On Theoretical Models of Dark Energy*

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Abstract In this talk I divide dark energy models (precisely speaking, models to explain origin of current cosmic acceleration) existing in literatures in to three classes. The first one is to ascribe the cosmic acceleration to modifications of general relativity at cosmological scales. The second one is due to the backreaction of perturbations, or say, the effect of inhomogeneity of the universe. The third one is some exotic component in the universe, which appears in the right hand side of Einstein's equations. For each class I demonstrate some examples.

Key words cosmology, dark energy, accelerated expansion

1 Introduction

The dark energy[1] has been one of the most active fields in modern cosmology since the discovery of the present accelerated expansion of the universe. The first evidence of the current accelerated expansion comes from the measurement of distant supernova[2, 3]. The existence of dark energy has also been crosschecked from the microwave background radiation[4, 5] and large scale structure[6, 7], etc. In certain sense, nowadays most people have widely accepted such a "standard model" of the universe: inflation $\oplus$ big bang $\oplus$ baryon matter $\oplus$ dark matter $\oplus$ dark energy: In the early time (maybe Planck time) the universe underwent a period of accelerated expansion (inflation); the quantum fluctuations produced during that period are the seed of the large scale structure observed today. Following the inflation is the standard hot big bang model of the universe; the universe was reheated via the decay of the inflaton to radiation and then matter dominated in the universe. During the radiation and matter epoches, the universe underwent a decelerated expansion. When the universe was about half of the current age, it transited from the decelerated expansion to an accelerated expansion due to the dark energy. A lot of astronomical observations indicate that the universe is flat, and consists of 4% baryon matter, 23% dark matter, 72% dark energy and negligible radiation matters. The dark matters are clustered like the usual baryon matters. In contrary, the dark energy is supposed to be distributed smoothly.

The dark energy is introduced to the universe in order to explain the acceleration expansion of the universe. To do that, the dark energy has to have a large negative pressure according to the Einstein equations. If one uses the equation of state w, defined as $w=p/\rho$ with p and ρ being the pressure and energy density, respectively, to describe the dark energy, the w has to satisfy $w < -1/3$. It is interesting to note that it is not an easy job to find a suitable candidate for the dark energy since usual matters have not such a negative pressure. For example, for radiation matter, $w = 1/3$, while $w = 0$ for dust matter. In some sense, therefore the dark energy is best known as the putative agent of the cosmic acceleration.

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There exist a lot of papers to understand the nature of dark energy in the literatures. For reviews see[1]. The most simple candidate of dark energy is just the cosmological constant introduced by Einstein himself in 1917. However, the cosmological constant acting as the dark energy suffers from a serious theoretical problem. According to the quantum field theory, the cosmological constant is nothing, but the vacuum expectation value of some quantum fields in standard model of particle physics. By a naive estimation, the cosmological constant should be in the order of Planck scale $(10^{19}\text{GeV})^4$, while the dark energy is of the order $(10^{-3}\text{eV})^4$. That is, it is quite difficult to understand why the cosmological constant is about 123 orders of magnitude smaller than its naive expectation. Even there exists a TeV SUSY, there is still a difference of 60 orders of magnitude between them. This is the so-called cosmological constant problem. Another puzzle of dark energy is the cosmological coincidence problem. Namely, why does our universe begin the accelerated expansion recently? Why are we living in an epoch in which the dark energy density and dark matter density are comparable?

To distinguish different dark energy models, it is quite important to stress the equation of state of dark energy. If one has $w=-1$, it must be the cosmological constant. If $-1<w<0$, it can be regarded as quintessence-like model[8]. If $w<-1$, it belongs to phantom-like model[9]. And in particular, current observation data even do not exclude the models with the equation of state crossing the phantom divide $w=-1$. Such a model is dubbed quintom model[10]. Here we stress that from the viewpoint of quantum field theory, if some fields have $w<-1$, they suffer from the causality problem and instability problem. However, models with $w<-1$ might be effective ones, as we will see shortly. In that case, those problems do not appear.

To find the nature of dark energy, let us look at the necessity to introduce the dark energy. Starting from the observation data, to explain those observation data, one has to make some theoretical assumptions. For cosmology, one has two main assumptions here: one is that Einstein's general relativity still holds for the cosmological scales. The other is the cosmological principle which says that our universe is homogeneous and isotropic, which implies that our universe can be described by the Freidmann-Robertson-Walk metric. With these two assumptions, to explain the cosmic acceleration, one has to introduce some exotic dark energy component in the right hand side of the Einstein equations. According to the above chain, based on the our current experiments on the Newton law and our observations on the universe, it is conceivable to consider modifying gravity theory at the cosmological scales and to suspect the cosmological principle so that one still can explain the observational data without introducing the exotic component (dark energy). Namely the dark energy is some effective component in Einstein's general relativity.

Based on the above arguments, I classify the theoretical models of dark energy existing in the literatures to three classes:

Model Ⅰ $\longrightarrow$ modify general relativity at cosmological scales.

Model Ⅱ $\longrightarrow$ give up the cosmological principle.

Model Ⅲ $\longrightarrow$ different candidates appear on the right hand side of gravitational field equations. In this talk, based on this classification, I will show some examples belonging to these three models. These examples show that we are now still very far to figure out the nature of dark energy. Here I should apologize to those authors whose interesting and important papers are not mentioned because of the limit of space.

2 Model Ⅰ

As is well-known, Einstein's general relativity is quite successful to explain various observations from the motion of celestial bodies in the solar system to the gravitational phenomena of macroscopic bodies. Namely, the general relativity is checked to hold in the range from large scales like the solar system to small scales in the order of millimeter. In the UV scale, it is widely accepted that quantum effect will modify the behavior of Newton law. Therefore there is not a priori reason to believe that the general relativity is not modifiable at cosmological scales (IR scales). Indeed, we have witnessed a lot of modifications of general relativity from various perspectives. One of the well-known examples is the Brans-Dick scalar-tensor gravity theory, in which the gravitational constant is dynamical and its evolution is governed by a scalar field.

Here we will show some interesting examples of modifying general relativity, which have significant consequence for the dark energy problem.

(1) The first example is the one with a consistent infrared modification of gravity by ghost condensation[11]. In that paper, the authors propose a theoretically consistent modification of gravity in the infrared, which is compatible with all current experimental observations. This is an analog of the Higgs mechanism in general relativity, and can be thought of as arising from ghost condensation, a background where a scalar field ϕ has a constant velocity, $\langle\dot{\phi}\rangle = M^2$. The ghost condensation of a new kind of fluid that can fill the universe, which has the same equation of state, $p = -\rho$, as a cosmological constant, can drive de Sitter expansion of the universe. Unlike a cosmological constant, however, it is a physical fluid with a physical scalar excitation, which can be described by a systematic effective field theory at low energies. The excitation has an unusual low energy dispersion relation $\omega^2 \sim k^4/M^2$. The Newtonian potential is modified with an oscillatory behavior starting at the distance scale $M_{\rm pl}/M^2$ and the time scale $M_{\rm pl}^2/M^3$. For the details see[11] and papers citing that paper. In words, this model provides a consistent modification of gravity at IR scale by a ghost condensation, and the ghost condensation can act as a candidate of dark energy and drives the accelerated expansion of the universe.

(2) The second example we will consider is the so-called $1/R$ gravity[12], here R is the curvature scalar of goemtry. Usually it is expected that higher order derivative terms of gravity appear at high energies due to quantum gravity effect. Indeed there is a lot of work to study the effect of these higher derivative terms on the evolution of early universe, in particular, on the inflation. In the paper[12], the authors propose that the current accelerated expansion of the universe may be due to a term proportional to $1/R$. As a result, the effective action of gravity is

$$S = \frac{M_{\rm pl}^2}{2}\int {\rm d}^4x\sqrt{-g}\left(R - \frac{\mu^4}{R}\right), \qquad (1)$$

where μ is a constant with energy dimension. To fit the observation data, μ is in the order of current Hubble parameter. Clearly, when $R \gg \mu^4$, namely, in higher energies, this term has no significant effect and the Hilbert-Einstein term R dominates. Thus general relativity gets recovered. On the other hand, when these two terms in Eq. (1) are comparable, the gravity receives significant modification at low energies. To see the properties of the gravity, let us make a conformal transformation, which changes the gravity to the form of Einstein's general relativity with a minimal coupling scalar field ϕ with potential

$$V(\phi) = \mu^2 M_{\rm pl}^2 \frac{\sqrt{p-1}}{p^2}\ , \qquad (2)$$

where $p = \exp(\sqrt{2/3}\phi/M_{\rm pl})$. Obviously, in this frame, the solution of the theory could have three different behaviors: (i) Eternal de Sitter solution, but it is unstable because the potential Eq. (2) is concave from up to down; (ii) the scalar field could produce a power-law acceleration; and (iii) the solution will encounter a future singularity. These three different behaviors depend on the initial conditions of the scalar field.

However, it was argued that the $1/R$ gravity is not consistent with the solar system test. This conclusion was drawn based on the post-Newtonian expansion of Eq. (1) in its vacuum solution, de Sitter solution. In the paper[13], we propose that the theory Eq. (1) is just an effective one in low energies. For the solar system, the term $1/R$ is negligible, one should regard this term as a correction and make the post-Newtonian expansion in the Minkowskian background. In this way the conflict between $1/R$ gravity and solar system test can be avoided.

The $1/R$ gravity Eq. (1) can be generalized in several ways. For example, replacing $1/R$ by $1/R^n$ with $n > 0$. In particular, in the second reference in Ref. [12], the authors study a more general case with term $f(R,P,Q) = -\dfrac{\mu^{4n+2}}{(aR^2+bP+cQ)^n}$, where a,

b and c are three constants, while $P=R_{\mu\nu}R^{\mu\nu}$ and $Q=R_{\mu\nu\gamma\delta}R^{\mu\nu\gamma\delta}$.

(3) Gravity in the brane world scenario. Over the past years there has been a lot of interest on the so-called brane world scenarios, in which our universe is supposed to be a brane embedded in a higher dimensional spacetime, the matter fields of standard model of particle physics are confined on the brane, while gravity can proporgate in the whole spacetime. There are two popular pictures in the brane world scenario. One is the so-called RSII model[14], in which a 3-brane is embedded in a 5-dimensional AdS space. The other is called the DGP model[15], there a brane is embedded in 5-dimensional Minkowskian spacetime. The latter could have a close relation to the current cosmic acceleration. Therefore we here stressed the DGP model, whose action is

$$S=M^3\int d^5x\sqrt{-G}\ {}^{(5)}R+m^2\int d^4x\sqrt{-g}(R+\mathscr{L}_m)\ . \quad (3)$$

Note that here an intrinsic curvature scalar R appears on the brane, while this term is absent in the RSII model. In the DGP model, the corresponding Friedmann equation is

$$H^2\pm\frac{H}{r_c}=\frac{1}{6m^2}(\rho+\Lambda), \quad (4)$$

where $r_c=m^2/M^3$, Λ is the cosmological constant on the brane, and ρ is the matter density. Here the constant r_c is the scale labeling the competition between 5-dimensional gravity in the bulk and 4-dimensional gravity on the brane. To fit the observation data, it is in the order of current Hubble horizon. We see from the above equation that there are two branches. For the "+" branch, when $\Lambda=0$, the evolution of the universe is the decelerated expansion like the usual one. However, as $\Lambda>0$, one can rewrite Eq. (3) to get an effective dark energy density $\rho_{\rm eff}=\Lambda-6m^2H/r_c$. This quantity is increased with the evolution of the universe. Therefore the effective dark energy has the behavior of the phantom dark energy. For the "−" branch, we notice that even as $\Lambda=0$, the expansion of the universe is accelerated and approaches to a de Sitter universe with $H_c=1/r_c$. Therefore, this branch is of great interest and can drive the late-time accelerated expansion of the universe even without any dark energy component.

Combining the RSII model with DGP model leads the authors of Ref. [16] to consider the accelerated expansion without dark energy in a more general setting. In this model one can view the dark energy as a geometric effect. The action in Ref. [16] is

$$S=\varepsilon M^3\left(\int d^5x\sqrt{-G}({}^{(5)}R-2\Lambda_b)-2\int d^4x\sqrt{-g}K\right)+\int d^4x\sqrt{-g}(m^2R-2\sigma+\mathscr{L}_m)\ . \quad (5)$$

The generalized Friedmann equation is

$$m^4\left(H^2+\frac{\kappa}{a^2}-\frac{\rho+\sigma}{3m^2}\right)^2=M^6\left(H^2+\frac{\kappa}{a^2}-\frac{\Lambda_b}{6}-\frac{C}{a^4}\right). \quad (6)$$

Like the DGP model, there are two branches again. One is of the phantom behavior and the other quintessence behavior. For details, see Ref. [16].

However, we notice that it is impossible to cross the phantom divide for both branches in this model. In the paper[17], we find that adding a Gauss-Bonnet term to the bulk action, one can realize crossing the phantom divide. Further, we find that even in the RSII model, one can have the super-acceleration and crossing the phantom divide without phantom energy, by considering the energy exchange between brane and bulk[18].

There are a lot of possibilities to modify general relativity and to drive the cosmic acceleration without dark energy in the literatures. In this section we have just demonstrated a few examples to realize the possibility.

3 Model Ⅱ

As is well-known, the cosmological principle is one of the foundation stones of modern cosmology. Indeed it is consistent with the cosmic observation at the cosmological scales. On the other hand, it is also a fact that the universe is not quite homogenous and isotropic at small scales. In addition, inflation predicts that there exist super-horizon fluctuations. This is an interesting issue to see whether these super-Hubble-radius perturbations have a physically influence on local observations (e.g., the local expansion rate). In the first version of the preprint astrophy/0410541, the authors claim that these perturbations have a physical influences on the local observable if the universe is filled with more than one fluid or if isocurvature perturbations are present[19]. The backreaction of those perturbation will drive the cosmic accelerated expansion[20]. However, in the revised version of that preprint, the authors change their conclusion, and claim that the perturbations have no physical influence on the local observables if the cosmological perturbations are of the adiabatic type. In the paper[21], the authors further elaborate the effect of backreaction of perturbations on the local evolution of the universe. They argue that the observed acceleration of the Universe is the result of the backreaction of cosmological perturbations, rather than the effect of a negative-pressure dark-energy fluid or a modification of general relativity. Through the effective Friedmann equations describing an inhomogeneous Universe after smoothing, they demonstrate that acceleration in our local Hubble patch is possible even if fluid elements do not individually undergo accelerated expansion. This invalidates the no-go theorem that there can be no acceleration in our local Hubble patch if the Universe only contains irrotational dust. They then study perturbatively the time behavior of general-relativistic cosmological perturbations, applying, where possible, the renormalization group to regularize the dynamics. They show that an instability occurs in the perturbative expansion involving sub-Hubble modes. Whether this is an indication that acceleration in our Hubble patch originates from the backreaction of cosmological perturbations on observable scales requires a fully non-perturbative approach.

Although there exist some contentions in the literatures on whether the backreaction of perturbations can drive the accelerated expansion of the universe, it opens a new window to understand the origin of the cosmic accelerated expansion.

Another interesting model with inhomogeneous model universe without dark energy from primordial inflation is given in Ref. [22]. In that manuscript, the author proposes a new model of the observed universe, using solutions to the full Einstein equations, which is developed from the hypothesis that our observable universe is an underdense bubble, with an internally inhomogeneous fractal bubble distribution of bound matter systems, in a spatially flat bulk universe. It is argued on the basis of primordial inflation and resulting structure formation, that the clocks of the isotropic observers in average galaxies coincide with clocks defined by the true surfaces of matter homogeneity of the bulk universe, rather than the comoving clocks at average spatial positions in the underdense bubble geometry, which are in voids. This understanding requires a systematic reanalysis of all observed quantities in cosmology. The author begins such a reanalysis by giving a model of the average geometry of the universe, which depends on two measured parameters: the present matter density parameter, $\Omega_{\rm m}$, and the Hubble constant, H_0. The observable universe is not accelerating. Nonetheless, the inferred luminosity distances are larger than naively expected, in accordance with the evidence of distant type Ia supernovae. The predicted age of the universe is 15.3 ± 0.7Gyr. The expansion age is larger than in competing models, and may account for the observed structure formation at large redshifts.

At the end of this section, let us mention another model, inhomogeneous spacetimes as dark energy [23]. In that work, Tolman-Bondi inhomogeneous spacetimes are used as a cosmological model for type Ia supernova data. It is found that with certain parameter choices the model fits the data as well as the standard ΛCDM cosmology does.

4 Model Ⅲ

In this class model of dark energy, the dark energy appears as a source in the right hand side of Einstein equations

$$G_{\mu\nu}=8\pi G T_{\mu\nu}(\Lambda), \tag{7}$$

where we have put the cosmological constant Λ in the right hand side of the equations, the gravity is still the general relativity. A lot of candidates of dark energy in this class have been proposed so far. In this section we will mention some of them.

(1) The cosmological constant[1]. The cosmologi-

cal constant is the most simple candidate of dark energy, which has the equation of state, $w=-1$. The cosmological constant as dark energy fits the observation data very well. But as mentioned above, acting as dark energy, the cosmological constant suffers from serious theoretical difficulties: fine tuning problem and coincidence problem[1]. One possible variant is that the cosmological constant is not a constant, but time-dependent, even with some coupling with other components in the universe.

(2) Holographic dark energy[24]. Inspired by black hole physics, energy density of quantum fluctuations cannot be arbitrarily large, but is bounded by infrared cutoff L[24]. The total energy inside a scale L cannot be beyond the mass of black hole with the same scale as its horizon. As a result, the energy density has a relation to its infrared scale as

$$\rho_\Lambda = 3c^2 M_{\rm pl}^2 L^{-2} \ , \tag{8}$$

where c is a constant with order $O(1)$. Now the problem is how to take a suitable scale as the infrared cutoff. If one takes the current Hubble radius as the infrared scale L, the holographic energy density Eq. (8) indeed gives us the observed dark energy density. However, as noticed in Ref. [24] by Hsu, such a holographic energy has the evolution behavior of dust matter, and hence cannot drive the accelerated expansion of the universe. Taking the particle horizon of the universe as the infrared cutoff, the situation is similar. On the other hand, once the event horizon is taken as the cutoff, the holographic energy not only gives the current observed dark energy density, but also can drive the accelerated expansion of the universe, which is observed first by Li[24]. While this model also suffers from some theoretical issues (for example, the event horizon exists only for the universe with accelerated expansion), it has some significant consequences for modern cosmology.

(3) Quintessence[8]. Recalling the role of the inflaton in inflation model, it is quite natural to consider a slowly varying scalar field as the candidate of dark energy. In particular, there exist the so-called tracker solutions with special potentials, in which the evolution of the scalar field will forget its initial condition, in this way, the coincidence problem can be resolved. Two examples which are of the tracker behavior are: (i) $V\sim\phi^{-n}$; (ii) $V\sim\exp(M/\phi-1)$.

(4) K-essence[25]. Like the K-inflation, where inflation is driven by kinetic terms of some scalar field, essentially the K-essence is just some non-canonical scalar field, where higher order kinetic terms appear. These kinetic terms drive the accelerated expansion of the universe. Born-Infeld scalar field (like tachyon) belongs to this class of scalar field. With suitable choice of the pressure of the K-essence, the coincidence problem also can be resolved in this model.

(5) Chaplygin gas[26]. The chaplygin gas has the equation of state, $p=-A/\rho$, where A is a constant. Integrating the continuity equation, one has

$$\rho = (A + B/a^6)^{1/2} \ , \tag{9}$$

where B is another constant and a is the scale factor. We can see from the energy density that in early times, the Chapygin gas behaves like a dust matter, while a cosmological constant at late times. Therefore the model was proposed initially as a unified model of dark matter and dark energy. Later, this model has been generalized in various ways, for example, $p=-A/\rho^\alpha$ with $0<\alpha<1$, and even to the case that A depends on the scale factor.

(6) Phantom[9]. The unique feature of phantom is $w<-1$. In that case, the energy density will increase with the evolution of the universe. The universe will therefore end its life with a big rip. Because of $w<-1$, the phantom matter suffers from the instability and causality problems. To realize such a phantom model, an easy way is to change the sign of kinetic term for a scalar field, namely, a scalar field with a “wrong” sign kinetic term.

(7) Quintom[27]. As noticed above, the quintessence has always the equation of state, $-1<w<1$, while $w<-1$ for phantom. Combining a quintessence with a phantom, one can realize a dark energy model with crossing the phantom divide $w=-1$. Considering some symmetry between the quintessence and phantom, one can build the so-called hessence model, in which the fate of big rip can be avoided[28]. Also using the idea of hybrid inflation, one can construct

hybrid dark energy model[29], in which one can control the moment that the equation of state crosses the phantom divide.

(8) Chameleon[30]. Scalar field mediating the gravitational interaction suffers from serious constraints from the fifth force and equivalence principle. However, it is possible to build a model, in which the scalar field acts as dark energy, while the constraints from the fifth force and equivalent principle can be satisfied, by properly considering the scalar field coupling with baryon matter and/or dark matter. Such a scalar field is named chameleon since its effective mass depends on its surroundings. Generalizing this idea to K-essence, one has the K-chameleon model[31]. The K-chameleon model can provide a natural solution to the cosmological coincidence problem.

(9) Vector fields. Usually one does not consider the role of vector field in the evolution of the universe, since vector field is not consistent with the isotropy of the universe. However, in the paper[32], the author investigates the possibility that a vector field can be the origin of the present stage of cosmic acceleration. In order to avoid violations of isotropy, the vector has to be part of a "cosmic triad", that is, a set of three identical vectors pointing in mutually orthogonal spatial directions. A triad is indeed able to drive a stage of late accelerated expansion in the universe, and there exist tracking attractors that render cosmic evolution insensitive to initial conditions. However, as in most other models, the onset of cosmic acceleration is determined by a parameter that has to be tuned to reproduce current observations. The triad equation of state can be sufficiently close to minus one today, and for tachyonic models it might be even less than that. In the paper[33], the authors further study the vector-field dark energy model by considering the interaction between the vector fields and dark matter. In that model, crossing the phantom divide can be realized without the phantom field, and the first and second cosmological coincidence problems can be alleviated at the same time.

In summary, we have divided the dark energy models (or precisely specking, models to explain the origin of the current cosmic acceleration) into three classes. The first one is to ascribe the cosmic acceleration to modifications of general relativity at cosmological scales. The second one is due to the backreaction of perturbations, or say, the effect of inhomogeneity of the universe. The third one is some exotic component in the universe, which appears in the right hand side of Einstein's equations. For each class we have demonstrated some examples. We can conclude from those examples that we still have a long way to go before finding out the nature of dark energy.

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暗能量的理论模型*

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摘要 将现有文献中存在的暗能量模型(严格的说是指解释现在宇宙的加速膨胀模型)分为三类. 第一类是将宇宙加速归因为在宇宙尺度上广义相对论的修改; 第二类是由于宇宙微扰的反作用或宇宙非均匀性的作用; 第三类为宇宙中存在的一类奇异能量成分, 它出现在爱因斯坦方程的右边. 对每一类模型, 举了几个例子, 并给以一些评述.

关键词 宇宙学 暗能量 加速膨胀

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