Cosmic Dawn ended 200 million years later than we thought!

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Astrophysics

Preliminaries

Quasars, Reionization, Dark Ages, Recombination and Lyman-α forest

Illustration of a quasar in deep space.

Quasars

- The center of a galaxy known as a quasar is where a supermassive black hole is chaotically feeding. With such ferocity, gas and dust in orbit around the black hole emit light in all spectrums. Particles from this spinning disk are captured by the strong black hole's magnetic field and ejected along its poles. We may observe these polar fountains as enormous jets of radio waves and X-rays.
- These galaxies' nuclei shine like stars even at great distances, which is how they come to be known as quasars, or quasi-stellar radio emitters.
- Quasars, on the other hand, are moving faster away from us than a star in our galaxy would; since we all reside in the same galaxy, we more or less travel in unison within this spinning disk. The quasars must be extremely brilliant distant galaxies, as only distant galaxies can leave us that swiftly. They are the brightest things in the entire universe.

Quasars

- Quasars can now be used as new “standard candles” to help measure cosmic distances and test other essential cosmological parameters since astronomers have discovered that the X-ray and ultraviolet luminosities of quasars are so closely connected, even for quasars at great cosmological distances.

Recombination

- Recombination, the first phase change of hydrogen in the universe, happened when the universe cooled to the point where the rate of electron and proton recombination to form neutral hydrogen was higher than the rate of reionization. This occurred at a redshift of $z = 1089$ (379,000 years after the Big Bang). Prior to the recombination, the world was opaque due to the scattering of photons (of all wavelengths) off free electrons (and free protons, to a much lesser extent), but as more electrons and protons united to create neutral hydrogen atoms, the universe became increasingly transparent.
- A universe comprised of neutral hydrogen will be relatively opaque only at certain absorbed wavelengths but transparent over the majority of the spectrum, even if neutral hydrogen electrons can absorb photons at some wavelengths by rising to an excited state. At that time, the cosmos entered its Dark Ages since there were no other light sources outside the cosmic background radiation, which was steadily redshifting.

Recombination

- The term “recombination” is misleading because it was coined before the Big Bang hypothesis was accepted as the prevailing theory for the origin of the universe, despite the fact that the Big Bang theory does not assume that protons and electrons have ever mixed before.
- The quark epoch was the period of time immediately following the Big Bang when the cosmos was a hot, dense plasma of photons, leptons, and quarks. At 10^{-6} seconds, the Universe had expanded and cooled sufficiently to allow for the production of protons: the hadron epoch. Because of Thomson scattering by free electrons, this plasma was effectively opaque to electromagnetic radiation because the mean free route that each photon could take before running into an electron was relatively short. This is how the sun’s inside is right now. The universe cooled as it grew larger. The proportion of free electrons and protons relative to neutral hydrogen eventually reduced to a few parts in 10,000 when the cosmos cooled to the point where the production of neutral hydrogen was energetically favored.

Dark Ages

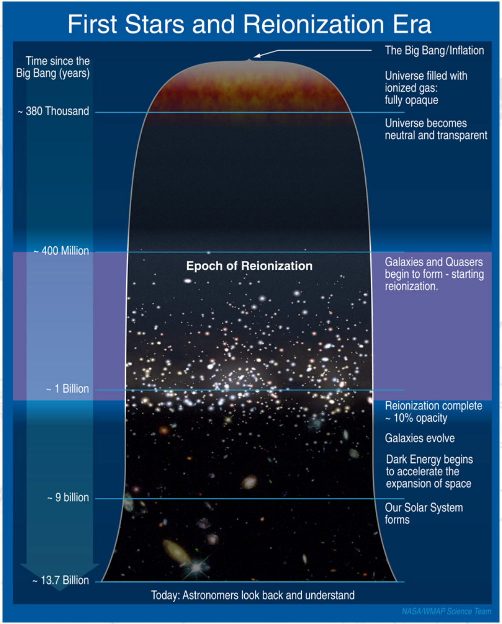
- There were no light-producing objects like stars and galaxies in the cosmos after recombination and decoupling, despite the fact that it was transparent and had cooled sufficiently for light to travel over great distances. It is thought that stars did not exist until hundreds of millions of years after recombination because the process of forming dense regions of gas under the influence of gravity takes a very long time within a near-uniform density of gas and on the scale necessary.

Dark Ages

- The so-called Dark Ages started some 370,000 years after the Big Bang. The cosmic microwave background (CMB), which we can still detect today, and the sporadic photons released by neutral hydrogen atoms, known as the 21 cm spin line of neutral hydrogen, were the only two sources of photons during the Dark Ages, when the universe's temperature decreased from approximately $4000K$ to about $60K$ ($3727^\circ C$ to approximately $-213^\circ C$).
- The CMB photons redshifted from visible light to infrared within 3 million years, and from that point until the birth of the first stars, there were no visible light photons. The hydrogen spin line lies in the microwave range of frequencies. The universe was truly dark, perhaps with a few unusual statistical abnormalities.

Reionization or "cosmic dawn"

- According to the fields of the Big Bang hypothesis and cosmology, reionization is the process that caused matter in the Universe to reionize following the end of the "dark ages".
- Reionization is the second of two key phase shifts of gas in the universe (the first is recombination). Despite the fact that the majority of the universe's baryonic matter is composed of hydrogen and helium, the term "reionization" usually primarily refers to the reionization of the element hydrogen.
- It is believed that the primordial helium underwent the same phase of reionization changes at different points during the history of the cosmos. Helium reionization is the name of this procedure.



Schematic universe timeline showing the position of reionization in the cosmos.

Lyman-α forest

- The Lyman-alpha forest is a collection of absorption lines found in the spectra of far-off galaxies and quasars that result from the neutral hydrogen atom's Lyman-alpha electron transition. Multiple absorption lines are created as the light passes through various gas clouds with various redshifts.
- Astronomer Roger Lynds made the initial discovery of the Lyman-alpha forest in 1970 while doing an observation of the quasar 4C 05.34. The farthest object seen at the time was Quasar 4C 05.34, and Lynds noticed an exceptionally high number of absorption lines in its spectrum.

Little practical

- 200 million years later than expected, the cosmic dawn came to an end.
- Using the light from 67 extremely distant quasars, astronomers have determined that the cosmic dawn, or the time when the first stars started to develop, ended 1.1 billion years after the big bang.

Little practical

- We now know when cosmic dawn ended. The early universe remained absolutely dark for a period of about 100 million years, beginning about 380,000 years after the big bang. Then, in a process known as reionization, or the cosmic dawn, stars and galaxies started to emerge, generating light and ionizing the intergalactic hydrogen gas. 1.1 billion years after the great bang, it came to an end with the ionization of all the hydrogen.
- This date was determined by Sarah Bosman at the Max Planck Institute for Astronomy in Germany using light from 67 quasars, which are extraordinarily luminous objects driven by supermassive black holes. With the help of the Very Large Telescope in Chile and the W. M. Keck Observatory in Hawaii, the quasars were observed, and since they are all so remote, we can be certain that they formed during the first billion years or so after the big bang.

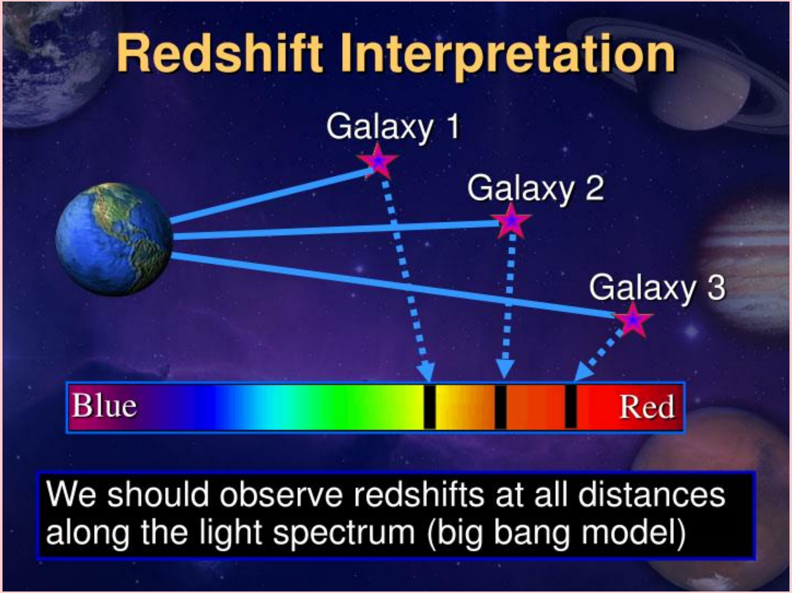
Little practical

- Different wavelengths of the quasar light would have been absorbed by hydrogen in both its ionized and non-ionized states as it made its way to Earth. Bosman and her team examined the dark absorption lines in the light's spectrum to determine when it stopped passing through non-ionized hydrogen and began running into solely ionized hydrogen in the gap between galaxies, taking into account the universe's constant expansion.
- According to Bosman, reionization has a bubble-like structure where galaxies clear out large bubbles around themselves. Until all of those bubbles combine and the hydrogen gas is ionized across the sky, at the locations of all of the quasars, reionization is not complete. When all the quasars concur that it is ionized everywhere, she claims, "We can tell it's the end of reionization".

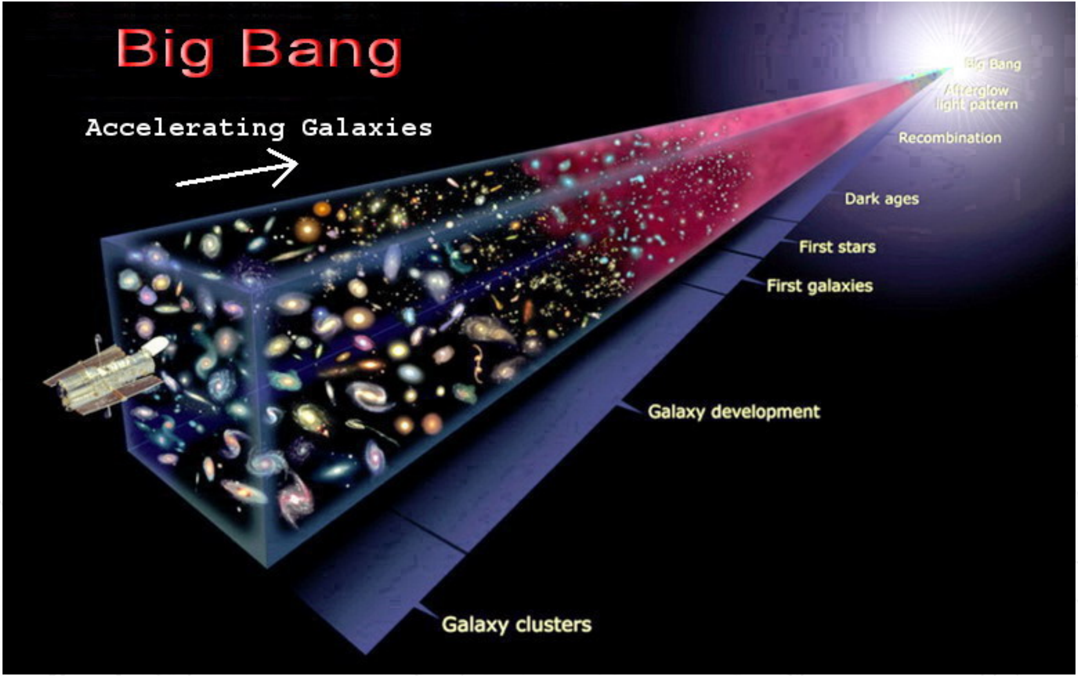
Little practical

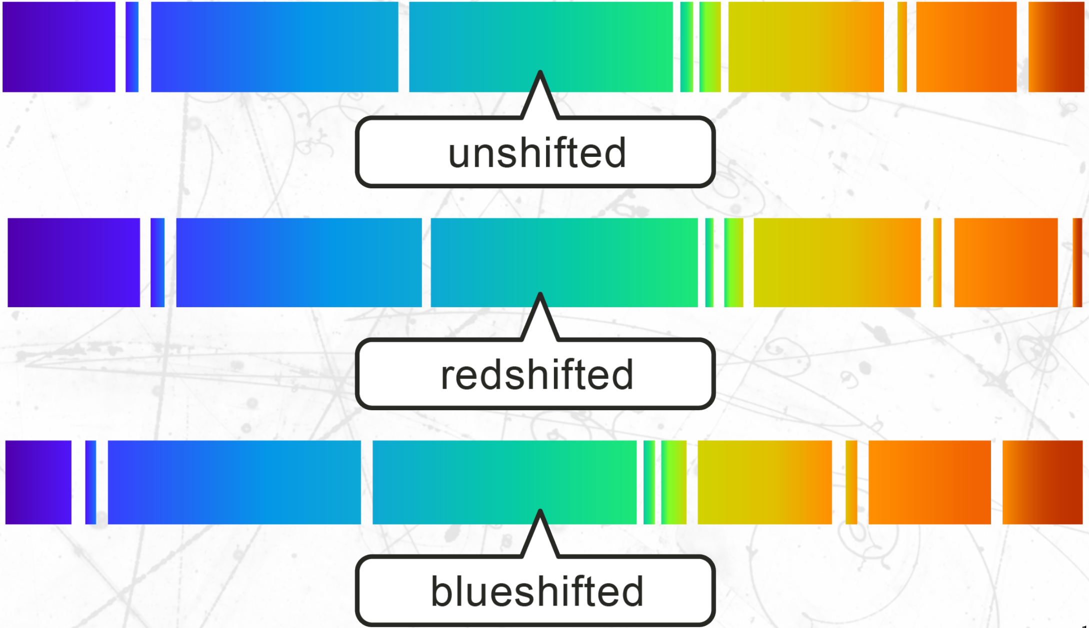
- It took 1.1 billion years after the big bang for this process to come to a close, which is 200 million years later than was previously thought. This suggests that the initial generation of stars and galaxies, which fueled reionization, may be closer and thus simpler to witness than cosmologists originally believed.
- Between the big bang and the present, the history of the universe has undergone numerous phases, and we are just now beginning to track all of them, according to Bosman. The last stage is to go back in time and connect the knowledge about reionization to the galaxies that are responsible for it, so we can actually witness the galaxies obliterating the gas.

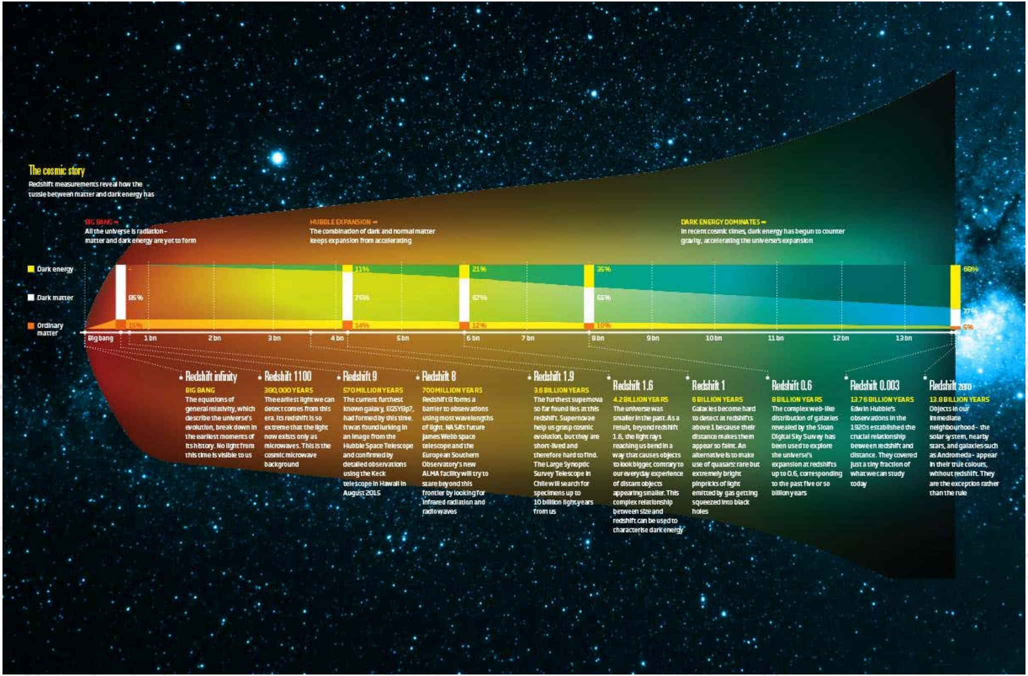
Redshift



Redshift Interpretation
Galaxy 1
Galaxy 2
Galaxy 3
Blue
Red
We should observe redshifts at all distances
along the light spectrum (big bang model)


Big Bang
Accelerating Galaxies
Big Bang
Afterglow light pattern
Recombination
Dark ages
First stars
First galaxies
Galaxy development
Galaxy clusters


unshifted
redshifted
blueshifted

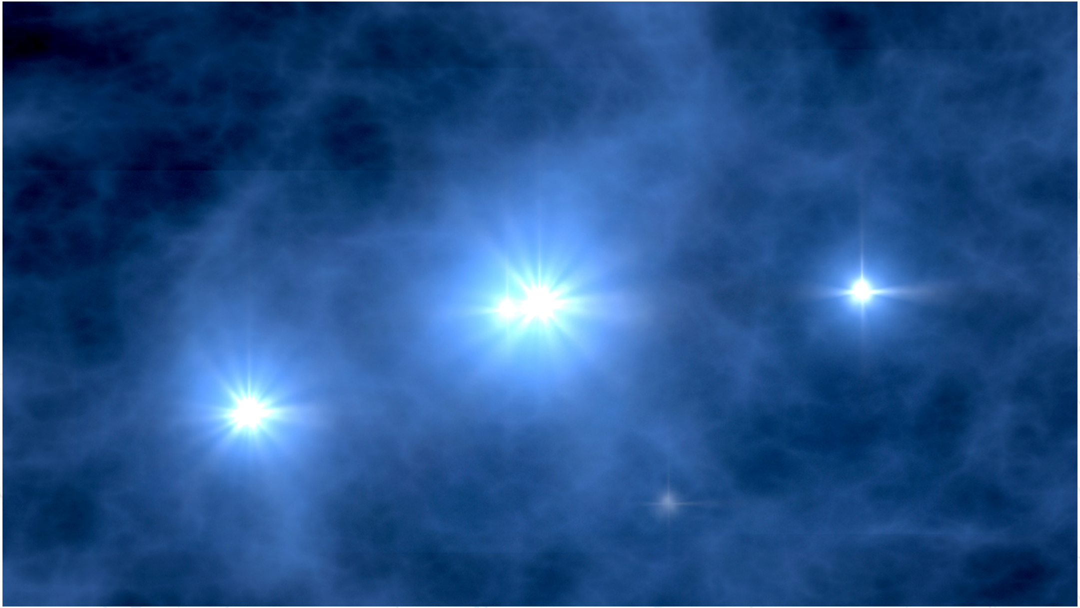

The cosmic story
Redshift measurements reveal how the tussle between matter and dark energy has
BIG BANG
All the universe is radiation – matter and dark energy are yet to form
HUBBLE EXPANSION
The combination of dark and normal matter keeps expansion from accelerating
DARK ENERGY DOMINATES
In recent cosmic times, dark energy has begun to counter gravity, accelerating the universe's expansion
Dark energy
Dark matter
Ordinary matter
85%
15%
11%
75%
14%
21%
67%
12%
35%
55%
10%
68%
27%
5%
Big bang
1 bn
2 bn
3 bn
4 bn
5 bn
6 bn
7 bn
8 bn
9 bn
10 bn
11 bn
12 bn
13 bn
Redshift infinity
BIG BANG
The equations of general relativity, which describe the universe's evolution, break down in the earliest moments of its history. No light from this time is visible to us
Redshift 1100
380,000 YEARS
The earliest light we can detect comes from this era. Its redshift is so extreme that the light now exists only as microwaves. This is the cosmic microwave background
Redshift 9
570 MILLION YEARS
The current furthest known galaxy, EGSY8p7, had formed by this time. It was found lurking in an image from the Hubble Space Telescope and confirmed by detailed observations using the Keck telescope in Hawaii in August 2015
Redshift 8
700 MILLION YEARS
Redshift 8 forms a barrier to observations using most wavelengths of light. NASA's future James Webb space telescope and the European Southern Observatory's new ALMA facility will try to stare beyond this frontier by looking for infrared radiation and radio waves
Redshift 1.9
3.6 BILLION YEARS
The furthest supernova so far found lies at this redshift. Supernovae help us grasp cosmic evolution, but they are short-lived and therefore hard to find. The Large Synoptic Survey Telescope in Chile will search for specimens up to 10 billion light years from us
Redshift 1.6
4.2 BILLION YEARS
The universe was smaller in the past. As a result, beyond redshift 1.6, the light rays reaching us bend in a way that causes objects to look bigger, contrary to our everyday experience of distant objects appearing smaller. This complex relationship between size and redshift can be used to characterise dark energy
Redshift 1
6 BILLION YEARS
Galaxies become hard to detect at redshifts above 1 because their distance makes them appear so faint. An alternative is to make use of quasars: rare but extremely bright pinpricks of light emitted by gas getting squeezed into black holes
Redshift 0.6
8 BILLION YEARS
The complex web-like distribution of galaxies revealed by the Sloan Digital Sky Survey has been used to explore the universe's expansion at redshifts up to 0.6, corresponding to the past five or so billion years
Redshift 0.003
13.76 BILLION YEARS
Edwin Hubble's observations in the 1920s established the crucial relationship between redshift and distance. They covered just a tiny fraction of what we can study today
Redshift zero
13.8 BILLION YEARS
Objects in our immediate neighbourhood – the solar system, nearby stars, and galaxies such as Andromeda – appear in their true colours, without redshift. They are the exception rather than the rule

CMB anisotropy and polarization

- Initial results from the 2003-released "Wilkinson Microwave Anisotropy Probe" revealed that reionization occurred from $30 > z > 11$. The results from analyzing quasar spectra were clearly at odds with this redshift range. A different conclusion was reached using the three-year WMAP data, which showed that the cosmos was ionized by $z = 7$ and that reionization started around $z = 11$. The quasar data is far more in agreement with this.
- The Planck mission's findings in 2018 give an instantaneous reionization redshift of $z = 7.68 \pm 0.79$.

Population III stars

- The first stars without elements more massive than hydrogen or helium were population III stars. Trace amounts of lithium were the only elements to emerge during the Big Bang nucleosynthesis process besides hydrogen and helium. However, quasar spectra have demonstrated the early occurrence of heavy atoms in the intergalactic medium. Large Population III stars that will create supernovae are one potential method for reionization because supernova explosions produce such heavy elements and are so intense.
- Astronomers discovered Population III stars in the Cosmos Redshift 7 galaxy at $z = 6.60$ in June 2015. Such stars were probably present in the early universe (i.e., at high redshift), and they may have begun to produce chemical elements heavier than hydrogen that were eventually required for the emergence of planets and life as we know it.



400 Myr after the Big Bang, a computer-generated depiction of the first stars.

Quasars and the Gunn-Peterson trough

- Since there is a significant distance between quasars and the telescopes that find them, the redshifting of light due to the universe's expansion is discernible. This means that wavelengths that had previously been below the Lyman Alpha limit are stretched as the light from the quasar travels through the intergalactic medium (IGM) and is redshifted, and as a result, they will start to fill in the Lyman absorption band. This means that the light from a quasar that has passed through a wide, diffuse region of neutral hydrogen will have a Gunn-Peterson trough instead of strong spectral absorption lines.

Quasars and the Gunn-Peterson trough

- Quasars releasing light before reionization will have a Gunn-Peterson trough, whereas quasars below a particular redshift (closer in space and time) do not show one (though they may show the Lyman-alpha forest). The Sloan Digital Sky Survey discovered four quasars in 2001, with redshifts ranging from $z = 5.82$ to $z = 6.28$.
- The IGM remained at least somewhat neutral in the quasars above $z = 6$, but it was ionized in those below, which did not exhibit a Gunn-Peterson trough. The findings imply that the cosmos was nearing the conclusion of reionization at $z = 6$ because reionization is anticipated to proceed over relatively short timeframes. This implies that at $z > 10$, the cosmos must still have been virtually totally neutral.

Calculations

Hydrogen reionisation ends by $z = 5.3$: Lyman-α optical depth measured by the XQR-30 sample

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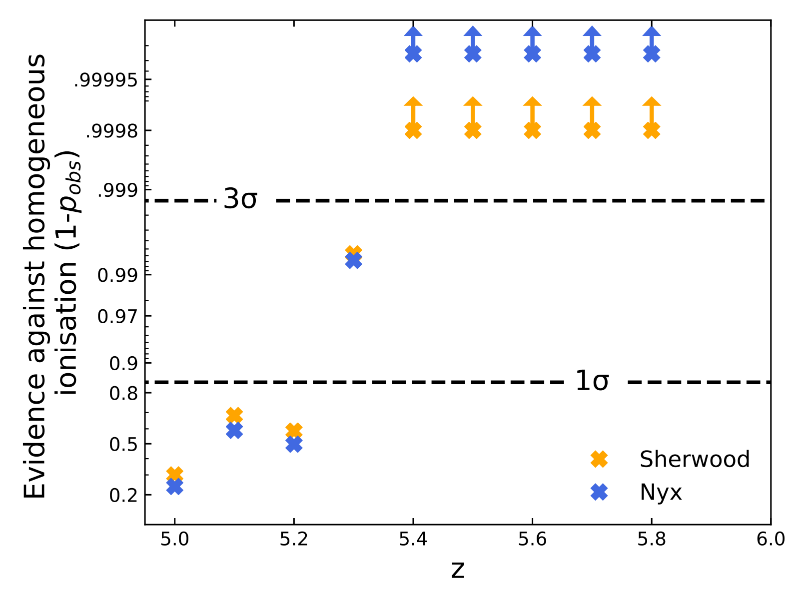
Calculations

ABSTRACT

The presence of excess scatter in the Ly-α forest at $z \sim 5.5$, together with the existence of sporadic extended opaque Gunn-Peterson troughs, has started to provide robust evidence for a late end of hydrogen reionisation. However, low data quality and systematic uncertainties complicate the use of Ly-α transmission as a precision probe of reionisation's end stages. In this paper, we assemble a sample of 67 quasar sightlines at $z > 5.5$ with high signal-to-noise ratios of > 10 per ≤ 15 km s^{-1} spectral pixel, relying largely on the new XQR-30 quasar sample. XQR-30 is a large program on VLT/X-Shooter which obtained deep (SNR$>$ 20 per pixel) spectra of 30 quasars at $z > 5.7$. We carefully account for systematics in continuum reconstruction, instrumentation, and contamination by damped Ly-α systems. We present improved measurements of the mean Ly-α transmission over $4.9 < z < 6.1$. Using all known systematics in a forward modelling analysis, we find excellent agreement between the observed Ly-α transmission distributions and the homogeneous-UVB simulations Sherwood and Nyx up to $z \leq 5.2$ ($< 1\sigma$), and mild tension ($\sim 2.5\sigma$) at $z = 5.3$. Homogeneous UVB models are ruled out by excess Ly-α transmission scatter at $z \geq 5.4$ with high confidence ($> 3.5\sigma$). Our results indicate that reionisation-related fluctuations, whether in the UVB, residual neutral hydrogen fraction, and/or IGM temperature, persist in the intergalactic medium until at least $z = 5.3$ ($t = 1.1$ Gyr after the Big Bang). This is further evidence for a late end to reionisation.

Key words: dark ages, reionisation, first stars – quasars: absorption lines – intergalactic medium – large-scale structure of Universe

Results



Evidence against homogeneous ionisation (1-p_{obs})
.99995
.9998
.999
0.99
0.97
0.9
0.8
0.5
0.2
3σ
1σ
Sherwood
Nyx
5.0
5.2
5.4
5.6
5.8
6.0
z

Results

- The probability analysis comparing the measured optical depth distributions to the homogeneous-UVB Sherwood (orange) and Nyx (blue) simulations is summarized in this picture. Both models offer a superb fit to the data at $z \leq 5.2$ but are in sharp conflict at $z \geq 5.4$ due to the forward modeling of all known uncertainties.
- See:

  Hydrogen reionization ends by $z = 5.3$: Lyman-α optical depth measured by the XQR-30 sample, Sarah E I Bosman et al., Monthly Notices of the Royal Astronomical Society, Volume 514, Issue 1, July 2022, Pages 55–76
  https://doi.org/10.1093/mnras/stac1046