Higgs criticality in and beyond the Standard Model

Thomas Steingasser

Massachusetts Institute of Technology, Black Hole Initiative at Harvard University

Overview

Assumptions:

1. Higgs parameters are tuned towards critical values marking transitions between different “phases” of the potential.
2. This is due to a mechanism favoring criticality.

Question: *How could such a mechanism affect BSM physics?*

Results:

1. Some fine-tunings **can** be considered plausible.
2. A model-independent* **conjecture** for the Wilson coefficient C_6,

$$C_6 \simeq \frac{|\beta_\lambda(\mu_I)|}{12\sqrt{e}} \cdot \frac{\Lambda_{\mathrm{UV}}^2}{\mu_I^2}, \quad \text{with } \lambda(\mu_I) = 0.$$

All details: [2307.10361]

Motivation

1. Higgs criticality: Both parameters of the Higgs potential seem fine-tuned

2. Large parameter spaces of many BSM models, need to identify interesting regions

3. Cosmological consequences & measurements

The near-criticality of the Higgs sector

The Higgs potential

Higgs potential:

$$V(H) \sim -m^2 H^2 + \lambda H^4 + V_0 \tag{1}$$

All parameters in this potential can be understood as fine-tuned:

$$m^2 \Leftrightarrow \text{hierarchy problem}$$

$$\lambda \Leftrightarrow \text{meta-stability of the electroweak vacuum}$$

$$V_0 \Leftrightarrow \text{cosmological constant problem}$$

The (gauge) hierarchy/Higgs naturalness problem

(Well motivated) assumption: ”More fundamental” physics at some high energy Λ_{UV}

Natural value for the Higgs mass parameter: $m^2 \sim \Lambda_{UV}^2$

Observations: No signs of new physics near the electroweak scale

$\rightarrow$ often requires fine-tuning of UV-parameters

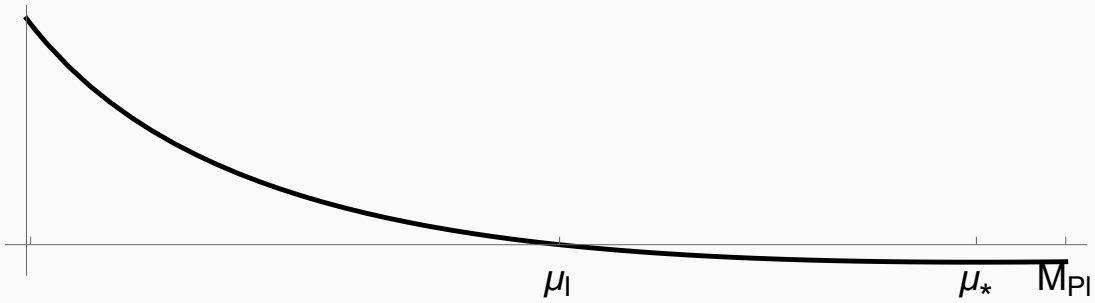
Metastability of the electroweak vacuum

Renormalization group: Parameters in the Higgs potential are scale dependent

Running of λ is determined by its Beta function,

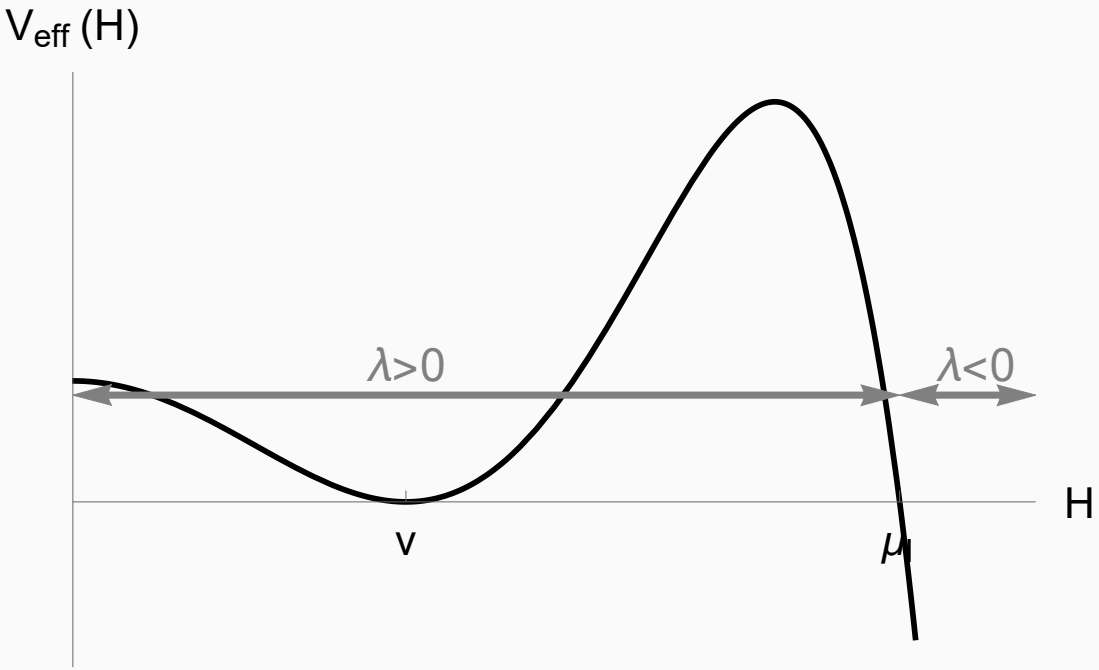
$$\beta_\lambda \sim (4\pi)^{-2}(\lambda^2 - y_t^4 + \dots)$$

Matching with LHC data:



Metastability of the electroweak vacuum

$\rightarrow$effective potential $V_{eff} \sim -m^2(H)H^2 + \lambda(H)H^4$:

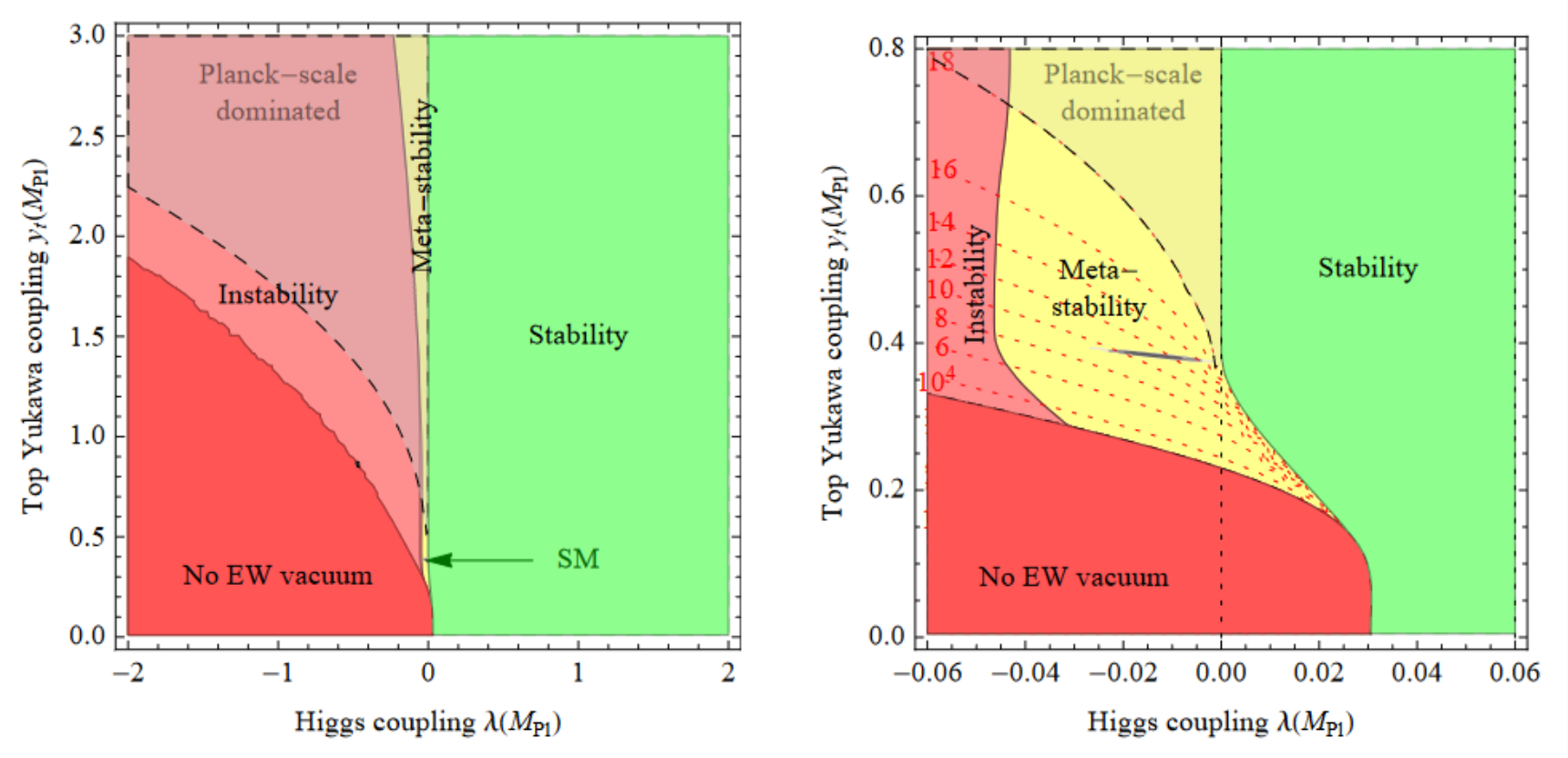


$\Rightarrow$ Higgs can tunnel through the potential barrier

Best* estimate for lifetime: 10^{983} years [2108.09315]

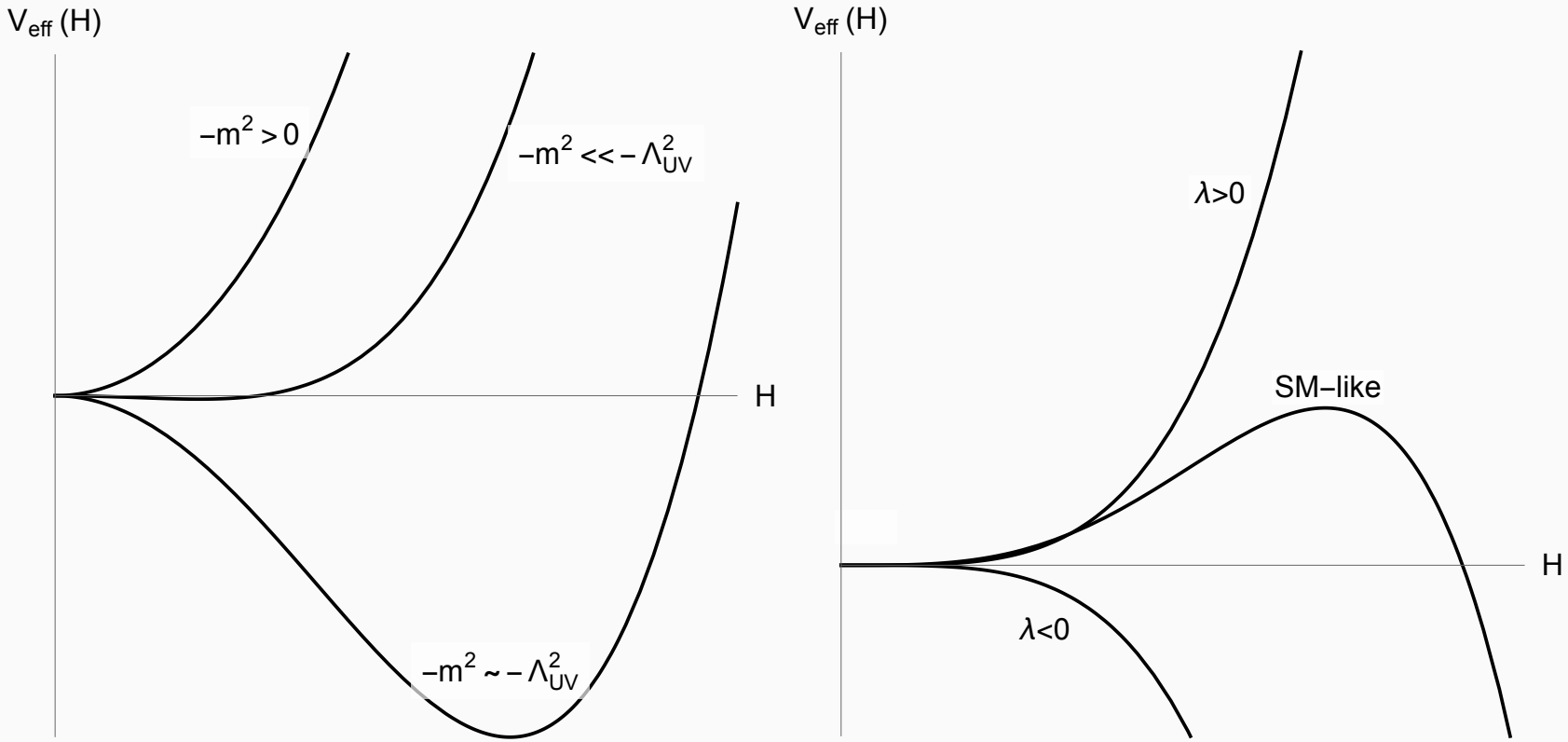
Metastability of the electroweak vacuum - fine-tuning?

Standard Model phase diagram [arXiv:1307.3536]:



Near-criticality and phases of the potential

Both “tunings” correspond to transitions between different phases of the potential!



Cosmological constant: Close to transition from dS to AdS!

Dynamical criticality

Near-criticality and phase transitions

Fine-tuning: Unexpected in fundamental parameters, but common feature of dynamical systems![1]

Idea: Higgs-parameters set through dynamical process...

... during inflation.

... on the landscape.

[1] *Self-organized criticality: An Explanation of 1/f noise* (P. Bak, C. Tang, K. Wiesenfeld)

Example 1: *Self-Organized Localization*

Developed in [2105.08617] (Giudice, McCullough, You)

Idea: Additional light scalar field(s) ϕ,

$$m^2 \to m^2(\phi), \quad \lambda \to \lambda(\phi), \quad \Lambda \to \Lambda(\phi),$$

and vice versa.

Focker-Planck equation + several assumptions + long computations
$\Rightarrow$ Probability distribution for ϕ peaked near phase transitions

$\Rightarrow$ Phase transitions as attractors

Example 2: *Self-Organized Critical Multiverse*

Developed in [1907.07693], [1912.06706], [2003.12594], [2106.12590], [2108.09315] (Khoury, Parrikar, Kartvelishvili, Sharma, TS)

Idea: Landscape as a network, vacuum decay as jump between nodes

Eternal inflation + "early" times $\Rightarrow$ metastability favored

General theorem: metastability $\Rightarrow$ large hierarchy [2108.09315]

Generalization

Bigger picture: Mechanisms leading to tuning against phase transitions feasible

Our interpretation: Fine-tunings might be plausible if they correspond to critical behavior/phase transitions!

Possible ways forward:

1. Take another perspective
2. Work on concrete mechanisms
3. Classify fine-tunings
4. Make mechanism-independent statements

Our approach

Effective picture

General UV theories: Many possible phases, critical points $\Rightarrow$ EFT?

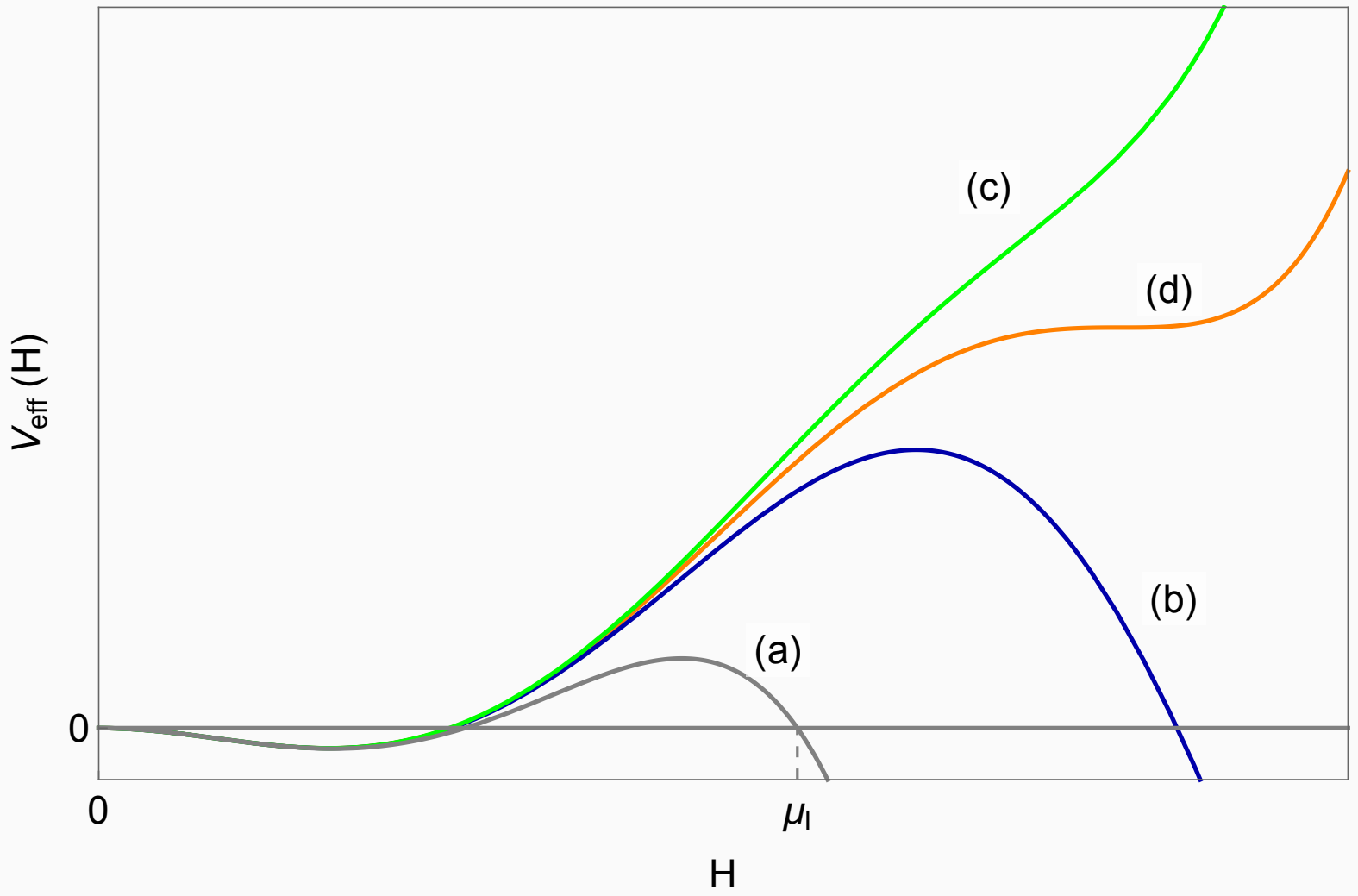
Simplest extension: $V_{\text{eff}} \to V_{\text{eff}} + \frac{C_6}{\Lambda_{\text{UV}}^2} H^6 + \ldots$

Motivation:

1. Universality*
2. Simple $\Rightarrow$ development of computational tools!
3. Only Higgs $\to$ observational consequences?

Phases with a dimension-six term

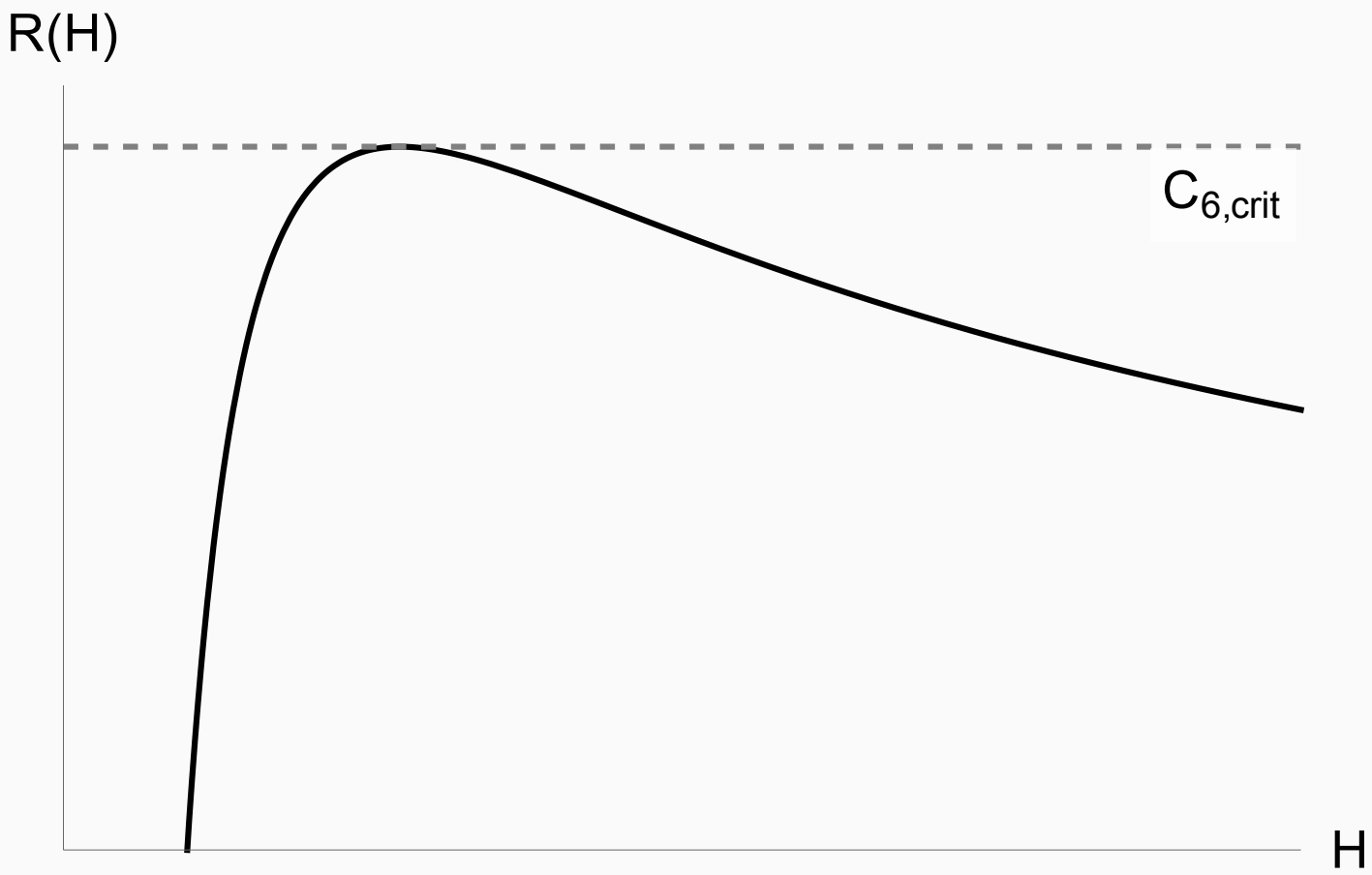
Single parameter → phases easy to identify!



Computation

Idea: Different phases $\Leftrightarrow$ different number of extrema

$\Rightarrow$ Rewrite $\partial_H V_{\text{eff}} = 0$ as $\text{parameter} = R(H)$



Critical dimension-six term

$$\text{Result}: \; C_{6,\text{crit}} \simeq \frac{|\beta_\lambda(\mu_I)|}{12\sqrt{e}} \cdot \frac{\Lambda_{\text{UV}}^2}{\mu_I^2}, \quad \text{with } \lambda(\mu_I) = 0.$$

$$\text{Plateau}: \; H_0^2 = \sqrt{e}\mu_I^2 = \frac{|\beta_\lambda(\mu_I)|}{12 \cdot C_6} \cdot \Lambda_{\text{UV}}^2,$$

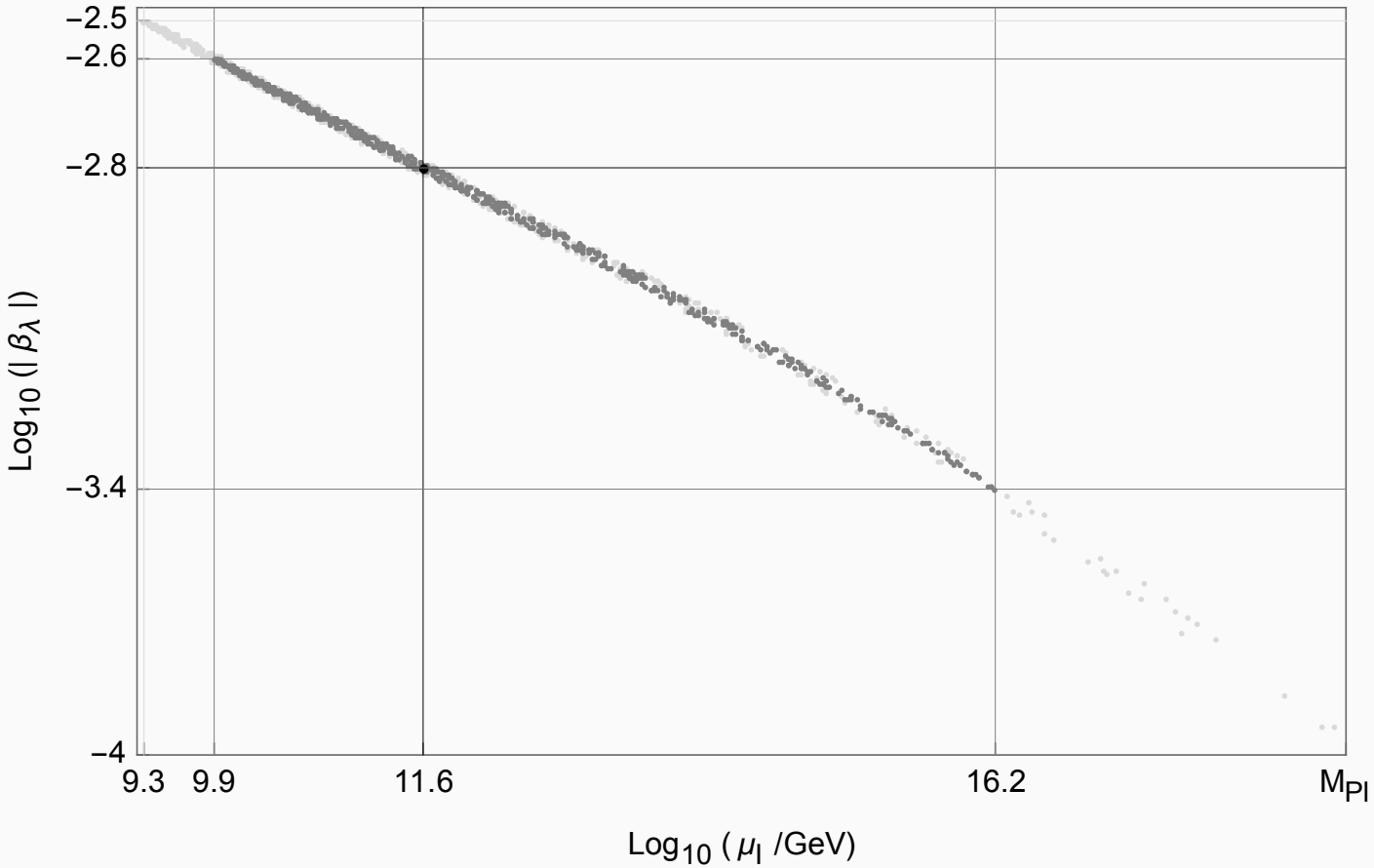
$$V(H_0) = \frac{e}{48}|\beta_\lambda(\mu_I)| \cdot \mu_I^4.$$

$\Rightarrow$ Validity of EFT controlled by C_6 and Λ_{UV}

$\Rightarrow$ Scale of new physics near the instability scale μ_I

$\Rightarrow$ Properties of plateau controlled by μ_I

Observational consequences



Upper end: Plateau influences Higgs inflation⇒PBHs!

Lower end: RHNs can lower μ_I to $O(10)\mathrm{TeV}$ [2304.08542]

Conclusion

Conclusion

- New perspective on fine-tuning: Result of dynamical mechanism

$\Rightarrow$ Tunings might be well-motivated if linked to phase transitions

$\Rightarrow$ Corresponding parameters interesting to study

$\Rightarrow$ Effect on BSM physics way to test “criticality paradigm”

- Effective approach: At least one possible phase transition for wide class of models

Thank you for your attention!

Questions: tstngssr@mit.edu