Title: Positive and Negative Energy Symmetry and the Cosmological Constant Problem

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Abstract: The Hamiltonian for the quantized gravitational and matter fields contains both positive and negative energy particle contributions, which leads through a positive and negative energy symmetry of the vacuum to a cancellation of the zero-point vacuum energy and a vanishing cosmological constant in the presence of a gravitational field. The positive and negative energy particles interact only weakly through gravity. As in the case of antimatter, the negative energy matter is not found naturally on Earth or in galaxies in the universe. We introduce a graviton momentum cutoff ΛG ≤ 2 x10-3 eV that leads to a gravitational stability of the Minkowski spacetime vacuum with a lifetime greater than the age of the universe. A positive energy spectrum and a consistent unitary field theory for a pseudo- Hermitian Hamiltonian is obtained by demanding that the pseudo-Hermitian Hamiltonian is PT symmetric. The quadratic divergences in the two-point vacuum fluctuations and the self- energy of a scalar field are removed. By adopting a Higgsless model of electroweak theory, we remove the fine-tuning associated with a spontaneous symmetry breaking vacuum density. We also postulate that there are no phase transitions associated with QCD and at higher particle physics energy scales, removing all theorized quark-gluon vacuum density condensates and their fine-tuned vacuum densities and cosmological constant contributions.

Positive and Negative Energy Symmetry and the Cosmological Constant Problem

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Invited talk given at the workshop on new prospects for solving the cosmological constant problem, May 25-27, 2009

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1. Why is there a Cosmological Constant Problem?

- Is empty space really empty?

- In QFT the notion of empty space has been replaced with that of a vacuum state, defined to be the ground (lowest energy density) state of a collection of quantum particle fields.

- A truly quantum mechanical feature of the quantum fields is that they exhibit zero-point fluctuations everywhere in space, even in regions which are otherwise "empty" i.e. devoid of matter and radiation.

- This vacuum energy density is believed to act as a contribution to the cosmological constant Λ appearing in Einstein's field equations from 1917:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

• Confrontation of Einstein's equation with observations shows that Λ is very small: the tightest bound comes from cosmology:

$$|\rho_{vac}| < 10^{-29}\ g/cm^3 \sim 10^{-47}\ GeV^4 \sim 10^{-9}\ erg/cm^3$$

$$|\Lambda| < 10^{-56} cm^{-2}$$

• Theoretical estimates of various contributions to the vacuum energy density in QFT exceed the observational bound by at least 40 orders of magnitude. This large discrepancy constitutes the cosmological constant problem. One can distinguish at least two different meanings to the notion of a cosmological constant problem:

1. Calculations of $\Lambda = 8\pi G\rho_{vac}$ from assuming real QFT vacuum fluctuations, lead to a huge fine-tuning problem.

2. A need for Λ to explain cosmological observations such as WMAP and the acceleration of the expansion of the universe.

• The cosmological constant has been in and out of Einstein's equation from the time that Einstein introduced it in 1917 to counter-balance gravitation and thus secure a static universe.

• Nernst already in 1916 proposed that the vacuum is not 'empty' but is a medium filled with radiation ["Licht äther"] which contains a large amount of energy (infinite without a frequency cut-off).

• Pauli already in the 1920s was concerned about the gravitational effects of such a zero-point energy. He calculated the gravitational effect of the EM zero-point energy, applying a cutoff at the classical electron radius, and found that the radius of the universe "would not even reach to the moon".

• Weinberg writes [1989]: "Perhaps surprisingly, it was a long time before particle physicists began seriously to worry about this problem, despite the demonstration in the Casimir effect of the reality of zero-point energies".

• The total zero-point quantum EM energy can be expressed by [Rugh and Zinkernagel 2001]:

$$E = < 0|\hat{H}|0 > = \frac{1}{2} < 0| \int d^3x (\hat{\mathbf{E}}^2 + \hat{\mathbf{B}}^2)|0 > = \delta^3(0) \int d^3k \frac{1}{2}\hbar\omega_{\mathbf{k}}$$

$$\rho_{vac} = \frac{E}{V} = \frac{1}{V}\sum_{\mathbf{k}} \frac{1}{2}\hbar\omega_{\mathbf{k}} \approx \frac{\hbar}{2\pi^2 c^3}\int_0^{\omega_{max}} \omega^3 d\omega = \frac{\hbar}{8\pi^2 c^3}\omega_{max}^4$$

• The energy in this expression is strongly divergent since the expression involves the product of two infinite (divergent) quantities. One can render the integration finite by imposing an ultraviolet frequency cut-off ω_{max}.

Assuming this energy to be of the QED zero-point energy type at the Planck energy $E_p \sim 10^{19}$ GeV, we get $\rho_{vac} \sim 10^{120}\, \rho_{vac}^{obs}$!!

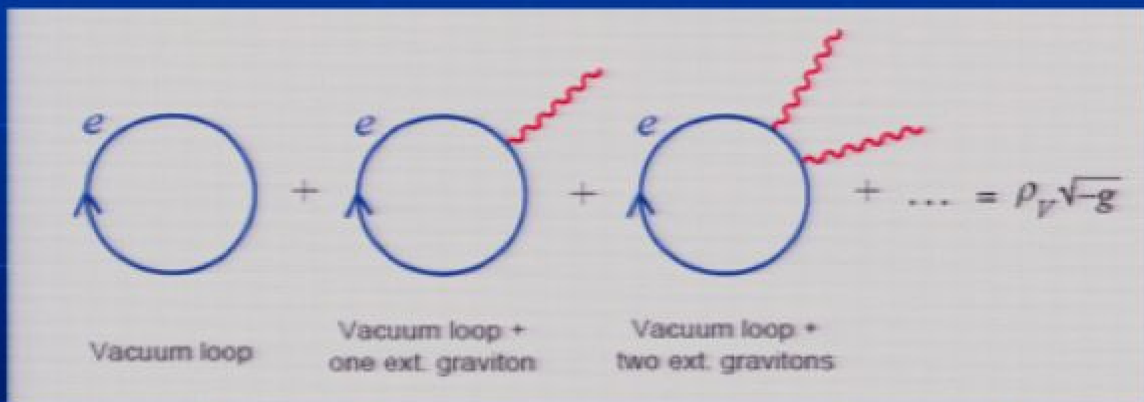
• Experimentally verified physical effects – such as the Casimir effect, the Lamb shift, spontaneous emission from atoms and the anomalous magnetic moment of the electron point to the reality of QED vacuum energy and vacuum field fluctuations. However, these effects are due to the measurements on material systems – the plates in the Casimir effect, the atom for the Lamb shift, so that maybe it is impossible to decide whether the experimental results are due to the "pure" empty space vacuum or of the material systems.

• Could it be that the QFT vacuum with non-zero energy in "empty space", in the absence of any material constituents, cannot be justified beyond what is experimentally observed?

• Could observations of Λ be an indication that there are no empty space vacuum fluctuations? I believe the answer is NO. Because the calculations of higher-order effects in e.g. the Lamb shift in hydrogen can only be done with real quantum vacuum fluctuations in QED.

2. Equivalence principle and "de-gravitating" the vacuum energy

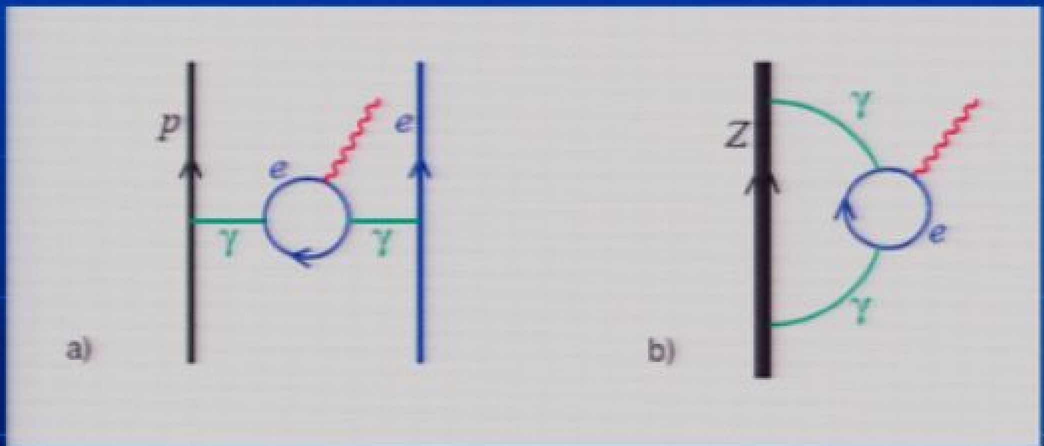
- Let us consider the QED electron zero-point energy. We can calculate this energy from the graphs [Polchinski 2006]:



$$\rho_V = O(M^4) + O(M^2 m_e^2) + O(m_e^4 \ln M/m_e)$$

- This produces a vacuum energy density more than 40 orders of magnitude to large!

• Consider "weighing" the hydrogen atom or the atomic system consisting of a vacuum polarization loop correction to the electrostatic energy of the nucleus in a classical gravitational field. The tree level exchange of a graviton and the earth can describe this weighing of the system in a gravitational field.



• Aluminum and platinum have the same ratio of gravitational to inertial mass to one part in 10^{12}. The nuclear electrostatic energy is roughly 10^{-3} of the rest energy in aluminum and 3×10^{-3} in platinum. We can say that this energy satisfies the equivalence principle to one part in 10^{9}.

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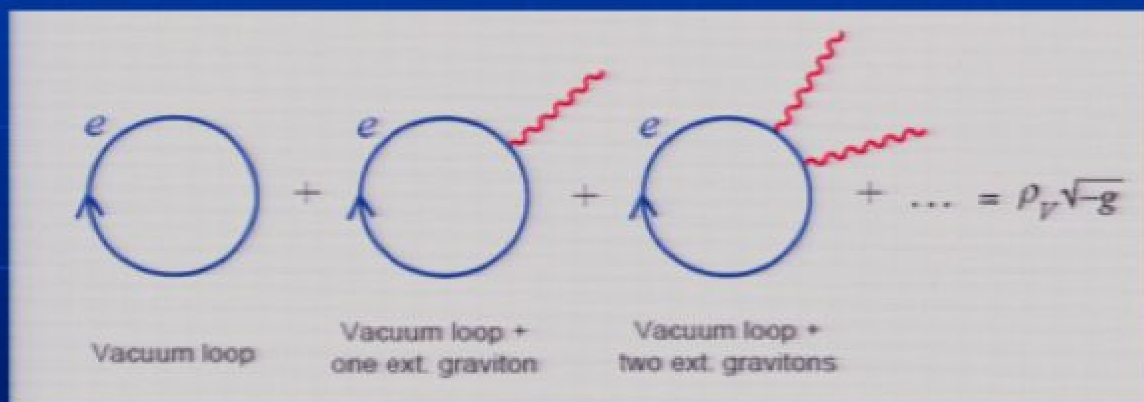

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• If you can suppress the pure vacuum graphs, so that we get $\rho_{vac}^{\ theo} \sim \rho_{vac}^{\ obs}$, without suppressing the matter nucleus electrostatic energy, then you can avoid violating the equivalence principle Eötvös experiment [Polchinski 2006, Masso 2009] and potentially solve the cosmological constant problem. However, if I suppress the pure vacuum graphs by suppressing the coupling at the graviton-matter vertices, or by suppressing either the graviton or matter propagators there is no way from a local Lagrangian to tell the difference between vertices/propagators inside matter versus those in a pure disconnected "bubble" graph. The electron and quark vacuum loops in the pure vacuum disconnected "bubble" graphs are the same as those in the atomic material vacuum polarization graphs. This is bad news for any "de-gravitating" of the vacuum mechanism in D=4, such as composite form factors etc. for graviton momentum cutoffs ~ 1/100 microns~ 10^{-3} eV.

• The problem is that we presuppose that the quantum zero-point energy gravitates as all other forms of energy. By suppressing the coupling of gravitons to zero-point energy so that $\rho_{vac} \sim (2 \times 10^{-3}\ \mathrm{eV})^4$, we run the risk of seriously violating experimental bounds on the equivalence principle.

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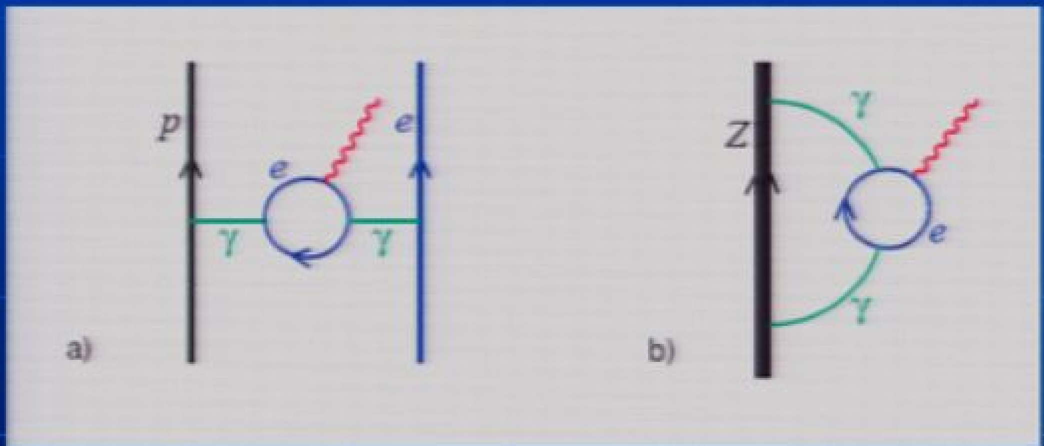

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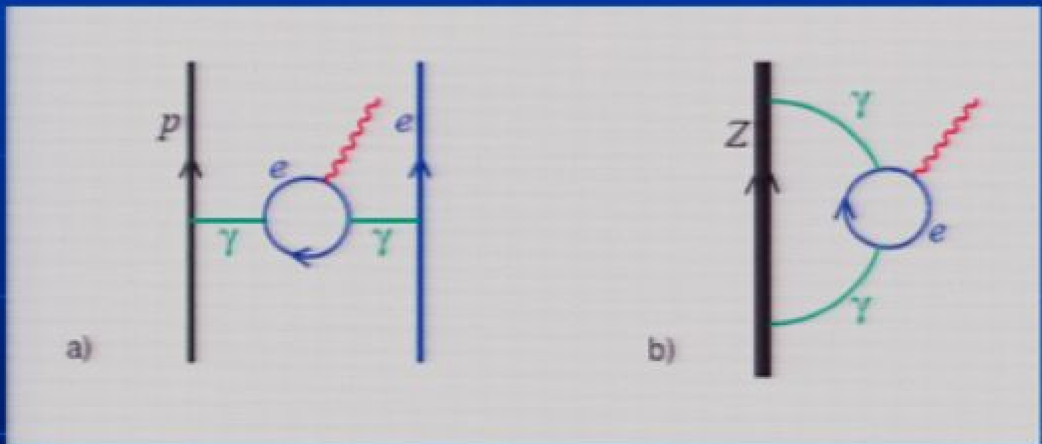

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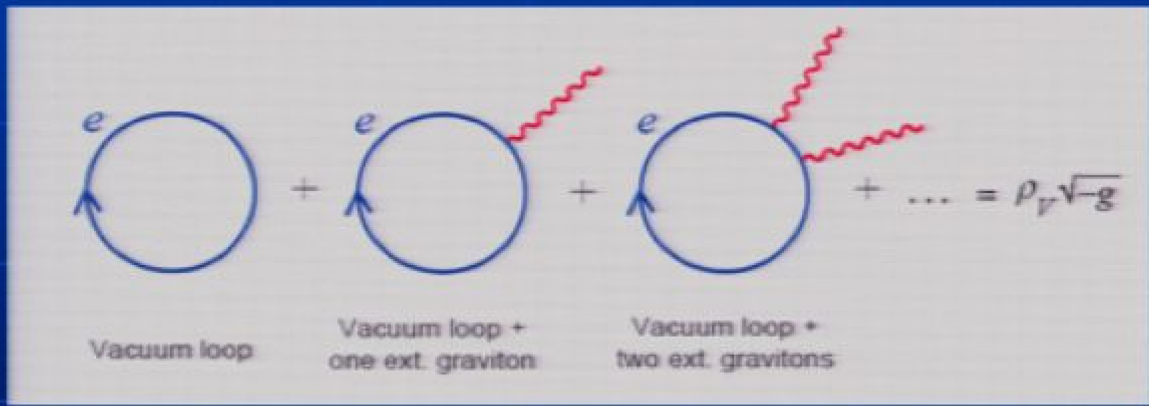

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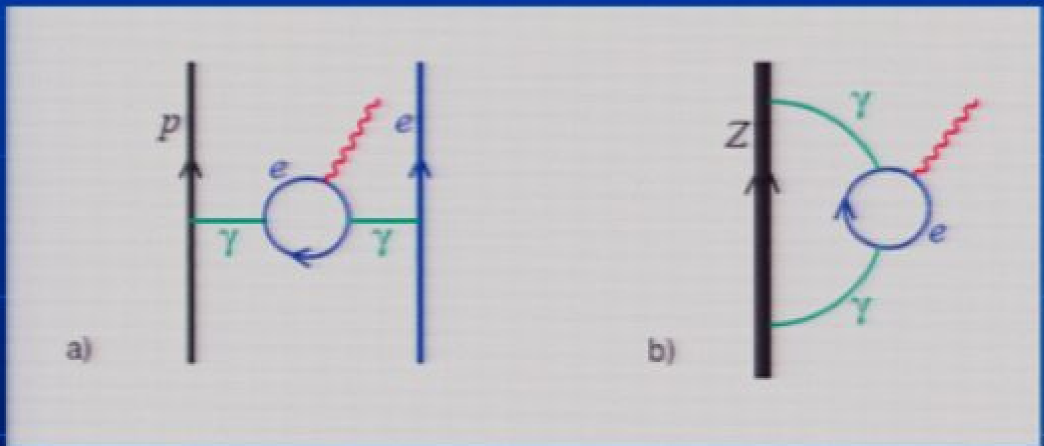

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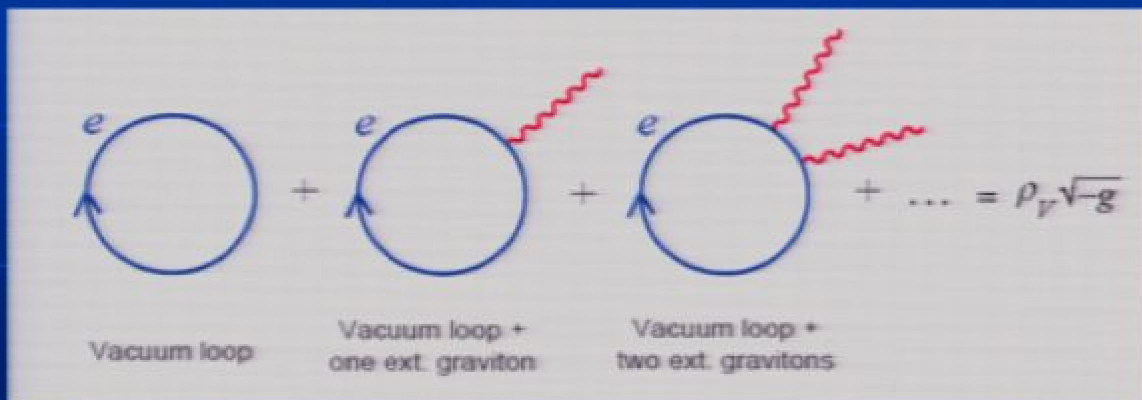

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3. Spontaneous symmetry breaking and the Higgs and QCD vacuum densities

- For a classical potential for a scalar field φ we can identify: $<T_{\mu\nu}>_0 = V(\varphi) = \rho_{vac}$. The Higgs field vacuum energy is calculated from the classical Higgs potential:

$$V(\phi) = V_0 - \mu^2\phi^2 + \lambda\phi^4 \qquad \langle 0|\phi|0\rangle = v$$

where v ~ 250 GeV is the EW energy scale. We have $\mu^4 = \lambda^2 v^4$. From the minimization of the Higgs potential we obtain $\varphi_{min} = \mu^2/2\lambda$, and $V_{min} = V_0 - \mu^4/4\lambda = \rho_{vac}^{ssb}$. Choosing V (0) = 0 we obtain

$$\rho_{\rm vac}^{\rm SSB} = -\frac{\mu^4}{4\lambda} \sim -\lambda v^4 \sim -10^5\,{\rm GeV}^4. \quad \rho_{\rm vac}^{\rm OBS} \sim 10^{-47}\, GeV^4 \quad |\rho_{\rm vac}^{\rm SSB}| \sim 10^{56}\rho_{\rm vac}^{\rm OBS}$$

(Vacuum energy) = (Vacuum zero-point energy)+ (The Higgs potential) +(QCD gluon and quark condensates)

• Veltman [1975, Dreitlein 1975] has concluded from this serious cosmological constant problem that the (classical) Higgs mechanism and the Higgs particle invoked to explain electroweak symmetry breaking may be at fault, and that maybe the Higgs particle does not exist. Indeed, after more than 40 years the Higgs particle has not been detected in collider experiments.

• A consistent regularized quantum field theory has been developed, which leads to a Higgless electroweak model that determines the masses of the W and Z particles from QFT self-energy loop diagrams, and retains a massless photon [JWM 1991, JWM 2007, JWM and V. T. Toth 2008]. Scattering amplitudes for $W^+W^- \to W^+W^-$ reactions and $e^+e^- \to W^+W^-$ annihilation have been obtain that can be distinguished at the LHC from those calculated in the standard Higgs electroweak model. Unitarity is not violated at high energies in this model.

• In the Higgless model there is no Higgs mass hierarchy problem and no cosmological constant problem generated by spontaneous symmetry breaking!

4. Positive and negative energy symmetry and canceling the QFT zero-point vacuum energy density.

- If we can find a means to cancel the zero-point quantum vacuum energy density and avoid classical potentials $V(\varphi_{\square})$ associated with classical spontaneous symmetry breaking and phase transitions, at QCD and EW energy scales then we can claim to have solved the cosmological constant problem.

- However, we are still faced with the problem of the quantum zero-point vacuum energy density.

- Does there exist a symmetry that cancels the quantum zero-point vacuum energy density?

- We know that supersymmetry does not work, because it is badly broken.

• Positive and negative energy symmetry can cancel the quantum zero-point vacuum energy [Linde 1988, Kaplan and Sundrum 2005, JWM 2005, JWM 2006].

• I have formulated a quantum field theory based on an indefinite metric in Hilbert space with a generalization of the Hermitian Hamiltonian operator $H = H^\dagger$ to an adjoint operator $\hat{H} = \eta^{-1} H^\dagger \eta$ (indefinite metric) and we have $\hat{H} = H$. The quantization of fields in the presence of gravity is performed with a positive and negative energy particle interpretation, which leads to the cancellation of the zero-point vacuum energy due to the positive and negative dual energy symmetry of the vacuum. We have

$$H = H_+ + H_-,$$

$$H_+|0\rangle = E_{\rm vac}|0\rangle, \quad H_-|0\rangle = -E_{\rm vac}|0\rangle,$$

$$\langle 0|H|0\rangle = 0.$$

- The action takes the form [JWM 2005, 2006]:

$$S = S_{\text{Grav}} + S_M(\phi_+) + S_M(\phi_-).$$

$$S_{\text{Grav}} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}[(R - 2\Lambda_0)].$$

- The R denotes the Ricci scalar, Λ_0 denotes the "bare" cosmological constant and the φ^+ and φ^- denote positive and negative energy matter fields. The positive and negative energy fields will be quantized using distinct quantization rules [JWM 2006].

- We expand the metric tensor $g_{\mu\nu}$ about Minkowski flat space.

Let us consider a real scalar field $\varphi(x)$ in the absence of interactions and we will restrict ourselves to a study of the lowest weak gravitational field approximation. The action is

$$S_\phi = \frac{1}{2}\int d^4x\left[\partial_\mu\phi\partial^\mu\phi - \mu^2\phi^2\right]$$

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$$S_\phi = \frac{1}{2}\int d^4x\left[\partial_\mu\phi\partial^\mu\phi - \mu^2\phi^2\right]$$

• As is well known, this equation has both positive and negative energy solutions, as is the case with the Dirac equation. We have for the non-covariant formulation:

$$k_0 \equiv \omega(\mathbf{k}) = \pm\sqrt{|\mathbf{k}|^2 + \mu^2}.$$

• We decompose φ into positive and negative energy parts:

$$\phi(x) = A(x) + \tilde{A}(x).$$

The φ and π operators are given by

$$\phi(\mathbf{x}) = \int \frac{d^3k}{[(2\pi)^3 2k_0]^{1/2}} \Big\{ (A_+(\mathbf{k}) + \tilde{A}_-(\mathbf{k})) \exp[i(\mathbf{k}\cdot\mathbf{x})] + (A_-(\mathbf{k}) + \tilde{A}_+(\mathbf{k})) \exp[i(-\mathbf{k}\cdot\mathbf{x})] \Big\},$$

$$\pi(\mathbf{x}) = \int \frac{d^3k}{[(2\pi)^3]}(-i)\sqrt{\frac{k_0}{2}} \Big\{ (A_+(\mathbf{k}) + \tilde{A}_-(\mathbf{k})) \exp[i(\mathbf{k}\cdot\mathbf{x})] - (A_-(\mathbf{k}) + \tilde{A}_+(\mathbf{k})) \exp[i(-\mathbf{k}\cdot\mathbf{x})] \Big\}.$$

$$[A_+(\mathbf{k}), \tilde{A}_+(\mathbf{k}')] = \delta^3(\mathbf{k}-\mathbf{k}'), \quad [A_-(\mathbf{k}), \tilde{A}_-(\mathbf{k}')] = -\delta^3(\mathbf{k}-\mathbf{k}').$$

- We obtain the Hamiltonian:

$$H = \frac{1}{(2\pi)^3}\int d^3k\omega(\mathbf{k})[(N_+(\mathbf{k}) + \frac{1}{2}) - (N_-(\mathbf{k}) + \frac{1}{2})]$$
$$= \frac{1}{(2\pi)^3}\int d^3k\omega(\mathbf{k})[N_+(\mathbf{k}) - N_-(\mathbf{k})],$$

- The zero-point vacuum energy contribution corresponding to the infinite c-number δ(0) has canceled.

- We now obtain <0|H|0> = 0 and the canceling of the zero-point vacuum energy can be shown to hold for all physical quantum fields.

• In standard quantum field theory the Hamiltonian is Hermitian, $H^\dagger = H$, and we are guaranteed that the energy spectrum is real and positive and that the time evolution of the operator $U = \exp(itH)$ is unitary and probabilities are positive and preserved for particle transitions. However, in recent years there has been a growth of activity in studying quantum theories with pseudo-Hermitian Hamiltonians, which satisfy the generalized property of adjointness, $\hat{H} = \eta^{-1} H^\dagger \eta$, associated with an indefinite metric in Hilbert space [Dirac 1942, Pauli 1943, Bender et al. 1998 -2008].

• If a Hamiltonian has an unbroken PT symmetry, then the energy levels can in special cases be real and the theory can be unitary and free of "ghosts". The operation of P leads to x -> - x, while the anti-linear operation of T leads to i -> -i. It follows that under the operation of PT the Hamiltonian H for the positive and negative energy φ^+ and φ^- is invariant under the PT transformation, which is necessary but not sufficient to assure the reality of the energy eigenvalues.

• The proof of unitarity follows from the construction of a linear operator C. This operator is used to define the inner product of state vectors in Hilbert space:

$$\langle \Psi | \Phi \rangle = \Psi^{\mathcal{CPT}} \cdot \Phi.$$

• With respect to this inner product, the time evolution of the quantum theory is unitary. In quantum mechanics and in quantum field theory, the operator C has the general form:

$$\mathcal{C} = \exp(Q)\mathcal{P},$$

The solution for C satisfies

$$\mathcal{C}^2 = 1, \quad [\mathcal{C}, \mathcal{PT}] = 0, \quad [\mathcal{C}, H] = 0.$$

- In standard QFT, the zero-point vacuum energy diverges quartically and is the root of the cosmological constant problem in the presence of a gravitational field, since gravitons can couple to the vacuum energy "bubble" graphs which cannot be time-ordered away, i.e., we cannot simply shift the infinite constant vacuum energy, E_0, such that only $E' = E - E_0$ is observed.
- We can prove that the zero-point vacuum energy for fermions also cancels. We quantize the gravitational fluctuations in a manner similar to the quantization of the scalar field φ and show that the graviton zero-point vacuum energy cancels.
- We can quantize the fields in the presence of interactions and avoid a catastrophic instability due to negative probabilities and negative energy particles.
- We assume the existence of a visible positive energy matter sector and a negative energy matter "shadow" sector, which are identical copies of the standard model of particles. These two sectors only couple weakly through gravity.

5. The stability of the vacuum.

- A two-body scattering process involving negative and positive energy particles can result in an increase in the magnitude of the energies of the particles. Suppose that the negative energy particle is massive so that we can consider it to be initially at rest. If the initial energy of a photon is E_i and it gravitationally scatters from the negative energy particle at angle θ, then its final energy is

$$E_f = E_i \left(\frac{m}{m - E_i(1 - \cos\theta)} \right) > E_i$$

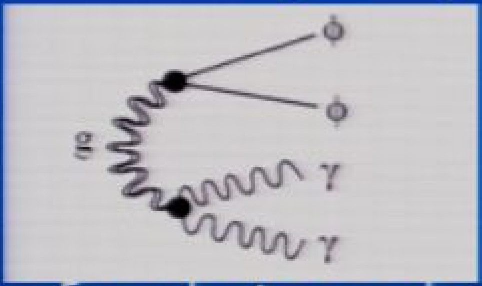
- In contrast to the positive energy case where photons can only lose energy in such scatterings, there exist initial energies $E_i = m/(1 - \cos\theta)$ such that the final energy is negative and divergent.

- We must allow the negative energy particles to interact gravitationally, since it is their gravitational interactions which are needed for them to have any cosmological consequences.

- It is postulate that the shadow negative energy matter (as with standard anti-matter) does not exist in a stable form in nature. Thus, the cosmological scenario with positive energy will be preserved, except possibly in the very early universe.

• We must face the possible instability of empty Minkowski spacetime when coupled to gravity. The question arises how rapidly the vacuum decays into negative energy particles in the presence of gravity. We have to consider

$$(\text{Nothing}) \to \phi_{1+} + \phi_{2+} + \phi_{1-} + \phi_{2-}.$$



• An estimate for the probability for the process for photons gives [Cline et al. 2004, Kaplan and Sundrum 2005]:

$$P \sim \frac{1}{4\pi}\left(\frac{1}{8\pi^2}\right)^2 \frac{\Lambda_G^8}{M_{PL}^4} \sim 2 \times 10^{-92}\left(\frac{\Lambda_G}{2 \times 10^{-3}\text{eV}}\right)^8 (\text{cm}^3 \times 10\text{Gyr})^{-1}.$$

The cutoff Λ_G on the off-shell gravitons must be Lorentz violating and the energy of the spectrum of photons is constrained by the EGRET observations of the diffuse gamma ray background. This limits $\Lambda_G < 3$ MeV for which the rate of decay of the vacuum is slow compared to the cosmological time scale of the universe.

• We cannot have a Lorentz invariant cutoff [Cline et al. 2004], because this will produce unacceptable photon number densities at energies ~ 10^{18} GeV unless $\Lambda_G \leq 10^{-3}$ eV, which is in disagreement with gravity measurements at the length scale > 0.2 millimeters [Adelberger et al. 2001].

• The need for a Lorentz violation is of concern due to the stringent experimental bounds on Lorentz symmetry breaking. However, there may be a more satisfactory theory in future that can resolve this problem and still maintain Lorentz symmetry and stabilize the vacuum.

• In any case, the postulate that the positive and negative energy particles only couple through gravity can allow for a sufficiently stable vacuum and a possible resolution of the cosmological constant problem.

6. The cosmology problem.

- The WMAP data combined with the supernova data (accelerating universe) says that in the standard model of cosmology there exists ~ 30% visible baryon matter and dark matter, and ~ 70% "dark energy". The latter is identified with $\Lambda = 8\pi G\rho_{vac}$ in the ΛCDM model.

- However, there is a modified gravity (MOG) model [JWM 2006, JWM and V. T. Toth 2007, 2008], based on a fully relativistic action principle that fits astronomical data, WMAP data and the supernovae data without exotic dark matter and without a cosmological constant Λ [JWM 2006, JWM and Toth 2007, 2009].

- There are now many alternative gravity models that claim to explain the accelerating expansion of the universe. Many of these models suffer from instability problems.

- There are models such as the Lemâitre-Tolman-Bondi solution of GR with voids and inhomogeneous late-time matter density that possibly can fit the supernovae data without dark energy and a cosmological constant Λ [JWM 2005, 2006, Célérier 2005, 2007, Tomita 2001, Räsänen 2004, Chung and Romano 2006, others].

7. Conclusions

• There are three significant points that may lead to a solution of the cosmological constant problem:

1) The basic action contains both distinct positive and negative energy matter terms, which only interact through gravity.

(2) While the positive energy term is quantized the usual way with a Hermitian Hamiltonian, the negative energy term is quantized using the pseudo-Hermitian Hamiltonian, changing the sign of the vacuum energy term (from +1/2 to -1/2), thus ensuring that the total vacuum zero-point energy density cancels to zero. Probabilities are positive and conserved and the S-matrix is unitary.

(3) A graviton momentum cutoff reduces the cross-section of positive energy matter to negative energy matter interactions to a negligible level, assuring the gravitational stability of the vacuum on cosmological time scales.