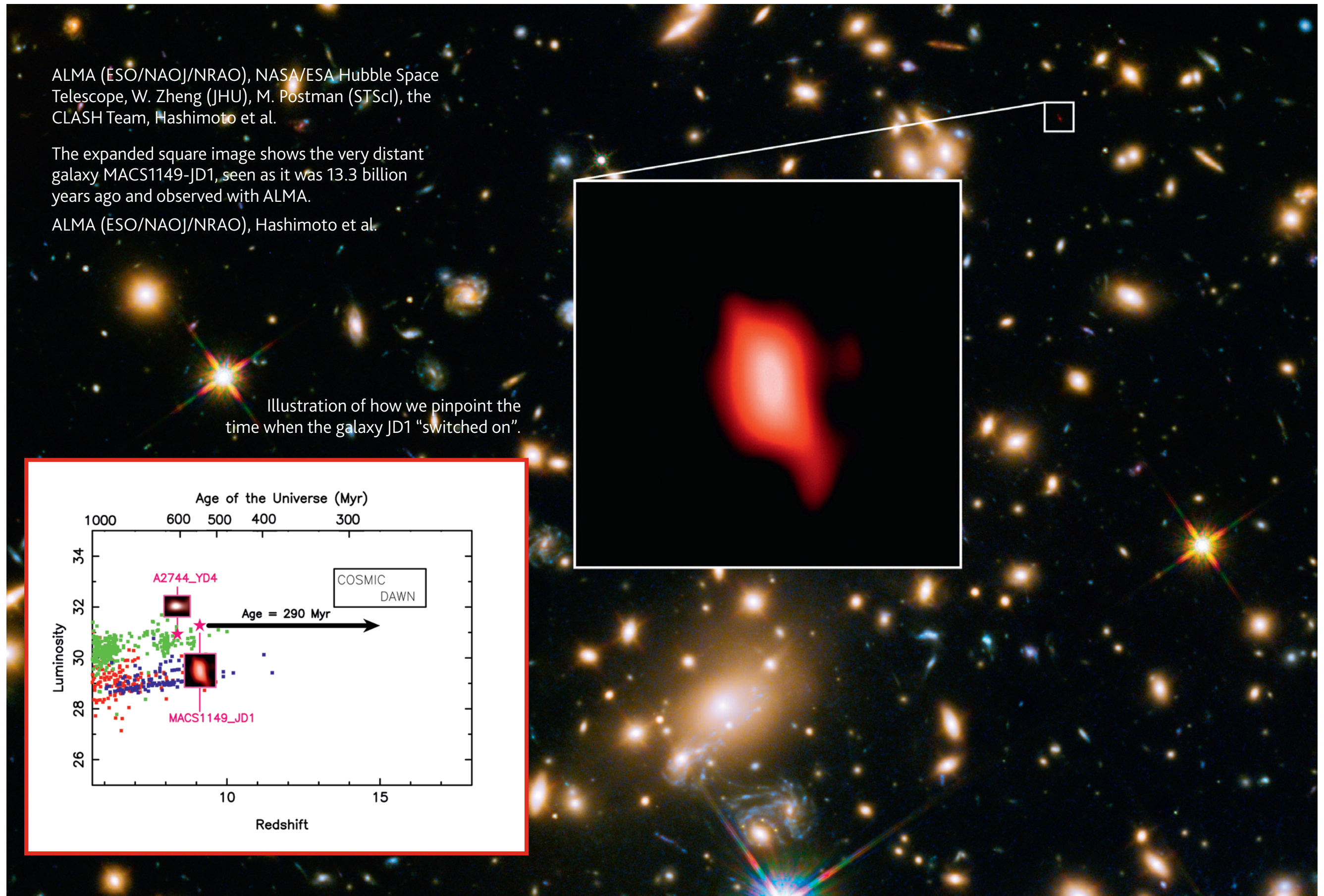


ALMA (ESO/NAOJ/NRAO), NASA/ESA Hubble Space Telescope, W. Zheng (JHU), M. Postman (STScI), the CLASH Team, Hashimoto et al.

The expanded square image shows the very distant galaxy MACS1149-JD1, seen as it was 13.3 billion years ago and observed with ALMA.

ALMA (ESO/NAOJ/NRAO), Hashimoto et al.

Illustration of how we pinpoint the time when the galaxy JD1 “switched on”.

Probing for the dawn of light in the universe

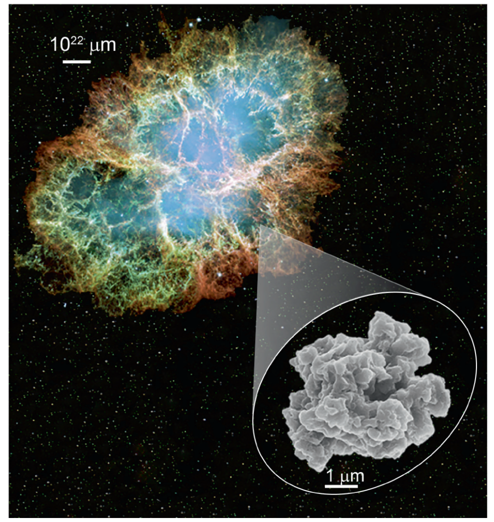
The first stars formed around 250 million years after the Big Bang, producing the chemical elements that we see all around us today. Researchers in the First Light project are looking back into cosmic history, aiming to pinpoint the time at which the universe was bathed in starlight for the first time, as Professor Richard Ellis explains.

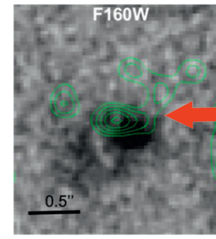
The Universe is believed to be around 13.8 billion years old, yet there were no stars during the early part of cosmic history. In fact, it was not until around 250 million years after the Big Bang that the first stars formed, as hydrogen clouds began to collapse under their own weight. “As these gas clouds collapsed, the energy that had kept them up was converted into heat. As the centre of these gas clouds became very hot, hydrogen was synthesised by nuclear burning into helium, and so the universe was bathed in starlight for the first time,” explains Richard Ellis, Professor of Astrophysics at University College London. As the Principal Investigator of the ERC-funded First Light project, Professor Ellis aims to pinpoint when this event occurred, a quest which he says holds profound implications. “We are all made up of material that was synthesised in stars,” he stresses. “We are thus searching for our own origins when we follow this exciting quest for `First Light'.”

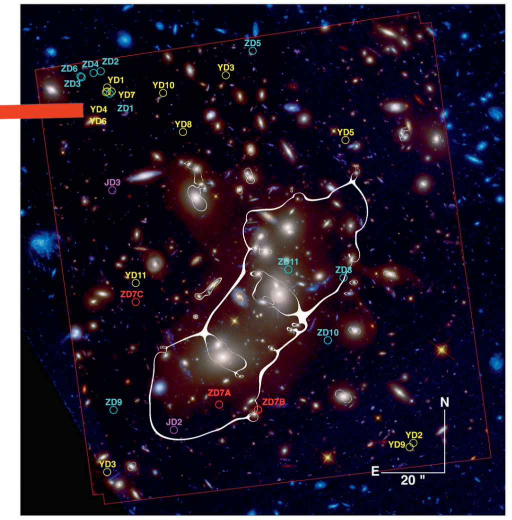
Researchers in the First Light project are using images and data from both space and ground-based telescopes to look back into cosmic history and observe early galaxies, formed at a time when the universe was barely 3 percent of its current age. Images from the Hubble and Spitzer Space Telescopes allow researchers to find where early galaxies are located, then more detailed insights can be gained through analysis of complementary data from ground-based telescopes. “Large ground-based telescopes such as ALMA, the VLT in Chile and the Keck telescopes in Hawaii,are ideal for getting spectra. These spectra are crucial for revealing how far away different galaxies are, and hence – taking into account the expansion of the universe – at what period in cosmic history we're seeing them,” explains Professor Ellis. This allows researchers to build a more complete picture.

The first glimpse of `First Light'

A number of important advances have been made over the course of Professor Ellis' project, including exciting spectroscopic observations of MACS1149-JD1, one of the furthest known galaxies, seen at a time around 500 million years after the Big Bang. His team confirmed that this galaxy is at a redshift (z) of around 9.1, meaning the universe has expanded more than ten-fold since light left it. “The universe is expanding, and as it expands, light rays from galaxies are stretched,” he explains. The team detected oxygen – the most distant ever detection of this element – from which new insights can be drawn on the previous







Detecting dust in the early Universe: Celestial dust comprises minute grains of silicon and other elements produced in supernova explosions (left). Dr Laporte and Professor Ellis detected the glowing radiation from warm dust in the galaxy YD4 (zoom) which is gravitationally-lensed by the massive cluster A2744.

history of this remote galaxy. “Oxygen is only synthesised by nuclear burning in stars. When a star collapses at the end of its life, it explodes in a supernova,” outlines Professor Ellis. “Supernovae are key to research on cosmic evolution because all the chemical elements that have been produced during the lifetime of a star are then expelled into space, and are ready as source material for any new stars that form.”

The presence of oxygen at z=9.1 suggests prior nuclear processing, which indicates even earlier periods of star formation. “We're inferring that there must have been starlight at earlier epochs in an object that we've studied at redshift 9.1,” says Professor Ellis. However, the most significant discovery Ellis' team found for MACS1149-JD1, in collaboration with Japanese colleagues at Osaka Sangyo University, is the clear signature of mature stars. Detailed models of the energy spectrum of the galaxy indicate this galaxy is already 290 million years old at z=9.1, indicating `First Light' occurred at a redshift of z~15 when the Universe was only 250 million years old. “Through this analysis, we have our first exciting glimpse of when the Universe emerged from darkness,” explains Professor Ellis.

Dust observations are similarly valuable in terms in assessing the ages of specific galaxies. “Like oxygen, dust is also produced in supernovae, and if we know roughly how much dust there is in a galaxy at early times, then it tells us how many supernovae must have exploded to produce that dust. That allows us to age-date a galaxy at early times,” explains Professor Ellis. “This then enables us to determine when First Light might have occurred, even if we can't yet observe it directly.”

One of Professor Ellis' postdoctoral assistants, Dr Nicolas Laporte, made an important contribution in this area through observations of dust in A2744_YD4, a very distant young galaxy, using the Atacama Large Millimetre Array (ALMA) - an interferometer based in the Atacama desert in Chile. Professor Ellis explains how ALMA can take two types of measurements. “It can scan across a certain frequency range, just like turning the dial on a radio. If there's suddenly a signal as you scan in frequency, that would tell you that there's a spectral feature, for instance from oxygen. We found an oxygen emission in A2744_YD4, which gives us the redshift of that galaxy at z=8.38,” he outlines. But ALMA is also sensitive to glowing dust, similar to background noise you might hear when tuning a radio. “This background noise represents the glow from interstellar dust heated by stars. Interstellar dust is composed of tiny particles of silicon that are only produced in supernovae at early times. They are sub-millimetre sized nuggets of silicon,” says Professor Ellis. “These particles are spinning in space and heated by starlight – then they glow, just like embers in a fire.”

Given Professor Ellis and his team has found that these dust particles existed just 600 million years after the Big Bang, they aim to build further on these findings. One major objective is to survey a larger population of early galaxies, see how much dust each contains, and build up a census.

“We can observe very early galaxies in their infancy, estimate their age, then from that assess when they were born,” outlines Professor Ellis.

The final piece of progress Professor Ellis' team has made is in determining exactly how these early galaxies drive cosmic reionisation – the transformation of hydrogen atoms in deep space into their constituent protons and electrons. “When the first stars switched on they were very hot, and they had enough energy to ionise the hydrogen around them. A very hot star produces very energetic ultraviolet light rays which have the energy to break hydrogen back into a proton and an electron. We call this process cosmic reionisation,” explains Professor Ellis. “In this context, we can estimate how numerous early galaxies were, but can we be sure all this energetic ultraviolet radiation escapes into deep space?”

The team has come up with a novel technique to address this important question by correlating the presence of early galaxies with fluctuations in the degree to which space is ionised as probed by hydrogen absorption seen in the detailed spectrum of a luminous background source, a quasar. “We are using the quasar, an intensely bright signal, as a beacon which illuminates the clouds of hydrogen along the line of sight towards us. Linking the presence or absence of hydrogen clouds

Large ground-based telescopes are ideal for getting **spectra.** These spectra are **crucial** for revealing **how far away different galaxies are,** and hence – taking into account the expansion of the universe – **at what period in cosmic history we're seeing them.**

FIRST LIGHT

Unveiling first light from the infant Universe

Project Objectives

Several hundred million years after the Universe was born the first stellar systems began to shine. Energetic photons from early hot stars, freionised the hydrogen in deep space. Ambitious observational facilities can directly chart this final frontier in cosmic history. The programme has three complementary themes. (i) Tracing the duration of the reionisation process by analysing the spectra of early galaxies; (ii) Determining whether star-forming galaxies are the sole agent of reionisation by addressing the number of ionising photons they produce and the fraction that escape; (iii) Inferring the abundance of the earliest galaxies whose direct detection is beyond reach of current facilities. Masses and ages of galaxies will be used to plan surveys for the James Webb Space Telescope.

Project Funding

The First Light programme is entirely funded by the ERC award which commenced on Oct 1 2015 and ends on Sept 30 2021.

Project Partners

Collaborators include astronomers at the Universities of Tokyo, Arizona, California (Santa Cruz, Davis), Lyons and Be'er Sheva (Israel).

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Professor Richard Ellis

Richard Ellis is Professor of Astrophysics at UCL with previous professorial positions at Durham, Cambridge and Caltech. He studies dark matter, the cosmic expansion and the first galaxies. His awards include the Gruber Cosmology and Breakthrough Foundation Prizes and the Gold Medal of the Royal Astronomical Society. He is a Fellow of the Royal Society and the Australian Academy of Sciences.

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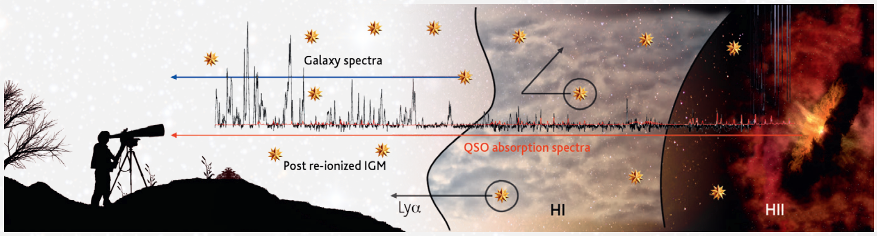
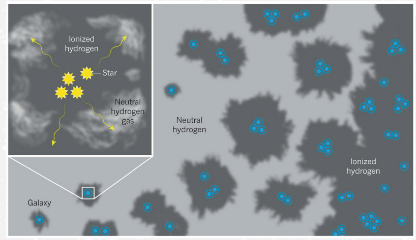


Drs Kakiichi and Bosman together with Ph.D. student Mr Meyer work with Professor Ellis to gather spectra of galaxies along the line of sight to a quasar (far right) luminous enough to highlight intervening absorbing clouds of neutral hydrogen. In this way they can determine how much ionizing radiation escapes a typical galaxy.



Star forming regions (yellow) produce ionising radiation but only a fraction of it reaches outer space due to re-absorption and scattering within each galaxy. Determining this fraction is a major challenge being addressed by the team.

to the proximity of galaxies allows us to examine the strength of the radiation that escapes from galaxies," adds Professor Ellis. This idea, first promoted by Dr Koki Kakiichi, one of Professor Ellis' postdoctoral assistants, is a major step forward in building the picture of how this cosmic reionisation occurred.

James Webb telescope

The James Webb telescope, currently scheduled for launch in March 2021, will allow astronomers to look further back than is currently possible and possibly observe `First Light' directly, an enormously exciting prospect. Competition for observing time with the telescope will be intense, so Professor Ellis and his colleagues are already making preparations. "We're reaching out to collaborators, so that we improve our chances of getting observing time," he explains. The James Webb telescope could also play an important role in other areas of research, such as the question of how quasars form. "As material falls into a black hole, it accelerates as it enters, and it produces radiation that is not related to starlight. Although these extraordinarily luminous quasars have been known about since the 1960s, we now know that quasars existed right back when the universe was about a billion years old, so about 8 percent of its present age," continues Professor Ellis. "So an obvious question is; how did these quasars form?"

The answer must be that the black holes they contain grew over time, and there must therefore be black holes in the early universe as well. This was the subject of a recent paper led by Dr Laporte. "We published a paper looking at the spectra of several of the most massive galaxies in the reionisation era. And indeed we found evidence that they may contain black holes," outlines Professor Ellis. This is an important consideration in terms of the future operation of the James Webb telescope. "When James Webb is launched, we should be open to the idea that we have another problem to solve, and that is; where do these quasars come from? And how fast did these black holes grow over time?" says Professor Ellis.