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Holographic dark energy from fluid/gravity duality constraint by cosmological observations

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ABSTRACT

In this paper, we obtain a holographic model of dark energy using the fluid/gravity duality. This model will be dual to a higher dimensional Schwarzschild black hole, and we would use fluid/gravity duality to relate to the parameters of this black hole to such a cosmological model. We will also analyze the thermodynamics of such a solution, and discuss the stability model. Finally, we use cosmological data to constraint the parametric space of this dark energy model. Thus, we will use observational data to perform cosmography for this holographic model based on fluid/gravity duality.

1. Introduction

The holographic principle states that the number of degrees of freedom in a region of space area equal to the degrees of freedom on the boundary of that region of space [1,2]. The AdS/CFT correspondence is a concrete realization of the holographic principle, as it states that the string theory/supergravity on AdS spacetime is dual to the superconformal field theory on the boundary of that AdS spacetime [3–5]. An interesting part of the AdS/CFT correspondence is that it can establish a duality between weakly coupled theories and strongly coupled theories. Thus, it has been used to study different aspects of strongly coupled theories which describe the quark–gluon plasma (QGP) [6–8], and this duality between the QCD and AdS is called AdS/QCD correspondence [9,10]. This correspondence has been used to study the field theory dual to STU model as a theory which could describe such physical systems [11–13]. In fact, various properties of QGP have been studied using this duality with STU black hole [14–16]. The AdS/CFT correspondence has also been used to study condense matter systems, and this holographic description of the condensed matter systems is called the AdS/CMT correspondence [17–19]. In fact, certain deformations of the AdS backgrounds have been used to holographically analyze superfluid [20] and superconductor [21].

An interesting use of the AdS/CFT correspondence is that it can be used to holographically analyze the hydrodynamic description of strongly coupled conformal field theories [22]. This holographic description of the hydrodynamic description of strongly coupled conformal field theories is usually called the gauge/fluid duality. The fluid/gravity duality is important, as it is hoped that certain problems in the fluid mechanics such as the global regular solutions of the Navier–Stokes equations and turbulence phenomena could be analyzed holographically using this duality. This duality can also be used to analyze fluids dual to certain black hole solutions. In fact, it has been proposed that a five dimensional Schwarzschild black hole is dual to an interesting fluid mechanical system [23]. It has also been proposed that cosmological solution can be studied holographically using this duality [24].

The dark energy of the universe has also been studied holographically [25–29]. Holographic dark energy with massive neutrinos has also been studied and constraints using cosmological data from the Planck CMB lensing data, Planck CMB temperature data, the JLA supernova data, the baryon acoustic oscillation data, the cosmic shear data of weak lensing, the Hubble constant direct measurement, and the redshift space distortions data [30]. The interacting holographic dark energy models have been studied for various different interactions [31,32]. It was observed that the type of interaction terms is constraint by the cosmological data for these interacting holographic dark energy models. Recently, it is demonstrated that any covariant gravity maybe described via such holographic dark energy [33]. Thus, it is important and interesting to study models of dark energy based on the holographic principle.

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We would like to clarify the various ways in which holographic principle can be used to study such a system. The holographic principle can be used directly to the physical universe, as is done in most models of holographic dark energy [25–29]. It is also possible to consider systems which have the same degrees of freedom as an AdS spacetime, and then use the holographic description to study such field theoretical systems. This is the approach that has been used in condensed matter systems, where a specific condensed matter system is analyzed using holography because the degrees of freedom describing such a system are the same as the degrees of freedom of an AdS spacetime [34,35]. This is the approach we will use to analyze holographic dark energy using fluid/gravity duality. Thus, as dark energy can be analyzed as a fluid dynamical system [36–39], and a fluid dynamical system can be analyzed using its gravity dual [40,41], we will analyze the dark energy using its gravity dual. We would like to point out that the main motivation for this work is that just like condensed matter systems can be studied by analyzing their gravity duals [34,35], the dark energy can also be analyzed as a fluid mechanical system using its gravity dual. This is different from earlier works on holographic dark energy, where the holographic principle was directly applied to the physical universe.

So, in this paper, we first note that fluid/gravity duality can be used to analyze various different fluid mechanical systems, and this can be done by mapping the properties of those fluids to an AdS spacetime [40,41]. Then we observe that it is possible to model the dark energy using fluid mechanical systems [36–39]. So, we use the fluid/gravity duality to map such a fluid mechanical systems, which can describe dark energy, to an AdS solution. We observe that the gravity dual to such a fluid mechanical system is a higher dimensional AdS-Schwarzschild black hole. We would like to point out that the AdS-Schwarzschild black hole is only used to obtain the dynamics of the fluid mechanical system which is dual to it. However, after we obtain such a boundary description of a fluid, we use cosmography to fix the values of parameters in this system, so that it describes dark energy in our universe. Thus, in this paper, we will use fluid/gravity duality to study the fluid dynamical properties of dark energy. It would be interesting to extend this work further and analyze other cosmological phenomena using such an approach. This can be done by first analyzing such a cosmological phenomena using a fluid dynamical system, and then finding a suitable gravity dual to such a fluid dynamical system.

So, we use results fluid/gravity duality [41] to analyze a fluid dynamical model of dark energy using its gravitational dual. This paper is organized as follows. In Section 2, we review procedure of obtaining equation of state of a fluid using its gravity dual. In Section 3, we use the equation of state obtained in Section 2, to construct dark energy model. In Section 4, we study thermodynamics of this dark energy model. In Section 5, we use observational data to fix the parameters in this model. Finally in Section 6, we summarize our results in the conclusion. So, in this paper, we start from fluid/gravity duality, and construct a model of dark energy using holography dual to a AdS Schwarzschild black hole. Then we study the thermodynamics of this holographic dark energy model, and finally constraint the parameters in this model using observational data.

2. Fluid/gravity duality

In this section we will review the fluid/gravity duality. We first noted that at long-wavelengths, the effective dynamics of a continuum system can be described using fluid mechanics. Furthermore, according to fluid/gravity duality, this fluid mechanical system on the boundary of an AdS spacetime is dual to the bulk Einstein equations in the AdS spacetime [40]. So, such a fluid mechanical system can be described by an asymptotically AdS spacetime given by the following line element,

$$ds^2 = \frac{L^2}{r^2}\left(-f(r)dt^2 + \frac{dr^2}{f(r)} + dX^2\right), \tag{2.1}$$

where L is the constant AdS radius, and

$$dX^2 = dx_1^2 + dx_2^2 + dx_3^2, \tag{2.2}$$

is the three dimensional metric of the flat space. If we consider the five dimensional AdS Schwarzschild black hole with the event horizon radius r_h, then,

$$f(r) = 1 - \frac{r^4}{r_h^4}. \tag{2.3}$$

The action governed our model given as,

$$S = \frac{1}{2\kappa}\int d^5x\sqrt{-g}(R - 2\Lambda) + S_Q + S_M, \tag{2.4}$$

where $\kappa = 8\pi G$, while S_Q and S_M are boundary actions corresponding to Neumann and Dirichlet boundary conditions respectively. It is indeed the FRW universe embedded in the five dimensional AdS Schwarzschild spacetime, and the properties of the fluid can be holographically obtained from the bulk [42]. We will obtain an induced metric, which resembles the FRW metric on a brane. Now we consider $u = \frac{1}{r}$, and change the variable, so that the coordinates u. Then, one can choose time parameter as τ, with the following condition,

$$\frac{1}{h(u)}\left(\frac{du}{d\tau}\right)^2 - h(u)\left(\frac{dt}{d\tau}\right)^2 = -1, \tag{2.5}$$

where $h(u)$ is given by

$$h(u) = L^2u^2f(u), \tag{2.6}$$

and $f(u)$ is given by

$$f(u) = 1 - \frac{u_h^4}{u^4}. \tag{2.7}$$

So, the induced metric takes the form of a standard FRW metric,

$$ds_4^2 = -d\tau^2 + u^2(\tau)d\Omega_3^2. \tag{2.8}$$

It should be noted that the size of the four dimensional universe is specified by the radial distance, u, from the black hole center.

We can now analyze kinematic properties of the fluid using this fluid/gravity duality. So, we can use the fluid/gravity duality [43,44] to obtain the equation of motion for this system

$$\begin{aligned} 0 = {} & \frac{\partial}{\partial r}\left(\frac{f(r)}{r^2}\frac{y'(r)}{\sqrt{L^4\left(1 - \frac{\dot{y}(r)^2}{r^2f(r)} + \frac{f(r)}{r^2}y'(r)^2\right)}}\right) \\ & + \frac{1}{r^4f(r)}\frac{\partial}{\partial t}\left(\frac{\dot{y}(r)}{\sqrt{L^4\left(1 - \frac{\dot{y}(r)^2}{r^2f(r)} + \frac{f(r)}{r^2}y'(r)^2\right)}}\right). \end{aligned} \tag{2.9}$$

As from the time independent profile, we have $\dot{y}(r) = 0$, so equation of motion can be expressed as

$$\frac{\partial}{\partial r}\left(\frac{f(r)}{L^2r^2}\frac{y'(r)}{\sqrt{1 + \frac{f(r)}{r^2}y'(r)^2}}\right) = 0. \tag{2.10}$$

The stress–energy tensor for this system can be written as [45,46],

$$T_{ab} = -\frac{L^3}{\kappa r^3}\left(K_{ab} - Kh_{ab} + \Sigma h_{ab} - \kappa T_{ab}^{(R)} - \kappa T_{ab}^{(ct)}\right), \tag{2.11}$$