

Dark Ages, First Stars, Early Galaxies, and Reionization

CHO-005 · Cosmic History and Its Observers

A Chronological Scientific History from the Early Universe to the Present

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Structured abstract

Context. Photon decoupling left a mainly neutral Universe whose small density variations continued to grow. There were no stars at the opening seam, yet the matter distribution already contained the gravitational conditions from which luminous structure could form.

Question. How did neutral gas become the first stellar and galactic populations, and how did their radiation transform the intergalactic medium?

Evidence and method. The history is reconstructed from cosmological simulations, atomic and molecular cooling physics, high-redshift galaxy spectroscopy, quasar absorption, cosmic-microwave-background polarisation, and searches for redshifted 21-cm radiation. These probes constrain different integrals, environments, and phases; none supplies a complete film of the first billion years.

Result. Dark-matter haloes assembled hierarchically. In some early minihaloes, primordial gas cooled through molecular hydrogen and collapsed toward star formation. The properties and timing of Population III stars remain model-dependent and no individual first star is observed. Galaxies are now confirmed at redshifts near and above 14, but record holders are the earliest yet detected, not necessarily the first that existed. Ultraviolet radiation and other energetic outputs produced expanding ionised regions that eventually overlapped, making reionization extended, patchy, and definition-dependent.

Conclusion. By 1.2 Gyr the article conservatively hands CHO-006 an intergalactic medium in which homogeneous-background models describe transmission at $z \leq 5.2$, while reionization-related fluctuations are observed to persist to at least $z = 5.3$; established galaxies, continuing star formation, and a developing cosmic web are also present. Observer status remains N0.

Keywords: cosmic dark ages; Population III; first stars; early galaxies; reionization; JWST; 21-cm cosmology

1. Chronological orientation

CHO-005 spans [0.5 Myr, 1.2 Gyr) after the formal hot-Big-Bang coordinate boundary. Its lower BOOK seam lies after photon decoupling. Its upper seam is a conservative containment boundary chosen to include the complete reionization history, including late neutral regions and uncertainty over what “complete” means.

The interval is not divided by exact birthdays. The first collapsing cloud, first sustained fusion source, first gravitationally associated stellar system, first object visible to a particular survey, and first large ionised bubble are different candidates. Simulation volumes sample probabilities; observations sample luminosity, wavelength, position, and selection. Priority statements are therefore treated as distributions or record-relative observations rather than exact birthdays.

2. Initial state inherited from CHO-004

CHO-004 passes forward neutral hydrogen and helium, freely streaming relic photons, dark matter, and density perturbations. Baryons have escaped the strong photon drag that previously resisted their collapse. Gravity now acts across a matter-dominated background, but gas cannot simply fall to an arbitrarily small scale: pressure, angular momentum, chemistry, radiation, and later feedback regulate collapse.

The adjective “dark” refers to the absence of ordinary luminous stars and galaxies, not to an absence of radiation or physical activity. The CMB persists; neutral hydrogen carries a hyperfine transition; dark matter clusters; gas flows into potential wells. The era is difficult to observe because its principal signals are faint, redshifted, and entangled with much brighter foregrounds.

3. From primordial perturbations to collapsed haloes

Collisionless dark matter can assemble gravitational structures without radiating away thermal energy. Small haloes form and merge within larger environments, producing a network of overdense nodes, filaments, sheets, and underdense regions. Baryonic gas falls into these potentials, is compressed and heated, then must transfer energy before further contraction.

The word “hierarchical” describes a statistical tendency in cold-dark-matter models, not a rule that every small object survives intact or that galaxies are built by one route. Smooth accretion, mergers, tidal stripping, shocks, and feedback all contribute. Rare high-density peaks can evolve earlier than the cosmic average, so “when the first halo formed” also depends on the volume considered.

4. Cooling primordial gas

Gas containing only the products of Big Bang nucleosynthesis lacks the metal-line and dust cooling channels familiar in later clouds. Molecular hydrogen can form through gas-phase reaction networks and radiate energy through rotational-vibrational transitions. In simulations, this permits the densest gas in some minihaloes to contract to a central protostellar core [1,2].

The calculation crosses enormous dynamic ranges. It must represent cosmological initial conditions, dark-matter collapse, non-equilibrium chemistry, cooling, turbulence, accretion, fragmentation, magnetic fields, and radiation from the growing protostar. Early simulations established a plausible route to collapse but did not determine a universal primordial stellar mass. Later calculations increasingly resolve fragmentation and feedback, yet the Population III initial-mass function remains uncertain.

Streaming velocities between baryons and dark matter, inherited from pre-decoupling acoustic dynamics, can delay gas accumulation in some haloes. Background radiation can dissociate molecules. Once stars form, ionising photons, supernovae, and enrichment can suppress or promote subsequent star formation depending on distance, density, timing, and halo depth. A single first-star date is therefore scientifically weaker than a conditional probability distribution.

5. Population III without a photographed first star

Population III denotes a theoretical metal-free stellar population. It does not designate every very old star, and “metal-free” is a chemical initial condition rather than a directly observed label for an individual primordial star. Massive stars are plausible because warm primordial gas has a relatively large characteristic fragmentation scale, but the claim that all first stars were extremely massive is no longer warranted without model qualifications.

No confirmed observation identifies the first star that existed. Candidate signatures are indirect: unusual abundance patterns in later stars, pair-instability supernova yields, ionising spectra, black-hole remnants, or integrated backgrounds. Each signature is degenerate with later stellar populations and astrophysical processing. CHO-007 owns the production channels of elements; CHO-005 uses enrichment only as feedback on cooling and population change.

The first stars altered their surroundings quickly. Ultraviolet photons ionised hydrogen locally and dissociated molecular hydrogen farther away. Stellar deaths injected kinetic energy and newly produced nuclei. Remnants could seed black holes. These effects made cosmic dawn a coupled ecological transition rather than a clean succession from one stellar generation to the next.

6. What counts as an early galaxy

A galaxy is not defined solely by the presence of one star. It is a gravitationally organised baryonic and dark-matter system with some combination of stars, gas, continuing assembly, and spatial coherence. At extreme redshift, observations often resolve only compact light distributions and spectra. Stellar mass, age, dust, star-formation rate, lensing magnification, and active-nucleus contribution are inferred through models.

JWST spectroscopy has moved the observed frontier dramatically. Carniani and collaborators confirmed two luminous systems near redshift 14, including JADES-GS-z14-0 [4]. Naidu and collaborators subsequently reported MoM-z14 at $z_{\text{spec}} = 14.44 \pm 0.02$, corresponding in their cosmological conversion to roughly 280 million years after the formal boundary [3]. The study is now published in *The Open Journal of Astrophysics*. The maintained frontier also includes PAN-z14-1 at $z_{\text{spec}} = 13.53$ [13], JADES-GS-z13-0 at $z_{\text{spec}} = 13.20 +0.03/-0.04$ [14], UNCOVER-z13 at $z_{\text{spec}} = 13.079 +0.013/-0.001$ [10], and JADES-GS-z13-1-LA near $z = 13.0$ [11,12]. No spectroscopically confirmed system above MoM-z14 was identified in literature eligible at the 12 September cutoff; this remains an absence-of-evidence result rather than evidence that no earlier system existed.

These are earliest *detected and spectroscopically supported* objects within particular programmes and criteria. They cannot be called the first galaxies. Fainter systems may precede them; survey volume and selection favour luminous objects; redshift measures when the observed light was emitted, not when the system's first constituent formed. Surprising brightness may require revised efficiencies, bursty star formation, unusual stellar populations, active nuclei, lensing assessment, or changes in abundance estimates. It does not by itself falsify the cosmological framework.

7. Ionised bubbles and a changing intergalactic medium

Energetic photons above the hydrogen ionisation threshold escape from some galaxies and create ionised regions. Recombination within dense gas consumes photons, while expansion, source clustering, spectral hardness, escape fractions, and feedback control bubble growth. Active galactic nuclei and other sources may contribute, particularly at some luminosities and epochs, but the fractional budget remains under investigation.

Reionization is therefore topological as well as temporal. Regions around clustered sources can ionise earlier; dense self-shielded systems can remain neutral after their surroundings change. Bubbles expand and overlap, yet residual neutral hydrogen survives in galaxies and absorbers. At $z \approx 13$, the bright Lyman-alpha emission from JADES-GS-z13-1-LA was interpreted as requiring a locally ionised region around a strong ionising source, and deeper 2026 spectroscopy reaffirmed the line and blue continuum [11,12]. This is evidence for early local ionisation, not for a globally ionised intergalactic medium. "Completion" requires an operational threshold, such as a small volume-averaged neutral fraction, not the ionisation of every hydrogen atom.

CHO-005 owns this entire transition. CHO-006 may inherit its effects on later gas supply and galaxy environments but must not retell the ionisation chronology as a second owner.

8. Evidence from integrated and line-of-sight probes

Large-angle CMB polarisation constrains the Thomson optical depth produced by free electrons between decoupling and today. The controlling Planck 2018 baseline analysis gives $\tau = 0.0544 \pm 0.0073$ [8]. Optical depth is an integral: different ionisation histories can yield similar totals. Converting it to an instantaneous reionization redshift is a model summary, not a measurement of a sudden global switch. The 2021 corrigendum revised bounds on an early ionised contribution, so older statements derived from those bounds are not silently retained.

High-redshift quasar and galaxy spectra probe neutral hydrogen along particular sightlines. The Gunn-Peterson optical depth becomes large even for a small neutral fraction, making complete absorption a sensitive indicator but a poor linear meter once saturated [5]. In the XQR-30 analysis of 67 quasar sightlines, homogeneous ultraviolet-background simulations agree with the transmission distribution through $z \leq 5.2$, while excess scatter at $z \geq 5.4$ indicates reionization-related fluctuations persisting to at least $z = 5.3$, approximately 1.1 Gyr in that cosmology [9]. Damping wings, transmission spikes, emission-line attenuation, and dark-gap statistics add information while depending on source environments and intrinsic spectra.

Galaxy luminosity functions estimate the abundance of ultraviolet-emitting sources. Turning light into an ionising budget requires extrapolation below detection limits, stellar-population assumptions, photon-production efficiency,

and an escape fraction. Agreement among these routes is evidence for a broad history, not proof of a unique source census.

9. The 21-cm opportunity and warning

Neutral hydrogen’s hyperfine transition, redshifted to metre wavelengths, can in principle map thermal and ionisation history across cosmic dawn. Its brightness relative to the radio background depends on neutral fraction, gas temperature, density, and the spin temperature set by collisions and radiation. Global experiments seek an all-sky spectral feature; interferometers seek fluctuations.

EDGES reported a flattened absorption profile centred near 78 MHz, commonly associated under a cosmological interpretation with redshift near 17 [6]. The reported amplitude prompted models involving unexpectedly cold gas or an enhanced radio background. SARAS 3 later reported a non-detection that disfavoured classes of profiles compatible with the EDGES result under its analysis [7]. Foregrounds are many orders of magnitude brighter than the target, and instrument chromaticity can couple sky structure into spectra.

CHO therefore records a contested measurement, not an established discovery of the first stars at one exact redshift. A future consistent detection across instruments and complementary power-spectrum measurements could transform the chronology. Until then, the disagreement is scientifically informative but unresolved.

10. Observer capacities present

The entire interval is N0. Stars process radiation and matter; galaxies retain records; neutral hydrogen can encode thermal history. None of this demonstrates biological detection, information use, or consciousness. “Observer” in CHO is not a synonym for any system that interacts physically.

Later telescopes act as retrospective observers. Their selection functions matter: a bright galaxy appears in a catalogue because light survives, enters a survey footprint, exceeds detection thresholds, and supports a redshift inference. The observed frontier is therefore partly a property of instruments and methods, not a moving label for the objectively first object.

11. Contingency and contemporaries

Cosmic dawn was not directed toward later observers. Its pathway depended on dark-matter clustering, molecular chemistry, primordial abundances, radiation backgrounds, feedback, and chance location within large-scale structure. Many minihaloes may have remained dark. Some early stars may have collapsed quietly; others exploded and altered wide regions. Ionised and neutral environments coexisted.

There is no single representative place whose history stands for the Universe. At a given cosmic time, one region could host a luminous galaxy while another remained chemically pristine. Chronology must therefore carry spatial variance rather than narrate the epoch as a uniform global march.

12. Competing interpretations and claim classes

Uncertainties include the Population III mass distribution, black-hole seed channels, the abundance and duty cycles of faint galaxies, ionising escape fractions, the role of active nuclei, the temperature of the intergalactic medium, and the interpretation of very bright $z > 10$ objects. Reionization constraints are often mutually informative but not interchangeable.

Class	CHO-005 use
E1 measured	Spectra, images, sky-frequency measurements, quasar transmission
E2 reconstructed	Redshifts, luminosities, optical depth, neutral fractions
E3 model-dependent	First-star distributions, ionising budgets, time conversions
E4 contested	EDGES feature, some extreme-galaxy interpretations, source shares
E5 speculative	Unconfirmed exotic cooling or radio-background mechanisms

13. Boundaries, closing state, and handoff

CHO-005 does not own primordial recombination, element-production channels, or post-reionization galaxy evolution. It owns the dark ages, first luminous-source problem, early galaxies, and full reionization interval within its BOOK envelope.

At 1.2 Gyr, the operational handoff is not “every atom ionised.” It means that homogeneous-background models describe the XQR-30 transmission distribution at $z \leq 5.2$, while the article retains the observed late fluctuations at $z = 5.3$ as part of reionization’s end stages [9]. Galaxies contain multiple stellar populations; feedback and enrichment have changed gas cooling; black holes and stellar remnants exist; and large-scale environments increasingly shape assembly. CHO-006 inherits these conditions toward the Solar-System seam.

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Disclosure

This document is a scholarly synthesis; it is not primary research and has not been peer reviewed. Juan Segurola is the sole author. He approved the final text and is responsible for its content.