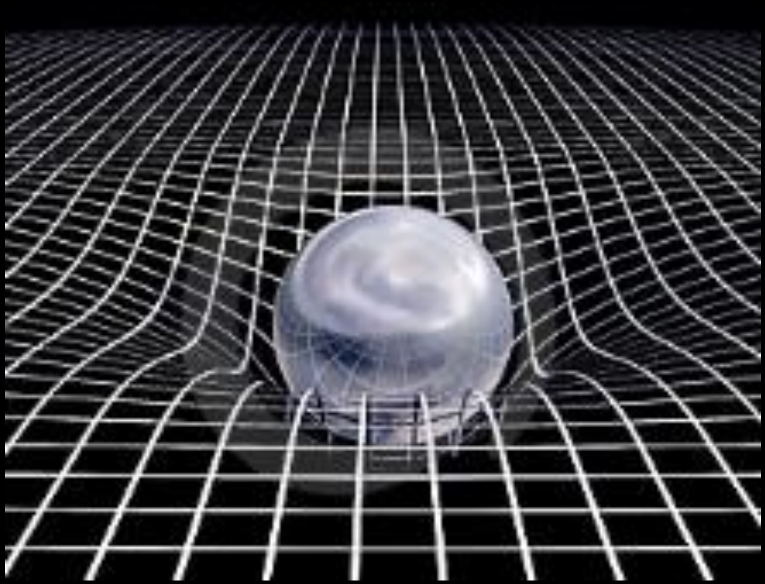


Getting Boosts from Extra Dims

de Sitter space and Inflation from Brane Back-reaction

1108.2553 with Leo van Nierop
1109.0532 with A Maharana, Leo van Nierop, A Nizami & F Quevedo

Outline

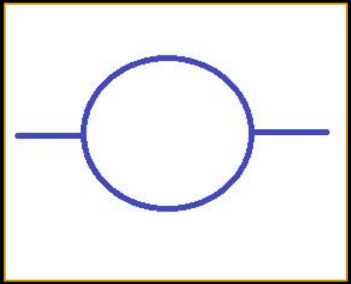
- New tool: high codim back-reaction
    - Implications for cosmological constant problem
        - see 1101.052 and 1108.0345 *(w L van Nierop)*

Outline

- New tool: high codim back-reaction
  - Implications for cosmological constant problem
    - see 1101.052 and 1108.0345 *(w L van Nierop)*
- Honest-to-God higher-dim inflation
  - de Sitter no-go loopholes
  - Inflationary models

New Tools

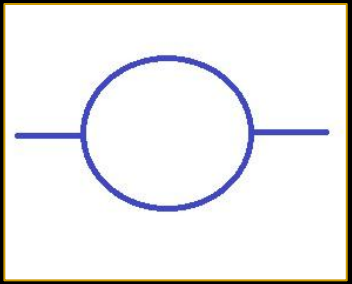
Extra dims and naturalness



- How can extra dimensions help?
  - scalars in 4D need not be scalars in higher D

eg ϕ *could arise as a component of* A_m *or* g_{mn}

Extra dims and naturalness



- How can extra dimensions help?
  - scalars in 4D need not be scalars in higher D
  - lowering the gravity scale helps by lowering the UV scales to which one can be sensitive

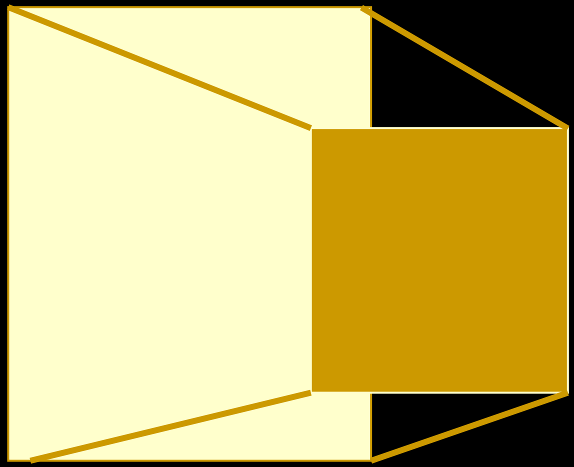
$$\boxed{\delta m^2 = \frac{\Lambda^4}{{M_4}^2}}$$

Extra dims and naturalness

- How can extra dimensions help?
  - scalars in 4D need not be scalars in higher D
  - lowering the gravity scale helps by lowering the UV scales to which one can be sensitive
  - back-reaction can be important for low energies (eg Randall-Sundrum models)

Extra dims and naturalness

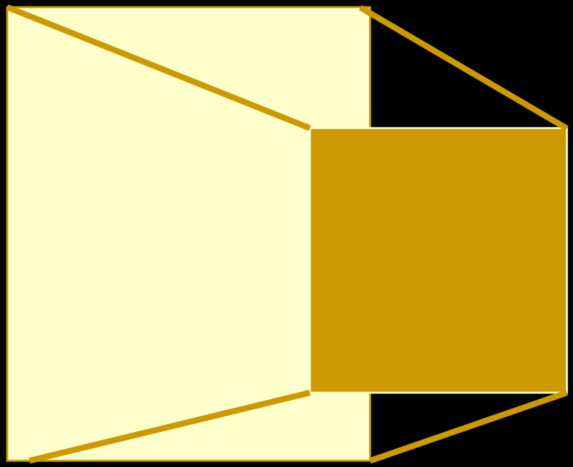
- How can extra dimensions help?
  - scalars in 4D r
  - lowering the g
    UV scales to v
  - back-reaction
    (eg Randall-Sundrum models)



Cod-1 back-reaction (warping) makes low E physics local in extra dims

Extra dims and naturalness

- How can extra dimensions help?
  - scalars in 4D r
  - lowering the g
    UV scales to v



Cod-1 back-reaction (warping) makes low E physics local in extra dims

Worked out in detail only for codimension-1

on

Sundrum models)

Higher-codimension back-reaction

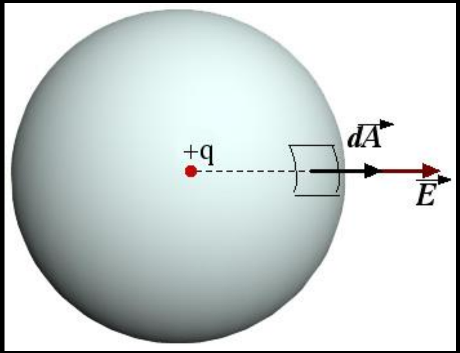
- Why are higher codimensions harder?
  - In d space dims massless fields vary as r^{2-d} and so tend to diverge at the source positions for $d > 1$

Higher-codimension back-reaction

- Why are higher codimensions harder?
  - In d space dims massless fields vary as r^{2-d} and so tend to diverge at the source positions for $d > 1$
- How is this dealt with?
  - Source action dictates near-source boundary conditions

Higher-codimension back-reaction

- Why are higher codimensions harder?
  - In *d* space dims ma nd so tend to diverge at t > *1*
- How is this dealt w
  - Source action dicta conditions

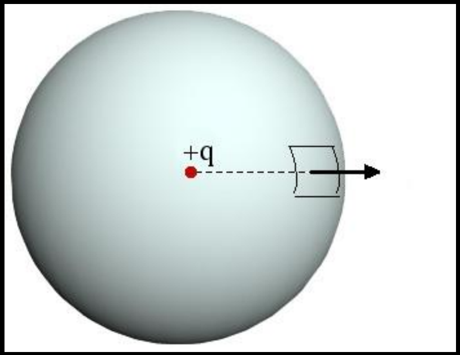


$$\int E \cdot dA \to Q$$

Higher-codimension back-reaction

Peloso, Sorbo & Tasinato
CB, Hoover, de Rham & Tasinato

- Why are higher codimensions harder?
  - In *d* space dims ma nd so tend to diverge at th > *1*
- How is this dealt w
  - Source action dicta conditions



$$r^{d-1}\,\frac{\partial \phi}{\partial r} \rightarrow \frac{\partial S}{\partial \phi}$$

….and similarly for g_{mn} etc

Codimension-2 back-reaction

CB, Hoover, de Rham & Tasinato

- Source boundary conditions:
  if $ds^2 = e^{2W}dx^2 + dr^2 + e^{2B}d\theta^2$ then

$$(e^B\phi')_b = \frac{\kappa^2}{2\pi}\left(\frac{\partial L_b}{\partial \phi}\right)$$

$$(e^B W')_b = \frac{\kappa^2}{4\pi}\left(\frac{\partial L_b}{\partial g_{\theta\theta}}\right) = U_b$$

$$(e^B B' - 1)_b = -\frac{\kappa^2}{2\pi}\left[\left(\frac{\partial L_b}{\partial \phi} + \frac{3}{2}\frac{\partial L_b}{\partial g_{\theta\theta}}\right)\right]$$

Constraint: $4U_b[2 - 2L_b - 3U_b] - \left(\frac{\partial L_b}{\partial \phi}\right)^2 = 0$

Higher-codimension back-reaction

Goldberger & Wise
de Rham

- Why are higher codimensions harder?
  - In d space dims massless fields vary as r^{2-d} and so tend to diverge at the source positions for $d > 1$

- How is this dealt with?
  - Source action dictates near-source boundary conditions
  - Must renormalize source action

de Sitter solutions

Back-reaction vs de Sitter no-go

- Few honest-to-God extra dimensional cosmologies exist
    - work in 4D effective theory
    - work with moving branes in static backgrounds

Back-reaction vs de Sitter no-go

Maldacena & Nunez;
Wesley & Steinhardt

- Few honest-to-God extra dimensional cosmologies exist
  - work in 4D effective theory
  - work with moving branes in static backgrounds
- Lower-dimensional dS solutions in higher dimensions difficult to find
  - Motivated no-go results for de Sitter solutions

Back-reaction vs de Sitter no-go

CB, Maharana, van Nierop,
Nizami & Quevedo

de Sitter solutions and no-go results:

if $$S = \frac{1}{2\kappa^2}\int \sqrt{-g}\,(R + L_m) + S_{source}$$

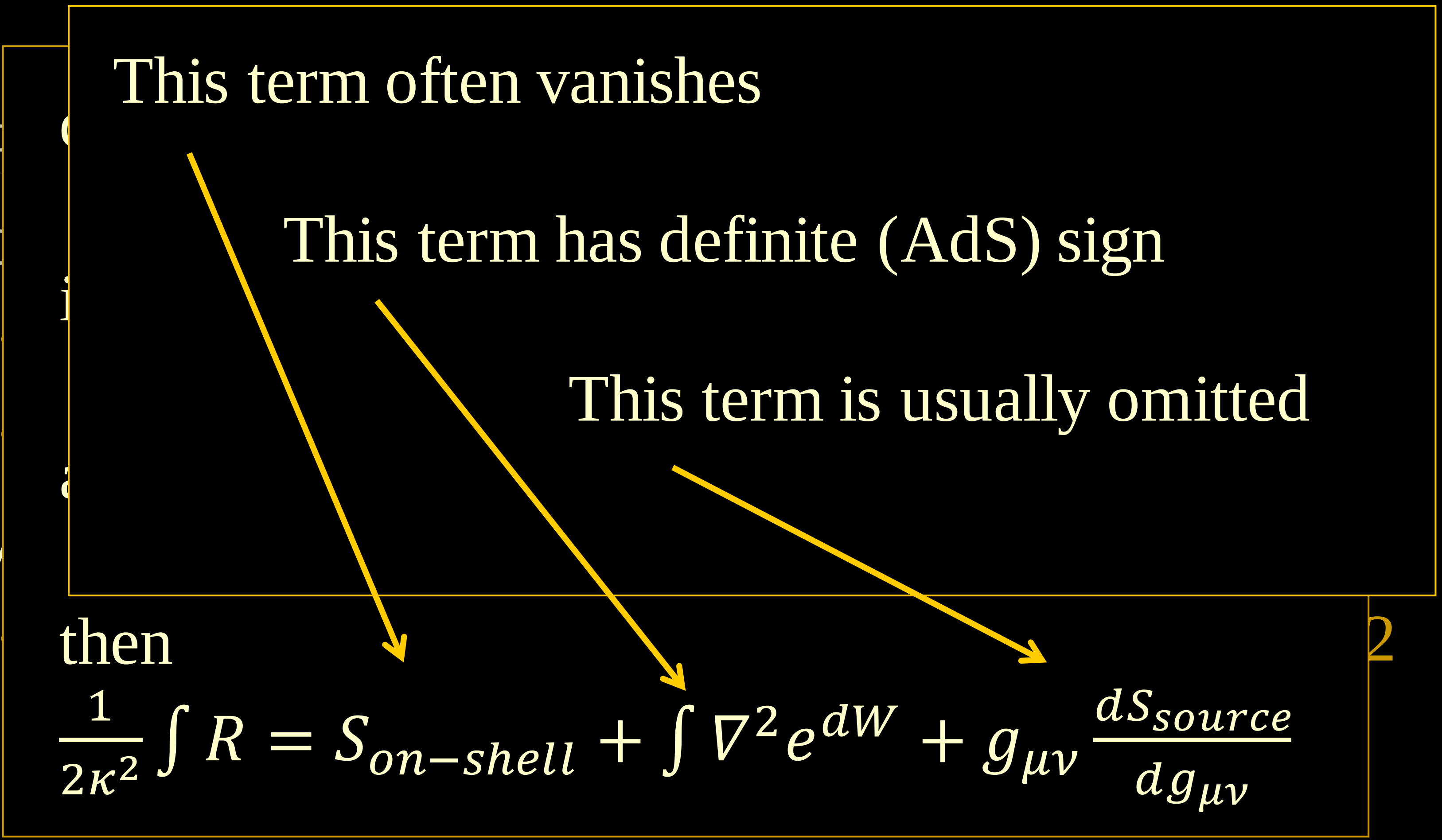
and $$ds^2 = e^{2W} g_{\mu\nu}\, dx^\mu dx^\nu + \hat{g}_{mn}\, dx^m dx^n$$

then in absence of space-filling fluxes

$$\frac{1}{2\kappa^2}\int R = S_{on-shell} + \int \nabla^2 e^{dW} + g_{\mu\nu}\frac{dS_{source}}{dg_{\mu\nu}}$$

Back-reaction vs de Sitter no-go

- F
  c
- V



This term often vanishes

This term has definite (AdS) sign

This term is usually omitted

then

$$\frac{1}{2\kappa^2}\int R = S_{on-shell} + \int \nabla^2 e^{dW} + g_{\mu\nu}\frac{dS_{source}}{dg_{\mu\nu}}$$

Back-reaction vs de Sitter no-go

CB, Maharana, van Nierop,
Nizami & Quevedo

- F
  c
- V

Source-brane matching conditions imply these terms exactly cancel one another for codim-2 sources

then

$$\frac{1}{2\kappa^2}\int R = S_{on-shell} + \cancel{\int \nabla^2 e^{dW}} + \cancel{g_{\mu\nu}\frac{dS_{source}}{dg_{\mu\nu}}}$$

Back-reaction vs de Sitter no-go

Aghababaie et al

Source-brane matching conditions imply these terms exactly cancel one another for codim-2 sources

This term is generically a total derivative for higher-dim supergravities: $S_{on-shell} = \int d\Omega$

- F c i a
- V

then 2

$$\frac{1}{2\kappa^2}\int R = S_{on-shell} + \cancel{\int \nabla^2 e^{dW}} + \cancel{g_{\mu\nu}\frac{dS_{source}}{dg_{\mu\nu}}}$$

Motivation

This can have de Sitter sign

Because it is a total derivative it does not depend on most of the details of back-reacted solutions.

ns imply these
r

derivative for

V

$$S_{on-shell} = \int d\Omega$$

then

$$\frac{1}{2\kappa^2}\int R = S_{on-shell} + \cancel{\int \nabla^2 e^{dW}} + \cancel{g_{\mu\nu}\frac{dS_{source}}{dg_{\mu\nu}}}$$

2

Explicit solutions

Higher-dimensional inflation

- What about time-dependent solutions?
  - Must generalize brane matching conditions to case where on-brane geometry is not maximally symmetric
  - Wish to solve higher-dimensional field equations exactly, including energetics of modulus stabilization

Higher-dimensional inflation

- What about time-dependent solutions?
  - Must generalize brane matching conditions to case where on-brane geometry is not maximally symmetric
  - Wish to solve higher-dimensional field equations exactly, including energetics of modulus stabilization
- For supersymmetric systems exact time-dependent scaling solutions are known
  - Can these be matched to sensible brane physics to see how brane properties control bulk fields?

Higher-dimensional inflation

Nishino & Sezgin

- 6D Einstein-Maxwell-scalar system

dS sign

$$L = \frac{1}{2\kappa^2}\left[R + (\partial\phi)^2\right] + e^{-\phi}F_{mn}F^{mn} + Ce^{\phi}$$

- Brane-localized inflaton, χ

$$L_{b1} = T_1 + e^{-\phi}\left[\,(\partial\chi)^2 + V_1 e^{\lambda\chi} + \cdots\right]$$

$$L_{b2} = T_2$$

Higher-dimensional inflation

Tolley, CB, de Rham

- Exact time-dependent solution $e^{-\phi} = (H_0\tau)^{c+2} e^{-\varphi(r)}$

$$ds^2 = (H_0\tau)^c\left[g_{mn}dx^m dx^n + \tau^2\left(g_{ij}dx^i dx^j\right)\right]$$

- FRW time in 4D Einstein frame $dt = \mp(H_0\tau)^{c+1}d\tau$

Higher-dimensional inflation

Tolley, CB, de Rham

- Exact time-dependent solution $e^{-\phi} = (H_0\tau)^{c+2}e^{-\varphi(r)}$

$$ds^2 = (H_0\tau)^c\left[g_{mn}dx^m dx^n + \tau^2\left(g_{ij}dx^i dx^j\right)\right]$$

- FRW time in 4D Einstein frame $dt = \mp(H_0\tau)^{c+1}d\tau$

- If *c* = -*2* then $a(t) = e^{H_0 t}$ and *r* constant
- 4D de Sitter geometry: evades no-go results due to near-brane asymptotics: $S_{on-shell} = \int \nabla^2\phi$

Higher-dimensional inflation

Tolley, CB, de Rham

- Exact time-dependent solution $e^{-\phi} = (H_0\tau)^{c+2} e^{-\varphi(r)}$

$$ds^2 = (H_0\tau)^c\left[g_{mn}dx^m dx^n + \tau^2\left(g_{ij}dx^i dx^j\right)\right]$$

- FRW time in 4D Einstein frame $dt = \mp(H_0\tau)^{c+1}d\tau$

- If $c \neq$ -2 then $a(t) = (H_0 t)^p$ and $r(t) = (H_0 t)^{1/2}$ with $p = (c+1)/(c+2)$

accelerated expansion if p > 1 and so c < -2

Higher-dimensional inflation

CB & van Nierop

- Source-bulk matching: how does it end?

- Add inflaton χ evolution to the equations

$$L_b = T + e^{-\phi}\left[\, (\partial\chi)^2 + V_0 + V_1 e^{\lambda\chi} + \cdots \right]$$

$$\chi = \chi_0 + \chi_1 \ln(H_0 \tau)$$

Then $c + 2 = -\lambda\chi_1$ controls the slow roll

and ${H_0}^2 = \lambda V_1 / [\chi_1(3 + 2\lambda\chi_1)]$

Higher-dimensional inflation

- Extra dimensions grow as the expanding noncompact four dimensions accelerate
    - Inflation could help understand why extra dimensions have particular properties in our epoch

Higher-dimensional inflation

- Extra dimensions grow as the expanding noncompact four dimensions accelerate
  - Inflation could help understand why extra dimensions have particular properties in our epoch
  - Evolving volume potentially allows the gravity scale to be high at horizon exit, but low at present *(similar to Conlon, Kallosh, Linde & Quevedo)*

Conclusions

- Relatively little is known about explicitly higher-dimensional cosmology
    - Higher-dimensional inflation with evolving x-dims

Conclusions

- Relatively little is known about explicitly higher-dimensional cosmology
  - Higher-dimensional inflation with evolving x-dims
- Branes and brane back-reaction can have important implications for low-energy theory
  - Little explored beyond codimension 1
  - Different parametric dependences in energy: unusual stability to quantum corrections

Conclusions

- Relatively little is known about explicitly higher-dimensional cosmology
  - Higher-dimensional inflation with evolving x-dims
- Branes and brane back-reaction can have important implications for low-energy theory
  - Little explored beyond
  - Different parametric de unusual stability to qua

Potentially wide-ranging observational implications for Dark Energy cosmology, the LHC and elsewhere…