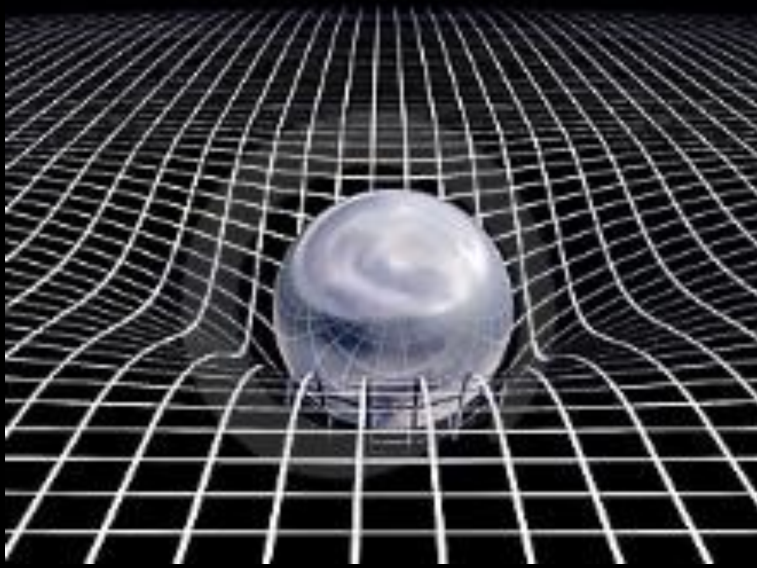

String Inflation

Higher-dimensional Inflation from brane back-reaction

w Leo van Nierop

On the shoulders of giants

With thanks to Ulf Danielsson

J. Conlon, L. McAllister, E. Silverstein, S. Kachru, J. Polchinski, R. Brandenberger, A. Salam, E. Sezgin, H. Nishino,G. Gibbons, S. Kachru E. Silverstein, R. Guven, C. Pope, K. Maeda, M. Sasaki, V. Rubakov, R. Gregory, I. Navarro, J. Santiago, S. Carroll, C. Guica, C. Wetterich, S. Randjbar-Daemi, F. Quevedo, Y. Aghababaie, S. Parameswaran, J. Cline, J. Matias, G. Azuelos, P-H. Beauchemin, A. Albrecht, C. Skordis, F. Ravndal, I. Zavala, G. Tasinato, J. Garriga, M. Porrati, H.P. Nilles, A. Papazoglou, H. Lee, N. Arkani-Hamad, S. Dimopoulos, N. Kaloper, R. Sundrum, D. Hoover, A. Tolley, C. de Rham, S. Forste, Z. Lalak, S. Lavingnac, C. Grojean, C. Csaki, J. Erlich, T. Hollowood, H. Firouzjahi, J. Chen, M. Luty, E. Ponton, P. Callin, D. Ghilencea, E. Copeland, O. Seto, V. Nair, S. Mukhoyama, Y. Sendouda, H. Yoshigushi, S. Kinoshita, A. Salvio, J. Duscheneau, J. Vinet, M. Giovannini, M. Graesser, J. Kile, P. Wang, P. Bostok, G. Kofinas, C. Ludeling, A. Nielsen, B. Carter, D. Wiltshire. C. K. Akama, S. Appleby, F. Arroja, D. Bailin, M. Bouhmadi-Lopez, M. Brook, R. Brown, C. Byrnes, G. Candlish, A. Cardoso, A. Chatterjee, D. Coule, S. Creek, B. Cuadros-Melgar, S. Davis, B. de Carlos, A. de Felice, G. de Risi, C. Deffayet, P. Brax, D. Easson, A. Fabbri, A. Flachi, S. Fujii, L. Gergely, C. Germani, D. Gorbunov, I. Gurwich, T. Hiramatsu, B. Hoyle, K. Izumi, P. Kanti, S. King, T. Kobayashi, K. Koyama, D. Langlois, J. Lidsey, F. Lobo, R. Maartens, N. Mavromatos, A. Mennim, M. Minamitsuji, B. Mistry, S. Mizuno, A. Padilla, S. Pal, G. Palma, L. Papantonopoulos, G. Procopio, M. Roberts, M. Sami, S. Seahra, Y. Sendouda, M. Shaeri, T. Shiromizu, P. Smyth, J. Soda, K. Stelle, Y. Takamizu, T. Tanaka, T. Torii, C. van de Bruck, D. Wands, V. Zamarias, H. Ziaeepour

Outline

- Inflation and the UV
- A simple model
  - Flux compactification
  - Brane back-reaction
- Higher-dimensional inflation

Inflation and the UV

- Cosmology provides rare access to UV physics
  - high energies directly accessed when generating primordial fluctuations
  - ingredients for successful cosmology (like light scalar fields) are difficult to embed into UV

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- Motivates searches for string inflation
  - can find plausible low-energy 4D EFTs with interesting cosmology – *is this good enough?*

Inflation and the UV

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eg in Higgs inflation: semiclassical approx controlled by E/Λ, where

$$\Lambda \sim {}^{M_p}/_{\xi} \quad \text{when } h \sim 0$$

and $$\Lambda \sim {}^{M_p}/_{\sqrt{\xi}} \quad \text{when } h \sim M_p$$

For comparison E ~ $H \sim {}^{M_p}/_{\xi}$ during inflation (h ~ Mp)

Inflation and the UV

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  - Compactification and control over all moduli

Inflation and the UV

- UV /
  - Co
    lim)
  - Co

$$V = V(\phi)$$

Inflation and the UV

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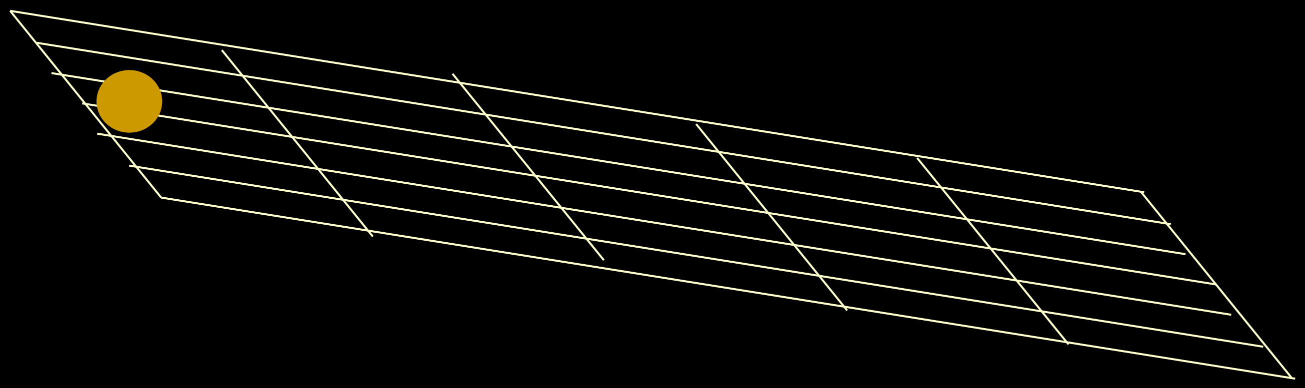

$$V = V(\phi, \psi)$$

Inflation and the UV

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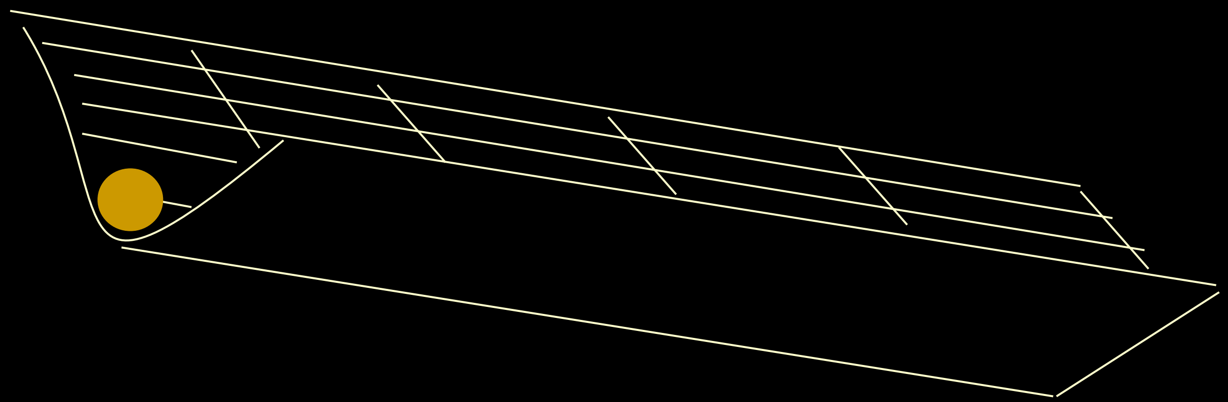

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Inflation and the UV

- UV / inflationary wish list:
  - Control over all approximations (semi-classical limit, low-energy EFT, consistency of ingredients)
  - Compactification and control over all moduli
  - Understanding of naturalness issues: the most dangerous interactions are usually those not written down…

Inflation and the UV

- UV /
  - Co
    lim)
  - Co
  - Un
    dar
    wr

eg: couplings to other heavy particles

$$V(\phi,\psi) = V_0(\phi) + M^2\,\psi^2 + g\,\phi^2\,\psi^2 + \cdots$$

$$\delta m_\phi \propto M$$

or: ‘Planck slop’

$$V(\phi) = V_0\left(1 + \frac{\phi^2}{{M_p}^2} + \cdots\right)$$

$$V_0 = H^2 {M_p}^2$$

Simple model

- Few explicit extra-dimensional cosmologies
  - work in 4D effective theory, or
  - work with moving branes in static backgrounds

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Simple model

- Few explicit extra-dimensional cosmologies
  - work in 4D effective theory, or
  - work with moving branes in static backgrounds
- What do extra dimensions do during inflation?
- Require explicit solution of higher-dim eqs
  - Must stabilize moduli
  - Include brane back-reaction

Simple model

- 6D Einstein-Maxwell-scalar system

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

6D supergravity: $a = 1$ and $V = \left(\frac{2{g_R}^2}{\kappa^4}\right) e^{\phi}$

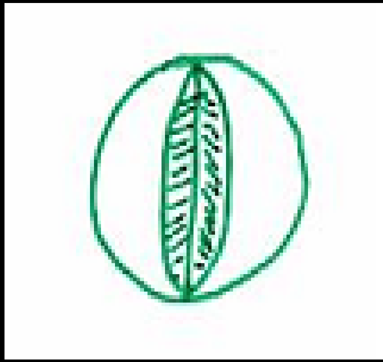
Scale invariance: $g_{\mu\nu} \to \lambda g_{\mu\nu}$ and $e^{-\phi} \to \lambda e^{-\phi}$

Simple model

- Simple solution

$$ds^2 = \hat{g}_{mn} dx^m \, dx^n + [dr^2 + \alpha^2 L^2 \sin^2\left(\frac{r}{L}\right) d\theta^2] e^{-a\phi_0}$$

$$F_{r\theta} = Q\alpha L \sin\left(\frac{r}{L}\right) e^{-a\phi_0} \qquad \phi = \phi_0$$



Flat direction: $r^2 = L^2 e^{\phi_0}$

Simple model

- Simple solution

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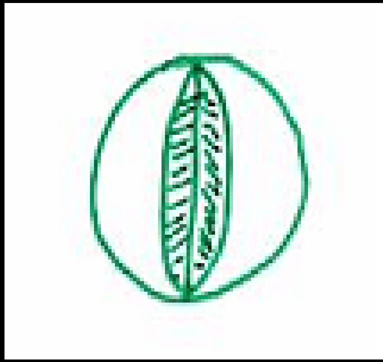


Field equations

$$\frac{2g_R^2}{\kappa^2} = \frac{\kappa^2 Q^2}{2}$$

$$\kappa^2 Q^2 L^2 = 1 \qquad \hat{R} = 0$$

Flux quantization

$$\frac{n}{g} = 2\alpha L^2 Q = \frac{\alpha}{g_R}$$

Simple model

- How does system respond to changes in brane tension: $T \longrightarrow T_0 + \delta T(\phi)$?

Flux quantization: $$\frac{n}{g} = 2\alpha L^2 Q = \frac{\alpha}{g_R}$$

Obstructs T to δT ?

$$1 - \alpha = \frac{\kappa^2 T}{2\pi}$$

Simple model

- Brane back-reaction: branes dictate boundary conditions in the near-brane limit

$$e.g.\quad r\frac{d\phi}{dr} \longrightarrow \frac{\kappa^2}{2\pi}\left(\frac{\delta S_b}{\delta\phi}\right)$$

- $S(\phi)$ stabilizes ϕ, giving exponentially large $r^2 = L^2\, e^{-\phi}$

Simple model

- Subdominant effects in the brane action are important for flux quantization

$$\text{if } L_b = T_b(\phi) + \Phi_b(\phi) \;\; {}^*F + \ldots$$

$$\text{then } \frac{n}{g} = Q \int dr\, e^{B-4W} + \frac{1}{2\pi} \textstyle\sum_b \Phi_b$$

- Φ has interpretation as brane-localized flux

Higher-dimensional inflation

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

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

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

Higher-dimensional inflation

- What is the source and how does it end?

- Add inflaton χ to one of the two source branes

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

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

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

Conclusions

- Inflation not easy (but not impossible) to plausibly embed into UV physics
- Many pitfalls
  - Control of approximations
  - Necessity to control potential for *all* light scalars
  - The danger of those fields not explicitly written: naturalness and decoupling of heavy states

Conclusions

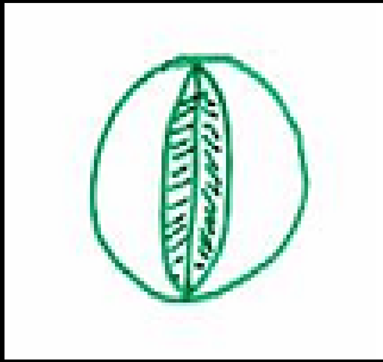
- Relatively little is known about explicitly higher-dimensional cosmology
- Branes and brane back-reaction can have important implications for low-energy theory
  - Little explored beyond codimension 1

Setup

- Simple solution (non-SUSY case)

$$ds^2 = \hat{g}_{mn} dx^m \, dx^n + dr^2 + \alpha^2 L^2 \sin^2\left(\frac{r}{L}\right) d\theta^2$$

$$F_{r\theta} = Q\alpha L \sin\left(\frac{r}{L}\right) \qquad \phi = \phi_0$$



Field equations

$$\frac{2}{L^2} = \kappa^2\left(\frac{3Q^2}{2} + \Lambda\right)$$

$$\hat{R} = \kappa^2(Q^2 - 2\Lambda)$$

Flux quantization

$$\frac{n}{g} = 2\alpha L^2 Q$$

Setup

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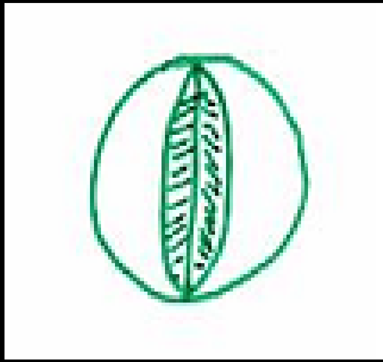

$$Q = \frac{n}{2\alpha g L^2} \qquad \hat{R} = \kappa^2 (Q^2 - 2\Lambda)$$

$$\frac{1}{L^2} = \frac{8\alpha^2 g^2}{3n^2\kappa^2}\left[1 \mp \sqrt{1 - \left(\frac{3n^2\kappa^4\Lambda}{8\alpha^2 g^2}\right)}\right]$$

Setup

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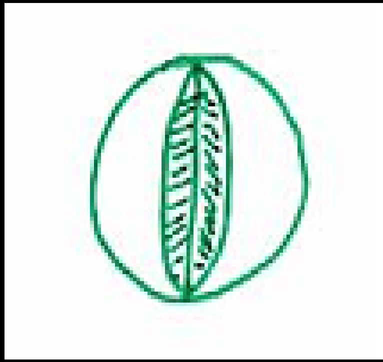

Tune $\Lambda = \frac{Q^2}{2}$ so $\hat{R} = 0$

If $T \to T + \delta T$ then $\hat{R} \to -\frac{\kappa^2 \rho}{\pi \alpha L^2}$ where $\rho = 2\,\delta T$

Calculation

- More general solutions

$$ds^2 = e^{2W}\hat{g}_{mn}dx^m\, dx^n + dr^2 + e^{2B}d\theta^2$$

$$F_{r\theta} = Qe^{B-4W} \qquad \phi = \phi(r)$$

Calculation

- Perturb brane properties

$$T \to T + \delta T(\phi)$$

- To evade time-dependence add current

$$\Delta L_{bulk} = J\phi \qquad \text{or} \qquad \Delta L_{bulk} = J$$

- Find general solution to linearized equations

$$\kappa^2 J L^2 \ll 1$$

Calculation

- Sample solutions

$$\delta W = W_0 + W_1 \cos\left(\frac{r}{L}\right)$$

$$\delta\phi = \phi_0 + \phi_1 \ln\left(\frac{1-\cos(r/L)}{\sin(r/L)}\right) - \kappa^2 J L^2 \ln\left[\sin\left(\frac{r}{L}\right)\right]$$

and so on

Calculation

- Brane-bulk boundary conditions:

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

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

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

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

Calculation

- Non-SUSY result:

$$V_{eff}(\phi) = \phi \int \frac{d\phi}{\phi^2}\left[\frac{\pi \alpha L^2 \hat{R}(\phi)}{\kappa^2}\right]$$

$$\rho = \sum_b \delta T_b(\phi_*) - 2Q\delta\Phi_b(\phi_*)$$

$$\left[\frac{\partial}{\partial\phi}\sum_b \delta T_b(\phi)\right]_{\phi_*} = 0$$

Calculation

- SUSY result:

$$\left[\sum_b \delta T_b - 2Q\delta\Phi_b + \frac{1}{2}\frac{\partial}{\partial\phi}\delta T_b(\phi)\right]_{\phi_*} = 0$$

ie Einstein frame potential: $V = U(\phi)e^{2\phi}$

Calculation

- SUSY result:

$$\left[\sum_b \delta T_b - 2Q\delta\Phi_b + \frac{1}{2}\frac{\partial}{\partial\phi}\delta T_b(\phi)\right]_{\phi_*} = 0$$

$$\rho = \sum_b \delta T_b(\phi_*) - 2Q\delta\Phi_b(\phi_*) = \frac{1}{2}\sum_b \left(\frac{\partial}{\partial\phi}\delta T_b\right)$$

Calculation

- Intriguing choice:

$$\delta T_b = A + B\phi$$

with B << A since

$$\rho = B \ll \delta T_b$$