Large-scale structure challenges dilaton gravity in a 5D brane scenario with AdS bulk

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Outline

- introduction
- at the brane: effective Einstein-like equation
- AdS_5 bulk: large-scale structure at the brane?
- conclusions

beyond General Relativity

- ongoing search for a unified description of
  - gravity
  - gauge interactions of the Standard Model
  - ↪ *string theories* as the most promising proposal
- *low-energy effective action* in string theories
  - *dilaton* (ϕ): scalar field accompanying gravity
  - at the leading order (when restricted to gravity and the dilaton)
  - ↪ Einstein gravity coupled to the dilaton
- additional spatial dimensions
  - required by the string theories' formulation
  - have to be compactified or warped
  - ↪ dilaton gravity in a 5D brane scenario

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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
  - ⥀ gravitational Lagrangians differ e.g. in the coefficient of the Ricci scalar
    - ↪ (generically) scalar field dependent coefficients
    - ⥀ Einstein frame: $\mathcal{L} = \frac{1}{2\kappa}\,\mathcal{R} + \cdots$ (coefficient: a constant)
    - ⥀ Jordan frame: e.g. $\mathcal{L} = \frac{1}{16\pi}\,\phi\,\mathcal{R} + \cdots$ (coefficient: a polynomial function of the scalar field)
    - ⥀ string frame: e.g. $\mathcal{L} = e^{-\phi}\,\frac{\alpha_1}{2}\,\mathcal{R} + \cdots$ (coefficient: an exponential function of the dilaton)
  - ⥀ related ($g_{\mu\nu}$ & $\widetilde{g}_{\mu\nu}$) by a conformal (Weyl) transformation: $g_{\mu\nu} = \Omega(x)^2\,\widetilde{g}_{\mu\nu}$

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 which frame the matter-dilaton coupling should be minimal?
- thus: a general *non-minimal coupling* $f(\phi)\,\mathcal{L}_m$

  of the dilaton to the matter content of the universe (localized on the brane)

the aim of the game

- framework:
  - dilaton gravity in a 5D brane scenario
  - non-minimal matter-dilaton coupling $f(\phi)\,\mathcal{L}_m$
- take assumptions crucial to many models in the modern literature:
  - *bulk*: exact anti de Sitter type spacetime (AdS$_5$)
  - *brane*: matter content of the universe described by a perfect fluid
- and answer the question:

can the large-scale structure of the universe

exist on the brane in an AdS-type bulk?

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at the brane: effective Einstein-like equation

AdS_5 bulk: large-scale structure at 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)

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

  - $\mathcal{R} - \frac{2}{3}\nabla^\sigma \partial^{(5)}_\sigma \phi - \frac{1}{3}(\partial^{(5)}\phi)^2$: 5D dilaton gravity
  - $\mathcal{L}_m$: (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 $\mathcal{L}_m$
- induced (projected) brane metric: $h_{\mu\nu} = g_{\mu\nu} - n_\mu n_\nu$ (covariant approach)
  - 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 position)
  - usually imposed ‘automatically’
  - crucial for the existence of the effective brane equations

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  - usually imposed ‘automatically’
  - crucial for the existence of the effective brane equations

at the brane: effective Einstein-like equation

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

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

  - $\overline{G}(\phi) = \frac{-1}{48\pi\alpha_1^2} f(\phi)\lambda(\phi)$ (effective brane Newton's constant)
  - $\tau_{\mu\nu} = h_{\mu\nu}\,\mathcal{L}_m - 2\,\frac{\delta\mathcal{L}_m}{\delta h^{\mu\nu}}$, $\tau_\phi = \frac{f'(\phi)}{f(\phi)}\,\mathcal{L}_m + \frac{\delta\mathcal{L}_m}{\delta\phi}$ (brane localized sources)
  - $\overline{\Lambda}(\phi) = \frac{1}{2\alpha_1} V - \frac{f^2}{4\alpha_1^2}\left[\frac{3}{4}\tau_\phi^2 + \frac{3\lambda'}{2f}\tau_\phi - \frac{\lambda^2}{3f^2} + \frac{3\lambda'^2}{4f^2}\right]$ (eff. brane cosmol. const.)
  - $\pi_{\mu\nu} = -\,\tau_{\mu\rho}\tau^{\rho}_{\nu} + \frac{1}{3}\,\tau\,\tau_{\mu\nu} + \frac{1}{2}\,h_{\mu\nu}\tau^{\sigma}_{\rho}\tau^{\rho}_{\sigma} - \frac{1}{6}\,h_{\mu\nu}\,\tau^2$
    (terms quadratic in the brane energy-momentum tensor)
  - bulk's influence *on the brane gravity*: $E_{\mu\nu} = n^\alpha h^\beta_\mu n^\gamma h^\delta_\nu\, \mathcal{C}_{\alpha\beta\gamma\delta}$
    (bulk Weyl tensor projected on the brane (generically non-vanishing))

- consistency condition (on the brane sources): $D_\lambda\big(f(\phi)\tau^\lambda_\mu\big) = f(\phi)\,\tau_\phi(\partial_\mu\phi)$
  (brane: 'generalized' covariant conservation of the energy-momentum tensor)

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on the brane: spatial derivative of the energy density

- OR: inhomogeneous perfect fluid on the brane in AdS$_5$ bulk?
- assumptions:
  - bulk: exact anti de Sitter type spacetime: AdS$_5$ → $E_{\mu\nu} = 0$

    (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: (dark) matter & radiation)
- calculus ingredients:
  - 4D Bianchi identity: $D^\nu \left(R_{\mu\nu} - \frac{1}{2} h_{\mu\nu} R \right) = 0$
  - effective gravitational (Einstein-like) equation at the brane:

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

  - 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: late universe

- consequently, the spatial derivative of the matter energy density reads

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

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

  (constraint on spatial inhomogeneities in brane matter)

- (at least) late universe: terms $\mathcal{O}((\partial\phi)(D\partial\phi))$ can be neglected, as
  - ↺ $\dot\phi_0 \lesssim 2.4\,H_0 \simeq 1.8\,(10^{10}\text{ yr})^{-1}$

    (derived: model-independent bound set by current observational data)
  - ↺ $|\ddot\phi_0| \ll \dot\phi_0^2$ can be assumed / expected

    (otherwise: currently observed $\phi_0 \approx \mathrm{const}$ would be another coincidence problem)
  - ↺ typical models: $|\phi_{,i}| \lesssim c_1|\dot\phi|$ ($c_1 > 0$ and of order 1)

    (any initial inhomogeneities of the dilaton washed out by inflation)
- hereafter: $\lambda \neq \lambda(\phi)$ ('cosmological constant'-type term in the energy-momentum tensor on the brane)

  (only a contribution to the effective brane cosmological constant $\overline{\Lambda}(\phi)$)

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late universe: spatial derivative of the energy density

- hence for the late universe we obtain

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

spatial inhomogeneities in matter energy density are highly *constrained*

for the common assumptions of AdS_5 bulk and perfect fluid on the brane

  - inhomogeneous perfect fluid ($\rho_{m\,,i} \neq 0$) on the brane? *only if:* *matter* content of the universe coupled non-minimally ($f' \neq 0$) to the *dilaton*
  - if dilaton spatially homogeneous: no matter inhomogeneities
    $\hookrightarrow$ already: $\dot{\phi}_0 \lesssim 2.4\,H_0 \simeq 1.8\,(10^{10}\ \text{yr})^{-1}$

let's quantify the constraint on $\rho_{m0\,,i}$:

- current observational limits: $|\dot{\overline{G}}_0/\overline{G}_0| < (10^{11}\,\mathrm{yr})^{-1}$ $(\overline{G} = \overline{G}(\phi)!)$

(pulsar timing, solar system, stellar, cosmological constraints)

$\hookrightarrow$ $\left|\tfrac{f'}{f}\,\phi_{0\,,i}\right| \lesssim 3.3\,c_1\,(10^5\,\mathrm{Mpc})^{-1}$ (for $|\phi_{,i}| \lesssim c_1\,|\dot{\phi}|$) *resulting in*

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confrontation with large-scale structure (LSS) data

compare: the *model's prediction* (constraint) on $\rho_{m0,i}$ with the *observational data*

- galaxy distribution: probed by galaxy redshift surveys

  (e.g. Sloan Digital Sky Survey (SDSS))

  (addressed: content and statistical properties of the LSS)
- approximations: (*aim*: just an estimation - allowing for the comparison)
  - for the spatial derivative: $\rho_{m,i} \simeq \frac{\rho_m(x_1)-\rho_m(x_2)}{|x_1-x_2|}$
  - LSS surveys probe the overall baryonic matter distribution
  - spatial distributions of baryonic and dark matter similar

    (typical of dark matter models)

$\rightsquigarrow$ and the outcome is . . .

$$\rho_{m,i}\,(max.\ model\ prediction) \ll \rho_{m,i}\,(LSS\ data)$$

(within the entire range of measured scales)

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

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

means NO today's large scale structure

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conclusions

- ⥀ dilaton gravity studied in a 5D brane scenario
  - ⥀ brane localized matter coupled to dilaton non-minimally: $f(\phi)\mathcal{L}_m$
  - ↪ derived: effective gravitational equations at the brane
- ⥀ *can large-scale structure of the universe exist on the brane*?

  (*inhomogeneous* matter content of the universe)

  ↪ investigated for AdS$_5$ bulk & perfect fluid on the brane (matter content of the universe)

⇝ spatial derivative of matter energy density *constrained*

- ⥀ non-minimal dilaton-matter coupling essential
- ⥀ result quantified with current limits

  from (non-)variation of the Newton's constant
- ⥀ and confronted with observational data from galaxy surveys

⇝ up to scales of the order of 10^4 Mpc (larger scales: measurements consistent with 0)

NO large-scale structure as observed today

dilaton gravity brane scenario ruled out? for exact AdS$_5$ bulk only!