High Scale Inflation and Low Scale Supersymmetry

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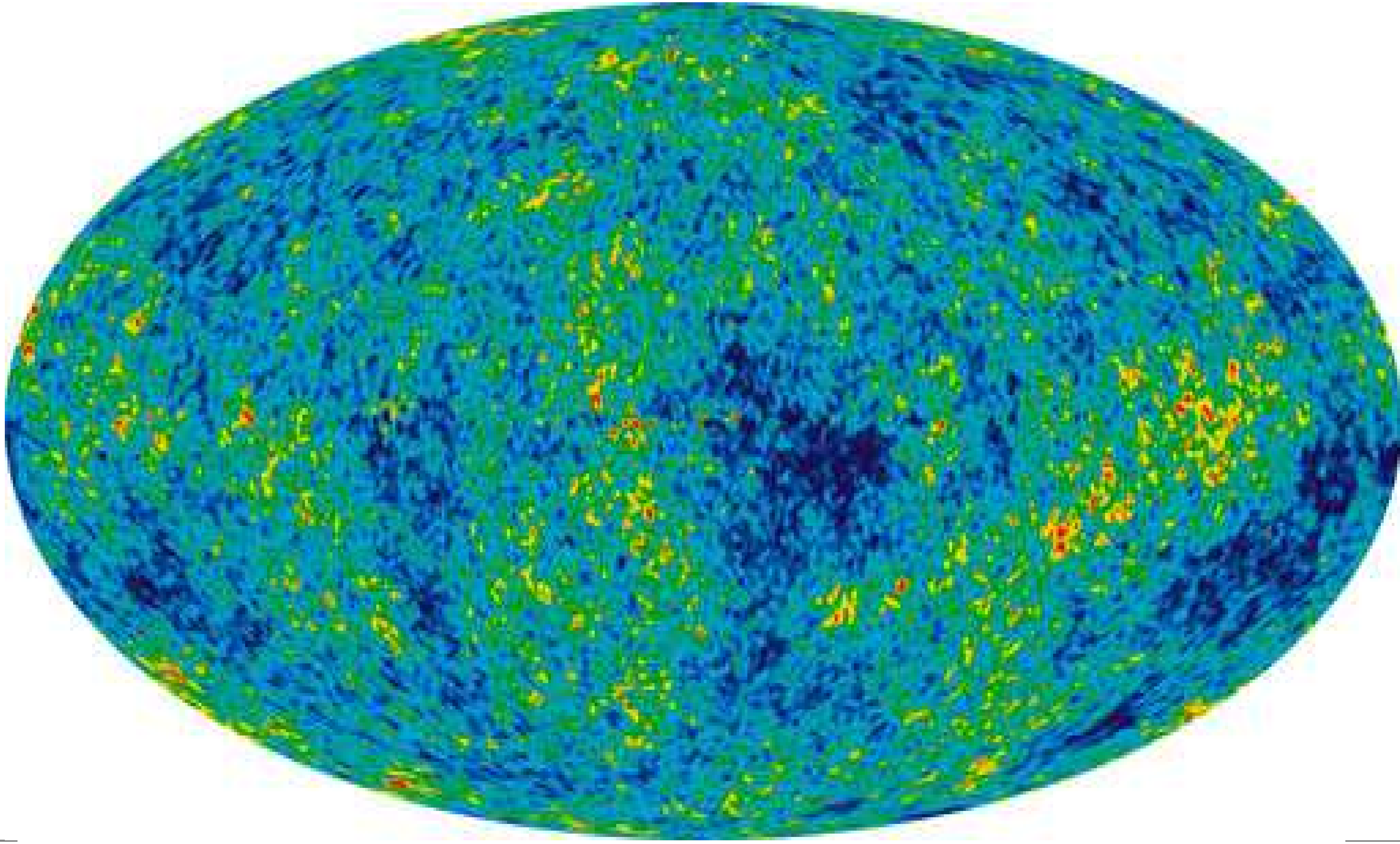
Cambridge University, February 2008

Two paradigms: inflation...



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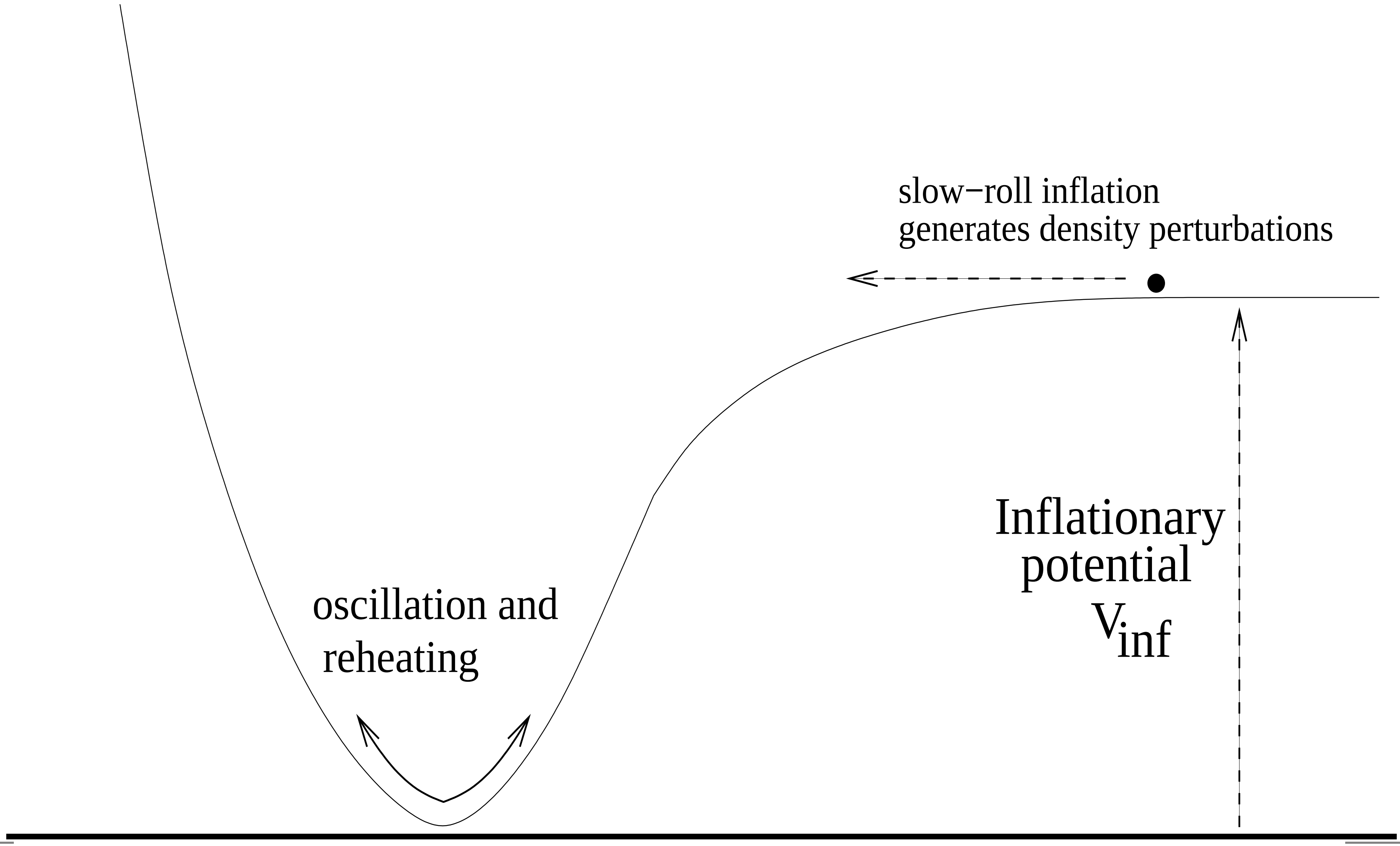


Two paradigms: inflation...

- Slow-roll inflation homogenises the universe and generates density perturbations.

$$\eta = \left(\frac{1}{M_P^2} \frac{V''}{V} \right) \ll 1, \qquad \epsilon = \frac{1}{2M_P^2} \left(\frac{V'}{V} \right)^2 \ll 1.$$

$$n_s = 1 + 2\eta - 6\epsilon.$$

The inflationary energy scale is

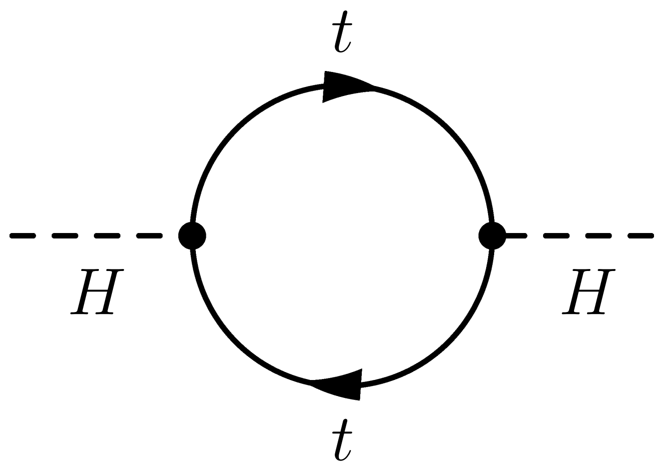
$$V_{inf} \sim \epsilon^{1/4} (6 \times 10^{16} \text{GeV}).$$

Unless ϵ is extremely small, the inflationary energy scale is high,

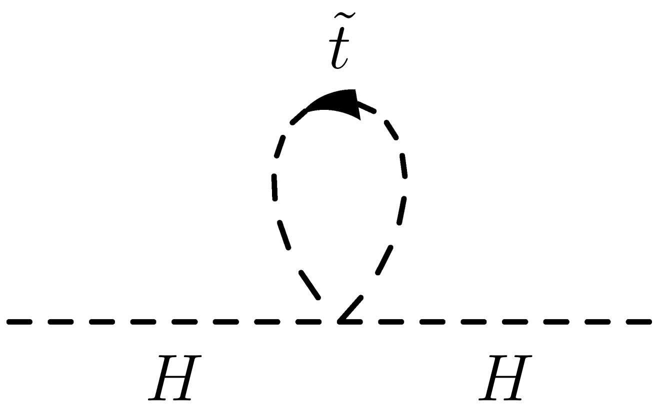
$$V_{inf} \gg 10^{11} \text{GeV}$$

...and TeV supersymmetry

Supersymmetry is a great solution to the gauge hierarchy problem:

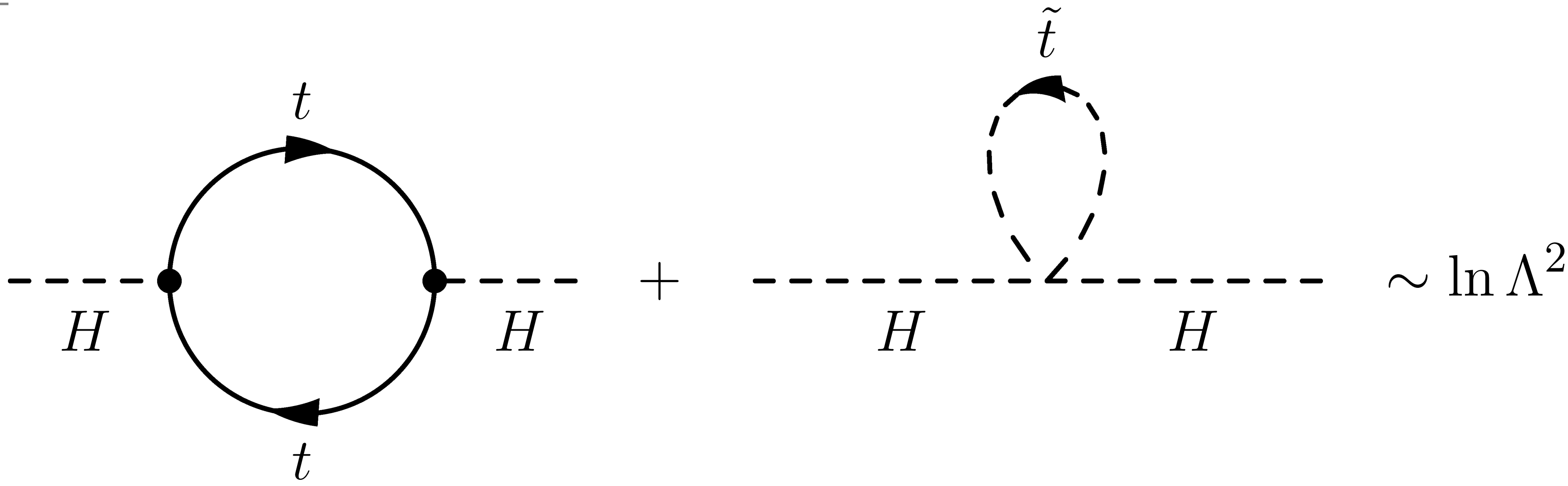


$$\sim \quad \Lambda^2$$



$$\sim \quad -\Lambda^2$$

...and TeV supersymmetry



TeV supersymmetry cancels the quadratic divergences in the Higgs potential.

...and TeV supersymmetry

...and TeV supersymmetry

TeV supersymmetry

- stabilises the Higgs mass against radiative corrections
- gives a good dark matter candidate
- explains gauge symmetry breaking through radiative electroweak symmetry breaking
- is compatible with LEP I precision electroweak data
- is the prime candidate for new physics discovered at the LHC

Tension

The supergravity scalar potential can be written as

$$V_{susy} = \sum_i |F^i|^2 - 3m_{3/2}^2 M_P^2.$$

$$\text{Gravity-mediation} : F^i \sim 10^{11}\text{GeV}, m_{3/2} \sim 1\text{TeV},$$

$$\text{Gauge mediation} : F^i \ll 10^{11}\text{GeV}, m_{3/2} \ll 1\text{TeV}.$$

V_{susy} has natural scale $F^2 \sim m_{3/2}^2 M_P^2 \ll (10^{16}\text{GeV})^4$.

- Sets scale of barrier height to overshooting
- Sets scale of structure in the potential

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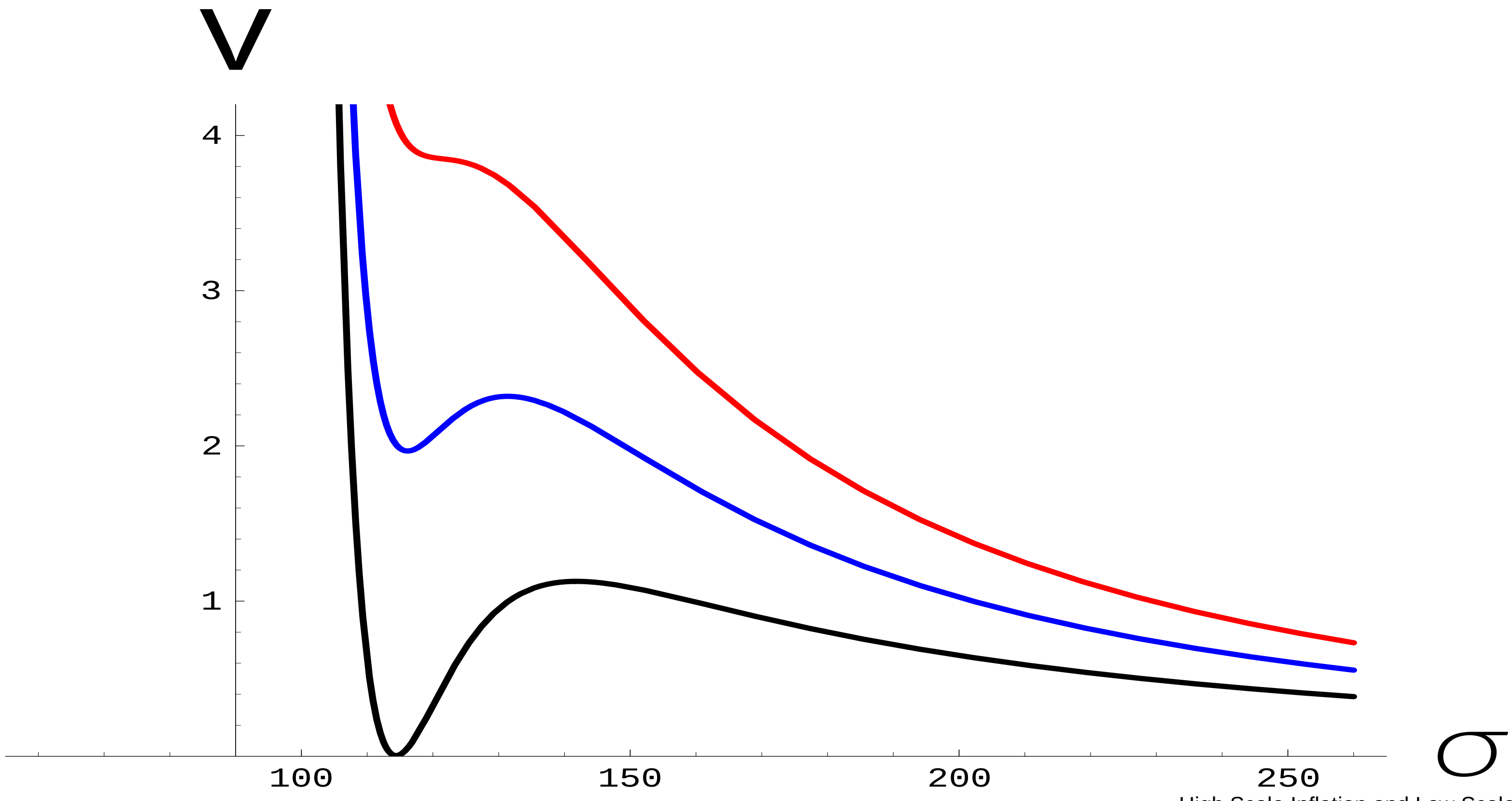
Most models of high-scale inflation are incompatible with TeV supersymmetry

Tension

- Supergravity (and string theories) generically have moduli.
- Moduli are light gravitationally coupled scalars whose vevs determine Yukawa couplings and gauge couplings.
- Moduli must be stabilised to avoid generating unobserved fifth forces.
- The supergravity potential breaks supersymmetry and stabilises the moduli, making them massive.

Tension

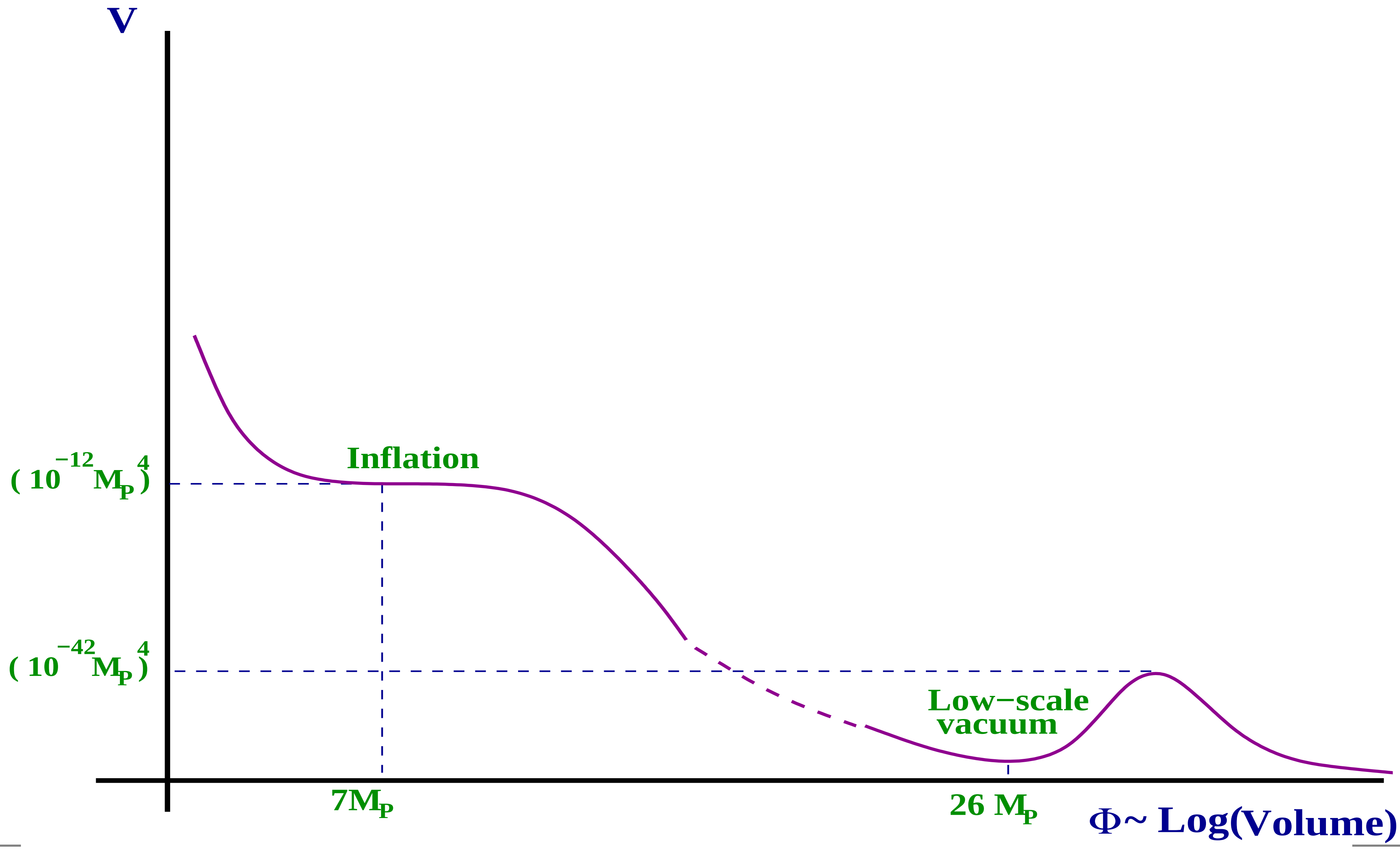
- Masses of stabilised moduli are typically $m \sim \mathcal{O}(m_{3/2})$ and the barrier to decompactification is $\sim m_{3/2}^2 M_P^2$.
- The presence of large vacuum energy destabilises this barrier.



Proposed Solution

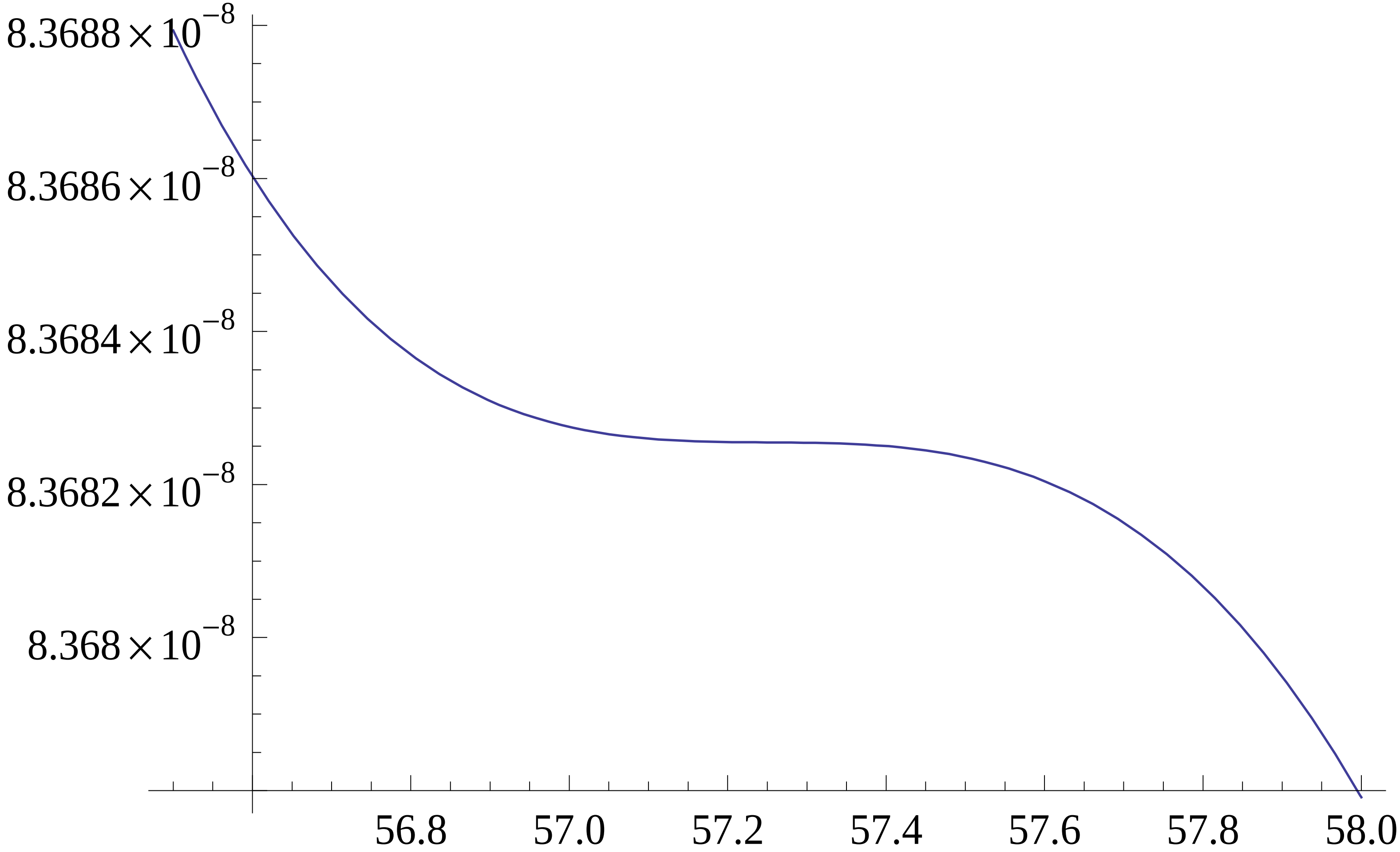
1. Inflation at $E \sim 10^{16}$GeV with $m_{3/2} \gg 1$TeV
2. Inflation ends with runaway and decompactification.
3. The global minimum has $E \ll 10^{16}$GeV and $m_{3/2} \sim 1$TeV
4. The global minimum lies many Planckian distances from where inflation occurred.
5. A tracker solution guides the moduli into the global minimum and avoids overshooting.

Proposed Evolution



Inflation with Runaway

Inflation near an inflection point leads to runaway.



Inflation with Runaway

To get an inflection point:

$$K = -3\ln(T+\bar{T}) + \frac{A}{(T+\bar{T})^{3/2}} + \frac{B}{(T+\bar{T})^{2}} + \frac{C}{(T+\bar{T})^{5/2}} + \ldots$$

$$W = W_0$$

- A, B and C can emerge from higher α' corrections, higher loop corrections ...
- Ugly but doable.

Inflation with Runaway

Potential is

$$V = \frac{A'|W_0|^2}{(T+\bar{T})^{9/2}} + \frac{B'|W_0|^2}{(T+\bar{T})^5} + \frac{C'|W_0|^2}{(T+\bar{T})^{11/2}} + \ldots$$

Canonically normalise $\Phi = \frac{\sqrt{6}}{(T+\bar{T})}$:

$$V = A''e^{-\sqrt{27/2}\Phi} + B''e^{-10\Phi/\sqrt{6}} + C''e^{-11\Phi/\sqrt{6}}.$$

Tuning A, B and C gives the simplest model of inflation with runaway.

A, B and C can be tuned to get $n_s = 0.95$ with the correct scale and number of efoldings.

Inflation with Runaway

This model does not work.

Problems:

- There is no vacuum and no low-energy supersymmetry.
- The fields decompactify to infinity.

Solution: embed into the large-volume models.

Large Volume Models

These arise in IIB flux compactifications and are characterised by exponentially large volume and broken supersymmetry.

$$K = -2\ln\left(\mathcal{V} + \xi\right),$$

$$W = W_0 + A_s e^{-a_s T_s}$$

$$V = e^K \left(K^{i\bar{j}} D_i W D_{\bar{j}} W - 3|W|^2 \right).$$

Simplest model ($\mathbb{P}^4_{[1,1,1,6,9]}$):

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

Large Volume Models

The supergravity potential is:

$$V = \underbrace{\frac{8\sqrt{\tau_s}a_s^2|A_s|^2 e^{-2a_s\tau_s}}{3\mathcal{V}} - \frac{4a_s|A_s W_0|\tau_s e^{-a_s\tau_s}}{\mathcal{V}^2}}_{\text{integrate out } \tau_s} + \frac{\xi|W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

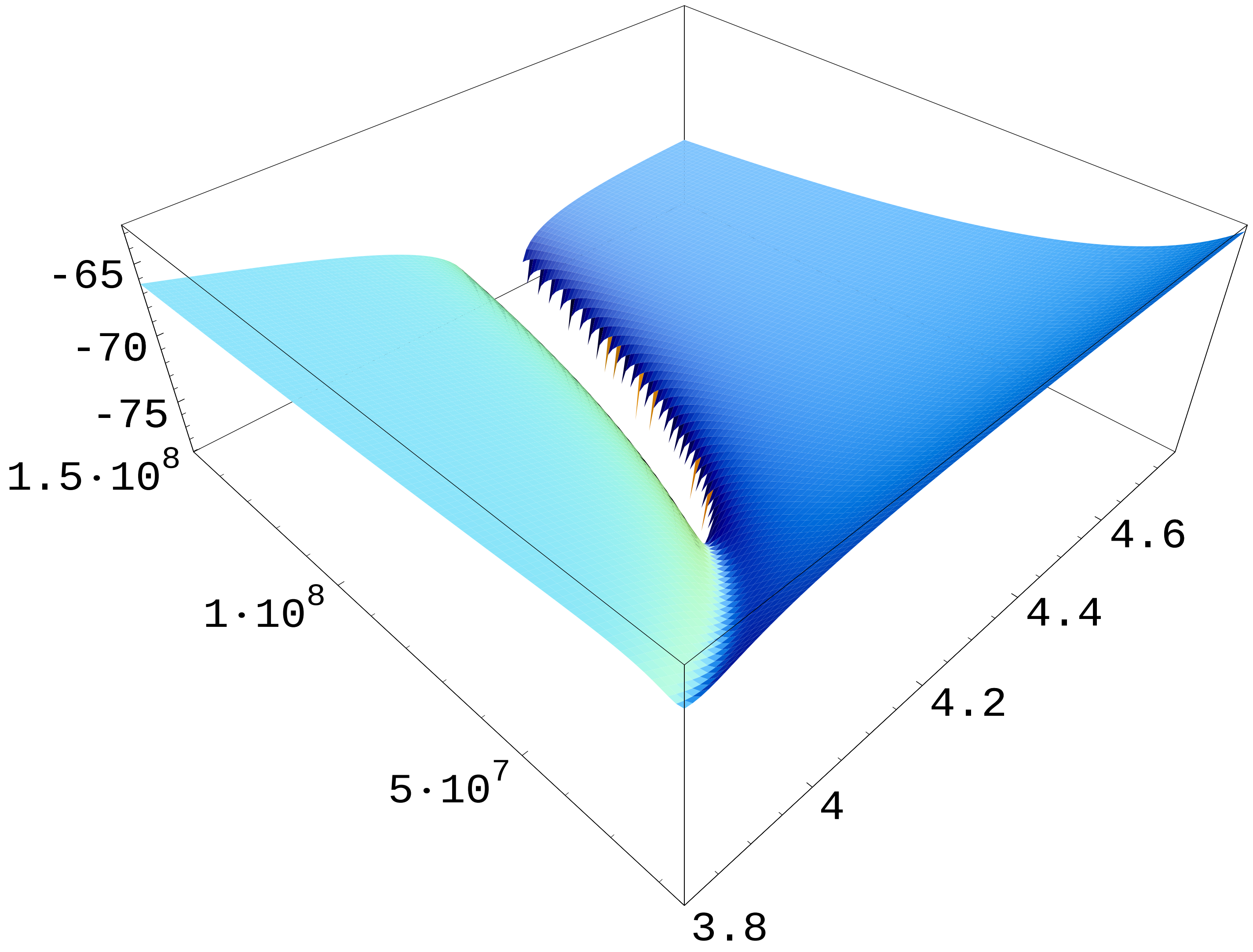
$$V = -\frac{|W_0|^2 (\ln \mathcal{V})^{3/2}}{\mathcal{V}^3} + \frac{\xi|W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

A minimum exists at

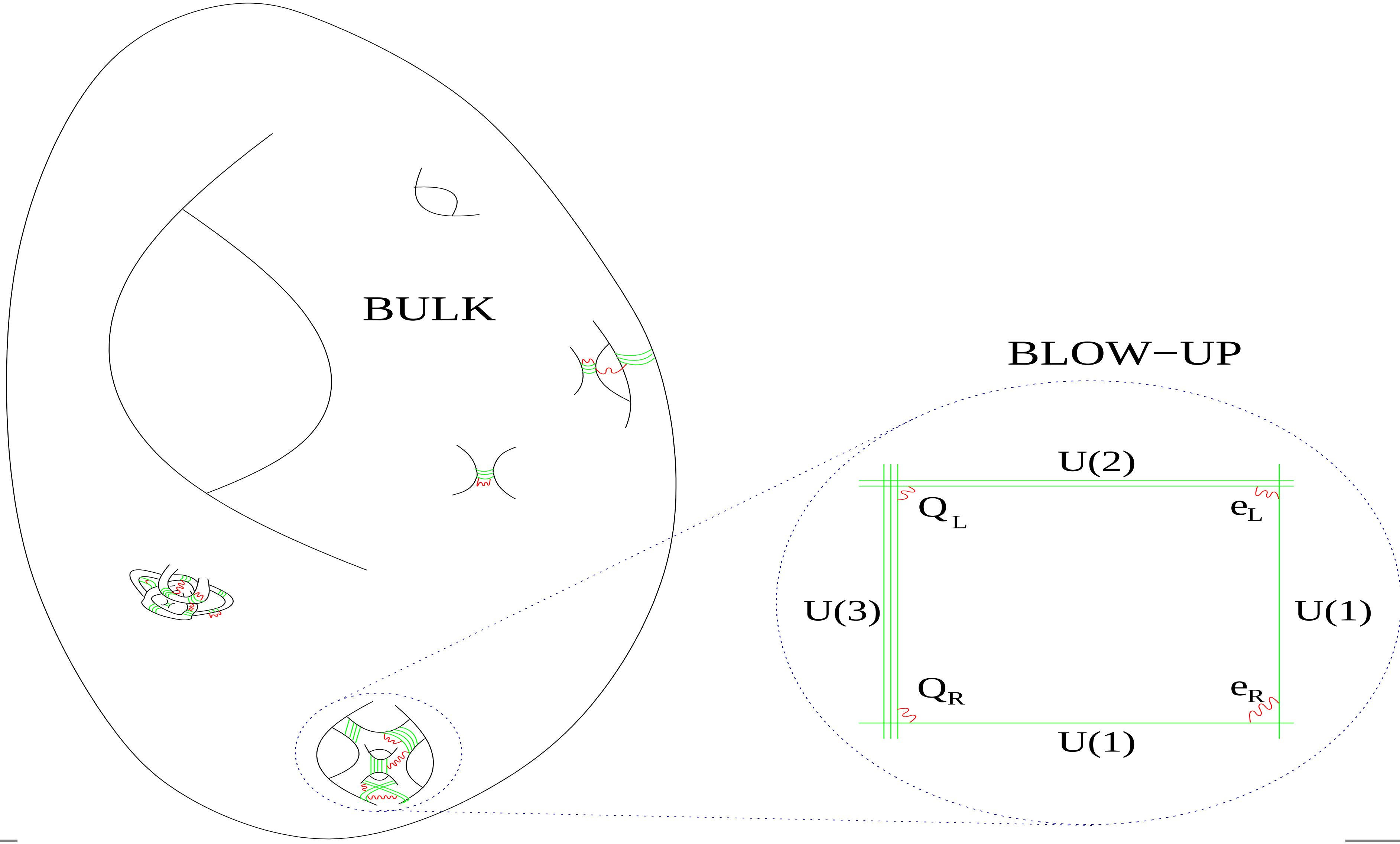
$$\mathcal{V} \sim |W_0| e^{c/g_s}, \qquad \tau_s \sim \ln \mathcal{V}.$$

This minimum is non-supersymmetric AdS and at exponentially large volume.

Large Volume Models



Large Volume Models



Large Volume Models

$$V = -\frac{|W_0|^2 \left(\ln \mathcal{V}\right)^{3/2}}{\mathcal{V}^3} + \frac{\xi |W_0|^2}{g_s^{3/2} \mathcal{V}^3}.$$

Canonically normalise $\Phi = \sqrt{\frac{3}{2}} \ln(T + \bar{T})$:

$$V = (-\epsilon \Phi^{3/2} + 1) e^{-\sqrt{\frac{27}{2}}\Phi}.$$

To solve gauge hierarchy problem, need $\mathcal{V} \sim 10^{15}$, with $\Phi \sim 26 M_P$.

Note: single-exponential potential!

The Model

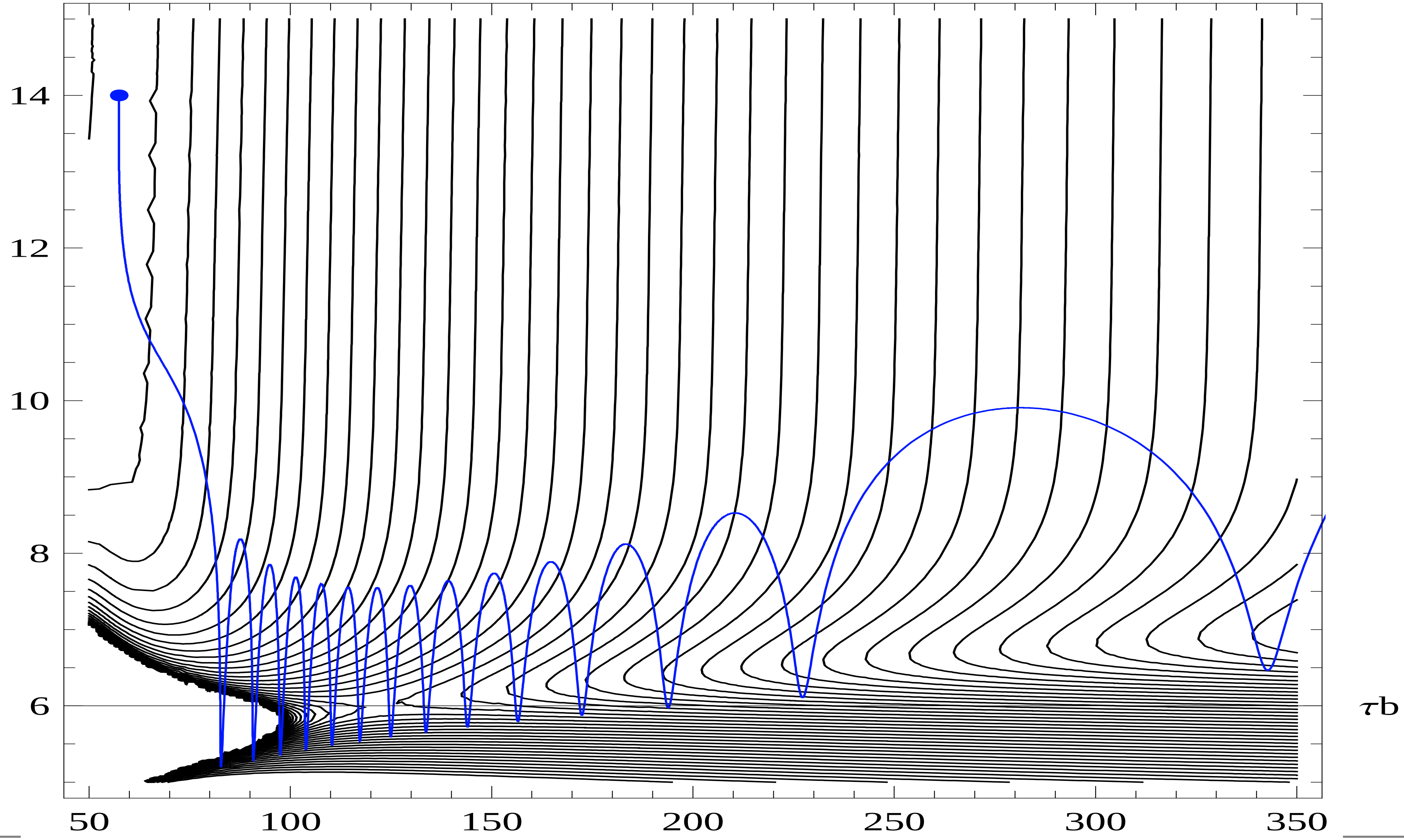
$$\begin{aligned}
\mathcal{V} &= \frac{1}{9\sqrt{2}}\left(\tau_b^{3/2} - \tau_s^{3/2}\right), \\
K &= -2\ln\left(\mathcal{V} + \xi + \frac{C}{\mathcal{V}^{1/3}} + \frac{D}{\mathcal{V}^{2/3}}\right), \\
W &= W_0 + Ae^{-a_s T_s}, \\
V &= e^K\left(K^{i\bar{j}} D_i W D_{\bar{j}} W - 3|W|^2\right).
\end{aligned}$$

Parameters:

$$\xi = 9, C = -18.29059, D = 14, W_0 = -0.1, A = 1, a_s = \frac{2\pi}{4}.$$

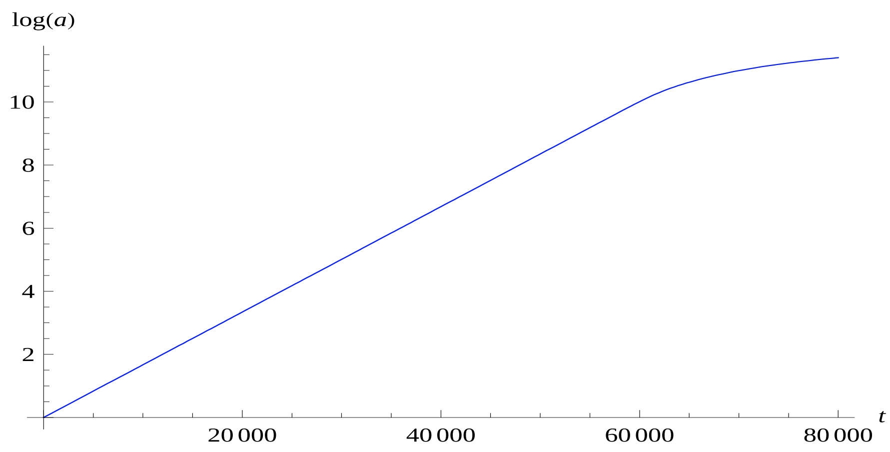
Initial conditions: $\tau_{b,init} = 57.4819,\ \ \tau_{s,init} = 14.$

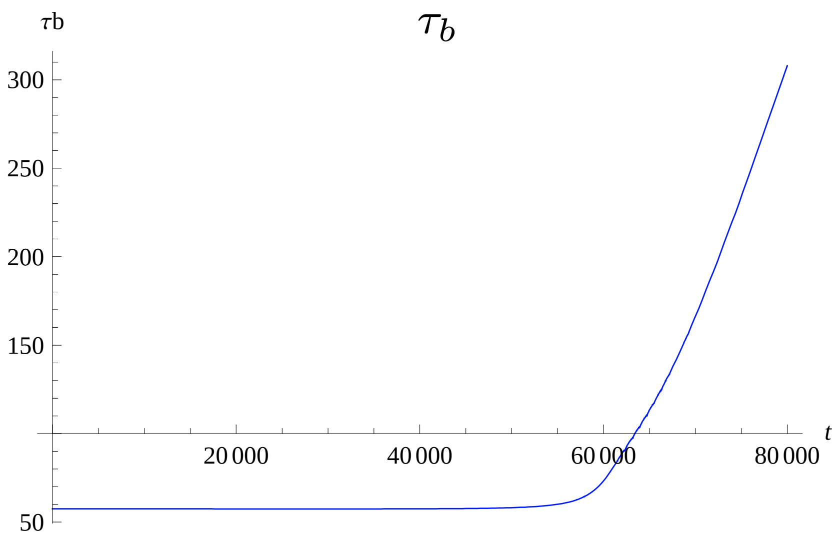
Moduli Evolution: Initial Behaviour

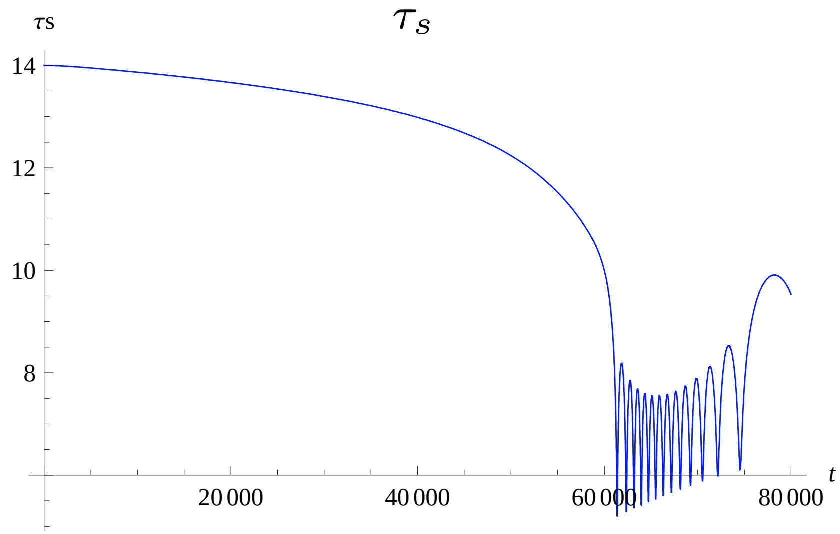


Moduli Evolution: Initial Behaviour

Scale factor







Moduli Evolution: Initial Behaviour

- Moduli evolution starts with a phase of slow-roll inflation.
- Parameters and initial conditions can be tuned to get sixty e-folds.
- Inflation occurs on an inflection point and ends with runaway in the volume direction and oscillations in the τ_s direction.
- The τ_s oscillations generate a post-inflationary radiation background.

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Inflation $\rightarrow$ Runaway + radiation

Moduli Evolution: Runaway

During runaway, $m_{\tau_b} \ll m_{\tau_s}$. We integrate out τ_s to get

$$V = -\frac{|W_0|^2 \left(\ln \mathcal{V}\right)^{3/2}}{\mathcal{V}^3} + \frac{\xi |W_0|^2}{g_s^{3/2} \mathcal{V}^3}.$$

Canonically normalise $\Phi = \sqrt{\frac{3}{2}} \ln(T + \bar{T})$:

$$V = (-\epsilon \Phi^{3/2} + 1) V_0 e^{-\sqrt{\frac{27}{2}}\Phi}.$$

During most of the evolution, the effective potential is

$$V = V_0 e^{-\sqrt{\frac{27}{2}}\Phi}!$$

Moduli Evolution: Runaway

Evolution of field in exponential potential and background radiation

$$V = V_0 e^{-\sqrt{\frac{27}{2}}\Phi}$$

An attractor scaling solution exists (Copeland, Liddle, Wands):

$$\Omega_\gamma = \frac{19}{27}, \qquad \Omega_{kin,\Phi} = \frac{16}{81}, \qquad \Omega_{V(\phi)} = \frac{8}{81}.$$

This attractor solution is valid for

$$7M_P \lesssim \Phi \lesssim 26M_P.$$

Moduli Evolution: Runaway

The full 2-modulus potential

$$V = \frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s |A_s W_0| \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{\xi |W_0|^2}{g_s^{3/2} \mathcal{V}^3}.$$

can be shown to have a tracker solution in the presence of radiation.

Numerically this is found to be an attractor with

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Moduli Evolution: Runaway

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As expected - we can integrate out τ_s as

$$m_{\tau_s} \sim \sqrt{\mathcal{V}} m_{\tau_b} \gg m_{\tau_b}.$$

Moduli Evolution: Final

Full potential is

$$V = (-\epsilon \Phi^{3/2} + 1) V_0 e^{-\sqrt{\frac{27}{2}}\Phi} + \underbrace{\epsilon' e^{-\sqrt{6}\Phi}}_{uplift}.$$

$\Phi \sim 25 M_P$: potential deviates from pure exponential.

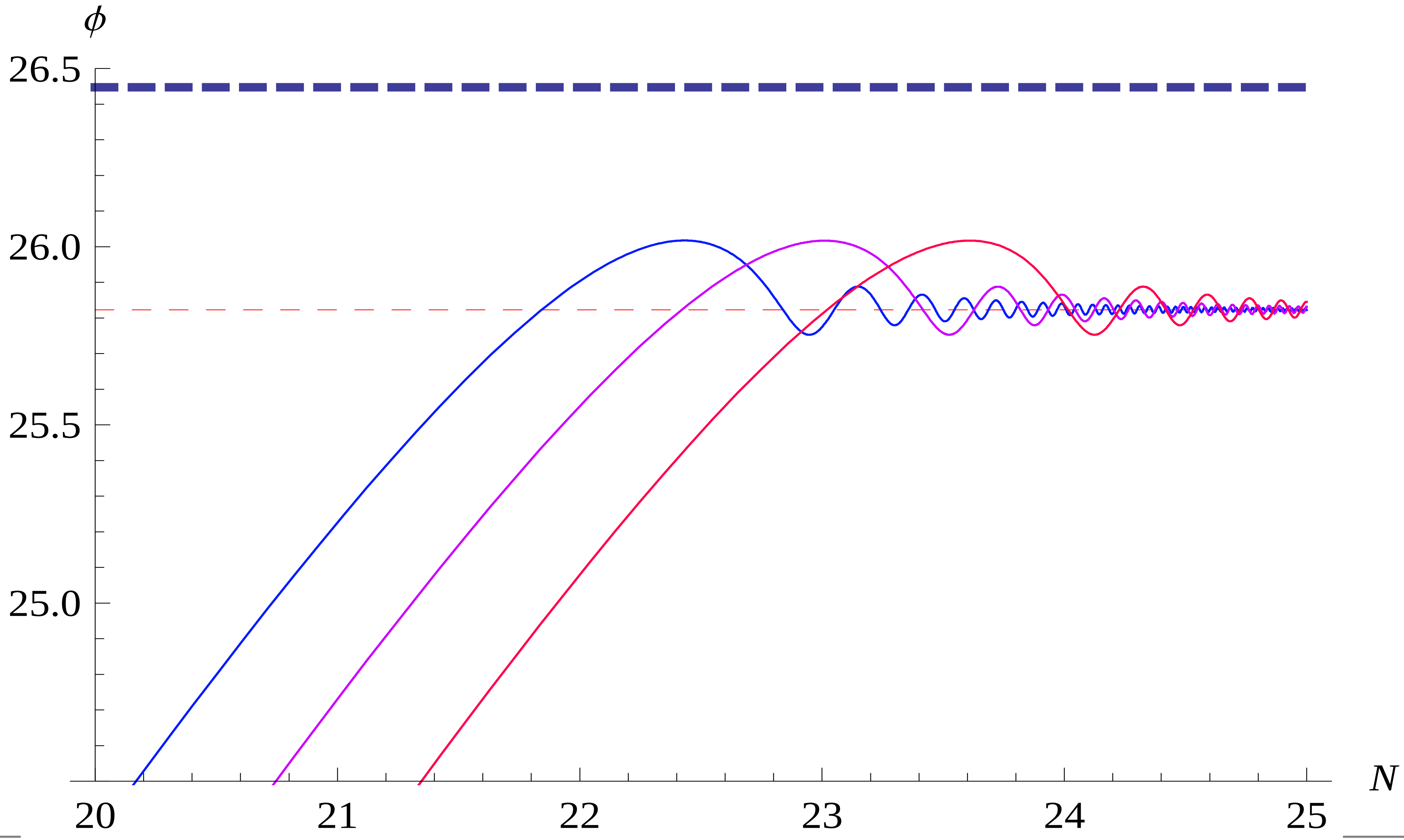
$\Phi \sim 25.7 M_P$: minimum exists

$\Phi \sim 26.5 M_P$: barrier to decompactification

$$V_{barrier} \sim m_{3/2}^3 M_P \sim m_{\tau_b}^2 M_P^2.$$

The tracker solution is radiation-dominated and never overshoots the barrier.

Moduli Evolution: Final

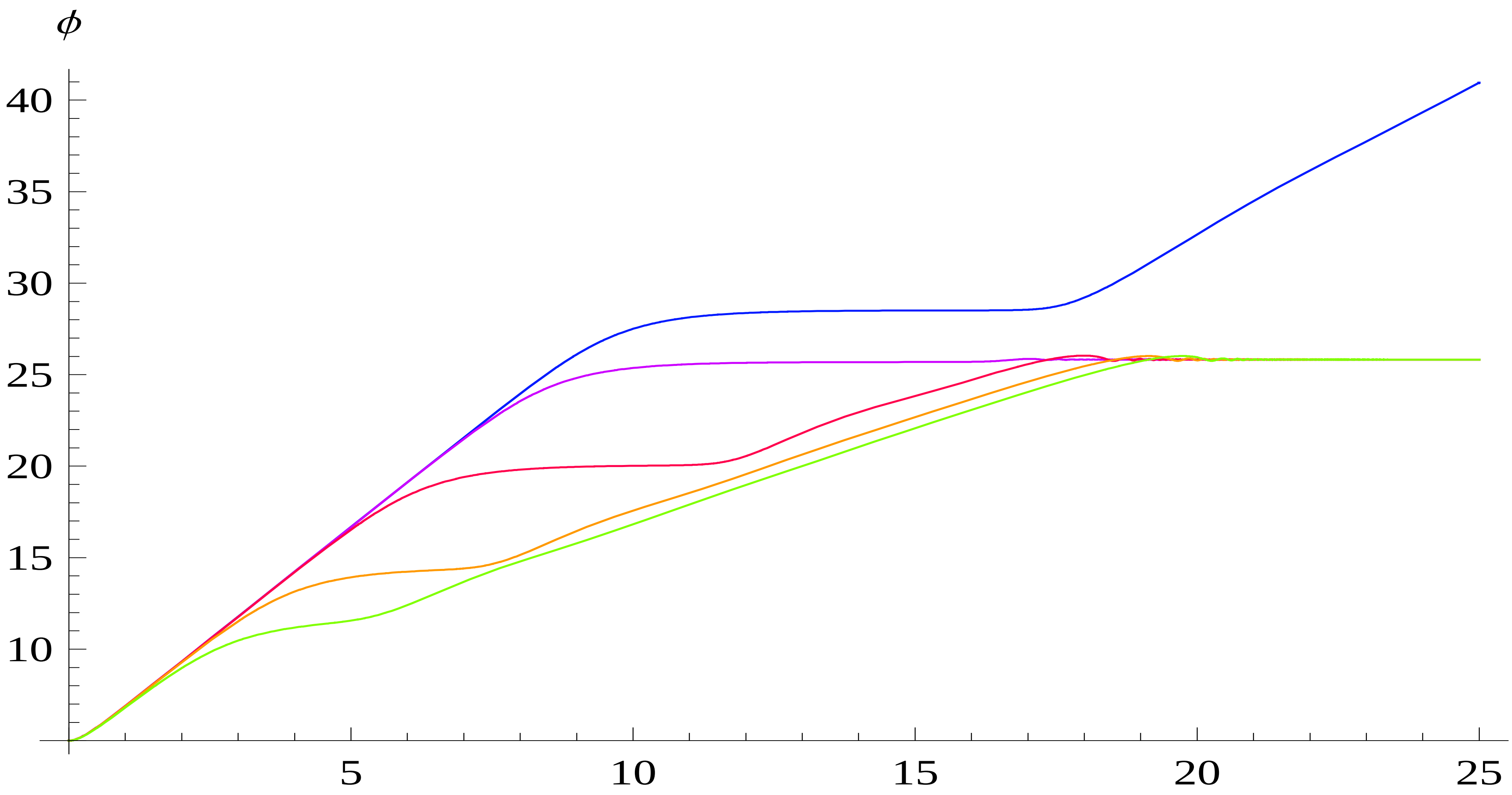


Moduli Evolution: Final

- To avoid overshooting must locate tracker.
- This requires sufficient initial radiation.
- We take $\Phi(t=0)=5, \dot{\Phi}(t=0)=0$ and vary $\Omega_{\gamma,0}$

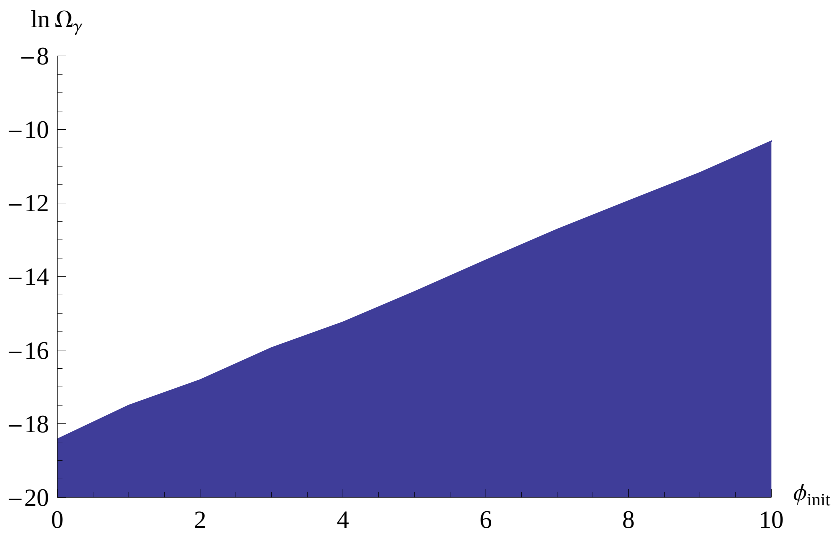
- Note: moduli potential is a single exponential $e^{-\Phi}$ rather than double exponential $e^{-\exp\Phi}$.
- Avoiding overshooting is much easier.

Moduli Evolution: Final

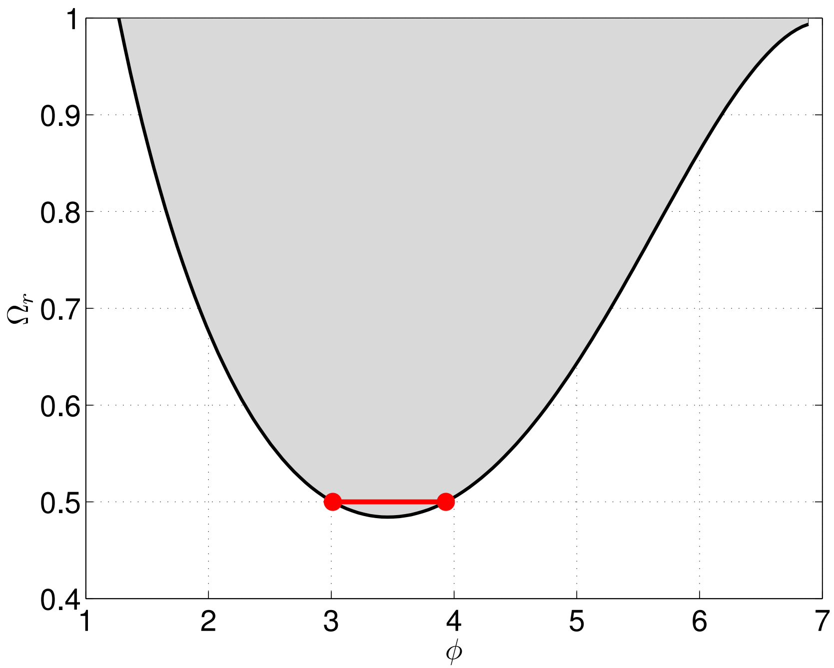


Modulus evolution with $\Omega_{\gamma,0} = 10^{-7}, 10^{-6}, 10^{-4}, 10^{-2}, 10^{-1}$.

Comparison with KKLT



Large-volume



KKLT

(from hep-th/0506045, Barreiro, de Carlos, Copeland, Nunes)

Overshooting avoided for $\Omega_{\gamma,init} \ll 1$!

Overshooting Problem

- Across the whole parameter space only trace initial amounts of radiation ($\Omega_\gamma \ll 1$) are required to avoid overshooting.
- The single-exponential potential is much shallower than double exponential potentials (KKLT, gaugino condensation).
- The large volume models solve the cosmological overshoot problem.

Conclusions

- Want high-scale inflation with low-scale supersymmetry breaking.
- To achieve this inflation should end with runaway towards decompactifications.
- End of inflation generates trace amounts of radiation.
- Radiation gives a tracker solution.
- Moduli evolve in the tracker solution to a susy-breaking minimum at $m_{3/2} \sim 1$TeV.
- Tracker solution does not overshoot minimum.

Conclusion

Runaway first, reheat later!