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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2025 October 10 at $16^{h}\,00^{m}$
in the Geological Society Lecture Theatre, Burlington House

Mike Lockwood, *President*
in the Chair

The President. This is a hybrid meeting. Questions can be asked during the lecture if they are put in the Q & A. Pam Rowell will read them out. Our first speaker is Professor Debora Sijacki. The title of her talk is 'The emergence of black holes at cosmic dawn'. She is a Professor at the Institute of Astronomy, Cambridge, and Deputy Director of the Kavli Institute, Cambridge. She completed her PhD at the Max Planck Institute for Astrophysics in Germany, graduating *summa cum laude*, and she was awarded a prestigious fellowship at the Institute of Astronomy, Cambridge, followed by a Hubble fellowship at the Center for Astrophysics, Harvard. Her research aims to develop realistic numerical models of the Universe which capture the formation and growth of cosmic structures with an unprecedented level of realism. She pioneered the field of supermassive black holes in cosmological simulations and demonstrated that black holes must be understood to extract exact cosmology from diverse observational methods. Her work highlights the role of high-performance computing (HPC) in cosmology and astrophysics. She has been awarded 330 million CPU-core hours on major supercomputers in the UK, EU, and USA. She received the Otto Hahn Medal and the ERC starting grant and in 2019 the Ada Lovelace Award for her outstanding contributions to and impact on HPC.

Professor Debora Sijacki. I would like to tell you about supermassive black holes and our current understanding of them, with a particular focus on the very early Universe, and to describe the new frontier we are entering as we begin to discover and study these black holes.

Black holes are some of the most exciting and enigmatic objects we know of. They lie at the intersection of mathematics, physics, and astronomy. The image from NASA shows the glow of matter as it circulates around a black hole [see Fig. 1]. What we see in this innermost region, just before the darkness at the very centre, is the last few photons orbiting the black hole that can still reach us. You have probably heard that black holes can form at the end of the evolution of massive stars. We think that stars with masses greater than about $25\,M_{\odot}$ end their lives as stellar-mass black holes.

There is a huge range of black-hole masses in our Universe, and black holes are likely the most compact objects known. In addition to stellar-mass black holes, we know of objects called supermassive black holes, with masses greater than $10^{6}\,M_{\odot}$. There is also an intriguing population in between, the so-called intermediate-mass black holes. We have several candidates and compelling theoretical arguments for why they should exist, and I will later explain why a Nobel Prize was awarded for work related to this area.

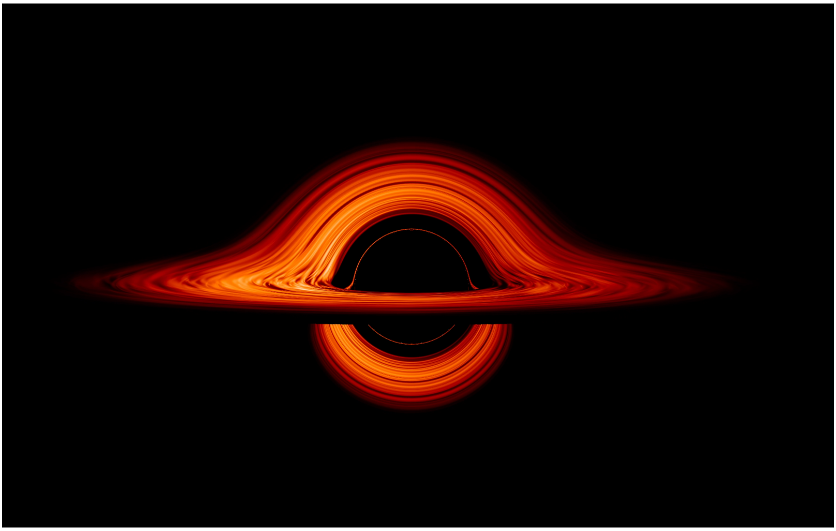

FIG. 1

Still from video at `https://svs.gsfc.nasa.gov/13326/` showing the glow of matter as it circulates around a black hole (see text). Credit: NASA's Goddard Space Flight Center/Jeremy Schnittman.

I want to explain why I believe we are in the golden age of black-hole science. The story begins with two Nobel Prizes. The first was awarded for the most precise measurement of a black hole's mass, specifically, the one at the centre of the Milky Way. Two independent teams painstakingly measured the orbits of stars very close to our Galaxy's central black hole. From the stellar orbits, and using Kepler's laws, one can deduce the mass of the central object. The mass is so large, and the object so compact, that it can only be a black hole.

Another major breakthrough in the study of stellar-mass black holes comes from gravitational-wave astronomy. The sensitivity of current detectors is high enough to detect gravitational waves produced when two stellar-mass black holes orbit and merge. Remarkably, the remnants of some of these mergers lie in the intermediate-mass–black-hole regime.

There is also extremely puzzling evidence concerning supermassive black holes. We now believe that they reside at the centres of most, if not all, galaxies. Moreover, there appears to be a fundamental link between black-hole properties, such as their mass, and key properties of their host galaxies, such as bulge mass or velocity dispersion. It is striking that although supermassive black holes are extremely compact, they seem to 'know' about the properties of the entire galaxies they inhabit. To understand how this link is established, we run large-scale cosmological simulations that model the key physical processes governing galaxy formation and evolution.

In the animation I am showing you, as the simulation of a representative sample of the Universe progresses, black holes at the centres of galaxies accrete significant amounts of matter, releasing copious energy and radiation. We believe this process regulates the supply of gas onto the black holes and ultimately sets the fundamental relation between black holes and their host galaxies.

To understand this process in more detail, we need to travel further back in time to study how galaxies and black holes assembled in the very early Universe, where our theories can be stress-tested. This is precisely where *JWST* comes in, allowing us to look much farther back in time than previously possible. We hope that *JWST* will reveal how the first black

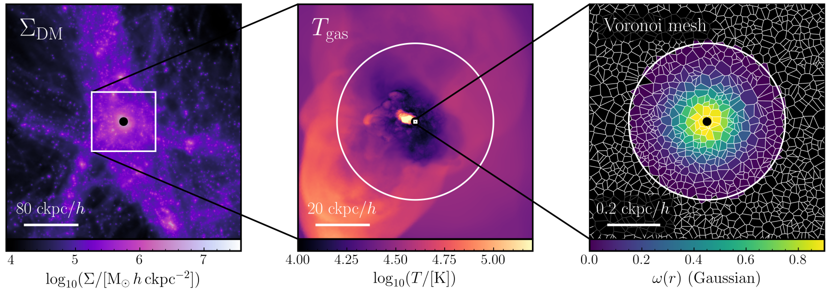

Fig. 2

Cosmological zoom-in simulation of a dwarf galaxy hosting an intermediate-mass black hole. From left to right, the panels show the dark-matter–surface-density map on large scales, the gas-temperature map (with the white circle indicating the virial radius), and the Voronoi-mesh discretization around the accreting black hole. The scale unit is *comoving* kpc/h. Adapted from Ortame *et al.*, in prep.

holes formed and grew.

The Cambridge team has already made two spectacular discoveries regarding the black holes detected by *JWST*. One involves a particularly peculiar galaxy, GN-z11, which hosted a massive black hole when the Universe was only about 3% of its current age. This surprising discovery has forced theorists to revise models in an attempt to explain it. Another intriguing object from the BlackThunder collaboration in Cambridge is a massive black hole in a tiny, compact galaxy. This black hole appears to be as massive as its host galaxy, or possibly even more massive. This is extremely puzzling, because we previously assumed that galaxies formed first, yet now it is unclear how such black holes could assemble so early in the Universe's history.

We are now finding a population of very massive black holes at high redshift that no longer appear to correlate with the properties of their host galaxies. They represent a significant fraction of the host galaxy's mass. This represents a paradigm shift, and we do not yet understand how these objects formed.

One of the pioneers of black-hole studies is Lord Martin Rees; among many achievements, he produced a foundational diagram outlining how black holes may have formed in the early Universe, showing many possible pathways. We still do not know which of these pathways is most likely to produce massive black holes. Our best hope is to use new theoretical models together with *JWST* observations to solve this puzzle.

How can we learn the physics that underpins these high-redshift black holes? We have several on-going projects. In the early Universe, we are now beginning to see low-mass galaxies hosting black holes. My PhD student, Giulia Ortame, has been developing a new approach: she is studying the elusive population of intermediate-mass black holes in dwarf galaxies and exploring how *JWST* can reveal how these black holes grow over time [see Fig. 2].

Warm gas surrounds these dwarf galaxies, and this gas is heated by the powerful energy release from the central black holes. Giulia is accurately measuring the accretion rates at which matter falls into the black holes, and her findings are tantalizing. There seem to be two distinct evolutionary pathways. In one pathway, the black hole does not grow very much, and the galaxy remains in a steady state for long periods of cosmic time, forming stars slowly and continuously. The other pathway is much more dramatic: the black hole grows rapidly, expelling large amounts of gas from the tiny galaxy and causing its star formation to shut down quickly [see Fig. 3]. Giulia has shown that these two pathways likely lead to two different outcomes, one producing black holes consistent with the local scaling relation, and the other producing likely progenitors of the high-redshift black holes observed by *JWST*.

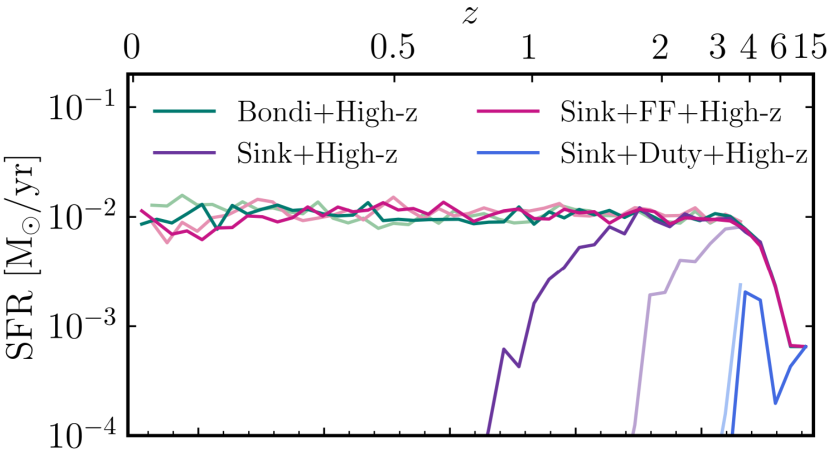

FIG. 3

The star-formation rate as a function of cosmic time for models in which the central black hole does not grow rapidly, resulting in roughly constant star formation for $z < 3$, as well as for models that allow efficient black-hole growth, which leads to rapid star-formation shutdown and dwarf-galaxy quenching (blue and purple curves). Adapted from Ortame *et al.*, in prep.

Another way to study these issues is to take a representative volume of the Universe and populate it with many black holes, an approach recently adopted by Sophie Koudmani. We want to explore both different black-hole seed masses at early cosmic times and the various ways in which these black holes may grow and influence their host galaxies. Excitingly, Sophie has shown that if you start with light black-hole seeds (around a hundred $M_\odot$), it is impossible, even with very generous prescriptions for their growth, to reproduce the *JWST* population of high-redshift black holes.

Furthermore, studying high-redshift quasars is extremely helpful for breaking the degeneracy between black-hole seed masses and their accretion histories. These quasars are powered by some of the most massive black holes known and provide some of the strongest constraints on theoretical models of black-hole growth over cosmic time. At $z \sim 6$, roughly one billion years after the Universe formed, the black-hole masses are already very large, between 10^9 and 10^{10} $M_\odot$. The only way we have found in simulations to grow these 'gargantuan' black holes is to seed them extremely early in the Universe, which is consistent with *JWST* findings, and to allow them to grow very efficiently [see Fig. 4]. However, for this scenario to work, they most likely need to exceed the Eddington limit, but only for brief periods of time [see Fig. 5].

If we now believe that there is a population of very massive black holes at high redshifts, are there any other ways to test these theories and check whether they make sense? One exciting and complementary approach is to study the gravitational-wave background. This is another remarkable discovery made within the last year or so: the detection of a gravitational-wave background that we believe is most likely produced by mergers of supermassive black holes throughout the history of the Universe. One of my PhD students, Stephanie Buttigieg, has been analysing the data and finds that standard simulations are in rough agreement with the signal, although slightly low. However, when the population of *JWST* black holes is

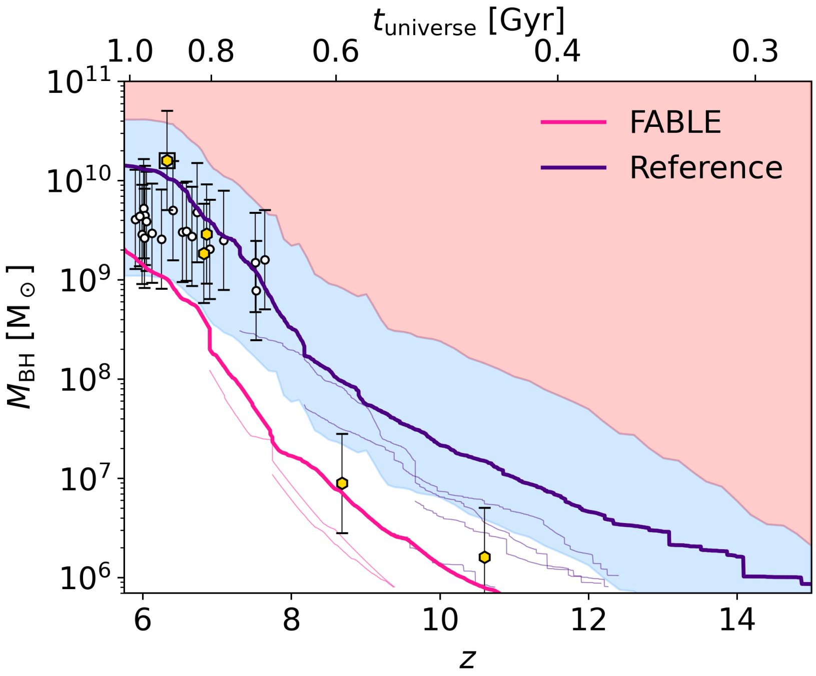

Fig. 4

Cosmological zoom-in simulation of a high-redshift protocluster hosting a bright quasar showing the growth of black-hole mass as a function of redshift for the most massive black hole in each simulation. Thinner lines indicate the mass growth of black holes that merge into the primary progenitor. Individual points represent observational black-hole measurements. Allowing for super-Eddington accretion enables black-hole growth that matches both the highest-redshift observed black holess and the brightest known high-redshift quasar. For further details on the FABLE simulation project see `https://www.kicc.cam.ac.uk/projects/fable`. Adapted from Bennett *et al.*, *MNRAS*, **527**, 1033, 2024.

included, the simulations can easily reproduce the observed signal.

Another promising and independent approach comes from cosmological probes. We know that galaxy groups and clusters are powerful cosmological tools. Recently, the major X-ray mission *eROSITA* found a deficit of gas in galaxy groups, which is highly puzzling. It may indicate that massive outflows driven by accreting black holes in these systems can push gas out of the groups. Such AGN jets can displace matter not only within groups and clusters but also much farther out. This has significant cosmological implications, especially as we aim to constrain the matter distribution in the Universe.

What does the future hold for this research area? We are fortunate to have many observational programmes on the horizon. The *ELT* will probe the formation sites of stars in the high-redshift galaxies that *JWST* is now revealing. We also have the *SKA*, which will hopefully detect numerous AGN jets and provide a new perspective on the accretion process onto black holes. And of course, we will have *LISA*, a space-borne mission designed to detect gravitational waves from merging black holes out to very high redshifts. The synergy between these different probes, combined with the latest theoretical advancements, promises to be truly transformative.

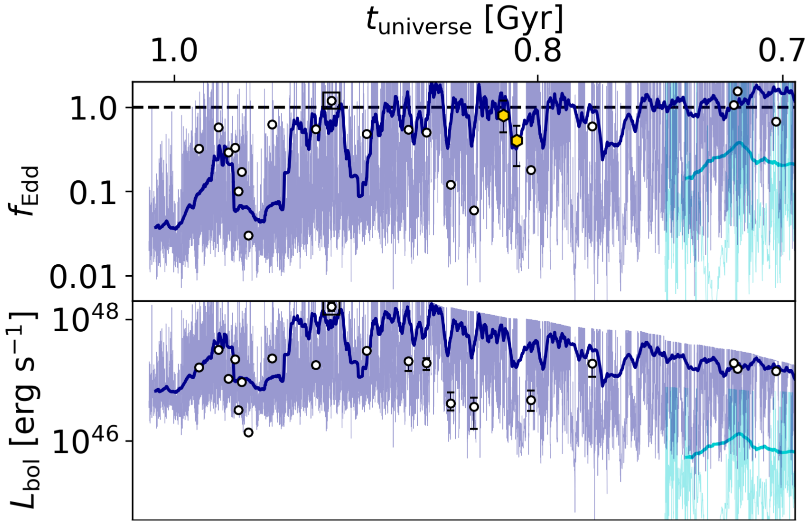

Fig. 5

The Eddington fraction (top row) and bolometric luminosity (bottom row) for the most massive black hole and its largest progenitor. Faded lines denote values at every time-step while darker lines indicate a rolling mean with a width of 100 time-steps. Observational data points are shown as open circles or gold hexagons (the latter representing *JWST* data), with uncertainties where available. The dashed horizontal line marks the Eddington limit. By modelling super-Eddington accretion, it is possible to explain the luminosities of very bright, high-redshift quasars. Adapted from Bennett *et al.*, *MNRAS*, **527**, 1033, 2024.

The President. I have to say that is something rather comforting that even with all those CPU hours available, when something gets difficult you go back to pen and paper. Do we have any questions for Debora?

Reverend Garth Barber. Does this evidence for early supermassive black holes indicate an age problem in the early Universe, in other words, are we getting the age at a certain redshift wrong?

Professor Sijacki. That is a very good question. Of course, it is very exciting — there was a lot of buzz and excitement when these black holes started to be discovered at high z. Fortunately, or unfortunately, we have sufficient astrophysical uncertainty in the formation and assembly of these black holes that by Occam's Razor there is currently no pressing need to invoke alternative cosmological models before we understand the astrophysics.

Dr. Pamela Rowden. I have a question from Ian Robson who asks "How well can you determine the mass of the *JWST* very high-z supermassive black holes?"

Professor Sijacki. This is again another thing that is very much debated currently and obviously these measurements are not easy. You have to be very careful. There are different groups that made the measurements so they give some solidity in that there is independent verification. One of the objects I showed you has a different type of measurement which is much more direct, rather than entirely relying on interpreting broadened spectral lines, which gives us more confidence about these black-hole masses. A consensus is growing that at least a subset of the population should be black holes and should be quite massive, which is really exciting.

Professor Richard Ellis. It has been suggested that some of the black holes are surrounded by dense gas and the broadening that we use for the kinematics of black holes to estimate masses is only part of the explanation and the scattering of radiation can make quite a big contribution, so do you believe some of the population of black-hole masses have been overestimated because it's assumed it's all kinematics?

Professor Sijacki. I think that with some of the earlier results one has to be quite careful about them. Again, I do not think that you revise all the results. There have been a couple of papers that show that the scattering cannot explain all *JWST* results — you cannot get away with removing a black hole entirely, and in some cases black-hole masses seem robust. There will be more observations and deeper data from *JWST*. There is a lot to deliver, so these things will be ironed out.

The President. Thank you very much. That was absolutely fascinating. [Applause.]

Our next speaker is Dr. Rob Eyles-Ferris. Rob is a Research Associate at the University of Leicester who works on high-energy transients to understand the largest explosions in the Universe. His particular research interests include tidal-disruption events, fast X-ray transients, and gamma-ray bursts.

Dr. Rob Eyles-Ferris. The *Einstein Probe* (*EP*) is a new and truly innovative mission dedicated to high-energy astrophysical transients and is redefining the landscape of its field. Its revolutionary *Wide-field X-ray Telescope* (*WXT*) takes inspiration from nature, specifically the eyes of lobsters and certain other crustaceans which use tiny pores in their surface to focus light onto the retina. *WXT* uses similar micropore (or microchannel) optics to focus X-ray photons into a cross-shaped PSF. While such 'lobster-eye' instruments are less sensitive than traditional Wolter X-ray telescopes, they offer two advantages: a much lower mass and, most importantly, a far wider field of view. With twelve individual modules, *WXT* has an unprecedented field of view of 3600 square degrees in the soft (0·5–4 keV) regime and has the largest grasp (sensitivity × FoV) of any X-ray telescope.

EP/*WXT* is transforming our view of X-ray transients, in particular, fast X-ray transients (FXTs). These are short bursts of X-rays lasting hundreds to thousands of seconds, previously identifiable only in archival data long after the transient. However, *WXT* is now finding these sources in real time and, for the first time, allowing prompt follow-up and identification of the systems that power these objects. While some have been linked to previously known classes of transient, such as long gamma-ray bursts (LGRBs), many have more unique origins.

EP250108a, detected in 2025 January, is one such FXT. The initial burst of X-rays lasted 2·5 ksec before rapidly fading beyond the reach of even the most sensitive X-ray telescopes. However, I used the 2-m *Liverpool Telescope* to find its much longer-lived optical counterpart. This source exhibited unusual properties, being much bluer (hotter) than expected for an LGRB counterpart, for instance. The counterpart faded and cooled quickly before rising again as a type-Ic broad-lined (Ic-BL) supernova. These supernovae are caused by the collapse of massive stars and are often observed following LGRBs, suggesting a common origin between these transients and EP250108a. Our extensive observing campaign, which included ground- and space-based telescopes from the *Very Large Telescope* in Chile to *JWST*, produced a wealth of data across the electromagnetic spectrum through which we could unravel the mysterious nature of EP250108a. [See Fig. 6].

There are two ways a collapsing star could produce the X-rays seen in EP250108a, through a convective engine or through launching a narrow jet of ejecta. Both engines accelerate material to speeds close to the speed of light but the mass required to produce the observed luminosity differs significantly with convective engines requiring significantly greater mass. The first phase of EP250108a's optical counterpart, which we dubbed the 'fast-cooling phase', is consistent with explosive ejecta expanding at speeds a few tenths the speed of light, and that provides a clue as to how the FXT is powered. For the material to have slowed to the measured speeds by the time of the optical detection, a relatively low mass is required pointing towards the jet engine. However, these jets, which also power LGRBs, normally produce much redder 'afterglow' emission and long-lived X-ray and radio counterparts, none of which is seen in EP250108a. Instead, we suggest the jet was trapped either within the

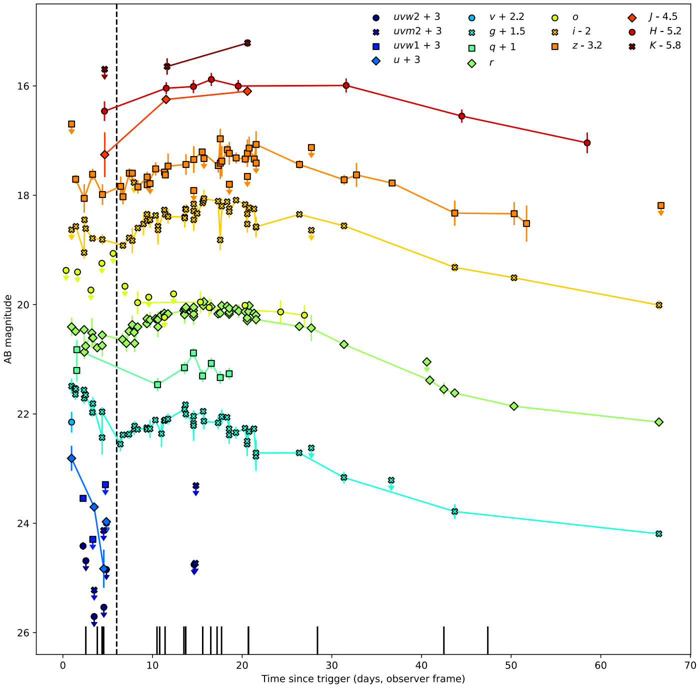

Fig. 6

The light-curve of EP250108a's counterpart across UV, optical, and infrared bands (bottom to top). The dashed vertical line indicates the cutoff between the fast-cooling phase and the rising Ic-BL supernova. The black vertical lines indicate our spectroscopic observations.

outer layers of the star or in the dense environment surrounding it to form a cocoon. These rarely observed cocoons produce blue optical emission as they rapidly expand, exactly as we saw in EP250108a. [see Fig. 7].

The later supernova provides further clues as to EP250108a's nature. It closely resembles Ic-BLs associated with LGRBs and other FXTs suggesting the same type of star powers all these transients. This is consistent with our progenitor analysis which points towards a Wolf–Rayet star 15 to 30 times the mass of the Sun. Our detailed spectra reveal further hints as to the environment of the star. In particular, we see both evidence of hydrogen and helium in the spectra. One particular hydrogen feature only briefly appears suggesting it could be evidence of an extended shell, while helium is detected by *JWST* but not in optical spectra. Together, these point towards a complex environment with significant earlier mass loss from the star, possibly through stellar winds or common-envelope ejection, and implies EP250108a's progenitor probably resided in a binary or possibly even triple system.

There are still a number of open questions in the case of EP250108a. The exact reason the jet failed to break out is still unknown — was the jet inherently weaker than typical for this type of stellar collapse or was it trapped due to an exceptionally dense and complex environment? The picture has been further complicated by *EP*'s detection of three more FXTs linked to Ic-BLs. In one case, EP240414a, a third red component was observed pointing towards a jet that just breaks out, while the other two sources display their own unique properties. Together this suggests there is a spectrum to the jet behaviour that we are only just starting

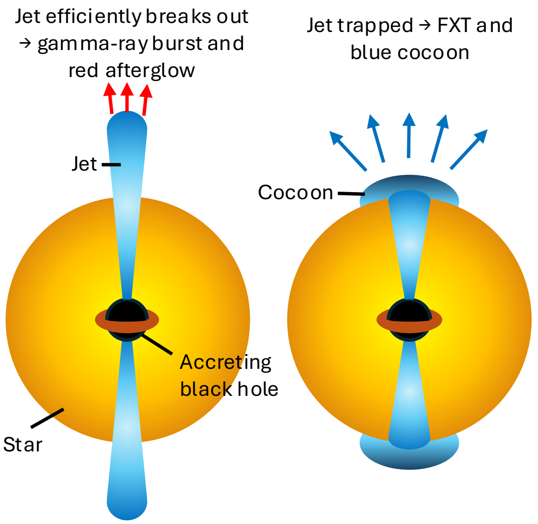

Fig. 7

The difference between LGRBs and FXTs with cocoons like EP250108a. On the left, the jet efficiently breaks out to produce the LGRB and an afterglow. The right hand-side shows the situation in EP250108a where the jet is unable to break out and instead forms the blue thermal cocoon.

to uncover thanks to *EP*. Future detections will be vital for answering these questions and determining exactly how the deaths of massive stars power these extreme events.

The President. Thank you very much. We have a question on-line.

Dr. Rowell. A question from an anonymous attendee: "What percentage of the mass–energy accreting onto BHs gets ejected in the jets? (I presume all jets are equal and opposite to conserve momentum.)"

Dr. Eyles-Ferris. Jet physics is very complicated. We are still not entirely sure how they work and I very much simplified the picture here. You don't always get just jets, you sometimes get outflows which are moving much more slowly but at much wider angles. Again we are not really sure how they happen or whether they occur in a core-collapse supernova. There is quite a lot of debate as to exactly what is going on. We don't know for sure how much mass is ejected. It is most of it, I think.

Professor Paul Crowther. Can you say anything about the size of the progenitor — was it a compact WR thing or a giant?

Dr. Eyles-Ferris. We presume it was a Wolf–Rayet probably with its atmosphere stripped. It seems a fairly typical supernova progenitor for a GRB.

Professor Crowther. Yes, along the lines of a typical SN Ic, broad-lined with a compact, hot, WR-like He-rich envelope.

Dr. Eyles-Ferris. Yes.

The President. Thank you very much. [Applause.] Before I introduce the next speaker I must tell you a story. When ChatGPT first arrived, my colleague Chris Scott decided to take my magnetohydrodynamics lectures and ask them to be re-written in the style of Monty Python. [Laughter.] Unfortunately, he didn't notice any difference, so he then asked them to be written in the style of the Goons. What is interesting is that it was identifiably my notes, it was identifiably the Goon Show, but after you got over the amusement of Bluebottle talking about magnetic reconnection, it was profoundly unfunny. Our next speaker is Niall Jeffrey from University College London. The reason I told you that story is because the title of his talk is 'What has AI ever done for us: learning about dark energy from dark matter'. Niall did his PhD at UCL in 2019 and then went to Paris at the École Normale Supérieure and he is currently a Senior Research Fellow back at UCL.

Dr. Niall Jeffrey. Understanding the cosmological model and the nature of the dark sector — dark matter and dark energy — remains one of the central challenges in fundamental physics. About 95% of the mass–energy content of the Universe is attributed to these components, yet their properties and physical origin are unknown.

Recent results from the *DESI* experiment suggest that dark energy could be a dynamic and exotic form of matter–energy rather than Einstein's cosmological constant, as previously thought.

The European Space Agency's *Euclid* mission, launched in 2023, and the *Rubin Observatory* Legacy Survey of Space and Time (LSST) are upcoming cosmological experiments designed to produce decisive constraints on dark-energy models. Among their primary probes is weak gravitational lensing, which traces the distribution of dark matter and provides a powerful test of dark-energy physics through its effect on cosmic structure.

Using new techniques from Artificial Intelligence (AI) within a rigorous statistical framework, we can unlock new signatures of dark energy in these data. This will allow us to discover or rule out different models of dark energy that would otherwise remain indistinguishable.

In advance of data from this new generation of cosmological experiments, current surveys have taken the lead in developing these methods. One such experiment is the Dark Energy Survey (DES) — an international collaboration to map hundreds of millions of galaxies. Using the gravitational-lensing effect, these data are used to trace the dark-matter distribution in the Universe.

Our team in DES has developed and applied a new AI framework, simulation-based inference (SBI), to analyse weak-lensing data and to measure dark energy with unprecedented precision. SBI is a novel technique that answers scientifically rigorous statistical questions, using AI as a mathematical tool to do so. In this sense, the results are both testable and interpretable — this is not 'black-box' AI.

In DES, SBI uses realistic simulations of the Universe to perform statistical inference directly on the data, without relying on statistical approximations (regarding the 'likelihood' of data) or relying on simplified summary statistics (*e.g.*, power spectra). Instead, with SBI we learn from simulated data that include observational realism, enabling information from the full lensing maps to be used in the inference. In this way, we use SBI to provide realism, so that we trust our results, which then means we can reliably extract more information from our data directly from the dark-matter maps.

This 'map-level' inference substantially improved the constraining power of DES. Applied to gravitational-lensing data, SBI has delivered the most precise dark-energy analysis to date, improving dark-energy constraints by more than a factor of two — equivalent to quadrupling the effective DES data volume.

These analyses were enabled by the Gower Street simulation suite, comprising nearly 5000 large-volume cosmological simulations spanning three dark-energy models. These simulations were produced using the UK's scientific supercomputing infrastructure, *DiRAC*. Developed for DES and extended for *Euclid*, this suite incorporates noise, masks, redshift uncertainties, and galaxy alignments. SBI then connects these simulated data and the 'true' cosmological model (used in the simulated universe) using techniques from probabilistic AI. Introducing the actual observed data to these learned statistical models leads to posterior probabilities on the cosmological parameters of our Universe.

The techniques established with DES are now being extended to *Euclid*, whose imaging data and survey volume will far exceed those of DES. By integrating SBI with *Euclid* analyses, we will obtain the most accurate and precise inference of dark energy from weak gravitational lensing.

If we want to exploit these ground-breaking data sets even further, we can use more of the *Euclid* data that probe relatively small cosmological scales (separations of roughly 5 Mpc).

This can introduce new challenges, as it requires simulations at increasingly small scales, where they become computationally expensive. However, new statistical machine-learning techniques motivated by this cosmological challenge are already being developed — and they promise to transform how we learn the physics of the dark Universe.

The President. Thank you very much, Niall. Do we have any questions?

Reverend Barber. You started by saying that using AI you build trust. How can you be sure that you are not baking in prejudice in your assumptions when you are training the AI?

Dr. Jeffrey. There are two different answers to that, one of which is in the AI system. Is it finding the optimal solution that we think it is? Has it converged? We have a statistical test to do that. I think that maybe what your question was about is whether the models that you are feeding the simulation are somehow wrong: there are assumptions going in that the AI system is using and are somehow wrong. I get this question after almost every talk and the answer is the same for all of science. Every time the Dark Energy Survey or the *Large Hadron Collider* does an analysis we have solutions and we are expected to be more clear about our assumptions. We do lay them out better than other analysts do. There is the usual problem of known unknowns and we can try and check if there are sources of systematic error there. There is a problem with unknown unknowns but that is not a problem for AI or this kind of analysis — that is a problem for anyone who has ever done a scientific analysis. Actually, because of the speed of this kind of thing we are able to do tests that people who are not using these tests are not able to do — goodness-of-fits — so it actually adds an extra layer of trust at the end as well.

The President. Actually I had a similar question. I was wondering if there was any advantage in going back to what we knew before AI discovery and then feeding it all through and seeing what it makes when we know we have missed something out.

Dr. Jeffrey. When these simulation-based inference techniques first came out, people did exactly that. They ran the pipeline through SN data, for example, to see if they recovered the discovery of dark energy and they got exactly the same error bars. For older results, no one trusts this at the moment, so for any analysis we have to re-do it on old theories and every single time it works.

The President. It is always the worry what would AI do when faced with something that we did not know about.

Dr. Jeffrey. That is true of all science. Plots before scatter plots and then there is an outlier. It is the scientific method that is the problem there.

Professor Ellis. There is the figure on the left with the two-point correlation function and then you said the great advantage with the new method is that you can do it very much faster. It is equivalent to having better data. I'm sure that the contours have shrunk but the answer is different so why is that?

Dr. Jeffrey. Do you know the answer? [Laughter.]

Professor Ellis. It's offset.

Dr. Jeffrey. It's offset, yes. You are looking at different data, in effect. When you measure the power spectrum you are taking a fraction of the DES data. If you did any experiment twice there would be an offset because its a random process so there is noise that is in the map level that is not in the power-spectrum analysis. They are not the same data, just with a different model, it is actually new data.

Professor Ellis. That is kind of worrying, though?

Dr. Jeffrey. No. If we did an experiment and then published our results, we shouldn't get the error bars in the same place, they should be offset because we both have different data. What is happening here is that the map-level stuff is actually seeing different data than what is in the two-point, so if this was in the same place that is the worrying thing because it means we have cheated.

Professor Ellis. So the original paper is wrong?

Dr. Jeffrey. No. It is a fact that the map level is seeing information data in some way that the two-point is not seeing, so you expect there to be a shift because it is stochastic.

Dr. Patrick Leahy. I'm not a total expert on this but I know that you don't have to stop at two-point. If you go to three-point, four-point, *etc*., do you end up summarizing all the information that is in the data?

Dr. Jeffrey. Technically not. Practically, if we do it in three-point, it improves it by 20%, not a factor of two. The reason why is because you can characterize a statistical process by a sum of n-point functions only if it is somehow perturbative. As soon as you have non-linear structure formation, in this case of dark matter crossing over each other, it became more non-perturbative so you are not guaranteed that that particular expansion would converge to all the information.

Dr. Quentin Stanley. There is an interesting thing that was pointed out to me recently and this is the danger of training data that is diagnosing on cancerous moles where a lot of training data was taken from images taken over many years and grew a data set. The trouble was that the final result was determined whether or not the rule that was used to measure the mole was present in those images. Metadata is one of those unknown unknowns which is present and you do not realize it has been there. We had a presentation last year when it was looking at lots of data from datasets and trying to get the same data from datasets to match is very difficult and therefore you have this added problem of making sure your simulations match the type of data you've got. It is a huge problem and it is a magical thing to get anywhere close to it.

Dr. Jeffrey. Simulating things is hard. If we don't include something in our simulation of the active data then these contours would be in the wrong place. There is a whole other aspect of this which is standard statistics, which is goodness-of-fit testing. If I have my data, what are my parameters which have been learned, but there is also an aspect which 'is do the simulations in our case look like the observations?' and there is significant work being done on that front as well. It is things that people are not doing in the standard analysis — people don't do these goodness-of-fit things like posterior-predicted distributions, prior-predicted distributions. We are forced to do it because of questions like this. Nobody else is doing it so we are actually going significantly beyond those goodness-of-fit-metrics.

Dr. Stanley. Could you define the phrase 'looks like'?

Dr. Jeffrey. No. It's mathematically well defined. It's just difficult to convert that statement into words. Every time you have a statistical process then there is some probability distribution which is millions of dimensions. This is a higher-dimension space of images that we expect and images that we don't expect, so if we can somehow change that higher-dimension probability space you can say, given the actual data I have got, whether it was high probability.

Dr. Stanley. I know that in the world there is a huge examination of the type of statistics you can use. It can differ and again, this is part of the learning process. In 100 years it will be a totally different scene.

The President. The problem is not a new one. When neural networks were first introduced they tried to use it on aircraft identification and it was getting Russian and US aircraft right every time, until they gave it a colour photo of a Russian plane. Any other questions?

A Fellow. It seems to me that in the last ten years there have been few occasions when theoreticians have told observers that their observations are wrong. Is that anybody else's experience? ΛCDM has proved itself to be extremely flexible — there are a couple of parameters in there which can be adjusted until the theory fits the facts. Can you design experiments with your AI which will actually test the theory, but a real scientific method which is to try and invalidate the theorem.

Dr. Jeffrey. When I say information-extraction, what it is doing is designing an experiment. It is saying that two-point statistics as an experiment are less good. Can you design some other summary of the data? In terms of questions like 'Can you invalidate. . . ?', I think it comes back to this question of goodness-of-fit, and obviously as a scientist that is what we would like, which is additionally 'Can our model not in every way describe our data?' I suppose that is almost always true and then you get rid of all sources of systematic error and hopefully find that it still doesn't match. I think that is like goodness-of-fit but I don't think that design is necessarily the way to go, partly because we are not limited by our data anymore. Cosmology is not a data-limited exercise, it is a methodology, a theoretical statistics-limited problem. At the moment all the dark-energy results combine galaxy observations, CMB, and SN. With *Euclid* weak lensing alone will be able to beat down the error bar on some things. Rather than trying to think what the next step is we will have our work cut out just trying to use that dataset alone.

The President. Thank you very much. [Applause.] I'm not sure what I have learned. [Laughter.] I'm actually wondering if I should give a talk on what differential calculus can do for us. A big thank you to our speakers this evening, it has been absolutely wonderful. The next Highlights meeting will be on Friday, November 14th. We are unable to offer drinks at Burlington House today due to a mixture of licensing laws and fire-regulation problems. We are looking at it and will find an alternative solution. Thanks for coming and thank you again to our speakers and we'll see you in a month.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2025 November 14 at $16^{h}\,00^{m}$
in the Geological Society Lecture Theatre, Burlington House

MIKE LOCKWOOD, *President*
in the Chair

The President. A couple of speakers were unable to make it today so we have two talks on-line and one in person. The first speaker is Nigel Meredith. Nigel started at UCL in 1984 and moved to the downland outstation at Mullard Space Science Laboratory in 1996. Since 2004 he has worked at the British Antarctic Survey in Cambridge and his work on the radiation belts won him the RAS Chapman Medal this year. He will be talking about 'Extreme relativistic electron fluxes in the Earth's outer radiation belt'.

Dr. Nigel Meredith. Relativistic electrons ($E > 0{\cdot}5$ MeV) are a major source of radiation damage to satellites. These, so-called 'killer electrons', can penetrate satellite surfaces and embed themselves in insulating materials and ungrounded conductors. Here, the charge accumulates over time, resulting in the build-up of high electric fields which may eventually exceed breakdown levels. The subsequent discharge may lead to phantom commands, logic errors, loss of functionality and, in rare cases, serious harm to a satellite.

Relativistic electrons in near-Earth space normally occupy two distinct zones. The inner radiation belt, which typically occurs in the region $1{\cdot}2 < L < 2{\cdot}0$, is relatively stable. Here L is the distance from the centre of the Earth to the magnetic equatorial crossing of a given geomagnetic field line measured in Earth radii. Further out, the outer radiation belt typically lies in region $3 < L < 8$ and is highly dynamic.

Our critical infrastructure extends to 6·6 Earth radii. As of 2023 there were over 7500 operational satellites in Earth orbit, including 6800 in low Earth orbit, 143 in medium Earth