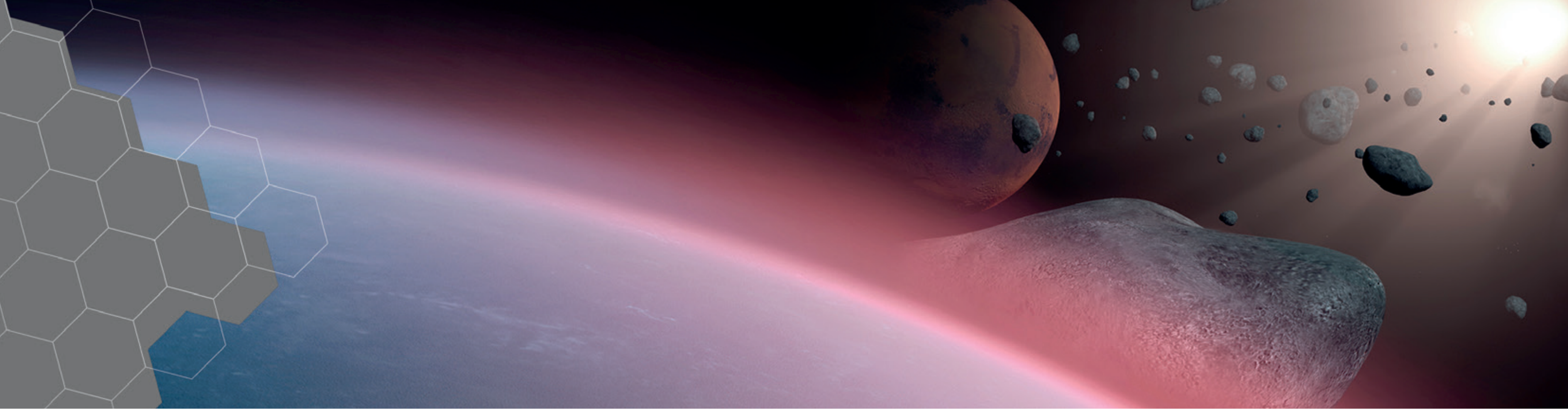
But the planet is so close to its star that even SPHERE – one of the best exoplanet direct imagers – had not been able to detect it. The only instrument that we knew could be up to the task was GRAVITY, on the beam combiner of the Very Large Telescope Interferometer. The only problem? GRAVITY is what we call a "fibred" instrument: it uses an optical fibre to collect the light and to bring it to the beam combiner. The fibre, which is quite small, needs to be perfectly centered on the planet location. So we cannot just look blindly for new planets with GRAVITY, we need to know exactly where to observe!

This is where the radial velocity detection came into play. Since the planet was indirectly discovered in 2019, we had an idea of its orbit. After conducting extensive follow-up observations of the system with many different instruments, we were able to refine our estimates of its orbit, and confidently predict its position around the star. On three nights in February and March 2020, we turned the four 8m-class telescopes of the VLTI towards this predicted position, in an attempt to "see" the hidden planet. And there it was! Exactly where it was supposed to be, just slightly less luminous than we were expecting.

This important observational step means that we can now combine the advantages of the two techniques: the interferometer gives us the light emitted by the atmosphere, hence the luminosity of the planet, while the radial-velocity measurements give the mass. For the time being, we are only able to do this for a few carefully selected targets, but we hope to be able to improve the strategy and reach many more targets in the near future. We have a clear objective in mind: to populate the mass/luminosity diagram of young planets, in the hope that it will shed some light on the physical processes governing planet formation.

This research was published in two papers: Nowak M. et al., A&A 642, L2 (2020). Lagrange A. M. et al., A&A 642, A18 (2020).

*The other giant planet in the system, Beta Pictoris b, was directly observed several times, but due to its long orbital period (greater than 20 yr), we still do not have a clear radial-velocity detection that could be used to measure its mass.*



# KICC Outreach

Matthew Bothwell

The coronavirus pandemic had a significant impact on our public-engagement activities over the past 12 months. With schools closing and all face-to-face public events cancelled, none of our events (which included the schools program, the Cambridge Festival, and more) could go ahead as planned. Instead, during the course of the pandemic we successfully took our public-engagement program online, providing a range of virtual events and activities that showcased KICC research in a virtual format.

## Online outreach activities

The virtual venue for many of our outreach activities over the past year has been our new YouTube channel: "Cambridge University Astronomy" (so named because it functions as a joint channel for both KICC and Institute of Astronomy public engagement). The channel was founded just a few weeks before the first UK national lockdown, and has **gained 7000 subscribers to date**. We used the channel to host the following virtual astronomy activities:

*Online talks for children.* Starting in March 2020, we initiated a program of weekly astronomy talks aimed at children. These talks covered a range of research topics under active investigation at KICC, from exoplanets to galaxy evolution and cosmology. These sessions were designed to be interactive, with audience members using an app to participate in polls and submit questions. These talks proved very popular, with a total (cumulative) audience of more than 85,000 people, 30% of whom were outside of the UK.

*Astronomy summer bookclub.* During the 2020 school summer holidays, we ran a virtual astronomy bookclub, again aimed at children. We assigned two books: "*Hidden Figures*" by Margot Lee Shetterly; and "*George's Secret Key to the Universe*" by Lucy and Stephen Hawking. We encouraged our audience to read these books, and live-streamed a round-table discussion and Q&A session where PhD students discussed the books with audience members.

*Astronomy on Tap.* These evenings, normally held face-to-face in pubs, consist of public-level research talks accompanied by astronomical games and quizzes. We continued to run these events throughout the lockdown, with an average attendance per evening of 290 people (around an order of magnitude higher than attendance for our usual in-person events).

## AstroEast

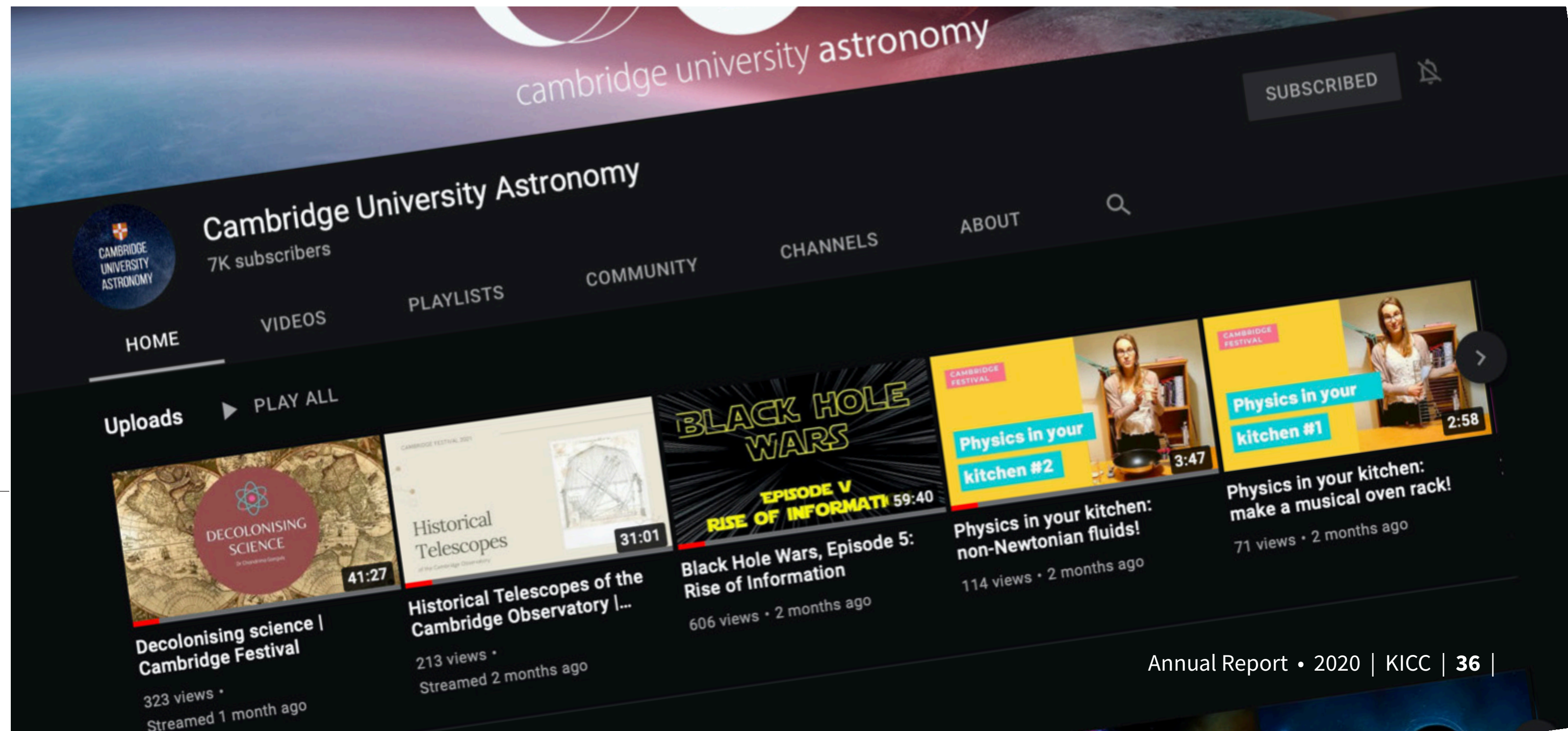
The past 12 months have been a challenging time for schools. We were unfortunately unable to run our program of AstroEast sessions scheduled for May–July 2020. (AstroEast is an innovative program to reach out to secondary-school students in communities to the north and east of Cambridge, who traditionally have limited exposure to cutting-edge science and are under-represented in University applications for STEM subjects.) We conducted a series of virtual classroom sessions for two of our partner schools, but several schools were unwilling to arrange virtual sessions due to safeguarding concerns. We look forward to continuing the program in the upcoming academic year.

## The 2021 Cambridge Festival

The 2021 Cambridge Festival was, of course, held completely virtually. The KICC hosted 17 separate events, ranging from children's activities – crafting exoplanets, making spectroscopes, and baking galaxy cakes – to online talks about music and astronomy, historical telescopes, decolonising science, the naming of planets ("*planetymology*"!), and a five-part Star-Wars-themed series about the black hole information paradox. In total, around 6000 people attended our virtual events.

## Communicating astronomy to visually impaired people

The KICC has recently partnered with Cam Sight, a Cambridgeshire charity that supports people with low vision and blindness. Starting in Summer 2021, we will be proving a mix of workshops and lectures to visually impaired children and adults. These activities, all relating to Kavli research themes (such as the search for life in the Universe, and the formation of galaxies), will combine our 3D printed models with multisensory information, such as data sonification, in order to communicate effectively the excitement of astronomy in a fully accessible way to the visually impared community.




CUA YouTube channel homepage - https://www.youtube.com/c/CambridgeUniversityAstronomy

# Hawking Centre Outreach

James Parke • Paul Shellard


Stephen Hawking was one of the best-known scientists of his generation. In addition to his visionary contributions to our understanding of black holes and the early universe, he was passionate about public outreach. The Stephen Hawking Centre for Theoretical Cosmology (CTC) is committed to taking forward his vision and legacy with frontline research communicated to the public.

The CTC and KICC have recently collaborated with Discovery on an extended video documentary series entitled *Universe Unravelled*, made possible by generous funding from the Kavli Foundation. It is aimed at anyone who is curious about the Universe we live in, with no previous knowledge of cosmology required. In 25 short episodes, the series explores what we already know about the Universe, what cosmologists are working on right now, and what they hope to find out in the future.

*Universe Unravelled* explores cutting-edge topics in cosmology and extreme gravity in a accessible way, describing how massive objects warp the fabric of spacetime and how they can collapse under their own gravity to form black holes. It explores how these black holes can send gravitational waves rippling across spacetime, and what happens if you were to fall into a black hole. And it explores the violent explosion that marked the beginning of our Universe, and how the Universe expanded from this initial Big Bang, forming all the structures we observe today – galaxies, stars and planets.

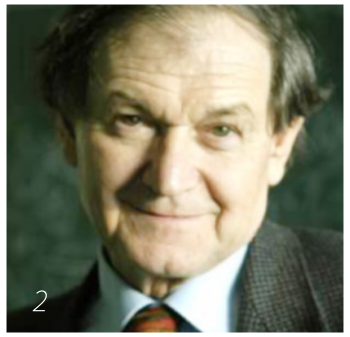





Fig 1. Dr Michalis Agathos (Kavli Senior Fellow) draws a black hole on the blackboard for the *Universe Unravelled* series.
Fig 2. Professor Sir Roger Penrose OM FRS Nobel Laureate 2020.
Fig3. Relativists outside the Centre for Mathematical Sciences being filmed for the trailer of *Universe Unravelled*.

The series also probes the mysteries that still puzzle cosmologists, such as dark energy and dark matter. It features stunning graphics, some produced in collaboration with Intel's Advanced Visualization team.

This was an exciting opportunity for CTC and KICC researchers to offer the public a glimpse of what it is like to work at the cutting edge of cosmology: confronting sophisticated mathematics with observational data, employing some of the world's fastest supercomputers, and even daring to challenge Einstein's highly successful theory in an attempt to explain what has so far defied explanation. Viewers not only learn about the deepest secrets of our Universe, but also find out about the everyday life of students and staff at a world-leading research centre.

The series was filmed in 2019 and premiered in November 2020 on Discovery's new digital channel, discovery+, where it can now be viewed. We have negotiated our own use of this video series, around which we anticipate constructing a public website soon.

To mark what would have been Stephen Hawking's 79$^{th}$ birthday, two online public outreach lectures were delivered on the evening of Friday, 8th January 2021 by Professor Sir Roger Penrose and Professor Eiichiro Komatsu. The event was organised jointly with Ludwig Maximillian University, Munich, as part of the Cambridge–LMU Strategic Partnership, a network also supported by KICC. After the lectures, PhD students and postdoctoral researchers from Munich and Cambridge (CTC and KICC) answered questions from members of the public.

Sir Roger Penrose was one of Stephen Hawking's earliest and most important collaborators. In 1964, he was the first person to show that the formation of black holes was unavoidable in Einstein's general theory of relativity. In 1969, with Stephen Hawking, he proved that all matter within a black hole collapses to a singularity, a point of infinite density and zero volume. He went on to postulate the cosmic censorship conjecture and the theory of twistors. He is also well known for his popular science books, including *The Emperor's New Mind*, for which he won the Royal Society Science Book Prize in 1990. In 2020, Sir Roger was awarded the Nobel Prize in Physics, the crowning achievement of a magnificent career in mathematics and physics.

In his lecture, Sir Roger described his Nobel prize-winning work showing that Einstein's general theory of relativity leads to the formation of black holes, something that Einstein himself did not believe happened in the real world. He also discussed his work with Stephen Hawking on broader types of singularities, including the Big Bang at the beginning of the Universe. Among other ideas, he presented his conformal cosmology proposal in which the Big Bang becomes only an apparent singularity.

# Hawking Centre Outreach

James Parke • Paul Shellard

Eiichiro Komatsu is a theoretical and observational cosmologist and Director of the Physical Cosmology division at the Max Planck Institute for Astrophysics in Germany (MPA is part of the Cambridge–Munich network sponsored by KICC). He studies cosmic inflation, the cosmic microwave background, the large-scale structure of the Universe, and why its expansion is accelerating. He was part of the WMAP science team at Princeton, before taking a faculty position at the University of Texas, Austin, where he became Director of the Texas Cosmology Center. He moved to MPA in 2012.

Professor Komatsu's gave an exciting talk about the cosmic microwave background (CMB), which offers a photographic image of the Universe when it was still an "*infant*". Its detailed measurements have given us a wealth of information about the composition and history of the Universe. CMB research has told us a remarkable story about the origin of the Universe: the structure we see such as galaxies, stars, and planets – ultimately even ourselves – arose from tiny quantum fluctuations in the early Universe. But is this picture true? In his lecture, Professor Komatsu reviewed the physics of the CMB and key evidence from recent experiments, while discussing future prospects in the quest to find out more about our origins.

The event was held entirely online because of lockdown restrictions due to the pandemic. Both speakers recorded their lectures several days in advance of the broadcast, though they were present on the evening for live online Q&A sessions; the main compère was Professor Anne Davis (DAMTP/KICC).

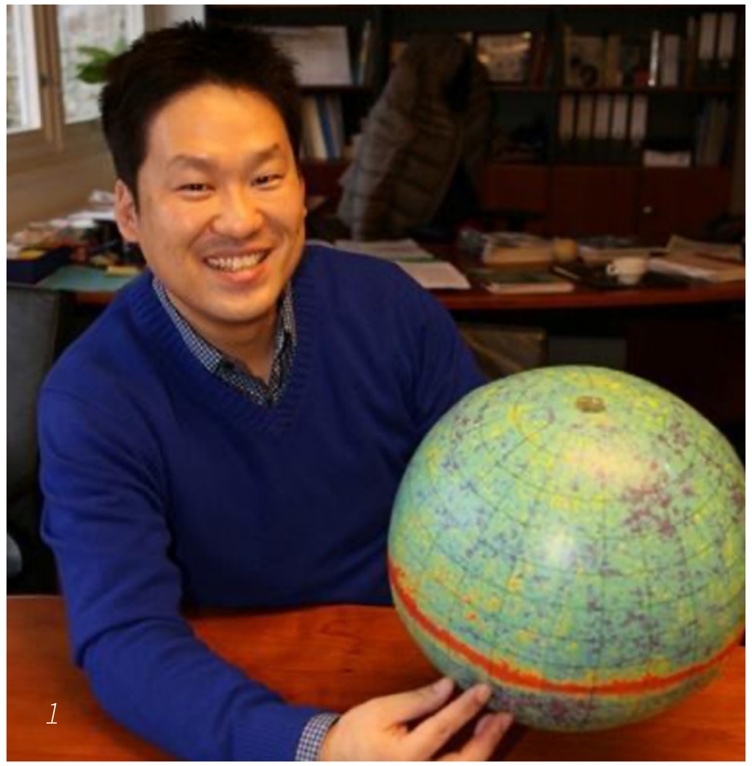


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Fig 1. Portrait of Professor Eiichiro Komatsu. Image credit: Hiroto Kawabata.
Fig 2. 2021 Stephen Hawking Lecture.
Fig 3. Panel of early-career researchers from Cambridge and Munich answering online questions from the general public after the Hawking Lecture.

Production was of a high standard thanks to a longstanding CTC partnership with Intel Studios. The livestream was broadcast on the University of Cambridge's YouTube channel and Facebook page, as well as the CTC's YouTube channel set up for the occasion and the websites of the Stephen Hawking Foundation and Munich University (LMU). The lectures reached a large public audience, with around 30,000 viewers during the evening, and the archived livestream is accumulating significantly more views over time.

The speakers, presenters and panel members received widespread positive feedback and the public sent in hundreds of interesting questions. The panel of young scientists from Cambridge and Munich were led by Dr Hayley Macpherson (DAMTP/KICC) and included Dr Michalis Agathos (Kavli Senior Fellow in Gravitational Waves). Only broadcast time constraints brought this session to an end, with plenty of questions left to answer at future outreach events.

The next Hawking Lecture will take place in 2022 and is likely to be part of the Cambridge Festival. We anticipate a high-profile event with prestigious speakers, marking what would have been Stephen Hawking's 80$^{th}$ birthday.

# Andy Fabian Awarded the 2020 Kavli Prize in Astrophysics

Richard McMahon

THE KAVLI PRIZE

The 2020 Kavli Prize in Astrophysics was awarded to Professor Andy Fabian of the Institute of Astronomy for his pioneering research into how supermassive black holes influence their surrounding galaxies on both large and small scales. This research provided evidence that supermassive black holes at the heart of galaxies are the engines that drive the flow of hot gas out of the galaxies, redistributing energy through the Universe and providing the building blocks for future galaxy formation.

Andy Fabian primarily employs X-ray astronomy to explore the physics of the Universe. For decades, researchers have struggled to understand the physical processes that drive the formation and evolution of galaxies. As the darkest objects in the Universe, black holes are observed via their gravitational effects on surrounding gas, dust and stars. These are accelerated by the gravity of the supermassive black holes to extremely high speeds with enormous kinetic energy, creating intense high-energy radiation, much of it X-rays.

Andy Fabian's body of work over a wide range of physical scales – from understanding large-scale galactic evolution to the physics of black holes at the centres of galaxies – enabled him to make connections between local conditions around supermassive black holes and the larger gas flows within and between galaxies.

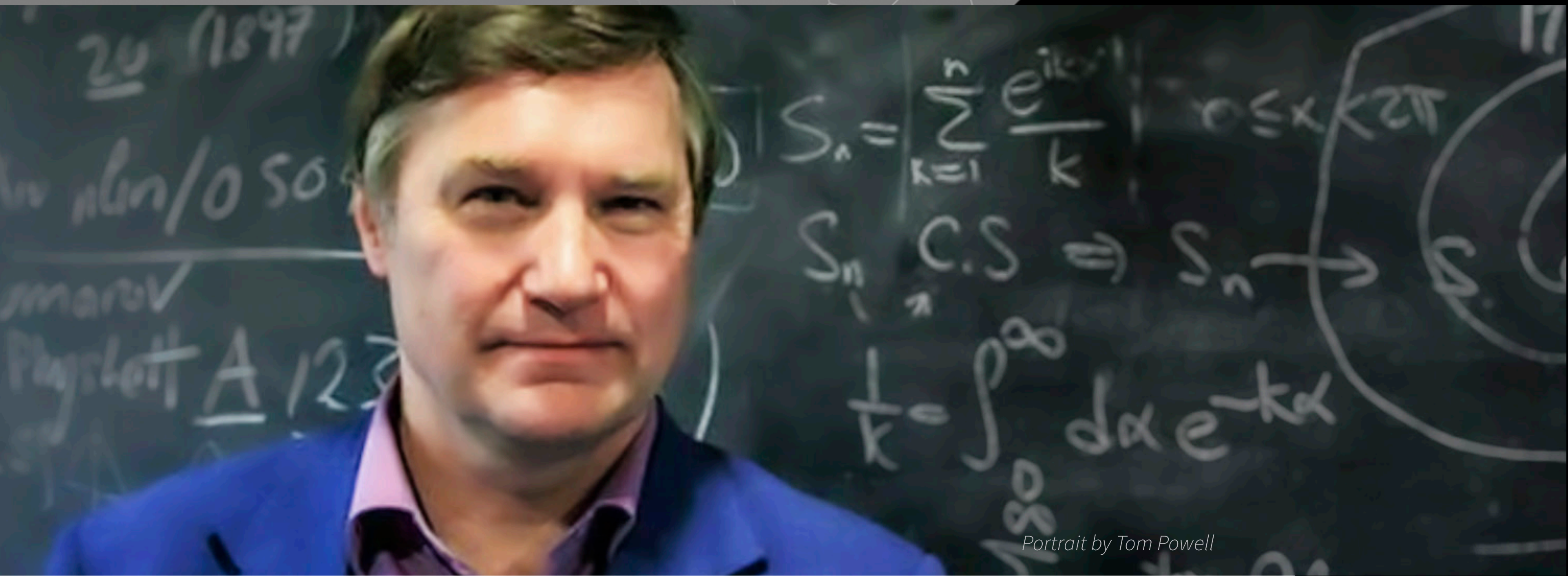
*"Fabian is one of the most prolific and influential astronomers of our time,"* said Viggo Hansteen, chair of the Kavli Prize Committee in Astrophysics. *"His research, breadth of knowledge and insights into the Universe provided the essential physical understanding of how disparate phenomena in this ecosystem are interconnected."*

The Kavli Prize medal was crafted by artist Eugene Daub, who also designed the portrait of prize sponsor Fred Kavli.


*"The Kavli Prizes are awarded in three areas: astrophysics, nanoscience, and neuroscience – the largest, the smallest, and the most complex. I believe these prizes are in the most exciting fields for the twenty-first century and beyond."* – Fred Kavli

# Professor John D. Barrow FRS, 1952–2020

Paul Shellard & James Parke



Portrait by Tom Powell

It is with great sadness that we report the passing of John Barrow, Professor of Mathematical Sciences in the Department of Applied Mathematics and Theoretical Physics (DAMTP) and Fellow of Clare Hall. He was a renowned cosmologist and mathematical physicist who also had a huge influence on the public understanding of science through his outreach lectures, his many popular science books, and his leadership of the Millennium Mathematics Project. Among his Cambridge colleagues, he was held in high regard for his wisdom and insight, and we shall feel the loss of his warm and engaging presence, which is remembered with great affection.

John Barrow grew up in Wembley and attended Ealing Grammar School in a part of London that he described as "*not conducive to observational astronomy*". After obtaining a degree in mathematics and physics from Durham University in 1974, he completed his doctorate in astrophysics at Oxford under the supervision of Dennis Sciama. From 1977 he held both Lindemann and Miller Fellowships at UC Berkeley and in 1981 he became a Lecturer at the University of Sussex, and then Professor and Director of the Astronomy Centre in 1989. He moved to Cambridge in 1999 when he was appointed Professor of Mathematical Sciences in DAMTP and was made Director of the newly initiated Millennium Mathematics Project. In 2003, he was elected Fellow of the Royal Society.

John Barrow's primary research interests lay in theoretical cosmology. His output was prodigious, publishing more than 500 research papers in astrophysics and cosmology, many as single-author papers. A major theme of his research was using astronomy to probe fundamental physics, proposing how measurements could be made at precisions beyond those possible in laboratory or accelerator experiments. A particular focus was on determining whether there may have been slow variations in the "*constants of nature*", like the fine-structure constant, during earlier epochs of cosmic history. Another key research interest was proposing and investigating models of cosmological inflation in the early Universe and also endeavouring to understand the mystery of dark energy that causes accelerated expansion in the late Universe. He also applied his deep understanding of conventional general relativity to cosmology, especially solutions that describe anisotropic and inhomogeneous cosmological models, while also investigating the extreme nature of singularities and the chaotic properties of matter near the Big Bang. He was also well known for exploring many aspects of the history and philosophy of cosmology, particularly his book with F.J. Tipler, *The Anthropic Cosmological Principle*, which examines the physical ingredients necessary for the emergence of life within our Universe.

Public engagement in science and education is a huge part of John Barrow's legacy. The Millennium Mathematics Project (MMP), which he directed since 1999, is an outreach programme for school students, teachers and the general public. Under his energetic direction it flourished, growing to work with thousands of students and teachers each year and reaching millions more online with innovative resources and activities. His imaginative leadership, encouraging colleagues to explore and experiment with new approaches, led to the MMP being awarded the 2006 Queen's Anniversary Prize, which celebrates excellence, innovation and public benefit in work carried out by UK colleges and universities. His personal interest in the mathematics of sport directly inspired the MMP's successful partnership with the London 2012 Olympic and Paralympic Games education programme. He contributed to the activities of KICC, notably helping to initiate and oversee the recent Discovery Channel Universe Unravelled series. Most recently, despite his illness, he was proud of the important contribution the MMP was able to make by helping with emergency support for home-schooling during the pandemic.

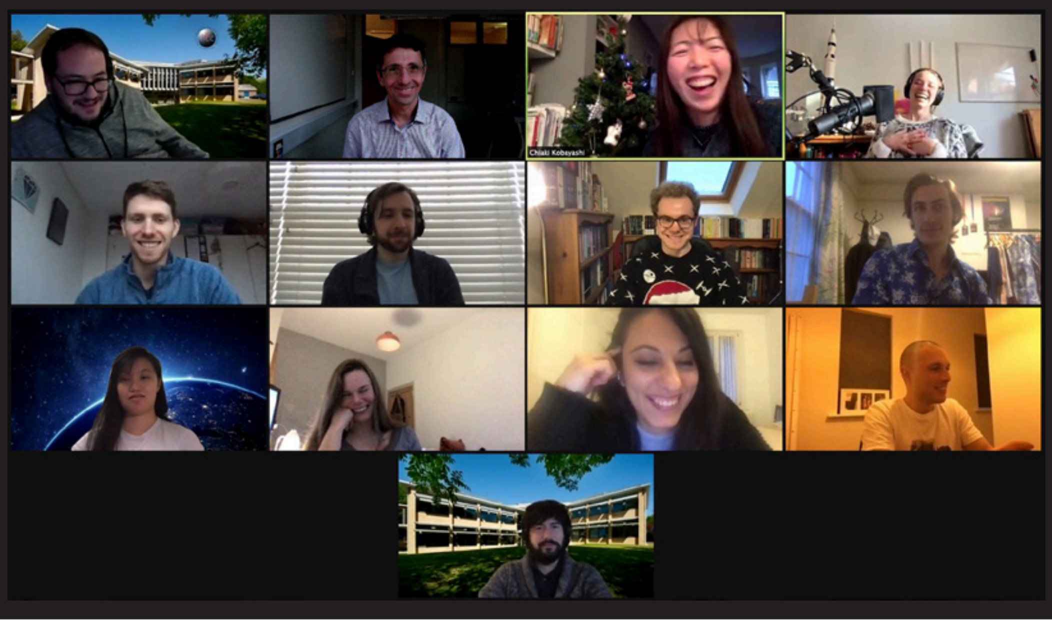
John Barrow wrote more than 20 books about many aspects of science and mathematics, which have been translated into 28 languages. In 2008 he won the Royal Society's Michael Faraday Prize for "*excellence in communicating science to UK audiences*". He delivered lectures to large and influential audiences in locations ranging from 10 Downing Street to the Venice Film Festival. He was the author of the (Italian-language) *Infinities*, which won the Italian Premi Ubu award for the best play in Italian theatre in 2002. In 2006 his forays into the relation between science, philosophy and religion were rewarded with the Templeton Prize.

John interacted extensively with a broad range of colleagues in Cambridge cosmology, offering careful and impartial guidance born of long experience. He was known as a highly approachable person, always treating others with equal respect, irrespective of their rank or status, and able to interact with anyone on any level on any subject. With his youthful demeanour and energy, none doubted that his immense productivity would continue into the next decade and beyond, so his untimely passing has been felt especially keenly.

John Barrow was the recipient of many honours. He was Gresham Professor of Astronomy (2003–7) and Gresham Professor of Geometry (2008–12) at Gresham College London, only the second Professor in Gresham's 400-year history to have been appointed to the two separate Chairs. He was awarded the 2012 Zeeman Medal of the London Mathematical Society, the 2009 Kelvin Medal and the 2015 Dirac Prize and Gold Medal of the Institute of Physics, the Gold Medal of the Royal Astronomical Society in 2016, and the 2019 Occhialini Prize of the Italian Physical Society and the Institute of Physics. He was elected FRS in 2003, and subsequently to other foreign academies, also receiving honorary doctorates from several universities. He derived special satisfaction from his election in 2020 to the Pontifical Academy of Sciences. This is the oldest supranational Academy in the world, limited to 80 members – of all faiths and none. Knowing his health was failing, he had arranged a video of the inaugural talk he had hoped to present at the Academy's plenary meeting in October. It was a fitting culmination to a long and distinguished career.

# Workshops, Meetings Events, Lectures

Further details and updates on all KICC events can be found at https://www.kicc.cam.ac.uk/events







In January 2020 KICC supported and hosted the '*Rocky Worlds: from the Solar System to Exoplanets*' workshop. The meeting brought together planetary scientists, earth scientists and astronomers to discuss topics related to rocky planets in our Solar System and beyond. Different scientific communities interacted to cover a wide range of topics under three conference themes, namely formation, interiors and atmospheres. Applying the detailed understanding of our Solar System's four 'telluric' planets is crucial in our interpretation of newly and yet-to-be-discovered exoplanetary systems. Break-out sessions every afternoon were the great success of the meeting, allowing participants to split into smaller groups to discuss the themed topics with an emphasis on blue-sky thinking and fun. It is now planned to continue a similar style of meeting termly within Cambridge. The workshop also benefited from strong local expertise spanning the Department of Earth Sciences, the Institute of Astronomy and the Battcock Centre for Astrophysics and a high fraction of participation from early-career scientists, who vastly dominated the meeting including as speakers and break-out session hosts. The success of the event was such that a sequel '*Rocky Worlds II*' is planned with some further KICC support, this time to be hosted in Oxford when conditions allow.

Regrettably, in March 2020, the global pandemic prevented most international meetings from taking place in-person and as a result, three further KICC events had to be postponed pending a review of the developing situation. These included workshops focussing on "*Distorted Astrophysical Discs*", the "*Epoch of Galaxy Quenching*" and "*Likelihood-Free Inference*", two of which were in the very late stages of planning.

As virtual events and meetings became the norm in 2020, KICC announced and hosted a summer series of online talks each Tuesday in August. These covered a wide range of astronomical topics and were delivered by a group of exciting speakers including Peter Plavchan (George Mason University), Debora Sijacki (IoA), Jonathan Gair (AEI Potsdam) and Catherine Heymans (Edinburgh).

With no immediate end of pandemic restrictions in sight, the organisers of the "*Epoch of Galaxy Quenching*" event decided to go ahead with an interim virtual/online workshop in September 2020. With the sub-title of "*Understanding the Decline in Star Formation from Cosmic Noon to the Present*", the goal of this conference was to bring together an international community of researchers in observational and theoretical astrophysics, to work towards a solution to one of the most important problems in modern extragalactic astronomy: why do galaxies stop forming stars? Thirty-six speakers provided their talks over three days providing a forum for early-career researchers to advertise their work in what had become a difficult year. The online logistics worked seamlessly resulting in a highly successful event.

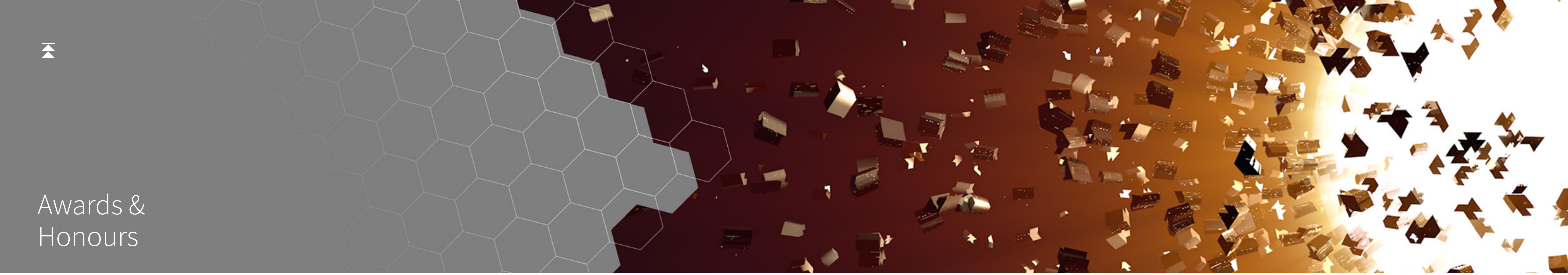
In October 2020 KICC also supported an online version of the "*Global 21-cm*" workshop, the third in a series of such meetings. Experimentalists and theoreticians met online to discuss recent progress and prospects in measuring and interpreting the global 21 cm signal from neutral hydrogen in the intergalactic medium at high redshift.

## Kavli Lectures

The highly popular Kavli Lecture programme continued this year with four excellent guest lecturers: Ravit Helled (University of Zurich) on "*Understanding Giant Planets*"; Claudia Maraston (University of Portsmouth) on "*Evolutionary population synthesis models*"; Stephen Smartt (Queen's University Belfast) on "*Mergers, magnetars and multi-messengers*"; and James Stone (Institute for Advanced Study, Princeton) on "*Radiation-Dominated Black Hole Accretion Flows*". We were fortunate to welcome James Stone in-person in January 2020, but all other lectures were held remotely.

In addition, on the 8th October 2020, a special lecture was provided by newly awarded Kavli Laureate Professor Andrew Fabian on the "*The Perseus Cluster of Galaxies*".

Of course, we hope to resume onsite events and welcome people back to Cambridge as soon as it is safe to do so.



# Awards & Honours


**Kaisey Mandel** (IoA, DPMMS and KICC) has been awarded a prestigious Consolidator Grant from the **European Research Council**. Kaisey's research focuses on utilising Type Ia supernovae to measure cosmological distances for tracing the history of cosmic expansion. He leads a project to develop state-of-the-art statistical models and advanced, data-driven techniques for analysing observations of these supernovae in optical and near-infrared light to determine more precise and accurate distances. Applying these novel methods to supernova data from the Hubble Space Telescope, new ground-based surveys, and, in the near future, the Vera Rubin Observatory's Legacy Survey of Space and Time, Kaisey and his team will pursue new and improved constraints on the accelerating expansion of the Universe and the nature of dark energy.


**Will Handley** (Cavendish Astrophysics and KICC) has been awarded a prestigious **Royal Society** University Research Fellowship to work on "*Bayesian machine learning and tensions in cosmology*". These fellowships are designed to allow outstanding early-career scientists, who have the potential to become leaders in their chosen fields, with the opportunity to build an independent research career. Will has also been awarded the **George Southgate visiting fellowship** at the University of Adelaide, Australia.


**Anastasia Fialkov** (IoA and KICC) and collaborators have been awarded the "2020 **Buchalter Cosmology Prize**" (3rd place) for their work entitled "*First star-forming structures in fuzzy cosmic filaments*" published in Physical Review Letters (2019). The work was recognized by the judging panel as "*a first-of-its-kind hydrodynamic simulation that explores the interplay between ordinary matter and the wave-like interference effects of fuzzy dark matter in the first galaxies, predicting distinct signatures of fuzzy dark matter that may be within reach of detection by forthcoming missions.*"

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


**Sunny Vagnozzi** (Newton–Kavli Fellow) has been awarded the **Symmetry 2020 Young Investigator Award** for his research at the interface of cosmology, astrophysics and particle physics, which "*has provided remarkable insight into the fate and composition of the Universe*". The citation notes his outstanding publication record and that he is "*widely recognised as a rising star in the field of cosmology*".


**Lukas Hergt**, a Ph.D. student at Cavendish Astrophysics and KICC who completed his thesis in 2020, has been awarded a **CITA National Fellowship and the 2020 Killam Postdoctoral Research Fellowship at the University of British Columbia**. He will use these fellowships to advance his work on testing the initial conditions of the Universe with cosmic microwave background data.


**Professor Roberto Maiolino**, Director of the Kavli Institute for Cosmology, Cambridge, has been awarded the prestigious **Royal Society Research Professorship**. This is the Royal Society's premier research award and "*provides long term support to world-class researchers of outstanding achievement*" and enables them "*to focus on ambitious and original research of the highest quality*".

Professor Maiolino will investigate the earliest phases of galaxy formation and their subsequent evolution across the cosmic epochs by using the next generation of cutting-edge observing facilities. He will undertake extensive and detailed studies of distant galaxies with the ultimate goal of understanding the mechanisms and physical processes that have driven galaxy evolution and transformation, from their earliest phases of formation to the current epoch.

# Further Information & Acknowledgements


## Further Information

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

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

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

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

## Acknowledgements

The numerous activities of KICC during 2020 were made possible by administrative and logistical support provided by Steven Brereton and Maria Lopez-Celi.

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

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

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