Dilaton gravity in brane scenarios and the large-scale structure challenge

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Outline

- introduction
- at the brane: effective Einstein-like equation
- AdS$_5$ bulk: large-scale structure on the brane?
- conclusions

beyond General Relativity

- ongoing search for a unified description of
  - gravity
  - gauge interactions of the Standard Model
  - ↪ *string theories* amongst the most promising proposals
- *low-energy effective action* in string theories (only massless modes)
  [Zwiebach(1985), Boulware,Deser(1985-1986), Metsaev,Tseytlin(1987), Gross,Sloan(1987)]
  - depending on the string theory type: includes terms for various particles
    - *dilaton* (ϕ): scalar field accompanying gravity (common for all string theories)
  - at the leading order (when restricted to gravity and the dilaton)
  - ↪ Einstein's gravity coupled to the dilaton
  - in a spacetime with additional spatial dimensions
  - ↪ i.e. an extended, higher-dimensional theory of gravity: *dilaton gravity*
- dilaton gravity in a 5d brane scenario
  - Standard Model localized on a 4d brane embedded in a 5d spacetime

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scalar-tensor theories of gravity & conformal frames

- *dilaton gravity*: a scalar-tensor theory of gravity
  - ↪ can be formulated in various conformally-related frames
    - ⥀ $g_{\mu\nu}$ & $\widetilde{g}_{\mu\nu}$ related by a Weyl (conformal) transformation: $g_{\mu\nu} = \Omega(x)^2\, \widetilde{g}_{\mu\nu}$
  - ⥀ gravitational Lagrangians differ e.g. in the coefficient of the Ricci scalar
    - ↪ (generically) scalar field dependent coefficients
    - ⥀ Einstein frame: $\mathcal{L} = \frac{1}{2\kappa}\,\mathcal{R} + \cdots$

      (natural in standard gravity & cosmology; coefficient: a constant)
    - ⥀ Jordan frame: e.g. $\mathcal{L} = \frac{1}{16\pi}\phi\,\mathcal{R} + \cdots$

      ("traditional" frame in scalar-tensor theories of gravity; coefficient: a polynomial function of the scalar field)
    - ⥀ string frame: e.g. $\mathcal{L} = e^{-\phi}\,\frac{\alpha_1}{2}\mathcal{R} + \cdots$

      (natural in string theories; coefficient: an exponential function of the dilaton)

non-minimal matter-dilaton coupling

- if a matter term $\mathcal{L}_m$ is included into the Lagrangian in one frame
  - ⥀ conformal transformation to another frame will change its coefficient
  - ↪ if constant in one frame, it will become dilaton dependent in others
- which conformal frame is the *natural physical* frame?
  - ⥀ no clear consensus in the literature (see e.g. [Faraoni,Gunzig,Nardone(1999)])
  - ↪ in which frame the matter-dilaton coupling should be minimal?
- thus here: a general *non-minimal coupling* $f(\phi)\,\mathcal{L}_m$
  - ⥀ of the dilaton ϕ
  - ↪ to the matter content of the universe $\mathcal{L}_m$ (localized on the brane)

the aim of the game

- framework:
  - dilaton gravity in a 5d brane scenario
  - non-minimal matter-dilaton coupling $f(\phi)\,\mathcal{L}_m$

    ($\mathcal{L}_m$: matter content of the universe localized on the brane)
- take assumptions crucial to many models in the modern literature:
  - *bulk*: exact anti de Sitter spacetime (AdS_5)

    (allows a 4d Minkowski foliation, vital for many higher-dimensional scenarios, e.g. [Randall,Sundrum(1999)])
  - *brane*: matter content of the universe (as in cosmological considerations) treated as an inhomogeneous perfect fluid
- and answer the question:

can the observed large-scale structure of the universe

exist on the brane for an AdS_5 bulk?

(or any other highly symmetrical spacetime)

i.e.: can the perfect fluid (and thus the large-scale structure) be “sufficiently” inhomogeneous?

another point of view

- for standard Einstein's gravity & exact AdS$_5$ [Shiromizu, Maeda, Sasaki (2000)]
  - ⥀ i.e. *no dilaton* & its non-minimal coupling to matter
  - ↪ ONLY a perfectly spatially homogeneous universe allowed

- here: including an "additional degree of freedom" - the dilaton
  - ⥀ and a non-minimal coupling to the matter content of the universe
  - ↪ will it be *enough* for a sufficiently inhomogeneous perfect fluid on the brane?
  - ⥀ as a crude description of our world
  - ↪ in terms of the cosmological large-scale structure as is observed today

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introduction

at the brane: effective Einstein-like equation

AdS$_5$ bulk: large-scale structure on the brane?

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dilaton gravity at the brane with general matter-dilaton coupling

- dilaton gravity in a 5d brane scenario: (Einstein frame)

$$\mathcal{L} = \frac{\alpha_1}{2}\left[\mathcal{R} - \frac{2}{3}\nabla^\sigma \partial_\sigma^{(5)}\phi - \frac{1}{3}(\partial^{(5)}\phi)^2\right] - V(\phi) + \left[f(\phi)\mathcal{L}_m + \lambda(\phi)\right]\delta_B$$

  - ○ $\left[\mathcal{R} - \frac{2}{3}\nabla^\sigma \partial_\sigma^{(5)}\phi - \frac{1}{3}(\partial^{(5)}\phi)^2\right]$: 5d dilaton gravity ($\alpha_1$: constant)

    ($V(\phi)$: scalar potential in the bulk)
  - ○ $\mathcal{L}_m$: (brane localized) matter content of the universe

    $\lambda(\phi)$: 'cosmological constant'-type term on the brane

    ↪ position of the co-dimension 1 brane: Dirac delta type distribution δ_B
  - ○ $f(\phi)\,\mathcal{L}_m$: (non-minimal) coupling of the dilaton ϕ to brane localized matter $\mathcal{L}_m$

- how does the (induced) gravity look like on the brane?

  ↪ its effective 4d description has to be established

derivation of the effective gravitational equations at the brane

- here: covariant approach [Shiromizu,Maeda,Sasaki(2000), DK,Olechowski(2010)]
- induced (projected) brane metric: $h_{\mu\nu} = g_{\mu\nu} - n_\mu n_\nu$
  - n^μ: vector field orthonormal to the brane at its position
  - $g_{\mu\nu}$: $\mathcal{R}_{\mu\nu}{}^{\rho\sigma}$ & ∇_μ vs $h_{\mu\nu}$: $R_{\mu\nu}{}^{\rho\sigma}$ & D_μ
- assume a $\mathbb{Z}_2$ symmetry for the bulk (with its fixed point at the brane's position)
  - ↪ usually imposed 'automatically'
  - crucial for the existence of the effective gravitational equations at the brane
- in the absence of the bulk $\mathbb{Z}_2$ symmetry

  only consistency condition (on the brane sources): $D_\lambda\left(f(\phi)\tau^\lambda_\mu\right) = f(\phi)\,\tau_\phi(\partial_\mu\phi)$

  (on the brane: "generalized" covariant conservation of the energy-momentum tensor)

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- assume a $\mathbb{Z}_2$ symmetry for the bulk (with its fixed point at the brane's position)
  - $\hookrightarrow$ usually imposed 'automatically'
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  only consistency condition (on the brane sources): $D_\lambda\left(f(\phi)\tau^\lambda_\mu\right) = f(\phi)\,\tau_\phi(\partial_\mu\phi)$

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at the brane: effective Einstein-like equation

- consequently, the *effective* Einstein-like equation at the brane reads

[DK(2011)]

$$R_{\mu\nu} - \frac{1}{2}\, h_{\mu\nu} R = 8\pi \overline{G}(\phi)\, \tau_{\mu\nu} - h_{\mu\nu} \overline{\Lambda}(\phi) + \frac{f^2(\phi)}{4\alpha_1^2} \pi_{\mu\nu} + \frac{2}{9}\, (\partial_\mu \phi)(\partial_\nu \phi) - \frac{5}{36}\, h_{\mu\nu}\, (\partial\phi)^2 - E_{\mu\nu}$$

  - $\overline{G}(\phi)$ & $\overline{\Lambda}(\phi)$: effective brane Newton's & cosmological constants
  - $\tau_{\mu\nu}$: (brane) energy-momentum tensor

- three types of 'corrections' to the standard Einstein equation
  - $\pi_{\mu\nu}$: terms quadratic in $\tau_{\mu\nu}$ (typical of brane gravity theories)
  - kinetic terms for the dilaton (typical of scalar-tensor theories of gravity)
  - explicit bulk's influence *on the brane gravity*: $E_{\mu\nu} = n^\alpha h_\mu^\beta n^\gamma h_\nu^\delta\, \mathcal{C}_{\alpha\beta\gamma\delta}$

    (bulk Weyl tensor projected on the brane: a single term, but generically non-vanishing)

  ↪ to describe gravity induced on the brane: solution of the e.o.m.'s for the bulk gravity necessary

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on the brane:

constraint on the spatial derivative of the matter energy density

- OR: "sufficiently" inhomogeneous perfect fluid on the brane in AdS$_5$ bulk?
- calculus ingredients:
  - effective gravitational equations at the brane:

$$R_{\mu\nu} - \tfrac{1}{2} h_{\mu\nu} R = 8\pi \overline{G}(\phi)\, \tau_{\mu\nu} - h_{\mu\nu} \overline{\Lambda}(\phi) + \frac{f^2(\phi)}{4\alpha_1^2} \pi_{\mu\nu} + \tfrac{2}{9} (\partial_\mu \phi)(\partial_\nu \phi) - \tfrac{5}{36} h_{\mu\nu} (\partial\phi)^2 - E_{\mu\nu}$$

$$D_\lambda \left(f(\phi) \tau^\lambda_\mu \right) = f(\phi)\, \tau_\phi (\partial_\mu \phi)$$

  - 4d Bianchi identity: $D^\nu \left(R_{\mu\nu} - \tfrac{1}{2} h_{\mu\nu} R \right) = 0$
- assumptions:
  - bulk: exact anti de Sitter spacetime: AdS$_5$ → $E_{\mu\nu} = 0$

    (or any other highly symmetrical spacetime) (no bulk influence on the brane gravity)
  - brane (matter content of the universe): perfect fluid → $\tau_{\mu\nu} = \rho_m\, t_\mu t_\nu + p_m\, \gamma_{\mu\nu}$

    ($\gamma_{\mu\nu}$: 3d spatial metric, ρ_m: [inhomogeneous] (dark) matter & radiation)

on the brane: late universe

- thus, spatial derivative of the matter energy density on the brane reads

$$\rho_{m,i} = -\left(\frac{f'}{f}\rho_m - \frac{\lambda'}{f}\right)\phi_{,i} + \frac{\alpha_1^2}{3f^2(\rho_m + p_m)}\left[D^\nu \partial_i \phi - \dot{\phi}^{-1}\phi_{,i}\, D^\nu \partial_t \phi\right](\partial_\nu \phi)$$

[DK(2011)]

↪ imposes a strict condition on the matter content of the universe

(potentially: a strong constraint on how inhomogeneous the matter distribution can be - and thus on the cosmological large-scale structure as is observed today)

- (at least) late universe: terms $\mathcal{O}((\partial\phi)(D\partial\phi))$ can be neglected, hence

$$\rho_{m0,i} \simeq -\frac{f'}{f}\rho_{m0}\,\phi_{0,i}$$

[DK(2011)]

strongly constrained: how *inhomogeneous* ($\rho_{m,i} \neq 0$)

the matter content of the universe can be (for the vanishing 5d Weyl tensor)

  - inhomogeneous matter on the brane? *only if:*

    matter coupled non-minimally ($f' \neq 0$) to the *dilaton*

  - if dilaton spatially homogeneous: no inhomogeneous matter (as for *no dilaton*)

    ↪ here already: $\dot{\phi}_0 \lesssim 2.4\, H_0 \simeq 1.8\,(10^{10}\ \mathrm{yr})^{-1}$

    (derived: model-independent bound set by current observational data)

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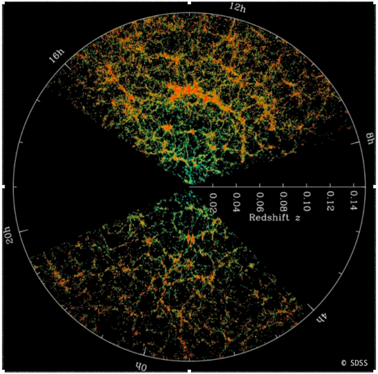
late universe: inhomogeneous matter vs. observations

- let us the quantify the implications of the constraint on $\rho_{m0,i}$
- current observational limits: $\left|\dot{\overline{G}}_0/\overline{G}_0\right| < \left(10^{11}\,\mathrm{yr}\right)^{-1}$ [Uzan(2011)]
  (searches for Newton's constant time variation: pulsar timing, solar system, stellar, cosmological constraints)
  - ⥀ $\overline{G} = \overline{G}(\phi) \rightsquigarrow \left|\frac{f'}{f}\phi_{0,i}\right| \lesssim 3.3\,c_1\left(10^5\,\mathrm{Mpc}\right)^{-1}$
  - ↪ a stringent upper bound:

$$|\rho_{m0,i}| \lesssim 3.3\,c_1\,\rho_{m0}\left(10^5\,\mathrm{Mpc}\right)^{-1}$$

- let us then confront it with cosmological observations:
  - ⥀ large-scale structure of the universe [here:SDSS]



cosmological large-scale structure data

- large-scale structure (LSS) of the universe
  - ↪ spatial distribution of galaxies, their groups and clusters
    (information on the overall matter distribution)
- galaxy distribution: LSS probed by galaxy redshift surveys
  (addressed: content and statistical properties of the LSS)
  (e.g. Sloan Digital Sky Survey (SDSS))
  - ↪ characterized statistically through the two-point correlation function $\xi(x)$
    (excess number of galaxy pairs separated by x relative to that expected for a random distribution)
- galaxy surveys ⇝ *estimation* of the two-point correlation function of galaxies
  [e.g. SDSS(2010)]
  - ⥀ data usually presented in the form of the power spectrum of the perturbation field
    (i.e. Fourier transformation of the two-point correlation function)

confrontation with LSS data

- *confront*: upper limit on $\rho_{m0,i}$ as *predicted* by the model [DK(2011)]

  (dilaton gravity, brane, AdS$_5$ or any other highly symmetrical spacetime)

  (& null searches for the Newton's constant variation)

  ↪ with $\rho_{m0,i}$ estimate from the *observational data* on the LSS of the universe

$$\rho_{m0,i}\left[\text{model's prediction: upper limit}\right] \ll \rho_{m0,i}\left[\text{LSS data estimate}\right]$$

(within the entire range of measured scales)

i.e. brane scenario of dilaton gravity with AdS$_5$ bulk

(or any other spacetime highly symmetrical spacetime - with vanishing Weyl tensor)

(and matter content of the universe described by a perfect fluid)

means NO large scale structure as is *observed today*

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what now?

- dilaton gravity, brane & AdS$_5$ (or other highly symmetrical spacetime) *shown:*
  - ↪ brane: NO cosmological large-scale structure as observed today
    - too little 'space' (in this simple string theory motivated scenario)
- dilaton ('degree of freedom') & its non-minimal coupling to matter
  - ↪ improved the situation (as compared to 5d Einstein's gravity)
  - however, null searches for the Newton's constant variation . . .
    - ↪ observational limits from *too restrictive*

- *what now?* allow for *even more* 'freedom' with $E_{\mu\nu} \neq 0$
  - abandon highly symmetrical spacetimes
  - study what constraints cosmological observations put on $E_{\mu\nu}$
  - ↪ is a *sufficient* bulk geometry contribution $E_{\mu\nu}$ allowed so that we can model the large-scale structure as is observed today?

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