New de Sitter Solutions

Work in progress with

M. Dodelson, X. Dong, G. Torroba

cf Douglas '10, Giddings
de Wolfe Freedman Gubser Karch
Kaloper, Chamblin/Reall ...

Precision Cosmology →

ΛCDM

Primordial power spectrum consistent with primordial inflation

- Some aspects UV-sensitive
- want a more complete framework

'80s Banks Linde Weinberg ...

1998 $\Lambda > 0$ observed

- some concern among string theorists
  - no S-matrix - but Marolf Morrison Srednicki '12
  - AdS solutions well-studied
- BP : many fluxes

$\gtrsim$ 2001 Moduli stabilization mechanisms

- Giddings, Kachru, Polchinski '01, KKLT '03
  ... LARGE Vol ...
- $D > 10$ Maloney ES Strominger '01
- perturbative sources $D = 10$

Relatively complicated (for good reason)

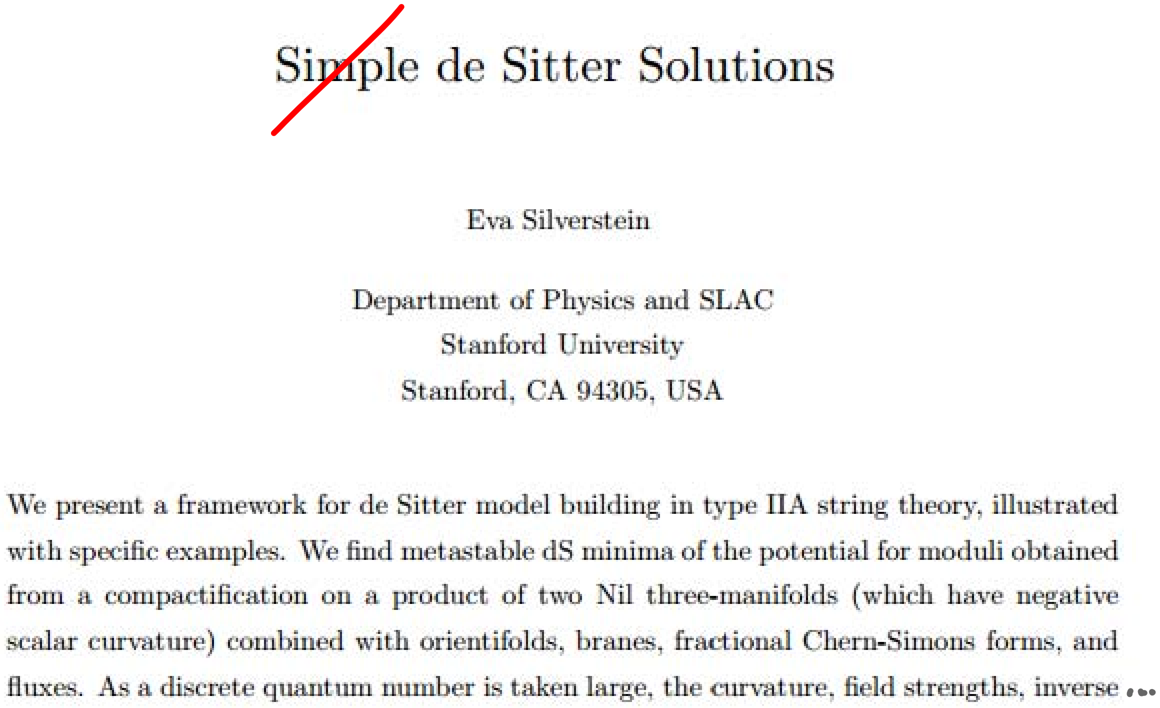
→ various inflation mechanisms, some simple & observationally testable

Simple backgrounds (p-branes, D-branes, Freund-Rubin) led to rapid progress in black hole physics, string dualities, and the AdS/CFT correspondence.

The cosmological (dS, FRW) case has been slower in part because of the complication of the solutions

cf 3d dS/dS Dong Horn ES Torroba

Higher spin Anninos Hartman, Strominger



~~Simple~~ de Sitter Solutions

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We present a framework for de Sitter model building in type IIA string theory, illustrated with specific examples. We find metastable dS minima of the potential for moduli obtained from a compactification on a product of two Nil three-manifolds (which have negative scalar curvature) combined with orientifolds, branes, fractional Chern-Simons forms, and fluxes. As a discrete quantum number is taken large, the curvature, field strengths, inverse ...

Alternate title

%%Complicated de Sitter Solutions h/t G. Shiu

Aharony, Danielson, Dong, de Wolfe, Douglas

Flauger, Gurarie, Hertzberg Horn, Kallosh,

Daban, Shiu, Taylor, Tegmark, Torroba, Wrase

...

String theory →

potential with structure

$$V(\Phi, \sigma; \cdots) \sim$$

dilaton   size   other sizes, axions, brane positions...

bulk   localized defects

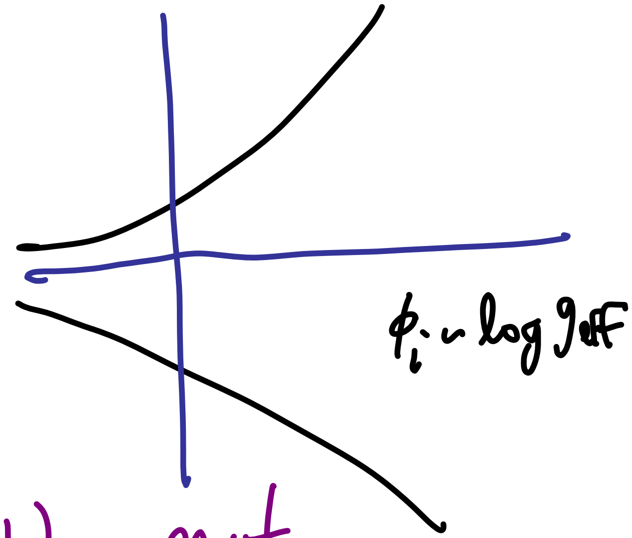
$$\sum_i \hat{V}_i e^{\tilde{\beta}_i \Phi + \tilde{\gamma}_i \sigma} + \sum_\ell \tilde{\sigma}_\ell e^{\tilde{\gamma}_i \Phi_i} \frac{\delta(w-w_\ell)}{\sqrt{g_{ww}}}$$

$$\tilde{\gamma}_i, \tilde{\beta}_i \sim \mathcal{O}(1/M_p)$$

+ warping effects (cf constraints)

+ quantum, non-perturbative

$$\sum_i \hat{V}_i \, e^{\beta_i \frac{\phi_{ic}}{M_p}}$$



- Here $\beta_i \sim \mathcal{O}(1)$, not suitable for slow roll

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e.g. IIB compactified from $\hat{D}=10 \to D=5$ on 5-sphere

$$\int d^{10}x \sqrt{-G_{(10)}}\, \mathcal{R} \to V_{\mathcal{R}} : \beta_{\mathcal{R}} = 4\sqrt{\frac{2}{15}}$$

$$\int d^{10}x \sqrt{-G_{(10)}}\, |F_5|^2 \to V_{F^2} : \beta_{F5} = 2\sqrt{\frac{10}{3}}$$

$$\text{"O3-planes"} \to \sigma_{O3} : \alpha_{O3} = \sqrt{\frac{10}{3}}$$

Bottom-up Warmup :

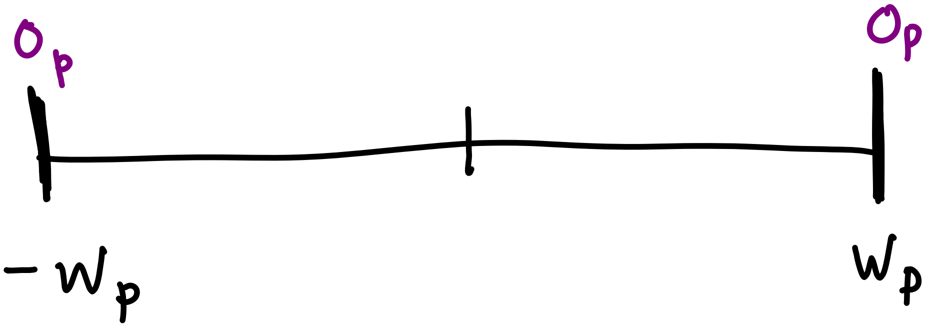
Consider $\underline{\underline{D=5}}$ theory with potential that is simply

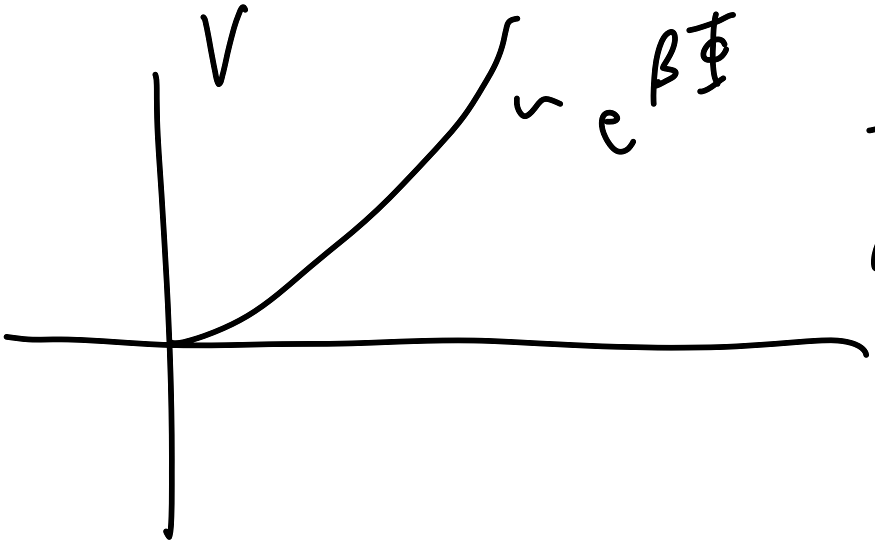
$$V = \hat{V} e^{\beta \phi}$$

plus a localized source (orientifold plane)

$$\sigma = -\hat{\sigma} \, e^{\gamma \phi} \left[\delta(w - w_p) + \delta(w + w_p) \right]$$

$(\hat{\sigma} > 0)$





tadpole
in D = 5

Reduce to d = 4 along one direction

$$ds^2 = a(w)^2 ds^2_{dS_4} + dw^2$$

$$\phi = \phi(w)$$

cf
Randall - Sundrum
Kaloper...
Chamblin/Reall
de Wolfe Freedman ...
Gubser Karch ...

O-planes $T_{loc} \sim -\hat{\sigma} e^{\alpha\phi} [\delta(w-w_p) + \delta(w+w_p)]$

$\Rightarrow$ boundary conditions

Equations (radial version of Friedmann eqn's)

($\kappa_5=1$ here)

$$\frac{1}{2}(D-1)(D-2)\,\frac{a'^2-1}{a^2} = \frac{1}{2}\phi'^2 - V(\phi)$$

$$\phi'' + (D-1)\frac{a'}{a}\phi' - V'(\phi) = 0$$

3 integration constants + w_p parameter

- $a'(-w_p) = -\dfrac{a\sigma(\phi)}{2(D-2)}$
- $\phi'(-w_p) = \frac{1}{2}\sigma'(\phi)$ $\quad w=-w_p$
- $a'(0) = 0 = \phi'(0)$

- Find numerical solutions ✓

- Analytically can show α, β are restricted : without additional structure (e.g. brane at $w=0$)

$$\alpha^2 \geq \frac{D-1}{D-2} \qquad \beta \leq \frac{2\alpha}{D-1}$$

is a no-go region

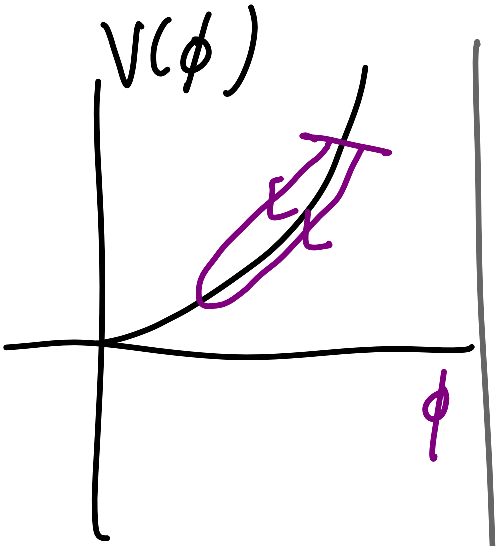
- Analytic sol'ns for special potentials
(e.g. continuation of FRW/FRW)

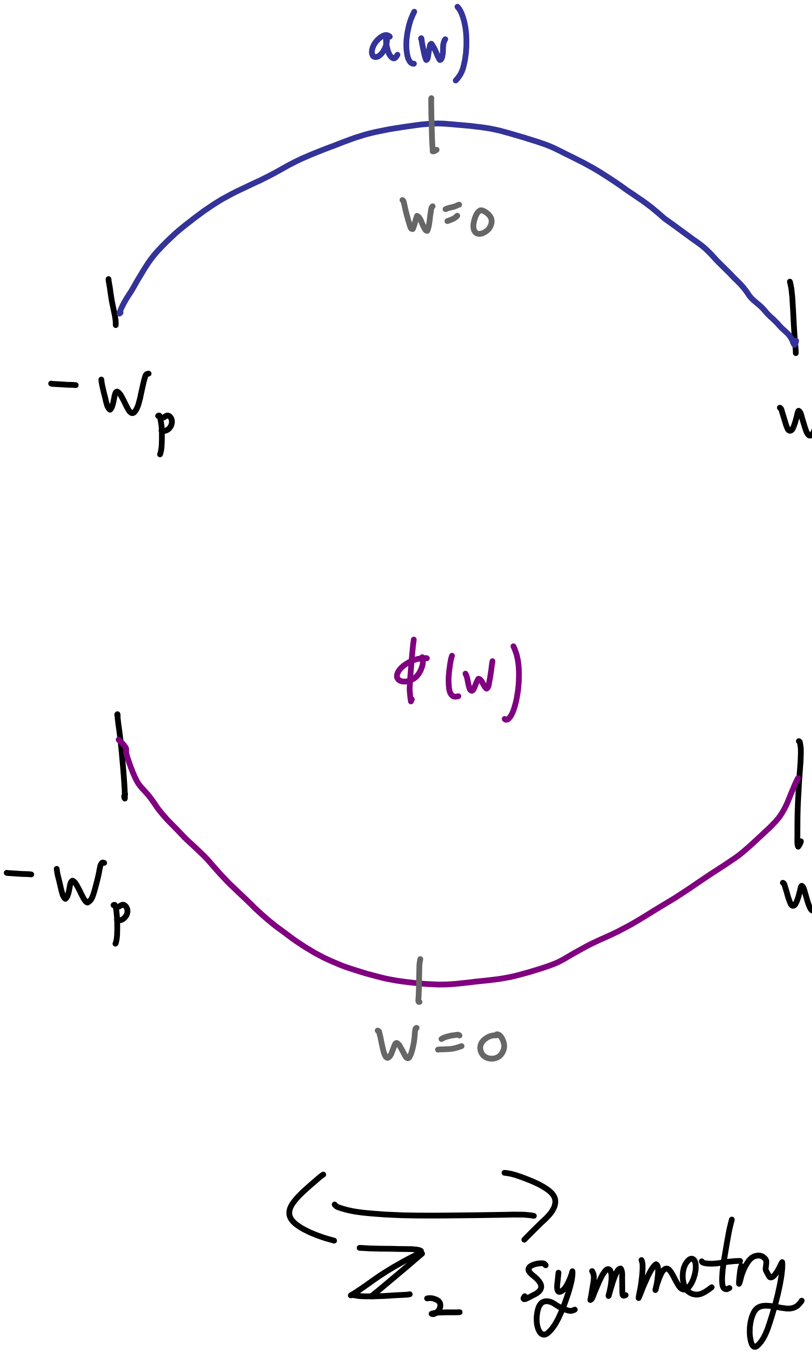
Analytic Example

$$V = -2a_1^2(d-1)^2 e^{-\frac{2\sqrt{2}c}{\sqrt{d-1}}} e^{\frac{2\sqrt{2}}{\sqrt{d-1}}\phi} + (2d-1)(d-1) e^{-\frac{\sqrt{2}c}{\sqrt{d-1}}} e^{\frac{\sqrt{2}}{\sqrt{d-1}}\phi}$$

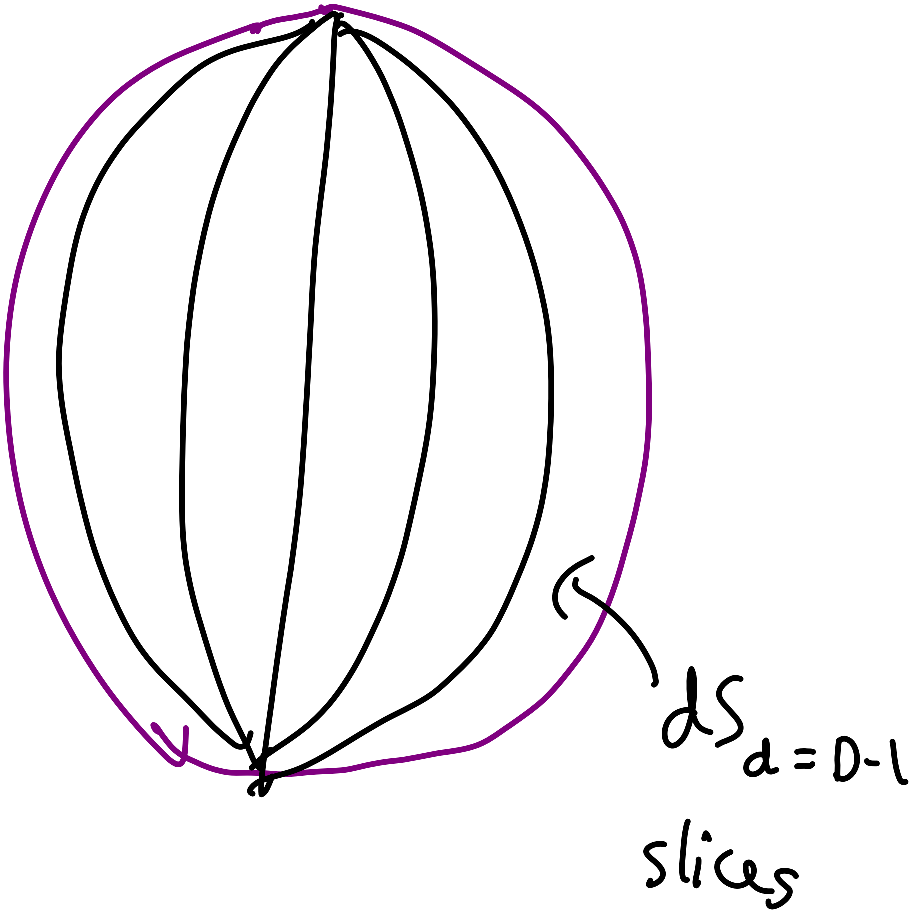
$$a(w) = a_1 - \frac{1}{2a_1} w^2$$

$$\phi(w) = c - \sqrt{\frac{d-1}{2}} \log\left(2a_1^2 - w^2\right)$$



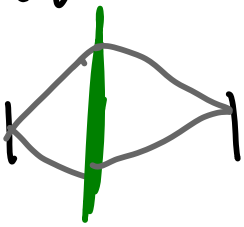


☆ Nonsingular dS_4 solution

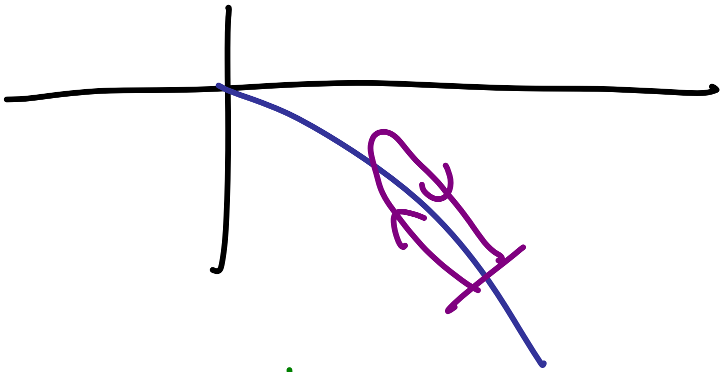


$$ds^2_{\underset{\underset{5}{\shortparallel}}{D}} = dw^2 + a(w)^2\, ds^2_{\underset{\underset{4}{\shortparallel}}{dS_{d=D-1}}}$$

- Similar analysis with "UV brane" $\sigma_{br} \propto e^{\alpha_{br}\phi}$



For intuition (if it helps), this is analogous to ($w \leftrightarrow$ time) to field rolling in time on $V < 0$ with negative curvature spatial slices



(This would have bang/crunch singularities, but in our case the Orientifolds cut off the interval at $\pm w_0$, excising singularities.)

- Explicit numerical solutions

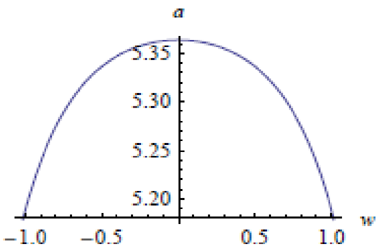


Figure 1: $V(\phi) = e^{3\phi}$, $\sigma(\phi) = -e^{3\phi}$.

$\alpha = \beta = 3$

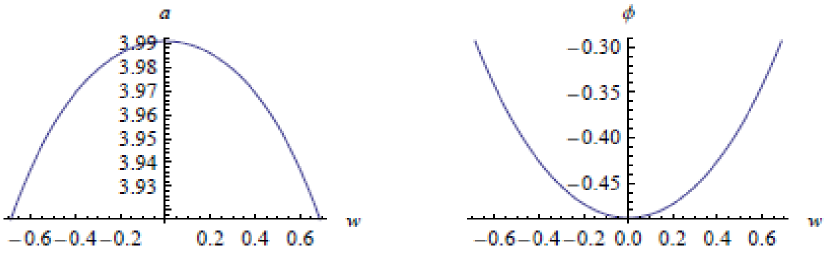


Figure 2: $V(\phi) = e^{2\phi}$, $\sigma(\phi) = -e^{3\phi}$.

$\alpha = 3, \beta = 2$

- $d = D-1$ naive (smeared) effective potential would not give sol'ns

- Some no-go regions in α, β but easy to avoid

- Similar solutions w/ UV brane

Top Down examples

- $D > 10$ $\quad V \propto (D-10)\, e^{\beta \phi_{\text{canonical}}}$ (orientifold (D-2)-plane)

  $\beta = \frac{2}{\sqrt{D-2}} \qquad \alpha = \frac{D}{2\sqrt{D-2}}$

- IIB $\tilde{D} = 10 \longrightarrow D = 5$ on $S^5/\mathbb{Z}_k$

  $V_{\text{flux}}, \quad \sigma_{O3}, \quad \sigma_{7B}$ (UV brane)

  $\beta = 2\sqrt{\frac{10}{3}}, \quad \alpha_{O3} = \sqrt{\frac{10}{3}}, \quad \alpha_{7B} = 2\sqrt{\frac{2}{15}}$

  (All depend <u>only</u> on $\phi_1 = \sqrt{\frac{5}{6}} \log \frac{g_s}{R^4}$)

etc (expect a zoo!)

Control Parametrics & Warping

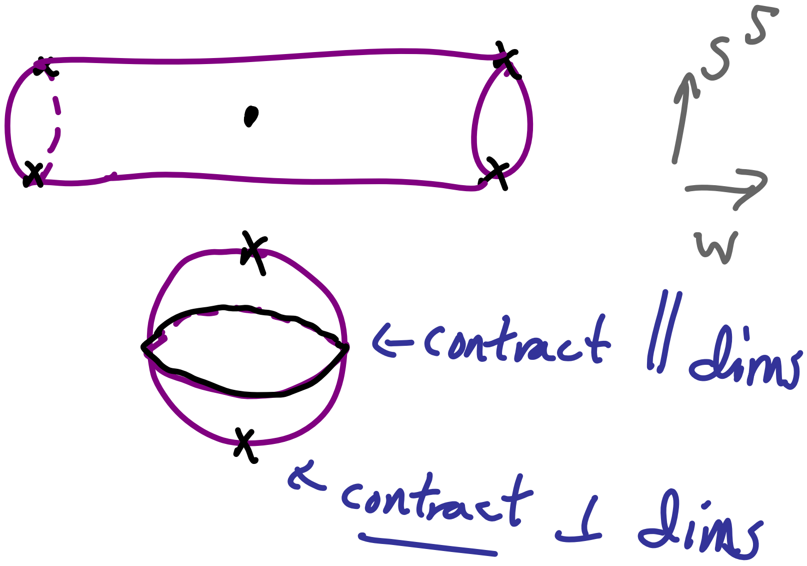
IIB example : naive $d=4$ potential:

$$V^{(4d)}_{Naive} \sim \left(\frac{g_s^2}{\ell R^5/k}\right)^2 \left\{ -\frac{1}{R^2 g_s^2}\cdot\frac{R^5 \ell}{k} - \overset{(O3)}{\frac{1}{g_s}} + \underset{(7B)}{\frac{N_f R^4}{g_s^2 k}} + \underset{(F_5^2)}{\frac{N_c^2 k}{R^5}\ell} \right\}$$

Does give good estimate of parametrics $\frac{R^4}{g_s} \sim \frac{k}{N_f}$, $\frac{R}{\ell} \sim N_c^2 N_f$

→ $V_{QR}/V \sim \frac{1}{N_c^2 N_f}$ corrections small

Remark: The ingredients here source $\log \frac{g_s}{R^4}$ but not $\log g_s$ at leading order. Microscopically an $SO(4)$-invariant S^5 squashing mode is locally sourced, but oppositely by O-planes & UV 7-brane.



Scalings continued :

dS_d Hubble : $H^2 \sim \frac{1}{\ell^2} \lesssim \mathcal{O}(m^2)$

mass squared of perturbations

(no additional small parameters)

Warping + gradients contribute to m^2, in some cases positively.

cf Douglas '10 Warping & constraints remove certain unphysical instabilities.

Redshift space distortions

So far, took $V_{D=5}(\phi)$ with a tadpole, and used radial evolution $\phi(w)$ & warping $a(w)$ with nonsingular b.c. to obtain $d=4$ de Sitter solution

⇒ at least new saddle points, next checking if $\delta\phi$, $\delta g_{\mu\nu}$ are stable at 2nd order (so far yes but not done.)

★ Tool : $V_{\text{eff}}[\delta\phi, \delta g_{ww}]$ | sol'n of constraints

with strong warping Douglas '10, Giddings ..

Perturbation Analysis

$$ds_D^2 = a(z)^2\left(e^{2\delta A(z,x)} dz^2 + e^{-\frac{2}{d-2}\delta A(z,x)} \tilde{g}_{\mu\nu} dx^\mu dx^\nu\right)$$

$$\phi \to \phi + \delta\phi(z,x)$$

- Impose constraints (off-shell, to quadradic order; on-shell to linear order)

$$\hookrightarrow \delta A' + (d-2)\frac{a'}{a}\delta A = \frac{d-2}{d-1}\phi'\delta\phi$$

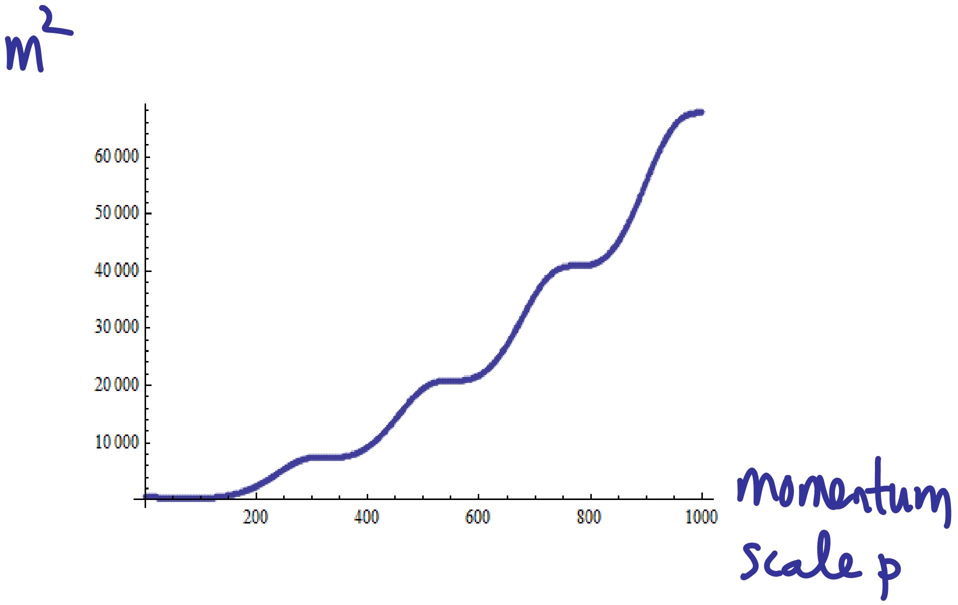
eliminate $\delta\phi$

Test functions (Not yet systematic)

$$\int dz\, a^{d-1}\left(\delta G_{zz} - \delta T_{zz}\right)\delta A = 0$$

$$\delta A = \sum \delta A_i u_i \qquad \tilde{\Box} u_i = m_i^2 u_i$$

$$m^2 \int a^{d-1}\delta A^2 = \int a^{d-1}\left\{\frac{d-2}{d-1}\delta\phi\left[\left(2a^2\delta V - d\frac{a'}{a}\phi'\right)\delta A + \phi'\delta A'\right] - \left(d - \frac{d-2}{d-1}\phi'^2\right)\delta A^2\right\}$$



- Still setting up the complete variational problem

Douglas '10 Warping helps (screens negative sources)

$$V_{\text{eff}}\, G_N^2 = \frac{-\frac{3}{2}}{\sum_i \frac{1}{\lambda_i} \left| \int \sqrt{g}\, u_i \right|^2}$$

where λ_i are energy eigenvalues & u_i normalized wavefunctions for the analogue Schrodinger problem

$$\lambda_i u_i = -\partial_w^2 u_i + \Big[\overbrace{-V[\phi(w)] - \phi'^2(w) - \sigma_{loc}}^{U_{Q.M.}(w)} \Big] u_i$$

In our case, $U(w)$ is a double well potential. $\delta\phi$, $\delta g_{\mu\nu}$ affect $\{\lambda_i, u_i\}$ (low-lying levels dominate)

in progress

Summary

- $V \sim e^{\beta\phi}$ tadpoles + O-planes

  $\rightarrow dS_d$ solutions

  (fewer ingredients, more explicit about internal fields)

- Quadratic stability in progress

  need $m^2_{All} > -H^2 \cdot \varepsilon$ or need more structure

  (so far ok)

- holographic description in progress.

  2 stages: $D \rightarrow D-1 \rightarrow D-2$

  $\nearrow$

  $U(N_c)^k$

  + IR O3

  UV 7B