Vacuum Metastability from Axion-Higgs Criticality

Based on 2412.03542

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PLANCK2025 – 27th International Conference from the Planck Scale to the Electroweak scale

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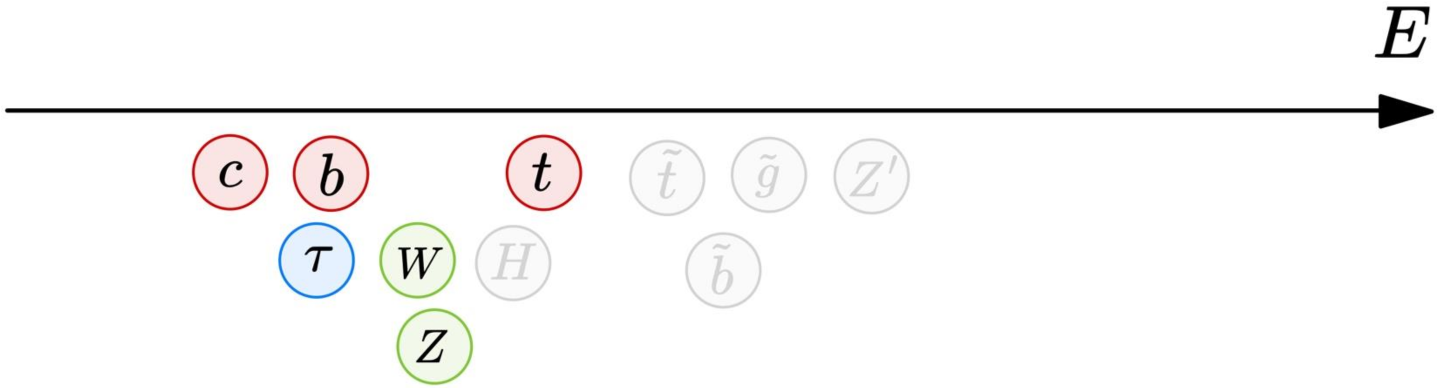

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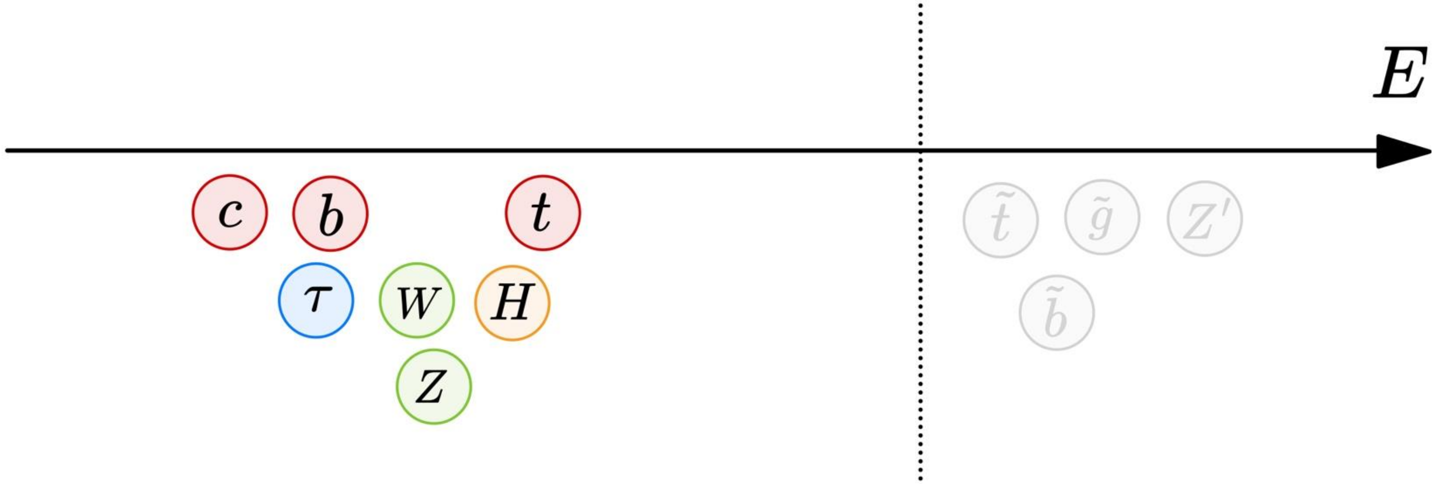
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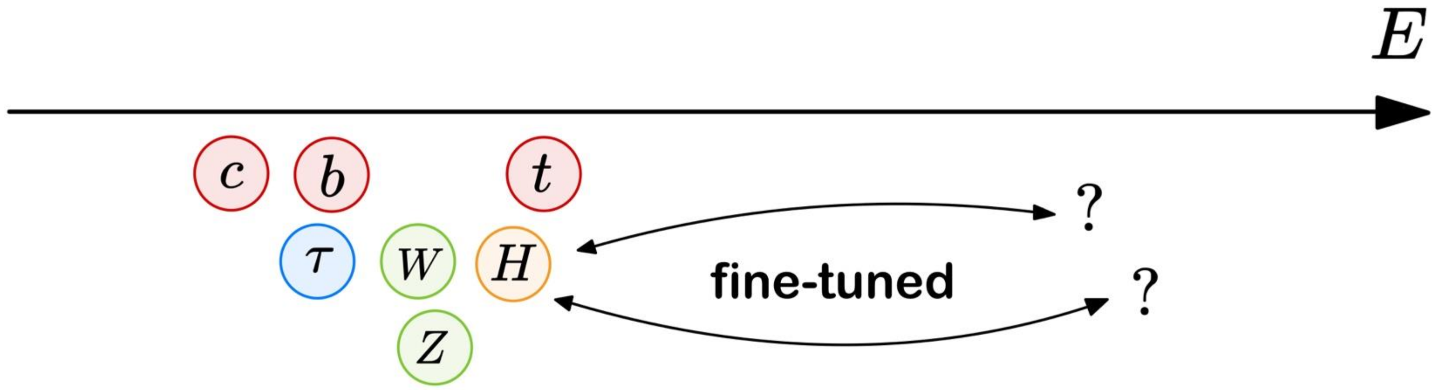

E
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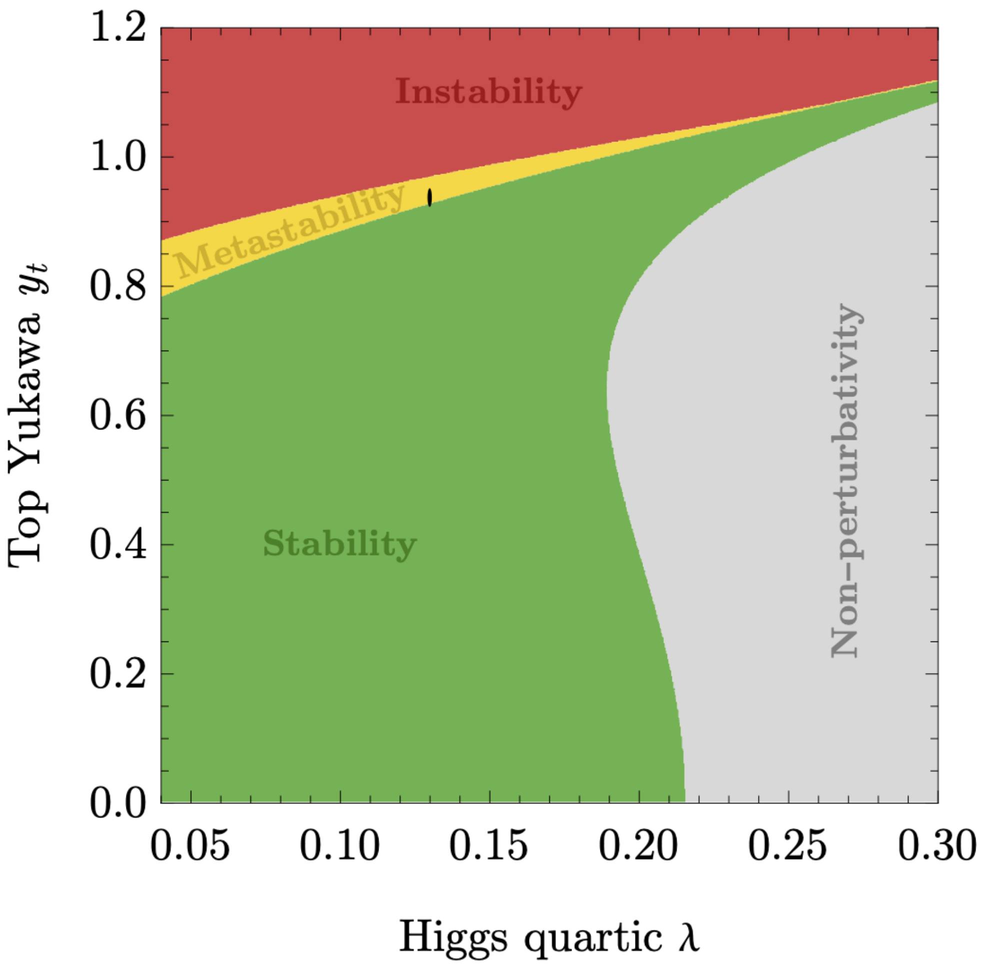
?
fine-tuned
?

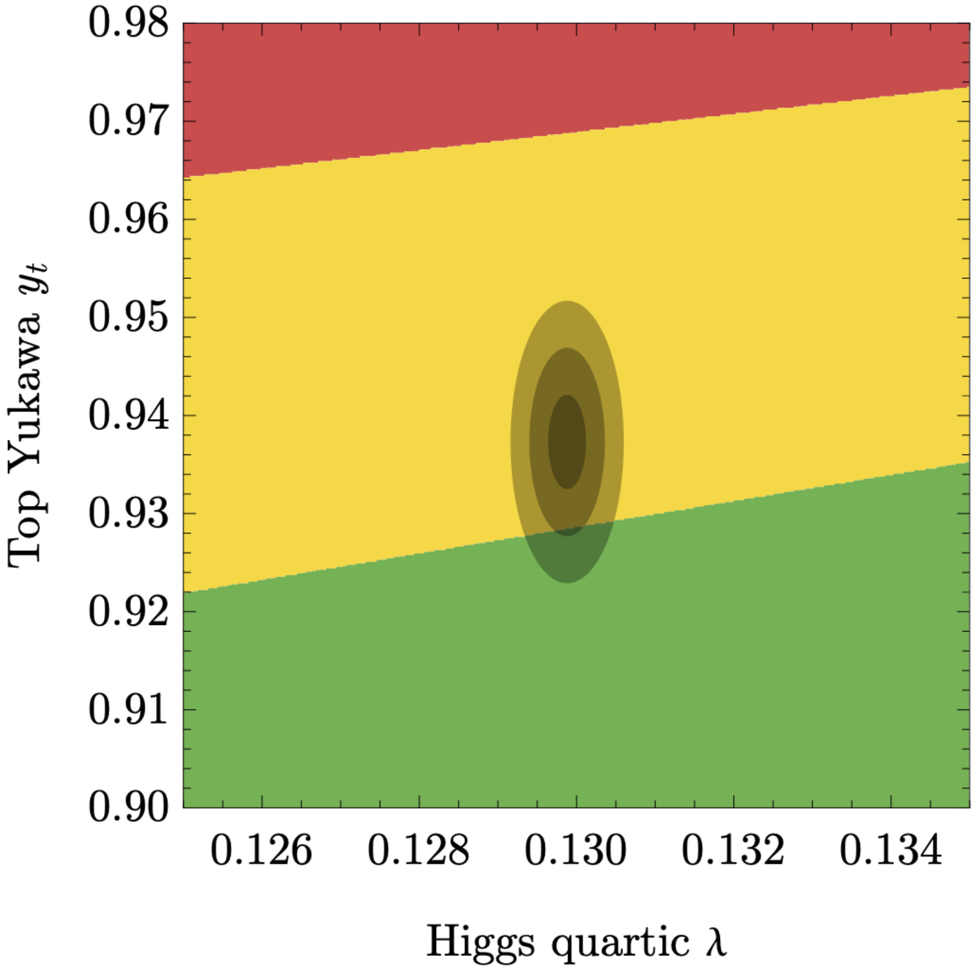
Higgs mass not a fundamental parameter but special value explained as critical point in parameter space

Criticality

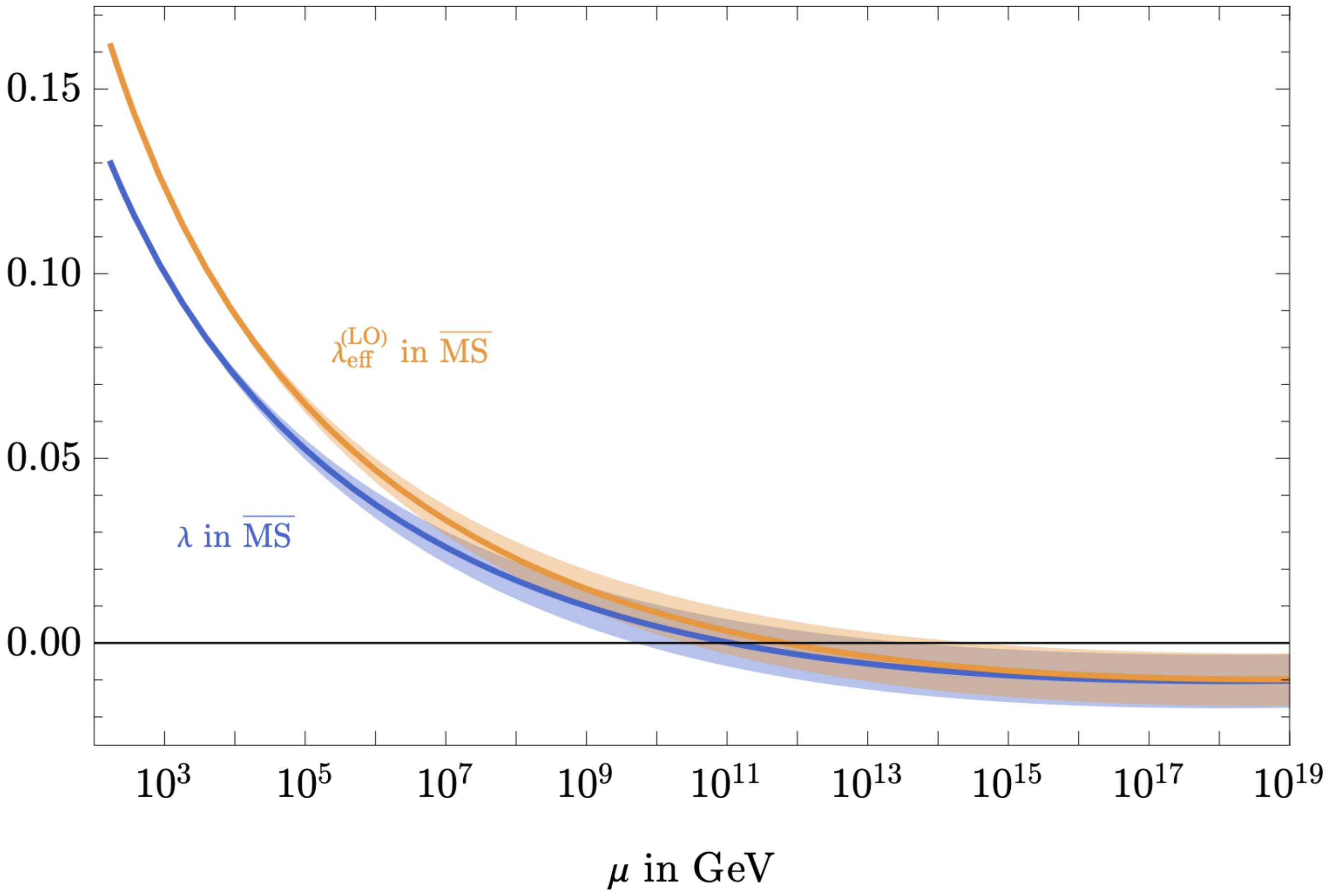
- **Classical (thermal)** phase transitions with varying thermodynamical parameters
- **Quantum** Phase Transition through change of external parameters
- **Critical values** of the parameters mark the transition
- Unconventional in particle physics context but **common in dynamical systems**

Phases of the Standard Model



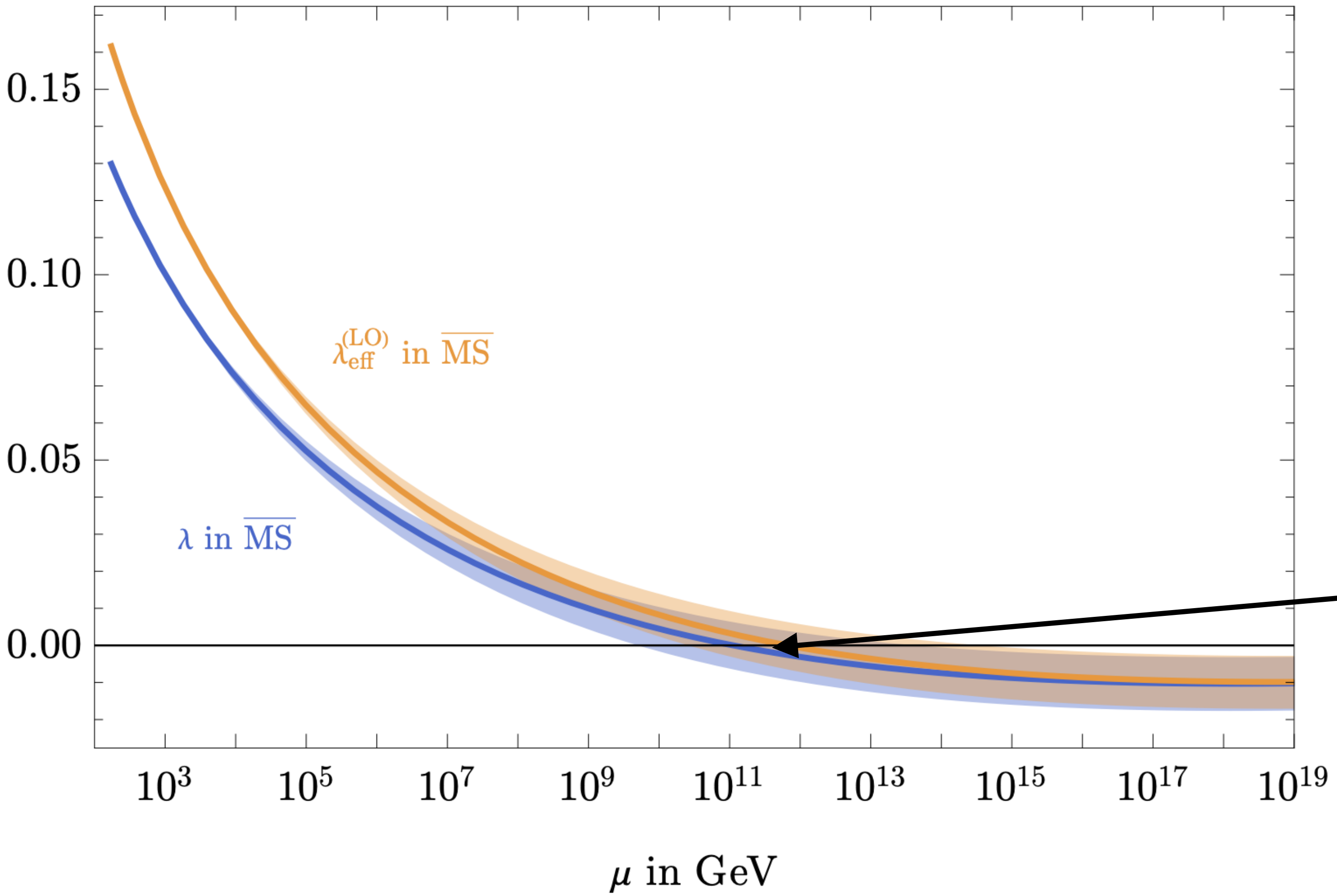


Electroweak Vacuum Metastability



$$\beta_\lambda^{(1)} \sim \lambda(\lambda + y_t^2 + \text{gauge terms})$$
$$- y_t^4 + \text{gauge terms}$$

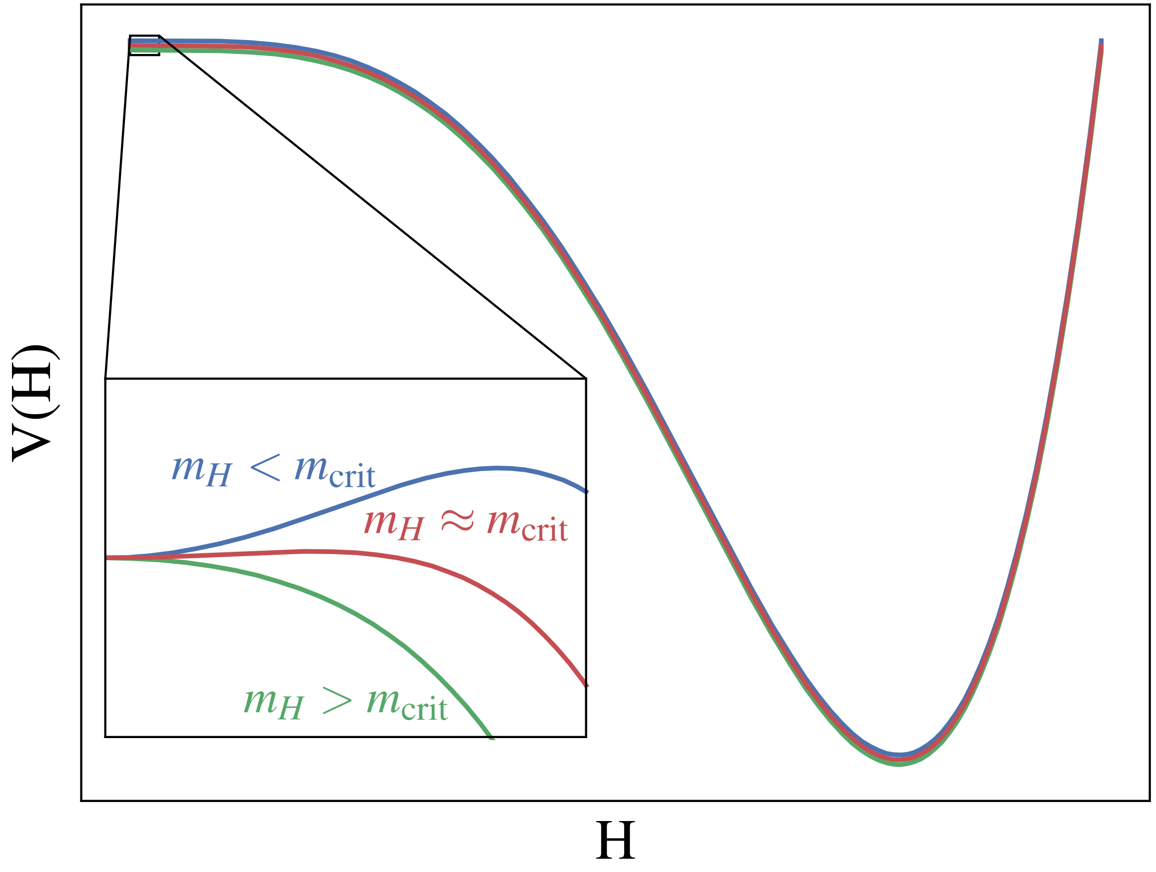
Electroweak Vacuum Metastability



$$\beta_\lambda^{(1)} \sim \lambda(\lambda + y_t^2 + \text{gauge terms}) - y_t^4 + \text{gauge terms}$$

$$\lambda(\mu_I) = 0$$

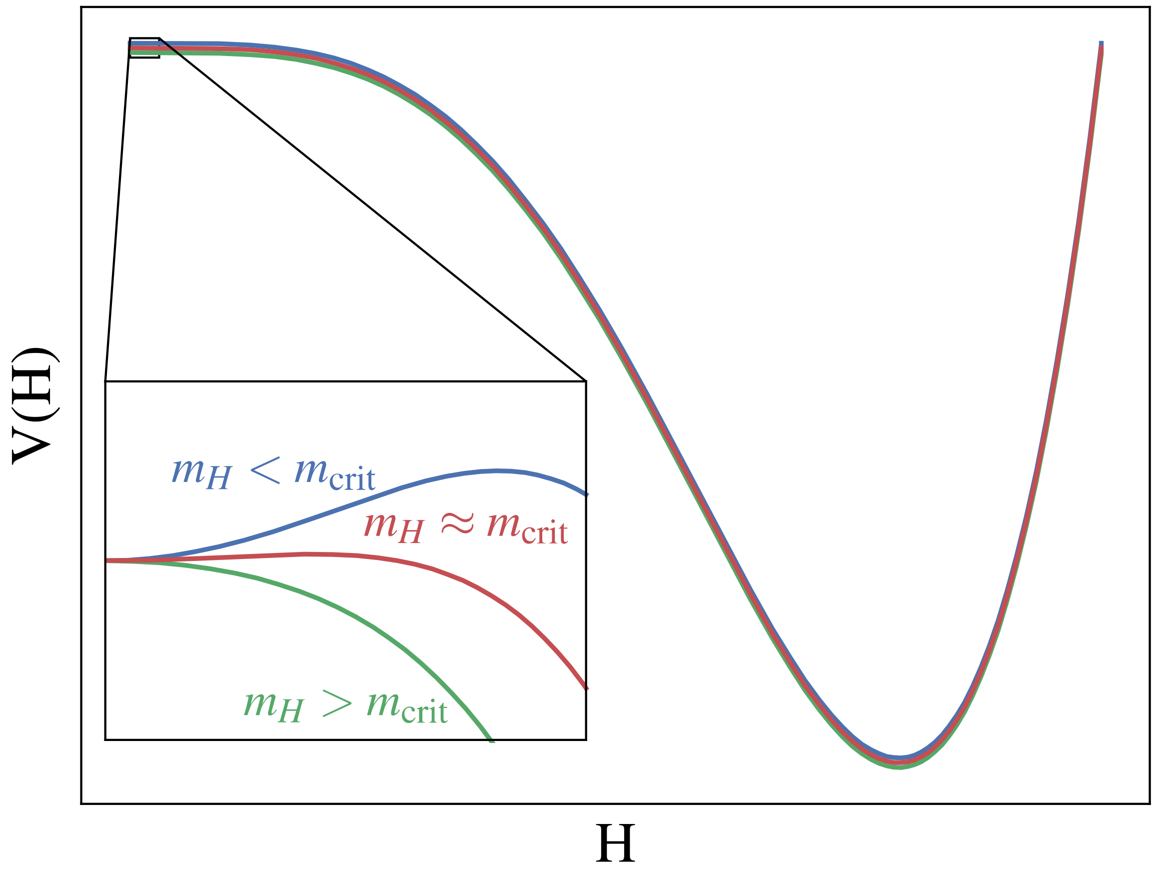
Higgs Criticality



- Instability scale implies critical value for Higgs mass parameter
- IR + UV vacuum for $m_H < m_{\rm crit}$
- Near-critical point $m_H \approx m_{\rm crit}$
- Only UV vacuum for $m_H > m_{\rm crit}$
- Metastability bound

$$m_H^2 < m_{crit}^2 = -\frac{1}{2}\, e^{-\frac{3}{2}}\, \beta_\lambda(\mu_I)\, \mu_I^2$$

Higgs Criticality



But why should we expect to live near a critical point?

Self-organised criticality

- Criticality acts as an attractor — Bak, Tang, Wiesenfeld ‘87
- Localisation near critical point during inflation — McCullough, Giudice, You ‘21
- Background field varies and coupled to some operator $\mathcal{O}$ whose expectation value changes as ϕ passes through some critical value ϕ_c

$$V = (\phi - \phi_c)\mathcal{O}$$

- If $\langle \mathcal{O} \rangle$ changes across ϕ_c, stochastic evolution could localise ϕ near ϕ_c
- Also from vacuum transition dynamics in the string landscape — Khoury, Parrikar ‘19

Vacuum Selection

- Small Higgs mass may just be the result of vacuum selection
- Given that we find ourselves in the IR vacuum, we expect an upper bound on the Higgs mass
- Does not explain *why* we are in the phase with an IR vacuum
  → selection could be realised through dynamical mechanisms mentioned
- General expectation: Higgs mass comparable to metastability bound
- But Higgs mass in the SM with substantial hierarchy to metastability bound
- Prediction: New physics leading to a saturated metastability bound

see also MD, V. Enguita, B. Gavela, T. Steingasser, T. You '25

Axion-Higgs Criticality

- **Motivated** BSM candidate (dark matter, pNGB of global symmetries, prevalent in string theories)
- Axion-like particles are **naturally light**
- Consider simple potential

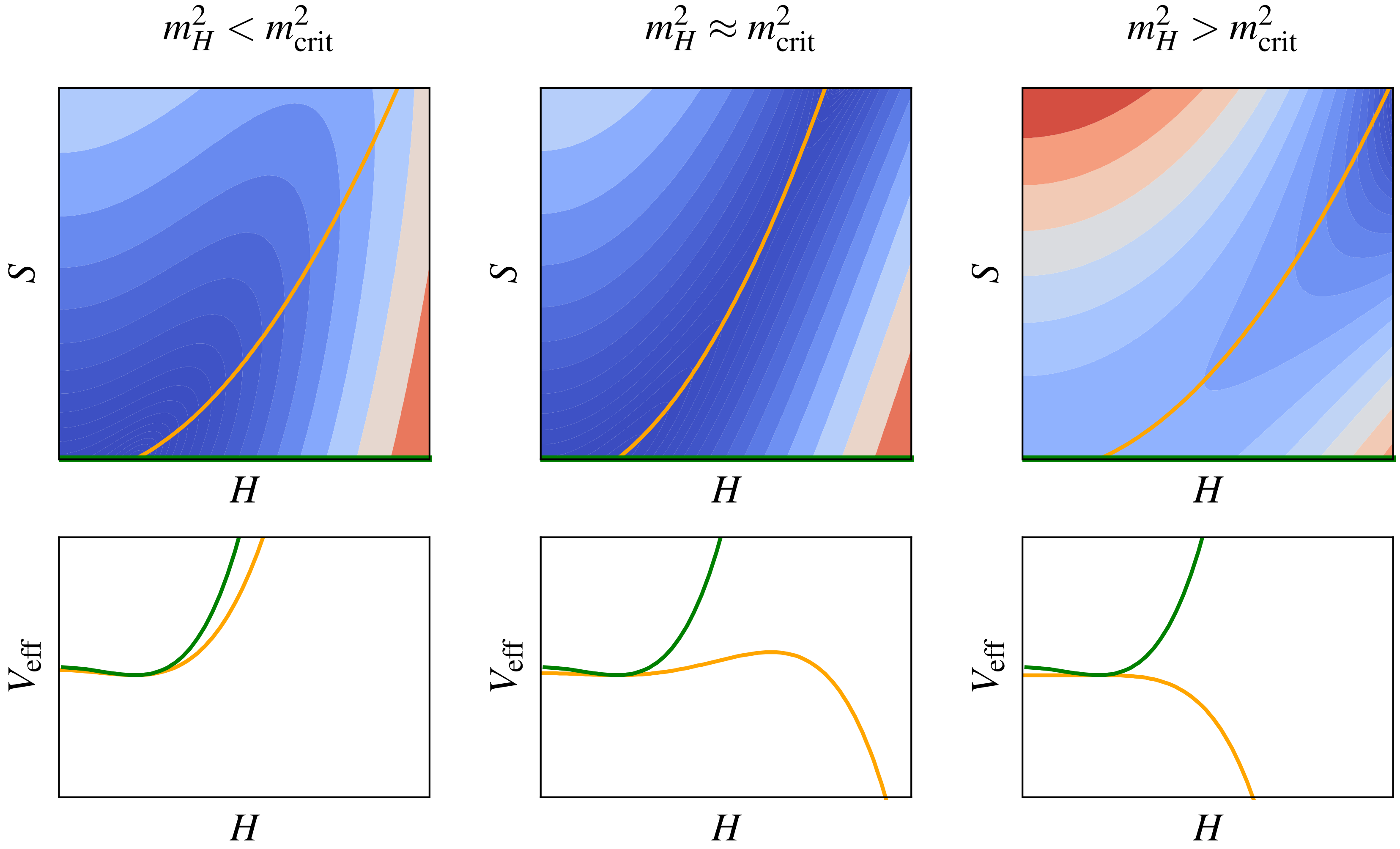
$$V_S = m_S^2 f^2 \left(1 - \cos\frac{S}{f}\right) - AfH^2 \cos\left(\frac{S}{f} - \delta\right)$$

- Large decay constant

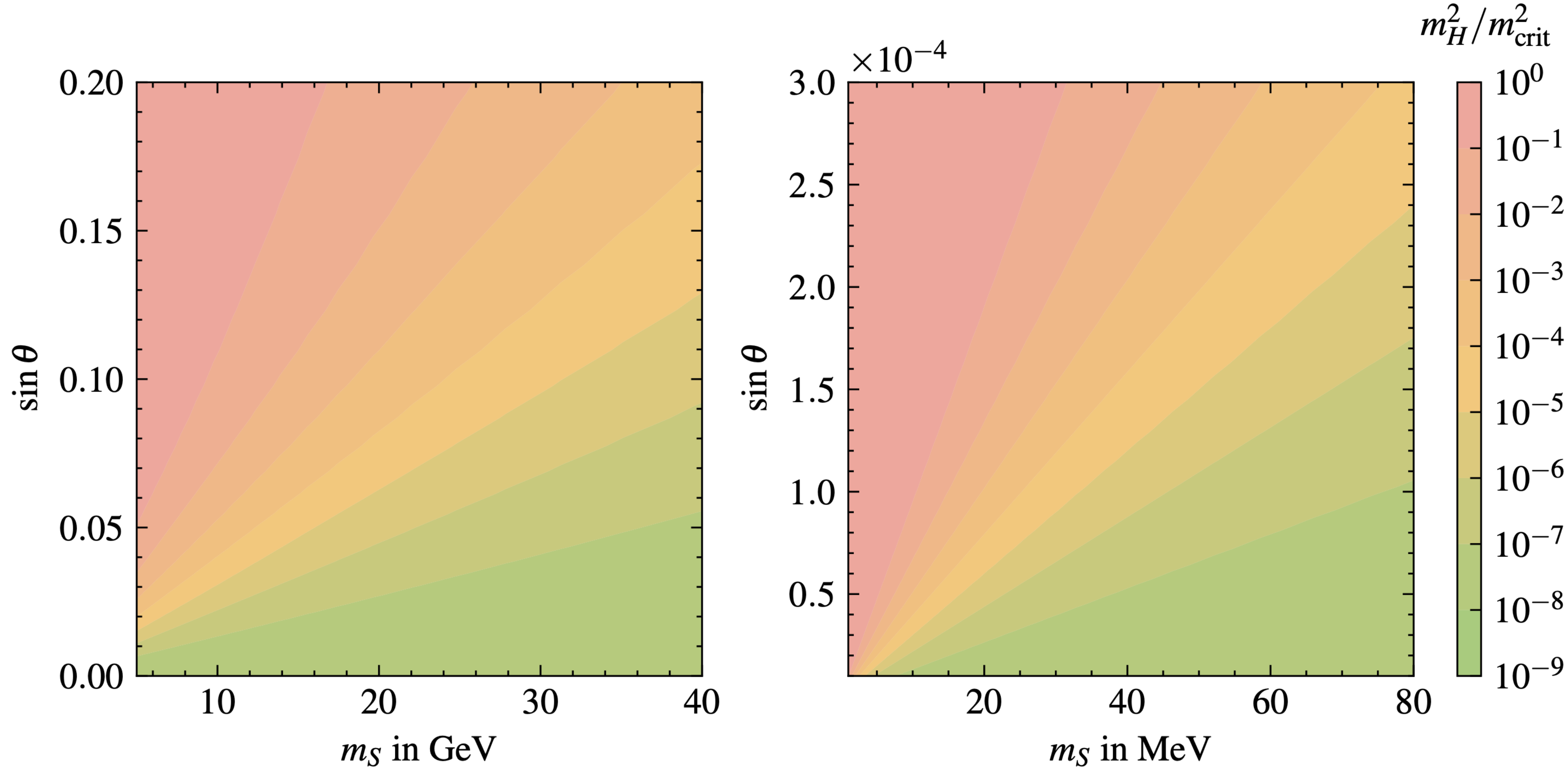
$$V_S = \frac{m_S^2}{2} S^2 - A \sin\delta\, SH^2$$

- Criticality through **mixing with Higgs** and **destabilising effect** on scalar potential

Axion-Higgs Criticality

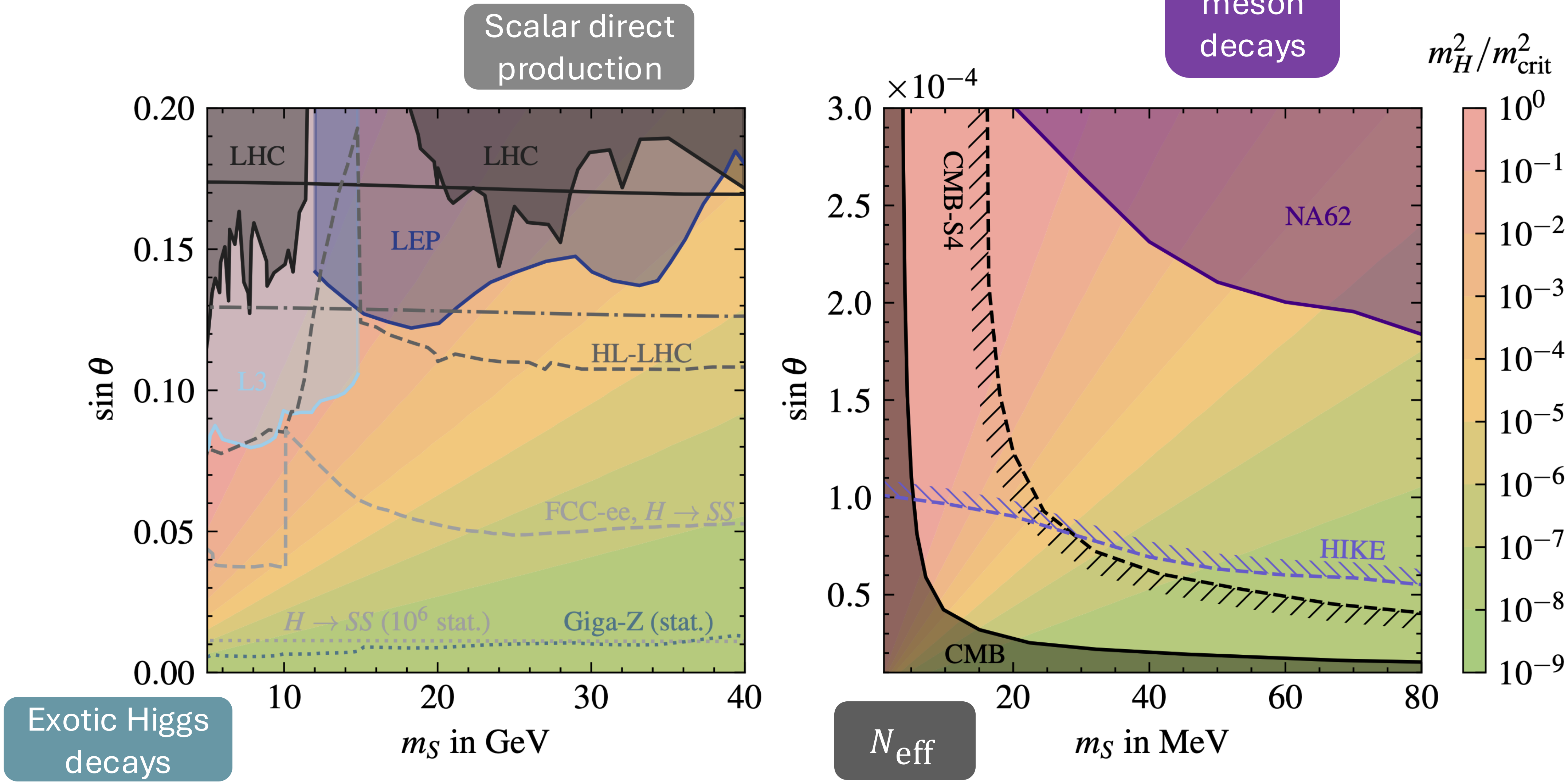


Axion-Higgs Criticality



MD, T. You '24

Axion-Higgs Criticality



Concluding Remarks

- Fine-tuning as result of **near-criticality**
- If Higgs mass is explained through cosmological criticality, then new physics coupled to the Higgs is expected
- **Criticality as new paradigm** for model building beyond naturalness
- Parameter space for Axion-Higgs Criticality **comprehensively probable** by future experiments