Cosmological Constant Problem and Equivalence Principle of Quantum Gravity

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Cosmological Constant Problem

- The vacuum energy behaves as the λ term in the Einstein's field equation

$$R_{\mu\nu} - g_{\mu\nu}R/2 - g_{\mu\nu}\lambda = 8\pi G T_{\mu\nu}$$

  known as the cosmological constant.
- The cosmological constant problem is that

  - Why the observed value so many order of magnitude smaller than that expected in quantum field theories?

  - Why it is of the same order of magnitude as the matter density of the universe at the present time?

- We have shown in the previous paper (arXiv:astro-ph/0105513) that if the space-time behaves as the phase of Higgs condensate and is discrete in nature, the vacuum energy could be extremely large in microscopic scale but comparatively very small in macroscopic scale.

Solution of the Cosmological Constant Problem

- This is analogous to the situation that the mass density inside the atomic nucleus (10^{18}kg/m^3) is extremely larger than the mass density of common material (~10^3kg/m^3) in the length scale of our daily life

- Under such hypothesis, the microscopic vacuum energy density $\langle V\rangle_{micro}$ should be averaged over the condensate in macroscopic scale and the cosmological constant can be found as

$$\lambda = 8\pi G\langle V\rangle_{macro} = m^7/(\pi^2 M_p{}^5) \sim (m_{EW})^7/(M_p)^5$$

By putting m_{EW}= 100 GeV, the value of the cosmological constant is then equal to $10^{-52}[m]^{-2}$ which corresponds to about 0.7 of the critical mass density of the universe.

- This result is in excellent agreement with the recent cosmological observations.

Evolution of the Universe

- The results also show that the cosmological constant depends on the VEV of the Higgs condensate and the cosmological constant for the Planck stage and GUT stage can be estimated as $(M_p)^2$ and $(m_{GUT})^7/(M_p)^5$ respectively.

- The time of which the universe changed from deceleration to acceleration in the Planck, GUT and Electroweak stage can be found as 10^{-42}s, 10^{-27}s and 8 billion years of the universe respectively.

- The time calculated for the universe changed from deceleration to acceleration at about 8 billion years is in excellent agreement with the recent cosmological observations (Riess, A.G. et al 2004 ApJ).

Evolution of the Universe

- The above mentioned relationship between matter density and cosmological constant also explains why the matter density of the present epoch is similar in the order of magnitude as vacuum energy density. Therefore, the cosmological constant problem can be solved.

- The above results indicate that the nature of cosmological constant would be fundamentally related to the quantum nature of space-time. The development of quantum gravity theory plays an important role for the quest of cosmological constant problem.

Equivalence Principle of General Relativity

- In this talk, we would further explore the underlying physical meaning of the space-time condensate hypothesis by introducing the equivalence principle of quantum gravity which would be the fundamental principle for the unification of the general relativity and quantum mechanics.

- In general relativity, the laws of physics must be of such a nature that they apply to systems of reference in any kind of motion.

- The general laws of nature are to be expressed by the equations which hold good for all systems of co-ordinates, that is, are covariant with respect to any substitutions whatever (i.e. generally covariant).

Review on Physical Meaning of Space-time

- In relativity, the space-time is relative to the observer frame which is defined by the coordinate system established by measuring-rods and synchronized clocks at rest relative to the observer for the descriptions of physical events.

- However, the quantum mechanical measuring device as an observer frame (i.e. quantum mechanical frames) are not considered in special and general relativity. Thus, the classical relativity is not valid in quantum mechanical frames.

- In essence, this is the fundamental difficulties in unifying general relativity with quantum mechanics in conception level.

- Then, what do the physical laws behave as observed in quantum mechanical frames of reference ?

Equivalence Principle of Quantum Gravity

- The fundamental principle of relativity is that there is no preferred reference frame and the physical laws are valid in reference frame in any kind of motion.

- We expect that such basic principle is also valid for quantum mechanical frame of reference. That means it is not possible for an observer to know whether he is in a quantum frame or not by physical experiments.

- Therefore, the equivalence principle of general relativity should be extended such that the meaning of any kind of motion shall also include the quantum mechanical motions

- We propose that the equivalence principle of quantum gravity is that "The laws of physics must be of such a nature that they apply to systems of reference in any kind of motion, both classical and quantum mechanical "

Equivalence Principle of Quantum Gravity

- Apparently, such extension of equivalence principle is not possible since the quantum mechanical effects depends upon the particle masses. That means the law of quantum mechanics for different particle masses varies with the energy scale of the quantum frame of reference.

- However, the ordinary space-time concept requires to be changed since, in quantum space-time measurements, the energy scale should also be specified to determine the measurement uncertainty.

- As we learned in relativity, we have to refer to the actual physical measurements of an observer in defining the space-time.

- The quantum frame of reference is therefore not just kinematical as in relativity but dynamical. It requires to include mass energy scale as a parameter for its determination.

Equivalence Principle of Quantum Gravity

- This could lead to a space-time-matter geometrical structure which is the suitable space for the equivalence principle of quantum gravity. The quantum mechanical frames would be described by this space-time-matter structure and it could be known as the quantum space-time.

- Furthermore, the extended equivalence principle provides a strong fundamental symmetry for quantum gravity.

- Under the equivalence principle, the quantum mechanical effects of particles can be varied by choosing the quantum mechanical frames of different energy scale.

- Analogous to the concept of free fall frame in general relativity, one could choose a quantum frame of reference for a quantum particle such that it behaves as a classical particle and general relativity holds for it.

Equivalence Principle of Quantum Gravity

- In such frame, the product of the space-time increment ds and mass scale m provides a local scale invariant quantity mds in quantum mechanics ($\hbar = c = 1$) which is the expression of space-time length in terms of ratio of Compton wavelength of a particle.

- The quantum mechanical effects become relative to the quantum frame of reference. Moreover, quantum mechanical properties of particles is due to the effects of quantum space-time as analogous to gravity in general relativity.

Equivalence Principle of Quantum Gravity

- Based on the local scale invariance nature of the equivalence principle, physical measurements in quantum frame of reference of different energy scale should associated with scale changes.

- That is analogous to the space and time measurements in curved space-time in general relativity.

Cosmological Constant in Quantum Gravity

- As similar to general relativity, vacuum energy could exist in quantum space-time as cosmological constant but its value will depend on the energy scale of measurement. This is in fact the characteristics of the quantum space-time.

- Because of the said scale factor, the vacuum energy would be very large in one energy scale of measurements but very small in another. This could be the reason for the explanation of cosmological constant problem.

- Such factor acts like the projection factor as mentioned in our space-time condensate hypothesis for explaining the cosmological constant problem.

Cosmological Constant in Quantum Gravity

- Under the equivalence principle, the classical and quantum mechanical picture, or say deterministic and probabilistic picture, are both valid representation of the physical phenomena and could be transformed from each other by the quantum frame of reference.

- Under the equivalence principle, the theory of quantum gravity is background independent as there is no preferred frame of reference. And the classical picture for particles is a local equivalent representation of the quantum mechanical ones.

Summary

- The fundamental hypothesis that the space-time behaves as the phase of Higgs condensate and discrete in nature provides the explanation of the cosmological constant problem by the averaged vacuum energy density of the space-time condensate.
- It shows that the nature of cosmological constant would be fundamentally related to the quantum nature of space-time.
- The space-time condensate hypothesis is further explained by introducing the equivalence principle of quantum gravity and it leads to the local scale invariance symmetry of the theory.
- The property of the cosmological constant that it is very large in microscopic scale but very small in macroscopic scale is the characteristics of quantum space-time under the equivalence principle.

Summary

- Under the equivalence principle, the theory of quantum gravity is background independent and the classical picture for particles is a local equivalent representation of the quantum mechanical ones.

- The above results reveal that our approach is on the right track and is worth pursuing in that direction.