Gravitational Waves Verify the Existence of Vacuum Energy

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Abstract: Analysis of the gravitational wave (GW) designated GW150914 shows that this wave encountered spacetime as being a very stiff elastic medium. The source of this stiffness can be determined by analyzing wave amplitude, frequency, intensity and propagation speed. The implication is that GW150914 encountered vacuum energy density (VE density) of about 6.7 x 10^{31} J/m^3 at 250 Hz. This energy density is about 10^{40} times more than the critical energy density of the universe. While this finding is incompatible with general relativity, it is compatible with the VE density expected for zero-point energy at 250 Hz. Higher frequency GWs should encounter higher energy density which reaches 10^{112} J/m^3 at Planck frequency. VE is proposed to be the biggest component of the universe by a factor of 10^{120}. The conflict with general relativity can be resolved if VE does not create its own gravity. Instead VE is proposed to be the homogeneous, passive energy which is distorted (curved) by the wave properties of matter. The multiple fields of the standard model are proposed to be multiple resonances of a single VE spacetime field.

Keywords: gravitational waves; vacuum energy; zero-point energy; impedance of spacetime

1 Introduction

The first detection [1] of a gravitational wave (GW) designated GW150914 has been hailed as a very important advance in astronomy. It opens up a new way of observing massive objects in the universe and confirms another prediction of general relativity. All of this is true, but this article makes the case that an unanticipated result of the observation of GW150914 is that it gives important new experimental support for the existence of vacuum energy (VE)

Quantum field theory can be interpreted as implying vacuum possesses a large VE (zero-point energy). The strongest case for zero-point energy in the vacuum is made by Milonni [2] in the book *The Quantum Vacuum*. Also, John Archibald Wheeler [3] said "Empty space is not empty… The density of field fluctuation energy in the vacuum argues that elementary particles represent percentage-wise almost completely negligible change in the locally violent conditions that characterize the vacuum." On the macroscopic scale, the vacuum appears to be a quiet, empty void. However, the quantum vacuum has vacuum fluctuations that have been described as being a locally violent quantum foam [4, 5].

Quantum field theory requires the vacuum to have a high energy density in order to achieve the incredible accuracy of quantum electrodynamics and quantum chromodynamics calculations. Also energetic vacuum fluctuations are required for virtual particle formation/annihilation, the uncertainty principle, the Lamb shift, the Unruh effect, the Casimir effect and zero-point energy in quantum systems. However, there is no undisputed experimental evidence that VE physically exists. For example, the Casimir effect [6–8] is often cited as experimental proof of VE. There is definitely a force between two closely spaced metalized plates which has been measured and agrees with the QED predictions for VE within a few percent. However, there are alternative explanations involving charges and currents [9] which generate the same magnitude of force between the plates.

Many physicists believe VE does not physically exist because the implied energy density of VE is about 10^{112} J/m^3. For comparison, the "critical" energy density of the universe required to achieve flat spacetime is about 10^{-9} J/m^3. According to general relativity, a larger energy density should cause the universe to be closed (positive curvature) and eventually collapse. However, energy density of 10^{112} J/m^3 appears to be ridiculous and completely incompatible with observations. This is the famous 10^{120} discrepancy between general relativity (cosmology) and the theoretical predictions of quantum mechanics. This has been described as the largest discrepancy in all of physics and the "vacuum catastrophe" [10, 11]. The critical energy density of the universe seems to be unquestionable. Observations made by the WMAP [12] and the Planck space mission [13] imply that spacetime is flat to within the 0.4 % observational accuracy. The Planck space mission also determined the energy content of the universe is about 4.9% baryonic matter, 26.8% dark matter and 68.3% dark energy. The dark energy appears to be a property of space itself and is sometimes referred to as the cosmological constant [14]. While VE is sometimes equated with dark energy or the cosmological constant, this paper is defining "VE" as the tremendously large energy density implied by quantum field theory.

2 Gravitational Wave Background Information

GWs were always considered to be a controversial prediction of general relativity. Their existence was debated at conferences and they were not detected even after 50 years of experimental attempts. Then in September 2015 the LIGO experiment started a new series of observations using instruments with increased sensitivity. Within a few days of restarting, the two separate LIGO interferometers detected the GWs emitted by the merging of two black holes at a distance of 1.3 billion light years. A second, weaker GW designated GW151226 was also detected in December 2015 [15].

GWs propagate in the medium of spacetime. They are transverse quadrupole waves which slightly distort the "fabric of space". For example, a GW propagating in the "Z" direction would cause a sphere made out of baryonic matter such as aluminum to become an oscillating ellipsoid. When the sphere expands in the X direction it contracts in the Y direction and vice versa. The GW produces: 1) no change in the total volume of the oscillating sphere 2) no change in the rate of time, 3) no displacement of the center of mass of the oscillating sphere.

Point #3 addresses an important point. If there are two isolated masses such as two LIGO interferometer mirrors suspended by wires [16], the passage of a GW does not move the mirror's center of mass. There is no momentum transferred from the GW to the center of mass of an object. Using the previous coordinates, if a rod is oriented in the X polarization direction when a GW passes, the GW will affect space in a way that changes the proper distance between the atoms of the rod. The atoms perceive the change in distance and attempt to restore the correct separation distance. This causes the length of the rod to expand and contract as the GW passes. The ends of the rod will be accelerated as the rod oscillates but the center of mass of the rod will not be displaced.

Similar to the effects on the atoms in a rod, the GW changes the properties of spacetime producing a redshift and a blue shift on LIGO's laser beams. This difference in wavelength is detected by the interferometer as a fringe shift that we will designate $\Delta\ell$. This measurement is made over the round trip length of the interferometer that will be designated L. If we assume that L is much smaller than the GW wavelength ($L << \lambda$), then the maximum strain (maximum slope of the sinusoidal GW) can be approximated as $\Delta\ell/L$. Knowing the maximum slope, it is possible to calculate the theoretical maximum optical path length displacement ΔL produced by a GW as $\Delta L \approx \lambdabar\Delta\ell/L$ where lambda bar is $\lambdabar = \lambda/2\pi$. The approximation incorporating interferometer length L is eliminated if we state the maximum spacetime displacement as $\Delta L = A_s\lambdabar$ or $A_s = \Delta L/\lambdabar$. The spacetime displacement amplitude ΔL has some analogies to the particle displacement δ of acoustic equations.

One of the most useful GW equations is Eq. (1) below which assumes a GW that is a weak plane wave. In texts on GWs [17] this equation is usually written with the strain amplitude designated with the symbol "h". However, to avoid confusion with Planck's constant, Eq. (1) uses the symbol A_s. for strain amplitude. Also we are standardizing on the use of angular frequency ω. The 2π difference between ω and frequency also requires the appropriate adjustment in the numerical constant.

$$I = \left(\frac{1}{16\pi}\right) A_S^2 \omega^2 \left(\frac{c^3}{G}\right) \quad (1)$$

Eq. (1) should be compared to the generalized intensity equation for the intensity of waves of any kind. This equation is: $I = kA^2\omega^2Z$. Comparing this to Eq. 1, it is obvious that in Eq. (1) the numerical constant $k = 1/16\pi$, the amplitude term $A = A_s$, and the impedance term is c^3/G. Blair [18] was the first person to identify the impedance of spacetime as $Z_s = c^3/G$. This is a very important insight into the properties of spacetime and will be used frequently later. Now we are armed with Z_s and $I = kA^2\omega^2Z$, we can write another equation for the energy density (U) of a wave propagating in spacetime at the speed of light. The following equation will be used later.

$$U = \frac{I}{c} = \frac{kA_S^2\omega^2 Z_S}{c} \tag{2}$$

3 Gravitational Wave Observation Verifies Vacuum Energy

It is possible to use the experimental observation [1, 19] of GW150914 to support the contention that spacetime contains a form of energy density which strongly interacts with GWs but is undetectable to fermion-based instruments. GW150914 had a maximum frequency of about 250 Hz. We will be standardizing on angular frequency ω and reduced wavelength $ƛ = c/\omega$. Therefore, GW150914 had a maximum angular frequency of $\omega = 1570$ s^{-1} and a reduced wavelength of $ƛ = 1.9 \times 10^5$ m. The measured strain amplitude was $A_s = \Delta L/ƛ = 10^{-21}$, therefore the displacement amplitude of the GW was $\Delta L = ƛA_s = 1.9 \times 10^{-16}$ m. Substituting $A_s = 10^{-21}$ and $\omega = 1570\ s^{-1}$ into Eq. (1), we obtain the observed GW intensity was $I = 0.02$ w/m^2. This is a substantial intensity but the GW encountered spacetime as a very stiff medium. The strain amplitude produced by the GW was only a dimensionless strain (slope) of 10^{-21}.

The maximum GW power emitted by GW150914 is reported [1] to be 3.6×10^{49} w which approaches Planck power ($c^5/G = 3.6 \times 10^{52}$ w). This emitted power is easily checked because it is the power required to achieve intensity of 0.02 w/m^2 over the area of a sphere with radius of 1.3 billion light years. The mass/energy radiated into GWs was equivalent to 3 solar masses (5×10^{47} J) which is about 4.6 % of the total mass of the two black holes before merging.

At a distance of 1 wavelength (1.2×10^6 m) from the merging black holes, the GW power of 3.6×10^{49} w achieves intensity of about $I \approx 2 \times 10^{36}$ w/m^2. The strain amplitude at the distance of 1 wavelength was $A_s = \Delta L/ƛ \approx .01$ which implies maximum transverse displacement of $\Delta L = 1.9$ km (ignoring nonlinearities) on a GW that had a reduced wavelength of 190 km. If a GW is considered to be produced by gravitons, then no further insight into the stiffness of spacetime is possible. However, the GW has amplitude, frequency, intensity, propagation speed and encounters impedance. All of these are properties we normally associate with a sound wave. We will treat this GW as if it is a sound wave and calculate the density and energy density of the medium propagating the GW.

The acoustic equation that will be used in this analysis is another variation of $I = kA^2\omega^2 Z$ shown below. In the following equation, c_a is the acoustic speed of sound and δ the particle's displacement amplitude with units of length.

$$I = kA^2\omega^2 Z = k\delta^2\omega^2(\rho c_a) \tag{3}$$

In Eq. (3) it is obvious that impedance term (Z) corresponds to the specific impedance $z_o = \rho c_a$ with units of kg/m^{2}s. In acoustics $k = 1$. Eq. (4) below rearranges the terms in Eq. (3) to yield the equivalent density ρ encountered by GW150914. Eq. (5) converts this to energy density. Both the weak GW detected at earth and the strong GW close to the merging black holes encountered the same spacetime density. Therefore, it should be possible to substitute either the earth data with intensity of 0.02 w/m^2 or the close data with intensity of 2 x 10^{36} w/m^2 and obtain the density answer.
Earth data substitutions: $I = 0.02$ w/m^2; $\delta = \Delta L = 1.9 \times 10^{-16}$ m, $\omega = 1570$ s^{-1}; and $c_a = c$.
Close data substitutions: $I = 2 \times 10^{36}$ w/m^2; $\delta = \Delta L = 1{,}900$ m; $\omega = 1570$ s^{-1}; and $c_a = c$.

$$\rho = \frac{I}{\omega^2\,\delta^2 c_a} = 7.4 \times 10^{14}\ \text{kg/m}^3 \tag{4}$$

$$U = \rho c^2 = 6.7 \times 10^{31}\ \text{J/m}^3 \tag{5}$$

Both sets of data give the same answer. GW150914 encountered a medium with stiffness equivalent to a density of $\rho = 7.4 \times 10^{14}$ kg/m^3 which converts to energy density of $U = 6.7 \times 10^{31}$ J/m^3. Is this reasonable? If the GW is treated like an acoustic wave, the energy density of the GW cannot exceed the energy density of the medium propagating the wave. Previously, we calculated energy density of 6.6 x 10^{27} J/m^3 and strain amplitude of $A_s = 0.01$ for the GW close to the source. The density of the medium at a particular frequency is obtained at the maximum possible strain amplitude which is $A_s = 1$. Inserting $A_s = 1$, $\omega = 1570$ s^{-1}; $k = 1/16\pi$ and $Z = Z_s = c^3/G$ into Eq. (2) gives energy density of 6.7 x 10^{31} J/m^3 which corresponds to the energy density of the medium obtained in Eq. (5).

The implication of this is that the GW150914 at 250 Hz not only encountering 6.7 x 10^{31} J/m^3 VE density, but also the GW is actually *propagating* in this medium of the VE. This energy density is about 10^{40} times greater than the "critical" energy density of the universe (~10^{-9} J/m^3). Stated another way, this energy density would form a black hole with Schwarzschild radius of about 500 km if it was fermions or bosons. Not only is VE not observable to fermion-based instruments, but apparently it also does not generate gravity. However, it strongly interacts with GWs and is the medium for GW propagation.

4 Interactive Impedance of Spacetime

A GW is a transverse wave that distorts a sphere as previously described. This has similarities to an acoustic wave, but there are also differences. We will analyze the similarities in the impedance encountered by both types of waves. In both sound waves and GWs, it is possible to express amplitude either as a displacement amplitude ΔL with units of length or as a strain amplitude which is a dimensionless ratio $\Delta L/ƛ$. The important difference is that the strain amplitude contains ƛ, the reduced wavelength. The strain amplitude (slope) created by a given displacement is wavelength/frequency dependent. This point is made because next we will compare the impedance encountered by GWs to the impedance encountered by acoustic waves. To accomplish this, we need to transfer the $1/ƛ^2$ term present in $A_s{}^2$ to a new definition of spacetime impedance which will be designated Z_i, with units of kg/m^{2}s. Starting with $I = \mathrm{k}A_s^2\omega^2 Z_s = k\Delta L^2\omega^2 Z_i$ we will solve for the interactive impedance Z_i.

$$\left(\frac{\Delta L}{ƛ}\right)^2 Z_s = \Delta L^2 Z_i \qquad (6)$$

$$Z_i \equiv \frac{Z_s}{ƛ^2} = \frac{c\omega^2}{G} \qquad (7)$$

Z_i has the same units and the same physical property as the specific acoustic impedance $z_o = \rho c_a$. It is now possible to make a comparison between these two types of impedances at a specified frequency. For example, a GW with frequency of 1,000 Hz (ƛ = 4.78 x 10^4 m) encounters spacetime as having an interactive impedance of $Z_i = Z_s/ƛ^2 \approx 1.8 \times 10^{26}$ kg/m^{2}s. We will compare this to the acoustic impedance of osmium which has the highest acoustic impedance of any solid ($z_o = 1.1 \times 10^8$ kg/m^{2}s). Therefore, at 1,000 Hz, the impedance of spacetime is a factor of about 10^{18} greater than the impedance of osmium.

Suppose we extend this comparison to the densest macroscopic material anywhere in the universe. Epstein [20] has analyzed the density, temperature and speed of sound in neutron stars. The central core of a neutron star has the highest density and a recently formed neutron star has the highest speed of sound because it has the highest temperature. For this analysis we will choose a plausible core density of $\rho = 3 \times 10^{17}$ kg/m^3 and temperature of 2.5 x 10^{11} ^{o}K. This temperature corresponds to a speed of sound of about $c_a \approx 6 \times 10^7$ m/s which is about 20% of the speed of light. Therefore, this hypothetical neutron star would have a specific acoustic impedance of about $z_o \approx 1.8 \times 10^{25}$ kg/m^{2}s. This is still a factor of about 10 less than the impedance of spacetime experienced by a GW at 1,000 Hz ($Z \approx 1.8 \times 10^{26}$ kg/m^{2}s). Furthermore, since the interactive impedance of spacetime scales with ω^2, this difference increases at higher frequencies. The largest interactive impedance occurs at the highest possible frequency which is Planck angular frequency $\omega_p = 1.8 \times 10^{43}$ s^{-1} where Planck interactive impedance is $Z_{ip} = c^6/\hbar G^2 \approx 1.55 \times 10^{105}$ kg/m^{2}s.

A model of spacetime that is compatible with these impedance characteristics will be briefly presented. VE is proposed to be a sea of Planck angular frequency (ω_p) spacetime waves which would have reduced wavelength equal to Planck length ($\lambda\!\!\!^{-} = c/\omega_p = L_p$). Such waves would be undetectable to fermion-based instruments, but GWs would compresses and expand these waves which slightly increases and decreases their frequency. This would introduce redshifts and blue shifts in these Planck frequency waves similar to the red/blue shifts which GW150914 produced in the LIGO laser beams. At Planck frequency, the interactive impedance of these waves would be $Z_{ip} = c^6/\hbar G^2$. Lower frequency GWs would encounter impedance mismatch which scales with $Z_i = c\omega^2/G = (\omega/\omega_p)^2 Z_{ip}$ where $(\omega/\omega_p)^2$ is the term that specifies the impedance mismatch.

5 Interactive Energy Density of Spacetime

Quantum field theory has been telling us there is a large energy density in the vacuum. Often this is considered to be energy fluctuations of point virtual particles. However, point particles have no volume and are isolated from each other. Therefore, they would be ignored by GWs. Only if vacuum fluctuations are energetic spacetime waves distributed over a volume of spacetime would they interact with a GW. Because of the frequency dependent impedance which scales with $(\omega/\omega_p)^2$, the energy density of VE is also frequency dependent. A new name is required to signify frequency dependent energy density. This name will be "interactive energy density U_i".

There are two ways of calculating U_i and they both give the same answer. First we will take the interactive impedance Z_i from Eq. (7) and set it equal to the specific impedance ($z_o = \rho c_a$) of acoustic equations. Z_i and z_o have the same units and both represent the impedance when wave amplitude is expressed as displacement with units of length. Therefore, we can determine the "interactive density of spacetime ρ_i" encountered by the GW from $Z_i = \rho_i c$. The following symbols are used: Planck angular frequency $\omega_p = \sqrt{c^5/\hbar G} \approx 1.85 \times 10^{43}$; Planck energy density $U_p = c^7/\hbar G^2 \approx 4.64 \times 10^{113}$ J/m^3, Planck density $\rho_p = c^5/\hbar G^2$ and the interactive energy density of spacetime $U_i = \rho_i c^2$.

$$Z_i = \rho_i c = \frac{c\omega^2}{G} \tag{8}$$

$$\rho_i = k\frac{\omega^2}{G} = k\left(\frac{\omega}{\omega_p}\right)^2 \rho_p \tag{9}$$

$$U_i = \rho_i c^2 = k\frac{\omega^2 c^2}{G} = k\left(\frac{\omega}{\omega_p}\right)^2 U_p \tag{10}$$

It is possible to check this because U_i can also be calculated from the energy density equation Eq. (2) which is $U = kA^2\omega^2 Z_s / c$. We will be solving for the interactive energy density of spacetime which occurs when a spacetime wave achieves the maximum possible strain amplitude ($A_s = 1$). In Eq. (11) below, we will set $A_s = 1$ and $Z = c^3/G$ into Eq. (2) and yield an answer that is the same as Eq. (10).

$$U = \frac{kA^2\omega^2 Z}{c} = \frac{k1^2\omega^2}{c}\left(\frac{c^3}{G}\right) = \frac{k\omega^2 c^2}{G} = U_i \tag{11}$$

VE is the largest component of the universe by a factor of 10^{120}. Baryonic matter, dark matter and dark energy are trivial in comparison. Failure to recognize the physical presence of VE removes a key element required to explain the cause of many of the laws of physics. An analogy would be a fish that lives at the bottom of the ocean but the fish fails to recognize the existence of water. This hypothetical fish would be able to designate laws of physics applicable to its world, but the underlying cause of these laws would be a mystery. For example, a bubble would be a mysterious particle to this hypothetical fish. Similarly, an electron appears to us to be a mysterious point particle that somehow possess energy of 511,000 eV, angular momentum of $\hbar/2$, wave properties and probabilistic characteristics. To make progress in analyzing and conceptually understanding these properties, it is necessary to realize the electron is immersed in a sea of spacetime waves with $\omega = \omega_p$, $\lambda\!\!\!^{-} = \lambda\!\!\!^{-}_c$ and $U = U_i$.

6 Virtual Particles Derived from Vacuum Energy

It is well established that virtual particles are continuously being formed and annihilated in the quantum vacuum. Feynman diagrams [21] give a visual picture of this process and quantum electrodynamics quantify effects of this process with exquisite accuracy. Something is physically happening in the vacuum but we lack a conceptually understandable model of the underlying physics that generates virtual particles.

It is proposed that Planck length vacuum fluctuation, combined with the properties of VE, creates the virtual particle characteristics described by quantum electrodynamics and quantum chromodynamics. To explain this, three points need to be established. 1) Planck length fluctuations are taking place in VE. 2) Fundamental particles have wave properties at the particle's Compton angular frequency (ω_c). 3) A Planck length vacuum fluctuation that lasts for a time period of $1/\omega_c$ achieves the energy required of a virtual particle. The expansion of these three points follows.

1) The uncertainty principle ($\Delta p \Delta x = \hbar/2$) establishes that all fundamental particles have a position uncertainty greater than Planck length. However, even for composite

objects with mass/energy greater than Planck mass it is physically impossible (device independent) to make distance measurements more accurate than Planck length [22 -26]. This is the background "noise" of the quantum vacuum. It is proposed that the distance between stationary points is being modulated by Planck length.

2) Moving fundamental particles exhibit de Broglie waves with wavelength $\lambda_d = h/mv$ and phase velocity $w_d = c^2/v$. This implies an underlying frequency generating these waves which can be calculated from: $w_d/\lambda_d = mc^2/h = \omega_c/2\pi$ where ω_c is the fundamental particle's Compton angular frequency. This is the frequency interacting with VE. The connection between the particle's Compton angular frequency and its de Broglie frequency has been analyzed [27] in more detail.
3) Inserting a fundamental particle's Compton angular frequency into Eq. (10) gives the VE density encountered by the particle. For example, an electron has $\omega_c = 7.8 \times 10^{20}$ s^{-1}, therefore, $U_i = k\omega^2 c^2/G \approx 10^{67}$ J/m^3. In words, an electron's wave properties encounter the VE as having energy density of about 10^{67} J/m^3. This is such a large energy density (10^{33} times larger than the core of a neutron star) that even a Planck length stretch or compression of a small volume of this energy density for a time period of $1/\omega_c$ will represent a substantial amount of energy. Next we will calculate this energy and show it corresponds to the energy of a virtual electron.

Introducing a Planck length distortion into a volume of VE can significantly affect a volume with dimensions much larger than Planck length. For example, introducing a Planck length vacuum fluctuation for a time period of $1/\omega_c$ would be distributed over a distance of $c/\omega_c = ƛ_c$. An electron's reduced Compton wavelength is $ƛ_c = 3.86 \times 10^{-13}$ m. Stretching or compressing VE by Planck length L_p over a distance of $ƛ_c$ for this time period introduces strain with amplitude of $A_s = L_p/ƛ_c$. Using Eq. (2), we can calculate how much energy this Planck length vacuum fluctuation has temporarily introduced to a volume $V = kƛ_c^3$ (all constants k are combined into a single constant k).

$$E = UV = \frac{kA_s^2\omega_c^2 Z_s V}{c} = k\frac{L_p^2}{ƛ_c^2}\frac{c^2}{ƛ_c^2}\frac{c^3}{G}\frac{ƛ_c^3}{c} = k\hbar\omega_c \tag{12}$$

$$\Delta E \Delta \omega_c^{-1} = k\hbar \tag{13}$$

Eq. (13) has rearranged the terms in Eq. (12) to the form of the uncertainty principle $\Delta E \Delta T = ½\,\hbar$. Therefore, Eq. (12, 13) are important because they show how a Planck length vacuum fluctuation can momentarily generate the energy of a virtual particle such as a virtual electron. For an electron, $\omega_c^{-1} \approx 1.29 \times 10^{-21}$ s. However, a vacuum fluctuation is a pulse that does not have a precise duration. Therefore, the value of $k = ½$ is plausible. The reason a Planck length vacuum fluctuation can achieve the approximate energy of an electron is because this duration vacuum fluctuation encounters VE density of 10^{67} J/m^3. A shorter Planck length fluctuation for a time of $1/\omega_c$ of a top quark would encounter energy density of about 10^{80} J/m^3 and generate the energy of a virtual top quark.

The standard model is a field theory that has 17 named particles which are considered to be "excitations" of multiple fields [28]. For example, an electron is an excitation of the electron field and the Higgs boson is an excitation of the Higgs field. Rather than many overlapping fields in spacetime, it is proposed that there is only 1 universal field – which will be called the "spacetime field". This is another name for VE. The multiple discrete fields of the standard model are replaced with a single spacetime field with multiple resonances. The more complete development of this idea including a particle model that generates forces is presented in the article titled, "Spacetime Based Foundation of Quantum Mechanics and General Relativity" [29].

7 Vacuum Energy Density vs. Critical Energy Density

Next we will attempt to estimate the fundamental VE density of the spacetime field using Eq. (2). We will assume the predominant frequency of zero-point harmonic oscillators is Planck angular frequency ω_p. Lower frequencies can be made by combinations of this higher frequency building block with slight frequency variations. However, here we are interested in the energy density of the Planck frequency zero-point energy. The energy of each harmonic oscillator is: $E = ½\ \hbar\omega_p = ½\ E_p$ (½ Planck energy). The proposed volume of the harmonic oscillators is a sphere Planck length in radius with volume $V_{zp} = (4\pi/3)L_p^3$. This energy in this volume implies that the energy density of zero-point energy has a numerical constant of $k = 3/8\pi$. This is an estimate but this constant will be shown to fit with some cosmological properties of the universe. We will first use $k = 3/8\pi$ in Eq. (2) to obtain the fundamental VE density of the universe. For this we use the highest frequency allowed by the properties of spacetime $\omega = \omega_p$ and the reduced wavelength associated with Planck angular frequency $\lambda\!\!\!^{-} = c/\omega_p = L_p$.

$$U_v = \frac{kA\omega Z}{c} = \left(\frac{3}{8\pi}\right)\left(\frac{L_p}{\lambda\!\!\!^{-}}\right)^2 \omega_p^2 \left(\frac{c^3}{G}\right)\frac{1}{c} = \left(\frac{3}{8\pi}\right)\frac{c^7}{\hbar G^2} = 5.5 \text{ x } 10^{112} \text{ J/m}^3 \qquad (14)$$

The idea that VE is made of Planck frequency components which can be organized to achieve lower frequencies in larger volumes differs from the conventional idea of zero-point energy which is independent harmonic oscillators where all frequencies are equally represented. There are two reasons for proposing this variation. First, there are clearly resonances which favor frequencies corresponding to the Compton frequencies of fundamental particles. For example, the electron and muon Compton frequencies are resonances which are responsible for the electron and muon fields of the standard model. Other non-resonant frequencies are therefore greatly depressed. Second, the interactive energy density $U_i = k(\omega/\omega_p)^2 U_p$ from

Eq. (10) can be interpreted as implying the fundamental angular frequency is ω_p and lower frequencies ω experience an impedance mismatch with coupling term of $(\omega/\omega_p)^2$.

So far these calculations have yielded energy densities vastly larger than the critical energy density of the universe. However, if we are claiming to be tapping into the underlying structure of spacetime, it should be possible to also calculate the critical energy density of the universe $U_c \approx 10^{-9}$ J/m^3. To do this, it is necessary to view the expansion of the universe as a portion of a wave with angular frequency equal to the inverse age of the universe $\omega_u = 1/t_u$ where t_u is the age of the universe in seconds. The actual age of the universe is about 13.8 billion years old, but this number incorporates nonlinear expansion rates over the age of the universe. To make a connection to the current critical density of the universe we need to use the age of the universe implied by the current expansion rate given by the Hubble constant $\mathcal{H}_o$. The Planck space mission [12] determined the value $\mathcal{H}_o = 67.8$ km/s/Mpc which converts to $\mathcal{H}_o = 2.2 \times 10^{-18}$ s^{-1} in SI units. Using this value of $\mathcal{H}_o$, the implied age of the universe is $t_u = 1/\mathcal{H}_o \approx 4.5 \times 10^{17}$ s = 14.4 billion years. Therefore, the calculation will use $\omega = \omega_u = \mathcal{H}_o$. We can also say $\omega_u = c/ƛ_u$ where $ƛ_u$ is the reduced wavelength of the expanding universe. Since this expansion started from virtually zero, then $\Delta L = ƛ_u$; $A_s = \Delta L/ƛ_u = ƛ_u/ƛ_u$. Making these substitutions and $k = 3/8\pi$ into Eq. (2) we have:

$$U = \frac{kA^2\omega^2 Z_s}{c} = \left(\frac{3}{8\pi}\right)\left(\frac{ƛ_u}{ƛ_u}\right)^2 \mathcal{H}_o^2 \left(\frac{c^3}{G}\right)\frac{1}{c} = \frac{3c^2\mathcal{H}_o^2}{8\pi G} \tag{15}$$

$$\rho_c = \frac{U_c}{c^2} = \frac{3\mathcal{H}_o^2}{8\pi G} \tag{16}$$

Eq. (15) yields the critical energy density of the universe $U_c = 7.8 \times 10^{-10}$ J/m $\approx 10^{-9}$ J/m^3. Also, Eq. (15) converts to Eq. (16) which is the standard equation for the critical density of the universe obtained from the Friedman equations of general relativity [30]. Therefore Eq. (2) generated both VE density of about 10^{112} J/m^3 and the critical energy density of the universe ($\sim 10^{-9}$ J/m^3). Furthermore, if you compare Eq. (14) and Eq. (15), the only difference is Eq. (14) uses $\omega = \omega_p$ and Eq. (15) uses $\omega = \mathcal{H}_o$. Both of these terms have units of s^{-1} and are squared in their respective equations. Therefore, the relationship between VE density (U_V) and the critical energy density of the universe U_c can be succinctly stated as:

$$\frac{U_V}{U_c} = \frac{\omega_p^2}{\mathcal{H}_o^2} = 7.1 \times 10^{121} \approx 10^{120} \tag{17}$$

8 Gravitational Collapse Avoided

General relativity has as a premise that: *all energy creates gravity* [31]. This is such a key foundation of general relativity that the theoretical evidence from quantum field theory supporting the existence of VE has been generally discounted by most physicists. Since the universe has not collapsed into a black hole, a common assumption is that there must be some large unknown effect which cancels out VE. Now the observation of GWs encounter spacetime as a stiff elastic medium forces us to reexamine whether ***all** energy creates gravity*. For example, the interactive density encountered by GW150914 ($\rho_i = 7.4 \times 10^{14}$ kg/m^3) is about 10^{40} times larger than the critical density ρ_c and should make the universe a black hole. Therefore, is it possible that VE is a type of energy which does not create gravity?

To examine this question, we will look for another example of energy that does not exhibit gravity. The photons of the cosmic microwave background were at a black body temperature of about 3,000 °K about 380,000 years after the Big Bang [12]. Today these same photons are at a blackbody temperature of 2.725 °K. Therefore, they have lost about 99.9% of their energy since this earlier time. If the Big Bang generated Planck energy photons, then those photons were about 10^{32} times more energetic than the photons currently in the cosmic microwave background. This "lost" energy did not leave the universe; so where did it go? The answer proposed here is that it became VE. When photons are redshifted due to cosmic expansion, they retain all of their ħ quantized angular momentum. Therefore, the energy transformed into VE possesses no quantized angular momentum. Apparently this form of energy lacking spin does not exert any forces including gravity. The statement "*all energy creates gravity"* should be modified to "*All energy* ***with spin*** *creates gravity*." Rather than causing gravity, VE is a passive, homogeneous energy which can be distorted by the wave properties of matter to form curved spacetime [29]. VE gives the vacuum its physical properties such as constants c, G, ħ and ε_o.

So far the point has been made that fermions do not interact with VE in a detectable way. There are two papers [32, 26] which propose photons strongly interact with VE, just like GWs. This analysis predicts that GWs should transform the homogeneous spacetime field into an oscillating birefringent medium which can slightly modulate the polarization of a laser beam. If this is correct, it would be possible to detect GWs by monitoring polarization rather than using interferometers. This would simplify the equipment, reduce the noise and give more information about the location of the source.

9 Conclusion

The first detection of a gravitational wave (GW) has important implications beyond cosmology. The experimentally observed characteristics of GW150914 confirm that this 250 Hz GW encountered spacetime as a very stiff elastic medium with impedance of $Z_s = c^3/G$. The detected intensity was 0.02 w/m^3 and this generated a dimensionless strain amplitude of 10^{-21}. This extremely small displacement of spacetime produced by intensity of 0.02 w/m^2 implies the GW strongly interacted with a large energy density distributed throughout the vacuum of spacetime. This energy density is not detectable by fermion-based instruments but is detected by GWs. The VE density encountered by GW150914 would have to be 6.6 x 10^{31} J/m^3 (equivalent to mass density of ρ = 7.4 x 10^{14} kg/m^3) to produce the observed strain amplitude and intensity at 250 Hz.

This speaks to the conflict between the VE predicted by quantum field theory and the critical density of the universe required by general relativity to achieve flat spacetime. GW150914 encountered energy density 10^{40} times larger than the critical energy density of the universe. Extending this to Planck frequency, the difference would be a factor of about 10^{120}. It is broadly assumed by the scientific community that the energy density predicted by quantum field theory must be canceled out by some unknown factor. Now GW150914 offers support to the physical existence of VE in spacetime. For example, the same equation has been used to derive both the very small critical energy density of the universe (~10^{-9} J/m^3) and the very large VE density of the universe (~10^{112} J/m^3). Also the ratio of these two energy densities can be succinctly stated as: $\omega_p^2/\mathcal{H}_o^2 = 7.1 \text{ x } 10^{121} \approx 10^{120}$.

It is proposed that VE is a high energy field consisting of Planck frequency spacetime waves which modulate the distance between points by Planck length. A Planck length fluctuation of VE has been shown to achieve the temporary energy required for the formation and annihilation of a virtual particle. The standard model assumes that spacetime is filled with multiple fields and fundamental particles are excitations of their respective fields. It has been proposed that the multiple overlapping fields of the standard model are actually multiple resonances of a single field – the spacetime field consisting of VE. Therefore, the elastic stiffness of spacetime encountered by GW150914 is proposed to be caused by the same spacetime field associated with the standard model.

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References

[1] Abbott, B. P. et al.: (LIGO Scientific Collaboration, Virgo Collaboration), Phys. Rev. Lett. 116, 061102 (2016), https://arxiv.org/abs/1602.03840
[2] Milonni, P. W.: The Quantum Vacuum: An Introduction to Quantum Electrodynamics. Academic Press, San Diego (1994) pp 1-74, p 49
[3] Misner, C. W., Thorne, K. S., Wheeler, J A.: Gravitation. (W. H. Freeman and Company, New York p 975. (1973)
[4] Wheeler, J. A., Ford, K.: Geons, Black Holes, and Quantum Foam. W. W. Norton & Co. NY, NY (1995)

[5] Cahill, R. T.: Gravity as Quantum Foam In-Flow. Apeiron, 11, 1-52 (2004) http://arxiv.org/pdf/physics/0307003.pdf
[6] Sparnaay, M. J.: Measurements of Attractive Forces between Flat Plates. Physica, 24, 751 (1958)
[7] Lamoreaux, S. K.: Demonstration of the Casimir Force in the 0.6 to 6μm Range. Phys. Rev. Lett. **78**, 5 (1997) Erratum: Phys. Rev. Lett. 81, 5475 (1998)
[8] Garcia-Sanchez, D., Fong, K. Y., Bhaskaran, H., Lamoreaux, S., Tang, H. X.: Casimir Force and *In Situ* Surface Potential Measurements on Nanomembranes. Phys. Rev. Lett. **109**, 027202 (2012)
[9] Jaffe, R. L.: The Casimir Effect and the Quantum Vacuum. Phys. Rev. D **72**, 021301(R) (2005), https://arxiv.org/pdf/hep-th/0503158v1.pdf
[10] Adler, R.J., Casey, B., Jacob, O. C.: Vacuum Catastrophe: An Elementary Exposition of the Cosmological Constant. American Journal of Physics, 63, 620-626 (1995)
[11] Reynaud, S., Lambrecht, A., Jaekel, M. T.: Quantum vacuum fluctuations. Comptes Rendus de l'Académie des Sciences - IV – Phys. 2, 1287-1298 (2001)
[12] Bennett, C.L., Larson, D., Weiland, J. L. et. al,: Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results, ApJS., **208**, 20B (2013)
[13*]* Bucher, P. A. R.; et al. (Planck Collaboration*)* Planck 2013 Results. I. Overview of Products and Scientific Results. Astronomy & Astrophysics 571, A&A *(2014) arXiv:1303.5062*
[14] Rugh, S.E., Zinkernagel H.: The Quantum Vacuum and the Cosmological Constant Problem. Studies in History and Philosophy of Science B, 33, 663-705 (2002) https://arxiv.org/pdf/hep-th/0012253v1.pdf
[15] LIGO Scientific Collaboration, Virgo Collaboration: GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence. Phys. Rev. Lett. **116**, 241103 (2016)
[16] Abbott B. P. *et al:* (LIGO Scientific Collaboration, Virgo Collaboration): GW150914: The Advanced LIGO Detectors in the Era of First Discoveries. Phys. Rev. Lett. **116**, 131103 (2016)
[17] Blair, D. G., Howell, E. J., Ju, L., Zhao, C.: Advanced Gravitational Wave Detectors. Cambridge University Press, Cambridge p 9 (2012)
[18] Blair, D. G., McClelland, D. E., Bachor, H. A., Sandeman, R. J.: The Detection of Gravitational Waves. Blair, D. G. (ed) p. 45 Cambridge University Press, Cambridge (1991)
[19] LIGO Scientific Collaboration, Virgo Collaboration: Tests of general relativity with GW150914. Phys. Rev. Lett. 116, 221101 (2016)
[20] Epstein, R. I.: Acoustic Properties of Neutron Stars. The Astrophysical Journal, **333**, 880-894 (1988) http://adsabs.harvard.edu/full/1988ApJ...333..880E
[21] Peskin, M.E., Schroeder, D.V.: An Introduction to Quantum Field Theory, Westview Press. (1995) p. 80
[22] Padmanabhan, T.: Limitations on the Operational Definition of Spacetime Events and Quantum Gravity. Class. Quantum Grav. 4 L107 (1987)
[23]Garay, L. J.: Quantum Gravity and Minimum Length. Int. J. Mod. Phys. **A10**, 145-166 (1995), arXiv:gr-qc/9403008
[24] Baez, J. C., Olson, S. J.: Uncertainty in Measurements of Distance. Class. Quantum Grav. **19**, L121-L125 (2002) http://arxiv.org/abs/gr-qc/0201030
[25] Calmet, X., Graesser, M., Hsu, S. D.: Minimum Length from Quantum Mechanics and General Relativity. Phys. Rev. Lett. **93**, 211101 (2004) http://arxiv.org/abs/hep-th/0405033
[26] Calmet, X.: On the Precision of Length Measurement. Eur. Phys. J. **C54**, 501-505. (2008) http://arxiv.org/abs/hep-th/0701073]
[27] Macken, J. A.: Energetic Spacetime: The New Aether. in: Roychoudhuri, C.;. Kracklauer, A. F., De Raedt H., (eds.) The Nature of Light: What are Photons? VI, Proc. of SPIE. **9570**, 957019 (2015) doi:10.1117/12.2186257
[28] Hobson, A.: There Are No Particles, There Are Only Fields. Am. J. Phys., **81**, 211-223, (2013)
[29] Macken, J. A.: Spacetime Based Foundation of Quantum Mechanics and General Relativity. in: Nascimento, M.A.; Maruani, J. et al; (eds.), Frontiers in Quantum Methods and Applications in Chemistry and Physics **29**, Springer, Switzerland pp. 219-245 (2015) doi: 10.1007/978-3-319-14397-2_13
[30] Rich, J,: Fundamentals of Cosmology. Springer, Heidelberg p 10 (2009)

[31] Das, S., Vagenas, E. C.: Universality of Quantum Gravity Corrections. Phys. Rev. Lett. **101**, 221301 (2008) http://arxiv.org/pdf/0810.5333.pdf
[32] Macken, J. A.: Spacetime-Based Model of EM Radiation. in: Roychoudhuri, C.; Kracklauer, A. F.; De Raedt, H. (eds.) The Nature of Light: What are Photons? Proc. SPIE **8832**, 88320Q (2013) doi: 10.1117/12.2021288