

Particle Epochs and Thermal Transitions

CHO-002 · Cosmic History and Its Observers

A Chronological Scientific History from the Early Universe to the Present

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Structured abstract

Context. Once a hot expanding plasma is established, the early Universe can be followed through a sequence of Standard Model regimes with greater physical specificity than is possible for inflation, reheating, or the ultimate lower boundary. The sequence was nevertheless continuous. Its usual labels describe changes in relevant degrees of freedom and interaction rates, not a row of instantaneous cosmic switches.

Evidence. Non-perturbative lattice calculations indicate that, for the measured Higgs mass, the Standard Model electroweak change is a smooth crossover. One cited calculation locates its susceptibility maximum at $159.5 \pm 1.5 \text{ GeV}$. Lattice QCD likewise places a pseudocritical chiral crossover at zero chemical potentials at $156.5 \pm 1.5 \text{ MeV}$, with the precise operational value dependent on the observable. At still lower temperatures, weak interactions progressively fail to maintain neutrino equilibrium and electron-positron annihilation redistributes entropy. A precision Standard Model transport calculation that includes flavour oscillations and finite-temperature QED obtains $N_{\text{eff}} = 3.0440 \pm 0.0002$, rather than the instantaneous-decoupling idealisation of exactly three.

Method. This synthesis separates measured laboratory inputs, numerical Standard Model calculations, and cosmological time conversions. Temperature is the most defensible ordering variable for the transitions. Approximate tBB orientations are derived within radiation-dominated cosmology and are not treated as directly observed dates.

Conclusion. Across the interval, the Universe cools from an electroweak plasma through QCD confinement and lepton redistribution; nuclear assembly overlaps its later thermal evolution. CHO-003 owns the nuclear network and its yields. Throughout CHO-002 the observer classification is N0: later observers can reconstruct traces, but no living or conscious observer is evidenced in the interval.

Keywords: early Universe; electroweak crossover; QCD crossover; hadronisation; neutrino decoupling; electron-positron annihilation; thermal history; observer capacities

1. Chronological orientation

CHO uses tBB for model-dependent cosmic time measured from the formal extrapolated boundary of a specified hot-Big-Bang solution. The lower boundary of this article, 10^{-11} s , is a BOOK seam. It is an order-of-magnitude editorial handoff from CHO-001, not the measured instant at which reheating ended or electroweak physics began. The upper boundary, 20 minutes, is likewise a conservative containment limit shared with the CHO-003 overlay. Nuclear reactions have effectively ceased by then in standard calculations, but the exact rate at which each abundance approaches its asymptote is nuclide- and precision-dependent.

The physical chronology is better ordered first by temperature, following the thermodynamic sequence synthesised in the Particle Data Group review [4]:

Regime	Temperature orientation	Approximate tBB orientation	Status of the orientation
Electroweak crossover	susceptibility maximum 159.5 ± 1.5 GeV in the cited calculation	order 10^{-11} s	temperature is a lattice result; time is model-derived
QCD crossover	pseudocritical 156.5 ± 1.5 MeV at zero chemical potentials	order tens of microseconds	temperature is observable-defined; time is model-derived
Hadronic and leptonic redistribution	from the QCD regime through MeV temperatures	microseconds to seconds	broad sequence; species-specific
Neutrino decoupling and electron-positron annihilation	MeV to sub-MeV regime	broadly seconds	overlapping transport processes
Thermal background for nucleosynthesis	around 0.1 MeV ; one detailed orientation uses 0.078 MeV	minutes	values describe different operational points in a distributed onset; network and yields owned by CHO-003

In radiation domination, temperature and time are related through the expansion rate and the effective energy density in relativistic species. The relation is not a universal clock independent of theory. The effective degrees of freedom change as species become non-relativistic, and finite-temperature interactions modify ideal-gas estimates. Accordingly, only order-of-magnitude cosmic times are reported here. The accompanying calculation retains the approximate coefficient and degree-of-freedom assumptions; no precise date or propagated confidence interval is claimed. The coarse orientations use the radiation-dominated relation in the cited PDG review [4], with effective relativistic degrees of freedom stated in the accompanying calculation record. They are scale checks rather than precise transition dates; late-time Planck parameters are not numerical inputs to this calculation.

2. Initial state inherited from CHO-001

CHO-001 passes forward a hot, expanding regime whose earlier origin remains incompletely constrained. Its primordial perturbations, matter-antimatter asymmetry, and radiation content are inherited conditions, not re-derived here. The word “particle” also requires care. CHO-002 does not describe creation from nothing. It describes a cooling quantum and thermal system in which the useful excitations, interaction ranges, equilibrium populations, and composite states change.

At sufficiently high temperature, many Standard Model degrees of freedom contribute to the plasma. Expansion lowers energy density. Interactions can maintain approximate equilibrium only when their rates remain fast relative to cosmic expansion. This comparison between microscopic rate and expansion rate is the organising mechanism of the article. It explains both why some transitions remain equilibrated crossovers and why some species progressively decouple.

3. The electroweak crossover

The electroweak theory unifies electromagnetic and weak interactions through a gauge structure whose low-temperature state includes a non-zero Higgs-field expectation value. At high temperature the thermodynamic state is different. For the measured Higgs mass, however, Standard Model calculations do not support a strong first-order phase transition. D’Onofrio and Rummukainen’s non-perturbative lattice treatment found a smooth crossover, with a narrow region of approximately 157-162 GeV and a susceptibility-defined temperature $T_c = 159.5 \pm 1.5$ GeV [1].

That result has three chronological consequences. First, “electroweak epoch” is a useful scale label, but the crossover does not provide an infinitesimally sharp cosmic date. Second, the quoted temperature belongs to an operational definition within a calculation; another thermodynamic observable can mark a nearby but not logically identical point. Third, converting it to seconds requires a cosmological expansion model and the radiation content at that temperature. The Master Index seam of 10^{-11} s therefore remains deliberately coarser than the lattice temperature.

The crossover changes masses, screening behaviour, and reaction rates as the plasma cools. It does not by itself explain why matter exceeds antimatter. Electroweak baryogenesis proposals ask whether additional dynamics could make this regime produce the observed asymmetry, but the known Standard Model crossover is not sufficient to establish such a history. CHO-001 owns baryogenesis as an unresolved mechanism; CHO-002 supplies only the thermal setting.

4. The QCD crossover and the rise of hadronic matter

Quantum chromodynamics describes quarks and gluons and their strong interactions. At high temperature its active degrees of freedom form a deconfined plasma. On cooling at the very small baryon chemical potential relevant to the early Universe, lattice calculations support a crossover rather than a simple first-order boundary. The HotQCD calculation by Bazavov and collaborators obtained a continuum-extrapolated pseudocritical value $T_c(0) = 156.5 \pm 1.5$ MeV by averaging five continuum-extrapolated definitions based on chiral observables at zero chemical potentials [2].

This number should not be narrated as “the instant the first proton appeared.” Across a crossover, susceptibilities and other observables change over a range. Hadronic correlations become increasingly appropriate descriptions while quark and gluon degrees of freedom cease to behave as a freely propagating plasma. Different observables can identify slightly different pseudocritical temperatures. Moreover, the thermal plasma continually creates and destroys short-lived excitations. A stable cosmic inventory emerges through changing equilibrium abundances, annihilations, decays, and conservation laws, not through one photographed first member of a species.

Relativistic heavy-ion collisions provide important empirical tests of QCD matter, but they do not reproduce the cosmic history as a whole. The collision system is small, short-lived, rapidly evolving, and can carry different conserved-charge conditions. Its evidence tests properties of QCD under extreme conditions; the early-Universe application still requires cosmological modelling. The lattice result is similarly not a direct observation of the past. It is a controlled numerical consequence of the theory using parameters anchored in particle experiments.

5. Thermal thresholds, annihilation, and freeze-out

After the QCD crossover, hadrons and leptons populate the plasma according to temperature, rest mass, and interaction rates. When temperature falls below the rest-energy scale of a species, pair production becomes inefficient and equilibrium abundance is exponentially suppressed. Particles and antiparticles annihilate or unstable particles decay, transferring energy and entropy to products that remain coupled. “Epoch” names such as hadron, lepton, or photon epoch compress this continuous redistribution into memorable headings.

Two distinct ideas must not be merged. A species becoming non-relativistic concerns the shape and energy of its distribution. Freeze-out or decoupling concerns whether reactions remain fast enough to maintain equilibrium. A massive species can continue interacting after becoming non-relativistic; a weakly interacting species can decouple while still relativistic. The threshold also depends on which reaction is under discussion. There is no single clock that simultaneously labels every disappearance.

The neutron-to-proton ratio becomes increasingly difficult for weak reactions to track as the Universe cools through the MeV regime. That change is part of the inherited thermal and weak-interaction context of nucleosynthesis [5]. CHO-003 will own its quantitative consequences, neutron decay before nuclear assembly, the reaction network, and the resulting abundances. CHO-002 deliberately stops short of converting a thermal history into nuclear yields.

6. Neutrino decoupling and electron-positron annihilation

At high enough temperature, neutrinos exchange energy and number through weak interactions with electrons, positrons, and one another. As expansion wins over those interactions, their distributions depart progressively from perfect equilibrium with the electromagnetic plasma. This is not an instantaneous event at one temperature or second. Different momenta and flavours respond differently, and neutrino oscillations redistribute distortions among flavours.

Electron-positron pairs also become rare as the temperature falls below the electron mass scale. Their annihilation transfers most of their entropy to photons. In an idealised calculation with completely instantaneous neutrino decoupling beforehand, the photon bath is heated relative to a separately cooling neutrino bath, leading to the familiar limiting temperature ratio. Real decoupling overlaps the annihilation process. Residual weak interactions pass a small amount of energy into neutrinos, finite-temperature QED changes the electromagnetic plasma, and flavour oscillations matter.

Bennett and collaborators solved the relevant transport problem with flavour oscillations, finite-temperature QED effects through their stated order, and full neutrino-neutrino collision integrals. They reported the Standard Model benchmark $N_{\text{eff}} = 3.0440 \pm 0.0002$ [3]. N_{eff} is an effective radiation-density parameter, not a literal count that implies

0.044 of a new neutrino species. The excess over three combines the thermal history, spectral distortions, flavour oscillations and finite-temperature QED effects into a quantity used by later cosmology.

This result illustrates CHO's evidence hierarchy. Laboratory measurements constrain weak and neutrino parameters. Kinetic theory and finite-temperature field theory specify interactions. Numerical transport evolves distribution functions through an expanding background. Later CMB and abundance observations constrain the radiation density. The ancient process is reconstructed through this chain; it is not directly timed by a surviving clock.

7. Evidence base, dating methods, and resolution limits

Three kinds of warrant operate in this interval.

First, collider and laboratory measurements determine particle masses, couplings, lifetimes, mixing parameters, and nuclear inputs. These are direct measurements within experimental frameworks, although their use at cosmic temperatures assumes the Standard Model and specified extrapolations.

Second, lattice field theory calculates equilibrium thermodynamics where ordinary perturbation theory is insufficient. The electroweak and QCD crossover temperatures cited here are numerical theoretical results constrained by measured parameters. Their uncertainties describe the calculation and its extrapolations; they are not stopwatch errors on a directly observed cosmic event.

Third, cosmological inference combines the Friedmann expansion with energy density, reaction networks, and transport equations. Approximate time-temperature relations are robust enough to order the sequence, but their printed precision must remain below the least certain model input. Unknown additional relativistic species, altered expansion, neutrino properties, or non-standard interactions would change the mapping and can be constrained precisely because they would leave later abundance or radiation signatures.

This article does not present a detailed time-temperature table. Nor does it infer the nature of the QCD crossover solely from heavy-ion phenomenology, treat a lattice pseudocritical temperature as an observation of the cosmos, or use the later success of BBN to erase uncertainty in every preceding thermal calculation.

8. Observer capacities present

CHO assigns N0 to the entire interval: physical traces exist, but there is no evidence of a system capable of biological detection, information use, sentience, or symbolic reflection. The category is not a rank below later life. It simply states that the observer-capacity criteria are not instantiated by the evidence available for this period.

The plasma nevertheless formed correlations and preserved consequences. The relative photon and neutrino energy densities, the neutron-proton history, and the later light-element abundances carry information about rates and expansion. Present observers extract that information using instruments and models billions of years later. Their later act of inference did not cause the transitions.

In statistical and quantum physics, “observer” can refer to a frame, an ideal measurement, or a subsystem in a formal description. No such usage licenses a claim that awareness was required for electroweak symmetry change, QCD confinement, annihilation, or decoupling. CHO's title concerns the later emergence of evidence-using systems, not conscious control of early physics.

9. Contingency and contemporaries

The sequence is not inevitable under every possible law or parameter set. The measured Higgs mass helps determine why the Standard Model electroweak transition is a crossover. Extensions of the theory can produce first-order behaviour, alter relic production, or generate gravitational-wave signals. Additional light particles could change the expansion rate and neutrino-radiation budget. Different quark masses or conserved-charge conditions would modify QCD thermodynamics.

Within the reconstructed history, many processes were contemporaneous: expansion, scattering, decay, annihilation, oscillation, and changing field correlations. The neat textbook sequence is a scale-dependent account of which processes dominated explanation. It is not evidence that the Universe paused between named epochs.

Contingency must also be separated from unconstrained possibility. Models that change the thermal history face later tests. Primordial abundances, CMB anisotropies, large-scale structure, and laboratory particle data restrict

departures. Alternative histories remain scientifically relevant only to the extent that they produce consistent and potentially discriminating consequences.

10. Competing interpretations and unresolved questions

Important open issues include the exact influence of higher-order effects on crossover thermodynamics, the most useful operational definition of pseudocritical temperatures, and the treatment of transport across overlapping thresholds. More radical questions ask whether undetected particles contributed to radiation, altered neutrino decoupling, or froze out as dark matter. Those questions belong partly to later thematic studies, but CHO-002 defines the thermal background against which they are posed.

Some language disputes are also substantive. “Phase transition” is often used broadly for both singular transitions and smooth crossovers. CHO specifies the latter where the cited Standard Model result requires it. “Quark-gluon plasma became hadrons” is acceptable as a scale summary only if it does not imply a universal instantaneous conversion. “Neutrinos decoupled at one second” is an orientation mnemonic, not a full transport result.

The accompanying source map distinguishes lattice results, transport calculations and coarse cosmic-time estimates. The latter establish the broad order of the sequence, not uncertainty intervals that cover every non-standard model.

11. Claim-class statement

Class	CHO-002 use
E1, directly measured	Laboratory particle parameters and collider observables in their stated experimental settings
E2, reconstructed	The broad hot thermal sequence and its consistency with later relic evidence
E3, model-dependent	Lattice crossover temperatures, transport prediction for N_{eff} , and every temperature-to- t_{BB} conversion
E4, actively contested	Non-standard particle content or transition histories where live alternatives materially change interpretation
E5, speculative/open	Undetected sectors or signals not established by the evidence set used here

No whole source or paragraph receives one confidence label. Individual propositions retain their own epistemic and evidential status; no single confidence label is assigned to an entire source or paragraph.

12. Boundaries and exclusions

CHO-002 begins at the BOOK seam 10^{-11} s and ends before 20 minutes. It owns Standard Model thermal transitions after the seam, including the electroweak and QCD crossovers, hadronic and leptonic redistribution, neutrino decoupling, and electron-positron annihilation.

CHO-001 retains inflation, reheating, and the baryogenesis problem. CHO-003 alone owns the Big Bang nucleosynthesis network, abundance predictions, observational abundance tests, and the lithium problem. CHO-007 owns later element-production channels. This article does not date a “first particle,” claim that heavy-ion collisions reproduce the cosmic plasma exactly, or infer conscious observation from physical record formation.

13. Closing state passed to CHO-003

Within the shared interval, cooling establishes a photon bath, a progressively decoupled but slightly reheated neutrino background, and nucleons whose weak interconversion becomes inefficient. Deuterium survival and nuclear assembly then proceed during the later part of this same interval. The handoff to CHO-003 is therefore thematic: it supplies thermal context for the nuclear calculation, rather than placing the onset of nucleosynthesis after the twenty-minute upper boundary.

CHO-003 now asks a different question: given those conditions, which reaction pathways convert neutrons and protons into light nuclei, what abundances follow, and how do later observations test the calculation? That transfer is a

change of topic ownership inside an authorised overlap, not a claim that thermal and nuclear processes occupy non-overlapping seconds.

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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.