Coupling Moduli to Inflation

Astroparticle workshop
Warsaw February 2007

Outline

Moduli

Mutated chaotic inflation

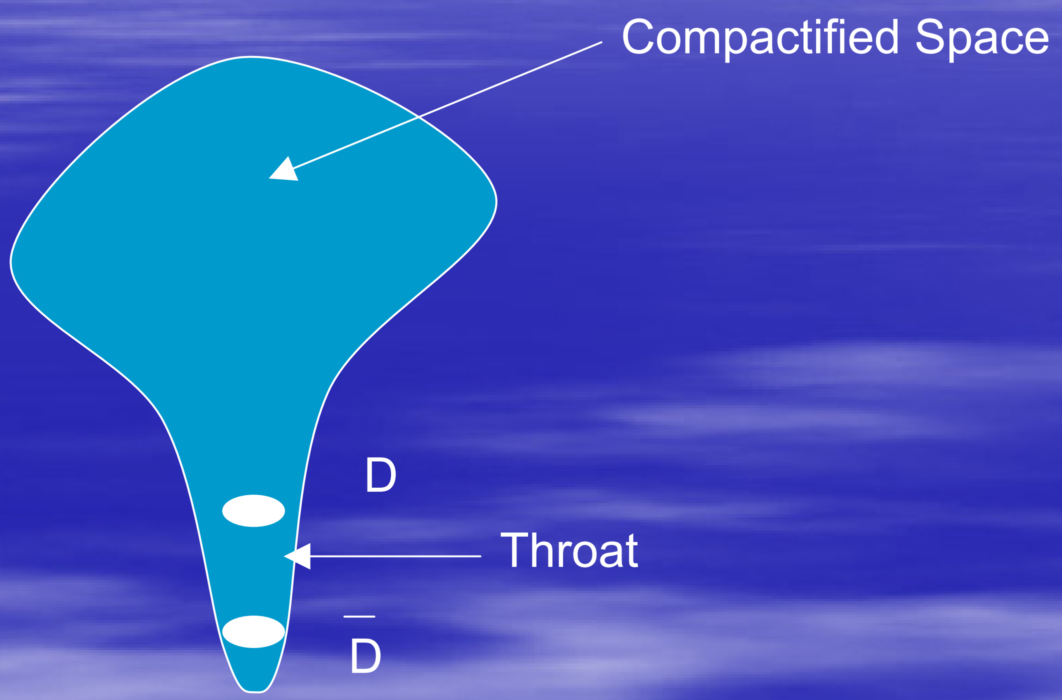
F-term hybrid inflation

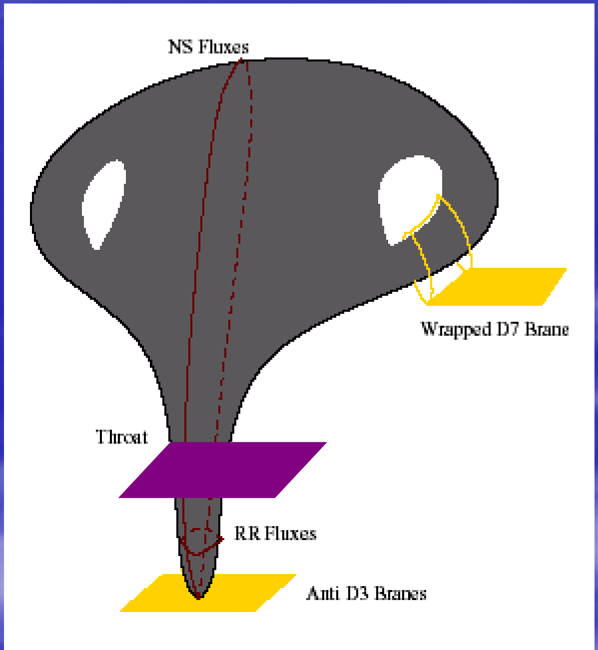
D-term hybrid inflation

Moduli Fields

- Moduli fields parameterise flat directions of the scalar potential in supersymmetric models
- Flat directions ubiquitous in susy gauge theories (even the MSSM)
- Flat directions can have a direct geometric origin, e.g. shape moduli (Kahler or complex structure moduli)
- The dilaton is a moduli as string perturbation theory does not fix its value.
- Moduli can have a dynamical origin, e.g. brane distances of BPS configurations (no force).

Compactification




NS Fluxes
Wrapped D7 Brane
Throat
RR Fluxes
Anti D3 Branes

The KKLT Scenario

- In type IIB string theory compactified on a Calabi-Yau manifold (10d to 4d), there are 3 types of moduli: the Kahler moduli, the complex structure moduli and the dilaton.
- Introducing fluxes, the complex structure moduli and the dilaton are stabilised.

$$\int F_3 = 4\pi^2\alpha' M, \ \int H_3 = -4\pi^2\alpha' N$$

- This is due to the superpotential:

$$W = \int \Omega \wedge G_3, G_3 = F_3 - \tau H_3, \ \tau = C_0 + ie^{-\phi}$$

- This leaves the Kahler moduli as flat directions.
- In general, only one Kahler moduli T: the size of the compact manifold: How to stabilise it??

No scale?

- The Kahler potential of the T modulus is of the no-scale type.

$$K = -3\ln(T+\bar{T})$$

- Once the dilaton and complex structure moduli have been stabilised, the resulting superpotential is constant

$$W = W_0$$

- Non-perturbative effect appear on D7 branes wrapped around 4-cycles of the CY compactification:

$$W = W_0 + Ae^{-aT}$$

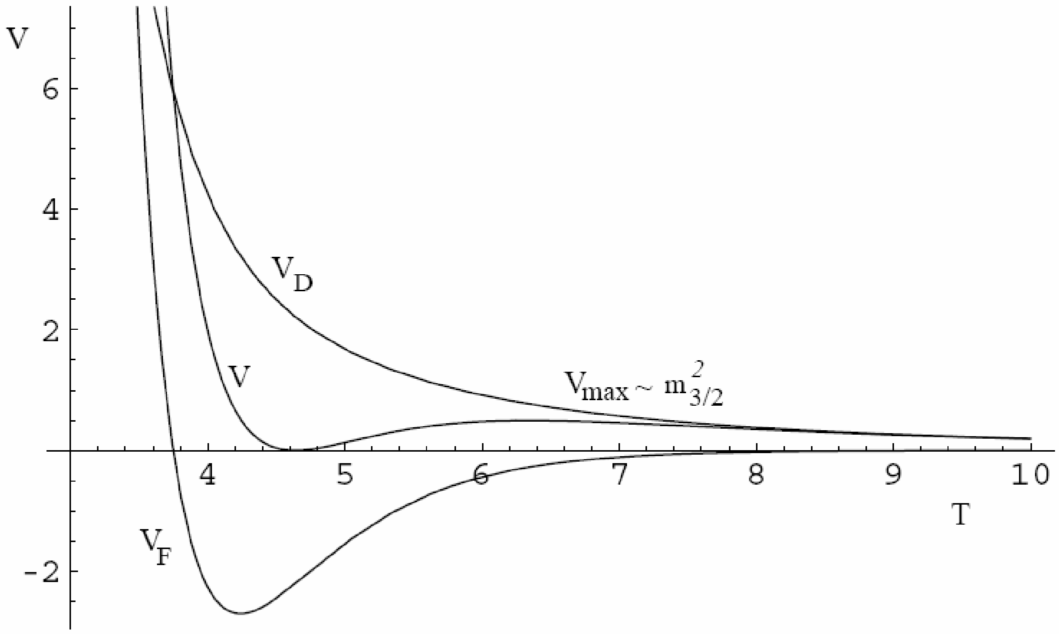
- The non-perturbative superpotential is nothing but an SQCD effect with a gauge function:

$$\frac{1}{g^2} = \Re T$$

- The size moduli T picks up a scalar potential with a negative minimum.
- The minimum describes an anti de Sitter space.

Uplifting

- Of course, we do not live in AdS space!!.
- Need to "uplift" the potential to get a vanishing (nearly) cosmological constant.
- Originally, "uplifting" by adding an anti-brane. Badly non-supersymmetric (mutated chaotic and F-term inflation).
- Lifting by F-terms, coupling to metastable susy breaking sectors.
- Lifting by D-terms: tricky due to gauge invariance and anomalies… the route we will follow for D-term inflation.


V
6
4
2
-2
V_D
V
$V_{max} \sim m_{3/2}^2$
V_F
4
5
6
7
8
9
10
T

Inflation and Supergravity

- Inflation requires flat potentials $\epsilon = m_p^2(\frac{V'}{V})^2 \leq 1$

- Almost scale invariant spectrum $n_s - 1 = -6\epsilon + 2\eta$

requiring $\eta = m_p^2 \frac{V''}{V} \ll 1$

- In global susy, easy to obtain chaotic inflation $K = \phi\bar{\phi},\ W = \frac{1}{2}m\phi^2 \rightarrow V = m^2|\phi|^2$

- In supergravity the potential depends on $G = K + \ln|W|^2$

K Kahler potential, W superpotential

$$V = e^G(G_i G^i - 3) + V_D$$

easy to obtain Hybrid inflation, tricky Chaotic inflation

KKLT Stabilisation and Inflation

- In string theory → Moduli (volume of the compactifying manifold)
- Stabilisation $W = W_0 + Ae^{-\beta T}$
- Inflation → motion of D3 branes $K = -3\ln(T+\bar{T}-\phi\bar{\phi})$
- Brane-antibrane potential lifts the potential

$$V = \frac{1}{3\Delta}\left|\frac{\partial W}{\partial T}\right|^2\left(1+\frac{1}{3\Delta}\phi\bar{\phi}\right)-\frac{1}{\Delta^2}\left(W\frac{\partial \bar{W}}{\partial \bar{T}}+\bar{W}\frac{\partial W}{\partial T}\right)+\frac{E}{\Delta^2}$$

- Around the stabilised modulus

$$V = V_{inf} + 2H_{inf}^2|\Phi|^2$$

mass of the inflaton of the Hubble scale

large value of $\eta = O(1)$

needs fine-tuning (KKLMMT scenario)

The flatness problem

- In supergravity models of inflation, the scalar potential

$$\exp(\kappa K(\phi,\bar\phi))V_{inf} = (1+\kappa K(\phi,\bar\phi)+\ldots)V_{inf}$$

- For canonically normalised fields, large mass for the inflaton

$$K(\phi,\bar\phi) = \phi\bar\phi \longrightarrow \eta = O(1)$$

- Generically, scalar index

$$|n_s - 1| \gg 1$$

Shift Symmetry

- Inflaton $\longrightarrow$ flat direction
- Lifted by interactions
- Along the flat direction $\longrightarrow$ shift symmetry

$$\phi \to \phi + c$$

- Natural in string theory $\longrightarrow$ motion of D3/D7

Special form of the superpotential

$$W(T,\phi) = e^{-s\phi^2/2} W(T - \sigma\frac{\phi^2}{2})$$

After a Kahler transformation

$$K = -3\ln(T + \bar{T} + \frac{\sigma}{2}(\phi - \bar{\phi})^2) - \frac{s}{2}(\phi - \bar{\phi})^2$$

$$W = W(T)$$

Inflation obtained by breaking shift symmetry in the superpotential

$$W(T) \longrightarrow W(T) + W(\phi)$$

Does not generate large values of the mass $m \neq O(H_{inf})$

Mutated chaotic inflation

- Superpotential for modulus $$W(T) = W_0 + Ae^{-\beta T}$$

Leads to AdS susy vacuum

Introduce a lifting term breaking susy $$\delta V = \frac{E}{(T+\bar{T})^3} \longrightarrow V_{vac} = 0$$

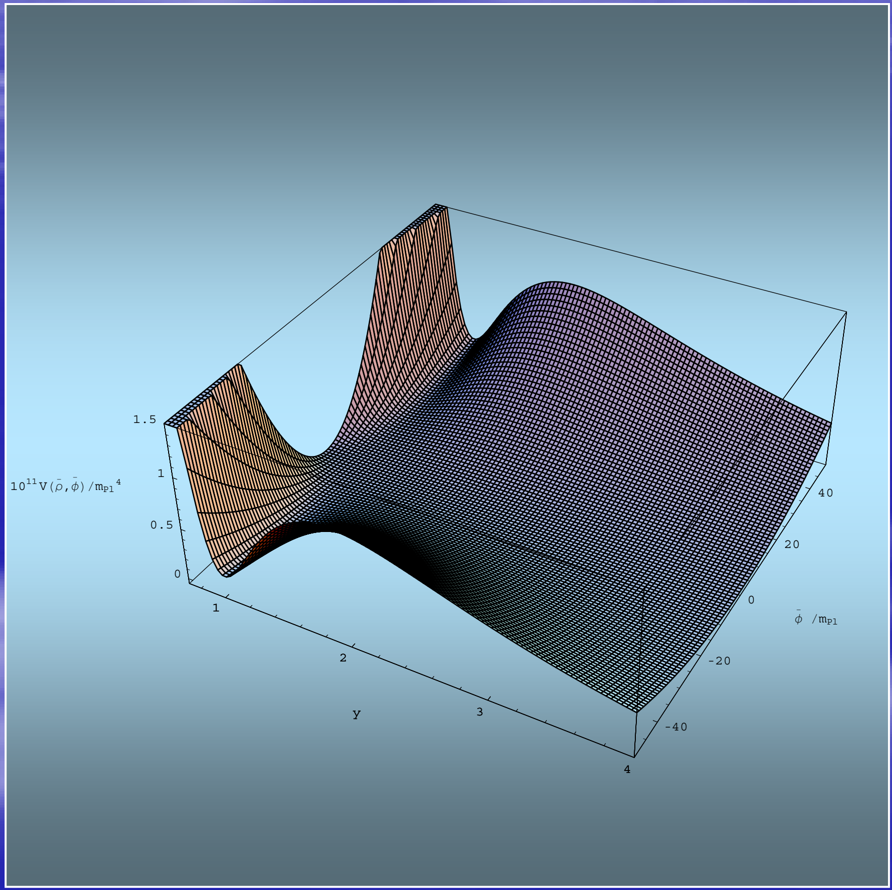
- Superpotential for inflation

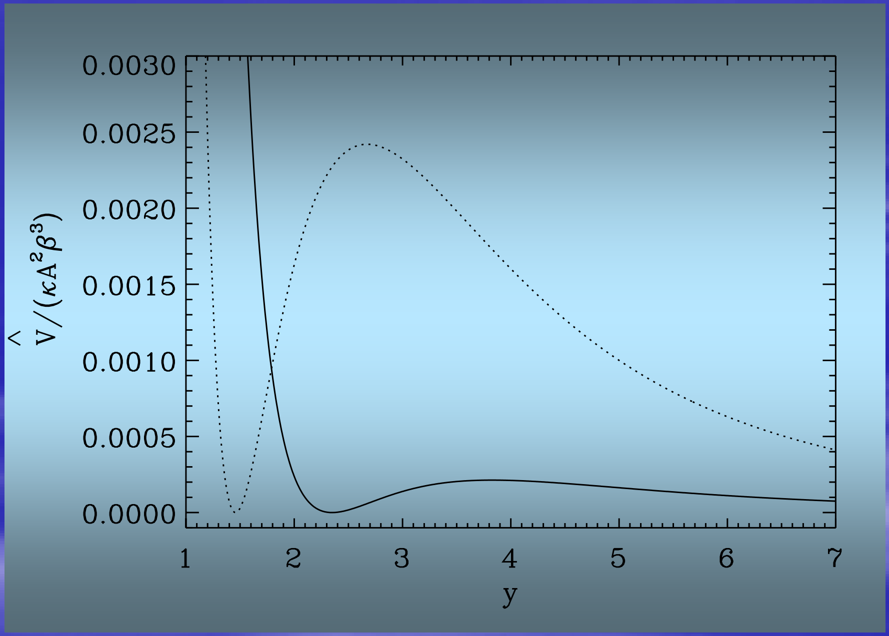
Chaotic inflation superpotential: $$W(\phi) = \frac{1}{2} m \phi^2$$

Can be obtained in the condensed phase of D3/D7 system

COBE normalisation $$m \sim 10^{-6} m_P$$

The scalar potential





Curved inflationary trajectory

- Scalar potential

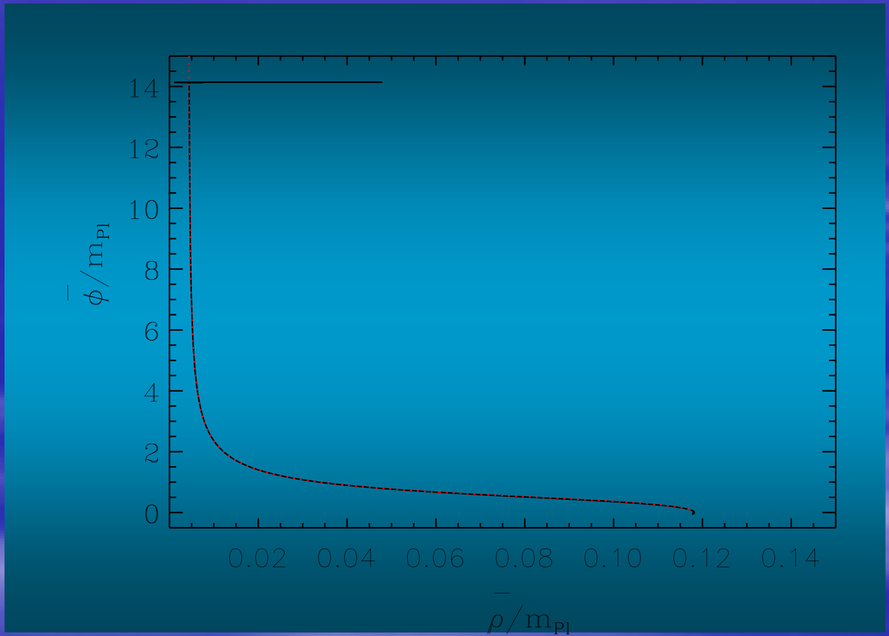
$$V(T,\phi) = v(T) + u(T)\phi^2$$

- Curved trajectory

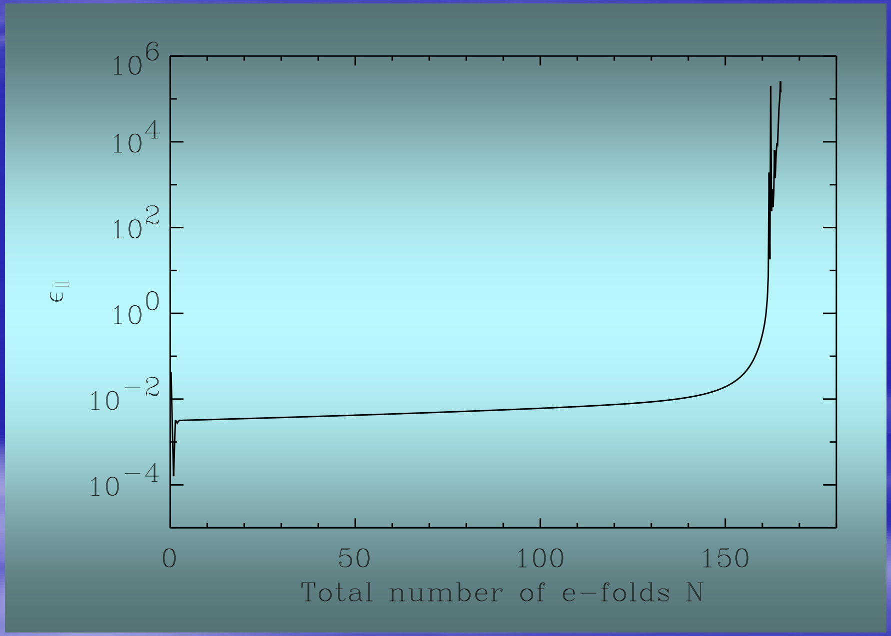
$$\phi^2 = -\frac{v'(T)}{u'(T)}$$

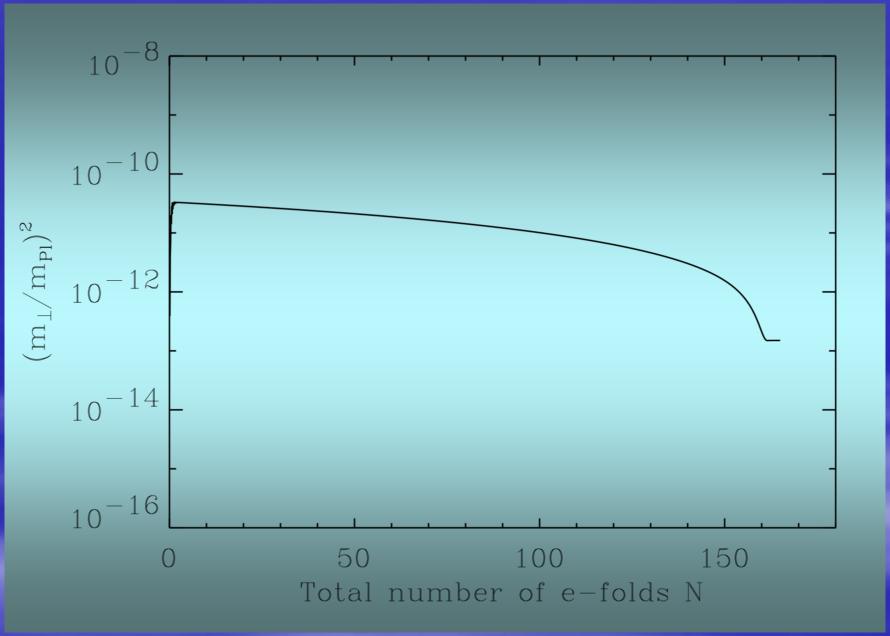
Inflationary valley

- End of inflation $\epsilon_{//} \sim 1$



Mutated vs Hybrid





Spectral Index

- Comparison with chaotic inflation

$$n_s \approx 0.967, \ n_T \approx -0.0165$$

- Mutated chaotic inflation

$$n_s \approx 0.979, \ n_T \approx -0.012$$

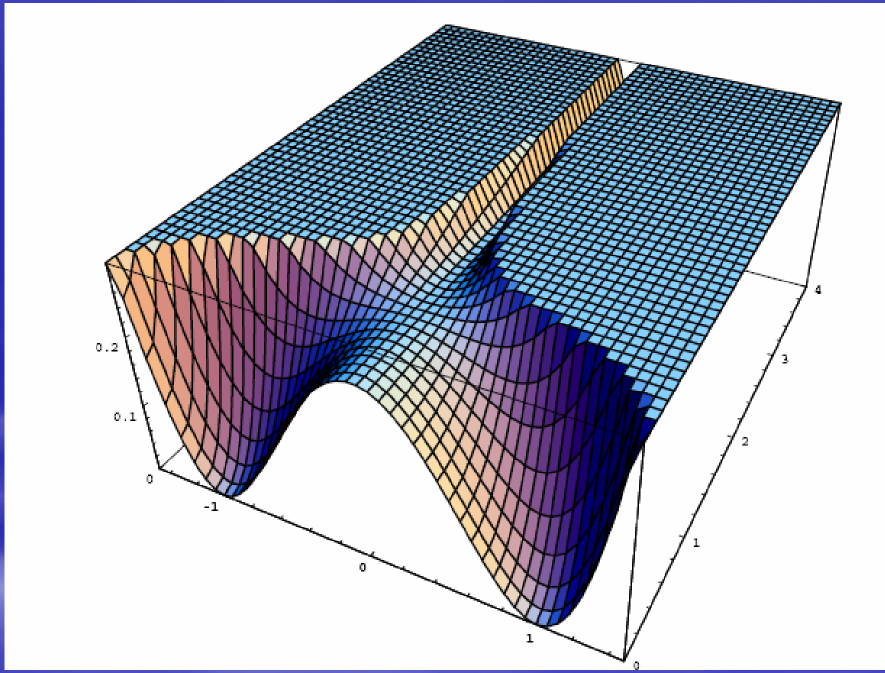
Hybrid inflation

- Moduli can have a strong influence on inflation.
- In the D3/D7 system, hybrid inflation occurs where the inflaton is the interbrane distance and the waterfall fields are the open strings connecting the branes. The resulting superpotential:

$$W = \lambda \phi \phi^{+} \phi^{-}$$

- At tree level, the potential is flat along the inflaton direction. Slope due to one loop corrections.
- At the end of inflation, the waterfall fields condense (due to a Fayet-Iliopoulos term) and cosmic strings can be formed.

- What is the influence of moduli?



F-term Hybrid Inflation

- Hybrid inflation coupled to moduli

$$W = \sqrt{2} g \phi (\phi^+ \phi^- - x^2) + W_{mod}$$

Stringy origin if x=0,

ϕ inflaton (interbrane distance)

$\phi^\pm$ waterfall fields (open strings)

- Shift symmetry

$$K = -\frac{1}{2}(\phi - \bar{\phi})^2 + (\phi^+ - \bar{\phi}^-)(\bar{\phi}^+ - \phi^-)$$

- The potential during inflation $\phi^{\pm} = 0$

$$V = V_{stab}(T) + V_0(T) - 2\sqrt{2} g x^2 e^K Re(V_1)\phi + 2g^2 x^4 e^K V_2 \phi^2$$

V_{stab} KKLT stabilisation potential

$V_0 = 2g^2 x^4 e^K$ Inflation scale

- End of inflation by instability

$$\phi_{\text{end}} = \sqrt{x^2 + \frac{V_1^2}{8g^2}} - \frac{V_1}{2\sqrt{2}g}$$

- Stability of moduli during inflation

$$m_{3/2} \geq \sqrt{\frac{N}{\delta} V_0}$$

very large gravitino mass, large sparticle masses

- Small inflation scale vs potential barrier

$$W_{mod} \geq g x^2$$

- Slow roll parameters

$$\epsilon \leq 1 \longrightarrow W_{mod} \leq g x^2$$

conflict only resolved by fine-tuning

Curved Inflation Trajectories

- Inflaton-moduli coupling leads to curved trajectories
- Close to the moduli minimum $\delta T(\phi)$
- Effective potential

$$\eta \approx -4\frac{[(e^K V_1)']^2}{m_T^2}$$

m_T mass of the moduli field

Eta problem

- In general η large unless

$$T W'_{mod}, T^2 W''_{mod} \ll (T^3 W'''_{mod} W_{mod})^{1/2}$$

- Fine-tuning of

$$W_{mod} = W_0 + A e^{-aT} + B e^{-bT}$$

may be possible…..

D-term Hybrid Inflation

- Inflation due to field dependent Fayet-Iliopoulos terms
- Uplifting due to a second Fayet-Iliopoulos term
- Superpotential

$$W = \lambda\phi\phi^{+}\phi^{-} + W_{mod}$$

non-analytic superpotential to lift an AdS vacuum

$$W_{mod} = W_0 + A\chi^{-b}e^{-aT}$$

Hybrid Inflation Coupled to Moduli

- Inflation can destabilise moduli if the inflation scale is much higher than the barrier scale of the moduli potential

$$\alpha \sim \frac{m_{3/2}^2}{g^2\xi^2}, \ \ \alpha \geq 1$$

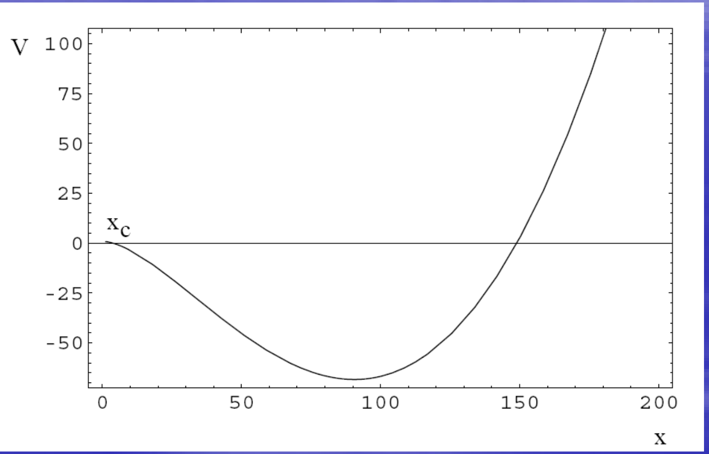
- Moduli modify the one loop potential

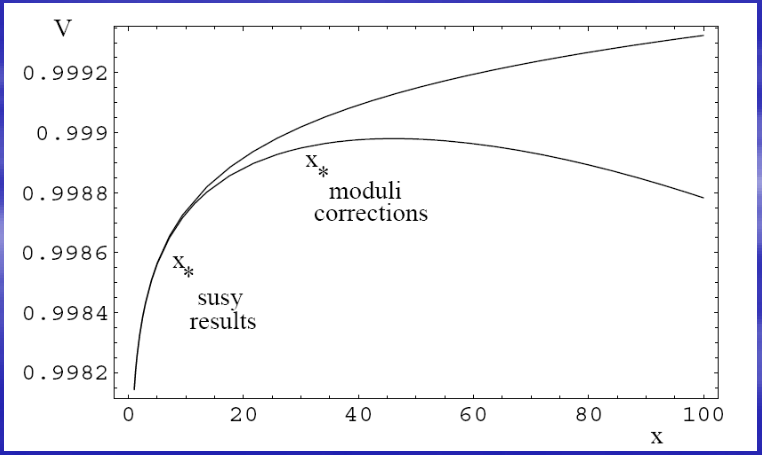
$$V = \frac{g^2\xi^2}{2}\left(1+\frac{g^2}{8\pi^2}\ln\frac{\lambda^2\phi^2}{2\Lambda^2 e^{-3/2}}+\frac{\lambda^2\phi^2}{24\pi^2}\left((\alpha+1)\ln\frac{\lambda^2\phi^2}{2\Lambda^2 e^{-3/2}}-1\right)\right)$$

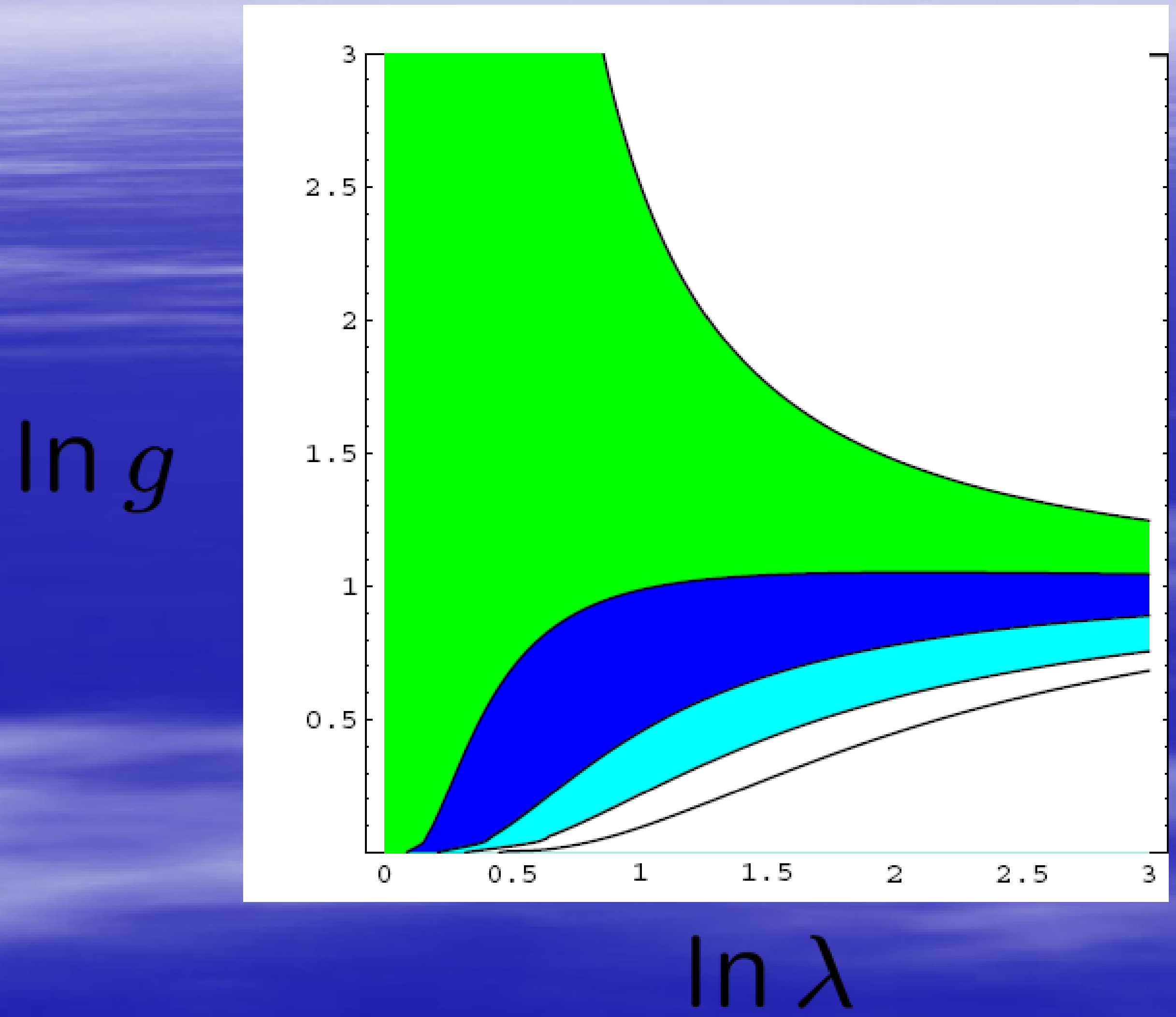
- Moduli can prevent graceful exit

$$\alpha\xi \leq 1$$

- Moduli can alter the spectral index (structure formation).







3
2.5
2
1.5
1
0.5
0
0.5
1
1.5
2
2.5
3
ln g
ln λ

Conclusions

- Inflationary model combining modulus stabilisation and inflation
- Curved inflationary trajectories
- Chaotic inflation preserved thanks to shift symmetry
- F-term hybrid requires fine-tuning
- D-term hybrid new features due to moduli sector