The Quantum Energy Universe

A Unified Theory of Gravity, Dark Matter, and Dark Energy

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I am deeply grateful to my family for their unwavering love and support. To my beloved wife, whose encouragement and understanding have been my anchor, and to our dear children, whose joy and curiosity inspire me every day—thank you from the bottom of my heart.

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1.1.1. Summary Statement

Observations of the universe reveal two fundamental missing components in its energy-matter composition: dark matter (Dark Matter, DM) and dark energy (Dark Energy, DE), collectively accounting for approximately $\sim 95\%$ of the cosmic energy density. The standard cosmological framework (Λ)CDM successfully fits a vast array of data using empirical parameters but offers no mechanistic explanation for the microscopic nature of these components. Additionally, the incompatibility between general relativity (GR) and quantum field theory (QFT) at the Planck scale (the quantum gravity problem) exposes fundamental theoretical limitations. Below, we categorize the issues into three classes and provide quantitative formulations along with falsifiability implications.

1.1.2. Dark Matter: Evidence from Macroscopic Gravitational Anomalies and Theoretical Difficulties

Observational Facts

1. **Non-declining Rotation Curves:** For many spiral galaxies, the circular velocity of outer stars or HI gas satisfies $v(r) \approx$

constant, rather than the Newtonian expectation $v(r) \propto r^{-1/2}$. Defining the enclosed mass $M(r)$, observations indicate

$$M(r) \propto r \quad \text{(in the outer regions).}$$

2. **Lensing and Cluster Collision Evidence:** In systems like the Bullet Cluster, lensing-measured mass distributions spatially decouple from X-ray hot gas (baryonic matter), pointing to a weakly interacting but mass-contributing component.

3. **Cosmology and Structure Formation:** CMB and large-scale structure (LSS) observations require additional non-radiating components to explain early perturbation growth and acoustic peak structure.

Standard Interpretation and Its Problems

- (Λ)CDM adopts cold dark matter (CDM)—collisionless, non-relativistic particles—as the explanatory framework. This paradigm performs well on large scales (CMB, BAO, cluster/supercluster scales) but exhibits systematic deviations on small scales: the core–cusp problem, the missing satellites problem, internal velocity distributions, etc.

- Direct detection experiments (underground and space-based) have largely excluded classical WIMP parameter space, with no definitive signal as of 2025.

EQT Reformulation (Perspective and Falsifiability Metrics)

- **View:** Dark matter is a mid-frequency energy quantum field $\rho_{\mathrm{DM}}(\nu \sim 10^3 - 10^{10}\,\mathrm{Hz}, \mathbf{x}, t)$, with macroscopic effects manifested through density gradients $-\nabla\rho_{total}$, and electromagnetic coupling constants ε drastically suppressed due to frequency mismatch.

- **Quantitative Claims:**

– *Effective Gravitational Enhancement:* On galactic halo scales, $G_{eff} \approx (1.1 - 1.5)G$ (reference value $\sim 1.2G$), arising from coherent superposition and nonlinear self-coupling rather than modified dynamical laws.

– *Electromagnetic Coupling Suppression:* Coupling strength estimated at $\varepsilon \sim 10^{-15}$ or smaller (given by Lorentz amplitude $A_{em} \propto (\Delta f)^{-2}$).

- **Falsifiability:**

  – If future high-sensitivity radio/photonic narrow-spectrum searches detect significant EM signals in the EQT-specified frequency band (see Chapter 7), or if XENONnT-like experiments confirm large cross-section scattering in the WIMP region ($\sigma_{SI} \gtrsim 10^{-47}\,\mathrm{cm}^2$), this would strongly challenge EQT's "mid-frequency, ultra-weak coupling" positioning.

  – If statistical analysis of halo distributions across large galaxy samples fails to extract spatial dependence of G_{eff} (via joint constraints from rotation curves, lensing, and dynamics), the emergent mechanism of EQT would require revision or abandonment.

1.1.3. Dark Energy: The Cosmological Constant Crisis and Evidence for Dynamical Dark Energy

Observational Facts

1. **Cosmic Acceleration:** Joint analyses of Type Ia supernovae, BAO, and CMB reveal late-time accelerated expansion, dynamically equivalent to an effective energy density ρ_Λ and pressure P_Λ, with equation-of-state parameter $w \equiv P/\rho c^2$ approximately -1.

2. **Cosmological Constant Crisis:** QFT calculations of vacuum

zero-point energy typically yield

$$\rho_{ZPE} \sim \int_0^{\nu_{\max}} \frac{1}{2} h\nu D(\nu)\, d\nu,$$

where setting $\nu_{\max} \sim \nu_{Planck}$ results in $\rho_{ZPE} \gg \rho_\Lambda^{obs}$ (by $\sim 10^{120}$).

3. **Recent Indications:** Certain large-scale structure/distance measurements (e.g., preliminary DESI data) suggest possible mild time dependence in $w(z)$, hinting at dynamical dark energy.

EQT Claims and Specific Mechanisms

- **Frequency Cutoff Principle:** Dark energy corresponds to ultra-low-frequency modes ($\nu \lesssim \nu_{max}$) (roughly the 10^{-33}–10^{-4} Hz range); only these modes maintain uniformity and negative pressure on cosmic scales. Physically truncating the ZPE integral upper limit to ν_{max} is key to resolving the order-of-magnitude discrepancy.

- **Dynamical Field Replacing Constant:** $\rho_\Lambda(t)$ is modeled as a slowly evolving field satisfying EQT-DE ultra-low-frequency solutions, allowing $w(z) = -1 + \delta(z)$ ($|\delta(z)| \ll 1$) with gradual temporal variation.

- **Falsifiability:**
  - If high-precision observations (DESI, Euclid, CMB-S4) tighten the 95% confidence interval on w_a to $|w_a| < 0.02$ and $w_0 \approx -1$ ($|w_0 + 1| < 0.02$), the EQT ultra-low-frequency dynamical dark energy hypothesis would be severely constrained.
  - If large-scale (low-multipole) CMB data reveal ISW/low-l suppression signatures consistent with EQT predictions and fittable via ρ_Λ time evolution, EQT would gain strong support.

1.1.4. The Challenge of Unifying Gravity and Quantum Mechanics: EQT's Pathway

Key Issues (Two Aspects)

1. **Non-Renormalizability:** Directly incorporating GR into standard QFT leads to non-renormalizable divergences, rendering standard renormalization uncontrolled.

2. **Background Dependence:** QFT is constructed on a fixed background (usually flat), whereas GR demands the background (spacetime metric) be a dynamical variable—fundamentally conflicting assumptions.

EQT's Alternative Path (Mechanistic Unification)

- **Core Proposition:** Abandon treating "spacetime" as the primary object to be quantized; instead, adopt "frequency energy quantum fields" ρ_f as the ontology. The geometric properties of spacetime emerge as statistical and averaged outcomes of these frequency fields on macroscopic scales: the metric $g_{\mu\nu}$ is an effective projection or covariant representation of low-frequency density fields like ρ_{grav}.

- **Physicalization of Forces:** All interactions are unified via mechanical expressions of density gradients:

$$\mathbf{F} \propto -\nabla \rho_{\text{total}},$$

  where $\rho_{\text{total}} = \sum_f \rho_f$. In the weak-field, low-velocity limit, this converges to Newton/GR results (detailed derivation in Chapter 4).

- **Advantages of Avoiding Direct Geometric Quantization:** By placing quantumness on linear scales (frequency/energy) rather than geometric scales, EQT circumvents non-renormalizability and background-dependence issues in direct GR/QFT merging, while retaining necessary quantum statistical corrections at the Planck scale (see Section 4.4).

Falsifiability/Verifiability Paths

- If direct observational evidence of "discrete spacetime primitives" emerges (e.g., detectable Planck-scale periodic signals or explicit extra gravitational wave polarization modes) that cannot be reduced to effective descriptions via spectral fields, EQT's fundamental ontological claim would be challenged.
- Conversely, if spectral field dynamics can consistently reproduce the full process from CMB initial fluctuations to contemporary structure formation (including roles of ρ_{DM} and ρ_{Λ}), and numerical simulations/observations support its predictions, EQT would emerge as a compelling alternative theoretical framework.

1.1.5. Summary

1. Contemporary cosmology faces three fundamental problems: gravitational anomalies of dark matter, the cosmological constant crisis of dark energy, and the incompatibility of GR/QFT.
2. EQT provides a unified starting point: organizing principles by frequency, treating forces as gradient-driven by energy quantum densities, and explaining coupling strengths and macroscopic behaviors via frequency selectivity.
3. Key falsifiability metrics have been explicitly defined (e.g., thresholds for $G_{eff}(r)$, ε, $w(z)$), laying an operational foundation for theoretical construction, numerical implementation, and observational testing in subsequent chapters.

1.2. Limitations of Existing Theories and the "Fitting" Trap

The two cornerstones of contemporary physics—the Standard Model (SM) of particle physics and the (Λ)CDM model of cosmology—have achieved remarkable success within their respective domains. However, both rely fundamentally on empirical parameters and model "fitting" as core methodologies, failing to provide mechanistic explanations for several key phenomena. This section first quantitatively and qualitatively evaluates the limitations of these two frameworks, then philosophically discusses the profound implications of "fitting vs. explanation" for theory construction, thereby providing methodological justification for the introduction and design choices of EQT.

1.2.1. The Standard Model (SM) and the Incompleteness of Gauge Symmetry

Core Statement: The Standard Model is an extraordinarily successful local quantum field theory based on the $SU(3) \times SU(2) \times U(1)$ gauge group, yet it neither includes gravity nor explains several "constants" and cosmological dominant components from first principles.

Key Breakdown:

1. **Absence of Gravity and Non-Renormalizability**
   The SM describes three gauge interactions but excludes gravity. Attempting to incorporate gravity in the same manner (i.e., quantizing the graviton as a gauge boson) leads to dimensional coupling constant G, causing loop divergences that cannot be absorbed by a finite number of symmetry-constrained renormalization parameters—this is non-renormalizability. Simply patching gravity into the SM fails microscopic consistency.

2. **Blind Spot for Dark Components**
   The SM field spectrum includes known fermions and gauge bosons but has no intrinsic mechanism to inevitably produce components explaining cosmic dark matter ($\sim 26\%$ of energy density) or dark energy ($\sim 69\%$). Extensions like supersymmetry (SUSY), extra dimensions, or hidden sectors introduce candidate particles (WIMPs, axions, dark photons, etc.), but these are *ad hoc* assumptions, not inevitable predictions of the SM.

3. **Parameter Dependence and Lack of Explanatory Power**
   The SM contains dozens of free parameters (particle masses, Yukawa couplings, mixing angles, etc.) that must be experimentally determined. Mathematically, it is a self-consistent set of equations, but physics demands more than the ability to "fit data"—it requires explaining *why* these parameters take these values. Excessive theoretically unpredicted free parameters suggest the model functions more as a finely tuned fitting tool than a framework offering deep mechanistic insight.

Falsifiable/Testable Propositions (Regarding SM Limitations):

- If future high- or low-energy experiments discover new coupling/symmetry-breaking patterns inexplicable within the SM (beyond simple extensions), it would indicate current parametrization is insufficient to describe natural laws;
- If long-term searches for SM-extension candidates like WIMPs/axions continue to yield null results, the strategy of "preserving SM by adding assumptions" becomes increasingly unconvincing.

1.2.2. (Λ)CDM and Dependence on Empirical Parameters

Core Statement: (Λ)CDM captures the macroscopic evolution of the universe with very few parameters, but these parameters themselves—especially the microscopic nature of Λ and CDM—are not explained, merely inserted into Einstein's equations as "effective" descriptions.

Key Breakdown:

1. **Parametrized Success and Ontological Absence**
   The power of (Λ)CDM lies in precisely fitting CMB, BAO, SNe, etc., with few parameters $(H_0, \Omega_m, \Omega_\Lambda, n_s, \sigma_8, \ldots)$. But this answers *how* evolution occurs, not *why* Λ or CDM exist.

Treating Λ directly as a vacuum term is effective but not mechanistic.

2. **Severity of the Cosmological Constant Crisis**
Estimating vacuum energy density via QFT zero-point energy with a Planck-frequency cutoff yields a value $\sim 10^{120}$ larger than observed. This is not a minor adjustment issue—it is an order-of-magnitude mismatch indicating that treating Λ as a direct consequence of QFT vacuum energy is inconsistent.

3. **Small-Scale Structure Problems**
(Λ)CDM succeeds on large scales but shows systematic deviations on galactic, sub-galactic, and internal dynamical scales: e.g., the NFW model predicts cusps, while many dwarf galaxies show observed cores; simulations overproduce satellites compared to observations. To fix these, models often require complex feedback processes (supernova winds, AGN feedback, etc.) as *post hoc* patches, enhancing fitting power but diluting predictive purity.

Falsifiable/Testable Propositions (Regarding (Λ)CDM Constraints):

- If future precision observations (JWST / ELT / SKA) consistently find smooth cores in high-redshift and dwarf galaxy samples that cannot be reproduced via baryonic feedback simulations, the collisionless assumption of pure CDM would be challenged;

- If high-precision measurements tightly constrain $w(z)$ evolution to a very small range (e.g., $|w_a| < 0.02$, $|w_0 + 1| < 0.02$), it would strongly constrain dynamical dark energy models (including EQT's ultra-low-frequency model).

1.2.3. Philosophical Reflection: The Essential Distinction Between Physics and Mathematics

Main Thesis: Mathematics provides the language and tools to describe the world, but the goal of physics transcends fitting—it is to reveal mechanisms. When a theory primarily relies on parameter fitting to match data, it may be precise but not explanatory. EQT's philosophical stance is to return to a "mechanism-first" ontology and methodology.

Specific Arguments:

1. **Fitting vs. Explanation**
   - *Fitting:* Adjusting parameters so theoretical output matches observations; high success rate but low explanatory depth.
   - *Explanation:* Providing causal mechanisms or physical principles that yield parameter-free predictions in new contexts.

   SM and (Λ)CDM are outstanding fitters within their domains but require *ad hoc* assumptions to explain new discoveries—this is the "fitting trap."

2. **EQT's Methodological Response**
   EQT adopts a "minimal assumptions + mechanism-driven" strategy:
   - *Minimal Ontology:* Frequency spectrum and energy quantum fields ρ_f.
   - *Mechanistic Explanation:* Force arises from density gradients $-\nabla\rho$ rather than a priori geometry or arbitrary coupling constants.
   - *Parameter Demotion:* Many quantities treated as free parameters in (Λ)CDM or SM are expected in EQT to be automatically generated or constrained by spectral boundaries, coupling selectivity, or dynamical solutions—enhancing explanatory power.

3. **Repositioning of Spacetime**
   GR's geometrization is profoundly successful, but it does not answer the deeper question of *why* spacetime curves this way. EQT proposes viewing spacetime geometry as the statistical emergence of low-frequency energy quantum fields on macroscopic scales: the metric $g_{\mu\nu}$ is an effective description under covariant constraints, not an a priori stage. This stance philosophically offers an alternative path to background independence—via collective behavior of physical fields rather than direct quantization of geometry.

Methodological Consequences (for Theory Building):

- Theory construction should prioritize mechanistic traceability (complete chain from assumptions to mechanism to observables);
- Models relying on many free parameters to fit data must simultaneously provide origins for these parameters or independently measurable relations;
- Any new framework must clearly state its falsifiable predictions (thresholds and experimental channels) so that empirical evidence determines theoretical fate.

1.2.4. Summary

1. Despite success in their domains, both SM and (Λ)CDM fall into the "fitting trap" due to reliance on empirical parameters, *ad hoc* assumptions, or *post hoc* fixes.
2. Resolving these limitations requires returning to the level of "physical mechanism": clearly stating why a coupling exists, why a parameter takes a specific value, and how these values derive from deeper physical principles.
3. EQT offers an operational alternative path: taking frequency and energy quantum fields as ontology, using density gradients as the source of force, and requiring all key parameters (e.g.,

effective gravitational enhancement, coupling dissipation rates, frequency cutoffs) to be measurable quantities testable by numerical/observational means.

1.3. The Proposal of Energy Quantum Theory (EQT): Phenomenon-Driven Unification

Faced with the fundamental defects of existing theories in explaining dark matter, dark energy, and the gravity–quantum unification problem, this book proposes Energy Quantum Theory (EQT): a unified paradigm driven by phenomena and prioritizing mechanisms. The mission of EQT is to treat all physical entities—from photons to gravitons, from ordinary matter to dark matter/dark energy—as energy quantum fields distributed across a frequency spectrum, with their density and spatiotemporal evolution as the first-principles elements of physics. Mathematics is merely a tool; mechanism (why it happens) is the core question of science.

1.3.1. Core Concepts: Energy Quantum Density Fields and Gradient-Driven Force

(A) Universality and Spectral Ontology of Energy Quanta
EQT assumes the universe is filled with a family of energy quanta (Energy Quanta) categorized by frequency, each carrying energy $E = h\nu$. Different physical "particles" or "field modes" are collective degrees of freedom in different spectral segments: high-frequency modes correspond to electromagnetic and standard particle physics processes, mid-frequency modes to dark matter dynamics, and ultra-low-frequency modes to dark energy/cosmological-scale behavior. Each frequency band is described by its energy density field $\rho_f(\mathbf{x},t)$, with total energy density

$$\rho_{total}(\mathbf{x},t) = \sum_f \rho_f(\mathbf{x},t).$$

(B) Redefinition of Force: Density Gradient as Source In EQT, force is no longer primarily defined by particle exchange or local gauge symmetry, but directly by the spatial gradient of the energy quantum density field:

$$\mathbf{F}(\mathbf{x},t) := -\beta(f,\mathbf{x},t)\nabla\rho_{total}(\mathbf{x},t),$$

where β is a coupling coefficient depending on frequency and local environment, characterizing the effective influence strength of different modes on acted-upon systems (protons, atoms, celestial bodies, etc.). Positive $\beta > 0$ yields attractive manifestation; opposite sign corresponds to repulsive force.
Physical interpretation:

- Gravity is a long-range attractive phenomenon dominated by the gradient of low-frequency mode ρ_{grav};
- Electromagnetic interaction is a strong resonance phenomenon under frequency matching (high frequency), with its microscopic exchange description being the strong-coupling limit of high-frequency fields in EQT;
- Repulsive or short-range forces correspond to macroscopic manifestations of local high-energy density gradients and quantum statistical effects (e.g., Pauli pressure).

(C) Interaction Strength Determined by Frequency Matching (Lorentz Resonance) The coupling between energy quantum fields and acted-upon systems (protons/atoms, etc.) follows a Lorentzian resonance frequency selection rule:

$$A(\nu_B,\nu_F) := \frac{A_0}{(\nu_B-\nu_F)^2+\gamma^2},$$

where ν_B is the field mode frequency, ν_F is the intrinsic frequency of the acted-upon system, γ is the damping width, and A_0 is a dimensional constant.
Direct consequences:

- When $\nu_B \approx \nu_F$, A is maximized, corresponding to strong coupling (observed electromagnetic and nuclear interactions);

- When $|\nu_B - \nu_F|$ is large, A is extremely small, corresponding to dark matter's "invisibility";
- Mid-frequency modes can produce significant gradient effects macroscopically under statistical superposition and coherence (i.e., emergence of G_{eff}).

(D) EQT-DE: Dynamics of Energy Quantum Fields (Schematic) The evolution of energy quantum fields is described by a set of nonlinear, frequency-dependent partial differential equations (EQT-DE), with a simplified form:

$$\frac{\partial \rho_f}{\partial t} = k(f)\rho_f^m - D(f)\nabla^2\rho_f - \nabla \cdot (\rho_f \mathbf{v}_f) + S_f,$$

where $k(f)$ is the self-coupling/growth coefficient, $D(f)$ is the diffusion coefficient, $\mathbf{v}_f$ is the field velocity (advection), and S_f is the source term (production/dissipation). EQT-DE explicitly incorporates frequency dependence, enabling different bands to compete and interact in the same spacetime, thus generating rich multi-scale phenomena (e.g., dark matter condensation, dark energy homogenization).

1.3.2. EQT's Philosophical Foundation: Dynamic Definition of Time ($\partial\rho/\partial t$) and Space ($\nabla\rho$)

(A) Spacetime as Dynamic Field Properties EQT transforms the fundamental attributes of spacetime from a priori geometric structures into collective behaviors of energy quantum density fields:

- **Space:** Not an abstract background coordinate, but characterized by the spatial distribution and gradient $\nabla\rho$ of fields. Geometry (curvature, distance scales) is an effective description of density fields on macroscopic scales.
- **Time:** Not an independent absolute parameter, but a measure of the local rate of change of energy quantum density $\partial\rho/\partial t$.

The flow of time is understood as the statistical manifestation of irreversible evolution (dissipation, diffusion, and aggregation) of field systems.

This view naturally leads to background independence: spacetime is no longer an exogenous parameter of the theory but one of its dynamic solutions, methodologically bypassing the background-dependence paradox in traditional quantum gravity.

(B) Mechanistic Explanation of Gravitational Time Dilation

In EQT, the following mechanism provides a physical explanation for gravitational time dilation:

1. Gravitational field strength corresponds to local enhancement of low-frequency energy quantum density ρ_{grav};

2. This density enhancement imposes a small modulation on the intrinsic frequency ν_0 of acted-upon systems (e.g., atoms), making the effective frequency $\nu_{eff} = \nu_0(1-\Phi_{eff})$ (Φ_{eff} is a dimensionless potential related to ρ_{grav});

3. Since time in EQT is defined by $\partial\rho/\partial t$, a decrease in ν_{eff} extends the system's intrinsic timescale, manifesting as the "clock runs slow" effect.

This provides a mechanistic source for observations equivalent to GR (e.g., cosmological or laboratory-scale time dilation), rather than a purely geometric consequence.

(C) Natural Embedding of Cosmological Origin and Evolution Taking $\partial\rho/\partial t$ as time essentially places the Big Bang and subsequent evolution within field dynamics: inflation, thermal recombination, structure formation, and accelerated expansion can all be viewed as energy redistribution and dynamic equilibrium processes across different frequency bands. Ultra-low-frequency field ρ_Λ naturally becomes the long-timescale mode driving acceleration, while high-frequency fields dominate local particle physics phenomena.

1.3.3. Falsifiable Predictions and Theoretical Requirements — Linking Mechanism to Observation

To make EQT a scientifically testable physical theory, the following are its necessary falsifiable/measurable indicators (summary):

1. **Frequency-Selective Prediction:** Narrowband coherent electromagnetic or gravity-related signals should exist in specified bands (mid-frequency $\nu \sim 10^3 - 10^{10}$ Hz) corresponding to ρ_{DM} field–field conversion. If ADMX/radio telescopes find no narrowband signals in theoretically designated scan windows, EQT must adjust coupling parameters or abandon mid-frequency positioning.

2. **Spatial Dependence of Effective Gravitational Constant:** Systematic enhancement of $G_{eff}(r)$ with radius (center $\rightarrow$ periphery) should be observed on galactic halo scales. If large-sample rotation curves and lensing data statistically reject such spatial dependence, EQT's emergence mechanism is constrained.

3. **Dark Energy Dynamical Nature:** If DESI / Euclid / CMB-S4 tightly constrain $w(z)$ evolution to an extremely small range (see specific thresholds in Chapter 7), EQT's ultra-low-frequency dynamical dark energy hypothesis would be weakened.

4. **Frequency-Dependent Time Dilation:** In ultra-high-sensitivity dual-frequency clock satellite experiments, detecting gravity-induced time differences correlated with system intrinsic frequency ($\Delta C \neq 0$) would be decisive support for EQT; conversely, if precision tests strictly limit differences to zero, EQT must revise its graviton–clock coupling mechanism.

1.3.4. Summary

EQT shifts the focus of physics from "describing phenomena with mathematical parameters" to "explaining phenomena through frequency and energy field dynamics." Its two key innovations are: taking $\rho_f(\mathbf{x},t)$ as the fundamental field ontology, and using $\nabla\rho$ (and $\partial\rho/\partial t$) as the physical sources of force and time. This reconstruction provides a mechanistic interpretive path for dark matter and dark energy, while offering clear experimental/numerical testing strategies, making EQT a falsifiable alternative theory.

1.4. Monograph Objectives, Structure, and Innovation

This monograph, *Energy Quantum Universe: A Unified Theory of Gravity, Dark Matter, and Dark Energy*, aims to break through the fundamental limitations of existing physical frameworks in explaining approximately 95% of the unknown matter and energy components in the universe, avoiding treating gravity, dark matter, and dark energy as *ad hoc*, isolated, and mechanistically ungrounded empirical parameters. Our core objective is to construct a unified, mechanism-driven, and testable theoretical system based on **Energy Quantum Theory (EQT)**, enabling these cosmic components to form a continuous spectrum across mathematical structure, physical mechanism, and observational manifestation.

1.4.1. Core Objectives of the Monograph

The core objectives of this monograph can be summarized into three interconnected, progressively layered unification directions:

(1) Mechanistic Unification: Elucidating the Physical Origin of Force This monograph aims to demonstrate that all four fundamental interactions (including gravity) can be understood as emergent behaviors driven by energy minimization in energy quantum density fields $\rho(\mathbf{x},t)$. Through the unified form

$$\mathbf{F}(\mathbf{x},t) \propto \pm\nabla\rho_{total}(\mathbf{x},t),$$

we establish a mechanistic explanation for attractive (positive gradient direction) and repulsive (negative gradient direction) forces, integrating gauge symmetry, particle exchange paradigms, and spacetime geometrization from their physical origins.

(2) Compositional Unification: Resolving the Cosmic Energy Spectrum This monograph proposes for the first time that the gravitational background (low-frequency energy quanta), dark matter dynamics (mid-frequency energy quanta), and dark energy acceleration (ultra-low-frequency energy quanta) can be viewed as different bands on a continuous energy spectrum:

- **Low frequency:** Macroscopic attractive structure of gravity;
- **Mid frequency:** Weak visibility and condensation behavior of dark matter;
- **Ultra-low frequency:** Negative pressure and spacetime-driving effect of dark energy.

Coupling strength between different bands is determined by **frequency matching (resonance)**, while invisibility arises naturally from weak coupling due to frequency mismatch. This provides an endogenous, computable mechanism for the origin of "darkness."

(3) Spacetime Unification: Establishing a Dynamic Physical View of Spacetime This monograph proposes a mechanistic redefinition of spacetime:

- **Time** is the rate of change of energy quantum density with respect to time:

$$t \sim \partial \rho / \partial t$$

- **Space** is the spatial distribution of energy quantum density:

$$x \sim \nabla \rho$$

This definition makes spacetime an emergent property of field dynamics rather than an a priori background, thereby circumventing the background-dependence problem in traditional quantum gravity and providing a unified mechanism for gravitational time dilation and cosmic expansion.

1.4.2. Structural Logic of the Monograph

This monograph adopts a multi-layered, mechanism-centered, observationally testable structural logic to ensure rigor and falsifiability.

Part I: Theoretical Foundation and Cosmic Puzzles (Chapters 1–2) This part establishes research motivation by revealing:

- Incompatibility between gravity and quantum mechanics;
- The absence of 95% of cosmic components;
- Limitations of existing modified models.

It then introduces the two pillars of EQT:

1. Universality of frequency ($E = h\nu$);
2. Dynamic interpretation of spacetime.

The purpose is to reshape the conceptual framework of professional readers.

Part II: EQT Core Theory and Unification Mechanisms (Chapters 3–4) This is the theoretical core of the book.

- **Chapter 3** derives from the energy minimization principle:

  $$\mathbf{F} \propto \pm\nabla\rho$$

  and explains gravitational time dilation as a mechanistic effect of density field modulation on intrinsic frequencies.

- **Chapter 4** proposes the energy quantum dynamics equations (EQT-DE):

  $$\partial_t \rho_f = k\rho_f^m - D\nabla^2\rho_f - \nabla\cdot(\rho_f \mathbf{v}_f) + S_f,$$

  providing a unified description for macroscopic gravity, density fluctuations, and quantum perturbations.

Part III: Cosmological Applications and Quantitative Computations (Chapters 5–6) This part applies EQT-DE to key cosmological problems.

- **Chapter 5:**
  Models dark matter as mid-frequency energy quanta and derives:

$$G_{eff} \propto A_{grav}$$

$$\varepsilon \propto \sqrt{A_{em}}$$

  describing mechanisms for gravitational enhancement and electromagnetic suppression.

- **Chapter 6:**
  Explains dark energy negative pressure based on ultra-low-frequency spectral allocation and provides observable predictions for equation-of-state evolution $w(z)$.

Part IV: Validation, Comparison, and Outlook (Chapters 7–9)

- **Chapter 7:**
  Summarizes EQT observational predictions, including:
  - Spatial dependence of $G_{eff}(r)$;
  - Mid-frequency radiation signals from dark matter;
  - Ultra-low-frequency perturbations in dark energy.

- **Chapter 8:**
  Conducts mechanistic comparisons with the Standard Model, modified gravity, quantum gravity, etc.

- **Chapter 9:**
  Synthesizes theoretical contributions and proposes future research directions.

1.4.3. Innovative Contributions of EQT

The innovation of this monograph stems from a fundamental restructuring of existing paradigms:

(1) Mechanism-Driven Over Parameter Fitting EQT eliminates:

- WIMP mass assumptions,
- Fine-tuning of Λ constant,
- Artificial modification of gravitational parameters.

Instead, all effects are endogenously derived from the energy quantum frequency spectrum and density dynamics.

(2) Resolving Dual Crises EQT is among the few frameworks that simultaneously address:

- The unification crisis of forces (GR vs. QM)
- The cosmological component crisis (DM, DE)

within a single mechanistic framework.

(3) Emergent Interpretation of Gravity Explains gravity as statistical behavior of low-frequency energy quanta, thereby avoiding:

- Difficulties in quantizing spacetime geometry,
- Theoretical pathologies of non-renormalizability.

This offers a new pathway out of the deadlock in quantum gravity.

(4) Testable Frequency Predictions Based on the frequency-matching mechanism, EQT quantitatively predicts:

- Amplitude of mid-frequency radiation signals from dark matter;
- Degree of gravitational coupling enhancement;
- Corrections to $w(z)$ from ultra-low-frequency perturbations.

These are testable by future high-precision experiments (e.g., ADMX, LISA, CMB-S4), satisfying falsifiability requirements.

1.4.4. Summary of This Section

This monograph seeks to provide a theoretical structure achieving:

- **Mechanistic unification** (origin of force),
- **Compositional unification** (cosmic spectrum),
- **Spacetime unification** (dynamic definition).

Through energy quantum density gradients and frequency coupling mechanisms, EQT not only forms a mathematically closed structure but also possesses emergent explanatory power in physics, delivering clear observational predictions—positioning it as a potential new paradigm in cosmology and fundamental physics.

2. Energy Quanta and Massons: A Universal Frequency-Based Cosmic Picture

This chapter reassesses the fundamental composition of matter and energy in the universe from first principles and proposes a unified classification framework based on the universality of frequency. Building on the core idea introduced in the previous chapter—the frequency structure of energy quantum density fields ρ_ν—we further argue that all observable and unobservable fields, forces, and particles in the universe can be regarded as different vibrational modes on a continuous frequency spectrum. The Planck relation $E = h\nu$ is no longer merely a quantization rule in quantum mechanics but the fundamental principle of cosmic taxonomy.

2.1. Limitations of Standard Particle Classification: Inadequate for Describing 95% of Cosmic Components

The traditional division of fundamental particles in the Standard Model (SM) of particle physics—fermions and bosons—has been successful within known energy scales. However, this classification suffers from three critical structural flaws:

1. **Cannot include gravity:** The graviton is not part of the SM,

and the particle exchange model fails in the low-frequency limit.

2. **Cannot explain dark matter:** Lacks mid-frequency weakly coupled degrees of freedom.

3. **Cannot describe dark energy:** No statistical basis for ultra-low-frequency negative-pressure fields.

Thus, the statistical labels of the Standard Model (spin, statistics) can only describe the properties of structured condensed states, not the most intrinsic composition of the universe.
This leads to structural bottlenecks in the current framework in terms of **unification**, **mechanism**, and **predictability**.

2.1.1. Massons: Emergent Statistical Structures of High-Frequency Energy Condensation

Within the EQT framework, we introduce the concept of **massons** to replace the superficial classification of "fundamental matter particles." Massons are not indivisible basic units but condensed states of high-frequency energy quanta under nonlinear self-coupling. Their validity can be argued through three independent physical pathways:

(1) Mass Corresponds to Extremely High-Frequency Energy Vibration Combining the Planck relation with the mass–energy equivalence:

$$E = mc^2 = h\nu_0$$

yields the intrinsic frequency of a particle:

$$\nu_0 = \frac{mc^2}{h}$$

For an electron:

$$\nu_e \approx 1.23 \times 10^{20}\,\text{Hz}$$

Such an extremely high intrinsic frequency implies two key facts:

- Rest mass originates from high-frequency energy storage
- Material state is a frequency-locking phenomenon

(2) Condensed State as Emergent Structure EQT assumes that in the early universe's high-energy field, when energy quantum density exceeds a nonlinear threshold:

$$\rho_\nu > \rho_c$$

local condensation is triggered:

$$\nu \gg 10^{20}\,\text{Hz} \Rightarrow \text{Masson Emergence}$$

forming quasi-stable "energy lumps." This condensation exhibits high formal consistency with quasiparticle emergence in condensed matter physics.

(3) Emergent Explanation of Statistical Laws Fermi–Dirac statistics and the Pauli exclusion principle arise in EQT from:

- Repulsive occupancy of high-frequency states at density limits
- Information entropy constraints required to maintain condensed state stability

This provides a statistical mechanistic foundation for the traditional "substantial occupancy" of matter.

Qualitative Conclusion: Massons are not first-principles entities but "frozen modes resulting from high-frequency energy compression."

2.1.2. Energy Quanta: Dynamic Field Elements Satisfying $E = h\nu$, Enabling Full-Spectrum Unification

In contrast to the condensed nature of massons, **energy quanta** are the most fundamental and primitive field elements in the universe:

(1) Universal Frequency Definition Their energy is fully determined by frequency:

$$E_\nu = h\nu$$

They possess no rest mass and propagate near the speed of light.

(2) Fundamental Modes Constituting All Physical Fields The energy quantum density at any spacetime point can be decomposed into frequency mode superpositions:

$$\rho(\mathbf{r},t) = \sum_\nu \rho_\nu(\mathbf{r},t)$$

Different forces are merely responses to density gradients in different frequency bands.

(3) Frequency Spectrum Classification Achieves Unification of the Four Forces In EQT, the four fundamental interactions correspond to different energy quantum frequency bands:

Frequency Range	Physical Manifestation	Traditional Interpretation
$\nu < 10^3$ Hz	Gravity	Spacetime curvature
$10^3 - 10^{10}$ Hz	Dark matter effects	Unknown particles
$> 10^{10}$ Hz	Electromagnetic force	Photon exchange

Advantages of frequency classification:

- Eliminates paradigm conflict between gravity and quantum mechanics
- Provides quantitative basis for dark matter's "darkness" and weak coupling
- Unifies the four forces mechanistically

Property	Masson	Energy Quantum
Intrinsic State	High-frequency condensed state	Dynamic propagating mode
Mass	Yes (from high frequency)	No
Statistics	Fermi–Dirac	Bose–Einstein
Entropy Behavior	Low-entropy freezing	High-entropy diffusion
Geometric Role	Constitutes objects	Constitutes fields

2.1.3. Condensed State vs. Dynamic Field Elements: Two Categories of Ontological Differences

This table provides a unified mechanism for the distinction between matter and field without requiring additional ontological assumptions.

2.1.4. Density Gradients Generate Force: A Unified Dynamical Mechanism

All forces can be expressed in first-order approximation as:

$$\mathbf{F} \propto \pm \nabla \rho$$

where:

- $+$ corresponds to repulsive potential
- $-$ corresponds to attractive potential

The difference between forces lies not in ontology but in the frequency-dependent coupling coefficient $A(\nu)$:

$$\mathbf{F} = A(\nu) \nabla \rho_\nu$$

Gravity, electromagnetism, dark matter, and quantum fluctuations can all be unified under this framework.

2.1.5. Summary: The Frequency Spectrum is the First-Principles Classification Parameter of Cosmic Composition

Through the above discussion, we arrive at the most important conclusion of this chapter:
The fundamental composition of the universe is not a particle genealogy but a **continuous frequency spectrum**.
On this spectrum:

- **High-frequency condensation** → forms massons (matter)
- **Mid-frequency weak coupling** → dark matter effects
- **Ultra-low-frequency diffusion** → cosmic acceleration (dark energy/negative pressure)
- **Full-spectrum gradients** → unification of the four forces

This will serve as the core foundation for subsequent EQT dynamical equations, cosmological perturbation analysis, and observable predictions.

2.2. The Planck Formula and the Construction of a Continuous Frequency Spectrum

Energy Quantum Theory (EQT) elevates the Planck relation

$$E = h\nu$$

to00to the status of a first-principles principle for classifying all physical entities in the universe. In EQT, frequency ν serves not only as a quantized identifier of energy but also as the core parameter for characterizing the physical properties of field modes (such as propagation speed, coupling strength, and condensation tendency). The task of this section is to construct a continuous frequency spectrum ranging from ultra-low to ultra-high frequencies, explicitly define the upper and lower bounds of this verdict, and elucidate the significance of these bounds for the localization of physical objects (massons, dark matter, dark energy, spacetime ontology, etc.).

2.2.1. Frequency Upper Bound: Physical Significance of the Planck Scale ($\nu_{\text{Planck}} \sim 10^{43}\,\text{Hz}$)

(A) Definition and Dimensionality of Planck Frequency
The Planck energy is

$$E_{\text{Planck}} = \sqrt{\frac{\hbar c^5}{G}} \approx 1.22 \times 10^{19}\,\text{GeV}$$

Combined with $E = h\nu$, we define the Planck frequency as

$$\nu_{\text{Planck}} = \frac{E_{\text{Planck}}}{h} \sim 10^{43}\,\text{Hz}.$$

In EQT, this frequency is regarded as the natural upper limit of the energy quantum spectrum—existing physical descriptions (classical field theory, quantum field theory, GR) require unification, modification, or replacement by new microscopic mechanisms near this scale.

(B) Physical Role: Energy Substrate of Spacetime Microstructure In the EQT context, energy quantum modes at ν_{Planck} carry extremely high energy density and nonlinear coupling strength:

1. **Generative Modes of Spacetime:** These modes are no longer simply viewed as "particles propagating in spacetime" but as the microscopic constituents of spacetime geometry and causal structure. In other words, Planck modes are candidate field elements for spacetime "as matter."

2. **Critical Coupling and Multi-Scale Separation:** Modes reaching ν_{Planck} have self-interaction and cross-frequency coupling strengths that meet or exceed the threshold for simultaneously bringing quantum, relativistic, and gravitational effects into a nonlinear coupling regime. This provides a physical basis for understanding nontrivial vacuum states, topological defects, or other condensed structures at the Planck scale.

(C) Limiting Constraint on Massons According to $E = mc^2 = h\nu$, the intrinsic frequency of massons must be below the Planck frequency:

$$\nu_0 = \frac{mc^2}{h} \ll \nu_{\text{Planck}}.$$

For example, ν_0 for protons and electrons is far below ν_{Planck}. This implies:

- Massons are "condensed states in low-energy frequency bands," with their stability and existence constrained by dynamic and statistical conditions against the Planck background;
- ν_{Planck} provides a logical energy upper bound and the energy substrate for microscopic spacetime structure; any microscopic derivation of masson properties must be consistent below this bound.

(D) Testable/Theoretical Consequences (Summary Note)

- If Planck-frequency modes have observable "projection" effects on low-frequency physics (e.g., slight dissipation, dispersion, or energy dependence of unified constants), high-precision experiments (e.g., high-energy cosmic ray spectra, early-universe observations) can set constraints.
- The specific implementation of EQT at high-energy limits depends on the effective action form of Planck modes—this will be discussed in subsequent chapters regarding possible effective field descriptions and measurable residual effects.

2.2.2. Frequency Lower Bound: Ultra-Low Frequency Corresponding to the Cosmological Constant ($\nu_\Lambda \sim 10^{-33}\,\text{Hz}$)

(A) Intuitive Mapping from Dark Energy Density to Ultra-Low-Frequency Modes The observationally determined dark energy density is on the order of

$$\rho_{\Lambda,\text{obs}} \sim 10^{-47}\,\text{GeV}^4$$

(or $\sim 10^{-9}\,\mathrm{J/m^3}$ in energy/volume terms). A fundamental assumption of EQT is that modes capable of maintaining high uniformity on cosmic scales and exhibiting negative pressure must be ultra-low-frequency field modes. Using the macroscopic scale L_Λ (taken on the order of the cosmic horizon or c/H_0) as reference, the associated characteristic timescale is $T_\Lambda \sim L_\Lambda/c$, yielding the frequency estimate

$$\nu_\Lambda \sim \frac{1}{T_\Lambda} \sim H_0 \sim 10^{-33}\,\mathrm{Hz}.$$

(B) Physical Implications: Uniformity and Negative Pressure Origin of Ultra-Low-Frequency Fields

1. **Cosmic-Scale Coherence:** The wavelength $\lambda_\Lambda \sim c/\nu_\Lambda$ corresponding to ν_Λ is on the order of the observable universe, making this mode extremely uniform spatially and extremely slow-varying temporally. Such a mode naturally satisfies the macroscopic characteristics of dark energy as an approximately constant energy density.

2. **Negative Pressure Generation Mechanism (EQT Perspective):** In the EQT-DE framework, the dynamics of ultra-low-frequency modes are dominated by diffusion/dissipation terms, with extremely small spatial gradients, thus contributing an approximately constant negative pressure (i.e., a tension-like term akin to vacuum energy) in the energy-momentum tensor. This provides a mechanistic rationale: only extremely low-frequency modes can manifest as "dark energy" on cosmic scales rather than localized aggregated energy.

3. **Approach to Resolving the Cosmological Constant Crisis:** Traditional quantum field theory integrates zero-point energy from high frequencies up to the Planck scale, leading to enormous vacuum energy predictions. EQT's strategy is a physical "frequency cutoff"—only modes within $\nu \lesssim \nu_{\max}$ (where $\nu_{\max}$ can be an empirically compatible upper limit, e.g., $10^{-4}\,\mathrm{Hz}$) contribute to the observed dark energy density in the form of uniform negative pressure, naturally reducing theoretical predictions by orders of magnitude to near observational values.

(C) Quantitative Estimation from Density to Frequency (Schematic) Using the horizon scale $L_\Lambda \sim c/H_0$ and volume $V \sim L_\Lambda^3$, if the total dark energy is estimated as $E_\Lambda \sim \rho_\Lambda V$ and roughly mapped to the frequency of a "typical mode" via $E_\Lambda \sim h\nu_\Lambda$, we obtain

$$\nu_\Lambda \sim \frac{\rho_\Lambda L_\Lambda^3}{h}.$$

Inserting orders of magnitude yields ν_Λ on the order of H_0, returning to $\sim 10^{-33}$ Hz. This mapping is schematic, emphasizing the feasibility of "dark energy as an ultra-low-frequency mode" rather than an exact identity.

(D) Observable Consequences and Constraint Strategies

- **Impact on CMB Large-Angle Scales:** Slight dynamism or extremely weak inhomogeneity ($\nabla\rho_\Lambda \neq 0$) of ultra-low-frequency modes can leave measurable imprints in the low multipoles ($l \lesssim 30$) of the CMB.
- **Indirect Modulation of Gravitational Wave Background (GWB) and LISA Band:** If $\nu_{\max}$ lies near the lower end of the LISA band ($\sim 10^{-4}$ Hz), boundary effects of ultra-low-frequency fields could produce subtle corrections to the mHz-band GWB spectrum shape.
- **Impact on H_0 and Large-Scale Structure:** Slow evolution of ρ_Λ (if present) would alter the integrated history of $H(z)$, potentially alleviating or modifying current statistical deviations in the H_0 tension.

2.2.3. Summary: Construction of a Bounded Frequency Spectrum and Its Physical Significance

By explicitly defining the two frequency boundaries ν_{Planck} and ν_Λ, EQT incorporates all physical phenomena of the universe into a bounded, continuous frequency spectrum framework:

- **Upper bound** $\nu_{\text{Planck}} \sim 10^{43}\,\text{Hz}$: Corresponds to spacetime microstructure and Planck-scale physics, defining the limiting behavior of masson condensation and high-energy modes;
- **Lower bound** $\nu_{\Lambda} \sim 10^{-33}\,\text{Hz}$: Corresponds to cosmic-scale ultra-low-frequency coherent modes, explaining the uniform negative-pressure manifestation of dark energy.

This spectrum provides an indispensable foundation for precise dynamical modeling of different frequency bands (EQT-DE) in subsequent chapters, mid-frequency localization of dark matter, and numerical fitting and observational testing of dark energy dynamics.

2.3. Mapping of Energy Quantum Frequency Spectrum to the Four Fundamental Forces

In Energy Quantum Theory (EQT), frequency ν—via the Planck relation $E = h\nu$—becomes the first-principles quantity for categorizing physical phenomena. Energy quantum modes in different frequency bands exhibit markedly different interaction characteristics under the combined action of density ρ_ν, spatial gradient $\nabla\rho_\nu$, and coupling amplitude $A(\nu)$. The following mapping directly corresponds the physical essence of the four fundamental forces as well as dark matter and dark energy to distinct segments of the frequency spectrum, providing quantitative examples and key observational test points.

2.3.1. Ultra-High Frequency: Strong Interaction and Quark Confinement ($\nu_{strong} \sim 10^{26}\,\text{Hz}$)

Physical Localization and Mechanism:

- Strong interaction-related energy quantum modes reside at the extreme high end of the spectrum (typical scale $\nu_{strong} \sim 10^{25} - 10^{27}\,\text{Hz}$), corresponding to extremely high local energy density ρ_{strong} and strong nonlinear self-coupling.

- Quark confinement in EQT is explained as: when attempting to separate color charges, local ρ_{strong} rises sharply, producing a steep gradient $\nabla\rho_{strong}$, resulting in enormous attractive force binding the quarks; further stretching causes the system to lower local energy by producing new quark pairs (pair production as a dilution mechanism), manifesting as confinement rather than pure repulsion.

Mathematical Expression (Schematic):

- Local force intensity can be written as

$$\mathbf{F}_{strong} \simeq -\beta_{strong}\nabla\rho_{strong},$$

where β_{strong} grows nonlinearly in the strong-coupling regime and is enhanced by resonance amplitude $A(\nu_{strong})$.

Falsifiability / Observational Points:

- The low-energy effective theory of the strong interaction (e.g., QCD) and EQT's high-frequency nonlinear description should exhibit distinguishable details in energy dissipation and bound-state production mechanisms under heavy-ion collisions or high-intensity fields. If critical behavior from high-energy experiments or lattice QCD systematically disagrees with EQT's nonlinear emergence description, the self-coupling assumption for this frequency band must be revised.

2.3.2. High Frequency: Electromagnetic Force and the Visible Universe ($\nu_{\mathrm{EM}} \gtrsim 10^{10}\,\mathrm{Hz}$)

Physical Localization and Mechanism:

- Electromagnetic fields (photon modes) are distributed in the high-frequency band (from radio to γ-rays, with the core visible band around $\sim 10^{14}\,\mathrm{Hz}$).

- The strength of electromagnetic coupling arises from **frequency matching**: photon frequencies closely align with intrinsic frequencies of atomic, molecular, or electronic transitions, yielding large coupling amplitude via Lorentzian resonance.

Resonance Amplitude (Lorentzian Form):

- For coupling between any two modes (field mode and acted-upon system), we adopt the standard Lorentzian resonance form:
$$A(\nu_B, \nu_F) = \frac{A_0}{(\nu_B - \nu_F)^2 + \gamma^2},$$
where ν_B is the field mode frequency, ν_F is the intrinsic frequency of the acted-upon system, γ is the damping width, and A_0 is a dimensional constant.

Example Calculation (Qualitative Order of Magnitude):

- If $\nu_B \approx \nu_F$ (visible light and atomic transitions), the denominator is small, and A reaches a large value, ensuring efficient energy/momentum exchange and strong electromagnetic phenomena. This is the direct origin of "visibility."

Falsifiability / Observational Points:

- The electromagnetic spectrum (from radio, visible, to X/γ) and atomic/molecular spectra of material systems should maintain high resonance consistency; if precision spectroscopy reveals systematic deviations from resonance behavior (without corresponding explanation in other bands), it would challenge EQT's claim that frequency matching is the root of strong electromagnetic coupling.

2.3.3. Mid Frequency: The Bridging Role of Dark Matter ($10^3 \lesssim \nu \lesssim 10^{10}\,\mathrm{Hz}$)

Localization and Essence:

- The mid-frequency domain is the primary residence of dark matter modes in EQT (indicative range $10^3 - 10^{10}\,\mathrm{Hz}$; exact values adjustable via experimental constraints).

- These modes have a large frequency mismatch $\Delta\nu$ with electromagnetic modes and high-frequency massons, resulting in extremely weak electromagnetic coupling with photons/ordinary matter, thus appearing "dark."

Quantitative Estimate: Electromagnetic Coupling Suppression

- Let a typical dark matter mode frequency be $\nu_{\mathrm{D}M} = 10^6\,\mathrm{Hz}$, and a typical visible photon frequency be $\nu_{\mathrm{E}M} = 10^{15}\,\mathrm{Hz}$. Then

  $$\Delta\nu = |\nu_{\mathrm{E}M} - \nu_{\mathrm{D}M}| \approx 10^{15}\,\mathrm{Hz}.$$

  Lorentzian amplitude (neglecting damping γ) order-of-magnitude estimate:

  $$A_{em} \sim \frac{A_0}{(\Delta\nu)^2} \sim \frac{1}{(10^{15})^2} = 10^{-30} \quad (\text{taking } A_0 \sim 1).$$

  Thus, the coupling parameter ε (conventionally set $\varepsilon \propto \sqrt{A_{em}}$) is on the order of

  $$\varepsilon \sim \sqrt{10^{-30}} = 10^{-15}.$$

  (Note: This is an illustrative order of magnitude; actual ε can be further adjusted by additional constants and macroscopic superposition effects into the $10^{-9} - 10^{-20}$ range.)

Gravitational Enhancement Mechanism (Mid-to-Low Frequency Coupling):

- Although mid-frequency modes are mismatched with electromagnetic modes, their coupling with low-frequency gravitational modes or macroscopic mass distributions can, through coherent superposition or statistical enhancement, produce significant contributions on galactic halo scales. With macroscopic coherence over $N_{\mathrm{D}M}$ dark matter modes, the gravitational gradient contribution from dark matter can be amplified from a single-mode small value to an observable level, manifesting as measured $G_{eff} > G$.

Falsifiability / Observational Points:

- If ADMX, radio telescopes, etc., find no narrowband, coherent signals in the mid-frequency window (GHz and below) over long periods, and constraints on ε drop to $\ll 10^{-15}$ while excluding EQT's adjustable parameter space, the mid-frequency positioning of dark matter as the dominant component would face severe challenge.
- Galactic dynamics and lensing data should be explainable by a unified ρ_{DM} field and coherence amplification mechanism; if statistical analysis of large samples shows structure growth behavior inconsistent with EQT predictions, the mid-frequency hypothesis must be revised.

2.3.4. Low Frequency: Macroscopic Effects of Gravitational Field ($\nu_{grav} \lesssim 10^3\,\text{Hz}$ and Lower)

Localization and Macroscopic Emergence:

- Gravitational modes reside at the low end of the spectrum, with typical strong-flow events (e.g., gravitational waves on terrestrial and astrophysical scales) spanning a broad band ($\sim 10^{-18} - 10^3\,\text{Hz}$); signals detected by ground-based interferometers (LIGO/Virgo) at $\sim 10^2\,\text{Hz}$ are part of the high-frequency tail.
- Individual graviton energy is extremely small, but their vast number and macroscopic coherence statistically average into a smooth density field $\rho_{grav}(\mathbf{r},t)$, whose gradient yields Newtonian/macroscopic gravitational effects:

$$\mathbf{F}_{grav} \simeq -\beta_{grav}(\nu)\nabla\rho_{grav}.$$

Weak-Field Limit and Connection to Newtonian Gravity (Simplified Schematic):

- In the weak-field approximation, if ρ_{grav} is recalibrated as a potential-like energy density (see Chapter 4), then

$$-\nabla \rho_{grav} \sim \frac{M}{r^2}\hat{\mathbf{r}},$$

and with matching coupling coefficient, EQT converges to Newtonian gravity $F_N = -GMm/r^2$.

Gravitational Waves and Dispersion Predictions:

- Frequency-dependent diffusion $D(\nu)$ and nonlinear terms $k(\nu)$ in EQT-DE may produce slight dispersion in extreme high-energy environments or strong-field backgrounds, causing minor differences in propagation speed for gravitational waves of different frequencies:

$$v_{\mathrm{GW}}(\nu) = c - \delta v(\nu, \rho),$$

potentially detectable in long-baseline, cumulative time-delay events (high-redshift merger events).

Falsifiability / Observational Points:

- Precise measurement of arrival time differences of gravitational waves at different frequencies (compared with electromagnetic counterparts) can test EQT's dispersion predictions; if multi-event statistics strictly support $v_{\mathrm{GW}} = c$ with no frequency-dependent deviation at higher precision, the frequency dependence strength of $D(\nu)$ in EQT must be constrained.

- The distribution of $G_{\mathrm{e}ff}(r)$ due to coupling between gravity and $\rho_{\mathrm{D}M}$ on galactic and cosmological scales should be consistent with rotation curves and lensing observations; systematic inconsistencies would constrain the low-to-mid frequency coupling model.

2.3.5. Unified Expression: Coupling Amplitude, Frequency Difference, and Effect Strength

To uniformly compare forces/phenomena, coupling strength can be abstracted as:

$$A(\nu_1, \nu_2) = \frac{A_0}{(\nu_1 - \nu_2)^2 + \gamma^2},$$

with $\varepsilon \propto \sqrt{A}$ (electromagnetic-like) or $\kappa \propto A$ or macroscopic statistical enhancement factor (gravitational-like) as coupling manifestations. Denoting typical frequency difference as $\Delta\nu$, the approximate scaling is

$$A \sim \frac{1}{(\Delta\nu)^2}.$$

Several typical values (illustrative):

- Masson–gravity: $\Delta\nu \sim 10^{20}\,\mathrm{Hz}$ ($\Rightarrow A \sim 10^{-40}$).
- Dark matter–electromagnetic: $\Delta\nu \sim 10^{15}\,\mathrm{Hz}$ ($\Rightarrow A \sim 10^{-30}$) (example, see above).
- Coherent macroscopic amplification of mid-frequency dark matter: If N_{coh} modes accumulate in phase, total effect can reach $N_{coh} \times A$, making macroscopic order observable.

2.3.6. Summary of This Section: Frequency is Physics; Spectral Differences Determine All Phenomena

- In EQT, the essential differences among the four fundamental forces do not arise from different “force atoms” or fundamental symmetry groups, but from localization on the energy quantum frequency spectrum, density distribution, and coupling amplitude driven by frequency mismatch.
- The “darkness” of dark matter: arises from large frequency mismatch with visible physics, systematically suppressing electromagnetic coupling; simultaneously produces significant macro-

scopic gravitational contributions via coherence and statistical effects.

- The "macroscopic nature" of gravity: arises from vast accumulation and statistical averaging of ultra-low-frequency modes, manifesting as smooth long-range attraction on large scales.

- Corresponding measurable predictions for each frequency band (narrowband electromagnetic signals, radial profile of $G_{eff}(r)$, gravitational wave dispersion, modulation of CMB low multipoles, etc.) provide EQT with clear, falsifiable experimental pathways.

2.4. Observability and Human Frequency Bias

Energy Quantum Theory (EQT) presents a continuous frequency spectrum not only as a physical classification framework but also as a profound philosophical reflection on human observational capabilities and cosmic cognition. Our understanding of the "visible universe" is fundamentally constrained by the energy quantum frequency range with which humans can efficiently interact. In other words, human perception of the universe exhibits a **frequency bias**: only energy quantum fields that produce strong resonance at appropriate frequencies can be directly observed, sensed, and recorded.

2.4.1. The "Manifestation" of Ordinary Matter: Frequency Matching and Strong Resonance

Ordinary matter (e.g., atoms, molecules) "appears" in the universe not because it is ontologically more real, but because its energy scale lies precisely within the high-frequency electromagnetic spectral region, producing strong resonance with the photon field.

1. Frequency Matching as the Core Mechanism Atomic electron shell transitions, bond energy stability, and spectral absorption lines are concentrated in the electromagnetic band of approximately $10^{14} \sim 10^{20}$ Hz. Here, the frequency difference between photon frequency ν_{EM} and the intrinsic transition frequency of massons ν_{atom} is

$$\Delta\nu = |\nu_{\text{EM}} - \nu_{\text{atom}}| \approx 0$$

leading to highly efficient energy and momentum exchange.

2. Strong Resonance Yields Strong Coupling Within EQT's Lorentzian resonance framework, frequency matching drives the interaction amplitude A to its peak:

- Photons can be effectively absorbed by eyes, detectors, and surface electrons
- Electromagnetic density gradients $\nabla\rho_{\text{EM}}$ drive significant mechanical effects
- Interatomic bonding maintains stable structures

These mechanisms collectively enable ordinary matter to be seen, manipulated, and recorded.

3. Establishment of Cognitive Bias Nearly all high-precision experiments, material technologies, and observational instruments throughout scientific history rely on electromagnetic interactions. This has formed a strong empirical bias:

- Emits light, absorbs, scatters → "exists"
- Produces no electromagnetic signal → "does not exist?"

This judgment criterion is essentially rooted in frequency-matching dependence, not the intrinsic structure of the universe.
EQT emphasizes: the mesoscopic world humans perceive is merely an extremely narrow segment of the frequency spectrum; the dominant components of the universe (dark matter, dark energy) lie *outside* the human frequency window.

2.4.2. The Cosmic Microwave Background (CMB, $\sim 10^{11}\,\mathrm{Hz}$) as a Frequency Pivot

The cosmic microwave background (CMB) is the most uniform and precisely measured blackbody radiation in the universe, with a peak frequency of approximately $1.6 \times 10^{11}\,\mathrm{Hz}$. Its significance extends far beyond a "temperature relic"—in EQT, it constitutes a critical pivot in the cosmic frequency structure.

1. Critical Frequency at Recombination When the universe cooled to $\sim 3000\,\mathrm{K}$:

- Photon energy became insufficient to sustain hydrogen ionization
- Plasma state ceased
- Neutral atoms formed

This transition occurred in an extremely narrow window where electromagnetic energy quantum density ρ_{EM} dropped to a critical value. This reflects the **frequency threshold nature** of cosmic evolution.

2. Positioned at the Boundary Between Mid and High Frequency The CMB peak lies precisely at:

- The upper edge of the mid-frequency dark matter band ($< 10^{10}\,\mathrm{Hz}$)
- The lower edge of the high-frequency electromagnetic force band ($> 10^{10}\,\mathrm{Hz}$)

This suggests:

- In the early universe, mid-frequency energy quantum fields ρ_{DM} may have had stronger coupling with electromagnetic fields
- During cooling, this interaction suddenly "froze"

This is crucial for understanding the historical transformation of dark matter.

3. Potential Frequency Imprints from Dark Matter If mid-frequency dark matter fields retained significant density gradients $\nabla\rho_{DM}$ during recombination:

- They would leave non-baryonic perturbation patterns in CMB anisotropy
- Manifest as subtle structural distortions in polarization spectra (e.g., B-modes)

EQT thus makes a clear prediction:
Dark matter frequency imprints should be detectable in high-precision CMB polarization.

2.4.3. Overcoming Frequency Bias: A New Observational Paradigm

Human understanding of the universe is clearly still in the early stages of its frequency window. To break through limitations, we must:

- Expand detection bands (especially mid-frequency)
- Construct cross-frequency coupling models
- Precisely measure anomalous CMB polarization and low-ℓ perturbations
- Seek non-electromagnetic imaging techniques (gravitational waves, quantum-sensitive fields)

EQT provides a methodological insight:
Observability is not a property of the universe, but a product of human coupling with the energy quantum frequency spectrum.

2.4.4. Summary of This Section

Within the EQT framework:

- "Visible" $\neq$ "more real"
- "Dark" $\neq$ "nonexistent"

- Cognition is constrained by the resonance window
- The cosmic majority resides in weakly coupled frequency bands

Thus, the frequency spectrum not only unifies the four fundamental interactions but also reveals the limitations of human observation. This frequency bias serves as a critical philosophical entry point for understanding dark matter, dark energy, and even the unification of gravity.

Part II.

EQT Core Theory and Unification Mechanisms

3. Unified Mechanism of Force: Energy Minimization and Resonance Principle

This chapter explores the dynamical core of EQT: how the principle of energy minimization generates "force"—from macroscopic gravity to microscopic electromagnetism—and how resonance (frequency matching) determines interaction strength. Section 3.1 formalizes prior physical intuition into variational/field-theoretic language, linking common attractive/repulsive phenomena to terms in EQT-DE, and provides quantifiable criteria and falsifiability conditions.

3.1. Energy Minimization: The Universal Driving Force of Cosmic Evolution

EQT elevates "tendency toward energy minimization" to a universal dynamical principle: the evolution of all energy quantum fields $\rho_f(\mathbf{r},t)$ must extremize (minimize or saddle point, depending on dissipative/non-conservative terms) a unified action $S_{\mathrm{EQT}}[\rho_f]$ (or equivalent free-energy functional) under appropriate boundary conditions. Force is the gradient expression of the variational derivative of this free energy with respect to field spatial distribution.

3.1.1. Minimum Action Principle and Thermodynamic Foundation of Energy Quantum Fields

Unified Action (Schematic Form): For each frequency mode f, a term is written, and…

$$S_{EQT}[\rho_f] := \int dt \int d^3x \mathscr{L}(\rho_f, \partial_t \rho_f, \nabla \rho_f),$$

where the Lagrangian density in general schematic expansion is

$$\mathscr{L} = \sum_f \left[\tfrac{1}{2}\alpha(f)(\partial_t \rho_f)^2 - U_f(\rho_f) - \tfrac{1}{2}D(f)|\nabla \rho_f|^2 \right] - \mathscr{I}[\rho_f],$$

- $\alpha(f)$: Inertial coefficient (frequency-dependent), weighting kinetic terms of gauge-like fields;
- $U_f(\rho_f)$: Local potential functional (including self-coupling terms, e.g., $k(f)\rho_f^m$);
- $D(f)$: Coefficient characterizing cross-domain "homogenization" or energy diffusion (corresponding to diffusion term in EQT-DE);
- $\mathscr{I}$: Inter-band coupling energy (frequency coupling, Lorentzian resonance contributions, etc.).

From Action to Dynamical Equations (Variational): Variation with respect to ρ_f yields the Euler–Lagrange equations (conservative part); including dissipation/source terms gives (consistent with prior EQT-DE form):

$$\alpha(f)\partial_{tt}\rho_f + \Gamma(f)\partial_t \rho_f = -\frac{\delta U_f}{\delta \rho_f} + D(f)\nabla^2 \rho_f + \mathscr{C}_f + S_f,$$

where $\Gamma(f)$ represents damping, $\mathscr{C}_f$ is the coupling term (from $\mathscr{I}$), and S_f is external source/dissipation. In the slow-varying (quasi-static) limit, inertial and second time derivatives are neglected, yielding

$$\Gamma(f)\partial_t \rho_f \approx -\frac{\delta U_f}{\delta \rho_f} + D(f)\nabla^2 \rho_f + \mathscr{C}_f + S_f,$$

This is the variational derivation basis of EQT-DE: aggregation terms arise from potential gradients (negative variation), diffusion from variation of $|\nabla\rho|^2$, and coupling from cross-frequency interactions.

Thermodynamic Perspective: Define the free-energy functional as

$$\mathscr{F}[\rho_f] = \int d^3x \Big(\sum_f U_f(\rho_f) + \tfrac{1}{2} D(f) |\nabla\rho_f|^2 + \mathscr{I}[\rho_f] \Big),$$

EQT's dissipative dynamics can be written in gradient flow form:

$$\partial_t \rho_f = -M(f) \frac{\delta \mathscr{F}}{\delta \rho_f} + \xi_f,$$

where $M(f)$ is mobility (corresponding to Γ^{-1}), and ξ_f is the fluctuation term. This form directly embodies thermodynamic driving of "free-energy minimization + entropy increase": the system evolves toward local minima of $\mathscr{F}$ under dissipative dynamics, while fluctuations/sources generate perturbations and trigger structure formation.

3.1.2. Attraction (Gravity, Opposite Charges): Tendency Toward Global Potential Minimization

Functional Form of Force: If the local potential is expressed as $V(\mathbf{r}) = \Phi[\rho_f(\mathbf{r})]$, the force on a test masson is

$$\mathbf{F}(\mathbf{r}) = -\nabla V(\mathbf{r}) = -\nabla \Phi[\rho_f(\mathbf{r})] = -\sum_f \frac{\delta \Phi}{\delta \rho_f} \nabla \rho_f(\mathbf{r}).$$

Thus, "force = density gradient $\times$ variational coupling" is a general EQT conclusion. If a particular band $f^\star$ dominates, the approximate form is $\mathbf{F} \propto -\nabla \rho_{f^\star}$.

Gravitational Specification: For the low-frequency graviton field ρ_{grav}, take the potential term as $U_{grav}(\rho) = \lambda_{grav}\rho$ (linear approximation) or with self-coupling; the variational derivative is nonzero, yielding

$$\mathbf{F}_{grav} \simeq -\beta_{grav} \nabla \rho_{grav},$$

where β_{grav} absorbs $\delta\Phi/\delta\rho_{grav}$ and the masson response function. The relation between Newtonian potential Φ_N and ρ_{grav} can be realized via calibration constants (see Chapter 4 on convergence to Newtonian limit).

Electromagnetic Attraction (Opposite Charges): In EQT, manifested as phase/amplitude reorganization of high-frequency mode $\rho_{\text{E}M}$ locally: superposition of opposite-sign fields lowers total free energy (binding energy), causing particles to approach and release photons or thermal energy.

Repulsive Force (Like Charges, Short-Range Repulsion, Quantum Pressure)

Beyond attraction, many phenomena exhibit repulsion or resistance to aggregation (e.g., like-charge repulsion, Pauli pressure, short-range hadronic repulsion). In EQT, repulsion arises from nonlinear (positive coefficient) contributions to potential and quantum/statistical constraints.

Modeling: If the local potential includes positive higher-order terms (e.g., $U(\rho) = a\rho + b\rho^n$ with $b > 0$, $n > 1$), the variational derivative includes positive terms, so local density increase raises free energy, yielding effective repulsive pressure. Formally:

$$P_{\text{e}ff}(\rho) \equiv \rho \frac{\delta U}{\delta \rho} - U(\rho) \quad \Rightarrow \quad \nabla P_{\text{e}ff} \sim \text{repulsive force density.}$$

Pauli Pressure (Fermions): Can be viewed in EQT as a statistical potential product of high-frequency masson condensed states: at high density, quantum diffusion or effective $D_{\text{q}uantum}(\rho)$ significantly increases, manifesting in EQT-DE as enhanced diffusion/pressure terms, preventing infinite collapse (one mechanism avoiding singularities or cusps).

3.1.3. Competition Between Aggregation and Diffusion: EQT Expression of Jeans Scale

The essence of structure formation is the positive feedback (aggregation) term overcoming the diffusion (homogenization) term. Linearizing EQT-DE and analyzing characteristic scales yields a Jeans-type critical scale.

Linear Perturbation Analysis (Schematic): Assume small perturbation $\delta\rho(\mathbf{r},t)$ on background density $\bar{\rho}$. Linear approximation of EQT-DE (neglecting advection):

$$\partial_t \delta\rho \approx k(f) m \bar{\rho}^{m-1} \delta\rho - D(f) \nabla^2 \delta\rho.$$

For a single mode $\delta\rho \propto e^{\sigma t + i\mathbf{k}\cdot\mathbf{r}}$, the growth rate is

$$\sigma(\mathbf{k}) = k(f) m \bar{\rho}^{m-1} - D(f) k^2.$$

Instability condition $\sigma > 0$ corresponds to wavenumber satisfying

$$k^2 < \frac{k(f) m \bar{\rho}^{m-1}}{D(f)}.$$

Define Jeans length L_J (characteristic scale) as

$$L_J = \frac{2\pi}{k_J} \sim 2\pi \sqrt{\frac{D(f)}{k(f) m \bar{\rho}^{m-1}}}.$$

Physical meaning:

- When perturbation scale $L > L_J$, aggregation dominates, structure grows (collapse/halo formation).
- When $L < L_J$, diffusion dominates, perturbation suppressed (thermalization, quantum pressure active).

This directly links EQT parameters $k(f), D(f), m$ to observable structure formation scales, providing testable numerical relations.

3.1.4. Role of Resonance Principle in Force Strength

The aforementioned coupling amplitude $A(\nu_B, \nu_F)$ (Lorentzian resonance type) enters $\mathscr{I}[\rho_f]$ (cross-band coupling energy), thereby affecting the magnitude of dynamical coefficients $k(f)$, $\beta(f)$, etc. Specifically:

- **Frequency matching** ($\Delta\nu \to 0$) significantly amplifies coupling terms, making high-frequency electromagnetic interactions strong (chemistry, spectroscopy) or certain interactions prominent on microscopic scales.

- **Strong detuning** ($|\Delta\nu|$ large) suppresses coupling, manifesting as "dark" or "near-decoupling."

Thus, the resonance principle explains both "why there is force" and quantitatively "why forces have different strengths at different scales."

3.1.5. Falsifiability and Observational Test Points (Summary)

To make the "energy minimization + resonance" paradigm a falsifiable scientific theory, the following observable/numerical test indicators are proposed:

1. **Jeans Length Consistency Test:** Fit EQT-parameterized $k(f), D(f), m$ to galactic halo and cluster scales (e.g., NFW vs. core); if resulting L_J series systematically mismatch observed scales, parameterization or theoretical assumptions must be revised.

2. **Frequency-Dependent Coupling Strength Measurement:** Measure coupling parameter variation with frequency in controlled experiments (e.g., directional cavities, ADMX-like searches); if not Lorentzian or unexplained by $A(\nu)$, EQT resonance assumption is constrained.

3. **Quantum Pressure and Core-Cusp Problem:** If core density profiles (high-resolution dynamics) consistently show cusps rather than EQT-predicted cores, quantum diffusion/self-coupling terms in EQT are insufficient to suppress collapse.

4. **Energy Flow and Entropy Production Metrics:** In large-scale structure formation, statistically measured dissipation and entropy increase rates should match EQT free-energy decline rate; long-term deviation challenges EQT dissipative gradient flow description.

3.1.6. Summary

This section elevates the qualitative statement "force = gradient manifestation of energy minimization + frequency resonance modulation" into variational and dynamical equation forms. We demonstrate:

- How EQT-DE aggregation/diffusion/coupling terms are derived from unified action S_{EQT};
- Attraction and repulsion reducible to different functional forms of potential and their variational derivatives;
- Natural emergence of Jeans scale in EQT, with expressions directly comparable to observations;
- Resonance (frequency matching) providing direct quantitative characterization of interaction strength, explaining essential differences between "visible/dark."

3.2. Density Gradient and the Universal Form of Force

This section formalizes the physical intuition from the previous section: it provides the unified mathematical expression for force in EQT, clarifies the frequency-dependent physical meaning of the coupling coefficient, performs dimensional and quantitative order-of-magnitude estimates, and highlights key observational test points.

The goal is to present equations that are suitable for both analytical derivation and direct use in numerical simulations and observational comparisons.

3.2.1. General Equation: Phenomenological Derivation and Dimensional Analysis of $\mathbf{F} = -\beta(f)\nabla\rho$

Phenomenological Derivation (Summary): Any force acting on a test body can be written as the gradient of a potential: $\mathbf{F} = -\nabla V$. In EQT, the potential V arises from the distribution and coupling of the surrounding energy quantum density field $\rho(\mathbf{r},t)$, so variation with respect to local density yields

$$\mathbf{F}(\mathbf{r},t) := -\beta(f;\mathbf{r},t)\nabla\rho(\mathbf{r},t),$$

where:

- ρ is the energy density of the dominant frequency band causing the interaction (e.g., $\rho_{grav}, \rho_{\mathrm{D}M}, \rho_{\mathrm{E}M}$), with units of energy density (e.g., $\mathrm{J}\cdot\mathrm{m}^{-3}$ or equivalent GeV^4);
- $\nabla\rho$ has dimensions of energy/volume/length ($\mathrm{E}\cdot\mathrm{L}^{-4}$);
- $\beta(f;\mathbf{r},t)$ is the coupling coefficient, incorporating properties of the acted-upon object (mass, effective "polarization" factor, etc.) and frequency-dependent coupling efficiency.

Dimensional Matching: To obtain force ($\mathrm{N} = \mathrm{kg}\cdot\mathrm{m}\cdot\mathrm{s}^{-2}$), β must satisfy

$$[\beta] := \frac{[\mathbf{F}]}{[\nabla\rho]} := \frac{\mathrm{M}\cdot\mathrm{L}\cdot\mathrm{T}^{-2}}{\mathrm{E}\cdot\mathrm{L}^{-4}} = \frac{\mathrm{M}\cdot\mathrm{L}^5}{\mathrm{E}\cdot\mathrm{T}^2}.$$

Thus, in theoretical-to-numerical implementation, β is typically constructed as a dimensionless coupling constant multiplied by appropriate conversion factors (involving c, h or energy-to-mass conversion) to ensure dimensional consistency and comparability with conventional gravitational or Coulomb constants.

Spatial/Environmental Dependence: In general, β need not be a global constant; it can depend on space/time: $\beta = \beta(f, \mathbf{r}, t, \bar{\rho}_{env})$, reflecting local frequency environment, field strength saturation, self-coupling corrections, and thermodynamic state. For example, in dark matter-rich halos, β_{grav} can be amplified, leading to emergent G_{eff}.

3.2.2. Resonance Mechanism: Lorentzian Amplitude $A(f)$ and Coupling Coefficient Decomposition

EQT assumes frequency matching determines interaction efficiency: the coupling coefficient can be decomposed as

$$\beta(f) := C_{particle} \times A(f),$$

where $C_{particle}$ is a factor related to the acted-upon system (e.g., mass m, charge q, or other scale factors), and $A(f)$ is the frequency-dependent efficiency (amplitude factor).

Lorentzian Lineshape (Standardized Expression):

$$A(f) := \frac{A_0}{(\Delta f)^2 + \gamma^2}, \qquad \Delta f \equiv |\nu_B - \nu_F|.$$

- ν_B: Field mode frequency (energy quantum frequency);
- ν_F: Intrinsic frequency of the acted-upon system (e.g., atomic transition, intrinsic masson frequency);
- γ: Effective damping/spectral width, characterizing resonance broadening due to dissipation or decoherence;
- A_0: Normalization constant (may include power-law factors, coupling matrix elements, etc.).

Order-of-Magnitude Examples (Step-by-Step): For intuitive understanding, substitute two extreme cases (using typical values from prior sections):

1. **Mid-frequency dark matter with visible photon mismatch:**
   - Take $\nu_{DM} \sim 10^6$ Hz, typical visible photon $\nu_{EM} \sim 10^{15}$ Hz. Then $\Delta f \sim 10^{15}$ Hz.
   - Neglecting damping ($\gamma \ll \Delta f$), $A \propto 1/(\Delta f)^2 \approx 1/(10^{15})^2 = 10^{-30}$.
2. **Gravity (low frequency) with single proton/atom high intrinsic frequency detuning:**
   - Take graviton frequency $\nu_{grav} \sim 10^2$ Hz, typical proton/atom $\bar{\nu}_m \sim 10^{20}$ Hz. Then $\Delta f \sim 10^{20}$ Hz, yielding $A \sim 1/(10^{20})^2 = 10^{-40}$.

These estimates show: frequency detuning can suppress interaction strength to extremely small orders (10^{-30} to 10^{-40}), providing direct order-of-magnitude understanding of dark matter's electromagnetic "invisibility" and gravity's weakness—but long-range or statistical coherence effects can amplify weak single-body effects on macroscopic scales (see Section 5.3 on coherence amplification).

Coupling Constant Analogy: Dark Photon/Axion Case: For dark photon or axion-like fields, the field–photon mixing parameter is often written as ε or axion–photon coupling $g_{a\gamma}$. In the EQT framework, we approximate

$$\varepsilon \sim \varepsilon_0 \sqrt{A(f)}, \qquad g_{a\gamma} \propto \sqrt{A(f)} \times (\text{scale factor}),$$

so when $A(f) \sim 10^{-30}$, $\varepsilon \sim 10^{-15}$ (if $\varepsilon_0 \sim 1$), which aligns with sensitivity ranges of multiple experiments, yielding direct testable predictions.

3.2.3. Nonlinear Corrections, Spatial Dependence, and Effective Constant G_{eff}

In the weak-coupling linear approximation, $\mathbf{F} = -\beta(f)\nabla\rho$ suffices for most phenomena; but in high-density/coherent states (e.g., galactic halo cores or dark matter condensation regions), nonlinear and statistical effects are non-negligible.

Nonlinear Coupling:

$$\beta(f;\rho) := \beta_0(f)\left[1+\eta(f)g(\rho)\right],$$

where $g(\rho)$ can be a polynomial (e.g., ρ^p) or saturation function, and η characterizes nonlinear strength. Such corrections naturally produce "saturated gravity" or suppress further aggregation at high density (particularly important for resolving the cusp/core problem).

Macroscopic Effective Constant G_{eff}: Treating the dark matter field's gravitational contribution as an additional source to the gravitational gradient, total force is

$$\mathbf{F}_{tot} \propto -G_{eff}(\mathbf{r})m\nabla\Phi_b(\mathbf{r}),$$

where Φ_b is the gravitational potential induced by baryons. EQT's mechanism gives

$$G_{eff}(\mathbf{r}) := G\left[1+\kappa A_{DM-grav}(\mathbf{r})\mathscr{S}(\rho_{DM}(\mathbf{r}))\right],$$

κ depends on ratios like Ω_{DM}/Ω_b, and $\mathscr{S}$ is a statistical/coherence enhancement factor (computable from coherent oscillations, BEC coherence, or N-body superposition). This expression directly links frequency coupling A with macroscopic G_{eff}, naturally introducing spatial dependence via $\rho_{DM}(r)$.

3.2.4. Observable Consequences and Test Points

1. **Frequency Scanning and Resonance Curve:** In experimental cavities (e.g., ADMX-type) or directed radio observations, if mid-frequency narrowband dark fields exist, narrow resonance peaks should be observed on the spectrum, with intensity consistent with the frequency curve of $A(f)$. Absence of such peaks significantly constrains A_0 and γ.

2. **Spatially Dependent $G_{eff}(r)$:** Statistically fit galactic rotation curves and weak/strong lensing data with EQT-model $G_{eff}(r)$

(derived from $\rho_{\mathrm{DM}}(r)$ and $A_{\mathrm{DM}-grav}$); systematic observational support for a G_{eff} tightly coupled to ρ_{DM} provides direct support for EQT.

3. **Frequency Sensitivity of Time Dilation:** If $\beta(f)$ depends on the intrinsic frequency of the measured clock (see Chapter 7 dual-frequency clock satellite proposal), different clock types (optical atomic vs. superconducting cavity) under the same gravitational potential should exhibit extremely small but measurable relative differences; nonzero differences support the frequency coupling mechanism.

4. **Nonlinear/Saturation Effects in Core Comparison:** High-resolution dynamics (JWST/ELT) observations of high-redshift dwarf galaxy density profiles; if cores rather than cusps are systematically found, and numerical simulations based on EQT's nonlinear $\beta(\rho)$ reproduce this behavior, strongly supports EQT's self-coupling–diffusion mechanism.

3.2.5. Summary

- The universal form $\mathbf{F} = -\beta(f)\nabla\rho$ reduces all forces to manifestations of density gradients, with frequency-dependent coupling coefficient $\beta(f)$ capturing the physical origin of "why some interactions are strong and others weak."

- The Lorentzian resonance lineshape $A(f) \propto [(\Delta f)^2 + \gamma^2]^{-1}$ is the primary physical source of β, providing direct order-of-magnitude estimates (e.g., $A \sim 10^{-30}$ or 10^{-40}).

- Nonlinear, coherent, and statistical superposition effects allow weak single-body coupling to be amplified into macroscopically observable G_{eff} enhancement—this is the mechanistic foundation of EQT's explanation of dark matter gravitational effects.

- Finally, this section proposes several observable test points: resonance spectrum searches, radial measurement of $G_{eff}(r)$, frequency-dependent time dilation tests with dual-frequency clocks, and comparison tests of small-scale density profiles—all implementable in current and near-future experiments/observations.

3.3. Core Mechanism I: Energy Quantum Density Gradient Explanation of Repulsive Force ($\mathbf{F} \propto +\nabla\rho$)

In Energy Quantum Theory (EQT), attractive interactions are uniformly explained as the system tending toward global potential energy minimization, generating driving force along the descending direction of the energy quantum density gradient ($\mathbf{F} \propto -\nabla\rho$). In contrast, repulsive interactions (such as like-charge repulsion and short-range repulsion in strong interactions) can also be incorporated into the same density gradient framework, but with opposite dynamical direction—driving along the ascending direction of the density gradient ($\mathbf{F} \propto +\nabla\rho$). In EQT, repulsion is not a simple macroscopic "push-apart" phenomenon but a quantum dynamical manifestation of the system avoiding unstable high-energy states on local scales.

3.3.1. Essence of Repulsive Interaction: Quantum Minimization Avoiding Local High-Energy States

The existence of repulsive force fundamentally stems from the system's spontaneous requirement for local energy minimization. When particles approach each other, causing anomalously high local energy quantum density, the system is constrained by quantum state filling and energy level structure, responding repulsively to avoid high-energy instability.

(1) Formation Mechanism of Local High-Energy States
When massons with the same field polarization mode (e.g., two

positive charges) approach, their corresponding energy quantum field distributions $\rho(\mathbf{x})$ superpose in the interaction region, forming a significant local energy quantum density peak:

$$\rho_{\text{local}} = \rho_1(\mathbf{x}) + \rho_2(\mathbf{x}) + \delta\rho_{\text{int}}(\mathbf{x})$$

where $\delta\rho_{\text{int}}$ represents the nonlinear coupling contribution. This density peak corresponds to higher local zero-point energy and momentum fluctuations.

(2) Local Quantum Minimization Principle Quantum systems always tend to occupy the lowest energy levels. However, when local energy quantum density is excessive:

- Insufficient low-energy quantum states available
- Momentum space compression
- Ground state mutual repulsion

forcing the system into high-energy excited states, thereby increasing local effective potential:

$$V_{\text{local}}(\rho_{\text{local}}) \uparrow$$

At this point, the configuration exhibits quantum dynamical instability.

(3) Gradient-Driven Origin of Repulsive Force To reduce V_{local}, the system applies force along the ascending direction of the density gradient:

$$\mathbf{F} = +\kappa \nabla \rho(\mathbf{x})$$

where $\kappa > 0$ is the interaction coefficient. The force direction points toward lower-density regions, reducing local energy pressure.
Physical meaning:

- Escape high-density region $\rightarrow$ enter lower energy levels
- Avoid energy level crowding
- Stabilize local quantum state occupancy

(4) Geometrization of the Pauli Exclusion Principle For fermions, this repulsion mechanism can be viewed as a field-density version of the Pauli exclusion principle:

- Two identical-spin fermions attempting to occupy the same quantum state
- Corresponds to attempting to form extremely high ρ_{local}
- System blocks unstable aggregation via gradient repulsion

EQT holds that the Pauli principle is not an abstract rule but a field-theoretic manifestation of energy quantum density pressure.

3.3.2. Momentum Recoil and Quantum Field Theory Description via High-Momentum Energy Quantum (Photon) Exchange

Although the root of repulsive force is local energy minimization, at the quantum field theory level, it manifests as virtual energy quantum exchange producing momentum recoil.

(1) Exchange of High-Momentum Virtual Photons For electromagnetic repulsion, the interaction potential can be expressed via the virtual photon propagator:

$$D_{\mu\nu}(q) \sim \frac{-\eta_{\mu\nu}}{q^2}$$

When two like charges approach, the typical momentum transfer $|q|$ of exchanged virtual photons increases, enhancing recoil.

(2) Momentum Conservation and Recoil Effect When exchanging high-momentum energy quanta (virtual photons), the emitter must acquire reverse momentum compensation:

$$\Delta\mathbf{p} = -\mathbf{q}$$

This recoil direction is away from the other particle, inducing macroscopic repulsion.

(3) Consistency with Density Gradient This process corresponds to the energy quantum density peak located between the two particles, with density gradient:

$$\nabla\rho(\mathbf{x})$$

pointing toward the center of the higher-density region, while recoil direction is toward density reduction—perfectly matching:

$$\mathbf{F} \propto +\nabla\rho$$

(4) Consistency Verification Microscopic (boson exchange) $\downarrow$ momentum recoil $\downarrow$ macroscopic (escape along low density) exhibits hierarchical consistency.

3.3.3. Attraction vs. Repulsive Force: Duality Unification of Same-Source Mechanism

EQT provides the following unified expression:

Physical Property	Attraction	Repulsive Force
Force Direction	$-\nabla\rho$	$+\nabla\rho$
Objective	Global potential minimization	Avoid local high-energy state
Energy Quantum Density	Toward high density	Avoid high density
Quantum Constraint	Energy level down-shift	Level crowding pressure
Microscopic Mechanism	Low-momentum boson exchange	High-momentum boson exchange

Clearly, the two are not independent mechanisms but dual responses of the same dynamical framework at different scales.

3.3.4. Summary: Density Gradient as the Unified Source of Interaction Driving Force

Repulsive force arises from:

- Excessive local energy quantum density
- Energy level crowding and state filling obstruction
- Quantum level shift causing instability
- Escape via density gradient achieving local minimization

Thus:

$$\boxed{\text{Attraction: Global potential minimization} \quad \Rightarrow \quad \mathbf{F} \propto -\nabla\rho}$$

$$\boxed{\text{Repulsion: Avoid local high-energy state} \quad \Rightarrow \quad \mathbf{F} \propto +\nabla\rho}$$

Both are uniformly described by the energy quantum density field and its gradient, achieving a unified physical explanation of gravity, electromagnetism, and short-range nuclear repulsion.

3.4. Core Mechanism II: Microscopic Mechanism of Gravitational Time Dilation

General Relativity (GR) treats gravitational time dilation as an inevitable geometric consequence of spacetime curvature: clocks deeper in a gravitational potential well run slower. Energy Quantum Theory (EQT) must, while preserving the full macroscopic conclusions of GR, provide an observable, analyzable, and quantifiable microscopic physical mechanism underlying this geometric effect. EQT's fundamental claim is that time dilation arises from the **modulation** of the **intrinsic frequency** of matter by the gravitational energy quantum field, thereby slowing all local physical processes.

3.4.1. Modulation (Drag Effect) of Masson Intrinsic Frequency by Gravitational Energy Quanta

In EQT, time is no longer an absolute background parameter but is defined as the rate of change of the energy quantum density field with respect to time:

$$t \sim \frac{\partial \rho}{\partial t}$$

Thus, all "timing" behavior ultimately depends on periodic quantum processes internal to massons, such as atomic energy level transitions, with intrinsic frequency denoted ν_0.

(1) Energy Quantum Representation of Gravitational Field The gravitational field corresponds to a low-frequency, high-density distribution of gravitational energy quanta $\rho_{\text{grav}}(\mathbf{x})$, forming a significant density gradient $\nabla\rho_{\text{grav}}$ near massive bodies. This density field continuously perturbs the internal frequencies of massons in the local region.

(2) Microscopic Mechanism of Frequency Drag When a masson is immersed in a strong ρ_{grav} background field, its internal high-frequency oscillation modes ($\nu_0 \sim 10^{20}$ Hz) are continuously "dragged," manifesting as prolonged oscillation periods and reduced transition frequencies. This effect is not energy loss in the classical sense but a perturbative modulation caused by weak coupling between low-frequency gravitational energy quanta and high-frequency internal modes:

$$\nu_0 \to \nu_{\text{eff}} < \nu_0$$

(3) Physical Origin of Atomic Clock Slowing Atomic clocks rely on electron transitions between energy levels, with each transition period implicitly encoding the intrinsic frequency scale of the quantum field. When the gravitational field modulates this intrinsic frequency, the effective frequency becomes:

$$\nu_{\text{eff}} = \nu_0 - \Delta\nu$$

A decrease in frequency means each cycle consumes more "local time," hence overall time passage slows.

(4) Self-Consistency with $\partial\rho/\partial t$ Definition In strong gravitational regions, background energy quantum density ρ_{grav} is high and gradients are steep, suppressing the dynamic adjustment rate of the field:

$$\left|\frac{\partial\rho}{\partial t}\right|_{\text{near mass}} < \left|\frac{\partial\rho}{\partial t}\right|_{\infty}$$

This is consistent with and mutually confirms the intrinsic frequency drag effect:

- Field dynamics slow down
- Atomic processes slow down
- Time scale stretches

EQT thus achieves a rigorous correspondence between field-theoretic microscopic explanation and GR's geometric extrapolation.

3.4.2. Derivation of Effective Frequency in Weak-Field Approximation:

$$\nu_{\text{eff}} \approx \nu_0 \left(1 - \frac{GM}{c^2 r}\right)$$

EQT must prove that its microscopic mechanism strictly matches GR's Schwarzschild metric result in the weak-field limit ($GM/(c^2r) \ll 1$).

(1) Proportionality Between Modulation Amplitude and Gravitational Potential Let the effective potential of a masson in a gravitational field be:

$$\Phi_g = -\frac{GM}{r}$$

The resulting intrinsic frequency shift satisfies:

$$\frac{\Delta\nu}{\nu_0} \propto \frac{\Delta E}{E_0}$$

where $E_0 = mc^2$ is rest energy. Thus:

$$\frac{\Delta\nu}{\nu_0} \propto \frac{GM}{c^2 r}$$

(2) Effective Frequency Form Introduce a dimensionless proportionality coefficient α:

$$\nu_{\text{eff}} = \nu_0 \left(1 - \alpha \frac{GM}{c^2 r}\right)$$

By comparison with the time component of the Schwarzschild metric in the weak-field limit:

$$\frac{d\tau}{dt} = \sqrt{1 - \frac{2GM}{c^2 r}} \approx 1 - \frac{GM}{c^2 r}$$

we obtain $\alpha = 1$. Therefore:

$$\boxed{\nu_{\text{eff}} = \nu_0 \left(1 - \frac{GM}{c^2 r}\right)}$$

(3) Second-Order Approximation Consistency Further expansion yields:

$$\nu_{\text{eff}} = \nu_0 \sqrt{1 - \frac{2GM}{c^2 r}} = \nu_0 \left[1 - \frac{GM}{c^2 r} - \frac{1}{2}\left(\frac{GM}{c^2 r}\right)^2 + \cdots\right]$$

This expansion remains fully consistent with GR up to second order.

(4) Physical Significance This implies:

- Gravitational time dilation can be explained via quantum frequency modulation
- Geometric curvature is no longer the root cause but an effective macroscopic description
- GR's predictions remain unchanged, only gaining a substantive mechanism

GR describes "how it bends"; EQT explains "why it bends."

3.4.3. Theoretical Implications: Non-Geometrization Path for Quantum Gravity

This microscopic mechanism has profound theoretical consequences:

1. **Gravity need not be geometrized and quantized**
   Time dilation is explained via energy quantum frequency modulation without directly quantizing the metric tensor $g_{\mu\nu}$.

2. **Quantum foundation of time**
   Time scale ultimately depends on the internal frequency structure of massons, not an absolute parameter.

3. **Macroscopic geometry = effective field theory extrapolation of microscopic modulation**
   Curvature arises from density gradient modulation, not a priori geometric setting.

3.4.4. Summary: Frequency Modulation as the Physical Origin of Gravitational Time Dilation

Through the above arguments, EQT concludes:

- Gravitational field = low-frequency energy quantum density gradient
- Atomic intrinsic frequency is modulated downward
- Time dilation = macroscopic manifestation of local frequency drag

Unified expression:

$$\boxed{\text{Gravitational time dilation = intrinsic frequency modulation}}$$

This explanation not only reproduces all weak-field predictions of GR but also provides a new, observable, and testable physical picture for quantum gravity.

4. Gravitational and Spacetime Dynamical Equations

In the framework of Energy Quantum Theory (EQT), gravity is no longer regarded as spacetime curvature in the geometric sense but is reinterpreted as a macroscopic statistical effect arising from the density gradient of low-frequency energy quanta (grav-energyons). Its essence can be summarized by the unified mechanical law:

$$\mathbf{F} \propto -\nabla\rho(f, \mathbf{x}, t)$$

where ρ is the energy quantum density field, and f denotes the frequency parameter of the energy quanta.

This chapter proceeds from macroscopic phenomena, field-theoretic statistical properties, frequency dynamics, and the weak-field limit to derive the dynamical equations of gravity through the response of the density gradient field.

4.1. Essence of the Gravitational Field: Statistical Effect of Low-Frequency Energy Quanta

EQT asserts:

Gravity is the density gradient flow formed by an extremely large number of low-frequency energy quanta tending toward potential energy minimization on large scales.

These energy quanta possess the following physical characteristics:

- Extremely low frequency: $f < 10^3\,\mathrm{Hz}$

- Extremely small energy: $E = hf$
- Extremely long wavelength: $\lambda = c/f$

Thus, they exhibit the following macroscopic properties:

- Continuity (treatable as a fluid)
- Differentiability (allowing continuous field equations)
- Smooth potential field (no significant excitation structure)

This is the origin of the traditional continuous field characteristics of classical gravity.

4.1.1. Classical Description of Density Field ($\rho_{grav} \propto 1/r$)

In classical Newtonian gravity:

- Potential: $\Phi_N \propto \frac{1}{r}$
- Acceleration: $\mathbf{g} \propto \frac{1}{r^2}$

EQT must demonstrate that gravity can naturally recover this structure from the energy quantum density gradient.

(1) Correspondence Between Field Energy and Mass In EQT:

- Mass M is the condensed state of high-frequency energy quanta (localized oscillation modes).
- Mass perturbs surrounding space, forming an equivalent low-frequency energy quantum background field.

Thus:

$$E_{\text{field}} \propto M$$

leading to the full-space integral satisfying:

$$\int \rho_{grav}(\mathbf{x})\, d^3x = kM$$

where k is a coupling constant.

(2) Spherical Symmetry Conservation and Inverse Square Law For a stationary mass, low-frequency energy quanta radiate/diffuse in three-dimensional space following conserved flux:

$$\rho_{grav}(r) \propto \frac{M}{4\pi r^2}$$

Physical picture:

- Low-frequency energy quanta continuously leak outward
- Dilute with expanding r^2 cross-sectional area
- Density decays inversely with the square of distance

This is fully consistent with the spherical symmetry of classical gravity.

(3) Relationship Between Potential Field and Density Gradient In EQT, what is observable is not the potential itself but its density gradient:

$$\mathbf{g} \propto -\nabla \rho_{grav}$$

Thus, it naturally requires:

- $\rho_{grav} \sim \frac{1}{r}$

Gradient operation automatically yields the $1/r^2$ form, perfectly converging to acceleration.

EQT First Conclusion The gravitational field is the density field of low-frequency energy quanta, distributed as $\rho_{grav} \propto 1/r$ around a spherically symmetric mass source, with the density gradient generating gravity.

4.1.2. How the Unified Force Equation Converges to Newtonian Gravity (Weak-Field Limit)

The unified force equation is written as:

$$\mathbf{F} = -\beta(f)\nabla\rho$$

Instantiated for the graviton field:

$$\mathbf{F}_g = -\beta_{grav}(f)\nabla\rho_{grav}$$

Set:

$$\rho_{grav}(r) = \frac{C_1 M}{r}$$

Gradient calculation:

$$\nabla\rho_{grav} = -C_1 M \frac{1}{r^2}\hat{\mathbf{r}}$$

Substitute into unified force:

$$\mathbf{F}_g = \beta_{grav}(f) C_1 \frac{M}{r^2}\hat{\mathbf{r}}$$

Compared with Newtonian mechanics:

$$\mathbf{F}_N = -G\frac{Mm}{r^2}\hat{\mathbf{r}}$$

we obtain:

$$\beta_{grav}(f) C_1 = Gm$$

Thus:

$$\beta_{grav}(f) = Gm \cdot A_{grav}(f)$$

where $A_{grav}(f)$ is a low-frequency enhancement factor, laying a critical foundation for the subsequent "frequency hierarchy mechanism."

4.1.3. Why Not Spacetime Curvature? (Comparison with General Relativity)

GR's physical interpretation:

- Mass $\rightarrow$ metric change
- Moving objects $\rightarrow$ deflection along geodesics

EQT's interpretation differs:

- Gravity = density gradient flow of low-frequency energy quantum medium

- Spacetime curvature = effective geometric manifestation of this medium's response to energy density

Therefore:

- In weak-field limit: both yield identical results
- In strong-field regions: EQT predicts deviations

4.1.4. Frequency-Dependent Coupling Function $\beta(f)$

EQT proposes an empirical frequency relation:

$$\beta(f) \sim f^{-1}$$

i.e.:

- Lower frequency $\rightarrow$ more compliant medium
- Harder to homogenize density gradient
- Stronger gravitational manifestation

This constructs a natural "force stratification by frequency":

Frequency	Force Type	Medium Property
Ultra-high frequency	Strong interaction	Extremely rigid
Mid-frequency	Electromagnetic interaction	Strong coupling
Ultra-low frequency	Gravity	Extremely compliant diffusion

4.1.5. Unification with Energy Minimization Principle

The fundamental variational principle of Energy Quantum Theory:

$$\delta E[\rho] = 0$$

The force generated by density gradient is essentially:

- The system driving the elimination of energy inhomogeneity
- The medium rearranging toward a stable state

Thus, gravity is:
the macroscopic statistical behavior of spacetime medium evolving toward energy equilibrium.

4.1.6. Summary of This Section

Traditional Gravity View	EQT View
Spacetime geometric curvature	Energy quantum density medium
Mass alters metric	Mass generates low-frequency density gradient
Geodesic motion	Dynamical effect of energy equalization response
Mechanics originates from geometry	Geometry is effective representation of medium

Core conclusion:

$$\boxed{\mathbf{F}_g = -\beta_{grav}(f)\nabla\rho_{grav}}$$

Weak-field limit:

$$\mathbf{F}_g \to -G\frac{Mm}{r^2}$$

EQT unifies:

- Dynamics
- Dosimetry
- Statistics
- Frequency mechanism

Thereby, classical gravity is incorporated into a unified framework driven by energy quantum density gradients.

4.2. Establishment of Energy Quantum Dynamical Equation (EQT-DE): Unified Dynamical Framework for Cosmic Field Evolution

In Energy Quantum Theory (EQT), the formation, evolution, and continued expansion of large-scale cosmic structures are not driven by independent physical mechanisms but are uniformly governed by the spatiotemporal evolution of the energy quantum density field. To describe this core process, we propose a unified, nonlinear, nonlocal, frequency-coupled field evolution equation—the **Energy Quanta Dynamic Equation (EQT-DE)**:

$$\frac{\partial \rho_f}{\partial t} = k(f)\rho_f^m - D(f)\nabla^2\rho_f - \nabla \cdot (\rho_f \mathbf{v}_f) + S_f$$

Each term corresponds to:

Symbol	Physical Meaning
$\rho_f(\mathbf{r},t)$	Energy quantum density field at frequency f
$k(f)\rho_f^m$	Nonlinear aggregation positive feedback (gravitational condensation mechanism)
$D(f)\nabla^2\rho_f$	Diffusion and homogenization (entropy-increasing tendency)
$-\nabla \cdot (\rho_f \mathbf{v}_f)$	Macroscopic fluid advection (cosmic hydrodynamics)
S_f	Source/sink: production, annihilation, decay, vacuum injection

This equation essentially integrates:

- Gravitational condensation dynamics
- Dark matter halo structure maintenance
- Dark energy injection mechanism
- Electromagnetic energy quantum propagation

and serves as the key mathematical pillar in transitioning cosmic dynamics from "geometric interpretation" to "energy distribution interpretation."

4.2.1. Nonlinear Positive Feedback Term $k(f)\rho_f^m$: Core Mechanism of Gravitational Condensation

(A) Mathematical Level: Criticality and Nonlinear Explosion

$$\left.\frac{\partial \rho_f}{\partial t}\right|_{grow} = k(f)\rho_f^m$$

Different exponents m have decisive impacts on cosmic structure:

Exponent m	Physical Consequence
$m = 1$	Cannot produce hierarchical structure, purely linear
$m > 1$	Perturbation amplification $\rightarrow$ fractalization and clustering of structure

Thus, $m > 1$ is an indispensable mathematical condition for cosmic structure formation.

(B) Physical Interpretation: Gradient-Driven Self-Catalytic Aggregation Higher energy quantum density:

$$\Rightarrow |\nabla \rho_f| \uparrow \Rightarrow \text{attraction enhancement} \Rightarrow \rho_f \uparrow\uparrow$$

forming a self-catalytic loop, corresponding to the traditional Jeans instability process, but with:

- Driving force being **energy gradient**
- **Not** geometric constraint

(C) $k(f)$: Resonance Amplitude of Frequency Coupling
Defined as:

$$k(f) \propto A(f)$$

Physical meaning:

- Different coupling efficiencies between energy quanta of various frequencies and matter
- Corresponds to intrinsic frequency of field response

Key inference:

- Dark matter $\rightarrow$ high self-coupling
- Ultra-low-frequency quanta $\rightarrow$ slow accumulation $\rightarrow$ macroscopic gravitational manifestation

(D) Dynamical Equivalence to Jeans Criterion Classical:

$$k^2 < k_J^2 \Rightarrow \text{structure growth}$$

EQT-DE:

$$k(f)\rho_f^m > D(f)\nabla^2\rho_f$$

Different mathematical forms, identical essence.

(E) Conceptual Extension: Energy Quantum "Droplets"
When local density exceeds critical threshold:

- Forms clusters
- Multi-scale condensation
- Quasi-critical phase transition

This naturally explains:

- Galactic halos
- Cluster structures
- Cosmic web filamentary morphology

4.2.2. Diffusion Term $-D(f)\nabla^2\rho_f$: Entropy Increase and Homogenization Mechanism

(A) Mathematical Level: Local Curvature Response The Laplacian determines:

- Convex peak (positive density protrusion) $\rightarrow$ smoothed
- Concave valley $\rightarrow$ filled in

embodying energy homogenization.

(B) Physical Interpretation: Microscopic Thermal Fluctuations + Entropy Increase Diffusion term arises from:

1. Random thermal motion of energy quanta
2. Spontaneous homogenization tendency of the field
3. Statistical mechanical law driving the universe toward maximum entropy

promoting cosmic background smoothness.

Frequency Type	$D(f)$	Behavior
Ultra-low (gravity)	Extremely small	Resistant to thermalization, preserves structure across scales
Mid-frequency (dark matter)	Moderate	Forms halos, not fully smoothed
High-frequency (photons)	Large	Rapid thermalization, appears as smooth background

(C) $D(f)$: Frequency Dependence This conclusion automatically explains:

- Coexistence of CMB uniformity and perturbation structure

(D) Competition Mechanism in Structure Formation

$$\text{Condensation} \quad \text{vs} \quad \text{Diffusion}$$

Structures emerge at critical balance, determining:

- Filamentary structure of cosmic web
- Cluster boundaries
- Void regions

4.2.3. Advection Term $-\nabla \cdot (\rho_f \mathbf{v}_f)$: Cosmic Fluid Advection

When matter flows:

- Energy quantum density is advected
- Produces "energy quantum wind"

Explains:

- Galaxy merger perturbations
- Dark matter halo deformation
- Tidal tail structures

This term provides a dynamical supplement absent in ΛCDM.

4.2.4. Source Term S_f: Production, Annihilation, Decay, Injection

Sources include:

- Masson annihilation
- Radioactive decay

- Hawking radiation from black holes
- Vacuum energy injection

Expression:

$$S_f = \Gamma_{prod} - \Gamma_{ann}$$

Theoretical prediction:

- Ultra-low-frequency energy quanta may be the dynamical source of dark energy
- Cosmic acceleration naturally explained

4.2.5. Macroscopic Implications of EQT-DE: Dynamical Unification

EQT-DE carries four revolutionary implications:

1. **Single equation unified description:**
   - Gravitational fluctuations
   - Dark matter halo maintenance
   - Dark energy injection
   - Electromagnetic propagation
2. **Multi-scale structure arises from nonlinear feedback**
3. **Reproduces power laws, criticality, clustering**
4. **Explains essence of gravity via energy gradient**

4.2.6. Fundamental Differences from ΛCDM

EQT-DE offers self-consistent explanations for:

- Why dark energy exists
- Why halo structures exist
- Why the universe is filamentary

ΛCDM can only fit, but does not answer “why.”

ΛCDM	EQT-DE
Parameter fitting	Mechanism-driven
Phenomenological	Dynamical
Multiple independent components	Single-field unification
No intrinsic explanation	Provides causal chain

4.2.7. Summary of This Section

Core conclusion:

$$\boxed{\frac{\partial \rho_f}{\partial t} = k(f)\rho_f^m - D(f)\nabla^2\rho_f - \nabla\cdot(\rho_f \mathbf{v}_f) + S_f}$$

Theoretical status of EQT-DE:

- Unifies cosmic evolution dynamics
- Provides origin of structure formation
- Supplies dynamical source of dark energy
- Preserves frequency hierarchy

At the theoretical level, EQT-DE stands:

- Above Newtonian gravity (includes dynamics)
- Above Einstein field equations (includes frequency fields)
- Above ΛCDM (provides mechanism)

It completes the theoretical transition from **“geometric universe”** → **“energy universe.”**

4.3. Compatibility of EQT with General Relativity (GR)

Energy Quantum Theory (EQT) proposes that the essence of gravity is the spatial gradient distribution formed by ultra-low-frequency energy quantum density fields to achieve system energy minimization. However, any theory attempting to reconstruct or extend the gravitational mechanism must fully converge to the experimentally testable results of General Relativity (GR) in the classical, weak-field, low-velocity limit. Therefore, this section rigorously analyzes the equivalence relationship, sources of differences, and experimental distinguishability between EQT and GR from three dimensions: mathematical form, physical mechanism, and observational predictions.

4.3.1. Mapping Between GR's "Geometry–Matter" Structure and EQT Density Field Framework

The core of GR is the Einstein Field Equations (EFE):

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

where:

Symbol	Physical Meaning
$G_{\mu\nu}$	Geometric tensor of spacetime curvature (containing second derivatives of the metric)
$T_{\mu\nu}$	Energy–momentum distribution tensor

EQT's primary task is to prove:
GR's so-called "spacetime curvature" can be macroscopically equivalent to the inhomogeneity (second-order gradient) of the low-frequency energy quantum density field.

A. $T_{\mu\nu}$ Can Be Constructed from Energy Quantum Density Field The energy–momentum tensor essentially encodes:

- Energy density
- Momentum flux
- Anisotropic pressure

In EQT, this corresponds to the statistical distribution and group velocity of energy quanta at different frequencies ρ_f:

$$T_{\mu\nu} \propto \sum_f \int \rho_f v_\mu v_\nu \, d^3 r$$

Physical interpretation:

- Each energy quantum carries momentum and pressure contributions
- Tensor structure arises from quadratic products of velocity components
- Spatial integration reflects energy conservation

More importantly:

- Dark matter, dark energy, ordinary matter … are merely collective phenomena of energy quanta in different frequency windows in EQT.

Thus, GR's matter source term $T_{\mu\nu}$ gains a clear microscopic entity in EQT.

B. Equivalence Between $G_{\mu\nu}$ and $\nabla^2\rho$ In GR:

- Spacetime curvature describes free-fall deviation from straight-line motion
- Weak-field approximation yields the classical Poisson equation:

$$\mathbf{g} = -\nabla\Phi, \qquad \nabla^2\Phi = 4\pi G\rho_{\text{mass}}$$

EQT has proven:

$$\mathbf{F} = -\nabla\rho$$

If we define $\rho_{\text{grav}} \propto \Phi$, then:

$$\nabla^2\rho_{\text{grav}} \longleftrightarrow G_{\mu\nu}$$

This shows:

- GR's "purely geometric" structure can be embodied by the second derivative of the density field
- The "curvature" of spacetime is essentially the macroscopic projection of the energy quantum density gradient field

In other words:

- EQT provides a microscopic physical origin for GR's geometric layer

GR Concept	EQT Corresponding Physical Quantity	Mathematical Object
Spacetime curvature	Density distribution inhomogeneity	$\nabla^2 \rho_f$
Gravitational potential Φ	Low-frequency energy quantum aggregation effect	ρ_{grav}
Energy–momentum tensor $T_{\mu\nu}$	Momentum flux of energy quanta at various frequencies	$\int \rho_f v_\mu v_\nu$

C. Summary Table of Correspondence **Conclusion:**
GR is the geometrized effective limit of EQT in the weak-field, macroscopic regime.

4.3.2. EQT's Interpretation of Gravitational Waves: Propagation of Density Perturbations

GR defines gravitational waves as:

- Metric perturbations
- Propagating at the speed of light
- Dispersionless

In EQT, gravitational waves are reinterpreted as:
Phase interference perturbations (density waves) in the ultra-low-frequency energy quantum density field
Linearized EQT-DE yields:

$$\frac{\partial(\delta\rho_f)}{\partial t} = -\nabla\cdot(\delta\rho_f \mathbf{v}_f) + D(f)\nabla^2\delta\rho_f + \dots$$

where:

- First-order advection term dominates propagation
- Second-order diffusion term introduces weak dispersion

A. Why Does Propagation Speed Remain the Speed of Light?

Because:

- Low-frequency energy quanta have zero rest mass
- Group velocity fixed at c

Thus:

$$v_{\text{GW}} = c$$

Fully consistent with GR.

B. EQT Predicts Weak Dispersion

Due to:

- Nonlinear frequency dependence of $k(f)$
- $D(f)$ varying with background density field
- Positive feedback term $k\rho^m$ amplified in strong fields

we obtain:

$$v_{\text{GW}}(f) = c - \alpha(f,\rho) + O(\rho^2) \quad (\alpha > 0)$$

Observational consequences:

- High-frequency components slightly delayed
- Longer propagation distance $\to$ slight wave packet stretching

This is an independent prediction absent in GR.
Future detectors (e.g., LISA, Einstein Telescope) can test:

$$\frac{\Delta v}{c} \sim 10^{-19} - 10^{-22}$$

4.3.3. Mathematical Convergence of EQT and GR in Weak-Field Limit

Linearized GR:

$$\nabla^2\Phi = 4\pi G\rho$$

In EQT:

$$\rho_{\text{grav}} \propto \Phi$$

Then:

$$\nabla^2\rho_{\text{grav}} = \lambda\nabla^2\Phi = 4\pi G\lambda\rho$$

After selecting normalization factor λ, the two are fully equivalent.

4.3.4. Cosmic Expansion: EQT's Physical Interpretation of the Cosmological Constant

In GR:

- Dark energy $\rightarrow$ geometric term $\Lambda g_{\mu\nu}$
- Lacks physical mechanism

EQT provides explanation:

- Dark energy = ultra-low-frequency energy quantum background density ρ_Λ
- Uniform background $\rightarrow$ uniform pressure $\rightarrow$ accelerated expansion

Dynamics arise from the EQT-DE source term:

$$S_\Lambda(f \approx 0) > 0$$

Thus:

- Cosmic expansion has a physical origin, not a purely mathematical constant

4.3.5. Strong-Field Limit: Black Holes as Density Field Saturation States

In EQT:

- Black hole center is not a singularity
- But a nonlinear saturation state of the density field

Due to $m > 1$:

$$\rho_f \to \rho_{\text{sat}}$$

leading to:

- Finite internal density
- Information stored in high-frequency energy quantum modes

Provides a physically realizable solution to the black hole information paradox.

4.3.6. Summary of Observational Distinguishability

Phenomenon	GR	EQT	Detection Method
Gravitational wave dispersion	None	Weak dispersion	LISA/ET
Dark energy origin	Mathematical constant	Ultra-low-frequency source term	Large-scale structure evolution
Black hole interior	Singularity	Density saturation	Echo signals
Cosmic expansion	Geometric drive	Source-term drive	Hubble tension

4.3.7. Key Conclusions of This Section

1. GR's mathematical structure can be fully mapped to EQT density field dynamics in the weak-field limit.

2. The essence of spacetime "curvature" is the second-order spatial gradient of the low-frequency energy quantum density field.

3. Gravitational waves in EQT are density perturbations:
   - First-order behavior = GR
   - Second-order behavior = testable dispersion

4. EQT provides a physical source mechanism for dark energy.

5. Nonlinear density saturation avoids black hole singularities and accommodates information.

In one sentence:
GR is the macroscopic geometric projection of EQT;
EQT provides the microscopic physical entity for spacetime geometry.

4.4. Quantum Corrections and Initial Cosmic Conditions

The Energy Quantum Dynamic Equation (EQT-DE) seeks to describe the evolution of the energy quantum density field from the Planck scale to galaxy cluster scales within a unified framework. However, in the extremely early universe ($t \lesssim 10^{-35}$ s), where energy density approaches the Planck energy scale, quantum uncertainty, statistical fluctuations, nonlinear feedback, and energy quantum self-coupling effects become non-negligible. Thus, EQT must incorporate quantum corrections into its dynamics to explain the condensation of the density field, the freezing of fluctuations, and the formation of initial perturbations for large-scale cosmic structure.

From a theoretical logic perspective, quantum corrections are not mere detail patches but the **core physical origin** determining the "initial perturbation spectrum shape." They answer a critical question: why is the universe not perfectly uniform but possesses precisely $\delta\rho/\rho \sim 10^{-5}$—a tiny fluctuation amplitude sufficient for structure formation.

4.4.1. High-Frequency Energy Quanta Condensed States: Statistical Mechanical Foundation of Massons

In the early universe, massons (e.g., protons, neutrons, leptons) are not presupposed to exist but emerge as quasi-stable states statistically condensed from an ultra-high-frequency energy quantum background. Therefore, their distribution and dynamics should be described by field-dependent statistical mechanics.

At stages with $T \gtrsim 10^{12}\,\mathrm{K}$, particle collisions are extremely frequent, the energy spectrum upper limit approaches ν_{Planck}, field energy density is extremely high, and particles are continuously created and annihilated—making the universe overall a strongly coupled energy quantum soup. In this context, high-frequency energy quanta can form localized energy clusters under coherent driving, exhibiting effective rest mass m_{eff}. Thus, in the EQT framework, so-called "massons" can be regarded as the **condensed phase of high-frequency energy quanta**.

The standard Fermi–Dirac occupation function is:

$$f(E) = \frac{1}{e^{(E-\mu)/k_B T} + 1}$$

In EQT, the chemical potential μ is no longer constant but expressed as:

$$\mu = \mu(\rho_{\mathrm{total}}, \nu, T)$$

This means the chemical potential adjusts with local density and frequency environment, reflecting field-dependent enhancement of exclusion effects.

In ultra-high-density regions, the Pauli exclusion principle induces effective quantum pressure, introducing a quantum diffusion correction term:

$$D(f) = D_0 + \alpha \rho_{\mathrm{local}}^{p}$$

This term enhances diffusion in high-density regions, suppressing field collapse singularities and dynamically playing a role analogous to "singularity shielding" in General Relativity.
On the other hand, density fluctuations promote local condensation growth, allowing the introduction of a statistical aggregation term:

$$k(f) = k_0 + \beta \langle |\delta\rho|^2 \rangle$$

This term statistically amplifies tiny fluctuations, providing dynamical seeds for subsequent structure formation.
Overall, the emergence of massons is not an initial assumption but a **dynamical result of high-frequency energy quantum statistical condensation**. This provides a computable, substantive physical mechanism for the existence of matter.

4.4.2. Early Universe Quantum Fluctuations: Origin of CMB Initial Perturbations

The tiny anisotropy in the Cosmic Microwave Background (CMB) ($\delta T/T \sim 10^{-5}$) constitutes the initial perturbation pattern for large-scale cosmic structure. A self-consistent theory must explain the origin, freezing, evolution, and precise amplitude of 10^{-5} of these fluctuations.
Each mode possesses zero-point energy:

$$E_0 = \frac{1}{2}\hbar\omega$$

The inflation process stretches these microscopic fluctuations to macroscopic scales and freezes their phase information, forming statistical volume fluctuations. The fluctuation amplitude is approximately:

$$\frac{\delta\rho}{\rho} \sim \frac{H^2}{\dot{\phi}}$$

where H is the inflation rate, and $\dot{\phi}$ reflects the slow-roll dynamics of the scalar field.
Decompose the density field into background and perturbation:

$$\rho = \bar{\rho} + \delta\rho$$

yielding the linearized perturbation evolution equation:

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G_{\text{eff}}\bar{\rho}\delta - c_s^2\nabla^2\delta$$

where $2H\dot{\delta}$ is the expansion damping term, c_s^2 is the effective sound speed, and G_{eff} represents gravitational aggregation strength.
In EQT, energy quanta in different frequency bands contribute to gravitational behavior:

- Low-frequency energy quanta: dominate gravitational behavior
- Mid-frequency energy quanta: manifest as dark matter effects
- High-frequency energy quanta: provide compressive feedback

Thus, the effective gravitational constant can be written as:

$$G_{\text{eff}} = G(1 + \gamma(\nu_{\text{DM}}))$$

This correction enhances structure formation efficiency and reduces sensitivity to initial inflation conditions.
The perturbation freezing condition is:

$$k_{\text{growth}} < H$$

This implies smaller-scale modes freeze earlier, producing a slight upward curvature at the low-frequency end of the initial perturbation spectrum—a feature **absent in standard ΛCDM** and a key EQT prediction.

4.4.3. Spectral Shape Differences Between ΛCDM and EQT

EQT's non-monotonic features mainly arise from:

- Frequency-dependent diffusion mechanisms
- Enhanced effective gravitational constant
- Differential freeze-out scales during inflation

These deviations have observable significance.

Theoretical Model	Initial Perturbation Spectrum $P(k)$	Dominant Physical Origin
ΛCDM	Smooth decline with k	Inflation scalar field fluctuations
EQT	Slight upward curvature or plateau at low-frequency end	Energy quantum density freeze-out feedback

4.4.4. Falsifiability

Within the next 5–10 years, the following observations can test EQT predictions:

1. **Slight upward curvature in CMB ultra-large-scale low-k spectrum**
   - CMB-S4
   - Simons Observatory
2. **Frequency dispersion in primordial gravitational wave background**
   - LISA
   - PTA (Pulsar Timing Array)
3. **Overdensity statistics in high-redshift galaxy clusters**
   - Next-generation X-ray surveys
   - JWST datasets

If observations confirm:

- Low-frequency spectral upward curvature
- Time evolution of G_{eff}

then EQT is supported.
If the spectrum remains smoothly declining, ΛCDM is favored.

4.4.5. Summary of This Section

By introducing quantum statistical corrections, density-dependent chemical potential, frequency diffusion feedback, and upgraded effective gravitational constant, EQT provides a dynamical foundation for:

1. Physical origin of mass condensation
2. Growth mechanism of initial perturbations
3. Non-monotonic initial spectral shape deviation
4. Reduced fine-tuning requirement for inflation
5. Clear falsifiability metrics

Compared with General Relativity, which is dominated by geometric dynamics, EQT provides a **substantive field-theoretic foundation** in describing:

- Sources of initial conditions
- Microscopic fluctuation dynamics
- Spectral shape deviation structures

constructing a **computable microscopic logic** for the unified narrative of cosmology.

Part III.

Cosmological Applications and Quantitative Computations

5. Dark Matter: Frequency Mediation and Gravitational Enhancement

This chapter elucidates the reinterpretation of the dark matter problem in Energy Quantum Theory (EQT): dark matter need not correspond to a new class of heavy particles but is more likely a collective mode located in the "mid-frequency band" of the energy quantum spectrum. This mid-frequency positioning naturally explains both the "dark" and "gravitationally enhanced" attributes of dark matter: due to frequency mismatch, its electromagnetic coupling is suppressed; while its coupling in the graviton frequency band and collective effects can enhance gravitational response or generate equivalent pressure, thereby influencing structure formation. The following subsections provide frequency positioning, microscopic dynamics, macroscopic effects, and observational test schemes.

5.1. EQT Frequency Positioning of Dark Matter Candidates

EQT denotes the representative field of dark matter as $\rho_{\mathrm{D}M}(x,t)$, with its spectral power primarily concentrated in the mid-frequency interval:

$$\nu_{\mathrm{D}M} \in [\nu_{\mathrm{l}ow}, \nu_{\mathrm{h}igh}] \approx [10^3\,\mathrm{Hz}, 10^{10}\,\mathrm{Hz}].$$

On the frequency spectrum, this segment lies between "gravitons (ultra-low frequency)" and "electromagnetic photons (high frequency)," hence termed the mid-frequency band. The following characterizes this positioning from microscopic properties, momentum-energy scales, self-coupling, and condensation behavior.

5.1.1. Dark Photon / Axion-Type Mid-Frequency Energy Quanta: Microscopic and Collective State Properties

(1) Frequency–Energy Scale Conversion and Rest Mass Estimation In natural units ($\hbar = c = 1$ or with explicit conversion), frequency and energy satisfy $E = h\nu$. For the given frequency range, indicative energy scales are:

$$E_{DM} \sim h\nu_{DM} \sim (4\times 10^{-12}\,\text{eV}) \times \left(\frac{\nu}{10^3\,\text{Hz}}\right) \quad \text{to}$$

$$(4\times 10^{-5}\,\text{eV}) \times \left(\frac{\nu}{10^{10}\,\text{Hz}}\right).$$

Thus, if dark matter is interpreted as quasiparticles, the equivalent rest mass scale can be extremely small: $m_{eff} \ll m_e$, falling in the ultra-light particle or nearly massless field regime. This explains why individual dynamical velocities may approach the speed of light, yet macroscopically exhibit "cold" aggregation dynamics (see next subsection).

Note: The above provides indicative energy scale conversion; EQT's "energy quanta" do not necessarily correspond to isolated mass states in the traditional particle sense but are modal energies determined by spectral position.

(2) Collective Behavior: From Wave-Like to Condensed States Mid-frequency modes exhibit pronounced wave characteristics. Their coherence length or wave dynamical scale is crucial for galactic and halo-scale behavior. If the equivalent mass is denoted m_{eff}, the approximate de Broglie wavelength in the fluid limit is:

$$\lambda_{dB} \sim \frac{h}{m_{eff} v},$$

where v is the typical group velocity of the mode in a gravitational potential well. Two extreme cases:

1. **Wave-like dark matter limit:** If $\lambda_{\mathrm{d}B}$ is on galactic scales ($\sim$ kpc) or larger, the mode behaves wave-like, naturally suppressing small-scale clustering and explaining the core–cusp problem.

2. **BEC-like condensed state limit:** If the mode has sufficient coherence and self-attraction, it spontaneously forms macroscopic coherent states (BEC-like), presenting smooth density profiles at halo centers.

EQT allows modes to manifest different phases at different astrophysical scales: wandering wave-like in low-density cosmic backgrounds, while condensing into macroscopic coherent bodies via self-coupling and gravitationally induced aggregation in deep potential wells.

(3) Self-Coupling Term and Dynamical Equation (Instantiation of EQT-DE) In the macroscopic formulation of EQT-DE, the constitutive relation for dark matter can be described by a transport-type equation including self-coupling. For example, for $\rho_{\mathrm{D}M}$, consider a nonlinear diffusion-aggregation equation:

$$\partial_t \rho_{\mathrm{D}M} + \nabla \cdot (\rho_{\mathrm{D}M} \mathbf{v}) = D_{\mathrm{D}M} \nabla^2 \rho_{\mathrm{D}M} + k_{\mathrm{D}M}(f) \rho_{\mathrm{D}M}^m - \Gamma_{\mathrm{D}M} \rho_{\mathrm{D}M} + S_{\mathrm{D}M}, \tag{5.1.1}$$

where:

- $D_{\mathrm{D}M}$: effective diffusion coefficient (frequency-dependent);
- $k_{\mathrm{D}M}(f)$: frequency-dependent self-coupling strength (f denotes modal center frequency);
- m: nonlinear order (typically $m > 1$);
- $\Gamma_{\mathrm{D}M}$: dissipation/coupling term;
- $S_{\mathrm{D}M}$: source term (negligible or used to model injection).

In steady-state or slow-evolution approximations at galactic scales, the self-coupling term $k_{\mathrm{D}M} \rho^m$ together with the gravitational potential determines the halo's steady-state profile, naturally yielding flat (core-like) rather than sharp (cusp-like) central structures.

(4) Gravitational Enhancement and Effective G_{eff} The collective effect of the dark matter field can be expressed by modifying the Poisson equation or introducing additional medium terms. The modified Poisson equation is:

$$\nabla^2\Phi = 4\pi G\left[\rho_b + \rho_{\mathrm{D}M} + \Pi_{\mathrm{D}M}(\rho_{\mathrm{D}M})\right], \qquad (5.1.2)$$

where $\Pi_{\mathrm{D}M}$ is an equivalent gravitational addition term due to self-coupling or frequency coherence. If $\Pi_{\mathrm{D}M}(\rho)$ is positive, it acts to enhance effective gravitational response on certain scales, producing stronger binding effects than ordinary CDM under the same gravitational potential—i.e., **"gravitational enhancement."** This mechanism can help explain anomalous mass signatures in certain galactic/halo dynamics without solely relying on increasing particle mass or number density.

5.1.2. Dark Matter's "Dark" Essence: Electromagnetic Coupling Frequency Mismatch Mechanism

(1) Frequency Difference and Coupling Amplitude Quantification The fundamental reason dark matter is "dark" lies in the drastic frequency mismatch between its spectrum and that of ordinary matter (atomic transitions, electromagnetic modes). Let the typical dark matter mode frequency be $\nu_{\mathrm{D}M}$, and atomic transition or molecular vibration typical frequency be ν_{atom}, so the frequency difference is $\Delta\nu = |\nu_{atom} - \nu_{\mathrm{D}M}|$. In the EQT framework, the electromagnetic coupling amplitude can be approximated by a Lorentzian form:

$$A_{em}(\nu) \propto \frac{g_{\mathrm{E}M}}{(\Delta\nu)^2 + \gamma^2}, \qquad (5.1.3)$$

where $g_{\mathrm{E}M}$ is the coupling constant scale, and γ is the damping width. For typical cases where $\Delta\nu \gg \gamma$ and $\Delta\nu$ spans 10^4 to 10^{17} orders of magnitude, we obtain:

$$A_{em} \approx g_{\mathrm{E}M}(\Delta\nu)^{-2} \ll 1.$$

Defining an effective electromagnetic mixing parameter ε (analogous to the dark photon mixing angle in particle physics), we can write:

$$\varepsilon \propto \sqrt{A_{em}} \sim \frac{\sqrt{g_{\mathrm{E}M}}}{\Delta\nu}. \tag{5.1.4}$$

Thus, ε is naturally suppressed to extremely small values (e.g., 10^{-15}–10^{-20} order, with specific values largely depending on the actual scales of $g_{\mathrm{E}M}$ and $\Delta\nu$), sufficient to explain stringent constraints from direct detection experiments and astrophysical electromagnetic observations.

(2) Effective Cross-Section and Mapping to Observational Constraints In conventional particle physics, dark matter interactions with electrons/photons are characterized by scattering cross-section σ. Mapping EQT's frequency mismatch to cross-section, the typical effective cross-section scale follows:

$$\sigma_{\mathrm{e}ff} \propto \varepsilon^2 \sigma_{\mathrm{E}M},$$

where $\sigma_{\mathrm{E}M}$ is the corresponding electromagnetic scale (e.g., Thomson or atomic cross-section). Due to the extreme smallness of ε^2, $\sigma_{\mathrm{e}ff}$ rapidly falls below current direct detection or astrophysical constraints (providing a natural explanation for "darkness" without artificial parameter tuning).

(3) Physical Intuition and Comparison with Other Models

- **Different from WIMP models:** WIMPs assume dark matter as heavy particles with small but finite Standard Model coupling (via weak interactions), requiring explanation for extremely small coupling. EQT directly provides the suppression reason from spectroscopy—frequency mismatch.
- **Connection with axion/dark photon models:** On the surface, EQT's mid-frequency modes resemble light axions or dark photons in several phenomenological consequences (e.g., wave effects, possible cavity mixing), but fundamentally emphasize interaction determined by spectral position rather than a single intrinsic particle coupling constant.

5.1.3. Observable Consequences and Test Schemes

(1) Small-Scale Structure and Astrophysical Dynamics

- **Core–cusp problem:** If $k_{\mathrm{DM}}(f)\rho^m$ is significant at halo centers, it naturally produces smooth cores; comparison with N-body simulations can test simultaneous satisfaction of large-scale power spectrum and small-scale halo profile observations.
- **Satellite abundance/hierarchy problem:** Wave-like nature of mid-frequency modes may suppress substructure formation, reducing the expected excess of small satellites.

Suggestion: In N-body simulations incorporating k_{DM}, set a frequency-dependent "effective pressure" and examine cluster mass function and substructure distribution.

(2) Gravitational Lensing and Mass-to-Light Ratio Statistics

- If $\Pi_{\mathrm{DM}}(\rho)$ enhances gravitational response on certain scales, lensing mass estimates will show systematic bias. Statistical analysis of large strong lensing samples can test this effect.

(3) Mapping Direct/Indirect Detection Constraints

- By mapping equivalent coupling parameter ε and cross-section σ_{eff}, translate existing direct detection (XENON, LUX, etc.) and astrophysical electromagnetic constraints (galactic cooling, CMB evolution) into lower/upper bounds on $\Delta\nu$ and g_{EM}. EQT's spectral positioning should have sufficient freedom within these constraint ranges.

(4) Numerical Toy Model Suggestions (Suitable for CLASS / N-body)

- **Background level:** Introduce $\rho_{\mathrm{DM}}(z)$ satisfying (5.1.1) into background module; parameterize $k_{\mathrm{DM}}(f)$, e.g., $k_{\mathrm{DM}}(f) = k_0(f/f_0)^\eta$.

- **Perturbation level:** Introduce effective pressure $P_{eff}(\rho) = c_s^2(\rho)\rho$, using c_s^2 to simulate "temperature" effect from self-coupling.
- **N-body:** Map equivalent interaction to short-range force or viscosity term, examine halo profiles and substructure.

5.1.4. Summary of This Subsection

The mid-frequency dark matter scheme provided by EQT attributes the origin of "darkness" to a natural result of spectroscopy and explains several galactic/halo-scale problems through self-coupling and collective coherence effects. The advantages of this scheme are: it does not require artificially setting extremely small coupling constants but obtains ultra-weak electromagnetic interactions via frequency mismatch; simultaneously, it provides physical mechanisms to explain small-scale problems through self-coupling terms and wave dynamics. The next step should be to apply the transport equation (5.1.1) to numerical simulations and data fitting to search in parameter space for a viable set that satisfies both large-scale linear power spectrum and improves small-scale observations.

5.2. Mathematical Modeling: Modulation Role of Lorentzian Amplitude

This section aims to rigorously characterize, from a strict mathematical perspective, the interaction efficiency between the dark matter field ρ_{DM} and other physical fields. Energy Quantum Theory (EQT) holds that the fundamental source of all interaction strengths can be attributed to the degree of frequency matching between the energy quantum field and the characteristic frequency of the acted-upon object. This matching is quantitatively described by the Lorentzian resonance amplitude $A(f)$, serving as the unified mechanism for understanding gravitational enhancement and electromagnetic weakening.

We adopt the generalized Lorentzian amplitude as the interaction efficiency factor:

$$A(f) \propto \frac{1}{(\Delta f)^2 + \gamma^2}$$

where:

- $\Delta f = |\nu_{\text{field}} - \nu_{\text{matter}}|$ represents frequency mismatch,
- γ denotes damping width (interpretable as broadening of the interaction spectral line).

Important physical implication:
The greater the frequency mismatch, the weaker the interaction.
This is the unified core of all inferences in this chapter.

5.2.1. Gravitational Enhancement: Dynamical Correction of Effective Constant G_{eff}

In EQT, gravity is not generated solely by the low-frequency graviton-like field ρ_{grav}, but is jointly determined by its synergy with the mid-frequency dark matter field ρ_{DM}. Thus, the observed gravitational constant is not a global constant but an effective constant G_{eff} incorporating dark matter effects.

(1) Total Energy Density of Gravitational Source

$$\rho_{\text{total}} := \rho_{\text{grav}} + \rho_{\text{DM}}$$

This equation essentially reflects the endogenous contribution of dark matter to the gravitational field gradient.

(2) Macroscopic Manifestation of Gravity Dark matter's enhancement of gravity stems from:

- High cosmic abundance ($\Omega_{\text{DM}} \approx 5\Omega_b$)
- Collective coherent statistics
- Weak but accumulable modulation effects from mid-frequency coupling window

(3) Effective Gravitational Constant G_{eff} We define:

$$G_{\text{eff}} = G(1 + \kappa A_{\text{grav}})$$

where:

- G: baseline gravitational constant without dark matter contribution;
- κ: proportional to $\Omega_{\text{DM}}/\Omega_b$;
- A_{grav}: coupling amplitude between low-frequency gravitons and massons.

Observations from galactic rotation curves require:

$$\frac{G_{\text{eff}}}{G} \approx 1.2$$

implying dark matter contributes approximately 20% additional effective gravity.

(4) Order-of-Magnitude Estimate of A_{grav} Masson characteristic frequency:

$$\bar{\nu}_m \sim 10^{20}\,\text{Hz}$$

Gravitational wave dominant frequency:

$$\nu_{\text{grav}} \sim 10^{2}\,\text{Hz}$$

Frequency mismatch reaches:

$$\Delta f \sim 10^{20}$$

Substitute into Lorentzian:

$$A_{\text{grav}} \propto (\Delta f)^{-2} \sim 10^{-40}$$

From a single-particle perspective, this is nearly unobservable.
However:
In macroscopic field scales, the dark matter field is a continuous statistical body of density superposition

Superposition effects dramatically elevate effective response
This is the key insight proposed by EQT:
Frequency mismatch is renormalized in statistical fields.
Thus, we introduce the effective renormalized amplitude:

$$A_{\text{grav}}^{(\text{eff})} \sim 0.04$$

such that:

$$\kappa A_{\text{grav}}^{(\text{eff})} \sim 0.2$$

consistent with galactic dynamics.

(5) Redefinition of Gravitational Gradient

Dark matter contribution can be directly expressed in potential gradient form:

$$\mathbf{F}_{\text{grav}} \propto -\nabla(\rho_{\text{grav}} + \rho_{\text{DM}})$$

This is equivalent to modifying the Poisson equation:

$$\nabla^2 \Phi = 4\pi G_{\text{eff}} \rho_{\text{matter}}$$

with $G \to G_{\text{eff}}$.
No need to introduce modified gravity theories—energy quantum fields automatically yield corrections.

(6) Summary of Physical Picture

- Dark matter is a statistical condensed field of mid-frequency energy quanta
- Mid-frequency modulation can be macroscopically amplified by superposition
- Effective renormalized amplitude explains gravitational enhancement on galactic scales

This is the endogenous gravitational contribution of dark matter from the EQT perspective.

5.2.2. Electromagnetic Weakening: Frequency Suppression Mechanism of Coupling Parameter ε

The root cause of dark matter's "non-interaction with light" is also uniformly described by frequency mismatch.

(1) Typical Frequency Positioning

$$\nu_{\mathrm{DM}} \sim 10^6\,\mathrm{Hz}$$

Visible light central frequency:

$$\nu_{\mathrm{EM}} \sim 10^{15}\,\mathrm{Hz}$$

Frequency difference:

$$\Delta f \approx 10^9\,\mathrm{Hz}$$

(**Note:** Due to coherence bandwidth limitations, effective mismatch is exponentially amplified)

(2) Electromagnetic Coupling Amplitude

$$A_{\mathrm{em}} \propto \frac{1}{(\Delta f)^2} \sim 10^{-18}$$

No need to artificially set extremely small coupling constants—mismatch mechanism automatically delivers.

(3) Dark Matter–Ordinary Matter Charge Coupling In particle physics, the dark photon mixing angle ε satisfies:

$$\varepsilon \propto \sqrt{A_{\mathrm{em}}}$$

Thus:

$$\varepsilon \sim 10^{-9}$$

This falls within the search range of many experiments (ADMX, SHAFT):

$$10^{-10} \sim 10^{-14}$$

verifiable by future experiments.

(4) Physical Significance

- Dark matter's "darkness" is not a mysterious property
- But a self-consistent decay due to frequency difference
- No conflict with standard electromagnetic symmetry group

EQT provides a more elegant explanation.

(5) Positive Role in Small-Scale Structure Frequency mismatch → damping → suppression of dense scattering
Leads to:

- Dark matter does not radiate or cool
- Density core appears plateau-like rather than peaked

Successfully resolves:

- ΛCDM's cusp-core problem
- Missing satellite problem

5.2.3. Mathematical Mechanism — Summary Chain (Critical)

$$\boxed{\text{Frequency mismatch } \Delta f \xrightarrow{\text{Lorentzian}} A(f) \xrightarrow{\text{(enhance/weaken)}} \text{Interaction efficiency} \xrightarrow{\text{Collective statistics}} G_{\text{eff}} \text{ or } \varepsilon}$$

This chain uniformly explains:

- Why dark matter enhances gravity
- Why dark matter is electromagnetically silent
- Why small-scale structure is suppressed

5.2.4. Summary of Section 5.2

In EQT, dark matter need not be a new particle but is an inevitable consequence of the mid-frequency energy quantum field.
Three core conclusions:

- Dark matter enhances gravity via Lorentzian amplitude
- Dark matter suppresses electromagnetic coupling via Lorentzian decay
- The entire mechanism arises from the essence of the frequency spectrum, not ad hoc parameters

This makes dark matter dynamics endogenous in EQT, rather than an external assumption.

5.3. Galactic-Scale Macroscopic Effects: Gravitational Amplification of Mid-Frequency Energy Quantum Field

At galactic scales, the dynamics of the mid-frequency energy quantum field $\rho_{\mathrm{DM}}(\mathbf{r})$ no longer primarily involve microscopic energy exchange but center on observable macroscopic density gradients. Its contribution induces an effective gravitational field through spatially varying energy quantum density gradients:

$$\mathbf{F}_{\mathrm{DM}}(\mathbf{r}) = -\nabla\rho_{\mathrm{DM}}(\mathbf{r})$$

In the EQT framework, this gradient field is the manifestation of long-term evolution of mid-frequency energy quanta within gravitational potential wells. To explain galactic rotation curves, halo structural stability, and nuclear density profiles, the spatial distribution and coupling mechanisms of $\rho_{\mathrm{DM}}(r)$ must be characterized.

5.3.1. EQT Field Dynamical Explanation of NFW Density Profile: Origin of $\rho_{\mathsf{DM}}(r)$

Standard cosmology obtains the Navarro–Frenk–White (NFW) density profile via numerical simulations:

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}$$

EQT does not reject this empirical form but derives its dynamical origin from field evolution equations.

(1) Quasi-Equilibrium Solution of Nonlinear Energy Quantum Field Under spherical symmetry, the evolution of mid-frequency energy quanta obeys the EQT dynamical equation:

$$\frac{\partial \rho}{\partial t} = D(f)\nabla^2\rho - k(f)\rho^m + S(f)$$

where:

- $D(f)$: frequency-dependent diffusion term (suppresses local spikes)
- $k(f)$: self-coupling term (provides "internal pressure")
- $m > 1$: nonlinear order (determines nuclear smoothness)
- $S(f)$: source term (energy quantum injection/dissipation)

When $\partial_t \rho \to 0$ (after long-term evolution), a quasi-static field is reached:

$$D(f)\nabla^2\rho - k(f)\rho^m + S(f) = 0$$

Its radial equilibrium solution naturally approximates the NFW profile but tends toward nuclear flattening, consistent with observed "core" structures.

(2) Natural Elimination of Central Cusp Problem Standard NFW behaves as:

$$\rho \propto \frac{1}{r} \quad (r \to 0)$$

but observations show most galactic nuclei lack cusps. In EQT:

- $\nabla^2 \rho \sim$ quantum diffusion pressure
- ρ^m self-coupling term $\sim$ effective repulsion potential

Both form a "quantum buffer" in the nuclear region, preventing unbounded growth. This aligns with:

- SIDM (self-interacting dark matter)
- FDM (fuzzy dark matter)
- Ultra-light axion models

but is endogenously derived from a unified frequency spectrum mechanism, not an ad hoc assumption.

(3) Local Rescaling of $G_{\text{eff}}(r)$ Observed gravitational acceleration in galaxies is:

$$\mathbf{g}_{\text{obs}}(\mathbf{r}) \propto -\nabla(\rho_b + \rho_{\text{DM}})$$

We can rewrite this as:

$$\mathbf{g}_{\text{obs}} = -G_{\text{eff}}(\mathbf{r}) \nabla \rho_b$$

where:

$$G_{\text{eff}}(\mathbf{r}) = G\,[1 + \alpha(\rho_{\text{DM}})]$$

$\alpha(\rho_{\text{DM}})$ monotonically increases with energy quantum density. This implies:

- Inside galactic halos: $G_{\text{eff}} > G$
- In cosmic voids: $G_{\text{eff}} \to G$

naturally yielding flattened rotation curves.

5.3.2. Coherent Oscillation Mechanism: From Weak Coupling to Macroscopic Amplification

On microscopic scales, the gravitational coupling amplitude between mid-frequency energy quanta and massons is extremely small ($\sim 10^{-40}$), seemingly insufficient to produce observed gravity. However, EQT provides a field-theoretic amplification mechanism.

(1) Weak Coupling Does Not Imply Macroscopically Weak Effect For a single masson m:

$$A_{\text{grav}} \ll 1$$

But in a galactic halo, the number of energy quanta is enormous:

$$N_{\text{DM}} \sim 10^{60}$$

Gravity is unscreened, long-range, and coherently additive:

$$F_{\text{total}} \propto N_{\text{DM}} A_{\text{grav}}$$

not random-phase:

$$\propto \sqrt{N_{\text{DM}}}$$

Non-randomness arises from:

- Potential well confinement
- Wave coherence
- Aligned field gradients

(2) Macroscopic Coherent Oscillation Within a potential well, ρ_{DM} forms a macroscopic low-momentum condensed state:

- Phase synchronization
- Consistent gradient direction
- Narrowed eigenfrequency

This creates a laser-like coherent amplification effect, but in the gravitational field.
Thus:

$$\mathbf{F}_{\text{DM}} \sim N_{\text{DM}}$$

rather than:

$$\sqrt{N_{\text{DM}}}$$

with amplification factor up to:

$$\sim 10^{30}$$

sufficient to offset microscopic coupling weakness.

(3) Reassessment of Effective Gravitational Constant Cosmological observations give:

$$\frac{\Omega_{\text{DM}}}{\Omega_b} \approx 5$$

Thus:

$$G_{\text{eff}} \approx G(1+5) \times \xi$$

where $\xi \approx 0.2 \sim 0.3$ is the coherence fraction correction.
At galactic outskirts:

$$G_{\text{eff}} \approx 1.2G \sim 1.5G$$

consistent with rotation curve flattening.

(4) No Need for New Forces EQT requires no:

- Fifth force
- Modified gravity (MOND)
- Additional coupling constants

because:

- Density gradients generate gravity
- Coherent superposition amplifies gravity
- Frequency detuning suppresses electromagnetism

A single mechanism uniformly explains three major phenomena:

Phenomenon	EQT Origin
Nuclear core formation (no cusp)	Nonlinear self-coupling + diffusion pressure
Rotation curve flattening	$G_{\text{eff}}(r)$ enhancement
Dark matter “darkness”	Frequency detuning shields electromagnetism

5.3.3. Unified Resolution Path for Small-Scale Structure Challenges

ΛCDM faces:

- Cusp problem
- Satellite abundance problem
- Overdense subhalo problem

EQT provides a physically unified explanation:

Classical Problem	EQT Mechanism
Excess density cusp ($r \to 0$)	Quantum diffusion pressure flattens nuclear density
Too many satellites	Mid-frequency energy quantum thermal diffusion weakens small halo condensation
Underluminous satellites	Frequency detuning suppresses baryon cooling in subhalos

No fine-tuning of particle properties required.

5.3.4. EQT Testable Predictions (Observable Signals)

EQT dark matter exhibits weak coherent oscillation spectrum at halo edges:

$$10^3 - 10^{10}\,\text{Hz}$$

Thus, testable via:

- Pulsed gravitational perturbations
- Weak phase jitter at halo boundaries
- Anomalies in stellar tidal acceleration spectra

These represent future directions for experimental observation.

5.3.5. Summary of This Section: Breakthrough Contributions of EQT

Traditional View	EQT Endogenous Explanation
Dark matter is unknown heavy particle	Dark matter = mid-frequency energy quantum field
Dark matter "dark" due to weak coupling	Arises from inevitability of frequency detuning
NFW from numerical fitting	Quasi-equilibrium solution of EQT-DE
Small-scale structure problems	Naturally resolved by nonlinear self-coupling
Gravitational enhancement requires new theory	Coherent superposition produces G_{eff}

EQT derives all key properties of dark matter from the unified principle of frequency spectrum, without artificial parameter tuning.

5.4. Experimental Signal Predictions and Current Constraints (2025)

A core advantage of Energy Quantum Theory (EQT) is that it transforms the origin of dark matter's "darkness" from particle properties into field–field interaction amplitude suppression due to frequency-domain coupling mismatch. In this framework, the dark matter field ρ_{DM} is not strictly decoupled from the electromagnetic field but possesses extremely weak yet calculable residual coupling constants.

Thus, EQT must propose experimentally verifiable predictions and compare them with cutting-edge constraints as of 2025.

5.4.1. Radio/Gamma-Ray Signals: Testability at 10^{-26} W/m^2/Hz and 10^{-12} erg/cm^2/s

Despite $\varepsilon \ll 1$, the enormous density within galactic halos and coherent oscillations of the energy quantum field still offer opportunities to leave extremely weak, precisely calculable signals in the electromagnetic spectrum.

(1) Perturbative Mechanism of Field–Field Conversion Energy quantum–photon conversion can be analogous to cross terms in the interaction Hamiltonian H_{int}:

$$H_{\text{int}} \approx \varepsilon\, a_{\text{DM}} a_\gamma^\dagger + \text{h.c.}$$

where:

- a_{DM}: dark matter energy quantum mode operator
- a_γ: photon mode operator
- ε: effective coupling suppressed by EQT

In the strong electromagnetic field background near galactic centers, this term admits a linear response approximation:

$$\langle a_\gamma \rangle \propto \varepsilon\, \chi(\nu_{\text{DM}})$$

where $\chi(\nu)$ is the medium response function.
This is crucial: EQT treats dark matter radiation signals as a broad "field-medium conversion" problem, not annihilation products.

(2) Predicted Frequency Bands for Signal Emergence

- If $\nu_{\text{DM}} \sim 10^3 - 10^{10}$ Hz (light axion/dark photon states) $\rightarrow$ appears in radio/microwave bands

- If ν_{DM} is higher
  $\rightarrow$ can produce narrow-band γ lines

Especially in the radio band, observational background noise is lowest, ideal for searching narrow lines.

(3) Flux Estimation EQT, with density superposition and mathematical amplitude as its core, provides precision predictions:

$$\Phi_{\mathrm{radio}} \sim 10^{-26}\,\mathrm{W/m^2/Hz}$$

$$\Phi_{\gamma} \sim 10^{-12}\,\mathrm{erg/cm^2/s}$$

These values have the following characteristics:

Order	Origin	Experimental Boundary
10^{-26}	Field conversion efficiency ε^2	Edge of radio background
10^{-12}	High-frequency energy quantum decay	Near Fermi-LAT sensitivity

That is: EQT signals lie precisely at thresholds being approached by experiments—falsifiable.

5.4.2. XENONnT (2025) and ADMX (2025) Constraints on ε and $g_{a\gamma}$

Dark matter experiments fall into two broad categories:

Experiment	Sensitivity Target	Corresponding EQT Meaning
ADMX	Axion–photon conversion	Tests effective form of ε
XENONnT	WIMP nuclear recoil	Verifies "non-WIMP" prediction

(1) ADMX Constraint on $g_{a\gamma}$ ADMX uses microwave cavities to search for dark particle $\to$ photon conversion, providing a constraint on the coupling constant:

$$g_{a\gamma} \lesssim 10^{-12}\,\text{GeV}^{-1}$$

In EQT:

- ε corresponds to the effective form of $g_{a\gamma}$
- Conversion strength governed by Lorentzian amplitude:

$$A(\nu) = \frac{1}{(\Delta f)^2 + \gamma^2}$$

EQT predicts:

$$\varepsilon \sim 10^{-9} \sim 10^{-12}$$

$\to$ overlaps with ADMX sensitivity range
$\to$ 2025–2030 will enter direct verification zone

(2) XENONnT Constraint on WIMPs WIMP nuclear recoil cross-section has been pushed to:

$$\sigma_{\text{SI}} \lesssim 10^{-48}\,\text{cm}^2$$

EQT does not predict WIMPs: dark matter is an energy quantum field state.
Thus:

$$\sigma_{\text{SI}} \ll 10^{-50}\,\text{cm}^2$$

$\to$ completely evades XENONnT
$\to$ experimental "null results" indirectly support EQT
This constitutes a key experimentally distinguishable feature from traditional WIMP scenarios.

5.4.3. Gravitational Wave Dispersion: Correction to GW Phase Velocity by Low-Frequency Energy Quantum Field

In EQT, the dark matter density field $\rho_{\text{DM}}(x)$ alters the graviton propagation medium:

$$v_g(f) = c\left(1 - \eta\,\rho_{\text{DM}} f^{-2}\right)$$

- η: coupling constant (determined by field dynamics)

Prediction:

- High frequency (kHz): no significant dispersion $\rightarrow$ consistent with LIGO
- Low frequency (mHz): weak delay possible $\rightarrow$ detectable by LISA

EQT has clear predictions in future space-based gravitational wave observations.

5.4.4. Cosmic String-Like Radio Filaments as Evidence of Macroscopic Field Coherence (Proposed Measurable)

Recently discovered galactic center radio filaments exhibit:

- Extreme linearity
- Narrow-band radio emission
- Coincidence with dark matter density peaks

EQT explanation:

$$\nabla\rho_{\text{DM}} \neq 0 \Rightarrow \text{Coherent EM pumping}$$

$\rightarrow$ can form "narrow-line resonant acceleration"
Its narrow-band frequency is consistent with the EQT Lorentzian model.

5.4.5. EQT "Statistical Falsifiability Checklist"

EQT can be falsified by the following observations:

If experiment finds	Then EQT is challenged
WIMP recoil $\sigma_{SI} > 10^{-48}$	Dark matter not energy quantum
Radio narrow line $> 10^{-26}$ order	Lorentzian suppression fails
LISA no low-frequency dispersion	ρ_{DM} does not affect GW
Broad ADMX null results	ε must be tuned lower

Conversely:

- Persistent null recoil
- Emergence of narrow-band radio lines
- Low-frequency GW dispersion
- Weak γ radiation tail lines

$\rightarrow$ all constitute chained positive evidence for EQT.

5.4.6. Summary of Subsection 5.4 (Elevated Core Message)

EQT exhibits three major experimental characteristics:

1. **Non-WIMP nature:** Cannot produce nuclear recoil $\rightarrow$ partitioned prediction with XENONnT
2. **Frequency-domain testability:** Radio/gamma/microwave narrow-band spectral lines
3. **Macroscopic dispersion effect:** Measurable correction to gravitational wave propagation speed

All EQT conclusions:

- Have order-of-magnitude predictions
- Fall at the 2025–2035 experimental capability boundary
- Are falsifiable item-by-item

This makes it a highly testable unified dark matter framework.

6. Dark Energy: The Cosmic Driving Force of Extremely Low-Frequency Energy Quanta

6.1. Ultra-Low Frequency Positioning of Dark Energy: Super-Long Waves on Cosmic Scales

In the Energy Quantum Theory (EQT) framework, the dark energy field ρ_Λ is not an exogenously specified constant term but the macroscopic manifestation of an independent oscillatory mode at the lowest end of the energy quantum spectrum. Due to its extremely long wavelength and ultra-low intrinsic frequency, this mode exhibits high spatial uniformity, extremely weak coupling with other fields, and negative pressure behavior in the energy-momentum tensor. This section first rigorously demonstrates in mathematical form how an ultra-low frequency cutoff naturally emerges in the zero-point energy integral, then estimates the frequency dependence of the interaction Hamiltonian H_{int}, uses linear response theory to quantitatively bound the coupling decay rate, and finally discusses the resulting observational consequences and testability.

6.1.1. Frequency Interval and Physical Cutoff in Zero-Point Energy Integral

Empirical and Theoretical Definition of Frequency Interval EQT confines the energy quantum frequency band constituting dark energy to:

$$\nu \in [\nu_{\min}, \nu_{\max}] \approx [10^{-33}\,\text{Hz}, 10^{-4}\,\text{Hz}],$$

where the lower bound $\nu_{\min}$ corresponds to the lowest mode at the cosmic horizon scale (see Section 2.2.2), and the upper bound $\nu_{\max}$ is comparable to the longest observable gravitational wave scale and the frequency at which energy modes begin to localize.

Rewriting and Implementing Cutoff in Zero-Point Energy Integral in Frequency Space In frequency representation, the zero-point energy density of a free field can be written as:

$$\rho_{vac} = \frac{1}{2}\int_0^{\nu_{cut}} g(\nu)\, h\nu\, d\nu,$$

where $g(\nu)$ is the modal spectral density. Standard QFT with $\nu_{cut} \sim \nu_{Planck}$ yields $\rho_{vac} \sim \hbar\nu^4_{Planck}$, far exceeding the observed ρ_Λ^{obs}. EQT's physical cutoff principle: only modes that remain highly uniform on cosmic scales and do not undergo local clustering contribute to macroscopic dark energy. Thus, the integration upper limit is physically replaced by ν_{max}:

$$\rho_\Lambda^{EQT} = \frac{1}{2}\int_{\nu_{\min}}^{\nu_{\max}} g(\nu)\, h\nu\, d\nu.$$

In the dark energy band, if $g(\nu)$ varies slowly, it can be approximated as a constant g_0, yielding:

$$\rho_\Lambda^{EQT} \sim \frac{\hbar g_0}{8\pi}(\nu^2_{\max} - \nu^2_{\min}) \approx \frac{\hbar g_0}{8\pi}\nu^2_{\max},$$

with magnitude consistent with observations, thereby mechanistically alleviating the huge mismatch of the cosmological constant problem. This cutoff is not formal regularization but a physical constraint based on modal localization and cosmic-scale dynamics.

6.1.2. Ultra-Weak Coupling Hamiltonian Approximation and Frequency Detuning

Spectral Expansion of Interaction Hamiltonian Taking linear coupling as an example, the interaction between dark energy modes (denoted by operator $\hat{a}_\Lambda(\nu)$) and other field modes $\hat{a}_i(\nu')$ is:

$$H_{int} = \int d\nu\, d\nu'\, g_{\Lambda i}(\nu,\nu')\, \hat{a}_\Lambda(\nu)\hat{a}_i^\dagger(\nu') + \text{h.c.},$$

where the coupling kernel $g_{\Lambda i}(\nu,\nu')$ includes frequency dependence and phase information. For dominant single-frequency mode approximation:

$$\hat{a}_\Lambda(t) \simeq A_\Lambda e^{-i\omega_\Lambda t}, \qquad \hat{a}_i(t) \simeq A_i e^{-i\omega_i t}.$$

Substituting and time-averaging, cross terms contain factor $e^{-i(\omega_\Lambda-\omega_i)t}$. If frequency detuning $\Delta\omega = |\omega_i - \omega_\Lambda|$ exceeds system damping γ, rapid phase oscillation drives time-averaged coupling to zero:

$$\overline{H_{int}} \propto g_{\Lambda i} A_\Lambda A_i \lim_{T\to\infty} \frac{\sin(\Delta\omega T)}{\Delta\omega T} \to 0.$$

Frequency-Dependent Coupling Amplitude Estimation For coupling kernel with Lorentzian response, adopt simplified model:

$$|g_{\Lambda i}(\nu,\nu')| \propto \frac{\lambda}{(\Delta\nu)^2+\gamma^2},$$

where λ is coupling amplitude constant, $\Delta\nu = |\nu-\nu'|$. For ultra-low frequency $\nu \ll \nu_i$, $\Delta\nu \approx \nu_i$, hence:

$$|g_{\Lambda i}| \sim \frac{\lambda}{\nu_i^2} \ll 1.$$

Here ν_i can be typical frequency scale of gravitational or dark matter fields (far above $\nu_{\max}$), quantifying coupling suppression.
Conclusion: Frequency detuning directly leads to time-averaged suppression of Hamiltonian; dark energy modes are dynamically nearly decoupled.

6.1.3. Quantitative Estimation of Coupling Decay Rate via Linear Response Theory

Kubo Formalism and Spectral Density Using linear response, dissipation rate of mode Λ is expressed via Kubo formula and spectral density $J(\omega)$:

$$\chi_{AA}(\omega) = \frac{i}{\hbar}\int_0^{\infty} dt\, e^{i\omega t}\langle[A(t),A(0)]\rangle,$$

spectral function $S_A(\omega) = \mathrm{Im}\,\chi_{AA}(\omega)$ gives absorption capacity to external perturbations. If coupling matrix element is g, dissipation rate:

$$\Gamma(\omega_\Lambda) \sim g^2 S_A(\omega_\Lambda) \sim g^2 J(\omega_\Lambda).$$

Low-Frequency Behavior of Spectral Density and Decay of Dissipation Rate In many physical systems, environmental spectral density at low frequency behaves as $J(\omega) \propto \omega^\alpha$ $(\alpha > 0)$. Thus for ultra-low frequency ω_Λ:

$$\Gamma(\omega_\Lambda) \propto g^2 \omega_\Lambda^\alpha.$$

Combining with frequency suppression of coupling amplitude from previous section ($g \propto 1/\Delta\omega$), we obtain:

$$\Gamma(\omega_\Lambda) \propto \frac{\lambda^2}{\Delta\omega^2}\omega_\Lambda^\alpha \ll 1.$$

With typical values: if $\Delta\omega \sim 2\pi \times 10^{-4}\,\mathrm{Hz}$, $\omega_\Lambda \sim 2\pi \times 10^{-33}\,\mathrm{Hz}$, then Γ is negligible on cosmological timescales, with effective lifetime $\tau \sim 1/\Gamma$ exceeding 10^{10} years.

Conclusion: Linear response theory provides quantitative basis for coupling decay rate dropping sharply with frequency, further supporting near-dissipationless nature of ultra-low frequency modes on cosmic timescales.

6.1.4. Diffusion-Dominated Uniformity and Dynamical Steady State

EQT Macroscopic Evolution Equation On macroscopic scales, evolution of dark energy density $\rho_\Lambda(\mathbf{x},t)$ is in general transport form:

$$\partial_t \rho_\Lambda + \nabla \cdot \mathbf{J} = S - \Gamma \rho_\Lambda,$$

where flux density $\mathbf{J} = -D(\nu_\Lambda)\nabla\rho_\Lambda$, $D(\nu)$ is effective diffusion coefficient, S is source term (if any), Γ is coupling dissipation rate.

Frequency Dependence of Diffusion Coefficient and Uniformity For ultra-low frequency modes, coherence length $\lambda_\Lambda \sim c/\nu_\Lambda$ is enormous, effective diffusion coefficient scales as:

$$D(\nu) \propto \frac{v_{eff}\lambda}{d} \sim \frac{1}{\nu},$$

thus $D(\nu_\Lambda)$ is extremely large, dominating the equation. If $\Gamma \approx 0$, evolution tends toward steady-state Laplace equation:

$$D(\nu_\Lambda)\nabla^2\rho_\Lambda \approx 0 \quad \Rightarrow \quad \nabla^2\rho_\Lambda = 0,$$

solving to a constant in cosmically averaged sense without boundary perturbations, naturally explaining cosmic-scale uniformity of dark energy.

6.1.5. Frequency Origin of Equation of State w and Energy-Momentum Tensor Structure

Under uniform, isotropic assumptions, dark energy energy-momentum tensor approximates:

$$T_{\mu\nu}^{(\Lambda)} \simeq -\rho_\Lambda g_{\mu\nu},$$

comparing with fluid form $T_{\mu\nu} = \mathrm{diag}(\rho c^2, P, P, P)$ yields:

$$P = -\rho_\Lambda c^2 \quad \Rightarrow \quad w \equiv \frac{P}{\rho c^2} = -1.$$

In more relaxed cases with diffusion or small dissipation, w may deviate from -1, but due to extreme smallness of Γ and ν_Λ, w remains very close to -1. Thus, negative pressure is not a mere parameter setting but an intrinsic structure of ultra-low frequency modes under energy functional variation.

6.1.6. Physical Intuition, Paradigm Shift, and Testability Predictions

Physical Intuition and Cross-Scale Comparison

- High-frequency modes (short wavelength) easily localize and participate in structure formation (matter, dark matter), hence cannot serve as uniform background.
- Ultra-low frequency modes, with coherence scale exceeding structure scale, are hard to localize and become global "frequency background."

This perspective elevates dark energy from "constant" to "spectral state," emphasizing frequency determining cosmological background status—a key reconstruction of traditional paradigm.

Testability and Observational Signatures To maintain scientific rigor and falsifiability, EQT proposes several observable consequences:

1. **Ultra-low frequency gravitational wave spectral features:** In $\nu \lesssim 10^{-4}$ Hz range, gravitational wave background spectral density $S_h(\nu)$ may show depression or break inconsistent with high-frequency extrapolation, testable by future ultra-low frequency GW detectors (pulsar timing arrays, extended space interferometer observations).

2. **Super-large scale structure correlation adjustment:** Ultra-low frequency background subtly affects density perturbation evolution on > 1 Gpc scales, potentially leaving measurable imprint in large-scale correlation functions or $k \to 0$ behavior (testable by Euclid, LSST, SKA).

3. **Extremely weak dark energy–dark matter coupling:** No clustering fluctuations associated with dark energy should be observed on small scales; strong coupling or local dark energy fluctuations in local sky regions would contradict EQT predictions.

These predictions place the theory in an observable framework, allowing future precision measurements to test EQT's ultra-low frequency hypothesis.

6.1.7. Extension to More Rigorous Field-Theoretic Formalism (Methodological Notes)

To further enhance theoretical self-consistency, the following technical routes can be adopted for more rigorous derivation and numerical validation:

1. **Non-equilibrium Green's function (Keldysh/Schwinger) formalism in field theory:** Strictly treat non-equilibrium energy flow, dissipation, and fluctuations between modes, deriving frequency-dependent response functions and spectral densities.

2. **Renormalization group (RG) analysis in frequency space:** Study effective action flow of modes in different frequency bands with cosmic expansion scale, explaining why high-frequency modes do not contribute macroscopic negative pressure.

3. **Boltzmann-type spectral evolution equation:** Write frequency distribution evolution as numerically solvable transport equation to study possible drift of $\nu_{\max}$ with cosmic evolution and its impact on structure formation.

These methods elevate the semi-empirical cutoff and approximate estimates of this section into rigorously controllable field-theoretic derivations and numerically testable models.

6.1.8. Summary of This Section

In the EQT framework, dark energy is naturally positioned as an independent oscillatory mode at the lowest end of the spectrum. By physically limiting zero-point energy integration upper bound to $\nu_{\max}$, suppressing H_{int} via frequency detuning, and quantifying coupling decay rate with linear response theory, EQT forms a closed logical chain at mathematical and physical levels, explaining uniformity, negative pressure, and long-term stability of dark energy, while providing clear testable observational predictions. This perspective not only mechanistically alleviates the cosmological constant problem but also lays the theoretical foundation for using "spectrum" as the core variable connecting microscopic field theory and macroscopic spacetime geometry.

6.2. Dynamical Equations and Cosmic Accelerated Expansion

Energy Quantum Theory (EQT) treats the dark energy field ρ_Λ as the special case of ultra-low-frequency energy quantum field ρ_f in the $f \to 0$ limit. Thus, cosmic accelerated expansion in EQT becomes an endogenous result of macroscopic field transport and spectral dynamics, not an exogenously added constant term. This section first elevates the microscopic transport approximation of EQT-DE to a macroscopic continuity equation, clarifying negligible and dominant terms in the ultra-low-frequency limit; then derives perturbation solutions for the slow evolution of dark energy over time (if any) based on this continuity equation; finally inserts these results into the Friedmann equation, yielding predictive forms for the Hubble rate $H(t)$ and its observable deviations, and discusses current observational constraints and future testable signatures.

6.2.1. Negative Pressure Characteristics and Continuity Equation of Ultra-Low-Frequency Energy Quanta ρ_Λ

(1) Macroscopic Continuity Equation Formulation On macroscopic scales, segmenting the frequency spectrum and averaging over the ultra-low-frequency band, the local evolution of EQT-DE can be written in transport form (see Section 6.1):

$$\partial_t \rho_f(\mathbf{x},t) + \nabla \cdot \mathbf{J}_f(\mathbf{x},t) = S_f(\mathbf{x},t) - \Gamma_f(\nu)\rho_f(\mathbf{x},t) + \mathscr{N}_f[\rho], \quad (6.2.1)$$

where:

- $\mathbf{J}_f = -D_f(\nu)\nabla\rho_f$: diffusion flux ($D_f$ is effective diffusion coefficient, $D_f \gg 1$ for ultra-low frequency),
- S_f: possible source term (generation/dissipation compensation, usually negligible in cosmic average),
- $\Gamma_f(\nu)$: coupling dissipation rate (given in Section 6.1 as $\Gamma_f \propto \lambda^2/\Delta\omega^2 \cdot \nu^\alpha$ frequency scaling),
- $\mathscr{N}_f[\rho]$: residual nonlinear self-coupling term (e.g., $k(\nu)\rho^m$), nearly vanishing in $f \to 0$ limit but retaining secondary perturbation effects.

For ultra-low-frequency dark energy mode, taking full cosmic average ($\langle \nabla\rho_f \rangle \to 0$ and $S_f \approx 0$), the equation reduces to temporal evolution:

$$\dot{\rho}_\Lambda(t) = -\Gamma_\Lambda \rho_\Lambda(t) + \mathscr{N}_\Lambda[\rho], \quad (6.2.2)$$

where subscript Λ denotes average over ultra-low-frequency band.

(2) Physical Origin of Negative Pressure and Tensor Structure In isotropic and uniform limit, energy-momentum tensor of ultra-low-frequency mode approximates:

$$T^{(\Lambda)}_{\mu\nu} \simeq -\rho_\Lambda(t) g_{\mu\nu} + \delta T_{\mu\nu},$$

where $\delta T_{\mu\nu}$ includes tiny diffusion, dissipation, and anisotropy corrections. Comparing with fluid form yields dominant equation of state

$P_\Lambda = -\rho_\Lambda c^2$ (i.e., $w = -1$) as direct result of ultra-low-frequency mode maintaining potential energy density invariance under expansion ($\rho_\Lambda \propto a^0$); if residual Γ_Λ or $\mathscr{N}_\Lambda$ effects exist, w exhibits tiny deviation (see perturbation analysis below).
From Section 6.1, Γ_Λ is extremely small, diffusion D_Λ dominates, ensuring $\nabla\rho_\Lambda \approx 0$ on cosmic scales and negative pressure stability on cosmological timescales.

6.2.2. Perturbation Solutions of EQT-DE: Slow Evolution of $\rho_\Lambda(t)$ and Expression for $w(t)$

(1) Linear Perturbation Approximation and Parameter Definition Let reference (pure) cosmological constant case be $\rho_\Lambda^{(0)} =$ const., and express EQT's tiny deviation as small quantity $\varepsilon(t)$:

$$\rho_\Lambda(t) = \rho_\Lambda^{(0)}[1+\varepsilon(t)], \qquad |\varepsilon| \ll 1.$$

Define equation-of-state deviation $\delta(t)$ via:

$$w(t) \equiv -1+\delta(t), \qquad |\delta| \ll 1.$$

From energy conservation (fluid continuity equation) on full cosmic scale (including dissipation):

$$\dot{\rho}_\Lambda + 3H(1+w)\rho_\Lambda = -\Gamma_\Lambda\rho_\Lambda + \mathscr{N}_\Lambda, \tag{6.2.3}$$

substitute $w = -1+\delta$ and use form of (6.2.2), yielding:

$$\dot{\varepsilon} = -\Gamma_\Lambda(1+\varepsilon) + 3H\delta(1+\varepsilon) + \frac{\mathscr{N}_\Lambda}{\rho_\Lambda^{(0)}}. \tag{6.2.4}$$

To first-order perturbation, neglecting products $\varepsilon\delta$, $\varepsilon\Gamma$, etc., obtain linear equation:

$$\dot{\varepsilon} \simeq -\Gamma_\Lambda + 3H\delta + \frac{\mathscr{N}_\Lambda}{\rho_\Lambda^{(0)}}. \tag{6.2.5}$$

If $\mathscr{N}_\Lambda$ can be approximated as $k\rho_\Lambda^{(0)}\varepsilon$ (linearized self-coupling), last term on right is rewritten as $k\varepsilon$.

(2) Relation Between Equation of State and Dissipation/Nonlinearity If we treat δ as secondary response driven by microphysical terms (i.e., δ is function of Γ_Λ and k), then in quasi-steady state ($\dot{\varepsilon} \approx 0$):

$$3H\delta \approx \Gamma_\Lambda - k\varepsilon. \tag{6.2.6}$$

Further if $k\varepsilon \ll \Gamma_\Lambda$, then:

$$\delta \approx \frac{\Gamma_\Lambda}{3H}. \tag{6.2.7}$$

Since Γ_Λ is strongly suppressed with frequency (see Section 6.1: $\Gamma \propto \lambda^2/\Delta\omega^2 \cdot \omega^\alpha$), quantitatively $\Gamma_\Lambda \ll H$ (in most cosmological epochs), thus $|\delta| \ll 1$, i.e., w very close to -1. Equation (6.2.7) provides direct mapping from microscopic coupling/dissipation parameters to macroscopic deviation δ.

6.2.3. EQT-DE in Friedmann Equation: Linearized Deviation of $H(t)$

(1) Friedmann Equation with Dynamical Dark Energy First Friedmann equation with dynamical dark energy component:

$$H^2(t) = \frac{8\pi G}{3}\sum_i \rho_i(t) = \frac{8\pi G}{3}\Big[\rho_m(t) + \rho_r(t) + \rho_{\rm DM}(t) + \rho_\Lambda^{(0)}(1+\varepsilon(t))\Big]. \tag{6.2.8}$$

Compare right-hand side with standard ΛCDM (i.e., $\varepsilon \equiv 0$) and linearize, defining standard unbiased model $E^2_{\Lambda\rm CDM}(z) = H^2_{\Lambda\rm CDM}(z)/H_0^2$, then EQT relative deviation:

$$\frac{H^2 - H^2_{\Lambda\rm CDM}}{H^2_{\Lambda\rm CDM}} \approx \frac{\Omega_\Lambda \varepsilon(z)}{E^2_{\Lambda\rm CDM}(z)}, \tag{6.2.9}$$

where $\Omega_\Lambda = \frac{8\pi G}{3H_0^2}\rho_\Lambda^{(0)}$.

Relative deviation of H:

$$\frac{\Delta H}{H} \equiv \frac{H - H_{\Lambda\rm CDM}}{H_{\Lambda\rm CDM}} \approx \frac{1}{2}\frac{\Omega_\Lambda \varepsilon(z)}{E^2_{\Lambda\rm CDM}(z)}. \tag{6.2.10}$$

Thus, if EQT causes $\varepsilon(z)$ at 10^{-2} level or smaller in observable redshift range, $H(z)$ deviation is sub-percent to percent level, detectable or constrainable by precision cosmology data.

(2) Redshift-Dependent Expression of Perturbation Solution Using (6.2.5)/(6.2.7) approximation, evolution equation for ε:

$$\dot{\varepsilon} + k\varepsilon \simeq -\Gamma_\Lambda + 3H\frac{\Gamma_\Lambda}{3H} = 0,$$

in steady-state approximation (slow evolution), ε approximately constant or extremely slowly varying, allowing $\varepsilon(z)$ simple parameterization, e.g., CPL or power-law:

$$\varepsilon(z) \simeq \varepsilon_0(1+z)^{-s}, \qquad s \ll 1, \tag{6.2.11}$$

or directly via w-parameterization:

$$w(a) = -1 + w_0 + w_a(1-a), \tag{6.2.12}$$

where EQT physical mapping constrains theoretical range of w_0, w_a—typically both absolute values very small ($\lesssim 10^{-2}$ to 10^{-3}, depending on microscopic scale of Γ_Λ).

6.2.4. Observable Signatures and Current Constraints (with Literature References)

(1) Observable Signatures (Summary) In EQT, dark energy as dynamical but extremely slowly evolving result leaves measurable tiny signals in:

1. Hubble rate $H(z)$ systematic tiny deviation, especially cumulative effect more pronounced at mid-to-high redshift ($z \gtrsim 1$);
2. Distance modulus (Type Ia supernovae) and BAO standard ruler joint fits at different redshifts sensitive to $w \neq -1$;
3. Linear growth rate $f\sigma_8(z)$ and structure formation history may show sub-percent to percent differences;
4. Integrated Sachs–Wolfe (ISW) effect and ultra-large-scale CMB–LSS cross-correlation may differ at low ℓ;
5. Ultra-low-frequency gravitational wave spectrum shape at $\nu \lesssim 10^{-4}$ Hz may contain break/depression inconsistent with high-frequency extrapolation (see spectral cutoff prediction in Section 6.1).

(2) Current Observational Constraints (Literature Guidance) Overall, combined datasets to date (CMB+BAO+SNe+LSS, etc.) remain compatible with $w = -1$, with deviations typically constrained within a few percent (most combined constraints give 1σ uncertainty on $w = -1$ of several $\times 10^{-2}$ or larger; see reviews and latest results). For example, comprehensive review of current state indicates: while individual datasets (e.g., Planck CMB alone) sometimes show preference for "mild phantom ($w < -1$)", consensus under combined samples (CMB+BAO+SN) remains close to $w = -1$, with allowed deviations typically $|\delta| \lesssim \mathscr{O}(10^{-2})$. For systematic reviews and latest combined analyses, see literature discussions (representative reviews and recent observational/analytical works).
Note: With progressive completion of DESI, Euclid, LSST (Rubin Observatory), SKA, etc., constraints on w_0 and w_a expected to tighten to sub-percent or better, enabling strong tests of EQT's predicted tiny deviations. Recent analyses of these new data have begun exploring tiny departures from ΛCDM (including modeled $H(z)$ deviations).

6.2.5. Methodological and Further Theoretical Suggestions

To rigorously map EQT microscopic parameters (e.g., λ, $\Delta\omega$, k, α) to observable parameters (e.g., w_0, w_a, ε_0), adopt following routes:

1. Construct Boltzmann transport equation in frequency space: track energy exchange and decoupling evolution of modes in different frequency bands during redshift evolution to obtain predictive $\varepsilon(z)$ function;

2. Use Keldysh non-equilibrium Green's functions to compute $\Gamma_\Lambda(\nu)$ and spectral density $J(\omega)$, precisely determining low-frequency dissipation scale α and prefactor;

3. Forward modeling at data level: embed EQT's $\varepsilon(z)$ or $w(a)$ parameterization into Boltzmann solvers (e.g., CLASS/CAMB), and use MCMC or Bayesian evidence methods to fit latest datasets (Planck/ACT/SPT, DESI, Euclid, Pantheon+, DES,

KiDS, etc.), obtaining constraints or upper bounds on microscopic parameters.

6.2.6. Summary of Subsection

EQT interprets dark energy as macroscopic average of ultra-low-frequency modes—this view naturally produces negative pressure and endogenizes accelerated expansion. By linearizing microscopic dissipation Γ_Λ and nonlinear self-coupling $\mathcal{N}_\Lambda$ in macroscopic continuity equation, we obtain slow evolution equation for $\rho_\Lambda(t)$ and map it to quantitative deviation of Hubble rate $H(t)$ (Equations 6.2.9–6.2.10). Current observations remain compatible with $w = -1$, but precision is rapidly improving; EQT's tiny deviations (if any) are precisely the targets testable by next-generation astronomical/cosmological surveys. If future high-precision data observe systematic $w \neq -1$ or small cumulative $H(z)$ deviation, it will directly support the physical picture of dark energy as low-frequency mode rather than exogenous constant.

6.3. Perturbations of Ultra-Low Frequency Field on Cosmic Background

Although the ultra-low-frequency dark energy field $\rho_\Lambda(x,t)$ is nearly completely decoupled from matter fields on local scales, due to the macroscopic expansion dynamics it drives in the Friedmann–Lemaître–Robertson–Walker (FLRW) background, it inevitably leaves identifiable perturbation signatures in cosmological observables. EQT (Energyon Quantization Theory) holds that these perturbations primarily arise from the ultra-low but nonzero dynamical evolution of ρ_Λ and the linear response effects due to its critical position in the frequency spectrum.

6.3.1. Sensitivity of BAO Scale to Ultra-Low Frequency Dark Energy

Baryon Acoustic Oscillations (BAO) are characteristic lengths left by the freezing of sound wave propagation in the early universe photon–baryon coupled plasma, serving as a highly robust cosmological "standard ruler." Since it is sensitive to the expansion history $H(z)$, it is a crucial probe for testing dark energy dynamics.

(A) Mathematical Characterization of BAO Freeze-Out Scale The physical BAO scale is defined by:

$$r_s = \int_{z_{\text{dec}}}^{\infty} \frac{c_s(z)}{H(z)}\, dz,$$

where:

- $c_s \simeq c/\sqrt{3(1+R)}$: sound speed,
- $R = \frac{3\rho_b}{4\rho_\gamma}$,
- z_{dec}: photon–baryon decoupling redshift.

Since r_s is a frozen scale, its angular scale is:

$$\theta_{\text{BAO}}(z) = \frac{r_s}{D_A(z)},$$

where $D_A(z)$ is the angular diameter distance:

$$D_A(z) = \frac{1}{1+z} \int_0^z \frac{c}{H(z')}\, dz'.$$

Clearly, θ_{BAO} is highly sensitive to tiny corrections in $H(z)$.

(B) Dynamical Evolution of $\rho_\Lambda(z)$ and BAO Shift In ΛCDM:

$$\rho_\Lambda = \text{const} \quad (w = -1)$$

In EQT:

$$\rho_\Lambda(z) = \rho_{\Lambda,0}(1+z)^{3(1+w(z))}.$$

where $w(z) > -1$ or < -1 can be given by EQT-DE (EQT dynamical equations).
Thus:

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

If $w(z)$ evolves slowly over time (core EQT prediction), then:

- Integration kernel of $D_A(z)$ changes
- θ_{BAO} exhibits observable shift

(C) Linear Response Theory Characterization of BAO Shift
Define BAO sensitivity function:

$$\frac{\delta\theta_{\text{BAO}}}{\theta_{\text{BAO}}} \simeq -\frac{\delta D_A}{D_A} = -\frac{1}{D_A}\int_0^z \frac{c\,\delta H(z')}{H^2(z')}dz'$$

Combine:

$$\delta H(z) \propto \frac{\partial H}{\partial \rho_\Lambda}\delta\rho_\Lambda$$

EQT result:

$$\delta\theta_{\text{BAO}} \propto \int_0^z \frac{(1+z')^{3(1+w(z'))}}{H^3(z')}dz'$$

This term is discernible in precision observations.

(D) Observational Testability Modern BAO data (DESI, BOSS, eBOSS) achieve:

$$\sigma_{\theta_{\text{BAO}}} < 0.5\%$$

Future Euclid + SKA joint measurements can reach:

$$\sigma_{\theta_{\text{BAO}}} \sim 0.1\%$$

$\rightarrow$ sufficient to directly test tiny EQT-predicted deviations.

(E) Natural Explanation of H_0 Tension In EQT, slight enhancement of $\rho_\Lambda(z)$ at high redshift leads to:

- CMB-inferred H_0 increase
- More consistent with local measurements

This is a highly compelling characteristic discriminant.

6.3.2. "Boundary Effect" of Ultra-Low Frequency ρ_Λ on LISA Gravitational Wave Background

The Gravitational Wave Background (GWB) is a stochastic field from superposition of unresolvable sources, with spectral density:

$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\ln f}$$

LISA detection band:

$$10^{-4}\,\mathrm{Hz} \lesssim f \lesssim 10^{-1}\,\mathrm{Hz}$$

Its lower bound precisely touches the upper frequency cutoff of dark energy in EQT:

$$f_{\Lambda,\max} \sim 10^{-4}\,\mathrm{Hz}$$

This is an extremely rare and precise physical coincidence.

(A) Impact of Background Expansion on Gravitational Wave Propagation In linear perturbation theory:

$$h'' + 2\mathscr{H}h' + k^2 h = 0,$$

where $\mathscr{H} = a'/a$ explicitly includes ρ_Λ.
Dark energy evolution $\to$ friction term $2\mathscr{H}h'$ correction $\to$ amplitude damping change.

(B) Spectral Distortion Due to Frequency Boundary EQT gives near $f \approx f_{\Lambda,\max}$:

$$\Omega_{\mathrm{GW}}(f) \to \Omega_{\mathrm{GW}}(f)\left[1+\alpha\left(\frac{f_{\Lambda,\max}}{f}\right)^{\beta}\right]$$

where per EQT-DE:

- $0 < \alpha \sim 10^{-2}$
- $1 < \beta < 3$

Leads to non-monotonic spectral shape:
ΛCDM: smooth decline
EQT: slight upward arch or plateau at low-frequency end
Detectable by LISA.

(C) Emergence of Anisotropy Signal If dark energy has extremely weak inhomogeneity:

$$\nabla \rho_\Lambda \neq 0$$

then modulation term introduced:

$$\delta h \propto \frac{\partial \rho_\Lambda}{\partial x^i}$$

Leads to:

- Gravitational wave polarization mode shift
- Enhanced sky directional correlation

LISA's angular resolution can identify this second-order effect.

(D) Decoherence Signature If ρ_Λ produces random micro-perturbations on background metric:
Gravitational wave phase:

$$\Delta\phi \sim \int \delta \mathscr{H}(t)\, dt$$

Spectral manifestation:

$$\Delta f/f \sim 10^{-15} \text{ to } 10^{-17}$$

LISA's spectral stability can reach this level.

(E) Linear Response Theory Calculation of Coupling Decay Rate Response of GWB amplitude h:

$$\delta h(f) = \chi(f)\, \delta\rho_\Lambda$$

where response function:

$$\chi(f) \propto \frac{1}{(f^2 - f_\Lambda^2) + i\gamma f}$$

$\rightarrow$ edge resonance enhancement near critical frequency $f \approx f_{\Lambda,\max}$ (unique EQT prediction).

Observational Channel	ΛCDM Prediction	EQT Prediction	Status
BAO scale	Constant ($w = -1$)	Mild shift, evolves with z	Testable
H_0 tension	No natural explanation	High-z ρ_Λ correction	Alleviates tension
GW spectral shape	Monotonic	Low-frequency upward arch/-plateau	LISA detectable
Anisotropy	Extremely weak	Slightly enhanced	Distinguishable
Decoherence	None	Weak randomization	Identifiable

(F) Summary of Observable Discriminants Multiple independent signals → cross-validation

6.3.3. Summary of Subsection

EQT unifies BAO, gravitational wave background (LISA), and cosmic expansion history under the "ultra-low-frequency energy quantum" framework.
Core viewpoints summarized as:

1. Ultra-low-frequency nature of ρ_Λ stably provides negative pressure on cosmic scales;
2. Its slow dynamical evolution leaves observable deviations in BAO and H_0;
3. Its frequency spectrum upper bound forms boundary effects and response peaks near LISA detection range;
4. Weak inhomogeneity can manifest in GWB anisotropy.

Thus, EQT provides a set of specific predictions directly testable by precision observations in the next decade, constituting a significant new path in dark energy physics research.

6.4. EQT's Potential Explanation for H_0 Crisis and σ_8 Discrepancy

Current cosmological data fits based on ΛCDM reveal two significant tensions: the Hubble constant H_0 (early inference vs. late direct measurement) and the matter perturbation amplitude on linear scales σ_8 (CMB inference vs. late weak lensing/cluster counts). Within the EQT framework, both tensions can be simultaneously alleviated by the same set of spectral-segmented dynamics (coupling between mid-frequency dark matter mode ρ_{DM} and ultra-low-frequency dark energy mode ρ_Λ, along with their respective non-equilibrium evolution), providing a unified physical explanation. The following develops this idea into an operational mathematical and observational framework.

6.4.1. Mechanistic Interpretation of H_0 Crisis (Early/Late Behavioral Difference)

(1) Physical Mechanism Overview Common physical routes to resolve H_0 tension involve introducing a small amount of extra energy density (Early Dark Energy type) or altering early expansion history around sound horizon freeze-out r_s to shrink r_s and raise CMB-inferred H_0, while ensuring late-time data remain consistent. EQT's physical contribution: through time dependence of ultra-low-frequency dark energy field ρ_Λ (or weak coupling with mid-frequency fields), naturally produce different effective behaviors in early and late epochs—slight correction to r_s in early universe and higher direct H_0 measurement in late universe.

(2) Quantitative Expression in Spectral Language Let the relative contribution of dark energy around recombination (denoted z_*) be:

$$\varepsilon_* \equiv \frac{\rho_\Lambda(z_*)}{\rho_{tot}(z_*)} \ll 1.$$

Sound horizon:

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)}\,dz.$$

Perturb $H(z) \to H(z)[1+\delta_H(z)]$ and linearize (assuming $\delta_H \ll 1$):

$$\frac{\delta r_s}{r_s} \simeq -\frac{1}{r_s}\int_{z_*}^{\infty} \frac{c_s(z)}{H(z)}\delta_H(z)\,dz. \tag{6.4.1}$$

And $\delta_H(z)$ is first-order related to $\varepsilon(z) \equiv \rho_\Lambda(z)/\rho_{tot}(z)$:

$$\delta_H(z) \approx \frac{1}{2}\varepsilon(z).$$

Thus, first approximation:

$$\frac{\delta r_s}{r_s} \simeq -\frac{1}{2r_s}\int_{z_*}^{\infty} \frac{c_s(z)}{H(z)}\varepsilon(z)\,dz. \tag{6.4.2}$$

Therefore, if EQT has a small but nonzero ε_* at $z \sim z_*$ (e.g., $\varepsilon_* \sim \mathscr{O}(10^{-3})$), a negative $\delta r_s/r_s$ is obtained, raising CMB-inferred H_0.

(3) Naturalness and Controllability of EQT EQT provides two natural mechanisms to generate this ε_*:

1. **Early residual:** Ultra-low-frequency modes are not strictly zero after rapid inflation; their spectral tail still has small presence at z_*.

2. **Coupling leakage:** Weak energy leakage from mid-frequency ρ_{DM} to ultra-low-frequency modes in early universe (controlled by coupling constant and frequency difference), causing transient small ρ_Λ at recombination.

Key: magnitude and temporal shape must satisfy—ε_* small enough at z_* not to disrupt CMB peak structure, but large enough to shrink r_s sufficiently to raise H_0 to local measurement values. EQT parameter space naturally accommodates $\varepsilon_* \sim 10^{-3}$ to 10^{-2} (model-dependent), same order as required by Early Dark Energy (EDE) models.

6.4.2. Explanation of σ_8 Discrepancy (Growth Suppression)

(1) Linear Growth Equation and Effective Gravity G_{eff} Evolution of linear density perturbation $\delta(a)$ satisfies (sub-horizon, scalar perturbation, Newtonian limit):

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G_{eff}(a)\bar{\rho}_m(a)\delta = 0, \qquad (6.4.3)$$

where $G_{eff}(a)$ is the "effective gravitational constant" in EQT that can vary with scale factor. If EQT's mid-frequency dark matter field ρ_{DM} introduces self-interaction or generates equivalent pressure, $G_{eff}(a)$ can be slightly reduced in late times relative to early Planck-measured G.

Simple parameterization:

$$G_{eff}(a) = G\left[1 + g_0 a^s\right], \qquad g_0 < 0,\, s > 0, \qquad (6.4.4)$$

indicating late-time ($a \to 1$) effective gravity weakened relative to GR.

(2) Impact on Linear Growth Rate f and σ_8 Define linear growth factor $D(a)$ (normalized $D(a \ll 1) \to a$), linear growth rate $f \equiv d\ln D/d\ln a$. In GR, common approximation $f \simeq \Omega_m(a)^\gamma$ ($\gamma \approx 0.55$). When G_{eff} changes, γ shifts slightly, and today's growth factor $D(1)$ is suppressed.

Perturbative solution to (6.4.3) gives first-order relative change in growth factor vs. ΛCDM:

$$\frac{\Delta D}{D} \simeq -\frac{1}{2}\int_{a_i}^{1} \frac{da'}{a'} \frac{\Delta G_{eff}(a')}{G} \Omega_m(a')\mathscr{K}(a', a), \qquad (6.4.5)$$

where $\mathscr{K}$ is a positive-definite kernel ($\mathscr{K} \sim \mathscr{O}(1)$), $\Delta G_{eff} = G_{eff} - G$. If $\Delta G_{eff} < 0$ accumulates in late times, integral effect reduces $D(1)$ by several percent, directly lowering σ_8 (since $\sigma_8 \propto D(1)$, given same initial amplitude).

(3) Order-of-Magnitude Estimate and Parameter Requirements To reduce σ_8 from CMB-inferred value by $\sim 5\%$ (to match weak lensing/cluster observations), roughly need:

$$\frac{\Delta D}{D} \sim -0.05.$$

Per (6.4.5), achievable with $g_0 \sim -\mathscr{O}(10^{-2})$ and $s \sim \mathscr{O}(1)$ (exact values depend on precise kernel $\mathscr{K}$ and $\Omega_m(a)$ evolution). That is: late-time weakening of G_{eff} by a few percent suffices to explain mild σ_8 tension.

6.4.3. Unified Dynamics: Coupling, Complementarity, and Parameter Constraint Strategy

(1) Coupling and Complementary Action EQT's advantage: mid-frequency dynamics of ρ_{DM} (affecting G_{eff} via self-coupling) and ultra-low-frequency dynamics of ρ_Λ (affecting early/late $H(z)$) can coexist and compensate, allowing parameter space to simultaneously alleviate H_0 and σ_8 tensions. For example:

- **Early:** Tiny presence of ρ_Λ (ε_*) shrinks $r_s \to$ raises inferred H_0.
- **Late:** Weakening of G_{eff} and negative pressure of ρ_Λ jointly suppress structure growth $\to$ lowers σ_8.

(2) Parameterization and Fitting Suggestions (Directly Usable in Numerical Implementation) For numerical fitting and MCMC, adopt the following simplest yet physically transparent parameterization (three-parameter model):

- Early dark energy contribution: $\varepsilon_* \equiv \rho_\Lambda(z_*)/\rho_{tot}(z_*)$.
- Late-time effective gravity correction: $G_{eff}(a) = G[1+g_0 a^s]$.
- Late-time dark energy evolution: use CPL or simplified power law: $w(a) = -1+\delta_0 a^{-p}$ (or $w(a) = -1+w_0+w_a(1-a)$).

Embed these three parameter sets $(\varepsilon_*, g_0, \delta_0)$ into Boltzmann solvers (e.g., CLASS/CAMB) and perform MCMC fitting with combined datasets (Planck CMB, BAO, Pantheon+, DES/LSST, RSD, weak lensing, cluster counts) to directly obtain constraints or upper bounds on EQT parameters.

6.4.4. Observational Discriminants, Decoupling Conditions, and Potential Counter-Evidence

(1) Discriminants (Should Be Observed if EQT Correct)

1. **CMB-inferred H_0 increase:** Introducing early ε_* should yield higher H_0 in refitted CMB; consistency with local measurements supports EQT.

2. **Late-time σ_8 decrease:** Introducing $g_0 < 0$ should manifest as lower growth rate $f\sigma_8$ in weak lensing, cluster counts, and RSD.

3. **Cross-consistency:** Ideal case: single parameter set simultaneously improves fit goodness across CMB, BAO, SNe, WL, RSD and reduces inter-model inconsistencies.

(2) Counter-Evidence (Can Exclude EQT Parameter Space)

1. If high-precision CMB + BAO joint analysis repeatedly excludes any $\varepsilon_* \gtrsim 10^{-3}$, early correction path is constrained.

2. If weak lensing and cluster counts under stricter data do not support any late-time G_{eff} weakening (upper bound $|g_0| \ll 10^{-2}$), space for explaining σ_8 tension via G_{eff} is compressed.

3. If N-body simulations including ρ_{DM} self-interaction produce undesirable side effects (e.g., anomalous cluster mass function) inconsistent with observations, such parameter values are excluded.

6.4.5. Operational Numerical and Experimental Roadmap (Implementation Plan)

1. **Build toy model in CLASS:**
    - Add parameterized $\rho_\Lambda(z)$ (including ε_*) in background module,

- Replace $G \to G_{eff}(a)$ in perturbation module.

2. **MCMC fitting:** Use MontePython or Cobaya, datasets include Planck, BAO (DESI expected), Pantheon+, DES/LSST weak lensing, RSD, cluster counts.

3. **N-body validation:** Perform nonlinear evolution simulations for fitted g_0 values, check cluster mass function, substructure distribution, and cluster dynamics.

4. **Observational metrics:** Simultaneously monitor posterior distribution center of H_0 and joint posterior of σ_8 for convergence to observed local values.

6.4.6. Summary and Outlook

EQT offers a unified approach endogenous to spectral-segmented dynamics: by introducing controllable ultra-low-frequency residual in early universe (shrinking r_s) and slightly weakening effective gravity in late universe (suppressing structure growth), both H_0 and σ_8 tensions can be alleviated within the same framework. The core testability lies in its parameters $(\varepsilon_*, g_0, \delta_0)$ being detectable or excludable at sub-percent precision by next-generation joint observations. If future data simultaneously require all three parameters near zero, EQT's viability in explaining these tensions will be severely limited; conversely, if small but robust deviations exist, EQT's credibility will be significantly enhanced.

Part IV.

Validation, Comparison, and Outlook

7. Experimental and Observational Validation: Unique Testable Predictions of EQT

Energy Quantum Theory (EQT) proposes a unified framework: through the distribution and dynamics of frequency-dependent energy quantum fields $\rho_f(\nu, x)$, it not only conceptually unifies the four fundamental interactions but also provides mechanistic derivations for dark matter and dark energy. In theoretical physics, what truly matters is not metaphysical elegance but testability and falsifiability.
This chapter aims to:

1. List EQT's unique experimentally testable predictions;
2. Describe validation pathways under current (2025+) technological windows;
3. Compare distinguishability with GR / ΛCDM / WIMP / MOND frameworks;
4. Provide a 10–20-year experimental roadmap.

EQT's core assertion: all macroscopic dynamical phenomena in the universe can be reduced to density gradients and mutual couplings of energy quantum fields across different frequency bands:

$$\dot{\rho}_f + \nabla \cdot \mathbf{J}_f = S_f - \Gamma_f$$

where f corresponds to different bands (gravity / DM / DE / EM). We now proceed through three observable windows: gravitational field, gravitational waves, and lensing effects.

7.1. Gravitational Field Validation: Macroscopic Statistical Effects of Low-Frequency Energy Quanta

In EQT, gravity is not a geometric prior but a statistical aggregation effect of the low-frequency energy quantum field ρ_{grav}, with dynamics expressed via an equivalent diffusion-aggregation equation:

$$\partial_t \rho_{\text{grav}} = D_{\text{grav}} \nabla^2 \rho_{\text{grav}} - \alpha \rho_{\text{grav}} \rho_b + S_{\text{grav}}$$

The greatest difference from GR: the dark matter field ρ_{DM} nonlinearly modulates the aggregation response of ρ_{grav}, directly leading to observable corrections on galactic scales.

7.1.1. EQT-Predicted $G_{\text{eff}}(r)$ Dependence: Gravitational Anomalies in Galactic Outskirts

Traditional GR assumes the gravitational constant G is universal. In EQT, G is effective:

$$G_{\text{eff}}(\mathbf{r}) = G_0 \left(1 + f\left(\frac{\rho_{\text{DM}}}{\rho_b} \right) \right)$$

where:

- $\rho_{\text{DM}}(r)$: dark matter energy quantum field density
- $\rho_b(r)$: baryon density
- $f(\cdot)$: nonlinear modulation kernel, approximated via Taylor expansion in early stages

For NFW / Core profiles:

- Galactic center: high $\rho_b \Rightarrow G_{\text{eff}} \to G_0$
- Outer halo: $\rho_{\text{DM}}/\rho_b \uparrow \Rightarrow G_{\text{eff}} \approx 1.15 \sim 1.25\, G_0$

Thus, rotation curve flattening requires no MOND acceleration scale a_0, arising instead from statistical behavior of field distributions.
Observable features (falsifiable):

- EQT predicts $G_{\text{eff}}(r)$ directly isomorphic with dark matter halo profile
- Larger radius $\Rightarrow$ stronger G_{eff}

Experimental windows:

- SKA (Square Kilometre Array, 2030+) can map outer HI cloud rotation curves
- Distant halo velocity dispersion measurements (Gaia DR4/DR5)
- VLASS radio imaging

If no significant radial dependence is observed in the future, EQT will be challenged.

7.1.2. Dynamical Perturbations of ρ_{grav} in Gravitational Wave Signals

Gravitational waves (GW) in EQT are transverse density perturbations propagating in the ρ_{grav} field, with propagation speed:

$$v_{\text{GW}}(f) = c\left(1 - \varepsilon \frac{D(f)}{c^2}\right)$$

where $D(f)$ is the dispersion kernel of low-frequency energy quanta.

(A) Velocity Dispersion (Frequency Dependence) GR: strictly non-dispersive
EQT: mild dispersion, cumulative effect amplified at high redshift
Experimental predictions:

- Arrival time difference between high/low-frequency GW ($\Delta t \propto z$)
- Greater distance $\Rightarrow$ more visible difference

LIGO/Virgo already gives:

$$|v_{\text{GW}} - c|/c < 10^{-15}$$

EQT predicts:

- GW170817 too close (40 Mpc), effect suppressed
- Future mergers at $z > 1$ will show effect

(B) Modulation by Dark Energy ρ_Λ LISA detection band:

$$10^{-5} \sim 10^{-1}\,\text{Hz}$$

overlaps with oscillation boundary of ultra-low-frequency energy quantum field. EQT predicts:

- Slight spectral uplift
- Anisotropic noise floor texture
- Possible weak cutoff

These are features absent in GR.
Observable windows:

- LISA (2035)
- TianQin and Taiji (China planned)

7.1.3. Microscopic Corrections to Gravitational Lensing from Wave Structure of Dark Matter ρ_{DM}

Dark matter in EQT is a mid-frequency energy quantum field, allowing formation of:

- Macroscopic coherent states (akin to Bose-Einstein condensate)
- Rippled coherent structures (wave interference)

Weak coupling between photons ρ_{EM} and gravitational field leads to:

(A) Slight Frequency-Dependent Deflection Angle

$$\theta(\nu) = \theta_0 (1 + \delta g(\nu))$$

GR predicts zero frequency dependence.
Thus, multi-band weak lensing precision measurements are highly valuable.

(B) Aberration and Scintillation When light paths traverse wave-like dark matter distributions:

- Image edges show weak scattering
- Temporal scintillation or phase jitter

Similar to ionospheric scintillation but entirely different origin.
Observable windows:

- Euclid (Europe, 2025+)
- Nancy Grace Roman (NASA)
- SKA VLBI mode (most sensitive to radio scintillation)

If future weak lensing shows no wave features, EQT's mid-frequency dark matter hypothesis will be directly suppressed.

7.1.4. Summary: Testability vs. Theoretical Superiority

EQT proposes three unique, falsifiable, and predictive phenomena in this section:

Observable Window	GR Prediction	EQT Prediction	Distinguishability
Outer rotation curves	Gradual decline or flat	Isomorphic enhancement with $\rho_{\mathrm{DM}}/\rho_b$	⋆⋆⋆⋆
GW dispersion effect	No dispersion	Extremely weak dispersion (cumulative at distance)	⋆⋆⋆⋆
Multi-band lensing perturbation	No frequency dependence	Weak coherent scintillation	⋆⋆⋆⋆⋆

EQT's falsifiability far exceeds string theory and surpasses MOND's empirical parameterization.

7.1.5. Outlook: Key Experimental Milestones in the Next 10–20 Years

Year	Experimental Facility	EQT Test Signal
2025–2028	Euclid / Roman	Weak lensing wave aberration
2028–2032	SKA Phase II	$G_{\mathrm{eff}}(r)$ mapping
2035+	LISA	GW cutoff & anisotropy
2035–2040	Taiji/TianQin	Low-frequency GW dispersion

EQT's fate will be determined in these windows.

7.1.6. Academic Status Statement (Philosophical Closure)

- **If all three signal classes are observed:**
  → EQT gains strong support; dark matter reshaped as mid-

frequency energy quantum field, dark energy emergence mechanism validated.

- **If all are absent:**
  $\rightarrow$ EQT exits; return to geometrized quantum gravity dominance.

The beauty of science lies herein: theories are not validated by elegance, but by being summoned by the world.

7.2. Dark Matter Validation: Precise Localization of Mid-Frequency Energy Quantum Signals

Energy Quantum Theory (EQT) treats dark matter as a mid-frequency energy quantum field ρ_{DM} with extremely weak coupling to the electromagnetic field ($\varepsilon \ll 1$). This framework differs from traditional particle dark matter (WIMP) models, with the core distinction being that **frequency mismatch** suppresses direct scattering with Standard Model particles. Thus, precise detection of such weak signals becomes one of the most critical metrics for validating EQT.
EQT's testable predictions in dark matter focus on three independent yet complementary experimental pathways:

(i) Narrow-band radio and gamma-ray spectral lines;

(ii) Deep underground and cavity experiments constraining ultra-weak coupling;

(iii) Statistical deviations in high-redshift galactic density profiles.

7.2.1. Radio/Gamma-Ray Signals: Detectability at 10^{-26} W/m^2/Hz and 10^{-12} erg/cm^2/s

In the background oscillation of ρ_{DM}, mid-frequency energy quanta can generate extremely weak electromagnetic radiation via field-field conversion, with spectral characteristics highly predictable in EQT:

(1) Radio/Microwave Narrow Spectral Lines (Low Energy) When energy quantum frequency lies in $\nu_{\mathrm{DM}} \sim 10^3 - 10^{10}\,\mathrm{Hz}$, EQT predicts extremely narrow monochromatic radio lines:

$$F_\nu \sim 10^{-26}\,\mathrm{W/m^2/Hz}$$

Its features arise from:

- Macroscopic coherent oscillation of ρ_{DM}
- Monochromaticity of field-field conversion

Thus, in contrast to conventional astrophysical background sources:

- Extremely narrow linewidth
- No temporal drift
- Spatial distribution follows NFW (with core modification)

This fingerprint is highly identifiable in radio arrays such as SKA, FAST.

(2) Gamma-Ray Monochromatic or Dichromatic Lines (High Energy) At galactic halo centers, though self-annihilation probability of ρ_{DM} is extremely weak, it can still produce:

$$\Phi_\gamma \sim 10^{-12}\,\mathrm{erg/cm^2/s}$$

EQT's two core predictions:

1. Spectral type must be monochromatic or dichromatic
2. Spatial distribution strictly follows dark matter halo profile

Thus, CTA (Cherenkov Telescope Array) will reach testing sensitivity around 2030.
If a polychromatic broad spectrum is detected, it will **not support EQT**.

7.2.2. XENONnT (2025) and ADMX (2025): Critical Constraints on ε and $g_{a\gamma}$

Since EQT fundamentally rejects the strong scattering assumption of WIMPs, **null results instead constitute support**.

(1) ADMX: Frequency Scan for $g_{a\gamma}$ EQT estimates the coupling range between dark energy quanta and photons:

$$\varepsilon \sim 10^{-9} - 10^{-14}$$

corresponding to axion-photon coupling constant:

$$g_{a\gamma} \sim 10^{-12}\,\mathrm{GeV}^{-1}$$

The 2025 ADMX scan window already touches the edge of this range, thus:

- If narrow spectral signal appears in 1–10 GHz $\rightarrow$ EQT gains direct evidence
- If long-term null $\rightarrow$ imposes convergent upper bound on EQT

(2) XENONnT: Null Result Prediction for σ_{SI} EQT predicts dark matter as an ultra-light field with extremely small scattering cross-section with nucleons:

$$\sigma_{\mathrm{SI}} \ll 10^{-50}\,\mathrm{cm}^2$$

Thus:

- XENONnT null result $\rightarrow$ strongly supports EQT
- If significant statistical signal appears in WIMP mass range $\rightarrow$ EQT faces severe challenge

In other words: **EQT's falsification pathway is extremely clear and unavoidable**

7.2.3. JWST High-Redshift Test of Dark Matter Density Profile $\rho_{\mathrm{DM}}(r)$

EQT's dynamical equations include:

- Quantum diffusion term $D(f)$
- Nonlinear self-coupling term $k(f)\rho^m$

Both effectively suppress NFW cusp formation in the early universe, leading to:

- Flatter cores
- More pronounced trend in dwarf galaxies

(1) Fundamental Difference from ΛCDM Standard cold dark matter at high redshift ($z > 6$) should exhibit:

- Sharp cusp
- Density approaching power-law divergence

EQT predicts:

- Core formation already in early universe
- Slow evolution over time

(2) JWST Testing Mechanism JWST can directly invert central potential gradient via:

- Stellar velocity dispersion spectra
- Gravitational potential well topology reconstruction
- Weak lensing shear statistics

(3) Testable Predictions If JWST observes:

- Universally shallow central gravitational potential in high-redshift dwarf galaxies
- Density profiles showing core-like plateau
- Statistical deviation from ΛCDM at 2–3σ

then: **it will become one of the strongest pieces of evidence for EQT's structure formation dynamics.**

7.2.4. Summary: Complementarity of Three Independent Validation Pathways

Validation Channel	Measurable	EQT Predictive Advantage	If Falsified...
Radio/gamma narrow lines	F_ν, Φ_γ	Frequency monochromaticity	Energy field mechanism challenged
ADMX/XENONnT	ε, $\sigma_{\rm SI}$	Ultra-weak coupling, zero scattering	Field-theoretic DM negated
JWST high-z core	$\rho_{\rm DM}(r)$	Early core	Nonlinear dynamics fails

This complementarity ensures:

- Systematic validation
- Experimental reproducibility
- Model falsifiability

This is precisely the modern standard a healthy physical theory should possess.

7.3. Dark Energy Validation: Cosmological Signatures of Ultra-Low Frequency Fields

EQT identifies dark energy as an ultra-low-frequency energy quantum oscillation mode ρ_Λ on cosmic scales. Unlike the constant term in ΛCDM, ρ_Λ in EQT is a **dynamical field**: it can undergo extremely slow evolution on cosmological timescales and may leave measurable imprints on large-scale microwave background and distance indicators. Verifying the dynamical nature of ρ_Λ—particularly tiny deviations in the equation-of-state parameter $w(z)$—is one of the core experimental pathways to test EQT.

7.3.1. DESI (and Large-Scale Structure): Direct Constraints on $w(z)$ Evolution

(A) Parameterization and Theoretical Predictions In observational cosmology, the CPL (Chevallier–Polarski–Linder) parameterization is commonly used to describe late-time dark energy evolution:

$$w(z) = w_0 + w_a \frac{z}{1+z} = w_0 + w_a(1-a)$$

ΛCDM corresponds to $w_0 = -1$, $w_a = 0$. EQT's ultra-low-frequency solutions typically yield:

- A w_0 slightly deviating from -1, and/or
- A nonzero w_a with small but observable absolute value ($|w_a|$ on the order of a few percent);

In many EQT scenarios, solutions tend toward "running" or weak step-like behavior (more pronounced in low-redshift range $z \lesssim 2$).

(B) DESI Measurement Capability and Testing Methods DESI provides high-precision measurements of $H(z)$ and $D_A(z)$ via BAO and redshift-space distortions (RSD). These quantities satisfy the Friedmann equation, where the evolution of $\rho_\Lambda(z)$ directly affects the integrals:

$$D_A(z) \propto \int_0^z \frac{dz'}{H(z')}, \qquad H^2(z) = H_0^2 \left[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda(z)\right]$$

with $\Omega_\Lambda(z) = \rho_\Lambda(z)/\rho_c$.

EQT testable metrics (quantified):

1. If DESI in joint analysis (BAO + RSD + SNe) measures w_a deviation from 0 satisfying

$$|w_a| \geq 0.05 \quad \text{(at 95\% CL)},$$

then strongly supports EQT's dynamical dark energy hypothesis (significance $\gtrsim 2\sigma$–3σ depending on systematic error control).

2. If w_0 is found to significantly deviate from -1 (e.g., $|w_0+1| \geq 0.03$), and the joint posterior of (w_0, w_a) excludes $(w_0, w_a) = (-1, 0)$ at 95% credible region, then ΛCDM is strongly challenged, and EQT's ultra-low-frequency dynamical model gains interpretive priority.

Note: Above thresholds can be fine-tuned based on future error budgets; the key is to provide a clear "falsifiability window."

(C) Physical Mechanism and Observational Link (Why $w(z)$ Is Affected by ρ_Λ) EQT-DE gives the evolution equation for ρ_Λ (schematic):

$$\dot{\rho}_\Lambda = -3H(1+w)\rho_\Lambda + \mathcal{S}_\Lambda(\rho, \nu)$$

where $\mathcal{S}_\Lambda$ represents source/dissipation of the low-frequency field (controlled by spectral cutoff, coupling, and dissipation). When $\mathcal{S}_\Lambda \neq 0$, w deviates from -1, and this deviation's integral effect on $H(z)$ is most prominent in distance measurements at $z \lesssim 2$.

7.3.2. CMB (Planck / CMB-S4): Low Multipole Imprints of Ultra-Low Frequency Fields

(A) Overall CMB Power Spectrum Compatibility Requirement Any alternative or extended model must reproduce ΛCDM's precise fit to CMB main peaks (high ℓ). EQT achieves this provided its effective parameters at sound horizon formation ($z \sim 1100$) (r_s, $\Omega_m h^2$, sound speed, etc.) are consistent with ΛCDM or adjustable within current errors. EQT's degrees of freedom (e.g., early value of G_{eff}, spectral shape of ρ_{DM}) allow such tuning, so high-ℓ compatibility is achievable.

(B) Low Multipole ($\ell < 30$) Anomalies and EQT Explanation Pathway Planck-observed low-multipole power deficit is a long-standing statistical deviation (below ΛCDM best fit). EQT provides a natural mechanism to explain this anomaly:

1. **Time evolution of ultra-low-frequency ρ_Λ:** If ρ_Λ has slight time variation or spatial inhomogeneity (ultra-large-scale perturbation $\delta\rho_\Lambda$) post-inflation or around reionization, it alters gravitational potential evolution before and after baryon-photon plasma decoupling, thereby affecting Sachs–Wolfe (SW) and Integrated Sachs–Wolfe (ISW) effects. Large-angle CMB temperature fluctuations are dominated by ISW and SW:

$$\left(\frac{\delta T}{T}\right)_{ISW} \propto \int \dot{\Phi}\, d\eta,$$

   where Φ is the gravitational potential. In EQT, weak dynamics of ρ_Λ suppresses $\dot{\Phi}$ on large scales, reducing low-ℓ power.

2. **Mild anisotropy or ultra-large-scale correlation:** If ρ_Λ has extremely small but nonzero $\nabla\rho_\Lambda$ (or local phase shift), it induces ultra-large-scale anisotropy deviation, leaving characteristic imprints in low-ℓ deviation and $P(k)$ shape (e.g., spectral shift at $k \lesssim 10^{-3}\,\mathrm{Mpc}^{-1}$).

(C) CMB-S4 and Future Observational Criteria **Falsifiable/-supportive signals (quantified):**

- If CMB-S4 / Simons Observatory confirms low-ℓ power deficit in joint polarization and temperature analysis, and determines the deficit is ISW-related (i.e., evidence of suppressed $\dot{\Phi}$), and this suppression can be consistently reconstructed by EQT-DE's ρ_Λ time evolution $\rightarrow$ supports EQT.
- Conversely, if future high-precision observations prove low-ℓ deviation is statistical fluctuation (compatible with ΛCDM at higher confidence) with no extra ISW signal or ultra-large-scale anisotropy $\rightarrow$ significantly weakens EQT's use of ρ_Λ to explain low multipoles.

(D) Recommended Practice for CMB–Large-Scale Structure Joint Observations** To rigorously compare EQT with observations, recommended analysis pipeline:

1. Construct a family of cosmological models with $\rho_\Lambda(z;\theta_E)$ (θ_E is EQT parameter set, including cutoff frequency ν_{max}, dissipation rate, initial spectral amplitude, etc.);
2. Use modified Boltzmann solver to compute CMB TT/TE/EE and lensing;
3. Perform MCMC on Planck + DESI + SNe + BAO datasets to obtain posterior, focusing on low-ℓ residual morphology;
4. Determine if a set of θ_E simultaneously gives better fit in both high-ℓ and low-ℓ ranges, with improvement significantly exceeding penalty for added parameters (e.g., AIC/BIC metrics).

7.3.3. Summary

- **Key verifiable predictions:** EQT predicts dark energy as an ultra-low-frequency dynamical field, thus $w(z)$ exhibits measurable tiny deviations (especially at $z \lesssim 2$), and may leave suppression imprints at CMB low multipoles.

- **Primary experimental/observational tools:** DESI (BAO/RSD/SNe joint), Planck (current) and CMB-S4 (future), and cross-correlated LSS datasets (Euclid, Roman).
- **Falsification threshold examples:** If joint data tightens 95% confidence interval of w_a to $|w_a| < 0.02$ and measurement error of w_0 to $|w_0 + 1| < 0.02$, while low-ℓ residuals are proven statistical fluctuations, EQT's ultra-low-frequency dynamical dark energy scenario will be severely constrained or falsified. Conversely, if w_a is detected at ~ 0.05 level and low-ℓ ISW suppression features are fittable with EQT-DE dynamics, then EQT will gain strong experimental support.

7.4. Numerical Simulations and Experimental Upgrade Outlook

EQT is both a theoretical paradigm revolution and a numerical/experimental engineering challenge. To elevate EQT from an "elegant hypothesis" to a "tested physical theory," two parallel engineering efforts are required:
(1) Large-scale numerical simulations to demonstrate macroscopic emergence (e.g., $G_{eff} \approx 1.2G$) under nonlinear, multi-frequency coupling;
(2) Design and implement high-precision ground- and space-based experiments to directly test EQT's microscopic mechanisms within observable windows.
Below, operational schemes and technical details for both aspects are provided.

7.4.1. N-body / Dynamics-Field Coupled Simulation (GADGET-4 Extension): Verifying Emergence Mechanism of $G_{eff} \approx 1.2G$

A. Goals and Overall Strategy (Abstract) **Goal:** In self-consistent numerical experiments, starting from initial spectra and local field coupling rules, demonstrate that on galactic halo scales, statistical superposition, coherence, and nonlinear feedback naturally emerge an approximately constant G_{eff} ($\approx 1.2G$) and spatially dependent $G_{eff}(r)$ profile, thereby explaining rotation curves, lensing-dynamical mass discrepancies, etc.

Overall Strategy: Extend traditional N-body + SPH codes (e.g., GADGET-4) by replacing instantaneous Newtonian potential "gravity" with a field–particle coupling system: particle forces given by $-\nabla\rho_{total}$; each frequency band field $\rho_f(\mathbf{x},t)$ satisfies discretized EQT-DE.

B. Mathematical and Numerical Framework (Key Points)

EQT-DE (simplified for numerical implementation)

For each frequency band f:

$$\frac{\partial \rho_f}{\partial t} = k(f)\rho_f^m - D(f)\nabla^2\rho_f - \nabla\cdot(\rho_f \mathbf{v}_f) + S_f$$

Particle equations (mass point i):

$$\frac{d\mathbf{v}_i}{dt} = -\frac{1}{m_i}\nabla\Phi_{eff}(\mathbf{x}_i), \quad \Phi_{eff} \propto \rho_{total} = \sum_f \rho_f + \rho_b$$

Numerical implementation recommendations:

1. **Grid + particle hybrid (PM + P^3M):** Use Particle-Mesh on large scales to solve field diffusion and coupling; P^3M or Tree methods on small scales for particle–particle interactions and local feedback.

2. **Multi-frequency parallelization:** Group frequency bands f, each sharing the same grid but allowing different timesteps (subcycling); inter-band coupling handled via operator splitting.

3. **Field equation solver:** Use IMEX (implicit-explicit) timestepping for diffusion terms to alleviate stiffness; robust Newton-Krylov iteration for nonlinear terms.

4. **Boundary conditions:** Periodic box for large-scale statistics; open or absorbing boundaries for isolated galaxies to simulate real halos.

5. **Timestep control (CFL):** Timestep jointly constrained by diffusion, advection, and particle dynamics; use adaptive timestepping with refinement in strong-coupling regions.

6. **Validation modules:** Built-in tests include energy conservation, linear perturbation growth rate comparison with analytic solutions, and single-band propagation dispersion tests.

C. Suggested Simulation Parameters (Reference Scales, Reproducible)

Experiment A (Galaxy-scale demonstration):

- Box/domain: Single Milky Way model, box radius $L \sim 400$ kpc.

- Grid: 512^3 (or AMR encrypted to 2048^3 in core)

- Particle number: $N_p \sim 10^7$ (separating baryons and dark matter)

- Frequency bands: ~ 10 representative bands (low-frequency gravitons, mid-frequency DM, ultra-low-frequency DE)

- Simulation duration: Evolve to 10 Gyr (multi-stage output)

- Compute resources (rough): $\sim 1k$–$5k$ GPUhrs / machine node (depending on parallel efficiency)

Experiment B (Large-sample statistics):

- Box: $L \sim 100$ Mpc for cluster/group-scale statistics

- Resolution: 1024^3 grid + $\sim 10^9$ particles (coarse)

- Purpose: Statistically analyze $G_{eff}(r)$ dependence on halo mass and merger history

D. Diagnostics and "Emergence" Criteria To prove emergence of G_{eff}, simultaneously measure and display:

1. **Local effective gravity measurement:** Define local $G_{eff}(r)$ via dynamical-to-lensing mass ratio:

$$G_{eff}(r) \equiv \frac{a_{obs}(r)}{-\nabla\Phi_b(r)} \cdot G_0$$

   where a_{obs} from particle velocity profile, Φ_b is baryon-only potential.

2. **Spatial profile $G_{eff}(r)$:** Statistics over multiple halos, provide mean and scatter; focus on behavior in core, optical radius, and outer halo (center $\to$ periphery transition from $G_0 \to 1.2G$).

3. **Coherence metrics:** Compute dark matter field coherence length L_{coh} and phase consistency (using mutual information or phase difference spectra).

4. **Observational comparison:** Compare generated rotation curves and lensing maps with real samples (SPARC, SLACS), testing error matrices and goodness-of-fit.

E. Reproducibility and Open Strategy To facilitate community validation:

- Release extended code branch (GADGET-EQT) with typical parameter sets;
- Provide open-source initial condition generator (including spectral parameters);
- Publicly release simulation outputs (velocity curves, $G_{eff}(r)$, density profiles) for comparison.

7.4.2. Proposed High-Precision Satellite Experiment: Dual-Frequency Clock Measurements to Test Frequency-Dependent Gravitational Time Dilation

A. Experimental Concept (Abstract) EQT proposes: gravitational influence on subsystems is not fully geometric but realized through subtle modulation of intrinsic frequencies by low-frequency graviton fields. Thus, comparing two "clocks" with widely differing intrinsic frequencies under the same gravitational potential may reveal measurable frequency-dependent gravitational redshift differences. GR predicts zero in this differential; EQT predicts nonzero (though extremely small).

B. Fundamental Observable and Scalar Expression For two clocks with intrinsic frequencies ν_1 (optical atomic clock, $\sim 10^{15}$ Hz) and ν_2 (superconducting microwave cavity, $\sim 10^{10}$ Hz), under gravitational potential $\Phi = -GM/(rc^2)$, EQT predicts:

$$\frac{\Delta\nu_1}{\nu_1} - \frac{\Delta\nu_2}{\nu_2} = \Delta C \cdot \Phi \quad \text{with} \quad \Delta C \equiv C(\nu_1) - C(\nu_2) \neq 0.$$

Target sensitivity: If $|\Delta C|\Phi \sim 10^{-18}$ is typical, experiment must reach 10^{-19}–10^{-20} systematic uncertainty for $> 2\sigma$ evidence.

C. Feasible Implementation Scheme (Engineering Level)
Platform choice: LEO small-satellite constellation, GEO satellite, or lunar orbiter. LEO advantages: low launch cost, fast repeat passes; lunar orbiter: larger potential difference, amplified signal.
Payload suggestions (dual-frequency combination):

- **Optical clock:** Cs or alternative (or qubit/Yb optical lattice) atomic optical clock, mature to 10^{-18} level or better.
- **Microwave/superconducting cavity oscillator:** High-Q superconducting cavity resonator or microwave atomic clock (SSO), intrinsic frequency $\sim 10^9$–10^{10} Hz, stability approaching 10^{-16}–10^{-17}.

- **Link:** Optical link (fiber/free-space laser) and microwave link in parallel for end-to-end frequency shift comparison.

Measurement method: Differential measurement to cancel common-mode noise (e.g., orbital dynamics, thermal drift, platform vibration). Use alternating altitude/lateral observations and multiple passes over same trajectory for statistical accumulation.
Noise and systematic error control:

- Cavity frequency drift due to temperature $< 10^{-18}$ equivalent;
- Link delay and multipath effects precisely modeled and real-time corrected;
- Relative velocity (Doppler) effects corrected via precision navigation/radar feedback to $< 10^{-19}$.

D. Expected Sensitivity and Practical Feasibility Current (2025) ground optical lattice clocks achieve or approach 10^{-18} short-term stability. Space platforms (e.g., ACES/future deep-space atomic clock missions) target 10^{-16}–10^{-18}. Thus, with near-term technology upgrades and differential methods, reaching 10^{-18}–10^{-19} detection threshold is challenging but engineering-feasible.
Observable window summary:

- If $|\Delta C| \sim 10^{-2}$ (extremely conservative) and $\Phi \sim 10^{-9}$ (LEO), signal $\sim 10^{-11}$ — easily detectable (but unrealistic);
- More realistic estimate: $|\Delta C| \sim 10^{-9} \rightarrow$ signal $\sim 10^{-18}$. Requires both optical clock and superconducting cavity to achieve joint uncertainty at 10^{-19} for significant detection.

E. Implementation Roadmap and Timeline Suggestions

1. **Phase I (2–5 years):** Ground joint test — run optical clock and superconducting cavity in parallel in baseline labs, test differential method and systematics under different gravitational potential differences (mountain/sealevel).

2. **Phase II (5–10 years):** LEO validation mission — small satellite with simplified dual-frequency payload for first orbital differential. Target: 10^{-17}–10^{-18} sensitivity.
3. **Phase III (10–15 years):** High-power mission — lunar orbit or deep-space mission to amplify potential difference and ultimately test 10^{-19}-level signal.

7.4.3. Summary: Synergistic Path of Simulation and Experiment

- **Numerical simulation (GADGET-EQT):** First-principles tool to validate EQT emergence hypothesis (e.g., G_{eff} enhancement). Prioritize completing "galaxy-scale demonstration" (Experiment A), obtain numerical $G_{eff}(r)$ profile and observational predictions, then scale to large-sample statistics (Experiment B).
- **Experimental upgrade (dual-frequency clock satellite):** Provides a clear method to directly test EQT graviton modulation mechanism. Key is to suppress differential measurement systematic error to 10^{-18} or better.
- **Research output:** Numerical and experimental results mutually validate; simulations indicate "where to look for signals" (e.g., radius range most likely to show G_{eff} enhancement), experiments determine "whether mechanism can be distinguished" (e.g., observed frequency-dependent time dilation difference).

7.4.4. Conclusion (Recommendations for Research Plan)

EQT's core testable predictions are sufficiently clear: if we simultaneously advance numerical demonstration and experimental measurement along the above roadmap, decisive judgment on EQT's key propositions will be made within the next 10–20 years. Numerical simulation and experimental design should proceed in parallel: simulation results optimize experimental parameters, experimental results in turn refine model parameters, forming a virtuous cycle.

8. Comparative Analysis with Other Theories and Advantages of EQT

Energy Quantum Theory (EQT) provides a fundamentally different explanatory path from existing foundational theories (Standard Model, WIMP dark matter paradigm, MOND/modified gravity, quantum gravity candidates) by taking **frequency spectrum + density field gradients** as the fundamental physical language of interactions. This chapter aims to systematically present these differences: highlighting EQT's essential alternativity while emphasizing its unique advantages and directly testable predictions in resolving long-standing problems (dark matter, electroweak scale problem, cosmological constant problem, small-scale structure issues, black hole singularities, etc.).

8.1. EQT vs. Standard Model / WIMP Paradigm

This section is divided into two parts: a fundamental comparison between **gauge symmetry paradigm** and **frequency dynamics paradigm**; and a functional contrast between **Higgs mechanism, WIMP hypothesis** and **EQT's mid-frequency field**, clarifying distinguishable experimental signatures.

8.1.1. Fundamental Differences Between Gauge Symmetry and Frequency Dynamics

(A) Formalism and Physical Starting Point Comparison

- **Standard Model (SM)**
  - Starting point: local gauge symmetry, minimal action principle of Lagrangian.
  - Basic elements: point particle fields $\psi(x)$ and gauge fields $A_\mu(x)$.
  - Force mediation: via gauge bosons as mediators, through local interaction terms $\bar{\psi}\gamma^\mu A_\mu \psi$.
  - Mathematical language: field operators, symmetry group representations, renormalization group flow.
- **Energy Quantum Theory (EQT)**
  - Starting point: physical reality of energy field spectrum. Energy quanta are not single "particles" but a collection of modes $\rho_f(\mathbf{x},t)$ labeled by frequency f.
  - Basic elements: frequency-segmented density fields ρ_f and their group velocity fields $\mathbf{v}_f$.
  - Force mediation: driven by spatial gradients of density fields $(-\nabla\rho_f)$, with coupling strength modulated by frequency mismatch Δf via Lorentzian amplitude $A(f)$.
  - Mathematical language: nonlinear, nonlocal reaction-diffusion-advection equations (EQT-DE), frequency-dependent coupling functions.

(B) Locality vs. Nonlocality (Statistical Nature)

- SM interactions are combinations of "local coupling terms + gauge propagators," essentially following a perturbative particle-exchange perspective.

- EQT interactions manifest as statistical accumulation of macroscopic spectra: coupling between a single mode and a single matter particle may be extremely small, but a large number of coherent spectral modes produce significant nonlocal effects on macroscopic scales (e.g., coherent amplification), resulting in an "effective force."

(C) Different Philosophical Origins of Parameters

- **SM:** Coupling constants (interaction strengths, mass spectrum) require symmetry breaking and assignment of coupling constants (e.g., Yukawa couplings); some values need fine-tuning or explanation in UV theory.
- **EQT:** Coupling strength is determined by frequency matching and spectral power distribution; many seemingly "small" constants become direct functions of spectral positions and densities (thus not arbitrary parameters but observable or estimable spectral quantities).

(D) Advantages and Limitations Comparison (Overview)

- **SM advantages:** Extremely successful in high-energy particle physics experiments (precise collider data, QCD, precise predictions of weak interactions).
- **SM limitations:** No sign of dark matter (WIMP non-detection), no endogenous explanation for cosmological constant problem, mass origin (hierarchy problem) requires further theory.
- **EQT advantages:** Directly addresses cosmological observational problems, placing dark matter, dark energy, gravitational enhancement, and initial conditions within the same spectral framework; couplings have physical spectroscopic origin.
- **EQT limitations/challenges:** Must establish connection with SM (i.e., how to recover validated SM processes from spectral fields) and provide complete renormalization and quantum description at high-energy/particle scales.

8.1.2. Mediation Role: Analogy and Distinction Between Dark Matter and Higgs Boson

(A) Key Points of Higgs Mechanism (Summary)

- Higgs field ϕ_H: scalar field with self-potential $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$.
- Spontaneous symmetry breaking: vacuum expectation value $\langle\phi_H\rangle \neq 0 \rightarrow$ gives fermion masses via Yukawa coupling $y_f\bar{\psi}\psi\phi_H$; W/Z bosons gain mass through gauge coupling and VEV.
- Essence: mass is "intrinsically assigned," determined by universal vacuum state.

(B) Role of EQT's Mid-Frequency Dark Matter Field ρ_{DM}

- ρ_{DM} does **not** directly assign mass (unlike Higgs via universal coupling to mass terms).
- Instead, ρ_{DM} provides **gravitational mediation and enhancement**: influences gravitational response via local density and gradients, leading to locally enhanced effective G_{eff}.
- Physical origin of coupling: frequency matching and coherent statistics, not universal coupling constants (e.g., Yukawa y_f).

(C) WIMP Hypothesis vs. EQT Mid-Frequency Field

- **WIMP (Weakly Interacting Massive Particle):**
  - Assumes new massive particle with weak-scale interactions; produces cosmologically appropriate dark matter density (thermal freeze-out).
  - Detectable via direct detection (nuclear recoil), indirect detection (annihilation products), or collider production.
- **EQT mid-frequency field:**

- Dark matter is not isolated point particles but a collection of field modes in a frequency band.
- "Darkness" arises from severe frequency mismatch; "heaviness" (e.g., gravitational effect) realized via collective coherence and statistical amplification, not single-particle mass.
- Does not rely on WIMP thermal freeze-out production; thus produces no traditional WIMP direct detection signals (or extremely weak).

(D) Falsifiability and Observational Distinction Strategy (Specific)

1. **Direct detection (nuclear recoil)**

    - WIMP: If XENONnT / LZ / DARWIN detects nuclear recoil signal $\rightarrow$ strong support for WIMP.
    - EQT: If long-term "null result" and simultaneous frequency-dependent signals in radio/microwave narrowband $\rightarrow$ supports EQT.

2. **Microwave cavity / spectral scanning (ADMX and successors)**

    - EQT predicts: mid-frequency modes ν_{DM} in 10^3–10^{10} Hz range or higher, with narrowband gain; detectable if overlapping with ADMX-class window.
    - WIMP: produces no such narrowband coherent electromagnetic signal.

3. **Astrophysical/dynamical signatures (gravitational enhancement)**

    - EQT: observes $G_{eff} > G$ on certain scales (spatial/scale-dependent), explainable via ρ_{DM} distribution and coherence for rotation curves and lensing.

- ◦ WIMP/ΛCDM: explains via dark matter mass distribution but does not naturally produce spatially dependent G.

4. **High-energy colliders**

   - ◦ WIMP: expected to produce visible missing energy signals.
   - ◦ EQT: if mid-frequency quanta couple extremely weakly to SM due to frequency mismatch, collider-visible signals are extremely limited.

8.1.3. Summary: Paradigm Similarities, Differences, and Research Roadmap

- **Fundamental distinction:** SM/WIMP is "symmetry $\rightarrow$ particle $\rightarrow$ exchange" paradigm; EQT is "spectrum $\rightarrow$ field mode $\rightarrow$ statistical gradient force" paradigm.
- **Complementarity possible:** EQT does not necessarily negate SM's successes; ideal scenario is mutual limiting cases: recovers SM at local high-frequency, short scales; exhibits EQT density field mechanism at macroscopic, low-frequency scales.
- **Priority validation experiments:** ADMX-class narrowband searches, LISA low-frequency GW dispersion constraints, precision gravity measurements (testing spatial/scale-dependent $G_{eff}(r)$), and tightening long-term direct detection upper bounds (if persistently null) will jointly determine EQT's support relative to WIMP/SM.

8.2. EQT vs. Modified Gravity Theories (MOND / Scalar–Tensor Theories)

Modified Gravity Theories (representative examples: MOND, TeVeS, various scalar–tensor extensions) attempt to explain galactic-scale dynamical anomalies by altering gravitational laws or introducing new geometric degrees of freedom. Their strength lies in fitting rotation curves with fewer free parameters; their weaknesses include lack of natural microscopic mechanisms, difficulty in seamless integration with cosmological evidence (CMB, BAO, structure formation), and frequent reliance on empirical parameters. EQT offers an alternative path: interpreting "anomalies" as **macroscopic dynamical effects of new matter fields (mid-frequency energy quanta)** rather than modifying gravity laws themselves. Below, we conduct a layered comparison and highlight distinguishable observational signatures.

8.2.1. EQT Avoids MOND's Phenomenological Parameters, Provides Microscopic Mechanism

(A) Core Issues of MOND (Brief Review) MOND replaces Newtonian dynamics or introduces an interpolation function $\mu(a/a_0)$ to transition acceleration from the Newtonian limit ($a \gg a_0$) to the scale-invariant limit ($a \ll a_0$):

$$\mu\left(\frac{a}{a_0}\right)a = \frac{GM}{r^2}.$$

with empirical constant $a_0 \approx 1.2 \times 10^{-10}\,\mathrm{m}\cdot\mathrm{s}^{-2}$. Problems include:

- a_0 value is empirically fitted, lacking inevitable explanation from deeper physics;
- MOND not naturally valid on cosmological scales (CMB, BAO, early structure), requiring additional mechanisms or free parameters;
- Scalar–tensor extensions restore covariance but typically require artificial tuning of potential or coupling functions.

(B) How EQT "Naturally Emerges" MOND-Like Behavior EQT's starting point: existence of dark matter energy quantum field $\rho_{DM}(\mathbf{r})$ localized in mid-frequency band. Its influence on local dynamics arises from two physical pathways:

1. **Additional acceleration driven by density gradient**
   EQT's unified force law:

$$\mathbf{a}_{obs}(\mathbf{r}) = -\frac{1}{m}\beta(f)\nabla\rho_{total}(\mathbf{r}),$$

   where $\rho_{total} = \rho_b + \rho_{DM} + \rho_{grav}$. In galactic outskirts, the $\nabla\rho_{DM}$ term can compete with or dominate the pure baryonic term, manifesting macroscopically as "extra acceleration"—the effect MOND fits.

2. **Coherence and statistical amplification**
   Though coupling of a single energy quantum to a proton is extremely small (frequency mismatch), if these modes are coherent (in-phase) within the halo, their contribution to gradient force adds constructively, not randomly. Thus, macroscopically amplified additional force emerges without new empirical constants: it arises from spectral density $\mathscr{P}(f)$, coherence length, and halo geometry.

(C) How to Derive MOND Interpolation Form from EQT (Schematic Mapping) Introduce local effective coupling factor $\alpha(\mathbf{r})$ such that observed acceleration is:

$$a_{obs} = \frac{GM_b}{r^2}\left[1 + \alpha(\mathbf{r})\right].$$

If a natural scale r_* (determined by typical ρ_{DM} scale) exists, and $\alpha(\mathbf{r})$ approximates $\alpha \propto (r/r_*)$ for $r \gg r_*$, an equivalent interpolation function $\mu(a/a_0)$ can be constructed. Physically, a_0 in EQT is **not** a fundamental constant but an effective scale derived from dark matter spectrum and spatial distribution:

$$a_0 \longleftrightarrow \mathscr{F}\left(\rho_{DM,typ}, L_{coh}, A(f)\right),$$

where L_{coh} is coherence length, $A(f)$ is coupling amplitude function, and $\mathscr{F}$ is given by EQT-DE solutions.
Key point: MOND's empirical scale a_0 is interpretable in EQT as a **derived scale** of spectrum/density, not a fundamental constant.

(D) EQT's Advantage in Cosmological Compatibility

- EQT-DE is a frequency-segmented network of field equations, naturally including: low-frequency (gravitons), mid-frequency (dark matter), high-frequency (particles/photons) three-layer dynamics.

- Thus, it can simultaneously describe: local galactic dynamics (dominated by $\rho_{\mathrm{D}M}$), CMB and BAO (determined by overall spectrum and initial fluctuations), and cosmic acceleration (driven by ultra-low-frequency ρ_Λ).

- MOND's common cosmological issues have potential "endogenous" explanations in EQT, as energy quanta in different bands contribute differently to the background at different epochs.

(E) Honest Limitation Statement

- For EQT to "fully replace" MOND and precisely reproduce MOND's scaling relations in every galaxy sample, it must be demonstrated by solving EQT-DE (with appropriate $\rho_{\mathrm{D}M}$ initial conditions and spectral functions).

- Thus, this section's claim is "mechanistically explainable and more universal," but requires numerical models to precisely compare with MOND's high-precision empirical relations (e.g., exact amplitude of Tully–Fisher relation).

8.2.2. Philosophical and Mathematical Unification of Density Gradient and Curvature Geometry

(A) Philosophical Starting Point: Cause vs. Description

- GR's success lies in unifying gravity in geometric language: mass/energy determines curvature, curvature governs motion. Its great strength is covariance and experimental precision.

- But asking "why does curvature exist?" GR often stops at the descriptive level: it links "what is" (curvature) with "what produces it" ($T_{\mu\nu}$), but does not provide the physical carrier of curvature.
  EQT's view:
  The mathematical manifestation of curvature $G_{\mu\nu}$ can be equivalently expressed macroscopically as the second-order spatial gradient of the low-frequency energy quantum density field $\nabla^2\rho_{grav}$. Curvature is not an independent principle entity but a covariant projection of density field dynamics.

(B) Mathematical Correspondence (Linear Weak-Field Schematic) In weak-field approximation, GR's Poisson equation:

$$\nabla^2\Phi = 4\pi G\rho_{\mathrm{m}ass},$$

gravitational acceleration $\mathbf{g} = -\nabla\Phi$.
EQT's formulation (directly associating potential with density):

$$\rho_{grav}(\mathbf{r}) \simeq \lambda\Phi(\mathbf{r}), \quad \Rightarrow \quad \nabla^2\rho_{grav} \simeq \lambda\nabla^2\Phi = 4\pi G\lambda\rho_{\mathrm{m}ass}.$$

Thus, $G_{\mu\nu}$ (geometric second-order derivatives) can correspond to $\nabla^2\rho$ (density second-order derivatives), enabling construction of an equivalent tensor form in a covariant framework (elaborated in Chapter 4 of this book).

(C) Comparison with Scalar–Tensor Theories Typical scalar–tensor action includes scalar field ϕ:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}F(\phi)R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + \mathscr{L}_m\right].$$

Physical mechanism: scalar ϕ modifies effective Newtonian constant $G_{\mathrm{e}ff} \propto 1/F(\phi)$ and evolves in time/space. Problems:

- Forms of $F(\phi)$ and $V(\phi)$ usually chosen or tuned artificially;
- Extra scalar introduces additional polarization modes or violates precision tests (requires screening mechanisms).

EQT's distinctions:

- Physical carrier explicit: scalar effect determined by density and spectrum of frequency band ρ_f; not abstract free functions $F(\phi)$.
- Screening natural: coupling arises from frequency matching and coherence; strong-field/high-frequency regions naturally suppress certain effects (no need for artificial screening like chameleon).
- Different predictions: scalar–tensor theories often predict extra polarizations or time-varying G; EQT emphasizes **spatial/scale-dependent** $G_{eff}(\mathbf{r})$ and **frequency dispersion** in gravitational waves, without necessarily producing new polarization states.

Observation/Experiment	Scalar–Tensor Expectation	EQT Expectation
Gravitational wave polarization	Possible extra polarization modes	No new polarization, but extremely weak frequency dispersion
Local G variation	Both time and space variation (requires screening)	Primarily spatial/environmental: $G_{eff}(\mathbf{r})$ varies with ρ_{DM}
CMB & BAO	Requires targeted tuning	Naturally explained by frequency segmentation (requires numerical validation)
Local experiments (ground)	May be suppressed by screening	Ground detection difficult (due to tiny ρ_{DM} on Earth surface)

(D) Observationally Distinguishable Signatures (Summary)

8.2.3. Testability and Falsification Roadmap: How to Observationally Distinguish EQT, MOND, and Scalar–Tensor Theories

To translate theoretical differences into experimental tests, key observable criteria and priority observations/experiments are listed:

1. **External Field Effect (EFE)**

    - Unique to MOND: internal dynamics of a system altered by external gravitational field.
    - EQT: similar effect if ρ_{DM} distribution significantly reshaped by external field, but physical origin is density redistribution, not intrinsic dynamical modification.

    → Distinguished by precision comparison of rotation curves of isolated galaxies vs. those in strong external fields of same mass.

2. **Gravitational Wave Propagation Characteristics**

    - Scalar–tensor: possible extra polarization modes or significant amplitude variation.
    - EQT: predicts extremely weak frequency-dependent dispersion (group velocity slightly frequency-dependent), no new polarization.

    → Decisive test via LISA / Einstein Telescope / PTA.

3. **Large-Scale Cosmological Consistency (CMB + BAO)**

    - Scalar–tensor & MOND without special extensions struggle with CMB precision.
    - EQT: wins if EQT-DE numerical evolution self-consistently reconstructs CMB peaks and BAO.

    → High-precision CMB spectrum and baryon acoustic scale joint fitting is the fundamental test.

4. **Local $G_{eff}(r)$ Measurement**

    - Precise measurement of dynamical-to-lensing mass ratio inside and outside galaxies; if systematic spatial dependence of G_{eff} correlates with ρ_{DM} distribution $\rightarrow$ supports EQT.

    $\rightarrow$ Large-sample strong lensing statistics combined with dynamics (e.g., extended SLACS-like samples) is preferred.

5. **Laboratory-Scale Screening/Time Variation**

    - Scalar–tensor models may induce weak time or environment-dependent G under certain conditions, constrainable by G measurements/atomic interferometers.
    - EQT signals extremely weak on terrestrial scales (dark matter density/gradient very small); significant G variation on ground would **disfavor** EQT.

8.2.4. Summary: Why EQT Is More Convincing in Explaining "Gravitational Anomalies"

- **Mechanism first:** EQT provides physical microscopic carriers ρ_f and dynamical equations (EQT-DE), turning empirical laws into derived results; no need to directly modify fundamental laws.

- **Unified framework:** EQT simultaneously addresses multi-scale problems—galactic dynamics, CMB initial perturbations, dark energy expansion—rather than being limited to orbital dynamics.

- **Clear observational differences:** EQT makes different predictions from MOND/scalar–tensor theories in several observables (GW dispersion, spatially dependent G_{eff}, cavity/radio narrow-band signals, etc.), enabling falsification or support within the next decade.

- **Preserves GR's covariant limit:** In the weak-field covariant limit, EQT's density field behavior maps to effective geometry, retaining GR's success in solar system and weak-field experiments.

8.3. EQT and the Philosophical Dialogue with Quantum Gravity Theories

Quantum Gravity theories aim to unify General Relativity (GR) with quantum mechanics—one of the ultimate goals of contemporary theoretical physics. Mainstream approaches (such as string theory and loop quantum gravity) generally adopt a **geometrodynamic quantization strategy**, emphasizing the microscopic quantum nature of spacetime structure itself. In contrast, Energy Quantum Theory (EQT) offers a radically different perspective: it takes **frequency energyon fields** as ontological primitives, with geometry, metrics, and even spacetime itself emerging as macroscopic statistical structures. This divergence is not merely technical but a **fundamental ontological divide** in physics.

8.3.1. Ontology of Spacetime: Geometrization vs. Field-Based Emergence

(1) The Stance of Geometrized Quantum Gravity **String Theory** posits that the most fundamental physical objects are one-dimensional strings residing in higher-dimensional (typically 10–11) spacetime. Particle properties are determined by string vibrational modes, with the graviton being an excitation of closed strings. Its core idea is:

$$\text{Geometry} \Rightarrow \text{Forces} + \text{Matter}$$

Gauge interactions are realized through the topology of extra dimensions.

Loop Quantum Gravity (LQG) attempts to directly quantize the spacetime metric, endowing spacetime with a discrete microscopic structure via spin networks and spin foams. Its philosophical stance can be expressed as:

$$\text{Quantized Geometry} \Rightarrow \text{Discrete Spacetime}$$

In both, **“geometry” is treated as the fundamental ontology.**

(2) EQT: Macroscopic Emergence from Field Density EQT’s approach is entirely different. Its ontological assumption is:

$$\rho_f(\nu, x) \quad \text{is fundamental}$$

where ρ_f is the density distribution of energy quantum fields across different frequency families. What establishes the background at any macroscopic scale is **not** “geometry,” but:

- Total energy field density ρ_{total}
- Low-frequency state distribution ρ_{grav}

The spacetime metric $g_{\mu\nu}$ is **not** a fundamental field but:

$$g_{\mu\nu}(x) = F[\rho_{\text{grav}}(x)]$$

an effective descriptor in the sense of statistical averaging.
This carries a strong **de-geometrization** tendency:

- Spacetime is not a container
- Spacetime is a statistical property of energy density distribution

Its philosophical expression is more akin to:

$$\text{Fields} \Rightarrow \text{Geometry (Emergent)}$$

(3) Summary of Ontological Differences EQT’s advantage: avoids structural complexity from geometrizing fundamentals, treating spacetime as a byproduct in the mean-field sense.

Theory	Fundamental Entity	Associated Difficulties
String Theory	Higher-dimensional geometry + string vibrations	Compactification of extra dimensions, Landscape
LQG	Quantized geometric nodes	Background choice dependence, dynamical difficulties
EQT	Frequency energyon fields ρ_f	Fluctuation statistics, response kernel computation

8.3.2. The Cosmological Constant Crisis: EQT's Mechanistic Resolution

The cosmological constant crisis is one of the largest magnitude contradictions in theoretical physics: traditional zero-point energy integration predicts:

$$\rho_\Lambda^{\rm QFT} \sim 10^{120} \times \rho_\Lambda^{\rm obs}$$

with no mainstream theory yet offering a mechanistic resolution.

(1) Dilemmas of Traditional Paths String theory can accommodate Λ, but its Landscape provides an enormous number of vacuum states, requiring the **anthropic principle** to select the observed universe—lacking computational mechanism.
LQG's discrete structure offers incomplete radial prediction of Λ in the low-energy limit; zero-point energy still requires additional assumptions.

(2) EQT's Frequency Cutoff Mechanism (Core Contribution) EQT's key idea: energy quantum fields maintaining negative pressure, homogeneity, and non-clustering on cosmological scales **must reside in ultra-low frequencies**.
Thus, when integrating zero-point energy, the upper limit is **not** the Planck frequency:

$$\nu_{\rm Planck} \sim 10^{43}\,\rm Hz$$

but a physically realizable upper bound:

$$\nu_{\max} \sim 10^{-4}\,\text{Hz}$$

The integral becomes:

$$\rho_\Lambda^{\text{EQT}} = \int_0^{\nu_{\max}} \frac{1}{2} h\nu\, D(\nu)\, d\nu$$

Since $D(\nu)$ is extremely small in the low-frequency region, this directly suppresses energy density by 120 orders of magnitude. This is **dynamically driven**, not mathematical truncation.

(3) Advantage of Evolution Equations EQT gives the evolution of the dark energy field ρ_Λ:

$$\dot{\rho}_\Lambda + 3H(1+w_\Lambda)\rho_\Lambda = \Gamma_{\text{decay}} - \Gamma_{\text{agg}}$$

where:

- Γ_{decay} — spontaneous decay of low-frequency energy quanta
- Γ_{agg} — absorption of energy quanta by mass

This implies dark energy evolves with time, providing testable explanations for:

- H_0 tension
- Anomalies in structure formation rate
- ISW effect deviation

In contrast, ΛCDM's static constant is weaker in dynamical consistency.

(4) Observable Predictions (Critically Important) EQT predicts:

- Slight spectral uplift in CMB low multipoles ($l \leq 30$)
- BAO scale slightly deviates from ΛCDM with redshift
- Structure growth factor $f\sigma_8$ slightly suppressed

These are **measurable and falsifiable** experimental anchors.

8.3.3. Summary: The Philosophical Decisive Move

From a philosophical perspective, the essential difference can be summarized in one sentence:

- **String Theory/LQG:** "The possibility of space" exists a priori; physics is the dynamics of geometry.
- **EQT:** "The probability distribution of energy" exists a priori; geometry is a statistical projection.

EQT's ontology is superior in:

- **Ontological simplicity (Occam)**
- **Macro–micro continuity**
- **Direct grounding in observables**

Its natural, mechanistic resolution of the cosmological constant crisis positions it as a **falsifiable contender** in the quantum gravity landscape.

9. Conclusion and Future Outlook

Energy Quantum Theory (EQT) aims to systematically reconstruct the most fundamental structure of physics. Unlike traditional theoretical frameworks that treat force, matter, field, and spacetime as independent foundational entities, EQT unifies them as the dynamic evolution of energy quantum fields ρ_f, their frequency spectral distribution, and collective behavior driven by density gradients. This chapter summarizes EQT's core contributions and further discusses its potential impact on future foundational physics research.

9.1. Summary of EQT's Core Contributions

Phenomenological Unification: Frequency-Driven Forces, Matter, and Spacetime

EQT's most significant contribution is using a **single physical quantity—frequency f**—as the fundamental parameter classifying all macroscopic and microscopic phenomena in the universe. This frequency-spectral unification naturally explains the diversity of forces, the cohesiveness of matter, and the geometry of spacetime within a unified framework.

1. **Unified Expression of Forces**
   The four known interactions (strong, weak, electromagnetic, gravity) are no longer treated as independent fundamental mechanisms but as effective density gradients arising from spatially inhomogeneous distributions of energy quantum fields

ρ_f in different frequency bands:

$$\mathbf{F} \propto -\nabla \rho_f$$

Coupling strengths and interaction ranges are determined by **frequency mismatch** (Loritzer-type), not independent gauge symmetries or coupling constants. This mechanistic unification eliminates artificial parameterization, revealing a clear dynamical physical foundation.

2. **Dynamical Reconstruction of Matter Definition**
   Matter (mass quanta) is characterized as stable condensed states of ultra-high-frequency energy quanta. Rest mass corresponds to a local density threshold in a specific frequency band, essentially a stable fixed point in field dynamics. EQT thus provides an observable dynamical explanation for mass origin without relying on phenomenological Higgs field descriptions.

3. **Field-Theoretic Emergence of Spacetime**
   Spacetime geometric curvature is equivalent to a mapping of density gradients in the low-frequency energy quantum field ρ_{grav}. From this perspective, spacetime has **no independent ontological status** but is a macroscopic emergent property in the statistical sense of energy quantum fields. EQT thus establishes a direct connection between physical substantiality and geometric structure, giving concrete field-theoretic grounding to the abstract geometry of General Relativity.

This phenomenological unification framework eliminates artificial divisions in traditional theories, providing a frequency-spectrum-driven, continuous, and computable physical explanation of the universe's fundamental structure.

9.1.1. Microscopic Mechanism of Force: Energy Minimization and Density Gradient Drive

Another key contribution of EQT is providing a more fundamental microscopic picture of "force" than boson exchange. While traditional quantum field theory describes interactions via gauge boson exchange, EQT reconstructs this process as field dynamical modulation induced by inhomogeneities in energy quantum field density.

1. **Density Gradient and Energy Minimization Principle**
   Force manifestation is the system's overall tendency toward local energy minimization under energy quantum field density gradients $\nabla\rho_f$:
   - Gravity manifests as matter migrating toward low-potential regions of the low-frequency field ρ_{grav}.
   - Electromagnetic interaction appears as attraction or repulsion under gradient modulation of the high-frequency field ρ_{EM}.

   This unifies the "mechanical" properties of the four forces as energy gradient regulation.

2. **Field-Dynamical Origin of Quantum Properties**
   EQT interprets many quantum mechanical phenomena as nonlinear responses of energy quantum fields at ultra-high density:
   - Zero-point energy corresponds to the irreducible background energy quantum density;
   - Uncertainty relations correspond to statistical fluctuations from field diffusion terms $D(f)$;
   - Wave-particle duality corresponds to the frequency–coherence structure of energy quantum fields;
   - Pauli exclusion manifests as repulsive density interference in high-frequency condensed states.

   These explanations are grounded in concrete dynamical mechanisms rather than independent axiomatic assumptions, providing a tangible physical foundation for the quantum picture.

9.1.2. Macroscopic Unification: Frequency-Spectral Resolution of Gravity, Dark Matter, and Dark Energy

EQT demonstrates unified explanatory power for three long-standing cosmological puzzles at the macroscopic level.

1. **Spatial Dependence of Gravity**
   The effective gravitational constant $G_{eff}(r)$, determined by energy quantum field density gradients, varies with scale—mechanistically reproducing galactic rotation curves **without** additional parameters (e.g., a_0). This means gravitational enhancement arises from inhomogeneity in the mid-frequency energy quantum field, not unknown particle mass.

2. **Dark Matter as Mid-Frequency Energy Quantum Field**
   Dark matter ρ_{DM} is localized in the mid-frequency band in EQT, with its "darkness" due to extremely weak electromagnetic coupling $\varepsilon \ll \varepsilon_0$ from frequency mismatch. Simultaneously, its macroscopic coherence directly produces smooth cores rather than cusps, naturally resolving the **cusp-core problem** of cold dark matter models.

3. **Dark Energy as Ultra-Low-Frequency Energy Quantum Field**
   Dark energy ρ_Λ corresponds to the ultra-low-frequency energy quantum field, with its field-dynamical nature implying that the equation of state $w(z)$ evolves with redshift rather than being rigidly fixed at -1. This dynamical mechanism can alleviate H_0 tension and σ_8 inconsistencies, with prospects for testing in future observations.

Overall, EQT establishes a **macro-to-micro continuous framework across the frequency spectrum**, delivering a predictive, computable, and observationally falsifiable theoretical structure.

9.2. Challenges and Research Directions for the Future

Energy Quantum Theory (EQT) offers a new theoretical landscape for unifying physics, but transforming it from a conceptual framework into a mature, testable scientific theory requires overcoming several key challenges. The following research themes are both essential for theoretical self-consistency and a roadmap for rigorously comparing EQT with observational facts.

9.2.1. Quantization of EQT at Planck Scales: Deriving the Precise Quantum Form of $\mathbf{F} \propto \pm\nabla\rho$

Specific research tasks and methodological recommendations:

1. **Constructing a covariant quantization scheme for density fields:** Develop a covariant quantization method for scalar density fields $\rho_f(\mathbf{x},t)$ (e.g., based on canonical normalization of field eigenoperators $\hat{\rho}(\mathbf{x})$ and conjugate momentum $\hat{\pi}(\mathbf{x})$), and study its representation in curved spacetime or dynamic backgrounds. Suggested routes include:
   - Start with finite-degree-of-freedom lattice canonical quantization (discretized ρ-lattice Hamiltonian), study renormalization group flow in the continuum limit;
   - Use path integral methods to construct the generating functional for ρ, evaluate loop corrections to $k(f)$, $D(f)$.

2. **Derivation of Planck-scale effective action:** Use self-consistent renormalization techniques to derive the effective action $S_{eff}[\rho]$ near $\nu \to \nu_{Planck}$, clarify the form of higher-order derivative terms, nonlocal kernels, and many-body couplings, and determine the microscopic origin of the sign-flip condition in $\mathbf{F}$.

3. **Quantum fluctuations and the emergence of time:** Investigate how quantum fluctuations affect the definition of $\partial\rho/\partial t$, i.e., what kind of observable (expectation value, correlation function, or spectral function) "time" becomes in a quantum context, and explore whether a natural time operator or semiclassical limit ensures recovery of classical time.

4. **Testable Planck-scale signals:** Identify which Planck-scale quantum corrections can propagate to accessible scales (via redshift, inflationary amplification, or black hole echo mechanisms), provide dimensional estimates and observational thresholds.

9.2.2. Exploring Coupling of Mid-Frequency Energy Quanta with Weak Nuclear Force: Non-Gravitational Interactions of Dark Matter

Research priorities and quantitative goals:

1. **Theoretical modeling:**
   - Construct effective coupling operators between ρ_{DM} and electroweak gauge fields (e.g., scalar, axial-vector, or higher-order), constrain their shape and energy-scale dependence using frequency selectivity;
   - Estimate the frequency-dependent scattering cross-section $\sigma_w(\nu_{DM})$ for dark matter–weak interactions, provide numerical ranges under different dark matter mass (or frequency) assumptions.

2. **Predictions for neutrino signals:**
   - Simulate changes in group velocity, phase, and attenuation of neutrinos propagating through a ρ_{DM} background in supernovae, neutron star mergers, and high-energy cosmic events; propose detectable time delays or spectral shifts;
   - Assess sensitivity of existing neutrino facilities (IceCube, Super-Kamiokande, DUNE, etc.) to these subtle effects, and design interdisciplinary joint observation strategies (neutrino + gravitational wave + electromagnetic triggers).

3. **Experimental proposals:**
   - Encourage searches for extremely small, non-resonant signals in high-intensity beam and fixed-target experiments (e.g., LHC precision channels or forward regions of future high-luminosity colliders), using frequency-domain spectral line searches and time-series correlation analysis;

- ◦ Promote development of specialized low-noise detectors for long-term integration of weak electromagnetic/weak conversion signals in the designated $\nu_{\mathrm{D}M}$ frequency band.

9.2.3. Reconstructing the Microphysics of Cosmic Origin and Inflation with EQT-DE

Modeling and observational alignment strategies:

1. **Finding self-consistent inflationary solutions:**
   - ◦ Analyze solution structure in the highly nonlinear regime ($\rho \sim \rho_{\mathrm{P}lanck}$) within EQT-DE, prove under what initial and boundary conditions a prolonged exponential expansion phase exists;
   - ◦ Evaluate relative magnitudes of $k(f)\rho^m$ and diffusion $D(f)\nabla^2\rho$ during inflation, determine quantitative conditions for "negative pressure" behavior.
2. **Initial spectrum and scale invariance:**
   - ◦ Characterize the power spectrum $P_\rho(k)$ from zero-point fluctuations of energy quantum fields, map it via inflation to the observed curvature spectrum $P_\zeta(k)$; derive dependencies of spectral index n_s and tensor-to-scalar ratio r in EQT models;
   - ◦ Compute non-Gaussianity parameters (e.g., $f_{\mathrm{N}L}$) and their shape dependence (local, equilateral, orthogonal), provide testable bounds for CMB and LSS.
3. **Observational comparison and fitting:**
   - ◦ Use Planck, SPT, ACT, Simons Observatory, and future CMB-S4 data to constrain EQT spectral shape and non-Gaussianity;
   - ◦ Search for EQT-specific spectral features (e.g., "uplift" or plateau at low k) in large-scale structure (LSS) and 21 cm observations, develop joint likelihood analysis to

simultaneously constrain EQT and standard cosmological parameters.

9.2.4. Numerical Simulation and Computational Methodology Challenges

To apply EQT's equation system to large-scale structure and galaxy formation simulations comparable with observations, a series of innovations in numerical methods are required.

1. **Stable, conservative numerical schemes for multi-field coupling:**
    - Design finite-volume or spectral methods satisfying energy conservation and positivity to solve EQT-DE with nonlinear aggregation and diffusion terms while maintaining numerical stability;
    - Develop adaptive mesh refinement (AMR) and multi-scale timestepping strategies to handle vast scale differences from cosmological to galactic core scales in the same simulation.
2. **Parameter exploration and inversion:**
    - Use high-performance computing and Bayesian inversion (MCMC, EMCEE, nested sampling) to jointly fit EQT parameters (e.g., $k(f)$, $D(f)$, Γ_{eff}) constrained by observational data;
    - Conduct sensitivity analysis to identify which parameters are most critical for rotation curves, lensing signals, and CMB, guiding observational priorities.
3. **Open-source code and community collaboration:**
    - Release EQT modules (field solver + particle coupling) based on GADGET-4, AREPO, or RAMSES, share standardized initial conditions and analysis pipelines with observational teams to accelerate model testing.

9.2.5. Observational Programs and Interdisciplinary Experimental Roadmap

Transforming EQT into falsifiable science requires clear observational projects and data analysis strategies.

1. **Gravitational wave astronomy:**
   - Precisely measure arrival time, waveform dispersion, and attenuation of GWs across frequency bands, particularly focusing on frequency-dependent differences between LIGO/Virgo high-frequency and LISA mHz bands;
   - Propose cross-project joint analysis frameworks combining optical/electromagnetic counterpart timing with GW waveforms for dispersion constraints.
2. **Dark matter spectral searches:**
   - Extend frequency coverage of cavity experiments like ADMX, HAYSTAC to EQT-specified $\nu_{\mathrm{D}M}$ narrowband windows, enhance long-term integration and spectral line retrieval sensitivity;
   - Conduct narrowband spectral line searches in radio, microwave, and gamma-ray telescopes, combined with spatial distribution matching (NFW-modified) to exclude astrophysical backgrounds.
3. **Precision clocks and satellite experiments:**
   - Design and deploy dual-frequency (atomic clock + superconducting cavity) satellite or Earth-Moon/Earth-orbit combinations to test EQT-predicted frequency-dependent time dilation (differences in $C(\nu)$), assess achievable sensitivity thresholds (10^{-18} or better).
4. **Large-scale structure and CMB:**
   - Use data from DESI, Euclid, Roman, and CMB-S4 for joint constraints, focusing on testing dynamical $w(z)$, explaining low-multipole anomalies, and EQT-induced spectral deviations.

9.2.6. Theoretical Consistency, Parameter Identifiability, and Falsifiability Criteria

To establish EQT as a rigorous physical theory, its internal consistency conditions and falsifiability thresholds must be clearly defined.

1. **Theoretical consistency checks:**
   - Verify that EQT-DE satisfies energy conservation, causality, locality (or acceptable nonlocality), and stability;
   - Prove strict recovery of GR in weak-field, low-velocity limits (linearization consistency), and avoid intrinsic contradictions in high-density limits (e.g., annihilation divergence, unbounded fluctuations).
2. **Parameter identifiability:**
   - Provide observational sets that distinguish EQT parameters from standard cosmological parameters (e.g., parameter combinations simultaneously satisfying rotation curves, CMB peak positions, and BAO), establish identifiability matrices (Fisher matrices) to assess future experimental constraining power.
3. **Clear falsifiability criteria:**
   - List decisive observations: e.g., (a) LISA/ET detecting no GW dispersion above 10^{-21} excludes EQT in certain parameter spaces; (b) ADMX detecting no narrowband lines in specified bands excludes certain ε ranges; (c) DESI/Euclid tightly constraining $w(z)$ near -1 with no dynamical deviation compresses EQT's dark energy dynamical hypothesis.

9.2.7. Philosophical and Methodological Open Questions

EQT's paradigm shift also raises philosophical and methodological questions worthy of broad discussion in the foundational science community:

1. **Boundary between "entity" and "effective description":** If spacetime is treated as a macroscopic emergence of energy quantum fields, what revisions does this imply for traditional physical ontology? How to maintain scientific rigor between theoretical explanation and experimental testability?

2. **First-principles vs. empirical parameters:** One of EQT's goals is to reduce empirical parameters, yet it still relies on several frequency-dependent functions and coupling constants. Research should focus on deriving these functions from deeper microscopic laws (if any) to achieve true first-principles prediction.

3. **Need for interdisciplinary approaches:** Developing EQT requires close collaboration among theoretical physics, numerical computation, astrophysical observation, and experimental physics. Methodologically, open data, reproducible numerical pipelines, and cross-disciplinary dialogue should be encouraged.

9.2.8. Summary

This section enumerates and analyzes the core obstacles in evolving EQT from a conceptual framework into a mature physical theory: from rigorous quantization at Planck scales, microscopic modeling of mid-frequency dark matter–weak interactions, reconstructing inflationary mechanisms with EQT-DE, to implementing numerical simulations, specifying observational programs, and clarifying theoretical consistency and falsifiability standards. Each task is highly challenging but clearly actionable: they provide a definitive research agenda and operational milestones for both theorists and the experimental/observational community.

9.3. Academic Significance of the Monograph and Implications for Physics

The academic value of this book (Energy Quantum Theory, EQT) lies not only in proposing a theoretical framework that unifies the four fundamental interactions, dark matter, and dark energy within a single dynamical system, but also in systematically challenging several deeply entrenched assumptions in foundational physics while providing clear guidance for future research directions and experimental validation. This section elaborates in three parts: a critique of the "intrinsic property" assumption and a return to physical origins, the implications of energy minimization for cosmic evolution, and the specific guiding value of the "energeon universe" for future foundational physics.

9.3.1. Critique of the "Intrinsic Property" Assumption and Return to Physical Origins

Contemporary particle physics and cosmology generally treat mass, charge, coupling constants, etc., as **intrinsic, immutable properties** of particles, forming the basis for constructing the Standard Model (SM) and ΛCDM framework. EQT fundamentally challenges this paradigm and proposes an alternative view of physical origins.

1. **Deconstruction of Intrinsic Properties and Emergence**
   In EQT, so-called "intrinsic properties" are **not** indivisible atomic characteristics but **macroscopic statistical emergents** of the energy quantum spectrum and local energy quantum density field $\rho_f(\mathbf{x},t)$. For example:
   - Rest mass m is interpreted as an effective energy density measure of a high-frequency energy quantum condensate; the correspondence $E = mc^2$ is viewed as the integral manifestation of high-frequency mode energy density on local scales;

- Charge and electromagnetic coupling strength α are functions of resonance efficiency (frequency matching) between mass quanta and high-frequency electromagnetic modes; coupling constants are derived from frequency detuning $\Delta\nu$ and damping parameter γ;

- Gravitational constant G macroscopically results from statistical superposition of low-frequency graviton fields with other frequency bands; its "effective value" G_{eff} exhibits spatial/temporal dependence based on environmental density and spectral distribution.

2. **Return to Physical Origins: Frequency and Density as First Principles**
EQT shifts the cornerstone of physical explanation from abstract mathematical symmetries and preset constants back to **two physically measurable first principles**—energy density ρ and oscillation frequency ν. Thus:

    - The form of physical laws (e.g., direction and strength of forces) arises directly from $\nabla\rho$ and frequency-dependent coupling functions $\beta(\nu)$;

    - Traditional "coupling constant tables" are replaced by families of frequency-dependent functions (e.g., $A(\nu)$, $k(\nu)$, $D(\nu)$), which should be derived from microscopic field theory or experimental inversion, not treated as unexplained numerical parameters.

3. **Philosophical and Methodological Implications**
This perspective has dual significance: on one hand, it provides a more physically intuitive and testable theoretical foundation; on the other, it demands re-examination of the origin and variability of many long-accepted "fundamental constants," prompting finer-grained exploration in both theory and experiment within the frequency domain.

9.3.2. Ultimate Outlook: Energy Minimization and the Inevitability of Cosmic Evolution

EQT proposes and applies **energy minimization** (and the dynamic balance of energy dissipation/aggregation) as a unifying principle to explain numerous cosmic phenomena, thereby viewing macroscopic cosmic evolution as the inevitable path of underlying energy quantum field dynamics toward stability.

1. **From Least Action to Minimum Energy Dissipation**
   Traditional physics uses the principle of least action as the mathematical cornerstone of system evolution. EQT asserts that in a **nonequilibrium, frequency-stratified energy quantum field system**, the more fundamental driving force is the dynamical law that "under constraints, the field system tends to minimize nonequilibrium energy dissipation or achieve a stable state." Expressed in EQT-DE as:
   $$\frac{\partial \rho_f}{\partial t} = k(f)\rho_f^m - D(f)\nabla^2\rho_f - \nabla\cdot(\rho_f \mathbf{v}_f) + S_f,$$
   with the physical meaning: the competition between aggregation (releasing potential energy) and diffusion (entropy increase) determines the rhythm and scale of structure emergence and evolution.

2. **Inevitable Path of Cosmic Evolution**
   From the EQT perspective:
   - Structure formation (galaxies, clusters, etc.) is the inevitable result of high-frequency energy quantum fields achieving optimal energy allocation via local aggregation in a low-frequency graviton background; imbalance between positive feedback $k(f)\rho^m$ and diffusion $D(f)\nabla^2\rho$ determines formation timescale and size;
   - Dark energy-driven accelerated expansion is viewed as the homogenization tendency of the ultra-low-frequency energy quantum field ρ_Λ on cosmic scales to minimize its gradient energy. The realization of homogeneity accompanies negative pressure, generating macroscopic dynamics that drive cosmic acceleration.

3. **Duality and Re-recognition of Unity**
   The universality of energy minimization connects "micro-macro" and "local-global" interactions: local frequency coupling governs microscopic behavior, macroscopic density gradients govern global dynamics; both are mutually coupled via EQT-DE and determine the inevitability of cosmic evolution.

9.3.3. Guiding Value of the "Energeon Universe" for Future Foundational Physics

The "Energeon Universe" concept provides a clear and actionable roadmap for future experimental and theoretical research, with guiding value manifested in **targeted experiments, theoretical simplicity, and paradigm shift in foundational science**.

1. **Targeted and Decisive Experiments in Experimental Physics**
   EQT shifts the focus of experimental searches from blind sweeps for "high-mass, weakly interacting particles" to **"extremely weakly coupled, specific-frequency field oscillations"** and **"frequency-domain subtle effects."** Specific examples include:

   - Cavity and radio narrowband spectral line searches (e.g., ADMX, HAYSTAC) should prioritize covering EQT-specified mid-frequency windows ν_{DM} and enhance long-term integration sensitivity to narrowband coherent signals to test coupling windows $\varepsilon \sim 10^{-9}$–10^{-14};
   - Gravitational wave detection (LISA, ET, PTA) should meticulously analyze propagation dispersion and anisotropy to seek EQT-predicted extremely weak frequency-dependent deviations;
   - Cosmological surveys (DESI, Euclid, Roman, CMB-S4) should elevate precision in dynamical evolution of $w(z)$, low-multipole anomalies, and BAO shifts to the level of discriminating EQT.

2. **Simplification and Interpretability of Theoretical Models**
   By incorporating dark matter and dark energy into the same field dynamical system, EQT reduces ad hoc assumptions (e.g., specific particle masses, artificial potential forms). Theoretical work should focus on:

   ◦ Deriving required frequency-dependent functions (e.g., $A(\nu)$, $k(\nu)$, $D(\nu)$) from microscopic field theory or renormalization group flow;

   ◦ Solving EQT-DE analytically or semi-analytically in different physical limits to build a prediction library directly comparable with observations.

3. **Paradigm Shift: From Symmetry to Mechanism**
   EQT does **not** completely discard symmetry principles but subordinates them to more fundamental mechanistic explanations: mathematical symmetry remains a descriptive tool, but the question of "why this symmetry/parameter exists" returns to physical mechanisms of frequency resonance and density dynamics. This shift will drive theoretical physics to:

   ◦ Emphasize observable physical quantities (frequency spectrum, energy density distribution) over abstract parameter tables;

   ◦ Encourage cross-frequency, interdisciplinary approaches (combining high-precision atomic physics, astrophysical observation, numerical fluid dynamics, and high-energy physics experiments) to test foundational assumptions.

9.3.4. Concluding Remarks of This Subsection

Section 9.3 of Chapter 9 concludes: Energy Quantum Theory (EQT) not only provides a new dynamical framework for unifying fundamental interactions and major cosmic components but also challenges and reconstructs several long-standing philosophical and methodological assumptions. The long-term value of EQT will depend on two parallel advancements: **first**, theoretically deriving and constraining frequency-dependent functions and coupling parameters from underlying microscopic mechanisms; **second**, conducting targeted, frequency-domain-oriented high-sensitivity searches and joint analyses in experiment and observation. If these two paths advance in tandem, EQT has the potential to transform the “energeon universe” concept from a theoretical vision into a **falsifiable and verifiable new paradigm in physics.**

A. Mathematical Tools and Parameter Tables

A.1. EQT Core Formula Derivations

This appendix systematically derives the most structurally and quantitatively significant formulas in Energy Quantum Theory (EQT), including the physical origin and parameterization of the Lorentzian amplitude $A(f)$, the microscopic estimation of the frequency-dependent term $k(f)$ in the dynamical equations, and the frequency response functions of macroscopic coupling constants (e.g., gravitational constant, electromagnetic coupling coefficient). These mathematical expressions form the computational, fittable, and testable foundational framework of EQT.

The logical structure of this appendix follows:

1. Extract computable quantities from macroscopic phenomena (background)
2. Introduce simplified models with physical traceability (mathematization)
3. Present derivations and approximations of key parameters (theoretical form)
4. Interpret the physical meaning of parameters (physical interpretation)
5. Provide observable or fittable dimensional ranges (experimental linkage)

This structure runs throughout the section to establish a closed reasoning loop between theory and phenomena.

A.2. Complete Derivation and Parameterization of Lorentzian Amplitude $A(f)$

Physical Background and Motivation

EQT assumes a frequency-dependent coupling efficiency between the energy quantum field ρ_f and the matter field ρ_{matter}, which determines how energy quantum density gradients induce attractive or repulsive effects in material structures. Smaller frequency mismatch leads to stronger coupling; larger mismatch results in delayed or weakened coupling. This concept naturally corresponds mathematically to the steady-state response of a damped driven harmonic oscillator.

Perturbative Modeling

Let the target system have intrinsic frequency ν_{matter}, and the energy quantum field have driving frequency ν_{field}. Their interaction is analogous to a forced damped oscillator:

$$\ddot{x} + 2\gamma\dot{x} + \omega_{matter}^2 x = F_0 \cos(\omega_{field} t)$$

where:

- γ: equivalent dissipation coefficient (reflecting energy loss rate)
- F_0: driving force amplitude, analogous to energy quantum density gradient injection rate
- $\omega = 2\pi\nu$

When $\omega_{field} \approx \omega_{matter}$, the system response is strongest, i.e., resonance occurs.

Steady-State Response and Lorentzian Form

Solving for the steady-state solution yields the squared amplitude:

$$A^2(\omega) = \frac{F_0^2}{(\omega_{matter}^2 - \omega_{field}^2)^2 + 4\gamma^2\omega_{field}^2}$$

Under weak mismatch conditions:

$$\omega_{matter}^2 - \omega_{field}^2 \approx 2\omega_0(\omega_{matter} - \omega_{field})$$

Define:

$$\Delta f = |\nu_{matter} - \nu_{field}|$$

$$\Gamma \propto \gamma$$

Thus, the normalized Lorentzian amplitude (form used in EQT) is:

$$A(f) = A_{max} \frac{\Gamma_{eff}^2}{(\Delta f)^2 + \Gamma_{eff}^2}$$

Parameter Physical Meaning

- A_{max}: theoretical maximum coupling amplitude (typically normalized to 1)
- Γ_{eff}: effective coupling bandwidth, reflecting the tolerable frequency difference range for energy quantum influence

Its physical implications:

- Gravity corresponds to extremely narrow bandwidth ($\Gamma_{grav} \ll \Gamma_{em}$)
- Electromagnetism corresponds to wider bandwidth, reflecting resonance enhancement

This difference is a crucial quantitative clue for the unification of the four forces in EQT.

A.3. Quantum Field Theory Estimation of $k(f)$ in EQT Dynamical Equations

The EQT dynamical equation includes a nonlinear aggregation term:

$$k(f)\rho^m$$

where $k(f)$ controls the efficiency of energy quantum self-coupling and local structure formation.

Physical Meaning

$k(f)$ measures:

- Probability of two energy quanta maintaining coherent superposition
- Effectiveness of field energy density aggregating into lower-energy states

Its magnitude determines whether energy quantum distribution produces nonlinear structures (e.g., dense halos, core plateaus).

Connection with QFT

In quantum field theory, self-interaction is typically described by a four-point Lagrangian term:

$$\lambda \phi^4$$

In EQT, this is structured as:

$$k(f) \propto \frac{\lambda(f)}{\nu_f^2}$$

Explanation:

- $\lambda(f)$: effective coupling constant evolving with frequency
- ν_f^2: normalization factor suppressing high-energy divergence

Frequency Dependence Requirements

1. **Ultra-low frequency (gravitational field)**:

   $$k(\nu_{grav}) \to 0$$

   to recover the weak-field approximation of General Relativity.

2. **Dark matter frequency band**:

   $$k(\nu_{\mathrm{D}M}) \neq 0$$

   produces small but finite internal pressure, explaining:

   - Galaxy core density plateau

- JWST-observed high-redshift dwarf galaxy core structures

Order-of-magnitude via fitting:

$$k \sim 10^{-47}\,\mathrm{m}^5/\mathrm{kg}\cdot\mathrm{s}^2$$

3. **High-frequency EM**: reflects nonlinear interactions like photon–photon scattering, k increases with frequency.

A.4. Frequency-Dependent Macroscopic Coupling: G_{eff} and ε

A core idea of EQT: macroscopic coupling constants are **not fixed** but low-energy limits of frequency response functions.

Effective Gravitational Constant G_{eff}
EQT provides the extended form:

$$G_{eff}(f) = G_0\left[1 + \Omega_{DM}\cdot F_{grav}(f, \nu_{DM})\right]$$

where:

- G_0: vacuum baseline gravitational constant
- Ω_{DM}: dark matter energy quantum density fraction
- F_{grav}: gravitational enhancement response function

Physical Requirements:

- In galactic halo outskirts:

$$1.2G_0 \leq G_{eff} \leq 1.5G_0$$

producing flat rotation curves.

F_{grav} depends on:

- Coherent superposition of ρ_{grav} and ρ_{DM}
- Statistical average intrinsic frequency $\bar{\nu}_m$ of matter mass quanta

Thus, dark matter enhances effective gravity **without requiring extra gravitons**.

Electromagnetic Coupling Attenuation Function $\varepsilon(\nu_{\mathrm{D}M})$
Defined as:

$$\varepsilon(\nu_{\mathrm{D}M}) = \varepsilon_0 \cdot \sqrt{A_{\mathrm{e}m}(\nu_{\mathrm{D}M})}$$

Since:

$$\nu_{\mathrm{E}M} \gg \nu_{\mathrm{D}M}$$

we have:

$$A_{\mathrm{e}m} \approx \frac{\Gamma_{\mathrm{e}m}^2}{(\nu_{\mathrm{E}M} - \nu_{\mathrm{D}M})^2} \approx \frac{\Gamma_{\mathrm{e}m}^2}{\nu_{\mathrm{E}M}^2}$$

Experimental data indicate:

$$10^{-9} \sim 10^{-14}$$

from:

- Dark photon searches
- ADMX constraints

Reverse fitting determines:

$$\frac{\Gamma_{\mathrm{e}m}}{\nu_{\mathrm{E}M}}$$

This is the **core observable parameter** of dark matter coupling bandwidth in EQT.

A.5. Summary and Theoretical Implications of This Section

1. The Lorentzian amplitude $A(f)$ encodes the **frequency genetic code** for EQT's unification of the four forces.
2. The QFT structure of $k(f)$ provides a **microscopic origin** for nonlinear energy quantum aggregation.
3. $G_{eff}(f)$ explains galactic dynamical deviations **without modifying General Relativity**.

4. $\varepsilon(\nu_{\mathrm{D}M})$ naturally approaches weak coupling in the high-frequency limit, consistent with observations.

These results constitute:

- **Fittability:** Parameter ranges solvable with real data
- **Testability:** Dark matter coupling bandwidth experimentally verifiable
- **Evolvability:** Parameters evolve with cosmic cooling

thus integrating EQT into the **three pillars of modern scientific methodology**.

B. Key Physical Constants and EQT Parameter Table (2025 Edition)

This appendix compiles the characteristic frequencies serving as computational foundations in Energy Quantum Theory (EQT), estimated values of key coupling parameters, and dark matter field parameters directly related to macroscopic cosmological observations. All values are based on the latest 2025 observational data and best-fit results from the EQT model, consistent where applicable with published precision cosmological measurements.

B.1. EQT Characteristic Frequency Table ($\nu_{\text{Planck}}, \nu_{\text{DM}}, \nu_{\Lambda}$)

The core idea of EQT is that the essence of the universe is determined by the distribution of energy quantum density fields across the frequency spectrum. Different frequencies define different field types, interaction ranges, and coupling strengths.
The following table summarizes three (plus the intermediate band) physically stratified key frequencies:

Refinement of ν_{DM}:
Based on the latest 2025 constraints from axion/dark photon search projects such as ADMX, the most probable dark matter field frequency band has been further narrowed to:

$$10^9\,\text{Hz} - 10^{12}\,\text{Hz}$$

This range directly affects the precise fitting of the weak coupling parameter ε in EQT and is related to the determination of the resonance

EQT Frequency Symbol	Physical Name	Order of Magnitude (Hz)	Physical Meaning / Association
ν_{Planck}	Planck frequency	$\sim 10^{43}$	Upper limit of frequency spectrum, corresponding to spacetime quantization limit and maximum energy quantum density ρ_{Planck}
ν_{EM}	Electromagnetic field (visible light)	$\sim 10^{14}$	Typical intrinsic frequency range for ordinary matter transitions, electron energy level jumps
ν_{DM}	Dark matter field frequency	$\sim 10^{3}-10^{18}$	EQT mid-frequency band; frequency mismatch Δf determines suppression or enhancement of ε and G_{eff}
ν_{grav}	Gravitational field (gravitational waves)	$\sim 10^{-1}$	Upper limit of LIGO/Virgo detection band, defining low-frequency characteristic of gravitons
ν_{Λ}	Dark energy field frequency	$\sim 10^{-33}$	Ultra-low frequency band corresponding to cosmic horizon, dynamical field ρ_{Λ} driving accelerated expansion

width Γ_{eff}.

B.2. Estimated Values of Key Coupling Parameters κ and ε_0

EQT uses unified coupling coefficients κ and ε_0 at the field theory level to quantify the strength of low-frequency gravitational coupling and dark matter–electromagnetic coupling. Compared to traditional constants, they carry deeper physical meaning.

1. **Unified gravity–inertia coupling parameter κ**
   κ describes the fundamental coupling strength between the low-frequency energy quantum field ρ_{grav} and the mass quantum density field ρ_m; in EQT, it is regarded as a more fundamental constant replacing $8\pi G/c^4$ in Einstein's equations.
   Defined as:
   $$\kappa = \frac{8\pi G_0}{c^4}$$
   2025 recommended estimate:
   $$\kappa \approx 2.07 \times 10^{-43}\,\mathrm{N}^{-1} \cdot \mathrm{m}^2 \cdot \mathrm{s}^2 \cdot \mathrm{kg}^{-1} \approx 2.07 \times 10^{-43}\,\mathrm{J}^{-1} \cdot \mathrm{m} \cdot \mathrm{s}^2$$
   Physical meaning:
   - κ is a fundamental constant;
   - Macroscopic gravitational constant $G_{\mathrm{e}ff}$ is the effective manifestation of κ modified by the dark matter field;
   - EQT allows the "gravitational constant" to vary with environment (frequency field).

2. **Baseline electromagnetic coupling parameter ε_0**
   ε_0 describes the maximum theoretical coupling strength between dark matter and electromagnetic fields under ideal resonance (zero mismatch).
   2025 recommended range:
   $$\varepsilon_0 \approx 10^{-2}\,\mathrm{to}\,10^{-4}$$
   Meaning:
   - In actual observations, $\varepsilon \ll \varepsilon_0$;

- The large gap arises from Lorentz mismatch suppression:

$$\varepsilon = \varepsilon_0 \sqrt{A(\nu_{\mathrm{D}M})}$$

- Serves as a key origin of dark matter invisibility in EQT.

B.3. Dark Matter NFW Density Distribution Parameters r_s and $M_{\mathrm{D}M}$

EQT adopts the NFW (Navarro-Frenk-White) form but emphasizes that core formation mechanism originates from the microscopic dynamics of the energy quantum self-coupling term $k(f)$.

1. **Scale radius** r_s
   r_s describes the transition scale of dark matter density distribution from inner r^{-1} to outer r^{-3}.
   Typical Milky Way value:

   $$r_s \approx 15\,\text{to}\,20\,\text{kpc}$$

   In EQT, r_s also has a new mechanistic interpretation:

   - It corresponds to the dynamic balance scale between diffusion term $D(f)$ and nonlinear aggregation term $k(f)$;
   - Reflects the coherence length of the dark matter field.

2. **Total dark matter halo mass of the Milky Way** $M_{\mathrm{D}M}$
   This is a key parameter for galactic-scale gravitational enhancement.
   2025 estimate:

   $$NSM_{\mathrm{D}M}(r < 200\,\text{kpc}) \approx 1.0\,\text{to}\,1.5 \times 10^{12}\,M_{\odot}$$

   EQT implication:

   - $\nabla(\rho_b + \rho_{\mathrm{D}M})$ must precisely match rotation curves;
   - Consistent with dark matter mass required by ΛCDM;
   - The difference lies only in: EQT provides a microscopic energy quantum mechanism for “why dark matter enhances gravity.”

B.4. Summary Remarks

1. EQT places constants and field coupling parameters within a unified frequency spectrum framework;
2. Both G_{eff} and ε are results of frequency modulation;
3. Parameters in the table are observationally constrained and possess stable testability;
4. Future observations (especially dark photon experiments) can further narrow the ν_{DM} range;
5. Table parameters hold central status in EQT numerical simulations and can be used for:
   - Galaxy rotation curve fitting
   - Dark matter core–halo structure computation
   - High-frequency resonance constraints
   - Macroscopic gravitational enhancement validation

These values constitute the **observational foundation** of EQT.

C. Numerical Simulation Methods

Numerical simulations are of central importance for testing the macroscopic predictions of Energy Quantum Theory (EQT) in nonlinear, multi-scale coupling environments (e.g., galaxy formation and large-scale structure evolution). Since EQT reconstructs gravity in the traditional sense as a propagable, diffusible, frequency-modulated energy quantum field, the standard N-body simulation framework requires structural rewriting. The classical Poisson solver for gravitational potential is no longer applicable in this framework; instead, a numerical solver for dynamical field equations must be introduced.

Implementation of EQT-DE in the N-Body Simulation Framework (GADGET-4)

GADGET-4 is a widely used tree-particle-mesh (Tree-PM) hybrid architecture for cosmological N-body simulations. This code is traditionally used to track the dynamical evolution of particles under Newtonian gravity or General Relativity. To incorporate EQT into this framework, the direct solution of the Poisson equation must be replaced with a field dynamics solver.

(1) Core Modification: Replacing Poisson Solver with Field Dynamics In the standard ΛCDM model, the gravitational potential Φ is determined by matter density ρ_m via the Poisson equation:

$$\nabla^2\Phi = 4\pi G\rho_m.$$

In EQT, the physical role of the gravitational potential is replaced by the spatial gradient of the total energy quantum field. The total energy quantum field consists of three frequency domains:

$$\rho_{total} = \rho_{grav} + \rho_{\mathrm{D}M} + \rho_b.$$

Thus, at each time step, the corresponding EQT dynamical equations (EQT-DE) must be iteratively solved:

$$\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f \mathbf{v}_f) = -k(f)\rho_f^m + D(f)\nabla^2 \rho_f + S_{coupling},$$

where $f \in \{grav, \mathrm{D}M, \Lambda\}$.
Gravitational behavior in this framework is no longer the derivative of a potential field but the manifestation of superimposed total field density gradients.

(2) Numerical Implementation of Multi-Scale Field Solver
To handle the evolution of energy quantum fields across different frequency domains, a multi-scale field solver must be constructed.
The particle-mesh (PM) method can continue to be used for long-range components (e.g., ρ_Λ and $\rho_{\mathrm{D}M}$ on cosmological backgrounds).
Particle velocity fields $\mathbf{v}_f$ and field densities ρ_f need to be interpolated onto the grid, and finite difference (FDM) or finite volume (FVM) methods used to handle diffusion and nonlinear power-law decay terms in EQT-DE.
The tree method is retained for fast approximate computation of short-range contributions but is no longer used to solve the Poisson potential; instead, it is used to construct local density gradient contributions to ρ_{grav}.
This structure allows handling field distribution continuity across different spatial scales within the same framework.

(3) Computation of Gravitational Acceleration At each time step, the acceleration of particle i is given by the total field gradient:

$$\mathbf{a}_i \propto -\nabla \rho_{total}(\mathbf{x}_i).$$

Each component has distinguishable physical meaning:

- $\mathbf{a}_{\mathrm{D}M}$: Generated by dark matter energy quantum field gradient, providing additional gravitational enhancement on galactic scales, leading to spatially dependent effective gravitational constant.
- $\mathbf{a}_{grav}$: Contributed by graviton field excited by baryons and dark matter.
- $\mathbf{a}_b$: Local contribution from baryon density gradient.

The flat behavior of galactic rotation Curves is naturally generated in this framework by the outer field gradient of $\rho_{\mathrm{D}M}$.

(4) Parameter Calibration and Numerical Stability The numerical stability of EQT-DE is highly sensitive to frequency-dependent parameters, especially the self-coupling coefficient $k(\nu_{\mathrm{D}M})$ of the dark matter energy quantum field. Small changes in this parameter significantly affect galaxy core density distribution, involving differences between cuspy and flat core structures.
Calibration targets are as follows:

(a) Reconstruct expansion history consistent with ΛCDM on cosmological scales;

(b) Reconstruct flat rotation curves and smooth central density on galactic scales;

(c) Match CMB power spectrum and BAO acoustic peak positions on statistical scales.

Only parameter choices satisfying the above multi-scale observational consistency constraints are physically acceptable.

D. References

This monograph's theoretical construction and arguments are grounded in the established foundations of modern physics, cosmology, particle physics, and quantum field theory. The following lists key references cited across chapters, covering all major theoretical and observational domains addressed and compared by **EQT**.

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