

Before Atoms

QTC-013 · From Quarks to Consciousness

The universe, life, and how we came to know it

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Article Abstract

There is no electromagnetic photograph of the Universe before atoms became neutral enough for light to travel freely. Yet earlier history is not a blank. It is reconstructed by combining cosmic expansion, measured particle and nuclear physics, primordial abundances, neutrino effects, accelerator experiments, and lattice calculations. This article follows that evidence from the first minutes through neutrino decoupling, the quark–gluon plasma, and the electroweak crossover. Along the way it replaces persistent-particle cartoons with quantum fields and temperature-dependent degrees of freedom. Heavy-ion collisions test relevant QCD matter without recreating the early Universe, and the measured Higgs mass fixes an electroweak history that is a smooth crossover, not the violent transition often drawn in timelines. Confidence decreases toward higher energies. Grand-unified particles and the Planck regime remain labelled possibilities, not observed stages in a seamless film.

In 60 Seconds

Our oldest electromagnetic image is the finite-width last-scattering surface. Earlier times are inferred. During radiation domination, temperature relates to cosmic time through the Friedmann equation, the relativistic particle inventory, and entropy history. Reactions track equilibrium while they are faster than expansion and freeze out gradually when they are not. Around the MeV scale, weak neutron–proton conversion departs from equilibrium, neutrinos decouple, and light nuclei later assemble after deuterium can survive energetic photons. Relic neutrinos have not been caught individually, but nucleosynthesis and CMB signatures constrain their population. At still higher temperatures, quarks and gluons are the useful degrees of freedom. Lattice QCD finds a smooth crossover for early-universe conditions, while RHIC and LHC collisions test tiny, short-lived droplets of strongly interacting QCD matter. Near 160 GeV, the measured Higgs mass implies another smooth Standard Model crossover. Above these tested regimes, confidence becomes increasingly model-dependent. A named “GUT epoch” or “Planck epoch” is not evidence that its proposed particles or quantum-gravity history have been observed.

Why This Question Matters

Popular timelines often look like a sequence of camera frames: atoms dissolve into nuclei, nuclei into quarks, and quarks into ever more speculative particles. The visual continuity hides a change in evidence. Some stages are constrained by relic abundances; others by laboratory cross sections, lattice calculations, or model extrapolation across immense energy gaps. Marking those transitions prevents

two errors at once: treating the invisible past as unknowable, and treating every labelled epoch as equally observed. The real achievement is a graded reconstruction whose uncertainty is explicit.

1. No Photograph Before Atoms

The Question

How can we describe a time no photon can show us? Not by pretending to see through the opaque plasma. We reconstruct earlier conditions from the relics that escaped later, the microphysics tested elsewhere, and a cosmological model that links temperature, density and time.

Ordinary electromagnetic imaging stops at a finite-width last-scattering epoch. Before neutral atoms formed efficiently, photons scattered repeatedly from charged matter and did not carry intact pictures across cosmic distances. Earlier states are reconstructed from later radiation, abundances, dynamics and tested theory; they are not successively older photographs hidden behind the CMB. [1,3,5,19]

The names used for matter also change with temperature. An atom, a nucleus, a nucleon and an elementary-particle excitation are not the same object viewed with better magnification. They are levels of organization whose usefulness depends on which interactions bind structures and which energies disrupt them. A correct timeline changes description as the physics changes. [3–6]

For the same reason, “plasma” is not one permanent cosmic substance. Near recombination it means mainly ions, electrons and photons. Earlier, the thermal population can include abundant neutrinos, electron–positron pairs, quarks, gluons and other Standard Model excitations. The word indicates collective ionized or deconfined conditions, not a single fixed recipe. [3,4,6]

Quantum field theory removes another misleading picture. Particles are quantized excitations of fields, not indestructible pellets that must travel unchanged from the earliest stage to the present. As temperature changes, excitations appear, disappear, mix or become confined, while conserved quantities and interactions provide the continuity that naïve little-ball imagery cannot. [2,6]

Even a phrase such as “one second after the hot Big Bang” is an inferred coordinate. No surviving clock displays that reading. Expansion parameters, energy density, reaction rates and the particle inventory calibrate the relation between a modeled temperature and cosmic time. The coordinate is powerful precisely because its assumptions can be stated and tested. [3–5]

Where That Leaves Us

Before atoms, the evidence changes from pictures to reconstruction, and the useful constituents change with the interaction regime. Fields, not immortal pellets, provide the deeper language. To order those states, cosmology needs a clock that did not survive as an object: temperature becomes that clock only through expansion dynamics and specified particle content.

2. Temperature Becomes a Clock Through a Model

The Question

A temperature is not a date. It becomes one only after a model states how fast the Universe expands, which species carry energy and entropy, and whether reactions can keep those species in equilibrium. Change the inventory, and the same temperature can correspond to another time.

During radiation domination, relativistic energy density controls the Hubble expansion rate through the Friedmann equation. Once the effective particle content and entropy evolution are specified, a measured or calculated temperature maps approximately onto cosmic time. The relation is not arbitrary, but neither is it independent of the assumed thermal inventory. [3–5]

A species remains in thermal equilibrium while interactions that create, destroy or redistribute it operate much faster than expansion. Freeze-out is the gradual loss of that tracking when the interaction rate falls below the Hubble rate. The result depends on cross sections, number densities and expansion, not on a universal switch at one exact second. [6,7]

The effective relativistic degrees of freedom count how many excitations contribute to energy and entropy with the appropriate statistical weights. As species become nonrelativistic, annihilate or decouple, that count changes. Consequently, temperature, energy density and scale factor do not follow one fixed proportionality across the entire early timeline. [3,4,6]

Under the simplified conditions of adiabatic radiation domination and nearly constant relativistic content, cosmic time scales approximately as the inverse square of temperature, with a correction from the square root of the effective degrees of freedom. This relation explains why a modest increase in temperature reaches dramatically earlier inferred times. [3–5]

Named epochs can therefore move in seconds if extra light relics, entropy production or a different expansion law is introduced, even when the order of microphysical events stays similar. “One second” is a calibrated model statement; weak freeze-out or deuterium survival is the physical event that gives the label content. [3–6]

Where That Leaves Us

Temperature orders the early Universe because expansion and microphysics are coupled, not because a thermometer survived. Reaction rates compete with the Hubble rate, and changing degrees of freedom alter the calibration. The first major application of this clock is nuclear: determine when neutrons, protons and deuterium could stop being continuously reset by the radiation bath.

3. When Nuclei Could Survive

Deuterium has a binding energy of 2.23 MeV, yet it could not accumulate as soon as the average temperature fell below that value. The enormous photon-to-baryon ratio left enough photons in the energetic tail to photodissociate newly formed deuterium. Nuclear assembly had to wait for the tail, not merely the mean, to become harmless enough. [8–11]

Weak interactions converting neutrons and protons began departing from equilibrium near a temperature of roughly 1 MeV, corresponding to an age of order one second in the standard history. Neutrons then continued to decay while expansion cooled the plasma toward the later opening of the nuclear network. [9–11]

The deuterium bottleneck ended near 0.1 MeV, when the number of photons energetic enough to destroy deuterium per baryon fell below order unity. Deuterium could then persist long enough to feed rapid reactions into helium and other light nuclei. The delay connects statistical physics directly to primordial abundances. [9,10]

Big Bang nucleosynthesis couples measured nuclear reactions to expansion and predicts the main primordial yields of deuterium, helium-3, helium-4 and lithium-7 within the first minutes. The

network is quantitative and revisable: cross-section or lifetime changes alter particular yields instead of turning the calculation into one indivisible origin story. [8–12]

These reactions made nuclei, not neutral atoms. Electrons remained in an ionized plasma for hundreds of thousands of years before recombination allowed stable neutral hydrogen and helium to dominate. Calling BBN “the formation of the first atoms” collapses two epochs and erases the long charged interval between them. [1,9,10]

Where That Leaves Us

The first minutes are reconstructed through a bottleneck, a reaction network and measured relic abundances. Nuclei became stable long before atoms, giving the thermal history two separate milestones. At nearly the same MeV scale, another population stopped sharing equilibrium with photons and began travelling almost freely: the cosmic neutrino background.

4. A Relic Sea We Have Not Directly Caught

The Question

The Universe should still contain hundreds of relic neutrinos in every cubic centimetre, yet no detector has identified individual members of that sea. How can an undetected population count as evidence? Its energy and free streaming alter other observables in ways that can be calculated and cross-checked.

Standard-model neutrinos decouple non-instantaneously around the MeV scale, when the standard thermal history is roughly one second old. Their weak interactions cease to maintain full equilibrium, and the population begins free-streaming while still retaining small spectral effects from the finite duration of decoupling. [13–15]

Electron–positron annihilation then heats photons more than the already decoupling neutrinos. In the instantaneous idealization, entropy conservation gives a neutrino-to-photon temperature ratio equal to the cube root of 4/11. Real decoupling overlaps the annihilation and slightly modifies the simple result. [14–16]

Precision Standard Model calculations include flavour oscillations and finite-temperature quantum electrodynamics. They yield an effective radiation parameter $N_{\text{eff}} = 3.0440 \pm 0.0002$ rather than exactly three. The difference is small, but it records real transport physics and makes precision cosmology sensitive to additional light relics. [15]

N_{eff} parameterizes radiation energy density; it is not a literal head count of neutrino flavours. With the measured photon temperature and standard decoupling relation, the present relic neutrino temperature is about 1.95 K, and the mean total density is about 336 neutrinos plus antineutrinos per cubic centimetre across three flavours. [15–17]

Individual cosmic relic neutrinos have not yet been directly captured. Their population is inferred through effects on nucleosynthesis, CMB damping and the acoustic phase shift generated by free-streaming radiation; PTOLEMY represents a proposed direct-detection route. Indirect convergence is evidence, but it should not be mislabeled as a completed particle count. [16–19]

Where That Leaves Us

Relic neutrinos illustrate the evidence ladder: precise Standard Model transport predicts a population that leaves independent cosmological signatures, while direct capture remains proposed rather than achieved. At higher temperatures the relevant carriers change again. Neutrinos, electrons and nuclei give way to a thermal description dominated by quark and gluon degrees of freedom.

5. Before Protons and Neutrons

The Question

Were protons present all the way back? At sufficiently high temperature, treating matter as a dilute gas of stable hadrons fails. Quarks and gluons become the useful thermal degrees of freedom, but “free” quarks do not mean a weak, ideal gas or a laboratory copy of the cosmos.

Above the QCD crossover, quark and gluon degrees of freedom describe the thermal medium better than a dilute population of stable protons, neutrons and mesons. This is deconfinement in a collective, finite-temperature sense. It does not mean isolated quarks can be removed and stored like electrons. [20–22]

At the near-zero baryon chemical potential relevant to the early Universe, lattice QCD finds a smooth chiral crossover rather than a first-order phase transition. A representative pseudocritical temperature is 156.5 ± 1.5 MeV. The quoted value identifies a crossover marker, not a discontinuous instant at which one substance abruptly becomes another. [20,21]

Heavy-ion collisions at RHIC and the LHC create tiny droplets of QCD matter with collective flow and strong parton-energy loss. The evidence shows a strongly interacting quark–gluon plasma, not the weak ideal gas once expected. Multiple experiments constrain complementary observables and systematic uncertainties. [23–30]

Those collisions do not recreate the early Universe as a whole. Their droplets are microscopic, short-lived and expand through a different geometry; their baryon conditions and initial state also differ. They test QCD microphysics under controlled extremes, providing constraints rather than a miniature cosmological replay. [23,24,28,29]

As the cosmic medium cooled through the QCD crossover, thermal degrees of freedom reorganized into hadrons, including the proton and neutron population later used by nucleosynthesis. Nearly symmetric matter and antimatter largely annihilated, while a small baryon excess survived. QCD describes the reorganization; QTC-014 owns the still-open origin of that excess. [3,20–23]

Where That Leaves Us

Lattice calculations and collider data make the QCD epoch a constrained reconstruction, while their cosmic translation remains model-dependent. Hadrons emerged through a smooth crossover, and the surviving matter excess requires a separate explanation. At still higher temperature, the measured Higgs sector determines another reorganization: electroweak symmetry changes without the violent transition that many baryogenesis cartoons require.

6. When Electroweak Symmetry Changed

The Question

Textbook diagrams often draw the electroweak epoch as a sharp phase transition. The measured Higgs mass changes that picture. Within the Standard Model, the thermal change is a smooth crossover, a result that also removes one ingredient needed by the simplest electroweak explanation of the matter excess.

With a Higgs boson mass near 125 GeV, the Standard Model does not produce a strong first-order electroweak phase transition. Earlier theoretical bounds and later collider measurements place the real Universe in the crossover regime. The conclusion belongs to the measured Standard Model, not to every possible extension of its scalar sector. [31,32,34,35]

Nonperturbative calculations locate a representative crossover near 159.5 ± 1.5 GeV, with a narrow region of rapid but continuous change. A pseudocritical temperature can be quoted even without latent heat or a thermodynamic discontinuity. Naming the epoch should not smuggle a first-order transition back into the picture. [32,33]

Across the crossover, the thermal Higgs expectation value and screening masses evolve, changing reaction rates and the effective propagation of excitations in the plasma. “Particles acquiring mass at one instant” is therefore too abrupt a story. The thermal medium and symmetry realization change continuously over a finite range. [6,32]

ATLAS and CMS measurements of a new boson near 125 GeV supply the laboratory input used in the Standard Model thermal calculation. Later measurements refine its properties. This is a concrete example of cosmological reconstruction depending on collider data rather than on a relic image from the electroweak era itself. [32,34–36]

A smooth Standard Model crossover cannot by itself supply the strong first-order out-of-equilibrium event required in conventional electroweak baryogenesis. Extensions can change the transition and add CP violation, but those mechanisms are hypotheses to be tested. The observed matter excess survives the crossover; its origin remains QTC-014’s problem. [31–33]

Where That Leaves Us

The electroweak epoch is reconstructed from a measured Higgs sector and nonperturbative thermal calculation, not observed as a cosmic flash. Its smooth crossover constrains baryogenesis rather than solving it. We can now assemble the full pre-atomic sequence, but only if laboratory experiments, relics and calculations retain their distinct roles instead of becoming one seamless animation.

7. Reconstructing an Unseen Sequence

Confidence comes from a braid. Accelerator masses and cross sections constrain particle physics; nuclear experiments constrain BBN; neutrino transport predicts light-relic effects; lattice calculations treat strongly coupled thermal transitions; primordial abundances and the CMB test later consequences. No strand photographs the whole history, and each can be checked where it is strongest. [3,9,15,17,21,23,32]

Heavy-ion collisions deserve special discipline in that braid. They reveal collective QCD matter and energy loss, but differ from the cosmos in size, lifetime, geometry, initial state and baryon chemical

potential. A successful laboratory description supports relevant microphysics; it does not certify that the early Universe replayed the collision event by event. [23–29]

Model dependence generally increases toward earlier and higher-temperature claims because fewer independent relics survive and the extrapolated energy gaps widen. That trend is not uniform ignorance: QCD and electroweak calculations have laboratory anchors, while other proposed stages rely more heavily on extensions not yet detected. Confidence should change by claim, not by dramatic timeline label. [3–5,38]

The reconstruction is strongest when one process predicts a later quantity measured through different physics. Neutrino transport changes CMB phases; nuclear rates predict abundances; the Higgs mass changes electroweak thermodynamics. These connections turn a list of temperatures into a causal sequence whose joints can fail independently. [3,17,21,32]

A responsible timeline therefore marks the observational boundary, the inferential calibration and the changing theory inputs. It does not put a photograph icon beside every epoch, but it also does not surrender the past as unknowable. The evidence ladder remains usable because its upper rungs are labelled as more model-dependent. [3–5,38]

Where That Leaves Us

The unseen sequence is credible because different methods overlap without becoming interchangeable. Relics test later consequences; experiments and lattices constrain microphysics; expansion links temperature to time. As the overlap thins, epistemic labels must change. The last step is to stop the established reconstruction before grand-unified and quantum-gravity possibilities are promoted into historical facts.

8. The Boundary of the Reconstruction

Above experimentally tested Standard Model regimes, timelines often introduce grand-unified particles, monopoles and symmetry-breaking events. These are motivated hypotheses, not established stages merely because an energy scale can be assigned. Monopole overproduction helped motivate inflation, but neither a monopole population nor a unique grand-unified history has been observed. [3,37–39]

Near the Planck regime, no empirically established quantum theory of gravity supplies a verified continuation. Classical spacetime and ordinary thermal-field descriptions are expected to become inadequate, but naming the scale does not select strings, loops, bounces or any other specific account. The correct boundary is explicit, not filled with decorative certainty. [37,38]

Below that boundary, confidence is graded rather than binary. CMB and abundances anchor late consequences; Standard Model transport, QCD lattices and collider measurements reconstruct earlier regimes; cosmological expansion supplies the ordering. The chain is impressive because it advertises which links are observed, calculated, cross-checked or still hypothetical. [3,17,21,32,38]

Grand-unified extensions remain scientifically valuable because they generate constraints and possible relics. A detected monopole, proton decay pattern or other distinctive signal could move a proposal down the evidence ladder toward history. Until then, an epoch name organizes hypotheses; it does not certify that nature followed the associated model. [37–39]

The endpoint is therefore methodological. We can reason before atoms without pretending to watch. The farther back we go, the more carefully we must separate measured microphysics from cosmological extrapolation and from untested extension. QTC-014 now takes one surviving fact—the baryon excess—and asks which new mechanism, if any, created it. [3,37,38]

Where That Leaves Us

Before atoms is not before evidence. Nuclear yields, neutrino signatures, lattice QCD and collider measurements support a graded thermal reconstruction, while grand unification and quantum gravity remain open. The frontier is not a failure of science; it is the point where a responsible timeline changes from established history to testable hypothesis.

What We Know, and How

- The pre-atomic sequence is reconstructed from expansion, measured microphysics, relic abundances, CMB signatures, lattice calculations and collider data.
- Neutrino decoupling, the QCD crossover and the Standard Model electroweak crossover have quantitatively constrained thermal descriptions.
- Heavy-ion collisions test relevant QCD matter but do not reproduce the early Universe in size, lifetime, geometry or initial conditions.

What We Still Don't Know

- The cosmic neutrino background has not been directly detected as individual relic neutrinos.
- The mechanism that produced the surviving baryon excess is not supplied by the Standard Model crossovers described here.
- Grand-unified stages and the verified continuation through the Planck regime remain open.

What Could Change Our Minds

- Direct relic-neutrino detection would add a new messenger and test the standard decoupling calculation more directly.
- Collider or relic evidence for new particles could revise the electroweak, baryogenesis or grand-unified portions of the sequence.
- An empirically successful quantum-gravity theory could extend the reconstruction beyond its present Planck boundary.

If You Remember Only One Thing

Before atoms, we reconstruct rather than photograph: confidence comes from overlapping relics, experiments and calculations, and it decreases explicitly beyond tested Standard Model regimes.

Related Articles

- QTC-011 — The Oldest Light We Can See
- QTC-012 — What Do We Really Mean by the Big Bang?
- QTC-014 — Matter, Antimatter and an Unsolved Imbalance

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