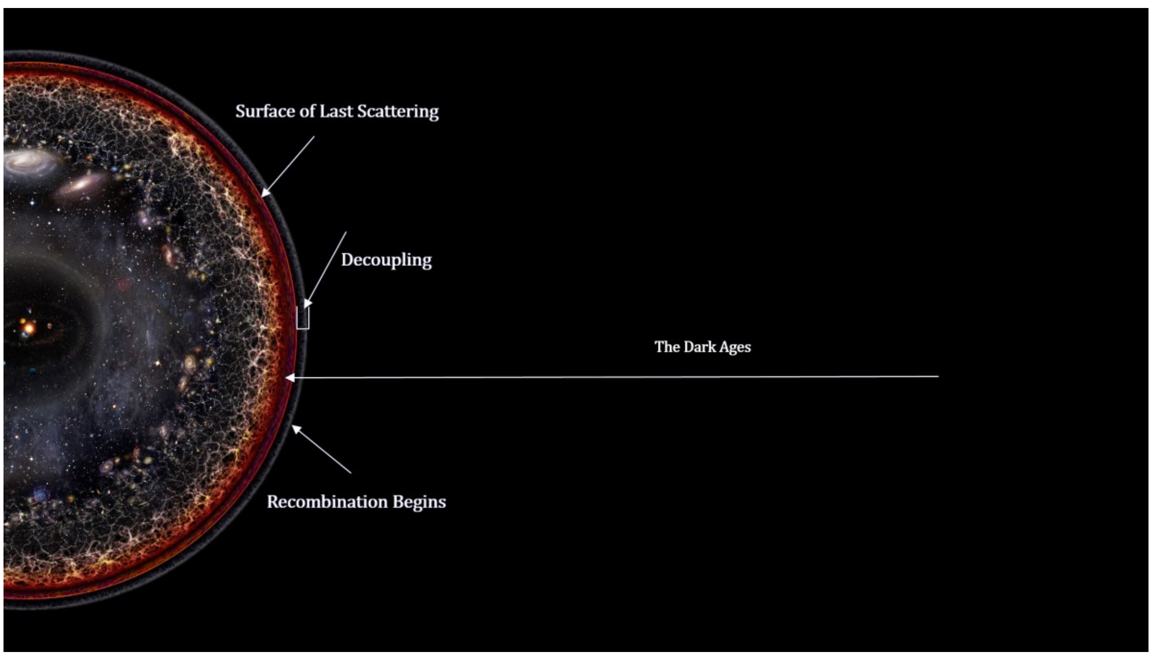
The Era of Reionization

Reionization Introduction

In our previous chapter on the ΛCDM benchmark model, we covered the Big Bang up to the Surface of Last Scattering that created the Cosmic Microwave Background. This was triggered by the Universe's cooling to the point where electrons could couple to protons to form hydrogen - Recombination. Before that, space was extremely dense and ionized with the protons and electrons moving separately. Light could not travel far before being absorbed by free electrons. After Recombination, only the light with the wavelengths associated with the energy levels of Hydrogen and Helium were absorbed. It could travel across the Universe. But no new light was being created. The dark ages had begun.

During the dark ages, that lasted between 370,000 to 150 million years after the Big Bang, the universe continued to expand and cool. Stars, black holes, and galaxies began to form. We call the space around and in between galaxies the Inter Galactic Medium or IGM for short. The universe was filled with neutral hydrogen and its temperature and density were decreasing. It was assumed to have stayed that way. But the discovery of the first quasar in the early 1960s, changed that view.

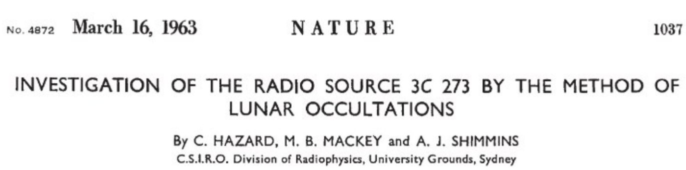


Discovering the 1st Quasar

In the 1950's, radio telescopes were searching the sky for celestial objects that radiated radio waves from spots on the sky where no visible light that could be detected. The objects were referred to as radio stars. A method for accurately determining the positions of radio sources was developed using lunar occultations.

Radio wave (in red) panorama of a section of the Milky Way in the constellations of Scutum and Aquila.

On March 16, 1963 three astronomers, C. Hazard, M.B. Mackey, and A. J. Simmons published a paper in Nature describing what they found in 1962 using lunar occultations with the new Parkes Radio Telescope in Australia to study the intense radio source 3C 273.



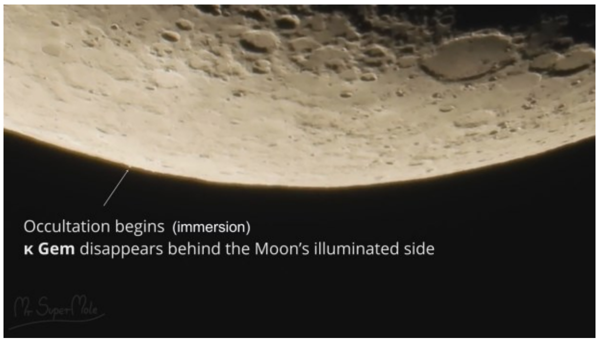
No. 4872 March 16, 1963 NATURE 1037

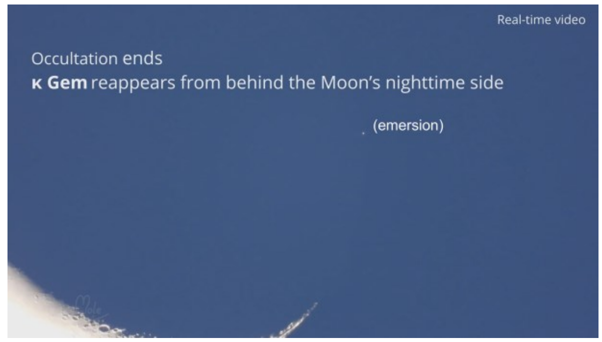
INVESTIGATION OF THE RADIO SOURCE 3C 273 BY THE METHOD OF LUNAR OCCULTATIONS

By C. HAZARD, M. B. MACKEY and A. J. SHIMMINS
C.S.I.R.O. Division of Radiophysics, University Grounds, Sydney

The moon would be occulting this radio star three times: one on April 15th; one on August 5th; and one on October 26th. They were able to locate its position to within 1 arc-second.

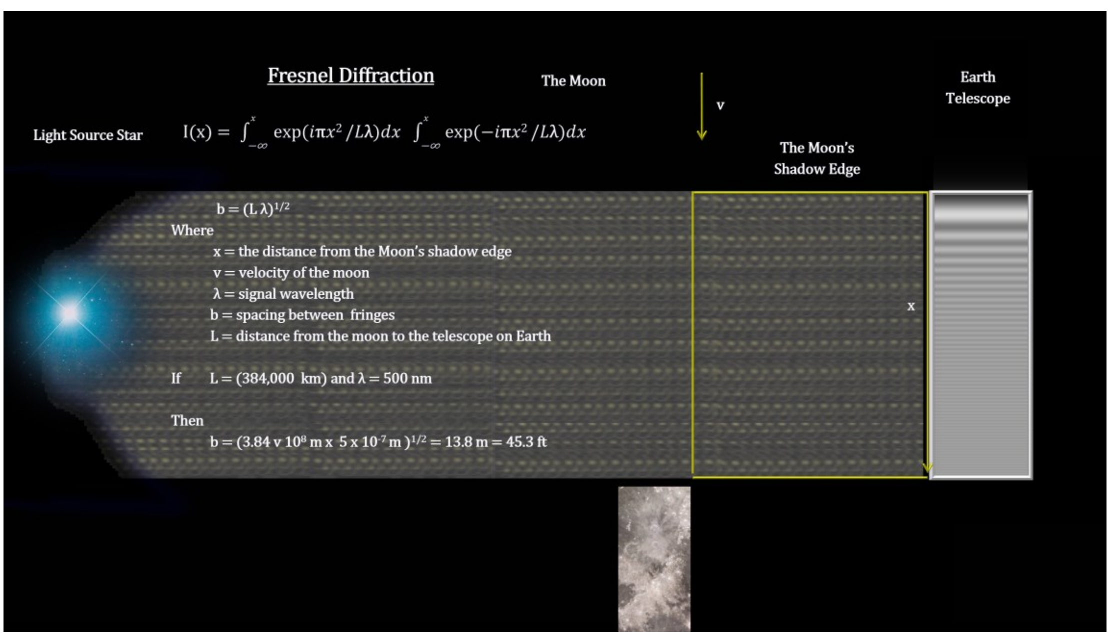
Here's a short clip illustrating how it works with a visible star. The disappearance of a light source behind the Moon is called immersion, and its subsequent re-appearance on the other side is called emersion. We can use the edged of the moon as a diffracting straight line at both events. The technique enables source location on the sky to within an arc second.



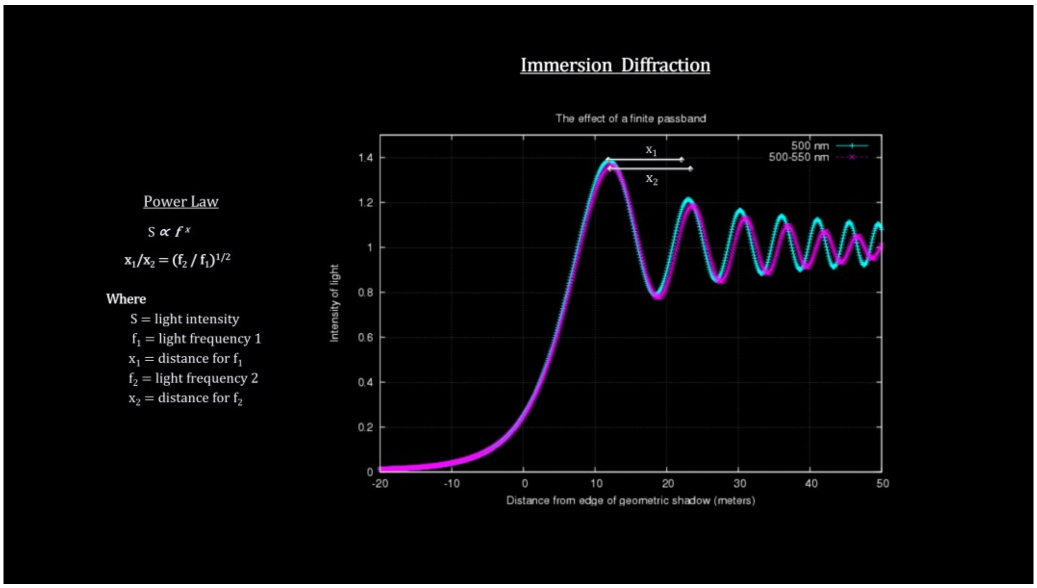


In addition, a diffractions pattern develops on the radio telescope that provides for additional information about the source. The optics are described by the French physicist Augustin Fresnel's equation developed in the early 1800s. Here's an illustration that covers how it works.

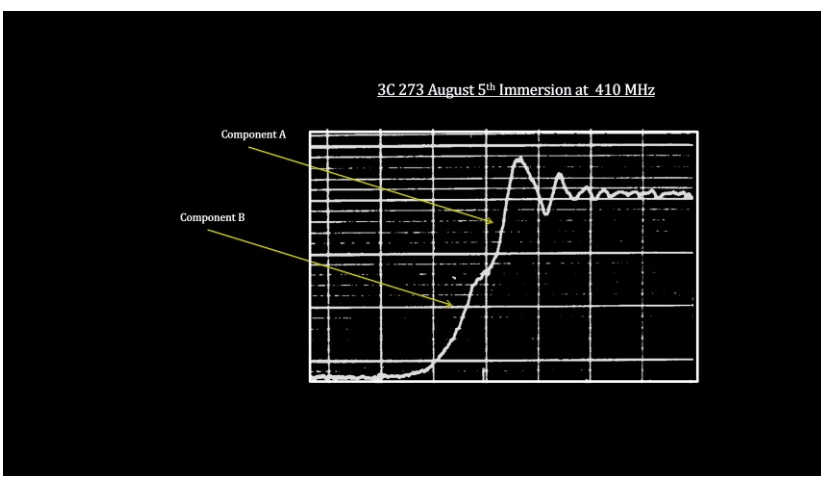
We have a star shining on a telescope on the Earth, with the moon's edge moving down between them. On immersion, the starting distance is 0 at the point where the moon's shadow blocks the leading edge of the starlight, and it's ending distance is at the point where the moon's shadow covers the entire star. The maximum peak occurs at the end. On emersion, the pattern starts with the maximum peak. Exact knowledge of the location and velocity of the Moon's edge gives us the exact location of the star on the sky. And it gives us the intensity of the light at any distance from the geometric shadow's starting point. This provides us with a measure of the intensity of the light across the plane of the star. It also provides us with the size of the source on the sky.



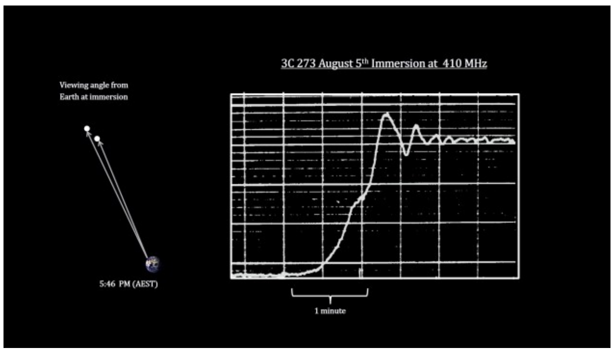
It is easier to see the quantitative behavior with a slice through the pattern. Radio astronomers take advantage of two main points. One is that the light intensity of the maximum peak is always around 40 % of the light intensity from the source when the telescope is viewing it without any blockage. If we zoom in a bit to focus on the largest peaks, we can get a measure of the ratios of the distance between peaks at different distances for different radiated frequencies. This provides a good measure of how the radiation from the object is distributed across the plane of the source with the selected frequencies. [All this might seem unnecessary because, with powerful enough optical telescopes, we can see where a star is located on the sky; how bright it is; how wide it is. But, in the 1960s, thousands of radio stars could not be seen in visible light. Lunar Occults were the only way to collect this precise information.]

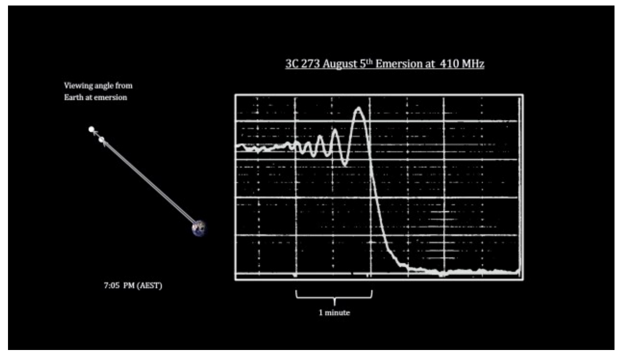


Now let's take a look at what the astronomers found when they actually monitored their three occlusions in 1962. Here's the immersion pattern on August 5th. This bump at the end indicated that the source had some sort of structure. It's not just one object.



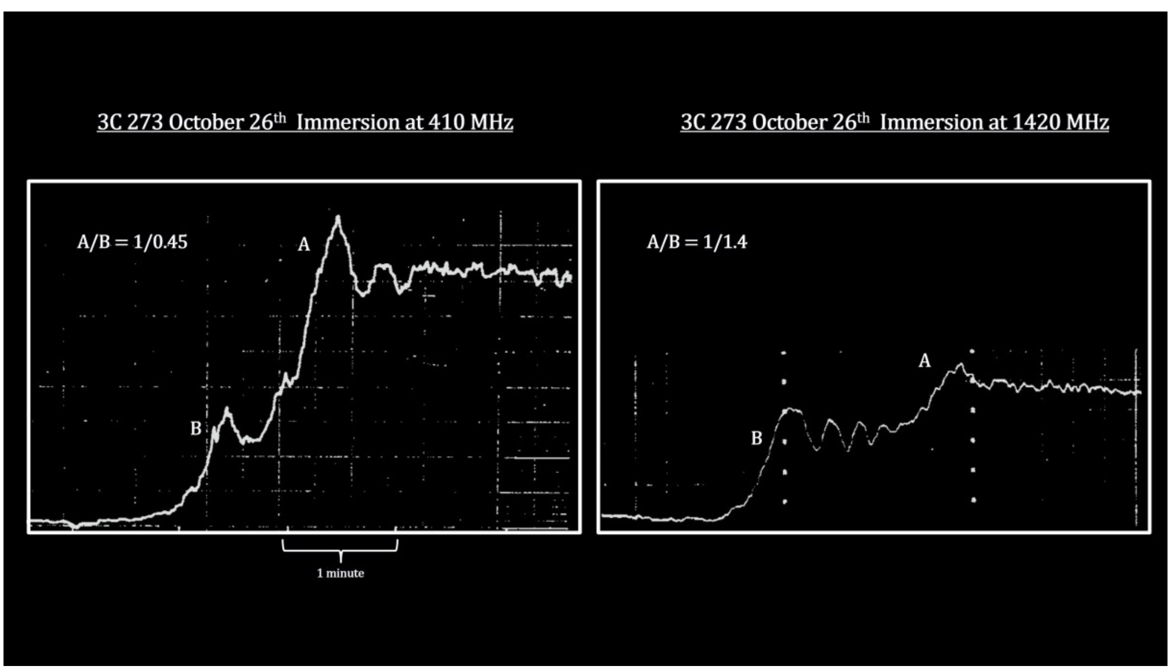
Here's the pattern on emersion. The bump is gone. This was interpreted to be caused by the alignment between Earth and the source changing with a small angle between the two on entry and aligned an hour and 19 minutes later on exit, as the Earth observers position changed, during the occlusion. With the angular data, the astronomers were able to calculate accurate positions for the two components.



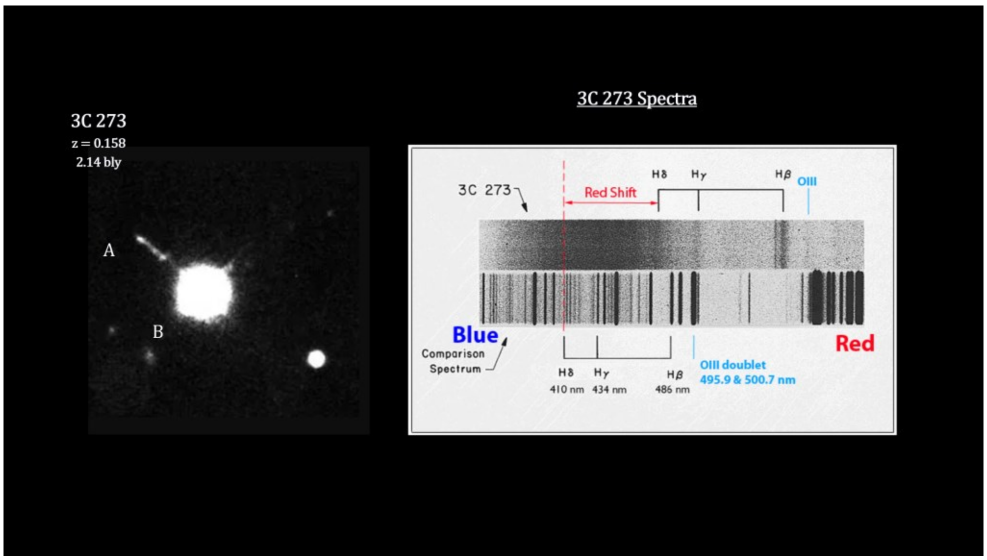


And here are two immersions at different frequencies collected on October 26. Note the significant reduction in intensity for component A at the higher frequency. The ratios along with the Power Law show component B producing the same radiation across its entire diameter, and component A producing most of its radiation from its center and fading at the edges.

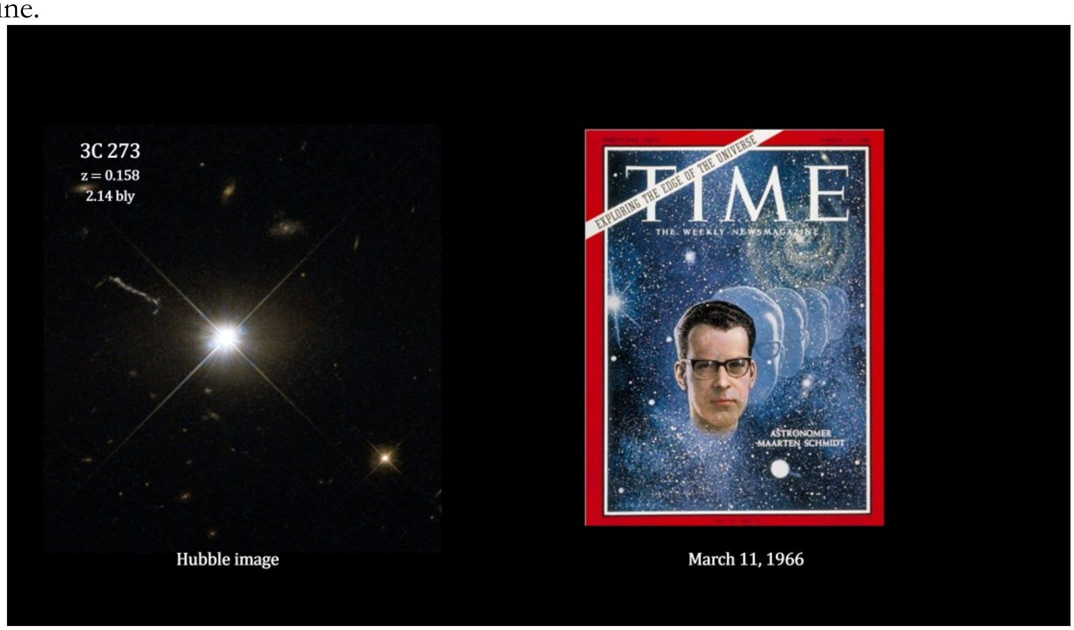
In addition, the radiation magnitudes show that component A is contributing 90% of all the radiation from the combined pair. The astronomers concluded that component A looked like a jet, but no one had ever seen anything like component B.



Without redshift information it was assumed to be a strange kind of star in our galaxy. It was called a “Quasi Stellar Object” later to be shortened to Quasar - an abbreviation of the phrase “quasi-stellar radio source”. In December 1962, the accurate position of 3C 273 obtained by Hazard was passed on to Caltech astronomer, Maarten Schmidt. Using the 200-inch Mount Palomar telescope, Schmidt obtained an image and spectra of the source. Using the baseline Balmer series for Hydrogen along with a strong line for Oxygen, he found a redshift of 0.158. He argued that either this was a relatively dim object inside our galaxy with enough mass packed into a 10 km radius to create a gravitational redshift this large, or its a galaxy 2.14 billion light years away with enough luminosity to be seen here. All known knowledge of stars ruled out the first possibility. He concluded that it was a distant galaxy.



This discovery had immense consequences for our understanding of the Universe including the discovery that the Inter-galactic medium had transformed from neutral to ionized hydrogen. We’ll cover this in our next segment. Here’s a Hubble image and Maarten Schmidt on the cover of Time Magazine.

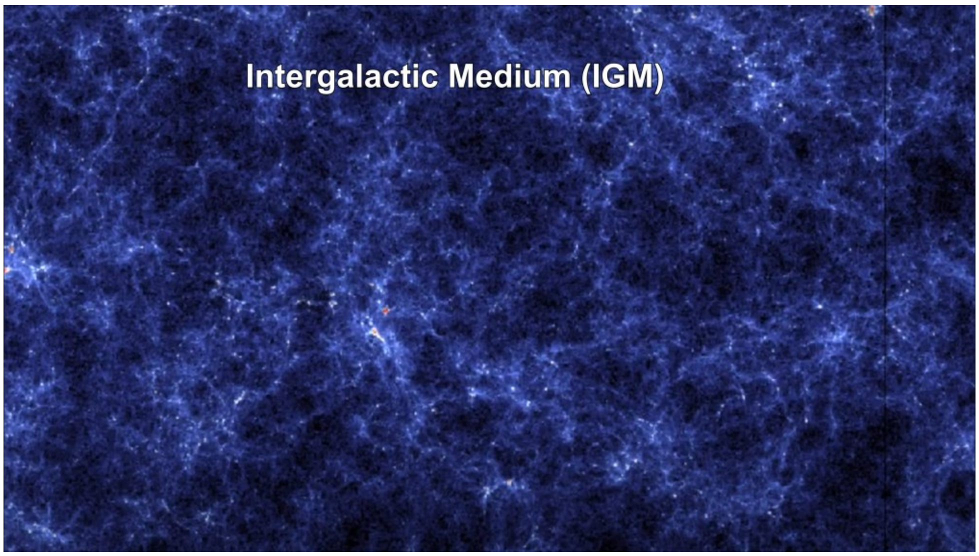


Hubble image

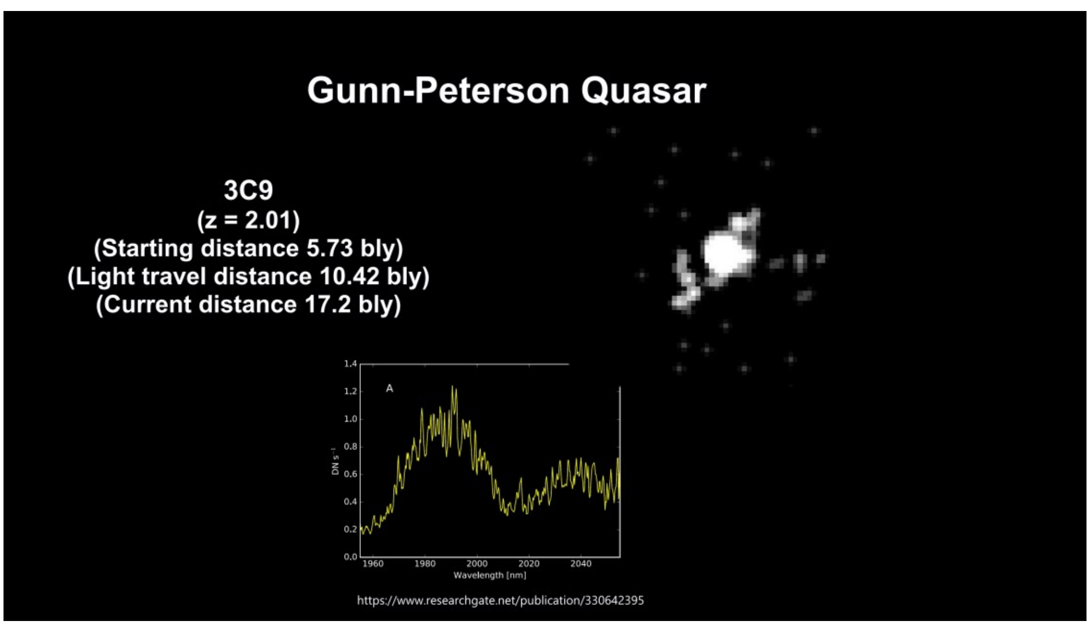
March 11, 1966

Reionization Discovery

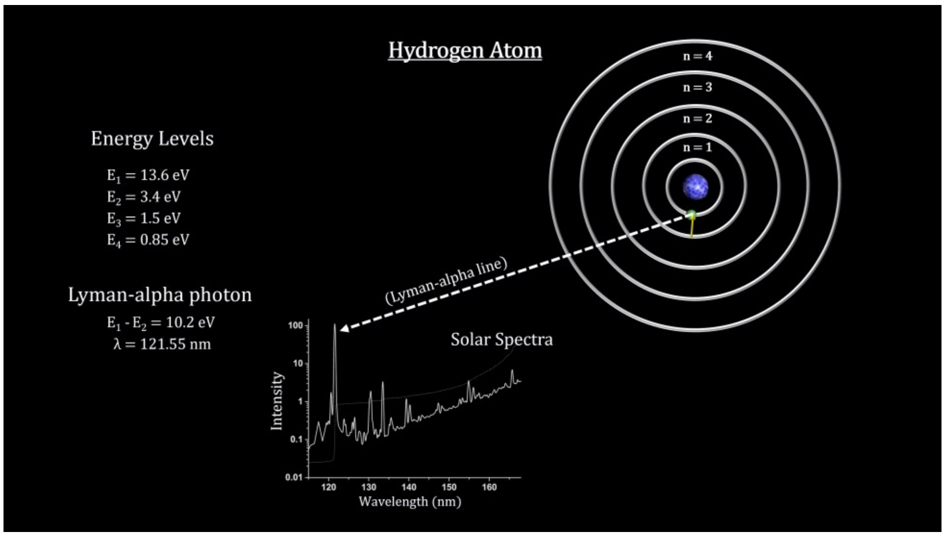
The Intergalactic Medium contains roughly half of the normal matter in the universe. The average density is about one atom per cubic meter. (That would be one atom per 35 cubic feet.) But the universe is so vast, that this accounts for around half of the total baryonic matter. The other half is in the 100s of billions to trillions of galaxies that populate the universe. Following Maarten Schmidt's discovery of Quasar 3C 273, astronomers around the world began searching for and studying quasar spectra.



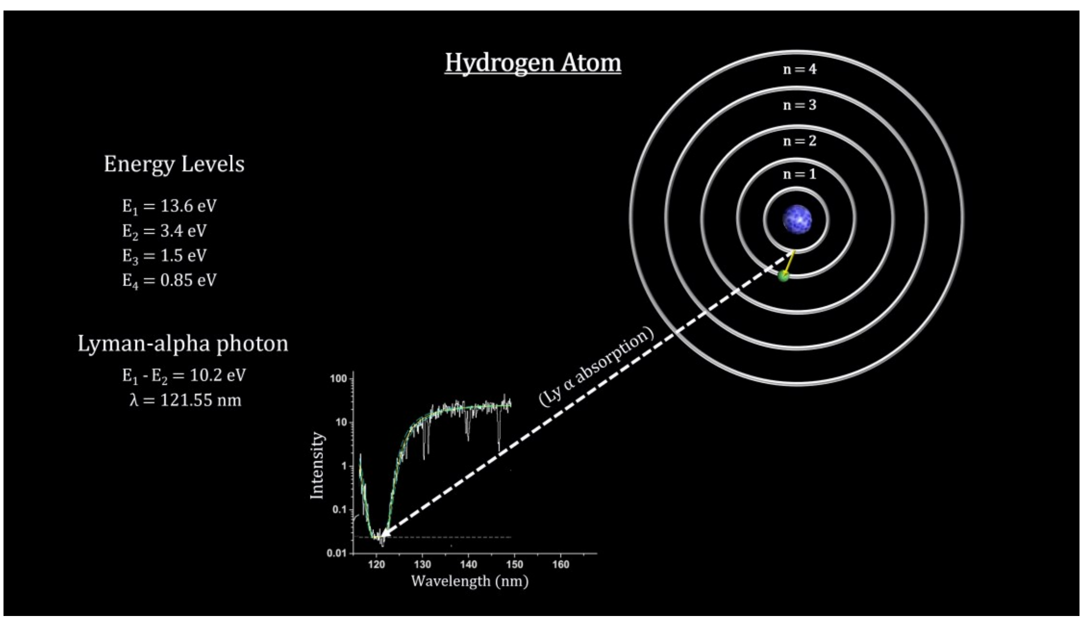
In 1965, astronomers James Gunn and Bruce Peterson used quasar 3C 9 spectra provided by Schmidt to calculate how much molecular hydrogen the light went through as it traveled 10.4 bly light years through the Intergalactic Medium to get here.



To do the measurements, Gunn and Peterson used the base hydrogen energy level transitions. In the 'How Small Is It' video book, we covered how light is created and absorbed when electrons change energy levels in an atom. For example, when an electron in a hydrogen atom drops from energy level 2 to the base energy level 1, a photon is immitted with a wavelength small enough to carry away exactly the amount of energy lost by the atom. This is called a Lyman-alpha photon after Theodore Lyman, the American physicist who discovered this series of spectral lines. It's in the ultra-violet range of the electromagnetic spectrum, and in large numbers they create the Lyman-alpha emission line in the spectra.

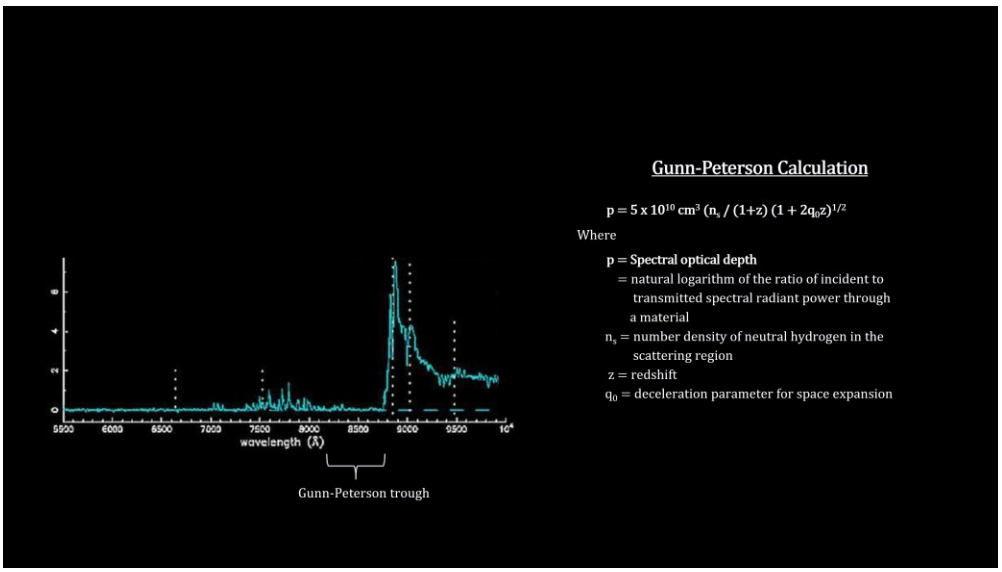


In the other direction, such a photon would be absorbed and scattered when it encounters a hydrogen atom in its ground state - driving the electron to the higher energy level. Passing through a large number of Hydrogen atoms in the ground sate, would create Lyman-alpha absorption in the light's spectra.

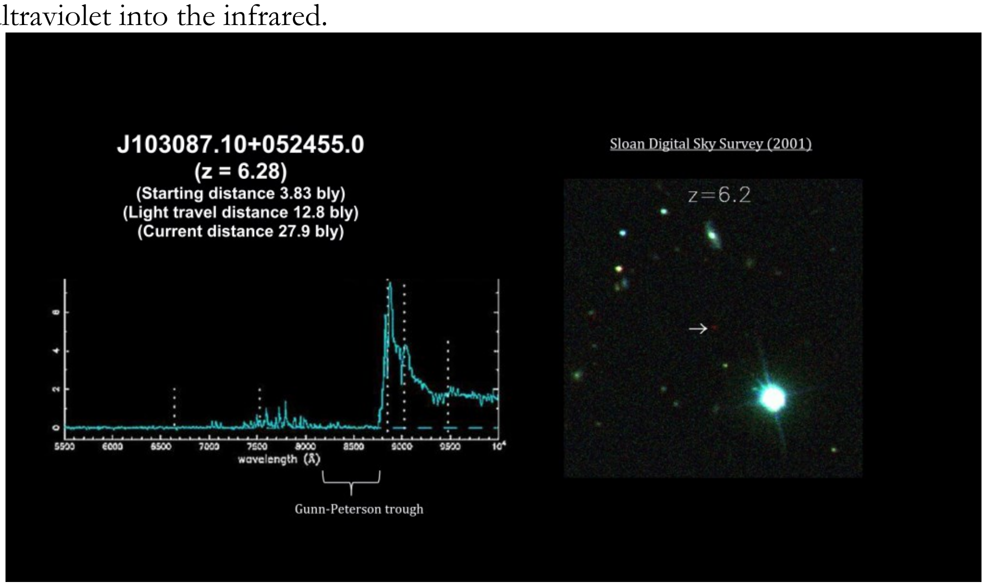


Gunn and Peterson reasoned that, as light bluer than Lyman-alpha is stretched with the expansion of the space it is passing through, it will reach the Lyman-alpha wavelength and also be absorbed by Hydrogen. They calculated that even a small amount of remaining hydrogen atoms - as few as one atom for every 100,000 ionized - would have enough of an effect to create a trough in the spectrum.

They predicted this trough (now named after them) would show up for quasars far enough away to be radiating through molecular Hydrogen. They never got to see one. The light from 3C9, that traveled over 10 billion light years, did not encounter enough molecular hydrogen to create the trough! They concluded that the IGM had already changed from molecular hydrogen to ionized hydrogen by the time the light they saw left 3C9.



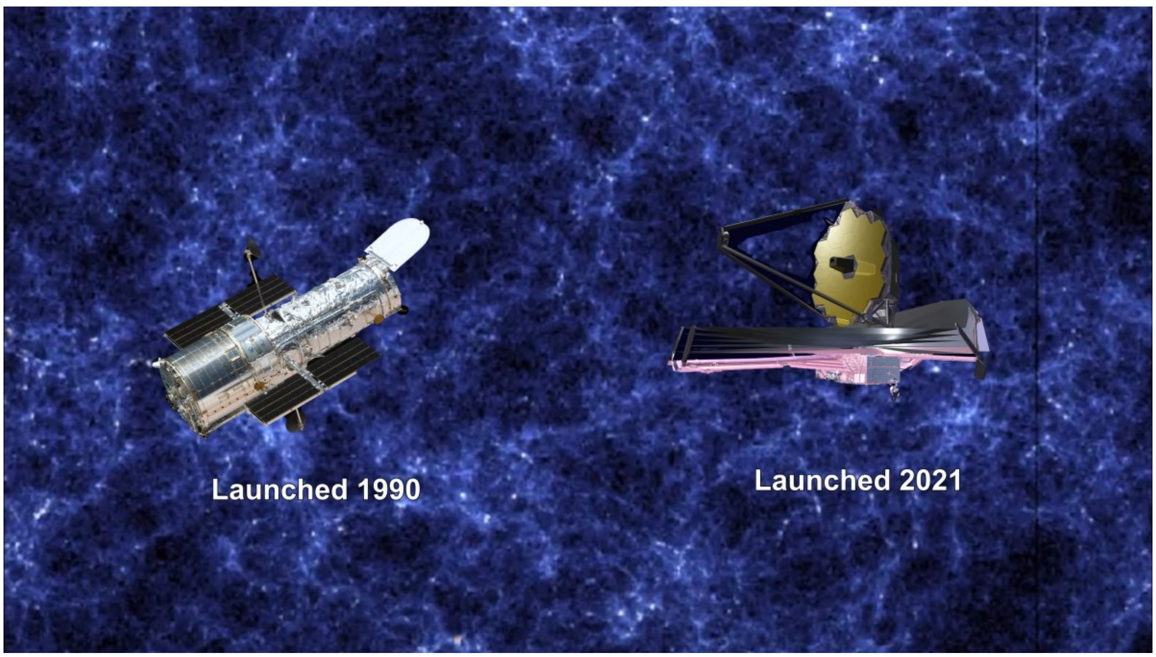
It wasn't until the summer of 2001, when Robert Becker from the Lawrence Livermore National Laboratory in California led a team of astronomers that examined the spectrum of this distant quasar located by the Sloan Digital Sky Survey. The light traveled 12.8 billion light years to get here. They found an unmistakable Gunn-Peterson trough in the quasar's spectra. Its trough was shifted from the ultraviolet into the infrared.



Gunn-Peterson analysis shocked the world of astronomy and created two long standing mysteries:

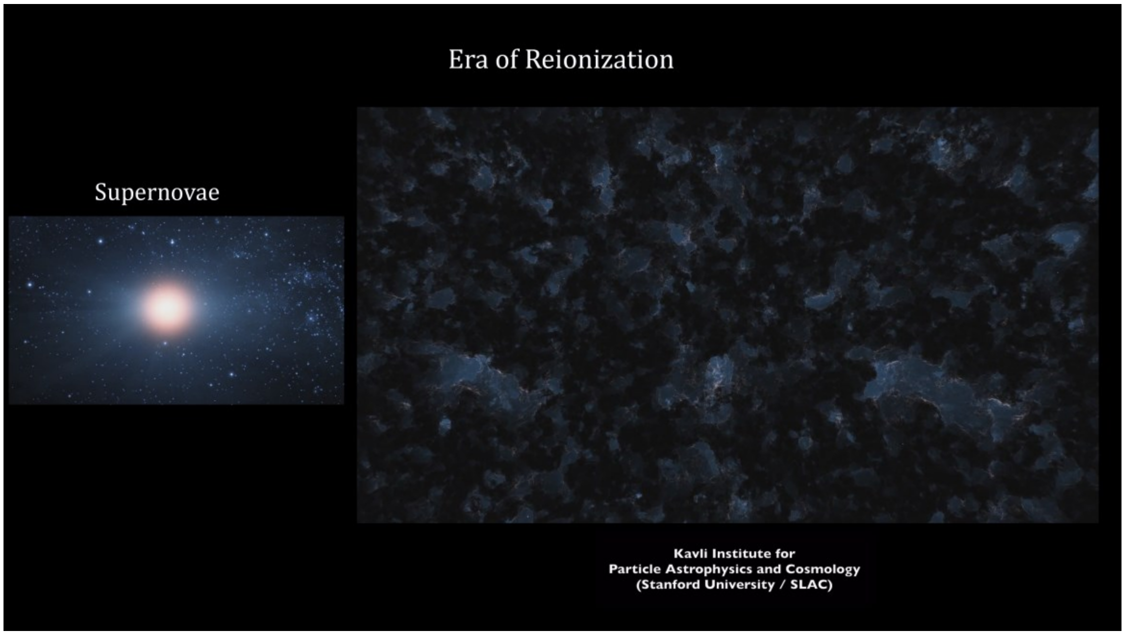
1) How did this transformation of the entire universe happen, and
2) How is it possible that any Lyman-alpha photons, created when the universe was still filled with molecular hydrogen, ever reach Earth.

To probe these mysteries, the world was going to need space-based telescopes with infrared capabilities.



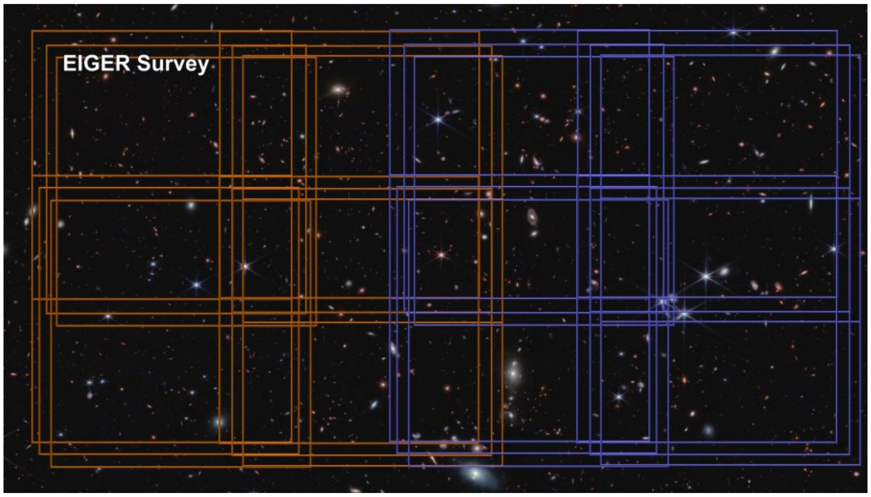
Reionization Timeline

Our current understanding about the timeline for reionization is that it started at the end of the Dark Ages – around 150 million years after the Big Bang. At that time, extremely strong ultraviolet radiation was produced with enough intensity to drive the electrons out of their orbits around protons. Light absorption by hydrogen atoms ceased, and light started to travel across the universe. In this simulation, the dark regions are filled with hydrogen atoms. The light areas have been 'ionized' and light can travel through it with minimal losses. Over time, the ionized regions around stars cleared entire galaxies, and ionized regions around galaxies cleared entire galaxy clusters, etc. This process ended around 1.1 billion years after the big-bang, with all of space cleared for light travel. To gain a deeper understanding of this timeline and how it started, the James Webb Space Telescope was created with near and mid-inferred capabilities.



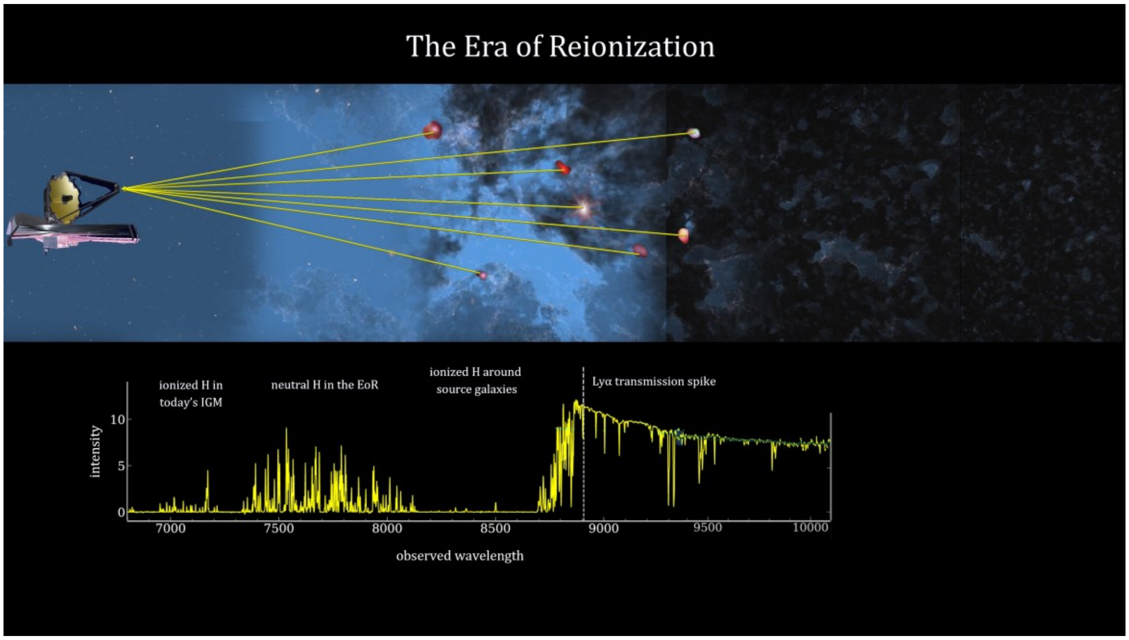
Here's an image take by Webb in 2023. There are more than 20,000 galaxies in this field. The Hyper-luminous quasar J0100+2802 is at the center. It is one of the most luminous quasars known. Its SMBH is 10 billion times more massive than our Sun. Its redshift is 6.327. That gives us the distance the light traveled to reach us at 12.8 billion light years.

A deep study of this area was conducted by the Emission-line galaxies and Intergalactic Gas in the Epoch of Reionization survey – EIGER for short. The survey used Webb's two near-infrared camera modules each with a 2.2 by 2.2 arcsec field of view. Here's their exposure map around the quasar.



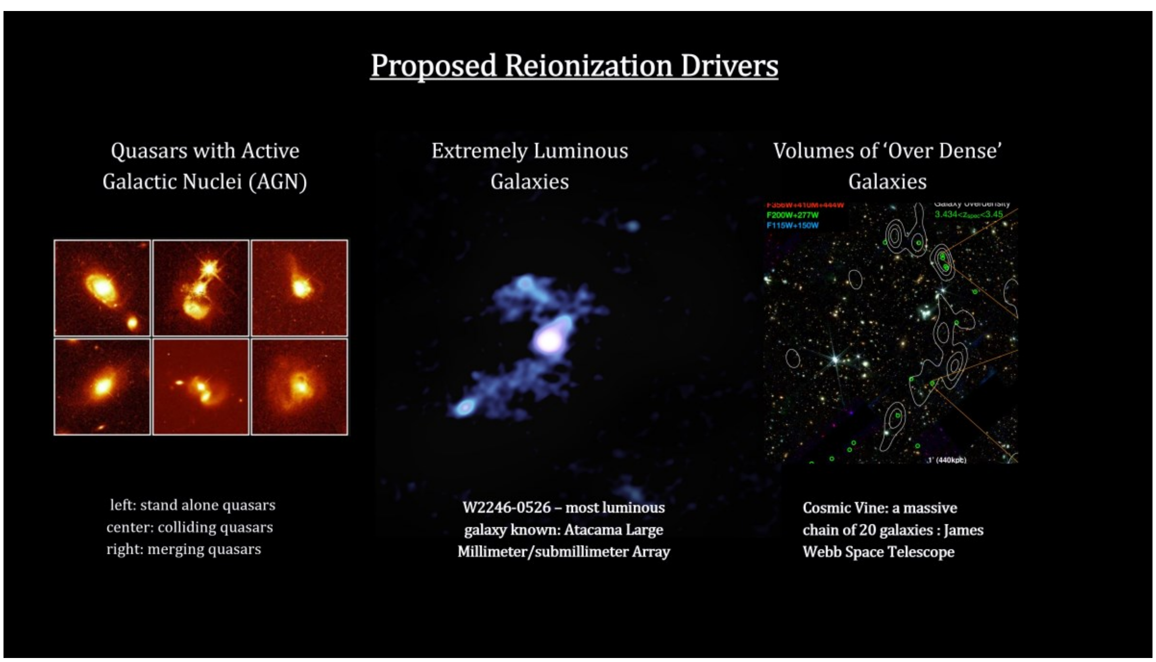
The study covers 117 galaxies within 650,000 light years of the quasar. Some are closer to us than the quasar and some are further away. All these galaxies existed near the end of the Era of Reionization.

As Lyman-alpha emitters, they will all be sending Lyman-alpha photons our way. As the photons pass through volumes of molecular hydrogen, we would see Gunn-Petterson troughs. As they pass through space with smaller volumes of molecular hydrogen and smaller volumes of ionized hydrogen, we would see a mix referred to as "Lyman Alpha forests". As they pass through large volumes of ionized hydrogen, we'd see normal emission lines. The survey clearly shows that the expected transparent regions do exist around galaxies. The results showed that galaxies near the quasar had fully ionized the gas within a 2 million light-year radius. That's approximately the same distance as the space between our Milky Way galaxy and Andromeda. And it showed that the ionization volumes increased over time as the light approached the expected timeframe for the fully ionized and transparent universe we have today. But the timeline doesn't explain what radiation ionized the hydrogen.



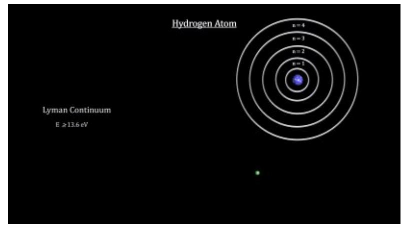
The Actual Reionization Drivers

The identification of sources driving cosmic reionization has been a matter of debate for decades. Some suggest that quasars could be the source. Others propose that bright galaxies generate sufficient ionizing radiation to drive this process. Others think it would take over densities of multiple galaxies to do it. So far, none of these have proven to be able to do the job. The James Webb Space Telescope was built in part to find the answer to 'what drove reionization across the entire Universe?'.

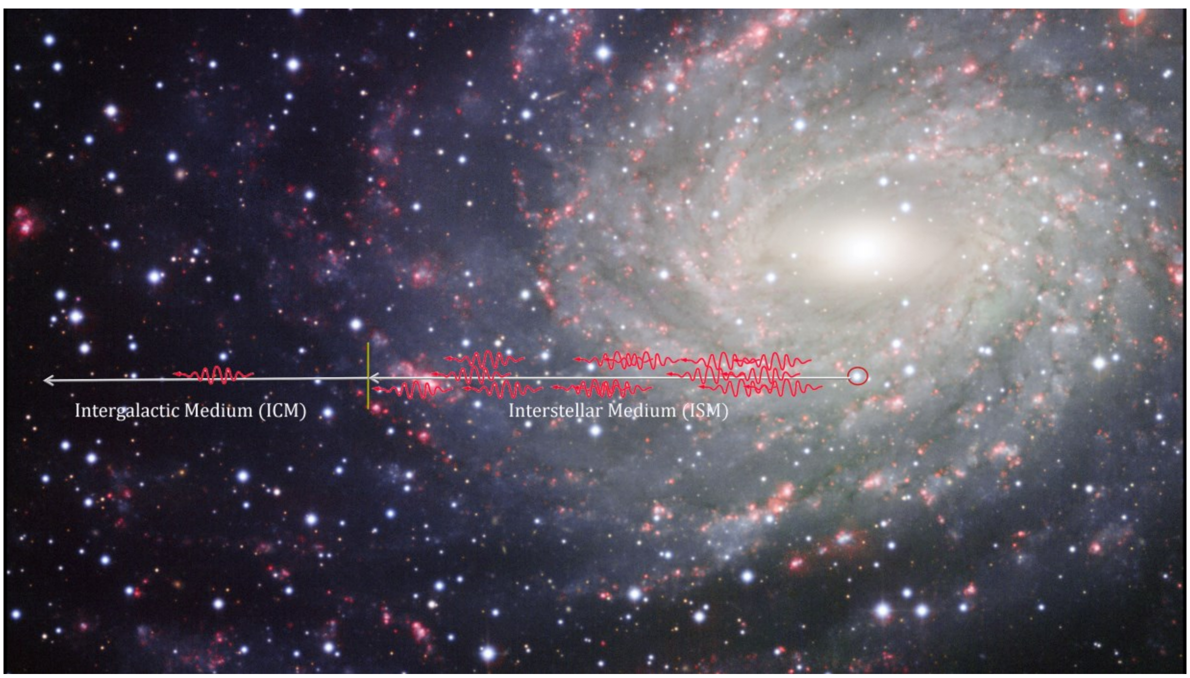


We've known since the early 1900s that it takes 13.6 eV to fully ionize a hydrogen molecule. This is now referred to as the 'Lyman Limit'.

And all Lyman photons above this limit are referred to as Lyman Continuum or Lyman C photons. These are the photons that can fully ionize a hydrogen atom. Lyman photons below this energy level cannot fully ionize a hydrogen atom.

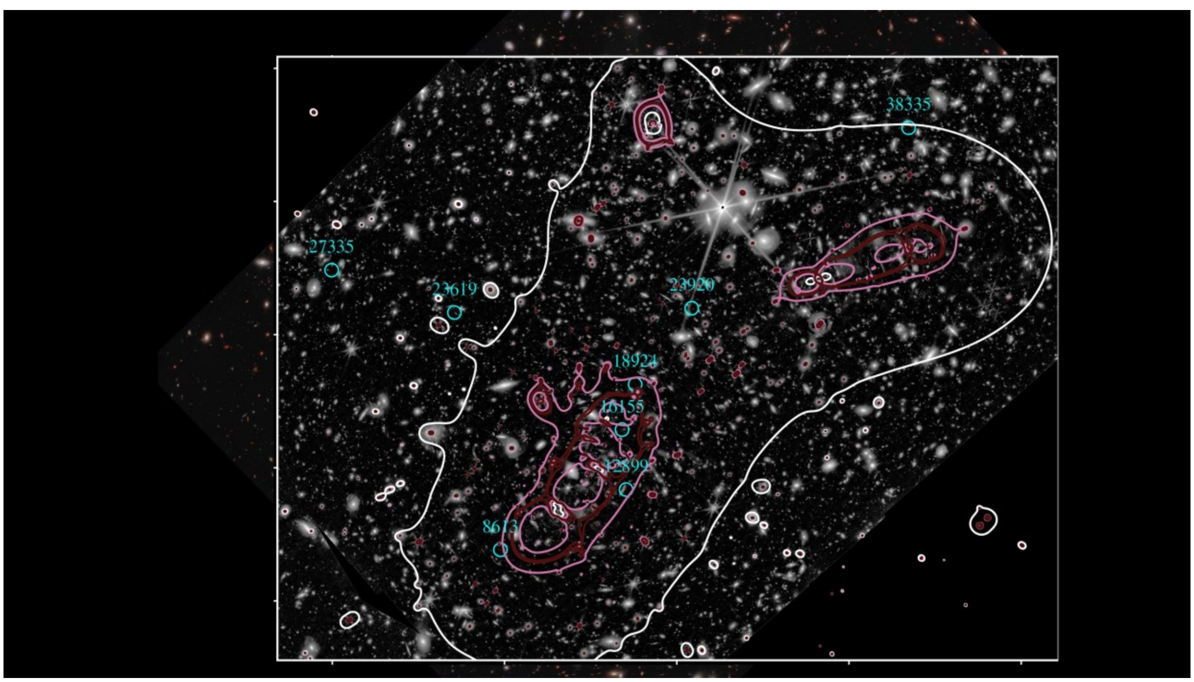


All galaxies produce massive stars, which in turn produce Lyman C photons. But most stars are formed deep inside their galaxies, and the Inter Stellar Medium (ISM) hydrogen gas inside these galaxies absorb nearly all the ionizing light, preventing it from escaping into the IGM where it can reionize the hydrogen there.

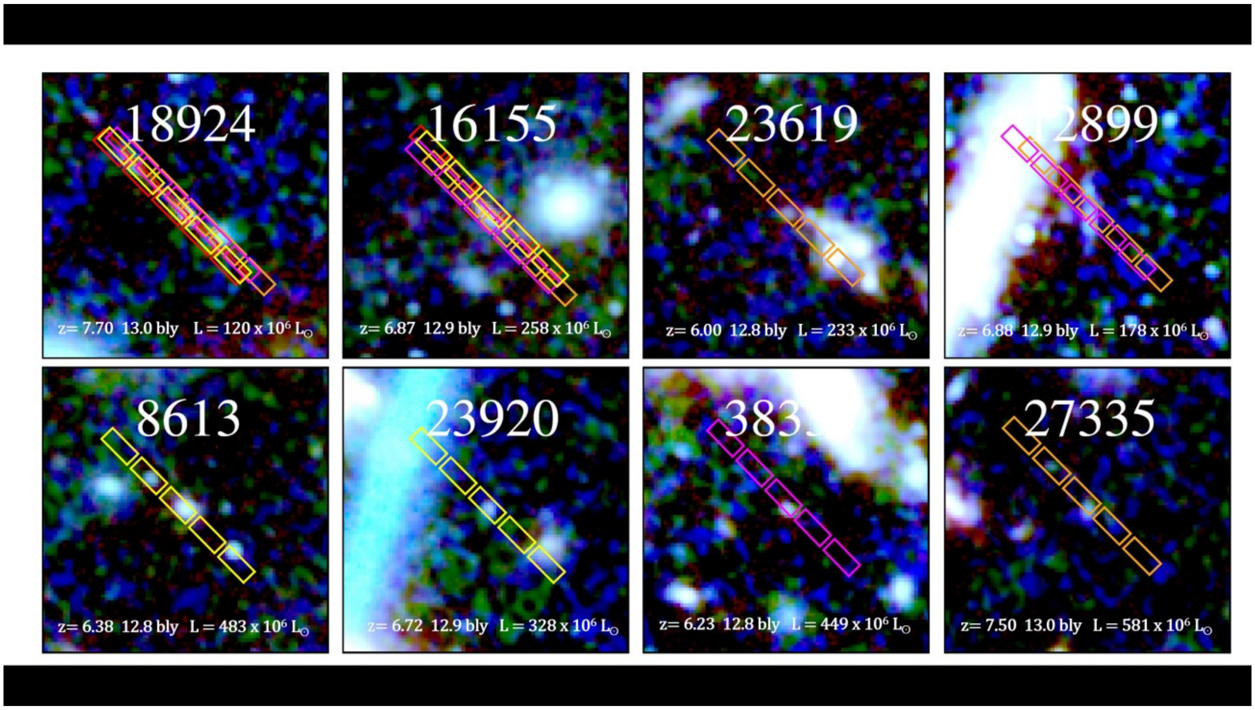


Here's a Webb program that consists of both imaging and spectroscopic observations of distant galaxies gravitationally lensed by the galaxy cluster Abell 2744 (also known as Pandora's Cluster). It was used in 2024 by an international team of astronomers to investigate potential sources for the era of reionisation.

The lensing magnification effect allowed the team to study very distant sources of light beyond the cluster. The white and red lines are the lensing critical curves. Lensing magnifications ranged from 2 to over 100 times their actual size. The team found eight extremely faint galaxies that would otherwise be undetectable. They are circled and numbered. Two of the sources (12899, and 16155) are thought to be multiple images of the same galaxy.



Here's an image of each source dwarf galaxy and the positions of the Near-Infrared Spectroscope slitlet on top of each one. Lyman-alpha light from these early faint galaxies traveled 13 billion light years to reach us. Their ultraviolet luminosity was measured and ranged from 120 to 581 million times greater than our Sun's.



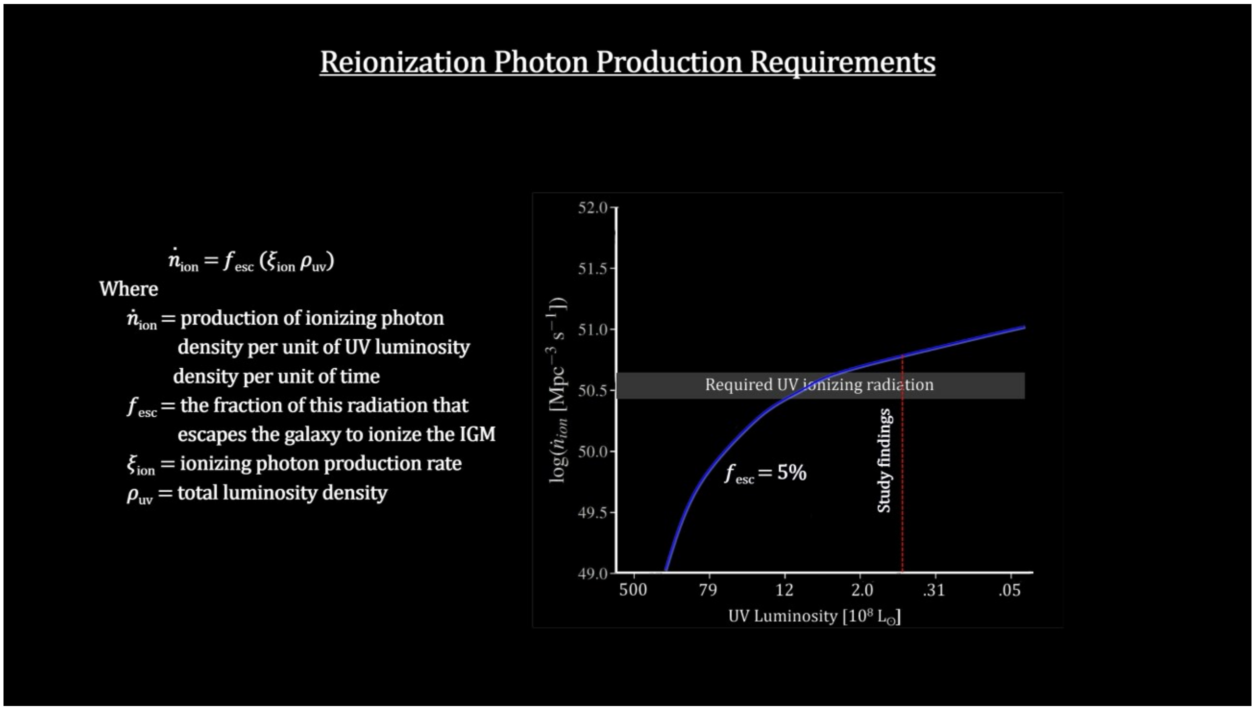
The ability of Lyman-alpha emitters like these faint galaxies to reionize the Universe depends on two things:

1) their production of ionizing Lyman photons with enough density per unit of time; and

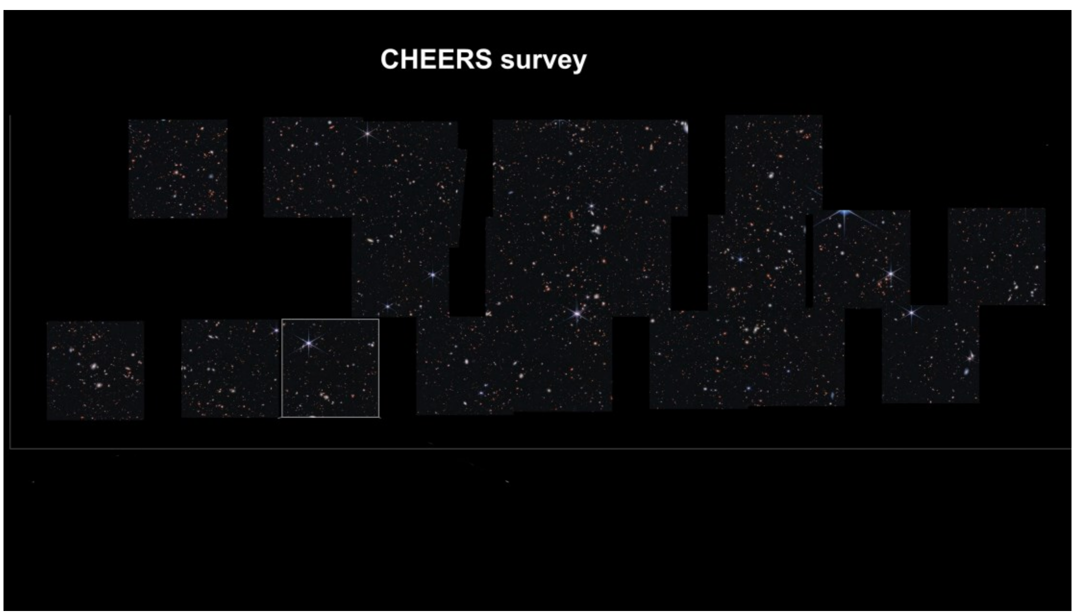
2) the fraction of this radiation that escapes the galaxy into the intergalactic medium.

The team found that these faint galaxies are immense producers of ionizing radiation, at levels that are four times larger than what was previously assumed.

The gray-shaded region is the threshold required to maintain the Universe ionized at $z = 7$. The blue curve represents the case when the escape fraction is 5%. And the red vertical line shows the limit probed by this work. The study concluded that, at this luminosity, galaxies produce enough radiation to reionize the Universe. If this small sample in one piece of the universe reflects the norm, then these result mean that most of the photons that reionized the Universe likely came from early dwarf galaxies even for escape fractions as small as 5%.

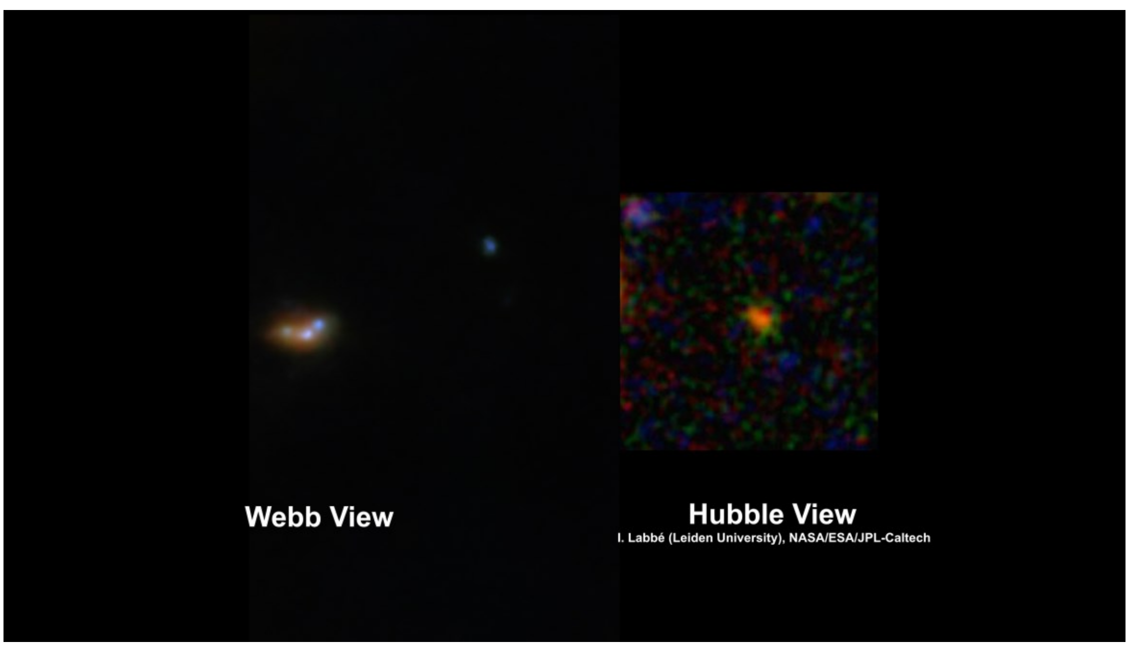


In the same year, another team of astronomers was searching for answers to the same question – 'What drove the era of reionization?' This team used the CHEERS survey data.

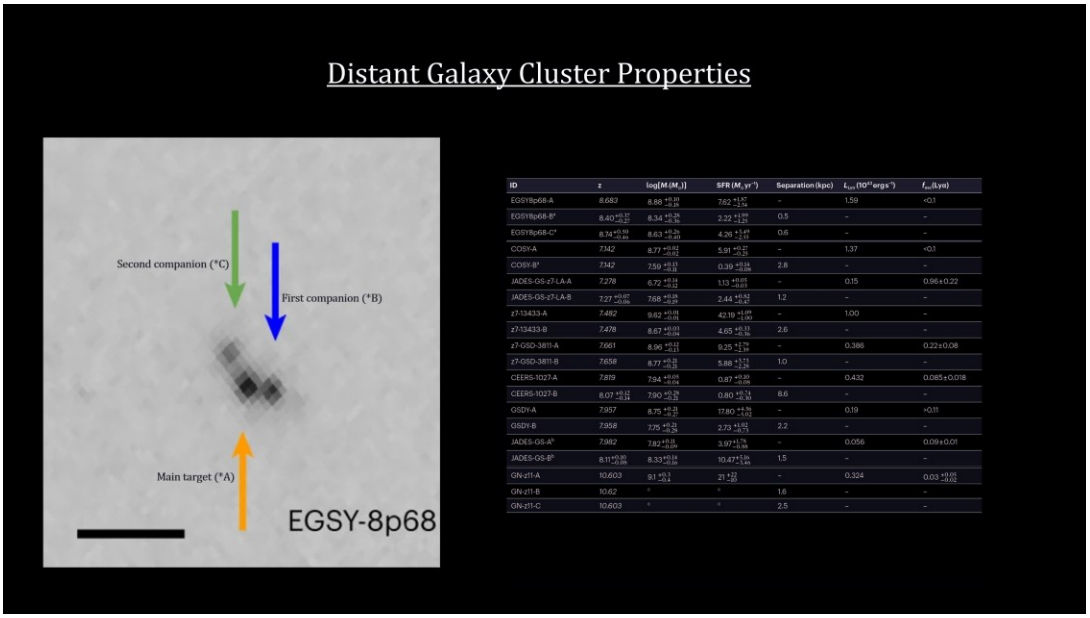


They found a galaxy they named EGSY8p7 with a redshift of 8.683. Its light traveled 13.1 billion light years to reach us. [It was only 3.1 billion light years away when the light started its journey, and is now 30.4 billion light years away.] We are now seeing this galaxy as it existed just 600 million years or so after the Big Bang. Note that the image shows 3 interacting galaxies.

Here's the view from Webb and Hubble. Where Hubble was seeing only one galaxy, Webb sees a cluster of smaller interacting galaxies. Webb's NIRCam instruments were able to resolve smaller, fainter galaxies that surround the bright galaxy.

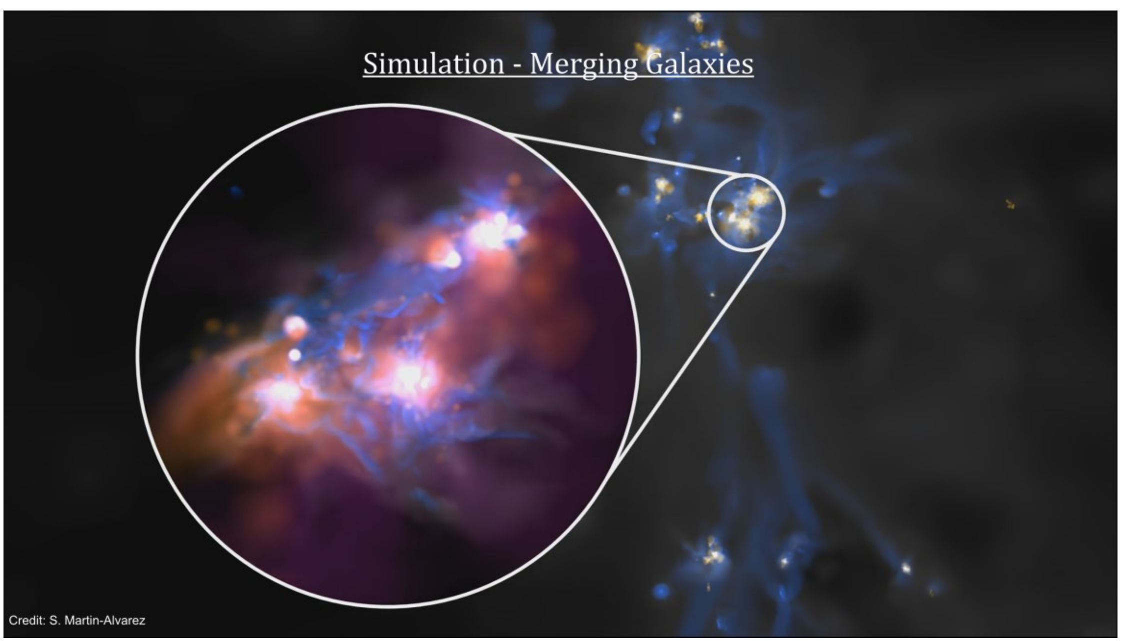


Here's a closer look. 'A' is the main target. It is the largest and brightest. 'B' is 16,000 light years to the right. 'C' is the dimmest. It's just under 20 thousand light years to the upper left. Crucially, these smaller galaxies were interacting and merging with one another. Expanding the research, they found that all galaxies in a sample of Lyα emitters with redshift >7 have close companions. This discovery has had a huge impact on our understanding of what drove the reionization of the Universe.



ID	z	$\log[M_*(M_\odot)]$	SFR ($M_\odot$ yr^{-1})	Separation (kpc)	$L_{Ly\alpha}$ (10^{43} erg s^{-1})	f_{esc}(Lyα)
EGSY8p68-A	8.683	$8.88^{+0.10}_{-0.18}$	$7.62^{+1.87}_{-2.54}$	-	1.59	<0.1
EGSY8p68-B[a]	$8.40^{+0.17}_{-0.27}$	$8.34^{+0.28}_{-0.36}$	$2.22^{+1.99}_{-1.25}$	0.5	-	-
EGSY8p68-C[a]	$8.74^{+0.30}_{-0.46}$	$8.63^{+0.26}_{-0.40}$	$4.26^{+3.49}_{-2.55}$	0.6	-	-
COSY-A	7.142	$8.77^{+0.02}_{-0.02}$	$5.91^{+0.27}_{-0.25}$	-	1.37	<0.1
COSY-B[a]	7.142	$7.59^{+0.13}_{-0.11}$	$0.39^{+0.14}_{-0.08}$	2.8	-	-
JADES-GS-z7-LA-A	7.278	$6.72^{+0.14}_{-0.12}$	$1.13^{+0.05}_{-0.03}$	-	0.15	0.96±0.22
JADES-GS-z7-LA-B	$7.27^{+0.07}_{-0.06}$	$7.68^{+0.18}_{-0.19}$	$2.44^{+0.82}_{-0.47}$	1.2	-	-
z7-13433-A	7.482	$9.62^{+0.01}_{-0.01}$	$42.19^{+1.09}_{-1.00}$	-	1.00	-
z7-13433-B	7.478	$8.67^{+0.03}_{-0.04}$	$4.65^{+0.33}_{-0.36}$	2.6	-	-
z7-GSD-3811-A	7.661	$8.96^{+0.12}_{-0.13}$	$9.25^{+2.79}_{-2.39}$	-	0.386	0.22±0.08
z7-GSD-3811-B	7.658	$8.77^{+0.21}_{-0.21}$	$5.88^{+3.71}_{-2.28}$	1.0	-	-
CEERS-1027-A	7.819	$7.94^{+0.05}_{-0.04}$	$0.87^{+0.30}_{-0.08}$	-	0.432	0.085±0.018
CEERS-1027-B	$8.07^{+0.12}_{-0.14}$	$7.90^{+0.28}_{-0.21}$	$0.80^{+0.74}_{-0.30}$	8.6	-	-
GSDY-A	7.957	$8.75^{+0.21}_{-0.27}$	$17.80^{+4.56}_{-5.02}$	-	0.19	>0.11
GSDY-B	7.958	$7.75^{+0.21}_{-0.28}$	$2.73^{+1.02}_{-0.73}$	2.2	-	-
JADES-GS-A[b]	7.982	$7.82^{+0.11}_{-0.09}$	$3.97^{+1.78}_{-0.88}$	-	0.056	0.09±0.01
JADES-GS-B[b]	$8.11^{+0.10}_{-0.08}$	$8.33^{+0.14}_{-0.16}$	$10.47^{+5.16}_{-3.46}$	1.5	-	-
GN-z11-A	10.603	$9.1^{+0.3}_{-0.4}$	21^{+22}_{-10}	-	0.324	$0.03^{+0.05}_{-0.02}$
GN-z11-B	10.62	[c]	[c]	1.6	-	-
GN-z11-C	10.603	[c]	[c]	2.5	-	-

This video showcases the dynamics of the system. Using the laws of magneto-hydrodynamics developed by Hannes Alfvén in the 1940s, the team found that the rapid build-up of stellar mass through galaxy mergers both drove strong Lyman emissions and facilitated the escape of that radiation via channels cleared of the molecular hydrogen gas. They concluded that the rapid buildup of stellar mass through mergers presents a compelling solution to the long-standing puzzle of what drove reionization.



In our next chapter, we'll cover how old are stars.

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

⇒ → ± ⊙ ∞ ↛ ∃ ∄ ∈ ∉ ∬ ∫ ≅ ≥ ≤ ≈ ≠ ≡ √ ∛ ~ ∝ ħ ÷