Thermal corrections to string compactifications and moduli cosmology

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Based on

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L. Anguelova, V.C., M. Cicoli JCAP(09)10 **0904.0051**

Unification of all forces related to the existence of extra-dimensions of space-time. (Kaluza 1921, Klein 1926)

M4 X R

$r \gg R$ the gravitational force law reduces to the familiar inverse square law

$E \ll \hbar/Rc$ quantum mechanical wave functions are independent on the position on the circle. The circle is invisible.

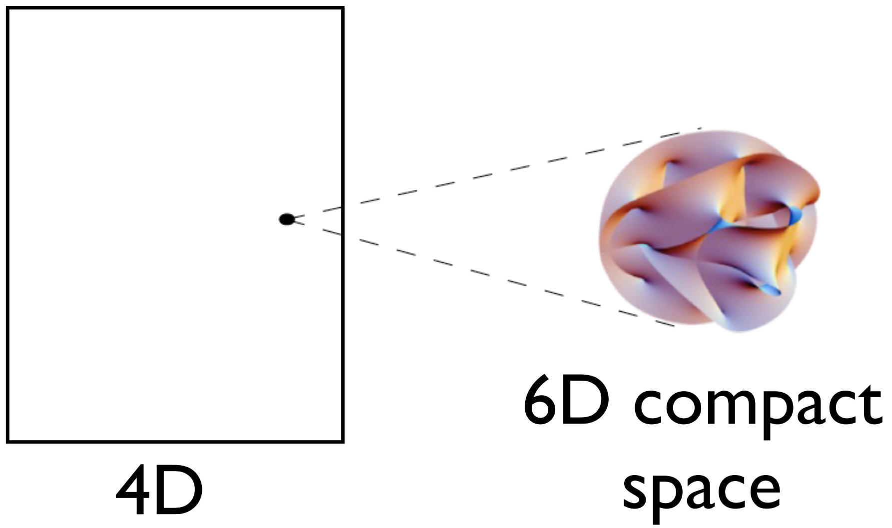
g_{MN}

$g_{\mu\nu}$	4-dim metric
$g_{\mu 4}$	4-dim vector field
g_{44}	4-dim massless scalar field

Long range forces
Time dependence of parameters

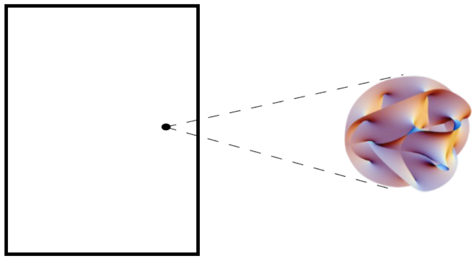
Superstring theory

Consistent quantum theory of gravity coupled to matter in 10 spacetime dimensions (1975-1985)



$E \ll \sqrt{\alpha'}$ Low energy effective theory is described by 10D supergravity

1985 Candelas et al. starting from heterotic string theory one could derive supersymmetric GUT.



4D Minkowski space

X

6D Ricci flat manifold: Calabi-Yau manifold

The classical equations of supergravity are scale invariant

$$g_{MN} \to \lambda g_{MN}$$

One-parameter family of solution differing on the value of $\mathcal{V}$

In general, hundreds of parameters called moduli (massless scalar fields)

How do the particular values we observe for the fundamental parameters of physics, such as the electron mass, actually emerge from the theory?

Proliferation of massless scalar fields

The origin of the fundamental parameters

Moduli space

Locally,

$$\mathcal{M} = \mathcal{M}_C \times \mathcal{M}_K$$

$\mathcal{M}_C$ Complex structure deformation of M

$\mathcal{M}_K$ Kaehler deformation of M

ϕ dilaton: interaction strength between strings

Proliferation of massless scalar fields:

•Solution: eom of general relativity and supergravity are scale invariant only at the classical level.

•Quantum theory can prefer a particular value of the moduli.

•Quantum effects can be summarized in an **effective potential**, defined as the total vacuum energy.

Plan of the talk

First part

•Review of IIB Flux compactifications

•Importance of pertubative and non perturbative corrections

•LARGE Volume compactifications

Second part

•Inclusion of thermal corrections

•Maximal temperature

•Moduli evolution

Review of IIB flux compactification

- Type IIB string in 10D

$$S_{\rm IIB} = \frac{1}{2k_{10}^2}\int d^{10}x\sqrt{-g_{\rm s}}\left\{e^{-2\phi}\left[\mathcal{R}_{\rm s}+4(\nabla\phi)^2\right]-\frac{F_{(1)}^2}{2}-\frac{1}{2\cdot 3!}G_{(3)}\cdot\bar{G}_{(3)}-\frac{\tilde{F}_{(5)}^2}{4\cdot 5!}\right\}$$
$$+\frac{1}{8ik_{10}^2}\int e^{\phi}C_{(4)}\wedge G_{(3)}\wedge\bar{G}_{(3)} + S_{\rm loc}$$

- Field strengths

$$F_1 = dC_0 \qquad F_3 = dC_2 \qquad F_5 = dC_4 \qquad H_3 = dB_2$$

$$G_{(3)} = F_{(3)} - \tau H_{(3)} \qquad \tau = C_{(0)} + ie^{-\phi}$$

$$\tilde{F}_{(5)} = F_{(5)} - \frac{1}{2}C_{(2)}\wedge H_{(3)} + \frac{1}{2}B_{(2)}\wedge F_{(3)} \qquad \tilde{F}_{(5)} = *\tilde{F}_{(5)}$$

- Look for solutions such that

$$g_{10} = e^{-2A(y)}dx_4^2 + e^{2A(y)}\tilde{g}_{mn}dy^m dy^n \quad F_3,\ H_3 \in H^3(M,Z) \quad \phi = \phi(y)$$

- Eom requires the presence of localized sources such as D3 branes and O3 planes, D7 branes wrapping the internal 3-cycles and anti-D3 branes

4D effective description

Giddings, Kachru, Polcinski 2001

- Described by N=1 supergravity with

Kaehler potential

Candelas, de la Ossa 1991

$$K = -2\ln\mathcal{V} - \ln\left[-i(\tau-\bar{\tau})\right] - \ln\left(i\int_{M_6}\Omega\wedge\bar{\Omega}\right)$$

Volume modulus | axio-dilaton | holomorphic (3,0) form

Superpotential $W = \int_{M_6}\Omega\wedge G_3$ Gukov Vafa Witten 1999

- Four-dimensional effective potential

$$V = e^K\left(G^{AB}D_AWD_BW - 3|W|^2\right)$$

$$D_AW = \partial_AW - W\partial_AK$$

- Kahler potential has <u>no-scale</u> form

$$\sum_{AB}G^{AB}\partial_AK\partial_BK = 3$$

(A, B) = K., CS moduli and dilaton

•Four-dimensional effective potential

$$V = e^K \left(G^{ij} D_i W D_j W \right)$$

(i, j) = CS moduli and dilaton

•The potential is positive semidefinite with vacua precisely when V=0!

•Dilaton and c.s. moduli are stabilized by solving

$$D_i W = 0$$

•In this approximation, Kaehler moduli are not stabilized.

•Quantum corrections will generally generate a potential for these moduli.

Perturbative and non-perturbative corrections

N=1 SUGRA has

- Kahler potential:

$$K = K_0 + K_p + K_{np} = K_0 + J$$

- Superpotential:

Conlon, Quevedo, Suruliz 05

$$W = W_0 + W_{np} = W_0 + \Omega$$

- (gauge kinetic function)
- Scalar potential

$$V = e^K \left(\underbrace{G^{AB} D_A W D_B W}_{V_F} - 3|W|^2 \right) + \text{D-terms}$$

$$V_F = \underbrace{V_0}_{\text{tree level}} + \underbrace{V_J}_{\text{perturbative correction}} + \underbrace{V_\Omega}_{\text{non-perturbative correction}}$$

This issues in IIB Flux Compactifications

Becker Becker Haack Louis 02

$$K = -2\ln\left(\mathcal{V}+\frac{\xi}{g_s^{3/2}}\right) - \ln\left(i\int\Omega\wedge\bar{\Omega}\right) - \ln\left(S+\bar{S}\right),$$

J

$$W = \int G_3\wedge\Omega + \sum_i A_i e^{-a_i T_i}.$$

Ω

$$\xi = -\frac{\chi\zeta(3)}{2(2\pi)^3}$$

- F-term potential is

$$V_F = e^K\left[G^{\rho_i\bar{\rho}_j}\left(\partial_{\rho_i}W\partial_{\bar{\rho}_j}\bar{W} + \left(\partial_{\rho_i}W(\partial_{\bar{\rho}_j}\bar{K})\bar{W} + c.c.\right)\right)\right] + 3e^K\frac{|W|^2\xi}{\mathcal{V}g_s^3/2}$$

- We want to ask when $|V_\Omega| > |V_J|$

- Consistent inclusion of perturbative corrections in the Kahler potential gives dramatic changes in the structure of the potential.

An example: the quintic

One-parameter Calabi-Yau

$$\mathcal{V} = \frac{\sqrt{2}}{3\sqrt{5}}\sigma^{3/2}$$

Scalar potential

$$V = e^K \left[\underbrace{\frac{4\sigma^2 a^2}{4} e^{-2a\sigma} - 4a\sigma e^{-a\sigma} W_0}_{V_\Omega} + \underbrace{\frac{9\sqrt{5}W_0^2}{4\sqrt{2}\sigma^{3/2} g_s^{3/2}}}_{V_J} \right]$$

Perturbative corrections dominate at both small and large volume.

If gs=0.1, a=2pi (D3-brane instantons) then

$$|V_\Omega| > |V_J| \qquad W_0 \sim 10^{-75}$$

In general, both pertubative and non-perturbative corrections must be included!

Large Volume compactification: a working model

Study scalar potential for a particular model, $\mathbb{P}^4_{[1,1,1,6,9]}$

Moduli $\quad h^{1,1} = 2 \qquad h^{2,1} = 272$

Volume $\quad \mathcal{V} = \frac{1}{9\sqrt{2}}\left(\tau_b^{3/2} - \tau_s^{3/2}\right)$

Fix complex structure moduli and dilaton

$$D_\tau W_{cs} = 0 \quad \text{and} \quad D_{\phi_i} W_{cs} = 0$$

Kaehler moduli appear non-perturbatively in the superpotential

$$W = W_0 + A_s e^{i a_s \rho_s} + A_b e^{i a \rho_b}$$

$$K = K_{cs} - 2\ln\left(\mathcal{V} + \frac{\xi}{2 g_s^{3/2}}\right) \qquad \rho_{s,b} = b_{s,b} + i\tau_{s,b}$$

Examine the potential in the LARGE Volume limit

$$\mathcal{V} = \frac{1}{9\sqrt{2}}\left(\tau_b^{3/2} - \tau_s^{3/2}\right) \gg 1, \quad \tau_b \gg \tau_s > 1$$

Scalar potential

$$V_F = \lambda\sqrt{\tau_s}\,(a_s A_s)^2\,\frac{e^{-2a_s\tau_s}}{\mathcal{V}} - \mu\tau_s W_0\,(a_s A_s)\,\frac{e^{-a_s\tau_s}}{\mathcal{V}^2} + \nu\xi\frac{W_0^2}{\mathcal{V}^3}$$

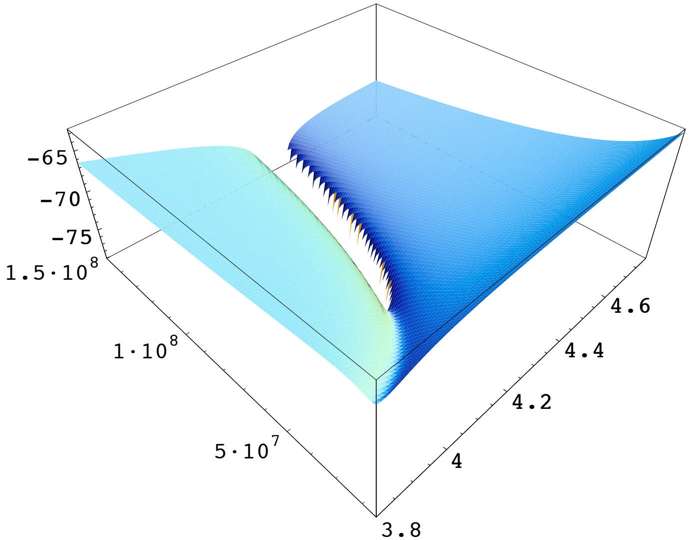
To see the structure, take the limit

$$\mathcal{V} \to \infty \qquad a_s A_s e^{-a_s\tau_s} = \frac{W_0}{\mathcal{V}}$$

The potential then becomes

$$V_F = \frac{W_0^2}{\mathcal{V}^3}\left(\lambda'\sqrt{\ln\mathcal{V}} - \mu'\ln\mathcal{V} + \nu'\right)$$

LARGE Volume minimum exists

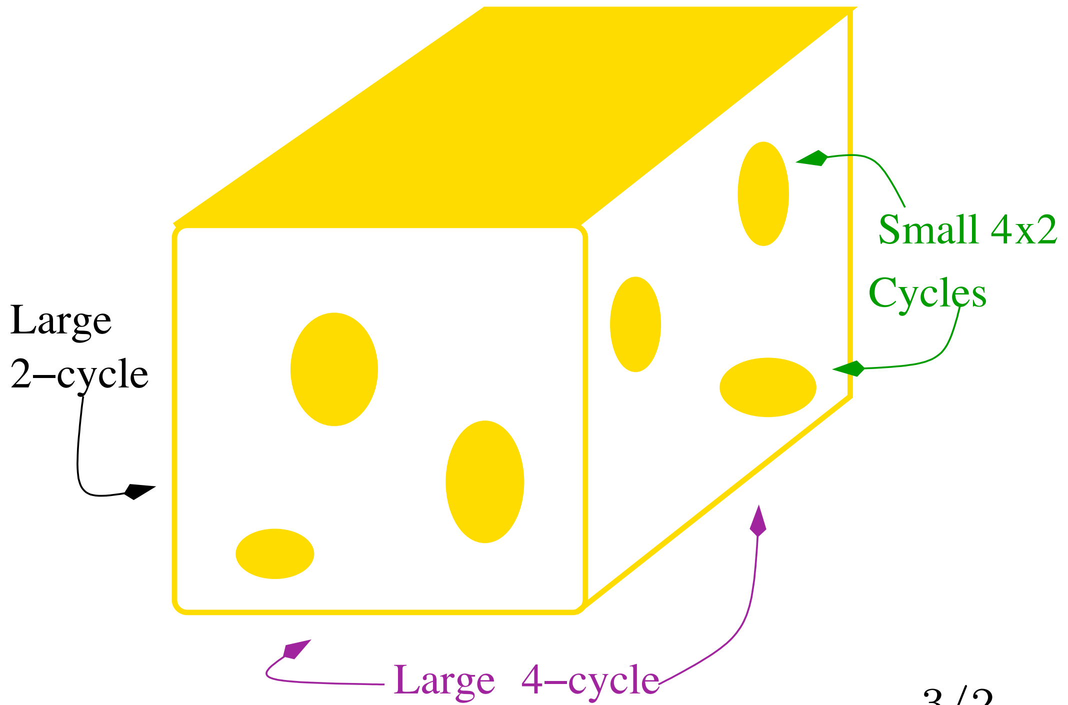


We can solve for the minimum analytically $\partial_{\tau_s} V = \partial_{\tau_b} V = 0$

$$\langle \tau_4 \rangle \sim \xi^{2/3} \qquad \langle \mathcal{V} \rangle \sim W_0 e^{\frac{a_4 \tau_4}{g_s}}$$

The minimum is a non-susy AdS

$$V_F^{min} \sim -\mathcal{O}\left(\frac{1}{\mathcal{V}^3}\right)$$



$$\mathcal{V} = \tau_b^{3/2} - \sum_i \tau_{s,i}^{3/2}$$

We have an explicit minimum and so we can compute the spectrum and soft terms.

Canonical normalization

Thermal equilibrium: masses and couplings depend on the vev of moduli fields.

expand in the vicinity of the T=0 minimum

$$\tau_b = \langle \tau_b \rangle + \delta\tau_b \,,$$
$$\tau_s = \langle \tau_s \rangle + \delta\tau_s$$

$$\mathcal{L} = K_{i\bar{j}} \partial_\mu(\delta\tau_i)\partial^\mu(\delta\tau_j) - \langle V_0 \rangle - \frac{1}{2} V_{i\bar{j}} \delta\tau_i \delta\tau_j + \mathcal{O}(\delta\tau^3)$$

introduce canonical normalized quantum fluctuations

$$\delta\tau_i = \frac{1}{\sqrt{2}} \left[(\vec{v}_\Phi)_i \Phi + (\vec{v}_\chi)_i \chi \right]$$

mixing of the quantum fluctuations

$$\delta\tau_b \sim \mathcal{O}\left(\mathcal{V}^{1/6}\right)\Phi + \mathcal{O}\left(\mathcal{V}^{2/3}\right)\chi$$
$$\delta\tau_s \sim \mathcal{O}\left(\mathcal{V}^{1/2}\right)\Phi + \mathcal{O}\left(1\right)\chi$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi \partial^\mu \Phi + \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - \langle V_0 \rangle - \frac{1}{2} m_\Phi^2 \Phi^2 - \frac{1}{2} m_\chi^2 \chi^2$$

Masses

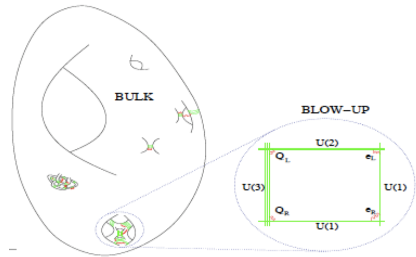
large hierarchy
of masses

$$m_\Phi^2 \simeq \left(\frac{\ln \mathcal{V}}{\mathcal{V}}\right)^2 M_P^2$$

$$m_\chi^2 \simeq \sim \frac{M_P^2}{\mathcal{V}^3 \ln \mathcal{V}}$$

Example: couplings to gauge bosons

MSSM: magnetized
D7-branes wrapping
the small 4-cycle



$$f_i = \frac{T_{MSSM}}{4\pi} + h_i(F)S$$

$$\mathcal{L}_{gauge} = -\frac{\tau_s}{M_P} F_{\mu\nu}F^{\mu\nu}$$

$$G_{\mu\nu} = \sqrt{\langle\tau_s\rangle} F_{\mu\nu}$$

$$\mathcal{L}_{\chi XX} \sim \left(\frac{1}{M_P \ln \mathcal{V}}\right) \chi G_{\mu\nu}G^{\mu\nu},$$

$$\mathcal{L}_{\Phi XX} \sim \left(\frac{\sqrt{\mathcal{V}}}{M_P}\right) \Phi G_{\mu\nu}G^{\mu\nu}$$

LARGE Volume Models

We take the overall volume to be $\mathcal{V} = 10^{14} l_s^6$.

The mass scales present are:

- Planck scale: $M_P = 2.4 \times 10^{18}$GeV.
- Neutrino/dimension-5 suppression scale: $\Lambda \sim 10^{14}$GeV.
- String scale: $M_S = \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{11}$GeV.
- Axion decay constant $f_a \sim M_S \sim 10^{11}$GeV.
- KK scale $M_{KK} = \frac{M_P}{\mathcal{V}^{2/3}} \sim 10^9$GeV.
- Gravitino mass $m_{3/2} = \frac{M_P}{\mathcal{V}} \sim 30$TeV.
- Soft terms $m_{susy} \sim \frac{m_{3/2}}{\ln(M_P/m_{3/2})} \sim 1$TeV.

Cosmological moduli problem

de Carlos, Casas, Quevedo, Roulet 1993

- Moduli are shifted from the zero temperature minimum O(Mp)
- Dominate the energy density of the Universe $\rho_\phi \sim \frac{1}{T^3}$
  - Moduli decay

$$\mathcal{L}_{gauge} = -\frac{\tau_s}{M_P} F_{\mu\nu} F^{\mu\nu} \qquad \Gamma_\phi \sim D \frac{m_\phi^3}{M_P^2}$$

  - Lifetime

$$\tau \sim \frac{M_p^2}{m_\phi^3} \gg 1 \qquad m_\phi \lesssim 1\mathrm{TeV}$$

  - Reheat the Universe

$$\Gamma_\phi \simeq H(T) \sim g_\star^{1/2} T^2 / M_P$$

The decay of the moduli will reheat the Universe to a temperature Tr

$$T_r \sim (\Gamma_\phi M_p)^{1/2} \sim m_\phi^{3/2} M_P^{-1/2}$$

It will destroy D, 4He and thus the successful nucleosynthesis predictions

$$T_r > 1\mathrm{MeV}$$

$$m_\phi > \mathcal{O}(10)\mathrm{TeV}$$

Similar bounds for modulinos and gravitino

Small cycle moduli

m~1000 TeV

$$T_r \sim 10^7 \mathrm{GeV}$$

Volume modulus

m~1 MeV

CMP!! (trapping mechanism, thermal inflation)

Solution of CMP? Thermal Inflation

Lyth Stewart (1995)

Flat directions lifted by supersymmetry breaking

Flaton fields $\langle\sigma\rangle \gg m_\sigma$

Flaton fields + matter in thermal equilibrium

$$V = V_0 + \left(T^2 - m_\sigma^2\right)\sigma^2 + \dots$$

maximum $\langle\sigma\rangle = 0$

minimum $\langle\sigma\rangle = M_\star \gg m_\sigma$

$T > m_\sigma = T_c$ Field trapped in the false vacuum

$T \sim V_0^{1/4} > T_c$ The potential energy dominates over the radiation energy. Inflation!

$T = T_c$ Inflation ends

$$N \sim \log\left(V_0^{1/4}/T_c\right) \sim \log(M_\star/m_\sigma)^{1/2}$$

$$\begin{aligned} M_\star &\sim 10^{11}\mathrm{GeV} \\ m_\sigma &\sim 10^{3}\mathrm{GeV} \end{aligned}$$

so far...

Zero temperature N=1 sugra

- Effective potential at tree level
- Inclusion of non-perturbative correction (KKLT)
- Inclusion of perturbative correction (LARGE Volume)
- Cosmological moduli problem

At non-zero temperature

Temperature-dependent corrections: general structure

$$V_{TOT} = V_{T=0} + V_{T\neq 0}$$

where

$$V_{T=0} = \delta V_{np} + \delta V_{\alpha'} + \delta V_{g_s}$$

VT has a generic loop expansion

$$V_T = V_T^{1-loop} + V_T^{2-loop} + \dots$$

1-loop → ideal gas of non-interacting particles

$$V_T^{1-loop} = \pm \frac{T^4}{2\pi^2}\int_0^\infty dx\, x^2 \ln\left(1 \mp e^{-\sqrt{x^2+m^2/T^2}}\right)$$

$T \gg m$ and for chiral superfields

moduli-dependent mass matrices

$$V_T^{1-loop} = -\frac{\pi^2 T^4}{90}\left(g_B + \frac{7}{8}g_F\right) + \frac{T^2}{24}\left(TrM_b^2 + TrM_f^2\right) + \mathcal{O}\left(TM_b^3\right)$$

d.o.f.

At non-zero temperature

Temperature-dependent corrections: general structure

$$V_{TOT} = V_{T=0} + V_{T\neq 0}$$

where

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VT has a generic loop expansion

$$V_T = V_T^{1-loop} + V_T^{2-loop} + \dots$$

2-loop (beyond ideal gas approximation)

$$V_T^{2-loops} = \alpha_2 T^4 \left(\sum_i f_i(g_i) \right) + \beta_2 T^2 \left(TrM_b^2 + TrM_f^2 \right) \left(\sum_i f_i(g_i) \right) + \dots$$

sum over the interactions
through which different species
reach thermal equilibrium

g.i.: $f(g) \sim g^2$

$\lambda\phi^4$ $f(g) \sim \lambda$

Thermal equilibrium in the expanding Universe

- Universe has for much of its history been in thermal equilibrium

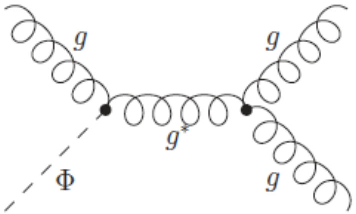
Particle interaction/decay rate $\Gamma > H$ Universe expansion rate

- Radiation dominated Universe

$$H \sim g_*^{1/2} T^2 / M_P$$

- Thermal equilibrium: 2-2 interactions

$$\langle \Gamma \rangle \sim n \langle \sigma v \rangle$$



scattering
annihilation
inverse pair production

- Thermal equilibrium: 1-2 interactions

$$\Gamma_D^R \sim \alpha m \qquad \Gamma_D^R \sim D \frac{m^3}{M^2}$$

decays
single particle production

Thermal equilibrium: 2-2 interactions

$$\langle\Gamma\rangle \sim n\langle\sigma v\rangle \longrightarrow \langle\Gamma\rangle \sim \langle\sigma\rangle T^3$$

- Renormalisable interactions

$$\langle\sigma\rangle \sim \alpha^2 \frac{T^2}{(T^2+M^2)^2}$$

long range $\langle\Gamma\rangle \sim \alpha^2 T$

short range $\langle\Gamma\rangle \sim \alpha^2 \frac{T^5}{M^4}$

- Gravity

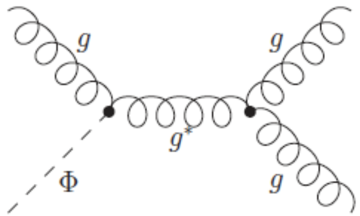
$$\langle\Gamma\rangle \sim d\frac{T^5}{M_P^4}$$

- 1 renormalisable and 1 gravitational vertex

$$\langle\Gamma\rangle \sim \sqrt{d}\frac{g^2T^3}{M_P^2}$$

- Thermal equilibrium for gravitational interactions

$$\langle \Gamma \rangle \sim \sqrt{d}\frac{g^2 T^3}{M_P^2} \gtrsim H \sim g_\star^{1/2} T^2 / M_P$$



$$T \gtrsim \frac{g_\star^{1/2} M_P}{g^2 \sqrt{d}}$$

- Gravitational interactions are not in thermal equilibrium

- No-thermal corrections for the moduli effective potential

- In LVS $d \sim \mathcal{V} \sim 10^{14}$

Moduli can be in thermal equilibrium below Planck scale

Thermal equilibrium: 1-2 interactions

$$\Gamma_D^R \sim \alpha m \qquad \Gamma_D^R \sim D\frac{m^3}{M^2}$$

long range short range

- Thermal average

$$\langle \Gamma_D \rangle = \Gamma_D^R \frac{m}{\langle E \rangle} \qquad \Gamma_{ID} = \Gamma_D \quad T \gtrsim m$$

- Renormalisable interactions

$$\langle \Gamma_D \rangle \simeq \begin{cases} g^2 \frac{m^2}{T}, & \text{for } T \gtrsim m \\ g^2 m, & \text{for } T \lesssim m \end{cases}, \qquad \langle \Gamma_{ID} \rangle \simeq \begin{cases} g^2 \frac{m^2}{T}, & \text{for } T \gtrsim m \\ g^2 m \left(\frac{m}{T}\right)^{3/2} e^{-m/T}, & \text{for } T \lesssim m \end{cases}$$

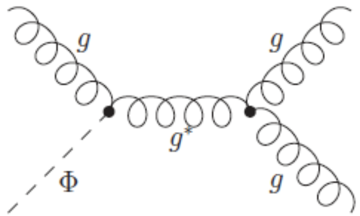
- Non-renormalisable interactions

$$\langle \Gamma_D \rangle \simeq \begin{cases} D \frac{m^4}{M^2 T}, & \text{for } T \gtrsim m \\ D \frac{m^3}{M^2}, & \text{for } T \lesssim m \end{cases}, \qquad \langle \Gamma_{ID} \rangle \simeq \begin{cases} D \frac{m^4}{M^2 T}, & \text{for } T \gtrsim m \\ D \frac{m^3}{M^2} \left(\frac{m}{T}\right)^{3/2} e^{-m/T}, & \text{for } T \lesssim m \end{cases}$$

What are the particles in thermal equilibrium? (Finite temperature corrections)

	Higgs ($\bar{H}H$)	Higgs-Fermions ($H\bar{\psi}\psi$)	SUSY scalars ($\bar{\varphi}\varphi$)	χ^2	Φ^2
χ	$\frac{M_P}{\mathcal{V}^2(\ln\mathcal{V})^2}$	$\frac{1}{M_P\mathcal{V}^{1/3}}$	$\frac{M_P}{\mathcal{V}^2(\ln\mathcal{V})^2}$	$\frac{M_P}{\mathcal{V}^3}$	$\frac{M_P}{\mathcal{V}^2}$
Φ	$\frac{M_P}{\mathcal{V}^{5/2}(\ln\mathcal{V})^2}$	$\frac{1}{M_P\mathcal{V}^{5/6}}$	$\frac{M_P}{\mathcal{V}^{5/2}(\ln\mathcal{V})^2}$	$\frac{M_P}{\mathcal{V}^{5/2}}$	$\frac{M_P}{\mathcal{V}^{3/2}}$

	Gauge bosons ($F_{\mu\nu}F^{\mu\nu}$)	Gauginos ($\bar{\lambda}\lambda$)	Matter fermions ($\bar{\psi}\psi$)	Higgsinos ($\bar{\tilde{H}}\tilde{H}$)
χ	$\frac{1}{M_p\ln\mathcal{V}}$	$\frac{1}{\mathcal{V}\ln\mathcal{V}}$	No coupling	$\frac{1}{\mathcal{V}\ln\mathcal{V}}$
Φ	$\frac{\sqrt{\mathcal{V}}}{M_p}$	$\frac{1}{\mathcal{V}^{3/2}\ln\mathcal{V}}$	No coupling	$\frac{1}{\sqrt{\mathcal{V}}\ln\mathcal{V}}$



$$\langle\Gamma\rangle \sim \sqrt{d}\frac{g^2T^3}{M_P^2} \gtrsim H \sim g_\star^{1/2}T^2/M_P$$

Equilibrium

$$T \gtrsim 10^3 m_{3/2}$$

first time!

Finite temperature corrections in LVS

MSSM particles + small modulus thermalize

$$\boxed{\begin{aligned} V_{TOT} &= V_0 + \frac{T^2}{24}\left(m_\Phi^2 + m_{\tilde\Phi}^2\right) \\ &\quad + T^4\left(\kappa_1 g_{MSSM}^2 + \kappa_2 g_{\Phi X X}^2 m_\Phi^2 + \kappa_3 g_{\tilde\Phi \tilde X X}^2 m_{\tilde\Phi}^2\right) + \ldots \end{aligned}}$$

1 loop: masses

2 loop: couplings

dimensional couplings

gMSSM: contribution from two loops involving MSSM particles

Corrections from the moduli are subleading

1) $T^4\left(\kappa_2 g_{\Phi X X}^2 m_\Phi^2 + \kappa_3 g_{\tilde\Phi \tilde X X}^2 m_{\tilde\Phi}^2\right) \sim T^2\left(m_\Phi^2 + m_{\tilde\Phi}^2\right) T^2 \frac{\mathcal{V}}{M_P^2}$

2) $V_0 \gg \frac{T^2}{24}\left(m_\Phi^2 + m_{\tilde\Phi}^2\right)$

finally...

$$V_{TOT} = V_{T=0} + 4\pi c_1 \frac{T^4}{\tau_s}$$

2-loops MSSM effects dominate

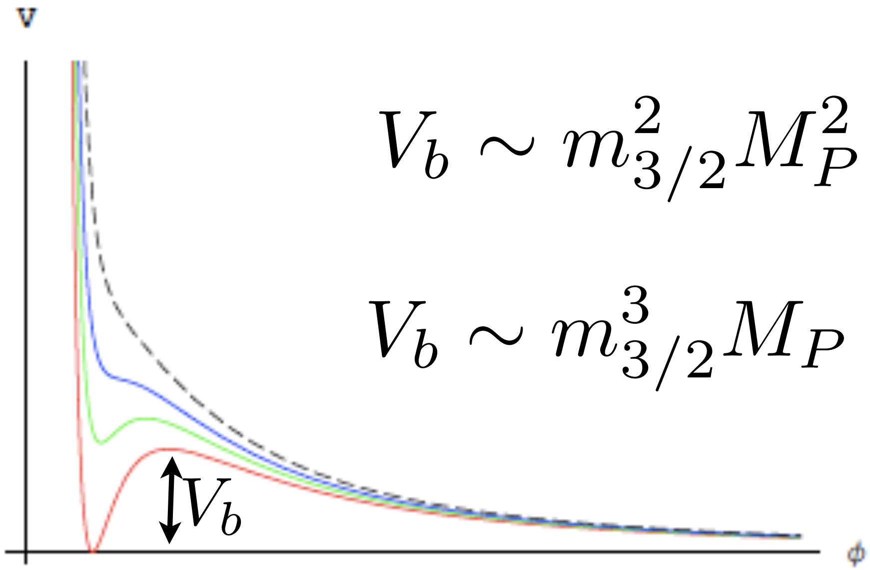
$$V_{T=0} = \lambda\sqrt{\tau_s}\,(a_s A_s)^2\,\frac{e^{-2a_s\tau_s}}{\mathcal{V}} - \mu\tau_s W_0\,(a_s A_s)\,\frac{e^{-a_s\tau_s}}{\mathcal{V}^2} + \nu\xi\frac{W_0^2}{\mathcal{V}^3}$$

- Phase transitions in the early Universe
- Thermal Inflation (bulk) and the cosmological moduli problem
- Runaway at high temperatures. (Maximal Temperature)
- Non-thermal production of dark matter (work in progress)

Decompactification temperature

- IIB flux compactification: metastable minimum
- Volume modulus couple to all form of energy
- Decompactification: source of energy greater than the barrier
- barrier ~ AdS minimum

$$m_{3/2} = \frac{|W_0|}{M_p^2 \mathcal{V}}$$



$$V_b \sim m_{3/2}^2 M_P^2$$ KKLT

$$V_b \sim m_{3/2}^3 M_P$$ LVS

Radiation Inflation

Decompactification due to thermal energy

Buchmuller, Hamaguchi, Lebedev, Ratz 0411109

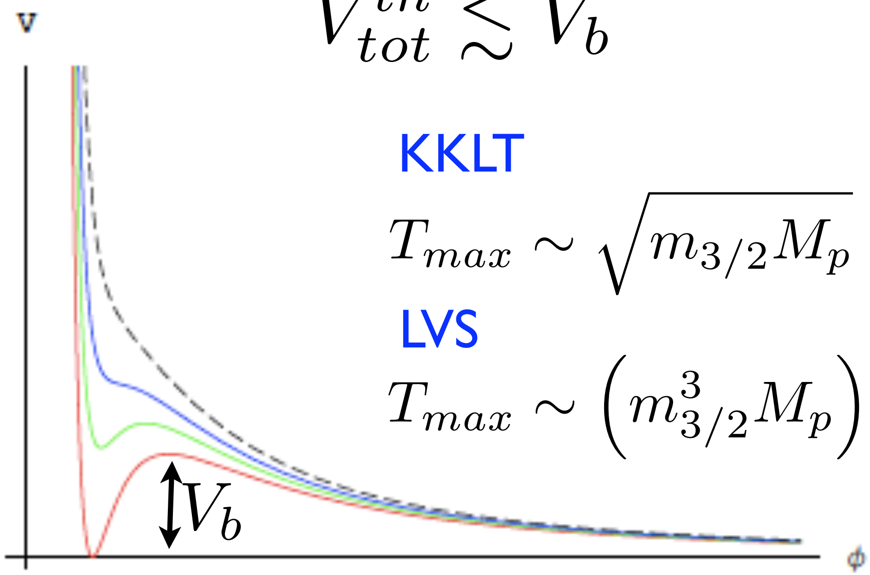
After inflation, inflaton decays to radiation

High-temperature thermal plasma: thermal corrections

$$V_{tot}^{th} \sim V(\mathcal{V}) + c\,T^4$$

$$V_{tot}^{th} \lesssim V_b$$

Cannot be cirvumvented by late entropy production because there is no local minimum for T>Tmax.



KKLT

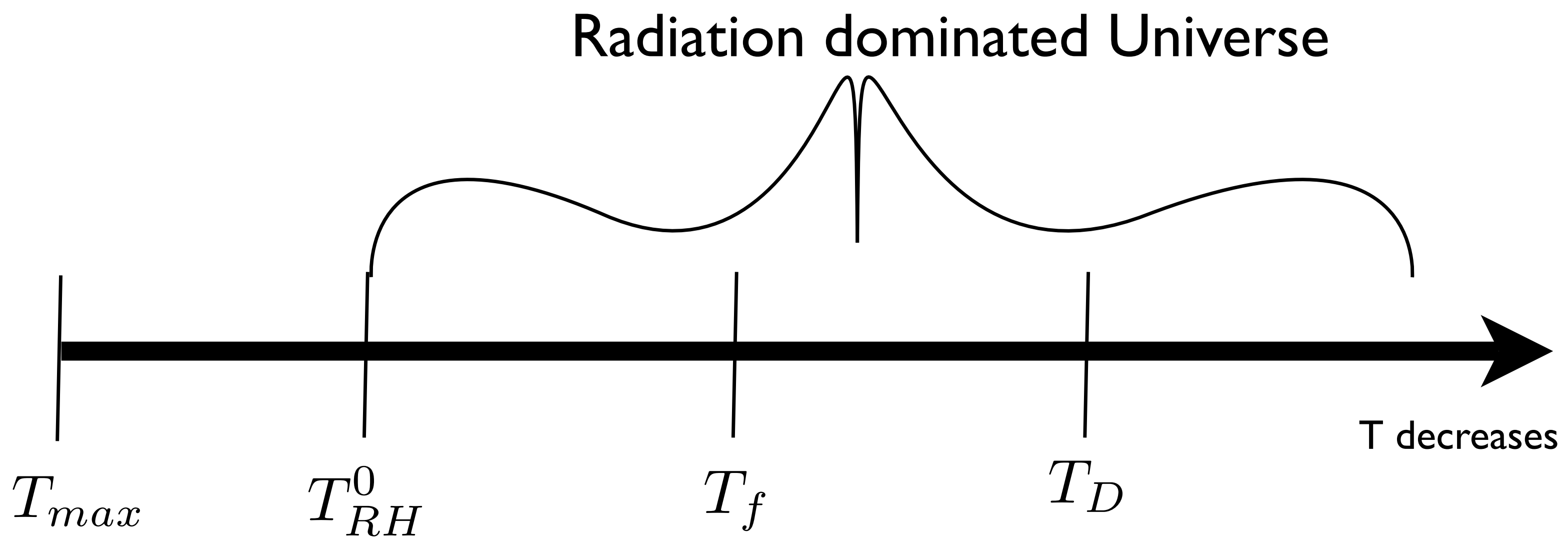
$$T_{max} \sim \sqrt{m_{3/2} M_p} \sim \sqrt{W_0} M_p$$

LVS

$$T_{max} \sim \left(m_{3/2}^3 M_p\right)^{1/4} \sim \frac{M_p}{\mathcal{V}^{3/4}}$$

$$T_{max} \sim 10^8 \mathrm{GeV}$$

Small moduli decay (II)

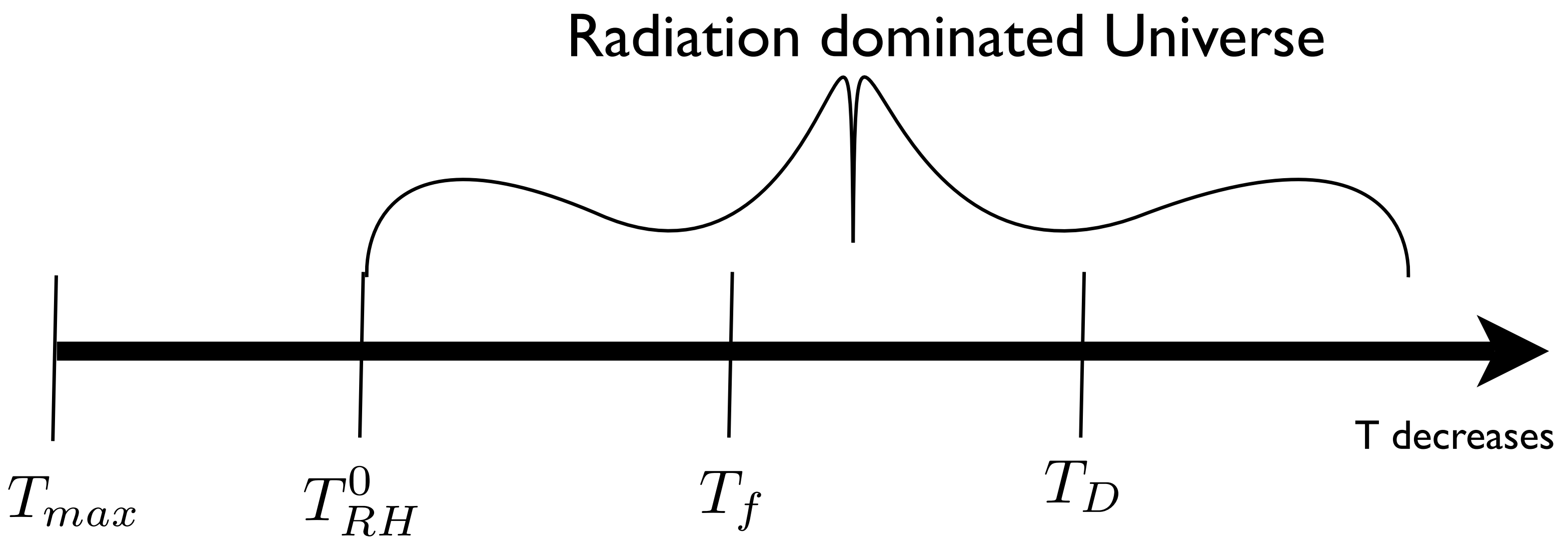


$$T_{max} \sim \left(m_{3/2}^3 M_p\right)^{1/4} \qquad T_D \equiv T_{RH} \sim \ln\left(\frac{M_p}{m_{3/2}}\right) m_{3/2}$$

$$\Delta \sim 1$$

No increase in entropy and CMP

Lower bound on the CY volume



$$T_{max} \sim \left(m_{3/2}^3 M_p\right)^{1/4} \qquad T_D \equiv T_{RH} \sim \ln\left(\frac{M_p}{m_{3/2}}\right) m_{3/2}$$

Impose:

$$T_D < T_{max}$$

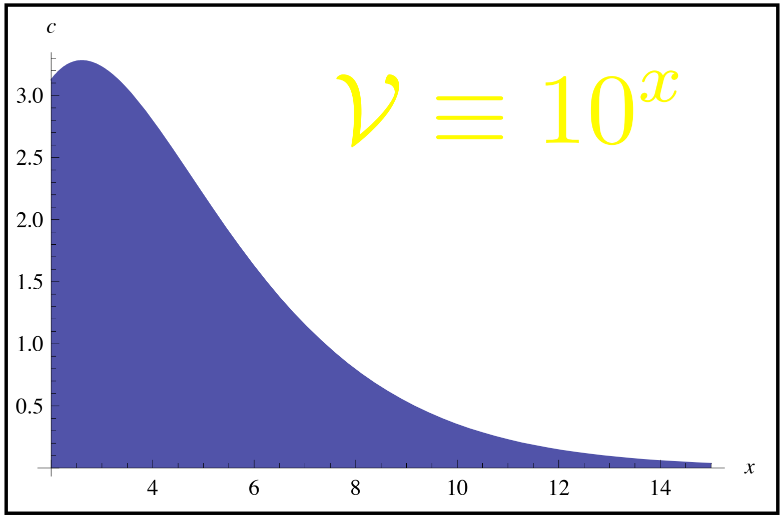
Lower bound on the CY volume

$$T_D < T_{max}$$

$$c \sim \frac{\tau_s^{11/8}}{W_0}$$

$$\ln\left(\frac{M_p}{m_{3/2}}\right)\left(\frac{m_{3/2}}{M_p}\right)^{1/4} < 1 \longrightarrow R \equiv c\,\frac{\mathcal{V}^{1/4}}{\ln\mathcal{V}} > 1$$

	$R > 1 \Leftrightarrow T_{max} > T_*$
$c = 4$	$\forall x$
$c = 3$	$x > 2.1$
$c = 2$	$x > 3.8$
$c = 1$	$x > 5.9$
$c = 0.5$	$x > 7.6$
$c = 0.1$	$x > 11.3$
$c = 0.05$	$x > 12.8$
$c = 0.01$	$x > 16.1$



Decompactification during Inflation

Energy of the inflaton = uplifting term (runaway)

$$V_{tot}^{inf} = V(\mathcal{V}) + \Delta V(\mathcal{V}, \phi)$$

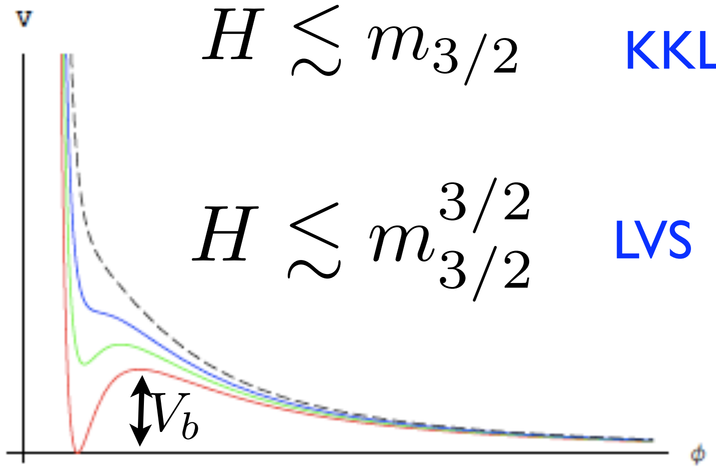
runaway is quite generic

$$\Delta V(\mathcal{V}, \phi) = \frac{V(\phi)}{\mathcal{V}^n}$$

D3-D7 brane inflation n=3

$$V_{tot}^{inf} \lesssim c V_b$$

Kallosh Linde 0401011



$$H \lesssim m_{3/2}$$ KKLT

$$H \lesssim m_{3/2}^{3/2}$$ LVS

- Low-scale inflation
- "Decouple" the height of the barrier from gravitino mass

Conlon Kallosh Linde Quevedo 0806.0809

Decay of moduli can produce a substantial amount of entropy

- During inflation, moduli are shifted from the zero temperature minimum O(Mp)
- After inflation, moduli oscillate freely around the true minimum: matter dominated Universe $\rho_\phi \sim \frac{1}{T^3}$
- Moduli decay $\Gamma_\phi \sim \frac{m_\phi^3}{M_P^2}$
- Entropy production $\Delta \equiv \frac{S_{fin}}{S_{in}} \sim \frac{T_{RH}^3}{T_D^3}$
- Primordial thermal abundances are washed away

$$\Omega_{cdm}^{thermal} \to \Omega_{cdm}^{thermal} \left(\frac{T_r}{T_f}\right)^3 \quad T_r < T_f \qquad m_\phi \sim 10\,\mathrm{TeV}$$

$$m_{WIMP} \sim 100\,\mathrm{GeV}$$

Non-thermal dark matter

$$\Omega_{cdm} = 0.233 \pm 0.013$$

Dark matter abundance from thermal production

$$\Omega_{cdm} = 0.23 \times \left(\frac{10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle} \right)$$

Weak scale physics

WIMP Miracle

Dark matter abundance from non-thermal production

$$\Omega_{cdm}^{NT} \rightarrow \Omega_{cdm} \left(\frac{T_f}{T_r} \right)$$

Particles with larger cross sections can yield the right amount of dark matter due to non-thermal production