The Wave Equation for the Cosmic Redshift

Wolfgang Quapp

Mathematisches Institut, Universität Leipzig, PF 100920, 04009 Leipzig, Germany, ORCID: 0000-0002-0366-1408.

Contributing authors: quapp@math.uni-leipzig.de;

Abstract

We combine the Heisenberg uncertainty principle with the Maxwell equations. It results a generalized wave equation. An approximate wave solution shows a redshift of the wavelength over huge period of time. It indicates a redshift-distance relationship, besides the well known redshift-velocity relationship by the Doppler principle.

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1 Introduction

Huygens' principle applies both in three-dimensional Euclidean space and in many three-dimensional curvilinear spaces [1, 2]. It allows us to see the light from cosmologic objects with quasi-sharp spectroscopical lines. For example, the James Webb Space Telescope (JWST) observes Lyman-α lines [3] from objects that are thought to be located at a distance of 13.5 billion light years with a redshift of $z > 14$ [4]. It means that light travels without transverse deflection [5], and a wave equation governs the propagation of light at all observable distances.

The background is that light is an electromagnetic wave described by the Maxwell equations [6]. To investigate a field propagating in space, we start with the classical electromagnetic equations in vacuum

$$\nabla \cdot \mathbf{B} = 0 \tag{1}$$

$$\nabla \cdot \mathbf{E} = 0 \tag{2}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{3}$$

$$\nabla \times \mathbf{B} = \epsilon_o \mu_o \frac{\partial \mathbf{E}}{\partial t} \tag{4}$$

where $\mathbf{E}$ is the electric field and $\mathbf{B}$ is the magnetic field, which are orthogonal to each other. ∇ is the operator of the spatial derivatives, and ϵ_o and μ_o are the constitutive parameters, the electric permittivity and the magnetic permeability of the free space. They combine to $\epsilon_o \mu_o = 1/c^2$. c is the constant speed of light. This constancy of c is therefore assumed from the early beginning of Maxwell's theory [7]. The Maxwell equations (1-4) combine to the wave equation

$$\frac{\partial^2 u}{\partial^2 t} - c^2 \nabla^2 u = 0 \tag{5}$$

for both fields. We use $\omega/k = c$ for the initial frequency and wave number of the observed wave, with the time period $T = 2\,\pi/\omega$ and the wavelength $\lambda = 2\pi/k$. A harmonic wave in one spatial dimension, say x, that satisfies the wave equation is given for the two special components of the electromagnetic fields, E_y and B_z

$$E_y(t, x) = E_o\; cos(\omega\, t - k\, x) \tag{6}$$
$$B_z(t, x) = B_o\; cos(\omega\, t - k\, x) \tag{7}$$

with the impedance V_o of the free space relation [8]

$$E_o = V_o B_o \;\; = \sqrt{\frac{\mu_o}{\epsilon_o}} B_o \;. \tag{8}$$

The vacuum impedance $V_o = \mu_o\, c$ is connected with the fine-structur constant [9, 10].

A general wave for the electric field can be represented, for example, by a Fourier series

$$W_y(t, x) = \sum_n E_n cos(n(\omega\, t - k\, x) + \phi_n) \tag{9}$$

with the possibly different phase parts ϕ_n. With time t the wave moves along the x axis. Eq.(9) can be used to describe wave packets [11].

The Doppler principle [12] applies for the observation of moving stars [13], and especially for the rotation of galaxies. A deeper discussion of exact values with a comparison of the Doppler effect and other effects is given in ref.[14]. However, the JWST observations raise profound questions about the application of 'only' Doppler shifts, as assumed by the standard cosmological model [15]. In contrast, some kinds of 'tired' light are coming back into the discussion [16–21].

A redshift is an increase in the wavelength, and corresponding decrease in the photon energy, of electromagnetic radiation. Redshifts are measurable quantities in cosmology. In this work, we assume that observed redshifts can arise from a combination of a Doppler shift and a shift caused by a generalized wave equation. This equation we develop here. To start with we simplify a static cosmos in Euclidean space, Minkovski space-time, and no 'cosmic expansion' [22].

In section 2 we introduce the model used. It revisits an argument for a generalized wave equation according to the Heisenberg uncertainty principle. Section 3 is a short general discussion of the meaning of the result. Finally we give some conclusions.

2 The generalized wave equation

We assume a homogeneous, isotropic, and flat universe, which is confirmed by observations of the cosmic microwave background (CMB) [23, 24]. Relativistic and gravitational properties of the cosmos will be postponed to later studies. Light travels through the cosmic vacuum via the electro-magnetic process 'hand over hand'. The two fields cross with each other.

In Maxwell equations (1-4) one assumes an exact relation of the two fields. However, we cannot beat the Heisenberg uncertainty principle [11]. It states for uncertainties δ of $\mathbf{E}$ and $\mathbf{B}$ in a volume δV and a length δL along the wave direction [11]

$$\delta \mathbf{E}\, \delta \mathbf{B} \geq \frac{h\, c}{\delta V\, \delta L}\ . \tag{10}$$

h is the Planck constant, and δL must be greater than the wave length λ. We choose $\delta L = 1$[m] for simplicity, and the interesting volume by a cube with side length δL as well; it should be larger than E_o. Because it is

$$c = \frac{1}{\sqrt{\mu_o \epsilon_o}} \tag{11}$$

we can move the two constants $\sqrt{\mu_o}$ and $\sqrt{\epsilon_o}$ to the other side of the approximation (10), and if we use Eq.(8), we can assume the best case of the so-called states of minimal uncertainty [25, 26], in which both weighted uncertainties are equal

$$\sqrt{\mu_o}\, \delta \mathbf{B} = \sqrt{\epsilon_o}\, \delta \mathbf{E} = q \tag{12}$$

with a common constant, q, taking symmetry between the electric and magnetic part. We get with (10)

$$q \geq \sqrt{h}\ . \tag{13}$$

We propose incorporating this fundamental relationship into the Maxwell Eqs.(3,4) where Eqs.(1,2) are unchanged. First, we assume that we have an uncertainty factor for each part of length $\delta L = 1$ over the wave, which needs a time of $\delta T = \delta L / c$, by

$$(1 \pm \delta T\, q) = (1 \pm \frac{1}{c}\sqrt{h}) \tag{14}$$

for both time derivatives. It was a suggestion from G. Lemaitre [27, 28] to include time in an uncertainty relationship. For n periods, we then have a correction factor

$$(1 \pm \frac{1}{c}\sqrt{h})^n \approx (1 \pm \frac{n}{c}\sqrt{h} + ...)\ . \tag{15}$$

With $n/c \approx t$ and with the symbol $q = \sqrt{h}$ we obtain the 'uncertainty' Maxwell equations

$$\nabla \times \mathbf{E} \ \approx\ -(1 \pm q\, t)\frac{\partial \mathbf{B}}{\partial t} \tag{16}$$

$$\nabla \times \mathbf{B} \approx (1 \pm q\,t)\epsilon_o \mu_o \frac{\partial \mathbf{E}}{\partial t}\ . \tag{17}$$

The lowest value for q is $\sqrt{h} = 2.58 * 10^{-17}/[sec]$. We must exclude the minus sign for $q\,t$ because it can lead to a singularity.

Solving the new equations can be difficult. However, the modified equations are approximately satisfied by the wave

$$u(t,x) = cos(\frac{1}{1+q\,t}(\omega\,t - k\,x)) \tag{18}$$

compare above Eqs.(6,7), and also Eq.(21) below. Note that the speed of light, c, is not changed. However, the wave undergoes a redshift at very long times. With typical short local times, the additional action of the extra factor on this equation is almost zero. The factor which determines the redshift in Eq.(18) is illustrated in Fig.1.

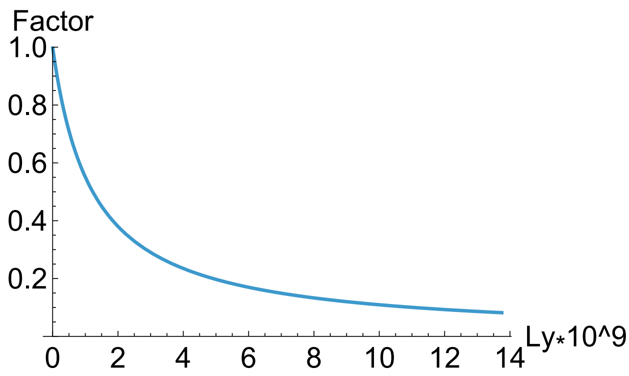

Fig. 1 Redshift factor 1/(1+qt) over billions of light years for $q = \sqrt{h}$.

The proposed value for the derivation of Eqs.(16,17) may still be adjusted to the measured redshifts. The estimate of $\tilde{q} = 3.356 * 10^{-17}/[sec]$ is a constant motivated by the quasar JADES-GS-z14-0 [29] with a redshift of 14.32 and an assumed age of 13.52 billion years. The frequency ω of the Lyman-α line with 2.47*10^{15} Hz for a cosmic event in the past, i.e. a wave with an ultraviolet wavelength of 1 215 Å is shifted to 18 625 Å. If one uses the approximated time of 13.52 billion years then one obtains the measured line in the microwave region in Eq.(18). This is observed by the JWST [29].

It is unlikely that the entire redshift of the observed lines will originate from approximation (18). However, it could be an alternative additional effect alongside the Doppler effect [15, 24, 30] and further effects such as gravitational redshift. For combined use of the effects, the constant $\tilde{q}$ should of course be further adapted.

On the other hand, if we apply the approach (18) with the minimal $q \approx \sqrt{h}$ directly to the quasar under investigation with the measured redshift of $z = 14.32$, we would obtain an age of $17.58 * 10^9$Ly, already beyond the celebrated $13.8 * 10^9$Ly.

The generalized wave equation is then again a combination of Eqs.(1,2) and (16,17)

$$\frac{\omega^2}{(1+q\,t)^2}\nabla u - k^2\frac{\partial^2 u}{\partial^2 t} = 0\ . \tag{19}$$

In general, $u(t, x, y, z)$ is the shape function of the signal we are trying to observe by a spectrometer. The distance to the observed cosmological object can be x. We use this 1D axis. We assume a Cartesian coordinate system, no Lorenz coordinate transformation, no relativistic time.

If we assume a simplified case of a periodic, trigonometric form of the signal using the approximation (18), we can immediately motivate the form of Eq.(19). It is

$$\frac{\partial^2 u(t,x)}{\partial^2 x} = -\frac{k^2}{(1+qt)^2}u(t,x) \tag{20}$$

and

$$\frac{\partial^2 u(t,x)}{\partial^2 t} = -\frac{\omega^2}{(1+q\,t)^4}u(t,x) - \tag{21}$$
$$q\,\Big(\frac{2(\omega+k\,q\,x)}{(1+qt)^3}sin(\frac{1}{1+qt}(\omega t-k\,x)) + \frac{(2\omega\,k\,q\,x+k^2q^2x^2)}{(1+qt)^4}cos(\frac{1}{1+qt}(\omega t-k\,x))\Big).$$

The second summand on the right-hand side of Eq.(21) is nearly zero for all times of interest. Because, the values of $(1+q\,t)$ and $(1+q\,x/c)$ are low numbers, and since q is close to zero. Using Eq.(18) we obtain a good approximation of a solution to the generalized wave equation (19).

3 Discussion

We do not discuss relativistic effects. And we do not discuss the gravitational redshift [31–35] and also not the gravitational curved spacetime [36–38]. We refer to the search for a theory of quantum gravity [39]. We also do not compare the redshift which is proposed by the theory of an expanding cosmos [22], the so-called cosmological redshift. A comparison with these theories is not within the scope of this paper. The aim of this paper is to propose the principle of a generalized wave equation (19). The proof of principle is the proposed oldness of observed objects with a redshift $z > 14$ which could be older than 'the time itself'.

The Doppler effect [12] is a fundamental principle of physics. Via Woldemar Voigt [40] and Hendrik Antoon Lorentz [41] and others, it inspired the special relativity theory of Albert Einstein [7]. The Doppler effect is usefull, of course, for describing the motion of galaxies relative to each other and detecting the rotation of galaxies [42]. However, linking all the measured redshifts to the Doppler effect may not be entirely correct [30, 43, 44].

The combination of the Doppler part of 'velocity-redshift' and the component of 'distance-redshift' proposed here, will lead to another constant $\tilde{q}$ than the one adjusted above, $\tilde{q} = 3.356 * 10^{-17}/[sec]$. Balancing this relationship will be a task for the near future.

We assume that the electromagnetic waves of light are excitations of the quantum vacuum [45–49]. Note that already in 1954 there was a propose to assume an intergalactic temperature of about 1.5 K by this effect [50]. Heisenberg's uncertainty principle [11] has the known consequence that the commutation relations in quantum electrodynamics imply zero-point fluctuations of the electromagnetic field even in the quantum vacuum [51]. So, the 'vacuum' is not empty [52–62]. We assume that the light waves require energy to travel through the quantum vacuum [63, 64]. They transform electromagnetic energy in heat: the uniform thermal energy on average 2.725 K [65]. It would explain the energy loss under the observed redshifts if one accepts a redshift-distance relationship.

Where ever does the energy go? We suspect that it feeds the cosmic microwave background radiation [66] which could be understood to be in an equilibrium flow with the temperature of the quantum vacuum. The spectrum of the CMB is an almost perfect Planck spectrum for the black body radiation [65] – the quantum vacuum is the 'black body'. The CMB is very smooth and uniform, but there are small temperature variations [67, 68]. The anisotropy structure is influenced by various interactions of matter. Note that a part of the CMB disappears to other energy reservoires such as rotational excitations of cosmic molecules [69]. The proposed energy transfer from the quantum vacuum could give rise to yet again another reasoning for the CMB, compare [70–75] and references therein.

4 Conclusions

We propose a generalized wave equation for a phenomenological description of a redshift-distance relationship. It results from a tiny perturbation of Maxwell's equations by the omnipresent Heisenberg uncertainty principle. An approximate wave solution shows a redshift of the wavelength of light over huge periods of time. This suggests a redshift-distance relationship, compare [35], in addition to the well known redshift-velocity relationship through the Doppler principle [12, 76–78], or the expanding universe [22]. The question of the origin of the redshift, put forward here, has the consequence that the average cosmological parameters must be recalibrated.

Declarations

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- Materials availability: Not applicable
- Code availability: Not applicable
- Author contribution: Not applicable

- Motto: "It will be light" (1. Mose 1,3).

References

[1] Günther, P.: Huygens Principle and Hyperbolic Equations. Academic Press, INC, Boston (1988). https://doi.org/10.1016/C2013-0-10776-3

[2] Zhang, C., Zhao, Z., Kong, M.: Study on mathematical essence of Huygens' principle. Optik **175**, 49–53 (2018) https://doi.org/10.1016/j.ijleo.2018.08.138

[3] Gunn, J.E., Peterson, B.A.: On the density of neutral Hydrogen in intergalactic space. Astrophys. J. **142**, 1633–1636 (1965) https://doi.org/10.1086/148444

[4] Gupta, R.P.: JWST early universe observations and λCDM cosmology. Monthly News Roy. Astro. Soc. **524**, 3385–3395 (2023) https://doi.org/10.1093/mnras/stad2032

[5] Hubble, E., Tolman, R.C.: Two methods of investigating the nature of the nebular redshift. Astrophys. J. **82**, 302 (1935)

[6] Maxwell, J.C.: VIII: A dynamical theory of the electromagnetic field. Phil. Trans. Roy. Soc. London **155**, 459–512 (1865) https://doi.org/10.1098/rstl.1865.0008

[7] Einstein, A.: Zur Elektrodynamik bewegter Körper. Annal. Phys. **322**(10), 891–921 (2005) https://doi.org/10.1002/andp.19053221004

[8] NIST: 2022 codata value: characteristic impedance of vacuum. The NIST Reference on Constants, Units, and Uncertainty, 2024–0518 (May 2024)

[9] Klitzing, K., Dorda, G., Pepper, M.: New Method for High-Accuracy Determination of the Fine Structure Constant Based on Quantized Hall Resistance. Phys. Rev. Lett **45**(6), 494–497 (1980) https://doi.org/10.1103/PhysRevLett.45.494

[10] Kalinski, M.: Qed-like simple high order perturbative relation between the gravitational constant G and the Planck constant h. J. High Energy Phys., Gravitation and Cosmology **7**, 595–601 (2021) https://doi.org/10.4236/jhepgc.2021.72034

[11] Heisenberg, W.: Die Physikalischen Prinzipien der Quantentheorie. S.Hirzel, Leipzig (1930)

[12] Doppler, C.: Ueber das farbige licht der Doppelsterne und einiger anderer Gestirne des Himmels. Abh. Königl. Böhm. Ges. Wiss. **2**, 465–482 (1842)

[13] Nolte, D.D.: The fall and rise of the Doppler effect. Phys. Today **73**(3), 30–35 (2020) https://doi.org/10.1063/PT.3.4429

[14] Colenbrander, B., Hulscher, W.: Keplerian Rotation Curve of the Milky Way. Am. J. Mod. Phys. **13**(4), 52–56 (2024) https://doi.org/10.11648/j.ajmp.20241304.11

[15] Weinberg, S.: Gravitation and Cosmology: Principles and Applications of the

General Theory of Relativity. John Wiley and Sons, Inc. (1972)

[16] Zwicky, F.: Die Rotverschiebung von extragalaktischen Nebeln. Helv. Phys. Acta. **6**, 110–127 (1933) https://doi.org/10.5169/seals-110267

[17] Zwicky, F.: On the masses of nebulae and of clusters of nebulae. Astrophys. J. **86**, 217–246 (1937) https://doi.org/10.1086/143864

[18] LaViolette, P.A.: Is the universe really expanding? Astrophys. J. **301**, 544–553 (1986) https://doi.org/10.1086/163922

[19] Burbidge, G.: Noncosmological Redshifts. Publ. Astr. Soc. Pacific **113**, 899–902 (2001) https://doi.org/10.1086/322152

[20] Shao, M.-H., Wang, N., Gao, Z.-F.: Tired light denies the big bang. In: Redefining Standard Model Cosmology vol. B1233, pp. 1–17. Intech, - (2018). https://doi.org/10.5772/intechopen.81233

[21] LaViolette, P.A.: Expanding or static universe: Emergence of a new paradigm. Int. J. Astro. Astrophys. **11**, 190–231 (2021) https://doi.org/10.4236/ijaa.2021.112011

[22] Tremblin, P., Chabrier, G.: Re-evaluating the cosmological redshift: Insights into inhomogeneities and irreversible processes. A & A **689**, 207 (2024) https://doi.org/10.1051/0004-6361/202450818

[23] Levin, J.: Topology and the cosmic microwave background. Phys. Rep. **365**, 251–333 (2002) https://doi.org/10.1016/S0370-1573(02)00018-2

[24] Planck Collaboration: N. Aghanim et al.: Planck 2018 results VI. Cosmological parameters. A&A **641**, 6 (2020) https://doi.org/10.1051/0004-6361/201833910

[25] Hoffman, D.K., Kouri, D.J.: Hierarchy of Local Minimum Solutions of Heisenberg's Uncertainty Principle. Phys. Rev. Lett. **85**, 5263–5267 (2000)

[26] Bian, K., Zheng, W., Zeng, X., Chen, X., Stöhr, R., Denisenko, A., Yang, S., Wrachtrup, J., Jiang, Y.: Nanoscale electric-field imaging based on a quantum sensor and its charge-state control under ambient condition. Nature Comm. **12**, 2457 (2021) https://doi.org/10.1038/s41467-021-22709-9

[27] Lemaitre, G.: L' indetermination de la loi de Coulomb. Ann. Soc. Sci. Bruxelles **51-B**(1), 12–16 (1931)

[28] Lemaitre, G.: The uncertainty of the electromagnetic field of a particle. Phys. Rev. **43**, 148 (1933)

[29] Carniani, S., and all: Spectroscopic confirmation of two luminous galaxies at a redshift of 14. Nature **633**, 318–328 (2024) https://doi.org/10.1038/

s41586-024-07860-9

[30] Weinberg, S.: Cosmology. Oxford University Press, - (2008). https://doi.org/10.1093/oso/9780198526827.001.0001

[31] Wheeler, J.A.: Geons. Phys. Rev. **97**, 511–536 (1955)

[32] Cappi, A.: Gravitational redshift in galaxy clusters. Astron. Astrophys. **301**(1), 6–10 (1995)

[33] Su, C.-C.: A local-ether wave equation, unifying quantum mechanics, electromagnetics, and gravitation. In: Quantum Electromagnetics. National Tsing Hua University Press, Hsinchu (2008)

[34] Bunn, E.F., Hogg, D.W.: The kinematic origin of the cosmological redshift. Am. J. Phys. **77**(8), 688–694 (2009) https://doi.org/10.1119/1.3129103

[35] Pereira, M.: Testing the correlation between host galaxy mass and redshift using the Pantheon Survey Data. Eng. Appl. Sci. J. **2**, 1–3 (2025)

[36] Einstein, A.: Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie. Königliche Preuss. Akad. Wiss., 142–152 (1917)

[37] Friedmann, A.: Über die Krümmung des Raumes. Z. Phys. **10**(1), 377–386 (1922) https://doi.org/10.1007/BF01332580

[38] Yagdjian, K.: Huygens' principle for the Dirac equation in spacetime of non-constant curvature. J. Math. Anal. Appli. **517**(1), 126614 (2023) https://doi.org/10.1016/j.jmaa.2022.126614

[39] Penrose, R.: The Road to Reality A Complete Guide to the Laws of the Universe. Vermilion, Bad Hersfeld (2006)

[40] Voigt, W.: Ueber das Doppler'sche Princip. Nachr. Königl. Gesell. Wiss. Georg-August-Uni. Göttingen **2**, 41–51 (1887)

[41] Lorentz, H.A.: Electromagnetic phenomena in a system moving with any velocity smaller than that of light. Proc.Roy.Netherl. Acad. Arts Sci. **6**, 809–831 (1904)

[42] Demyansky, M., Doroshkevich, A., Larchenkovac, T., Pilipenko, S.: Galaxies and clusters of galaxies in observations and numerical models. Astro. Rep. **66**(9), 766–777 (2022)

[43] Bedran, M.L.: A comparison between the Doppler and cosmological redshifts. Am. J. Phys. **70**, 406–408 (2002) https://doi.org/10.1119/1.1446856

[44] Wang, L.J.: An alternative cosmology to the big bang–dispersive extinction theory of red shift. Appl. Phys. Res. **5**, 47–62 (2017) https://doi.org/10.5539/apr.

v5n2p47

[45] Glauber, R.J.: Coherent and incoherent states of the radiation field. Phys. Rev. **131**(6), 2766–2788 (1963)

[46] Eisenstein, D.J., Bennett, C.L.: Cosmic sound waves rule. Phys. Today **61**(4), 44–50 (2008) https://doi.org/10.1063/1.2911177

[47] Chang, D.C., Lee, Y.: Study on the Physical Basis of Wave-Particle Duality: Modelling the Vacuum as a Continuous Mechanical Medium. J. Mod. Phys. **6**(08), 1056 (2015) https://doi.org/10.4236/jmp.2015.68110

[48] Chang, D.C.: Review on the physical basis of wave-particle duality: Conceptual connection between quantum mechanics and the Maxwell theory. Modern Phys. Lett. B **35**(13), 2130004 (2021)

[49] Bennett, R., Barlow, T.M., Beige, A.: A physically motivated quantization of the electromagnetic field. Eur. J. Phys. **37**, 014001 (2016) https://doi.org/10.1088/0143-0807/37/1/014001

[50] Finlay-Freundlich, E.: Red-shifts in the spectra of celestial bodies. Proc. Phys. Soc. A **67**, 192–193 (1954) https://doi.org/10.1088/0370-1298/67/2/114

[51] Lindel, F., Bennett, R., Buhmann, S.Y.: Theory of quantum-vacuum detection. Phys. Rev. A **102**, 041701 (2020) https://doi.org/10.1103/PhysRevA.102.041701

[52] Nernst, W.: Über einen Versuch, von quantentheoretischen Betrachtungen zur Annahme stetiger Energieänderungen zurückzukehren. Verh. Deutsch. Phys. Ges. **18**, 83–116 (1916)

[53] Wilson, C.M., Johansson, G., Pourkabirian, A., Simoen, M., Johansson, J.R., Duty, T., Nori, F., Delsing, P.: Observation of the dynamical Casimir effect in a superconducting circuit. Nature **479**, 376–379 (2011) https://doi.org/10.1038/nature10561

[54] Hoi, I.-C., Kockum, A.F., Tornberg, L., Pourkabirian, A., Johansson, G., Delsing, P., Wilson, C.M.: Probing the quantum vacuum with an artificial atom in front of a mirror. Nature Phys. **11**, 1045–1049 (2015) https://doi.org/10.1038/nphys3484

[55] Flick, J., Welakuh, D.M., Ruggenthaler, M., Appel, H., Rubio, A.: Light-matter response in nonrelativistic quantum electrodynamics. ACS Photonics **6**, 2757–2778 (2019) https://doi.org/10.1021/acsphotonics.9b00768

[56] Wang, H., Blencowe, M.P., Wilson, C.M., Rimberg, A.J.: Mechanically generating entangled photons from the vacuum: A microwave circuit-acoustic resonator analog of the oscillatory unruh effect. Phys. Rev. A **99**, 053833 (2019) https://doi.org/10.1103/PhysRevA.99.053833

[57] Zhang, Z., Hirori, H., Sekiguchi, F., Shimazaki, A., Iwasaki, Y., Nakamura, T., Wakamiya, A., Kanemitsu, Y.: Ultrastrong coupling between THz phonons and photons caused by an enhanced vacuum electric field. Phys. Rev. Res. **3**, 032021 (2021) https://doi.org/10.1103/PhysRevResearch.3.L032021

[58] Roques-Carmes, C., Salamin, Y., Sloan, J., Choi, S., Velez, G., Koskas, E., Rivera, N., Kooi, S.E., Joannopoulos, J.D., Soljačić, M.: Biasing the quantum vacuum to control macroscopic probability distributions. Science **381**, 205–209 (2023) https://doi.org/10.1126/science.adh4920

[59] Settembrini, F.F., Lindel, F., Herter, A.M., Buhmann, S.Y., Faist, J.: Detection of quantum-vacuum field correlations outside the light cone. Nature Comm. **13**, 3383 (2022) https://doi.org/10.1038/s41467-022-31081-1

[60] Settembrini, F.F., Herter, A.M., Faist, J.: Third order nonlinear correlation of the electromagnetic vacuum at near-infrared frequencies. New J. Phys. **26**, 043017 (2024) https://doi.org/10.1088/1367-2630/ad3b32

[61] Leonhardt, U.: Wave correlations and quantum noise in cosmology. J. Phys. A **56**, 024001 (2023) https://doi.org/10.1088/1751-8121/acb027

[62] Benea-Chelmus, I.-C., Faist, J., Leitenstorfer, A., Moskalenko, A.S., Pupeza, I., Seletskiy, D.V., Vodopyanov, K.L.: Electro-optic sampling of classical and quantum light. Optica **12**, 546 (2025) https://doi.org/10.1364/OPTICA.544333

[63] Wang, L.J.: The dispersive extinction theory of red shifts. Phys. Essays **18**, 177–181 (2005) https://doi.org/10.4006/1.3025736

[64] Wang, L.J.: An experimental method to test DET. Phys. Essays **21**, 233–237 (2008) https://doi.org/10.4006/1.3028141

[65] Fixsen, D.J.: The temperature of the cosmic microwave background. Astrophys. J. **707**(2), 916–920 (2009) https://doi.org/10.1088/0004-637X/707/2/916

[66] Ćirković, M.M., Perović, S.: Alternative explanations of the cosmic microwave background: A historical and an epistemological perspective. Studies Hist. Phil. Sci. Part B **62**, 1–18 (2018) https://doi.org/10.1016/j.shpsb.2017.04.005

[67] Larson, D., *et al.*: Seven-year Wilkinson microwave anisotropy probe (WMAP) observations: Power spectra and WMAP-derived parameters. Astrophys. J., Suppl. Ser. **192**, 1–19 (2011) https://doi.org/10.1088/0067-0049/192/2/16

[68] Komatsu, E., *et al.*: Seven-year Wilkinson microwave anisotropy probe (WMAP) observations: Cosmological interpretation. Astrophys. J., Suppl. Ser. **192**, 1–47 (2011) https://doi.org/10.1088/0067-0049/192/2/18

[69] Noterdaeme, P., Petitjean, P., Srianand, R., Ledoux, C., Lopez, S.: The evolution

of the cosmic microwave background temperature - measurements of T_{CMB} at high redshift from carbon monoxide excitation. A & A **526**, 7 (2011) https://doi.org/10.1051/0004-6361/201016140

[70] Eddington, A.S.: Internal Constitution of the Stars. Cambridge University Press, Cambridge, UK (1926). https://doi.org/10.1017/CBO9780511600005

[71] Nernst, W.: Weitere Prüfung der Annahme eines stationären Zustandes im Weltall. Zeit. Phys. **106**, 633–661 (1937)

[72] Riek, C., Seletskiy, D.V., Moskalenko, A.S., Schmidt, J.F., Krauspe, P., Eckart, S., Eggert, S., Burkard, G., Leitenstorfer, A.: Direct sampling of electric-field vacuum fluctuations. Science **350**, 420–423 (2015) https://doi.org/10.1126/science.aac9788

[73] Riek, C., Seletskiy, D.V., Leitenstorfer, A.: Femtosecond measurements of electric fields: from classical amplitudes to quantum fluctuations. Europ. J. Phys. **38**, 024003 (2017) https://doi.org/10.1088/1361-6404/aa53a2

[74] Hertzog, M., Wang, M., Mony, J., Börjesson, K.: Strong light-matter interactions: a new direction within chemistry. Chem. Soc. Rev. **48**, 937–961 (2019) https://doi.org/10.1039/c8cs00193f

[75] Montani, G., Maniccia, G., Fazzari, E., Melchiorri, A.: Running Einstein constant and a possible vacuum state of the universe. Europ. Phys. J c **85**, 881 (2025) https://doi.org/10.1140/epjc/s10052-025-14618-8

[76] Hubble, E.: A relation between distance and radial velocity among extra-galactic nebulae. Proc. Nat. Acad. Sci. USA **15**(3), 168–173 (1929) https://doi.org/10.1073/pnas.15.3.168

[77] Krizek, M., Somer, L.: A critique of the standard cosmological model. Neural Network World **5**, 435–461 (2014) https://doi.org/10.14311/NNW.2014.24.026

[78] Lovyagin, N., Raikov, A., Yershov, V., Lovyagin, Y.: Cosmological model tests with JWST. Galaxies **10**, 108 (2022) https://doi.org/10.3390/galaxies10060108