

Catch-Me-If-You-Can: The Overshoot Problem and the Weak/Inflation Hierarchy

21st **STRING PHENOMENOLOGY**
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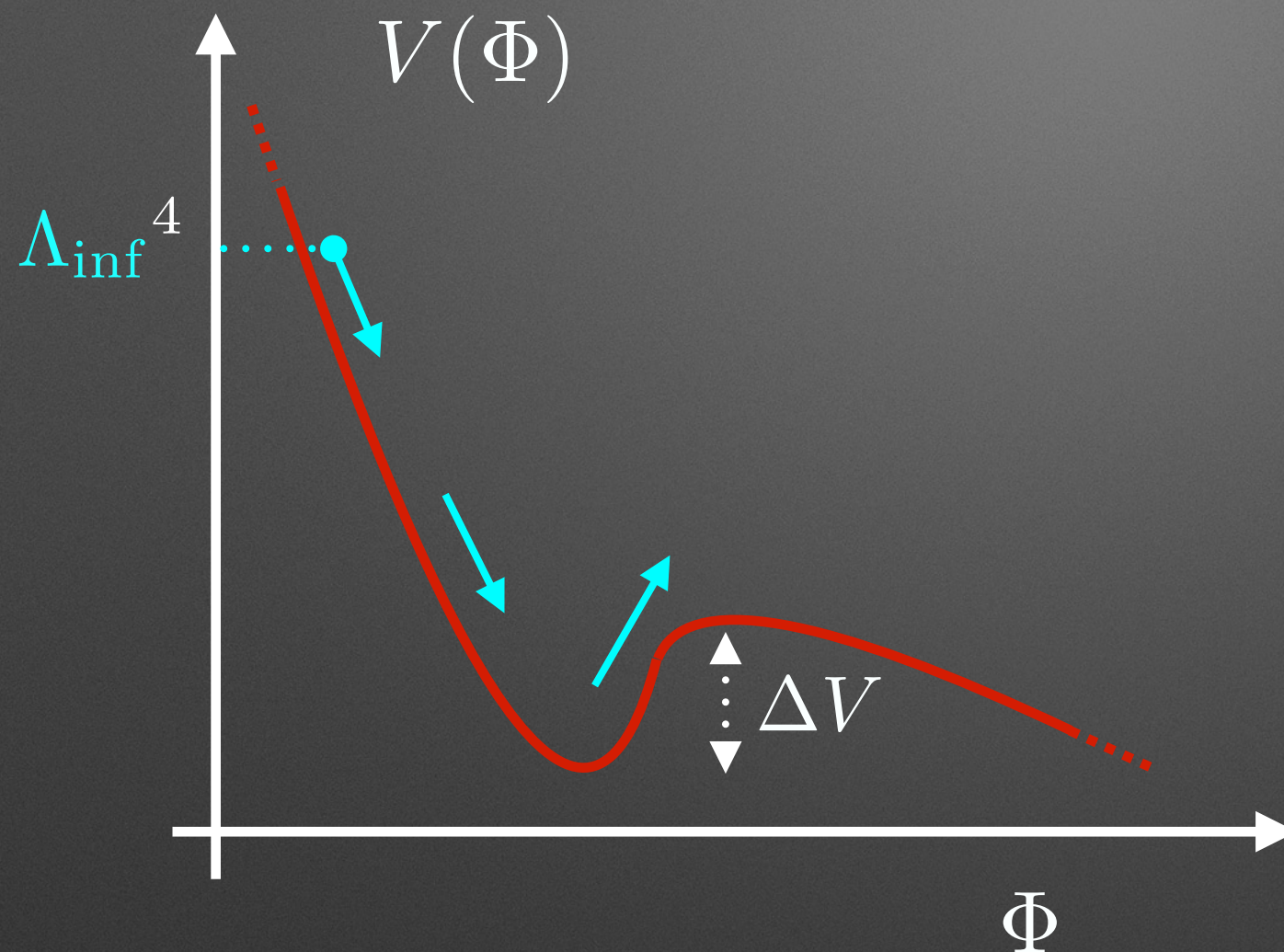
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Based on: [2207.00567](#) [Joseph Conlon, FR]

(See also Joe Conlon's talk)

The overshoot problem

Setting: post-inflationary string cosmology



(See also Fernando Quevedo's talk)

$$\Delta V \sim m_{3/2}^2 M_P^2$$

$$(\sim m_{3/2}^3 M_P \text{ in LVS})$$

$$\Lambda_{\text{inf}} = 10^{15} \text{ GeV}$$



$$\frac{\Delta V}{V_{\text{inf}}} \sim 10^{-13}$$

Volume kineticates and can overshoot

[Brustein, Steinhardt '93]

Two classes of solutions

- **Structural:** Lower the scale of inflation [German, Ross, Sarkar '01 +...]
or raise the barrier to decompactification [Kallosh, Linde '04]

This Talk

- **Dynamical:**

$$\rho_{\text{kin}} \sim a^{-6}$$

vs

$$\rho_{\text{mat}} \sim a^{-3}$$

$$\rho_{\text{rad}} \sim a^{-4}$$

will take over

$$H^2 = \frac{1}{3M_P^2} \left(\rho_{\text{extra}} + \frac{1}{2} \dot{\Phi}^2 + V(\Phi) \right)$$

Hubble Friction halts evolution & 'traps' volume modulus

[Conlon, Kallosh, Linde, Quevedo '08]

Rolling down the slope

Scalar rolling down a steep potential: 'kination'

$$\ddot{\phi} + 3H\dot{\phi} = - \cancel{\frac{\partial V}{\partial \phi}},$$

$$H^2 = \frac{1}{3M_P^2} \left(\cancel{V(\phi)} + \frac{\dot{\phi}^2}{2} \right)$$

$$\phi = \phi_0 + \sqrt{\frac{2}{3}} M_P \ln \left(\frac{t}{t_0} \right)$$

$$\rho_{\text{kin}}(t) \sim \frac{1}{a(t)^6}$$

stringy realisation

$\Delta\Phi \gtrsim 1$:

what about the distance conjecture?

[Ooguri, Vafa '08;
Ooguri, Palti, Shiu, Vafa '19]

Decompactification limit under control

(KK modes as usual)

The Large Volume Scenario (LVS)

LVS: Type IIB flux compactification, with all moduli stabilised

[Balasubramanian, Berglund, Conlon, Quevedo '05] [Conlon, Quevedo, Suruliz '05]

$$V = V_0 e^{-\lambda \Phi / M_P} \left(- \left(\frac{\Phi}{M_P} \right)^{3/2} + A \right) \quad \Phi = \sqrt{\frac{2}{3}} \ln \nu$$

$$\lambda = \sqrt{\frac{27}{2}}$$

↑
canonically normalised
volume modulus

Minimum for an exponentially large volume $\nu \sim e^{1/g_s}$

Generates Hierarchies:

$$m_s \sim \frac{M_P}{\sqrt{\nu}} \quad m_{3/2} \sim \frac{M_P}{\nu}$$

The tracker solution

$$\left\{ \begin{array}{l} \textcolor{red}{H}^2 = \frac{1}{3M_P^2} \left(\rho_\gamma + \frac{1}{2} \dot{\Phi}^2 + V(\Phi) \right) \\ \textcolor{red}{\dot{H}} = -\frac{1}{2M_P^2} \left(\rho_\gamma + P_\gamma + \dot{\Phi}^2 \right) = -\frac{1}{2M_P^2} \left(\gamma \rho_\gamma + \dot{\Phi}^2 \right) \end{array} \right. \quad \text{Friedmann Equations}$$

$$+ \quad \dot{\rho}_\gamma = -3\textcolor{red}{H} (\rho_\gamma + P_\gamma) = -3\textcolor{red}{H} \gamma \rho_\gamma \quad \text{Energy conservation}$$

Attractor solution

$$V = V_0 e^{-\frac{\textcolor{teal}{\lambda}\Phi}{M_P}}$$

$$\Omega_{\text{kin}} = \frac{3}{2} \frac{\gamma^2}{\textcolor{teal}{\lambda}^2} \quad \Omega_{\text{pot}} = \frac{3(2-\gamma)\gamma}{2\textcolor{teal}{\lambda}^2} \quad \Omega_\gamma = 1 - \Omega_{\text{kin}} - \Omega_{\text{pot}} = 1 - \frac{3\gamma}{\textcolor{teal}{\lambda}^2}$$

[Wetterich '88; Copeland, Liddle, Wands '98; Ferreira, Joyce '98]

Catch me if you can

radiation must catch up before the minimum:

$$\mathcal{V}_{\min} \gtrsim \mathcal{V}_c = \mathcal{V}_0 \Omega_{\gamma,0}^{-3/2}$$

How?

- More radiation: higher inflation scale as $\Omega_{\gamma,0} \sim \left(\frac{H_{\text{inf}}}{M_P} \right)^n$
for generic source
- More space to roll: smaller initial volume, larger final one

LVS only

Minimum at
large volume

Low electroweak
scale



~~dicaprio~~

~~hanks~~

Kinating volume

Radiation

catch me

if you can

The true story of a real fake. ~~—~~ *modulus*

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Sources of radiation (1)

Thermal spectrum with $T_{\text{dS}} = \frac{H_{\text{inf}}}{2\pi}$

$$\Omega_{\text{th}}^0 = g^* \frac{\pi^2}{30} \left(\frac{H_{\text{inf}}}{2\pi} \right)^4 \frac{1}{3H_{\text{inf}}^2 M_P^2} = \frac{g^*}{270 \times 16\pi^2} \left(\frac{\Lambda_{\text{inf}}}{M_P} \right)^4$$

	$\Lambda_{\text{inf}} (\text{GeV})$	$3 \cdot 10^{16}$	$3 \cdot 10^{15}$	$3 \cdot 10^{14}$
$g^* = 10^2$	$\mathcal{V}_{\text{min}}$	$8.0 \cdot 10^{17}$	$1.7 \cdot 10^{25}$	$3.7 \cdot 10^{32}$
$g^* = 10^4$	$\mathcal{V}_{\text{min}}$	$8.0 \cdot 10^{14}$	$1.7 \cdot 10^{22}$	$3.7 \cdot 10^{29}$
$g^* = M_P^2 / \Lambda_{\text{inf}}^2$	$\mathcal{V}_{\text{min}}$	$1.6 \cdot 10^{15}$	$3.3 \cdot 10^{19}$	$7.2 \cdot 10^{23}$

semi- realistic

$$\mathcal{V}_{\text{min}} \gtrsim 8.0 \times 10^{17} \left(\frac{g^*}{100} \right)^{-3/2} \left(\frac{V_0}{M_P^4} \right)^{1/3} \left(\frac{\Lambda_{\text{inf}}}{3 \cdot 10^{16} \text{ GeV}} \right)^{-22/3}$$

Sources of radiation (2)

Perturbative decays to i.e. axions

$$\Omega_{\text{dec}}^0 = \frac{3\sqrt{3}}{2} \sum_i \alpha_i \left(\frac{\lambda^3}{16\pi} \right) \frac{H^2}{M_P^2} = \boxed{\frac{9\sqrt{3}}{2} g_{\text{dec}} \left(\frac{\lambda^3}{16\pi} \right)} \left(\frac{\Lambda_{\text{inf}}}{M_P} \right)^4$$

same scaling

Enhanced coefficient

	$\Lambda_{\text{inf}}(\text{GeV})$	$3 \cdot 10^{16}$	$3 \cdot 10^{15}$	$3 \cdot 10^{14}$	$3 \cdot 10^{13}$
$g_{\text{dec}} = 1$	$\mathcal{V}_{\text{min}}$	$4.1 \cdot 10^{12}$	$8.9 \cdot 10^{19}$	$1.9 \cdot 10^{27}$	$4.1 \cdot 10^{34}$
$g_{\text{dec}} = 10^2$	$\mathcal{V}_{\text{min}}$	$4.1 \cdot 10^9$	$8.9 \cdot 10^{16}$	$1.9 \cdot 10^{24}$	$4.1 \cdot 10^{31}$
$g_{\text{dec}} = 10^4$	$\mathcal{V}_{\text{min}}$	$4.1 \cdot 10^6$	$8.9 \cdot 10^{13}$	$1.9 \cdot 10^{21}$	$4.1 \cdot 10^{28}$

realistic

$$\mathcal{V} \gtrsim 4.2 \times 10^9 \left(\frac{g_{\text{dec}}}{100} \right)^{-3/2} \left(\frac{V_0}{M_P^4} \right)^{1/3} \left(\frac{\Lambda_{\text{inf}}}{3 \cdot 10^{16} \text{ GeV}} \right)^{-22/3}$$

Cosmic fundamental strings?

Cosmic strings after brane inflation

[Dvali, Tye '99; Sarangi Tye '02]

[Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi '03; Baumann, Dymarsky, Klebanov, McAllister '07 + ...]

scaling regime $\rho_{\text{string}} \sim \mu H^2$

parametrically better scaling with H!

Constraints

Today $G\mu \lesssim 10^{-7}$ (CMB) but $\mu \sim m_s^2 \sim \frac{M_P^2}{\nu}$

string scale after inflation can be high

$$10^{12} \text{ GeV} \lesssim m_s \lesssim 10^{16} \text{ GeV} \longleftrightarrow 10^{-11} \lesssim G\mu \lesssim 10^{-7}$$

Decay to GWs



GW dominated epoch?

Conclusions and outlook

- Lots of interest on scenarios with $\Delta\Phi \gtrsim 1$, e.g. large field inflation. What about early phase of *kination*?

Overshoot problem in *LVS*:

solved by a *hierarchy* between *EW* and *inflation* scales

- Not just qualitative but quantitatively accounts for EW h_c

Open questions/future work

- Non perturbative particle production
- Fundamental cosmic string network [Motivation to study brane inflation in *LVS*]
- *Gravitation* epoch?

Thank you for your attention!