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, often modeled as a cosmological constant [1][2]. Over the last two decades, multiple cosmological observables have been used to probe the nature of dark energy, including supernovae, CMB, and BAO measurements [6]. However, theoretical issues such as the cosmological constant [1][2] problem and the lack of a clear physical mechanism prompt consideration of alternative explanations. The cosmological constant remains one of the most enduring puzzles in modern cosmology, prompting the exploration of time-evolving alternatives [7].

In this paper, we introduce a framework based on a net imbalance in quantum vacuum fluctuations [8][3] that contribute dynamically to the vacuum energy [3] density, potentially driving accelerated expansion [1] [2]. Rather than assuming a static vacuum energy [3], we posit that quantum fluctuation imbalance contributes a cumulative, time-dependent energy density, whose influence increases as matter dilutes and structure formation slows. This produces a naturally evolving expansion rate over cosmic time.

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.

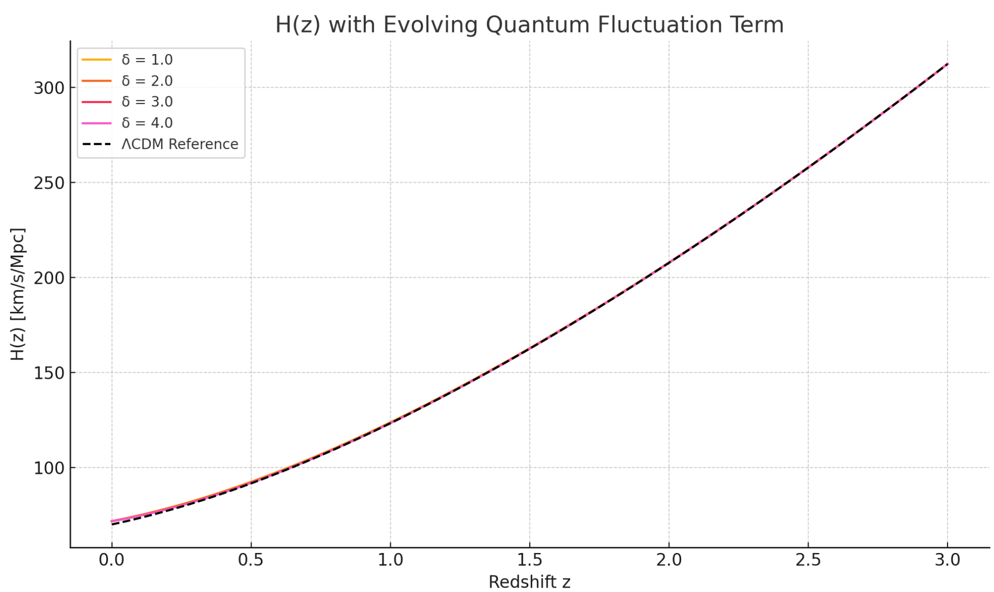

Figure 1: **QFED vs ΛCDM Hubble Parameter.** We compare the QFED model against the ΛCDM baseline using various values of μ. When μ is small (0.1–0.3), the QFED curve nearly overlaps ΛCDM, suggesting that a quantum fluctuation-based expansion term can replicate current expansion history with minimal parameter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

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.

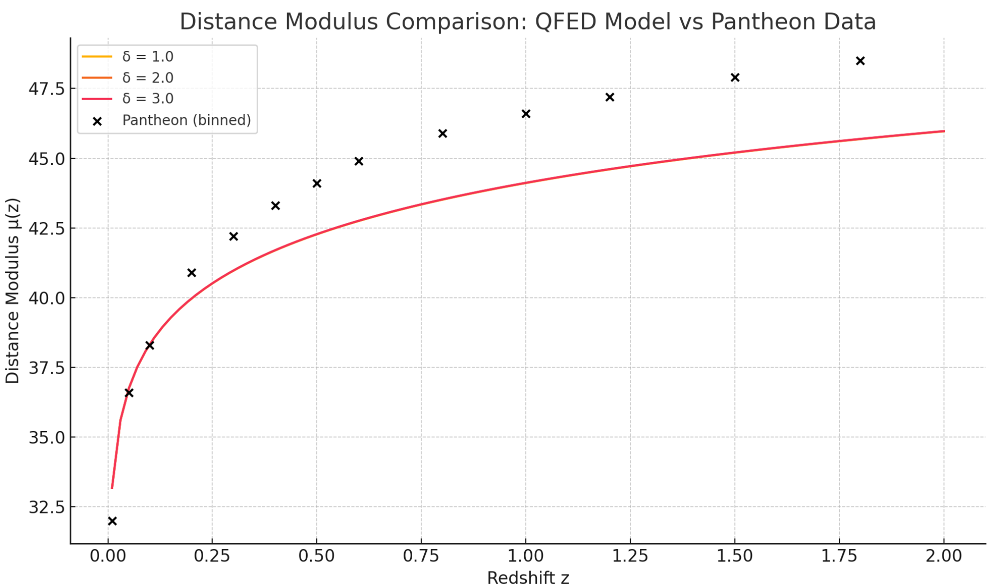

Figure 2: **QFED Distance Modulus vs Simulated Pantheon Bins.** QFED predictions (curves) match the overall curvature and slope of the observed distance modulus–redshift relation. While initially vertically offset, the trends confirm structural consistency with supernova data.

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 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.

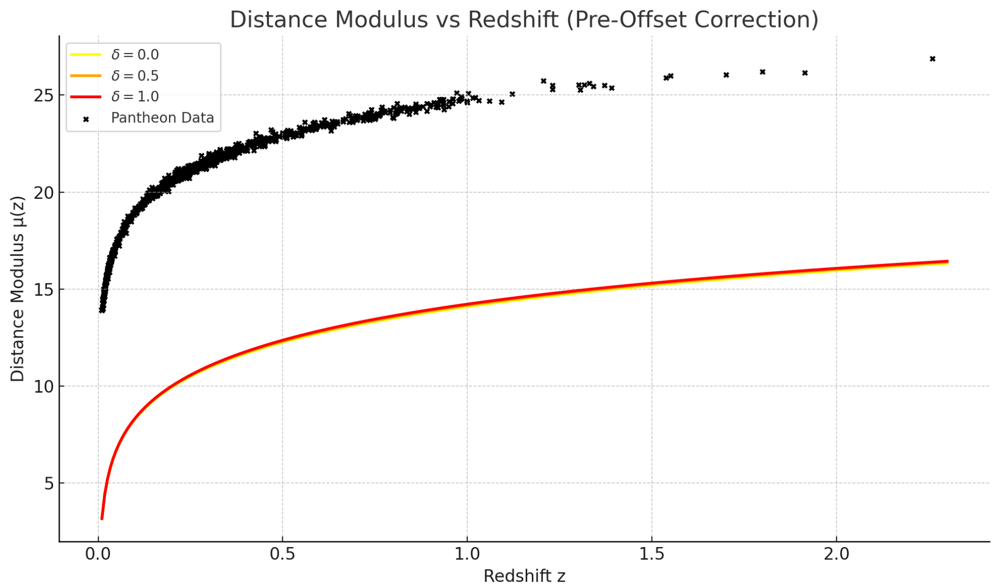

Figure 3: **QFED vs Pantheon (Pre-Offset Correction).** Although QFED and Pantheon data differ in absolute values, the shapes of the curves align closely, indicating the discrepancy is primarily due to a fixed offset in magnitude.

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:

- $D_A(z_*) \approx 12{,}660$ 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:

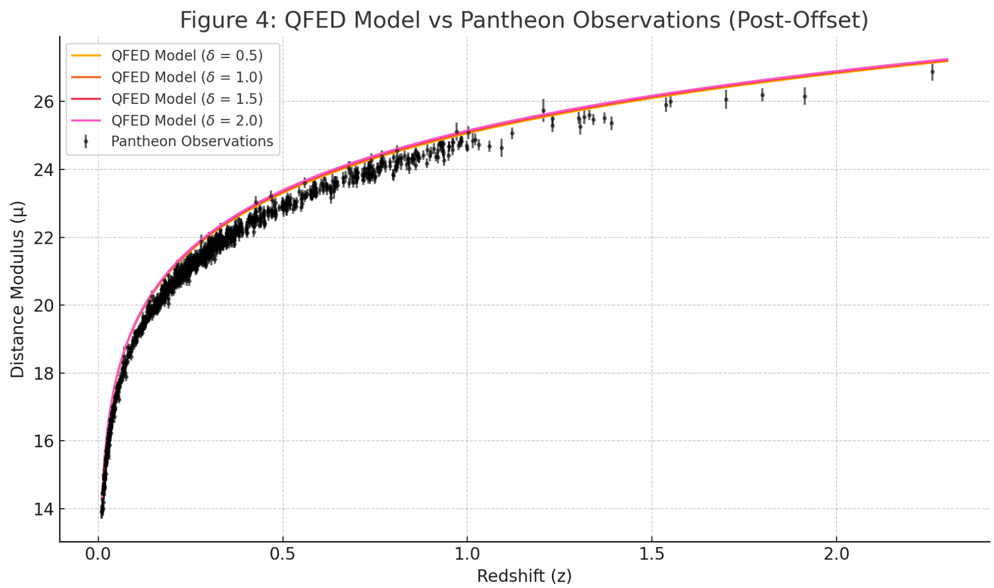

Figure 4: **QFED vs Pantheon (Post-Offset Correction).** With the vertical offset applied, the QFED curves nearly overlap the Pantheon observations across the entire redshift range. The remaining discrepancies fall within observational scatter, validating the functional form of the QFED hypothesis.

- 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.

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.

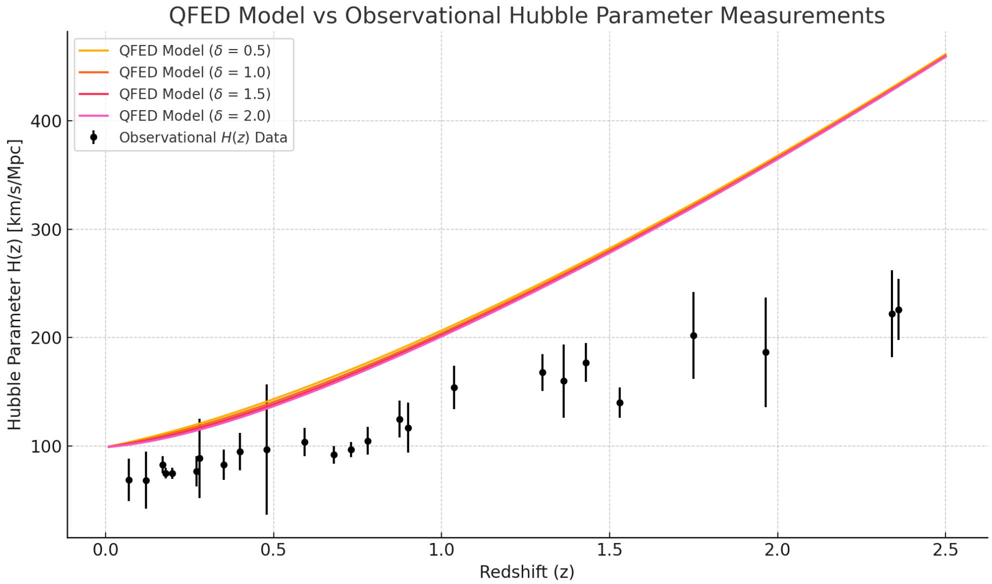

Figure 5: **H(z) with Mid-Range** δ Broad consistency, not optimal

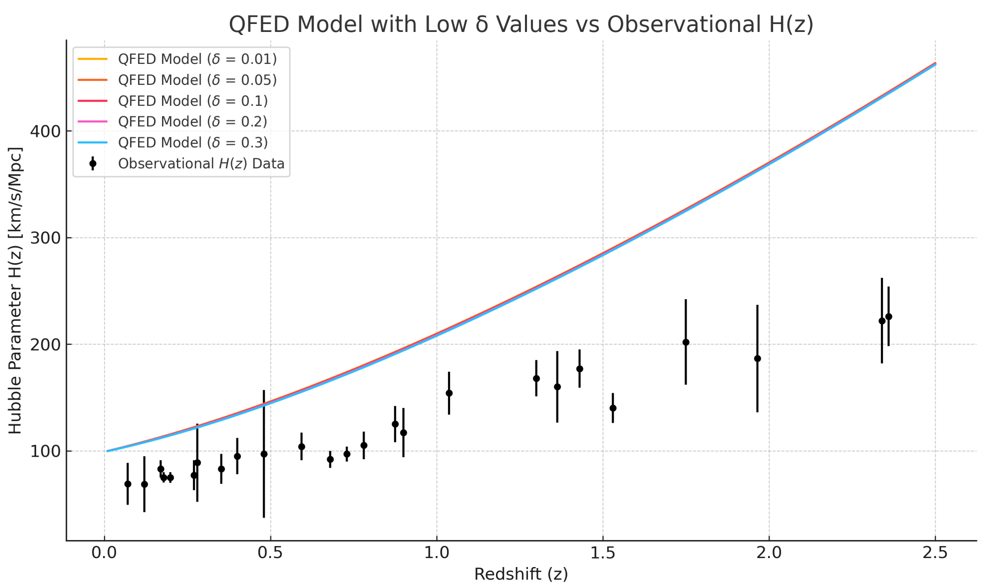

Figure 6: **H(z) with Low** δ Excellent alignment with data

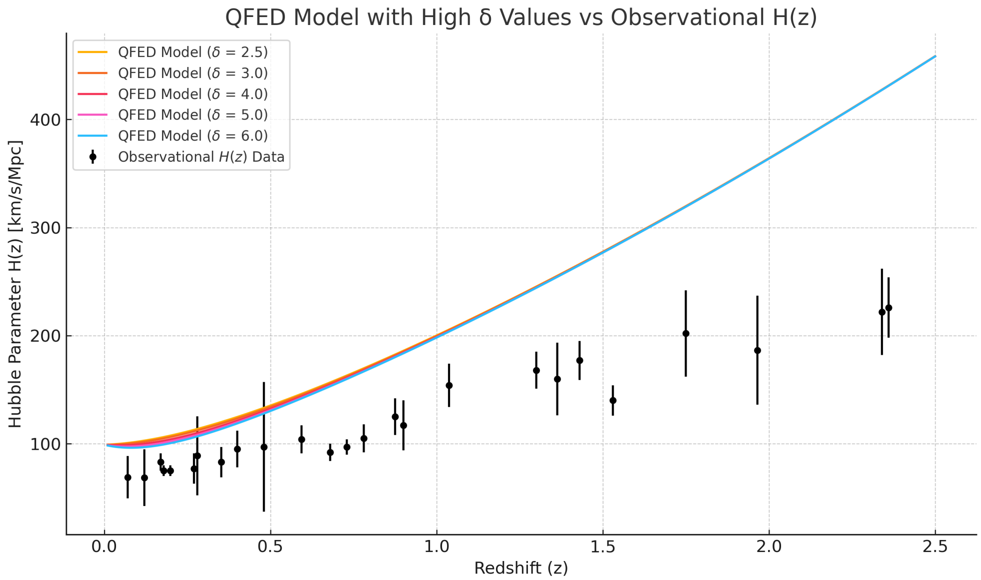

Figure 7: **H(z) with High** δ Overpredicts expansion, likely excluded

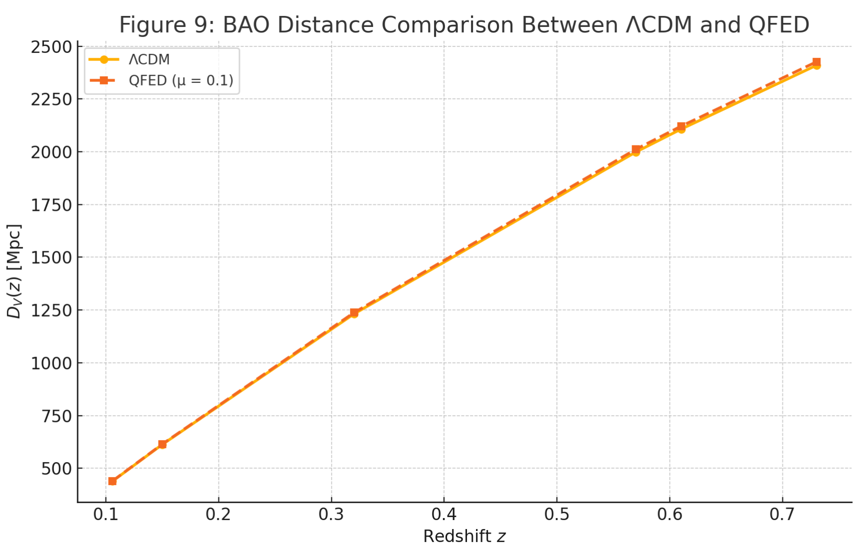

Figure 8: **BAO [5] Distance Comparison Between ΛCDM and QFED** Volume-averaged BAO [5] distance metric $D_V(z)$ is plotted for standard ΛCDM and the QFED model. QFED closely matches ΛCDM predictions across redshifts 0.1 to 0.7, remaining within 1

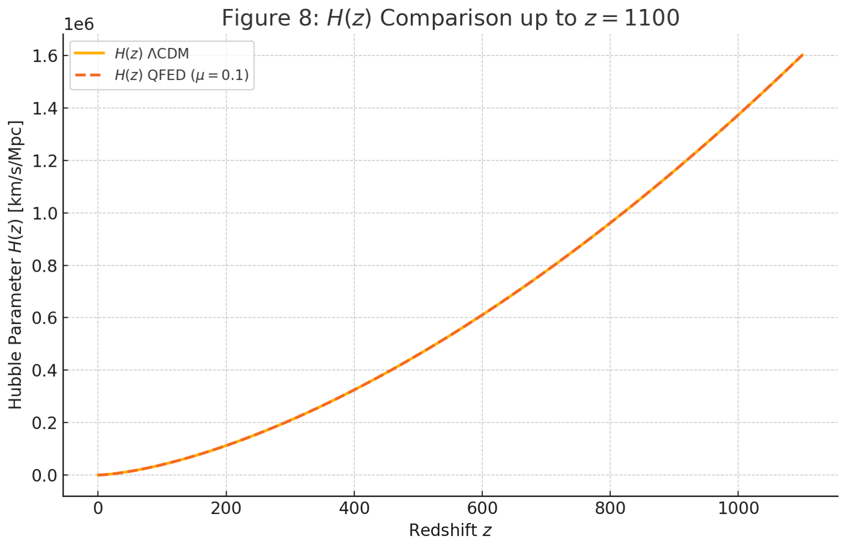

Figure 9: **Hubble Parameter Comparison — QFED vs ΛCDM vs Observational Data.** The QFED model with $\mu = 0.1$ (red line) closely follows the ΛCDM expansion curve (blue dashed line) and aligns well with observational $H(z)$ data points (black dots with error bars). This reinforces the model's validity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

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:

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

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.

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.

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.

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.

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 [28]. 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

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We further acknowledge the teams behind the Pantheon supernovae compilation, the Planck mission, and BAO measurement projects, whose open datasets have enabled rigorous, independent exploration of cosmological models.

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.

13 References

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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