Holographic self tuning of the cosmological constant

Based on: CC, Kiritsis, Nitti hep-th/1704.05075

LPT Orsay, CNRS

COSMOGRAV:2018

1 Introduction: gravity and the cosmological constant

2 Self-tuning

3 Revisiting self tuning for a brane Universe

4 The holographic picture

5 Conclusions

GR is a unique theory

- Theoretical consistency: In 4 dimensions, consider $\mathcal{L} = \mathcal{L}(\mathcal{M}, g, \nabla g, \nabla\nabla g)$. Then Lovelock's theorem in $D = 4$ states that GR with cosmological constant is the unique metric theory emerging from,

$$S_{(4)} = \int_{\mathcal{M}} d^4x \sqrt{-g^{(4)}} \, [R - 2\Lambda]$$

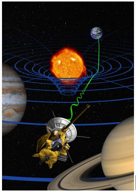
giving,

  - Equations of motion of 2^{nd}-order (Ostrogradski no-go theorem 1850!)
  - given by a symmetric two-tensor, $G_{\mu\nu} + \Lambda g_{\mu\nu}$
  - and admitting Bianchi identities.

Under these hypotheses GR is the unique massless-tensorial 4 dimensional theory of gravity!

Observational data

- Experimental consistency:
  -Excellent agreement with solar system tests and strong gravity tests on binary pulsars
  -Observational breakthrough GW170817: Non local, $40Mpc$ and strong gravity test from binary neutron stars. $c_T = 1 \pm 10^{-15}$

Time delay of light  Planetary tajectories 

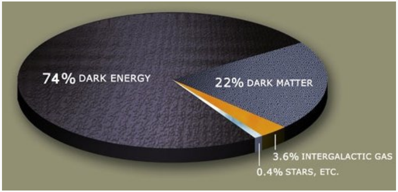

Neutron star binary

Q: What is the matter content of the Universe today?

Assuming homogeinity-isotropy and GR

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

cosmological and astrophysical observations dictate the matter content of the Universe today:



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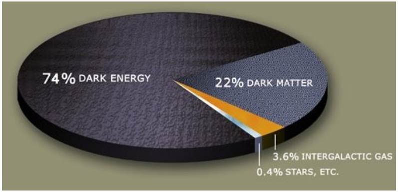

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If we assume only ordinary sources of matter (DM included) there is disagreement between local, astrophysical and cosmological data.

Universe is accelerating $\rightarrow$ Enter the cosmological constant

Easiest way out: Assume a tiny cosmological constant $\rho_\Lambda = \frac{\Lambda_{obs}}{8\pi G} = (10^{-3} eV)^4$, ie modify Einstein's equation by,

$$G_{\mu\nu} + \Lambda_{obs} g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- Cosmological constant introduces $\sqrt{\Lambda}$ and generates a cosmological horizon
- $\sqrt{\Lambda}$ is as tiny as the inverse size of the Universe today, $r_0 = H_0^{-1}$
- Note that $\frac{\text{Solar system scales}}{\text{Cosmological Scales}} \sim \frac{10 \text{ A.U.}}{H_0^{-1}} = 10^{-14}$
- Theoretically the cosmological constant should be huge: Λ
- Is gravity modified at large distances? Can modified gravity hide the cosmological constant?

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Example modified gravity theories

- Assume extra dimensions : Extension of GR to Lovelock theory with modified yet second order field equations. Braneworlds models, String theory and holography, emergent gravity...
- Graviton is not massless but massive! dRGT and bigravity theory.
- 4-dimensional modification of GR:
  - Scalar-tensor theories, $f(R)$, Galileon/Hornedski theories $\rightarrow$ Beyond Horndeski and DHOST theories.
  - Vector-tensor theories
- Lorentz breaking theories: Horava gravity, Einstein Aether theories
- Theories modifying geometry: inclusion of torsion, choice of geometric connection

Can additional degrees of freedom be used to self tune the cosmological constant to small or zero value?

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Self-Tuning idea

- Expected value of the cosmological constant is enormous compared to the observed value
- Weinberg's no go theorem states that we cannot have a Poincare invariant vacuum without fine-tuning $\Lambda = 0$
- Question: Can we break Poincare invariance for some additional field?
- Keep $g_{\mu\nu} = \eta_{\mu\nu}$ locally but allow for $\phi \neq \textit{constant}$.
- Can we have a portion of flat spacetime whatever the value of the cosmological constant...
- which can change values in time,
- and without fine-tuning any of the parameters of the theory?
- Toy model theory of self-adjusting scalar field.

We will discuss:

- A holographic brane universe in 5 dimensions

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Self tuning scalar tensor theories in 4 dimensions

- Higher order scalar tensor theories allow for theories with self-tuning properties, Fab 4 [CC,Copeland, Padilla, Saffin]...can be extended to self tuning theories of de Sitter [Gubitosi, Linder, Appleby]
- Self tuning black hole solutions can be found in a large class of shift symmetric Horndeski and $c_T = 1$ theories [Babichev, CC], [Babichev, CC, Esposito-Farèse, Lehébel]
- Simple example solution :

$$ds^2 = -A(r)\,dt^2 + \frac{dr^2}{A(r)} + r^2\left(d\theta^2 + \sin^2\theta\,d\phi^2\right),$$

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$$q^2 = \Lambda - \Lambda_{\text{eff}}$$

- Λ_{eff} depends on couplings of the theory. q self tuning integration constant
- Solution agrees with local GR constraints and has identical spin 2 perturbations to GR ($c_T = 1$)
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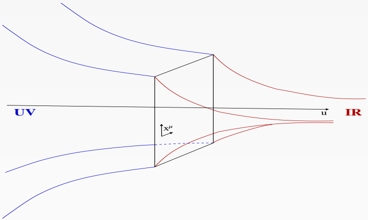
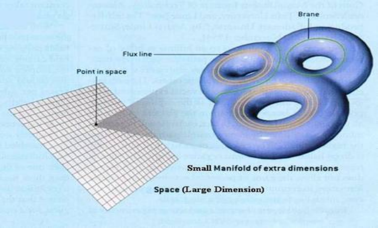
Gravity in higher dimensions



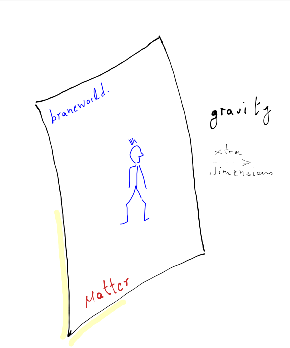


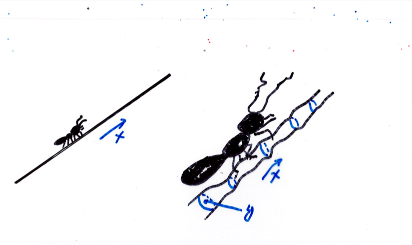
- Inspired from string theory
- small compact extra dimensions, the Kaluza-Klein paradigm relates higher dimensional metric theories to 4 dimensional modified gravity theories. Origin of Horndeski theory
- Braneworld idea : A negative cosmological constant can accommodate large extra dimensions (RS models).
  Interplay in-between induced and bulk gravity can modify gravity at large distances (DGP model).
- Cutting and pasting, using junction conditions, of portions of adS or flat spacetime

Braneworld

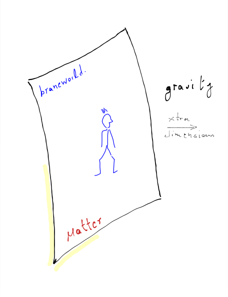
Central idea

Matter lives on a distributional brane
gravity lives in a higher dimensional space-time





The RS model [Randall, Sundrum '99]



Can we perceive 4 d gravity in an infinite 5 d spacetime?

Yes, in adS cutting off the UV boundary $ds^2 = du^2 + e^{-2u/l}\eta_{\mu\nu}dx^\mu dx^\nu$.
Brane at $u = 0$
we are keeping $u \in [0, +\infty[$ (IR) on both sides of the brane.
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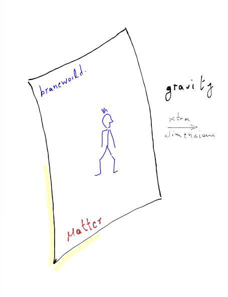
- Consider a 4 dimensional brane separating two IR copies of 5 dimensional adS. IR=Finite proper volume.
- Flat brane solution imposes fine tuning in between positive brane tension and negative bulk cosmological constant.
- cosmological constant problem for braneworlds

The RS model [Randall, Sundrum '99]

Can we perceive 4 d gravity in a infinite 5 d spacetime?

- Gravity fluctuations tell us that we have a localised 4 dimensional graviton due to the warped IR properties of adS. Gravity becomes 5 dimensional at high enough energies (UV)
- For RS we cut off the UV boundary of adS. Had we kept the UV we would have delocalised the graviton and localised the (normalisable) radion with a negative tension brane.

The RS model [Randall, Sundrum '99]



Can we self tune the CC? Relax tuning between brane tension and bulk cc?

- Introduce a bulk scalar field in order to relieve the fine tuning [Arkani-Hamed, Dimopoulos, Kaloper, Sundrum, 2000], [Kachru, Schulz, Silverstein, 2000]

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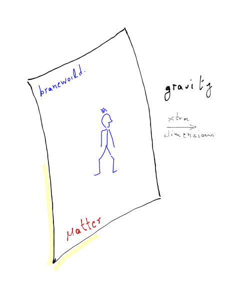

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Braneworld self tuning [Arkani-Hamed, Dimopoulos, Kaloper, Sundrum, 2000], [Kachru, Schulz, Silverstein, 2000],...,[Csaki, Erlich, Grojean, Hollowood]

- Consider a 4 dimensional brane separating two bulk spacetimes with scalar field and cosmological constant
- Presence of scalar permits additional integration constant(s) which permits an arbitrary position of the brane (radion) and self tuned brane tension
- But, we either have good 4 dim gravity on the brane but a bad naked singularity in the bulk, or,
- We have self tuning regular geometry but with non standard gravity on the brane
- IR spoils regularity and UV spoils gravity

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- Consider a 4 dimensional brane separating two bulk spacetimes with scalar field and cosmological constant
- Presence of scalar permits additional integration constant(s) which permits an arbitrary position of the brane (radion) and self tuned brane tension
- But, we either have good 4 dim gravity on the brane but a bad naked singularity in the bulk, or,
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1 Introduction: gravity and the cosmological constant

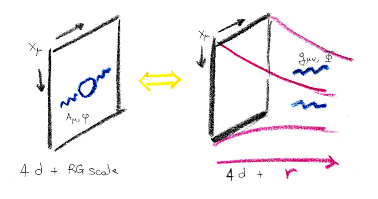
2 Self-tuning

3 Revisiting self tuning for a brane Universe

4 The holographic picture

5 Conclusions

Holographic picture



AdS/CFT conjectures that certain QFT's are equivalent to gravity theories in higher dimensions [Maldacena]

- CFT in d dimensions $\longleftrightarrow$ adS in $d+1$ dimensions
  $ds^2 = du^2 + e^{-2u/l}\eta_{\mu\nu}dx^\mu dx^\nu$ with u dual to $E \sim e^{-u/l}$
  $u \in [-\infty, +\infty] \equiv [UV\partial, IR]$
- Bulk scalar $\phi = \phi(u)$ corresponds to the breaking of conformal invariance
  $ds^2 = du^2 + e^{A(u)}\eta_{\mu\nu}dx^\mu dx^\nu$ with $E \sim e^{A(u)}$ and $\beta = \frac{d\phi}{dA}$
- Scalar is dual to a relevant scalar operator $\mathcal{O}$ breaking the CFT,
  $S_{QFT} = S_{CFT} + g_0 \int d^4x\, \mathcal{O}$
  Metric is dual to the stress tensor of the CFT

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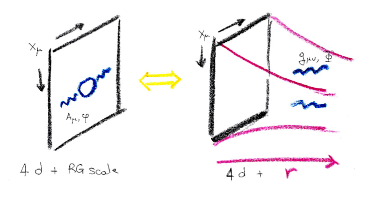

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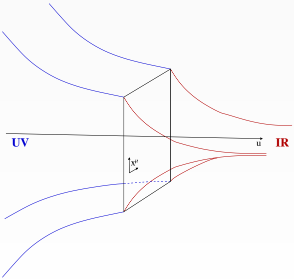
Holographic Ingredients

We will consider the following :

- A 4 dim large N strongly coupled (C$\xrightarrow{\mathcal{O}}$Q)FT deformed by a relevant operator $\mathcal{O}$
- The weakly coupled standard model including an arbitrary cosmological constant and radiative corrections
- Some heavy messengers of large mass scale Λ coupling the 2 theories together.



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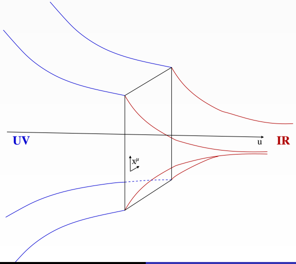

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- The weakly coupled standard model including an arbitrary cosmological constant and radiative corrections$\longrightarrow$ 4 dim brane coupled to bulk fields $r >> \frac{1}{\Lambda}$
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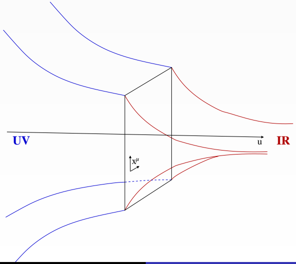
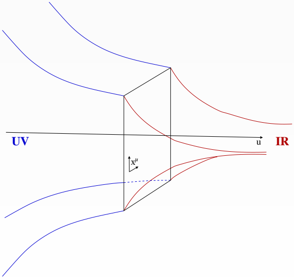


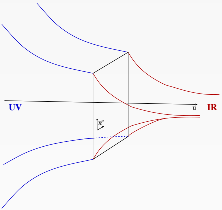
Holographic Ingredients

We will consider the following :
semi-holographic description :

- 5 dimensional dual gravity theory with metric and bulk scalar asymptoting a UV complete theory at the boundary
- A 4 dim localised brane sandwiched in between a UV and IR region of bulk gravity
- Brane includes all possible two derivative couplings of matter to bulk quantities including induced gravity term ([DGP] model)



Action



$$S = M^3 \int d^4x \int du \sqrt{-g} \left[R - \frac{1}{2} g^{ab} \partial_a \varphi \partial_b \varphi - V(\varphi) \right]$$

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- The potential $V(\phi)$ sets the bulk theory
- Quantum effects from localized fields induce localized effective potentials $W_B(\phi), Z(\phi), U(\phi)$ [DGP]. Generically, $W_B \sim \Lambda^4$ and $Z = U \sim \Lambda^2$
- Λ is the UV cutoff and W_B includes brane fields vacuum energy.

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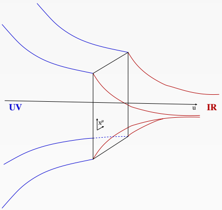

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- Define : $\dot{A} = -\frac{1}{6} W(\phi)$ and $\dot{\phi} = \frac{dW(\phi)}{d\phi}$ [De Wolfe, Freedman, Gubser, Karch]
- where $W(\phi) = W_{UV}(\phi)$ for $\phi < \phi_0$ and $W(\phi) = W_{IR}(\phi)$ for $\phi > \phi_0$
- Dynamics : Einstein bulk and Israel matching conditions.
- Bulk on each side : $-\frac{1}{3} W(\phi)^2 + \frac{1}{2} \left(\frac{dW(\phi)}{d\varphi} \right)^2 = V(\phi)$ giving C_{UV}, C_{IR} integration constants on each side
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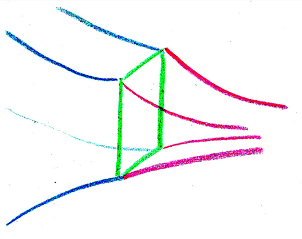

The model has the following ingredients/characteristics:

- The UV boundary of adS with the strongly coupled CFT.
- The IR
- An induced gravity term
- Brane Universe with SM flowing from the UV to IR.
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- Is there a stable flat brane solution which self tunes? Is there an emergent and stable gravity which is 4 dimensional?

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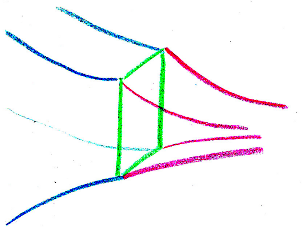

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UV bulk behavior

In the UV: $u \in]-\infty, u_0]$, we impose $e^A(u) \sim e^{-u/l} \xrightarrow[u\to-\infty]{} +\infty$ (asymptotically close to an adS boundary).

- We require that V has a local maximum, typically $V \sim -\frac{d(d-1)}{l^2} + \frac{m^2}{2}\phi^2 + \ldots$
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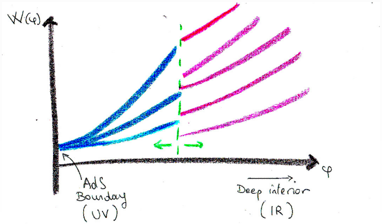
- We flow to a UV fixed point which is an attractor
- This is true for a family of solutions parametrized by some C_{UV} which are regular and converge as we flow to the UV.
- In other words in the UV we have regularity and a free integration constant but infinite volume.



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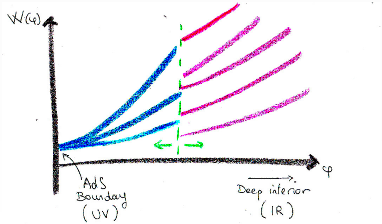

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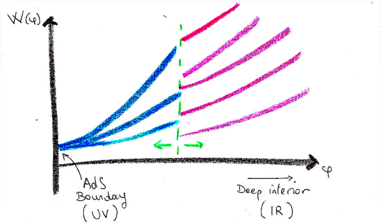

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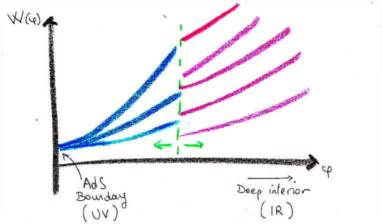

IR bulk behavior

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We have three differing asymptotic solutions: 1 regular, 2 singular.

- We can flow back to AdS (IR conformal fixed point) when $\phi \sim \phi_{IR}$
  Our metric is regular $e^{A(u)} \sim e^{-u/l}$ and $V(\phi), W_{IR}$ have a local minimum (similar to RS). We are asymptoting the Poincaré horizon in adS interior. This is an isolated solution.
- $V(\phi)$ has a runaway behaviour $V(\phi) \sim -V_\infty e^{b\phi}$ with $b > 0$ and $V_\infty > 0$ giving two distinct classes
- A solution parametrized by an integration constant with bad singularity [Gubser]
  $W_{IR}(\phi) \sim C_{IR} e^{Q\phi}$ as $\phi \to \infty$ and $Q = \sqrt{\frac{d}{2(d-1)}}$
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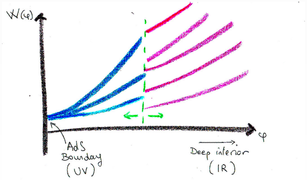

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- $V(\phi)$ has a runaway behaviour $V(\phi) \sim -V_\infty e^{b\phi}$ with $b > 0$ and $V_\infty > 0$ giving two distinct classes
- A solution parametrized by an integration constant with bad singularity [Gubser] $W_{IR}(\phi) \sim C_{IR} e^{Q\phi}$ as $\phi \to \infty$ and $Q = \sqrt{\frac{d}{2(d-1)}}$
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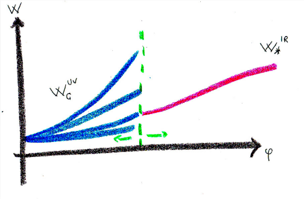
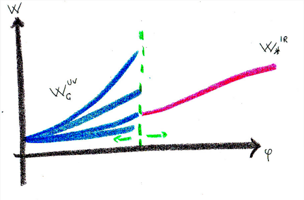


Self tuning



- Regularity fixes completely the IR side.
- Junction conditions:
  $W^{UV}(\varphi_0) = W^{IR}(\varphi_0) - W^B(\varphi_0) \qquad \partial_\varphi W^{UV}(\varphi_0) = \left(\partial_\varphi W^{IR} - \partial_\varphi W^B\right)(\varphi_0)$
  Bulk equation : $-\frac{1}{3}W(\phi)^2 + \frac{1}{2}\left(\frac{dW(\phi)}{d\varphi}\right)^2 = V(\phi)$
- The IR fixes completely the brane position $\phi = \phi_0$. No massless radion in the setup.
- On the UV side C_{UV} on the other hand parametrizes a family of solutions that flow to the UV fixed point for "any" W_B.
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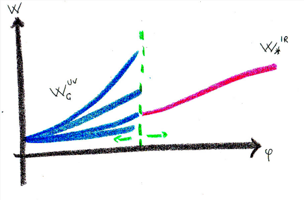

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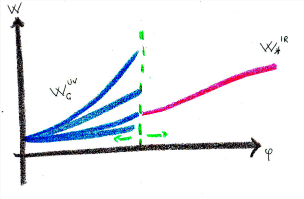

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Brane and bulk fluctuations

$$S = M^3 \int d^4x \int du \sqrt{-g}\left[R - \frac{1}{2}g^{ab}\partial_a\varphi\partial_b\varphi - V(\varphi)\right]$$
$$+M^3 \int_{\Sigma_0} d^4\sigma \sqrt{-\gamma}\left[-W_B(\varphi) - \frac{1}{2}Z(\varphi)\gamma^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + U(\varphi)R^{(\gamma)} + \dots\right].$$

Gravity fluctuations around our self tuning vacuum will tell us :
-the nature of emergent 4 dim gravity and
-stability (no ghosts no tachyons).
one tensor and two scalar modes (brane bending mode and bulk scalar)

There are three important ingredients in the model: the DGP term, the scalar bulk fluctuations and non trivial bulk gravity

- The DGP term dictates that up to some scale we will have 4 dim massless gravity for $r < r_c = \frac{U(\phi_0)}{2}$
- Non trivial bulk will modify DGP type phenomenology. The relevant scale here is $r_t = \frac{e^{A_0}}{W_{UV}(\phi_0)}$ and induces 4 dim massive gravity $r > r_t$
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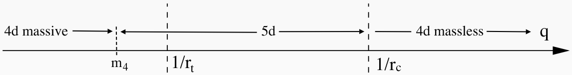
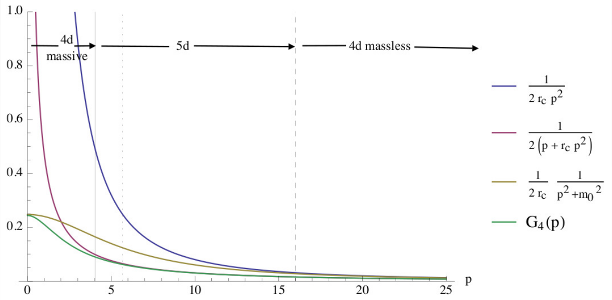
$r_c \sim U(\phi_0) < r_t \sim e^{A_0}/W_{UV}(\phi_0)$

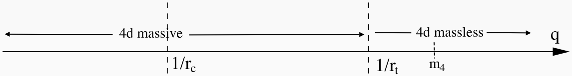


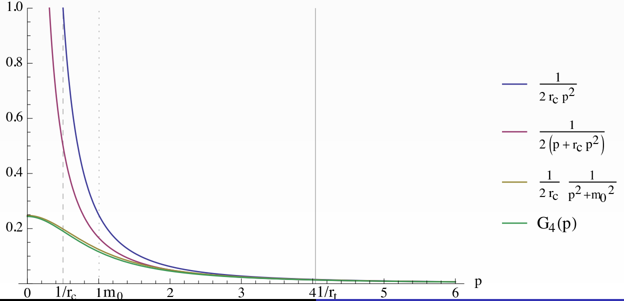


Spin 2 fluctuations

$r_c \sim U(\phi_0) > r_t \sim e^{A_0}/W_{UV}(\phi_0)$

Typically, $M_{Pl}^2 \sim M^3 U_0$ and $m_g^2 \sim W_{UV}(\phi_0)/U_0$





Scalar fluctuations

Scalar perturbations dictate the presence of two scalars: a heavy radion and a light scalar associated to brane bending

Light scalars have to be dealt with beyond linear order

- Absence of ghosts if :

  $$\tau_0 = 6\left(6\frac{W_B}{W_{IR}W_{UV}}\bigg|_{\varphi_0} - U_0\right) > 0, \quad Z_0 > 0, \quad Z_0\tau_0 > 36\left(\frac{dU_B}{d\varphi}\bigg|_{\varphi_0}\right)^2$$

  at the brane position $\phi = \phi_0$. For example for negative tension branes have to analyse individual model.

- Absence of tachyons if : $\tilde{\mathcal{M}}^2 = \left(\frac{d^2 W_B}{d\varphi^2}(\varphi_0) - \left[\frac{d^2 W}{d\varphi^2}\right]_{UV}^{IR}\right) > 0$

1 Introduction: gravity and the cosmological constant

2 Self-tuning

3 Revisiting self tuning for a brane Universe

4 The holographic picture

5 Conclusions

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- Although self tuning can be implemented even in black hole cases, viability of the mechanism is difficult.
- Need more space to eventually hide the cosmological constant-although it may pop up somewhere else.
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