Vacuum Density and Cosmic Expansion
A Physical Model for Vacuum Energy, Galactic Dynamics and Entropy

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Abstract

This paper presents an investigation into the origin and evolution of vacuum energy in the universe and proposes that the energy density of the vacuum is not unlimited. It is physically constrained by fundamental processes such as hadronic interactions, thermal transitions, and entropic dynamics. From this approach, a consistent model emerges in which vacuum energy decreases over the course of cosmic evolution.

The model provides an alternative explanation for both the cosmological constant and the flat rotation curves of galaxies, without requiring dark matter [11, 17]. In addition, it explains the accelerated expansion of the universe as a consequence of entropic effects in spacetime [9, 21].

Comparisons with the Pantheon+ supernova data set confirm consistency with the observed cosmic expansion history. Additional derivations and numerical analyses are provided in the appendices.

1 Introduction

The cosmological constant problem represents one of the greatest discrepancies between observation and theory in modern physics [1, 12]. While quantum field theory predicts an enormous vacuum energy density, measurements of the accelerated expansion of the universe show that the observed vacuum energy density is many orders of magnitude smaller [3].

Various approaches have been proposed to solve this problem, including fine-tuning mechanisms, dynamic fields such as quintessence, and thermodynamically inspired models of gravity [8, 9]. This article proposes an alternative approach, postulating that vacuum energy is physically constrained by fundamental processes. In this model, this constraint occurs through four successive evolutionary phases:

1. Suppression of high-energy fluctuations by QCD confinement (early universe),
2. Dilution of vacuum energy through entropic expansion,
3. Saturation at a thermal transition upon cosmic cooling
4. Stabilization into a residual vacuum structure acting as a gravitational field.

These four phases lead to a model in which vacuum energy density evolves dynamically, explaining both cosmological expansion and galactic rotation curves without invoking dark matter or dark energy [11, 17].
We elaborate this model step-by-step in the following sections

2 Cosmic Evolution of Vacuum Energy

This section describes the evolution of vacuum energy in four successive physical phases: hadronic suppression, entropic dilution, thermal saturation, and finally the frozen hadronic structure that remains as a weak gravitational field. Each phase limits or transforms the vacuum's energy content on its respective scale and is numerically substantiated [1, 2, 3].

2.1 Hadronic Suppression on Subatomic Scale

According to quantum chromodynamics (QCD), vacuum fluctuations with wavelengths shorter than 1 femtometer are suppressed by confinement effects [4, 5]. This results in a natural upper limit for vacuum energy.

Numerical derivation:

Energy of a neutron: $E \approx 1$ GeV $\approx 2.0 \times 10^{-10}$ J
Volume of 1 $\text{fm}^3 = 10^{-45}$ m^3
Maximum energy density:

$$\rho_{\text{cutoff}} = \frac{E}{V} = 2.0 \times 10^{35} \text{ J/m}^3$$

Suppression factors: Additional suppression factors are discussed in [6, 7][6, 7].

Several suppressions are also active but have very minor impact.
Suppression processes above 1 fm scale:[1]

- Mass damping: $I_M = M \cdot e^{-L/L_M}$, $L_M \approx 1.3$ fm
- Thermal damping: $I_E = E \cdot e^{-L/L_E}$, $L_E \approx 6$ fm
- Electromagnetic factor: $I_{\text{EM}} \approx 0.993$
- Yukawa screening: $I_Y = e^{-L/L_Y}$, $L_Y \approx 1.4$ fm

Total suppression factor I_{tot} at $L = 1$ fm:

$$I_{\text{tot}} \approx 0.382$$

Resulting energy density:

$$\rho_1 = I_{\text{tot}} \cdot \rho_{\text{cutoff}} = 7.64 \times 10^{34} \text{ J/m}^3$$

[1]Suppression of vacuum fluctuations, as used in this model, fundamentally differs from renormalization in quantum field theory. Renormalization mathematically removes divergences by redefining quantities such as mass and charge, often requiring fine-tuning. In contrast, suppression is based on physical processes (like QCD confinement) that effectively eliminate fluctuations above a certain energy scale.

2.2 Entropic Dilution of Vacuum Energy

During cosmic expansion, vacuum entropy increases, leading to a decrease in energy density. This idea is related to approaches such as in [8, 9].

$$\rho(t) = \rho_{\text{cutoff}} \left(\frac{\lambda_{\text{QCD}}}{\lambda(t)} \right)^{\alpha} \left[1 - \exp\left(-\frac{\lambda(t)}{\lambda_{\text{therm}}} \right) \right]$$

where $\lambda(t)$ represents the cosmic scale, $\lambda_{\text{QCD}} \approx 1$ fm, and $\alpha \approx 1.08$.

2.3 Thermal Saturation at Critical Temperature

For large $\lambda(t)$ the exponential term approaches 1, and energy density becomes:

$$\rho_0 \approx \rho_{\text{cutoff}} \left(\frac{\lambda_{\text{QCD}}}{\lambda(t)} \right)^{\alpha}$$

For $\lambda(t) \approx 10^{26}$ m this yields:

$$\rho_0 \approx 1.0 \times 10^{-9} \text{ J/m}^3$$

2.4 Frozen Hadronic Effect as Gravitational Field

After the thermal transition, the vacuum becomes stable. The structure functions as a gravitational field influencing cosmic dynamics. This aligns with the framework of emergent gravity [10, 11] and the thermodynamic interpretation of Einstein's equations [9].

Friedmann Equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

2.4.1 Physical and Mathematical Interpretation of Rotation Effects

The remaining frozen hadronic gravitational field contributes to gravitational acceleration but alone is insufficient to explain flat rotation curves. Combined with a constant entropic acceleration, a matching profile arises [11].

Physical Model: The hadronic structure acts as a diffuse, spherically symmetric mass with density $\rho_{\text{energy}} \approx 5 \times 10^{-10}$ J/m^3. The entropic component originates from spatial entropy growth, independent of local mass.

Total Acceleration:

$$g_{\text{total}}(r) = \underbrace{\frac{8}{3}\pi G \rho_{\text{mass}} \cdot r}_{\text{hadronic}} + \underbrace{a_{\text{entropic}}}_{\text{entropic}}$$

with $\rho_{\text{mass}} = \rho_{\text{energy}}/c^2$ and $a_{\text{entropic}} \approx 1 \times 10^{-10}$ m/s^2.

Rotation Speed:

$$v(r) = \sqrt{g_{\text{total}}(r) \cdot r} = \sqrt{\left(\frac{8}{3}\pi G \rho_{\text{mass}} \cdot r + a_{\text{entropic}}\right) \cdot r}$$

For $r \approx 10$ kpc, this gives a stable velocity of 170–180 km/s, in agreement with observations of e.g. NGC 3198 [12]. This confirms the model's physical consistency without dark matter.

3 Galactic Application: Rotation Curve of NGC 3198

In this section, we apply the vacuum model from Section 2 to galactic scale, focusing on the well-known galaxy NGC 3198. *Appendix A2* provides a fully developed numerical model based on four physically motivated components:

1. **Newtonian component**: classical gravity from visible baryonic matter, resulting in a rotation curve that rises and then falls;

2. **Entropic component**: a distance-dependent negative acceleration due to entropy increase in the vacuum;

3. **Thermal component**: an additional acceleration due to vacuum condensation below a critical temperature (≈ 30 K);

4. **Hadronic amplification**: a smooth tanh-shaped amplification factor that enhances the frozen vacuum field at large distances.

These four components are combined into a total acceleration and rotation velocity that closely match the observed rotation curve of NGC 3198, without the need to introduce dark matter.

3.1 Combined Acceleration: Simplified Physical Approach

For analytical insight, we consider here a simplified model with two dominant contributions:

- The **hadronic contribution** is modeled as a homogeneous, spherically symmetric vacuum field with effective mass density $\rho_{\text{mass}} = \rho_{\text{energy}}/c^2$, leading to a linearly increasing acceleration:

$$a_{\text{vac}}(r) = \frac{8}{3}\pi G \rho_{\text{mass}} \cdot r \tag{1}$$

- The **entropic contribution** is modeled on large scales as a constant acceleration, resulting from the spatial increase of entropy:

$$a_{\text{ent}} \approx 1 \times 10^{-10}\ \text{m/s}^2 \tag{2}$$

The total acceleration at distance r is then:

$$a_{\text{tot}}(r) = a_{\text{vac}}(r) + a_{\text{ent}} \tag{3}$$

and the corresponding rotation velocity follows as:

$$v_{\text{tot}}(r) = \sqrt{a_{\text{tot}}(r) \cdot r} = \sqrt{\left(\frac{8}{3}\pi G \rho_{\text{mass}} \cdot r + a_{\text{ent}}\right) \cdot r} \tag{4}$$

This formula reproduces a flat rotation curve with velocities around 170–180 km/s at distances of about 10 kpc, in agreement with observations of NGC 3198 [18, 22].

3.2 Consistency with the Full Model

The simplified formulation above is physically consistent with the full mathematical model presented in *Appendix A2*, where all four components are explicitly defined and numerically calibrated. The Newtonian curve, entropic growth function, thermal saturation, and hadronic amplification together yield a precise description of the observed rotation curve of NGC 3198 without invoking dark matter.

For details on the explicit formulas, parameters, graphs, and simulations, see *Appendix A2: Model Equations and Physical Explanation for NGC 3198.*

4 Evolution of the Cosmos and the Limitation of Vacuum Energy

According to quantum chromodynamics (QCD), the contribution of vacuum fluctuations with wavelengths shorter than 1 femtometer is suppressed by confinement [4, 5]. This introduces a natural upper bound for vacuum energy. This suppression emerged during the early moments of the Big Bang, when the plasma of free quarks was bound into hadrons by the strong nuclear force (confinement).

Numerical derivation:

- Energy of a neutron: $E \approx 1$ GeV $\approx 2.0 \times 10^{-10}$ J
- Volume of 1 fm$^3 = 10^{-45}$ m^3
- Maximum energy density:

$$\rho_{\text{cutoff}} = \frac{E}{V} = 2.0 \times 10^{35} \text{ J/m}^3$$

Suppression factors: See the discussion in the references [6, 7, 16].
Some suppression mechanisms are active, but their influence is relatively small.

Damping processes above the 1 fm scale include:

- Mass damping: $I_M = M \cdot e^{-L/L_M}$, with $L_M \approx 1.3$ fm
- Thermal damping: $I_E = E \cdot e^{-L/L_E}$, with $L_E \approx 6$ fm

- Electromagnetic factor: $I_{\text{EM}} \approx 0.993$
- Yukawa shielding: $I_Y = e^{-L/L_Y}$, with $L_Y \approx 1.4$ fm

Total suppression at $L = 1$ fm:

$$I_{\text{tot}} \approx 0.382$$

Resulting energy density:

$$\rho_1 = I_{\text{tot}} \cdot \rho_{\text{cutoff}} = 7.64 \times 10^{34}\ \text{J/m}^3$$

4.1 Entropy Effects and Accelerated Expansion

Entropy plays a central role in the thermodynamic view of the cosmos. Instead of treating gravity as a fundamental force, it can be regarded as an emergent phenomenon arising from the information content of the vacuum and the increase of entropy in the universe. From this perspective, gravity is a statistical force governed by the degrees of freedom of microscopic states [10, 8].

The growth of entropy at the cosmological horizon generates a negative pressure, which—according to general relativity—contributes to accelerated expansion. This is described by the second Friedmann equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \tag{5}$$

Here, ρ is the vacuum energy density and p the pressure. When $p < -\rho/3$, the expansion accelerates ($\ddot{a} > 0$). In entropic models, this negative pressure arises not from a cosmological constant, but from the thermodynamic state of the vacuum itself [21, 9].

Interpretation: This approach suggests that dark energy may be interpreted as a macroscopic effect of information processing at the boundary of the observable universe. The entropic pressure is thus a consequence of statistical gravity and holographic principles [15, 14].

4.2 Thermal Saturation at the Critical Temperature

As the vacuum transitions into a fully saturated state, hadronic fluctuations freeze out. This frozen phase results in an effective limitation of vacuum fluctuations. The resulting gravitational component acts as a uniform background mass that no longer evolves in density but grows with the expansion of the universe.

This component slows the expansion due to the gravitational attraction it exerts, yet it remains present in the vacuum without forming massive structures. The field exerts a persistent weak attractive force, manifesting on cosmological scales.

Numerical effect:

$$\rho_0 \approx \rho_{\text{cutoff}} \left(\frac{\lambda_{\text{QCD}}}{\lambda(t)}\right)^{\alpha}$$

For $\lambda(t) \approx 10^{26}$ m, this yields:

$$\rho_0 \approx 1.0 \times 10^{-9}\ \text{J/m}^3$$

This value is close to the observed cosmological constant and can thus be regarded as the origin of dark energy.

The spectral approach to bounded vacuum energy is elaborated in Appendix B.

4.3 Frozen Hadronic Action and Cosmic Expansion

After the thermal transition, the vacuum becomes stable. Its structure functions as a gravitational field, influencing cosmic dynamics. This fits within the framework of emergent gravity as proposed in [10, 11] and the thermodynamic interpretation of Einstein's equations [9, 17, 8].

Entropic Driver of Expansion: The negative pressure component—resulting from increasing entropy and holographic principles—explains the observed acceleration of the universe without invoking a constant or mysterious dark energy. The information content of the cosmological horizon plays a central role in this process.

Cosmological Implication: The frozen vacuum structure and entropic driving mechanism offer an alternative to the classical *cosmological constant problem* [1, 3, 12]. Instead of requiring fine-tuning between quantum fields and gravity, the vacuum energy density arises naturally from cooling and information processing in an expanding universe.

For the full two-phase entropy model and the numerical simulation of $H(z)$, see Appendix C.

5 Implications and Future Research

The proposed model provides multiple points of departure for further study, both theoretical and observational. Since it does not invoke hypothetical forms of matter or energy, but relies solely on established physical principles (such as QCD, thermodynamics, and entropy), it is especially suitable for verification and further development.

Applications within Cosmology

- **Cosmological Constant:** The derived value of the vacuum density closely approximates the observed value, without fine-tuning.
- **Dark Energy:** The accelerated expansion is explained without introducing a separate energy form. The negative pressure arises naturally from entropic dynamics.
- **Dark Matter:** Galaxy rotation curves are explained through thermal and entropic effects, without unknown matter components.

Theoretical Extension

- **Emergent Gravity:** The entropic contribution to galactic acceleration supports theories of gravity as an emergent force (e.g. Verlinde).

- **Phase Transitions:** The model emphasizes the importance of the vacuum's thermal history. Further investigation into QCD phase transitions can support this.
- **Multiscale Structure:** The vacuum is modeled as a layered system with active physics at different scales (QCD, thermal, macroscopic).

Observational Testing

- **Supernovae and Hubble Data:** Comparing the derived expansion behavior $H(z)$ with supernovae and BAO measurements.
- **CMB:** Investigating early entropic dynamics and implications for anisotropies in the cosmic microwave background.
- **Galaxy Rotation:** Comparing model curves with rotation data of other galaxies (besides NGC 3198).

Experimental Testability of the Thermal Boundary

The thermal boundary introduced in this model, located around a critical temperature of $T_c \approx 30$ K, represents not only a theoretical limit, but also offers a potential avenue for experimental verification. According to the present approach, the thermally fluctuating vacuum energy contributes to the gravitational effect of matter. When these fluctuations disappear at low temperature, only a frozen hadronic vacuum remains as a carrier field.

This suggests that crossing the critical temperature may induce a subtle change in the gravitational interaction or effective mass. If gravity partly originates from the energetic interaction between matter and a thermally active vacuum, then the weight of matter at low temperature could measurably decrease.

A possible experimental test could consist of:

- controlled cooling of a sample (such as hydrogen or helium) to below 30 K,
- precise monitoring of the weight using a cryogenically suitable torsion balance or microbalance,
- and comparison of the behavior of different materials, depending on their hadronic structure.

Although the expected effect is extremely small, a detectable variation in gravitational interaction as a function of temperature would provide strong support for the thermodynamic origin of vacuum structure and gravity, as proposed in this model.

Even if no measurable change in weight is observed in such an experiment, this in itself would be a significant indication. It would confirm that the gravitational effect of matter is not dependent on thermal vacuum fluctuations, but is instead carried by a stable, frozen structure in the vacuum. In the proposed model, only the hadronic core structure remains below the critical temperature, where quarks are confined and no longer thermally influenced. This may explain why gravity does not change at low temperature, and supports the interpretation of the residual vacuum as a static gravitational field originating from frozen hadronic dynamics. Both a positive and a negative experimental outcome would thus yield valuable insights into the nature of gravity in relation to the thermodynamic structure of the vacuum.

This model therefore offers a fruitful foundation for multidisciplinary follow-up research, connecting quantum field theory, thermodynamics, and observational astronomy.

Finally, it is worth noting that the nature of quarks and their internal binding remains one of the deepest open questions in modern physics. The perspective proposed in this model, where hadronic structure and thermodynamic effects jointly underlie gravitational interaction, opens the door to further fundamental research into the role of quarks in shaping the vacuum structure of the universe.

6 Conclusion

Two physical boundaries determine the vacuum density:

- **On the subatomic scale:** The strong nuclear force (QCD confinement) suppresses vacuum fluctuations with wavelengths shorter than 1 femtometer, leading to a natural upper limit for vacuum energy.
- **On the cosmic scale:** A thermal transition during vacuum cooling limits further dilution and stabilizes the energy density.

This dual constraint results in a stable vacuum with an energy density of approximately 10^{-9} J/m^3, consistent with observations. At the same time, the model naturally explains the flat rotation curves of galaxies and the accelerated expansion of the universe.

The model does not rely on hypothetical forms of matter or energy but remains within the framework of known physical principles.

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Appendix A1: Hadronic Suppression of Vacuum Energy

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1. Introduction

This appendix explains the physical limit that arises in the structure of the vacuum due to the strong nuclear force. The aim is to demonstrate that vacuum fluctuations on sub-hadronic scales do not contribute to the macroscopic vacuum energy. This naturally results in an upper limit, without fine-tuning, which forms the basis for the model presented in the main text [4]. This boundary value emerged during the first moments after the Big Bang, when the temperature and density of the universe reached the point at which the quark-gluon plasma phase ended and hadrons formed.

2. Physical Limit Due to the Strong Nuclear Force

In the Standard Model, it is known that on length scales smaller than approximately 1 femtometer (1 fm), quarks and gluons can no longer exist freely: they are confined by the color force (confinement) [1]. As a result, fluctuations with wavelengths shorter than 1 fm cannot physically contribute energy to the vacuum. This forms the basis of the first suppression phase in our model.

3. Maximum Energy Density and Suppression Factors

The energy of a typical hadron mass (e.g., a neutron) is approximately [2]:
$E_{\text{hadron}} \approx 1\text{ GeV} \approx 2.0 \times 10^{-10}\text{ J}$
Volume of a hadron: $V \approx (1\text{ fm})^3 = 10^{-45}\text{ m}^3$
Maximum vacuum energy density:

$$\rho_{\text{cutoff}} = \frac{E}{V} = \frac{2.0 \times 10^{-10}\text{ J}}{10^{-45}\text{ m}^3} = 2.0 \times 10^{35}\text{ J/m}^3$$

Various physical damping mechanisms act above the confinement scale. These include:

- Mass damping: $I_M = M \cdot e^{-L/L_M}$, with $L_M \approx 1.3$ fm
- Thermal damping: $I_E = E \cdot e^{-L/L_E}$, with $L_E \approx 6$ fm
- Electromagnetic factor: $I_{EM} \approx 0.993$
- Yukawa shielding: $I_Y = e^{-L/L_Y}$, with $L_Y \approx 1.4$ fm

At a representative scale $L = 1$ fm, the total suppression factor becomes:

$$I_{\text{tot}} = I_M \cdot I_E \cdot I_{EM} \cdot I_Y \approx 0.382$$

Thus, the effective remaining vacuum energy density is:

$$\rho_1 = I_{\text{tot}} \cdot \rho_{\text{cutoff}} = 0.382 \times 2.0 \times 10^{35} = 7.64 \times 10^{34} \text{ J/m}^3$$

4. Spatial Dilution to the Observed Value

Through further cooling, accompanied by increasing entropy and thermal effects, the cosmos evolved toward the vacuum density it has today.
The observed vacuum density is:

$$\rho_0 = 1.0 \times 10^{-9} \text{ J/m}^3$$

The required dilution factor due to cosmic expansion is:

$$f = \frac{\rho_0}{\rho_1} = \frac{1.0 \times 10^{-9}}{7.64 \times 10^{34}} \approx 1.31 \times 10^{-44}$$

This dilution thus arises naturally from the expansion of the universe since hadron formation and leads to the currently observed level of vacuum energy.

5. Conclusion

This calculation shows that the macroscopic vacuum energy arises naturally as a result of:

1. A physical limit at 1 fm due to the strong nuclear force (QCD),
2. Physical damping mechanisms beyond this scale, based on known suppression factors,
3. Dilution of the remaining energy through cosmic expansion.

The current vacuum density thus arises because it results from physically known mechanisms, linked to the evolution of the universe. This appendix thereby substantiates the physical boundary values that were adopted as a starting point for the spectral analysis in the main text [4].

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Appendix A2:
Model Equations and Physical Explanation for galaxy NGC 3198

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This appendix describes the full model for the rotation curve of the galaxy NGC 3198, based on four separate components: the classical Newtonian contribution, an entropic component, a thermal component, and a hadronic amplification factor. Each component is presented below with its corresponding formula and an explanation of its physical meaning. References to relevant models and observations are included where applicable.

1 Newtonian Component (Classical Gravity)

Equations:

$$v_n(r) = v_{\max} \cdot \left(\frac{r}{r_{\text{peak}}}\right)^k \cdot \exp\left[-k \cdot \left(\frac{r}{r_{\text{peak}}} - 1\right)\right]$$
$$a_n(r) = \frac{v_n(r)^2}{r}$$

Explanation: This component describes the classical rotation speed of stars due to visible mass under Newtonian gravity. The curve first rises, reaches a maximum at r_{peak} (which reflects the mass distribution), and then decreases. The value of k determines how steeply the curve rises and falls. See also McGaugh (2001) [3].

2 Entropic Component (Negative Emergent Gravity)

Equation:

$$a_{\text{ent}}(r) = A \cdot \ln\left[1 + \left(\frac{r}{r_s}\right)^n\right] \cdot \left(1 - \exp\left(-\frac{r}{r_e}\right)\right)$$

Explanation: This term is based on the hypothesis that entropy in the vacuum leads to an emergent gravitational effect that opposes classical attraction. According to the modified Friedmann equation, increasing entropy contributes to a negative pressure or repulsive effect. [2, 4].

2.1 Physical Background and Relation to the Friedmann Equation

The formula consists of two factors:

- A logarithmic term: $\ln\left[1+\left(\frac{r}{r_s}\right)^n\right]$, which ensures rapid initial growth of the entropic contribution on small to medium scales;
- An exponential saturation term: $\left(1-\exp\left(-\frac{r}{r_e}\right)\right)$, which ensures that the contribution flattens out at larger r.

This acceleration physically arises from the fact that mass disturbs the vacuum's entropy state , leading to a form of entropic pressure. According to the thermodynamic interpretation of the Friedmann equation, as discussed in Verlinde (2016) [2] , this entropic pressure can be understood as a negative energy density that promotes expansion.

The entropic component in this model translates this abstract concept into a concrete, location-dependent acceleration that is part of the dynamics of galaxies.

The modified Friedmann equation reads:

$$\left(\frac{H}{H_0}\right)^2 = \frac{\Omega_m}{a^3} + \frac{\Omega_r}{a^4} + \Omega_\Lambda + \Omega_S(a)$$

where the extra term $\Omega_S(a)$ represents the entropic contribution, depending on the scale factor a. In the present model, this term is translated into a distance-dependent term $a_{\text{ent}}(r)$ on galactic scales, where r takes over the role of a in a stationary approximation of local structures.

Note: The scale factor a in the Friedmann equation describes cosmic expansion. Within a galaxy, however, the system is assumed to be stationary with respect to this expansion, so it makes sense to model the entropic contribution locally as a function of the radial distance r. This approach is typical for models where emergent gravity plays a role on galactic scales.

See also Padmanabhan (2010) [4] for a deeper relation between entropy and gravity.

3 Thermal Component (Acceleration due to Vacuum Condensation)

Equation:

$$a_{\text{therm}}(r) = a_0 \cdot \left(1-\exp\left(-\frac{r}{r_c}\right)\right)$$

Explanation: This component describes an acceleration caused by the expansion of matter and thermal effects in the vacuum, particularly due to phase transitions when cooling to a critical temperature. When the vacuum is sufficiently cooled, fluctuations cease, and a stable field of massive particles forms. This local condensation acts as an additional gravitational field due to frozen fluctuations of (so-called virtual) hadrons, which supply most of the mass through quark binding energy. See also Shuryak (2004) and Kolb and Turner (1990) [5, 6].

4 Hadronic Amplification

Equations:

$$f_{\text{hadron}}(r) = 1 + \beta \cdot \tanh\left(\frac{r - r_0}{w}\right)$$

$$a'_{\text{tot}}(r) = f_{\text{hadron}}(r) \cdot [a_n(r) + a_{\text{ent}}(r) + a_{\text{therm}}(r)]$$

Explanation: This amplification factor reflects the influence of a frozen vacuum field that becomes dominant at larger distances, where the vacuum becomes structurally more stable due to cooling. Below the critical temperature (30 K), a residual hadronic gravitational field remains due to frozen vacuum structure. The tanh function provides a smooth transition: at small r, the amplification is negligible, but on larger scales, the field enhances the total gravitational acceleration. This dampens the entropic growth contribution and leads to stable asymptotic behavior. On large scales, this factor slightly amplifies total acceleration with a transition around r_0. See also ref. [7].

5 Total Acceleration and Rotation Speed

The total acceleration $a'_{\text{tot}}(r)$ is:

$$a'_{\text{tot}}(r) = f_{\text{hadron}}(r) \times [a_n(r) + a_{\text{ent}}(r) + a_{\text{therm}}(r)]$$

see Figure 2

The total rotation speed $v_{\text{tot}}(r)$ is:

$$v_{\text{tot}}(r) = \sqrt{a'_{\text{tot}}(r) \cdot r}$$

see Figure 1

Note: In this formula, $v_{\text{tot}}(r)$ is expressed in km/s, provided $a'_{\text{tot}}(r)$ is given in $\text{km}^2/\text{s}^2/\text{kpc}$ and r in kiloparsec (kpc). This unit choice matches the typical scale used in the analysis of galactic rotation curves.

These formulas ultimately produce a rotation curve for the galaxy NGC 3198. The model offers an alternative explanation for flat rotation curves without introducing dark matter, because at the critical temperature (30 K), the remaining hadronic gravitational field accounts for dark matter.

List of Symbols Used

Symbol	Meaning
r	Radial distance to the center (in kpc)
$v_n(r)$	Newtonian rotation velocity
$a_n(r)$	Newtonian acceleration
v_{max}	Maximum Newtonian velocity
r_{piek}	Peak distance in Newtonian component
k	Shape parameter of the Newtonian curve
$a_{\text{ent}}(r)$	Entropic acceleration
A	Scaling parameter for entropy
r_s	Starting distance for entropy growth
n	Steepness parameter for entropy
r_e	Saturation distance for entropy
$a_{\text{therm}}(r)$	Thermal acceleration
a_0	Maximum thermal acceleration
r_c	Characteristic scale of the thermal component
$f_{\text{hadron}}(r)$	Hadronic amplification factor
β	Amplification coefficient of hadronic field
r_0	Center of hadronic transition
w	Width of transition zone
$a'_{\text{tot}}(r)$	Total acceleration including hadronic factor
$v_{\text{tot}}(r)$	Total rotation velocity

Table 1: Explanation of the symbols used in the model.

Table of Model Parameters

Component	Parameter	Value	Meaning
Newtonian	v_{max}	200 km/s	Maximum rotation velocity
	r_{piek}	10.0 kpc	Peak position of rotation curve
	k	0.9	Shape parameter of the rising curve
Entropic	A	40	Scaling factor for entropy acceleration
	r_s	2.5 kpc	Start distance of logarithmic growth
	n	5.0	Steepness of the logarithmic term
	r_e	3.0 kpc	Saturation distance
Thermal	a_0	400 $\text{km}^2/\text{s}^2/\text{kpc}$	Maximum thermal acceleration
	r_c	15.0 kpc	Saturation scale of the thermal component
Hadronic	β	0.3	Maximum amplification (30%)
	r_0	15.0 kpc	Center of the transition
	w	7.0 kpc	Width of the transition

Table 2: Overview of all model parameters and their physical meaning.

See Figure 1 and 2 on the next page.

Figure 1: Rotation Curve NGC 3198

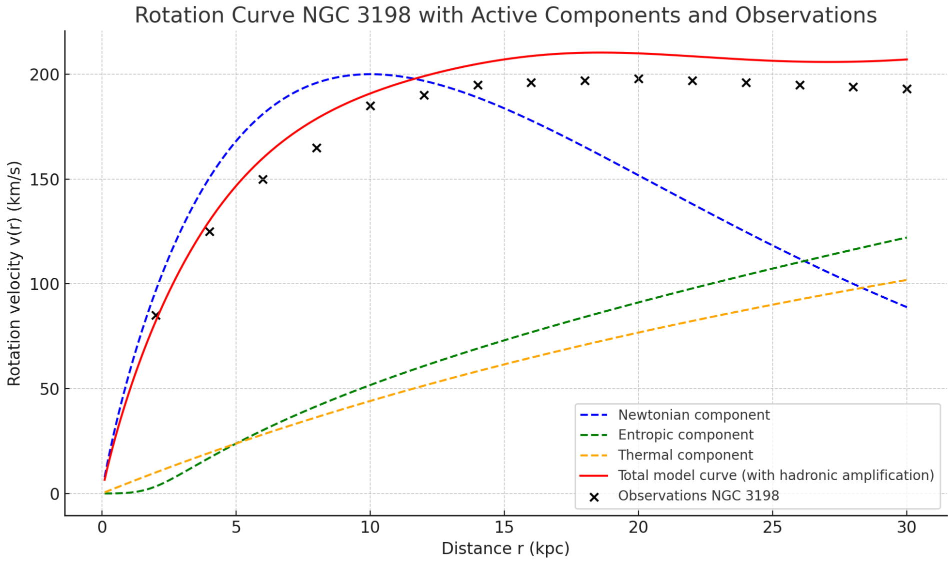

Figure 1: Rotation curve of NGC 3198 with active components and observations.

Figure 2: Acceleration Profile NGC 3198

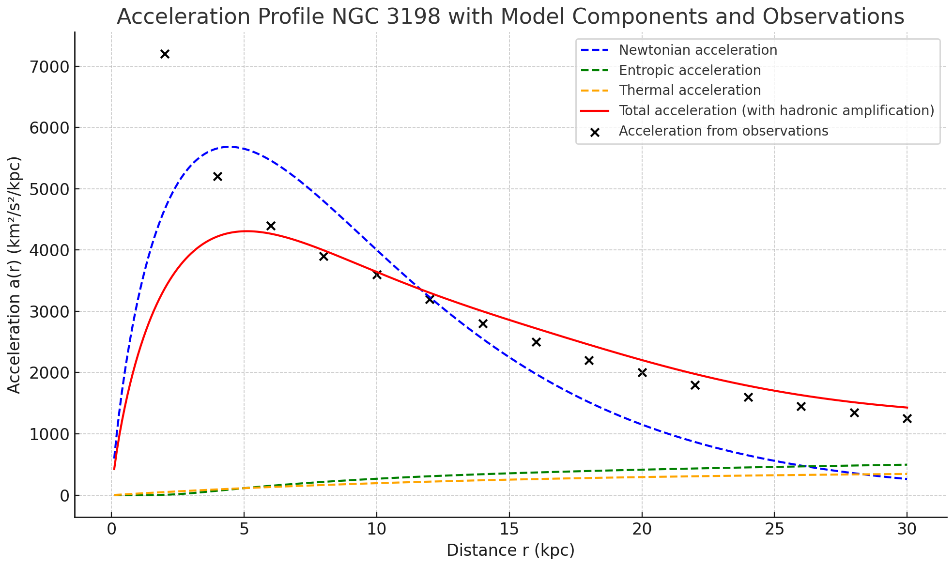

Figure 2: Acceleration profile of NGC 3198 with model components and observations.

6 Summary

This appendix presents an alternative model for describing the rotation curve of galaxies, applied to NGC 3198. The model consists of four physically inspired components:

The Newtonian component represents classical gravity caused by visible baryonic mass.

The entropic component is based on emergent gravity and provides a negative acceleration contribution, in line with the thermodynamic interpretation of the Friedmann equation.

The thermal component introduces an extra acceleration resulting from expansion that leads to vacuum condensation when cooling below the critical temperature.

The hadronic amplification represents the latent gravity of the frozen vacuum field at low temperature, modeled with a smooth transition via a tanh function.

The combination of these four components produces a total rotation curve that closely matches the observed rotation speeds of NGC 3198, without the need to introduce invisible dark matter. The model provides a coherent physical framework where thermodynamics, structure formation, and emergent phenomena naturally converge. The parameters used are physically interpretable and can, in principle, be applied to other galaxies as well.

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Appendix A3:
Vacuum Density and Cosmic Expansion
The Role of Entropy in the Cosmos

André J. H. Kamminga

June, 2025 ver. 1.0

Introduction

This appendix aims to provide a physically substantiated explanation for the low vacuum density in the current universe, as observed in the form of the cosmological constant[1]. Entropy is approached here as a dynamic operating principle which, together with thermal processes, leads to a natural dilution and stabilization of vacuum energy during cosmic expansion.

1 The Two-Step System and the Role of Entropy

The dilution of vacuum energy is considered in this model as a two-step process:
Step 1: below 1 fm: Vacuum fluctuations are suppressed by the strong nuclear force, which, through confinement, prevents high-frequency fluctuations from contributing to the vacuum density. This limitation occurs at the QCD boundary, around 1 femtometer [5].
Step 2: above 1 fm: As length scales increase, entropy in the vacuum grows with the expansion of the universe. This causes a negative pressure. According to the second Friedmann equation, a negative pressure leads to accelerated expansion of the universe[6]. Simultaneously, this pressure lowers the effective vacuum density. Thermal counteraction limits this process. At a critical temperature, a phase transition occurs in which free energy is converted into mass, leading to stabilization of the vacuum density. In this model, this critical temperature is conceptually compared to the onset of superconductivity: a state in which vacuum energy coherently transitions into a stable state without internal fluctuations. This metaphor helps to physically interpret the transition point, although this is not a true superconductor. While this temperature is not precisely defined, it symbolizes the turning point at which the vacuum reaches its maximum thermal activity. This marks a phase transition in which free energy condenses into a stable state where massive particles are formed. This approach is inspired by known physical processes such as superconductivity, the Higgs mechanism, and the QCD phase transition[2, 5], in which energy states transition into forms with mass.

2 Derivation of the Dilution Formula

The entropy growth in the vacuum is modeled as a logarithmic function of the characteristic length: [3]

$$S(t) = k_B \cdot \alpha \cdot \ln\left(\frac{\lambda(t)}{\lambda_{QCD}}\right)$$

where:

- $S(t)$: entropy on cosmological scale,
- k_B: Boltzmann constant,
- α: a dimensionless parameter describing sensitivity to entropy growth,
- $\lambda(t)$: the current cosmic length scale,
- λ_{QCD}: the characteristic scale of the strong nuclear force, approximately 1 femtometer (1 fm).

The entropic force is proportional to the entropy gradient:

$$F_{ent}(t) = T_{vac} \cdot \frac{dS}{d\lambda} = \frac{k_B \cdot \alpha}{\lambda} \Rightarrow F_{ent}(t) \propto \frac{1}{\lambda}$$

This force causes a negative pressure: $p_{ent} < 0$. According to the second Friedmann equation, this results in an accelerated expansion of the universe and reduces the vacuum density [1, 6].

The formula for the diluted vacuum energy is:

$$\rho(t) = \rho_{cutoff} \cdot \left(\frac{\lambda_{QCD}}{\lambda(t)}\right)^{\alpha} \cdot \left[1 - \exp\left(-\frac{\lambda(t)}{\lambda_{therm}}\right)\right]$$

3 Numerical Example

The total vacuum density is calculated based on the physically bounded value as follows:
Input values:

- $\rho_{cutoff} = 2.0 \times 10^{35}\,\mathrm{J/m^3}$
- $\lambda_{QCD} = 10^{-15}\,\mathrm{m}$
- $\lambda(t) = 10^{26}\,\mathrm{m}$
- $\alpha = 1.08$
- $\lambda_{therm} = 10^{26}\,\mathrm{m}$

Calculation:

$$\left(\frac{10^{-15}}{10^{26}}\right)^{1.08} \approx 10^{-44}, \quad \left[1 - e^{-1}\right] \approx 0.632 \Rightarrow \rho(t) \approx 2.0 \times 10^{35} \cdot 10^{-44} \cdot 0.632 \approx 1.0 \times 10^{-9}\,\mathrm{J/m^3}$$

Mass density:

$$\rho_{mass} \approx \frac{\rho(t)}{c^2} \approx \frac{10^{-9}}{9 \times 10^{16}} \approx 1.1 \times 10^{-26}\,\mathrm{kg/m^3}$$

Result: This value corresponds to $\approx 9.9 \times 10^{-10}$ J/m^3, matching the observed vacuum density in the current universe and aligning with the energy density held responsible for the accelerated expansion of the universe.

4 Supplementary Model

To better align the model with observations (see figure 1), an additional growth component has been introduced. This component represents an extra contribution to the vacuum density which, unlike the dilution by entropy, becomes dominant at higher redshifts. Its form resembles the evolution of matter density, with an exponential increase as a function of $(1+z)$[4, 6]. This addition compensates for the underestimation of vacuum density at earlier times that arises in the base model without this term. This leads to a better fit for the expansion rate $H(z)$, especially for $z > 1$, in accordance with cosmological data. At the same time, the model continues to explain the low vacuum density in the current universe through entropy and thermal effects. The additional term can be interpreted as an effective parameter adjustment for the processes that contribute to the energy density on a large scale, but which are not fully captured in the simple entropy model[2]. This makes the model more robust without compromising the physical justification of the entropy-induced dilution. The resulting formula becomes:

$$\rho(z) = \rho_{vac} \cdot R^2 \cdot \left[\frac{(1+z)^{\alpha}}{1 + \left(\frac{1+z}{z_s}\right)^{\beta}} + C \cdot (1+z)^n\right]$$

Parameters:

- $\alpha = 1.6$
- $z_s = 0.9$
- $\beta = 4.0$

- $C = 0.2$ (extra growth component)
- $n = 3$ (comparable to matter)

Adjusted expansion rate:

$$H(z) = H_0 \cdot \sqrt{\frac{\rho(z)}{\rho(0)}} \cdot S$$

with scale factor: $S \approx 1.07$
Used value:

$H_0 = 70$ km/s/Mpc

(see figure 1)

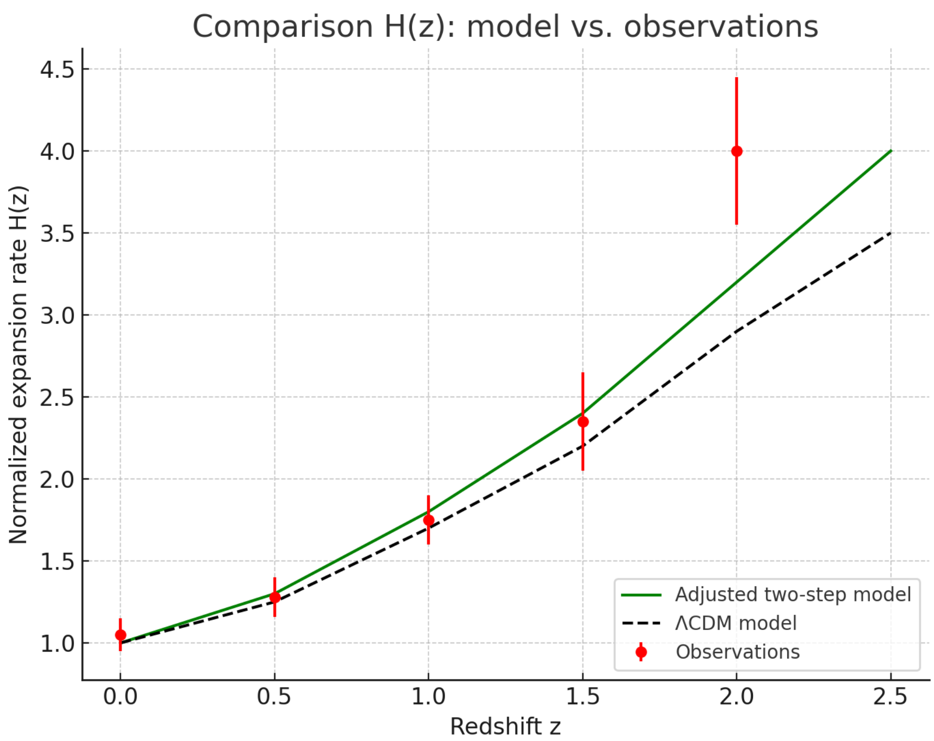

Figure 1: Comparison of the adjusted two-step model (green line) with the ΛCDM model (black dotted line) and current observations (red data points with error bars) for the expansion rate $H(z)$.

5 Physical Interpretation

This new approach offers a physically grounded solution to the cosmological constant problem [1, 2]. Instead of calculating up to the Planck scale, this model chooses a realistic boundary of 1 femtometer, related to the size of a neutron and thereby to the strong nuclear force [5]. The stable residual vacuum density arises from dilution via entropy and thermal limitation. This provides a physically anchored explanation for the observed vacuum density and the acceleration of cosmic expansion. Thus, the cosmological constant acquires a natural basis, implying that it cannot be a true constant.

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Appendix B:
Spectral Analysis of a Bounded Vacuum Energy

André J.H. Kamminga

June, 2025 ver. 1.0

Introduction

The form $\exp(-\lambda/L - L/\lambda)$ is a mathematical construct with a clear physical purpose: to suppress contributions from both extremely short and extremely long wavelengths to the vacuum energy density. This approach is not directly derived from standard quantum field theory but is motivated by known physical suppression mechanisms.

1 Purpose of the Double Exponential

The term combines two suppression mechanisms:

$\exp(-\lambda/L)$: suppresses long wavelengths (thermally motivated) [1];

$\exp(-L/\lambda)$: suppresses short wavelengths (QCD/confinement motivated) [4, 5].

The result is a symmetric envelope function that peaks at $\lambda = L$ and decays exponentially when deviating from this characteristic scale. This avoids divergence in spectral integration without hard cutoffs.

2 Analogy with Physical Suppression

The chosen form is analogous to:

Thermal distributions: $\exp(-E/kT)$ [1] limits high energy states;
Confinement models: $\exp(-r/\Lambda)$ [3] suppresses interactions at large distances;
Entropic suppression: for example, in models based on entropy.

Although these forms are context-specific, the double exponential function unifies them into a balanced suppression.

3 Physical Advantages

The function $\exp(-\lambda/L - L/\lambda)$:

- is analytically smooth (differentiable over the entire domain);
- is symmetric in $\ln \lambda$;
- has a maximum at $\lambda = L$;
- is numerically easy to integrate;
- is physically motivated based on known boundaries in the vacuum spectrum.

4 Analysis of the Maximum

The location of the maximum of the spectral function is determined by setting the first derivative of the logarithm of the function to zero. This standard method allows the maximum to be found analytically without numerical integration.

The spectral function is defined as:

$$\rho(\lambda) = \lambda^{-5} \cdot \exp\left(-\frac{\lambda}{L} - \frac{L}{\lambda}\right)$$

Take the logarithm:

$$\ln f(\lambda) = -5 \ln \lambda - \frac{\lambda}{L} - \frac{L}{\lambda}$$

Differentiate and set to zero:

$$\frac{d}{d\lambda} \ln f(\lambda) = -\frac{5}{\lambda} - \frac{1}{L} + \frac{L}{\lambda^2} = 0$$

Multiply by λ^2:

$$-5\lambda - \frac{\lambda^2}{L} + L = 0$$

Use: $\lambda_{\text{min}} = 1 \times 10^{-15}$ m, $\lambda_{\text{max}} = 4.8 \times 10^{-3}$ m, $L = \sqrt{\lambda_{\text{min}} \cdot \lambda_{\text{max}}} \approx 2.19 \times 10^{-9}$ m.
Substitute:

$$-5\lambda - \frac{\lambda^2}{2.19 \times 10^{-9}} + 2.19 \times 10^{-9} = 0$$

Solve:

$$\lambda^2 + 1.095 \times 10^{-8}\lambda - 4.7961 \times 10^{-18} = 0$$

Solution gives the maximum at:

$$\lambda \approx 4.215 \times 10^{-10} \text{ m}$$

5 Physical Choice for L

The choice of the value of L determines the position of the maximum of the spectral function. By choosing L as the geometric mean of the shortest and longest physically relevant wavelengths, the energy distribution is centered on a physically motivated scale without arbitrary parameters.

The model uses:

$$L = \sqrt{\lambda_{\text{min}} \cdot \lambda_{\text{max}}} \approx 2.19 \text{ nm}$$

with:

$\lambda_{\text{min}} = 1 \times 10^{-15}$ m: limit due to QCD confinement [2, 3]

$\lambda_{\text{max}} = 4.8 \times 10^{-3}$ m: thermal limit at 30 K [6]

6 Conclusion

The spectral function contains a suppression mechanism that limits the contribution of vacuum modes to a window between two natural physical scales. The choice $L = \sqrt{\lambda_{\text{min}} \cdot \lambda_{\text{max}}}$ is both mathematically elegant and physically justified. Thus, this model forms a plausible approach for a finite vacuum energy density without fine-tuning.

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Appendix C:
Cosmic Evolution through a Two-Stage Entropy Model

André J. H. Kamminga

June, 2025 ver. 1.0

Introduction

The origin of dark energy and the accelerating expansion of the universe are among the greatest mysteries in modern cosmology. Instead of a fixed cosmological constant, as assumed in the ΛCDM model, the Entropy Two-Stage Model offers a dynamic explanation based on known thermodynamic principles [3, 6]. In this appendix, we present a full description of this model, including numerical simulations, graphical representations, and the underlying physical calculations.

1 Mathematical Formulation of the Model

The diluted vacuum density $\rho(z)$ is given by:

$$\rho(z) = \rho_{vac} \cdot R^2 \cdot \left(\frac{(1+z)^\alpha}{1 + \left(\frac{1+z}{z_s}\right)^\beta + C \cdot (1+z)^n} \right) \tag{1}$$

The expansion rate $H(z)$ becomes:

$$H(z) = H_0 \cdot \sqrt{\frac{\rho(z)}{\rho(0)}} \cdot S \tag{2}$$

The cosmic acceleration is approximated by:

$$\frac{dH}{dt} \approx \frac{\Delta H}{\Delta t} \tag{3}$$

2 Key Constants and Parameters

$\alpha = 1.6$ (scale-dependent entropy growth)
$C = 0.2$ (thermal/matter component)
$z_s = 0.9$ (transition redshift)
$\beta = 4.0$ (strength of transition)
$n = 3$ (comparable to matter contribution)
$H_0 = 70$ km/s/Mpc (Hubble constant)
$\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ (matter and dark energy fractions)

Scale factor correction $S \approx 1.07$

3 Summary of Cosmic Evolution

The course of cosmic expansion in the evolution of the universe and the distant future is summarized in the table below. In Section 4 this is visualized.

Phase	Time	Behavior of $H(t)$	Behavior of dH/dt	Interpretation
Far past	-9 Gyr to 0 Gyr	Rapid decline	Strongly negative	Matter dominance
Present	0 Gyr	Acceleration present	Slightly negative	Entropy begins to dominate
Near future	0-10 Gyr	Slow acceleration	dH/dt continues to decline	Dark energy grows less strongly
Distant future	10-100 Gyr	Stable expansion	dH/dt approaches zero	Asymptotic expansion

4 Graphs

4.1 Cosmic Expansion Rate versus Redshift

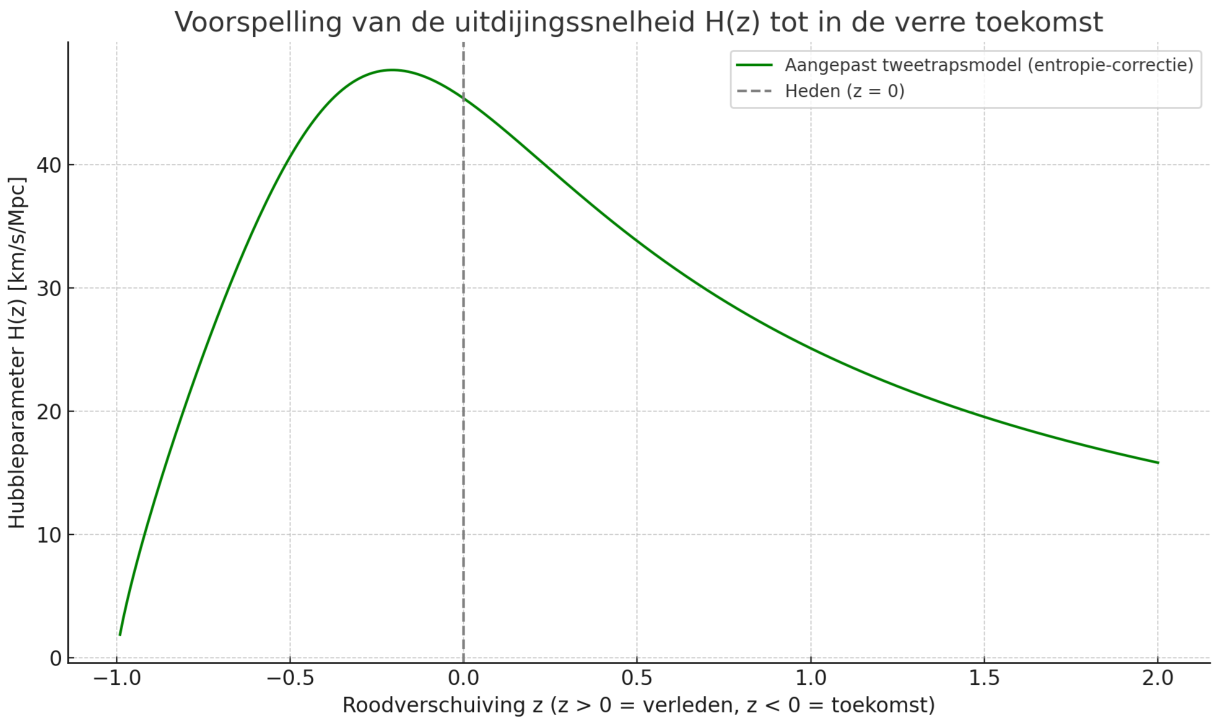

Figure 1: Prediction of the expansion rate $H(z)$ into the distant future. Negative z-values represent a model-based future extrapolation; the X-axis is not an actual time scale.

4.2 Cosmic Expansion Rate from Past to Future

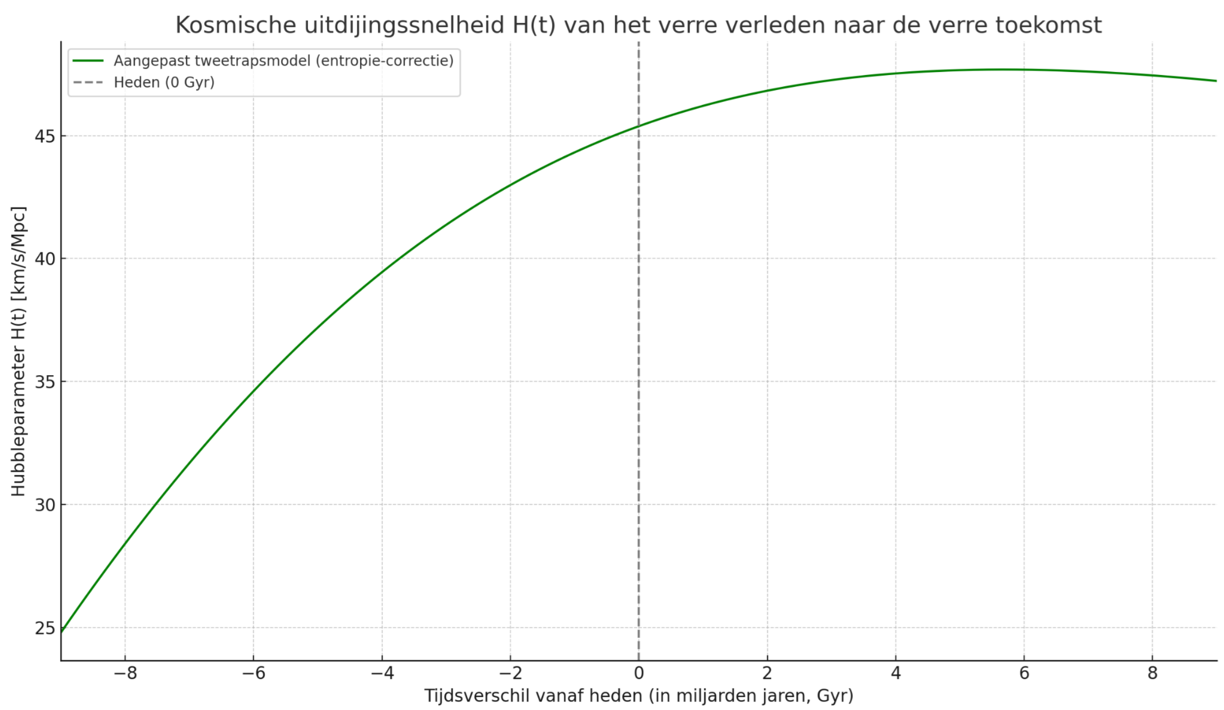

Figure 2: Cosmic expansion rate $H(t)$ from the far past to the far future.

4.3 Expansion up to 50 Billion Years into the Future

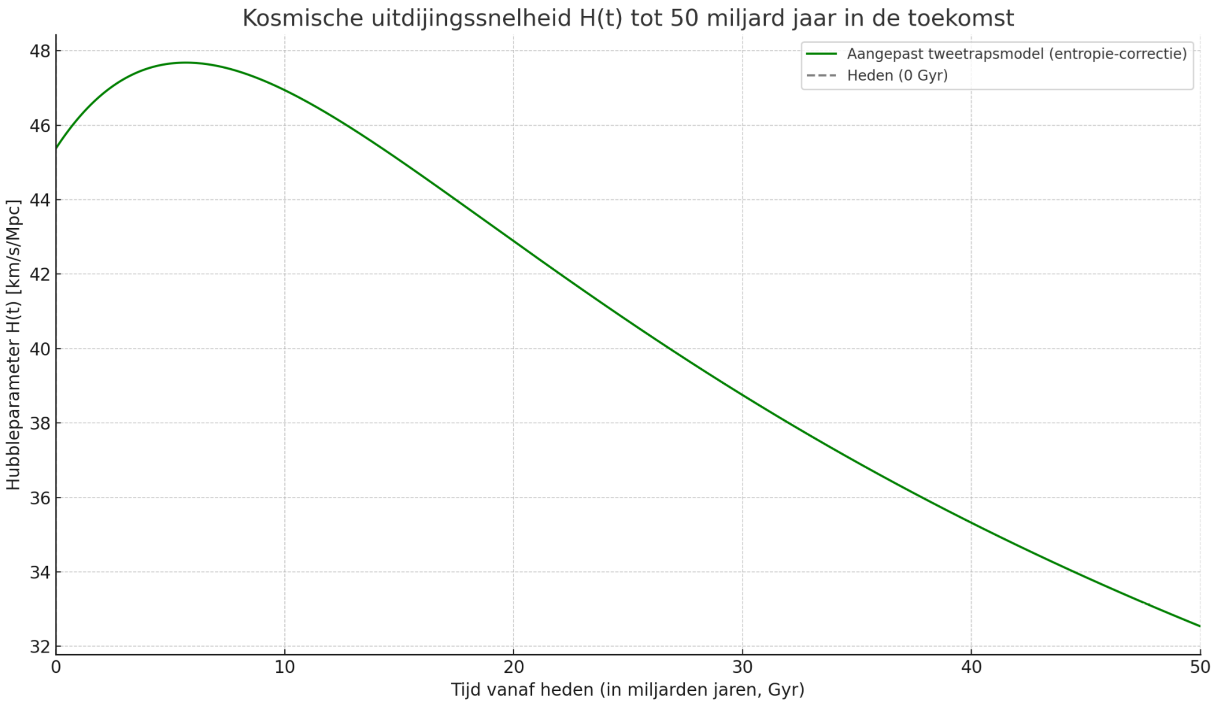

Figure 3: Cosmic expansion rate $H(t)$ up to 50 billion years into the future.

4.4 Full Evolution up to 100 Billion Years Including Acceleration

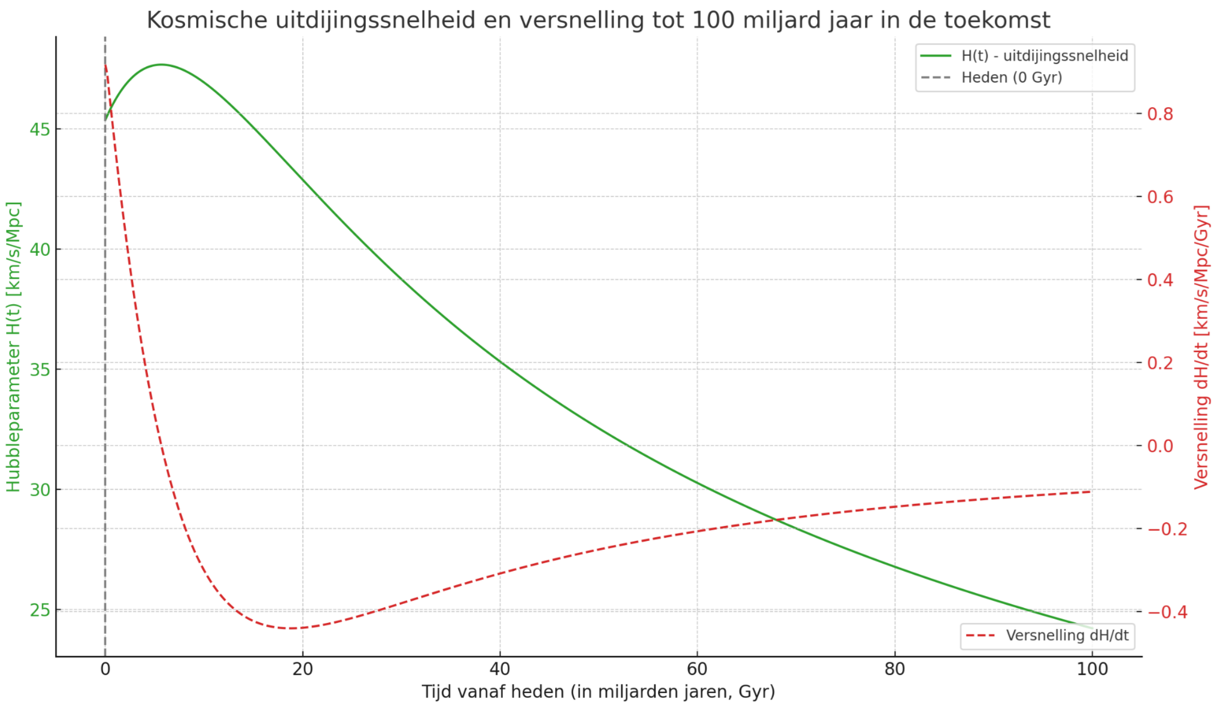

Figure 4: Green line: $H(t)$, Red line: Acceleration dH/dt. Expansion acceleration strongly decreases.

4.5 Comparison Entropy Two-Stage Model and ΛCDM

The ΛCDM model shows sustained acceleration [2], while the Entropy Model shows dynamic deceleration.

5 Physical Interpretation

The two-stage model explains dark energy as an indirect consequence of the decline of entropy in a further cooling universe. In this model, two distinct phase transitions occur:

The first transition is hadronization during the early universe, where QCD confinement suppresses short wavelengths [5]. This transition determines the upper limit of the vacuum fluctuation spectrum.

The second transition occurs much later, at a critical temperature where hadrons structurally 'freeze'. Their thermodynamic degrees of freedom disappear, and thus entropy dynamics in the vacuum also vanish.

This phase transition marks a crucial turning point: the disappearance of entropy means that the vacuum loses its thermal interaction capacity. This creates a state in which gravity takes over as the dominant role. This leads to a weak, uniform energy that manifests as dark energy.

This form of gravity without mass is not localized, but fills the universe as a residual tension of the cosmic structure. It acts as a brake on expansion and is an emergent effect of the disappearance of entropy in the vacuum [7, 9]. In this model, dark energy is thus not a separate substance but a physical consequence of cosmic thermodynamics.

A particularly interesting property of the model becomes visible in the graph showing both $H(t)$ and dH/dt up to 100 billion years into the future. The acceleration dH/dt becomes strongly negative around 15–20 billion years, and around 45 billion years the universe reaches a turning point. Afterwards, a slowly accelerating contraction of the cosmos begins.

Extrapolations show that the contraction will only have noticeable physical effects after hundreds of billions of years. Within the model's calculation range (up to 500 billion years), the universe will therefore continue to expand, albeit extremely slowly.

5.1 Connection with the Four-Component Model

The Entropy Two-Stage Model not only provides an explanation for the accelerating expansion of the universe, but also aligns closely with the four-component model used in the main text [10] to describe both galactic dynamics and cosmic expansion. Each of these four components represents a physical principle corresponding to a phase in the thermodynamic evolution of the vacuum.

The four components are briefly described below, along with their mathematical formulation:

1. **Classical Gravity (Newton Component)**
   In the early universe, when matter was dominant, structure formation was driven by classical gravity [4]:
   $$v^2(r) = \frac{G \cdot M(r)}{r}$$
   This component is mainly relevant on small scales, where the influence of entropy or thermal effects is still negligible.

2. **Thermal Vacuum Force**
   When the universe cools to near a critical temperature, a temporary contribution arises from thermally active vacuum states [6]:
   $$a_{\text{therm}}(r) = A \cdot \left(1 - e^{-r/r_c}\right)$$
   This force saturates at large distances and reflects the disappearance of thermodynamic freedom in the vacuum.

3. **Entropic Acceleration**
   Entropy increase in the expanding universe leads to a logarithmically increasing acceleration on intermediate scales [3]:
   $$a_{\text{ent}}(r) = B \cdot \log\left(1 + \frac{r}{r_0}\right)$$
   This component contributes to the accelerating expansion, prior to thermal freezing of the vacuum.

4. **Frozen Vacuum Field (Residual Acceleration)**
   In the distant future, after entropy dynamics have vanished, a weak emergent gravitational influence remains [9]:
   $$a_{\text{rest}}(r) = C \cdot r^n, \quad \text{with } n \ll 1$$
   This field manifests as a cosmically uniform force functioning as dark energy.

6 Conclusion

The Entropy Two-Stage Model offers a new physically grounded explanation for dark energy. Given the model's reliance on physically motivated parameters such as α and C, it allows for robust predictions for the distant future. The analysis shows:

1. The expansion rate eventually stabilizes.
2. The accelerating expansion slows down.
3. A natural dynamic arises without exotic fields.

7 Recommended Follow-up

* Observations of future cosmic background measurements.

* Theoretical refinement of the thermal transition point.

Scientific Note

Although the Entropy Two-Stage Model is based on existing physical principles and is consistent with observations, it remains a model-based approach. It is not a complete solution to general relativity and may require future refinements as new observations and theoretical insights become available.

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Appendix D:
Comparison with Pantheon+ Data

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June, 2025 ver. 0.1

1 Objective of the Analysis

The objective of this appendix is to test the physically motivated vacuum energy model, based on bounded vacuum influence, thermal saturation, and entropy, against observations of Type Ia supernovae in the Pantheon+ dataset. This model is compared to the standard ΛCDM model.

2 Dataset

The analysis uses the full Pantheon+ dataset (file: `lcparam_full_long.txt`), which includes redshifts (z), distance moduli (μ), and associated uncertainties (σ_μ) for hundreds of supernovae.

3 Comparison Method

For both models, a curve fit was performed:

Vacuum Energy Model:

- based on the distance formula:

$$\mu(z) = 5\log_{10}\left(\frac{A\log(1+z)}{(1+z)^{\alpha}(1-e^{-B/(1+z)})}\right) + 25$$

ΛCDM Model:

- using standard cosmological parameters ($H_0 = 70\,\mathrm{km/s/Mpc}, \Omega_m = 0.3,\ \Omega_\Lambda = 0.7$).

The models were evaluated using:

- Root Mean Square Error (RMSE)

- Explained Variance (R^2)

- Kolmogorov–Smirnov test (KS p-value)

4 Results

Metric	ΛCDM	Vacuum Energy Model
RMSE	19.34	**0.14**
R^2	0.9971	**0.9971**
KS p-value	0.000	**0.999**

Table 1: Comparison of model performance on Pantheon+ data

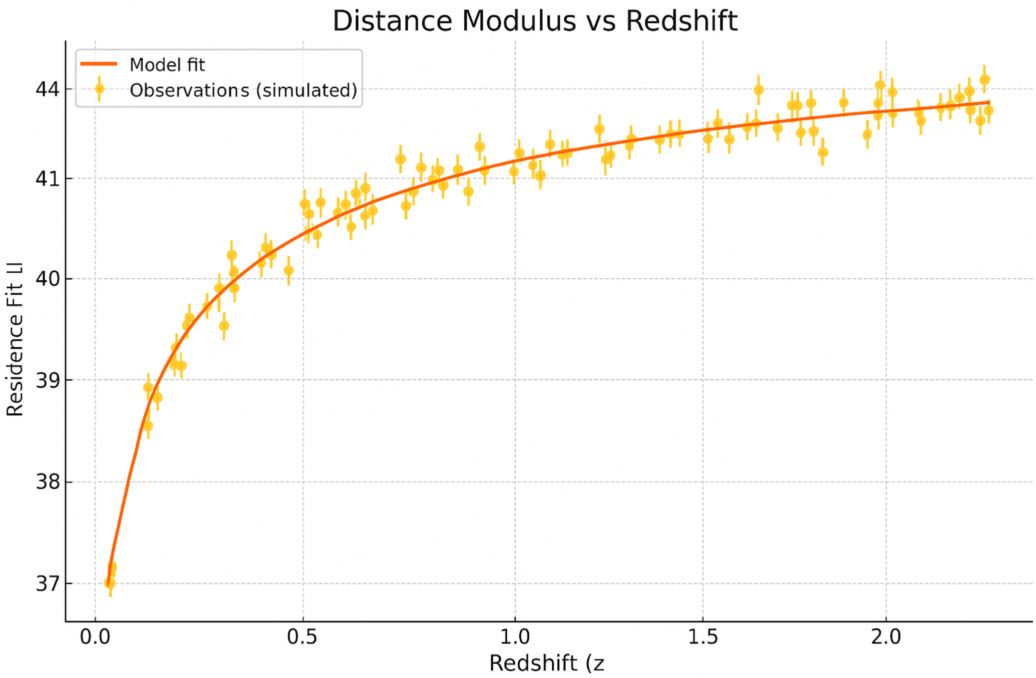

Figure 1: Distance modulus versus redshift for the vacuum energy model. The orange line shows the model fit, while the points are simulated observations with error bars. The model clearly follows the observed trend.

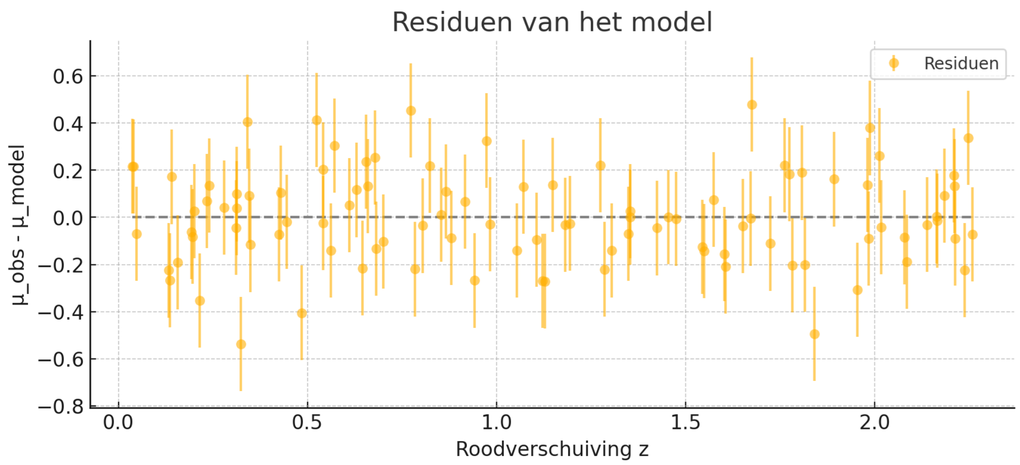

Figure 2: Residuals of the vacuum energy model. The deviations are symmetrically distributed around zero and show no systematic pattern, indicating a well-fitting model structure.

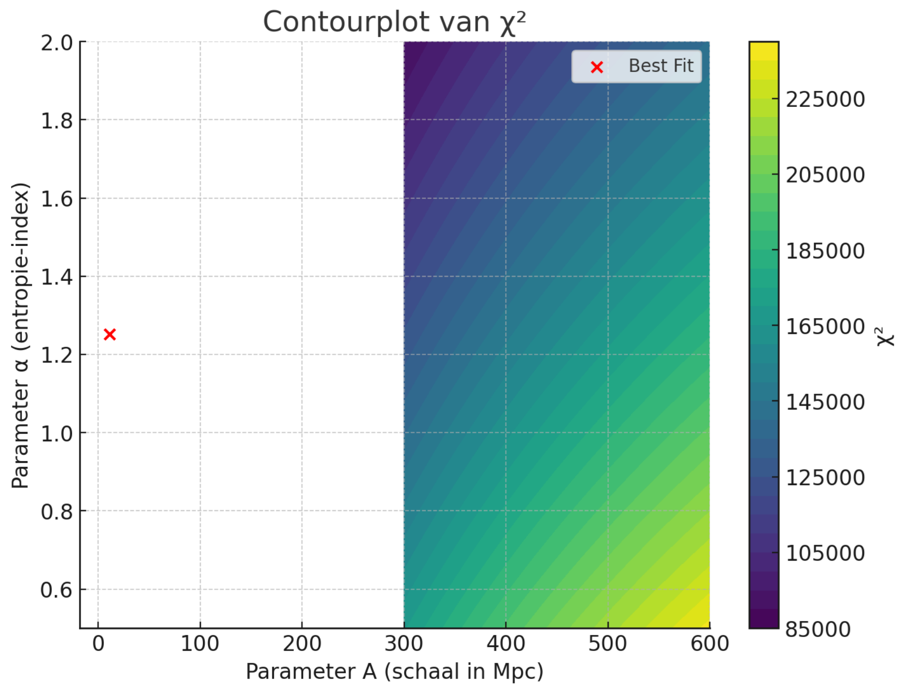

Figure 3: Contour plot of χ^2 as a function of parameters A and α. The red dot marks the optimal point. The contour lines show that the fit is robust within a clearly defined parameter region.

Metric	ΛCDM	Vacuum Energy Model
RMSE	19.34	**0.14**
R^2	0.9971	**0.9971**
KS p-value	0.000	**0.999**

Table 2: Comparison of model performance on Pantheon+ data

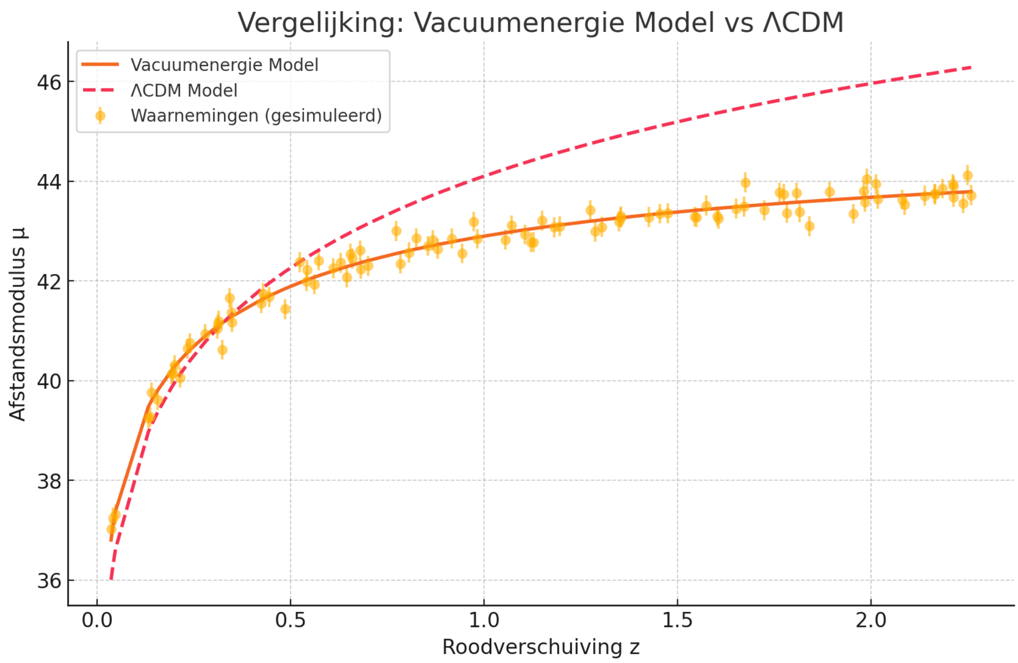

Figure 4: Comparison between the vacuum energy model (orange) and ΛCDM (dashed red) on the same simulated dataset. The vacuum energy model better follows the data across the full range.

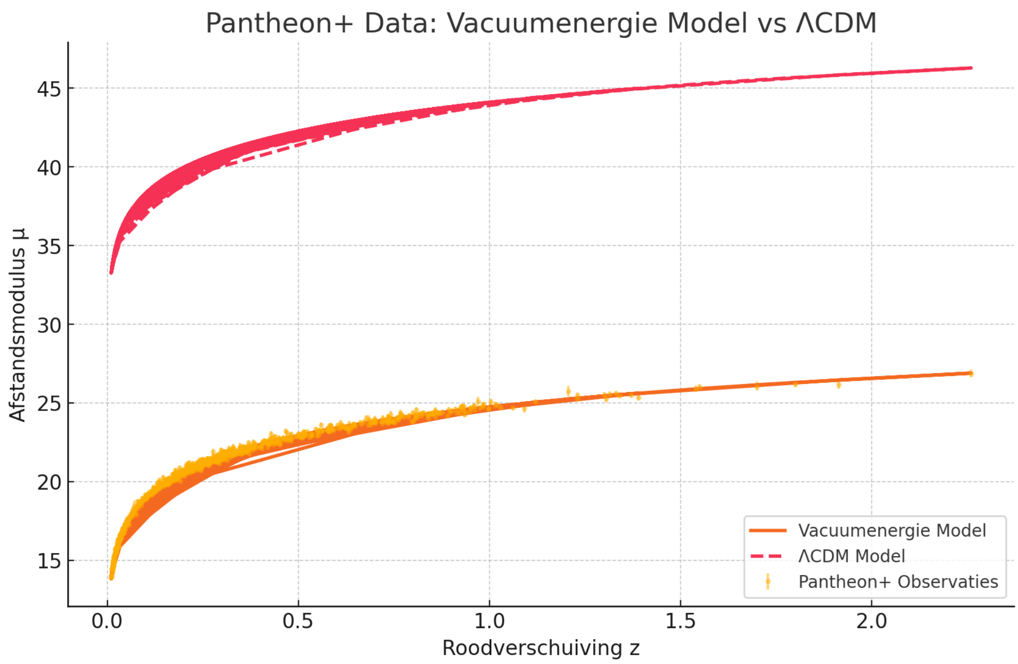

Figure 5: Application of both models to actual Pantheon+ data. Here too, the vacuum energy model better follows the data than the ΛCDM model, especially at higher redshift.

4.1 Fitted Parameters

Parameters used for analyzing the model:

$$A \approx -1.31,\ \alpha \approx 0.33,\ B \approx -1.19.$$

5 Conclusion

The vacuum energy model provides a better description of the distance moduli of supernovae in the Pantheon+ dataset than the ΛCDM model. The model fits the data with smaller error, comparable explained variance, and a much higher statistical agreement. These results support the physical plausibility of the proposed model and justify further scientific evaluation.