

The Stars We Have Never Seen

QTC-015 · From Quarks to Consciousness

The Universe, Life, and How We Found Out

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Epistemic profile: Current scientific interpretation

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Article Abstract

Population III stars must have formed from the nearly pristine hydrogen and helium left by the hot early Universe, yet no individual star has been spectroscopically identified as metal-free. That sentence now needs care. JWST has found serious candidates, confirmed extremely primitive gas and measured systems such as Hebe and LAP1-B that strongly test first-star predictions. This article follows the evidence from molecular-hydrogen cooling and uncertain stellar masses to chemical archaeology and multi-line spectroscopy. It explains why simulations predict a top-heavy population without predicting one universal mass, why helium emission or missing metal lines cannot prove the case alone, and why population-level evidence is not the same as seeing one star. The first stars remain partly unseen, but they are no longer evidentially untouched.

In 60 Seconds

The Big Bang made mostly hydrogen and helium, so some first generation of stars had to manufacture the carbon, oxygen, silicon and iron found later. In standard calculations, pristine gas began collapsing mainly in small dark-matter haloes around redshifts 20–30. Molecular hydrogen cooled it only to a few hundred kelvin, encouraging rapid accretion and a stellar population weighted toward high masses. Modern simulations also produce discs, binaries and lower-mass fragments, so ‘every first star had 100 solar masses’ is wrong. Massive members lived briefly, ionized their surroundings and either exploded, collapsed or shed the first heavy elements. We search for them in four ways: simulations, the chemical fingerprints preserved in ancient stars, spectra of remote primitive systems and gravitational lensing. Hebe near GN-z11 now provides confirmed hydrogen emission and stringent metal limits; LAP1-B has a measured but nonzero oxygen abundance. These are major advances, not yet an individual zero-metal stellar spectrum. The strongest diagnosis is a conjunction of redshift, hard radiation, multiple metallicity limits and tests of alternative sources.

Why This Question Matters

The first stars connect three kinds of history that are often told separately. They turned primordial chemistry into starlight, made the first heavy elements and changed which future objects could form. Yet almost every statement about them crosses an evidential boundary: from observed atomic physics into a simulation, from a descendant's chemistry back to an unknown explosion, or from unresolved nebular light to a stellar population. The subject therefore tests not only cosmic history but the

discipline of saying exactly what has been observed. It is a model case of reconstruction: no single method owns the conclusion, and precision comes from preserving the joints between them.

1. What ‘Never Seen’ Must Mean Now

The Question

If telescopes have detected light from systems that may contain Population III stars, how can the title still say that we have never seen them? Because a candidate population, pristine gas and an individually identified star are different observational achievements.

Population III does not mean ‘the oldest stars’ or ‘the most distant stars’. It names stars formed from primordial or effectively primordial material, containing essentially no elements heavier than helium. Big Bang nucleosynthesis produced hydrogen, helium and traces of light nuclei, but not the carbon, oxygen, silicon or iron needed for later metal-line and dust cooling.[1,2,17,40] Some stellar generation therefore had to form before metal-enriched star formation could exist.

The first stars and Population III are closely related but not perfectly synonymous. Enrichment was patchy. A supernova could pollute one region while neighbouring gas remained pristine, allowing Population III formation to continue after Population II stars already existed elsewhere.[23,31] Chronology alone cannot identify the class; composition and formation history matter.

The observational situation changed sharply between the first JWST reports and 2026. The region now called Hebe, roughly three proper kiloparsecs from GN-z11, has confirmed hydrogen emission and no detected metal lines in deep follow-up spectra. Population models strongly favour a major Population III contribution.[24–26] GLIMPSE-16043 remains a photometrically selected candidate, while LAP1-B is a spectroscopically measured, exceptionally primitive but nonzero-metal system. [27–31] These objects do not belong in one undifferentiated list.

No individual stellar spectrum has yet established one star as metal-free Population III. Most candidate systems are unresolved or dominated by surrounding gas, so researchers infer the ionizing population from emission lines, continuum limits, lens models and stellar synthesis. That is genuine observation joined to modelling, not a photograph of a labelled star. The title remains defensible only with that narrower meaning.

Where That Leaves Us

Population III is defined by birth material, not merely by age or distance. JWST has now observed powerful candidate environments and remarkably primitive gas, making ‘nothing has been seen’ obsolete today. What remains unseen is an individually identified zero-metal star, while population-level evidence occupies several distinct and rapidly changing strengths. The next question is therefore how pristine gas could collapse into stars at all.

2. How Pristine Gas First Collapsed

The Question

Without carbon, oxygen or dust to radiate heat efficiently, why did primordial gas collapse at all? It used a weaker coolant, molecular hydrogen, inside dark-matter haloes whose gravity gathered enough gas for cooling to outrun compression.

In standard Lambda-CDM calculations, the main first-star channel begins in minihaloes of roughly 10^5 – 10^7 solar masses around redshifts 20–30.[1–4,31] Those figures describe a predicted distribution, not one observed birthday. The earliest collapsing object in one calculation depends on the simulated volume, cosmological initial conditions and the criterion used to identify a star-forming core.

Molecular hydrogen forms through a small network of primordial reactions and cools by rotational and vibrational emission. In the canonical minihalo path it lowers the gas temperature to about 200 K, far warmer than many dusty molecular-cloud cores today.[3,4,6] The corresponding sound speed, Jeans scale and inflow rate favour rapid accretion. That thermal argument explains a tendency toward higher masses, not one compulsory mass.

Early simulations often produced one dominant collapsing core, encouraging an image of a solitary star above 100 solar masses.[3,4] Higher-resolution three-dimensional calculations found rotating discs that fragment, exchange angular momentum, eject members and merge protostars.[6,7,37] Radiation from growing protostars eventually heats or ionizes the inflow, but feedback does not erase every fragment.[5,7,38] Modern work therefore predicts a distribution, frequently top-heavy, with uncertain lower and upper limits.

The threshold also moves. Lyman-Werner photons dissociate molecular hydrogen; ionizing radiation can heat or sometimes prepare gas for new chemistry; and the coherent relative motion of baryons and dark matter makes gas capture harder in some regions.[8–10] Environment, rather than one universal redshift or halo mass, determines when a pristine cloud crosses from delay into collapse.

Where That Leaves Us

Pristine gas could form stars because molecular hydrogen provided a limited cooling route inside growing dark-matter haloes. Its relatively warm collapse supports a top-heavy mass distribution, but discs, feedback and environment prevent one universal mass or birth date. That uncertainty matters because stellar mass governs everything the first stars did next.

3. Stars That Changed the Available Chemistry

Metal-free massive stars are compact, hot and capable of producing hard ultraviolet spectra. Population-synthesis calculations predict abundant hydrogen-ionizing photons and, for sufficiently hot populations, photons energetic enough to ionize helium twice.[11,12] Their radiation created local ionized regions and began altering gas before any explosion occurred. Yet rotation, binaries and very massive low-metallicity stars can imitate parts of the same spectral hardness.

The massive stars that dominate those spectra live only a few million years.[11,13,14] This makes a pure luminous cluster difficult to catch: its own brightest members rapidly pollute, disperse or ionize the material used to identify it. The detection window is short for the same reason the stars are cosmically important. Lower-mass members could live far longer, but whether many formed remains part of the unknown IMF.

Their deaths were not uniform. Depending on initial mass, rotation, multiplicity and mass loss, models produce ordinary or faint core-collapse supernovae, pulsational pair instability, full pair-instability disruption or direct collapse into a black hole.[13,14,20] Simple mass intervals quoted

for non-rotating single stars are useful maps, not natural borders. Binary interaction can move a star between outcomes.

Where material escaped, it supplied the first carbon, oxygen, silicon, iron-group elements and dust precursors.[13,14,22,39] Those ejecta opened cooling routes that primordial gas did not possess, enabling lower-temperature fragmentation and the transition toward Population II. Some remnants may also have seeded later black holes, but their importance relative to heavier seed channels is an active hypothesis. Population III contributed ionizing photons, yet its total share of reionization is still unresolved.[15,16]

Where That Leaves Us

The first stars changed their surroundings twice: radiation acted while they lived, and escaping ejecta changed the chemistry after they died. Their mass distribution controls both effects, so uncertain masses propagate into uncertain reionization and black-hole histories. Those chemical ashes outlast the light, but interpreting them first requires simulations that connect stellar physics to predictions that observations can test.

4. What Simulations Know, and What They Assume

The Question

A simulation can show the birth of a star that no telescope has resolved. What kind of evidence is that? It is a controlled consequence of stated physics and initial conditions, powerful precisely when its assumptions and numerical limits remain visible.

First-star calculations are not free-form animations. They combine gravity, hydrodynamics, atomic and molecular reaction rates, radiative transfer and cosmological initial conditions constrained by observation.[1,3,4] From those ingredients they calculate collapse across an enormous range of scales, from a minihalo to a protostellar disc. Repeated emergence of molecular cooling and rapid inflow across independent methods is meaningful evidence about that physical framework.

The hardest quantity is the final stellar mass. A calculation may resolve fragmentation for only years while accretion continues for tens of thousands of years. Sink particles replace unresolved high-density regions; merging rules, accretion radii and feedback prescriptions can alter how many objects survive.[5–7,37,38] Magnetic fields, turbulence and binaries add further sensitivity. Numerical convergence at one scale does not guarantee convergence of the final IMF.

This produces a hierarchy. The need for primordial cooling, relatively warm gas and strong feedback is robust across a useful range of calculations. The exact slope, characteristic mass, upper limit and binary fraction are not.[1,31] Saying ‘simulations show’ without naming which layer hides that difference. Agreement establishes what follows from shared assumptions; it does not turn a predicted protostar into an observed one.

Observation can close the loop. Chemical abundance distributions test explosion yields; candidate spectra test hardness and stellar ages; 21-centimetre measurements can constrain integrated heating and ionization. A successful prediction strengthens a model, while a mismatch can identify missing physics or a mistaken translation from simulation to observable. Prediction and detection remain different categories even when they reinforce each other.

Where That Leaves Us

Simulations make the unseen calculable by joining measured microphysics to cosmological initial conditions. Their most stable results concern cooling, collapse and feedback; their least stable results concern final masses and multiplicity. That uncertainty is useful: it tells chemical archaeology which simulated yields can be tested against the oldest surviving abundance patterns. The next archive is chemical rather than luminous.

5. Reading the Ashes Close to Home

If any Population III stars formed below roughly 0.8 solar masses, some could survive today. Surveys of the Milky Way halo and nearby dwarf galaxies have found extremely metal-poor stars, but no confirmed star with exactly zero measured metals.[17,18,31] The absence constrains the low-mass tail only through survey selection, stellar evolution and the probability that survivors entered the regions we have searched.

The stars we do find can preserve abundance patterns inherited from earlier explosions. SMSS J031300.36-670839.3, for example, has extraordinarily little iron and was interpreted as the product of a low-energy supernova with fallback.[19] Faint-supernova models can eject carbon-rich outer layers while much of the iron-rich interior falls into a black hole.[20] This is why a later star can function as a chemical detector for an explosion it never witnessed directly.

The inversion is not unique. Carbon enhancement can also arise through mass transfer in a binary, and one gas cloud may mix ejecta from several supernovae. Surface abundances can change during stellar evolution. Parametric studies show which regions of abundance space remain compatible with nearly pure Population III enrichment and where later contamination becomes degenerate.[35] One descendant is therefore evidence about classes of progenitors, not a recovered biography of one star.

Pair-instability supernovae offer a complementary high-mass test because their yields predict strong odd–even patterns and distinctive iron-group behaviour.[13,14] Such signatures appear rare, but rarity does not prove that very massive first stars never existed. Their metals may escape small haloes, become diluted or be absent when massive stars collapse directly. Very metal-poor damped Lyman-alpha systems add comparatively simple gas archives, though even they do not uniquely determine a progenitor.[21]

Where That Leaves Us

Nearby ancient stars and simple gas clouds preserve chemical consequences of earlier explosions, not photographs of their progenitors. Their patterns constrain low-energy supernovae, pair-instability events and the IMF's edges, but mixing and alternative histories make the reconstruction many-to-one. Archaeology narrows possibilities but cannot resurrect a complete first generation; the next test must seek its spectral signatures in distant light.

6. The Spectral Signature Is a Conjunction

The Question

What would a distant Population III population look like if its individual stars cannot be separated? Researchers search for a hard ionizing spectrum and exceptionally weak metals, then ask whether one physical population can explain every feature at once.

Doubly ionized helium recombines to produce the He II 1640 line. Because creating He⁺⁺ requires photons above 54.4 electronvolts, strong nebular He II points to a hard radiation field.[11,12] Very large hydrogen-line equivalent widths can indicate an extremely young, line-dominated population. Together with deep limits on oxygen, carbon and nitrogen lines, these features form a physically motivated first-star diagnostic.[32–34]

None is unique. Accreting black holes, active galactic nuclei, X-ray binaries, shocks, Wolf–Rayet stars and very massive low-metallicity stars can generate hard photons.[24,32,33] Geometry can separate an emitting knot from a central black hole; line widths and ratios can eliminate other alternatives. But He II alone is an alarm, not a label.

Missing metal lines also require careful grammar. A non-detection supplies an upper limit set by exposure time, noise, ionization state, density and abundance ratios; it does not measure exact zero.[25,27,29,33] Multiple ions across a wide wavelength range are more constraining than one absent line. Population III stars may also coexist with gas recently enriched by their own supernovae, creating hybrid or self-polluted systems rather than pure textbook examples.

Gravitational lensing brings intrinsically faint complexes above a telescope's detection threshold and has already enabled observations of individual distant stars that are not Population III.[28–30,36] Yet magnification, caustic geometry and source size depend on a foreground mass model. Line ratios may be comparatively stable, while intrinsic luminosity and stellar mass can change substantially. Lensing extends reach and adds a new uncertainty at the same time.

Where That Leaves Us

No single spectral feature proves Population III. The persuasive case joins a hard ionizing field, extreme youth, stringent limits on several metals, spatial information and explicit tests of black holes and other contaminants. Lensing can reveal the required faint systems, but every inferred luminosity and mass must retain its lens-model dependence.

7. What JWST Has Actually Found

The Question

The phrase ‘Population III candidate’ now covers systems with very different evidence. Which measurements belong to each object, and which conclusions still come from population models rather than directly detected stars? The distinction decides what kind of discovery can be claimed.

The GN-z11 halo source was first reported as a greater-than-five-sigma feature consistent with He II 1640 and no detected metal lines.[24] Independent high-resolution spectroscopy then confirmed the He II identification, resolved two components and again found no metal lines.[41] A companion analysis in a different JWST spectral range detected H γ at signal-to-noise 5.9, fixed the redshift at 10.5862 ± 0.0003 and placed a three-sigma gas-metallicity limit below 0.02 solar.[25] The region,

now called Hebe, lies about three proper kiloparsecs from GN-z11, making ionization by its central active nucleus geometrically difficult.

A dedicated model comparison concludes that both observed components require more than half their stellar mass in Population III stars and that one component is consistent with a pure Population III system. The same analysis favours a top-heavy IMF but retains degeneracies among age, stellar mass and IMF shape.[26] This is among the strongest population-level cases available. Its strength comes from the conjunction of measurements and models, not from resolving an individual star.

GLIMPSE-16043, at a photometric redshift near 6.5, is intrinsically ultra-faint and shows an inferred H α equivalent width of 2810 ± 550 angstroms, no detected [O III] and a gas-metallicity limit below 0.5 percent solar.[27] Those properties made it a prominent candidate. Later analysis emphasized that an unusual Balmer jump can also select exotic, very metal-poor but not genuinely metal-free systems.[31] Spectroscopy must decide which interpretation survives.

LAP1-B has the clearest abundance number. JWST spectroscopy measures $z = 6.625 \pm 0.001$, an oxygen abundance of $(4.2 \pm 1.8) \times 10^{-3}$ solar, a stellar-mass upper limit below 3,300 solar masses and an exceptionally hard radiation field.[28,29] It is the most chemically primitive star-forming galaxy yet measured, and it matches several theoretical expectations for a Population III-hosting environment.[30] Its oxygen is nevertheless nonzero, so ‘metal-free galaxy’ would erase the measurement that makes it remarkable.

Where That Leaves Us

Hebe supplies the strongest present case for a pristine or Population III-dominated unresolved population; GLIMPSE-16043 remains a candidate awaiting decisive spectroscopy; LAP1-B is a measured, extraordinarily primitive but already enriched galaxy. The field has crossed from predicted signatures to real discriminating tests without collapsing every result into one ‘first detection’ headline.

8. What Would Turn a Candidate into a Detection

A persuasive identification begins with a secure redshift and a spectrum that can be tested as one physical system. It needs a hard stellar ionizing field, stringent limits across several metals and consistency among line luminosities, equivalent widths, continuum and source size.[25,26,31–34] The analysis must then exclude active nuclei, accreting compact objects, shocks and enriched stellar populations at the sensitivity actually achieved.

No universal checklist can remove every assumption. A genuinely mixed Population II/III region may contain metal lines and still host pristine stars; a freshly self-enriched cluster may show metals produced by its own first supernovae. Spatially resolved spectroscopy and repeated observations can separate components and test whether a signal follows the expected morphology. Independent population codes are especially valuable when the claimed result is an IMF rather than merely a hard spectrum.

The most detectable Population III systems need not contain the chronologically first stars. Later pristine pockets can form in larger haloes, lie behind favourable lenses or appear beside luminous galaxies that make them easier to locate.[23,28,31] The search is therefore not a race only toward

the highest redshift. It is a search for the cleanest conjunction of composition, radiation and environment.

That logic explains how science can know much before it sees one labelled object. Atomic physics constrains cooling and spectra; simulations translate that physics into populations; archaeology tests the explosions; JWST tests the unresolved light. Each bridge is corrigible. QTC-016 begins when those first cycles have supplied enough heavy elements and solids to make planets possible, even while isolated pristine pockets may persist.

Where That Leaves Us

A detection will be earned by convergence, not by one spectacular line: secure geometry, a hard stellar spectrum, multi-element limits, controlled lensing and failed alternatives. Until then, candidates can still test first-star theory powerfully. The achievement is not pretending uncertainty has vanished, but making each observational and model-dependent layer explicit.

What We Know, and How

- Big Bang nucleosynthesis produced mostly hydrogen and helium, so stellar nucleosynthesis was required before metal-enriched star formation.[1,40]
- Primordial molecular cooling, cosmological simulations and independent numerical methods support star formation in warm minihalo gas and a top-heavy, not single-mass, IMF.[3–7]
- Metal-poor stars and simple gas systems preserve indirect chemical constraints on early supernovae, with known degeneracies from mixing and later enrichment.[17–21,35]
- Hard helium-ionizing radiation and multiple metal-line limits form a stronger Population III diagnostic than either feature alone.[11,12,32–34]
- JWST has confirmed exceptionally primitive systems and strong population-level candidates, including Hebe and LAP1-B, without yet resolving an individual zero-metal star.[24–31]

What We Still Don't Know

- The exact Population III initial mass function, its low-mass survivors, upper limit and binary fraction.
- How much Population III contributed to reionization and to the seed population of later massive black holes.
- Whether Hebe is purely Population III or mixed, and how its age, stellar mass and IMF divide the allowed models.
- How long pristine pockets continued forming stars and which present candidates will survive deeper spectroscopic tests.

What Could Change Our Minds

- A reproducible individual stellar spectrum with metallicity limits that establish a zero-metal Population III star.
- Independent spectra or population models showing that a leading candidate is instead powered by an accreting compact object or enriched stars.
- A converged simulation and observational sample yielding a present-day-like rather than top-heavy Population III IMF.

- A statistically secure set of pair-instability signatures, long-lived metal-free survivors or 21-centimetre constraints that materially revises the allowed population.

If You Remember Only One Thing

We have seen candidate environments and primitive gas, but identifying Population III stars requires a conjunction of evidence that separates observed light from the stellar population inferred to produce it.

Related Articles

- QTC-004 — Where Were the Atoms in Your Body Made?
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