

Matter, Antimatter and an Unsolved Imbalance

QTC-014 · From Quarks to Consciousness

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

Author: Juan Segurola

Version: v1.0 EN · 2 September 2026

Epistemic profile: Open Problem

License: All Rights Reserved

Article Abstract

Antimatter is not missing from physics. It is produced in accelerators, appears in radioactive decays and cosmic rays, and is used in medical imaging. The cosmological puzzle is narrower and deeper: after matter and antimatter mostly annihilated in the hot early Universe, roughly one net baryon remained for every 1.6 billion photons. Big Bang nucleosynthesis and the cosmic microwave background agree on that leftover, but they do not identify its cause. This article follows the conditional logic proposed by Sakharov, the discovery of CP violation, and the electroweak sphaleron processes that can create, redistribute or erase asymmetries. It then compares active mechanisms—grand-unified decays, leptogenesis, extended electroweak baryogenesis and Affleck–Dine dynamics—without declaring a winner. The number is precision cosmology; the generating particles, scale, CP source and nonequilibrium history remain an open problem.

In 60 Seconds

Particles and antiparticles annihilate into other excitations; they do not vanish into literal nothing. In a nearly symmetric hot plasma, annihilation removes matched pairs and leaves whatever small net excess already exists or has been generated. Cosmology measures that excess as a baryon-to-photon ratio near 6.1×10^{-10} , or an entropy-normalized yield near 8.6×10^{-11} . Sakharov showed that, within the standard CPT-respecting thermal framework, a dynamical explanation needs baryon-number violation, C and CP violation, and departure from equilibrium, or a failure of the assumptions behind that argument. Weak interactions do violate CP, and electroweak sphalerons violate B+L while conserving B-L. Yet the measured CKM phase is too weak and the 125 GeV Higgs gives a smooth electroweak crossover, so the minimal Standard Model does not generate the observed asymmetry. Multiple extensions can reproduce the final number, but fitting the number does not prove their particles or initial conditions existed. Experiments therefore test ingredients—proton decay, dipole moments, neutrino properties, new Higgs physics, sterile neutrinos or gravitational waves—rather than one universal baryogenesis machine.

Why This Question Matters

The matter–antimatter question is often enlarged until it becomes “why is there something rather than nothing?” Physics has earned a more specific question. We know the observable domain contains a tiny net baryon excess, and we know several necessary ingredients for generating one dynamically.

We do not know which mechanism operated. Holding that boundary matters because annihilation is not creation from nothing, CP violation is not automatically enough, and a candidate that reproduces the final ratio has not yet reconstructed history. The open problem is experimentally structured, not metaphysically solved.

1. The Leftover, Not a Missing Half

The Question

If matter and antimatter can be created in pairs, why is the Universe not half of each today? The answer is not that antimatter is fictional or that annihilation erased only one side. Paired annihilation preserves any tiny imbalance that existed before the pairs disappeared.

Antimatter is ordinary, repeatedly tested particle physics. Positrons and antiprotons are produced, detected and stored; antiparticles participate in decays and collisions according to measured quantum laws. The cosmic puzzle is not absence from nature but the overwhelming matter dominance of the observable baryonic domain. [3,5]

When a particle meets its antiparticle, conserved energy and momentum are redistributed into other excitations, often photons or lighter pairs. Annihilation is conversion, not disappearance of physical content into nothing. The products can create new pairs if sufficiently energetic, and the reaction runs both ways in a hot equilibrium plasma. [3,8]

As the Universe cools, a nearly symmetric baryon–antibaryon population annihilates until pair creation becomes inefficient. That process removes matched numbers from both sides. It cannot generate a net baryon number by itself; a pre-existing or dynamically produced excess remains because there are no antiparticles left to cancel it. [3]

The surviving excess is small: the baryon-to-photon ratio is approximately 6.1×10^{-10} , corresponding to about one net baryon per 1.6 billion photons. Expressed relative to entropy, the baryon yield is about 8.6×10^{-11} . Small in fraction, it supplied essentially all ordinary matter that later formed gas, stars, planets and us. [1–3]

Big Bang nucleosynthesis and CMB acoustic structure infer consistent baryon densities through different epochs and physics. Their agreement fixes the magnitude of the leftover rather than the mechanism that made it. Precision on the output should not be mistaken for knowledge of the generating history. [1,2]

Where That Leaves Us

The imbalance is a leftover with a precise measured scale, not evidence that antimatter never existed or that annihilation made something from nothing. Independent cosmic probes agree on the residue and remain silent about its cause. The next task is observational: establish how far matter dominance extends and what searches for primordial antimatter actually exclude.

2. How We Know the Visible Domain Is Matter-Dominated

The Question

A positron in a detector is real antimatter, but it does not imply an antistar nearby. High-energy collisions and radioactive processes produce antiparticles secondarily. To identify a primordial

antimatter domain, we need evidence that cannot be explained by ordinary matter making antiparticles locally.

Directly sampled material, nearby stars and gas are matter-dominated. Cosmic rays contain positrons and antiprotons, but ordinary collisions can make them as secondary products. Their existence confirms antimatter physics while leaving the primordial composition of distant sources undecided unless heavier, cleaner signatures are established. [3,5]

Large adjacent matter and antimatter domains would meet at boundaries. Under simple domain models, annihilation there would produce diffuse gamma rays and alter the ionization and thermal history visible in the CMB. The absence of the expected signals strongly restricts a patchwork universe within the observable volume, given the model's assumptions about mixing and boundaries. [4]

No antihelium or heavier antinucleus has been confirmed as a primordial cosmic-ray detection. AMS-02 has reported candidate antihelium events, but their instrumental status, background and origin remain unresolved. A candidate event should not be silently promoted into an antistar or primordial domain. [5,6]

The conclusion is deliberately horizon-limited. Evidence supports an overwhelmingly baryonic observable Universe and constrains simple antimatter-domain scenarios within it. It says nothing empirical about regions causally inaccessible beyond the cosmological horizon, because no signal from them can reach the measurements used here. [3,4]

Dark matter is not a hidden reservoir of ordinary antimatter. Antibaryonic material would interact electromagnetically, participate in nucleosynthesis and annihilate at matter boundaries. Those behaviours conflict with the dominant dark-matter component inferred gravitationally. Sharing the word matter does not make the two categories interchangeable. [35]

Where That Leaves Us

Cosmic rays prove that antiparticles occur; gamma-ray, CMB and antinucleus searches constrain primordial antimatter on much larger scales. The evidence is strong within the observable domain and silent beyond the horizon. Having established the asymmetry rather than its cause, we can ask what a dynamical mechanism would have to do without yet choosing one.

3. Sakharov's Conditional Logic

The Question

What must change for a symmetric plasma to acquire a lasting net baryon number? Sakharov's answer was not a finished history but a set of conditions. They are conditional on thermal equilibrium, CPT and the assumed charges, which makes them powerful logic rather than a mechanism selected by observation.

Within the standard hot-expanding, CPT-respecting framework, dynamical baryogenesis requires baryon-number violation, C and CP violation, and departure from thermal equilibrium—or an equivalent failure of assumptions behind the equilibrium argument. The list states obstacles that a model must overcome; it does not identify when or how nature overcame them. [7,8]

The Sakharov conditions are therefore a diagnostic, not proof that one named baryogenesis event occurred. A candidate can satisfy them in many ways, at very different energy scales, and still be wrong. Conversely, alternative initial conditions or departures from the standard assumptions can reorganize the logical requirements. [7,8]

Baryon-number violation is needed because an exactly conserved net baryon number cannot evolve from zero to a nonzero value. The Standard Model contains anomalous processes that violate $B+L$, while many extensions add decays or interactions that violate baryon or lepton number more directly. The relevant conserved combination matters. [7,8,15]

C and CP violation prevent matter-producing and antimatter-producing channels from having exactly cancelling net rates. A microscopic CP asymmetry is a necessary ingredient in the standard logic, but its mere existence does not guarantee a large enough cosmic effect. The strength, participating reactions and thermal history must be calculated. [7–9]

Thermal equilibrium supplies the final obstacle. CPT symmetry and detailed balance prevent the required reactions from building a persistent net asymmetry in equilibrium. Expansion, decays or a first-order phase transition can drive a departure, but every candidate must show quantitatively that generation outpaces washout and survives later evolution. [7,8]

Where That Leaves Us

Sakharov turned the mystery into conditional tasks: change baryon number, distinguish matter from antimatter in rates, and escape equilibrium strongly enough to preserve the result. Those requirements organize mechanisms but do not rank them. The next question is whether known weak-interaction CP violation and electroweak dynamics already complete the job. They do not.

4. A Broken Symmetry That Is Still Not Enough

The Question

CP violation proves that weak interactions distinguish matter from antimatter. Why does that not solve baryogenesis? Because the relevant question is quantitative and thermal: is the measured asymmetry strong enough, in reactions that operate out of equilibrium, to survive every washout process and yield the cosmic number?

In 1964, Christenson, Cronin, Fitch and Turlay observed CP violation in neutral-kaon decays. The result established that the combined transformation exchanging particles with antiparticles and reflecting space is not exact in weak interactions. It supplied a real Sakharov ingredient, not a complete cosmic mechanism. [9]

Kobayashi and Maskawa showed in 1973 that a quark sector with three generations permits an irreducible CP-violating phase in the weak mixing matrix. What began as theoretical structure became part of the Standard Model once the required quark families and flavour-changing phenomena were established experimentally. [10]

Kaon and B-meson measurements now determine the CKM description as the dominant observed source of CP violation in quark flavour-changing weak processes. The Jarlskog invariant captures its basis-independent strength. Agreement across flavour experiments is a triumph, but cosmological adequacy is a separate calculation. [11–14]

At high temperature, nonperturbative electroweak transitions associated with the anomaly violate $B+L$ while conserving $B-L$. Their thermal rate is established within Standard Model calculations. These sphaleron processes provide baryon-number-changing dynamics, yet their conservation law and washout behaviour constrain what asymmetry can persist. [15–17]

Minimal Standard Model electroweak baryogenesis fails quantitatively: CKM CP violation is far too weak, and the 125 GeV Higgs gives a smooth crossover rather than a strong first-order transition. The observed excess therefore requires an asymmetric initial condition or additional physics, but present data do not select one unique mechanism. [3,18–20]

Where That Leaves Us

Known weak physics supplies CP violation and baryon-changing sphalerons, but not enough asymmetry in the required nonequilibrium setting. The failure is quantitative, not philosophical, and it points beyond the minimal Standard Model without naming a winner. To compare candidates, we first need to understand sphalerons as converters and erasers as well as possible creators.

5. Sphalerons: Create, Convert or Erase

Electroweak sphaleron transitions violate baryon plus lepton number, $B+L$, while conserving their difference, $B-L$. The distinction is decisive. A process can change baryon number and still preserve a particular combination of charges, so the source and timing of any initial asymmetry determine what remains. [15–17]

While sphalerons are rapid, they can wash out a pre-existing $B+L$ asymmetry with no protected $B-L$ component. Generating baryon number early is therefore not sufficient; a candidate must track every process that can reprocess the charges before freeze-out. Survival is a network property, not a one-time creation event. [15–17]

The same reactions can convert part of a lepton asymmetry into baryon number. This is the central bridge in leptogenesis: new neutrino-sector dynamics first create flavour or total lepton asymmetries, and sphalerons redistribute some of the result into the baryonic sector before they cease to be efficient. [15–17,22,24]

The sphaleron rate changes across the electroweak crossover and eventually becomes too slow compared with expansion and other relevant dynamics. Freeze-out then preserves the surviving baryon asymmetry against further sphaleron reprocessing. The precise conversion depends on the particle content and chemical-equilibrium relations of the model. [15–17]

Sphalerons can thus help create, convert, redistribute or erase an asymmetry. Calling them simply a baryon-making engine hides their dependence on $B-L$, CP sources, rates and sequence. They are established Standard Model microphysics that candidate baryogenesis histories must use or evade consistently. [15,17,19]

Where That Leaves Us

Sphalerons are a conditional bridge, not the missing cause. They preserve $B-L$, wash out some histories and convert others, depending on the charge network and timing. That is why viable baryogenesis proposals differ not only in the particles they add but also in when and in which conserved combination they first place the asymmetry.

6. Candidate Mechanisms, Not a Solved History

The Question

Several mechanisms can be adjusted to leave the observed baryon yield. That agreement is necessary and weak: one number cannot prove a heavy particle, a sterile-neutrino population, a first-order transition or a scalar condensate. Each candidate must earn its history through additional, distinctive evidence.

Grand-unified baryogenesis proposes that very heavy particles decay out of equilibrium through channels that violate baryon number and CP. The scale is often far beyond direct production. Proton decay provides a major, model-dependent test because the same unification structure can connect unstable baryons to the interactions used for asymmetry generation. [21,36]

Thermal leptogenesis instead uses CP-violating, out-of-equilibrium decays of heavy Majorana neutrinos to create a lepton asymmetry. Electroweak sphalerons convert part into baryon number. The mechanism links cosmic matter to neutrino mass generation, but its high scale and unknown heavy states leave substantial degeneracy. [22,23,38]

Low-scale oscillation leptogenesis moves the new states closer to possible experiments. CP-violating oscillations of sterile neutrinos generate flavour asymmetries before sphaleron freeze-out. Viable parameter regions can be constrained by neutrino and intensity-frontier searches, yet no sterile-neutrino baryogenesis history has been established. [24]

Extended electroweak baryogenesis adds new CP violation and a sufficiently strong first-order electroweak transition absent from the minimal Standard Model. Higgs precision, colliders and electric-dipole limits test the required particles and phases; a gravitational-wave background could test the transition. No one signature alone demonstrates baryon production. [19,20,27,32–34]

Affleck–Dine baryogenesis uses coherent scalar fields carrying baryon or lepton charge, often within supersymmetric settings, to generate a large asymmetry. Like the other candidates, it can match the final yield over broad choices. Reproducing η is a consistency condition, not evidence that the proposed field, potential, decay history or initial condensate existed. [3,8,25,26]

Where That Leaves Us

Each candidate supplies missing ingredients in a different place: unified decays, heavy or oscillating neutrinos, an extended electroweak transition, or a charged scalar condensate. All can be constrained and none is established. Progress therefore comes from mapping experiments to ingredients, so that a discovery narrows mechanisms instead of being advertised as an automatic solution.

7. What Experiments Can Actually Decide

Observation of proton decay or neutron–antineutron oscillation would establish baryon-number violation, one central Sakharov ingredient. It would be transformative, but it would not by itself identify the CP source, establish the relevant thermal departure from equilibrium, or prove which early-universe reaction network generated the measured yield. [29,30]

Electric dipole moments test new CP phases; neutrino oscillations test leptonic CP violation; neutrinoless double-beta decay tests Majorana character; sterile-neutrino searches probe low-scale states; Higgs and collider measurements test extended electroweak sectors. These observables

constrain different families and parameter combinations rather than one universal mechanism. [27–33]

A stochastic gravitational-wave background compatible with a first-order electroweak transition would support an ingredient missing from minimal electroweak baryogenesis. It would not show that the transition produced baryons or identify the CP violation required. A background can diagnose cosmic dynamics while leaving the charge-generation story incomplete. [34]

The experimental programme is therefore a matrix, not a single decisive detector. A proton-decay signal favours some unification structures; an EDM constrains phases; neutrino results reshape leptogenesis; collider and gravitational-wave data test thermal potentials. Combining them can remove large candidate regions even before one mechanism is uniquely selected. [27–34]

Null results also carry unequal implications. Stronger proton-lifetime limits do not directly kill low-scale leptogenesis, and tighter electron-EDM bounds do not test every Affleck–Dine model. Honest progress reports specify which ingredient, scale and parameter space changed, preserving the distinction between evidence against a model and evidence against baryogenesis as a whole. [29–34]

Where That Leaves Us

Experiments can establish ingredients and eliminate parameter space long before they reconstruct the complete cosmic event. That is not a weakness: it turns an origin mystery into linked, falsifiable questions. The final ledger must therefore keep two columns apart—the magnitude and domain of the asymmetry that we know, and the particles, scale and sequence that we do not.

8. The Number We Know and the Cause We Do Not

The magnitude of the baryon asymmetry and the matter dominance of the observable domain are established. The generating scale, new particles, CP source, nonequilibrium dynamics and possible connection to neutrino mass remain open. Multiple active mechanisms satisfy the broad logic, and current evidence does not discriminate decisively among them. [3,8,19,23–25,37,38]

Baryogenesis is an attempted physical account of how an evolving Universe acquired or preserved a matter–antimatter imbalance. It does not explain why there is a Universe, why quantum fields or laws exist, or why the initial framework is possible. Those larger questions may be legitimate, but they are not solved by adding a CP-violating decay. [3,37]

The asymmetry’s precision remains a scientific anchor. BBN and CMB data can refine η and Y_B , test extra radiation or entropy release, and expose inconsistency. A revised number would reshape viable parameter space, yet a more precise output alone would still not identify which candidate history produced it. [1–3]

A successful explanation must connect additional observables to the same mechanism: a proton lifetime, neutrino mass pattern, EDM, new scalar sector, sterile state or gravitational-wave spectrum. The more distinctive and overconstrained that network becomes, the less freedom remains to tune one final number without recovering actual history. [3,37]

For now, the correct conclusion is asymmetrical in confidence. We know the leftover extraordinarily well and know that minimal Standard Model electroweak baryogenesis is inadequate. We do not know whether the answer lies in unification, neutrinos, extended Higgs

physics, scalar condensates, an initial condition or another mechanism not yet proposed.
[3,8,37,38]

Where That Leaves Us

One net baryon per roughly 1.6 billion photons is a precision result whose causal history remains unknown. Sakharov conditions and experimental constraints organize the search; no candidate has earned the status of cosmic history. The honest endpoint is not “antimatter vanished,” but a sharper statement: the leftover is measured, and its origin is open.

What We Know, and How

- The observable baryonic domain is overwhelmingly matter-dominated, while antimatter is routinely produced and detected locally.
- BBN and CMB measurements consistently fix a baryon-to-photon ratio near 6.1×10^{-10} .
- Known CP violation and electroweak sphalerons are real, but minimal Standard Model electroweak baryogenesis is quantitatively insufficient.

What We Still Don't Know

- No generating scale, particle content, CP source or nonequilibrium history has been selected by present evidence.
- AMS-02 antihelium candidates have not established a primordial antimatter population.
- The relation, if any, between baryogenesis, neutrino mass, unification and new Higgs physics remains unresolved.

What Could Change Our Minds

- Proton decay, neutron–antineutron oscillation or another baryon-number-violating signal would establish a missing ingredient and reshape candidate space.
- A correlated network of new CP violation, particle states and thermal-transition evidence could identify a specific mechanism.
- Confirmed primordial antinuclei or annihilation-domain signals would revise the inferred spatial scope of matter dominance.

If You Remember Only One Thing

We know the tiny baryon excess with precision; we do not know which particles, CP source, scale and nonequilibrium history generated it.

Related Articles

- QTC-012 — What Do We Really Mean by the Big Bang?
- QTC-013 — Before Atoms

References

[1] Planck Collaboration. Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics* 641, A6 (2020). DOI 10.1051/0004-6361/201833910. <https://arxiv.org/abs/1807.06209>

- [2] B. D. Fields; P. Molaro; S. Sarkar / Particle Data Group. Big Bang Nucleosynthesis. Review of Particle Physics, section 24 (2024). DOI 10.1103/PhysRevD.110.030001.
<https://pdg.lbl.gov/2024/reviews/rpp2024-rev-bbang-nucleosynthesis.pdf>
- [3] Laurent Canetti; Marco Drewes; Mikhail Shaposhnikov. Matter and Antimatter in the Universe. New Journal of Physics 14, 095012 (2012). DOI 10.1088/1367-2630/14/9/095012.
<https://arxiv.org/abs/1204.4186>
- [4] A. G. Cohen; A. De Rújula; S. L. Glashow. A Matter-Antimatter Universe? Astrophysical Journal 495, 539-549 (1998). DOI 10.1086/305328. <https://arxiv.org/abs/astro-ph/9707087>
- [5] J. Alvarez-Muñiz; Z. Cao; U. F. Katz; P. Mertsch; C. Spiering / Particle Data Group. Cosmic Rays. Review of Particle Physics, section 30 (2024). DOI 10.1103/PhysRevD.110.030001.
<https://pdg.lbl.gov/2024/reviews/rpp2024-rev-cosmic-rays.pdf>
- [6] J. Alcaraz et al. (AMS Collaboration). Search for antihelium in cosmic rays. Physics Letters B 461, 387-396 (1999). DOI 10.1016/S0370-2693(99)00874-6.
<https://www.sciencedirect.com/science/article/pii/S0370269399008746>
- [7] A. D. Sakharov. Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe. JETP Letters 5, 24-27 (1967). <https://ui.adsabs.harvard.edu/abs/1967JETPL...5...24S/abstract>
- [8] Antonio Riotto; Mark Trodden. Recent progress in baryogenesis. Annual Review of Nuclear and Particle Science 49, 35-75 (1999). DOI 10.1146/annurev.nucl.49.1.35.
<https://arxiv.org/abs/hep-ph/9901362>
- [9] J. H. Christenson; J. W. Cronin; V. L. Fitch; R. Turlay. Evidence for the 2-pion decay of the K₂(0) meson. Physical Review Letters 13, 138-140 (1964). DOI 10.1103/PhysRevLett.13.138.
<https://doi.org/10.1103/PhysRevLett.13.138>
- [10] Makoto Kobayashi; Toshihide Maskawa. CP-Violation in the Renormalizable Theory of Weak Interaction. Progress of Theoretical Physics 49, 652-657 (1973). DOI 10.1143/PTP.49.652.
<https://doi.org/10.1143/PTP.49.652>
- [11] C. Jarlskog. Commutator of the quark mass matrices in the standard electroweak model and a measure of maximal CP nonconservation. Physical Review Letters 55, 1039-1042 (1985). DOI 10.1103/PhysRevLett.55.1039. <https://doi.org/10.1103/PhysRevLett.55.1039>
- [12] B. Aubert et al. (BABAR Collaboration). Observation of CP violation in the B₀ meson system. Physical Review Letters 87, 091801 (2001). DOI 10.1103/PhysRevLett.87.091801.
<https://doi.org/10.1103/PhysRevLett.87.091801>
- [13] K. Abe et al. (Belle Collaboration). Observation of large CP violation in the neutral B meson system. Physical Review Letters 87, 091802 (2001). DOI 10.1103/PhysRevLett.87.091802.
<https://doi.org/10.1103/PhysRevLett.87.091802>
- [14] A. Ceccucci; Z. Ligeti; Y. Sakai / Particle Data Group. CKM Quark-Mixing Matrix. Review of Particle Physics, section 12 (2024). DOI 10.1103/PhysRevD.110.030001.
<https://pdg.lbl.gov/2024/reviews/rpp2024-rev-ckm-matrix.pdf>
- [15] G. 't Hooft. Symmetry Breaking through Bell-Jackiw Anomalies. Physical Review Letters 37, 8-11 (1976). DOI 10.1103/PhysRevLett.37.8. <https://doi.org/10.1103/PhysRevLett.37.8>

- [16] V. A. Kuzmin; V. A. Rubakov; M. E. Shaposhnikov. On anomalous electroweak baryon-number non-conservation in the early universe. *Physics Letters B* 155, 36-42 (1985). DOI 10.1016/0370-2693(85)91028-7. [https://doi.org/10.1016/0370-2693\(85\)91028-7](https://doi.org/10.1016/0370-2693(85)91028-7)
- [17] Michela D'Onofrio; Kari Rummukainen; Anders Tranberg. Sphaleron Rate in the Minimal Standard Model. *Physical Review Letters* 113, 141602 (2014). DOI 10.1103/PhysRevLett.113.141602. <https://arxiv.org/abs/1404.3565>
- [18] M. B. Gavela; P. Hernandez; J. Orloff; O. Pène; C. Quimbay. Standard model CP-violation and baryon asymmetry (II). Finite temperature. *Nuclear Physics B* 430, 382-426 (1994). DOI 10.1016/0550-3213(94)00410-2. <https://arxiv.org/abs/hep-ph/9406289>
- [19] David E. Morrissey; Michael J. Ramsey-Musolf. Electroweak baryogenesis. *New Journal of Physics* 14, 125003 (2012). DOI 10.1088/1367-2630/14/12/125003. <https://arxiv.org/abs/1206.2942>
- [20] Michela D'Onofrio; Kari Rummukainen. Standard model cross-over on the lattice. *Physical Review D* 93, 025003 (2016). DOI 10.1103/PhysRevD.93.025003. <https://arxiv.org/abs/1508.07161>
- [21] Motohiko Yoshimura. Unified Gauge Theories and the Baryon Number of the Universe. *Physical Review Letters* 41, 281-284; erratum 42, 746 (1978). DOI 10.1103/PhysRevLett.41.281. <https://doi.org/10.1103/PhysRevLett.41.281>
- [22] M. Fukugita; T. Yanagida. Baryogenesis Without Grand Unification. *Physics Letters B* 174, 45-47 (1986). DOI 10.1016/0370-2693(86)91126-3. [https://doi.org/10.1016/0370-2693\(86\)91126-3](https://doi.org/10.1016/0370-2693(86)91126-3)
- [23] W. Buchmüller; R. D. Peccei; T. Yanagida. Leptogenesis as the origin of matter. *Annual Review of Nuclear and Particle Science* 55, 311-355 (2005). DOI 10.1146/annurev.nucl.55.090704.151558. <https://arxiv.org/abs/hep-ph/0502169>
- [24] E. Kh. Akhmedov; V. A. Rubakov; A. Yu. Smirnov. Baryogenesis via Neutrino Oscillations. *Physical Review Letters* 81, 1359-1362 (1998). DOI 10.1103/PhysRevLett.81.1359. <https://arxiv.org/abs/hep-ph/9803255>
- [25] Ian Affleck; Michael Dine. A New Mechanism for Baryogenesis. *Nuclear Physics B* 249, 361-380 (1985). DOI 10.1016/0550-3213(85)90021-5. [https://doi.org/10.1016/0550-3213\(85\)90021-5](https://doi.org/10.1016/0550-3213(85)90021-5)
- [26] Michael Dine; Alexander Kusenko. Origin of the matter-antimatter asymmetry. *Reviews of Modern Physics* 76, 1-30 (2003). DOI 10.1103/RevModPhys.76.1. <https://arxiv.org/abs/hep-ph/0303065>
- [27] ACME Collaboration. Improved limit on the electric dipole moment of the electron. *Nature* 562, 355-360 (2018). DOI 10.1038/s41586-018-0599-8. <https://doi.org/10.1038/s41586-018-0599-8>
- [28] The T2K Collaboration. Constraint on the matter-antimatter symmetry-violating phase in neutrino oscillations. *Nature* 580, 339-344 (2020). DOI 10.1038/s41586-020-2177-0. <https://doi.org/10.1038/s41586-020-2177-0>
- [29] A. Takenaka et al. (Super-Kamiokande Collaboration). Search for proton decay via $p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$ with an enlarged fiducial volume in Super-Kamiokande I-IV. *Physical Review D* 102, 112011 (2020). DOI 10.1103/PhysRevD.102.112011. <https://doi.org/10.1103/PhysRevD.102.112011>
- [30] K. Abe et al. (Super-Kamiokande Collaboration). Neutron-antineutron oscillation search using a 0.37 megaton-years exposure of Super-Kamiokande. *Physical Review D* 103, 012008 (2021). DOI 10.1103/PhysRevD.103.012008. <https://doi.org/10.1103/PhysRevD.103.012008>

- [31] S. Abe et al. (KamLAND-Zen Collaboration). Search for the Majorana Nature of Neutrinos in the Inverted Mass Ordering Region with KamLAND-Zen. *Physical Review Letters* 130, 051801 (2023). DOI 10.1103/PhysRevLett.130.051801. <https://doi.org/10.1103/PhysRevLett.130.051801>
- [32] G. Aad et al. (ATLAS Collaboration). Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B* 716, 1-29 (2012). DOI 10.1016/j.physletb.2012.08.020. <https://arxiv.org/abs/1207.7214>
- [33] S. Chatrchyan et al. (CMS Collaboration). Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Physics Letters B* 716, 30-61 (2012). DOI 10.1016/j.physletb.2012.08.021. <https://arxiv.org/abs/1207.7235>
- [34] David J. Weir. Gravitational waves from a first-order electroweak phase transition: a brief review. *Philosophical Transactions A* 376, 20170126 (2018). DOI 10.1098/rsta.2017.0126. <https://arxiv.org/abs/1705.01783>
- [35] L. Baudis; S. Profumo / Particle Data Group. Dark Matter. *Review of Particle Physics*, section 27 (2024). DOI 10.1103/PhysRevD.110.030001. <https://pdg.lbl.gov/2024/reviews/rpp2024-rev-dark-matter.pdf>
- [36] A. Hebecker; J. Hisano; N. Nagata / Particle Data Group. Grand Unified Theories. *Review of Particle Physics*, section 93 (2024). DOI 10.1103/PhysRevD.110.030001. <https://pdg.lbl.gov/2024/reviews/rpp2024-rev-guts.pdf>
- [37] James M. Cline. Baryogenesis. *Les Houches lecture review* (2006). <https://arxiv.org/abs/hep-ph/0609145>
- [38] Sacha Davidson; Enrico Nardi; Yosef Nir. Leptogenesis. *Physics Reports* 466, 105-177 (2008). DOI 10.1016/j.physrep.2008.06.002. <https://arxiv.org/abs/0802.2962>