Self tuning the cosmological constant

Based on: CC, Copeland, Padilla, Saffin hep-th/1106.2000
CC, Kiritsis, Nitti hep-th/1704.05075

LPT Orsay, CNRS

Corfu Summer Institute: Workshop on the Standard Model and Beyond

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,

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

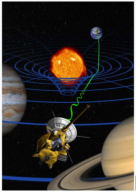
giving,

  - Equations of motion of 2^{nd}-order
  - given by a symmetric two-tensor, $G_{\mu\nu} + \Lambda g_{\mu\nu}$
  - and admitting Bianchi identities.

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

Experimental and observational data for local scales

- Experimental consistency:
  -Excellent agreement with solar system tests
  -Strong gravity tests on binary pulsars
  -Gravity waves
  -Laboratory tests of Newton's law (tests on extra dimensions)

Time delay of light  Planetary tajectories 

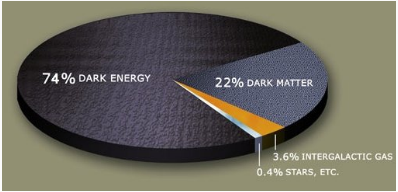
...

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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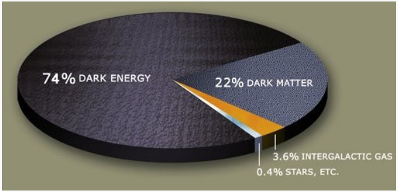

A: -Only a 4% of matter has been discovered in the laboratory. We hope to see more at LHC. But even then...

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

Universe is accelerating → 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 $\frac{\text{Solar system scales}}{\text{Cosmological Scales}} \sim \frac{10 \text{ A.U.}}{H_0^{-1}} = 10^{-14}$
- Typical mass scale for neutrinos...
- Theoretically the cosmological constant should be huge.

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Cosmological constant behaves as vacuum energy which according to the strong equivalence principle gravitates,

- Vacuum energy fluctuations are at the UV cutoff of the QFT $\Lambda_{vac}/8\pi G \sim m_{Pl}^4 \cdots$
- Vacuum potential energy from spontaneous symmetry breaking $\Lambda_{EW} \sim (200 GeV)^4$
- Bare gravitational cosmological constant Λ_{bare}

$\Lambda_{obs} \sim \Lambda_{vac} + \Lambda_{pot} + \Lambda_{bare}$

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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 with $\Lambda \neq 0$
- Question: Can we break Poincare invariance for some additional field?
- Keep $g_{\mu\nu} = \eta_{\mu\nu}$ locally but allow for $\phi \neq \mathit{constant}$.
- 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 investigate:

1. A general scalar tensor theory in 4 dimensions
2. A holographic brane universe in 5 dimensions

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General scalar tensor theory

- Consider ϕ and $g_{\mu\nu}$ as gravitational DoF.
- Consider $\mathcal{L} = \mathcal{L}(g_{\mu\nu}, g_{\mu\nu,i_1}, \dots, g_{\mu\nu,i_1 \dots i_p}, \phi, \phi_{,i_1}, \dots, \phi_{,i_1 \dots i_q})$ with $p, q \geq 2$ but finite
- $\mathcal{L}$ has higher than second derivatives

What is the most general scalar-tensor theory giving second order field equations?

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What is the most general scalar-tensor theory giving second order field equations?

Horndeski theory [Horndeski 1973]

What is the most general scalar-tensor theory

with second order field equations [Horndeski 1973]?

Horndeski has shown that the most general action with this property is

$$S_H = \int d^4x \sqrt{-g}\,(L_2 + L_3 + L_4 + L_5)$$

$$\begin{aligned}
L_2 &= K(\phi, X), \\
L_3 &= -G_3(\phi, X)\Box\phi, \\
L_4 &= G_4(\phi, X)R + G_{4X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right], \\
L_5 &= G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{G_{5X}}{6}\left[(\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]
\end{aligned}$$

the G_i are free functions of ϕ and $X \equiv -\frac{1}{2}\nabla^\mu\phi\nabla_\mu\phi$ and $G_{iX} \equiv \partial G_i/\partial X$.

Which subset of Horndeski self-tunes the cc?

Starting from general scalar-tensor theory with a cosmological constant, Horndeski

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-Admitting flat space time solution with a time dependent scalar
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$$\begin{aligned}
\mathcal{L}_{john} &= \sqrt{-g}\, V_{john}(\phi) G^{\mu\nu} \nabla_\mu\phi \nabla_\nu\phi \\
\mathcal{L}_{paul} &= \sqrt{-g}\, V_{paul}(\phi) (*R*)^{\mu\nu\alpha\beta} \nabla_\mu\phi \nabla_\alpha\phi \nabla_\nu\nabla_\beta\phi \\
\mathcal{L}_{george} &= \sqrt{-g}\, V_{george}(\phi) R \\
\mathcal{L}_{ringo} &= \sqrt{-g}\, V_{ringo}(\phi) \hat{G}
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- All are scalar-tensor interaction terms. In fact they are unique all emerging from KK reduction of Lovelock theory.
- Theory depends on 4 arbitrary potentials $V = V_{fab4}(\phi)$.
- Fab 4 theory self-tunes the cosmological constant to flat space. Note that at the absence of curvature Fab 4 terms drop out.
- Adding a standard kinetic term self tunes to de Sitter [Gubitosy, Linder]

Example self tuning solution

Consider a slowly varying scalar field in the presence of an arbitrary cc in a time evolving universe,

- Fab 4 Potentials analytic expansion:

$$V_{john} = C_j \, , V_{paul} = C_p \, , V_{george} = C_g + C_g^1 \, \phi \, , V_{ringo} = C_r + C_r^1 \, \phi - \frac{1}{4} C_j \, \phi^2$$

- Flat spacetime: Milne metric $ds^2 = -dt^2 + t^2 \left(\frac{d\chi^2}{1+\chi^2} + \chi^2 d\Omega^2 \right)$
- Friedmann equation reads,

$$c_j(\dot{\phi}H)^2 - c_p(\dot{\phi}H)^3 - c_g^1(\dot{\phi}H) + \rho_\Lambda = 0$$

  with matter source $\rho_\Lambda = \Lambda$, vacuum cosmological constant. Note that $\dot{\phi}H$ appear as homogeneous powers of time.
- Hence since $H = 1/t$ for Milne, taking $\phi = \phi_0 + \phi_1 t^2$ gives $c_j(\phi_1)^2 - c_p(\phi_1)^3 - c_g^1(\phi_1) + \rho_\Lambda = 0$ a constant constraint.
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- Hence since $H = 1/t$ for Milne, taking $\phi = \phi_0 + \phi_1 t^2$ gives $c_j(\phi_1)^2 - c_p(\phi_1)^3 - c_g^1(\phi_1) + \rho_\Lambda = 0$ a constant constraint.
- Integration constant ϕ_1 is fixed by the cosmological constant for arbitrary values of the theory potentials.

Example self tuning solution

Consider a slowly varying scalar field in the presence of an arbitrary cc in a time evolving universe,

- Fab 4 Potentials analytic expansion:

$$V_{john} = C_j \, , V_{paul} = C_p \, , V_{george} = C_g + C_g^1 \, \phi \, , V_{ringo} = C_r + C_r^1 \, \phi - \frac{1}{4} C_j \, \phi^2$$

- Flat spacetime: Milne metric $ds^2 = -dt^2 + t^2 \left(\frac{d\chi^2}{1+\chi^2} + \chi^2 d\Omega^2 \right)$
- Friedmann equation reads,

$$c_j(\dot{\phi}H)^2 - c_p(\dot{\phi}H)^3 - c_g^1(\dot{\phi}H) + \rho_\Lambda = 0$$

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The RS model [Randall, Sundrum '99]

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

Yes, in adS cutting off the UV boundary

$ds^2 = du^2 + e^{-2u/l}\eta_{\mu\nu}dx^\mu dx^\nu$

- 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. CC problem

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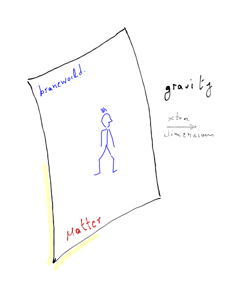

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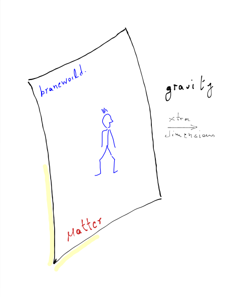

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- Gravity fluctuations tell us that we have a localised 4 dimensional graviton due to the IR properties of adS. Gravity becomes 5 dimensional at high enough energies
- For RS we cut off the UV boundary of adS. Had we kept the UV we would have delocalised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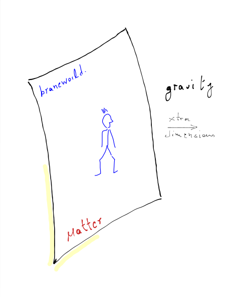

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Braneworld self tuning [Csaki, Erlich, Grojean, Hollowood]

- 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 not fine 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
- One can try several ways to remedy the situation which always lead to some stability, fine tuning or phenomenological problems
- IR spoils regularity and UV spoils gravity

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Holographic self tuning

However, developments in holography and modification of gravity give us two novel ingredients:

- In holography certain milder singularities are permissible in the sense that they are resolvable. They admit two basic properties:
  - An infinitesimal temperature fluctuation cloaks the singularity with an event horizon (Gubser criterion).
  - The relevant Sturm Liouville problem is well defined (IR completeness).
  - Regularity severely restricts the IR side.
- We need the UV in order to have freedom in the dynamics.
- In order to have 4 dimensional effective gravity on the brane we can use an induced gravity term. But yet again an induced gravity term can lead to a ghost scalar [CC, Gregory, Padilla]

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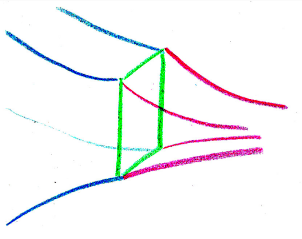

The model has the following ingredients/characteristics:

- The UV boundary of adS with the strongly coupled CFT.
- An IR fixed point or an IR resolvable singularity.
- The 5d gravity dual metric and scalar representing the running coupling of an operator deforming the CFT.
- Brane Universe with SM matter flows dynamically from the UV to the IR.
- Junction conditions glue together the UV and IR region.
- Is there a stable flat solution which self tunes? Is there an emergent gravity which is 4 dimensional?

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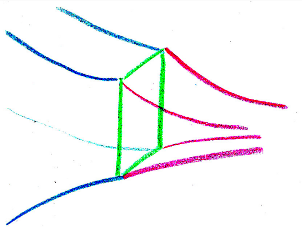

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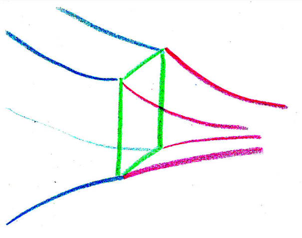

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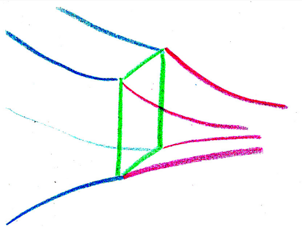

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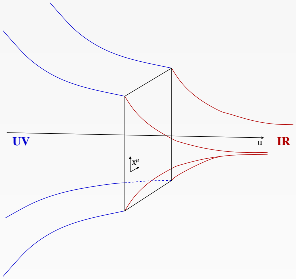
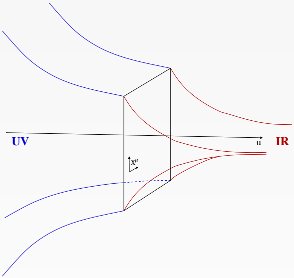


$$S = M^3 \int d^4x \int du \sqrt{-g}\left[R - \frac{1}{2} g^{ab}\partial_a\varphi\partial_b\varphi - V(\varphi)\right]$$

$$+M^3 \int_{\Sigma_0} d^4\sigma \sqrt{-\gamma}\left[-W_B(\varphi) - \frac{1}{2} Z(\varphi)\gamma^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + U(\varphi)R^{(\gamma)} + \ldots\right].$$

- The potential V parametrizes completely the bulk theory. It is parametrized by two superpotentials W_{UV} and W_{IR}, [De Wolfe, Freedman, Gubser, Karch] at the UV and IR side
- The brane potentials are induced from the bulk scalar tensor dynamics. W_B corresponds to a generic potential including the cosmological constant on the brane.



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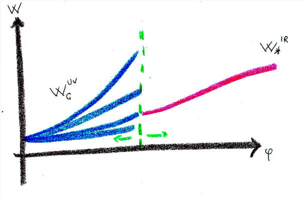
- The brane potentials are induced from the bulk scalar tensor dynamics. W_B corresponds to the potential including the cosmological constant on the brane.
- Dynamics are driven from the Einstein bulk and Israel matching conditions. Bulk: $-\frac{1}{3}W^2 + \frac{1}{2}\left(\frac{dW}{d\varphi}\right)^2 = V$
  Brane: $W_{IR} - W_{UV}\big|_{\varphi_0} = W_B(\varphi_0)$, $\frac{dW_{IR}}{d\varphi} - \frac{dW_{UV}}{d\varphi}\Big|_{\varphi_0} = \frac{dW_B}{d\phi}(\varphi_0)$

Self tuning



- Generically we have two integration constants issued from the bulk field equation. C_{UV} and C_{IR}. We have also two junction conditions to satisfy.
- Regularity fixes completely the IR side of the solution. Otherwise we always have a bad naked singularity.
- The IR fixes completely the brane position. No radion in the setup.
- C_{UV} on the other hand is completely free and parametrizes a family of solutions that flow to the UV fixed point (attractor) for any W_B.
  Any W_B therefore is fixed by an integration constant C_{UV}
- Gravity fluctuations tell us of the stability and effective gravity of the brane universe. Model is stable for large range of parameters due to the presence of bulk scalar. Two effective scales appear: the DGP scale and the crossover scale. Their relative values fix the gravitational spectrum within these class of models. Gravity interpolates in between a $4d$ massless to $4d$ massive gravity theory at large distances.

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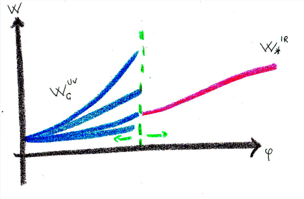

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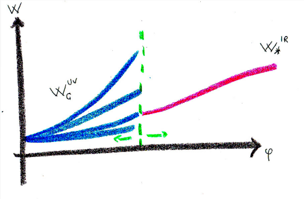

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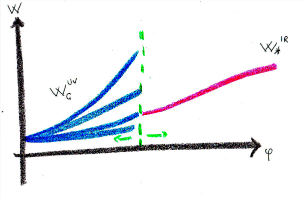

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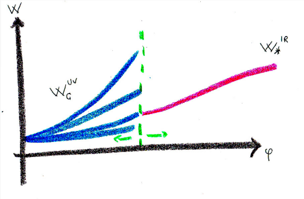

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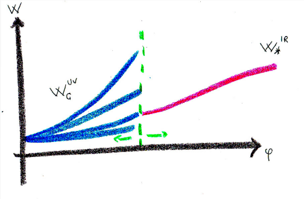

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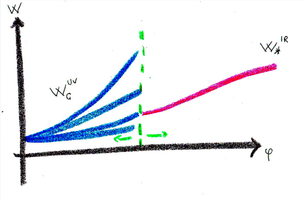

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