String Geometry and String Phenomenology Institute

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On de Sitter realisations in gravity and string theory

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Bibliography

Ongoing work with:

Alexander Tsouros (University of Crete)

Davide Forcella, Francesco Nitti, Lukas Witkowski, Jewel Ghosh, (APC, Paris)

Antonio Amariti (Milano), C. Charmousis (Orsay)

Published work in:

- ArXiv:1904.02727
- ArXiv:1901.04546
- ArXiv:1807.09794
- ArXiv:1704.05075

Introduction

• Particle Physics practitioners do QFT in static (flat) space-time.

• Cosmologists, always described a changing universe, staticity being an unusual, fine-tuned phenomenon.

• Equilibrium in physics is the phenomenon we study most.

• But: "there is never equilibrium in nature".

• String theory is the first theory where particle physics and gravity are interlinked from the whole structure of theory.

• For decades, supersymmetry was used to fine tune the theory so that it has a flat space-time, (and be manageable).

• All the data we have from the universe suggest that the universe is "unstable" (varying with time). It is about time to take them seriously.

• The simplest spaces with maximal symmetry we entertain (in string theory) are dS, AdS and flat space.

• Each has a virtue: dS is a good approximation to what we believe was the early universe, flat is a good approximation to our neighborhood, and AdS is the space emerging from holographic QFTs.

• The structure of these spaces is VERY different:

• In a gravitational theory (as string theory) their observables are located at their respective boundaries.

(Asymptotically) flat space

♠ Flat space has two null boundaries, $\mathcal{I}^{\pm}$ associated with past and future null infinity.

• The gravitational observables are associated with sources on both $\mathcal{I}^{+}$ and $\mathcal{I}^{-}$ and are known as the flat space S-matrix.

• The string theories with asymptotically flat space, are those associated to 2d NSR σ-models and are well-controlled.

(Asymptotically) AdS space

♠ Anti-de-Sitter space has a single space-like boundary.

• The gravitational observables are associated with sources on the boundary and are known as the AdS S-matrix.

• It is conjectured to be dual to the Schwinger functional of a quantum field theory.

• The definition of such string theories is more straightforward using 3, 4 (and probably 6 dimensional) CFTs, where the strings are the (generalized) Wilson loops.

• Moreover, thinking along these lines, one can deduce the existence of several new string theories, with (critical) dimensions lying between 26 and 10 dimensions.

E. Kiritsis, 2013

• The holographic conjecture provides the only non-perturbative definition we have for string theories.

• It is (currently) our only hope in understanding Planck-scale or beyond the Planck scale physics for gravity.

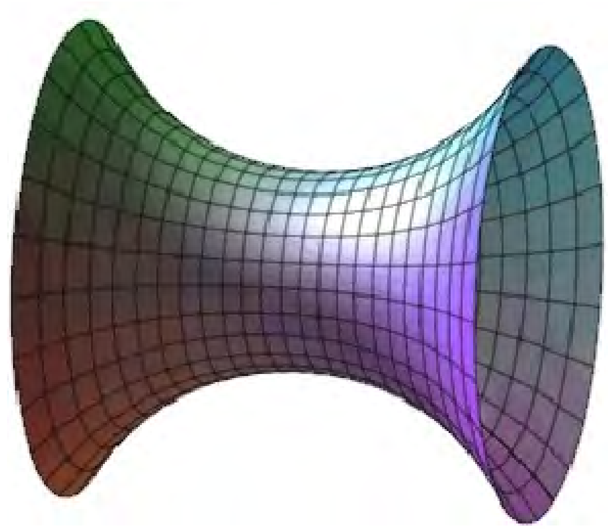
• Moreover it seems to dispel the myth of a unique theory and conjectures a map between the landscape of QFTs to the landscape of Asymptotically AdS string theories.

(Asymptotically) de Sitter space

• dS space in global coordinates

$$ds^2 = -dt^2 + R^2 \cosh^2(t/R)\ d\Omega^2_{d-1})$$

♠ dS space has two time-like boundaries, $\mathcal{I}^{\pm}$, associated with past and future infinity.



• The gravitational observables are associated with sources on both $\mathcal{I}^{+}$ and $\mathcal{I}^{-}$ and form the (less well-studied) dS S-matrix.

• There have been many attempts in formulating a holographic dual for the dS S-matrix.

Strominger, Skenderis+MacFadden, Anninos, E. Kiritsis

• None of them uses the full dS S-matrix, and their status is more uncertain.

• Weakly coupled, nearly massless QFTs on dS have serious problems that have contributed to the bad reputation of dS space.

Starobinsky, Polyakov, Gorbenko+Senatore

• Moreover, it has been argued that QFTs and gravity give a major back-reaction to the background geometry in dS.

Tsamis+Woodard, Abramo+Brandenberger

• In critical superstring theory, it seems thatdS is difficult to come by.

• On one hand, KKLT have a framework that is clear but difficult to controllably realize.

• On the other, there are conjectures (that are varying with time) to the extend that dS is not realizable in string theory.

Ooguri+Vafa+.........

The (many) roads to dS

• Consider non-critical string theory.

• It is well known that in $D < 10$ there is an AdS-like dilaton potential while in $D > 10$ there is a dS-like dilaton potential.

• This has been disfavored in the past because:

♠ Non-critical string theory has generically solutions with curvatures at the string scale.

♠ As the dilaton is involved, the solutions become non-perturbative.

• Some cosmological solutions have been described.

Strominger, Aharony+Silverstein

• Consider dS domains in asymptotically AdS spaces.

• It has been motivated by holography, and tried in the past without success.

Freivogel+Maloney+Hubeny+Myers+Rangamani+Shenker,Lowe+Roy

• It has been resurrected recently by Anninos+Hofman by producing Centaur solutions in 2-dimensional Jackiw-Teitelboim gravity.

• Our recent work, indicates that things are not so good in more than two dimensions, and it seems there are non-go theorems for a regular transition between an AdS boundary and a dS interior.

Kiritsis+Tsouros

♠ Another possibility is to consider asymptotically AdS geometries, and a bulk that is fully in the AdS regime ($V < 0$), but have dS realized as the induced geometry on branes.

Ghosh+kiritsis+Nitti+Witkowski

• Although this seems possible, it can be generically realized only with dS boundary conditions on the AdS boundary.

The Centaur Solutions

• They are two-dimensional and have been found in the context of Jackiw-Teitelboim gravity+scalar.

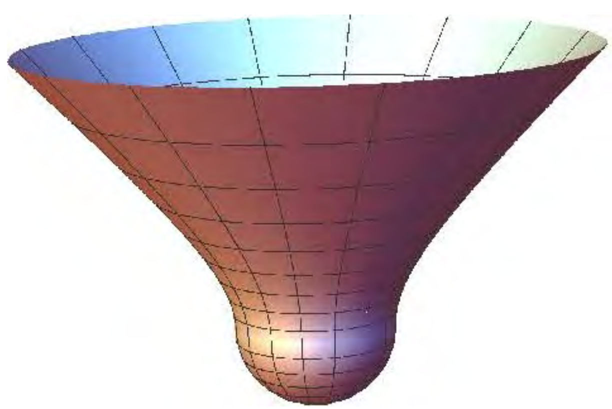
Anninos+Hofman

$$S = -\frac{1}{16\pi G}\int d^2x\sqrt{-g}\left[(\phi - \phi_0)\ R + \ell^2 V(\phi)\right]$$

The simplest such solution is

$$ds^2 = -\left(1 + \frac{r^3}{|r|}\right)dt^2 + \frac{dr^2}{\left(1 + \frac{r^3}{|r|}\right)} \quad , \quad r \in (-1, +\infty)$$

• The Euclidean geometry is the hyperbolic cylinder, capped by an S^2



• The Minkowskian geometry, has an AdS$_2$ boundary and a dS_2 interior.

$$ds^2 = -\left(1 - r^2\right) dt^2 + \frac{dr^2}{\left(1 - r^2\right)} \quad , \quad r \in (-1, 0)$$

• This is half of the static patch geometry of dS$_2$

• For $r > 0$ it becomes

$$ds^2 = -\left(1 + r^2\right) dt^2 + \frac{dr^2}{\left(1 + r^2\right)} \quad , \quad r \in (0, +\infty)$$

which is AdS$_2$ in the global coordinates.

• The AdS$_2$ boundary is at $r \to \infty$.

• By varying the scalar potential various intermediate behaviors can be obtained always interpolating between a dS$_2$ interior and an AdS$_2$ boundary.

The next Goal

- We would like to explore to what extend there are ”Centaur-like” solutions in $D > 2$

- There are three natural interpolating ansatze in $D > 2$

- *The black hole ansatz with a flat slicing.*

$$ds^2_{d+1} = \frac{du^2}{f(u)} + e^{2A(u)}\left[-f(u)dt^2 + dx_i dx^i\right].$$

- When $f = 1$ and $e^A = e^{-\frac{u}{\ell}}$, this is AdS in Poincaré coordinates.

- $f = -1$ and $e^A = e^{-\frac{u}{\ell}}$ it reduces to dS space in Poincaré coordinates (where u is now time-like).

- *The black hole ansatz with a spherical slicing.*

$$ds^2_{d+1} = \frac{du^2}{f(u)} + e^{2A(u)}\left[-f(u)dt^2 + d\Omega^2_{d-1}\right]$$

• With $e^A = e^{-\frac{u}{\ell}}$, $f = 1 + e^{2\frac{u}{\ell}}$ we obtain AdS.

• With $e^A = e^{Hu}$, $f = -1 + e^{-2Hu}$ we obtain dS in the static patch.

• *The dS sliced ansatz.*

$$ds^2_{d+1} = du^2 + e^{2A(u)} \left(-dt^2 + \frac{\cosh^2(Ht)}{H^2} d\Omega^2_{d-1} \right).$$

• Choosing $e^A = \sinh \frac{u}{\ell}$ we obtain AdS.

• Choosing $e^A = \sin Hu$ we obtain dS .

• This last ansatz is studied by L. Witkowski. It differs in two ways from the two previous ones:

(a) The metric has one function instead of two.

(b) The scalar field does not end up at fixed points of the potential.

Flows in the landscape

• To answer our questions we must look for regular solutions in one of interpolating ansatze.

• For simplicity and clarity I will consider the bulk theory to contain only the metric and a single scalar (Einstein-dilaton gravity).

• It turns out that all multiscalar flows can be mapped to this example*.

• The two-derivative action (after field redefinitions) is

$$S_{bulk} = M^{d-1} \int d^{d+1}x \, \sqrt{-g} \left[R - \frac{1}{2}(\partial\phi)^2 - V(\phi) \right] + S_{GH}$$

• We assume $V(\phi)$ is analytic everywhere except possibly at $\phi = \pm\infty$ (boundary of field space).

• The AdS regime is where $V < 0$

• The dS regime is where $V > 0$

• Solutions in the AdS regime with

$$ds^2 = du^2 + e^{2A(u)} dx_\mu dx^\mu \quad , \quad \phi(u)$$

are dual to RG flows of relativistic holographic CFTs.

• All such (regular) solutions were classified recently.

Kiritsis+Nitti+Silva-Pimenta, Nitti+Silva-Pimenta+Steer

• The Einstein equations can be ALWAYS turned to first order equations using the (fake) "superpotential" (no-supersymmetry here).

$$\dot{A} = -\frac{1}{2(d-1)} W(\phi) \quad , \quad \dot{\phi} = W'(\phi) \quad , \quad dot = \frac{d}{du}$$

$$-\frac{d}{4(d-1)} W(\phi)^2 + \frac{1}{2} W(\phi)'^2 = V(\phi) \quad , \quad ' = \frac{d}{d\phi}$$

Skenderis+Townsend, De Wolfe+Freedman+Gubser+Karch, de Boer+Verlinde²

• Given a $W(\phi)$, $A(u)$ and $\phi(u)$ can be found by integrating the first order flow equations.

• Therefore:

The solutions (and the dual RG flows) are in one-to one correspondence with the solutions of the "superpotential equation".

$$-\frac{d}{4(d-1)}W(\phi)^2 + \frac{1}{2}W(\phi)'^2 = V(\phi)$$

• Regularity of the bulk solution fixes the W-equation integration constant (uniquely in generic cases).

• The only singular solutions are those that end up at $\phi \to \pm\infty$.

• All regular solutions to the equations are flows from an extremum of V to another extremum of V (for finite ϕ).

• Near an extremum of the potential there are always TWO distinct branches of solutions: $W_\pm$.

• W_+ is always an isolated solution both at maxima and minima of V.

• W_- is a one-parameter family of solutions near a maximum of V (UV fixed point).

• W_- is an isolated solution near a minimum of V (IR fixed point).

• These facts are crucial in order to understand qualitatively when there are generically regular solutions, or when such solutions exist for "fine-tuned" potentials.

dS flows

• We now consider the dS regime.

$$ds^2 = -dt^2 + e^{2A(t)} dx^\mu dx^\mu$$

• This describes the cosmology of an expanding universe with flat spatial slices.

• The whole superpotential formalism works equally well in the dS regime.

Salopek+Bond, Kiritsis, Binetruy+Kiritsis+Mabillard+Pieroni+Rosset, Kiritsis+Tsouros

• The solutions correspond to (regular cosmologies) that start and end in dS patches.

• They are "rotated" AdS RG Flows.

Kiritsis

• All regular solutions have been classified.

Kiritsis+Tsouros

• Everything we said about AdS applies here with minor changes:

• Maxima of V in dS regime correspond to the $e^A \to 0$ limit and are therefore "big bang" regimes.

• Mimima of V in dS regime correspond to the $e^A \to \infty$ limit and are therefore "large universe" regimes.

• Now W_- contains a free integration constant near minima of V, but not near maxima.

Flows between AdS and dS

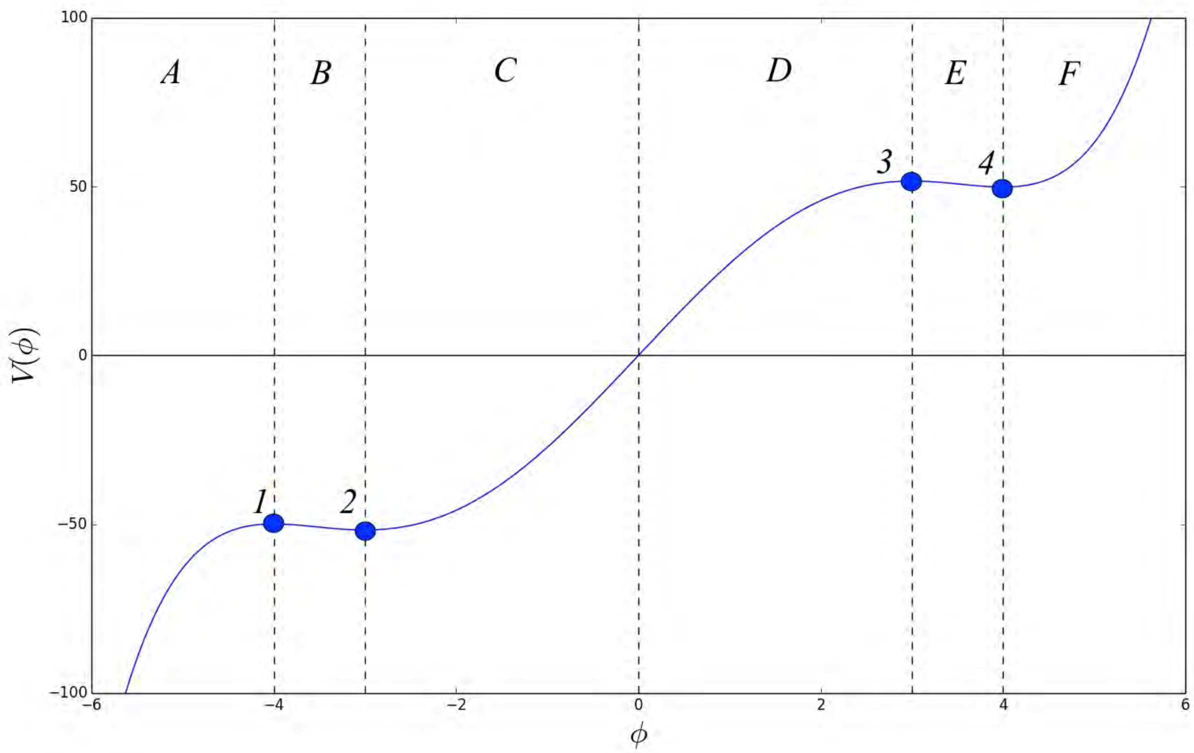
• We now consider the flat interpolating ansatz:

$$ds^2_{d+1} = \frac{du^2}{f(u)} + e^{2A(u)} \left[-f(u)dt^2 + dx_i dx^i \right].$$

• Any flow that interpolates between dS and AdS must contain a vanishing of $f(u)$.

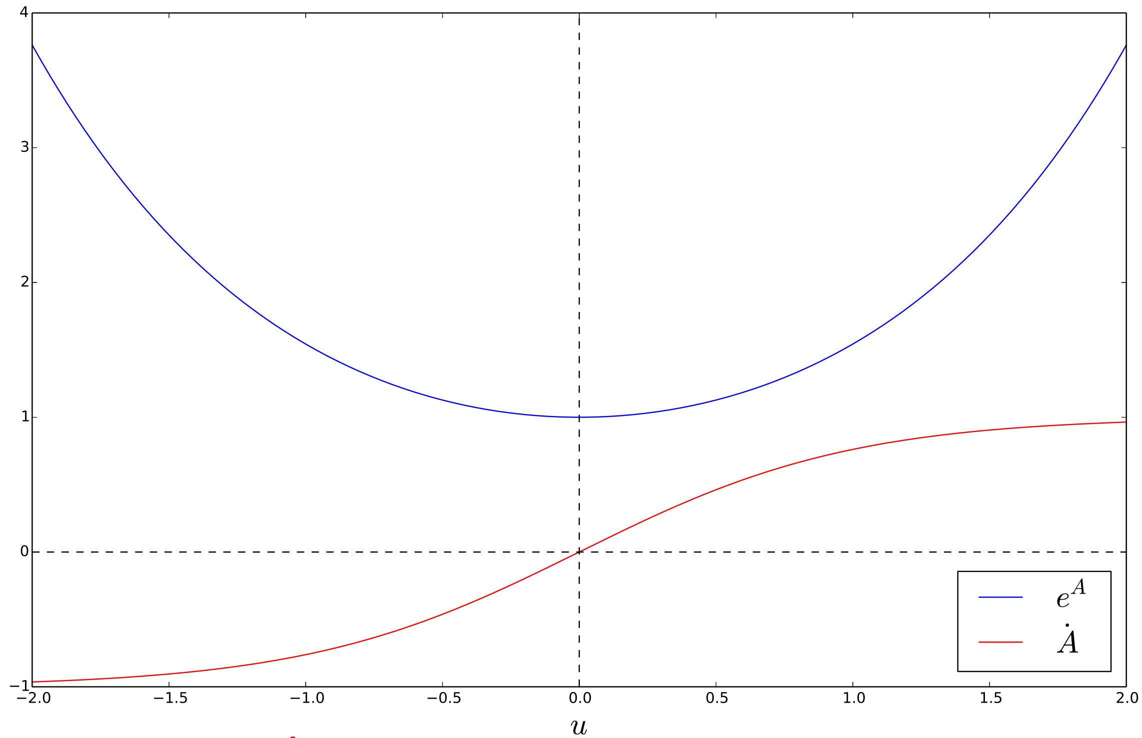
• In order for this point to be a horizon and not a singularity, one parameter of the solution must be tuned.

• We also know that a regular solution must interpolate between a dS extremum of V and an AdS extremum of V.



• The only solution that has a chance of being regular without tuning the potential is from point 4 to point 1.

• But even for this case, there is no regular solution.



A in blue, $\dot{A}$ in red

.

- This contradicts the equations of motion $\ddot{A} \sim -\dot{\phi}^2$.

- All other solutions that require tuning the potential, can also be shown to be singular.

• Therefore, there is no regular interpolating solution with flat slices.

• We may now consider the spherical interpolating ansatz:

$$ds^2_{d+1} = \frac{du^2}{f(u)} + e^{2A(u)}\left[-f(u)dt^2 + d\Omega^2_{d-1}\right]$$

• Similar arguments apply to this case as well although the solutions are a bit more complicated due to the sphere curvature.

• We can still show that there are no regular flows for generic potentials.

• We suspect that this applies to tuned potentials also, but we have no proof as yet.

A different (local) dS realization

• Consider asymptotically AdS string theory and its low energy (supergravity).

• I will simplify matters and consider the bulk to contain gravity and a scalar field.

$$S_{bulk} = M^{d-1} \int d^{d+1}x \, \sqrt{-g} \left[R - \frac{1}{2}(\partial\Phi)^2 - V(\Phi) \right] + S_{GH}$$

• I will also consider a brane with codimension 1, embedded in the bulk.

$$S_{brane} = M_P^{d-1} \int d^d x \sqrt{-\gamma} \left(-W_B(\Phi) - \frac{1}{2} Z(\Phi) \gamma^{\mu\nu} \partial_\mu \Phi \partial_\nu \Phi + U(\Phi) R_B(\gamma) \right) + \cdots$$

• The bulk solution will be a standard "vacuum" flow,

$$\Phi = \Phi(u), \qquad ds^2 = du^2 + e^{2A(u)}\zeta_{\mu\nu}(x)dx^\mu dx^\nu \quad , \quad R(\zeta)_{\mu\nu} = \kappa\ \zeta_{\mu\nu}$$

dual to the ground state of a QFT on the boundary metric $\zeta_{\mu\nu}$.

$$\kappa = \begin{cases} \frac{(d-1)}{\alpha^2} & \text{dS}_d \\ 0 & \mathcal{M}^d \\ -\frac{(d-1)}{\alpha^2} & \text{AdS}_d \end{cases} ,$$

where α is the radius of curvature.

• The question we will pose is: although the bulk solution is in the AdS regime $(V(\Phi) < 0)$, is it possible to have $\gamma_{\mu\nu}$ be a dS metric.

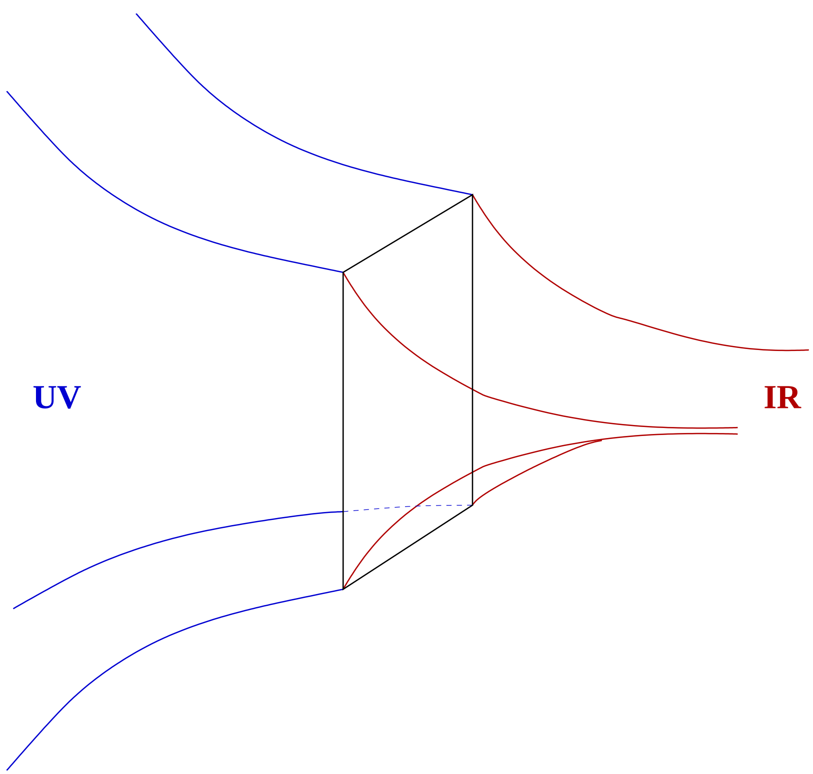
• If yes, then the inhabitants on the brane, experience a dS space.

The bulk and brane equations

• The bulk equations involve the Einstein and scalar equations

• The brane affects the solution via the Israel matching conditions.

• We assume the brane to be inserted at some fixed value u_* of the holographic bulk coordinate, with $\Phi(u_*) \equiv \Phi_*$.



- The Israel matching conditions read

$$\Big[g_{ab}\Big]_{IR}^{UV} = 0\,, \qquad \Big[\Phi\Big]_{UV}^{IR} = 0\,.$$

$$\Big[K_{\mu\nu} - \gamma_{\mu\nu}K\Big]_{UV}^{IR} = \frac{1}{\sqrt{-\gamma}}\frac{\delta S_{brane}}{\delta\gamma^{\mu\nu}}, \qquad \Big[n^a\partial_a\Phi\Big]_{UV}^{IR} = -\frac{1}{\sqrt{-\gamma}}\frac{\delta S_{brane}}{\delta\Phi}.$$

- Using the brane action, we can calculate

$$\Big[K_{\mu\nu}-\gamma_{\mu\nu}K\Big]_{UV}^{IR} = \Big[\frac{1}{2}W_B(\Phi)\gamma_{\mu\nu} + U(\Phi)G^B_{\mu\nu} - \frac{1}{2}Z(\Phi)\left(\partial_\mu\Phi\partial_\nu\Phi - \frac{1}{2}\gamma_{\mu\nu}(\partial\Phi)^2\right)$$

$$+ (\gamma_{\mu\nu}\gamma^{\rho\sigma}\nabla_\rho\nabla_\sigma - \nabla_\mu\nabla_\nu)\,U(\Phi)\Big]_{\Phi_\star} \quad ,$$

$$\Big[n^a\partial_a\Phi\Big]_{UV}^{IR} = \left[\frac{dW_B}{d\Phi} - \frac{dU}{d\Phi}R_B + \frac{1}{2}\frac{dZ}{d\Phi}(\partial\Phi)^2 - \frac{1}{\sqrt{-\gamma}}\partial_\mu\left(Z(\Phi)\sqrt{-\gamma}\gamma^{\mu\nu}\partial_\nu\Phi\right)\right]_{\Phi_\star},$$

Detour: the self-tuning of the brane cosmological constant

• This framework was shown recently to accommodate the self-tuning mechanism for the brane cosmological constant.

Charmousis+Kiritsis+Nitti

• This relies on the answer to the question: is it possible to have $W_B(\Phi) \neq 0$, and to have $\gamma_{\mu\nu}$ be flat?

• If this is possible, then the brane cosmological constant W_B is "hidden" from the brane inhabitants.

• We will assume a boundary QFT on flat Minkowski space.

• Then the bulk metric is

$$ds^2 = du^2 + e^{2A(u)} dx_\mu dx^\mu \quad , \quad \Phi(u)$$

and the bulk solution is dual to a holographic RG Flow driven by the dual to the scalar Φ.

• The Israel matching conditions are simple if we write the bulk equations in the first order formalism using W:

$$\dot{A} = -\frac{1}{2(d-1)} W(\phi) \quad , \quad \dot{\phi} = W'(\phi) \quad , \quad dot = \frac{d}{du}$$

$$-\frac{d}{4(d-1)} W(\phi)^2 + \frac{1}{2} W(\phi)'^2 = V(\phi) \quad , \quad ' = \frac{d}{d\phi}$$

We need a W_{UV} and a W_{IR} that both solve the superpotential equation. Each is determined up to one integration constant C_{UV}, C_{IR}.

• Then, the Israel matching conditions become:

$$A^{UV}(u_*) = A^{IR}(u_*) = A_*, \qquad \Phi^{UV}(u_*) = \Phi^{IR}(u_*) = \Phi_*.$$

$$W^{IR} - W^{UV}\Big|_{\Phi_*} = W^B(\Phi_*) \quad , \quad \frac{dW^{IR}}{d\Phi} - \frac{dW^{UV}}{d\Phi}\Bigg|_{\Phi_*} = \frac{dW^B}{d\Phi}(\Phi_*)$$

• The W_{IR} solution is UNIQUELY fixed from the bulk regularity condition. Therefore there is no free parameter in it. • One of the matching conditions fixes the C_{UV} parameter in W_{UV}.

• The remaining matching condition is a (transcendental) equation for Φ_*.

• It can be shown to have non-trivial solutions in generic cases.

• The solutions can be shown to correspond to minima in an "effective" potential felt by the brane, as it is embedded in the bulk.

Amariti+Charmousis+Forcella+Kiritsis+Nitti

dS metrics on the brane

• Can the induced metric $\gamma_{\mu\nu}(\Phi_*)$ be dS?

• Generically no, unless the QFT, dual to the bulk solution is defined on dS space.

• In that case the bulk metric is

$$ds^2 = du^2 + e^{2A(u)}\zeta_{\mu\nu}(x)dx^\mu dx^\nu \quad , \quad \zeta_{\mu\nu} \to \text{de Sitter}$$

• To rewrite the Israel matching conditions now, we must establish the first order formalism for curved slices.

Ghosh+Kiritsis+Nitti+Witkowski

$$\dot{A}(u) = -\frac{1}{2(d-1)}W(\Phi(u)) \quad , \quad \dot{\Phi}(u) = S(\Phi(u)),$$

with W, S satisfying the two first order equations:

$$\frac{d}{2(d-1)}W^2 + (d-1)S^2 - d\ SW' + 2V = 0$$

$$SS' - \frac{d}{2(d-1)}SW - V' = 0\,.$$

• The two dimensionless integration constants $C, \mathcal{R}$ are related to the curvature and the scalar vev.

• The Israel conditions now become:

$$W_{IR} - W_{UV}|_{\Phi_*} = W_B + \frac{(2-d)}{d} U\, T\Big|_{\Phi_\star}$$

$$S_{IR} - S_{UV}|_{\Phi_*} = W_B{}' - U'\, T\Big|_{\Phi_\star}$$

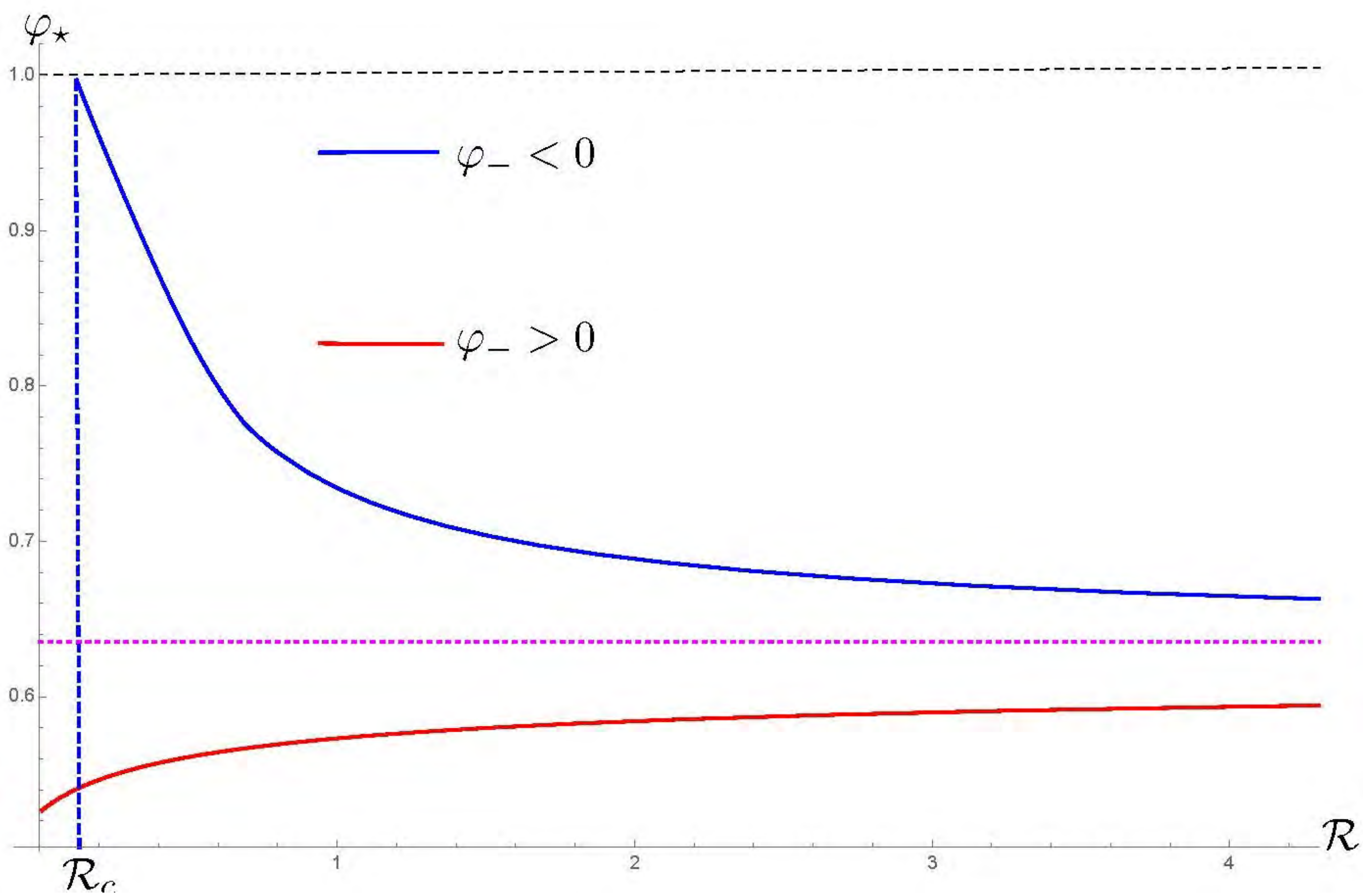
with

$$T \equiv \frac{d}{2} S(S - W') \sim e^{-2A} \quad , \quad T_{UV}(\Phi_*) = T_{IR}(\Phi_*)$$

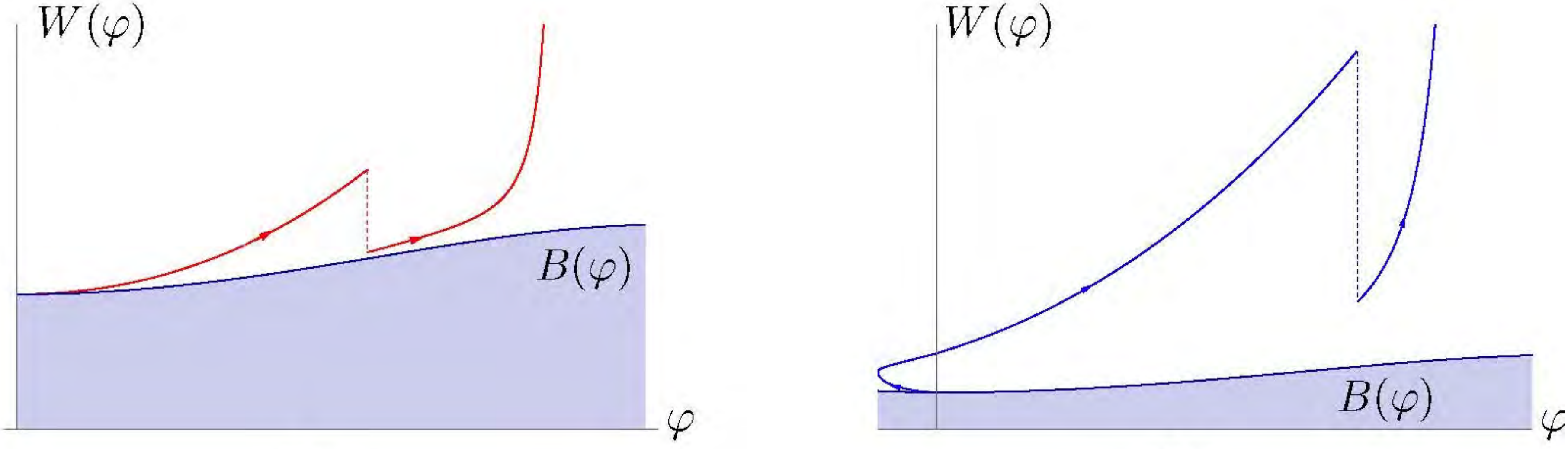
• Similarly to the flat case, we specify the dimensionless ratio $\mathcal{R}$ in the boundary theory (boundary condition), and we solve for W, S and Φ_*.

• We then calculate $\gamma_{\mu\nu}(\Phi_*)$ and calculate its dS curvature.

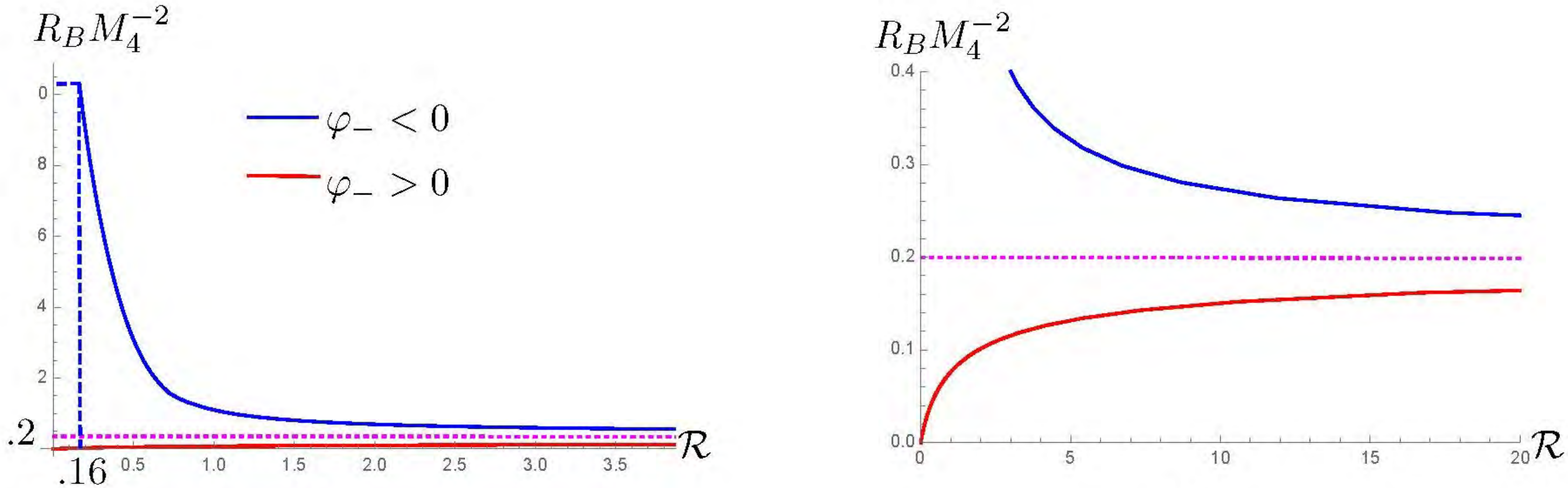
(Numerical) Results



• The blue line corresponds to solutions with $\Phi_- < 0$ while the red line denotes solutions with $\Phi_- > 0$.


W(φ)
B(φ)
φ
W(φ)
B(φ)
φ

(a) (b)


$R_B M_4^{-2}$
0
8
6
4
2
.2
.16
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$\mathcal{R}$
$\varphi_- < 0$
$\varphi_- > 0$
$R_B M_4^{-2}$
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
$\mathcal{R}$

(a) (b)

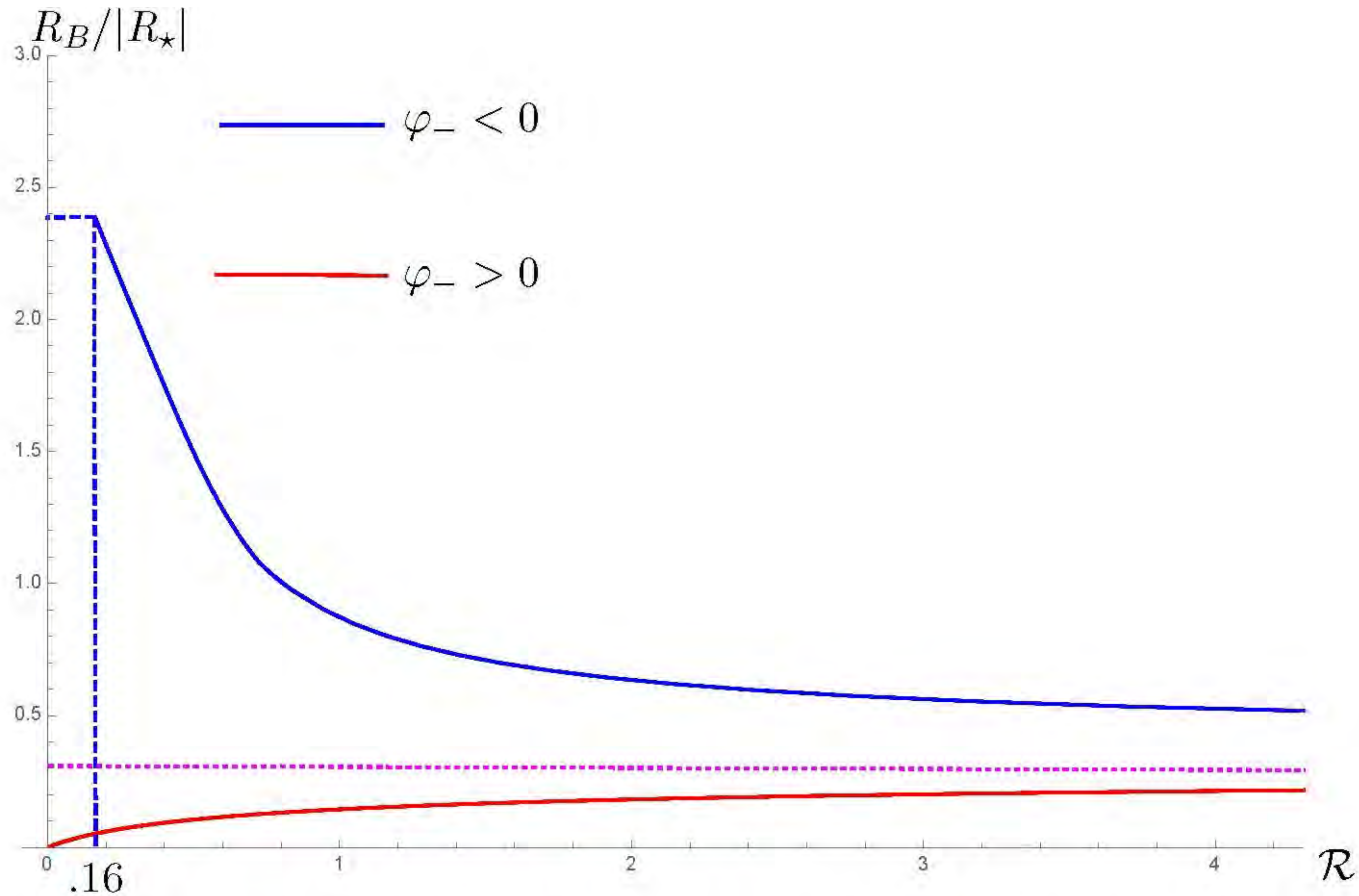


Figure 9: $R_B/|R_\star|$ as a function of $\mathcal{R}$ for bulk potential (3.1), brane quantities (3.2) and parameter values (3.3). $|R_\star|$ is defined as the 'expected' brane curvature related to the brane cosmological constant $W_B(\varphi_\star)$ in the absence of a 5d bulk. For $\mathcal{R} \to \infty$ both the red and blue branch asymptote to the value for $R_B/|R_\star|$ indicated by the dotted magenta line.

• For any given value of $R^{(\zeta)}$ there typically exists at least one self-stabilising solution. Frequently, there exist several branches of solutions as a function of $R^{(\zeta)}$.

• For $R^{(\zeta)} \to 0$ one of the branches connects continuously to a solution with $R^{(\zeta)} = 0$ and $R_B = 0$.

• Interestingly, there also exist solutions where R_B stays finite for $R^{(\zeta)} \to 0$. In this case there is no solution with $R^{(\zeta)} = 0$ exactly. The reason is that the 'would-be solution' with $R^{(\zeta)} = 0$ can be shown to be a solution with finite $R^{(\zeta)}$ associated with a different UV fixed point.

• Last, for solutions with $R^{(\zeta)} \to \infty$, the brane curvature does not diverge, but rather asymptotes to a finite value.

• However, for the models studied here, the typical scale of the brane curvature is the 4d Planck scale M_4 on the brane, i.e. $R_B \sim M_4^2$. Only on the branch connected to the flat brane solution we can achieve $R_B \ll M_4^2$ by tuning $R^{(\zeta)}$ to a sufficiently small value.

Outlook

- Unlike the D=2 Centaur solutions it seems that there exist no regular interpolating solutions between the dS and the AdS regime.

- There are several loop-holes in the above: tuned potentials and different ansatze.

- There are ways of constructing dS metrics on branes, while the bulk being in the an AdS regime, ONLY if we have dS boundary conditions in the AdS boundary.

- There seems to be a rather rich set of such solutions.

- Their realization in a top-down setting in string theory should be investigated.

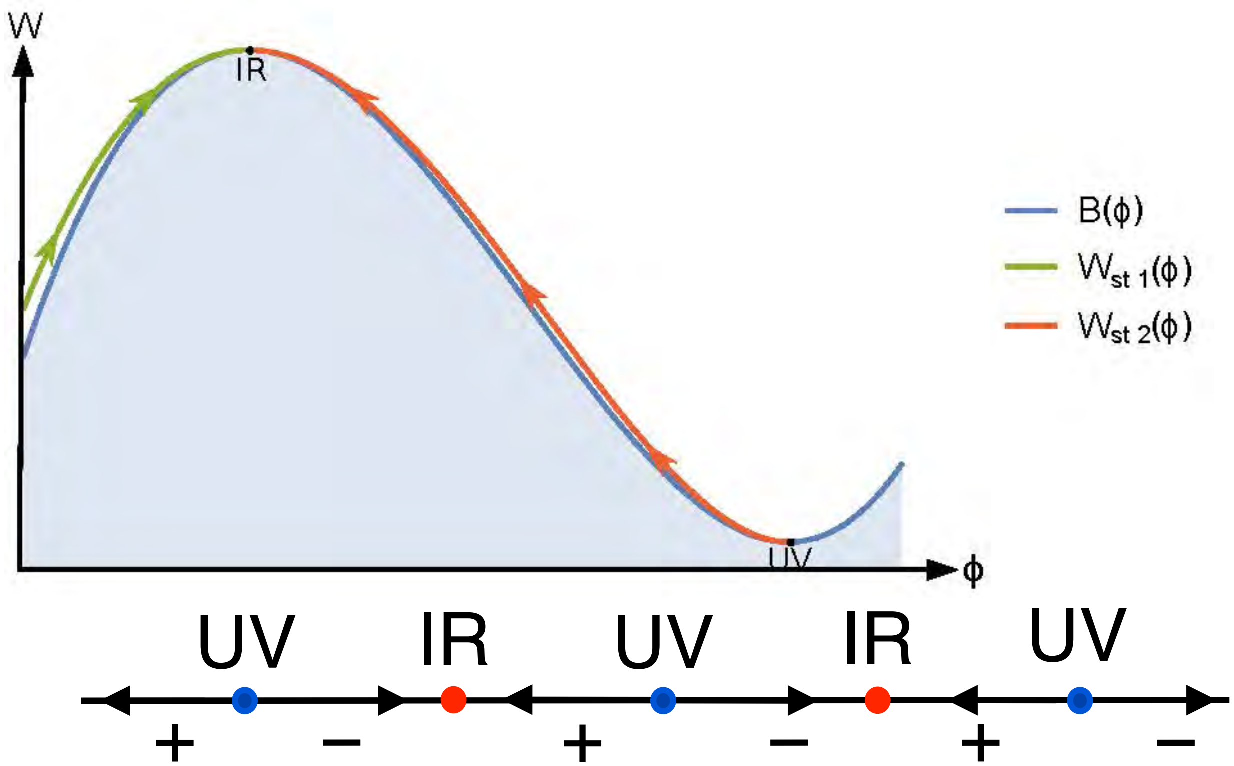
- The solutions are related to similar solutions where the brane is flat and the brane cosmological constant is self-tuned.

- A complete cosmological setup should be developed.

THANK YOU!

The standard holographic RG flows

• The standard lore says that the maxima of the potential correspond to UV fixed points, the minima to IR fixed points, and the flow from a maximum is to the next minimum.



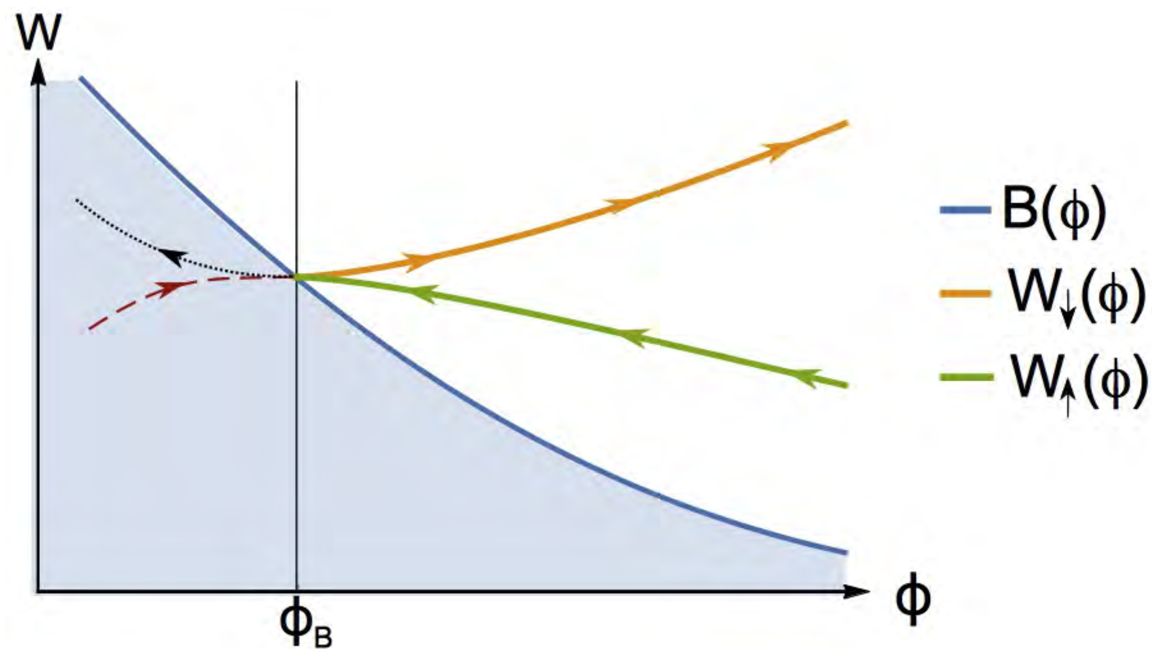
• The real story is a bit more complicated.

Bounces

- When W reaches the boundary region $B(\phi)$ at a generic point, it develops a generic non-analyticity.

$$W_{\pm}(\phi) = B(\phi_B) \pm (\phi - \phi_B)^{\frac{3}{2}} + \cdots$$

- There are two branches that arrive at such a point.



• Although W is not analytic at ϕ_B, the full solution (geometry+ϕ) is regular at the bounce.

• The only special thing that happens is that $\dot{\phi} = 0$ at the bounce.

• All bulk curvature invariants are regular at the bounce!

• All fluctuation equations of the bulk fields are regular at the bounce!

• The holographic β-function behaves as

$$\beta \equiv \frac{d\phi}{dA} = \pm\sqrt{-2d(d-1)\frac{V'(\phi_B)}{V(\phi_B)}(\phi - \phi_B)} + \mathcal{O}(\phi - \phi_B)$$

• The β-function is patch-wise defined. It has a branch cut at the position of the bounce.

• It vanishes at the bounce without the flow stopping there.

• This is non-perturbative behavior.

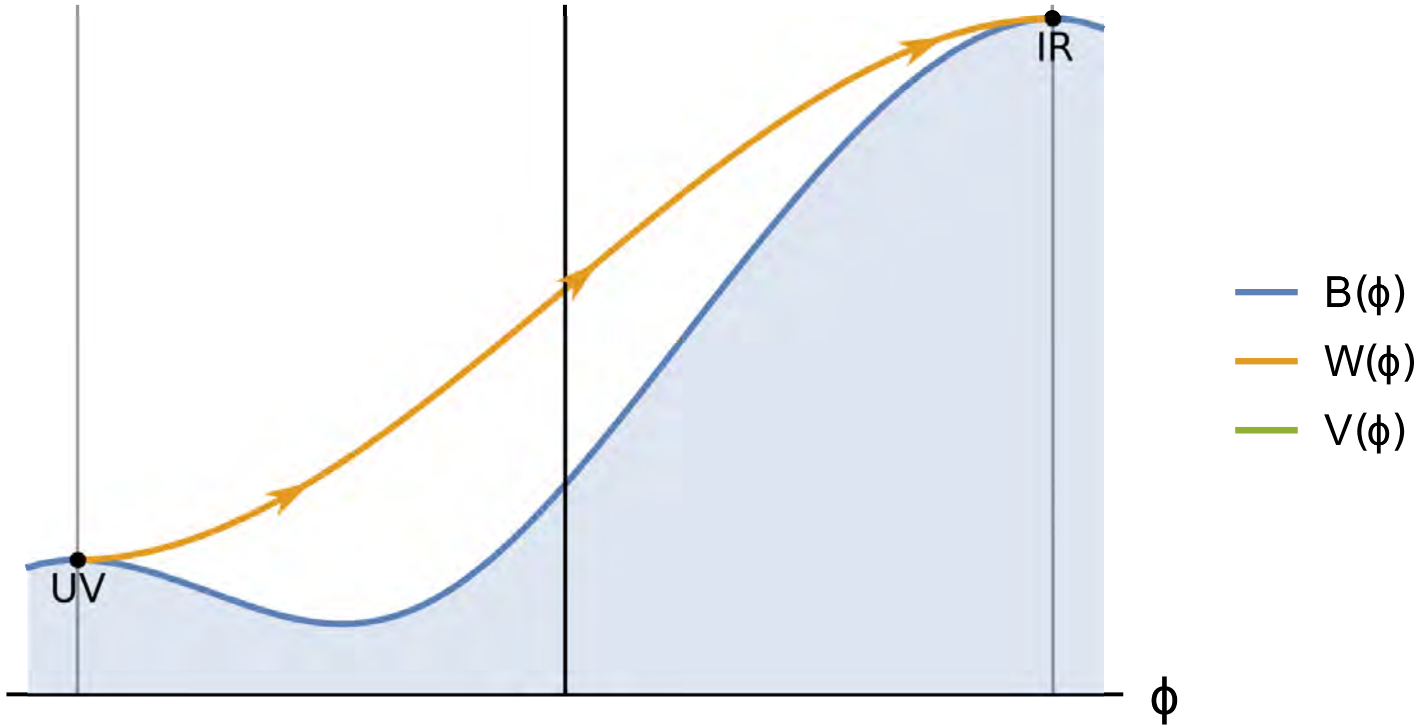
• Such behavior was conjectured that could lead to limit cycles without violation of the a-theorem.

Curtright+Zachos

• We can show that limit cycles cannot happen in theories with holographic duals (and no extra "active" dimensions).

Exotica

- Vev flow between two minima of the potential

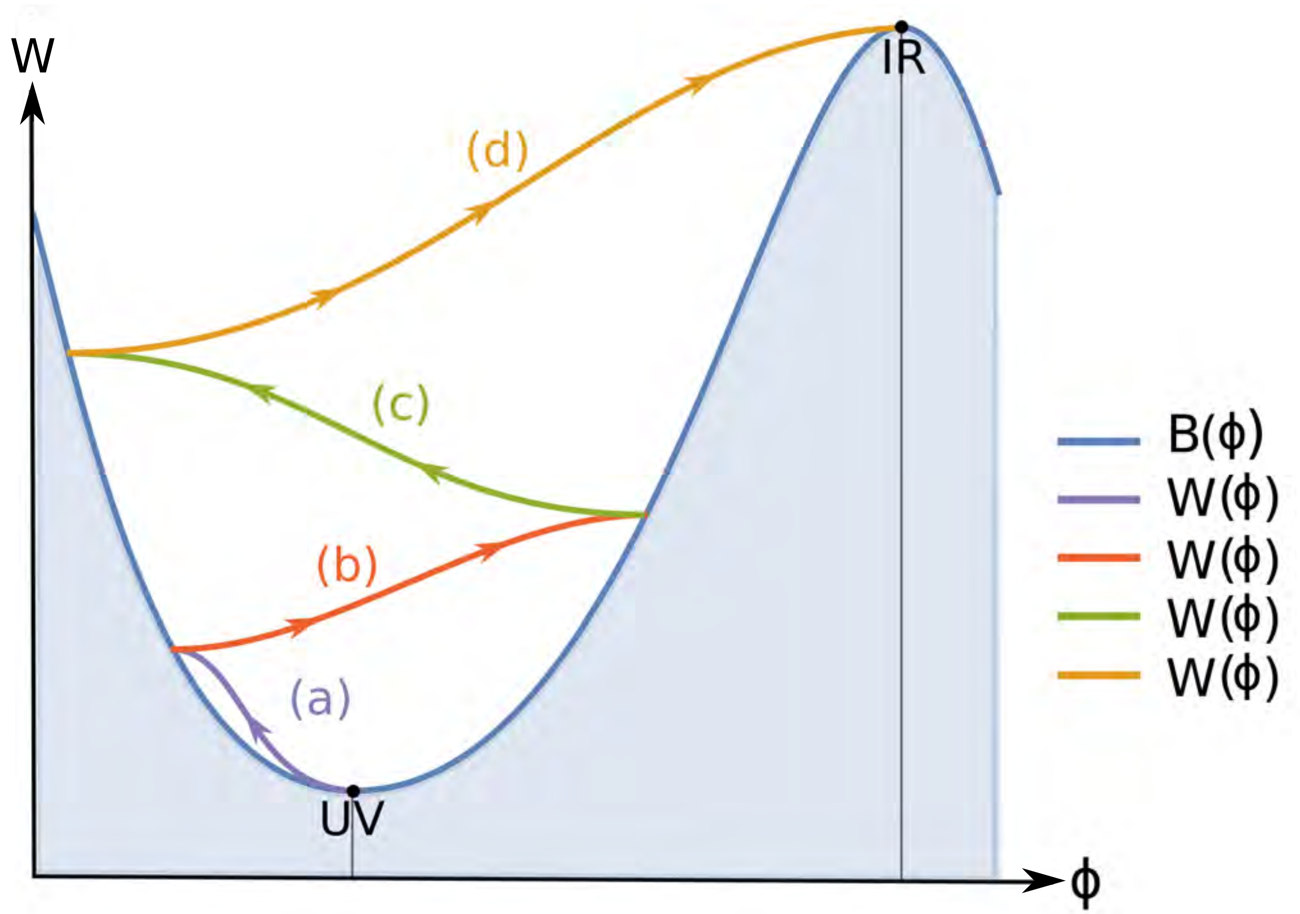


- Exists only for special potentials. It is a flow driven by the vev of an irrelevant operator.

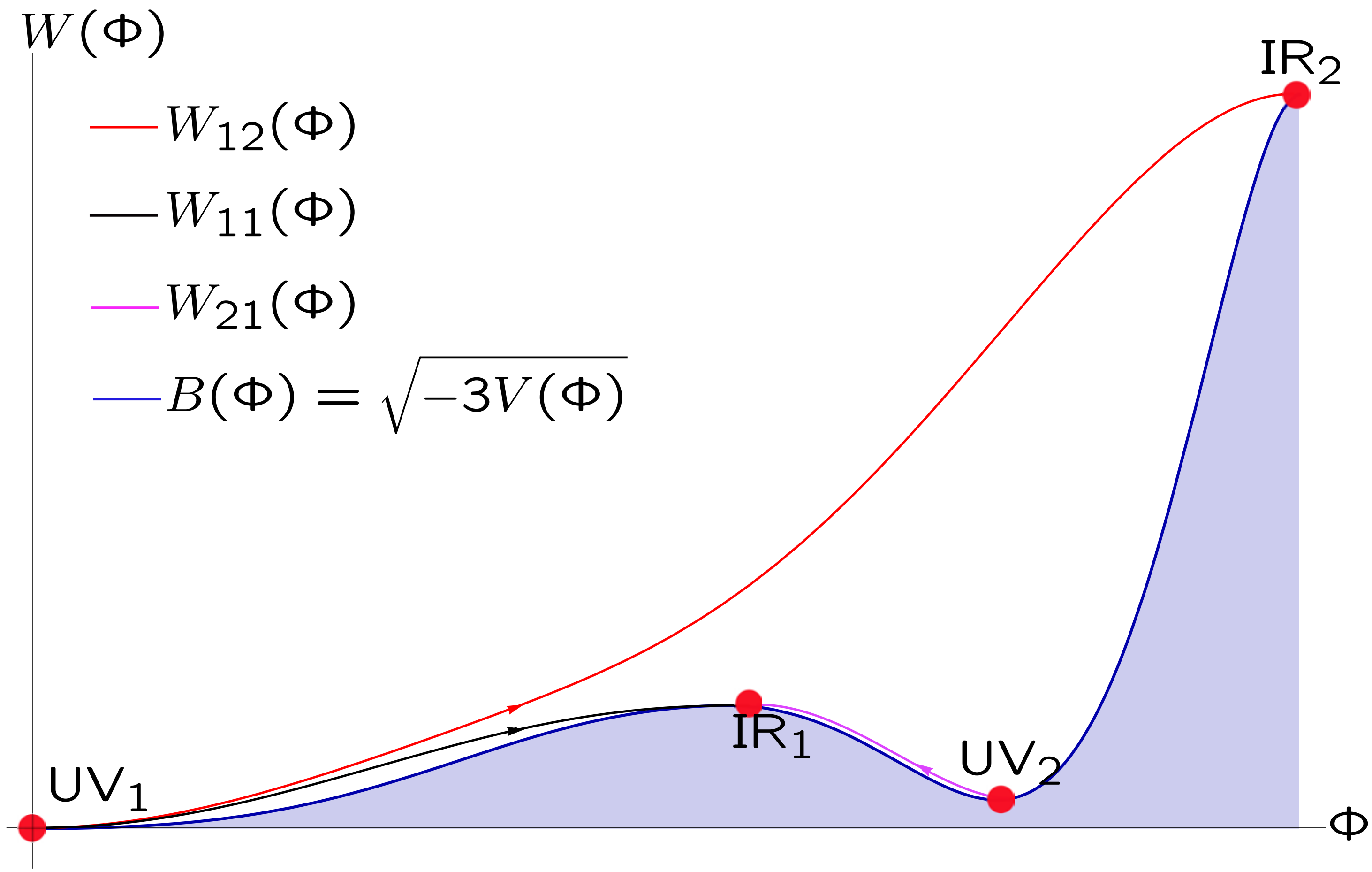
- A analogous phenomenon happens in N=1 sQCD.

Seiberg, Aharony

Regular multibounce flows



Skipping fixed points



Detailed plan of the presentation

- Title page 0 minutes
- Bibliography 1 minutes
- Introduction 3 minutes
- (Asymptotically) Flat Space 4 minutes
- (Asymptotically) AdS Space 6 minutes
- (Asymptotically) dS Space 8 minutes
- The (many) roads to de Sitter 10 minutes
- The Centaur solutions 12 minutes
- The next goal 15 minutes
- Flows in the landscape 20 minutes
- dS flows 22 minutes
- flows from AdS to dS 26 minutes
- A different (local) dS realization 28 minutes
- The bulk and brane equations 30 minutes
- Detour: the self-tuning of the cosmological constant 34 minutes
- dS metrics on the brane 36 minutes
- (Numerical) results 41 minutes
- Outlook 42 minutes

- The standard holographic RG Flows 43 minutes
- Bounces 46 minutes
- Exotica 47 minutes
- Regular Multibounce flows 47 minutes
- Skipping fixed points 48 minutes