

Higgs-criticality in and beyond the Standard Model

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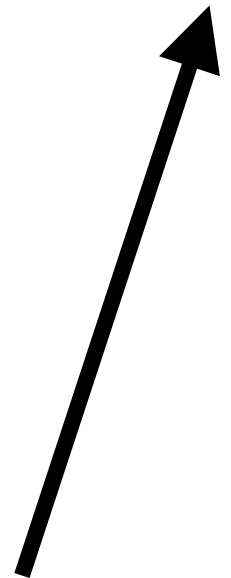
Motivation

Higgs Potential: $V_{\text{eff}}(\phi) = V_0 - \frac{1}{2}m_{\text{eff}}^2\phi^2 + \frac{1}{4}\lambda_{\text{eff}}\phi^4$

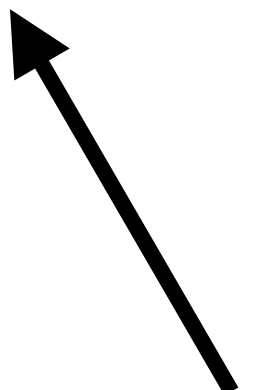
Cosmological
constant problem



Hierarchy
problem



Metastability of the
electroweak
vacuum



Motivation

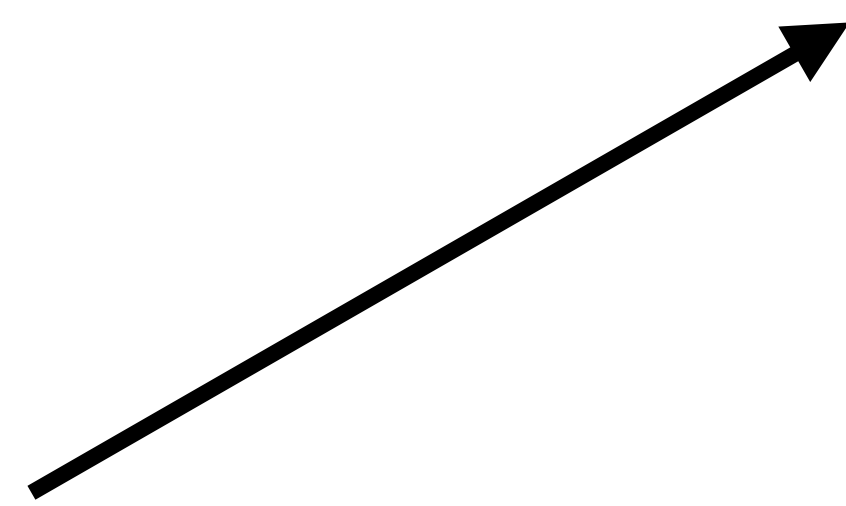
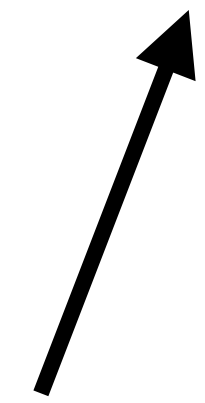
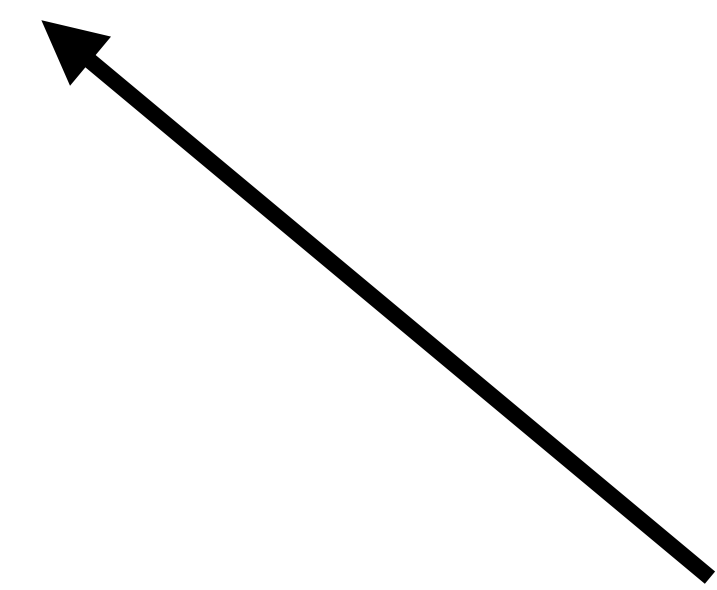
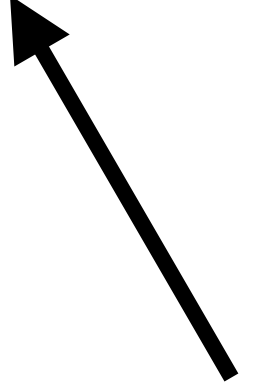
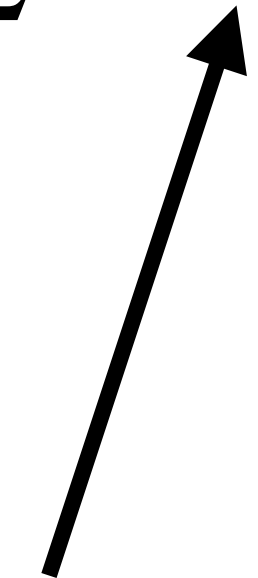
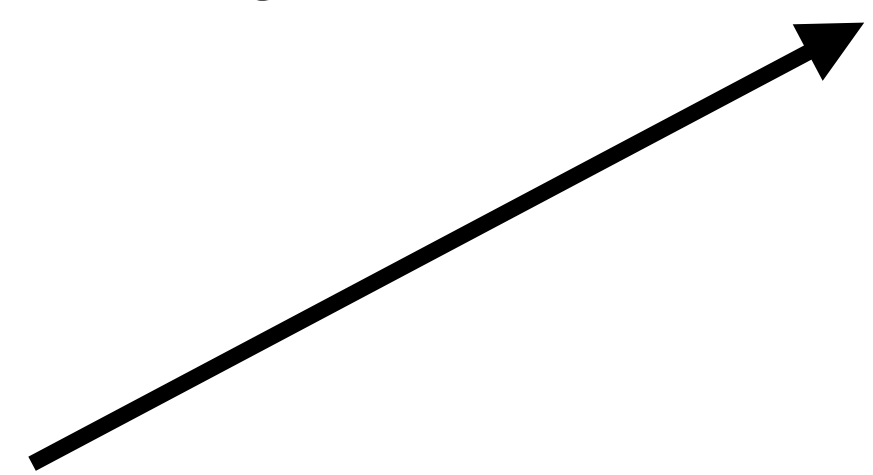
Higgs Potential: $V_{\text{eff}}(\phi) = V_0 - \frac{1}{2}m_{\text{eff}}^2\phi^2 + \frac{1}{4}\lambda_{\text{eff}}\phi^4$

Cosmological
constant problem

Hierarchy
problem

Metastability of the
electroweak
vacuum

Tuning* problems



The hierarchy problem*

SM as an EFT: $m_{\text{eff}}^2 = m_{\text{UV}}^2 + \delta m^2$

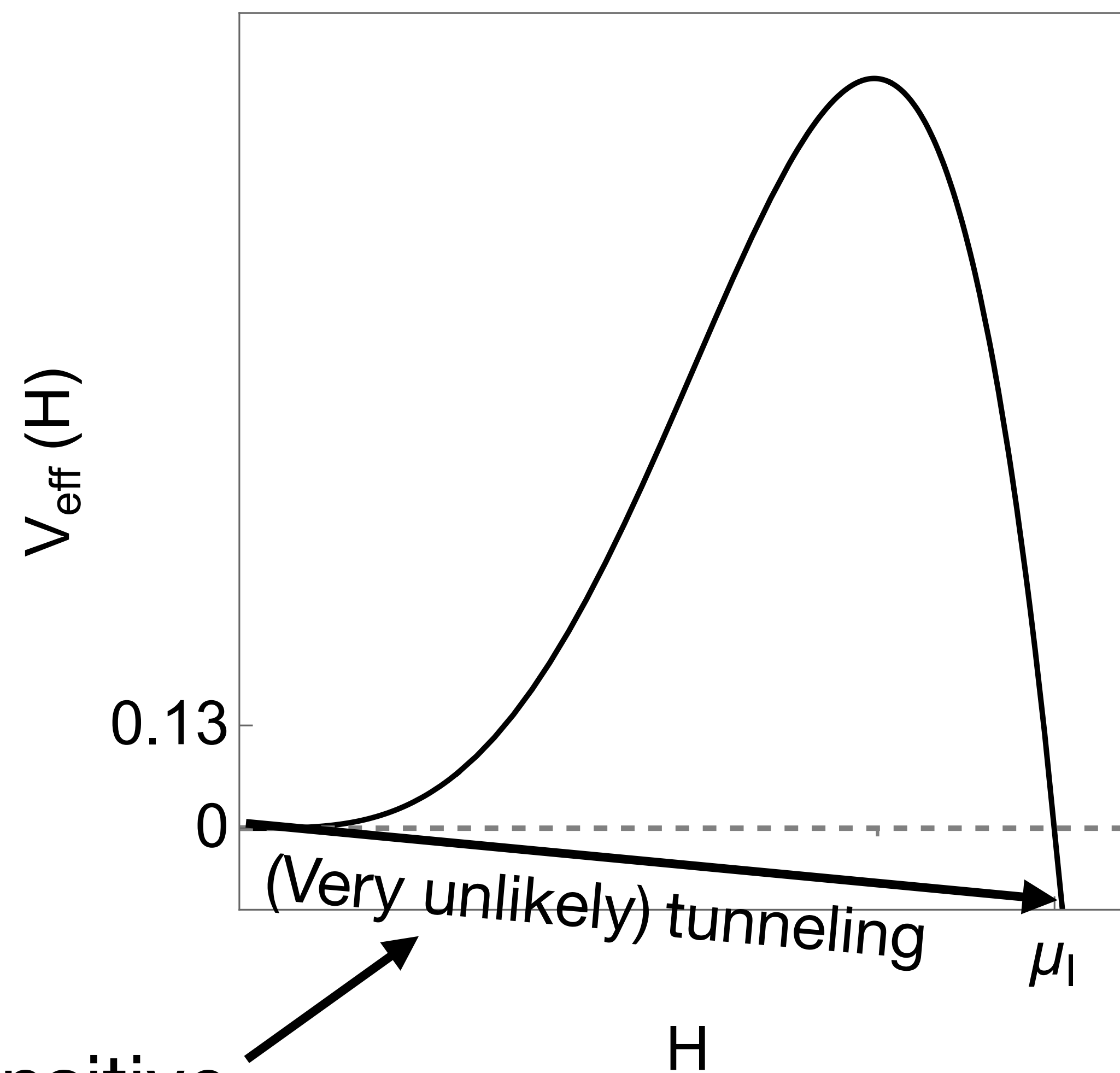
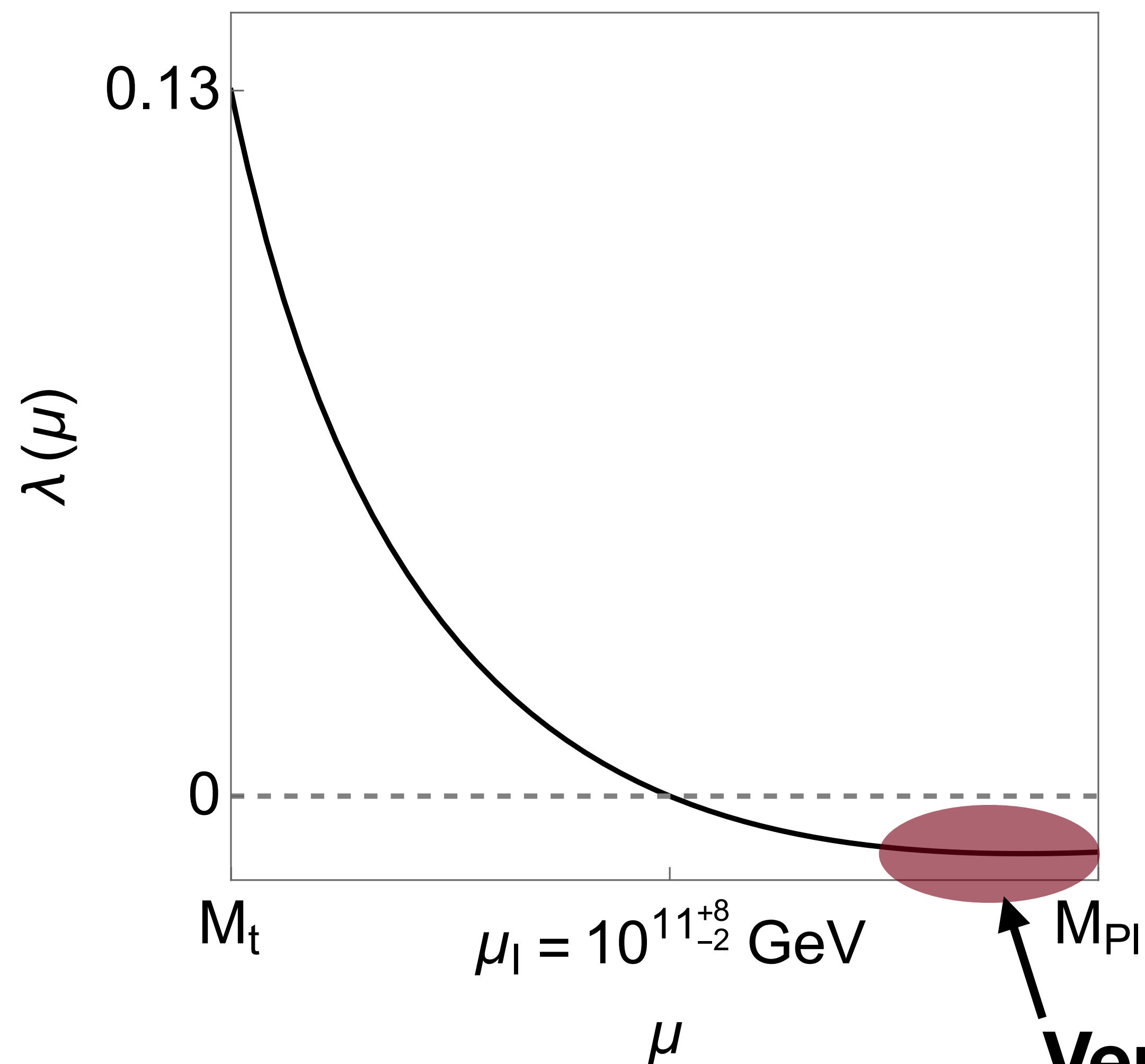
Typically of order $\sim \Lambda_{\text{UV}}^2 \sim M_{\text{heavy}}^2$

The diagram consists of two arrows. One arrow points vertically upwards from the text 'Typically of order' to the m_{UV}^2 term in the equation above. The other arrow points diagonally upwards and to the right from the text 'Typically of order' to the δm^2 term in the equation above.

$\Rightarrow m_{\text{eff}}^2 \ll M_{\text{heavy}}^2$ requires cancellations

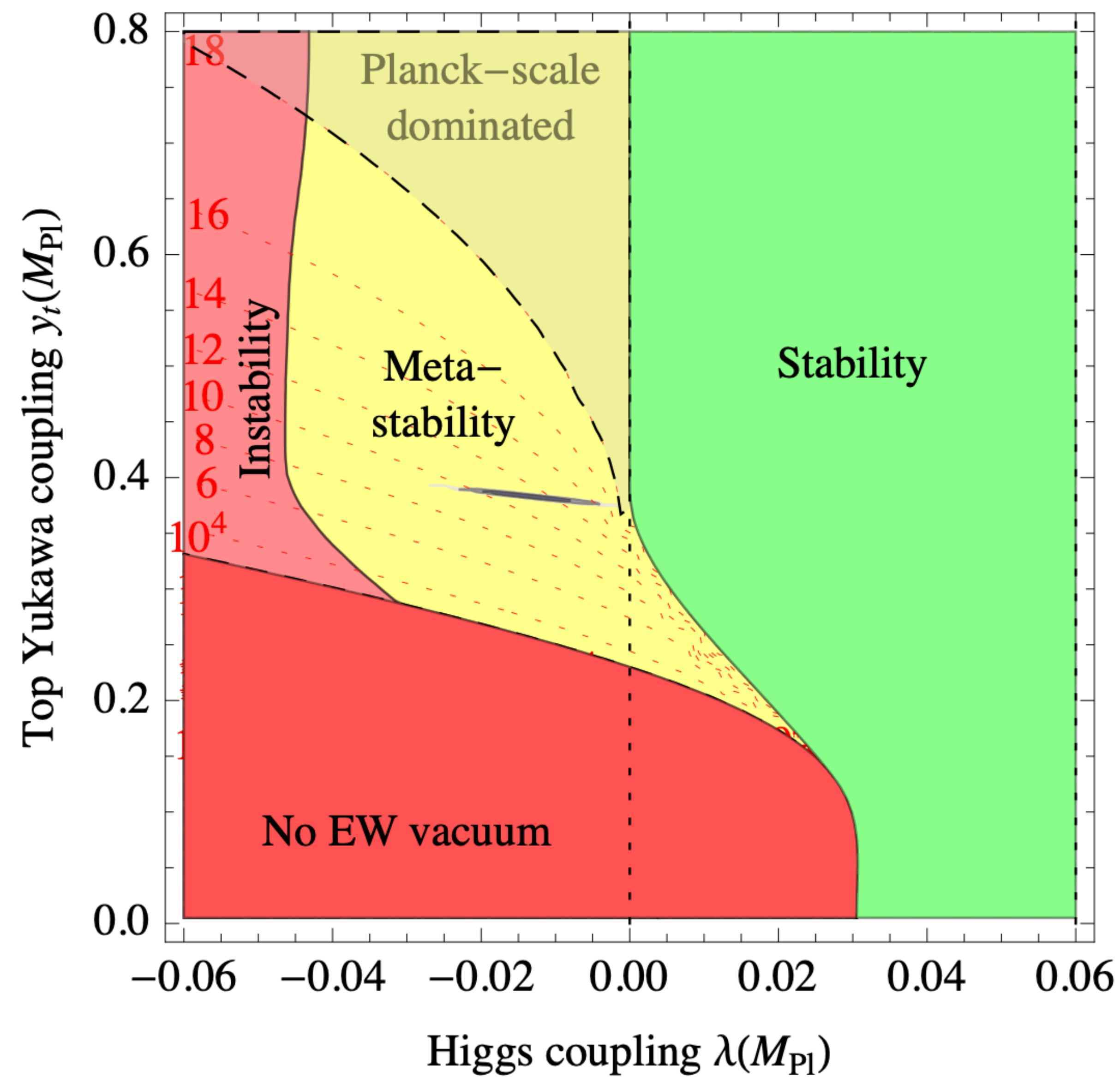
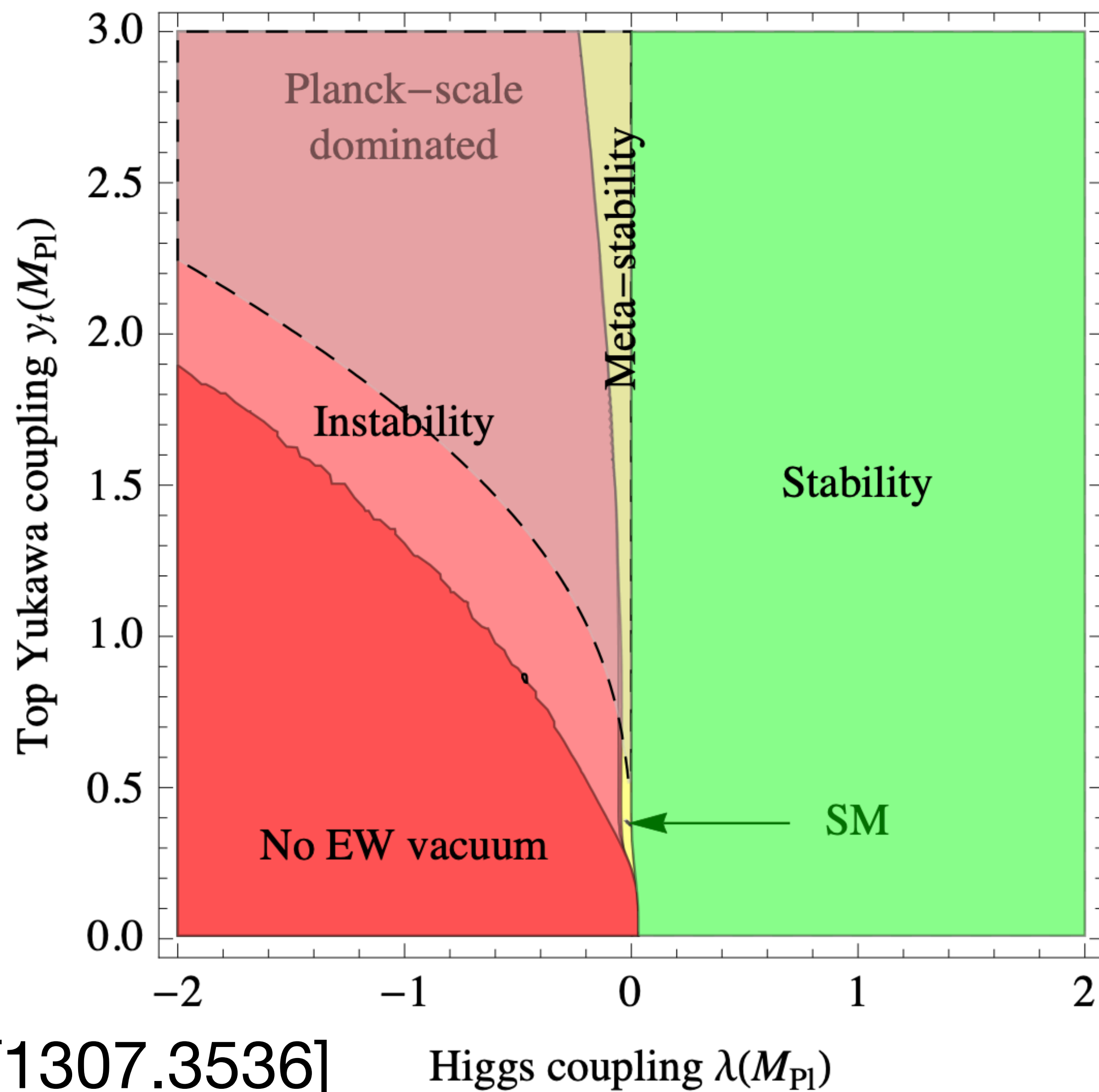
Metastability of the electroweak vacuum

Higgs Potential at high energies: $V_{\text{eff}}(H) \simeq \frac{1}{4} \lambda_{\text{eff}}(\mu = H) H^4$



Very sensitive

Metastability of the electroweak vacuum



Near-criticality in the SM

Higgs Potential:
$$V_{\text{eff}}(\phi) = V_0 - \frac{1}{2}m_{\text{eff}}^2\phi^2 + \frac{1}{4}\lambda_{\text{eff}}\phi^4$$

V_0 : close to transition “dS” \leftrightarrow ”AdS”

m_{eff}^2 : close to transition “SSB” \leftrightarrow ”no SSB”

λ_{eff} : close to transition “ v_{EW} stable” \leftrightarrow ” v_{EW} unstable”

Near-criticality in the SM

Higgs Potential:
$$V_{\text{eff}}(\phi) = V_0 - \frac{1}{2}m_{\text{eff}}^2\phi^2 + \frac{1}{4}\lambda_{\text{eff}}\phi^4$$

V_0 :
 m_{eff}^2 :
 λ_{eff} :

close to transition

close to transition

close to transition

“dS” ↔ “AdS”

“SSB” ↔ “no SSB”

“ v_{EW} stable” ↔ “ v_{EW} unstable”

↑
“Critical values”

↑
“Quantum phase transitions”

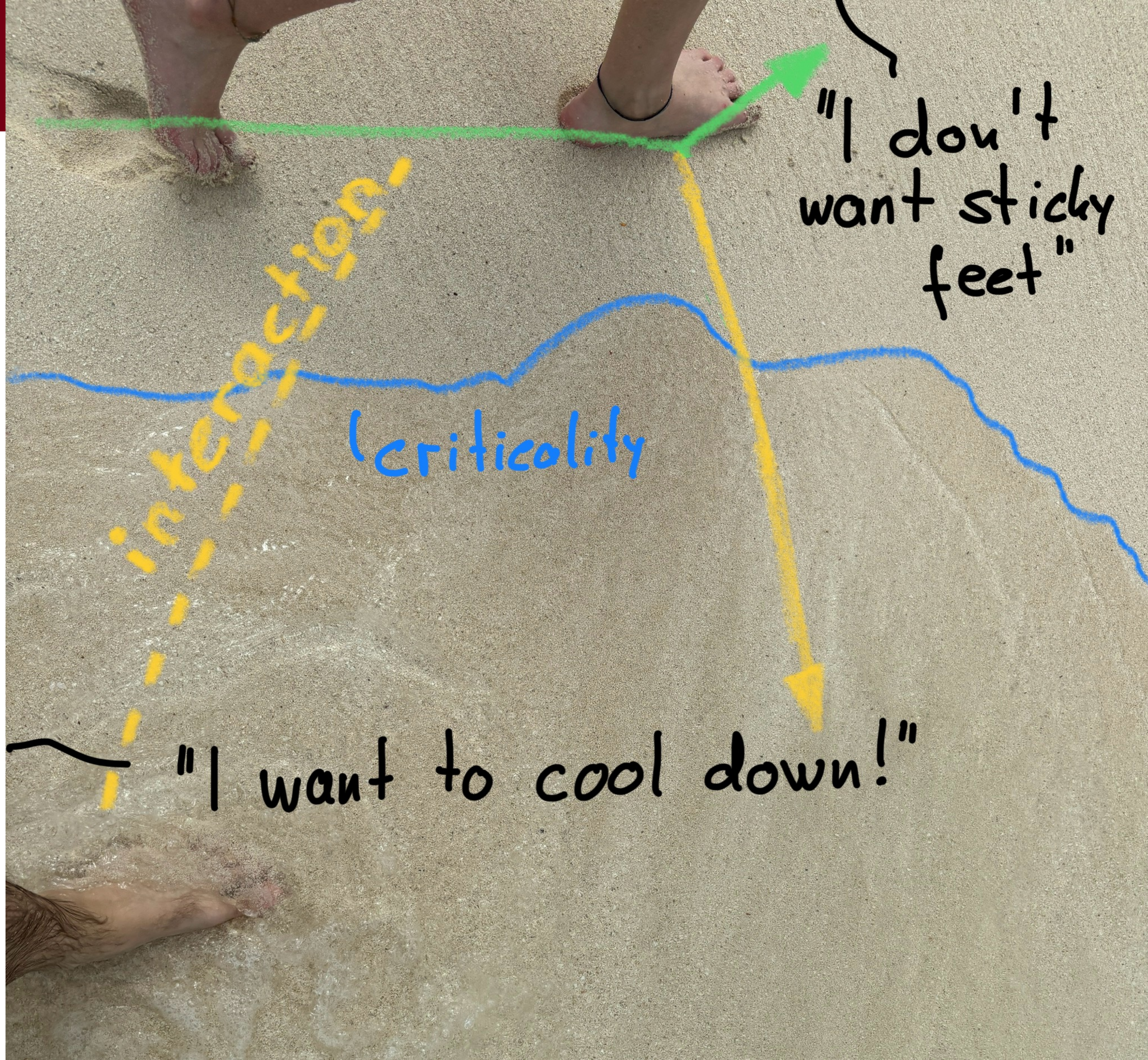
Analogy

Real life
particle physics
problem:



Analogy

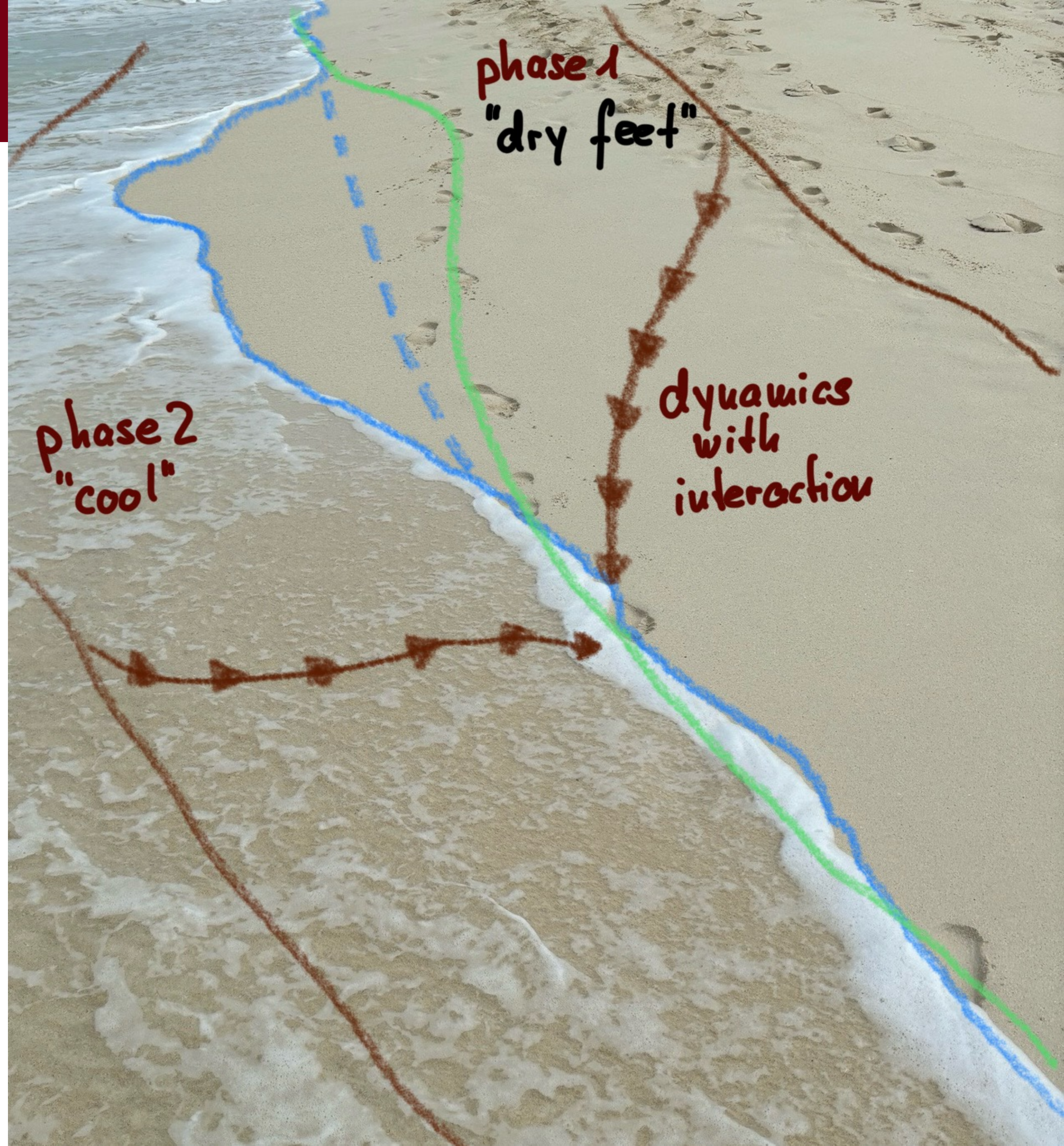
Dynamical system:



Analogy

“Criticality”
acts as attractor

→ “Self-organized
criticality”

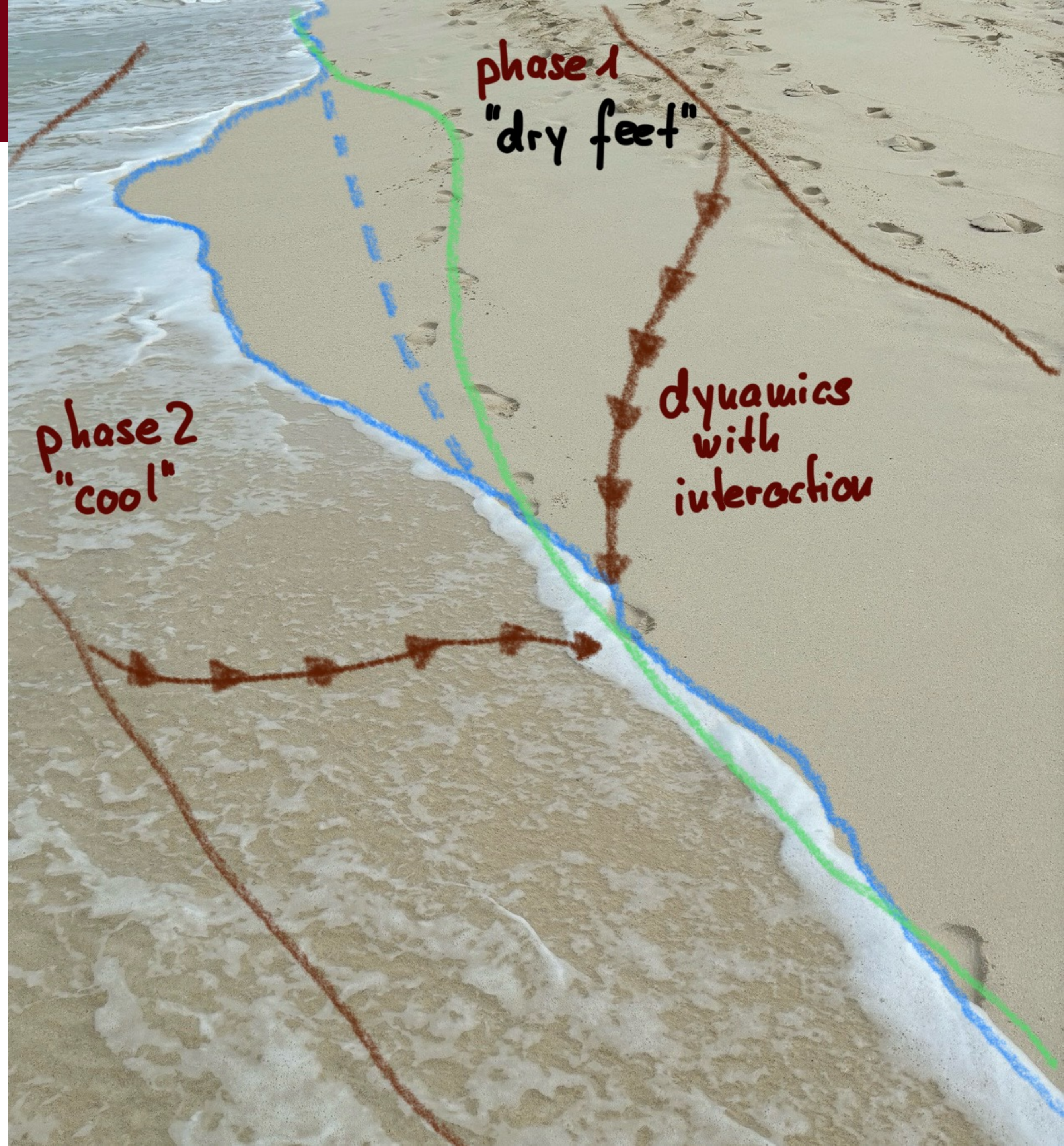


Analogy

“Criticality”
acts as attractor

→ “Self-organized
criticality”

→ Higgs parameters set
dynamically?
 (“Vacuum selection”)



Dynamical vacuum selection - Concrete examples

Self-organized localisation

$$[2105.08617]: V_{\text{eff}}(\phi) = V_0 - \frac{1}{2}m_{\text{eff}}^2\phi^2 + \frac{1}{4}\lambda_{\text{eff}}\phi^4$$

↓ New scalar

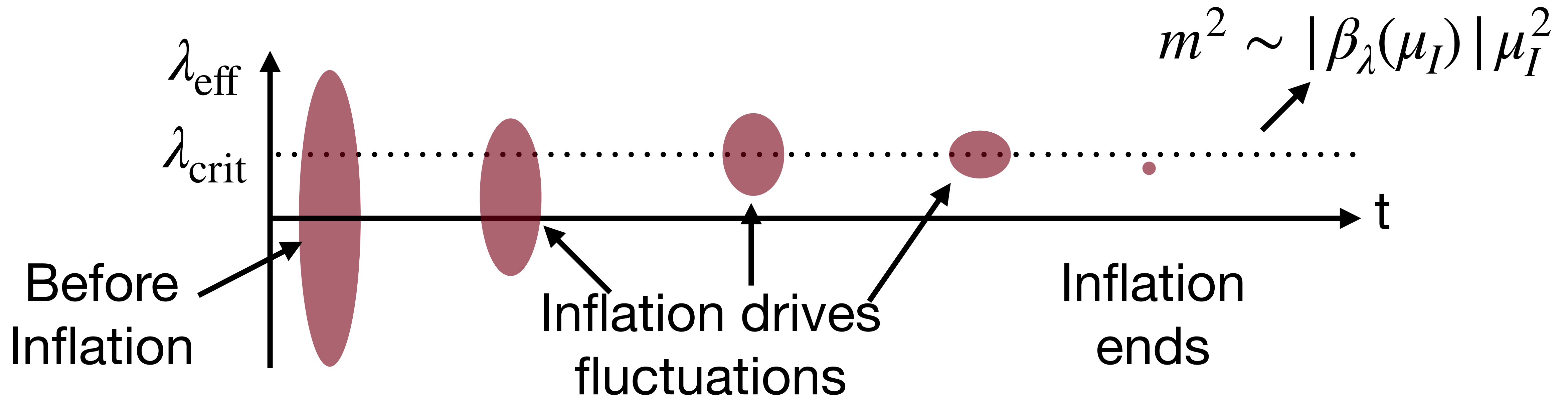
$$V_{\text{eff}}(\phi, \sigma) = V_0 - \frac{1}{2}m_{\text{eff}}^2(\sigma)\phi^2 + \frac{1}{4}\lambda_{\text{eff}}(\sigma)\phi^4 + \dots$$

Self-organized localisation

[2105.08617]:
$$V_{\text{eff}}(\phi) = V_0 - \frac{1}{2}m_{\text{eff}}^2\phi^2 + \frac{1}{4}\lambda_{\text{eff}}\phi^4$$

New scalar

$$V_{\text{eff}}(\phi, \sigma) = V_0 - \frac{1}{2}m_{\text{eff}}^2(\sigma)\phi^2 + \frac{1}{4}\lambda_{\text{eff}}(\sigma)\phi^4 + \dots$$



Landscape statistics



[1907.07693]

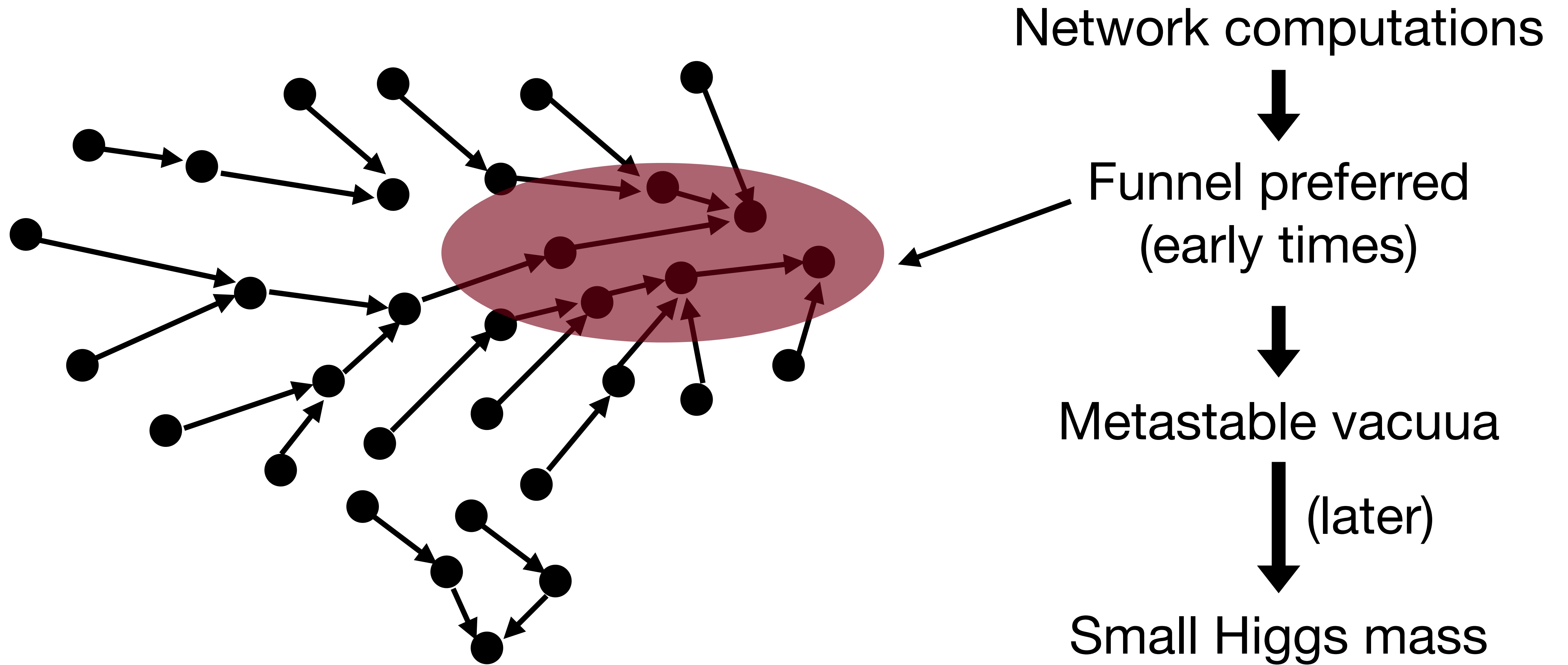


landscape
= network,

vacuum
= node,

tunneling
= links

Landscape statistics



Overview

→ Standard Model Higgs:

~~Naturalness~~ → (Near-)Criticality?

Overview

→ Standard Model Higgs:

~~Naturalness~~ → (Near-)Criticality?

Our work: effect on BSM physics?

→ Reasonable: BSM physics also near-critical?

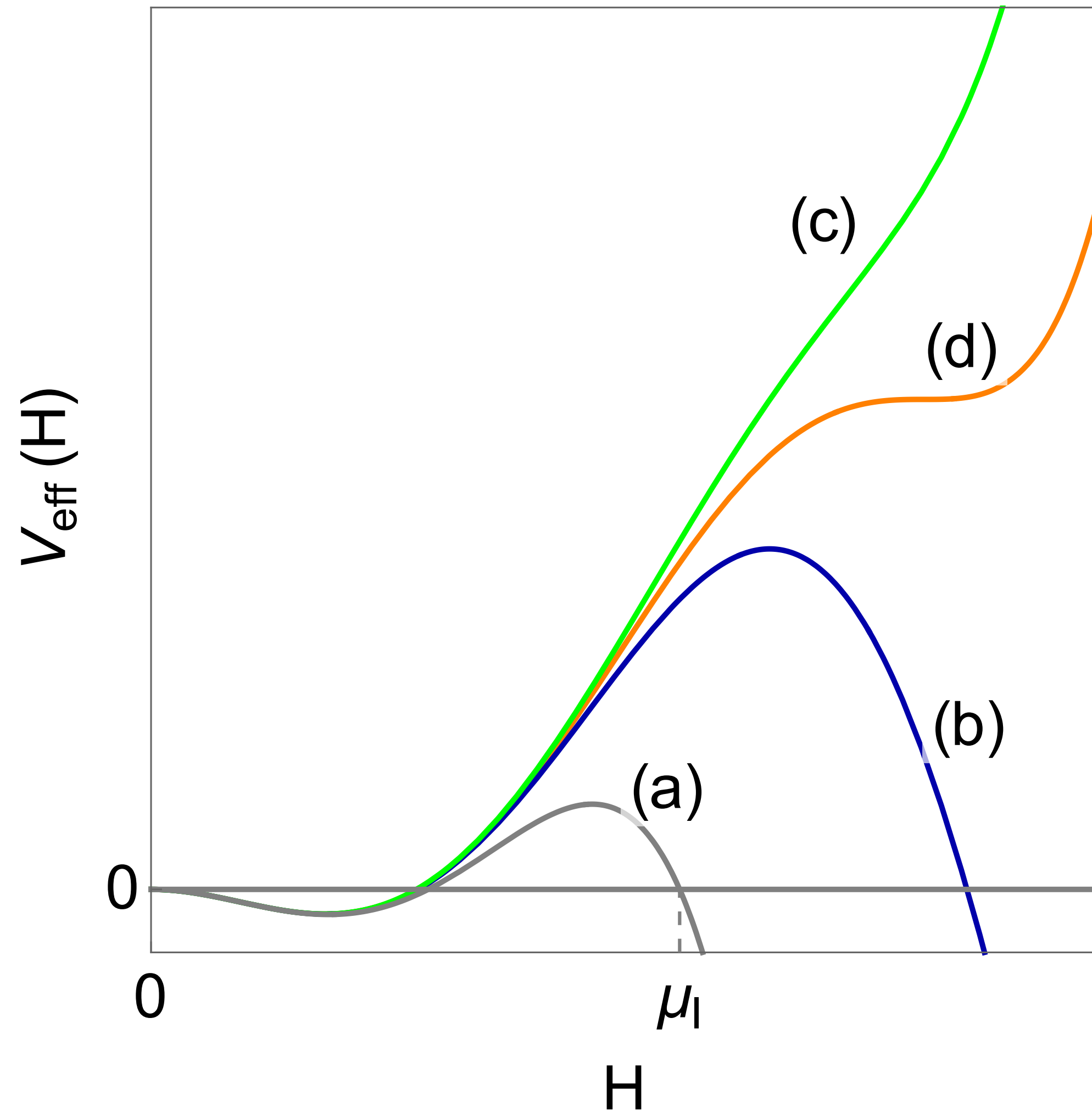
↙
Phenomenological
consequences

↘
Investigate quantum phases
more generally

Near-critical BSM model building

Critical BSM physics - toy model

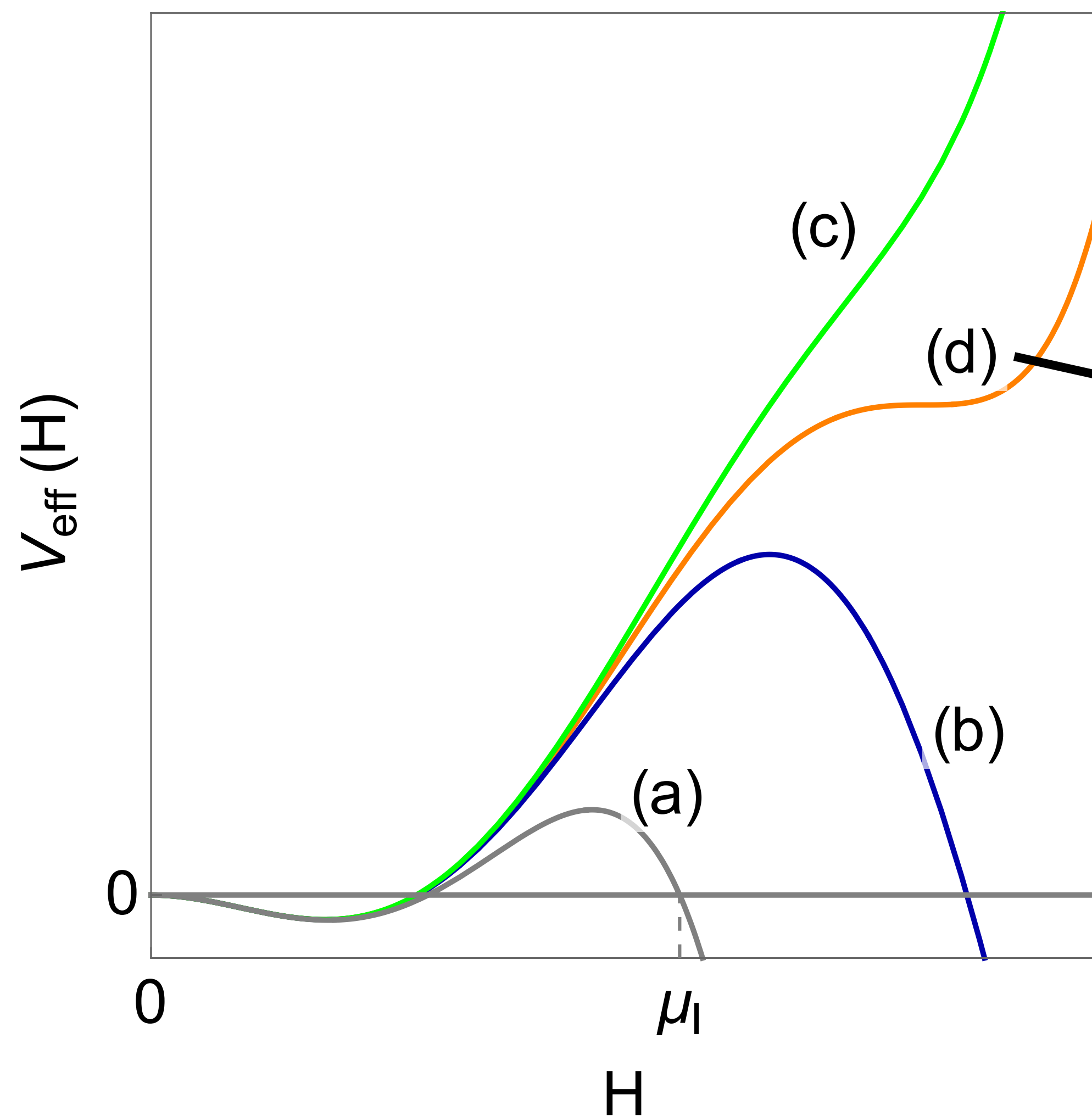
Simplest scenario: $V_{\text{eff}}(\phi) \rightarrow V_{\text{eff}}(\phi) + \frac{C_6}{\Lambda_{\text{UV}}^2} \phi^6 + \dots$



[2307.10361]

Critical BSM physics - toy model

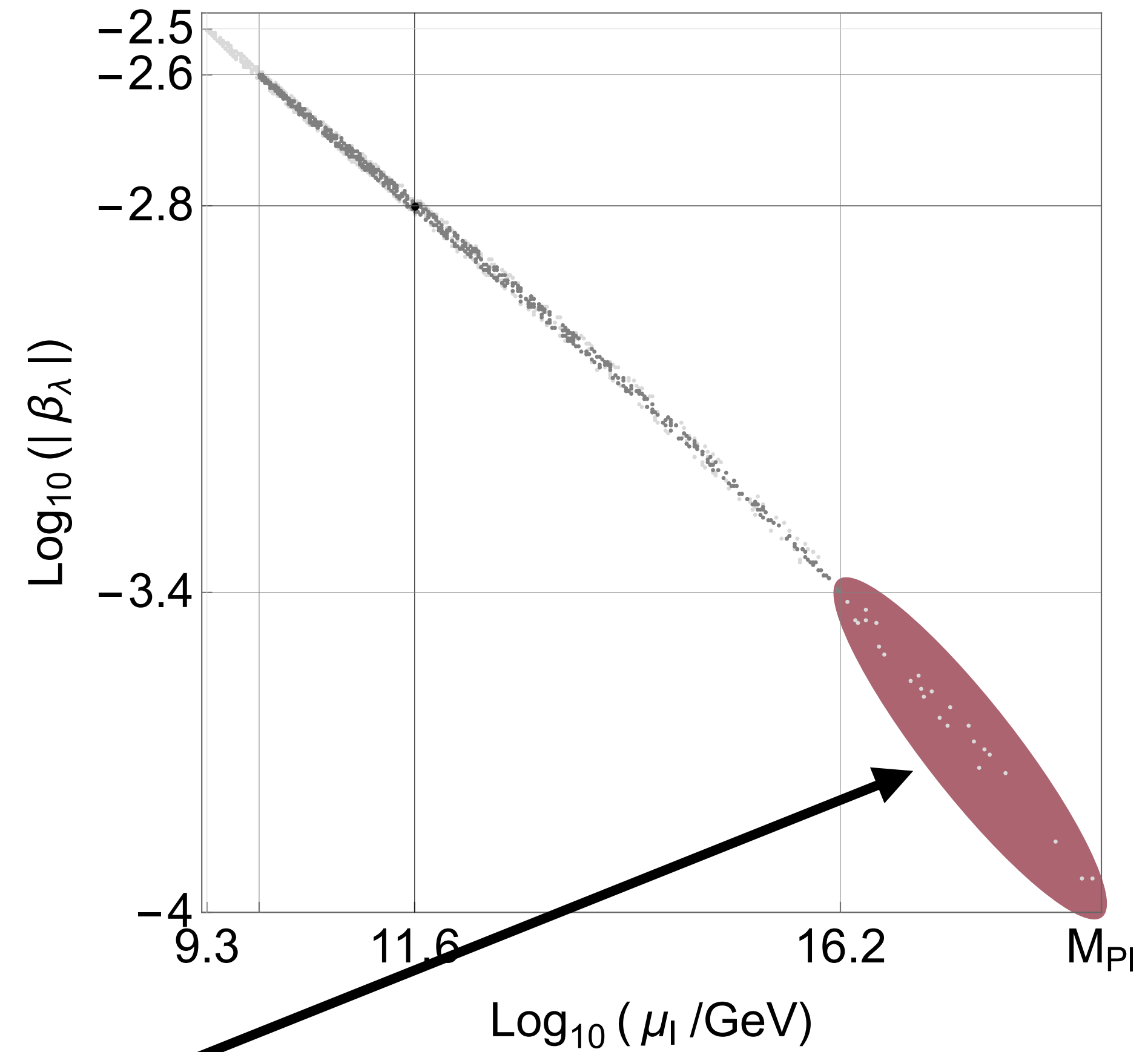
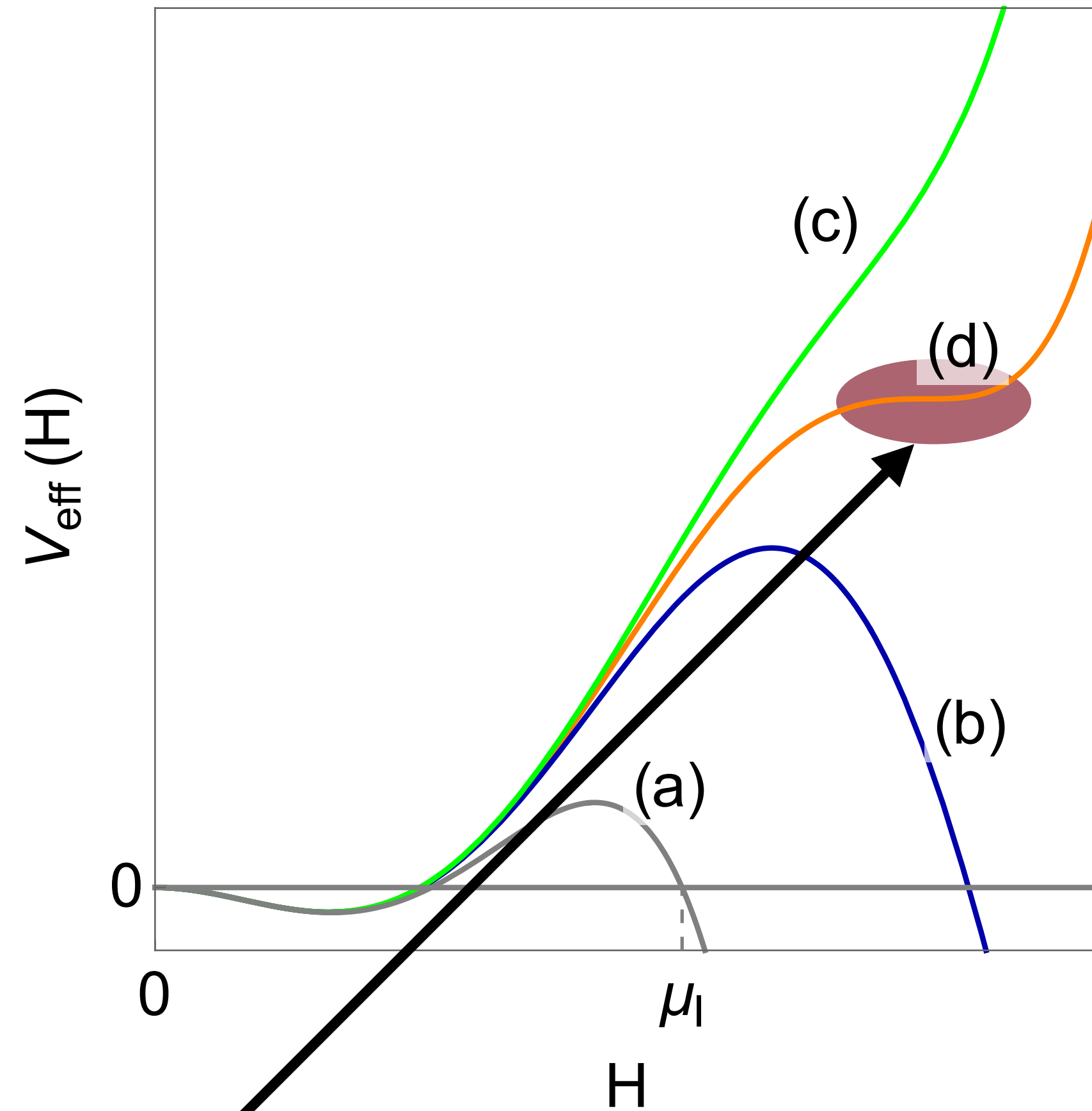
Simplest scenario: $V_{\text{eff}}(\phi) \rightarrow V_{\text{eff}}(\phi) + \frac{C_6}{\Lambda_{\text{UV}}^2} \phi^6 + \dots$



$$\left(\frac{C_6}{\Lambda_{\text{UV}}^2} \right)_{\text{crit.}} = (12\sqrt{e})^{-1} \cdot \frac{|\beta_\lambda(\mu_I)|}{\mu_I^2}$$

[2307.10361]

Critical BSM physics - relevant scales?



Saddle point near Planck scale \longrightarrow Inflation, PBHs?

General feature! ([2205.04471])

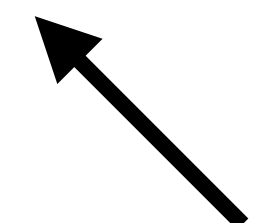
Critical BSM physics - low scales?

Running of λ : $\beta_\lambda = (4\pi)^{-2} [24\lambda^2 - 6y_t^4 + \dots]$

RHN: $\beta_\lambda \rightarrow \beta_\lambda - 2\text{Tr}(Y_\nu^\dagger Y_\nu Y_\nu^\dagger Y_\nu)/(4\pi)^2$

$$\beta_{y_t} \rightarrow \beta_{y_t} + 2\text{Tr}(Y_\nu^\dagger Y_\nu)/(4\pi)^2$$

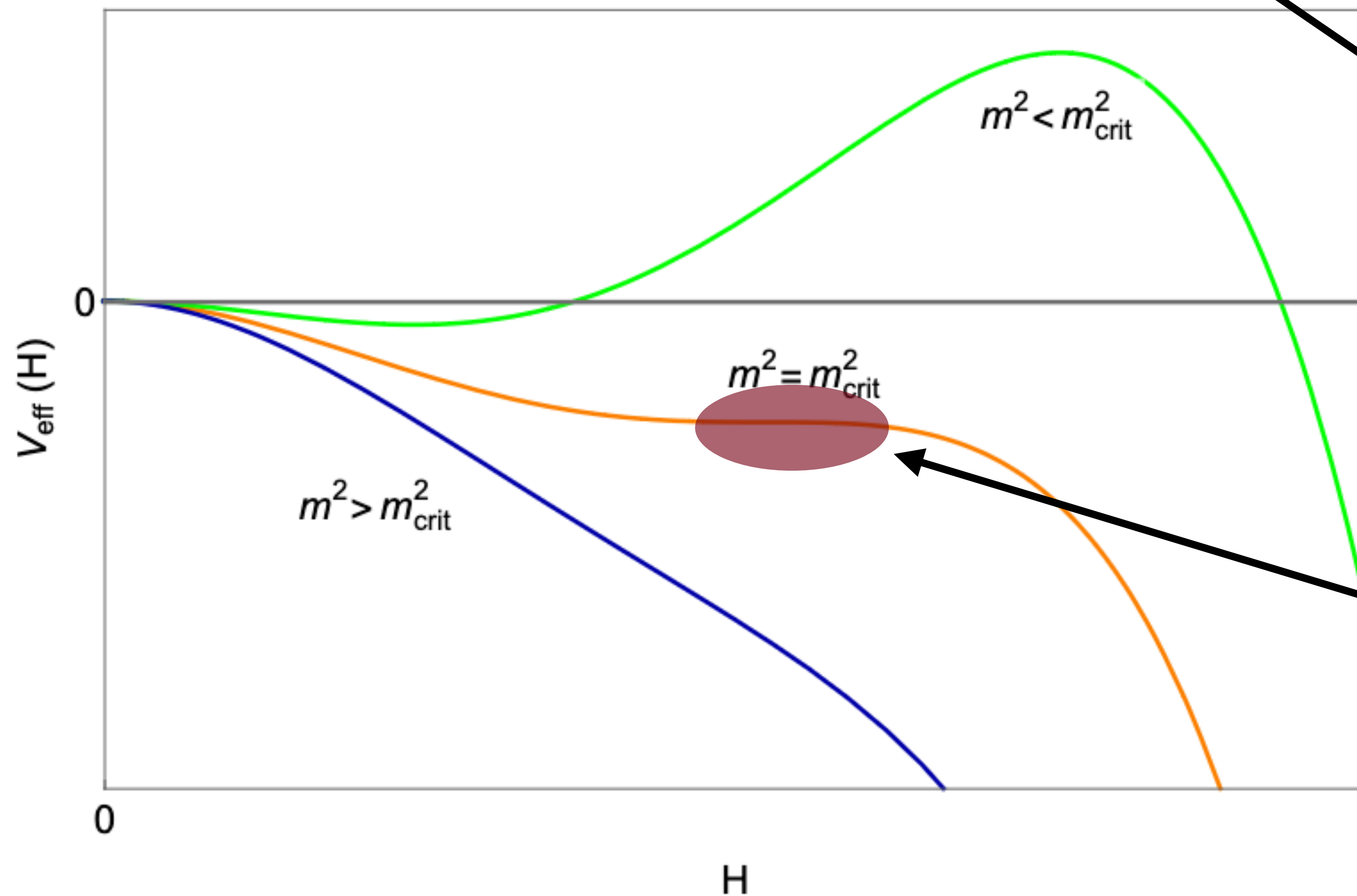
EWPD + RHN: $\mu_I \gtrsim \mathcal{O}(\text{TeV})$

 [2410.xxxxxx]

Understanding quantum phases & metastability bounds

Metastability bounds - a new phase transition

$$[1307.3536]: |m^2| \lesssim |\beta_\lambda(\mu_I)| \mu_I^2$$



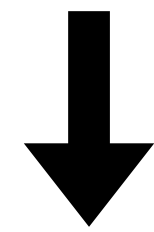
Hierarchy and
metastability!

Phase transition!

→ SOL

Metastability bounds - idea

SM tunings not independent?



One less explanation necessary

Very
technical

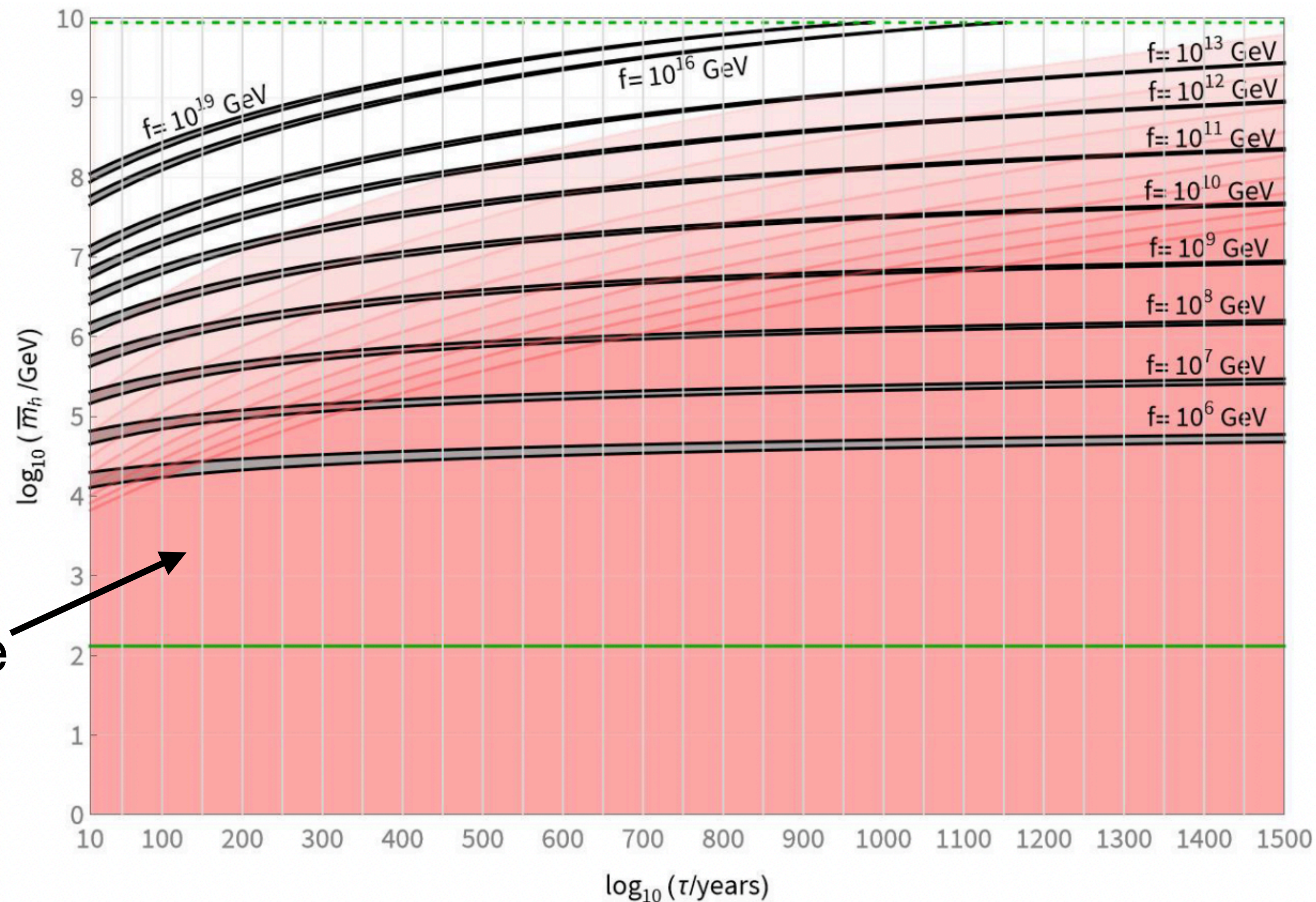
Metastability+SSB $\rightarrow |m^2| \lesssim |\beta_\lambda(\mu_I)| \mu_I^2 \ll \Lambda_{UV}^2$



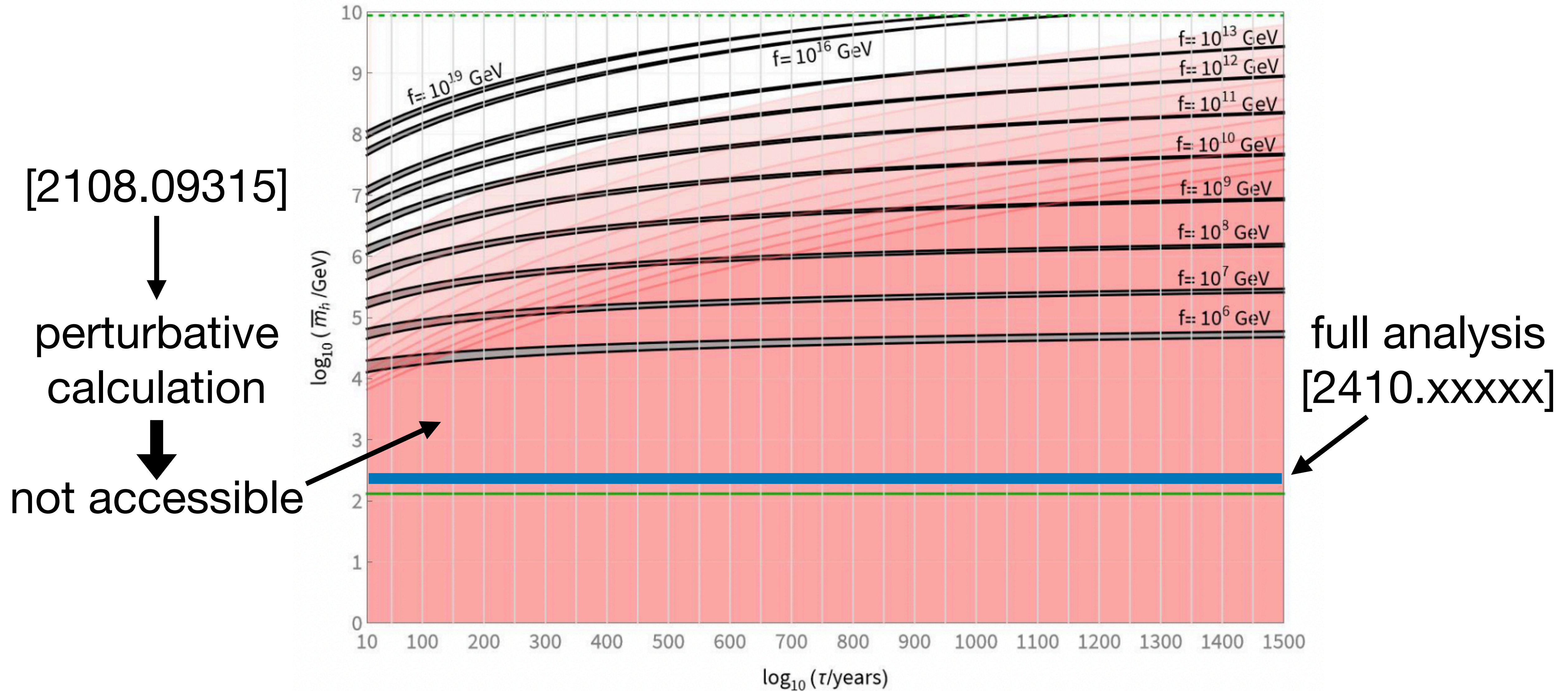
For **any** reason!

Metastability bounds - numerical results

[2108.09315]
↓
perturbative
calculation
↓
not accessible

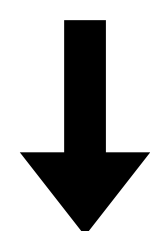


Metastability bounds - numerical results



Metastability bounds - idea

SM tunings not independent?



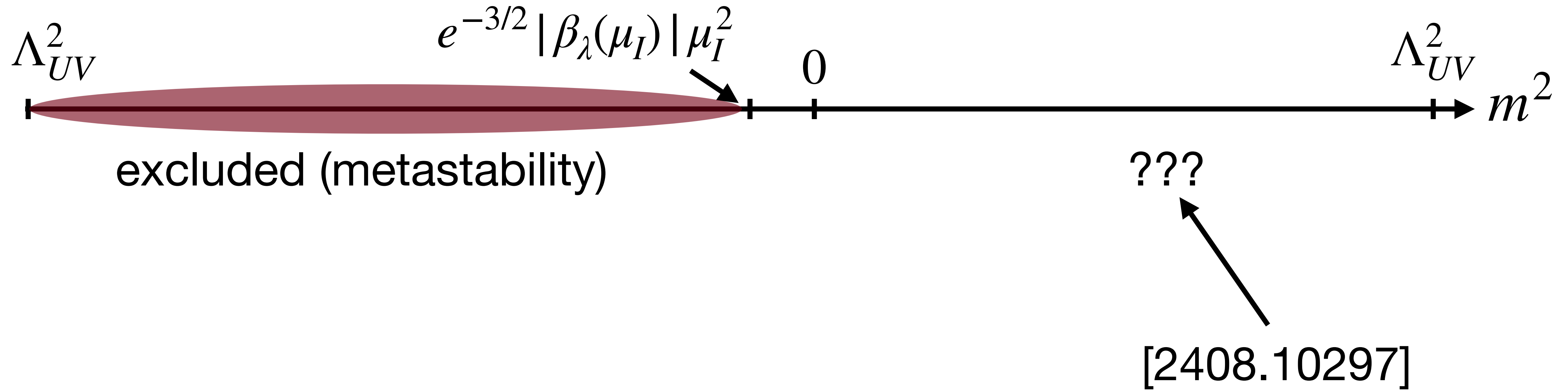
One less explanation necessary

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technical

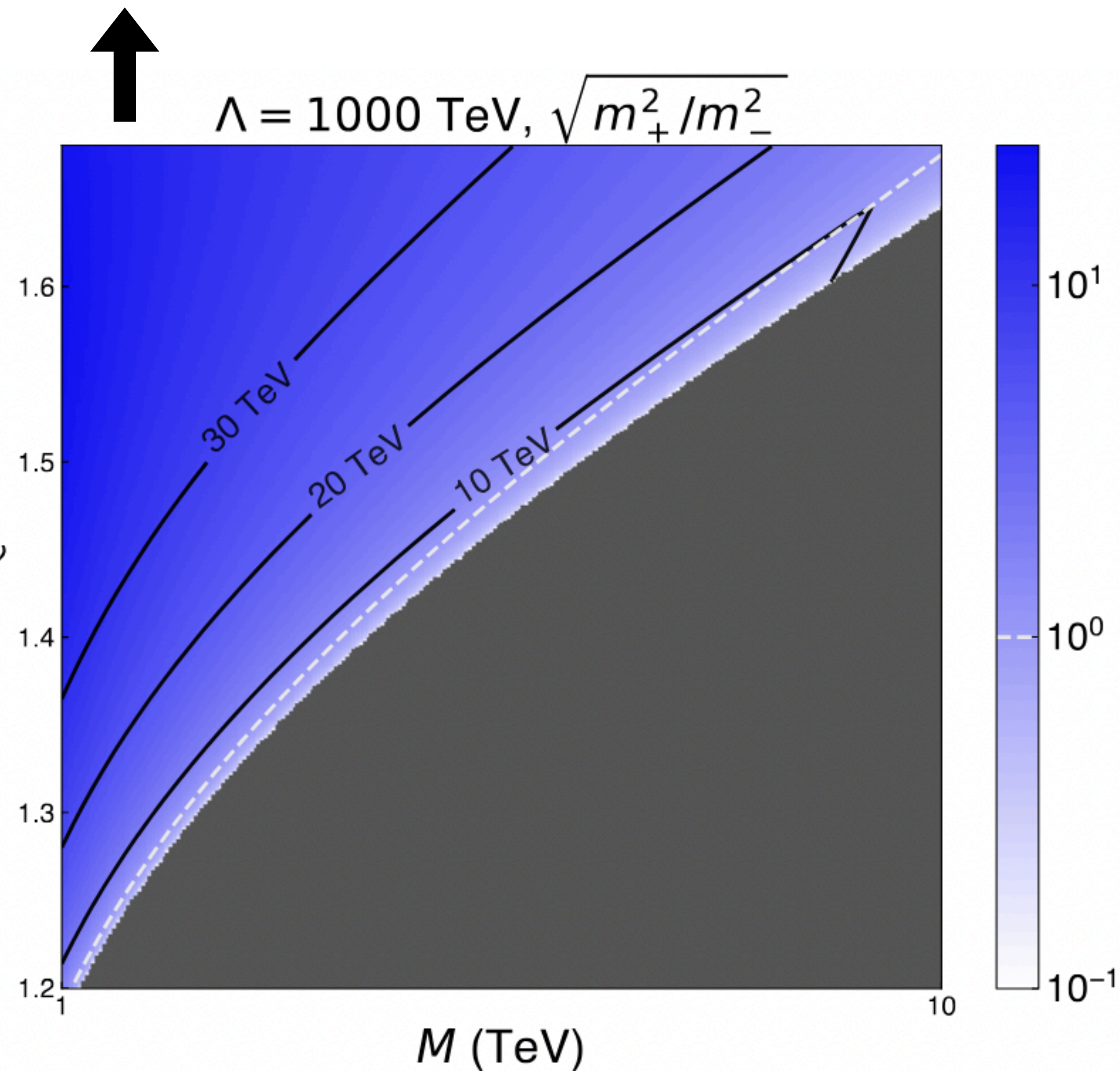
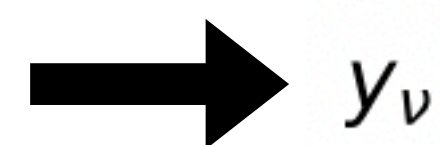
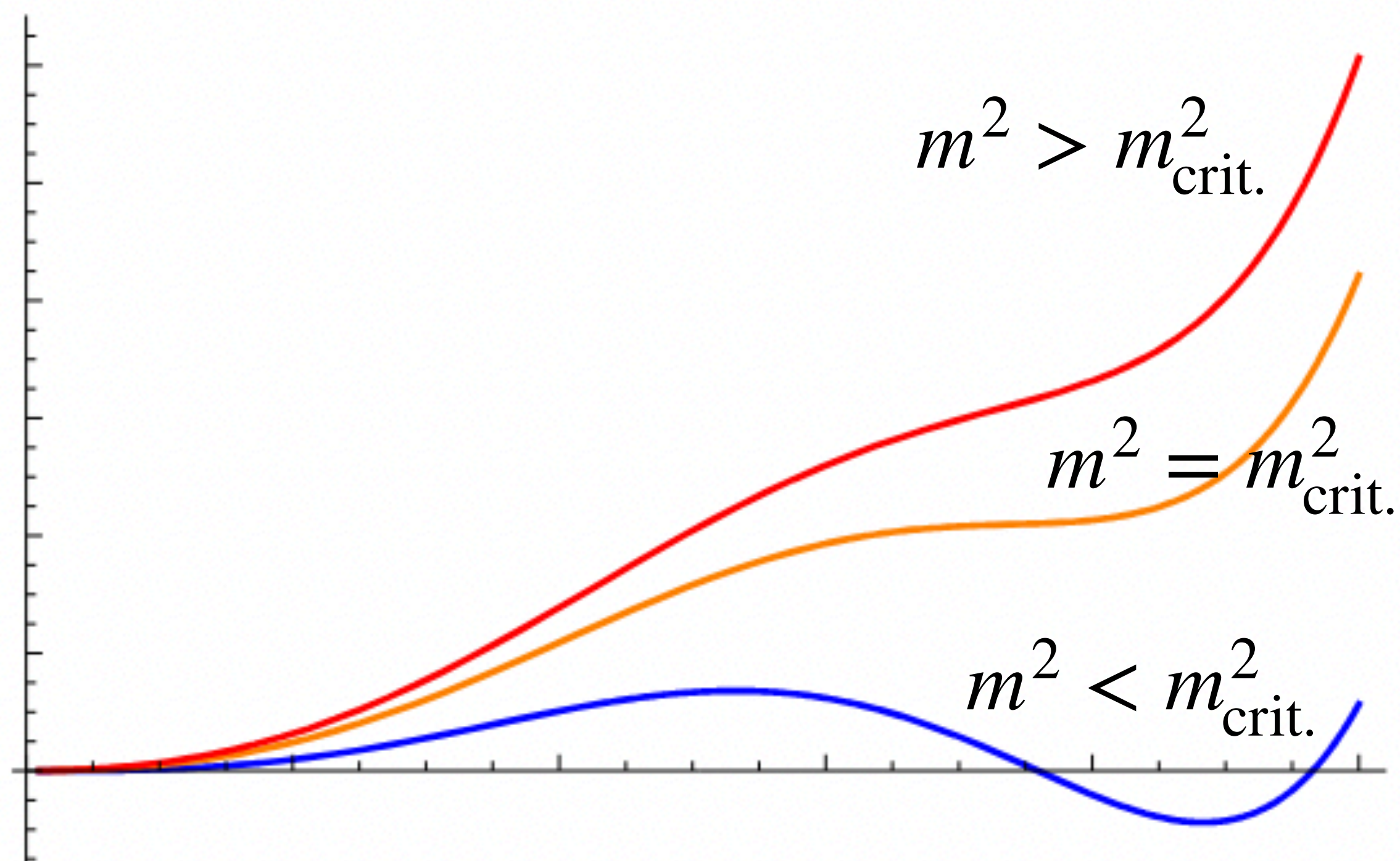
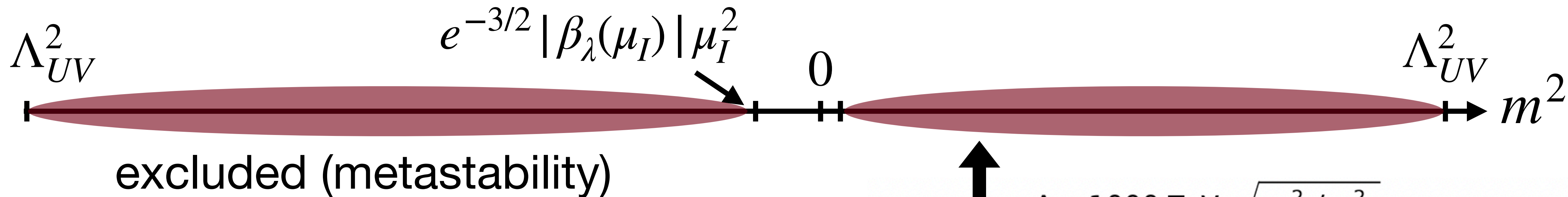
Metastability + SSB $\rightarrow |m^2| \lesssim |\beta_\lambda(\mu_I)| \mu_I^2 \ll \Lambda_{UV}^2$

For **any** reason!

Metastability bounds - explaining SSB?

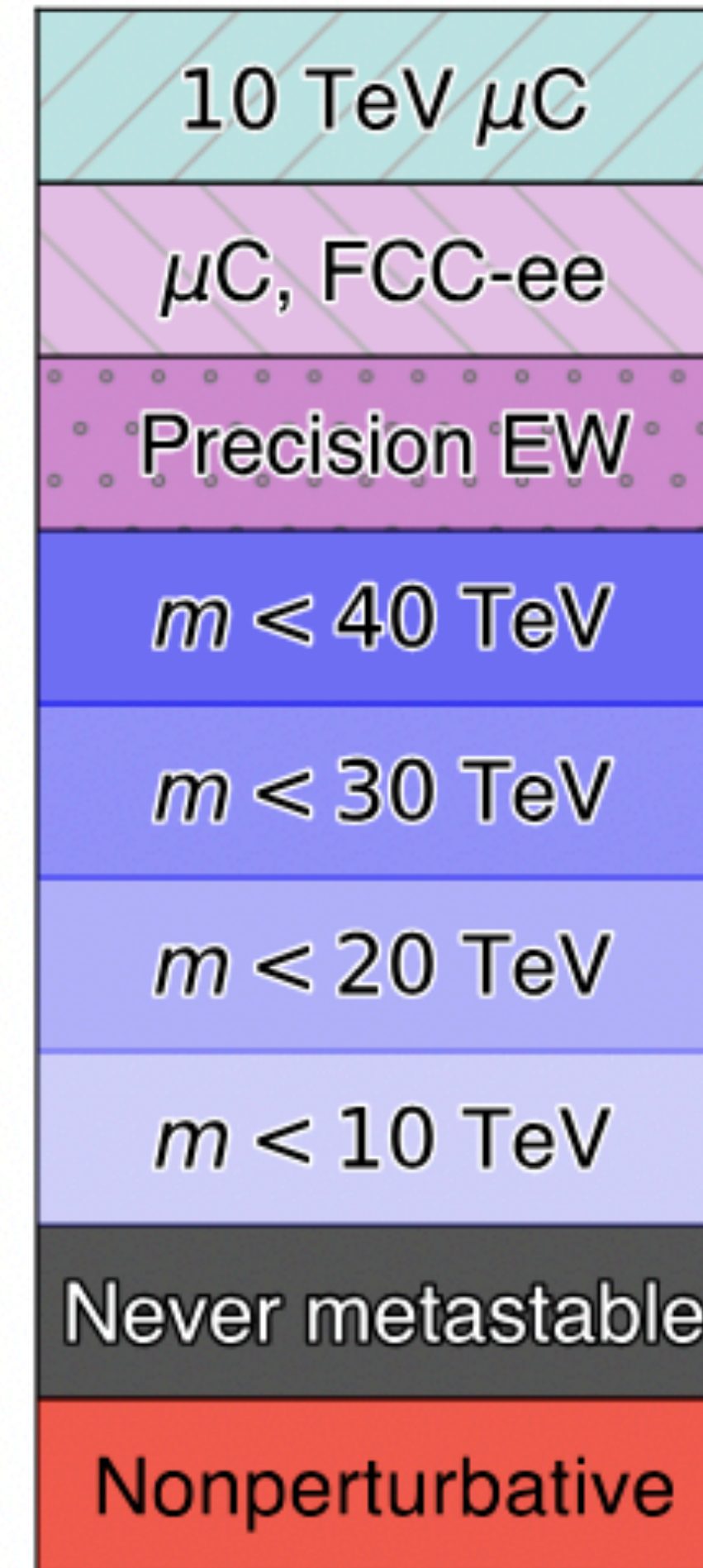
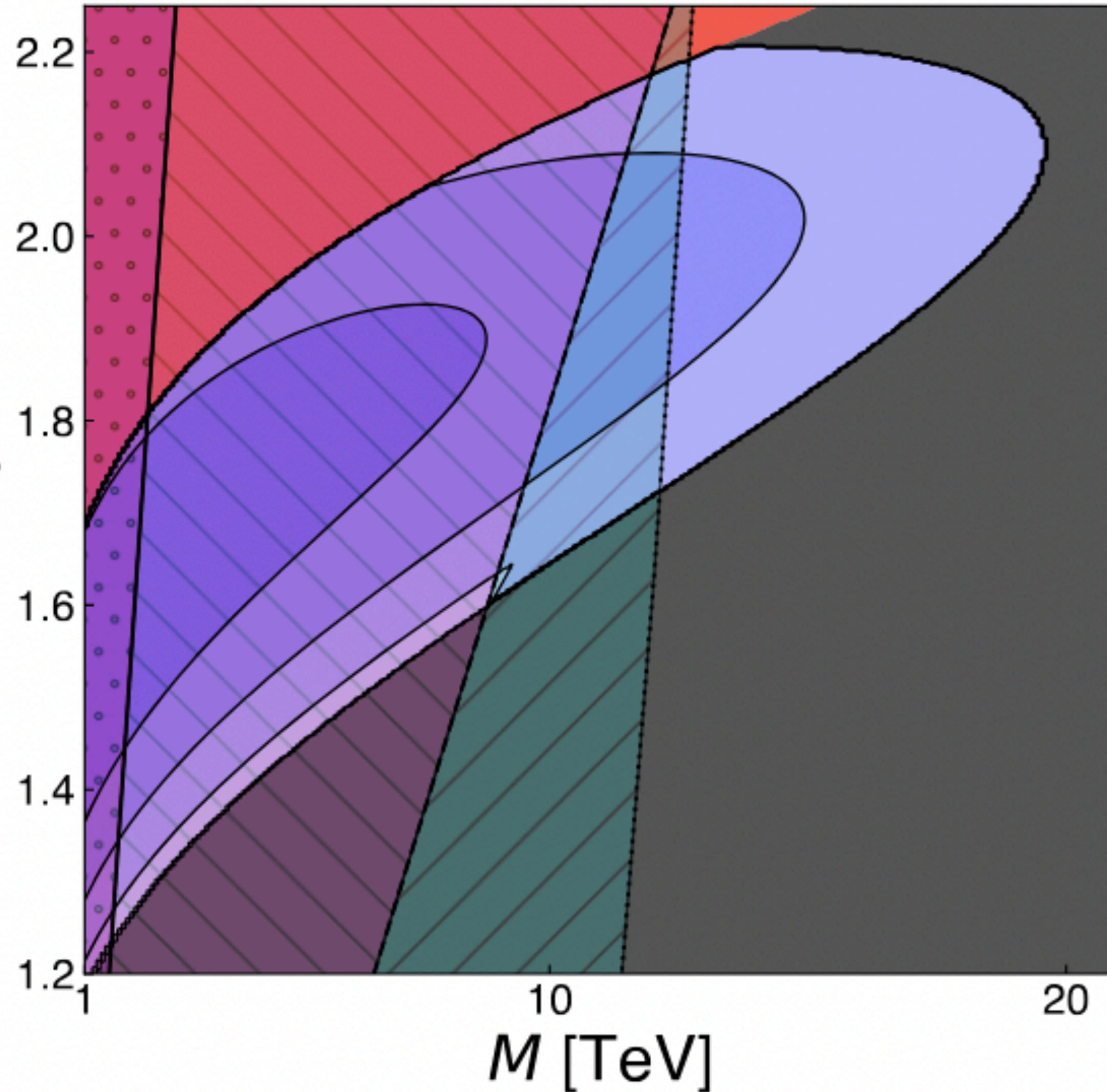


Metastability bounds - explaining SSB?



Metastability bounds - explaining SSB?

$\Lambda = 1000$ TeV, combined bound



stabilizing
physics



[2410.xxxxxx]

[2408.10297]: y_ν



Thank you for your attention!

tstngssr@mit.edu

Summary: [2405.02415]