Temperature-dependent vacuum effects in high-energy astrophysics: from gamma-ray Bursts to the Hubble tension

Octavian Postavaru and Virgil M. Craciun

Astronomical Institute of the Romanian Academy,
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Overview I

Physical Framework

- **Motivation & Context:** Cosmological puzzles, Hubble tension, and limitations of previous VSL approaches.
- **Vacuum as a Medium:** Modeling the vacuum as a temperature-sensitive optical environment.
- **Theoretical Foundations:** Lorentz polarizability, statistical averaging, and finite-temperature propagators.
- **Refractive Vacuum Model:** Sellmeier-type dispersion and temperature-dependent light propagation.
- **Critical Temperature:** Transition regime above $T_c \approx 4 \times 10^9$ K.

Overview II

Astrophysical and Cosmological Applications

- **Supernovae & GRBs:** Photon delays and light-curve structure in high-temperature environments.
- **Quasars:** Intrinsic thermal redshift and luminosity-distance reinterpretation.
- **Cosmological Consequences:** Hubble tension, JWST observations, and dark-energy-free cosmology.
- **Fine Structure Constant:** Temperature dependence and observational constraints.
- **Conclusion & Outlook:** Testability, observational signatures, and future directions.

The Cosmological Challenge

Persistent Problems in Standard Cosmology

- **Horizon problem:** Why are causally disconnected regions in thermal equilibrium?
- **Flatness problem:** Why is the universe so close to spatial flatness?
- **Hubble tension:** Disagreement between local measurements and CMB predictions of H_0 [7].
- **Dark energy problem:** What drives the apparent accelerated expansion?
- **JWST observations:** Presence of unexpectedly massive and luminous early galaxies.
- **Quasar redshift anomalies:** Quasars often exhibit larger redshifts than nearby associated galaxies.

Working Hypothesis:

- Vacuum properties depend on temperature.
- Redshift contains an intrinsic thermal component.
- High-temperature environments modify photon propagation.

Variable Light Speed (VLS) Proposals

Historical Motivation

- VLS theories were introduced as alternatives to inflationary cosmology.
- Main goals:
  - Explain causal contact in the early universe.
  - Reduce extreme fine-tuning of spatial curvature.
  - Address relic problems from grand unified theories.
- Key models:
  - **Moffat (1993):** superluminal phase transition.
  - **Albrecht–Magueijo (1999):** dynamical varying-c cosmology.
- Central assumption:

$$c_{\mathrm{early}} \gg c_0$$

- Consequence: Enlarged causal horizon in the primordial universe.
- Limitation: The variation of c is usually postulated rather than derived from microscopic physics.

Critique of Early VLS Models

Conceptual Limitations

- **Phenomenological construction:** Variation of c is typically imposed rather than derived from microscopic physics.
- **Examples:**
  - Moffat's superluminal phase transition model [5].
  - Albrecht–Magueijo varying-c cosmology [1].
- **Limited physical interpretation:**
  - No explicit vacuum mechanism for modifying photon propagation.
  - Weak connection to finite-temperature QFT or electrodynamics.
- **Observational ambiguity:** Difficult to distinguish from inflationary or quantum-gravity effects.
- **Motivation for this work:** Derive varying-c behavior from thermodynamics, vacuum polarization, and high-temperature astrophysical environments.

Toward a Physically-Based Alternative

From Phenomenology to Microscopic Physics

- Existing VLS theories often rely on:
  - Scalar-field constructions,
  - Discontinuous phase transitions,
  - or purely phenomenological assumptions.
- **Our guiding idea:** Variations in light propagation should emerge from known matter–field interactions.
- **Physical ingredients:**
  - Quantum vacuum fluctuations,
  - Finite-temperature field theory,
  - Electromagnetic response of polarizable media,
  - Thermodynamic vacuum effects.
- **Working hypothesis:** The vacuum behaves as a temperature-dependent optical medium.
- **Implication:** High-temperature environments can modify photon propagation through an effective refractive mechanism.

Conceptual Hypothesis

Vacuum as a Thermally Responsive Medium

- This work proposes that the electromagnetic vacuum exhibits a temperature-dependent permittivity:

$$\varepsilon = \varepsilon(T)$$

- As temperature increases (e.g., supernova or quasar), vacuum fluctuations are modified, reducing ε.
- The reduced permittivity leads to an increased phase velocity of light:

$$v_{\mathrm{ph}} = \frac{1}{\sqrt{\varepsilon(T)\mu_0}}$$

- **Implication:** Photon propagation becomes temperature-sensitive, offering a physical basis for observable light-speed variations in astrophysical settings.

Analogy: Light in Media

Classical Electromagnetic Reference

- In optical media, bound charges polarize in response to an electric field:

$$D = \varepsilon E \quad \text{with} \quad \varepsilon = \varepsilon(T)$$

- At higher temperatures, thermal motion disrupts polarization, reducing ε and increasing the speed of light in the material. (known fact!)
- **Analogy:** The vacuum is treated as a limiting case of such a medium:
  - No actual matter, but quantum vacuum fluctuations respond to temperature,
  - Permittivity varies with thermal radiation background.
- This analogy supports modeling the vacuum as an effective medium — without introducing exotic physics.

Quantum Field Theory Ingredients

Vacuum Fluctuations as Physical Reality

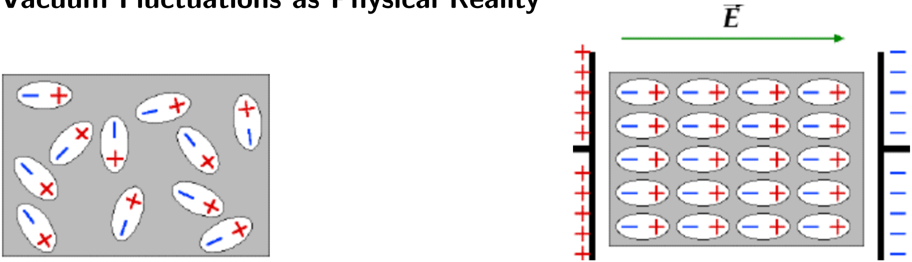


Figure: **Left:** Randomly oriented dipoles in the absence of an external field. **Right:** Dipoles align along the direction of the applied electric field.

- Quantum vacuum fluctuations are treated as physically real in:
  - Hawking Radiation (one photon becomes real),
  - Casimir effect (vacuum under boundaries),
  - Lamb shift (vacuum affecting atomic levels).
- This work takes vacuum fluctuations seriously as the basis for thermally modifiable electromagnetic response.

Thermodynamic Inspirations (Is the vacuum real?)

Known fact: Vacuum is Not Empty — It is Thermodynamically Active

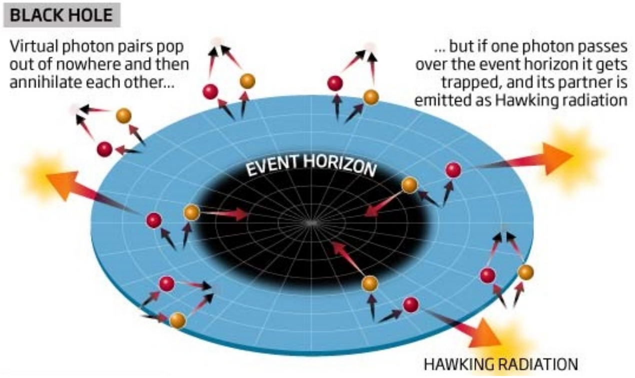


Figure: Hawking Radiation

Thermodynamic Inspirations

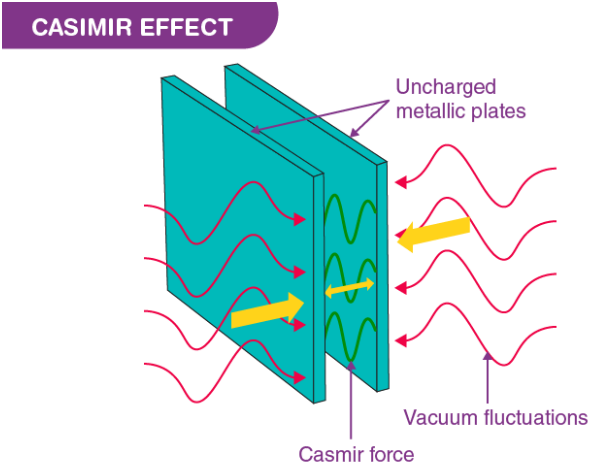


Figure: Casimir Effect: shows vacuum energy density is influenced by boundary conditions.

Thermodynamic Inspirations

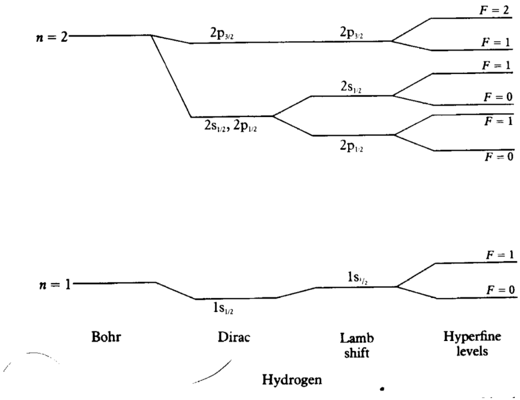


Figure: Lamb shift is a tiny difference in energy.

Key Message: These phenomena indicate the vacuum has a *state*, and this state can depend on external conditions–such as temperature.

Classical Electrodynamics Link

Microscopic Polarizability and Macroscopic Permittivity

- Bound electrons respond to external electric fields via dipole moments:

$$\vec{p} = \alpha \vec{E}$$

  with scalar polarizability α.
- The macroscopic polarization is:

$$\vec{P} = N\langle \vec{p} \rangle = N\alpha \vec{E}$$

- This links to electric susceptibility:

$$\vec{P} = \varepsilon_0 \chi_e \vec{E} \quad \Rightarrow \quad \chi_e = \frac{N\alpha}{\varepsilon_0}$$

- Therefore, the permittivity becomes:

$$\varepsilon = \varepsilon_0 (1 + \chi_e)$$

- **Result:** Permittivity encodes how microscopic dipoles in a medium respond collectively to applied fields.

Microscopic Polarizability: Lorentz Oscillator

Force on a bound electron in an electric field:

$$F = -m\omega_0^2 x = -eE$$

Solving for the displacement:

$$x = \frac{e}{m\omega_0^2} E$$

Dipole moment:

$$p = -ex = \frac{e^2}{m\omega_0^2} E \quad \Rightarrow \quad \boxed{\alpha_0 = \frac{e^2}{m\omega_0^2}}$$

Interpretation: The electron behaves like a spring-mass system; the stronger the restoring force, the smaller the polarizability.

Statistical Polarizability: Boltzmann Averaging

Harmonic potential in electric field:

$$U(x) = \frac{1}{2}m\omega_0^2 x^2 - eEx$$

Probability distribution:

$$P(x) \propto \exp\left(-\frac{1}{k_B T}U(x)\right)$$

Complete the square:

$$U(x) = \frac{1}{2}m\omega_0^2\left(x - \frac{eE}{m\omega_0^2}\right)^2 + \text{const}$$

Average dipole moment:

$$\langle x \rangle = \frac{eE}{m\omega_0^2} \quad \Rightarrow \quad \langle p \rangle = -e\langle x \rangle = \frac{e^2}{m\omega_0^2}E$$

Identical result to Lorentz model!

Unified Polarizability Concept

Two Paths, One Result

- Both the Lorentz model and Boltzmann averaging yield:

$$\alpha = \frac{e^2}{m\omega_0^2}$$

- **Temperature scaling:** In Boltzmann statistics, energy scale links to temperature via:

$$\frac{3}{2}k_B T = \hbar\omega_0 \quad \Rightarrow \quad \omega_0 \propto T$$

implying:

$$\alpha(T) \propto \frac{1}{T^2}$$

- **Implication:** The temperature dependence of microscopic polarizability cascades into macroscopic permittivity and ultimately light speed.

From Dipoles to Permittivity

Thermal Corrections

- In a polarizable vacuum, we modify the standard relation:

$$\varepsilon(T)\vec{E} = \varepsilon_0\vec{E} + \vec{P}, \quad \vec{P} = N\alpha(T)\vec{E}$$

- Using the derived result:

$$\alpha(T) = \frac{e^2}{m\omega_0^2} \propto \frac{1}{T^2}$$

- Therefore:

$$\varepsilon(T) = \varepsilon_0 + \frac{C}{T^2}, \quad C = Ne^2/m$$

- **Key takeaway:** A temperature-dependent dipole model yields a physically motivated variation in vacuum permittivity.

Temperature-Dependent Vacuum Permittivity

Sellmeier–Lorentz-Based Interpretation

- We model vacuum permittivity as:

$$\varepsilon(T) = \frac{k_p}{T^2}$$

  valid for:

$$T > T_c \approx 4 \times 10^9\,\mathrm{K}$$

- **Assumption:** Set initial condition

$$\varepsilon_{BB} = 0$$

  because near the Big Bang, vacuum fluctuations dominate and no bare permittivity remains.

- **Constant:** The proportionality constant is:

$$k_p \approx 1.4 \times 10^8\,\mathrm{F} \cdot \mathrm{m}^{-1} \cdot \mathrm{K}^{-2}$$

- **Result:** Thermal environments (e.g., near supernovae) can imprint measurable signatures via light-speed variation.

Propagator at Finite Temperature

Zero Temperature (Feynman Gauge)

$$D(p) = \frac{-i}{p^2 - \dfrac{m^2 c^2}{\hbar^2} + i\epsilon}, \qquad p^2 = p_0^2 - \vec{p}^2.$$

Finite Temperature (Matsubara Formalism)

$$p_0 \to i\omega_n, \qquad \omega_n = 2\pi n T, \qquad n \in \mathbb{Z}.$$

$$D(i\omega_n, \vec{p}) = \frac{1}{\dfrac{\omega_n^2}{c^2} + \vec{p}^2 + \dfrac{m^2 c^2}{\hbar^2}}.$$

- Temperature enters through the Matsubara frequencies.
- The mass term remains unchanged.
- The thermal scale is encoded in ω_n.

Thermal Frequency and Effective Mass

The lowest non-zero Matsubara mode is taken as the dominant thermal contribution:

$$n = 1, \qquad E_T = \hbar\omega_1.$$

Using the vacuum oscillator relation

$$\hbar\omega_1 = \frac{3}{2}k_B T,$$

and Einstein's relation

$$E_T = m_T c^2,$$

the thermal mode can be interpreted as an effective mass

$$m_T = \frac{3k_B T}{2c^2}.$$

Hence,

$$m_T^2 = \frac{9}{4}\frac{k_B^2 T^2}{c^4}.$$

Thermal Correction and Critical Temperature

The inverse propagator contains both the vacuum mass and the thermal contribution:

$$D^{-1}(p, T) = p^2 + \frac{m^2c^2}{\hbar^2} + \frac{9}{4}\frac{k_B^2 T^2}{\hbar^2 c^2}.$$

The critical temperature is defined by

$$m^2 = m_T^2.$$

Therefore,

$$T_c = \frac{2mc^2}{3k_B} \approx 4 \times 10^9\,\mathrm{K}$$

(for the electron).

- $T \ll T_c$: vacuum mass dominates.
- $T \sim T_c$: thermal corrections become significant.
- $T > T_c$: thermal effects dominate propagation.

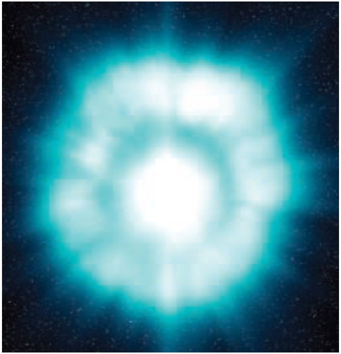
Gamma-Ray Bursts—A Puzzle

- GRBs are the most energetic electromagnetic events known.
- Some are linked to supernovae (e.g., GRB 980425 and SN 1998bw) [3].

These associations raise a paradox: **the energy observed exceeds what standard supernova models can explain**.

Observational Clues

- "Photon photo finish" experiments show **arrival-time anomalies** in GRBs [2].
- Suggests: **photons emitted simultaneously don't arrive together**.



A. Cho Science 307 (2005)

Traditional Explanations (and Limits)

Existing Interpretations of Photon Delays in GRBs

- **Quantum Gravity Models**
  - Predict energy-dependent light speed from spacetime quantization.
  - Delays arise from modified dispersion relations.
  - *Issue:* Effects typically suppressed by Planck scale ($\sim 10^{19}\,\mathrm{GeV}$); hard to test.
- **Lorentz Invariance Violation (LIV)**
  - Modifies fundamental symmetries to allow energy-dependent speed of light:

$$c(E) = c_0 \left(1 \pm \frac{E}{E_{\mathrm{LIV}}}\right)$$

  - High-energy photons travel slightly slower or faster depending on sign.
  - *Issue:* LIV tightly constrained by other astrophysical observations (e.g., polarization, UHECRs).
- **Cosmological Dispersion**
  - Attributes delay to travel effects through intergalactic medium.
  - *Issue:* Cannot explain observed energy scaling and short burst profiles.

Critique of Earlier VLS Theories

Motivations, Approaches, and Limitations

- *Motivation for VLS theories:*
  - Proposed in the 1990s as alternatives to inflation to address key cosmological problems:
    - **Horizon problem:** Uniform temperature of the cosmic microwave background (CMB) across causally disconnected regions.
    - **Flatness problem:** Extreme fine-tuning of initial curvature to yield today's nearly flat universe.
    - **Monopole problem:** Absence of magnetic monopoles predicted by grand unified theories.
  - VLS attempts to solve these by temporarily allowing $c \gg c_0$ in the early universe.
- *Representative models:*
  - **Moffat (1993)** — Superluminal phase transition model:
    - Introduced a spontaneous symmetry-breaking mechanism that causes c to drop from a very large initial value.
    - Achieves causal contact without inflation.
  - **Albrecht–Magueijo (1999)** — Scalar field VLS model:
    - Postulates a scalar field coupled to the metric or matter, dynamically

Toward a Physically Grounded Approach

- This framework [6] draws from and integrates:
  - *Quantum field theory:* Vacuum fluctuations are physically real and can interact with external conditions (e.g., temperature, boundary conditions).
  - *Thermodynamic analogs:* Phenomena like Hawking radiation and the Casimir effect reveal that quantum vacuum properties are *state-dependent*.
  - *Classical electrodynamics:* Descriptions of light propagation in media (e.g., dispersion, permittivity) provide a natural analogy [4].
- **Idea:** The vacuum may exhibit optical-like behavior in extreme environments, with properties affected by thermal or radiative energy density.
- *Implication:* Such a medium could lead to apparent variation in the speed of light, offering a testable explanation for high-energy astrophysical observations.

Link to Supernova Explosions

GRBs and Their Thermally Active Environments

- Many long-duration GRBs are linked to core-collapse supernovae (e.g., GRB 980425/SN 1998bw, GRB 030329/SN 2003dh).
- The collapse and explosion generate intense thermal radiation and relativistic ejecta:
  - Temperatures near the central engine can reach $T \sim 10^{10}$–$10^{11}\,\mathrm{K}$— modifying local quantum vacuum properties.
- **Hypothesis:** The thermal background modifies the permittivity $\varepsilon(T)$ of the vacuum near the GRB site.
- This leads to a local variation in the speed of light:

$$c(T) = \frac{1}{\sqrt{\varepsilon(T)\mu_0}} \quad \text{with} \quad \varepsilon(T) < 1 \Rightarrow c(T) > c_0$$

- **Implication:** Photons emitted during the explosion experience different effective travel speeds depending on when and where they originate — explaining observed delays.

Figure: Temperature Dependence in Vacuum Response

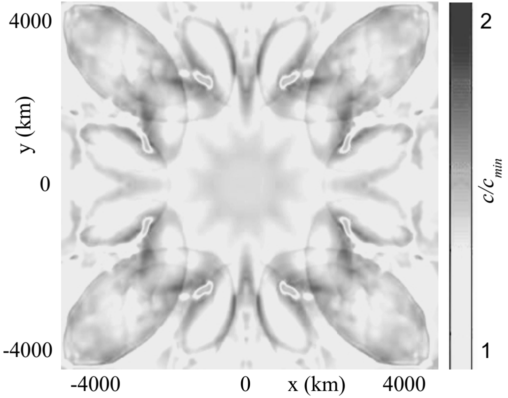


Figure: The adimensional speed of light dependence with distance in a 2D simulation of a supernova explosion. $c_{\min}$ corresponds to a temperature of $2.5 \times 10^9\,\mathrm{K}$. The simulation is consistent with photon photo finish observations.[2]

Schematic of the temperature distribution

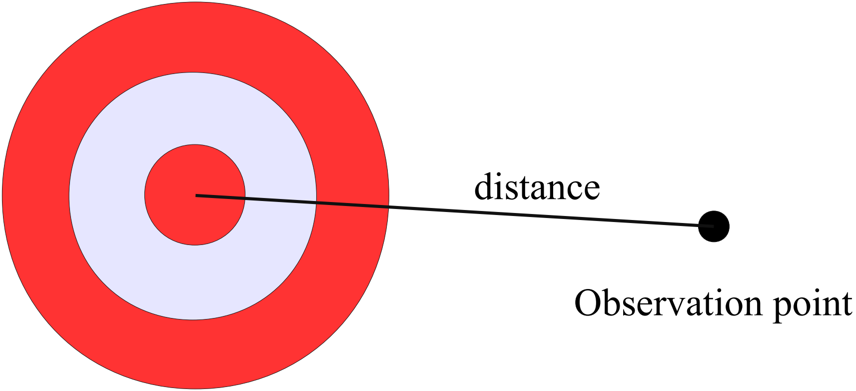
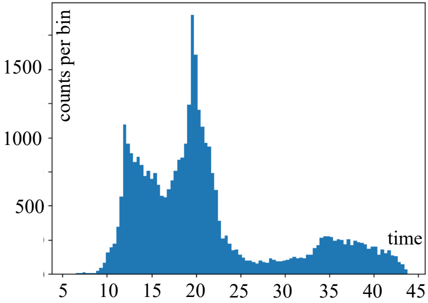


Figure: Schematic of the temperature distribution around a supernova. At a fixed distance, photon counts are recorded as a function of arrival time.

Figures: Temperature Dependence and Light Curves



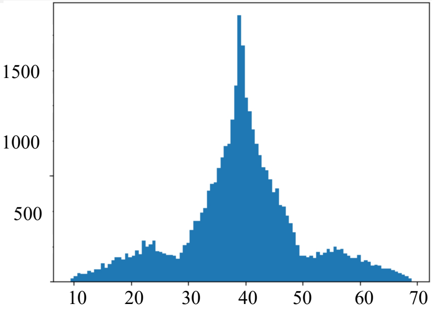


Figure: **Left:** Simulated light curve for a supernova at an arbitrary distance with temperature-dependent speed of light. **Right:** Same simulation assuming constant light speed.

- Thermal modulation of vacuum permittivity leads to structured photon arrival times.
- The left panel reproduces key features of observed GRB light curves.
- The right panel lacks this structure, showing the importance of including temperature dependence in $c(T)$.

Temperature-Dependent Speed of Light

Vacuum Permittivity

$$\varepsilon(T) = \frac{k_P}{T^2}, \qquad \varepsilon(T_c) = \frac{k_P}{T_c^2}$$

$$\frac{\varepsilon(T)}{\varepsilon(T_c)} = \frac{T_c^2}{T^2}, \quad (\varepsilon(T_c) = \varepsilon_0)$$

$$c(T) = \frac{1}{\sqrt{\varepsilon(T)\mu_0}}$$

$$c(T) = \begin{cases} c_0, & T \leq T_c, \\ c_0 \dfrac{T}{T_c}, & T > T_c. \end{cases}$$

Quasars as Extreme Thermal Sources

Figure: They are distant galaxies whose incredibly bright cores are powered by supermassive black holes.

Quasars as Extreme Thermal Sources

Physical Environment

- Quasars are among the most luminous objects known.
- Radiation originates from the accretion disk surrounding a supermassive black hole.
- Gas and dust are heated by accretion and friction.
- Brightness temperatures may reach

$$T \sim 10^{13}\ \mathrm{K},$$

  far above

$$T_c \approx 4 \times 10^9\ \mathrm{K}.$$

Observational Clue

Several studies report statistically significant associations between high-redshift quasars and nearby galaxies:

- NGC1842: $P \sim 10^{-6}$
- NGC1073: $P \sim 2 \times 10^{-5}$

Temperature–Redshift Relation

Thermal contribution to the observed redshift [1]

$$z + 1 = \frac{\nu_e(T)}{\nu_o}$$

- z represents the measured redshift.
- The observed redshift contains both cosmological and intrinsic thermal contributions.
- $\nu_e(T)$ denotes the emission frequency in a thermal environment.
- Using finite-temperature arguments:

$$\frac{\nu_e(T)}{\nu_e} = \frac{T}{T_c} \quad \left(h\nu = \frac{3}{2}k_B T\right)$$

- The temperature-independent component is defined as:

$$z_0 + 1 = \frac{\nu_e}{\nu_o}$$

[1] C.W. Misner, K.S. Thorne, J.A.Wheeler, Gravitation (W. H. Freeman and Company, San Francisco, 1973)

Intrinsic Thermal Redshift

Separation of cosmological and thermal components

Starting from

$$z + 1 = \frac{\nu_e(T)}{\nu_e} \frac{\nu_e}{\nu_o}$$

which can be rewritten as

$$z_0 + 1 = (z + 1)\frac{T_c}{T}$$

- z_0: temperature-independent redshift
- T: local source temperature
- T_c: critical temperature

Implication: High-temperature environments may generate an intrinsic redshift contribution.

Alternative Derivation

Wavelength-frequency formulation

Starting from

$$\lambda\nu = c$$

the redshift becomes

$$z + 1 = \frac{\lambda_0}{\lambda_e}\frac{c(T)}{c_0}$$

or equivalently

$$z + 1 = (z_0 + 1)\frac{c(T)}{c_0}$$

- λ_e: wavelength at the thermal edge
- λ_0: wavelength for $T < T_c$
- $c(T)$: temperature-dependent light speed

Interpretation: Thermal vacuum effects modify photon propagation and

Connection with Varying-c Cosmology

Thermal interpretation of varying light speed

Using

$$\frac{c(T)}{c_0} = \frac{T}{T_c}$$

we recover

$$z + 1 = (z_0 + 1)\frac{T}{T_c}$$

The model proposed by Devasia gives

$$1 + z = \frac{c}{c_0}$$

- effective varying-c behavior emerges naturally,
- no phenomenological modification is required,
- the mechanism follows from temperature-dependent vacuum response.

Intrinsic Redshift Hypothesis

Quasar Redshift Anomalies

- Some studies report associations between high-redshift quasars and nearby galaxies.
- This suggests that the observed redshift may contain a non-cosmological component.

Working Hypothesis

- high-temperature environments modify vacuum properties,
- photon propagation becomes temperature dependent,
- part of the observed redshift may be intrinsic.

Spectroscopy and Temperature Regimes

Standard Spectroscopy

$$T \sim 10^4\,\mathrm{K}$$

- atoms remain stable,
- atomic transitions are observable,
- spectroscopic redshift can be measured.

Critical Temperature

$$T_c \approx 4 \times 10^9\,\mathrm{K}$$

- matter becomes fully ionized plasma,
- atomic transitions disappear,
- standard spectroscopy breaks down.

High-Temperature Quasar Environments

Thermal Structure

- outer regions:

$$T \sim 10^4\,\mathrm{K}$$

- relativistic jets:

$$T \gg T_c$$

Implication

- spectroscopic measurements probe cooler regions,
- thermal vacuum effects originate in hotter regions,
- the two environments may contribute differently to the observed redshift.

Luminosity Distance

The luminosity distance is defined by

$$d_L^2 = \frac{L}{4\pi F},$$

where

- L: intrinsic luminosity,
- F: observed flux.

In a Friedmann universe,

$$d_L = (1+z)\, a_0\, r_1(z_0).$$

Using

$$1+z = (1+z_0)\frac{T}{T_c},$$

we obtain

$$d_L = (1+z_0)\, a_0\, r_1(z_0)\frac{T}{T_c}.$$

Flat Matter-Dominated Universe

For

$$\Omega_M = 1, \qquad \Omega_\Lambda = 0,$$

the Hubble function becomes

$$h(z) = (1+z)^{3/2}.$$

The comoving distance is

$$\chi(z_0) = \frac{c_0}{a_0 H_0} \int_0^{z_0} \frac{dz'}{h(z')}.$$

After integration,

$$d_L = \frac{2c_0}{H_0}(1+z_0)\left(1 - \frac{1}{\sqrt{1+z_0}}\right)\frac{T}{T_c}.$$

Determining the Thermal Contribution

The distance modulus is

$$\mu_0 = m - M = 5\log\left(\frac{d_L}{\mathrm{Mpc}}\right) + 25.$$

Procedure:

1. Measure z and μ_0.
2. Determine d_L.
3. Use the luminosity-distance relation to obtain

$$\frac{T}{T_c}.$$

4. Compute the temperature-independent redshift z_0.

$$1 + z = (1 + z_0)\frac{T}{T_c}.$$

Quasar Results

QSO	143112.39 +093915.4	112310.06 +134622.5	115132.69 +550317.3	125718.02 +374729.9	131808.44 +215437.0
z	7.01	6.03	5.33	4.74	4.25
μ_0	49.38	49.07	48.78	48.30	47.78
T/T_c	1.63	1.67	1.68	1.53	1.36
z_0	3.91	3.20	2.76	2.73	2.84

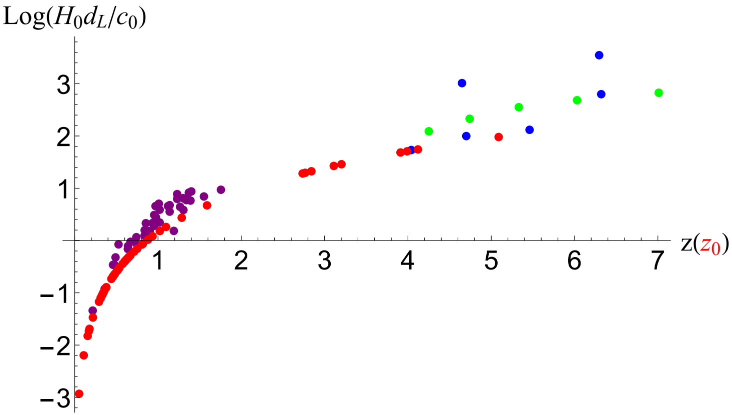
Key Result

- All quasars satisfy $T > T_c$.
- The corrected redshift is significantly reduced:

$$z_0 < z.$$

- A substantial fraction of the observed redshift may be associated with thermal effects.

Comparison with Observations



- SN (purple), GRB (blue), and QSO (green): observed values.
- Red points: temperature-corrected values.
- Thermal effects reduce both the inferred redshift and luminosity distance.

The Hubble Tension

Current Measurements of H_0

- CMB (Planck):

$$H_0 \approx 67.4 \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

- Distance ladder (Cepheids + SN):

$$H_0 \approx 73 \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

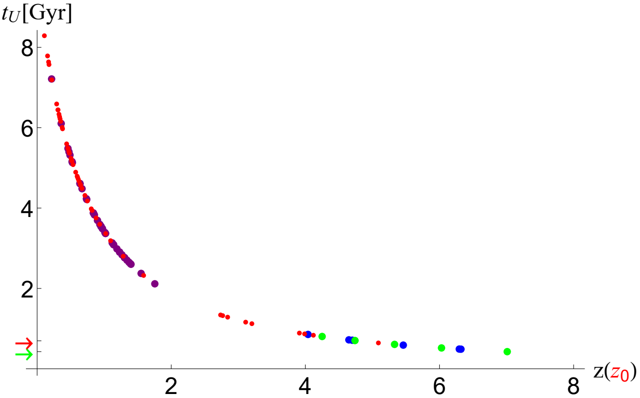
Problem

The discrepancy exceeds observational uncertainties and remains one of the main challenges of modern cosmology.

$$t_U(z) = \frac{9.67}{(1+z)^{3/2}} \ \mathrm{Gyr}$$

The inferred age of the universe depends directly on the measured redshift.

Effect of Thermal Redshift



- SN (purple), GRB (blue), and QSO (green): observed redshifts.
- Red points: temperature-corrected values z_0.
- Thermal effects systematically reduce redshift.

$$\max z = 7.01 \quad \Rightarrow \quad t_U = 0.42\ \mathrm{Gyr}$$

$$\max z_0 = 5.08 \quad \Rightarrow \quad t_U = 0.64\ \mathrm{Gyr}$$

Implications for Cosmology

Low-Temperature Observables

- BAO measurements are imprinted near recombination,
- $T \ll T_c$,
- $c(T) = c_0$.

High-Temperature Sources

- supernovae,
- quasars,
- gamma-ray bursts.

For $T > T_c$,

$$1 + z = (1 + z_0)\frac{T}{T_c}.$$

Consequence

Part of the observed redshift may be thermal rather than cosmological, reducing the need for dark energy and helping to reconcile different determinations of H_0.

Summary of Key Points I

Core Concept

- The vacuum is modeled as a temperature-sensitive optical medium.
- This leads to a modified permittivity $\varepsilon(T)$ and thus a temperature-dependent speed of light $c(T)$.

Theoretical Foundations

- Derived from classical electrodynamics: Lorentz and Boltzmann polarizability models.
- Thermal effects introduced via statistical averaging and Matsubara formalism.
- Result: $c(T) = c_0\, T/T_c$ above a critical temperature T_c.

Astrophysical Application

- GRBs and SN environments provide high-temperature regimes.
- Explains energy-dependent photon delays as optical propagation effects in a modified vacuum.
- Offers a testable, physically grounded alternative to speculative VLS theories.

Summary of Key Points II

Quasars and Redshift

- Quasar environments can reach temperatures far above T_c.
- Thermal vacuum effects may contribute an intrinsic component to the observed redshift.
- Observed redshifts may contain both cosmological and local thermal contributions.

Connection with Varying-c Cosmology

- Effective varying-c behavior emerges naturally from vacuum thermodynamics.
- No ad hoc modification of fundamental constants is required.
- Provides a physical mechanism underlying earlier VLS proposals.

Cosmological Implications

- Potential explanation for quasar redshift anomalies.
- May contribute to resolving part of the Hubble tension.
- Suggests new observational tests in high-energy astrophysics and cosmology.

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Thank you for your attention.