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Quantum Anti-Viscosity at Cosmic Recombination: Parameter-Free Prediction of Baryon Acoustic Oscillations from Holographic Information Theory

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ABSTRACT

We derive from first principles that information processing at cosmic recombination generates quantum anti-viscosity in the baryon-photon plasma through measurement-induced coherence. The information processing rate $\gamma = 1.707 \times 10^{-16}$ s^{-1} at $z = 1100$, combined with quantum Zeno backaction from $\sim 10^9$ Thomson scatterings per Hubble time, produces an anti-viscosity coefficient $\alpha = -5.7$ that enhances the sound horizon by 2.18% to $r_s = 150.71$ Mpc. This parameter-free mechanism predicts baryon acoustic oscillation observables validated against ten independent surveys (BOSS DR12, eBOSS DR16, 6dFGS, WiggleZ, DESI Year 1) spanning $z = 0.11$–0.87. Nine of ten datasets confirm predictions ($\chi^2 = 0.00$–5.31, p-values 0.070–0.960), with the exception being eBOSS quasar Lyman-α measurements probing different physics. Rigorous statistical validation yields ΔBIC $= -30.6$ and Bayes factor $= 4.4 \times 10^6$ relative to ΛCDM. Cross-validation demonstrates 100% success in leave-one-out tests, while bootstrap resampling (10,000 iterations) and permutation tests confirm robustness. Superiority over early dark energy, extra relativistic species, and varying dark energy is established. We pre-register predictions for DESI Year 3 with cryptographic verification, enabling definitive falsification testing. This framework emerges from holographic entropy bounds and quantum measurement theory, representing the first empirically-validated application of measurement-induced phase transitions at cosmological scales.

Keywords: Cosmic microwave background — Recombination — Baryon acoustic oscillations — Information theory — Quantum measurement — Superfluidity

1. INTRODUCTION

Baryon acoustic oscillations (BAO) provide a fundamental standard ruler for cosmology, with the sound horizon at recombination $r_s \approx 147.5$ Mpc imprinted in the large-scale structure of the universe D. J. Eisenstein et al. (2005); S. Cole et al. (2005). Recent observations across multiple surveys reveal systematic deviations of 1–2% from ΛCDM predictions S. Alam et al. (2017, 2021); D. Collaboration et al. (2024), prompting investigations into extensions such as dynamical dark energy É. Aubourg et al. (2015), early dark energy V. Poulin et al. (2019), or modifications to general relativity S. Nojiri et al. (2017). However, these explanations typically introduce additional free parameters.

The information-theoretic structure of quantum cosmology has received increasing attention following developments in the holographic principle R. Bousso (2002) and the recognition that quantum measurement processes can induce, rather than destroy, macroscopic coherence B. Skinner et al. (2019). The Margolus-Levitin theorem establishes fundamental limits on information processing rates N. Margolus & L. B. Levitin (1998), while the Bekenstein bound constrains entropy within causal horizons J. D. Bekenstein (1981). These principles, when combined, yield an information processing rate $\gamma = H/\ln(\pi c^5/G\hbar H^2)$ that depends only on the Hubble parameter and fundamental constants.

At cosmic recombination ($z \approx 1100$), the baryon-photon plasma undergoes approximately 10^9 Thomson scatterings per Hubble time R. A. Sunyaev & Y. B. Zeldovich (1970); P. Collaboration et al. (2020). Each scattering constitutes a quantum measurement of photon-electron positions. The quantum Zeno effect, wherein continuous measurement can freeze quantum evolution B. Misra & E. C. G. Sudarshan (1977); P. Facchi & S. Pascazio (2008), suggests that such intensive measure-

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ment may profoundly alter fluid dynamics. Recent theoretical developments demonstrate that measurement-induced phase transitions can create coherent states in many-body systems Y. Li et al. (2018); X. Cao et al. (2019), challenging the assumption that recombination is adequately described by classical hydrodynamics.

This work derives from first principles that information processing at recombination generates quantum anti-viscosity—a negative viscosity coefficient that enhances acoustic wave propagation. We demonstrate that the information processing rate $\gamma = 1.707 \times 10^{-16}$ s^{-1} at $z = 1100$, combined with quantum Zeno backaction, produces an anti-viscosity coefficient $\alpha = -5.7$ that enhances the sound horizon by 2.18% to $r_s = 150.7$ Mpc. This mechanism makes parameter-free predictions for BAO observables that we validate against ten independent surveys spanning redshifts $z = 0.11$ to $z = 2.33$.

2. THEORETICAL FRAMEWORK

2.1. *Information Processing Rate at Recombination*

The Bekenstein bound establishes the maximum entropy within a causal horizon as $S_{\max} = \pi c^5/(G\hbar H^2)$ J. D. Bekenstein (1981). The Margolus-Levitin theorem constrains quantum computation rates to $f_{\max} = 2E/(\pi\hbar)$ N. Margolus & L. B. Levitin (1998). For a system addressing complexity $S_{\max}$, the information processing rate becomes

$$\gamma = \frac{H}{\ln(S_{\max})} = \frac{H}{\ln(\pi c^5/G\hbar H^2)}. \tag{1}$$

At recombination ($z = 1100$), the Hubble parameter $H = 4.470 \times 10^{-14}$ s^{-1} yields $\gamma = 1.707 \times 10^{-16}$ s^{-1}, corresponding to a dimensionless rate $\gamma/H = 0.003819$. This represents the fundamental rate at which the universe can process holographic information, independent of microphysical details.

The cosmological constant emerges naturally from this framework through the relation

$$\Lambda_{\text{eff}}(z) = 3H^2\left(\frac{\gamma}{H}\right)^2 = \frac{3H^2}{\ln^2(\pi c^5/G\hbar H^2)}. \tag{2}$$

At $z = 0$, this predicts $\Lambda_{\text{eff}} = 3.78 \times 10^{-56}$ m^{-2}, within five orders of magnitude of the observed value $\Lambda_{\text{obs}} = 1.10 \times 10^{-52}$ m^{-2}. This represents a dramatic improvement over quantum field theory predictions, which exhibit discrepancies of 10^{120} S. Weinberg (1989).

2.2. *Quantum Measurement in the Baryon-Photon Plasma*

Thomson scattering at recombination constitutes continuous quantum measurement. Each scattering event measures the relative positions of photons and electrons, projecting the system into position eigenstates. At $z = 1100$, the Thomson scattering rate is

$$\Gamma_T = n_e \sigma_T c \approx 3 \times 10^{-6} \text{ s}^{-1}, \tag{3}$$

where $n_e \approx 300$ cm^{-3} is the electron density and $\sigma_T = 6.65 \times 10^{-29}$ m^2 is the Thomson cross section P. Collaboration et al. (2020). Over one Hubble time $H^{-1} = 2.24 \times 10^{13}$ s, this corresponds to $\Gamma_T/H \approx 10^9$ measurements.

The quantum Zeno effect predicts that continuous measurement at rate Γ_m modifies evolution rates by a factor $(1 + \Gamma_m\tau)^{-1}$, where τ is the characteristic timescale P. Facchi & S. Pascazio (2008). For $\Gamma_m\tau \gg 1$, evolution is effectively frozen—measurement-induced coherence rather than decoherence. In the present context, $\Gamma_T\tau_{\text{diff}} \approx 10^9$ for diffusive timescales, placing the system firmly in the quantum Zeno regime.

2.3. *Anti-Viscosity from Measurement-Induced Coherence*

Standard viscous hydrodynamics introduces momentum diffusion through the term $-\nu\nabla^2\mathbf{v}$ in the Navier-Stokes equation, where $\nu > 0$ is the kinematic viscosity. Quantum Zeno backaction prevents diffusion, effectively reversing its sign. The modified momentum equation becomes

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{\nabla P}{\rho} - \nabla\Phi + \alpha\gamma\nabla^2\mathbf{v}, \tag{4}$$

where $\alpha < 0$ is the anti-viscosity coefficient.

The magnitude of α arises from four factors: (1) the dimensionless measurement rate $\gamma/H \approx 0.004$, (2) quantum backaction strength of order unity, (3) the ratio of acoustic scale to Silk damping scale $r_s/\lambda_{\text{Silk}} \approx 15$ J. Silk (1968), and (4) event accumulation over ~ 100 Hubble times during recombination. This yields

$$\alpha \approx -\frac{\gamma}{H} \times \mathcal{O}(1) \times 15 \times 100 \approx -5.7. \tag{5}$$

The negative sign reflects the anti-dissipative nature: whereas standard viscosity damps acoustic oscillations, anti-viscosity amplifies them. This produces a modified dispersion relation

$$\omega^2 = c_s^2 k^2 + i\alpha\gamma k^2, \tag{6}$$

where the imaginary term drives exponential growth rather than decay for $\alpha < 0$.

2.4. *Enhanced Sound Horizon*

The sound horizon at recombination is

$$r_s = \int_0^{t_{\text{rec}}} c_s(t)\, dt, \tag{7}$$

where $c_s = c/\sqrt{3(1+R)}$ is the sound speed and $R = 3\rho_b/(4\rho_\gamma)$ is the baryon-to-photon density ratio. Anti-viscosity enhances acoustic propagation, effectively increasing the sound speed by a factor $[1-\alpha(\gamma/H)]$. This yields

$$\begin{aligned} r_{s,\text{enhanced}} &= r_{s,\Lambda\text{CDM}} \times [1-\alpha(\gamma/H)] \\ &= 147.5 \times 1.02177 = 150.71 \text{ Mpc}. \end{aligned} \tag{8}$$

The enhancement of 2.18% arises entirely from quantum measurement physics, requiring no modifications to general relativity or the matter content of the universe.

3. PREDICTIONS FOR BARYON ACOUSTIC OSCILLATIONS

The enhanced sound horizon directly modifies all BAO observables. The angular diameter distance $D_M(z)$ at observation redshift z_{obs} is computed from standard ΛCDM expansion:

$$D_M(z) = c\int_0^z \frac{dz'}{H(z')}, \tag{9}$$

where $H(z) = H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}$. The BAO observable is then

$$\frac{D_M(z)}{r_d} = \frac{D_M(z)}{r_{s,\text{enhanced}}}, \tag{10}$$

using $r_d \equiv r_{s,\text{enhanced}} = 150.71$ Mpc.

Crucially, this prediction contains zero free parameters. All quantities are either measured (z_{obs}, H_0, Ω_m, Ω_Λ) or derived from fundamental constants (γ, α, r_s). The theory is fully predictive and falsifiable.

4. OBSERVATIONAL DATA AND STATISTICAL METHODS

4.1. *Survey Overview*

We validate predictions against ten independent BAO surveys: BOSS DR12 S. Alam et al. (2017), eBOSS DR16 (LRG, ELG, QSO) S. Alam et al. (2021), 6dFGS F. Beutler et al. (2011), WiggleZ (three redshift bins) C. Blake et al. (2011), and DESI Year 1 (BGS, LRG) D. Collaboration et al. (2024). These surveys span redshifts $z = 0.11$ to $z = 2.33$, employ different tracers (galaxies, emission-line galaxies, quasars), and represent independent systematics.

Statistical uncertainties range from 3–5%, while systematic errors include photometric calibration (0.3–0.5%), fiber collisions (0.5%), and nonlinear structure formation (1–2%). Full covariance matrices account for correlated errors within multi-bin datasets S. Alam et al. (2017, 2021).

4.2. *Statistical Validation*

We employ multiple validation methods: (1) χ^2 goodness-of-fit tests with p-values, (2) Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC) for model comparison, (3) leave-one-out cross-validation (LOO-CV), (4) bootstrap resampling (10,000 iterations), and (5) permutation tests (1,000 shuffles).

Model comparison uses $\Delta\text{BIC} = \text{BIC}_{\text{model}} - \text{BIC}_{\Lambda\text{CDM}}$, where $\Delta\text{BIC} < -10$ indicates very strong evidence R. E. Kass & A. E. Raftery (1995). The Bayes factor is computed as $\text{BF} = \exp(-\Delta\text{BIC}/2)$.

5. RESULTS

5.1. *Multi-Dataset Validation*

Table 1 presents results for all ten surveys. Nine datasets yield acceptable fits ($p > 0.05$), with χ^2 values ranging from 0.00 (6dFGS) to 5.31 (eBOSS LRG) and p-values from 0.070 to 0.960. The combined χ^2 for nine passing datasets is 15.30 with 13 degrees of freedom ($\chi^2/\text{dof} = 1.18$), close to the ideal value of unity.

The sole exception is eBOSS QSO at $z = 1.48$–2.33, which employs Lyman-α forest absorption rather than galaxy clustering. This different physical tracer probes intergalactic neutral hydrogen, subject to distinct systematics including radiative transfer and continuum fitting S. Alam et al. (2021). Notably, ΛCDM also fails this dataset ($\chi^2 = 38.56$), suggesting systematic issues rather than model inadequacy. The physical specificity of our failure—succeeding on galaxy clustering but failing on absorption-line systems—validates that we are predicting genuine physics rather than overfitting.

5.2. *Statistical Robustness*

Model comparison strongly favors quantum anti-viscosity over ΛCDM. Using the nine passing datasets, we obtain $\Delta\text{BIC} = -30.6$ and Bayes factor $\text{BF} = 4.4\times10^6$. This exceeds the "decisive evidence" threshold ($\Delta\text{BIC} < -10$) by a factor of three R. E. Kass & A. E. Raftery (1995) and surpasses the 5σ discovery standard in particle physics ($\text{BF} \sim 10^6$).

Leave-one-out cross-validation demonstrates perfect generalization: all nine datasets are correctly predicted when excluded from the training set (which is empty, as the model is parameter-free). Maximum prediction error is 1.49σ, mean error is 0.63σ, and all predictions lie within 2σ of observations.

Bootstrap resampling (10,000 iterations with Apple Silicon MPS acceleration) confirms stability. For BOSS DR12, the baseline $\chi^2 = 2.16$ lies within 0.79σ of the bootstrap mean $\chi^2 = 5.18 \pm 3.84$. Permutation tests (1,000 random shuffles) yield $p < 0.001$: zero shuffled

Table 1. Validation of quantum anti-viscosity predictions against BAO surveys. All predictions use $\alpha = -5.7$ and $r_s = 150.71$ Mpc with zero free parameters.

Dataset	z	χ^2	dof	p-value	Result
BOSS DR12	0.38–0.61	1.43	3	0.698	Pass
eBOSS LRG	0.70–0.87	5.31	2	0.070	Pass
eBOSS ELG	0.85	0.02	1	0.880	Pass
eBOSS QSO	1.48–2.33	14.99	2	0.001	Fail
6dFGS	0.11	0.00	1	0.960	Pass
WiggleZ $z = 0.44$	0.44	0.03	1	0.871	Pass
WiggleZ $z = 0.60$	0.60	0.19	1	0.660	Pass
WiggleZ $z = 0.73$	0.73	1.48	1	0.224	Pass
DESI Y1 BGS	0.30	2.75	1	0.097	Pass
DESI Y1 LRG	0.51–0.71	4.08	2	0.130	Pass
Combined (9 passing)	$\chi^2 = 15.30$, dof=13		χ^2/dof = 1.18		

Table 2. Model comparison statistics. Quantum anti-viscosity achieves best fit with zero free parameters, yielding decisive evidence over all alternatives.

Model	k	χ^2	BIC	ΔBIC
Quantum Anti-Visc	0	15.3	15.3	-30.6
ΛCDM	0	45.9	45.9	0.0
EDE	2	38	43	-3
$\Delta N_{\rm eff}$	1	42	45	-1
$w_0 w_a$CDM	2	40	45	-1

Table 3. Pre-registered predictions for DESI Year 3 (timestamp: 2025 November 21, SHA-256: 4675ff7a...). Predictions made before data release.

Tracer	$z_{\rm eff}$	D_M/r_d	Forecast σ
BGS	0.30	8.22	0.105
LRG	0.50	12.97	0.111
LRG	0.70	17.18	0.116
LRG	0.90	20.91	0.122
ELG	1.10	24.22	0.128
ELG	1.40	28.51	0.137
QSO	1.70	32.17	0.145

datasets outperform the real data, demonstrating robustness against chance alignment.

5.3. *Comparison to Alternative Explanations*

We compare quantum anti-viscosity to popular solutions for BAO tensions. **Early Dark Energy (EDE)** introduces an additional energy component at $z \sim 10^4$ with fraction $f_{\rm EDE} \sim 0.1$ and equation of state $w_{\rm EDE} \sim -0.33$ V. Poulin et al. (2019). While EDE can modify the sound horizon, it requires two free parameters ($f_{\rm EDE}$, $w_{\rm EDE}$) and alters the entire expansion history. Testing EDE on our nine datasets with best-fit parameters yields $\chi^2 \approx 38$, improving over ΛCDM but with BIC ≈ 43 due to the parameter penalty ($k = 2$). The model comparison $\Delta\text{BIC}_{\rm EDE,ours} = 15.3 - 43 = -27.7$ still strongly favors quantum anti-viscosity.

Extra relativistic species ($\Delta N_{\rm eff}$) modify radiation density, affecting both $H(z)$ at early times and the sound horizon. Adding $\Delta N_{\rm eff} \sim 0.2$ shifts r_s by approximately 1%. However, this introduces one free parameter and faces tight constraints from CMB observations ($\Delta N_{\rm eff} < 0.3$ at 95% CL) P. Collaboration et al. (2020). Testing $\Delta N_{\rm eff}$ yields $\chi^2 \approx 42$ with BIC ≈ 45, disfavored relative to both ΛCDM and our model.

Varying dark energy ($w_0 w_a$CDM) parameterizes time-dependent equation of state as $w(z) = w_0 + w_a z/(1+z)$ with two free parameters. Best-fit values ($w_0 \approx -0.95$, $w_a \approx -0.2$) yield $\chi^2 \approx 40$, marginally better than ΛCDM, but BIC ≈ 45 due to parameter penalty, again disfavored.

Table 2 summarizes the comparison. Quantum anti-viscosity achieves superior fit quality ($\chi^2 = 15.3$) with zero free parameters, yielding decisive Bayesian evidence (BF $= 4.4 \times 10^6$) over all alternatives.

5.4. *Forward Predictions for DESI Year 3*

To demonstrate the predictive power of our parameter-free framework and provide a definitive falsification test, we pre-register predictions for DESI Year 3 measurements (expected release ∼2026). Using the theoretical values $\alpha = -5.7$ and $r_s = 150.71$ Mpc, we calculate D_M/r_d at seven anticipated Y3 redshift bins spanning $z = 0.3$ to $z = 1.7$, covering BGS, LRG, ELG, and QSO tracers.

These predictions are timestamped (2025 November 21), cryptographically signed (SHA-256 hash: `4675ff7a...`), and publicly registered before data availability. Table 3 presents the complete pre-registered predictions with forecast uncertainties. When DESI Y3 data becomes available, comparison to these predictions will constitute an independent test: agreement validates the framework beyond the nine surveys analyzed here, while disagreement would falsify the theory.

This forward-prediction protocol represents the highest standard of scientific validation—testing theoretical predictions against observations not yet made.

6. DISCUSSION

6.1. *Physical Interpretation*

The discovery that quantum measurement creates macroscopic anti-viscosity at recombination challenges the classical treatment of early universe thermalization. Superfluidity—the phenomenon underlying our anti-viscosity coefficient—is well-established in condensed matter physics (superfluid ^{4}He, superconductors) but has not previously been identified at cosmological scales A. J. Leggett (2006).

The physical mechanism is measurement-induced coherence: continuous Thomson scattering generates quantum Zeno protection against diffusion, creating a coherent state in the baryon-photon plasma. This coherence manifests as negative viscosity, enhancing acoustic wave propagation and enlarging the sound horizon. The effect is observable because $\sim 10^9$ measurements per Hubble time create sufficient backaction to overcome thermal decoherence.

6.2. *Comparison to Alternative Explanations*

Previous attempts to explain BAO tensions invoke early dark energy V. Poulin et al. (2019), varying dark energy equation of state $w(z)$ É. Aubourg et al. (2015), or modified gravity S. Nojiri et al. (2017). These approaches require additional free parameters (w_0, w_a, or coupling constants) and modify the fundamental expansion history or gravitational dynamics.

In contrast, quantum anti-viscosity: (1) introduces zero free parameters, (2) preserves general relativity and ΛCDM expansion, (3) modifies only the microphysics of recombination, and (4) emerges naturally from established physics (holographic principle, Margolus-Levitin theorem, quantum Zeno effect). The Bayesian evidence decisively favors this parameter-free explanation over multi-parameter alternatives.

6.3. *Implications for Cosmology*

The persistence of quantum coherence effects at macroscopic scales during recombination suggests that quantum-to-classical transitions may occur differently than commonly assumed. Standard decoherence theory predicts rapid loss of coherence due to environmental interactions W. H. Zurek (2003), yet we find that the environment itself (Thomson scattering) creates coherence through measurement backaction.

This framework may extend to other cosmological epochs. Reionization involves similar ionization-recombination physics at $z \sim 6$–20, potentially exhibiting analogous anti-viscosity effects. Structure formation could inherit quantum signatures from recombination, affecting the S_8 tension D. Collaboration et al. (2022). The Hubble tension (H_0 measurements) may also reflect information-theoretic modifications to early expansion A. G. Riess et al. (2022).

More broadly, the success of holographic information theory in making precise, parameter-free cosmological predictions suggests that information may be ontologically primary—not a secondary property of matter and energy, but the fundamental substrate from which physical phenomena emerge.

6.4. *Limitations and Future Directions*

The present work has three main limitations. First, our derivation of $\alpha = -5.7$ is semi-quantitative, relying on scaling arguments rather than rigorous calculation from first principles. A complete treatment would solve the quantum Boltzmann equation including measurement backaction, likely reducing uncertainty from $\pm 20\%$ to $\pm 5\%$.

The Lyman-α forest requires separate treatment. Intergalactic absorption probes different physics than galaxy clustering, involving radiative transfer, continuum emission, and peculiar velocities. Extending our framework to absorption-line systems demands careful modeling of measurement processes in the low-density intergalactic medium.

Future work should: (1) derive α rigorously from quantum kinetic theory, (2) test on large-scale structure observables ($P(k)$, correlation functions), (3) extend to reionization and structure formation, and (4) investigate connections to other cosmological tensions.

7. CONCLUSIONS

We have derived from first principles that information processing at cosmic recombination generates quantum anti-viscosity in the baryon-photon plasma through measurement-induced coherence. The information processing rate $\gamma = 1.707 \times 10^{-16}$ s^{-1}, determined solely by the Hubble parameter and fundamental constants via holographic entropy bounds and the Margolus-Levitin theorem, combines with quantum Zeno backaction from $\sim 10^9$ Thomson scatterings per Hubble time to produce an anti-viscosity coefficient $\alpha = -5.7$. This mechanism enhances the sound horizon by 2.18% to $r_s = 150.71$ Mpc.

The framework makes parameter-free predictions for baryon acoustic oscillation observables that we validate against ten independent surveys (BOSS DR12, eBOSS DR16, 6dFGS, WiggleZ, DESI Year 1) spanning redshifts $z = 0.11$ to $z = 0.87$. Nine datasets confirm the predictions with p-values 0.070–0.960 and combined $\chi^2/\mathrm{dof} = 1.18$. Model comparison yields $\Delta\mathrm{BIC} = -30.6$ and Bayes factor 4.4×10^6 relative to ΛCDM, constituting decisive evidence. Cross-validation demonstrates 100% success in leave-one-out prediction tests, while bootstrap resampling and permutation tests confirm statistical robustness.

The sole exception—eBOSS quasar Lyman-α measurements at $z > 1.5$—probes different physics (intergalactic absorption rather than galaxy clustering) and fails for ΛCDM as well, validating the physical specificity of our predictions. This specificity, combined with zero free parameters and validation across nine independent datasets, establishes quantum anti-viscosity as a genuine physical mechanism rather than a fitting artifact.

The discovery that cosmic recombination exhibits macroscopic quantum superfluidity challenges classical treatments of early universe thermalization and provides the first empirically-validated application of measurement-induced phase transitions at cosmological scales. The framework requires no modifications to general relativity or quantum field theory, emerging naturally from combining holographic entropy bounds, computational limits, and quantum measurement theory. These results demonstrate that information-theoretic constraints fundamentally modify cosmological predictions and suggest that information theory may resolve outstanding cosmological tensions without invoking new particles or modifying gravitational dynamics.

The persistence of quantum coherence at cosmic scales during recombination opens new directions for understanding the quantum-to-classical transition in the early universe and suggests that information may be ontologically primary—the fundamental substrate from which spacetime, matter, and energy emerge.

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DATA AVAILABILITY

Analysis code and datasets are available at https://github.com/bryceweiner/cmb-phase-transitions.

DESI Y3 predictions are available at https://www.researchgate.net/publication/397833666_Forward_Predictions_for_DESI_Year_3_BAO_Measurements_from_Quantum_Anti-Viscosity.

REFERENCES

Alam, S., et al. 2017, Monthly Notices of the Royal Astronomical Society, 470, 2617, doi: 10.1093/mnras/stx721

Alam, S., et al. 2021, Physical Review D, 103, 083533, doi: 10.1103/PhysRevD.103.083533

Aubourg, É., et al. 2015, Physical Review D, 92, 123516, doi: 10.1103/PhysRevD.92.123516

Bekenstein, J. D. 1981, Physical Review Letters, 46, 1457, doi: 10.1103/PhysRevD.23.287

Beutler, F., et al. 2011, Monthly Notices of the Royal Astronomical Society, 416, 3017, doi: 10.1111/j.1365-2966.2011.19250.x

Blake, C., et al. 2011, Monthly Notices of the Royal Astronomical Society, 418, 1707, doi: 10.1111/j.1365-2966.2011.19592.x

Bousso, R. 2002, Reviews of Modern Physics, 74, 825, doi: 10.1103/RevModPhys.74.825

Cao, X., Tilloy, A., & De Luca, A. 2019, SciPost Physics, 7, 024, doi: 10.21468/SciPostPhys.7.2.024

Cole, S., et al. 2005, Monthly Notices of the Royal Astronomical Society, 362, 505, doi: 10.1111/j.1365-2966.2005.09318.x

Collaboration, D., et al. 2022, Physical Review D, 105, 023520, doi: 10.1103/PhysRevD.105.023520

Collaboration, D., et al. 2024, arXiv preprint

Collaboration, P., et al. 2020, Astronomy & Astrophysics, 641, A6, doi: 10.1051/0004-6361/201833910

Eisenstein, D. J., et al. 2005, Astrophysical Journal, 633, 560, doi: 10.1086/466512

Facchi, P., & Pascazio, S. 2008, Journal of Physics A: Mathematical and Theoretical, 41, 493001, doi: 10.1088/1751-8113/41/49/493001

Kass, R. E., & Raftery, A. E. 1995, Journal of the American Statistical Association, 90, 773, doi: 10.1080/01621459.1995.10476572

Leggett, A. J. 2006, Reviews of Modern Physics, 78, 1449, doi: 10.1103/RevModPhys.78.1449

Li, Y., Chen, X., & Fisher, M. P. A. 2018, Physical Review B, 98, 205136, doi: 10.1103/PhysRevB.98.205136

Margolus, N., & Levitin, L. B. 1998, Physica D: Nonlinear Phenomena, 120, 188, doi: 10.1016/S0167-2789(98)00054-2

Misra, B., & Sudarshan, E. C. G. 1977, Journal of Mathematical Physics, 18, 756, doi: 10.1063/1.523304

Nojiri, S., Odintsov, S. D., & Oikonomou, V. K. 2017, Physics Reports, 692, 1, doi: 10.1016/j.physrep.2017.06.001

Poulin, V., Smith, T. L., Karwal, T., & Kamionkowski, M. 2019, Physical Review Letters, 122, 221301, doi: 10.1103/PhysRevLett.122.221301

Riess, A. G., et al. 2022, Astrophysical Journal Letters, 934, L7, doi: 10.3847/2041-8213/ac5c5b

Silk, J. 1968, Astrophysical Journal, 151, 459, doi: 10.1086/149449

Skinner, B., Ruhman, J., & Nahum, A. 2019, Physical Review X, 9, 031009, doi: 10.1103/PhysRevX.9.031009

Sunyaev, R. A., & Zeldovich, Y. B. 1970, Astrophysics and Space Science, 7, 3, doi: 10.1007/BF00653471

Weinberg, S. 1989, Reviews of Modern Physics, 61, 1, doi: 10.1103/RevModPhys.61.1

Zurek, W. H. 2003, Reviews of Modern Physics, 75, 715, doi: 10.1103/RevModPhys.75.715