Superstrings and cosmological dark energy

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Abstract

Results of study of a superstring model for the cosmological dark energy are presented. In this model the Universe is considered as an unstable brane. We use the Cubic String Field Theory to describe the unstable brane decay. The dynamics of the brane is accumulated in the dynamics of the string tachyon and the acceleration of the Universe is driven by a nonlocal stringy Higgs mechanism. This model exhibits a phantom behaviour at early time as well as a crossing of the $w = -1$ barrier at later time.

1 Introduction

The accelerated expansion of the Universe confirmed by several independent observations [1]-[5] indicates that the present day the Universe is dominated by a smoothly distributed slowly varying Dark Energy (DE). The DE occupies about 73% of the total energy of our Universe. The nature of the DE is one of the outstanding physical problems of 21st century. There are ambitious observation programs to determine the DE properties [6, 7].

Two important characteristics of the DE are the energy density ε and the state parameter w. They parameterize the space isotropic and homogeneous DE energy-momentum density tensor

$$T_\mu^\nu = \delta_\mu^\nu \varepsilon_\mu, \quad \text{(no summation on } \mu), \quad \varepsilon_0 = \varepsilon, \qquad \varepsilon_1 = \varepsilon_2 = \varepsilon_3 = w\varepsilon. \tag{1}$$

ε and w are time dependent quantities. At present ε is a very small quantity,

$$\varepsilon \simeq 10^{-47} GeV^4. \tag{2}$$

Recent results of WMAP [8] together with Ia supernovae data give a strong support that the present time dark energy state parameter w is close to -1:

$$w = -0.97^{+0.07}_{-0.09}. \tag{3}$$

or without an a priori assumption that the Universe is flat and together with large-scale structure and supernovae data $w = -1.06^{+0.13}_{-0.08}$.

A theoretical problem is to propose a model that can explain why ε is so small, (2), and why w is close to -1. From a theoretical point of view the domain (3) of w covers three essentially different cases:

- $w > -1$,
- $w = -1$,
- $w < -1$

The first case is achieved in quintessence models [9, 10]. The second one correspond to the cosmological constant [12, 13]. The third case is called a "phantom" one[14] since a simple way to realize this case is given by a scalar field with a ghost (phantom) kinetic term.

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The problems related with these three cases are the following:

- In the first case, quintessence models have to contain an extra light scalar field which is not in the Standard Model set of fields[11].
- To realized the second case from fundamental principles one has to find general arguments to add the cosmological term to an action and to have a mechanism explaining why the cosmological constant is so small.
- In the case $w < -1$ all natural energy conditions are violated and there are problems of an instability at classical and quantum levels [14, 15].

In this talk we will discuss the third case. Let us note, that experimental data do not contradict to $w < -1$. By this reason a study of such models attracts a lot of attention and some of these attempts are presented at this conference. Note that a direct search strategy to test inequality $w < -1$ has been proposed [16]. A time dependence of w is discussed in [17].

A possible way to evade the instability problem for models with $w < -1$ is to yield a phantom model as an effective one arising in some period of evolution from a more fundamental theory without a problem with stability. In this talk we present results of study of a cosmological SFT tachyon model where this possibility is realized [20, 21, 22, 23, 24].

In this model we consider our Universe as a D3-brane embedding in 10-dimensional space time. D3-brane is a non-BPS D-brane and 6 extra-dimensions are supposed to be small (see [25] and refs therein for others brane-world scenarios). We describe this D3-brane dynamics by the string field GSO$-$ tachyon field.

The dynamics of the string field tachyon is non-local. Non-locality is a special property of the string theory and it is related with a form of string vertex operators and Veneziano amplitudes[27] that are originated by dispersion sum relations[26] and duality. It is turn out that this non-locality produces a non-standard behavior of the tachyon [30] and it can be effectively described by an cosmic fluid with an equation of state parameter $w < -1$. Note, that there are general arguments [28] that there does not exist a local scalar field model for a phantom Universe without an UV pathology. In a recent paper [29] it has been proposed a phantom model without UV pathology in which a vector field is used.

We also assume a minimal coupling of gravity with the open string tachyon. The D3-brane tension as well as the vacuum energy of the tachyon in the true vacuum contribute to the cosmological constant in 4-dimensional space time. We find the value of cosmological constant in terms of parameters of the theory from a requirement of an existence a rolling tachyon solution. To provide the smallness of the cosmological constant we have to make special assumptions on the parameter of theory. We argue that an assumption that the scale of compactification M_{Pl}^{-1} is much small that the string length scale M_s^{-1} is enough to have a small later cosmological constant. To get a realistic order of the magnitude for the current Hubble parameter we assume that $M_s \sim 10^{-6.6} M_{Pl}$.

2 Model

2.1 Action

Our model is given by the following action [20]

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{2\kappa^2} + \frac{1}{\lambda_4^2}\left(-\frac{\xi^2\alpha'}{2}g^{\mu\nu}\partial_\mu\phi(x)\partial_\nu\phi(x) + \frac{1}{2}\phi^2(x) - \frac{1}{4}\Phi^4(x) - T\right)\right), \qquad (4)$$

$g_{\mu\nu}$ is the metric, κ is a gravitational coupling constant, λ_4^2 is a 4-dimensional coupling constant related with parameters of the initial 10-dimensional theory (see formula (5) below), ϕ is a tachyon field, Φ is a field related with the tachyon field ϕ (see formula (6) below), T is a tension of the D3-brane and $\xi^2 \approx 0.9556$ is a constant dictated by a string field interaction.

Let us make few comments about the action (4).

- The action (4) is a minimal generalization to a non-flat case of the GSO- string field tachyon action [30] that describes approximately a non-BPS D3-brane embedded in the flat 10-dimensional space time.
- We describe non-BPS D3-brane dynamics by the fermionic Neveu-Schwarz-Ramon (NSR) string ended on the brane[31, 32]. This string has a tachyon in the Gliozzi-Olive-Scherk (GSO)$-$ sector[27].
- We use the cubic String Field Theory (SFT) to describe dynamics of NSR string[33].
- Following the Sen conjecture that the open string tachyon incorporates essential features of D-brane dynamics [34] in flat space-time we do believe that this is also true for smooth non-flat background and a dynamical transition of a non-BPS D-brane from unstable vacuum to a stable vacuum (see [35] for review) can be described by an evolution of the open string tachyon from a perturbative vacuum to the true non-perturbative one.
- The action (4) is obtained just via dimensional reduction of the 10-dimensional tachyon action. Therefore, 4-dimensional coupling constant λ_4 is related with the open string dimensionless coupling constant g_o via the following formula,

$$\frac{1}{\lambda_4^2} = \frac{v_6 M_s^4}{g_o}(\frac{M_s}{M_c})^6 \tag{5}$$

  here M_s is a characteristic string scale $M_s = 1/\sqrt{\alpha'}$, related with the string tension α', M_c is a characteristic scale of the compactification, v_6 is a dimensionless volume of the 6-dimensional compact space.
- The action (4) in the flat case has been obtain within a level truncation approximation from cubic Superstring Field Theory, more precisely from the fermionic NSR cubic String Field Theory including the GSO$-$ sector[32]. This level truncation method in some sense is an analog of the Tamm-Dankoff method.
- Due to a nonlocal character of the string interaction we have a very special form-factor and the interaction in (4) depends on the non-local field

$$\Phi = e^{\frac{\alpha'}{8}\Box_g}\phi, \tag{6}$$

  where

$$\Box_g = \frac{1}{\sqrt{-g}}\partial_\mu\sqrt{-g}g^{\mu\nu}\partial_\nu,$$

- We find T from an requirement of an existence a rolling tachyon solution. According the second Sen conjecture in the flat space time the sum of the D3-brane tension and the vacuum energy of the tachyon in the true vacuum is equal zero (this has been check for the bosonic string in [36] and for the NSR fermionic string in [31, 32]). In a non-flat space we modified this conjecture by a requirement that this sum in the Friedmann space-time should be such to admit a rolling tachyon solution[20]. This permits to find the value of cosmological constant from parameters of the theory.
- To provide the smallness of the cosmological constant we assume that the scale of compactification M_{Pl}^{-1} is much small that string length scale M_s^{-1}, namely $M_s \sim 10^{-6.6} M_{Pl}$.

2.2 Equation of Motion

Varying the action (4) on the metric and the tachyon field we get the system of equations. In the spatially flat FRW metric with a scale factor $a(t)$

$$ds^2 = -\,dt^2 + a^2(t)\left(dx_1^2 + dx_2^2 + dx_3^2\right).$$

and the space homogenous tachyon field we get the Friedmann equations with non-local right hand side and non-local equation for the tachyon field. The Friedmann equations in terms of a dimensionless time $t \to t\sqrt{\alpha'}$ have the form [20]

$$\begin{aligned} 3H^2 &= \frac{\kappa^2}{\lambda_4^2}\left(\frac{\xi^2}{2}\dot\phi^2 - \frac{1}{2}\phi^2 + \frac{1}{4}\Phi^4 + \mathcal{E}_1 + \mathcal{E}_2 + T\right), && (7)\\ \dot H &= \frac{\kappa^2}{\lambda_4^2}\left(-\frac{\xi^2}{2}\dot\phi^2 - \mathcal{E}_2\right) && (8)\end{aligned}$$

where

$$\begin{aligned} \mathcal{E}_1 &= -\frac{1}{8}\int_0^1 ds(e^{\frac{1}{8}s\mathcal{D}}\Phi^3)\mathcal{D}e^{-\frac{1}{8}s\mathcal{D}}\Phi, && (9)\\ \mathcal{E}_2 &= -\frac{1}{8}\int_0^1 ds(\partial_t e^{\frac{1}{8}s\mathcal{D}}\Phi^3)\partial_t e^{-\frac{1}{8}s\mathcal{D}}\Phi && (10)\end{aligned}$$

and

$$\Phi = e^{\frac{1}{8}\mathcal{D}}\phi, \quad \mathcal{D} = -\partial_t^2 - 3H(t)\partial_t.$$

$H \equiv \dot a/a$ is the Hubble parameter and the dot denotes the time derivative.

The equation of motion for the tachyon is

$$\left(\xi^2\mathcal{D} + 1\right)e^{-\frac{1}{4}\mathcal{D}}\Phi = \Phi^3. \qquad (11)$$

A similar equation appears for a model originated from the bosonic string [37].

Equations (7)-(11) are complicated because of the presence of an infinite number of derivatives and a non-flat metric.

Let us make few comments about the form of the Friedmann equations (7), (8). The form of these equations indicates that the non-local terms $\mathcal{E}_1$ and $\mathcal{E}_2$ play the role of extra potential and kinetic terms respectively. If it turns out that during an evolution $\mathcal{E}_2$ became negative and moreover compensates the positive usual kinetic term $-\frac{\xi^2}{2}\dot\phi^2$ then one can says that in this period of evolution we have an effective phantom behaviour.

3 Rolling Tachyon in the flat background

Equation of motion (11) in the flat background is

$$\left(-\xi^2\partial_t^2 + 1\right)e^{\frac{1}{4}\partial_t^2}\Phi(t) = \Phi(t)^3. \qquad (12)$$

Note that in the flat case Φ is related with the original tachyon field ϕ as

$$\Phi = e^{-\frac{1}{8}\partial_t^2}\phi.$$

Equation (12) and analogous equations for a cubic bosonic string action have been studied in [38, 39, 40, 41, 42].

Ignoring the factor $e^{-\frac{1}{8}\partial_t^2}$ in the R.H.S. of (12) one gets the equation for a homogeneous scalar field in the usual Higgs potential. The Higgs potential has two minima located at

$$\Phi_0 = \pm 1.$$

The operator $e^{s\partial_t^2}$ on smooth functions for positive s can be rewritten in an integral form and this allows to rewrite this equation as

$$\mathcal{C}\Phi(t) = \Phi(t)^3 \tag{13}$$

where

$$\mathcal{C}\Phi(t) = \int dt' C(t-t')\Phi(t') \tag{14}$$

and

$$C(t) = \frac{\xi^2(1-4t^2)+1}{\sqrt{\pi}} e^{-t^2} \tag{15}$$

A numeric solution of the boundary problem

$$\mathcal{C}\Phi(t) = \Phi(t)^3, \qquad \Phi(\pm\infty) = \pm 1 \tag{16}$$

has been found in [39] using an iteration procedure. On Fig. 1 A. we present this solution (it is valid for $\xi^2 < \xi_{\rm cr} \approx 1.38$).

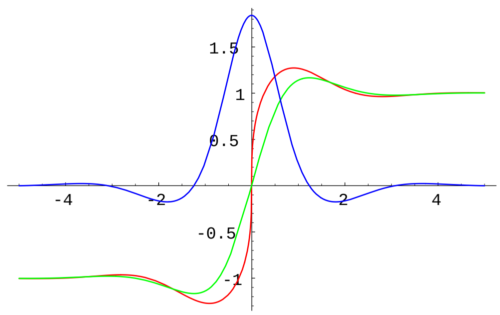

Figure 1: Numerical solution Φ to the boundary problem (16) (a line tangent to a vertical line at the zero time) and the corresponding smoothed field ϕ (a line interpolating between ± 1 and having a finite velocity at zero time) and its velocity $\dot{\phi}$ (a line with a maximum at zero)

For $\xi^2 = 0$ the tachyon field ϕ starts from $t = 0$ with a non-zero velocity, rolls down to the minimum of the tachyon potential and eventually stops in the minimum. For $\xi^2 \neq 0$ and $\xi^2 < \xi_{\rm cr}^2$ there are damping fluctuations near the minimum of the potental (for $\xi = 0$ there are no fluctuations).

Let us remind behavior of the energy and the pressure for this solution[30]. As has been mentioned in Sect.2 the non-local energy $\mathcal{E}_2$ plays the role of an extra kinetic term. It is instructive to write $\mathcal{E}_2$ in the form

$$\mathcal{E}_2 = -\mathcal{K}[\Phi]\frac{\dot{\phi}^2}{2}. \tag{17}$$

When

$$\mathcal{K}[\Phi] > \xi^2$$

the model has a ghost like total kinetic term.

Numerical calculations show that for $q^2 = 0$ the values of $\mathcal{K}[\Phi]$ are always positive, see Fig.2.A. Therefore the model has phantom behaviour during all time of evolution. But for the case $\xi^2 = 0.96$ (string case) the model has phantom behaviour only during some periods of the evolution. The effective kinetic energy $\frac{q^2}{2}\dot{\phi}^2 + \mathcal{E}_2$ for this solution is presented on Fig.2.B. We see that the model for small time has phantom behavior but it has not the phantom behaviour always. This change occurs when Φ is closed to ± 1 and here one can use the linear approximation for a detail study of dynamics of the model[24].

The main conclusion from these examples is that non-local operator $e^{\partial_t^2}$ changes drastically the evolution of the system. Without the usual kinetic term in the L.H.S. of equation (12) the

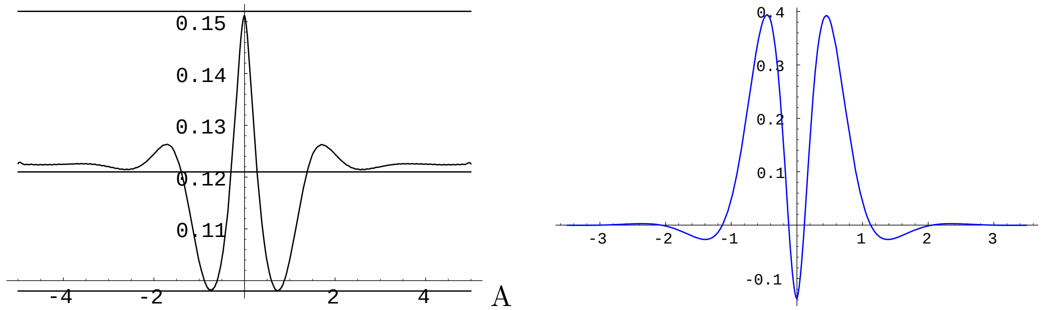

Figure 2: A.$\mathcal{K}[\Phi](t)$ for $q^2 = 0$; B. The effective kinetic energy $\mathcal{E}_2 + \frac{q^2}{2}\dot{\phi}^2$ for $q^2 = 0.96$

late time behavior of the tachyon is just stopping with monotonically decreasing velocity in the minimum of the potential. This is a property of a phantom and the above analysis justifies the phantom approximation used in [20, 21]. The usual kinetic term in the L.H.S. of equation (12) accelerates the field but for actual ξ^2 the phantom character reveals and the tachyon eventually stops in the minimum.

4 Rolling Tachyon in the FRW Universe

The above consideration indicates that in the non-flat case one can use two approximations: a phantom approximation and a linearization. It is natural to expect that the first one works for a small time and the second for a later time. For the rolling in the flat case the value of T is note essential, but from the Sen conjecture it is equal to $1/4$ (this corresponds to zero cosmological constant in the non-perturbative vacuum $\phi = \pm 1$). In the non-flat case the D3-brane tension should be shifted[20] to be $T = 1/4 + \Lambda$ and Λ is found from the requirement of an existence of a rolling solution. To make this proposal more transparent it is worth to consider a model with dynamical Λ such that it does not disturb the form of the Higgs potential. Such model has been proposed in [21], see also [22].

4.1 Phantom Approximation

In the phantom approximation we have

$$\dot{H} = \frac{1}{2m_p^2}\dot{\phi}^2, \qquad 3H^2 = \frac{1}{m_p^2}\left(-\frac{1}{2}\dot{\phi}^2 + V(\phi)\right). \tag{18}$$

where $m_p^2 = \lambda_4^2 M_s^2/\kappa^2$ and we make a rescaling of time $t \to t\sqrt{[< K(\phi) > -\xi^2]}$, $< K(\phi) >$ is an average of $K(\phi)$ at a first stage of evolution. For a special potential [21]

$$V(\phi) = \frac{1}{2}(1-\phi^2)^2 + \frac{1}{12m_p^2}\phi^2(3-\phi^2)^2$$

the solution to (18) is

$$\phi(t) = \tanh(t), \qquad H = \frac{1}{2m_p^2}(\phi - \frac{1}{3}\phi^3). \tag{19}$$

For this model

$$H_0 \approx H(\infty) = 1/3m_p^2.$$

Assuming that M_c and M_s are two different parameters and ignoring all factors of order 1, as well as the coupling constant and v_6 we get for the Hubble parameter in the real time

$$H_0 \sim M_s/m_p^2 \sim M_s\frac{M_s^2}{M_p^2}(\frac{M_s}{M_c})^6.$$

Assuming that $M_c \sim M_p$ we get

$$H_0 \sim M_p(\frac{M_s}{M_p})^9.$$

An assumption

$$M_s \sim 10^{-6.6} M_p$$

gives

$$H \sim 10^{-60} M_p.$$

4.2 A Late time Linearization

The linearization $\phi = 1 + \psi$ of (11) has the form

$$3H^2 = \frac{\kappa^2}{\lambda_4^2}\left(\frac{\xi^2}{2}\dot{\psi}^2 - \frac{1}{2}\psi^2 + \frac{3}{2}\Psi^2 + \mathcal{E}_1 + \mathcal{E}_2 + T\right), \quad (20)$$

$$\dot{H} = \frac{\kappa^2}{\lambda_4^2}\left(-\frac{\xi^2}{2}\dot{\psi}^2 - \mathcal{E}_2\right) \quad (21)$$

where

$$\mathcal{E}_1 = -\frac{3}{8}\int_0^1 ds e^{\frac{1}{8}s\mathcal{D}}\Psi \mathcal{D} e^{-\frac{1}{8}s\mathcal{D}}\Psi,$$

$$\mathcal{E}_2 = -\frac{3}{8}\int_0^1 ds \partial_t e^{\frac{1}{8}s\mathcal{D}}\Psi \partial_t e^{-\frac{1}{8}s\mathcal{D}}\Psi$$

and $T = -\frac{1}{4} + \Lambda_0$. The equation of motion for ψ (11) is

$$(\xi^2\mathcal{D} + 1)e^{-\frac{1}{4}\mathcal{D}}\Psi = 3\Psi. \quad (22)$$

Assuming that

$$H \approx H_0 = \frac{\kappa}{\lambda_4}\sqrt{\frac{\Lambda_0}{3}}$$

and keeping only the the decreasing solution we get

$$\Psi = Ae^{-\bar{r}t}\sin(\bar{\nu}t + \bar{\varphi})$$

where

$$\bar{r} + i\bar{\nu} = \frac{3}{2}H_0 + \sqrt{\frac{9H_0^2}{4} + m^2},$$

$$m = r + i\nu, \quad r \approx 1.1365, \ \nu \approx 1.7051$$

and corrections to the Hubble parameter is

$$H = \frac{\kappa}{\lambda_4}\sqrt{\frac{\Lambda_0}{3}} - \frac{\kappa^2}{g_o^2}C_H e^{-2\bar{r}t}\sin(2\bar{\nu}t + \varphi_H),$$

see [24] for more details.

I am grateful to L.V. Joukovskaya, A.S. Koshelev, S.Yu. Vernov and I.V. Volovich for collaboration and useful discussions. The work is supported in part by RFBR grant 05-01-00758, INTAS grant 03-51-6346 and Russian President's grant NSh-2052.2003.1.

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[6] Future Supernova programs:

Ground based projects:

SNLS/ESSENCE (The Supernova Legacy Survey), http://www.cfht.hawaii.edu/SNLS/

The Pan-STARRS Large Survey Telescope Project, http://www.aas.org/publications/baas/v37n3/dps2005/801.htm

LSST(Large Synoptic Survey Telescope): Precision Studies of Dark Energy with LSST, astro-ph/0609516

Space projects:

SNAP (Supernova Acceleration Probe): *Seeing the nature of the accelerating physics: It's a SNAP*, astro-ph/0507458

JDEM (Joint Dark Energy Mission): *Destiny: A Candidate Architecture for the Joint Dark Energy Mission*, astro-ph/0608413

DUNE (Dark Universe Explorer), astro-ph/0610062

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