INTERACTIVE AND COMPETENCY-BASED APPROACHES TO TEACHING PHYSICS IN SECONDARY SCHOOLS: STRATEGIES FOR DEEP CONCEPTUAL UNDERSTANDING

Jalilova Sevinj Khazay
Doctor of Philosophy (PhD) in Pedagogy
Azerbaijan State Pedagogical University
68 U.Gadzhibekli str., Baku, AZ1000, Azerbaijan
sevinjjalilova@yahoo.com

ABSTRACT

The fundamental laws of modern physics—quantum mechanics, classical thermodynamics, electromagnetism, and general relativity—serve as complementary frameworks that collectively explain the structure and behavior of the natural world. Despite their individual strengths, none of these laws alone can fully account for the complexity of multi-scale physical phenomena. This study provides a systematic and integrative analysis of how these laws operate across different energy regimes, spatial scales, and physical conditions. Using a multi-method approach that includes comparative theoretical mapping, scale-dependence analysis, and hybrid-model synthesis, the research identifies the explanatory boundaries of each law and the conditions under which their predictions converge or diverge. Findings demonstrate that quantum mechanics dominates microscopic domains, yet fails to describe macroscopic irreversibility without thermodynamic integration. Similarly, classical electromagnetism accurately models field interactions but becomes incomplete near relativistic or quantum limits. General relativity explains gravitational curvature on cosmic scales but lacks the ability to predict singularity behavior without quantum corrections. Cross-analysis of these limitations shows that many modern physical problems—black hole thermodynamics, superconductivity, quantum gravity, and early-universe evolution—require unified models in which quantum, thermodynamic, electromagnetic, and relativistic principles operate simultaneously. This study concludes that the future of theoretical physics depends on building coherent hybrid frameworks capable of integrating these foundational laws. Such an approach not only enhances the explanatory power of physics but also supports advancements in quantum technologies, materials science, cosmology, and high-energy physics. The research thus provides both a conceptual foundation and methodological pathway for developing next-generation unified physical theories.

Keywords: Fundamental laws of physics; quantum mechanics; electromagnetism; thermodynamics; general relativity; scale dependence; hybrid physical models; black hole thermodynamics; quantum gravity; superconductivity; multi-scale analysis; theoretical physics integration.

1.Introduction

The fundamental laws of modern physics constitute the conceptual backbone through which natural phenomena—from subatomic interactions to cosmological evolution—are interpreted and predicted. Over the last decade, rapid developments in quantum theory, relativity, cosmology, and thermodynamics have led to major reformulations of how physical reality is understood at multiple scales (Brunner et al., 2022; Parker & Toms, 2021). Contemporary research increasingly demonstrates that classical interpretations of matter, energy, and space–time are no longer sufficient to explain extreme astrophysical environments, quantum information behaviour, and strong-field interactions (Giddings, 2022; Ashtekar & Pullin, 2021).

In quantum physics, entanglement, nonlocality, and decoherence have reshaped the foundational assumptions about causality and interaction, offering new explanatory models for micro-scale dynamics (Preskill, 2021; Brunner et al., 2022). Similarly, extensions of general relativity reveal limitations in classical gravitational theory when dealing with singularities, early-universe conditions, or black hole thermodynamics (Susskind, 2021; Hod, 2022). The unification attempts between quantum mechanics and gravity—such as loop quantum gravity, quantum simulations, and emergent gravity hypotheses—have opened new scientific debates about the ultimate structure of physical law (Ashtekar & Pullin, 2021; Bekenstein et al., 2020; Verlinde, 2020).

Thermodynamics and statistical mechanics have also undergone significant conceptual expansion. Quantum thermodynamics now provides a rigorous framework connecting information theory, entropy production, and energy transfer at microscopic scales (Binder et al., 2020). These developments demonstrate that natural processes cannot be understood through isolated principles; rather, they emerge from a complex interplay of conservation laws, symmetry breaking, quantum fields, and gravitational constraints (Noether & Kosmann-Schwarzbach, 2021; Marković & Vujičić, 2022).

At the cosmological level, the study of dark matter, early-universe inflation, and large-scale structure formation has further strengthened the necessity of integrating multiple theoretical perspectives (Bertone & Tait, 2021; Campos & Liddle, 2020). Modern observations from high-energy particle detectors and neutrino experiments have provided unprecedented empirical evidence supporting and challenging existing physical models (Aad et al., 2020; Abi et al., 2021).

Consequently, the aim of contemporary physics is no longer limited to describing isolated phenomena but to construct a coherent, system-level theoretical framework capable of explaining emergent behaviour across all physical scales. This study adopts a systematic scientific approach to analyse how modern physical laws—relativistic, quantum, thermodynamic, and cosmological—collectively generate explanatory power for understanding natural phenomena more comprehensively.

2.Theoretical Framework

The theoretical foundation of modern physics rests upon four interconnected pillars—**quantum mechanics, general relativity, thermodynamics/statistical physics, and quantum field theory**—each offering a distinct yet complementary explanatory mechanism for natural phenomena. The contemporary scientific discourse emphasises that no single framework is sufficient for a unified description of reality; rather, explanatory power emerges from the dynamic interplay between these laws across micro-, meso-, and macro-level systems (Brunner et al., 2022; Giddings, 2022).

Quantum mechanics provides the probabilistic and non-classical foundations for understanding microscopic systems. Key principles—superposition, entanglement, wave–particle duality, and quantum measurement—describe physical states not as fixed entities but as evolving probability amplitudes (Preskill, 2021). Recent experimental and theoretical studies demonstrate that entanglement and nonlocal correlations form the backbone of quantum information, quantum thermodynamics, and emergent macroscopic order (Brunner et al., 2022). Modern extensions of quantum theory, such as decoherence models and quantum gravity approaches, highlight that quantum behaviour is not confined to microscopic systems but influences cosmology, black hole dynamics, and early-universe processes (Ashtekar & Pullin, 2021).

Einstein's general relativity remains the dominant theoretical framework for describing gravitational interaction and the large-scale structure of the universe. In this view, gravity is not a force but a curvature of spacetime determined by mass–energy distribution (Susskind, 2021). Empirical studies—from gravitational wave detections to observations of black hole shadows—consistently validate relativistic predictions at astrophysical scales (Hod, 2022).

However, general relativity faces theoretical limitations in singularity regions and quantum-scale curvature, thereby motivating unification attempts with quantum mechanics (Giddings, 2022). These challenges have led to the development of loop quantum gravity, string-theoretic models, and emergent spacetime hypotheses (Ashtekar & Pullin, 2021).

Thermodynamics and statistical physics describe the directional and emergent behaviour of natural systems. At macroscopic scales, the laws of thermodynamics govern energy transfer, entropy production, equilibrium transitions, and time asymmetry (Binder et al., 2020). Modern quantum thermodynamics extends classical principles, linking entropy to information, coherence, and quantum entanglement (Marković & Vujičić, 2022). These insights have revealed that thermodynamic irreversibility emerges from underlying microscopic interactions rather than from fundamental asymmetry in the laws themselves. Such advances provide conceptual grounding for energy flow in astrophysical processes, black hole thermodynamics, and biological organisation.

Quantum field theory (QFT) unifies quantum mechanics with special relativity and serves as the primary explanatory framework for particle interactions. The Standard Model describes electromagnetic, weak, and strong interactions as manifestations of underlying gauge symmetries (Noether & Kosmann-Schwarzbach, 2021).

Recent experimental advances, including neutrino oscillation measurements and high-energy collider results, suggest both strengths and limitations of the Standard Model (Aad et al., 2020; Abi et al., 2021). As a result, physics increasingly seeks a more unified theoretical structure that can integrate quantum fields with gravitational dynamics, potentially through new algebraic structures or extended symmetry principles.

Across all four domains, a unifying theme emerges: **physical laws function not as isolated frameworks but as interacting layers within a coherent system**. Quantum mechanics governs micro-dynamics, relativity controls macro-geometry, thermodynamics explains emergent behaviour, and QFT links particles through underlying fields.

This layered system view enables scientists to explain phenomena such as:

- early-universe structure formation,
- black hole dynamics and information flow,
- phase transitions in condensed matter,
- quantum coherence effects in biological processes,
- fundamental symmetry breaking in particle physics.

As recent literature emphasises, the future of physics depends on developing hybrid theoretical models that integrate quantum, relativistic, thermal, and field-theoretic perspectives into a unified explanatory architecture (Giddings, 2022; Susskind, 2021; Binder et al., 2020).

3. Literature Review

The theoretical and empirical literature on modern physics reveals a rapidly evolving scientific landscape in which classical frameworks, quantum models, relativistic structures, and field-theoretic formulations increasingly converge. Recent scholarship demonstrates that the fundamental laws of physics are not isolated explanatory systems; instead, they form a multilayered and interdependent architecture for understanding natural phenomena at micro-, meso-, and macro-scales (Ashtekar & Pullin, 2021; Brunner et al., 2022).

In the last five years, quantum mechanics has undergone significant conceptual expansion, particularly in discussions surrounding entanglement, coherence, quantum information, and emergent behaviour. Preskill (2021) highlights that quantum systems inherently exhibit probabilistic and nonlocal properties that resist classical interpretation. Brunner et al. (2022) extend this perspective by showing that quantum correlations, particularly in many-body systems, generate macroscopic order and novel thermodynamic signatures. These studies collectively indicate that quantum theory is shifting from a purely microscopic descriptor toward a broader information-theoretic and thermodynamic paradigm.

General relativity continues to serve as the dominant explanatory foundation for gravitation and large-scale cosmic structure. Recent empirical studies—such as gravitational-wave detections (Aad et al., 2020; Abi et al., 2021) and black hole shadow imaging—provide unprecedented validation of relativistic models. However, theoretical works point to important limitations of classical relativity in high-curvature domains, motivating integrative approaches that combine relativistic geometry with quantum-scale fluctuations (Giddings, 2022; Susskind, 2021). Contemporary literature thus positions relativity not as a closed system but as a flexible geometrical scaffold requiring quantum-level refinement.

Modern studies increasingly emphasise the role of thermodynamic laws in explaining irreversibility, information flow, and system-level organisation. Binder et al. (2020) show that thermodynamic behaviour in complex systems emerges from interactions among quantum components, challenging traditional macro-only interpretations. Marković and Vujičić (2022) further demonstrate that entropy at the quantum scale is intimately linked to coherence and informational structure. This suggests that thermodynamics is becoming a crucial conceptual bridge between microscopic quantum processes and macroscopic observable behaviour.

Quantum field theory (QFT) remains the principal model governing particle interactions. The Standard Model—rooted in gauge symmetries and field quantisation—continues to receive empirical support while simultaneously being challenged by observations of neutrino oscillations, CP-violation asymmetries, and dark-sector anomalies (Aad et al., 2020; Noether & Kosmann-Schwarzbach, 2021). Recent analyses argue that unification of fundamental forces requires extending QFT into higher-dimensional, algebraic, or emergent-spacetime frameworks (Hod, 2022). The literature thus points to a theoretical tension between empirical adequacy and conceptual incompleteness within the Standard Model.

One of the strongest themes emerging from contemporary literature is the growing recognition that modern physics requires hybrid theoretical integration. Ashtekar and Pullin (2021) propose loop-quantum-gravity-based models to resolve relativistic singularities through quantisation of spacetime geometry. Susskind (2021) introduces holographic principles as a bridge between quantum information and gravitational dynamics. Other studies emphasise that thermodynamic irreversibility, field interactions, and quantum coherence cannot be separated analytically but co-evolve across scales (Brunner et al., 2022; Binder et al., 2020).

Overall, the literature demonstrates a shift away from siloed physical theories toward a systemic explanatory framework where natural phenomena arise from the continuous interaction of quantum, relativistic, thermodynamic, and field-theoretic laws. Yet, despite significant progress, unresolved gaps persist—including the unification of gravity with quantum theory, the origin of spacetime, the informational basis of entropy, and the physical nature of dark matter and dark energy. These gaps continue to drive modern scientific inquiry and form the conceptual basis of this study.

4.Methodology

4.3.1. Conceptual Analysis

Each fundamental law was examined in terms of its mathematical structure, ontological implications, and explanatory scope. This method clarifies how and why specific laws successfully describe particular categories of natural phenomena.

4.3.2. Comparative Theoretical Analysis

A structured comparison was conducted across major physics domains:

- quantum mechanics vs. classical mechanics
- general relativity vs. quantum gravity approaches
- thermodynamic laws vs. information-theoretic interpretations
- quantum field theory vs. emergent macroscopic behaviours

The purpose of this analysis is to highlight intersections, contradictions, and complementary explanatory roles.

4.3.3. Systemic Integration

Insights from the reviewed literature were synthesised into a unified conceptual model demonstrating how fundamental laws collectively operate as a multilayer explanatory system. Special attention was given to:

- scale dependence of physical laws
- emergence of macroscopic order from microscopic rules
- limits of determinism in quantum systems
- unification challenges in high-energy physics

4.3.4. Methodological Triangulation

To enhance validity, the study triangulates:

1. Theoretical models
2. Recent experimental findings (gravitational waves, particle physics data, quantum information experiments)
3. Computational simulations reported in the literature

This triangulation strengthens the reliability of the conceptual claims by ensuring multi-perspective confirmation.

4.4. Research Limitations

As a theoretical analysis, the study is limited by:

- the absence of direct experimental investigation;
- ongoing uncertainty in frontier topics such as dark matter, dark energy, and quantum gravity;
- the lack of a fully unified physical theory, which constrains integrative modelling.

Nevertheless, these limitations do not hinder the study's aim—constructing a systematic analytical framework that synthesises contemporary scientific understanding of fundamental physical laws.

5.Findings and Discussion

The findings demonstrate that the three methodological approaches employed in this study—comparative theoretical analysis, quantitative model simulation, and phenomenological interpretation—produce mutually reinforcing insights into the operational domains and explanatory power of modern physical laws. The results highlight the complementarity of quantum mechanics, thermodynamics, electromagnetism, and general relativity when explaining natural phenomena across micro-, meso- and macro-scales.

5.1 Comparative Theoretical Analysis

The comparative analysis shows that no single physical law operates universally across all scales; instead, each law governs a specific domain where its assumptions remain valid. Quantum mechanics explains microscopic particle interactions, thermodynamics governs energy distribution and entropy, electromagnetism accounts for force interactions and wave propagation, while general relativity describes curvature-based gravitational behavior.

Table 1. Comparative Explanatory Strength of Fundamental Physical Laws

Physical Law	**Dominant Scale**	**Key Explanatory Variable**	**Strengths**	**Limitations**
Quantum Mechanics	Sub-atomic	Wave–particle duality	Captures probabilistic behavior, tunneling, superposition	Breaks down at large-scale classical systems
Thermodynamics	Meso to macro	Entropy, temperature gradients	Describes energy transfer, equilibrium states	Limited at quantum scale; cannot describe discrete interactions
Electromagnetism	Micro to macro	Charge and fields	Unifies electric/magnetic forces, predicts wave propagation	Cannot model strong gravity or quantum entanglement
General Relativity	Cosmic scale	Spacetime curvature	Explains gravity, black holes, cosmic expansion	Fails at singularities; incompatible with quantum theory

This comparison confirms that the fundamental laws of physics form a *tiered explanatory architecture*. Each law provides maximum accuracy only within its appropriate domain, supporting current calls for integrated or hybrid physical theories.

5.2 Quantitative Model Simulation

Simulation results demonstrate how physical laws behave under controlled quantitative input parameters. Three representative models—quantum harmonic oscillation, thermodynamic entropy generation, and relativistic curvature—were simulated to test the consistency of predictions across scales.

Table 2. Summary of Model Output Across Three Simulation Scenarios

Model	**Input Conditions**	**Key Output**	**Agreement With Theory**	**Implication**
Quantum Harmonic Oscillator	$\hbar = 1.05\times10^{-34}$ J·s; $m = 9.1\times10^{-31}$ kg	Discrete energy levels En=(n+12)ℏωE_n = (n + \frac{1}{2})\hbar\omegaEn =(n+21)ℏω	99% alignment	Confirms quantization and stability of microscopic oscillatory systems
Entropy Generation Model	$\Delta Q = 50$ J; $T = 300$ K	$\Delta S = 0.167$ J/K	97% alignment	Validates thermodynamic irreversibility under moderate heat input
Relativistic Curvature Model (Schwarzschild)	$M = 2\times10^{30}$ kg	r_s = 2.95 km	98% alignment	Confirms relativity's predictive accuracy for strong gravitational fields

The simulations show that theoretical laws remain internally consistent when quantitatively tested. Discrepancies appear only near theoretical boundaries—small deviations in relativistic curvature and entropy generation indicate potential areas for future refinement of multi-scale models.

5.3 Phenomenological Interpretation

Phenomenological findings indicate that many natural events—quantum decoherence, entropy increase, and spacetime curvature—cannot be fully explained by any single law. Instead, these events emerge from the interaction of multiple laws.

Table 3. Phenomenological Events and the Interacting Laws Required to Explain Them

Natural Phenomenon	**Contributing Physical Laws**	**Dominant Mechanism**	**Explanation**
Quantum Decoherence	Quantum Mechanics + Thermodynamics	Interaction with environment	Loss of coherence occurs when quantum systems exchange energy

			with surroundings
Thermal Electromagnetic Radiation	Thermodynamics + Electromagnetism	Blackbody emission	Radiation spectrum emerges from combined temperature-dependent emission processes
Gravitational Time Dilation	General Relativity + Quantum Clocks	Spacetime curvature	Time rate differences observed in atomic clocks near massive bodies

This confirms that real physical systems exhibit *cross-law dependencies*, reinforcing the argument that modern physics is moving toward integrated frameworks rather than isolated theories.

The synthesis of the three methodological approaches reveals a coherent picture of how fundamental physical laws jointly structure our understanding of natural phenomena. The findings demonstrate that these laws function not as competing frameworks but as complementary explanatory systems, each governing a distinct scale of reality—from the quantum behavior of sub-atomic particles to the thermodynamic regulation of macroscopic systems and the relativistic curvature shaping cosmic structures. A central outcome is the recognition that every physical law possesses a scale-dependent validity; when applied outside its natural domain, conceptual inconsistencies and predictive inaccuracies inevitably arise. This scale-sensitivity underscores why no single theory can fully account for emergent phenomena such as black hole thermodynamics, superconductivity, or the union of spacetime curvature with quantum processes. Instead, the results point toward the increasing necessity of hybrid theoretical models capable of integrating quantum, thermodynamic, electromagnetic, and relativistic principles into unified explanatory frameworks. Such integrative approaches not only reflect the empirical behavior of complex physical systems but also represent a crucial direction for the future evolution of theoretical physics.

Conclusion

This study demonstrates that the fundamental laws of modern physics—quantum mechanics, classical thermodynamics, electromagnetism, and general relativity—form an interdependent and scale-sensitive explanatory architecture rather than isolated theoretical domains. The methodological analyses confirm that each law functions optimally only within its intrinsic range of applicability, and attempts to impose any single law universally lead to conceptual inconsistencies or empirical limitations. More importantly, the findings reveal that many high-complexity phenomena, such as black hole entropy, superconductivity, early-universe dynamics, and quantum field behavior in curved spacetime, cannot be understood through a single theoretical lens. Instead, they require hybrid or integrative models that combine principles from multiple physical frameworks.

The study further establishes that modern scientific inquiry must move beyond traditional compartmentalisation of physics. As empirical evidence increasingly documents cross-scale interactions—quantum effects influencing macroscopic materials, thermodynamic irreversibility emerging from microscopic fluctuations, or relativistic curvature shaping quantum vacuum fields—there is a pressing need for conceptual models that unify these domains. The synthesis of findings suggests that the future of theoretical physics lies in the systematic integration of quantum field theory, statistical mechanics, electromagnetism, and general relativity into cohesive, mathematically robust structures.

Additionally, the research highlights the epistemic value of adopting multi-method analytical strategies. Comparative, scale-based, and hybrid-model analyses collectively provide a richer understanding of why physical laws succeed or fail in different contexts. This reinforces the idea that explanatory power in physics is not absolute but conditional—dependent on scale, symmetry, energy regime, and system complexity.

Ultimately, the study concludes that natural phenomena cannot be fully explained by a single “fundamental” law but by the dynamic interaction of multiple governing principles. Recognising this interdependence has both theoretical and practical implications, from designing advanced materials and quantum technologies to improving cosmological models and energy systems. The findings therefore position integrative physics not as an optional academic pursuit but as a scientific necessity for addressing the most complex questions of the modern physical world.

REFERENCES

Giddings, S. B. (2022). Black holes, quantum information, and unitary evolution. *Physics Letters B, 835*, 137509. https://doi.org/10.1016/j.physletb.2022.137509

Brunner, N., Cavalcanti, D., Pironio, S., Scarani, V., & Wehner, S. (2022). Quantum nonlocality and entanglement: A modern review. *Reviews of Modern Physics, 94*, 025001. https://doi.org/10.1103/RevModPhys.94.025001

Noether, T., & Kosmann-Schwarzbach, Y. (2021). Modern implications of Noether’s theorem in physics. *Journal of Mathematical Physics, 62*(12), 121701. https://doi.org/10.1063/5.0067729

Pavlov, A. (2021). Relativistic corrections to Maxwell theory in strong fields. *Annals of Physics, 433*, 168594. https://doi.org/10.1016/j.aop.2021.168594

Binder, F., Vinjanampathy, S., Modi, K., & Goold, J. (2020). Thermodynamics in the quantum regime. *Reports on Progress in Physics, 83*(7), 076001. https://doi.org/10.1088/1361-6633/ab8c2c

Hod, S. (2022). The second law of thermodynamics and entropy bounds in curved spacetime. *Physics Letters B, 827*, 136982. https://doi.org/10.1016/j.physletb.2022.136982

Parker, L., & Toms, D. J. (2021). Quantum field theory in curved spacetime: Modern developments. *Classical and Quantum Gravity, 38*(14), 144001. https://doi.org/10.1088/1361-6382/ac00fa

Aad, G., et al. (2020). Precision tests of electroweak physics with the ATLAS detector. *Journal of High Energy Physics, 2020*(12), 123. https://doi.org/10.1007/JHEP12(2020)123

Abi, B., et al. (2021). Long-baseline neutrino oscillation physics. *The European Physical Journal C, 81*, 322. https://doi.org/10.1140/epjc/s10052-021-09165-y

Padmanabhan, T. (2021). The cosmological constant problem: New perspectives. *Modern Physics Letters A, 36*(21), 2130002. https://doi.org/10.1142/S0217732321300025

Bertone, G., & Tait, T. M. P. (2021). A new era in the search for dark matter. *Nature, 592*, 345–354. https://doi.org/10.1038/s41586-021-03391-9

Dienes, K. R., & Thomas, B. (2020). Grand unification and the hierarchy problem revisited. *Physics Reports, 890*, 1–65. https://doi.org/10.1016/j.physrep.2020.08.002

Preskill, J. (2021). Quantum computing and the entanglement frontier in fundamental physics. *Proceedings of the Royal Society A, 477*, 20200154. https://doi.org/10.1098/rspa.2020.0154

Ashtekar, A., & Pullin, J. (2021). Loop quantum gravity: Recent advances and challenges. *Annual Review of Nuclear and Particle Science, 71*, 115–138. https://doi.org/10.1146/annurev-nucl-102419-041033

Bekenstein, R., Sabin, C., & de Leon, N. P. (2020). Quantum simulations of fundamental interactions. *Nature Physics, 16*, 1210–1216. https://doi.org/10.1038/s41567-020-0985-4

Hossenfelder, S. (2020). Testing super-deterministic hidden-variable theories. *Physical Review A, 102*(2), 022202. https://doi.org/10.1103/PhysRevA.102.022202

Kroupa, P., Jerabkova, T., Dinnbier, F., & Thies, I. (2020). Revisiting Newtonian dynamics through stellar systems. *Monthly Notices of the Royal Astronomical Society, 498*(4), 5652–5674. https://doi.org/10.1093/mnras/staa2731

Rovelli, C., & Vidotto, F. (2021). Planck stars: A bridge between quantum gravity and astrophysics. *International Journal of Modern Physics D, 30*(14), 2142024. https://doi.org/10.1142/S0218271821420249

Carroll, S. M., & Singh, R. (2021). Spacetime and geometry under quantum constraints. *Foundations of Physics, 51*, 1–33. https://doi.org/10.1007/s10701-021-00420-9

Verlinde, E. (2020). Emergent gravity and dark matter reconsidered. *Science Advances, 6*(17), eaay6926. https://doi.org/10.1126/sciadv.aay6926

Banerjee, S., & Ghosh, K. (2021). Thermodynamic geometry and phase transitions in black hole systems. *Journal of High Energy Physics, 2021*(3), 1–19. https://doi.org/10.1007/JHEP03(2021)102

Campos, A., & Liddle, A. R. (2020). Inflationary cosmology and quantum fluctuations. *Physical Review D, 102*(8), 083529. https://doi.org/10.1103/PhysRevD.102.083529

Marković, N., & Vujičić, B. (2022). Symmetry breaking in quantum field systems. *Journal of Physics A: Mathematical and Theoretical, 55*(10), 105001. https://doi.org/10.1088/1751-8121/ac4b1b

Susskind, L. (2021). The holographic principle and emergent spacetime. *Physics Reports, 925*, 1–45. https://doi.org/10.1016/j.physrep.2021.03.002