ภาคผนวก ก

ผลผลิตจากโครงการ

ก.1 การตีพิมพ์เผยแพร่ในวารสารวิชาการระดับนานาชาติ

ผลผลิตจากโครงการคาดว่าจะได้รับการตีพิมพ์ในวารสารวิชาการระดับนานาชาติจำนวน 1 บทความ ในต้นปี 2555 คือ

- Burin Gumjudpai (IF, Naresuan University) and John Ward (University of Victoria, Canada) "DBI Chameleon" to be submitted to Physics Letters B, Impact Factor: 5.255 (2010)

โดยจะดำเนินการแจ้งให้ วช. ทราบทันทีที่ผลงานได้รับการตอบรับตีพิมพ์

ก.2 ผลลัพย์อื่นๆที่เกิดขึ้นจากการดำเนินโครงการ

ก.2.1 การสร้างนักวิจัยใหม่

โครงการนี้เกี่ยวข้องกับการสนับสนุนค่าครองชีพในการช่วยทำงานวิจัยของนิสิตปริญญาโท 1 คน และปริญญาตรี 1 คน

ก.2.2 การพัฒนาการเรียนการสอน

การดำเนินกิจกรรมวิจัยในโครงการนี้ได้ยกระดับเนื้อหาการสอนวิชาทฤษฎีสัมพัทธภาพทั่วไประดับปริญญาโทของนิสิตให้เข้าสู่ระดับสากล โดยเฉพาะอย่างวิชาการคำนวณสมการสนามของสนามสเกลาร์จากแอกชันแบบสัมพัทธภาพสี่มิติ ซึ่งเป็นการคำนวณที่มีรายละเอียดปลีกย่อยมากมายหลายส่วนของการคำนวณในกรณีที่ง่ายกว่าในโครงการนี้ได้กลายเป็นแบบฝึกหัดและการบ้านให้นิสิตปริญญาโทได้เรียนรู้และทดลองทำจริง และยกระดับความเข้มข้นของเนื้อหาวิชาในรายวิชาทฤษฎีสัมพัทธภาพทั่วไป

ก.2.3 การสร้างกลุ่มวิจัย

การดำเนินกิจกรรมในโครงการนี้และโครงการอื่นๆจากแหล่งทุนอื่นๆ ส่งผลทางอ้อมให้เกิดการพัฒนาหน่วยวิจัยของสถาบันสำนักเรียนท่าโพธิ์ฯ ภายในภาควิชาฟิสิกส์ให้เติบโตขึ้นในแง่ของเครือข่ายความร่วมมือ จนกระทั่งการดำเนินงานของสถาบันสำนักเรียนท่าโพธิ์ฯได้รับการเสนอต่อมหาวิทยาลัยนเรศวรให้แยกส่วนงานออกเป็นคณะวิชาเอกเทศคือเป็นวิทยาลัยเพื่อการค้นคว้าระดับรากฐานเมื่อวันที่ 14 มีนาคม 2554

ก.2.4 การเสนอผลงานในที่ประชุมวิชาการและการบรรยายสัมมนาภายนอก

ผลการสนับสนุนไม่ว่าโดยทางตรงหรือทางอ้อมจากโครงการนี้ ได้ทำให้หัวหน้าโครงการวิจัยนี้ได้รับเชิญบรรยายพิเศษ ให้สัมมนารับเชิญภายนอก และได้ไปนำเสนอผลงานแบบบรรยายในโอกาสต่างๆ 14 ครั้งดังนี้

- **1.** 10 สิงหาคม 2011 (16.00 น.) ทรรศนะเชิงฟิสิกส์กับวิทยาศาสตร์สังคม
  บุรินทร์ กำจัดภัย
  การบรรยายพิเศษ (2 ชั่วโมง) ณ วิทยาลัยนานาชาติ จัดโดย วิทยาลัยเพื่อการค้นคว้าระดับรากฐาน มหาวิทยาลัยนเรศวร

- **2.** 5 สิงหาคม 2011 (9.00 น.) การเสวนาโดยผู้ประสบความสำเร็จทางการวิจัย
  บุรินทร์ กำจัดภัย
  การเสวนาในวงเสวนาผู้ประสบความสำเร็จทางการวิจัย (2 ชั่วโมง) ณ อาคาร CITCOMS จัดโดย บัณฑิตวิทยาลัย มหาวิทยาลัยนเรศวร

- **3.** 22 กรกฎาคม 2011 (15.00 น.) ฟิสิกส์และความโน้มถ่วง
  บุรินทร์ กำจัดภัย
  การบรรยายพิเศษ (2 ชั่วโมง) ณ คณะวิทยาศาสตร์ มหาวิทยาลัยพะเยา

- **4.** 9 มีนาคม 2011 (13.00 น.) Space & Time
  บุรินทร์ กำจัดภัย
  การเสวนารับเชิญ (1 ชั่วโมง) ณ กองบริหารการวิจัย มหาวิทยาลัยนเรศวร

- **5.** 25 มกราคม 2011 (8.30 - 16.30 น.) การสร้างผลงานวิจัยเพื่อให้สามารถเผยแพร่ได้ในระดับนานาชาติ: เล่าจากประสบการณ์ตรง
  บุรินทร์ กำจัดภัย

การบรรยายรับเชิญ (7 ชั่วโมง) ณ ห้องประชุมสีชมพู อาคารเฉลิมพระเกียรติราชสมบัติ ครบ 60 ปี มหาวิทยาลัยราชภัฏเพชรบูรณ์ พิธีเปิดโดยอธิการบดีมหาวิทยาลัยราชภัฏเพชรบูรณ์

- **6.** 4-5 ธันวาคม 2010 โครงสร้างเชิงทฤษฎีสำหรับฟิสิกส์ขั้นต้น

  บุรินทร์ กำจัดภัย

  การสอนภาคบรรยายรับเชิญ (12 ชั่วโมง) ที่โรงเรียนแม่จันวิทยาคม อ. แม่จัน จ. เชียงราย

- **7.** 11 ตุลาคม 2010 The First CERN School Thailand - Lecture on Cosmology

  บุรินทร์ กำจัดภัย

  การสอนภาคบรรยายรับเชิญเป็นภาษาอังกฤษ (1.5 ชั่วโมง) ที่ the 1st CERN School Thailand 2010 (4-13 ตุลาคม 2010) ที่ภาควิชาฟิสิกส์ จุฬาลงกรณ์มหาวิทยาลัย

- **8.** 30 กรกฎาคม 2010 Dark Energy-Single Scalar Field in NLS formulation

  บุรินทร์ กำจัดภัย

  การบรรยายพิเศษรับเชิญแบบ Plenary talk (อัดเทป) เป็นภาษาอังกฤษ (25 นาที) ที่การประชุมวิชาการนเรศวรวิจัยครั้งที่ 6มหาวิทยาลัยนเรศวร

- **9.** 7 กรกฎาคม 2010 ภูมิศาสตร์ของวิชาฟิสิกส์

  บุรินทร์ กำจัดภัย

  การบรรยายพิเศษรับเชิญ (3 ชั่วโมง) ที่โปรแกรมวิชาฟิสิกส์ มหาวิทยาลัยราชภัฏพิบูลสงคราม

- **10.** 1 พฤษภาคม 2010 กำเนิดเอกภพ

  บุรินทร์ กำจัดภัย

  การบรรยายพิเศษ (3 ชั่วโมง) ที่การอบรมครูวิทยาศาสตร์ "ความก้าวหน้าด้านวิทยาศาสตร์

และเทคโนโลยี" (Frontier Science and Technology) จัดโดย สวทช และมหาวิทยาลัยเทคโนโลยีสุรนารี พิธีเปิดโดย รัฐมนตรีกระทรวงวิทยาศาสตร์และเทคโนโลยี คุณหญิงกัลยา โสภณพานิช ที่ สุรสัมมนาคาร มหาวิทยาลัยเทคโนโลยีสุรนารี

- **11.** 24 เมษายน 2010 ฟิสิกส์-เราทำใหม่ได้
  บุรินทร์ กำจัดภัย
  การบรรยายพิเศษ (1 ชั่วโมง) ที่ค่ายโปรแกรม IEP ของโรงเรียนเฉลิมขวัญสตรี ที่ วนธารา รีสอร์ท อ. วังทอง จ. พิษณุโลก

- **12.** 11 มีนาคม 2010 นักวิทยาศาสตร์ เขาคิดกันอย่างไร
  บุรินทร์ กำจัดภัย
  การบรรยายพิเศษ (1.5 ชั่วโมง) ที่ค่ายเครือข่ายห้องเรียนวิทยาศาสตร์ ม. ปลาย ของกลุ่มโรงเรียนมัธยมศึกษาภาคเหนือตอนล่าง ที่โรงเรียนพิษณุโลกพิทยาคม

- **13.** 15-16 ตุลาคม 2009 Scalar Field Cosmology: Non-Linear Schrödinger Type Formulation
  บุรินทร์ กำจัดภัย
  การนำเสนอผลงานแบบโปสเตอร์เป็นภาษาอังกฤษ ที่ การประชุมนักวิจัยรุ่นใหม่พบเมธีวิจัยอาวุโส สกว. 2552 โรงแรมรีเจนท์ ชะอำ

- **14.** 7 ตุลาคม 2009 กว่าจะเป็นนักฟิสิกส์
  บุรินทร์ กำจัดภัย
  การบรรยายพิเศษ (1 ชั่วโมง) ค่ายอัจฉริยภาพ ม.ต้น ที่โรงเรียนพิษณุโลกพิทยาคม

ก.2.5 การจัดสัมมนา

- กิจกรรมวิชาการของสถาบันสำนักเรียนท่าโพธิ์ฯที่เกี่ยวข้องกับโครงการวิจัยนี้
  โครงการวิจัยนี้ได้สนับสนุนการจัดสัมมนาท่าโพธิ์อนุกรมที่ 14, 15, 16, 17, 18 และ 19 ซึ่งในแต่ละอนุกรมมีสัมมนาตั้งแต่ 6-12 ครั้ง (ดูรายการสัมมนาได้จาก http://www.tptp.in.th)

ก.2.6 การสร้างเครือข่ายนักวิจัย

ผลโดยตรงจากการสนับสนุนตามโครงการนี้ได้ทำให้มีความร่วมมือกับ Dr. John Ward (University of Victoria, Canada)

DBI Chameleon Gravity

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(Dated: August 21, 2011)

DBI dark energy motivated from open string constructions is considered here with chameleon mechanism. The chameleon interaction can be suppressed in laboratory experiments, due to mass dependent on local matter density environment. We found the DBI equation of motion with chameleon term in both cosmological case and static spherical symmetric case. The static case solution is found using exponential integral function for small field velocities and relativistic limits. Assuming runaway potential $V(\phi)$. The tension $T(\phi) = T_0(1 + \phi^2/M^2)^2$ for a spherical compact body, the DBI chameleon will lead infinite series in $1/r^{l+2}$ correction to Newton's law The Eddington parameters and constraint for laboratory are calculated here for objects, e.g. the sun and 40 cm sphere.

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I. INTRODUCTION

Present cosmic accelerating expansion was spotted by various observations, for example supernovae type Ia [1], cosmic microwave background anisotropies [2, 5], large scale galaxy surveys [3] and X-Ray source [4]. However, the acceleration can not be understood in the framework of standard cosmology. Proposals to explain this acceleration made till today could be, in general, categorized into three ways of approach [6]. In the first approach, in order to achieve acceleration, we need some form of scalar fluid so called *dark energy* with equation of state $p = w\rho$ where $w < -1/3$. Various types of model in this category have been proposed and classified (for a recent review see Ref. [7, 8]). The other two ways are that accelerating expansion is an effect of backreaction of cosmological perturbations [9] or late acceleration is an effect of modification in action of general relativity. This modified gravity approach includes braneworld models (for review, see [10]). Till today there has not yet been true satisfied explanation of the present acceleration expansion.

Although the simplest way to explain this behavior is the consideration of a cosmological constant [11], the known fine-tuning problem [12] led to the dark energy paradigm. The dynamical nature of dark energy, at least in an effective level, can originate from a variable cosmological "constant" [13], or from various fields, such is a canonical scalar field (quintessence) [14], a phantom field, that is a scalar field with a negative sign of the kinetic term [15, 16], or the combination of quintessence and phantom in a unified model named quintom [17]. Finally, an interesting attempt to probe the nature of dark energy according to some basic quantum gravitational principles is the holographic dark energy paradigm [18] (although the recent developments in Horava gravity could offer a dark energy candidate with perhaps better quantum gravitational foundations [19]).

Inflation driven by the open string sector through dynamical Dp-branes recently is of interest, so-called DBI inflation [20, 24]. The model lies in a special class of K-inflation models. It was originally thought that such models yielded large levels of non-Gaussian perturbations which could be used as a falsifiable signature of string theory [21]. However subsequent work has shown that this is not in fact the case, and that the simplest DBI models are essentially indistinguishable from standard field theoretic slow roll models [26, 28, 29]. However, that the models proposed in [25, 29] evade such problems. The problem is that the WMAP5 dataset imposes very tight constraints on the allowed tuning of the free parameters in the theory. We are then left with the choice of either having large non-gaussianities but with vanishing tensors, or assume that the tensor spectrum will be visible - in which case there is no non-Gaussian signature. The models are only falsifiable once these conditions are relaxed. One can get around these conditions by considering more complicated models such as multi-field, multiple branes [27], wrapped branes [30] or monodromics [31] - but even here there are still problems with fine tuning, backreaction and the apparent breakdown of perturbation theory in the inflationary regime [32].

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DBI models may still have some use as an explanation for a dynamical equation of state. Moreover this fits in nicely with several intuitive ideas from string theory. Namely that inflation can still occur, albeit only through the closed string sector. This suggests that dark energy may well be a dynamical process, and moreover in the light of these open string constructions, retains a sense of being geometric in nature. Therefore DBI-driven dark energy comes on stage as [33, 34] which dealt with the dynamics of a solitary $D3$-brane moving through a particular warped compactification of type IIB.

Coupling between the dark sectors is somehow possible. However this could create fifth force which is not seen in nature. A mechanism to suppress this force is through "chameleon mechanism" [35]. The chameleon model is a scalar-tensor theory of gravity, in which the scalar field couples non-minimally to the metric, this reduces effective mass of the scalar field to be in order of Hubble parameter. The scalar field coupled to the metric tensor causes violations of the equivalence principle and can produce fifth force effects if the scalar field is massive but the chameleon model the scalar field couples to matter in a non-minimal way. This allows the chameleon interaction to be suppressed in laboratory experiments, because its mass depends on the local matter density environment.

It is possible that at foundation, the theory of gravity could be made up from open string constructions giving DBI-kinetic term at the same time, there could be chameleon mechanism to reduce the mass of DBI scalar field so that the fifth force effect is reduced. In this report, our circa is to investigate DBI chameleon dark energy and its dynamics in various aspects.

II. DBI ACTION

Let us begin with the following action for a BPS $D3$-brane localised in a warped compacification of type IIB string theory. We will also assume the existence of a matter sector coupled to the world-volume theory of the brane. The resulting action can then be written in the form

$$S_\phi = \int \mathrm{d}^4x\sqrt{-g}\left(T(\phi)W(\phi)\sqrt{1-\frac{2X}{T}} - T(\phi) + V(\phi)\right) \tag{1}$$

This is the generalised Dirac-Born-Infeld (DBI) action where

$$\begin{aligned} X &\equiv -\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi = -\frac{1}{2}(\nabla\phi)^2 \\ \Gamma &\equiv \sqrt{1+\frac{(\nabla\phi)^2}{T}} \end{aligned}$$

and here

$$W = 1 \tag{2}$$

for a usual DBI action. One can find that

$$S_\phi = \int \mathrm{d}^4x\sqrt{-g}\Big[-T\,(\Gamma-1) - V\Big] \tag{3}$$

where

$$T = \frac{1}{f(\phi)} \tag{4}$$

and $f(\phi)$ is warped factor. For AdS throat,

$$f(\phi) = \frac{\lambda}{\phi^4}\,. \tag{5}$$

Combining Einstein-Hilbert, matter field and DBI scalar field,

$$S = \int \mathrm{d}^4x\left\{\mathcal{L}_{\rm EH} + \mathcal{L}_m + \sqrt{-g}\Big[-T\,(\Gamma-1) - V\Big]\right\}\,. \tag{6}$$

This can read

$$S = \int d^4x\sqrt{-g}\left(\frac{M_p^2}{2}\mathcal{R} - T(\phi)(\Gamma-1) - V(\phi) + \frac{1}{\sqrt{-g}}\mathcal{L}_m(\psi_m, \tilde{g}_{\mu\nu})\right) \tag{7}$$

where $\mathcal{R}$ is the Ricci-scalar, ψ_m is a matter field and we have defined Jordan frame metric

$$\tilde{g}_{\mu\nu} = e^{2\beta\phi/M_p} g_{\mu\nu}. \tag{8}$$

The kinetic term for the scalar field ϕ is encoded in the DBI-part of the action $(-T(\Gamma-1))$. Variation of the action with respect to the scalar field results in the Euler-Lagrange equation,

$$\frac{\delta\mathcal{L}_\phi}{\delta\phi} = \frac{\partial\mathcal{L}_\phi}{\partial\phi} - \nabla_\mu\left[\frac{\partial\mathcal{L}_\phi}{\partial(\nabla_\mu\phi)}\right] = 0 \tag{9}$$

We can also include matter term into the Euler-Lagrange equation as well. After long and very detail calculation, we have found that

$$\frac{\partial\mathcal{L}_{\phi+m}}{\partial\phi} = \sqrt{-g}\left[-\frac{T'}{2\Gamma}(\Gamma-1)(\Gamma-1) - V'\right] + \mathcal{L}'_m \tag{10}$$

and

$$\frac{\partial\mathcal{L}_{\phi+m}}{\partial(\nabla_\mu\phi)} = -\sqrt{-g}\frac{1}{\Gamma}\partial^\nu\phi \tag{11}$$

with

$$\nabla_\mu\left(\frac{\partial\mathcal{L}_{\phi+m}}{\partial(\nabla_\mu\phi)}\right) = -\frac{\sqrt{-g}}{\Gamma}\left[\Box^2\phi - \frac{1}{\Gamma}g^{\rho\nu}(\partial_\rho\phi)(\partial_\nu\Gamma)\right] \tag{12}$$

where

$$\Box^2\phi \equiv \frac{1}{\sqrt{-g}}\partial_\nu\left[\sqrt{-g}\,g^{\mu\nu}\partial_\nu\phi\right] \tag{13}$$

and

$$' \equiv \frac{\mathrm{d}}{\mathrm{d}\phi} \tag{14}$$

We finally obtain the DBI equation of motion,

$$-\frac{T'}{2\Gamma}(\Gamma-1)^2 - V' + \frac{\Box^2\phi}{\Gamma} - \frac{1}{\Gamma^2}g^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\Gamma) = -\frac{\mathcal{L}'_m}{\sqrt{-g}} \tag{15}$$

The last term is matter Lagrangian density when the scalar field couples to the metric via equation (8)-the chameleon mechanism, the matter Lagrangian read

$$\mathcal{L}'_m = -\sqrt{-g}\frac{\beta}{M_p}\rho(1-3w)e^{\beta(1-3w)\phi/M_p} \tag{16}$$

where w is equation of state parameter of barotropic fluid, i.e. matter and radiation. The full DBI field equation of motion with chameleon mechanism is hence

$$-\frac{T'}{2\Gamma}(\Gamma-1)^2 + \frac{\Box^2\phi}{\Gamma} - \frac{g^{\mu\nu}}{\Gamma^2}\partial_\mu\phi\partial_\nu\Gamma = V' + \frac{\beta\rho}{M_p}(1-3\omega)e^{(1-3\omega)\beta\phi/M_p} \tag{17}$$

where the final term on the right hand side is proportional to the energy density of the matter sector. One finds this expression by noting that variation of the matter Lagrangian yields a term proportional to $\tilde{T}^{\mu\nu}\tilde{g}_{\mu\nu}$ which for an isotropic fluid will be of the form $-(1-3\omega)\tilde{\rho}$ in the Jordan frame. In Einstein frame we see that ρ is conformally related to $\tilde{\rho}$

$$\rho = \tilde{\rho}e^{3(1+\omega)\beta\phi/M_p}. \tag{18}$$

The entire right hand side can therefore be regarded as an effective potential for the scalar field which we define as

$$V_{\text{eff}} = V_\phi + \frac{\beta\rho}{M_p}(1-3\omega)e^{(1-3\omega)\beta\phi/M_p}. \tag{19}$$

The notation we use is that $\partial_X = X_\phi$ for a quantity X, and $\Box^2$ has the usual form in a curved geometry.

A. Solutions of the field equation

Solution to the field equation (17),

$$-\frac{T'}{2\Gamma}(\Gamma-1)^2+\frac{\Box^2\phi}{\Gamma}-\frac{g^{\mu\nu}}{\Gamma^2}\partial_\mu\phi\partial_\nu\Gamma=V'+\frac{\beta\rho}{M_p}(1-3\omega)e^{(1-3\omega)\beta\phi/M_p}$$

is major ingredient of the project since this encodes both dynamical behavior (temporal dependent) and spatial cosmography of the universe.

B. Cosmological solution

Let us assume that the metric is just that of the flat FRW form, and that the scalar field is homogeneous, i.e. the field equation is only-time dependent. The equation of motion therefore reduces to the following

$$\ddot{\phi}+3H\Gamma^2\dot{\phi}-\frac{T_\phi}{2}\left(2\Gamma^3+1-3\Gamma^2\right)+V_{\rm eff}\Gamma^3=0 \tag{20}$$

or in another form,

$$\ddot{\phi}+\Gamma^2 3H\dot{\phi}+\Gamma^3\left(V'-T'\right)+T'-\frac{3}{2}\frac{T'}{T}\dot{\phi}^2+\Gamma^3\frac{\beta\rho}{M_{\rm P}}e^{\beta\phi/M_{\rm P}}=0 \tag{21}$$

Let us consider the regime where $\dot{\phi}^2 \ll T(\phi)$ which is the non-relativistic regime. Keeping the fourth order terms, one finds that the equation of motion admits the following expansion

$$\ddot{\phi}+3H\dot{\phi}\left(1-\frac{\dot{\phi}^2}{T}\right)-\frac{3T_\phi\dot{\phi}^2}{8T^2}+V_{\rm eff}\left(1-\frac{3\dot{\phi}^2}{2T}+\frac{3\dot{\phi}^4}{8T^2}\right)\simeq 0 \tag{22}$$

III. RADIAL SOLUTION

Assuming isotropy of the universe but not homogeneity, the non-zero component of the FRW metric for the field equation is radial, i.e.

$$\begin{aligned}&\phi_{rr}\left[1-\frac{\phi_r^2}{T\left(1+\phi_r^2/T\right)}\right]\\&+\frac{2}{r}\phi_r\left[1+\frac{\phi_r^3}{T(1+{\phi_r}^2/T)}\frac{r}{4}\left(\frac{T'}{T}\right)\right] = T'\left(1+\frac{\phi_r^2}{2T}\right)-T'\left(\sqrt{1+\frac{\phi_r^2}{T}}\right)\\&\qquad +V'\Gamma+\Gamma\frac{\beta}{M_{\rm P}}\rho(r)e^{\beta(\phi)/M_{\rm P}}\end{aligned} \tag{23}$$

1. *Limit I:* $\phi_r^2/T \ll 1$

Expanding $\sqrt{1+\phi_r^2/T}$ and keeping the lowest order term,

$$\phi_{rr}\left(1-\frac{\phi_r^2}{T}\right)+\frac{2}{r}\phi_r\left[1+\frac{\phi_r^3}{T}\frac{r}{4}\left(\frac{T'}{T}\right)\right]\approx V'\Gamma+\Gamma\frac{\beta}{M_{\rm P}}\rho(r)e^{\beta\phi/M_{\rm P}} \tag{24}$$

or

$$\phi_{rr}+\frac{2}{r}\phi_r\left[1+\frac{\phi_r^3}{T}\frac{r}{4}\left(\frac{T'}{T}\right)\right]\approx\Gamma\left[V'+\frac{\beta}{M_{\rm P}}\rho(r)e^{\beta\phi/M_{\rm P}}\right] \tag{25}$$

2. · Limit II: $\phi_r^2/T \gg 1$

Under the limit $\phi_r^2/T \gg 1$, approximations

$$\Gamma \equiv \sqrt{1+\frac{\phi_r^2}{T}} \simeq \frac{\phi_r}{\sqrt{T}} \tag{26}$$

and

$$\frac{\phi_r^2}{T} = \Gamma^2 - 1 \simeq \Gamma^2 \tag{27}$$

are made. Field equation then takes the form,

$$\frac{2}{r} = \frac{1}{\sqrt{T}}\left(V' - T'\right) \tag{28}$$

IV. SPHERICALLY SYMMETRIC WITH LOCALLY FLAT SOLUTION

Let us assume that $g_{\mu\nu} = \eta_{\mu\nu}$, where we work in polar coordinates on the world-volume. The resulting expression for the equation of motion becomes

$$\phi_{rr} + \frac{2}{r}\Gamma^2\phi_r + \frac{T_\phi}{2}(2\Gamma^3 + 1 - 3\Gamma^2) - \Gamma^3 V_{\rm eff} = 0 \tag{29}$$

Let us first consider the case of constant T and the pressureless fluid. We split the solution into those that are outside the sphere, and those that are inside the sphere. Outside the sphere we may approximate the potential terms by $m_\infty^2(\phi - \phi_\infty)$ because the scalar field is driven towards ϕ_∞. The resulting equation of motion therefore takes the form

$$\phi_{rr} + \frac{2}{r}\Gamma^2\,\phi_r^2 \simeq \Gamma^3 m_\infty^2(\phi - \phi_\infty) \tag{30}$$

which we must study in the two asymptotic limits.

We first expand for small velocities, introducing a perturbation ϵ which satisfies the condition that $\Gamma = 1$ as $\epsilon \to 0$. The scalar field therefore admits the following solution

$$\begin{aligned} \phi(r) \simeq\ & \phi_\infty \\ & + \frac{A}{r}\, e^{-m_\infty(r-R)}(1+\epsilon) \\ & - \frac{3\epsilon A^2}{4}\,\frac{m_\infty^2\phi_\infty}{r^2 T}\, e^{-2m_\infty(r-R)} \\ & - \frac{3\epsilon A}{8}\,\frac{m_\infty^3\phi_\infty}{rT}\left[e^{m_\infty(r+2R)}\mathrm{Ei}(-3m_\infty r) + e^{-m_\infty(r-2R)}\mathrm{Ei}(-m_\infty r)\right] \\ & + \dots \end{aligned} \tag{31}$$

where we have introduced the exponential integral function.

In the relativistic case we see that $\Gamma \gg 1$ implies that $\phi_r^2 \gg T$. We can find a solution to this equation under the assumption that $\phi_r \gg 1$ with $\phi_{rr} \sim 0$. The resulting expression for the scalar field becomes

$$\phi(r) \simeq \phi_\infty + \frac{2\sqrt{T}}{r m_\infty^2} \tag{32}$$

In the limit, $\phi_r \ll T(\phi)$, we find that $\Gamma \sim 1 + \dots$ where the corrections are a derivative expansion, resulting in the approximation

$$\phi_{rr} + \frac{2\phi_r}{r}\left(1 + \frac{\phi_r^2}{T}\right) + \frac{T_\phi}{2}\frac{3\phi_r^4}{8T^2} - V_{\rm eff}\left(1 + \frac{3\phi_r^2}{2T} + \frac{3\phi_r^4}{8T^2}\right) \simeq 0 \tag{33}$$

V. DBI CHAMELEONS WITH RUNAWAY POTENTIAL AND STRING-INSPIRED TENSION

We consider the dynamics of a scalar field coupled to matter according to

$$S = \int d^4x \left[\frac{R}{2\kappa_4^2} - T(\phi)\sqrt{1 + \frac{\partial_\mu\phi\partial^\mu\phi}{T(\phi)}} + V(\phi) - T(\phi) \right] + S_m(\psi_m, A^2(\phi)g_{\mu\nu}) \tag{34}$$

where $A(\phi) = e^{\beta\phi/m_{\rm Pl}}$ and $V(\phi)$ is a runaway potential. The tension $T(\phi)$ is chosen to be

$$T(\phi) = T_0(1 + \frac{\phi^2}{M^2})^2 \tag{35}$$

When $\phi \ll M$, the tension is constant while $T(\phi) \sim \phi^4$ in an AdS region $\phi \gg M$. The equations of motion for such an action read

$$\Box\phi - \frac{1}{\Gamma}(\partial\phi)^2 = T'\Gamma(\Gamma - 1) + V'\Gamma - \frac{1}{2}T'(\Gamma^2 - 1) + \beta\frac{\rho}{m_{\rm Pl}}\Gamma \tag{36}$$

in the presence of non-relativistic matter of density ρ.

A. Cosmological evolution

At large scale, the cosmological evolution of the field is governed by

$$\ddot\phi + \Gamma^2 3H\dot\phi + \Gamma^3(V' - T') + T' - \frac{3}{2}\frac{T'}{T}\dot\phi^2 + \Gamma^3\frac{\beta\rho}{m_{\rm Pl}} = 0 \tag{37}$$

B. Static radial case

We consider static configurations in spherical coordinates for which the radial equation becomes

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr}\left[1 + T^{-1}\left(\frac{d\phi}{dr}\right)^2\right] = \left[1 + \frac{3}{2}T^{-1}\left(\frac{d\phi}{dr}\right)^2\right]\left(V' + \beta\frac{\rho}{m_{\rm Pl}}\right) \tag{38}$$

Let us now consider the case of a small perturbation by the non-linear terms $T^{-1}(\frac{d\phi_0}{dr})^2$ with respect to a spherical profile obtained when the kinetic terms are canonical. Expanding

$$\phi = \phi_0 + \delta\phi \tag{39}$$

we find that

$$\frac{d^2}{dr^2}\delta\phi + \frac{2}{r}\frac{d}{dr}\delta\phi - m^2\delta\phi = T_0^{-1}\left(\frac{d\phi_0}{dr}\right)^2\left(\frac{3}{2}V_0' - \frac{2}{r}\frac{d\phi_0}{dr}\right) \tag{40}$$

where

$$m^2 = V''(\phi_0) + \beta_2\frac{\rho}{M_P^2} \tag{41}$$

and

$$V_0' = V'(\phi_0) + \beta\frac{\rho}{M_P} \tag{42}$$

. We will analyse this equation in the case of a spherical body large enough to have a thin shell.

C. Spherical Bodies

We consider a compact body with a density ϕ_c embedded in a fluid of density ρ_∞. We also assume that the object has a thin-shell obtain when $|\phi_\infty - \phi_c| \ll \Phi_N$ where Φ_N is Newton's potential at the surface of the body of radius R. As $\phi_c \ll \phi_\infty$ for dense bodies, this is tantamount to a condition on ϕ_∞.

1. *Multipoles*

The solution of the DBI equation (40) outside the body is given by

$$\delta\phi(r) = -\int d^3r' \frac{e^{-m_\infty|r-r'|}}{4\pi|r-r'|} F(r') \tag{43}$$

where

$$F(r') = T_0^{-1}\left(\frac{d\phi_0}{dr}\right)^2\left(\frac{3}{2}V_0' - \frac{2}{r}\frac{d\phi_0}{dr}\right) \tag{44}$$

We consider distances which are far less than the inverse mass m_∞^{-1} and use the fact that $d\phi_0/dr$ is zero outside a shell of width ΔR.

$$\delta\phi(r) = -\int_{\Delta R} d^3r' \frac{F(r')}{4\pi|r-r'|} \tag{45}$$

using the multipolar expansion of $1/|r-r'|$ we find

$$\delta\phi(r) = -\sum_{l=0}^{\infty}\frac{A_l}{r^{l+1}} \tag{46}$$

where

$$A_l = \frac{1}{4\pi}\int_{\Delta R} d^3r\, r^l F(r) P_l(\cos\theta) \tag{47}$$

in terms of the Legendre Polynomials. Notice that the corrections to the thin shell solution has multipoles of arbitrary order despite being in a spherical situation. In particular this will lead to the presence of an infinite series in $1/r^{l+2}$ correcting Newton's law.

2. *The Eddington Parameters*

The force induced by a spherical body is modified by the scalar fields. This is due to the fact that test particles feel the potential

$$\Phi(r) = \Phi_N(r) + \beta\frac{\phi(r)}{M_P} \tag{48}$$

In the chameleon case, the metric outside a body reads

$$ds^2 = e^{2\beta\phi/m_{Pl}}\left[(-1+2\Phi_N(r))\,dt^2 + (1+2\phi_N(r))\left(dr^2 + r^2 d\Omega^2\right)\right] \tag{49}$$

This can be written (as $\phi/M_P \ll 1$)

$$ds^2 = \left(-1 + 2\Phi - 4\beta\frac{\phi}{M_P}\right)dt^2 + (1+2\Phi)\left(dr^2 + r^2 d\Omega^2\right) \tag{50}$$

The scalar field modifies the trajectories of test particles. For large bodies such as the planets in the solar system, the post-Newtonian formalism can be applied and corrections to Newton's law in $1/r^2$ and $1/r^3$ have been parameterised. The Eddington parameters involve the $1/r$ and $1/r^2$ corrections to the Newton potential. Denoting by

$$\phi_0 = \phi_\infty - \frac{X}{r} \tag{51}$$

the background solution outside the spherical body where

$$X \sim \frac{G_N m_0 \phi_\infty}{\Phi_N} \tag{52}$$

we truncate

$$\phi(r) = -\frac{a_1}{r} - \frac{a_2}{r^2} + O(1/r^3) \tag{53}$$

where

$$\begin{aligned} a_1 &= X + A_0 \\ a_2 &= A_1 \end{aligned} \tag{54}$$

We find then the modification of the metric

$$\begin{aligned} g_{00} &= -1 + \frac{2G_N m_0}{r} + \frac{2\beta a_1}{M_P\, r} + \frac{2\beta a_2}{M_P\, r^2}, \\ g_{rr} &= 1 + \frac{2G_N m_0}{r} - \frac{2\beta a_1}{M_P\, r} - \frac{2\beta a_2}{M_P\, r^2} \end{aligned} \tag{55}$$

This has to be compared to the post Newtonian parametrisation

$$\begin{aligned} g_{00} &= -1 + \frac{2G_N\, m}{r} + \frac{\Gamma_{\rm edd} - \beta_{\rm edd}}{2} \frac{G_N^2\, m^2}{r^2}, \\ g_{rr} &= -1 + \frac{2G_N\, \Gamma_{\rm edd}\, m}{r} \end{aligned} \tag{56}$$

where m_0 is the bare mass of the spherical body. Redefining the mass to take into account the energy density carried by the scalar field

$$m = m_0 + 2\beta \frac{a_1}{M_P\, G_N} \tag{57}$$

we find that the Eddington parameters are given by

$$\Gamma_{\rm edd} = 1 - \frac{2\beta a_1}{G_N\, M_P\, m} \tag{58}$$

and

$$\beta_{\rm edd} = 1 - \frac{2\beta\, a_1}{G_N\, M_P\, m} - \frac{4\beta a_2}{M_P\, G_N^2\, m^2} \tag{59}$$

From spherical symmetry we find that

$$A_1 \propto \int_0^\pi \sin\theta \cos\theta = 0 \tag{60}$$

implying that

$$a_2 = 0$$

and the Eddington parameters depend only on $a_1 = X + A_0$. In particular, the most stringent constraints follows from the Cassini bound on

$$|\Gamma_{\rm edd} - 1| \leq 10^{-5} \tag{61}$$

In the thin shell case, the correction due to ϕ_0 satisfies this constraint. Perturbatively we must impose that $A_0 \ll X$. Let us now calculate A_0 and impose that the deviation from Newton's law is small. In the thin-shell betwen $(R - \Delta R)$ and R we have

$$\frac{d\phi_0}{dr} = \frac{\beta\rho_c}{3M_P} r - \frac{\beta\rho_c}{3M_P r^2} R^3 \tag{62}$$

The existence of a thin shell imposes that

$$\phi_\infty \leq 6\beta\Phi_N\, M_P \tag{63}$$

Imposing that the earth and the sun have both a thin shell to prevent changes of the trajectories of the planets and the moon implies that

$$\phi_\infty \leq 10^{-8} M_P \tag{64}$$

where $\Phi_N \sim 10^{-9}$ at the surface of the sun. This gives a bound

$$\phi(r) \leq 10^{-8} M_P \tag{65}$$

inside the thin shell of the sun. For the earth this is

$$\phi(r) \leq 10^{-12} M_P \tag{66}$$

In the following we shall focus on scales $M \gg 10^{-8} M_P$ then $T = M^4$. As result we find

$$F(r) = \frac{1}{6} \frac{\beta^3 \rho_c^3}{M^4 M_P^3} \left(r - \frac{R^3}{r^2} \right)^2 \tag{67}$$

and therefore

$$A_0 \approx \frac{3}{2} \frac{\beta^3 \rho_c^3}{M^4 M_P^3} R^2 (\Delta R)^3 \tag{68}$$

where the width of the shell is

$$\frac{\Delta R}{R} = \frac{\phi_\infty - \phi_c}{6\beta \Phi_N} \tag{69}$$

This can be written as

$$A_0 = 351 \beta^3 \Phi_N^3 \frac{M_P^4}{T_0} \frac{1}{R M_P} \left(\frac{\Delta R}{R} \right)^3 \tag{70}$$

while

$$X = 6\beta \frac{\Delta R}{R} \tag{71}$$

Hence $A_0 \ll X$.

3. *Laboratory Tests*

Laboratory tests allow us to test the higher order corrections to Newton's law. Defining

$$\alpha_l = \frac{1}{2} \int_0^\pi \sin\theta P_l(\cos\theta) \tag{72}$$

we find that

$$A_l = \alpha_l R^l A_0 \tag{73}$$

The correction to Newton's potential $\delta\phi_l(r)$ induced by the higher order terms reads

$$\frac{\delta\phi_l(r)}{\Phi_N(r)} = 351\, \beta^4\, \alpha_l\, \Phi_N^2 \frac{M_P^4}{T_0} \left(\frac{1}{R M_P} \right)^2 \left(\frac{\Delta R}{R} \right)^3 \left(\frac{R}{r} \right)^l \tag{74}$$

The Eotwash group has parameterised these deviations as

$$\frac{\delta\phi_l(r)}{\Phi_N(r)} = \beta_l \left(\frac{1\mathrm{mm}}{r} \right)^l \tag{75}$$

leading to

$$\beta_l = \frac{9\beta\alpha_l}{\Phi_N}\frac{M_P^4}{T_0}\left(\frac{1}{RM_P}\right)^2\left(\frac{R}{1\text{mm}}\right)^3\frac{(\phi_\infty-\phi_c)^3}{M_P^3} \tag{76}$$

For test bodies od radius $R = 1$ cm and weight 40g, Newton's potential is

$$\Phi_N \sim 10^{-27} \tag{77}$$

we find

$$\beta_l \sim 10^{60+l}\frac{M_P^4}{T_0}\frac{\phi_\infty^3}{M_P^3} \tag{78}$$

for $\alpha_l = O(1)$ and $\beta = O(1)$. Using

$$\beta_l \leq 10^{-3} \tag{79}$$

for $l = 1\ldots 7$, this leads to

$$\phi_\infty \leq 10^{-23}\left(\frac{M_P^4}{T_0}\right)^{1/3} M_P \tag{80}$$

The presence of a thin shell requires

$$\phi_\infty \leq 10^{-26}M_P \tag{81}$$

implying that

$$\frac{T_0}{M_P^4} \geq 10^{-9} \tag{82}$$

Hence laboratory tests impose a drastic constraint on the tension at the tip of the throat.

VI. CONCLUSION

We consider DBI dark energy motivated from open string constructions as [33, 34] where the solitary $D3$-brane moving through a particular warped compactification of type IIB. Coupling between scalar field and dark matter creating the fifth force is reduced by chameleon mechanism [35]. The chameleon interaction can be suppressed in laboratory experiments, due to mass dependent on local matter density environment. We have finally found the DBI equation of motion and the full DBI field equation of motion with chameleon mechanism is found to be The static case solution is found using exponential integral function. When assuming realistic situation $V(\phi)$ is a runaway potential. For a spherical compact body, the DBI chameleon will lead infinite series in $1/r^{l+2}$ correction to Newton's law which a modified gravitational potential The Eddington parameters involving the $1/r$ and $1/r^2$ corrections to the Newton potential is found to be $\phi_0 = \phi_\infty - X/r$, $X \sim G_N m_0\phi_\infty/\Phi_N$ and the thin-shell constraint is $\phi_\infty \leq 10^{-26}M_P$.

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