Gravity stabilizes itself

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III SAHA THEORY WORKSHOP
ASPECTS OF EARLY UNIVERSE COSMOLOGY

Based on the work

D.Choudhury, S.Anand, A.A. Sen, S. SenGupta : Phys.Rev. D92 (2015) 2, 026008

S.Chakraborty, S.SenGupta : Eur.Phys.J. C75 (2015) 1, 11

A.Das, H. Mukherjee, T. Paul, S. SenGupta , e-Print: arXiv:1701.01571

S. Chakraborty, S. SenGupta, , e-Print: arXiv:1701.01032

Einstein's Gravity

1. Einstein's General Relativity is a description of force of gravitation in four dimensions through space-time geometry
2. Einstein's theory is successful in explaining many observed gravitational phenomena at different energy scales for macroscopic bodies
3. Does it have any role to play at microscopic world ?
4. Before answering this question we note that the theory becomes inconsistent at Planckian energy scale or the scale of quantum gravity

What is Planck scale ?

Einstein's equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} - \Lambda g_{\mu\nu} = -8\pi G T_{\mu\nu}$$

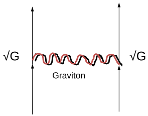
Consider a small fluctuation over flat space metric

$$g_{\mu\nu} = \eta_{\mu\nu} + \sqrt{G} h_{\mu\nu}$$

Gravitational coupling to a scalar field

$$g_{\mu\nu}\partial^\mu \Phi \partial^\nu \Phi = \partial_\mu \Phi \partial^\mu \Phi \; + \; \sqrt{G} h_{\mu\nu}\partial^\mu \Phi \partial^\nu \Phi$$

Graviton exchange amplitude



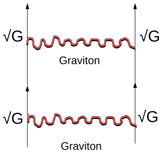
The amplitude $\sim (E^2 G)$ in natural units

Even for micro-particles the gravity becomes strong at energy scale $E \sim \frac{1}{\sqrt{G}} = 10^{19} Gev = M_{Planck}$

Thus Planck scale is a natural cut-off for the standard model of elementary particles which does not include gravity

Problem of quantum gravity

Graviton loop,



Amplitude $\sim \frac{\Lambda^4}{M^4}$ —- UV divergent and non-renormalizable – Problem of quantum gravity

Thus at larger and larger energy scale, the effects of quantum gravity can not be ignored and Einstein's theory is inadequate to address this

A path to quantum gravity

String theory provides a path for consistent description of quantum gravity by identifying the elementary particles as string excitations with appropriate boundary conditions

Gravity appears as a massless close string excitation

String theory brings in two important modifications over Einstein's gravity

(a) Extra spatial dimensions – Leading to various internal moduli (say radius)

(b) Higher curvature terms in the action such as R^2, $R^{\mu\nu}R_{\mu\nu}$, $R^{\mu\nu\alpha\beta}R_{\mu\nu\alpha\beta}$ each suppressed by $1/M_P^2$

Such modifications however can also be introduced from the requirement of diffeomorphism invariance without bringing in string theory

Two unnatural fine tuning

Radiative correction,

$$m_H^2 = m_0^2 + 3\frac{\Lambda^2}{8\pi^2 v^2}(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2)$$

This implies

$$\delta m_H^2 \sim \Lambda^2$$

where Λ is the cutoff scale say Planck scale

To keep m_H within Tev, one needs extreme fine tuning of two Planck scale quantities to produce a Tev scale quantity i.e tuning $\sim 10^{-32}$

UNNATURAL

Challenge for standard model?

Vacuum energy in standard model – Naturalness problem again !

Consider the scalar field potential in SM,

$$V = V_0 - \mu^2 \phi^+ \phi + g(\phi^+ \phi)^2$$

$$\rho = V_{min} = V_0 - \frac{\mu^4}{4g} = V_0 - 10^6 Gev^4$$

This implies V_0 must be tuned to 53 place of decimal to get the desired value

$\sim 10^{-47}$– UNNATURAL !!

Gravity in higher dimension and SM Naturalness

We have seen that 4-dimensional Einstein's gravity can not have any role in BSM Physics at low energy apart from setting a cut-off for the theory

However the scenario changes drastically in presence of extra spatial dimensions

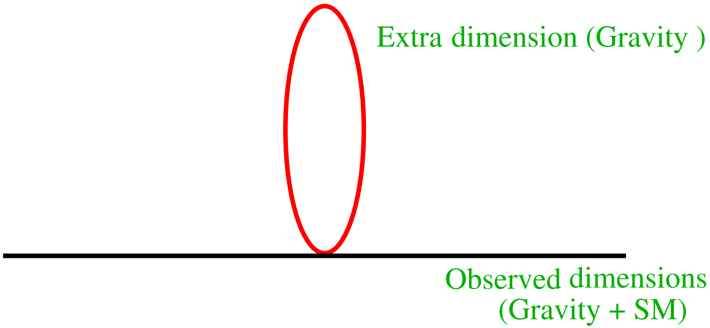
Two models (along with their variants) are extremely popular from theoretical and experimental points of view.

Moreover they have their origin in more fundamental theories like string theory

We briefly explain them now

Large extra dimensions

ADD Scenario:



Einstein action in d dimensions:
$S = \frac{1}{16\pi G_d} \int d^d x \sqrt{-g_d}\ R_d$

Assume:

$$ds_d{}^2 = ds_4^2{}_{Observed} - dy_I dy^I{}_{Unobserved}$$

Then

$$S = \frac{V_{d-4}}{16\pi G_d} \int d^4 x \sqrt{-g_4}\ R_4 \quad = \frac{1}{16\pi G_4} \int d^4 x \sqrt{-g_4}\ R_4$$

$G_4 = \frac{G_d}{V_{d-4}}$

Four dimensional (observed) Planck scale
$M_{Pl(4)} = 10^{19}\,GeV$

$[M_{Pl(d)}^{d-2} = (\frac{1}{L})^{d-4} M_{Pl(4)}^2]$

(i) $d = 6$, $L = 100\ \mu m \quad \Rightarrow \quad M_{Pl(6)} = 1\ TeV$

(ii) $d = 10$, $L = 1\ Fermi \quad \Rightarrow \quad M_{Pl(10)} = 1\ TeV$

Instead of the question why m_W is small compared M_P now we have the question why V_n (modulus) is so large? – how to stabilize this ?

Warped Geometry – an alternative Model

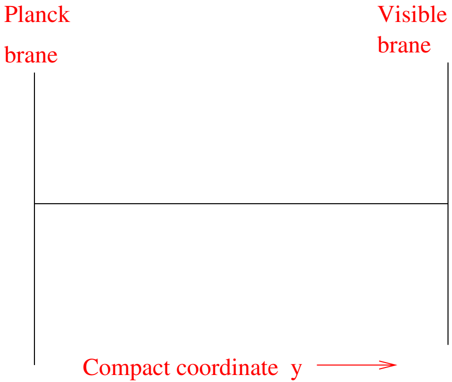
The Einstein action in 5 dimensional ADS_5 space

$$S = \frac{1}{16 G_5} \int d^5x \sqrt{-g_5} \, [\mathcal{R} - \Lambda]$$

Compactify the extra coordinate $y = r\phi$ on S_1/Z_2 orbifold

Place two 3-branes at the two orbifold fixed points $\phi = 0, \pi$

r is the radius of S_1



The Z_2 orbifolded coordinate $y = r\phi$ with $0 \leq \phi \leq \pi$ and r is the radius of the S_1

Action

$$S = S_{Gravity} + S_{vis} + S_{hid}$$

$$S_{Gravity} = \int d^4x \; r \; d\phi \sqrt{-G} \; [2M^3 R - \underbrace{\Lambda}_{5-dim}]$$

$$S_{vis} = \int d^4x \sqrt{-g_{vis}} \; [L_{vis} - V_{vis}]$$

$$S_{hid} = \int d^4x \sqrt{-g_{hid}} \; [L_{hid} - V_{hid}]$$

Metric ansatz:

$$ds^2 = e^{-A(\phi)}\ \eta_{\mu\nu} dx^\mu dx^\nu + r^2 d\phi^2$$

Warp factor and the brane tensions are found by solving the 5 dimensional

Einstein's equation with orbifolded boundary conditions

$$A = 2kr\phi$$

$$V_{hid} = -V_{vis} = 24M^3 k$$

and

$$k^2 = \frac{-\Lambda}{24M^3}$$

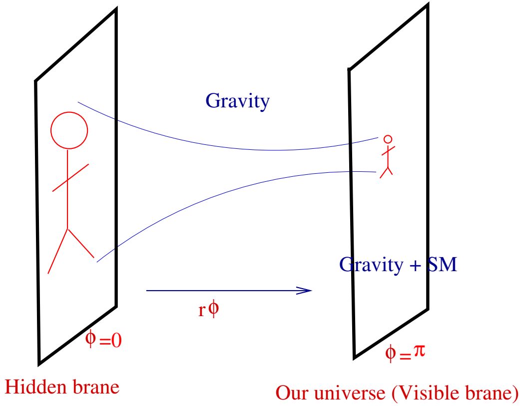
For $\Lambda \sim M^5$, the parameter $k \sim M$, where $M \sim M_{Pl}$

Warping

$$\left(\frac{m_H}{m_0}\right)^2 = e^{-2A}|_{\phi=\pi} = e^{-2kr\pi} \sim (10^{-16})^2$$

$\Rightarrow kr = \frac{16}{\pi}\ln(10) = 11.6279 \quad \leftarrow$ RS value with $k \sim M_P$ and $r \sim l_P$

So hierarchy problem is resolved not by introducing any new scale but by diluting the scale through a warped geometry



The four dimensional cosmological constant on the brane is given by,

$$\Lambda_4 = \frac{1}{2}\kappa_5^2\left(\Lambda + \frac{1}{6}\kappa_5^2 V_{vis}^2\right)$$

Substituting for Λ and V_{vis} in terms of k and M, we find that $\Lambda_4 = 0$
i.e the brane is flat with effective metric to be Minkowskian

How to stabilize the radius r ?

Experimental signatures – Kaluza-Klein graviton and modular field (Radion)

In effective 4-dimensional theories graviton Fourier modes appear as tower of particles called Kaluza-Klein particles with mass $\sim$ *Tev*

Also the radius $r(x, y, z, t)$ appear as a scalar field (modulus) in the 4-dimensional effective theory

They interact with standard models fields to produce new phenomenology e.g. RS graviton KK modes in LHC (ATLAS and CMS) as well as radion phenomenology

Radion also has significant influence on cosmological evolution

Modulus field and stabilization

1. In extra dimensional models the radius of the extra dimension appears as a scalar field known as modulus

2. This scalar degree of freedom needs to be stabilized to a value r – which appears as a parameter in the low energy effective 4-dimensional theory

3. The fluctuation around this stable value is called radion field – which couples with standard model fields to produce new phenomenology in the collider and also couples to space-time curvature to produce new cosmology – till it rolls down to a stable value

4. However to stabilize one needs to have a potential for this field – whose minimum corresponds to that stable value

1. The origin of this potential for the moduli fields in the 4-dimensional effective action is a crucial issue
2. In general the modulus potential is generated by introducing an external scalar field Φ in the bulk with appropriate potential $V(\Phi)$
3. For a given bulk metric and scalar potential solve for Φ
4. Tune the values of the scalar field at the two boundaries, substitute the solution of Φ into the action and integrate out the extra coordinate to generate a potential for r
5. For $V(\Phi) = m^2\Phi^2$ (Goldberger and Wise) the minimum of the potential is
6. $rk \sim \frac{k^2}{m^2} log \frac{\Phi_P}{\Phi_T} \sim 12$
7. But no back-reaction of the bulk field is taken and the inclusion of the bulk scalar action is quite ad-hoc
8. Subsequently the addition of a quartic term in the potential led to a warped geometry description with back-reaction (Freedman et.al, Csaki et.al)
9. Can we find a natural or geometric origin of these potentials ?

F(R) gravity as higher curvature correction

As the bulk of the higher dimensional models have very high curvature $\sim M_{Pl}$ therefore Einstein's gravity is inadequate and one should include higher order corrections in the bulk

We turn our attention to certain class of higher curvature gravity models namely $F(R)$ model

We start from the following action for $F(R)$ gravity on the bulk

$$S = \int d^5x\sqrt{-G}\left(M^3F(R) - \Lambda\right) + \int d^4x\sqrt{-g_i}V_i$$

where Λ is the bulk cosmological constant, R is the five dimensional Ricci scalar and V_i is the brane tension for ith brane.
The warped metric ansatz is:

$$ds^2 = e^{-2A(y)}g_{\mu\nu}dx^\mu dx^\nu + r_c^2dy^2$$

Such metric ansatz is motivated to resolve fine tuning problem discussed earlier

Solving bulk equations equation we could obtain the following solution for the variable A as,

$$\begin{aligned} e^{-A} &= \omega \cosh\left(ln\frac{\omega}{c_1} + k_F y \right) \\ k_F^2 &= -\frac{1}{6}\left(\frac{\frac{\Lambda}{2M^3} - \frac{f}{2}}{1 - \frac{2}{3}f'} \right) \end{aligned}$$

The bulk cosmological constant Λ is negative for anti-deSitter bulk
$f'(R)$ imply derivative of the function $f(R)$ with respect to R

The respective brane tensions are being given by,

$$\begin{aligned} V_{vis} &= 12M^3 k_F \left[\frac{\frac{\omega^2}{c_1^2} e^{2kr_c\pi} - 1}{\frac{\omega^2}{c_1^2} e^{2kr_c\pi} + 1} \right] \\ V_{hid} &= 12M^3 k_F \left[\frac{1 - \frac{\omega^2}{c_1^2}}{1 + \frac{\omega^2}{c_1^2}} \right] \end{aligned}$$

The 4-dimensional cosmological constant is now given as

$$\Lambda_4 = \frac{1}{2}\kappa_5^2 \left(\frac{\Lambda}{f'(\mathcal{R})} + \frac{1}{6}\kappa_5^2 V_{vis}^2 \right)$$

Now unlike RS model, an appropriate choice for $f(R)$ can render the brane non-flat with tiny cosmological constant – consistent with observed value.

Thus both the fine tuning issues can be addressed by the presence of higher curvature terms in the bulk

Important question

Can the higher curvature terms lead to modulus stabilization ?

A geometric modulus stabilization

The F(R) action

$$S = (1/2\kappa^2)\int d^4x d\phi \sqrt{G} F(R)$$

$\frac{1}{2\kappa^2}$ as taken as $2M^3$ where M is the five dimensional Planck scale

Introducing an auxiliary field $A(x,\phi)$, above action can be equivalently written as,

$$S = (1/2\kappa^2)\int d^4x d\phi \sqrt{G}[F'(A)(R-A)+F(A)]$$

By the variation of the auxiliary field $A(x,\phi)$, one easily obtains $A = R$. Plugging back this solution $A = R$ into the action , the initial action can be reproduced

Make a conformal transformation of the metric as

$$G_{MN}(x,\phi) \to \tilde{G}_{MN} = \exp\left(\sigma(x,\phi\right) G_{MN}(x,\phi)$$

M, N run form 0 to 5.
$\sigma(x,\phi)$ is conformal factor and related to the auxiliary field as $\sigma = (2/3)\ln F'(A)$.

Using these relations we have the scalar-tensor action

$$S = (1/2\kappa^2) \int d^4x d\phi \sqrt{\tilde{G}}[\tilde{R} + 3\tilde{G}^{MN}\partial_M\sigma\partial_N\sigma - (\frac{A}{F'(A)^{2/3}} - \frac{F(A)}{F'(A)^{5/3}})]$$

where $\tilde{R}$ is the Ricci scalar formed by $\tilde{G}_{MN}$

$\sigma(x, \phi)$ is the scalar field emerged from higher curvature degrees of freedom.

Defining $\sigma \rightarrow \Phi(x,\phi) = \sqrt{3}\frac{\sigma(x,\phi)}{\kappa}$ the above action takes the form,

$$S = \int d^4x d\phi \sqrt{\tilde{G}}[\frac{\tilde{R}}{2\kappa^2} + \frac{1}{2}\tilde{G}^{MN}\partial_M\Phi\partial_N\Phi - V(\Phi)]$$

where $V(\Phi) = \frac{1}{2\kappa^2}[\frac{A}{F'(A)^{2/3}} - \frac{F(A)}{F'(A)^{5/3}}]$ is the scalar field potential which depends on the form of $F(R)$

Thus the action of $F(R)$ gravity in five dimension is transformed into the action of a scalar-tensor theory by a conformal transformation of the metric.

Consider a five dimensional AdS spacetime with two 3-brane scenario in F(R) model

The form of $F(R)$ is taken as $F(R) = R + \alpha R^2$ where α is a constant with square of the inverse mass dimension
The action for this model is :

$$S = \int d^4x d\phi \sqrt{G} [\frac{1}{2\kappa^2}(R + \alpha R^2) + \Lambda + V_h \delta(\phi) + V_v \delta(\phi - \pi)]$$

where $\Lambda (< 0)$ is the bulk cosmological constant and V_h, V_v are the brane tensions on hidden, visible brane respectively.

Performing a conformal transformation of the metric as

$$G_{MN}(x,\phi) \to \tilde{G}_{MN} = \exp\left(\frac{1}{\sqrt{3}}\kappa\Phi(x,\phi)\right)G_{MN}(x,\phi))$$

the above action can be expressed as a scalar-tensor theory as:

$$\begin{aligned} S &= \int d^4x d\phi \sqrt{\tilde{G}}[\frac{\tilde{R}}{2\kappa^2} + \frac{1}{2}\tilde{G}^{MN}\partial_M\Phi\partial_N\Phi - V(\Phi) \\ &+ \Lambda + \exp\left(-\frac{5}{2\sqrt{3}}\kappa\Phi\right)V_h\delta(\phi) \\ &+ \exp\left(-\frac{5}{2\sqrt{3}}\kappa\Phi\right)V_v\delta(\phi-\pi)] \end{aligned}$$

The quantities in tilde are reserved for ST theory. $\tilde{R}$ is the Ricci curvature formed by the transformed metric $\tilde{G}_{MN}$.

$\Phi(x,\phi)$ is the scalar field corresponds to higher curvature degrees of freedom and $V(\Phi)$ is the scalar potential which for this specific choice form of $F(R)$ has the form,

$$\begin{aligned} V(\Phi) &= \frac{1}{8\kappa^2\alpha}\exp\left(-\frac{5}{2\sqrt{3}}\kappa\Phi\right)\left[\exp\left(\frac{3}{2\sqrt{3}}\kappa\Phi\right)-1\right]^2 \\ &- \Lambda\left[\exp\left(-\frac{5}{2\sqrt{3}}\kappa\Phi\right)-1\right] \end{aligned}$$

The above potential is stable for the parametric regime $\alpha > 0$.
The stable value ($< \Phi >$) as well as the mass squared (m_Φ^2) of the scalar field (Φ) are given by the following two equations

$$\exp\left(\frac{3}{2\sqrt{3}}\kappa < \Phi >\right) = [\sqrt{9 - 40\kappa^2\alpha\Lambda} - 2]$$

and

$$m_\Phi^2 = \frac{1}{8\alpha}[\sqrt{9 - 40\kappa^2\alpha\Lambda}][\sqrt{9 - 40\kappa^2\alpha\Lambda} - 2]^{-\frac{2}{3}}$$

The minimum value of the potential i.e. $V(< \Phi >)$ is non zero and serves as a cosmological constant. Thus the effective cosmological constant in scalar-tensor theory is $\Lambda_{eff} = \Lambda - V(< \Phi >)$ which is also negative indicating an AdS like bulk spacetime

Considering ξ as the fluctuation of the scalar field over its vev, the final form of action for the scalar-tensor theory in the bulk can be written as,

$$\begin{aligned} S &= \int d^4x d\phi \sqrt{\tilde{G}}[\frac{\tilde{R}}{2\kappa^2} + \frac{1}{2}\tilde{G}^{MN}\partial_M\xi\partial_N\xi \\ &- (1/2)m_\Phi^2\xi^2 + \Lambda_{eff}] \end{aligned}$$

where the terms up to quadratic order in ξ are retained for $\kappa\xi < 1$.

This is same as the free massive scalar field action (Goldberger-Wise) for which the stability condition is given as

$$k\pi r_c = \frac{4k^2}{m_\Phi^2} \ln\left[\frac{v_h}{v_v}\right]$$

Expression of m_Φ^2 indicates that r_c in is positive only for $\alpha > 0$.

Thus the chosen $F(R)$ model only with positive α can be transformed to a scalar-tensor theory where the scalar field has positive squared mass and the modulus of the ST theory can be stabilized

Radion field

Consider a fluctuation of branes around the stable separation (r_c). So the inter-brane separation can be considered as a field, and here, for simplicity we assume that this new field depends only on the brane coordinates. The corresponding metric ansatz is,

$$d\tilde{s}^2 = e^{-2kT(x)|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - \tilde{T}^2(x)^2 d\phi^2$$

From the perspective of four dimensional effective theory, $\tilde{T}(x)$ is known as radion field. Remember that the quantities in tilde are reserved for ST theory.

To find the radion mass, a Kaluza-Klein reduction for the five dimensional Einstein-Hilbert action reduces to four dimensional effective action as,

$$S_{kin}[\tilde{T}] = \frac{12M^3}{k} \int d^4x \partial_\mu (e^{-k\pi \tilde{T}(x)}) \partial^\mu (e^{-k\pi \tilde{T}(x)})$$

As we see that $T(x)$ is not canonical and thus we redefine the field by the following transformation,

$$\tilde{T}(x) \longrightarrow \tilde{\Psi}(x) = \sqrt{\frac{24M^3}{k}} e^{-k\pi \tilde{T}(x)}$$

In terms of $\tilde{\Psi}$, the kinetic part of radion field becomes

$$S_{kin}[\tilde{\Psi}] = \frac{1}{2} \int d^4x (\partial_\mu \tilde{\Psi})(\partial^\mu \tilde{\Psi})$$

From the quadratic term of the radion potential the mass term is obtained as

$$\tilde{m}^2_{rad}(ST) = \frac{k^2 v_v^2}{3M^3}\epsilon^2 e^{-2kr_c\pi}$$

with $\epsilon = m_\Phi^2/4k^2$.
Similarly being a gravitational degree of freedom, radion field interacts with brane energy-momentum tensor and the couplings of interaction are constrained by four dimensional general covariance
This coupling between radion and SM fields (Higgs for example) is given by

$$\tilde{\lambda}_{(H-\tilde{\Psi})} = \mu^2\sqrt{\frac{12M^3}{k}}\exp\left(k\pi r_c\right)$$

where μ is mass of Higgs particle

Going back to original F(R) model

Now we turn our focus on modulus stabilization as well as on radion mass for the original $F(R)$ model by using the stabilization condition of the corresponding scalar-tensor theory.

Solutions of metric (G_{MN}) for this $F(R)$ model can be extracted from the solutions of corresponding scalar-tensor theory as

$$ds^2 = e^{-\frac{\kappa}{\sqrt{3}}\Phi(\phi)}[e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2]$$

This immediately leads to the separation between hidden ($\phi = 0$) and visible ($\phi = \pi$) branes along the path of constant x^μ as follows :

$$\pi d = r_c \int_0^\pi d\phi e^{-\frac{\kappa}{2\sqrt{3}}\Phi(\phi)}$$

where d is the inter-brane separation in $F(R)$ model.

Using the explicit functional form of $\Phi(\phi)$, above equation can be integrated out to have

$$k\pi d = k\pi r_c - \frac{4k^2}{m_\Phi^2}\frac{\kappa v_v}{2\sqrt{3}}[\frac{v_h}{v_v} - 1]$$

where the sub-leading terms of $\kappa\xi$ are neglected.

r_c is the modulus in the corresponding ST theory and it is shown to be stabilized

So, it can be argued that due to the stabilization of ST theory, the modulus d in $F(R)$ model is also stabilized with a value,

$$k\pi d = \frac{4k^2}{m_\Phi^2}[\ln(\frac{v_h}{v_v}) - \frac{\kappa v_v}{2\sqrt{3}}(\frac{v_h}{v_v} - 1)]$$

Hence it can be concluded that $F(R)$ model where the only independent field is spacetime metric (G_{MN}), is a self stabilizing system.

From the expression of m_{Φ}^2 , it is clear that d goes to zero at the limit $\alpha \to 0$.

Moreover for $\alpha < 0$, m_{Φ}^2 becomes negative which in turn makes the modulus d negative which is an unphysical situation.

Therefore the self stabilization in $F(R)$ model arises entirely due to the presence of higher curvature term αR^2 only when $\alpha > 0$.

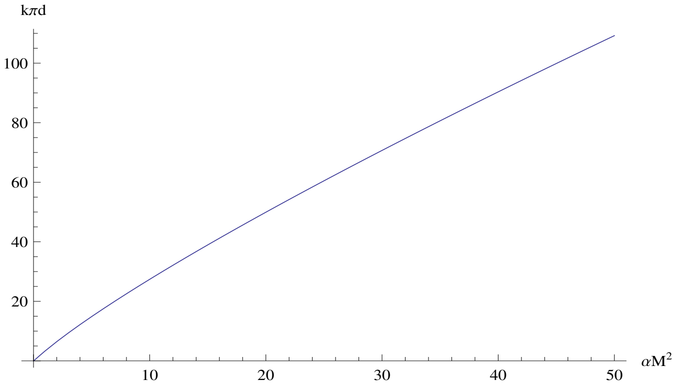


Figure: $k\pi d$ vs αM^2

The figure demonstrates that the brane separation (d) increases with the higher curvature parameter α.

A fluctuation of branes around the stable configuration d is now considered. This fluctuation can be taken as a field ($T(x)$)
The metric takes the form,

$$ds^2 = e^{-\frac{\kappa}{\sqrt{3}}\Phi(x,\phi)} \quad [\quad e^{-2kT(x)|\phi|}\eta_{\mu\nu}dx^{\mu}dx^{\nu} - T(x)^2 d\phi^2]$$

Following similarly,the potential part of radion field is

$$V(\Psi) \quad = \quad \frac{20}{\sqrt{3}}\frac{\alpha k^5}{M^6}\Psi^4[v_v - (v_h - \frac{\kappa v_h^2}{2\sqrt{3}} + \frac{\kappa v_h v_v}{2\sqrt{3}})(\Psi/f)^{\epsilon}]^2$$

From this the squared mass of radion field in the F(R) model is ,

$$m_{rad}^2(F(R)) \quad = \quad \frac{20}{\sqrt{3}}\frac{\alpha k^4}{M^6}\epsilon^2 e_h^{-2kd\pi 2} v_v^2$$
$$[\quad 1 + \frac{40}{\sqrt{3}}\alpha k^2 \kappa v_h][\frac{v_h}{v_v} - 1]^2$$

It is noticed that the mass of radion field is enhanced by the higher curvature terms in five dimensional gravitational action.

Using the result of scalar-tensor model, the coupling between Higgs and the radion in the F(R) model is

$$\lambda_{(H-\delta\Psi)} \quad = \quad \mu^2\sqrt{\frac{k}{24M^3}}e^{k\pi d}[1-\frac{20}{\sqrt{3}}\alpha k^2\kappa v_h]$$

in the leading order of κ.

We see that the coupling between radion and SM fields is suppressed due to the presence of higher curvature parameter α which in turn modifies the phenomenology on visible 3-brane by lowering the detectability of radion

1. The modulus field in the warped geometry scenario can be stabilized in purely geometrical way
2. Appealing to plausible quantum corrections to the Einstein-Hilbert action, we trade the higher derivatives of the metric tensor for an equivalent scalar field with a potential depending on the nature of higher curvature terms
3. On going over to the scalar tensor theory the corresponding potential is seen to have a local minimum leading to an negative effective bulk cosmological constant, and a fluctuation field with a naturally small mass
4. The resulting framework leads to the stabilization of the modulus and correct hierarchy for a wide range of parameters
5. The analysis was generalized to $F(R) = R + \alpha R^2 + \beta R^4$ leading to the Freedman et.al quartic scalar potential where backreaction can be included

Conclusion

1. Warped geometry models with Einstein's gravity in the bulk – has modulus stability problem
2. To stabilize the modulus one needs to include ad-hoc scalar field
3. Go beyond Einstein's gravity in the bulk due to it's Planckian curvature scale and include higher curvature quantum gravity terms
4. They may now produce geometric modulus stabilization in a natural way – where the degrees of freedom in the higher curvature terms play the role of a stabilizing field
5. To determine the modulus stabilization and corresponding radion dynamics around the stable value the higher curvature gravity theory can be mapped to corresponding scalar tensor theory where calculation becomes simpler
6. Higher curvature corrections lead to the stability of the modulus in a natural way