Mike Boylan-Kolchin | How did the universe light up?

Cosmos Ex Machina

The universe exists on scales of time and distance that lie entirely outside the range of human experience. It is dominated by two substances—dark matter and dark energy—that we cannot yet create, capture, or even measure in a lab. In the face of our ignorance, relegated as we are to a fleeting moment on one small planet, it may seem an absurd ambition for us to make sense of it all. Yet that is exactly what we cosmologists attempt to do.

We work to combine observations, mathematical models, and computer simulations to retrace the path from the chaos of the Big Bang to the modern universe. Astonishing as it may seem, we are succeeding. Propelled by a succession of ever-more-powerful telescopes, along with modern supercomputers that can perform millions of calculations in a trillionth of a second, we can now provide a detailed account of the growth and development of galaxies over cosmic time.

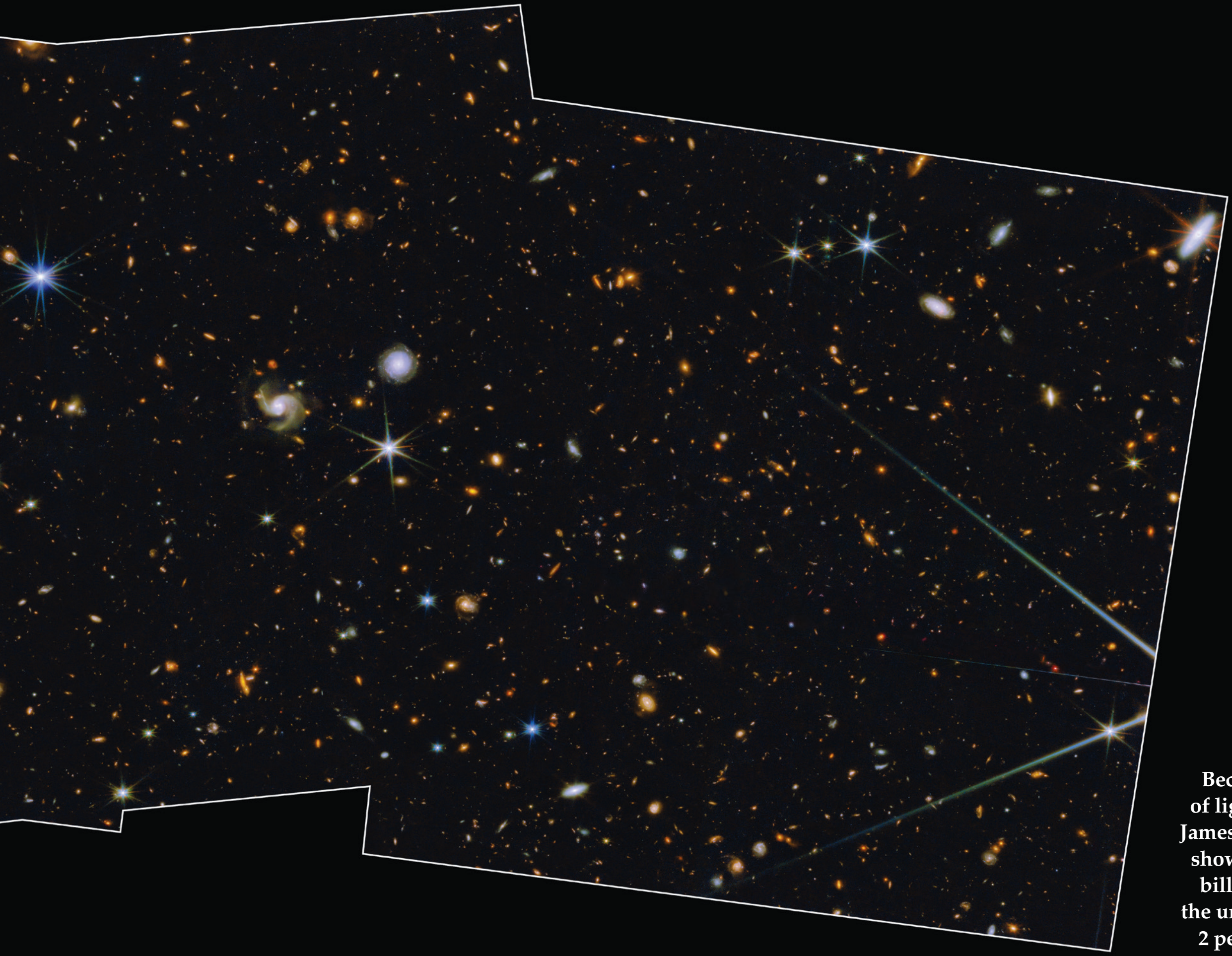
Just a few decades ago, it was not at all clear that we would be able to reach this point. As recently as the 1990s, cosmologists had not yet discovered dark energy, an omnipresent and elusive form of energy that is now recognized as the driver of the accelerating expansion of the universe. Researchers disagreed about the expansion rate of the universe by a factor of two, a discrepancy that provoked bitter arguments at scientific conferences. And astrophysicists could only speculate about when the first galaxies began to form.

Then in the 2010s, the European Space Agency's Planck satellite pinned down the recipe for the modern universe: 68 percent dark energy, 27 percent dark matter, and just 5 percent atomic matter. Planck's high-precision measurements of cosmic radiation also indicated that the universe is 13.8 billion years old, with an error of just 23 million years. Analyses of distant stars and supernovas have determined the expansion rate of the universe to within 10 percent. Most recently, the powerful James Webb Space Telescope (JWST)—which launched in December 2021—has shown us that the era of galaxies stretches back at least to the time when the universe was a mere 320 million years old and was about 1/14th its current size.

JWST is also keeping us humble. Its early observations indicate that galaxies formed earlier and faster than we had expected, in ways that our models did not predict. These findings are forcing us to reexamine our ideas about the earliest generation of stars and galaxies. But out of this current confusion could emerge the next revolution in our understanding of the universe.

Universe in a Box

In some ways, nature has made it remarkably easy to simulate the universe. If we can know the energy content of the universe at any one time (with matter defined in terms of its equivalent energy via $E=mc^2$), we can



Because of the finite speed of light, this image from the James Webb Space Telescope shows galaxies as they were billions of years ago, when the universe was as young as 2 percent of its present age. Many of these early galaxies appear unexpectedly mature.

NASA, ESA, CSA, A. Pagan (STScI), and R. Jansen (ASU)

simply plug those numbers into the equations of general relativity and understand how the energy density of the universe has evolved at all other times. Nature has also provided a blueprint of what the early cosmos looked like. We can observe the *cosmic microwave background*—relic radiation that has traveled to us unimpeded from a time 370,000 years after the Big Bang—to study the highly homogeneous (but not perfectly so) primordial distribution of matter and energy that seeded the galaxies we see today.

With this knowledge, we can predict how dark and atomic matter assembled into collections called *halos*, the formation sites of galaxies. Using the biggest supercomputers and cranking through the equations for gravity, my colleagues and I can evolve simulated mini-universes and see how they change over time. Our models, combined with observations of the real universe, tell us that structure grows hierarchically. Small halos form first, dominated by dark matter; their atomic matter is too sparsely distributed to form stars. The inexorable pull of gravity subsequently brings together many smaller dark halos to form larger ones. It takes time for them to grow massive enough to trigger the formation of galaxies.

Ordinary matter may make up only 5 percent of the universe, but it produces most of its complexity. Protons, neutrons, and electrons interact in varied and complicated ways. The laws that govern atomic matter and its interactions with radiation (and, through gravity, with dark matter) are well known, but the outcomes are hard to predict. Gas cools, condenses, and forms stars; the stars, in turn, inject energy and momentum into ambient gas during their lives and their often-spectacular deaths.

It is essentially impossible to analyze these competing processes by hand. Instead, we feed the equations of gas dynamics into our supercomputer simulations and explore the consequences. We use two complementary classes of simulations to model the universe. The *ensemble technique* attempts to simulate many galaxies from a representative section of the universe, encompassing a volume that is hundreds of millions to billions of light-years across. The *zoom-in technique* places a computational magnifying glass on individual galactic systems and explores these in great detail. Each approach has its benefits and its limitations. The ensemble technique allows us to make predictions about collections of galaxies but can resolve individual systems only fairly coarsely; the zoom-in technique can provide spectacular detail but only on a galaxy-by-galaxy basis.

Although my background lies in conducting big-picture, ensemble studies, I have been captured by the allure of zoom-in simulations, because they allow us to limit our assumptions and pose more specific questions. Can we form individual galaxies that have thin disks and spiral structures like the Milky Way? Can we also form huge, featureless balls of stars like the biggest known galaxies? Can we track the details of individual star-forming regions and show how thousands of them interact to produce realistic galaxies? It is exhilarating to put the laws of physics into software code, watch the world's biggest supercomputers evaluate these laws trillions of times, and get back the entire history of a galaxy, showing its gas, stars, and dark matter.

Then comes the hard reality check of comparing our computer simulations with astronomical observations. The physical processes that influence galaxy formation are so complex and operate on such a range of scales—from Solar-System–sized disks of hot gas swirling around black holes to galaxy superclusters that are 10 trillion times larger than those black-hole disks—that we cannot fully simulate them all from first principles. We have to make simplifying assumptions about how physics operates, convert those assumptions into rules that we can express in computer code, and then rigorously evaluate how closely our results resemble the actual universe. When our simulations agree with reality, that is good—but surprisingly, it is not good enough to know that the simulation is accurate. Multiple large simulation efforts can match a wide array of observations, even though the simulations often rely on very different physical models. Agreement with observations is merely a necessary condition, not a sufficient one, to claim that a given model is a physically realistic, predictive theory of galaxy formation.

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Often, we learn the most from disagreement. When observations and modeling disagree, we are forced to scrutinize the source of the discrepancy and to consider whether our modeling merely needs minor adjustments (a few more supernovas here, some more cosmic rays there) or if we are missing fundamental aspects of nature.

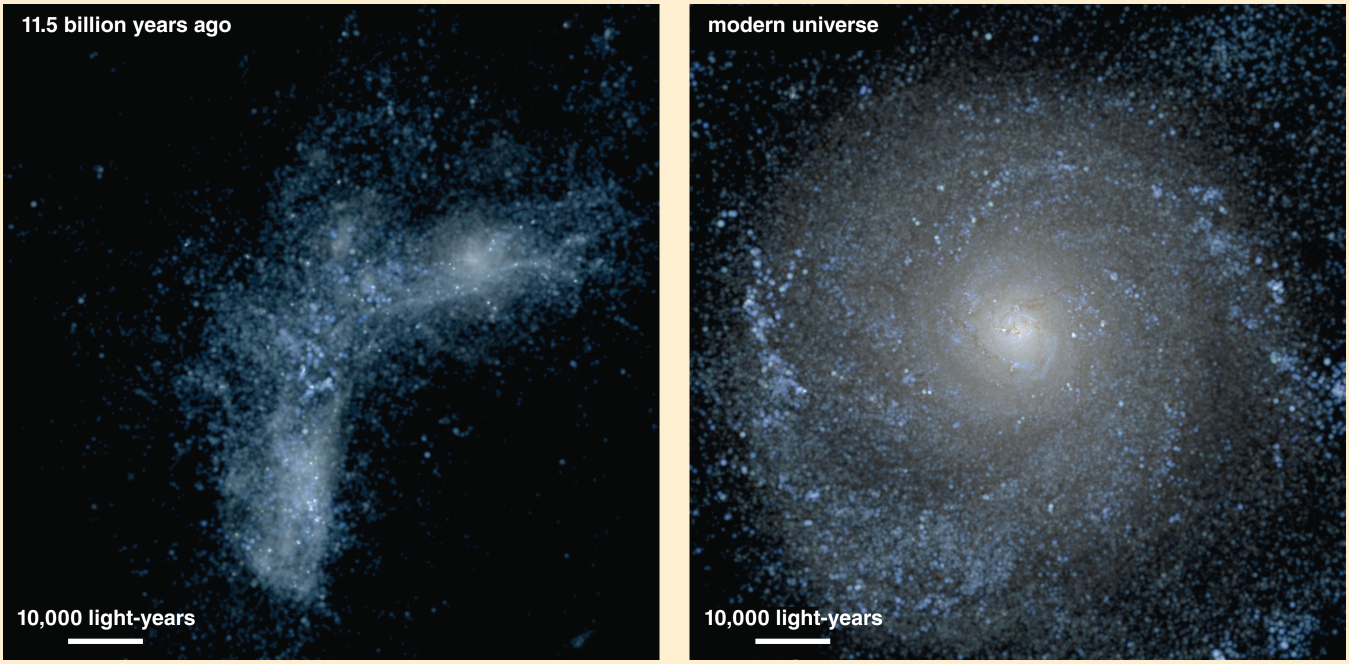
One major disagreement between simulations and observations led to the gradual realization over the past 25 years that black holes have a powerful influence on the properties of massive galaxies. This realization began, as many do, with a seeming contradiction. Massive galaxies at the centers of galaxy clusters are known to contain tremendous reservoirs of gas. All of our knowledge of gas physics said that the gas should be able to cool quickly and collapse, forming a large population of young stars. Observations showed that those galaxies are actually composed predominantly of extremely old stars. Evidently something prevented the gas from turning into stars—but what?

Astronomers knew that the supermassive black holes at the centers of some galaxies can release enormous amounts of energy as they pull in surrounding material. That seemed like a possible mechanism that would heat gas in the galaxies and prevent it from forming stars, but how that process could work was unclear. A breakthrough came when new observations from the Hubble Space Telescope and other facilities demonstrated that supermassive black holes are present in almost all galactic nuclei; meanwhile, theoretical models began to show how energy from those black holes is released and flows through the surrounding galaxy. We now believe that supermassive black holes are indeed crucial to suppressing star formation in massive galaxies, although the details remain a matter of debate. The universe is not so quick to give up its secrets.

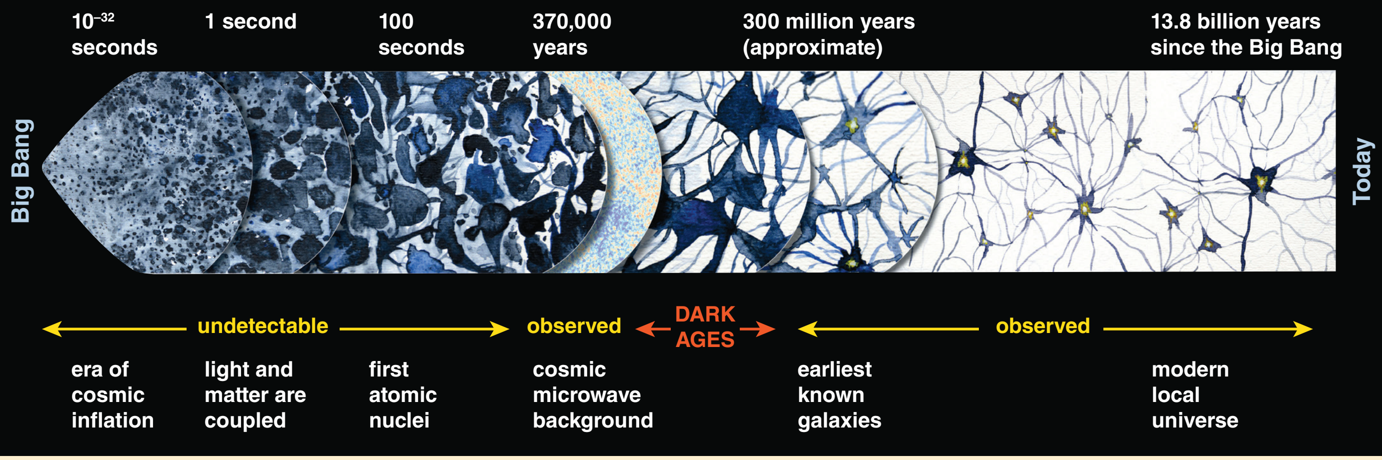
Observing the Past

One of the most exciting capabilities of JWST is its ability to catch light from some of the earliest-forming galaxies.

Computer-generated galaxies from the Feedback in Realistic Environments (FIRE) project allow researchers to rerun the history of the universe. FIRE incorporates detailed information about energy, momentum, mass, and composition to show how formless clouds of gas in the early cosmos (*left*) developed into the well-formed structures seen today (*right*). Such simulations keep getting more accurate, but they still cannot match all the observations.



Jacob Shen/FIRE Collaboration



ESA/Planck, adapted by Barbara Aulicino

This cosmic time line highlights how much of the universe we can observe. It is fundamentally impossible to observe events from before the time of the cosmic microwave background. After that, there was a long gap—the dark ages—before galaxies formed and became visible to us. New telescopes are exploring ever-deeper into the dark ages in search of the earliest stars and galaxies.

Those galaxies are so distant that their radiation has taken billions of years to reach us; over that long journey, the expansion of the universe has stretched energetic light from young stars in those galaxies into longer-wavelength infrared rays that cannot be detected by the Hubble telescope or by ground-based observatories.

JWST was designed to search for the infrared glow of those early stars, and the results are already exceeding expectations. In its first months of operation, the telescope uncovered a startling abundance of well-developed galaxies that appear to have taken shape within the first billion years after the Big Bang. If these observations check out—astronomers are now racing to confirm them—then stars must have formed much faster, and in much greater abundance, in the early universe than previous studies and models indicated.

This news has created an anxious buzz among those of us who study galaxy formation and evolution. Are we misinterpreting the JWST findings? Are we missing something fundamental in our simulations of early galaxy formation? Or do we need to modify the underlying cosmological model on which those simulations are based?

Perhaps JWST has, by chance, observed a highly unusual portion of the sky. Perhaps star formation proceeded differently in the very early universe, when gas clouds did not yet contain the heavy elements that were created by later generations of stars. Perhaps we are actually seeing emissions from black holes and confusing it with starlight. Or, most speculatively, maybe these observations point to a fundamental shortcoming in our cosmological model.

One hypothesis is that there could be a distinct form of dark energy that operated very early in cosmic history (just 50,000 years after the Big Bang), catalyzing the growth of galaxies. As wild as this "early dark energy" scenario may sound, it is not ruled out by observations; in fact, it could help explain a small but notable discrepancy seen between two different ways of measuring the expansion rate of the universe, a problem known as the *Hubble tension*.

Many diverse groups of scientists are investigating these ideas, coming up with models, arguing with one another about both observations and predictions, and disagreeing about the underlying causes. The process may look messy or confusing from the outside, but each of these possibilities is being carefully vetted. Disagreement between our expectations and observations is what drives improved understanding, and sometimes overturns established models. This situation is the cauldron of progress, caught in mid-boil.

We are likely to learn more soon: These surprises come from a relatively small amount of data taken from just the initial JWST observations. Much more data have already been collected and are being analyzed. JWST was so efficient in getting to its observation location (an orbit that keeps it 1 million miles from Earth) that its nominal five-year mission may be extended to 20 years or more. And over the coming decade, many other new observatories—from the European Space Agency's Euclid satellite, to NASA's upcoming Roman Space Telescope, to the Dark Energy Spectroscopic Instrument in Arizona, to the Vera C. Rubin Observatory taking shape in Chile—are set to explore the nature of dark matter, dark energy, and galaxy formation.

There will almost certainly be additional surprises, and we will have to update our models for how galaxies form and evolve, perhaps in major ways. Personally, I am waiting with bated breath for the Rubin Observatory to make sensitive observations of the numerous dwarf satellite galaxies that surround the Milky Way. The number and distribution of those satellites are strongly influenced by the properties of the galactic halos in which they formed, so they should provide insights into the nature of dark matter. The dwarfs are also some of the oldest and least evolved galaxies in the nearby universe; they may be living fossils from the early era of the cosmos that JWST is starting to directly reveal.

By combining new observations, theoretical models, and computer simulations, we are getting closer than ever to our goal of understanding how the universe works. What will our picture of galaxy formation and cosmology look like in 20 years? I cannot say, and I cannot wait to see.

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