Bridging the gap between particle physics and inflation

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Hot topics in Modern Cosmology

Spontaneous Workshop X

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Inflation and particle physics

- Inflation requires physics beyond the SM:

1.At least a new degree of freedom (the inflaton)

2. Couplings: reheating and DM production

Difficulty to connect known particle physics and inflation:
large separation of energy scales

Couplings of the inflaton

First part of the talk:

- Can they affect how inflation takes place?

Example: monomial chaotic inflation
(arXiv:1510.05669)

Second part of the talk (if time permits):

- What is the interplay between inflation and the SM?

Example: stability of the SM effective potential
(arXiv:1505.07476)

G. Ballesteros & C. Tamarit

First part of the talk:

- Can they affect how inflation takes place?

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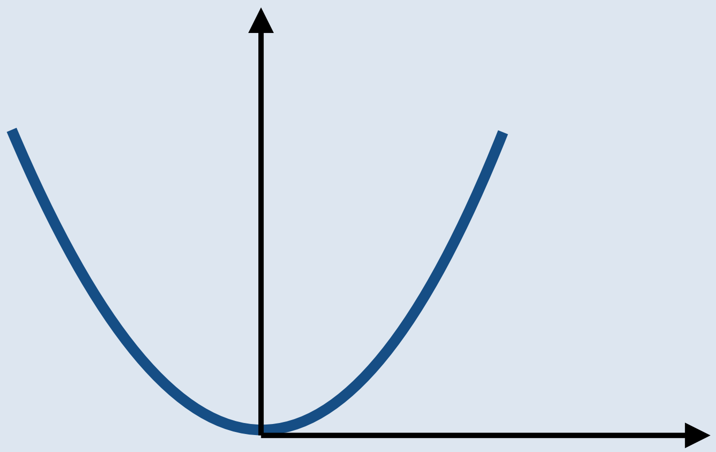
Summary of part one

$V \propto \Phi^N$



Tensor-to-scalar ratio: $r \propto M_P^2 (V'/V)^2$

$r \simeq 4N/N_e$ N_e = number of e-folds

$N = 4 \longrightarrow r \sim 0.26$

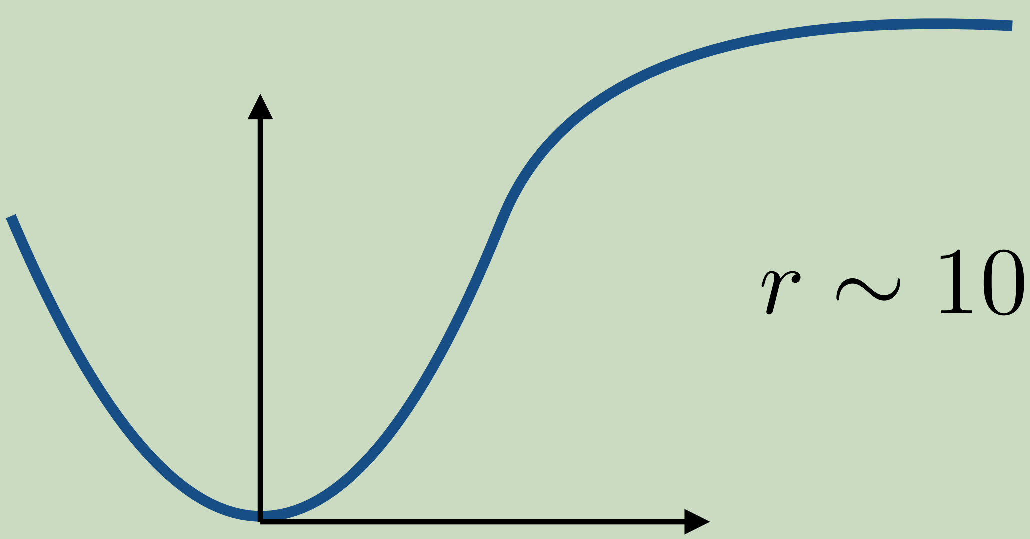
$N = 2 \longrightarrow r \sim 0.13$

CMB: $r \lesssim 0.07$

Future sensitivity: $\Delta r \sim 10^{-3}$

Solution: radiative corrections can flatten the potential

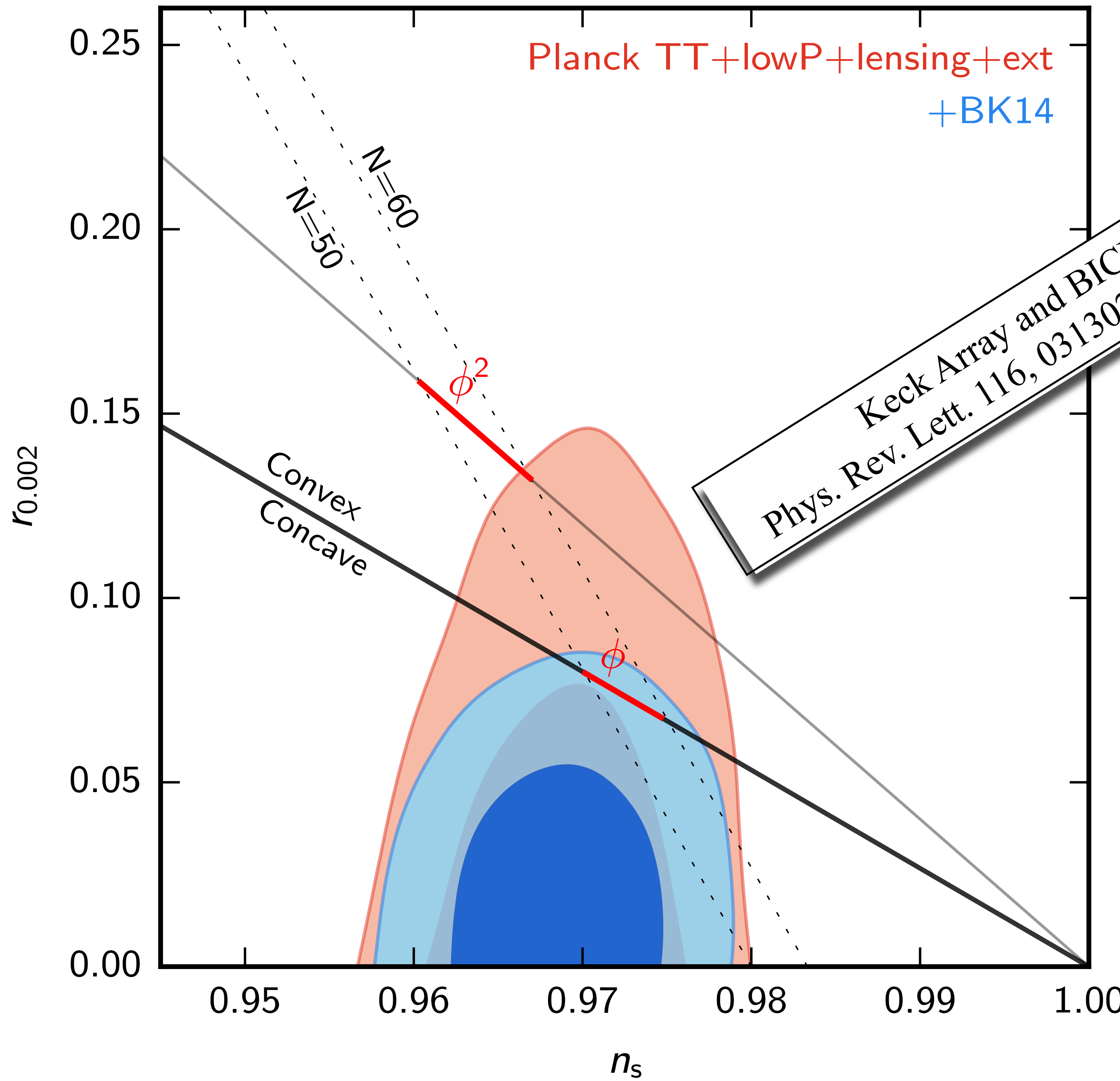
Require couplings to: fermions and scalar or gauge bosons



$r \sim 10^{-3}$

Last constraints on chaotic inflation

$$r_{0.05} < 0.07 \text{ at } 95\% \text{ confidence}$$



Keck Array and BICEP2 Collaborations
Phys. Rev. Lett. 116, 031302 – Published 20 January 2016

Future sensitivity

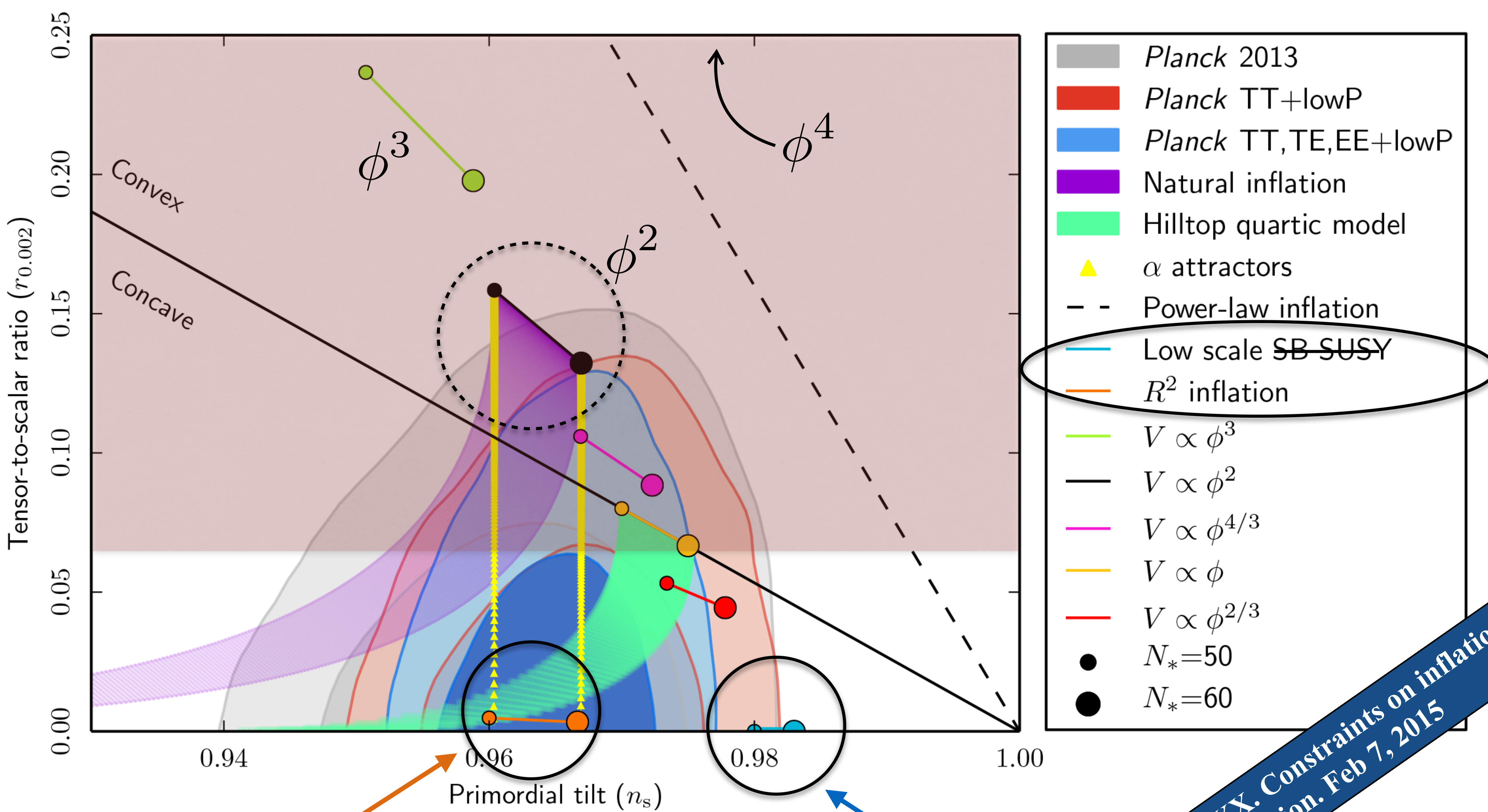
$$\Delta r \sim 10^{-3}$$

LiteBird

Core+

...

Constraints on inflation from Planck



$$V(\phi) = \Lambda^4 \left(1 - e^{-\sqrt{2/3}\phi/M_{\rm pl}}\right)^2$$

$$V(\phi) = \Lambda^4 \left[1 + \alpha_h \log(\phi/M_{\rm pl})\right]$$

Planck 2015 results. XX. Constraints on inflation
Planck Collaboration. Feb 7, 2015

The CMB data selects mainly very flat (**plateau**) potentials
(and rules out shapes like ϕ^N)

Inflationary observables ~ Shape of the potential

Scalar amplitude

$$A_s \simeq \frac{V}{24\pi^2 \, M_P^4 \, \epsilon} \simeq 2.5 \times 10^{-9}$$

Scalar spectral index

$$n_s \simeq 1 + 2\eta - 6\epsilon \simeq 0.967$$

$$\log P_s(k) = \log A_s + \left(n_s - 1 + \frac{\alpha}{2} \log \frac{k}{k_*} + \cdots \right) \log \left(\frac{k}{k_*}\right) ,$$

$$\log P_t(k) = \log A_t + (n_t + \cdots) \log \left(\frac{k}{k_*}\right) ,$$

$$k_* = 0.05 \ \mathrm{Mpc}^{-1}$$

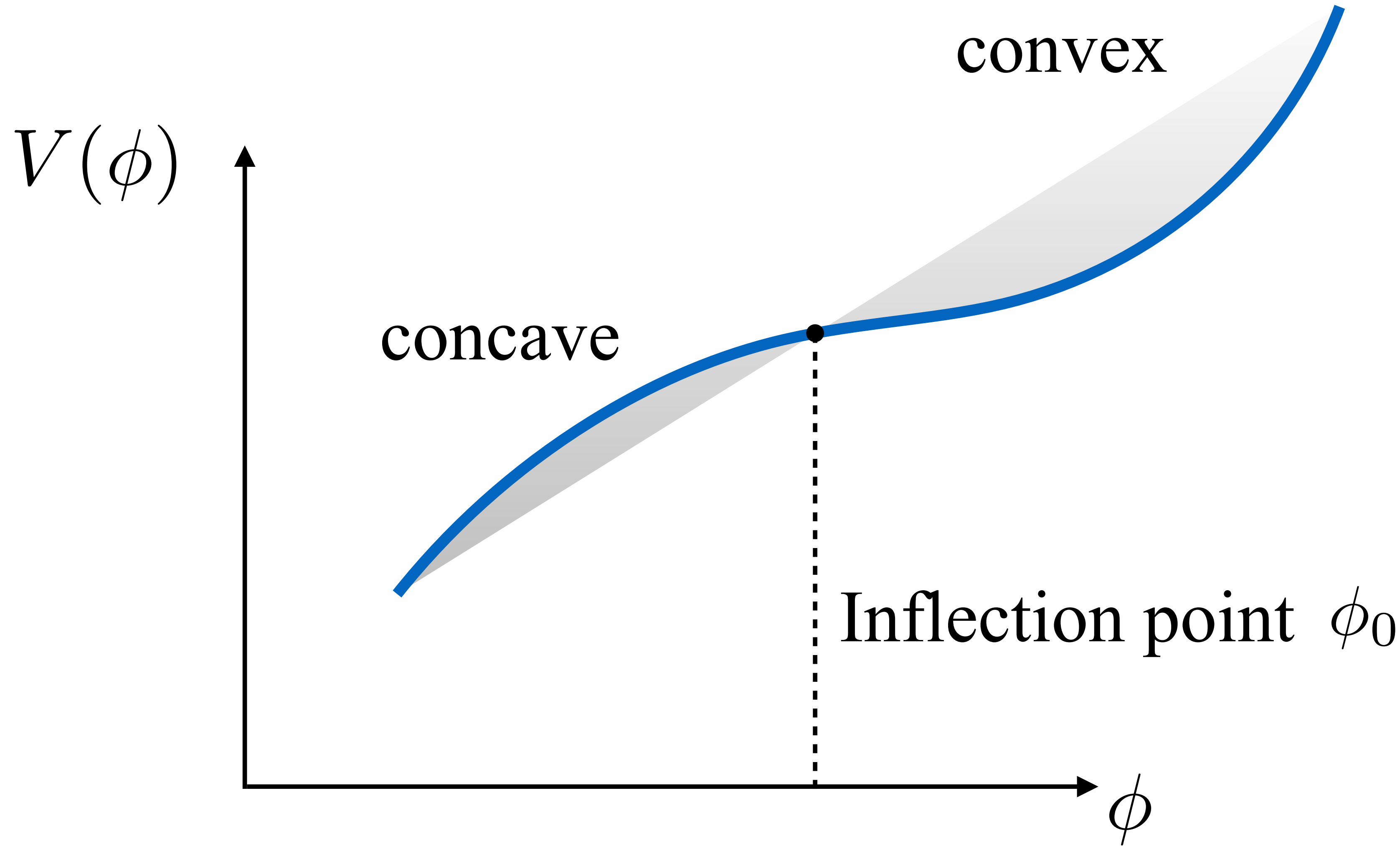
$$r = \frac{A_t}{A_s} \simeq 16\epsilon \lesssim 0.07$$

Tensor amplitude A_t (gravitational waves)

$$\epsilon = \frac{M_P^2}{2} \left(\frac{V'}{V}\right)^2 , \quad \eta = M_P^2 \frac{V''}{V}$$

Slow-roll parameters

Plateau potential



$$\frac{dV}{d\phi} = 0\,, \quad \frac{d^2V}{d\phi^2} = 0$$

A radiative plateau for chaotic inflation

Assume a renormalizable potential and zero non-minimal couplings to the curvature, for simplicity

$$V \propto \phi^2 \text{ or } \phi^4$$

Monomial chaotic inflation cannot be regarded a complete model

Coupling the inflaton to a fermion or another scalar (e.g. the Higgs) generates radiatively all possible renormalizable terms:

$$V = v_0 + m_1^3\phi + \frac{1}{2}m^2\phi^2 + m_3\phi^3 + \frac{c_4}{4!}\phi^4$$

Still, for sufficiently large field values:

$$V \simeq \frac{\lambda(\phi)}{4!}\phi^4$$

A radiative plateau for chaotic inflation

$$V \simeq \frac{\lambda(\phi)}{4!}\phi^4, \qquad \lambda(\phi) = \lambda(\phi_0) + \frac{1}{2}c_1(\phi_0)\log\frac{\phi^2}{\phi_0^2} + \frac{1}{8}c_2(\phi_0)\left(\log\frac{\phi^2}{\phi_0^2}\right)^2 + \cdots$$

ϕ_0 will be the location of the plateau

Coleman-Weinberg effective potential:

$$V(\phi) = \Omega(\mu) + V_0(\phi) + \frac{1}{64\pi^2}\sum_i M_i^4(\phi)\left(\log\frac{M_i^2(\phi)}{\mu^2} - C_i\right) + \cdots$$

$$\lim_{\phi\to\infty} M_i^2 \propto \phi^2 \longrightarrow \mu = \varepsilon\,\phi_0\,, \quad \varepsilon \ll 1$$

A radiative plateau for chaotic inflation

$$V \simeq \frac{\lambda(\phi)}{4!}\phi^4, \qquad \lambda(\phi) = \lambda(\phi_0) + \frac{1}{2}c_1(\phi_0)\log\frac{\phi^2}{\phi_0^2} + \frac{1}{8}c_2(\phi_0)\left(\log\frac{\phi^2}{\phi_0^2}\right)^2 + \cdots$$

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$$\lim_{\phi\to\infty} M_i^2 \propto \phi^2 \longrightarrow \mu = \varepsilon\,\phi_0\,, \quad \varepsilon \ll 1$$

Or, use $\mu = \varepsilon\,\phi\,,\ \varepsilon \ll 1$ and expand around ϕ_0

$$\lambda(\phi) = \lambda(\phi_0) + \frac{1}{2}\beta_\lambda(\phi_0)\log\frac{\phi^2}{\phi_0^2} + \frac{1}{8}\beta'_\lambda(\phi_0)\left(\log\frac{\phi^2}{\phi_0^2}\right)^2 + \cdots$$

$\beta_\lambda = \partial\lambda/\partial\log\mu$

A radiative plateau for chaotic inflation

$$\lambda(\phi) = \lambda(\phi_0) + \frac{1}{2} c_1(\phi_0) \log \frac{\phi^2}{\phi_0^2} + \frac{1}{8} c_2(\phi_0) \left(\log \frac{\phi^2}{\phi_0^2} \right)^2 + \cdots$$

$$\frac{dV}{d\phi} = 0\,, \quad \frac{d^2V}{d\phi^2} = 0 \quad \longrightarrow \quad c_2(\phi_0) = -4\, c_1(\phi_0) = 16\lambda(\phi_0)$$

$$\lambda(\mu_0) \sim |\beta_\lambda(\mu_0)| \sim \beta'_\lambda(\mu_0) \sim 10^{-13}$$

$\lambda \sim 10^{-13}$

like in standard ϕ^4

$$V(\phi) = \frac{\lambda}{4!} \left(1 - 2\big(1 - b_1\big) \log \frac{\phi^2}{\phi_0^2} + 2\big(1 + b_2\big) \left(\log \frac{\phi^2}{\phi_0^2} \right)^2 \right) \phi^4$$

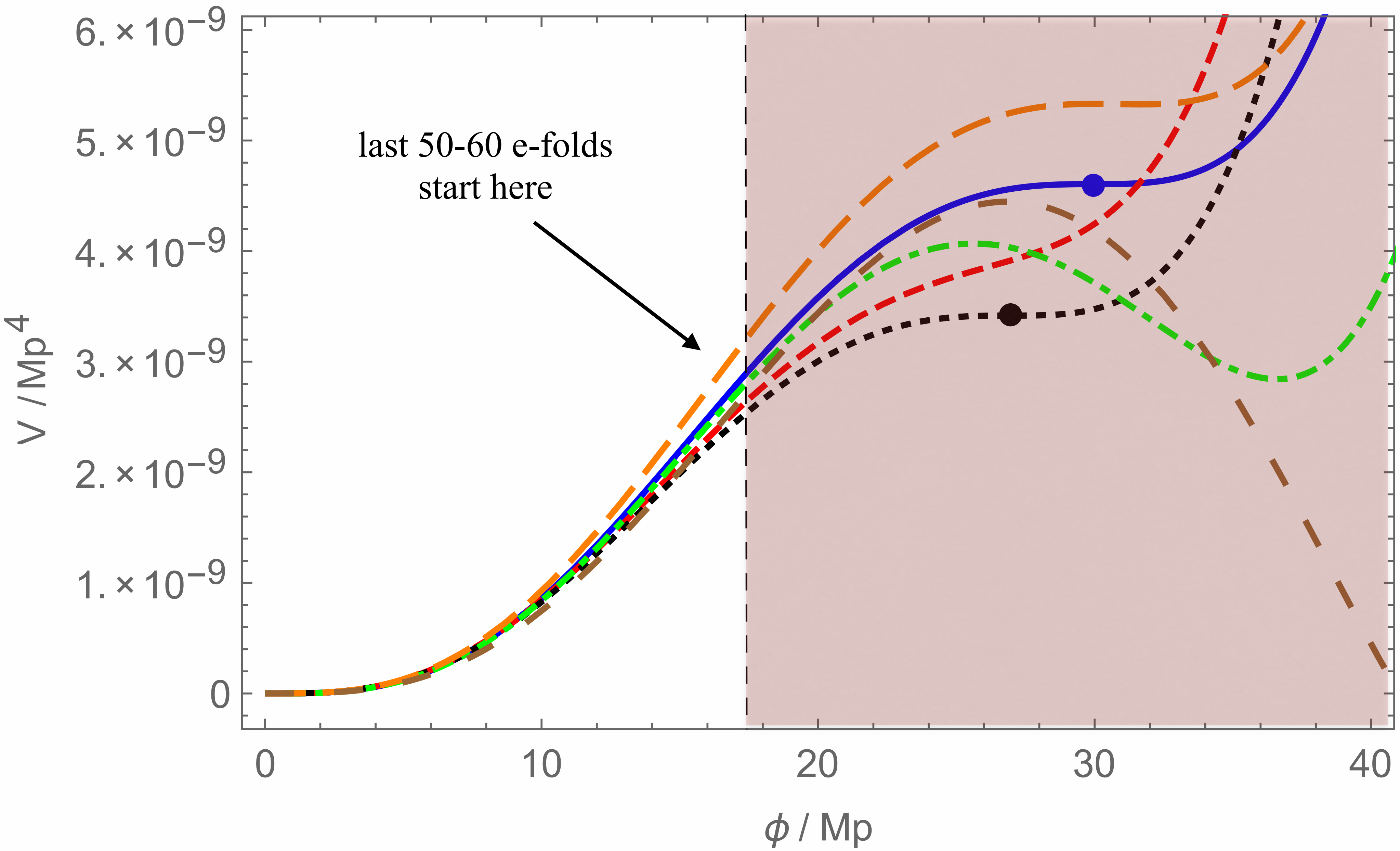
deformations of the plateau

$|b_1|\,, |b_2| < 1$

Similarly, for ϕ^2 : $\lambda(\phi) \to m^2(\phi) \sim 10^{-12} M_P^2$

High-r branch of quartic (deformed) plateaus

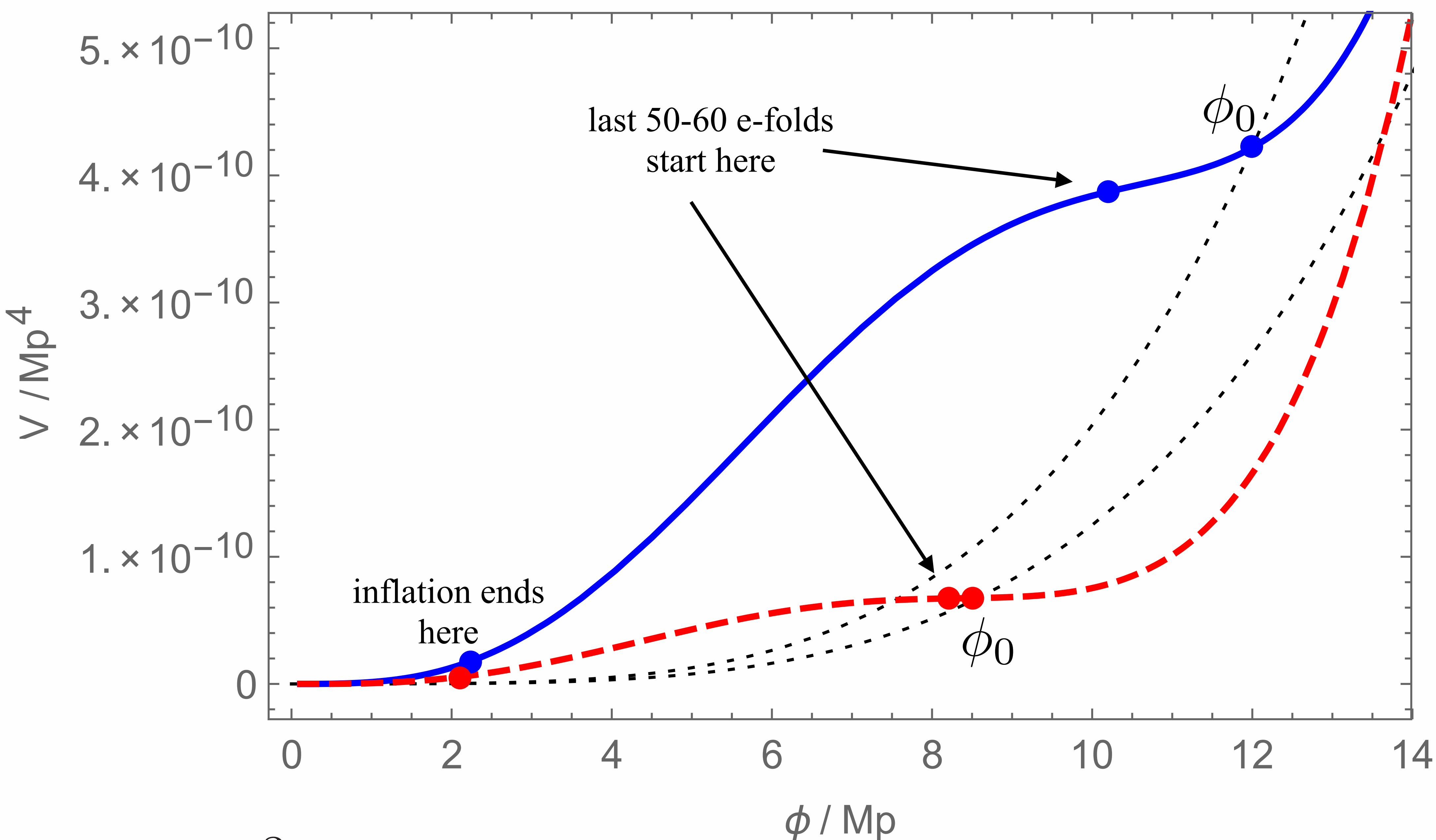
$$10^{-2} \lesssim r \lesssim 0.07 \qquad \text{(recall, CMB: } r \lesssim 0.07 \text{)}$$



$$-\alpha \sim 5 \times 10^{-4} \qquad\qquad M_P = m_P/\sqrt{8\pi}$$

Low-r branch quartic plateaus

$$10^{-3} \lesssim r \lesssim 10^{-2}$$ (recall, CMB: $r \lesssim 0.07$)



$-\alpha \sim 10^{-3}$

$M_P = m_P/\sqrt{8\pi}$

Particle physics realizations

Analytical solutions

$$\frac{dV}{d\phi} = 0\,, \quad \frac{d^2V}{d\phi^2} = 0 \quad \longrightarrow \quad c_2(\phi_0) = -4\,c_1(\phi_0) = 16\lambda(\phi_0)$$

two-loop one-loop tree-level

$$\beta_\lambda(\phi_0) = -4\lambda(\phi_0), \quad \beta'_\lambda(\phi_0) = -4\beta_\lambda(\phi_0)$$

Computing the two-loop effective potential can be involved

Shortcut: one-loop RG improvement of the tree-level potential
(Resummation of the potential at leading log order: the N-th log is given with N loops)

necessary conditions for the existence of a plateau

$$\beta_\lambda^{(1)}(\phi_0) \simeq 0 \quad \text{and} \quad \beta_\lambda'^{(2)}(\phi_0) > 0$$

$$\gamma_i = \gamma_i^{(0)} + \kappa\gamma_i^{(1)} + \kappa^2\gamma_i^{(2)} + \cdots \qquad \kappa = 1/(16\pi^2)$$

Particle physics realizations

Sufficient conditions for a plateau.

The inflaton must couple to fermions and to:
another scalar (with weak fermionic couplings) or a U(1) gauge field

Examples of quartic plateaus:

1. Singlet inflaton coupled to the Higgs and new fermions

2. As in 1. but also charging the fermions under a U(1) → hypercharge; another U(1) → *fermions could be WIMPS (TeV)*

3. Standard Model Higgs: $\lambda_H \gg 10^{-13}$

4. Inflaton and two pairs of (Weyl) fermions charged under a U(1)
(the role of the extra scalar is now played by a vector gauge boson)
(U(1) could be hypercharge if the fermion charges are ~ 0.01)

Conclusions (for the first part)

Monomial chaotic inflation is ruled-out by CMB data.

However, QFT loop corrections implied by the need of reheating can actually “rescue” these models

Three-parameter general description of radiatively corrected monomial inflation:

$$V(\phi) = \frac{\lambda}{4!}\left(1 - 2\big(1 - b_1\big)\log\frac{\phi^2}{\phi_0^2} + 2\big(1 + b_2\big)\left(\log\frac{\phi^2}{\phi_0^2}\right)^2\right)\phi^4$$

Concrete examples of plateaus require couplings of the inflaton to fermions and to another scalar (e.g. the Higgs) or a gauge group

Second part of the talk:

- **What is the interplay between inflation and the SM?**

Example: stability of the SM effective potential (arXiv:1505.07476)

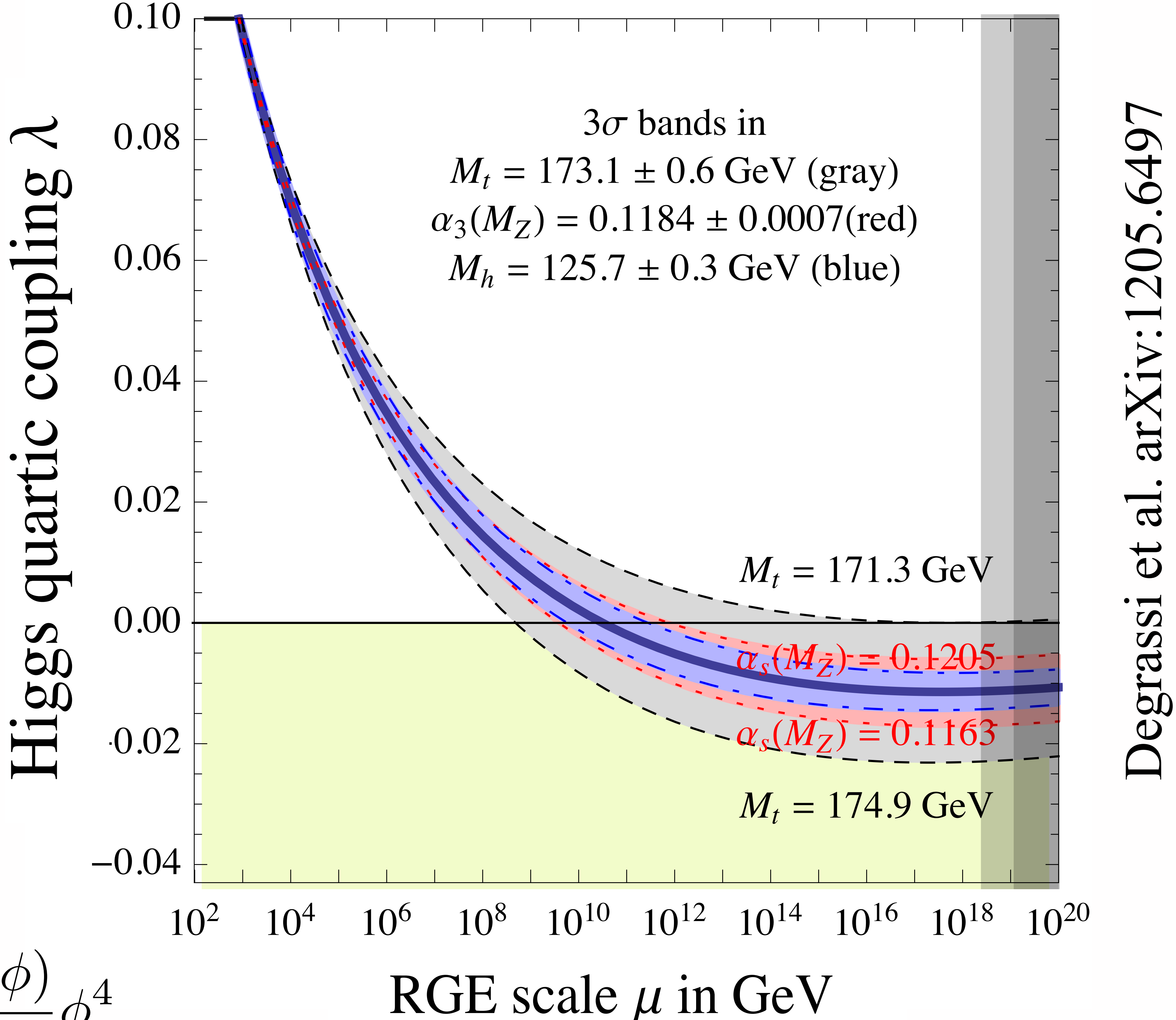
Summary of part two

Fact 1: Quantum fluctuations of the Higgs during inflation that are of the order of the Hubble scale (large!)

Fact 2: Given the Higgs and top quark masses, the SM potential might be negative for large Higgs values

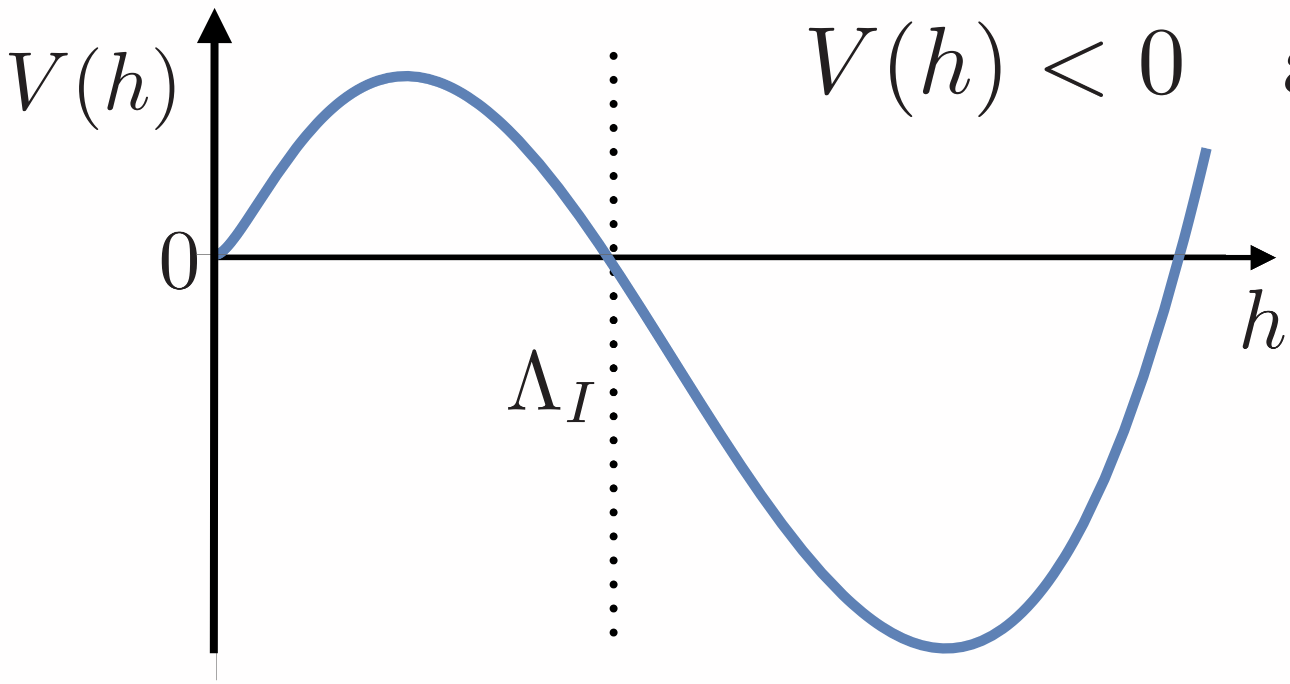
Problem: the Higgs is likely to end up in the instability instead of in the right EW vacuum

Can the inflaton stabilize the effective potential?



$$V \simeq \frac{\lambda(\phi)}{4!}\phi^4$$

Inflation and the Higgs



$$V(h) < 0 \quad \text{at} \quad h = \Lambda_I \sim 10^{11}\text{GeV}$$

$$V(h) \simeq \frac{\lambda(h)}{4} h^4$$

Quantum fluctuations of the Higgs:

$$\sqrt{\langle h^2 \rangle} \sim H \sim \frac{\sqrt{V_{\text{inf}}(\phi)}}{M_P} \sim 10^{-5} M_P \sim 10^{14}\text{GeV} \gg \Lambda_I$$

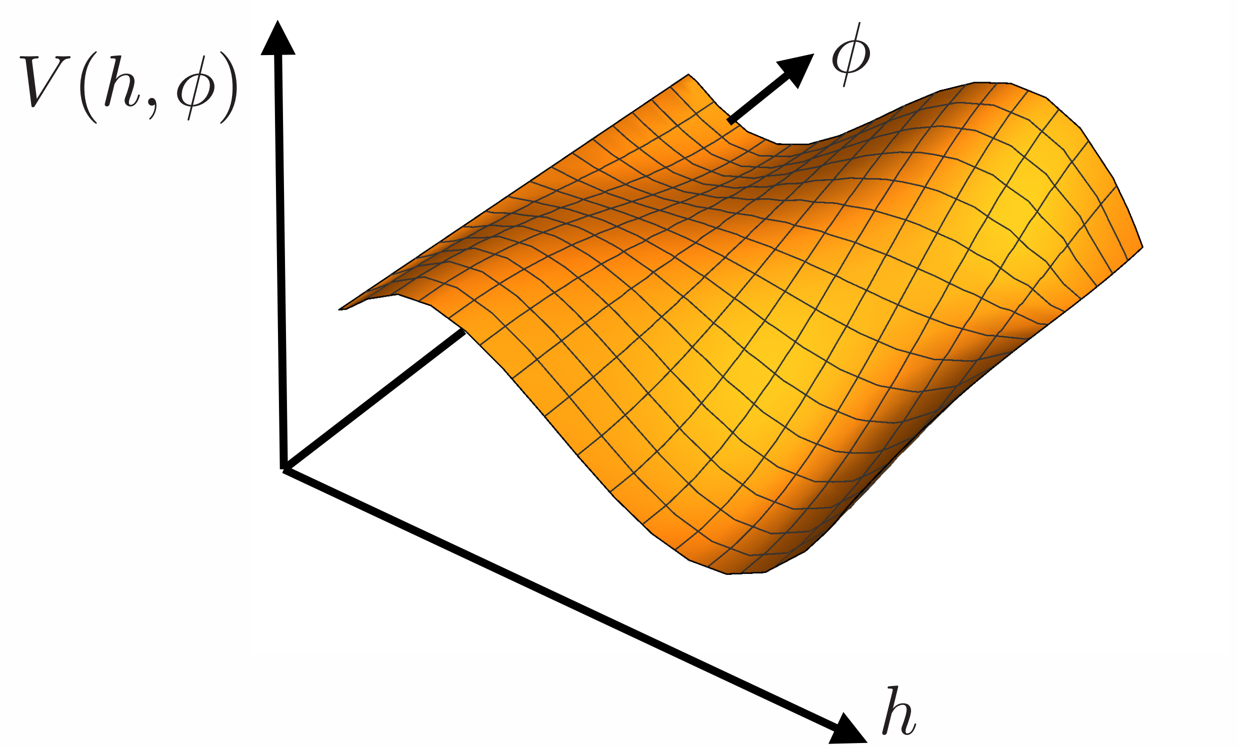
$$M_P = 1/\sqrt{8\pi G} \simeq 2.435 \cdot 10^{18}\,\text{GeV}$$

Inflation and the Higgs

Recall:
The inflaton must couple to the SM for reheating

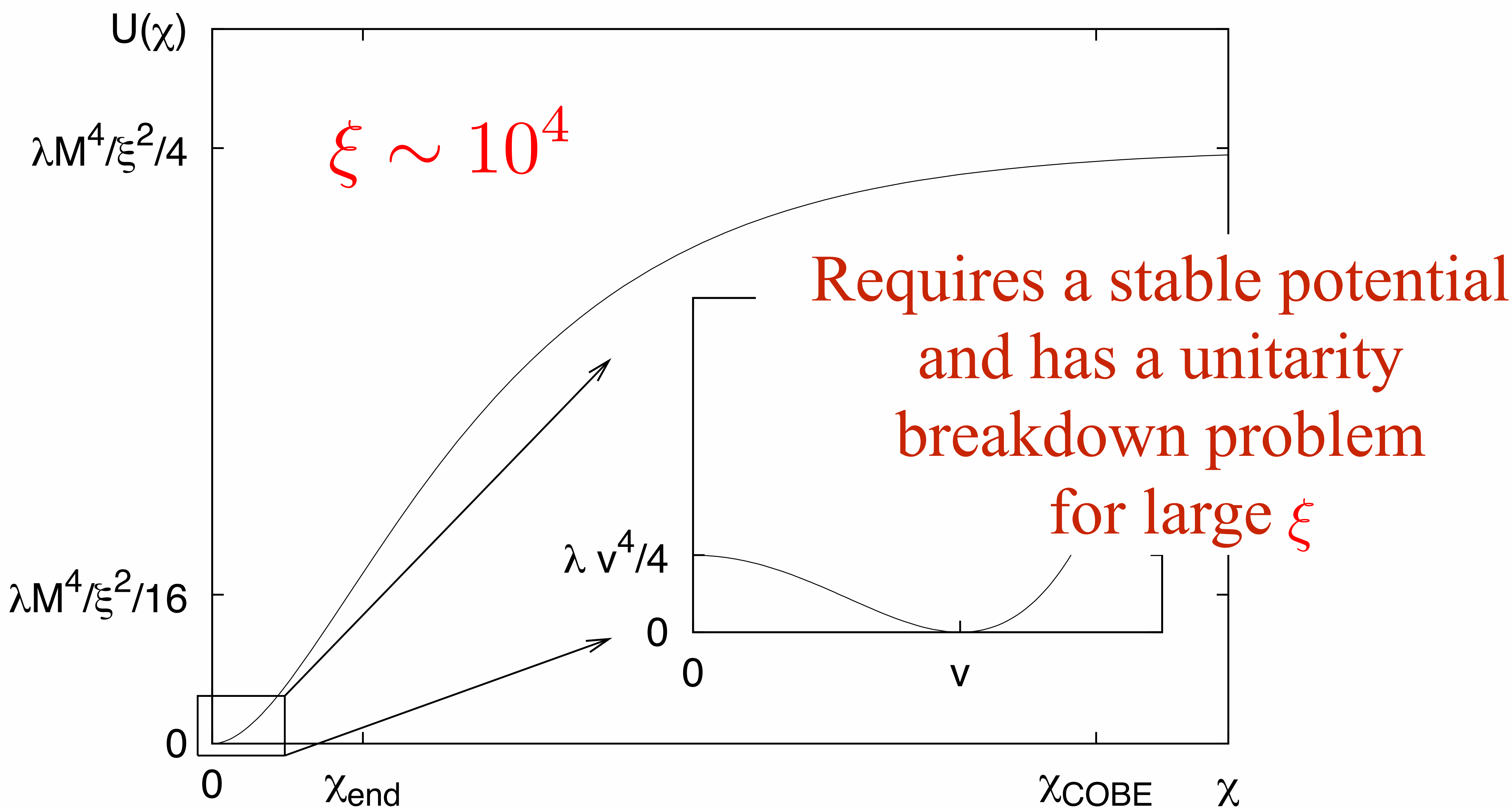
Another complication:

If the inflaton couples directly to the Higgs,
the inflationary trajectory is (in general) two-dimensional



Higgs = inflaton?

$\sqrt{-g}\,\xi\,h^2\,R \subset \mathcal{L}$ (ξ suppresses quantum fluctuations)



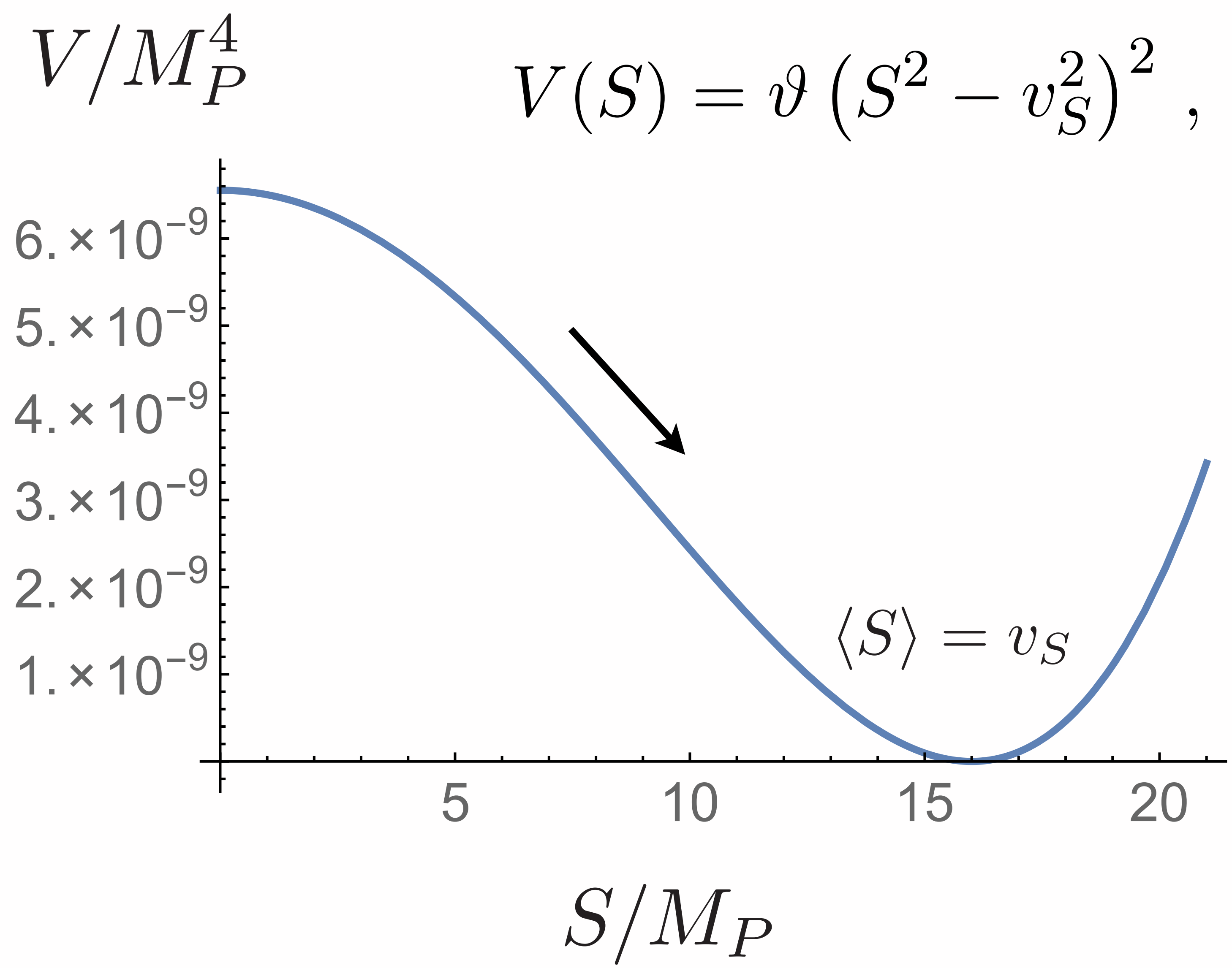
Bezrukov and Shaposhnikov arXiv:0710.3755

Can the inflaton stabilize the potential?

A simple Higgs portal inflation model

$$V = m_H^2 H^\dagger H + \frac{m_S^2}{2} S^2 + \frac{\lambda}{2}(H^\dagger H)^2 + \frac{\lambda_S}{4!} S^4 + \frac{\lambda_{SH}}{2} H^\dagger H S^2$$

$$V(S) = \vartheta \left(S^2 - v_S^2\right)^2 \,, \quad \vartheta = \frac{\lambda_S}{4!}\frac{\tilde{\lambda}}{\lambda} \lesssim 10^{-13}$$



$$15 M_P \lesssim \langle S \rangle \lesssim 25 M_P$$

$$-m_S^2 \sim 10^{13}\text{GeV}$$

$$0.04 \lesssim r \lesssim 0.07$$

CMB upper bound

Stability

$$V = m_H^2 H^\dagger H + \frac{m_S^2}{2} S^2 + \frac{\lambda}{2}(H^\dagger H)^2 + \frac{\lambda_S}{4!} S^4 + \frac{\lambda_{SH}}{2} H^\dagger H S^2$$

At large field values, $V > 0$ requires:

$$\lambda > 0\,, \quad \lambda_S > 0\,, \quad \lambda_{SH} > -\sqrt{\lambda \lambda_S / 3}$$

$$\beta_\lambda = \frac{1}{16\pi^2}\left[-12y_t^4 + \lambda\left(-\frac{9}{5}g_1^2 - 9g_2^2 + 12y_t^2\right) + \frac{27}{100}g_1^4 + \frac{9}{10}g_2^2 g_1^2 + \frac{9}{4}g_2^4 + 12\lambda^2 + \lambda_{SH}^2\right]$$

$$\beta_{\lambda_S} = \frac{1}{16\pi^2}\left[3\lambda_S^2 + 12\lambda_{SH}^2\right]$$

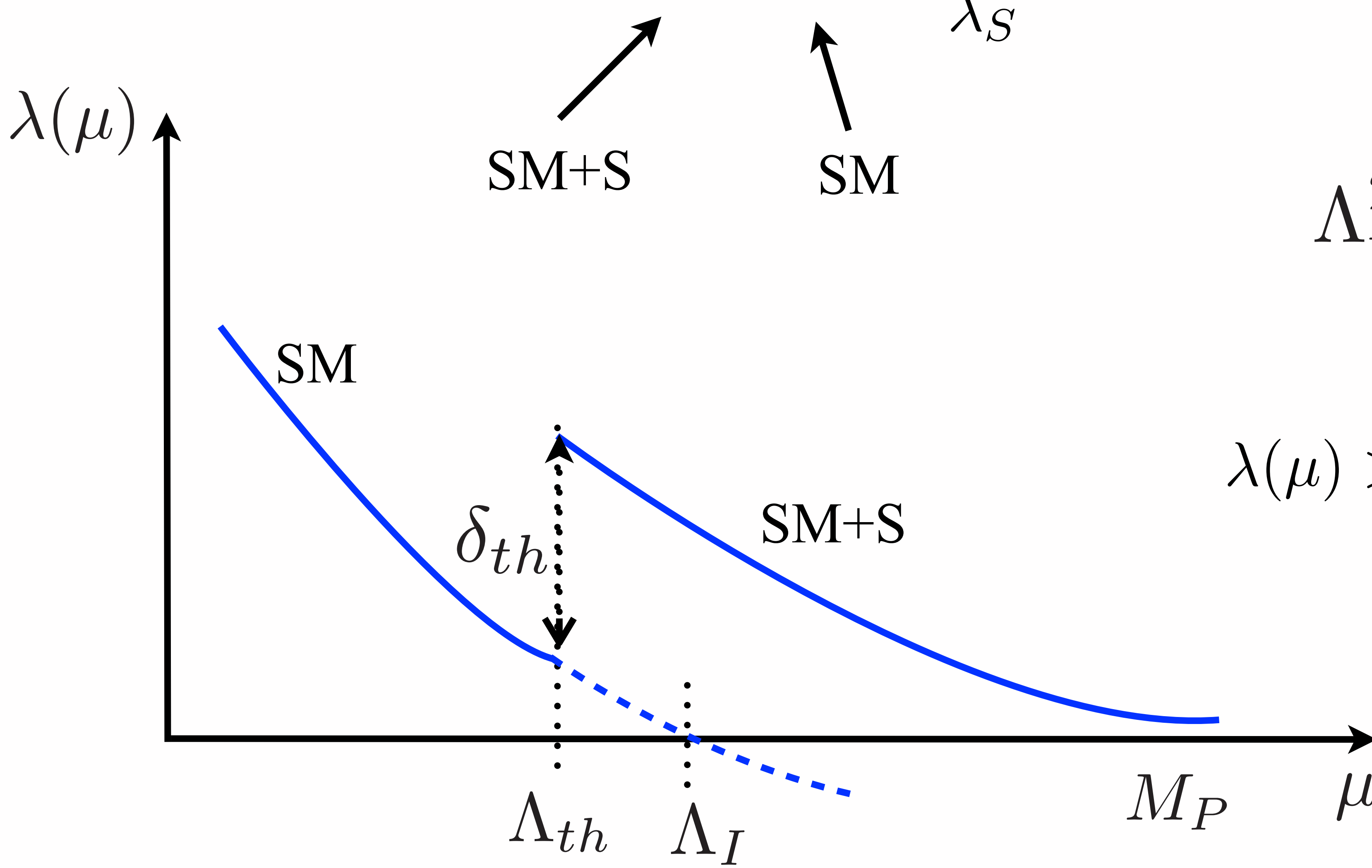
$$\beta_{\lambda_{SH}} = \frac{1}{16\pi^2}\left[\lambda_{SH}\left(-\frac{9}{10}g_1^2 - \frac{9}{2}g_2^2 + 6\lambda + \lambda_S + 6y_t^2\right) + 4\lambda_{SH}^2\right]$$

larger λ_{SH}^2 than what inflation permits

Threshold stabilization

$$V = m_H^2 H^\dagger H + \frac{m_S^2}{2} S^2 + \frac{\lambda}{2}(H^\dagger H)^2 + \frac{\lambda_S}{4!} S^4 + \frac{\lambda_{SH}}{2} H^\dagger H S^2$$

$$\tilde{\lambda} = \lambda - \frac{3\lambda_{SH}^2}{\lambda_S} = \lambda - \delta_{th}$$



$$\Lambda_{th}^2 \sim |m_S^2| < \Lambda_I^2$$

$$\lambda(\mu) > \begin{cases} \delta_{th} & \text{for} \quad \mu \lesssim \Lambda_{th} \\ 0 & \quad\quad\; \mu \gg \Lambda_{th} \end{cases}$$

Lebedev 1203.0156,
Elias-Miro et al. 1203.0237

Problem with scales

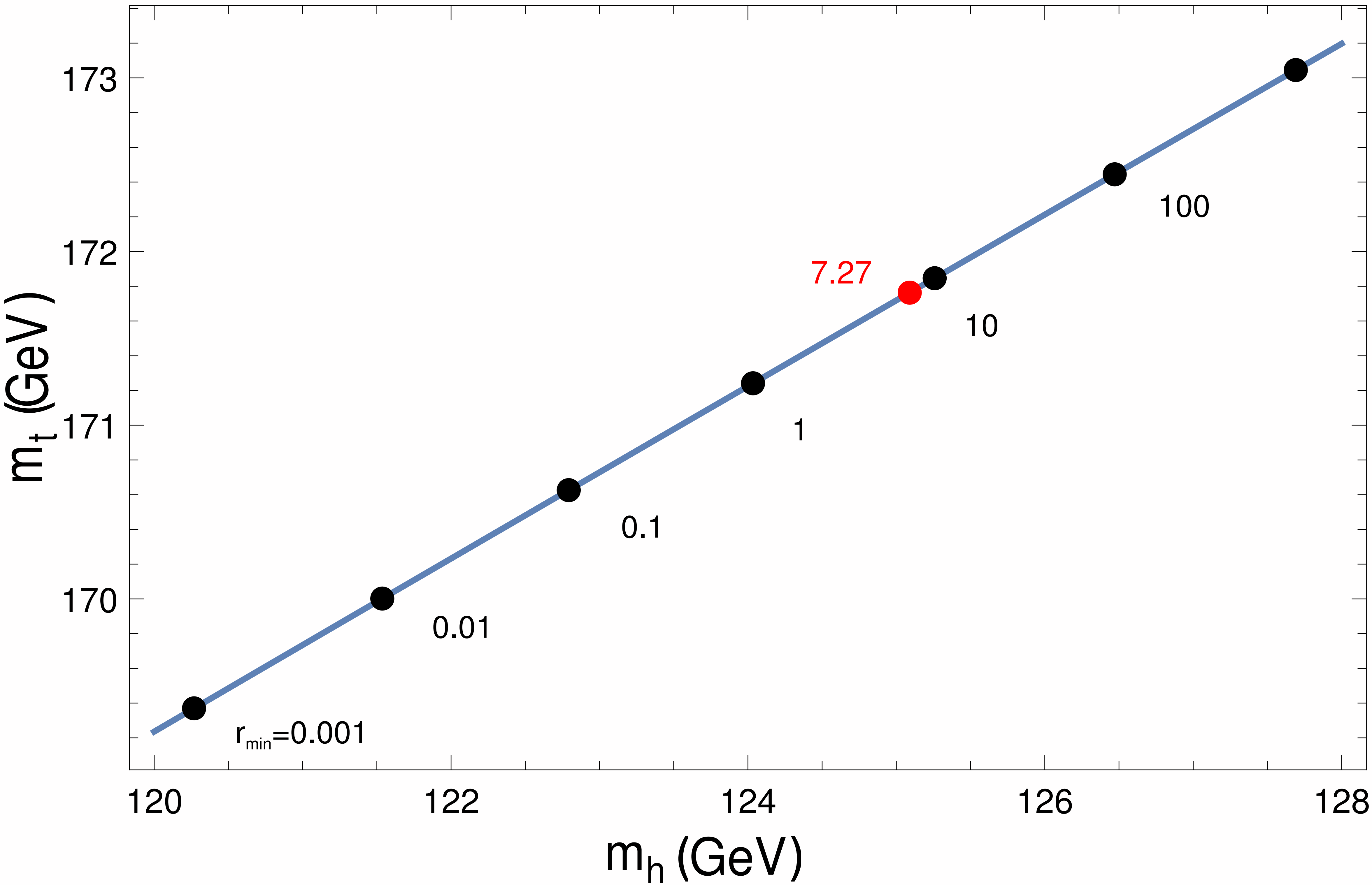
$$10^{13}\mathrm{GeV} \sim \sqrt{|m_S^2|} > \Lambda_I \sim 10^{11}\mathrm{GeV}$$

hierarchy of scales forbids
Higgs portal threshold stabilization with singlet inflaton

ways out:
- small enough top mass (marginally possible with current data)
- another scalar (not the Higgs)
- non-minimal couplings to the scalar curvature (with caveats)

(killing) Higgs false-vacuum inflation

Tuning the top quark mass for given values of the Higgs mass and α_s
a plateau appears in the Higgs direction and fades gradually as S grows.



Final remarks

Inflation needs to explain how the universe reheats.

Generically, this implies couplings to other fields,
and in particular to the SM.

These couplings may affect the dynamics of inflation
and are essential to understand the SM-inflaton interplay.