Thank you for the invitation.

HOLOGRAPHIC PRINCIPLE AND THE SURFACE OF LAST SCATTER

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References

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Solution to the Dark Energy Problem
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Accelerating expansion

In fundamental theoretical physics, there was, at the beginning of the twenty-first century, an impossible seeming problem which might not be solved for a hundred years. The problem was the dark energy in cosmology, comprising some seventy percent of the universe.

Another cosmological problem, closely entwined with the dark energy problem, is the question well posed, now almost eight decades ago, by Tolman whether one can construct a consistent cyclic model, given the seemingly contradictory constraint imposed by the second law of thermodynamics. The most developed solution, of this Tolman conundrum, is that suggested by Baum and myself in Phys. Rev. Lett. 2007.

The most important observational advance in cosmology, since the early studies of cosmic expansion in the 1920's ,was the dramatic and, at that time, surprising discovery, in the waning years of the twentieth century, that the expansion rate is accelerating. This was first announced in February 1998, based on the concordance of two groups' data.

Many subsequent experiments concerning the Cosmic Microwave Background (CMB), Large Scale Structure (LSS), and other measurements have all confirmed the 1998 claim. We may therefore adopt the position, that the accelerated expansion rate is an observed fact.

Assuming general relativity, together with the cosmological principle of homogeneity and isotropy, the scale factor $a(t)$ in the FRW metric satisfies the Friedmann-Lemaître equation

$$H(t)^2 = \left(\frac{\dot{a}}{a}\right)^2 = \left(\frac{8\pi G}{3}\right)\rho \qquad (1)$$

where I shall normalize $a(t_0) = 1$ at the present, time $t = t_0$, and ρ is an energy density source which drives the expansion of the universe.

Two established contributions to ρ are ρ_m from matter (including dark matter) and ρ_γ radiation, so that

$$\rho \supseteq \rho_m + \rho_\gamma \tag{2}$$

with $\rho_m(t) = \rho_m(t_0)a(t)^{-3}$ and $\rho_\gamma(t) = \rho_\gamma(t_0)a(t)^{-4}$.

For the observed accelerated expansion, the most popular approach is to add to the sources, in Eq.(1), a dark energy term $\rho_{DE}(t)$ with

$$\rho_{DE}(t) = \rho_{DE}(t_0)a(t)^{-3(1+\omega)} \tag{3}$$

where $\omega = p/\rho$ is the equation of state. For the case $\omega = -1$, as for a cosmological constant, Λ, and discarding the matter and radiation terms which are smaller I can easily integrate the Friedmann-Lemaître equation to find

$$a(t) = a(t_0)\; e^{Ht} \tag{4}$$

where $\sqrt{3}H = \sqrt{\Lambda} = \sqrt{8\pi G\rho_{DE}}$.

By differentiation with respect to time p times, we obtain for the p^{th} derivative

$$\frac{d^p}{dt^p}a(t)|_{t=0} = (\sqrt{\Lambda/3})^p \tag{5}$$

Therefore, if $\Lambda > 0$ is positive, as in a De Sitter geometry, not only is the acceleration ($p = 2$) positive and non-zero, but so are the jerk ($p = 3$), the snap ($p = 4$), the crackle ($p = 5$), the pop ($p = 6$) and all $p \geq 7$.

The insertion of the dark energy term works very well as a part of the ΛCDM model. However, it is an *ad hoc* procedure which gives no insight into what dark energy is.

Dark Energy Problem

With this background, I shall now move to my different explanation for the accelerated expansion which obviates any dark energy, including any need for a cosmological constant.

I now adopt a different approach, with no dark energy, where instead the central role is played by the assumption of the holographic principle, and by the overiding concept of entropy.

The essential assumption is the aforementioned holographic principle, by which I understand that all the information about the universe is encoded on its two-dimensional surface. What this implies is, however unlikely it seems and however contrary to everyday experience, that the three-dimensional world I apparently observe, is somehow an illusion. This can lead to a reinterpretation of the cosmic acceleration, and possibly the most dramatic new insight into gravity in over three centuries.

Consider the Schwarzschild radius (r_s), and the physical radius (r), of the Sun ($\odot$). They are $(r_s)_\odot = 3km$ and $r_\odot = 800,000km$. Their ratio is $(\epsilon)_\odot \equiv (r_s/r)_\odot = 3 \times 10^{-6}$. One can readily check that, for the Earth or for the Milky Way, that the ratio $\epsilon = (r_s/r)$ is likewise much smaller than one: $\epsilon << 1$. Such objects are nowhere close to being black hole. Now consider the visible universe (VU), with mass $M_{VU} = afewtimes 10^{23} M_\odot$. It has $(r_s)_{VU} \sim 45Gly$, and $(r)_{VU} \sim 48Gly$, hence $(\epsilon)_{VU} \sim 1$. The visible universe, within which we all live, is close to being a black hole. The solution to the dark energy problem follows, providing I so approximate the visible universe.

At this horizon, there is PBH temperature, T_β, which I can estimate as

$$T_\beta = \frac{\hbar}{k_B}\,\frac{H}{2\pi} \sim 3 \times 10^{-30} K. \tag{6}$$

This temperature of the horizon information screen leads to a concomitant FDU acceleration $a_{Horizon}$, outward, of the horizon given by the relationship

$$a_{Horizon} = \left(\frac{2\pi c k_B T_\beta}{\hbar}\right) = cH \sim 10^{-9}\, m/s^2\,. \tag{7}$$

When T_β is used in Eq. (7), I arrive at a cosmic acceleration which is essentially in agreement with the observations.

From this viewpoint, the dark energy is non-existent. Instead there is a consequence of the second law of thermodynamics, acting to create the appearance of a dark energy component of the driving density on the right-hand-side of the Friedman-Lemaître equation, Eq.(1).

I have discussed a theory underlying the accelerated expansion of the universe based on entropy. This approach provides a physical understanding of the acceleration phenomenon which was lacking in the description as dark energy.

The entropy of the universe has received some recent attention, in part because it relates to the feasibility of constructing a consistent cyclic model. For example, the cyclic model, assuming its internal consistency will indeed be fully confirmed, provides the solution to a difficult entropy question originally posed, seventy-five years earlier, by Tolman. The accelerated expansion rate is no longer surprising. It is the inevitable consequence of information storage on the surface of the visible universe.

Emergent Gravity

This solution of the dark energy problem not only solves a cosmological problem, it casts a completely new light on the nature of the gravitational force. Since the expansion of the universe, including the acceleration thereof, can only be a gravitational phenomenon, I arrive at the viewpoint that gravity is a classical result of the second law of thermodynamics. This means that gravity cannot be regarded as, on a footing with, the electroweak and strong interactions.

Although this can be the most radical change, in gravity theory, for over three centuries, it is worth emphasizing that general relativity, and its classical tests, remain unscathed, as does the prediction of gravitational waves.

My result calls into question almost all of the work done on quantum gravity, since the discovery of quantum mechanics. For gravity, there is no longer necessity for a graviton. In the case of string theory, the principal motivation for the profound and historical suggestion by Scherk and Schwarz that string theory be reinterpreted, not as a theory of the strong interaction, but instead as a theory of the gravitational interaction, came from the natural appearance of a massless graviton in the closed string sector.

I am not saying that string theory is dead. What I am saying is, that string theory cannot be a theory of the fundamental gravitational interaction, since there is no fundamental gravitational interaction.

The way this new insight emerged, and the solution of the dark energy problem itself, was as a natural line of thought, following the discovery of a cyclic model and the subsequent investigations of the entropy of the universe, including a possible candidate for dark matter.

Another ramification, of my solution of the dark energy, problem is the status, fundamental versus emergent, of the three spatial dimensions, that we all observe every day. Because the solution assumes the holographic principle, at least one spatial dimension appears as emergent. Regarding the visible universe as a sphere, with radius of about 48 Gly, the emergent space dimension is then, in spherical polar coordinates, the radial coordinate, while the other two coordinates, the polar and azimuthal angles, remain fundamental. Physical intuition, related to the isotropy of space, may suggest that, if one space dimension is emergent, then so must be all three. This merits further investigation, and may require a generalization of the holographic principle. On the other hand, a fundamental time coordinate is useful in dynamics.

Of course, this present discussion of cosmic acceleration, is merely one small step towards the ultimate goal, of a cyclic model, in which time never begins or ends.

Once we accept that gravity is emergent, and a result of the 2nd law of thermodynamics, then in the law $F = Gm_1m_2/r^2$ at least one of the systems 1 and 2 must be large, meaning that it has at least $e^3 \sim 20$ particles. The gravitational force between two elementary particles *e.g.* two protons, is zero. So, at LHC, gravity is not only irrelevant, it is zero!

Holographic principle

For the case of a sphere, with mass M, of radius R, where R will be the co-moving radius for the expanding universe, a simplified, and non-covariant form, of the holographic principle, states that the entropy, S/k, has an upper limit equal to that of a black hole, *i.e.*

$$\left(\frac{S}{k}\right) \leq \left(\frac{S}{k}\right)_{BH} = \left(\frac{1}{4}\right)\left(\frac{4\pi R_S^2}{l_{Planck}^2}\right) \tag{8}$$

where G is Newton's constant, $R_S = 2GM$ is the Schwarzschild radius and l_{Planck} is the Planck length. It is interesting, from the viewpoint of the physical understanding of the visible universe, to use accurate observational data to check, whether the simplied, and non-covariant, Eq.(8) is satisfied at the present time, $t = t_0$, and in the past, cognizant that, with dark energy, if R sufficiently increases, Eq.(8) will, in any case, eventually be violated.

The holographic principle is supported, by string theory. The AdS/CFT correspondence is an explicit realization of Eq.(8), and so, apart from the non-trivial subtlety that our universe is dS, not AdS, from the viewpoint of string theory, there is every reason to believe the covariant holographic principle, and to wish to check Eq.(8). It is related to recent considerations of the entropy of the universe.

However, physics is an empirical science, and therefore the scientific method dictates that we should find a physical example, in which Eq.(8) can be calculated. The result, reported here, is that a detailed and accurate check of Eq.(8), as applied to the visible universe, fails, by a statistically-significant amount, although in the past, a few billion years ago, it was satisfied.

I should define, precisely, what is meant by the visible universe. It is the sphere, centered for convenience at the Earth, and with a radius $d_A(Z^*) = 14.0 \pm 0.1 Gpc$. The value of $d_A(Z^*)$ is the particle horizon corresponding to the recombination red shift $Z^* = 1090 \pm 1$, i and is measured directly by WMAP7, without needing the details of the expansion history. Thus, "visible" means with respect to electromagnetic radiation.

Observable Universe

The motion is that the visible universe, so defined, is a physical object which should be subject to the holographic principle. It is an expanding, rather than a static, object, yet my understanding is that the principle, at least in its covariant form, is still expected to be valid. I shall use the notation employed by the WMAP7 paper, from which all observational data are taken.

The present age, t_0, of the universe is measured to be

$$t_0 = 13.75 \pm 0.13 Gy \tag{9}$$

The comoving radius, $d_A(Z^*)$, of the visible universe, is, likewise, measured to one percent accuracy, as

$$d_A(Z^*) \equiv (1+Z^*)D_A(Z^*) = c\int_{t^*}^{t_0} \frac{dt}{a(t)} = 14.0 \pm 0.1 Gpc \tag{10}$$

where it is noted that the measurement, of $d_A(Z^*)$, does not require knowledge, of the expansion history, $a(t)$, for $t^* \leq t \leq t_0$.

The critical density, ρ_c, is provided by the formula

$$\rho_c = \left(\frac{3H_0^2}{8\pi G}\right) \tag{11}$$

whose value depends on H_0, as does the total, baryonic plus dark, matter density, ρ_m

$$\rho_m \equiv \Omega_m \rho_c \tag{12}$$

Because the error on the Hubble parameter, H_0, is several per cent, it is best to avoid H_0, in checking the holographic principle.

The mass of the matter, M(Z*), contained in the visible universe, is

$$M(Z^*) = \frac{4\pi}{3} d_A(Z^*)^3 \rho_m \qquad (13)$$

and the Schwarzschild radius, $R_S(Z^*)$, is given by

$$R_S(Z^*) \equiv 2GM(Z^*) \qquad (14)$$

Collecting results enables the desired accurate check of the holographic principle. The mass is $M(Z*) = 5.5 \times 10^{23} M_{\odot}$.

The holographic pronciple requires that

$$\left[\frac{\left(\frac{S}{k}\right)_{V.U.}}{\left(\frac{S}{k}\right)_{BH}}\right] \leq 1 \tag{15}$$

A shift parameter, R, was defined by Bond, Efstathiou and Tegmark (BET) as

$$R = \frac{\sqrt{\Omega_m H_0^2}}{c}(1 + Z^*)D_A(Z^*) \tag{16}$$

which was, with great prescience, introduced by BET, as a dimensionless quantity, to be measured, accurately, by CMB observations.

This BET shift parameter, R, of Eq. (16), is given in WMAP7, as

$$R = 1.725 \pm 0.018 \tag{17}$$

A little algebra shows that the BET shift parameter R provides the most accurate available check, of the holographic principle, by virtue of the result

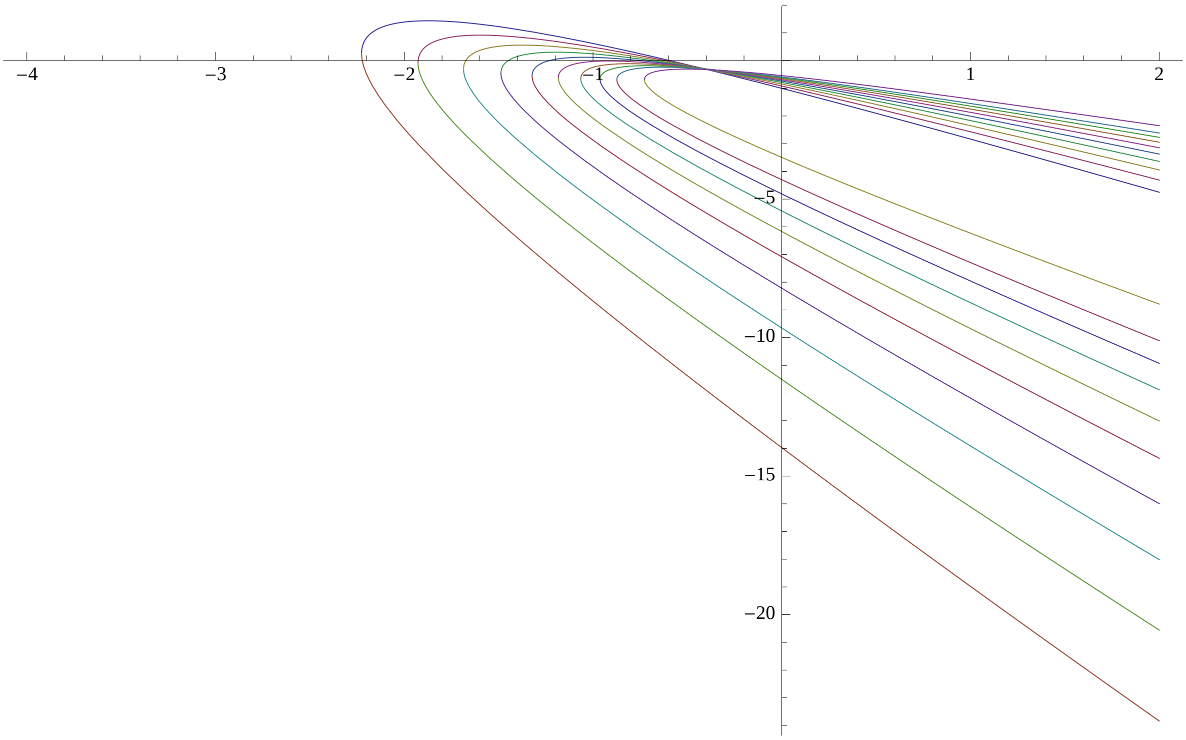
$$\left[\frac{\left(\frac{S}{k}\right)_{V.U.}}{\left(\frac{S}{k}\right)_{BH}} \right] \equiv R^4 = 8.85 \pm 0.37 \tag{18}$$

showing a violation, by 21σ.

To my knowledge, the visible universe is, at present, the only physical object, for which it is possible to calculate, and compare with experiment, or observation, the simplified holographic principle.

From Eq. (15), the radius $d_A(Z_{HP}) = (1 + Z_{HP})D_A(Z_{HP})$, at which the violation of Eq.(8), begins, is $d_A(Z_{HP}) = 8.4 \pm 0.1 Gpc$, at a time, comparable to when the cosmic deceleration ends, and becomes acceleration. This is strongly supportive of the idea of an entropic accelerating universe.

The original aim, of the present work, was to *confirm*, at $t = t_0$, the inequality, Eq.(15). It was, therefore, surprising to learn that it is violated, with high statistical significance, and has been so, for five billion years.



Thank you for your attention.