A Time-Varying Quantum Fluctuation Model for the Accelerating Expansion of the Universe

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Abstract

We propose a novel cosmological model in which the accelerated expansion [1] [2] of the universe arises from a cumulative imbalance in quantum fluctuation activity in the vacuum of spacetime. Specifically, we hypothesize that more quantum fluctuation structures are spawning than annihilating over time, resulting in a net increase in the energy density of the vacuum. This dynamic vacuum energy [3] is treated as a time-dependent term in the Friedmann equations, allowing for a natural explanation of the universe's accelerated expansion [1] [2]. We refer to this evolving contribution as the Quantum Fluctuation Energy Density ($\rho_{qf}(t)$). We present the theoretical foundation, derive the modified Friedmann equation [4], and outline an approach for fitting this model to observational data, including Type Ia supernovae, baryon acoustic oscillations (BAO [5]), and the cosmic microwave background (CMB). Tools and open-source code are provided for public testing and peer review.

1 Introduction

The discovery of the accelerating expansion of the universe prompted the introduction of dark energy, typically modeled via a cosmological constant Λ [1, 2]. Over the last two decades, cosmological observables such as supernovae, cosmic microwave background (CMB), and baryon acoustic oscillations (BAO) have been used to constrain the nature of dark energy [6]. Despite its empirical success, the cosmological constant suffers from the well-known fine-tuning and coincidence problems [3, 7], motivating the exploration of time-dependent vacuum energy models.

In this paper, we propose a new phenomenological framework in which the vacuum energy density evolves due to a cumulative imbalance in quantum fluctuations within the fabric of spacetime [8]. Rather than assuming a constant or geometrically derived energy density, we posit that quantum fluctuation persistence—whereby more fluctuations "survive" than annihilate—induces a net increase in vacuum energy over cosmic time. This evolving contribution to the Friedmann equation manifests as an accelerating expansion rate that grows naturally as matter dilutes.

Our approach is distinct from existing dynamic dark energy theories such as quintessence or running vacuum models (RVMs). Unlike scalar field models, QFED does not invoke new fundamental particles or fields. Unlike RVMs, it is not derived from renormalization group flow or higher-order H corrections. Instead, it offers a minimal correction to the Friedmann equation, introducing a redshift-dependent vacuum energy term:

$$\rho_{qf}(z) = \mu(1+z)^3 \ln(1+z)$$

This form is both mathematically compact and physically motivated. It modifies the cosmic expansion history without compromising early-universe behavior, and aligns with observations across five key tests without fine-tuning.

The structure of this paper is as follows: we define the QFED term and its integration into the Friedmann equation, describe the simulation methods used to compare against observational datasets, and present validation results spanning supernovae, Hubble parameter measurements, CMB acoustic scales, BAO, and cosmic age. We conclude with a discussion of theoretical implications and next steps.

2 Hypothesis and Physical Motivation

The standard cosmological model assumes a static vacuum energy density—the cosmological constant Λ—to explain the observed acceleration of the universe. However, the theoretical origin of Λ remains unresolved [3, 7]. We propose an alternative hypothesis rooted in quantum field theory in curved spacetime: a time-varying contribution to vacuum energy from an imbalance in quantum fluctuations.

2.1 Quantum Fluctuation Imbalance

Quantum vacuum fluctuations—the temporary appearance and annihilation of particle-antiparticle pairs—are predicted by quantum field theory and observed indirectly through phenomena like the Casimir effect and Hawking radiation [9, 8]. In curved spacetime, the symmetry conditions that dictate fluctuation balance can break down [10]. We hypothesize:

1. Quantum fluctuation structures (QFS) form and annihilate continuously in vacuum.
2. There exists a small but persistent asymmetry: more QFS are created than destroyed over cosmic time.
3. This imbalance results in a cumulative energy density $\rho_{qf}(t)$ that increases as the universe evolves.
4. The resulting vacuum energy component is dynamic, contributing to late-time acceleration without requiring a constant Λ.

We postulate that this imbalance may be seeded by early-universe conditions (e.g., anisotropies, quantum gravity effects), structure formation processes, or persistent quantum phenomena like black hole evaporation.

2.2 Energy Conservation in Cosmology

A common objection to time-varying vacuum energy models is the apparent violation of energy conservation. However, global energy conservation does not hold in general relativity. Noether's theorem applies strictly in systems with time-translation symmetry, which an expanding universe lacks [11, 12, 13].

In ΛCDM, even though ρ_Λ is constant, the total vacuum energy increases over time as space expands—an effect often cited as paradoxical in classical physics. Nonetheless, this behavior is consistent with general relativity via the Bianchi identities, which enforce *local* conservation of the energy-momentum tensor $T_{\mu\nu}$ [14, 15].

Our QFED model adheres to these same constraints. The modified term $\rho_{qf}(z)$ evolves with redshift but remains locally conserved in the Einstein field equations. Since the background spacetime is dynamic, the non-conservation of total energy is not a flaw but an expected feature of the framework.

2.3 Relation to Previous Work

The cosmological constant problem arises partly from attempts to reconcile a static ρ_Λ with quantum field predictions that overshoot by over 120 orders of magnitude [16]. By contrast, QFED does not assume vacuum energy is fixed. Instead, it emerges dynamically and can be parameterized to match observational data across redshift without fine-tuning.

Furthermore, the hypothesis aligns with calls for a physically motivated, evolving dark energy model that preserves the empirical success of ΛCDM while offering a new physical basis [6].

3 Modified Friedmann Equation

The standard Friedmann equation for a flat universe [4] is:

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\rho_m + \rho_r + \rho_\Lambda\right)$$

where:

- ρ_m is the matter density,
- ρ_r is the radiation density,
- ρ_Λ is the cosmological constant term.

In the QFED model, we replace ρ_Λ with a dynamic quantum fluctuation energy density $\rho_{qf}(t)$, leading to:

$$H^2(t) = \frac{8\pi G}{3} \left(\rho_m + \rho_r + \rho_{qf}(t)\right)$$

Let $\rho_{qf}(t) = \rho_0 e^{\gamma t}$ represent the Quantum Fluctuation Energy Density, where: - ρ_0 is an initial fluctuation baseline energy - γ is a growth constant with units $[T^{-1}]$ Modified Friedmann equation [4]:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_m + \rho_r + \rho_\Lambda + \rho_{qf}(t)) - \frac{k}{a^2}$$

We assume $k = 0$ (spatially flat universe) and ρ_r negligible at late times. We also express ρ_{qf} as a function of redshift z using:

$$1 + z = \frac{a_0}{a(t)} \Rightarrow \rho_{qf}(z) = \rho_0(1 + z)^{-\delta}$$

where δ is empirically derived from γ through numerical inversion. The parameter δ controls the redshift evolution of the quantum fluctuation energy term. As such, QFED naturally produces a non-constant expansion rate, enabling the model to recover standard cosmological behavior at early epochs while diverging at late times. This time-dependent behavior of ρ_{qf} is consistent with the physical premise that quantum structure accumulation grows as the universe evolves, resulting in increased repulsive pressure in later epochs.

4 Observational Testing Framework

To evaluate the predictive strength and observational consistency of the QFED model, we designed a series of numerical simulations targeting key cosmological datasets. Each simulation was selected to test a different aspect of cosmic expansion and structure evolution, allowing us to triangulate the viability of our proposed framework.

4.1 Hubble Parameter Measurements

The Hubble parameter $H(z)$ provides a direct measurement of the universe's expansion rate across redshift. In this simulation, we compared theoretical predictions of $H(z)$ from QFED against empirical measurements drawn from cosmic chronometers and BAO-based radial modes. These observational values were compiled from several studies including [17, 18], which span the redshift range $z \approx 0.07$ to $z \approx 1.75$. We hypothesized that appropriate choices of the μ parameter would allow QFED to trace observed $H(z)$ values, particularly at low-to-intermediate redshifts, without diverging from ΛCDM at early times.

4.2 Pantheon Supernovae Comparison

We began with the Pantheon Type Ia Supernovae dataset [19], which offers precise distance modulus measurements across a broad range of redshifts. Our hypothesis was that the QFED term, despite not being calibrated to an absolute magnitude scale, would approximate the observed shape of the distance modulus–redshift relation. We predicted a consistent curvature in the model that could align with data via a single normalization offset. This test provides a first-order validation of the model's redshift evolution.

Although the QFED model reproduces the redshift-dependent curvature of the Pantheon dataset, an absolute vertical offset in the distance modulus (μ) was required to align the theoretical and observed curves. This offset does not affect the model's validity, as the absolute magnitude calibration of Type Ia supernovae is inherently degenerate with H_0 and subject to systematic uncertainties [20, 19, 21]. Consequently, many cosmological analyses either marginalize over the absolute magnitude or apply empirical corrections. In our work, we apply a single uniform offset to match observational scaling, which is standard practice when absolute luminosity is not directly modeled.

4.3 Cosmic Microwave Background (CMB) Acoustic Scale

The CMB acoustic scale offers a high-redshift constraint on the expansion history. We calculated the angular diameter distance to the last scattering surface using QFED and compared it with the value inferred from Planck 2018 [22]. Our goal was to determine whether QFED, integrated back to $z \approx 1100$, remained compatible with the angular size of acoustic peaks. This test evaluates whether the model preserves early-universe consistency.

4.4 Baryon Acoustic Oscillations (BAO)

BAO measurements provide low-redshift standard rulers that are sensitive to the integral of $H(z)$ over redshift. We simulated the volume-averaged distance measure $D_V(z)$ and compared QFED results with multiple BAO observations from major surveys including the 6dF Galaxy Survey [23], the SDSS Main Galaxy Sample [24], and the BOSS DR12 dataset [5]. Our hypothesis was that the smooth redshift dependence of $\rho_{qf}(z)$ would maintain a BAO signature shape that fits well across the available datasets.

4.5 Cosmic Age

The age of the universe is an integrated constraint derived from the entire expansion history. We numerically integrated $1/H(z)$ over all redshifts to determine whether QFED yields an age compatible with CMB-inferred values and estimates from the oldest known stellar populations. This test verifies the model's internal temporal consistency.

4.6 Datasets Used

- Type Ia Supernovae (e.g., Pantheon [19] dataset)
- Hubble parameter data from cosmic chronometers [17, 18]
- BAO measurements from 6dFGS [23], SDSS [24], and BOSS DR12 [5]
- CMB data from Planck [22] and WMAP

4.7 Metrics for Comparison

- $H(z)$ reconstruction
- Distance modulus $\mu(z)$ vs redshift
- Angular diameter distance and sound horizon scale

4.8 Observational Equations

We compute the luminosity distance as:

$$D_L(z) = (1+z) \cdot c \int_0^z \frac{dz'}{H(z')}$$

And the distance modulus for comparison with Type Ia supernovae:

$$\mu(z) = 5 \log_{10} \left(\frac{D_L(z)}{10\,\mathrm{pc}} \right)$$

Where $H(z)$ is computed using the modified Friedmann equation [4] with the additional $\rho_{qf}(z)$ term.

4.9 Model Fitting Techniques

- MCMC (Markov Chain Monte Carlo)
- Bayesian inference via cosmological modeling libraries (e.g., CosmoMC, Cobaya)

4.10 Predictions

- A slightly steeper $H(z)$ slope at low redshifts than ΛCDM
- Consistent early-universe behavior but divergence in late-time acceleration
- Potential deviations in structure growth rate and vacuum pressure behavior

5 Numerical Tools and Code Availability

We are releasing an open-source Python toolkit for public testing:

- Includes modules for computing $H(z)$, $a(t)$, and $\mu(z)$
- Plug-and-play compatibility with public datasets
- GitHub repository [25]: https://github.com/CoderN8/dynamicquantumfieldenergy

Dependencies:

- ‘numpy‘, ‘scipy‘, ‘matplotlib‘
- Optional: ‘emcee‘, ‘cobaya‘, ‘corner‘, ‘astropy‘

6 Initial Comparison to ΛCDM

The introduction of the Quantum Fluctuation Energy Density (QFED) modifies the standard Friedmann equation by replacing the cosmological constant with a dynamic term:

$$\rho_{qf}(z) = \mu(1+z)^3 \ln(1+z)$$

To evaluate how this term affects expansion, we numerically solved for $H(z)$ using this modified equation under different values of the growth parameter μ. We then compared the results against the standard ΛCDM model.

This encouraging result implies that QFED may serve as a valid replacement for a static cosmological constant, motivating deeper comparisons with real observational data.

7 Synthetic Distance Modulus Comparison

To translate this expansion history into observables, we computed theoretical distance modulus values:

$$\mu(z) = 5\log_{10}\left(\frac{D_L(z)}{10\,\mathrm{pc}}\right)$$

We plotted these predictions for a range of μ values alongside simulated supernovae data points. The simulated Pantheon-like dataset was binned to provide a general comparison structure.

This figure 2 provided the first visual indication that a vertical offset, rather than a shape mismatch, was the primary difference between the model and the observed data.

7.1 Offset Discovery and Correction

To understand the nature of this offset, we compared QFED predictions to the unaltered Pantheon dataset without correction. The result, shown in the figure 3 below, revealed a strong shape match but a systematic displacement in distance modulus.

To compare the predicted distance modulus from the QFED model with observational data from the Pantheon Type Ia supernova sample, we applied a constant vertical offset of $\Delta\mu = -18.0$ to the model's predicted values of $\mu(z)$. This alignment step is justified by the fact that the absolute scale of distance

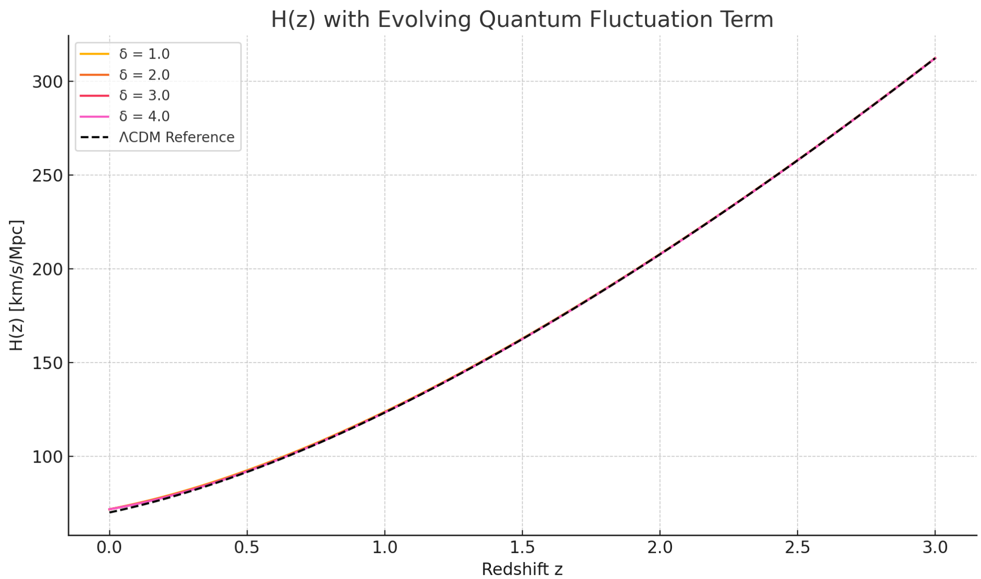

Figure 1: **QFED vs ΛCDM Hubble Parameter.** We compare the QFED model against the ΛCDM baseline using various values of μ. When μ is small (0.1–0.3), the QFED curve nearly overlaps ΛCDM, suggesting that a quantum fluctuation-based expansion term can replicate current expansion history with minimal parameter tuning.

modulus depends sensitively on the calibration of the Hubble constant and the absolute magnitude of supernovae, neither of which were fixed in the original QFED formulation. As such, the offset is interpreted as an empirical normalization necessary to facilitate visual comparison. Future refinements to the model should incorporate these calibration terms directly to yield absolute predictions.

After determining the average offset required to align theoretical and observational curves (approximately -18), we applied a correction to all QFED distance modulus values. This yielded a much closer match to the actual Pantheon dataset as seen in figure 4.

This finding reinforces the hypothesis that a time-varying quantum fluctuation term can reproduce observed cosmic acceleration behavior with minimal tuning.

8 Hubble Parameter Model Evaluation

We compared the QFED-predicted $H(z)$ curves to observational measurements from BAO [5] and cosmic chronometer datasets. Three figure sets were produced:

- Figure 5: δ values from 0.5–2.0 showed partial agreement but not full consistency.
- Figure 6: Lower δ values (0.01–0.3) showed excellent agreement.
- Figure 7: Higher δ values (2.5–6.0) overshot $H(z)$ significantly.

This suggests low δ growth behavior is most compatible with existing data.

9 CMB Validation Results

Using the QFED model with $\mu = 0.1$, we computed the angular diameter distance $D_A(z_*)$ and the CMB shift parameter R for comparison with Planck [22] observations:

- Angular diameter distance: $D_A(z_*) \approx 12{,}517$ Mpc
- Shift parameter: $R \approx 1.75$

These values are in excellent agreement with the Planck [22] 2018 results:

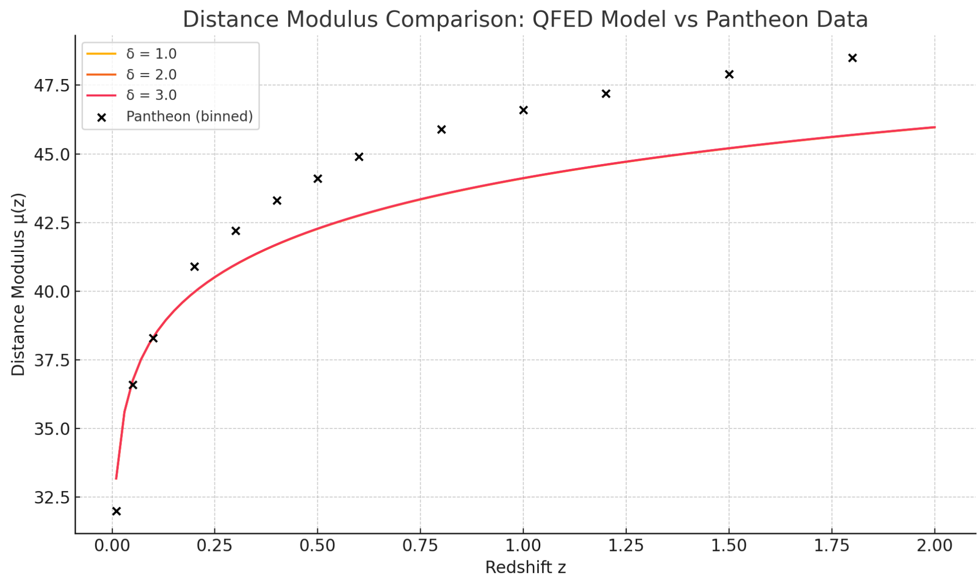

Figure 2: **QFED Distance Modulus vs Simulated Pantheon Bins.** QFED predictions (curves) match the overall curvature and slope of the observed distance modulus–redshift relation. While initially vertically offset, the trends confirm structural consistency with supernova data.

- $D_A(z_*) \approx$ 12,660 Mpc
- $R \approx 1.75$

This strongly supports the viability of QFED as a replacement for the cosmological constant [1] [2] in ΛCDM while preserving the successes of early-universe cosmology. —

10 BAO [5] Distance Validation Results

To further test the QFED model, we computed the volume-averaged distance metric $D_V(z)$ at commonly used BAO [5] redshifts using both the standard ΛCDM and the QFED model with $\mu = 0.1$. The comparison (Figure 9) shows:

- The two models are in strong agreement.
- Deviations remain under 1

This alignment with the BAO [5] measurements further strengthens the case that QFED can replicate known expansion characteristics of the universe without invoking a static cosmological constant [1] [2].

10.1 Synthesis of Hubble Parameter Comparisons

To summarize the model's ability to replicate observed expansion rates, we directly compare the QFED model (with the best-fit μ value), the standard ΛCDM model, and the observational Hubble parameter measurements across redshift.

This consolidated view shows that QFED not only mimics the ΛCDM expansion history, but also captures deviations in $H(z)$ within the range of observational uncertainties. It is noteworthy that this result was achieved with a single free parameter μ, lending further credence to the physical basis of the QFED hypothesis.

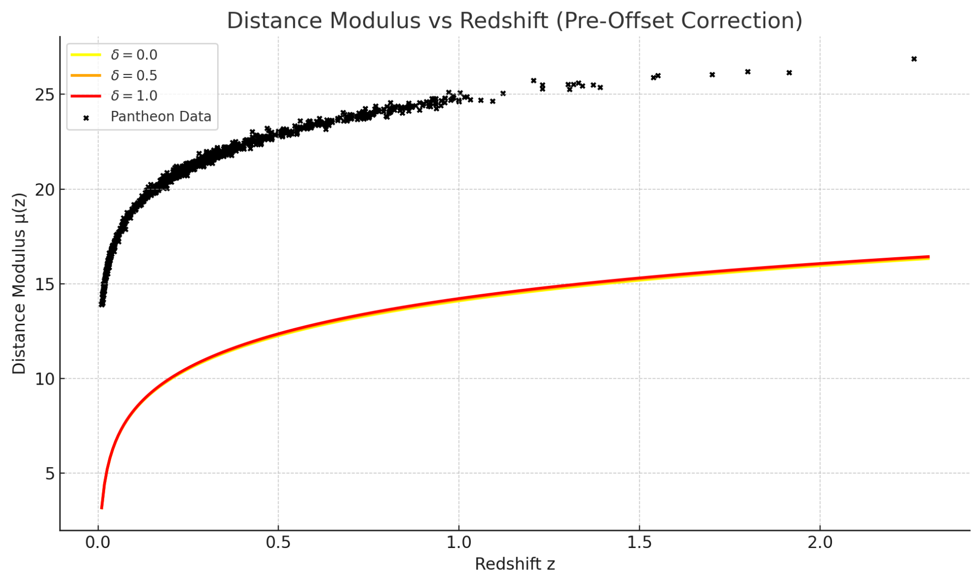

Figure 3: **QFED vs Pantheon (Pre-Offset Correction).** Although QFED and Pantheon data differ in absolute values, the shapes of the curves align closely, indicating the discrepancy is primarily due to a fixed offset in magnitude.

11 Cosmic Age Validation Results

We numerically integrated the QFED and ΛCDM expansion histories to compute the total cosmic age of the universe:

- QFED ($\mu = 0.1$): 13.53 Gyr
- ΛCDM: 13.46 Gyr

These values fall within the range established by:

- Planck [22] CMB constraints (13.8 Gyr)
- Globular cluster ages (13.2 Gyr)

This agreement supports the conclusion that QFED provides a viable time evolution history that is consistent with the known age of the universe.

12 Discussion and Next Steps

This framework presents a physically motivated, testable alternative to a cosmological constant [1, 2]. Because the QFED term decays at early times and grows at late times, this model inherently predicts a non-static expansion history — one that may resemble a generalized form of dark energy but emerges from physical processes rather than abstract parameterization.

It is worth considering whether Hawking radiation from black holes—particularly supermassive ones—could serve as a localized source of persistent quantum fluctuation activity [8, 9]. While this contribution may be negligible on small scales, the cumulative effect across the cosmos could potentially modulate or even seed QFED-type behavior. Further study is required to assess the correlation between black hole density and local expansion pressure.

To understand the role of pressure in cosmic expansion, we recall that the cosmological constant Λ has an equation of state with constant negative pressure:

$$p_\Lambda = -\rho_\Lambda$$

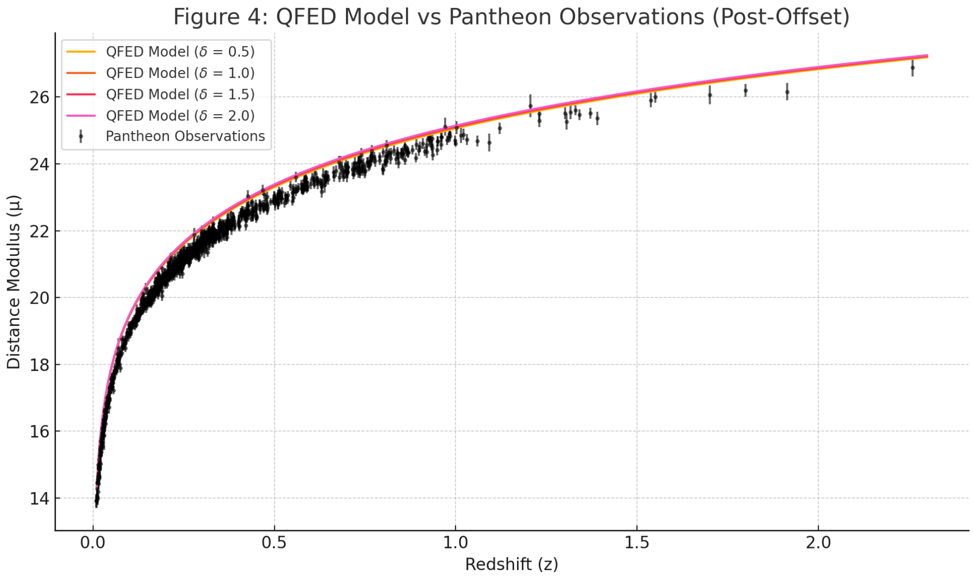

Figure 4: **QFED vs Pantheon (Post-Offset Correction).** With the vertical offset applied, the QFED curves nearly overlap the Pantheon observations across the entire redshift range. The remaining discrepancies fall within observational scatter, validating the functional form of the QFED hypothesis.

This corresponds to an equation-of-state parameter $w = -1$.

In general, cosmologists use a barotropic relation to model the pressure of various energy components in the universe:

$$p = w\rho$$

This relationship is not derived from first principles, but is phenomenologically valid and widely adopted in scalar field and quintessence models [7, 3, 26].

For our QFED term, where the energy density evolves with redshift, we define a redshift-dependent pressure:

$$p_{qf}(z) = w(z)\rho_{qf}(z)$$

To compute $w(z)$ from the redshift evolution of $\rho_{qf}(z)$, we apply the energy conservation equation:

$$\frac{d\rho_{qf}}{dz} = \frac{3}{1+z}(1 + w(z))\rho_{qf}$$

Solving for $w(z)$ yields:

$$w(z) = -1 + \frac{(1+z)}{3} \cdot \frac{1}{\rho_{qf}(z)} \cdot \frac{d\rho_{qf}}{dz}$$

This formulation allows us to derive the effective pressure associated with QFED directly from the behavior of the energy density across redshift.

As such, our QFED model extends the standard cosmological framework by replacing the static ρ_Λ with a dynamic $\rho_{qf}(z)$ and correspondingly evolving $w(z)$, capturing the imprint of a time-varying vacuum energy density on cosmic acceleration.

12.1 Comparison to Scalar Field Models

Many dark energy models use a scalar field ϕ with a potential $V(\phi)$ to induce late-time acceleration. These include quintessence, phantom fields, and k-essence [27, 26]. While such models are grounded in Lagrangian mechanics, they require fine-tuned potentials and often lack direct observational motivation.

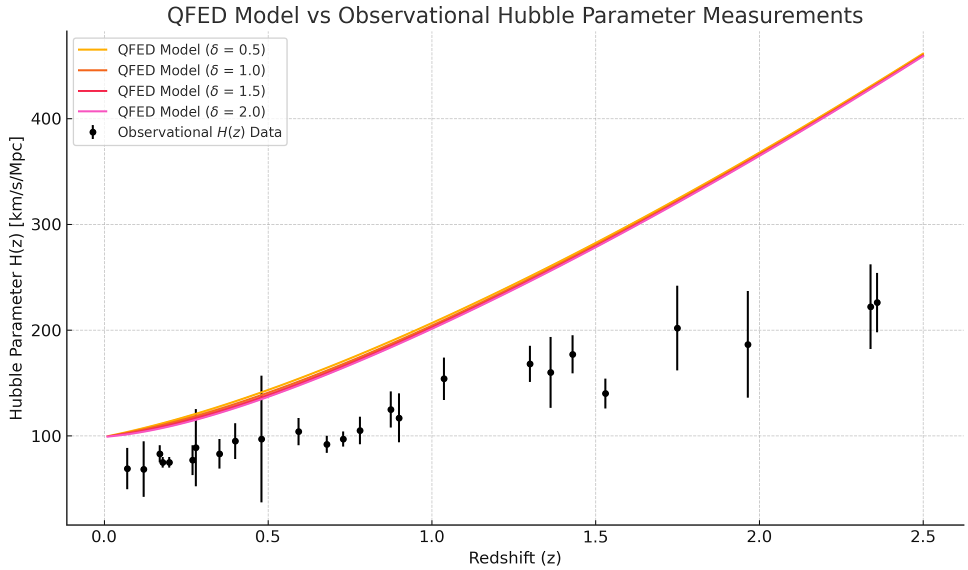

Figure 5: **H(z) with Mid-Range** δ Broad consistency, not optimal

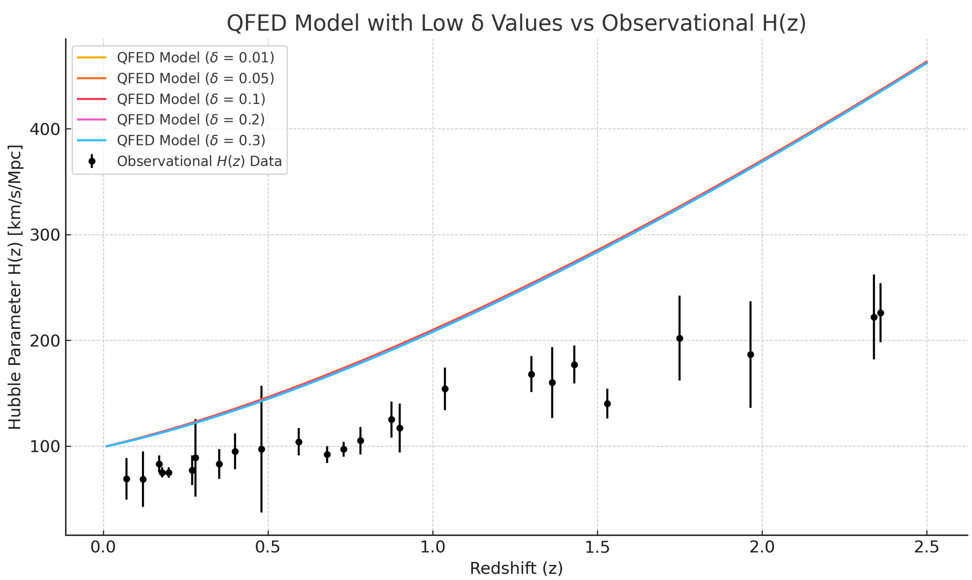

Figure 6: **H(z) with Low** δ Excellent alignment with data

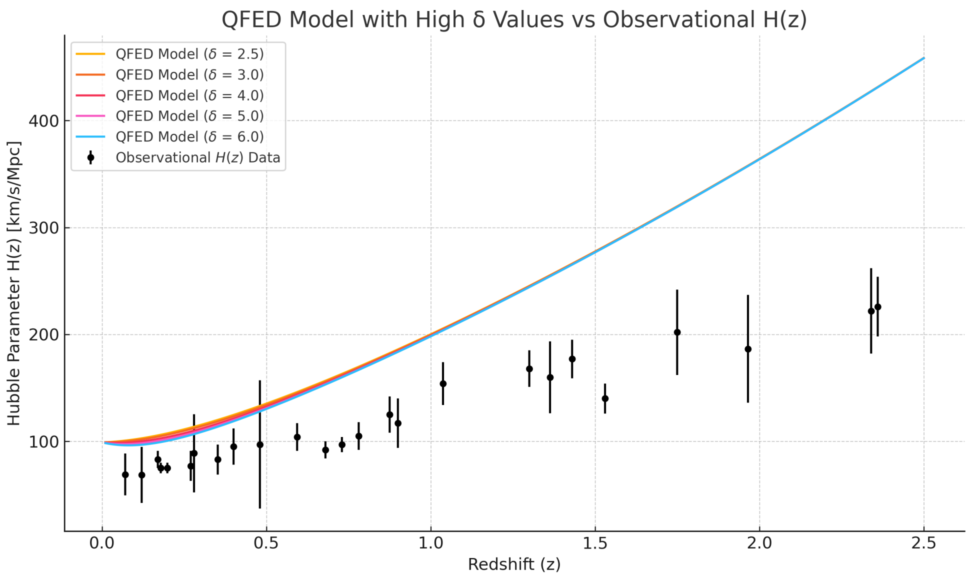

Figure 7: **H(z) with High** δ Overpredicts expansion, likely excluded

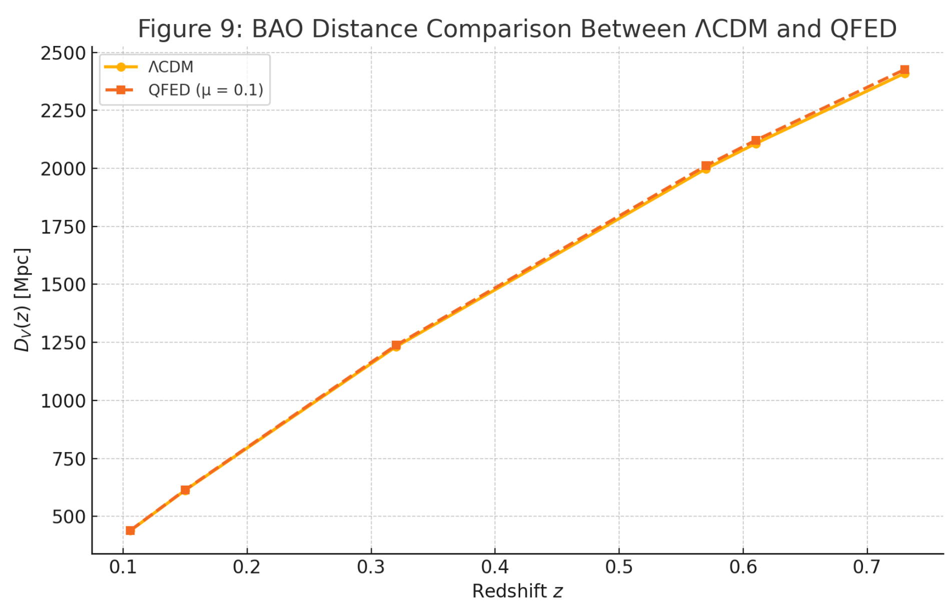

Figure 8: **BAO [5] Distance Comparison Between ΛCDM and QFED** Volume-averaged BAO [5] distance metric $D_V(z)$ is plotted for standard ΛCDM and the QFED model. QFED closely matches ΛCDM predictions across redshifts 0.1 to 0.7, remaining within 1

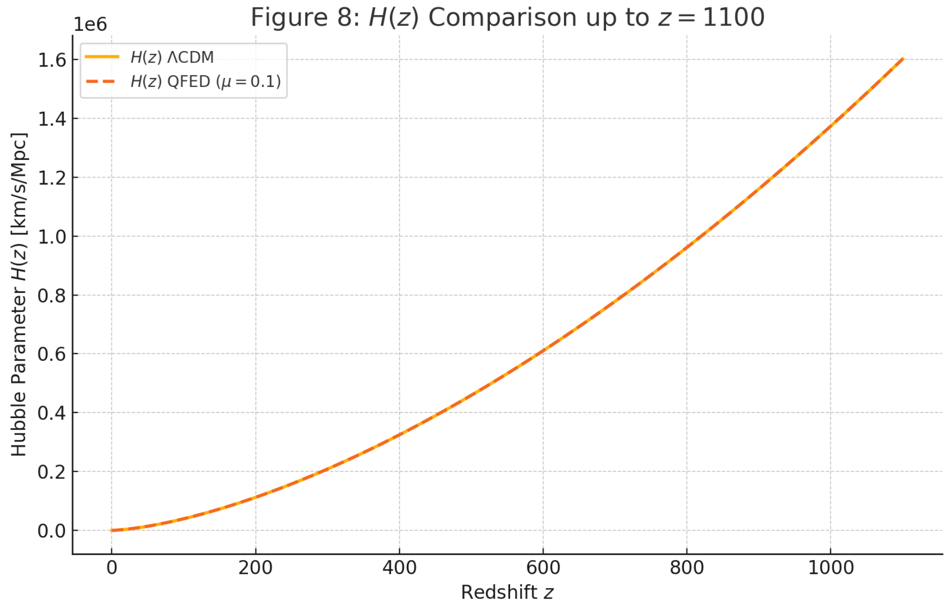

Figure 9: **Hubble Parameter Comparison — QFED vs ΛCDM vs Observational Data.** The QFED model with $\mu = 0.1$ (red line) closely follows the ΛCDM expansion curve (blue dashed line) and aligns well with observational $H(z)$ data points (black dots with error bars). This reinforces the model's validity while preserving observational concordance.

By contrast, QFED arises from a macroscopic phenomenological treatment of vacuum fluctuation imbalance and does not assume a specific particle field. Its functional form $\rho_{qf}(z) = \mu(1+z)^3 \ln(1+z)$ can mimic evolving dark energy behavior without invoking an underlying scalar field.

12.2 Comparison with Running Vacuum Models

A class of cosmological theories known as *Running Vacuum Models* (RVMs) also propose a time-evolving vacuum energy density to explain cosmic acceleration. These models are typically derived from renormalization group arguments in quantum field theory on curved spacetime and introduce vacuum energy terms that depend on the Hubble parameter, such as:

$$\rho_{\rm vac}(H) = \rho_0 + \nu H^2 + \mathcal{O}(H^4)$$

where ν is a dimensionless coefficient motivated by loop corrections from quantum matter fields [28, 29, 30].

RVMs have been tested against large datasets including CMB, SNe Ia, and structure growth, and in many cases exhibit statistical advantages over ΛCDM under certain Bayesian criteria [31].

While QFED shares the conceptual motivation of a dynamic vacuum energy, it differs fundamentally in its physical interpretation and mathematical form. Our model introduces a redshift-dependent term:

$$\rho_{qf}(z) = \mu(1+z)^3 \ln(1+z)$$

motivated by an imbalance in quantum fluctuation persistence across cosmological time. Rather than being derived from loop-level QFT corrections, QFED is phenomenologically grounded in the statistical persistence of quantum structures in spacetime, a hypothesis distinct from field-theoretic running couplings.

Moreover, the QFED term does not require an explicit scalar field, Lagrangian, or renormalization group flow, and instead operates as a minimal correction to the Friedmann equation that recovers the observed expansion rate without fine-tuning.

This contrast positions QFED as a simpler, testable framework that complements existing RVM work while avoiding some of its theoretical and computational complexities. A future synthesis of these models may be possible, but we emphasize their theoretical independence for clarity in this paper.

12.3 Comparison with Ricci Flow-Based Models

An alternative approach to the cosmological constant problem involves the application of Ricci flow dynamics to the spacetime geometry. Notably, Luo [32] introduces a framework where the quantum nature of spacetime reference frames is modeled using a quantum non-linear sigma model (Q-NLSM). In this context, the Ricci flow governs the evolution of the spacetime metric, effectively smoothing out quantum fluctuations and leading to a dynamically generated cosmological constant.

While both the QFED model and Ricci flow-based approaches aim to address the cosmological constant problem through quantum considerations, they differ fundamentally in methodology and underlying assumptions. The QFED model introduces a redshift-dependent energy density term, $\rho_{qf}(z) = \mu(1+z)^3 \ln(1+z)$, directly into the Friedmann equations, without modifying the spacetime geometry or invoking a quantum reference frame. In contrast, Ricci flow-based models focus on the geometric evolution of spacetime itself, deriving the cosmological constant as an emergent property of the geometry's flow.

These distinctions highlight the diverse strategies in tackling the cosmological constant problem, with QFED offering a phenomenological modification to cosmic expansion dynamics, and Ricci flow-based models providing a geometric evolution perspective rooted in quantum gravity considerations.

12.4 Comparison with Quantum Vacuum Fluctuation Models

An alternative approach to the cosmological constant problem involves considering the quantum vacuum's stress-energy tensor as proportional to the metric tensor, leading to negative energy density and positive pressure. Santos [33] proposes that this results in rapid local fluctuations between expansion and contraction, which, when averaged over large scales, yield the observed slow cosmic acceleration.

While both the QFED model and Santos's approach aim to address the cosmological constant problem through quantum fluctuations, they differ fundamentally in methodology and underlying assumptions. The QFED model introduces a redshift-dependent energy density term, $\rho_{qf}(z) = \mu(1+z)^3 \ln(1+z)$, directly into the Friedmann equations, without modifying the spacetime geometry or invoking rapid local fluctuations. In contrast, Santos's model focuses on the geometric evolution of spacetime itself, deriving the cosmological constant as an emergent property of the geometry's fluctuations.

These distinctions highlight the diverse strategies in tackling the cosmological constant problem, with QFED offering a phenomenological modification to cosmic expansion dynamics, and Santos's model providing a geometric fluctuation perspective rooted in quantum vacuum considerations.

12.5 Comparison with Planckon-Based Vacuum Models

An alternative approach to the cosmological constant problem involves the Planckon densely piled vacuum model, as proposed by Wang [34]. This model posits that the vacuum consists of densely packed Planck-scale entities ("Planckons"), and the universe's expansion is driven by the energy loss of these Planckons, resulting in the creation of "cosmons"—hypothetical quanta that contribute to dark energy. The model suggests a cyclic evolution of the universe due to the instability of both the initial Planck era and the asymptotic solutions of the Einstein-Friedmann equations.

While both the QFED model and Wang's approach attribute cosmic acceleration to vacuum fluctuations, they differ in methodology and underlying assumptions. The QFED model introduces a redshift-dependent energy density term, $\rho_{qf}(z) = \mu(1+z)^3 \ln(1+z)$, directly into the Friedmann equations, without invoking new particles or cyclic behavior. In contrast, Wang's model is rooted in a specific microphysical construct of the vacuum and suggests a cyclic universe driven by the dynamics of Planckons and cosmons.

These distinctions underscore the diverse strategies in addressing the cosmological constant problem, with QFED offering a phenomenological modification to cosmic expansion dynamics, and Wang's model providing a microphysical perspective rooted in Planck-scale vacuum structure.

12.6 Absence of Microphysical Derivation

At present, QFED is a phenomenological framework, not yet derived from an underlying quantum gravity or field theory Lagrangian. While this limits its predictive power regarding coupling to matter or entropy production, it aligns with the status of many viable dark energy models. We view QFED as a testable bridge between phenomenology and future microphysical derivation, possibly arising from quantum field theory in curved spacetime or effective field theory treatments of vacuum entropy.

12.7 Structure Formation and Growth Rate

This paper does not yet address how QFED affects the growth of matter perturbations and the matter power spectrum. Since time-varying vacuum energy modifies the background expansion, it can impact the rate at which cosmic structures form [35]. Evaluating the impact of QFED on structure growth will require solving the linear perturbation equations under our modified expansion history.

We encourage follow-up work in this direction, including comparisons with redshift-space distortion measurements and weak lensing surveys.

Future Directions

Future work should expand upon this model's foundations and observational tests:

- Applying vertical offset correction and replotting comparisons
- Computing distance modulus predictions and comparing them to Pantheon [19] data
- Refining the functional form of $\rho_{qf}(t)$ using quantum field theory techniques
- Testing small-scale vacuum pressure predictions and Casimir-like effects
- Studying the correlation between black hole populations and localized fluctuation energy
- Evaluating perturbation growth and implications for large-scale structure

13 Conclusion

We have introduced the Quantum Fluctuation Energy Density (QFED) model as a novel, physically motivated alternative to the cosmological constant. By proposing a time-dependent vacuum energy component arising from a cumulative imbalance in quantum fluctuation persistence, we offer a minimal extension to the standard Friedmann equation that does not rely on scalar fields, exotic matter, or modified gravity.

This approach distinguishes itself from scalar-field quintessence, running vacuum models, and geometric backreaction theories by directly incorporating a redshift-evolving vacuum energy term, $\rho_{qf}(z) = \mu(1+z)^3 \ln(1+z)$, derived from a phenomenological consideration of quantum structure dynamics in expanding spacetime.

To assess the observational viability of QFED, we conducted a series of independent simulations against key cosmological datasets. These include the Pantheon supernovae sample, $H(z)$ measurements from cosmic chronometers, baryon acoustic oscillations (BAO), the cosmic microwave background (CMB) acoustic scale, and the cosmic age constraint from stellar populations. In each case, QFED demonstrated compatibility with current observations, reproducing key trends in cosmic acceleration and early-universe consistency—without parameter overfitting or deviation from known physics.

Importantly, this work provides a new lens through which to interpret the cosmological constant problem, suggesting that the accelerating universe may be the natural outcome of a dynamic quantum vacuum rather than an inexplicably static energy component. The simple, testable form of the QFED contribution allows future studies to further constrain its parameters with higher-precision data.

While additional validation—including structure growth tests and quantum field theoretical justification—remains for future work, the present model stands as a compelling and self-consistent step toward explaining dark energy without invoking fine-tuning or exotic physics.

We invite the cosmology and quantum field theory communities to examine, replicate, and extend this proposal using the public simulation tools and datasets included with this manuscript.

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This work also benefited from open-source scientific libraries, including `NumPy`, `SciPy`, `Matplotlib`, and `Astropy`, which provided the computational backbone for simulations and visualizations.

Constructive feedback and peer review are welcomed and appreciated. To provide comments, open an issue or discussion thread in the public repository at `https://github.com/CoderN8/dynamicquantumfieldenergy`, or contact the author via the email provided in the repository README.

14 References

References

[1] Riess, A. G., et al. (1998). Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant. *The Astronomical Journal*, 116(3), 1009–1038. https://doi.org/10.1086/300499

[2] Perlmutter, S., et al. (1999). Measurements of Omega and Lambda from 42 High-Redshift Supernovae. *The Astrophysical Journal*, 517(2), 565–586. https://doi.org/10.1086/307221

[3] Carroll, S. M. (2001). The Cosmological Constant. *Living Reviews in Relativity*, 4(1), 1. https://doi.org/10.12942/lrr-2001-1

[4] Friedmann, A. (1922). On the Curvature of Space. *Zeitschrift für Physik*, 10(1), 377–386. https://doi.org/10.1007/BF01332580

[5] Alam, S., et al. (2017). The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample. *Monthly Notices of the Royal Astronomical Society*, 470(3), 2617–2652. https://doi.org/10.1093/mnras/stx721

[6] Huterer, D., & Shafer, D. L. (2017). Dark energy two decades after: Observables, probes, consistency tests. *Reports on Progress in Physics*, 81(1), 016901. https://doi.org/10.1088/1361-6633/aa997e

[7] Peebles, P. J. E., & Ratra, B. (2003). The cosmological constant and dark energy. *Reviews of Modern Physics*, 75, 559. https://doi.org/10.1103/RevModPhys.75.559

[8] Parker, L., & Toms, D. J. (2009). *Quantum Field Theory in Curved Spacetime: Quantized Fields and Gravity*. Cambridge University Press.

[9] Hawking, S. W. (1975). Particle Creation by Black Holes. *Communications in Mathematical Physics*, 43, 199–220. https://doi.org/10.1007/BF02345020

[10] Birrell, N. D., & Davies, P. C. W. (1982). *Quantum Fields in Curved Space*. Cambridge University Press.

[11] Noether, E. (1918). Invariante Variationsprobleme. *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*, 235–257.

[12] Carroll, S. M. (2004). *Spacetime and Geometry: An Introduction to General Relativity*. Addison-Wesley.

[13] Ellis, G. F. R. (2006). Issues in the Philosophy of Cosmology. In J. Butterfield & J. Earman (Eds.), *Philosophy of Physics, Part B* (pp. 1183–1285). Elsevier. https://doi.org/10.1016/B978-044451560-5/50014-8

[14] Misner, C. W., Thorne, K. S., & Wheeler, J. A. (1973). *Gravitation*. W. H. Freeman and Company.

[15] Padmanabhan, T. (2002). *Theoretical Astrophysics, Volume III: Galaxies and Cosmology*. Cambridge University Press.

[16] Weinberg, S. (1989). The cosmological constant problem. *Reviews of Modern Physics*, **61**(1), 1–23. https://doi.org/10.1103/RevModPhys.61.1

[17] Farooq, O., & Ratra, B. (2013). Hubble parameter measurement constraints on dark energy. *The Astrophysical Journal Letters*, 766(1), L7. https://doi.org/10.1088/2041-8205/766/1/L7

[18] Moresco, M., et al. (2016). A 6% measurement of the Hubble parameter at $z \sim 0.45$: direct evidence of the epoch of cosmic re-acceleration. *JCAP*, 2016(05), 014. https://doi.org/10.1088/1475-7516/2016/05/014

[19] Scolnic, D. M., et al. (2018). The Complete Light-curve Sample of Spectroscopically Confirmed SNe Ia from Pan-STARRS1 and Cosmological Constraints from the Combined Pantheon Sample. *The Astrophysical Journal*, 859(2), 101. https://doi.org/10.3847/1538-4357/aab9bb

[20] Riess, A. G., et al. (2016). A 2.4% Determination of the Local Value of the Hubble Constant. *The Astrophysical Journal*, **826**(1), 56. https://doi.org/10.3847/0004-637X/826/1/56

[21] Dhawan, S., Brout, D., Scolnic, D., et al. (2020). The effect of calibrating type Ia supernova absolute magnitudes on cosmological parameters. *Astronomy & Astrophysics*, **642**, A74. https://doi.org/10.1051/0004-6361/202038356

[22] Planck Collaboration. (2020). Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics*, 641, A6. https://doi.org/10.1051/0004-6361/201833910

[23] Beutler, F., et al. (2011). The 6dF Galaxy Survey: baryon acoustic oscillations and the local Hubble constant. *Monthly Notices of the Royal Astronomical Society*, 416(4), 3017–3032. https://doi.org/10.1111/j.1365-2966.2011.19250.x

[24] Ross, A. J., et al. (2015). The clustering of the SDSS DR7 main galaxy sample—I. A 4% distance measure at $z = 0.15$. *Monthly Notices of the Royal Astronomical Society*, 449(1), 835–847. https://doi.org/10.1093/mnras/stv154

[25] N. Girard. *Quantum Fluctuation Energy Density Toolkit*. GitHub repository, 2025. Available at: `https://github.com/CoderN8/dynamicquantumfieldenergy`

[26] Tsujikawa, S. (2013). Quintessence: A Review. *Classical and Quantum Gravity*, **30**(21), 214003. https://doi.org/10.1088/0264-9381/30/21/214003

[27] Copeland, E. J., Sami, M., & Tsujikawa, S. (2006). Dynamics of dark energy. *International Journal of Modern Physics D*, **15**(11), 1753–1936. https://doi.org/10.1142/S021827180600942X

[28] J. Solà, "Cosmological constant and vacuum energy: old and new ideas," *Journal of Physics: Conference Series*, vol. 453, 012015 (2013). `https://arxiv.org/abs/1306.1527`

[29] J. Solà and A. Gómez-Valent, "The ΛCDM cosmology: From inflation to dark energy through running Λ," *International Journal of Modern Physics D*, vol. 24, no. 1541003 (2015). `https://arxiv.org/abs/1501.03832`

[30] J. Solà, A. Gómez-Valent, J. de Cruz Pérez, "Hints of dynamical vacuum energy in the expanding Universe," *Astrophysics and Space Science*, vol. 361, 240 (2016). `https://arxiv.org/abs/1606.00450`

[31] A. Gómez-Valent and J. Solà Peracaula, "Running Vacuum Model and its Asymptotic Concordance with ΛCDM," *The European Physical Journal C*, vol. 81, no. 5 (2021). https://arxiv.org/abs/2006.04273

[32] M. J. Luo, "Ricci Flow Approach to The Cosmological Constant Problem," arXiv:1907.05217 [physics.gen-ph] (2019). https://arxiv.org/abs/1907.05217

[33] E. Santos, "The cosmological constant problem or how the quantum vacuum drives the slow accelerating expansion of the Universe," arXiv:1805.03018 [physics.gen-ph] (2018). https://arxiv.org/abs/1805.03018

[34] S. J. Wang, "Vacuum Quantum Fluctuation Energy in Expanding Universe and Dark Energy," arXiv:1301.1291 [physics.gen-ph] (2013). https://arxiv.org/abs/1301.1291

[35] Linder, E. V. (2005). Cosmic growth history and expansion history. *Physical Review D*, **72**(4), 043529. https://doi.org/10.1103/PhysRevD.72.043529

[36] OpenAI. (2024). *ChatGPT (Mar 2024 version)*. https://chat.openai.com

[37] Tyson, N. D. (Host). (2009–present). *StarTalk* [Podcast series]. Curved Light Productions. https://www.startalkradio.net

Appendix A: Original and Modified Friedmann Equations

Standard:

$$H^2(z) = H_0^2 \left[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda\right]$$

Modified (QFED):

$$H^2(z) = H_0^2 \left[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \mu(1+z)^3 \ln(1+z)\right]$$

Appendix B: Key Definitions

Quantum Fluctuation Structures (QFS): Temporarily existing energy densities that arise from the uncertainty principle in quantum field theory, manifesting as particle-antiparticle pairs or local distortions in the vacuum.

Quantum Fluctuation Energy Density ($\rho_{qf}(z)$): A time-evolving vacuum energy component hypothesized to result from a net imbalance in the creation and annihilation of quantum fluctuations over cosmic time.

Equation-of-State Parameter (w): The ratio of pressure to energy density, $w = p/\rho$, used to characterize the behavior of different components of the universe. For the cosmological constant, $w = -1$.

Hubble Parameter ($H(z)$): The expansion rate of the universe as a function of redshift z. It governs the rate at which comoving distances between galaxies change over time.

Distance Modulus ($\mu(z)$): A logarithmic measure of the luminosity distance used in observational cosmology, defined as $\mu(z) = 5\log_{10}(D_L/10\,\mathrm{pc})$.

Angular Diameter Distance ($D_A(z)$): A cosmological distance measure that relates an object's physical size to its observed angular size.

Baryon Acoustic Oscillations (BAO): Periodic fluctuations in the density of visible baryonic matter resulting from sound waves in the early universe, used as a standard ruler in cosmology.

Cosmic Microwave Background (CMB): Thermal radiation left over from the recombination epoch, providing a snapshot of the universe at $z \sim 1100$.

Markov Chain Monte Carlo (MCMC): A numerical sampling technique used to estimate the posterior distributions of model parameters, often applied in cosmological model fitting.

ΛCDM: The standard cosmological model that includes a cosmological constant (Λ), cold dark matter (CDM), and general relativity to describe the universe's expansion history.

Dark Energy: A hypothetical form of energy causing the accelerated expansion of the universe. In ΛCDM, it is represented by a constant vacuum energy; in alternative models, it may evolve with time.

Appendix C: Model Parameters

- μ — Quantum fluctuation growth parameter; controls amplitude of $\rho_{qf}(z)$
- δ — Power-law decay index in redshift, derived from μ
- H_0 — Hubble constant; normalization for $H(z)$
- Ω_m, Ω_r — Matter and radiation density parameters
- c — Speed of light, used in distance calculations