

Cosmic Dark to
Cosmic Dawn:
A Science Outreach Website

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Project Overview

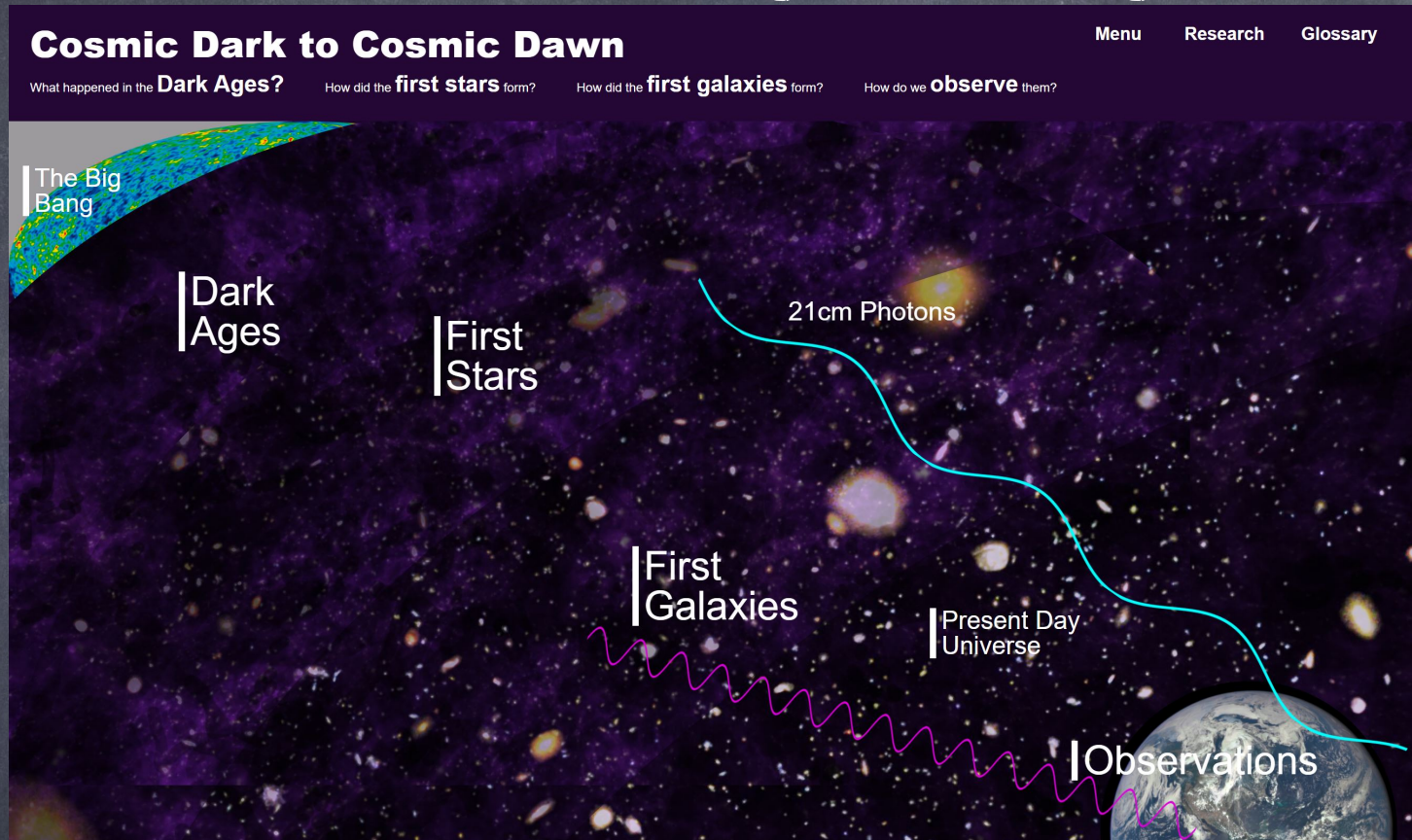
- There are no dedicated websites explaining the Dark Ages, Cosmic Dawn, and the epoch of reionization for laypeople
- We HOPE many people will soon be searching for more information - with DAPPER, EDGES, JWST, HERA, etc.
- We aim to fill that gap with an accessible and informative site covering the science and the instruments
- Project is jointly funded by NESS and NSF

Project Overview

- Eventually, will include versions for:
 - Interested laypeople (~Scientific American level)
 - Kids (targeting late elementary)
- Eventually, will include animations and tutorials
- First goal: complete science overview for adults
 - We will go "live" once we have this portion complete (target: early spring)

DRAFT Screenshots!

Landing Page



- Goals:
 - Easy drop-in navigation
 - Graphically clean and attractive
- Variety of engagement levels
- Science and technology tracks

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Example Science Pages

- Self-contained opening paragraph
- Main text expands on these points (with images)
- Sidebar points toward observations

Cosmic Dark to Cosmic Dawn

[What happened in the Dark Ages?](#) [How did the first stars form?](#) [How did the first galaxies form?](#) [How do we observe them?](#)

SPINNING THE COSMIC WEB

The cosmic microwave background began its journey to us 400,000 years after the Big Bang, when neutral hydrogen formed. After that, light and matter stopped interacting for tens of millions of years. During this period, the hydrogen gas cooled rapidly as it began to respond to the gravity of dark matter. Dark matter is a form of matter that only interacts through gravity – its identity remains a mystery, but its gravity drove the formation of all structure in the Universe. Over these tens of millions of years, the dark matter assembled into a complex network of intersecting filaments called the Cosmic Web. These strands were only slightly denser than the rest of the Universe, but along them tiny clumps of dark matter grew into small clumps, and eventually into clumps large enough to attract hydrogen gas. But all this occurred without producing any light: the Dark Ages of the Universe.

Image Credit:

Previous: The Big Bang and CMB

Next: Exotic Physics



How does dark matter create the cosmic web?

Using a variety of methods, astronomers have inferred the existence of a mysterious form of matter called dark matter. Dark matter exerts gravity, just like any other matter, but otherwise it barely interacts with normal matter. It has not yet been directly detected, but its gravity is essential for holding galaxies together – about 80% of all the matter in the Universe is dark matter, not the ordinary kind that makes atoms! Its gravity is also crucial for growing galaxies. Imagine a tiny clump of dark matter in the Universe. The extra gravity it exerts collects more dark (and ordinary matter), so the clump grows bigger and bigger over time. In our three-dimensional Universe, this gravitational growth turns out to be asymmetric, and the clumps take the form of a network of intersecting sheets and filaments, separated by large regions with relatively little matter. The result resembles a sink full of soap bubbles, with the clumps of matter arrayed along the walls of the bubbles (and especially where those walls intersect each other) and largely empty regions in between. This is the cosmic web, and it forms the “skeleton” through cosmic history.

Image: 31.25 Mpc/h across the cosmic web at redshift $z=18.3$ (0.21 Gyr), $z=5.7$ (1.0 Gyr), and $z=1.4$ (4.7 Gyr) respectively.
Credit: Springel et al. (2005)

What happens to the cosmic web later in the Universe's history?

The Dark Ages, which extend from about 400,000 years after the Big Bang to about 50 million years later, saw the initial formation of the cosmic web: gravity takes time to interact, and it was only during this time that it could establish itself. Over time, the contrast between the sheets and filaments of the cosmic web grew – the gravity of the extra matter in the web continued to collect more and more matter – and the “voids” in between grew emptier and emptier. Today, nearly all galaxies are arrayed along the filaments of the cosmic web, and their intersections host vast clusters of thousands of galaxies.

Image: Again 31.25 Mpc/h across the cosmic web, but for present day redshift $z=0$ (13.8 Gyr)
Credit: Springel et al. (2005)



What happens to the hydrogen gas during the Dark Ages?

After the cosmic microwave background formed, the hydrogen atoms could no longer interact with those photons. They could only do two things: cool off or

What telescopes are trying to observe this?



Radio Telescopes

Because luminous sources did not yet exist in the Dark Ages, the only way to study this era is to look for subtle signatures from the hydrogen gas itself. These are extraordinarily difficult to detect, but the DAPPER mission hopes to observe them in the coming decade.

Vocab:

Dark Matter, Star, Population III, Gravity, Luminosity, Gas, Neutral Hydrogen Light-year

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Cosmic Dark to Cosmic Dawn

[What happened in the Dark Ages?](#)[How did the first STARS form?](#)[How did the first galaxies form?](#)[How do we Observe them?](#)

THE FIRST STARS

About 75 million years after the Big Bang, gravity caused dark matter to coalesce into clumps that could hold gas. This gas cooled and condensed, forming the first stars. They were likely far more massive than the Sun, meaning also hundreds of thousands of times more luminous. The first stars consumed their fuel quickly and died violently, but despite brief lives, lit the Universe up in the "Cosmic Dawn."

An artist's conception of blue giant, a star similar to those in the Cosmic Dawn.
Image Credit: NASA's Goddard Space Flight Center/S. Weisinger

Previous: Exotic Physics

Next: The First Black Holes

What is a star?

A star is a massive ball of gas bound together so tightly by gravity that it heats up to enormous temperatures – tens of millions of degrees Celsius at its center – in order to keep itself against further collapse. At such high temperatures, the atoms in these stars undergo nuclear fusion, in which light elements (like hydrogen) collide and stick together as heavier elements. In our Sun, fusion transforms enormous quantities of hydrogen into helium each second. During each of these reactions, a tiny bit of matter is converted into energy, providing the extraordinary luminosity of the Sun. The properties of a star are mostly driven by its mass: more massive stars have more extreme gravity, and hence higher temperatures, and hence produce more light. In the Milky Way, there is a wide range of stellar masses: our Sun is about average, but there are stars ten times smaller and a few stars more than one hundred times more massive.

Image: Full disk view of the sun from SDO, telescope AIA 335 on June 2, 2010.
Credit: NASA Goddard

How did the first star forming clouds form?

Star formation begins with a cloud of relatively dense gas. At the end of the cosmic Dark Ages, the gravity of dark matter clumps grew strong enough to pull neutral matter into them. Inside these clumps, gas clouds began to form. Unfortunately, these clouds were not nearly dense enough to form stars, because they were too hot. Over time, the hydrogen atoms inside them collided and formed molecular hydrogen (two hydrogen atoms stuck together), which themselves would also collide. After these latter collisions, the hydrogen molecules lost some of the collision energy as light – which escaped the gas cloud, cooling it off and allowing it to contract. After many millions of years, this slow process allowed enough matter to accumulate at the center to form the first stars in the Universe.

Image: An artist's impression of early star formation.
Artist Credit: Adam Schultz for STSC
Science Credit: NASA and J. Lora

What were the first stars like?

While the Sun is a very typical star in the Milky Way galaxy, the first stars to form were likely many times more massive than our Sun – while their detailed properties are as yet unknown, their formation process suggests that they are likely tens or even hundreds of times more massive than the Sun. Because of these extreme sizes, these stars had prodigious luminosities, and they consumed their fuel supplies in just a few million years. (The Sun, even though it is so much less massive than these stars, consumes its fuel far more slowly – it will take about ten billion years before it runs out of fuel.)

Image: A depiction of the first stars created with supercomputers.
Credit: Tom Abel and Paul Fisher

How did the first stars end their lives?

Because they are so massive and compact, the material inside stars feels strong gravity. The only way to support itself against this gravity is for the material to be extremely hot, so that its intense pressure can resist gravity. But once a star runs out of fuel for nuclear fusion, it has no way to maintain a high temperature – and gravity wins! For the very first, very massive stars, the end of the fuel supply leads to either a supernova explosion, in which nearly the entire star explodes with enormous energies, or the formation of a black hole – a region of such intense gravity that nothing, not even light, can escape.

Image: The Crab Nebula is a modern example of a supernova remnant, a type of dead star.
Credit: NASA, ESA, J. Hester, A. Loll (A&U)

What telescopes are trying to observe this?

Radio Telescopes and Space Telescopes

These first stars form at such great distances, and in such small clumps. But they cannot be seen by galaxy surveys! In the coming years, we hope to observe them indirectly through their effects on the spin-flip background with radio telescopes, and we may be able to detect them directly with the help of gravitational lensing or when they explode as supernovae at the end of their lives.

Vocab:

Dark Matter, Star, Population III, Gravity, Luminosity, Gas, Neutral Hydrogen, Light-year

Previous: Exotic Physics

Next: The First Black Holes

Want to know more?

External Links




This article from the James Webb Space Telescope also discusses the first stars.
This article provides much more detail on how the first stars form.
This article explains the computer simulations that have been a part of driving our expectations for the first stars.

Our Mission:

The site is intended as a free educational resource about the frontiers of galaxy formation.

Creation and Funding:

Conceived and supervised by Professor Steven Furlanetto, website design by Erika Hoffman, funding from NASA NESS & NSF



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Example Science Pages

- Self-contained opening paragraph
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- Sidebar points toward observations
- Some pages have a third "layer" with focused research questions (these will become tutorials)

landmark of the first generations of galaxies, marking the transition from the Cosmic Dawn to the later evolution of galaxies.

Star cluster NGC 3603, a modern example of young cluster surrounded by gas and dust, helping us understand massive star formation in the early universe.

Image Credit: NASA/Goddard

Previous

Next

How is hydrogen ionized?

Hydrogen is the simplest of all atoms: normal hydrogen consists of a single proton, with a positive electric charge, and a single electron, with a negative charge. The mutual electrical attraction of these particles holds the atom together, but if light with enough energy hits the atom, it can knock the electron free. This is called ionization. At the beginning of the Cosmic Dawn - during the Universe's Dark Ages - nearly all of its hydrogen was electrically neutral. But stars - at least those much more massive than our own Sun - produce a great deal of ionizing light.

Image: IC 342, and its core which is a specific type of central region known as an H II nucleus - a name that indicates the presence of ionized hydrogen - that is likely to be creating many hot new stars.

Credit: NASA/Goddard

How do galaxies reionize the Universe?

All galaxies, including those today, produce massive stars, which in turn produce ionizing light. But most stars are formed deep inside their galaxies, and today the hydrogen gas of those galaxies absorbs nearly all the ionizing light, preventing any from escaping. However, during the Cosmic Dawn, astronomers believe that the small galaxies were violent places, full of ionizing gas that occasionally opened up escape paths for that ionizing light. Once it escaped, that light would be absorbed by hydrogen gas surrounding the galaxy - making a bubble of ionized gas around each galaxy. But these galaxies were common enough that those bubbles quickly overlapped. As more and more galaxies formed, and as each galaxy grew larger, these bubbles grew and merged, until they filled the Universe. This is reionization, the last time in the history of the Universe when hydrogen throughout the Universe changed its state. Studying the process will help us learn both about how hydrogen gas pervades the Universe and about the galaxies driving it - even those we cannot see individually.

Image Credit:

When did reionization occur?

Astronomers have worked hard over the past twenty years to understand the reionization process. But we cannot yet study the how of reionization; no observations exist yet that can probe that aspect of the process. However, there are many ways to begin to answer the question of when reionization occurred. (Reionization is actually a process, occurring over a period of time, but most observations try to understand either when it ended or when about half the Universe was reionized.) Because the hydrogen gas itself produces only the weakest of light (in the spin-flip background, which has not yet been observed in this period), these techniques are all based on finding a distant source of light and observing how the intervening gas affects that source's light. For details on some such methods, see below.

Image Credit:

How does reionization affect the Universe?

Reionization is fascinating on its own terms, because it teaches us both about galaxies during the Cosmic Dawn and the remaining matter at that time - when only about 25% of the Universe's hydrogen was inside a galaxy. But it also has important implications for later generations of galaxies. In addition to ionizing the gas, reionization also heats - heats by a factor of several thousand. The increased gas temperature makes it harder for other galaxies, especially small ones, to attract this gas. Thus reionization shifts galaxy growth toward larger objects, halting some of the smallest from continuing to form stars. That effect may even explain the properties of some of the Milky Way galaxy's smaller neighbors.

Image Credit:

How can we learn about galaxies by studying reionization?

The sizes of the ionized bubbles that grow during reionization depend on the galaxies producing them, in both obvious and subtle ways. By studying the size distribution of these bubbles, we can learn about the galaxies themselves. This image shows some "snapshots" of reionization according to a computer simulation. Each panel shows the mixture of ionized (white) and neutral (black) gas. Each row takes a different phase of reionization (early, middle, late, top to bottom), and each column uses a different set of galaxies to drive reionization, with the size of the galaxies increasing from left to right.

If we follow one of these computer simulations through the stages, we see the ionized bubbles growing as they complete reionization. The first thing we learn by measuring the bubble sizes is the timing of reionization. However, if we compare all the snapshots in an individual row - all taken at the same point during reionization - we also see that the bubbles grow bigger as the galaxies grow bigger! This is not for what might seem the most obvious reason - after all, bigger galaxies have more stars so make more ionizing light. This is because these ionized bubbles have hundreds or thousands of sources - even the largest galaxy can only make a very small bubble. Instead, it is because the largest galaxies are most likely to have neighbors, which can combine forces to create even larger bubbles. Thus the second thing we learn about reionization is how large the galaxies driving it are.

This is particularly useful because, in most predictions of the Cosmic Dawn, the vast majority of the starlight is produced by extremely small galaxies that we cannot otherwise easily detect. But by studying the reionization process, we can infer their properties even without seeing them!

Figure Credit: McQuinn et al. 2007

What are some methods of determining when reionization occurred?

The CMB was produced 400,000 years after the Big Bang, so on its way to our telescopes the microwave light must pass through the neutral gas (before reionization) and the ionized gas (afterward). The neutral hydrogen has no effect on most of the CMB, but once the electrons are liberated from their atoms, the electrons scatter the microwave light. Each time a microwave collides with an electron, the path of the microwave is bent slightly, blurring out the cosmic microwave background just a bit. But this scattering also imprints a direction to the oscillation of the light, called polarization (while linearly polarized light has a single plane of oscillation, circularly polarized light has a plane of oscillation that rotates). The latter estimates that reionization reached its midpoint roughly 700 million years after the Big Bang.

Although neutral hydrogen doesn't have a significant effect on microwave photons, it can strongly absorb ultraviolet light. Astronomers can search for the signatures of this absorption on light from sources from before the end of reionization. This is easiest to do with extremely bright sources, such as quasars (whose exceptional luminosity is generated by gas falling onto supermassive black holes). Recent analyses of two of these objects also suggest that reionization was ongoing about 700 million years after the Big Bang. Meanwhile, measurements of many other quasars that existed about a billion years after the Big Bang suggest that reionization is ending all roughly that time.

Hydrogen absorption can also be seen via galaxies - although normal galaxies are far fainter than quasars, they are also far more common. In the future, it may be possible to map out the ionized bubbles by looking at how intervening hydrogen affects their light. But for now, this is challenging because of how little we understand the galaxies.

Credit: NASA / WMAP Science Team

What telescopes are trying to observe this?

Everything!

The epoch of reionization is such an important event in the history of galaxy formation that astronomers are trying to probe it with a number of techniques. The intergalactic hydrogen itself can be studied with low-frequency radio telescopes, using the spin-flip background. But the hydrogen gas also affects measurements of galaxies and quasars with near-infrared telescopes, including both space observatories like the James Webb Space Telescope and ground-based instruments like the Thirty-Meter Telescope.

Vocab:

Dark Matter, Electron, Proton, Ionize, Intergalactic Gas, Cosmic Microwave Background (CMB)

Example Telescope Pages

- Opening "splash" page highlights several techniques
- Includes a visual map that highlights lunar work

Cosmic Dark to Cosmic Dawn

What happened in the Dark Ages? How did the first stars form? How did the first galaxies form? How do we observe them?

Menu Research Glossary

Dark Ages Polarimetry Pathfinder
Location: Moon Orbit
*Launch: 2022

James Webb Space Telescope
Location: Second Lagrange Point
*Launch: October 2020

Keck Telescopes
Location: Hawaii

Hydrogen Epoch of Reionization Array
Location: South Africa

Astronomers have studied the first billions of years of galaxy formation for many years, but many mysteries remain. Fortunately, a host of new telescopes - many involving powerful new technologies - will focus on these questions over the next several years, and we hope to learn a great deal more about them soon. These efforts will include new space and ground telescopes to observe the first galaxies, as well as radio telescopes on Earth and the Moon aiming to observe the signature of hydrogen in the early Universe. (See more details below!)

Previous: Next: Near-Infrared Space Telescopes

Near-Infrared Space Telescopes

Although the first stars and galaxies were luminous in optical and even ultraviolet light, their light is stretched out, or redshifted, as it travels through the Universe toward Earth. For such distant sources, the stretching is so extreme that their ultraviolet light is shifted all the way to the near-infrared - a regime in which Earth's atmosphere makes observations difficult. Fortunately, the Hubble Space Telescope has near-infrared cameras that have taken exquisite pictures of distant galaxies, and studying these objects in even more detail is one of the key projects of the James Webb Space Telescope, due for launch in late 2021.

Image: James Webb Space Telescope concept
Credit: Northrop Grumman

Ground-based Near-Infrared Telescopes

Although the atmosphere presents challenges for observing in the near-infrared, it is far from impossible. Ground-based telescopes have the advantage of size, which determines how much light a telescope can collect from these distant galaxies. The Keck Telescopes and other large observatories (with mirrors about 30 feet, or 10 meters, across - four times more than the Hubble's mirror) have helped us to understand some of the detailed properties of distant galaxies. This decade will see the construction of several even larger telescopes, up to 100 or so feet across - four times larger than the James Webb Space Telescope. This new generation of telescopes, such as the Thirty Meter Telescope, will be crucial for making careful measurements of galaxies in the Cosmic Dawn.

Image: Keck Observatory
Credit: Ethan Tweedie Photography/W. M. Keck Observatory

Low-Frequency Radio Telescopes

During most of the Cosmic Dawn, the vast majority of matter in the Universe remains outside of galaxies, and to measure its properties we must use different techniques. Amongst the most exciting is to study the spin-flip background generated by these atoms, which we hope to observe with radio telescopes operating in a similar frequency range to television antennae. Such observations are extremely challenging, in part because of interference from Earth, so some hope to deploy to the far side of the Moon!

Image: HERA 2019
Credit: HERA Construction Photo log.

Other Telescopes

Astronomers are always seeking new ways to study the Cosmic Dawn. Some telescopes, such as SPHEREx, will map emission from galaxies with telescopes that are intentionally blurry - because in that case they can observe the total emission from galaxies - including the faint ones often hidden from view! In the future, gravitational wave telescopes will detect the signatures of colliding black holes at enormous distances - even into the Cosmic Dawn.

Image: SPHEREx concept
Credit: JPL

Previous: Next: Near-Infrared Space Telescopes

Our Mission:
The site is intended as a free educational resource about the frontiers of galaxy formation.

Creation and Funding:
Content and supervision by Professor Steven Furlanetto, website design by Erika Hoffman, funding from NASA NESS & NSF

NASA NESS NSF

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