Inflation and moduli backreaction in string-effective supergravities

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Based on work with W. Buchmuller, E. Dudas, L. Heurtier, A. Westphal, M.W. Winkler

What to expect

Motivation: High-scale inflation and heavy scalar fields

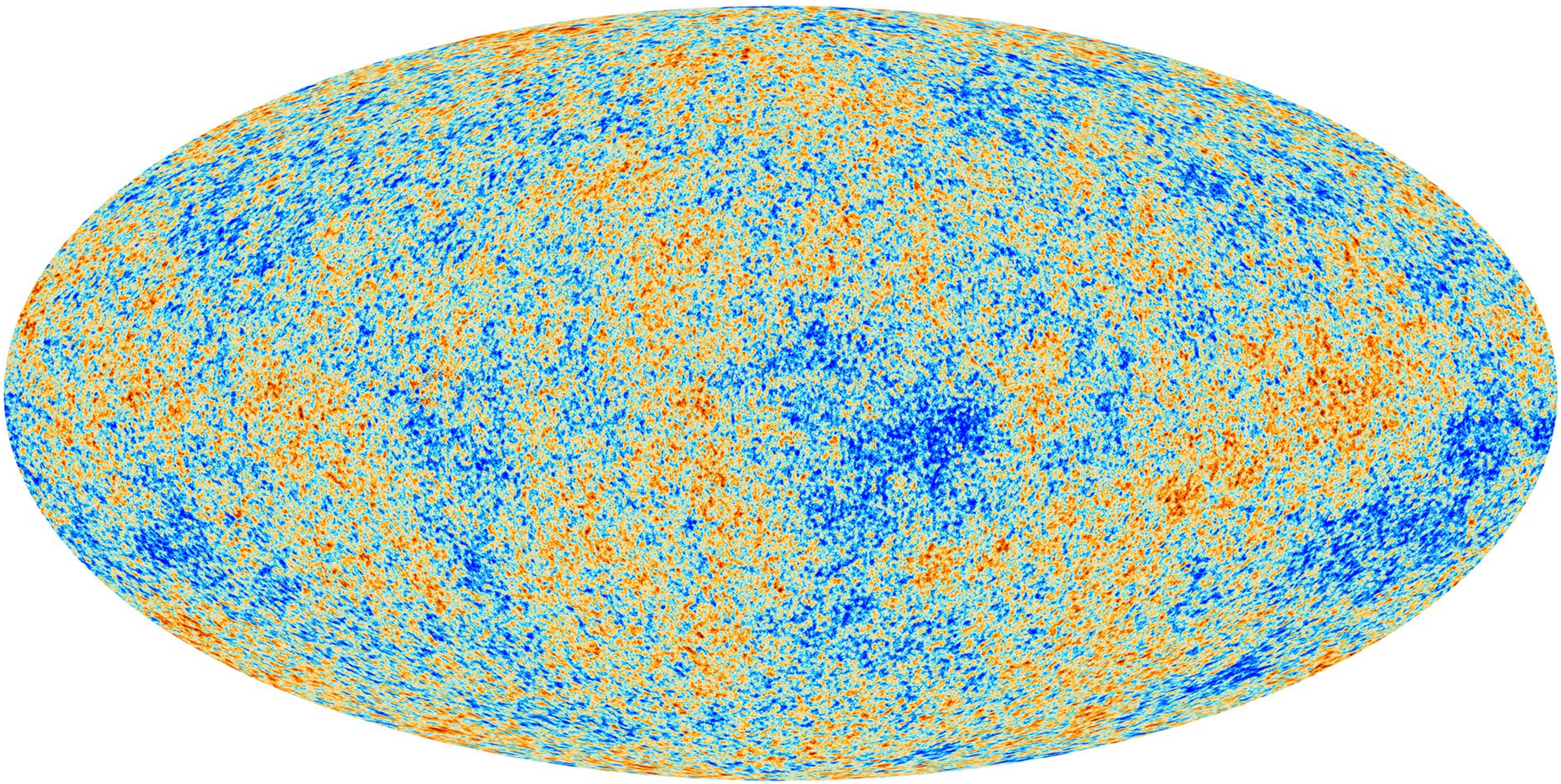
Introduction: Inflation and moduli stabilization in supergravity

Results: Backreaction of heavy moduli and stabilizer fields

Conclusion and outlook

1. High-scale inflation and extra dimensions

Hints in the universe



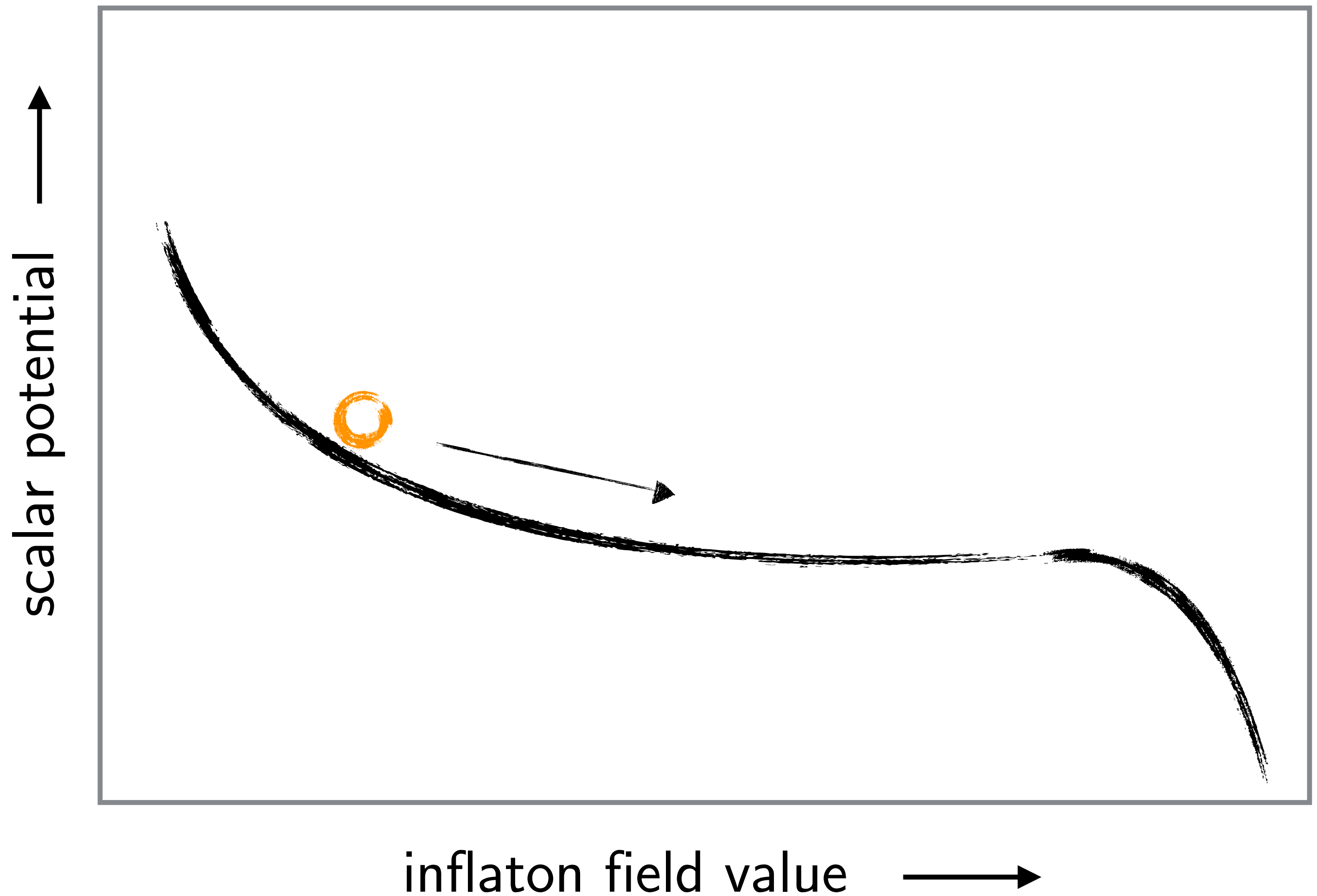
Cosmic inflation

- How can the CMB radiation be so isotropic?
- What is the origin of the primordial perturbations in the CMB?
- Why is the universe as flat as it is?
- And where are all those magnetic monopoles?

$\longrightarrow$ Cosmic inflation, quasi-exponential expansion of space

[Guth '81, Linde '82]

Cosmic inflation



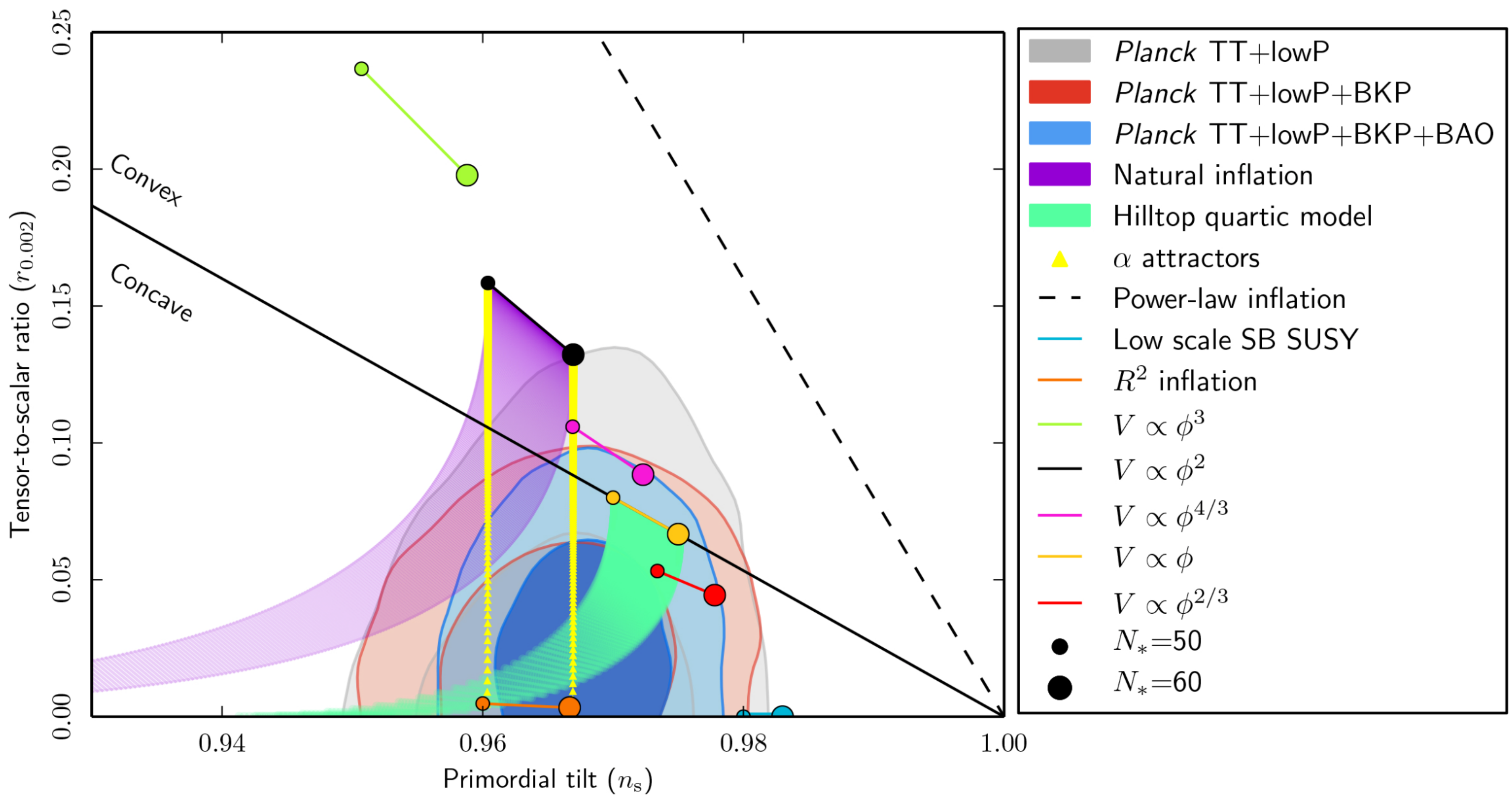
- Expansion driven by vacuum energy of slowly rolling spin-0 field

- Quantum fluctuations source CMB inhomogeneities

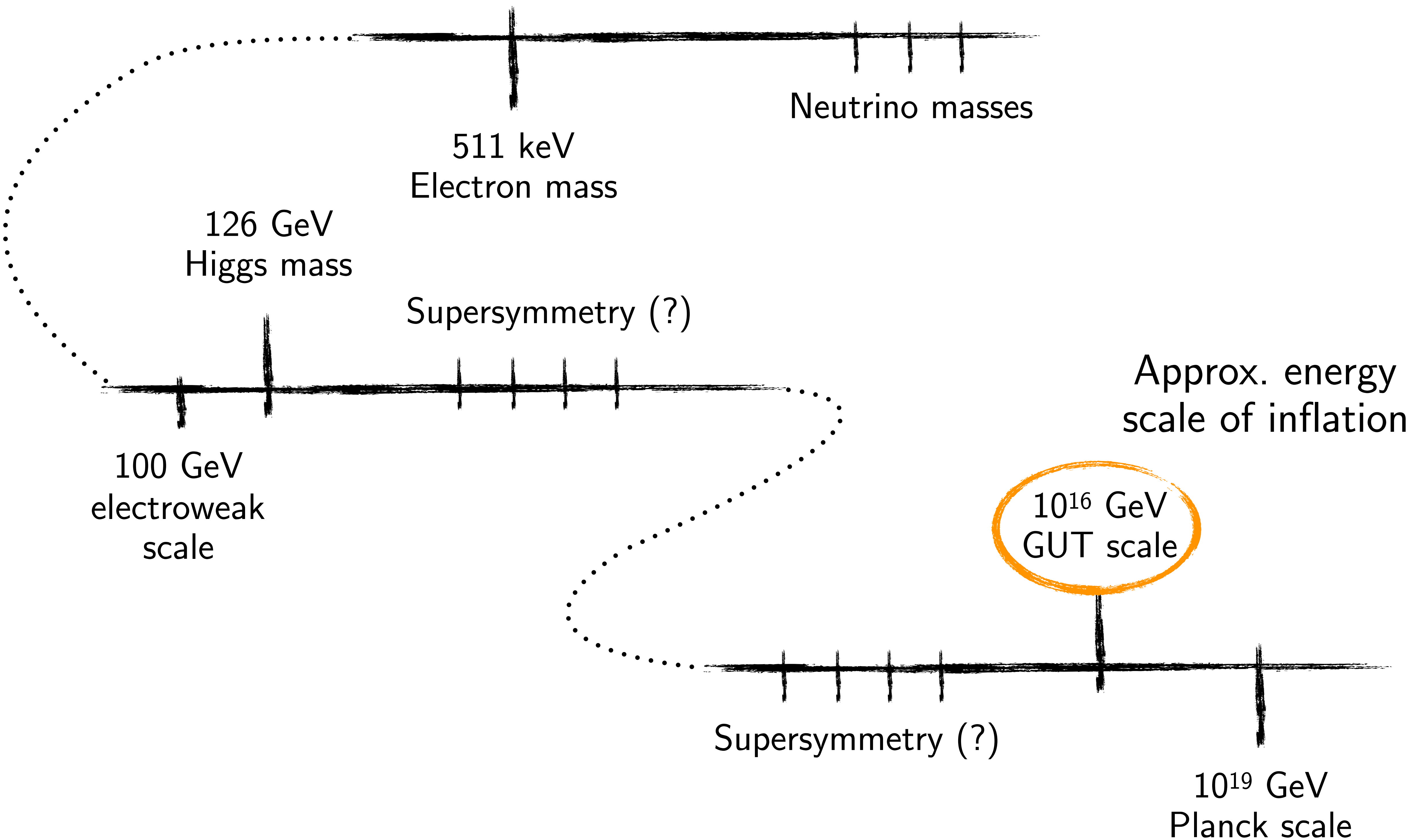
- Observations constrain possible potential shapes, still no clear favorite has emerged

Constraints from observations

Observations constrain scalar spectral tilt n_s and tensor-to-scalar ratio r, among others...



Energy scales



Ultraviolet sensitivity

Slow-roll conditions

$$\epsilon = \frac{V'(\varphi)^2}{2V(\varphi)^2} \ll 1\,, \quad \eta = \left|\frac{V''(\varphi)}{V(\varphi)}\right| \ll 1$$

Scalar potential very flat, susceptible to Planck-scale suppressed operators

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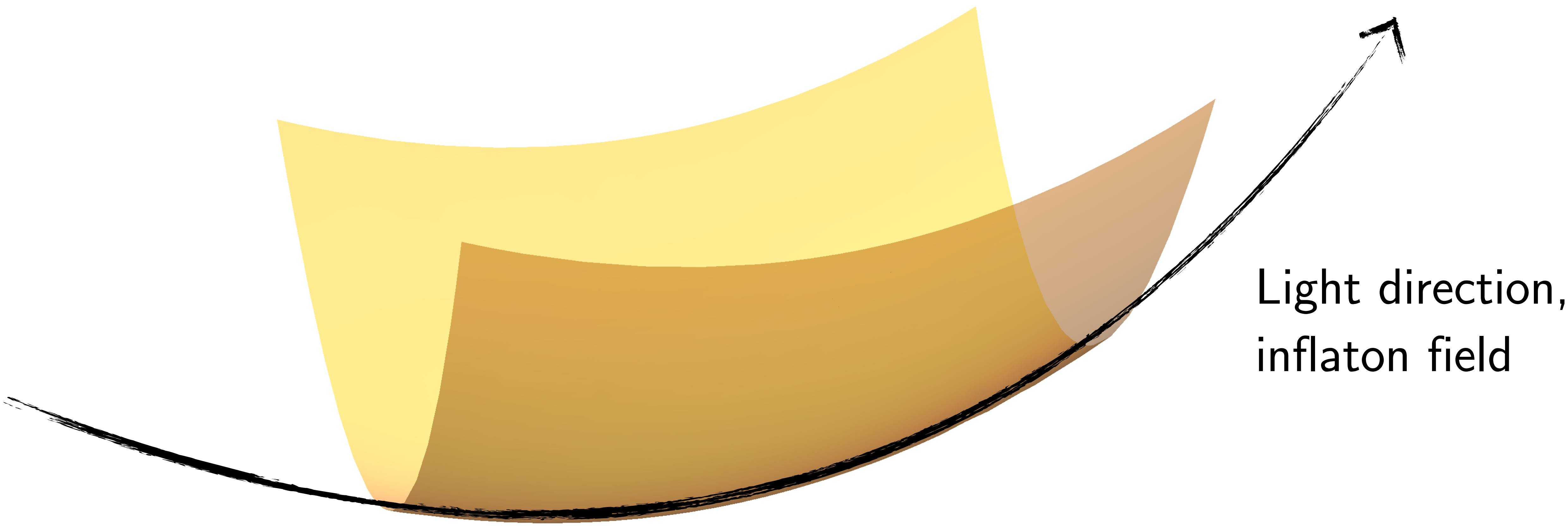
$$\mathcal{L} = -\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{1}{2}m^2\varphi^2 - \frac{1}{4}\lambda\varphi^4 - \underbrace{\sum_k \mathcal{O}_k \frac{\varphi^{2k}}{M_{\mathsf{P}}^{2k}}}_{\text{dangerous operators}}\,.$$

$\longrightarrow$ specify UV complete theory, e.g. string theory, to compute the $\mathcal{O}_k$

Additional scalar fields



Vacuum expectation values of heavy fields can be inflaton-dependent

$\longrightarrow$ backreaction on inflaton potential

[cf. also Davis et al. '07-'08, Dong et al. '10, Achucarro et al. '10-'15, ...]

2. Inflation and moduli stabilization in supergravity

Inflation in supergravity

Single-field inflation described by the action

$$S = \int \mathrm{d}^4x\sqrt{-g}\left(\frac{1}{2}R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi)\right)$$

Scalar potential in supergravity

$$V = e^K\left(K^{I\bar{J}}D_IW\overline{D_JW} - 3|W|^2\right) + V_D$$

$\longrightarrow$ Generically too steep to accommodate inflation, "eta-problem"

Inflation in supergravity

$$V_F = e^K \left(K^{I\bar{J}} D_I W \overline{D_J W} - 3|W|^2 \right)$$

Possible solutions to the eta-problem include

1. Shift symmetry

   $\longrightarrow$ e.g. axions in string theory

2. No-scale symmetry

   $\longrightarrow$ generic in string compactifications

3. Stabilizer fields

   $\longrightarrow$ stringy origin less obvious

A simple example

Consider chaotic inflation with a quadratic potential

$$V = \frac{1}{2}m^2\varphi^2$$

[Linde '83]

Naive approach in supergravity via shift symmetry,

$$W = \frac{1}{2}m\Phi^2\,, \qquad K = \frac{1}{2}(\Phi + \overline{\Phi})^2$$

Inflaton $\varphi \propto \mathrm{Im}\,\Phi$ does not appear in Kahler potential

However,

$$V = \frac{1}{2}m^2\varphi^2 - \frac{3}{16}m^2\varphi^4$$

A simple example

Possible solution: Involve a stabilizer field,

$$W = mSf(\Phi)\,, \qquad K = \frac{1}{2}(\Phi + \overline{\Phi})^2 + |S|^2$$

[Kawasaki et al. '00]
[Kallosh et al. '10]

Inflaton potential, with $\langle S \rangle = 0$ and $\langle \mathrm{Re}\,\Phi \rangle = 0$ stabilized,

$$V = |mf(\varphi)|^2$$

$\longrightarrow$ Well-suited for single-field slow-roll inflation

Geometric moduli

- In Calabi-Yau compactifications, deformations of metric appear as scalar fields in 4d effective theory, geometric moduli
- Number of complex structure moduli and Kahler moduli fixed by topological quantities
- In type IIB, fix complex structure moduli (and axio-dilaton) with fluxes in internal manifold

  [Giddings et al. '02]
- Kahler moduli appear with no-scale symmetry, massless at perturbative tree-level

  [Witten '85]

$\longrightarrow$ Moduli stabilization?

Moduli stabilization

Consider quantum corrections to Kahler and/or superpotential, e.g.

$$K = -3\log(T+\overline{T})\,, \qquad W = W_0 + Ae^{-aT}$$

[Kachru et al. '03]

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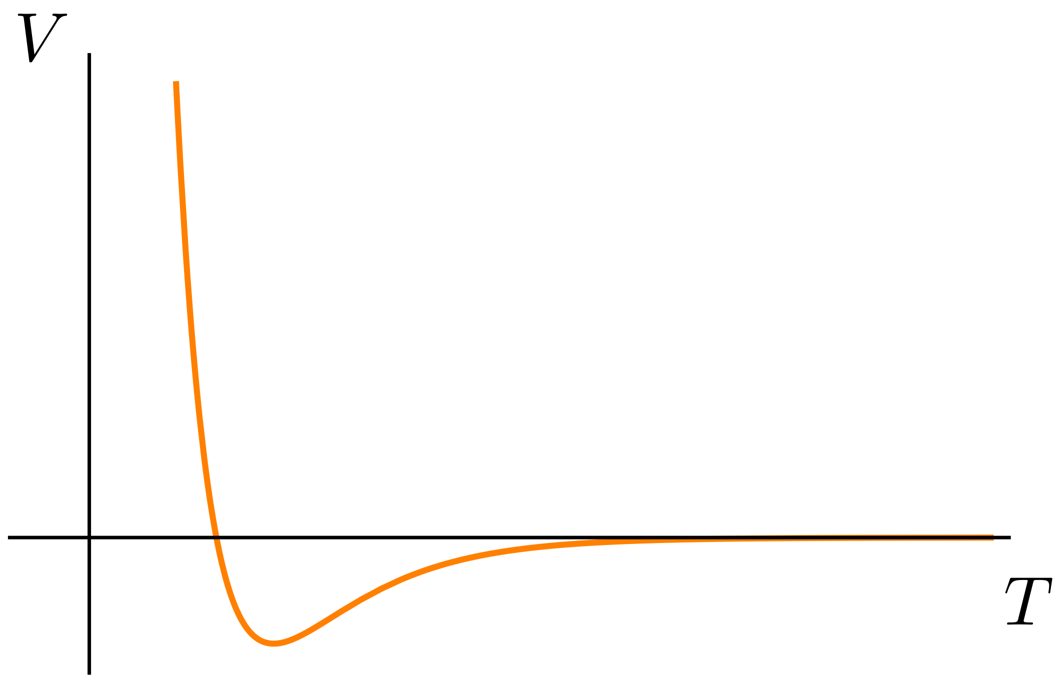
Solve $D_T W = 0$ to obtain supersymmetric AdS vacuum



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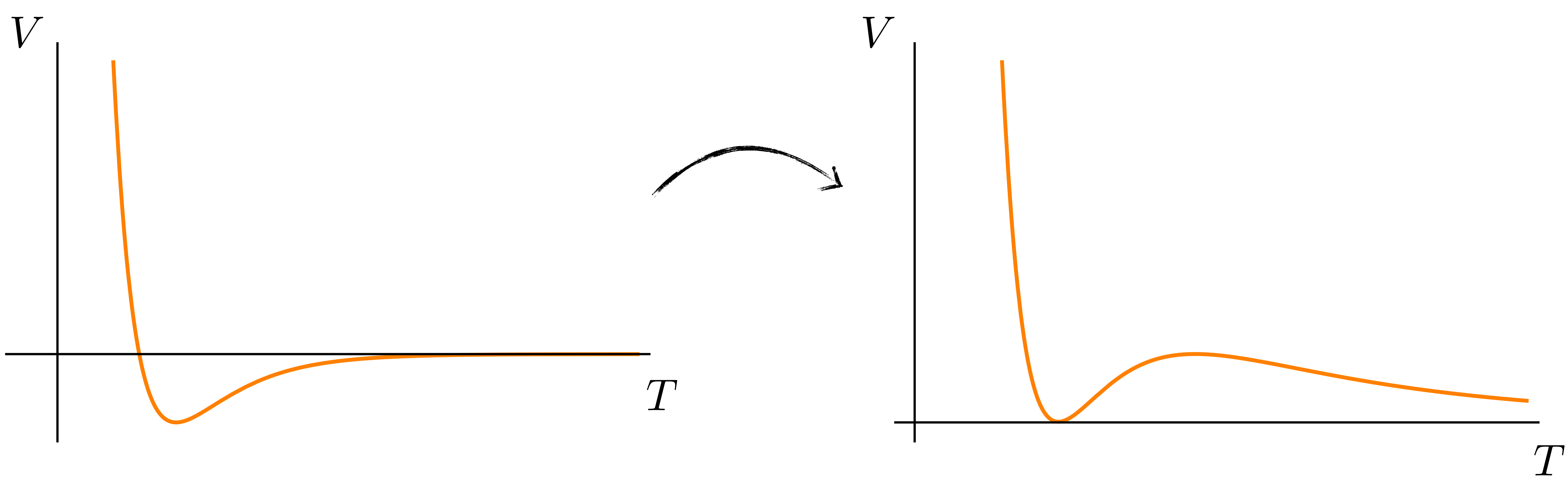
Uplift vacuum using D-terms of F-terms, e.g. Polonyi mechanism



Moduli stabilization

Caveat: Modulus mass and potential barrier scale with gravitino mass

$\longrightarrow$ Require $m_{3/2} > H_{\text{inf}} \sim 10^{14}$ GeV to guarantee moduli stability during inflation

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Caveat: Modulus mass and potential barrier scale with gravitino mass

→ Require $m_{3/2} > H_{\text{inf}} \sim 10^{14}\,\text{GeV}$ to guarantee moduli stability during inflation

Alternative: "Supersymmetric moduli stabilization", use

$$W = W_0 + Ae^{-aT} + Be^{-bT} \qquad \text{or} \qquad W = S(e^{-aT} - m)$$

[Kallosh, Linde '04] [CW, Winkler '14]

→ Stabilize T in supersymmetric Minkowski vacuum

3. Backreaction of heavy moduli and stabilizer fields

a) Heavy Kahler moduli

Backreaction of Kahler moduli

Ansatz: Supergravity Lagrangian with two gravitationally coupled sectors,

$$K = K_0(T, \overline{T}) + \frac{1}{2}(\Phi + \overline{\Phi})^2 K_1(T, \overline{T})$$
$$W = W_{\text{mod}}(T) + W_{\text{inf}}(\Phi_\alpha)$$

Captures many string inflation models, but not Kahler moduli inflation

During inflation modulus minimum depends on inflaton, heavy field traces light field adiabatically and instantaneously

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Captures many string inflation models, but not Kahler moduli inflation

Special case: Impose $\boxed{W_{\mathsf{mod}}(T_0) = 0\,, \qquad D_T W_{\mathsf{mod}}(T_0) = 0}$

During inflation modulus minimum depends on inflaton, heavy field traces light field adiabatically and instantaneously

Backreaction of supersymmetric moduli

Expand supergravity Lagrangian around $T(\Phi_\alpha) = T_0 + \delta T(\Phi_\alpha)$

$\longrightarrow$ Insert back into Lagrangian and obtain effective inflaton potential

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For special case of supersymmetric stabilization, all effects decouple for very large mass hierarchies

$$V(\Phi_\alpha) = V_{\mathsf{inf}}(\Phi_\alpha)\left[1 + \frac{H}{m_T} f_1(\Phi_\alpha) + \frac{H^2}{m_T^2} f_2(\Phi_\alpha) + \dots\right]$$

[Buchmüller, CW, Winkler ’14]

Supersymmetry-breaking moduli

What happens if we allow for large F-terms of the modulus?

Generic situation in KKLT, Large Volume Scenario, Kahler uplifting, ...

[Kachru et al. '03, Balasubramanian et al. '05, Conlon et al. '05, Balasubramanian & Berglund '04, Westphal '07]

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Expectation: Supersymmetry breaking induces non-decoupling effects, like soft terms

Example I: Chaotic inflation

Ansatz similar as before:

$$K = -3\log(T+\overline{T}) + \frac{1}{2}(\Phi+\overline{\Phi})^2\,, \qquad W = W_{\mathsf{mod}}(T) + \frac{1}{2}m\Phi^2$$

$+$ uplift

Integrate out T at high scale to obtain effective inflaton potential

Choose: $\quad W_{\mathsf{mod}}(T) = W_0 + Ae^{-aT}$

Example I: Chaotic inflation and KKLT

Gravitino mass $m_{3/2} = W_0/(2T_0)^{3/2}$

$$V(\varphi) = \frac{1}{2}\tilde{m}^2\varphi^2 + \frac{3}{2}\tilde{m}m_{3/2}\varphi^2 - \frac{3}{16}\tilde{m}^2\varphi^4 - \frac{3}{4aT_0}\left(3\tilde{m}m_{3/2}\varphi^2 + \frac{3}{4}\tilde{m}^2\varphi^4\right) + \ldots$$

[Buchmüller, Dudas, Heurtier, Westphal, CW, Winkler '15]

Example: KKLT and chaotic inflation

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supersymmetric mass term

dangerous term still there, oh no...

Example: KKLT and chaotic inflation

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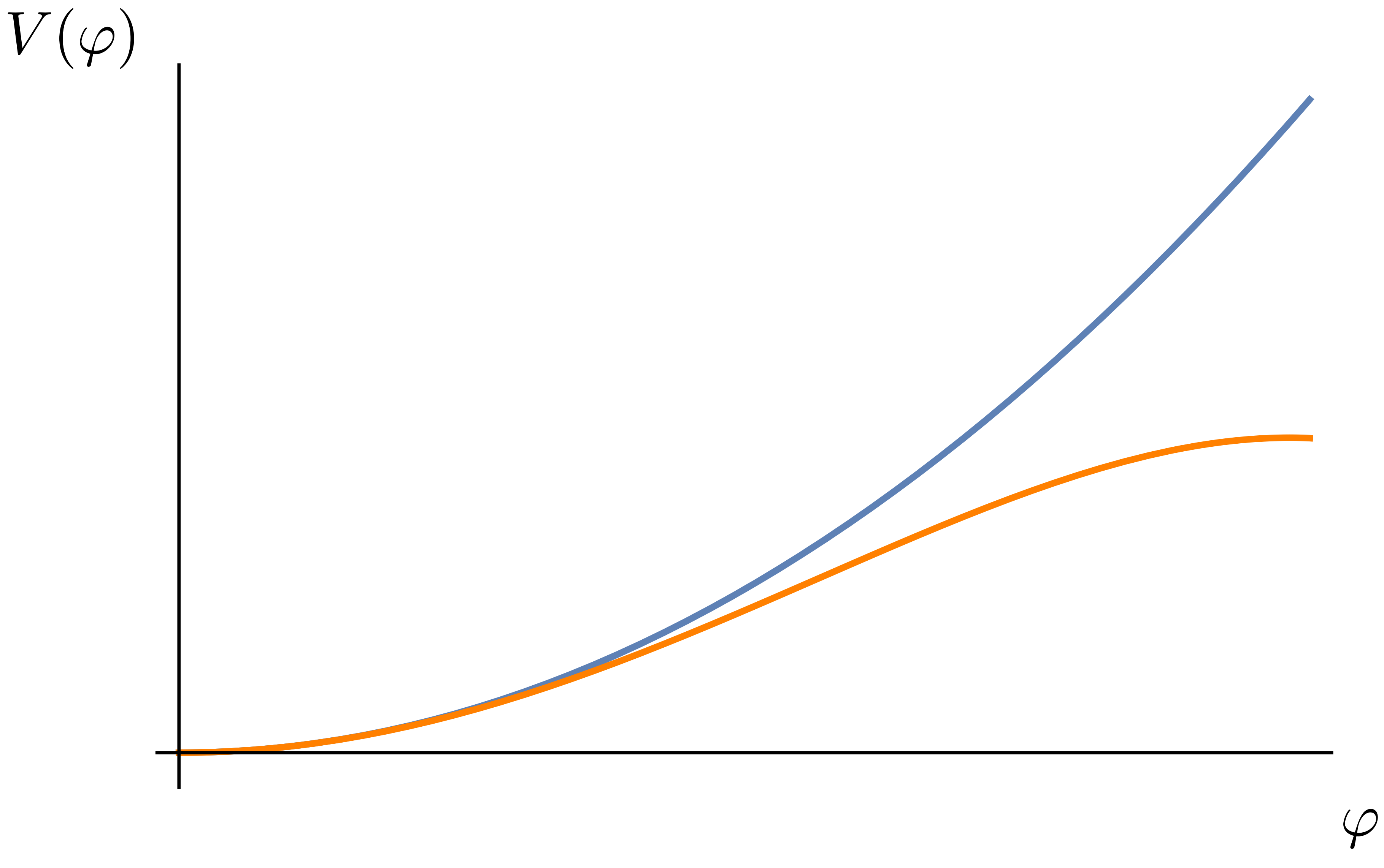
soft mass term,
drives inflation if $m_{3/2}$ large enough

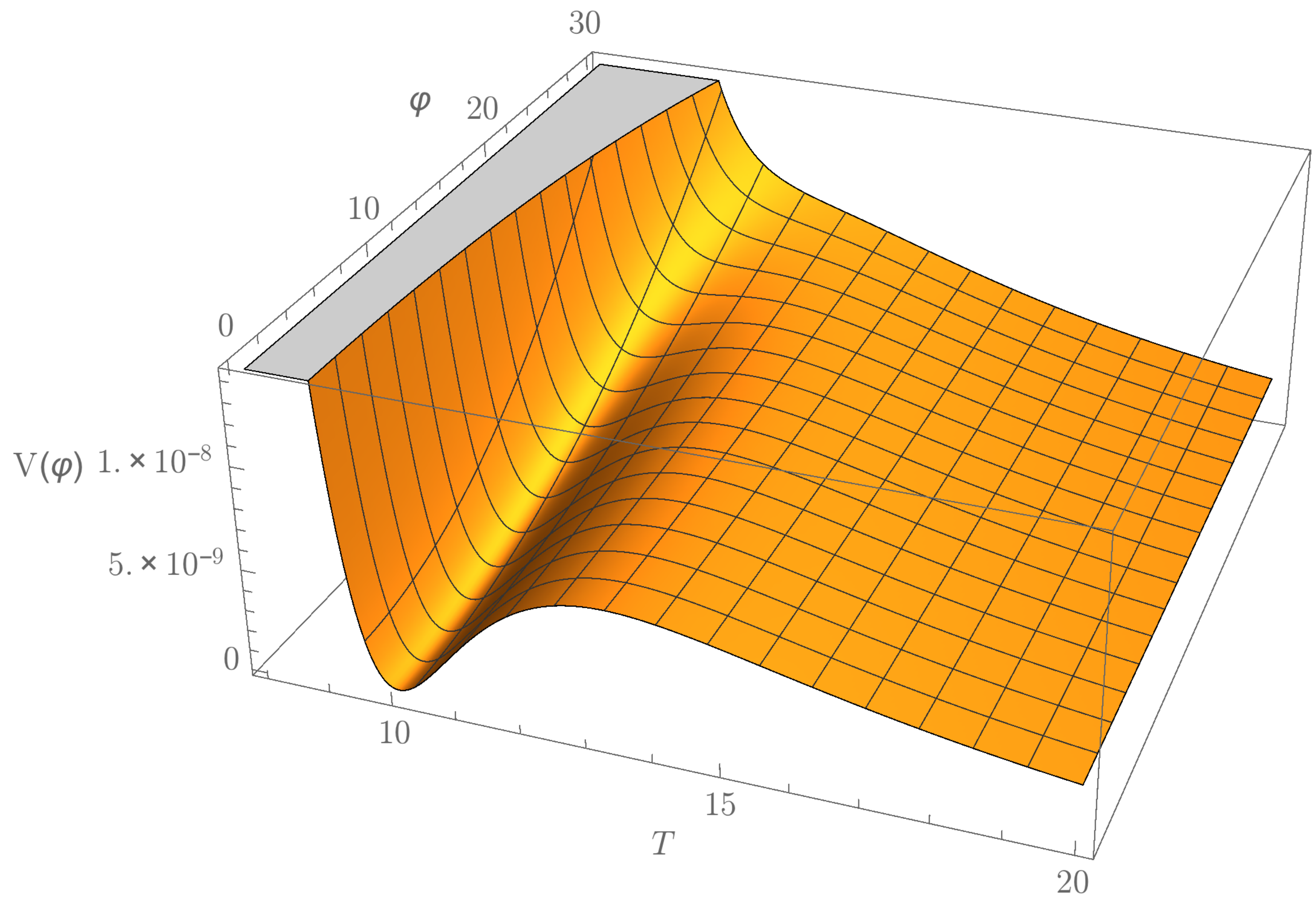
Example: KKLT and chaotic inflation

Result: Flattened chaotic inflation



Example: KKLT and chaotic inflation

Careful: Modulus is destabilized if φ too large or $m_{3/2}$ too small



Initial conditions and allowed parameter range tightly constrained. Typically require

$$\boxed{m_{3/2} \gtrsim 10^{15}\ \text{GeV}}$$

Alternatives to KKLT

Large Volume Scenario: Compactification on "swiss-cheese" manifold with exponentially large volume

Flattened chaotic inflation, driven by soft term, parameter space even more constrained

Kahler Uplifting: Stabilize and uplift single volume modulus using perturbative correction in Kahler potential

Flattened chaotic inflation, driven by soft term or supersymmetric term, similar constraints

Example II: Starobinsky inflation

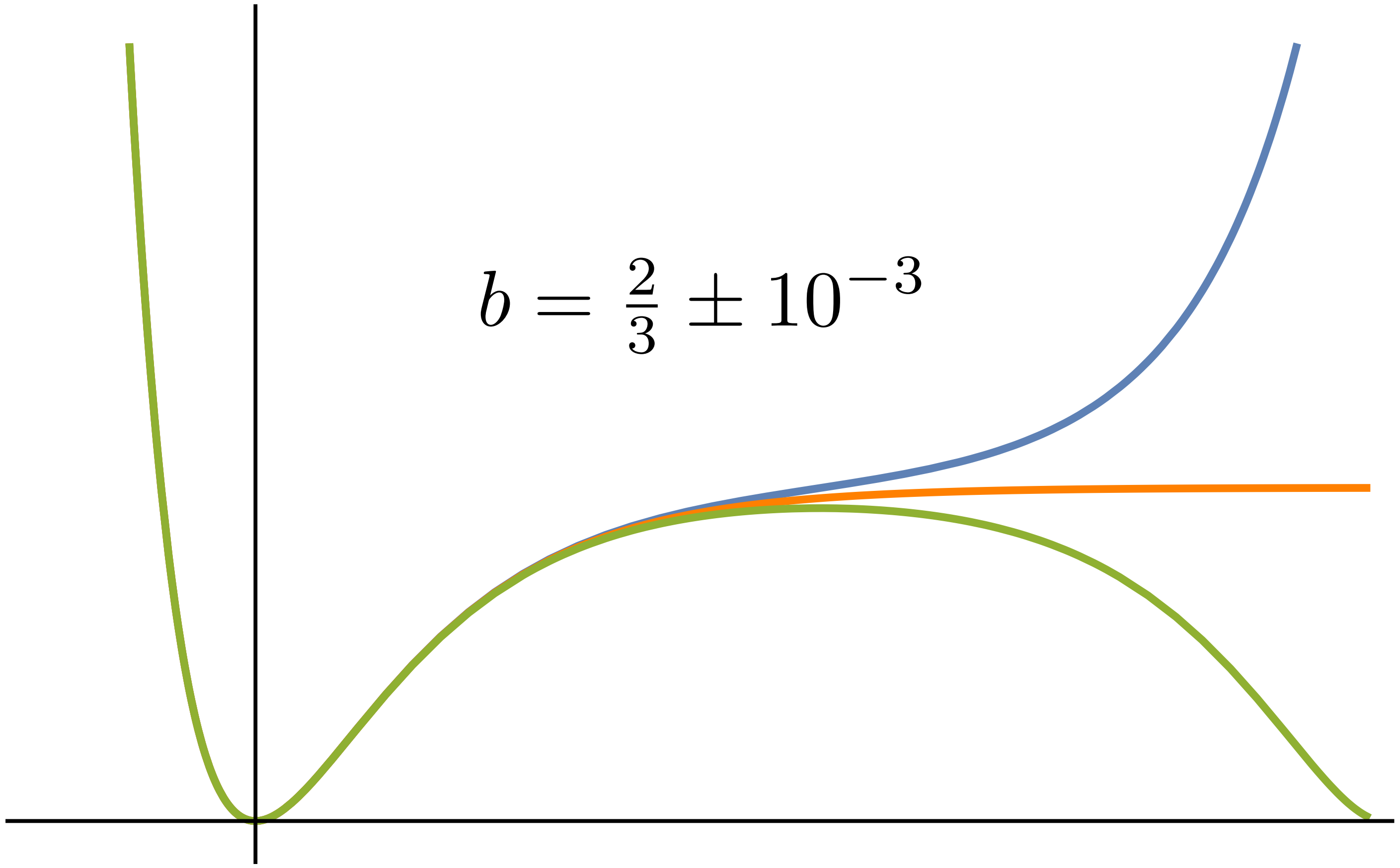
$$K = -3\log\left(T + \overline{T} - \tfrac{1}{3}|\Phi^2|\right),$$

$$W = M(\Phi^2 + b\Phi^3)$$

Fine-tune b, assume T stabilized at some $T_0 \gg 1$:

$$V_{\mathsf{inf}}(\varphi) \sim M^2(1 - e^{-\varphi})^2$$

[Ellis et al. '13, '14, '15]



Example II: Starobinsky inflation

How can T be stabilized consistently?

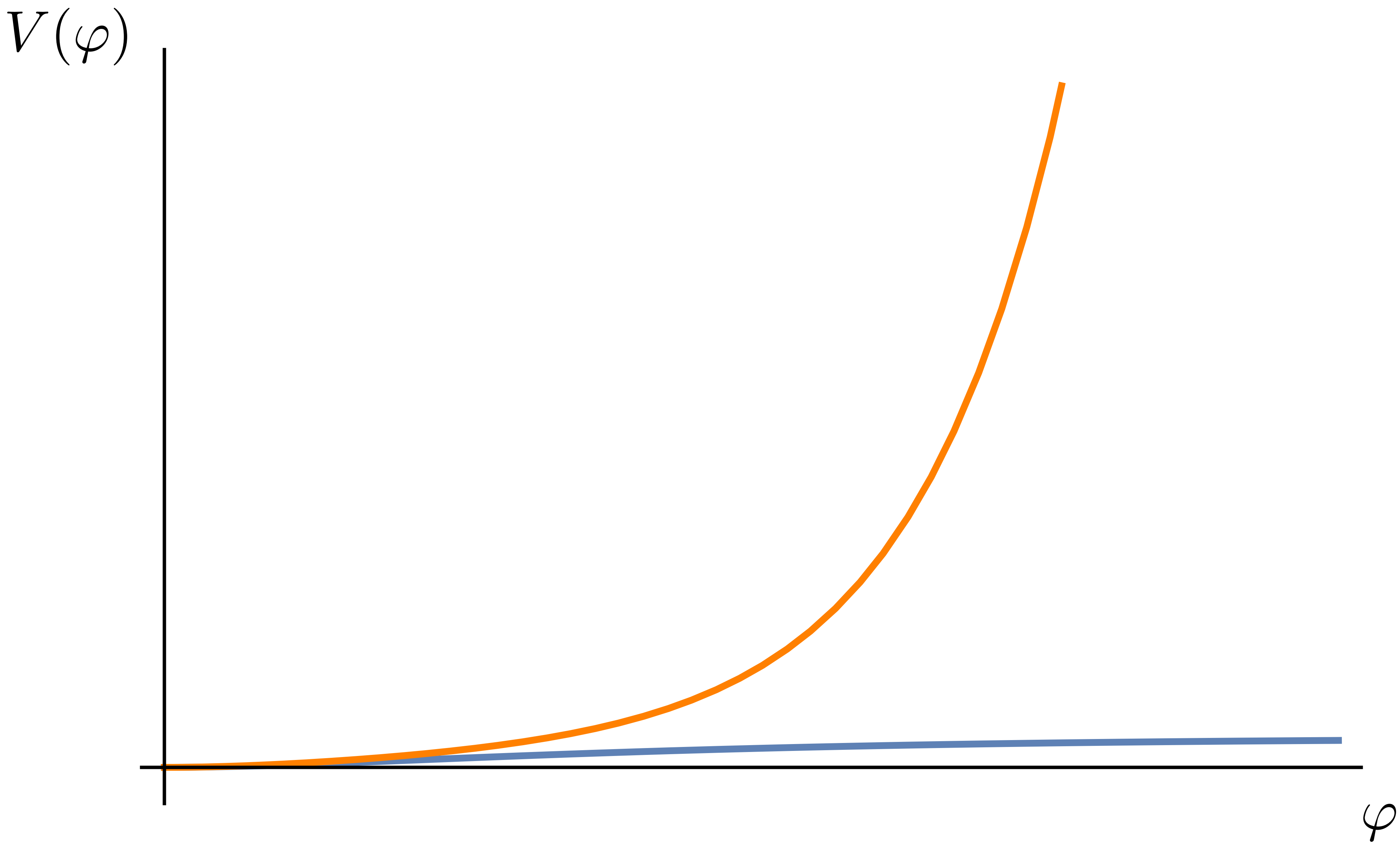
$$K = -3\log\left(T + \overline{T} - \tfrac{1}{3}|\Phi^2|\right),$$

$$W = M(\Phi^2 + b\Phi^3) + W_{\mathsf{mod}}(T)$$

$\longrightarrow$ Backreaction of T sources steep terms which make inflation impossible:

$$\ldots \quad V(\varphi) \sim V_{\mathsf{inf}}(\varphi) + \underbrace{M m_{3/2}\sinh^2\varphi}_{\text{soft term, if } T \text{ breaks supersymmetry}} - \underbrace{M^2 \sinh^4\frac{\varphi}{2}}_{\text{from } -3|W|^2\text{, generic}} + \ldots$$

Example II: Starobinsky inflation



3. Backreaction of heavy moduli and stabilizer fields

b) Is the stabilizer field stable?

Backreaction of stabilizer fields

Can the stabilizer field tolerate high-scale supersymmetry breaking?

Backreaction of stabilizer fields

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$\boxed{\text{No.}}$

[Buchmuller et al. ’14, Dudas, CW ‘15]

Backreaction of stabilizer fields

Remember generic setups with a stabilizer field,

$$W = mSf(\Phi) + W_{\mathsf{mod}}(T) + \ldots$$

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Supersymmetry breaking induces coupling between inflaton and stabilizer, sourcing a backreaction

$$V_{\mathsf{soft}} \sim m_{3/2} S g(\varphi)$$

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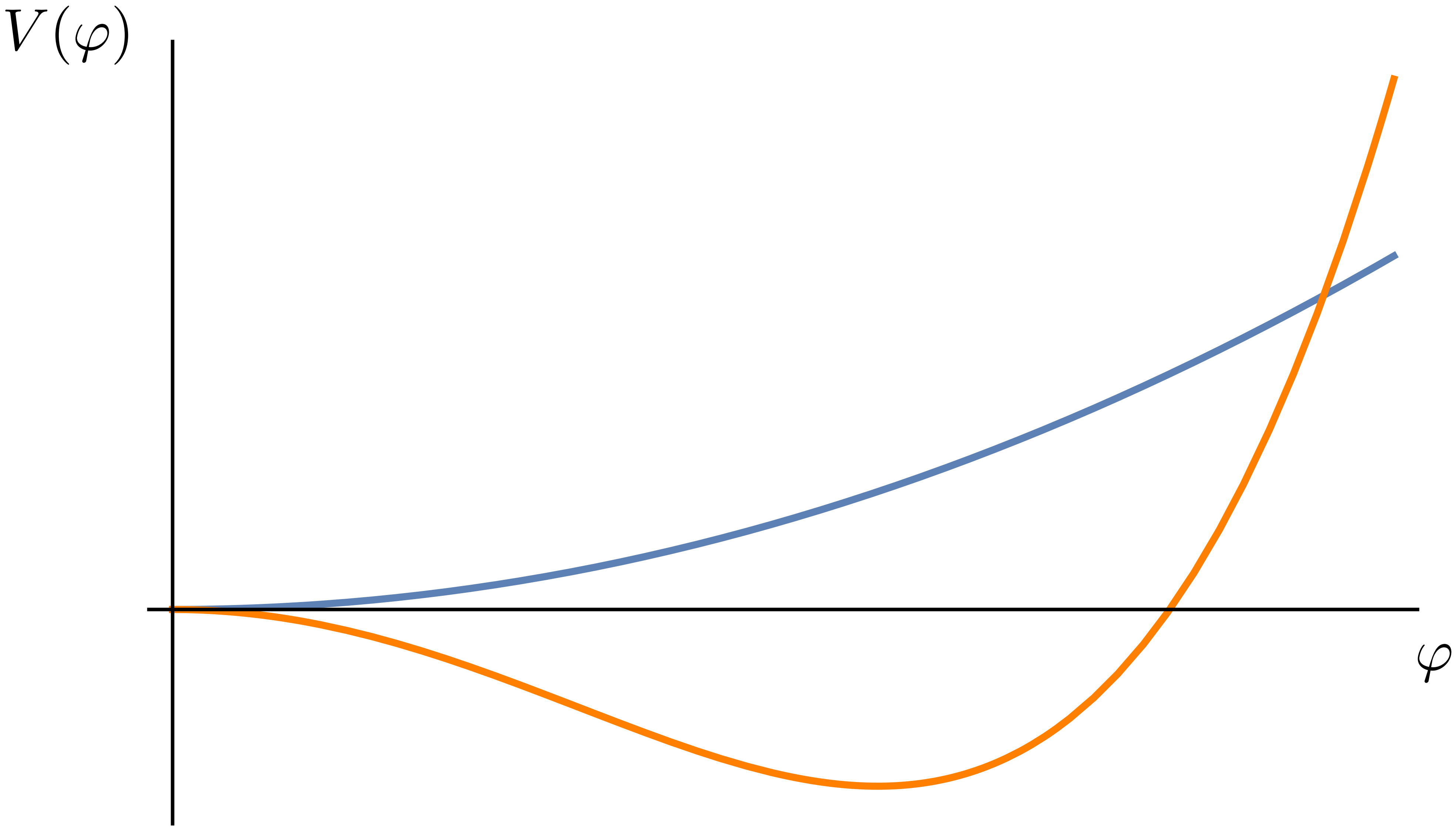
$$V_{\text{soft}} \sim m_{3/2} S g(\varphi)$$

$$V(\varphi) = |mf(\varphi)|^2 - m_{3/2}^2 \frac{g(\varphi)^2}{M_S^2} + \ldots$$

In most models inflation impossible if $m_{3/2} \gtrsim 10^{13}$ GeV

KKLT,
LVS, ...

Example: Chaotic inflation



4. Conclusion and outlook

Conclusions and outlook

- Stability of heavy scalars during inflation is non-trivial
- Backreaction of heavy moduli are generically important, can be studied in 4d effective supergravity

  Helpful in some models, destructive in others

- If moduli break supersymmetry, some effects grow stronger with increasing modulus mass
- Stabilizer fields do not fare well with high-scale supersymmetry
- Results apply to many - but not all - string inflation models in recent literature

[e.g. Marchesano et al., Hebecker et al., Grimm et al., Blumenhagen et al., Ibañez et al., Ellis et al., Nilles et al., Westphal et al.]