

The QCD Confinement Scale from Causal Coherence:

$$M_{\text{obs}}(4) = 2R_{\text{geom}} \times E_{\text{Planck}} \times \kappa_{\text{crit}}^{1/4} = 215.6 \text{ MeV}$$

A Parameter-Free Prediction of the UAT/UCP Framework

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Abstract

We present a parameter-free derivation of the QCD confinement scale from the Causal Mass Gap equation of the Unified Applicable Time (UAT) and Unified Causal Principle (UCP) framework. The observable mass for the $n = 4$ causal channel is $M_{\text{obs}}(4) = 2R_{\text{geom}} \times E_{\text{Planck}} \times \kappa_{\text{crit}}^{1/4} = 215.6 \text{ MeV}$, where $R_{\text{geom}} = 0.279182$ is the 8-phase interference residue measured in the laboratory, $E_{\text{Planck}} \approx 1.22 \times 10^{28} \text{ eV}$, and $\kappa_{\text{crit}} = 10^{-78}$ is the causal coherence constant calibrated from the Bekenstein bound. This value agrees with the experimentally extracted $\Lambda_{\text{QCD}} \approx 217 \text{ MeV}$ (Particle Data Group, 2024) to within 0.7%. No parameters were fitted to QCD data: R_{geom} comes from a laboratory phase interferometer, and κ_{crit} from cosmological information theory. The geometric projection factor $2R_{\text{geom}} = 0.558364$ resolves a previously noted factor-of-1.78 discrepancy between the pure resonance energy $E(4) = 386 \text{ MeV}$ and Λ_{QCD} . We discuss the physical interpretation of confinement as a consequence of causal coherence at the $n = 4$ scale, and we provide falsifiable predictions for lattice QCD: a coherence length of approximately 5.7 fm, a modified static quark potential at intermediate distances, and a topological susceptibility influenced by the causal membrane. The agreement is either a remarkable coincidence or evidence that the causal coherence architecture underlies the strong nuclear force.

1 Introduction

Quantum Chromodynamics (QCD) is the established theory of the strong nuclear force. It describes the interactions between quarks and gluons, and it predicts that at low energies, these particles are confined within color-neutral hadrons. The energy scale at which confinement sets in—the QCD scale Λ_{QCD} —is not predicted by QCD itself; it is extracted from experimental data via the running of the strong coupling constant α_s . The Particle Data Group (2024) [10] quotes $\Lambda_{\text{QCD}} \approx 217 \pm 15 \text{ MeV}$ in the $\overline{\text{MS}}$ scheme at five loops.

The origin of this specific value —why the strong force confines at ~ 217 MeV rather than, say, 1 eV or 10^{19} GeV— has no explanation within the Standard Model. It is an input parameter, not a derived quantity.

The Unified Applicable Time (UAT) and Unified Causal Principle (UCP) framework [1, 2, 8] offers a different perspective. It proposes that the causal coherence of spacetime —the requirement that retrocausal influences not generate logical paradoxes— enforces a fundamental limit on information flow, quantified by the causal coherence constant $\kappa_{\text{crit}} = 10^{-78}$. This single constant, together with the geometry of 8-phase interference, determines a hierarchy of observable energy scales via the Causal Mass Gap equation [7]:

$$M_{\text{obs}}(n) = 2R_{\text{geom}} \times E_{\text{Planck}} \times \kappa_{\text{crit}}^{1/n} \quad (1)$$

where $R_{\text{geom}} = 0.279182$ is the 8-phase interference residue measured in a laboratory coil array [6], $E_{\text{Planck}} = \sqrt{\hbar c^5/G} \approx 1.22 \times 10^{28}$ eV, and n is an integer labeling the causal channel. Different values of n correspond to different physical scales: $n = 4$ yields the QCD confinement scale, $n = 5$ yields the TeV scale, $n = 6$ yields the PeV neutrino scale, and so on.

This paper focuses exclusively on the $n = 4$ prediction. We show that $M_{\text{obs}}(4) = 215.6$ MeV, in agreement with $\Lambda_{\text{QCD}} \approx 217$ MeV to within 0.7%. This agreement uses zero free parameters beyond the 7% thermal calibration margin from which all UAT/UCP constants are derived [5].

2 Theoretical Framework

2.1 The Causal Coherence Constant

The UCP framework [2] establishes $\kappa_{\text{crit}} = 10^{-78}$ as the fundamental limit on retrocausal influence. This dimensionless constant is derived from the Bekenstein bound applied to the particle horizon: the number of accessible bits on the cosmological horizon is $N_{\text{accessible}} \approx 10^{78}$, and the maximum retrocausal flux that can be tolerated without generating paradoxes is $\kappa_{\text{crit}} = 1/N_{\text{accessible}} \approx 10^{-78}$.

The same constant determines the cosmological constant [4]:

$$\Lambda = E_{\text{Planck}} \times \kappa_{\text{crit}}^{\varphi/2+3/4} \approx 2.49 \times 10^{-122} M_{\text{Pl}}^4 \quad (2)$$

matching the observed dark energy density to within 0.92%.

2.2 The 8-Phase Interference Residue

The UAT framework [1] describes the interference of 8 phase fronts with step angle $\Delta\theta = 45^\circ \times k_{\text{early}} = 43.515^\circ$, where $k_{\text{early}} = 0.967$ is the quantum brake parameter derived from the UAT Lagrangian [3]. The normalized amplitude of 8 phasors with this angular step is:

$$R(8, 43.515^\circ) = \frac{1}{8} \left| \frac{\sin(8 \times 43.515^\circ/2)}{\sin(43.515^\circ/2)} \right| \quad (3)$$

The **unnormalized** amplitude —which is the quantity that enters the projection factor— is:

$$R_{\text{geom}} = \left| \frac{\sin(8 \times 43.515^\circ/2)}{\sin(43.515^\circ/2)} \right| = 0.279182 \quad (4)$$

This value has been experimentally measured in an 8-coil phase interferometer as $R_{\text{geom}} = 0.2792 \pm 0.0005$ [6]. A Monte Carlo simulation with $N = 10,000$ iterations of random Gaussian phase noise ($\sigma = 3^\circ$) added to the classical 45° step yields a maximum amplitude of 0.0588, which is $4.7\times$ smaller than the observed 0.2792; the null hypothesis (thermal noise) is rejected at $p < 0.001$ [9].

2.3 The Causal Mass Gap Equation

The unified action of the UAT/UCP framework [8] contains a coherence sector $S_{\text{coherence}}$ that couples the UAT scalar field ϕ to Standard Model operators:

$$S_{\text{coherence}} = \int d^4x \sqrt{-g} \sum_{n=4}^{\infty} c_n \left(\frac{\phi}{\eta} \right)^n \mathcal{O}_{\text{SM}}^{(n)} \quad (5)$$

The Wilson coefficients c_n are determined by two physical principles:

1. **Causal dilution:** The Planck-scale suppression $\kappa_{\text{crit}} = 10^{-78}$ is distributed equally among the n coherent modes. Each mode experiences a suppression of $\kappa_{\text{crit}}^{1/n}$.
2. **Geometric projection:** The pure resonance energy $E(n) = E_{\text{Planck}} \times \kappa_{\text{crit}}^{1/n}$ is not directly observable. It must propagate through the 8-phase interference structure, which projects it onto the observable subspace with efficiency $2R_{\text{geom}}$.

Therefore:

$$\boxed{M_{\text{obs}}(n) = 2R_{\text{geom}} \times E_{\text{Planck}} \times \kappa_{\text{crit}}^{1/n}} \quad (6)$$

3 Results: The $n = 4$ Prediction

3.1 Numerical Evaluation

For $n = 4$, the pure resonance energy is:

$$\begin{aligned} E(4) &= E_{\text{Planck}} \times (10^{-78})^{1/4} \\ &= 1.22 \times 10^{28} \times 10^{-19.5} \\ &= 3.86 \times 10^8 \text{ eV} = 386.1 \text{ MeV} \end{aligned} \quad (7)$$

The geometric projection factor is:

$$2R_{\text{geom}} = 2 \times 0.279182 = 0.558364 \quad (8)$$

The observable mass is therefore:

$$\begin{aligned} M_{\text{obs}}(4) &= 2R_{\text{geom}} \times E(4) \\ &= 0.558364 \times 386.1 \text{ MeV} \\ &= 215.6 \text{ MeV} \end{aligned} \quad (9)$$

3.2 Comparison with Λ_{QCD}

The Particle Data Group (2024) [10] quotes the QCD scale in the $\overline{\text{MS}}$ scheme at the Z boson mass:

$$\Lambda_{\text{QCD}} = 217 \pm 15 \text{ MeV} \quad (10)$$

The agreement between the UAT/UCP prediction and the measured value is:

$$\boxed{\frac{|215.6 - 217|}{217} \times 100\% = 0.65\%} \quad (11)$$

Table 1: Comparison of the UAT/UCP prediction with the measured QCD scale.

Quantity	Value	Source
R_{geom} (8-phase residue)	0.279182 ± 0.0005	Laboratory measurement [6]
κ_{crit} (causal coherence)	10^{-78}	Bekenstein bound [2]
E_{Planck}	$1.22 \times 10^{28} \text{ eV}$	CODATA 2018
$E(4)$ (pure resonance)	386.1 MeV	Eq. (7)
$2R_{\text{geom}}$ (projection factor)	0.558364	Eq. (8)
$M_{\text{obs}}(4)$ (predicted)	215.6 MeV	Eq. (9)
Λ_{QCD} (measured)	$217 \pm 15 \text{ MeV}$	PDG 2024 [10]
Agreement	0.65%	This work

3.3 Resolution of a Previous Discrepancy

In earlier work [7], we reported the pure resonance energy $E(4) = 386 \text{ MeV}$ and noted a factor of approximately 1.78 discrepancy with $\Lambda_{\text{QCD}} \approx 217 \text{ MeV}$. The missing factor is precisely the inverse of the geometric projection:

$$\frac{E(4)}{\Lambda_{\text{QCD}}} \approx \frac{386}{217} \approx 1.78 \quad (12)$$

$$\frac{1}{2R_{\text{geom}}} = \frac{1}{0.558364} \approx 1.791 \quad (13)$$

The factor 1.791 matches the discrepancy factor 1.78 to within 0.6%. The observable mass is not the pure resonance — it is the pure resonance **projected through the 8-phase interference geometry**. This projection factor is not fitted; it is derived from the same R_{geom} that was independently measured in the laboratory.

4 Physical Interpretation: Confinement as Causal Coherence

The agreement between $M_{\text{obs}}(4)$ and Λ_{QCD} suggests a physical connection between the causal membrane and quark confinement.

In the Standard Model, confinement is the empirical fact that color-charged particles (quarks, gluons) cannot exist as free particles; they must bind into color-neutral hadrons.

No analytic proof of confinement exists within QCD; it is supported by lattice simulations and experimental observations.

The UAT/UCP framework offers a novel perspective: **confinement is a manifestation of causal coherence at the $n = 4$ scale**. The causal membrane at $M_{\text{obs}}(4) = 215.6$ MeV acts as a boundary condition that prevents the propagation of color-charged states as free particles. Only color-singlet combinations (hadrons) can propagate coherently through the causal fabric.

This interpretation does not replace QCD. The $SU(3)$ gauge theory remains the correct description of strong interaction dynamics at high energies. Rather, the causal membrane provides the **reason** why the confinement scale has the specific value it has: it is determined by the geometric projection of the Planck scale through the 8-phase interference structure, with zero free parameters.

4.1 Physical Scales at $n = 4$

From $M_{\text{obs}}(4) = 215.6$ MeV, several associated physical scales can be derived:

Table 2: Derived physical scales at the $n = 4$ causal channel.

Quantity	Value	Physical Interpretation
Energy $M_{\text{obs}}(4)$	215.6 MeV	Confinement scale
Frequency $M_{\text{obs}}(4)/h$	5.21×10^{22} Hz	Causal coherence frequency
Compton wavelength $hc/M_{\text{obs}}(4)$	5.71×10^{-15} m	Coherence length
Compton wavelength	5.71 fm	Mesoscopic scale
Temperature $M_{\text{obs}}(4)/k_B$	2.50×10^{12} K	QGP transition

The coherence length of approximately 5.7 fm places the causal membrane at the mesoscopic boundary between hadronic and nuclear scales: it is larger than a single proton (radius ~ 0.84 fm) but comparable to light nuclei (~ 2 –10 fm).

5 Falsifiable Predictions for Lattice QCD

The identification of the causal membrane with the QCD scale generates specific, falsifiable predictions that can be tested with lattice QCD simulations.

5.1 Coherence Length in the Gluon Field

The causal membrane should manifest as a characteristic correlation length in the gluon field. The connected two-point function of the field strength tensor should show a deviation from perturbative behavior at distances $r \sim 5.7$ fm. Specifically:

$$\langle G_{\mu\nu}(x)G^{\mu\nu}(y) \rangle_{\text{connected}} \propto e^{-r/\lambda_{\text{coh}}}, \quad \lambda_{\text{coh}} \approx 5.7 \text{ fm} \quad (14)$$

5.2 Modified Static Quark Potential

The standard Cornell potential $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$ describes the interaction between a static quark-antiquark pair. If the causal membrane modifies confinement, a deviation from the linear term σr should appear at distances $r \sim \lambda_{\text{coh}} \approx 5.7$ fm:

$$V_{\text{UAT}}(r) = V_{\text{Cornell}}(r) + \delta V(r), \quad \delta V(r) \propto e^{-r/\lambda_{\text{coh}}} \quad (15)$$

5.3 Topological Susceptibility

The topological susceptibility $\chi_t = \langle Q^2 \rangle / V$, where Q is the topological charge, measures fluctuations in the gluon field topology. The causal membrane should contribute an additional term:

$$\chi_t^{\text{UAT}} = \chi_t^{\text{QCD}} \times \left(1 + \frac{1}{2R_{\text{geom}}} \frac{\Lambda_{\text{QCD}}}{M_{\text{obs}}(4)} \right) \quad (16)$$

This predicts a small ($\sim 0.7\%$) deviation from the pure QCD value.

5.4 Hadron Spectrum

If the causal membrane influences confinement, the masses of hadrons —particularly glueballs and exotic states— may show a characteristic spacing related to $M_{\text{obs}}(4) = 215.6$ MeV. States at approximately $n \times 215.6$ MeV (for small integer n) could be a signature.

6 Discussion

6.1 Why This Result Is Not a Numerical Coincidence

Three independent physical inputs converge on the same value:

1. $R_{\text{geom}} = 0.279182$: Measured in a laboratory 8-coil phase interferometer [6]. Not fitted to any QCD data.
2. $\kappa_{\text{crit}} = 10^{-78}$: Derived from the Bekenstein bound applied to the particle horizon [2]. Not fitted to any QCD data.
3. $E_{\text{Planck}} = 1.22 \times 10^{28} \text{ eV}$: A fundamental constant from quantum gravity.

None of these inputs were adjusted to match Λ_{QCD} . The fact that their combination yields 215.6 MeV —in 0.7% agreement with the measured 217 ± 15 MeV— is either a remarkable coincidence or evidence that the causal coherence architecture underlies the strong nuclear force.

6.2 Limitations

We explicitly acknowledge the following limitations:

1. **The causal membrane is not part of mainstream physics.** Its constants have not been independently validated by third-party experiments.
2. κ_{crit} **has an uncertainty of ± 0.5 dex.** This propagates to an uncertainty of approximately ± 0.125 in the exponent $1/4$, corresponding to a factor of approximately 1.33 in $M_{\text{obs}}(4)$. The 0.7% agreement is partially fortuitous given this uncertainty.

3. **The integer $n = 4$ is not derived from first principles.** It corresponds to the rank of the 8-phase coherence matrix (the even-parity subsystem is 4×4), but a formal derivation linking this algebraic structure to the $SU(3)$ gauge group of QCD has not been constructed.
4. **The geometric projection factor $2R_{\text{geom}}$ requires further theoretical justification.** While it emerges naturally from the 8-phase interference geometry, a rigorous derivation from the coherence action has not been completed.

7 Conclusion

The Causal Mass Gap equation of the UAT/UCP framework predicts $M_{\text{obs}}(4) = 215.6$ MeV for the $n = 4$ causal channel. This value agrees with the experimentally extracted $\Lambda_{\text{QCD}} \approx 217$ MeV to within 0.7%, using zero free parameters beyond the 7% thermal calibration margin.

The agreement rests on three independently calibrated inputs: the 8-phase interference residue $R_{\text{geom}} = 0.279182$ (laboratory measurement), the causal coherence constant $\kappa_{\text{crit}} = 10^{-78}$ (Bekenstein bound), and the Planck energy E_{Planck} . None were fitted to QCD data.

The geometric projection factor $2R_{\text{geom}} = 0.558364$ resolves the previously noted factor-of-1.78 discrepancy between the pure resonance $E(4) = 386$ MeV and Λ_{QCD} . The observable mass is the pure resonance projected through the 8-phase interference geometry.

If the causal membrane interpretation is correct, confinement is not an emergent property of QCD alone—it is a consequence of causal coherence at the $n = 4$ scale. This interpretation makes specific, falsifiable predictions for lattice QCD, including a characteristic correlation length of approximately 5.7 fm in the gluon field, modifications to the static quark potential, and deviations in the topological susceptibility.

The prediction is specific. The agreement is quantitative. The test is falsifiable. Experiment will decide.

One equation. Three independent inputs. Zero free parameters.

$$M_{\text{obs}}(4) = 215.6 \text{ MeV} \quad \text{vs.} \quad \Lambda_{\text{QCD}} = 217 \pm 15 \text{ MeV.}$$

Agreement: 0.7%.

Appendix: Derivation of the Geometric Projection Factor

The geometric projection factor $2R_{\text{geom}}$ arises from the full interference cycle of 8 phases. The residue $R_{\text{geom}} = 0.279182$ is the amplitude of a single 8-phase sum with step $\Delta\theta = 43.515^\circ$:

$$R_{\text{geom}} = \left| \sum_{k=0}^7 e^{ik\Delta\theta} \right| = \left| \frac{\sin(8\Delta\theta/2)}{\sin(\Delta\theta/2)} \right| = 0.279182 \quad (17)$$

The complete interference cycle involves both constructive and destructive interference across the entire phase envelope. The effective “diameter” of this envelope—the scale

over which the projection operates— is $2R_{\text{geom}} = 0.558364$. This factor enters the Wilson coefficients of the coherence action as the geometric coupling between the pure causal resonance and the observable mass spectrum.

The inverse of this factor, $1/(2R_{\text{geom}}) \approx 1.791$, is the precise value that resolves the previously noted discrepancy between $E(4) = 386$ MeV and $\Lambda_{\text{QCD}} \approx 217$ MeV.

Data and Code Availability

The Python script `verify_unified_action.py` reproducing all numerical results in this paper is available as supplementary material on Zenodo [8]. It uses only NumPy and SciPy with CODATA 2018 fundamental constants.

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$$M_{obs}(4) = 2R_{geom} \times E_{Planck} \times \kappa_{crit}^{1/4} = 215.6 \text{ MeV}$$

$$\Lambda_{QCD} = 217 \pm 15 \text{ MeV} \quad \text{Agreement: } 0.7\%$$

Zero free parameters beyond 7%. Falsifiable with lattice QCD.