Higgs criticality and the stability of the universe

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Physics on the Riviera: an isthmus between high energy and condensed matter theoretical physics

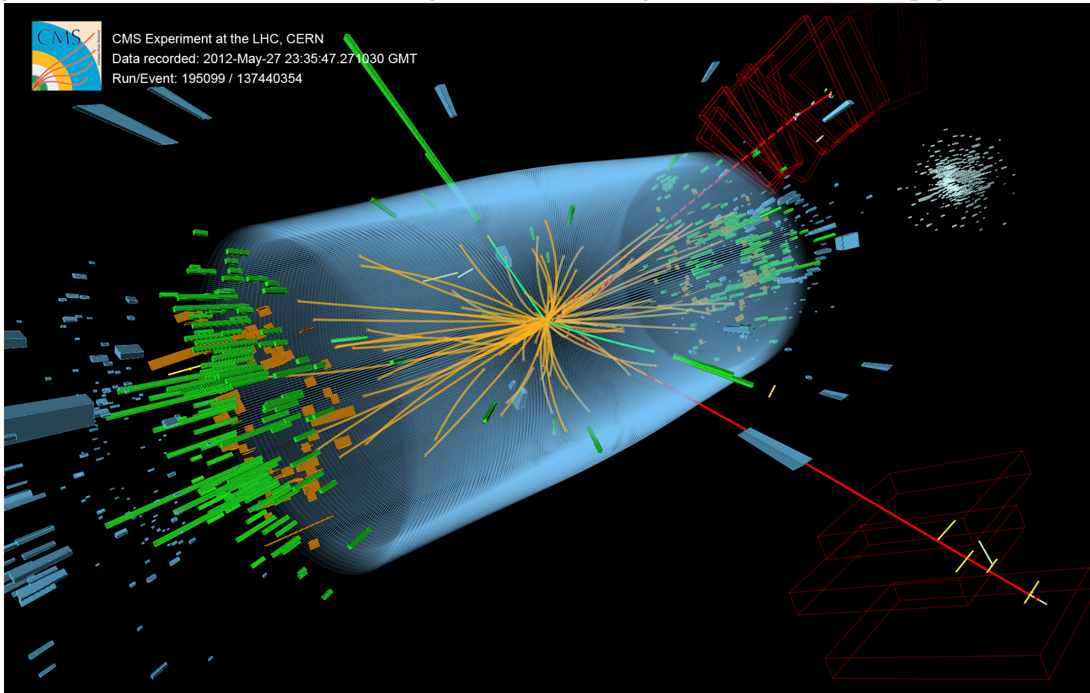
Sestri Levante 16-18 September 2015

While the phenomenon of ~~EW~~ had already been established before LHC...

- gauge structure also in TGC (γWW, ZWW)
- *W* and *Z* longitudinal polarizations
- masses of *W*, *Z*, quarks

propagating particles do not share the full symmetry of interactions
(spontaneous symmetry breaking)

... the LHC discovered its UV completion



Closing a chapter... and opening a new one

Almost all problems of the SM originate from Higgs interactions

$$L = \left(h_{ij}\bar{\psi}_i \psi_j H + \text{h.c.}\right) - \lambda \left|H\right|^4 + \mu^2 \left|H\right|^2 - \Lambda_{CC}^4$$

Flavor puzzle

Stability of the potential

Hierarchy problem

Cosmological constant problem

Just because the 5th force is not a gauge force...

Gauge forces: $$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$$

- elegant
- robust
- predictive

Not the case for the 5th force...

Can we reconcile the 5th force with the symmetry paradigm or can we find a new paradigm?

1) Flavor puzzle

$$L = \left(h_{ij}\bar{\psi}_i \psi_j H + \text{h.c.}\right) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda_{CC}^4$$

$$h_u = V_{q_L}^{+} \begin{pmatrix} 7.3\times 10^{-6} & & \\ & 3.6\times 10^{-3} & \\ & & 0.99 \end{pmatrix} V_{u_R} \qquad \text{at } \mu = M_Z$$

$$h_d = V_{q_L}^{+} \begin{pmatrix} 0.97 & 0.23 & 4.1\times 10^{-3} \\ 0.23 & 0.99 & 4.1\times 10^{-2} \\ 8.4\times 10^{-3} & 4.0\times 10^{-2} & 1.0 \end{pmatrix} \begin{pmatrix} 1.7\times 10^{-5} & & \\ & 3.2\times 10^{-4} & \\ & & 1.7\times 10^{-2} \end{pmatrix} V_{d_R}$$

$$h_e = V_{\ell_L}^{+} \begin{pmatrix} 2.8\times 10^{-6} & & \\ & 5.9\times 10^{-4} & \\ & & 1.0\times 10^{-2} \end{pmatrix} V_{e_R}$$

A pattern is manifest, but a successful symmetry explanation has never been found

2) Cosmological constant

$$L = \left(h_{ij}\bar{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda_{CC}^4$$

$\rho_{CC} = \Lambda_{CC}^4 < 6\times10^{-30}\ \text{g cm}^{-3} \Rightarrow \Lambda_{CC} < 2\times10^{-3}\ \text{eV}$

Symmetry + dynamics ???

Weinberg: environmental explanation

- Numerology

Largest scale = Hubble length $H^{-1} = 10^{26}$ m

Smallest scale = Planck length $M_{Pl}^{-1} = 10^{-35}$ m

$\rho_{CC} = H^2 M_{Pl}^2 \Rightarrow \Lambda_{CC} = 5\times10^{-3}\ \text{eV}$

$\Lambda_{CC} = (\text{TeV})^2 / M_P \Rightarrow \Lambda_{CC} = 0.4\times10^{-3}\ \text{eV}$

IR/UV connection signals breakdown of EFT understanding?

3) Hierarchy problem

$$L = \left(h_{ij}\bar{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda_{CC}^4$$

- Bringing back the 5th force into the gauge paradigm... **technicolor**

  → **Dead !**

- Using symmetry to enforce $\mu^2 = 0$

  Supersymmetry (+ chiral symmetry)

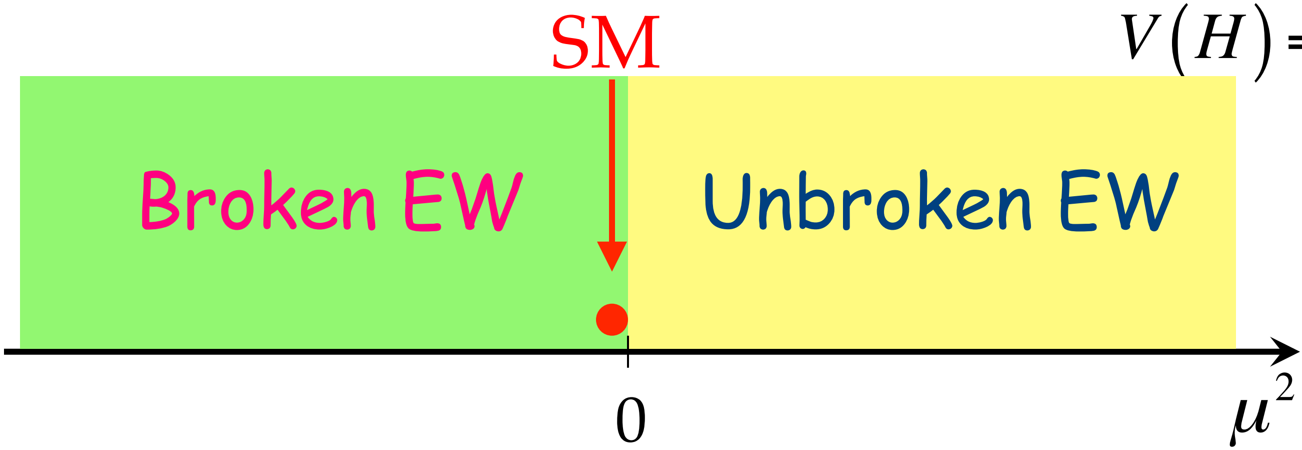
  Shift symmetry (Goldstone)

  → **Dying...?**

Characterizing the tuning as a "criticality" condition

Giudice-Rattazzi 2006

$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$



Why is nature so close to the critical line?

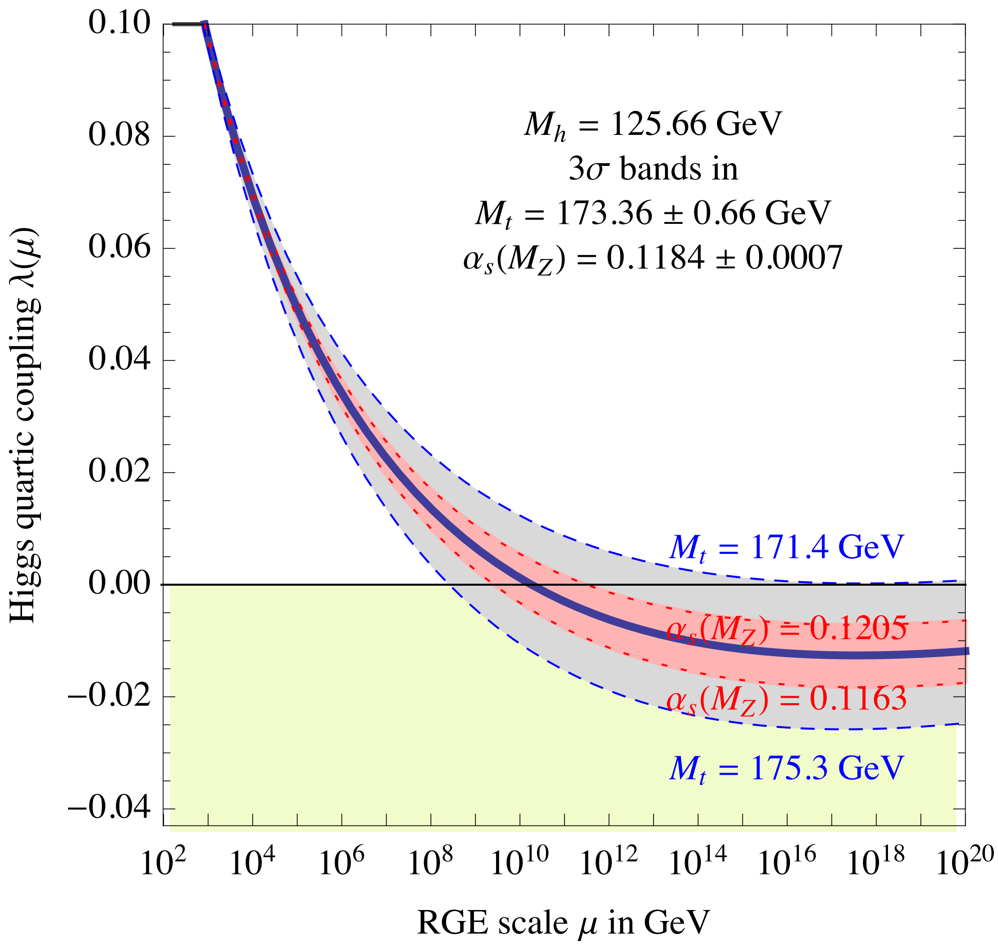
- Self-organized criticality?
- Relaxation mechanism? Graham-Kaplan-Rajendran 2015

See talk by Alex Pomarol

4) Stability of the Higgs potential

$$L = \left(h_{ij} \bar{\psi}_i \psi_j H + \text{h.c} \right) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda_{CC}^4$$

An indication for un unknown underlying phenomenon?



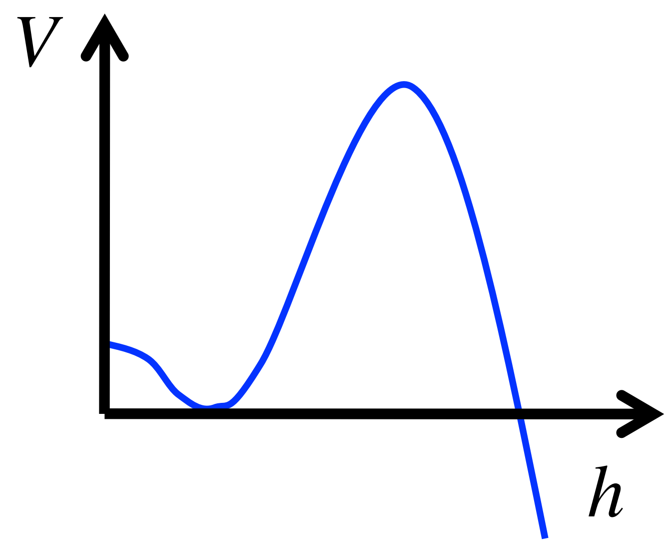
Extrapolate the SM up to very high energies

↑Higgs mass

↓Top quark mass

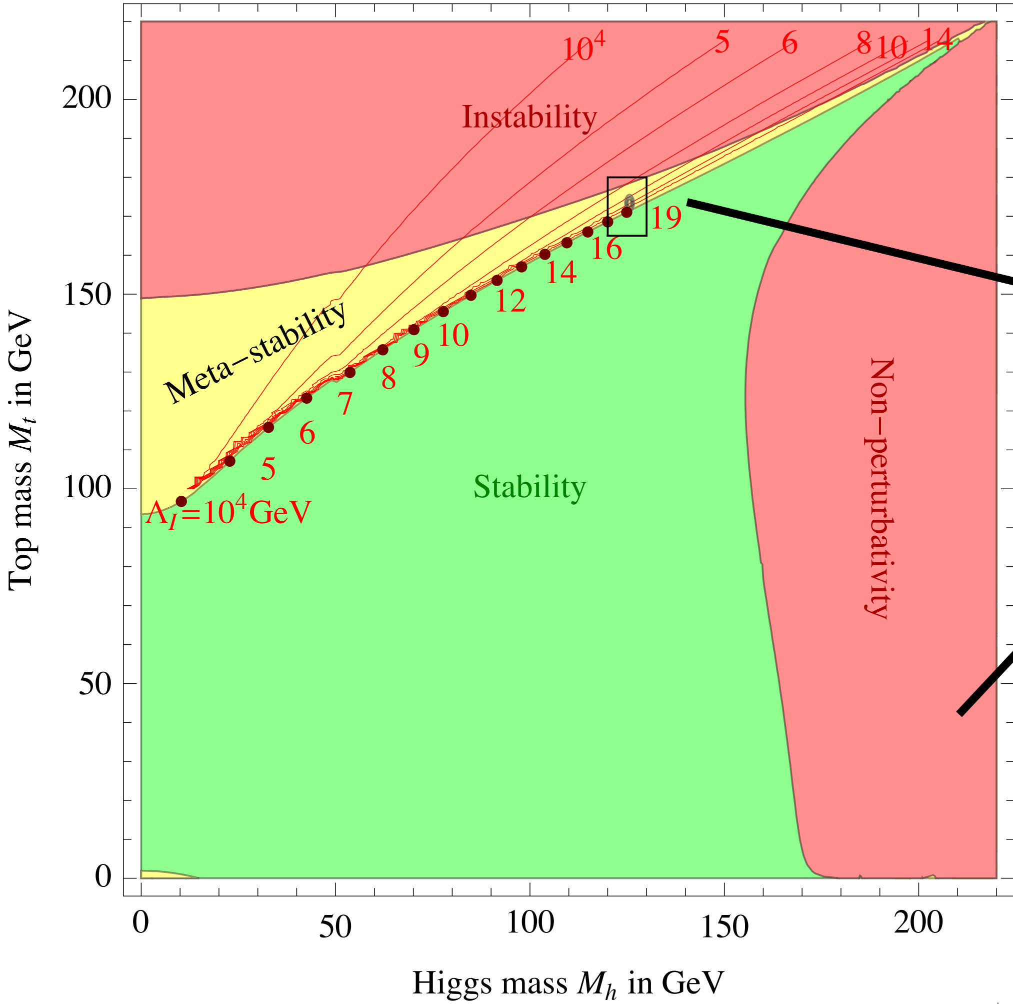
$$\frac{16\pi^2}{3}\mu\frac{d\lambda}{d\mu} = -2y_t^4 + 4y_t^2\lambda + 8\lambda^2 +$$

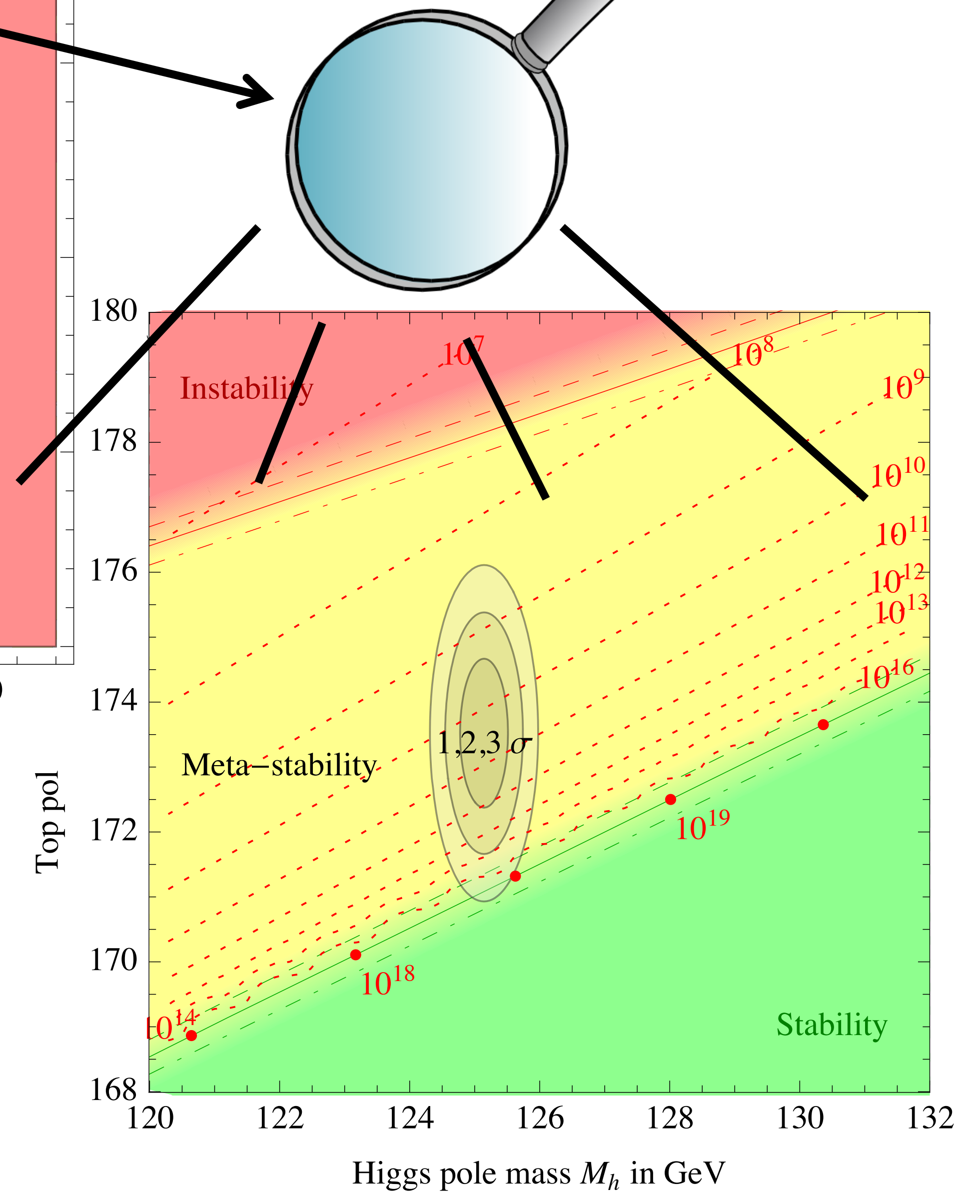
$$V = \frac{\lambda}{4}\left(h^2 - v^2\right)^2$$



Basic assumption: SM!

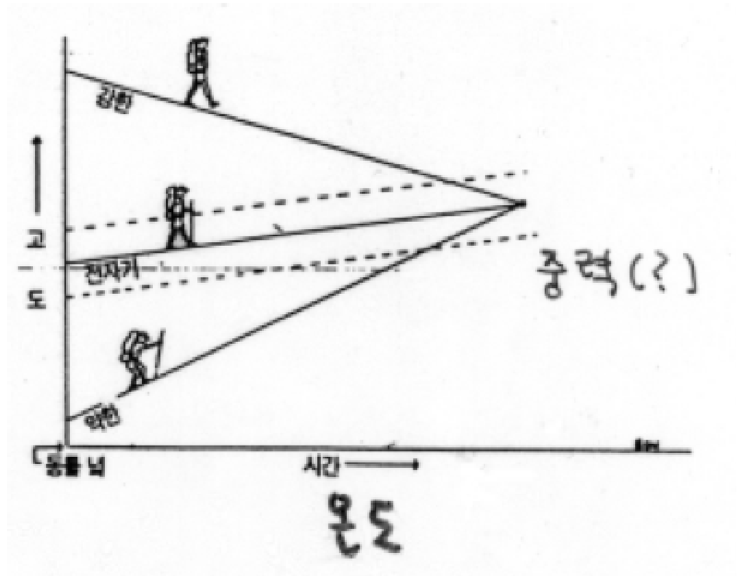
Daring or conservative?





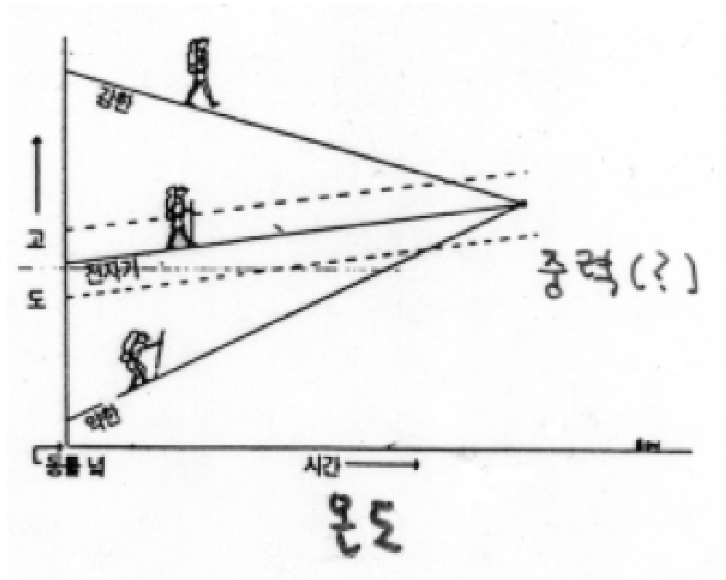
Is there a message?

Gauge couplings give hints for a Grand story



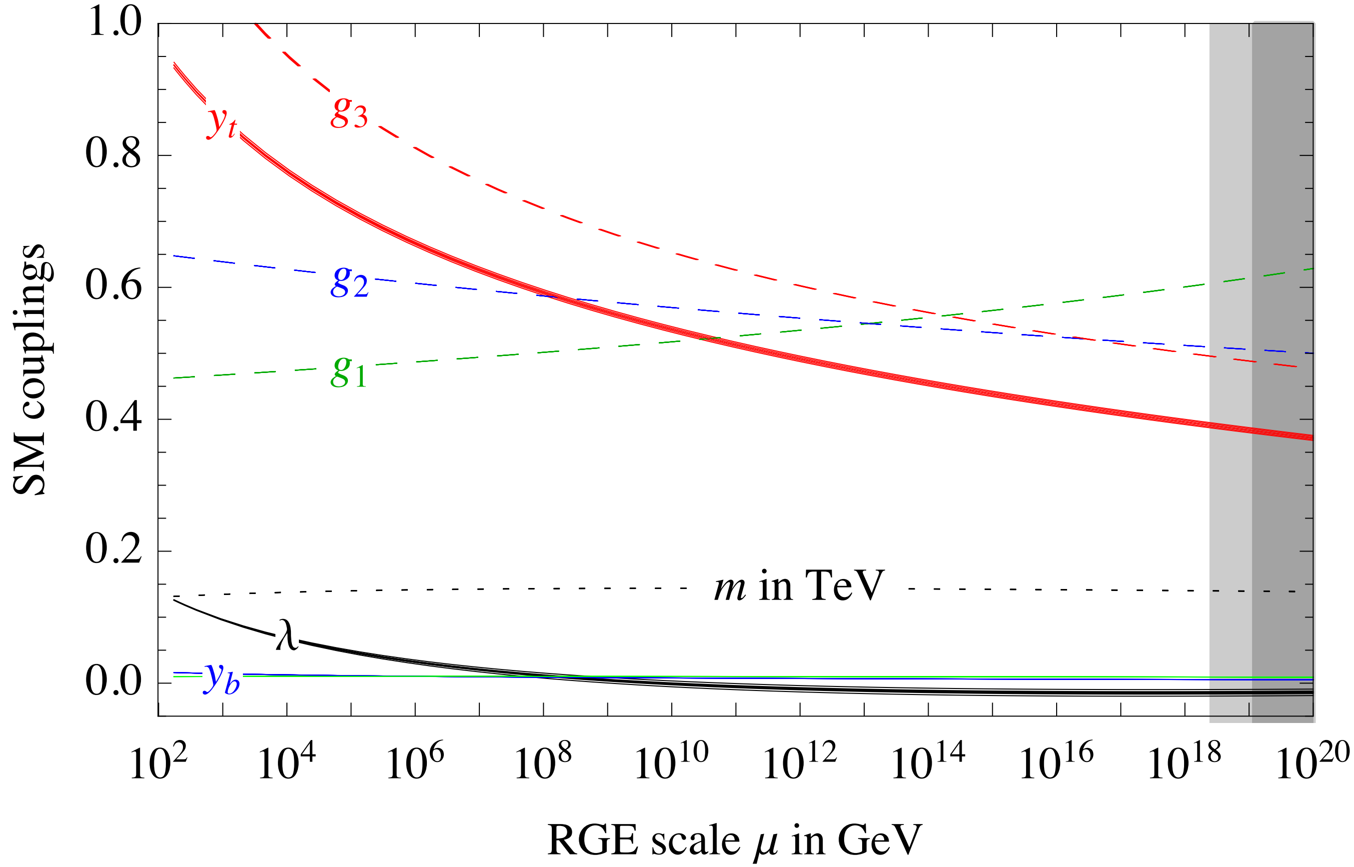
Higgs criticality: is there a story behind it?

Gauge couplings give hints for a Grand story



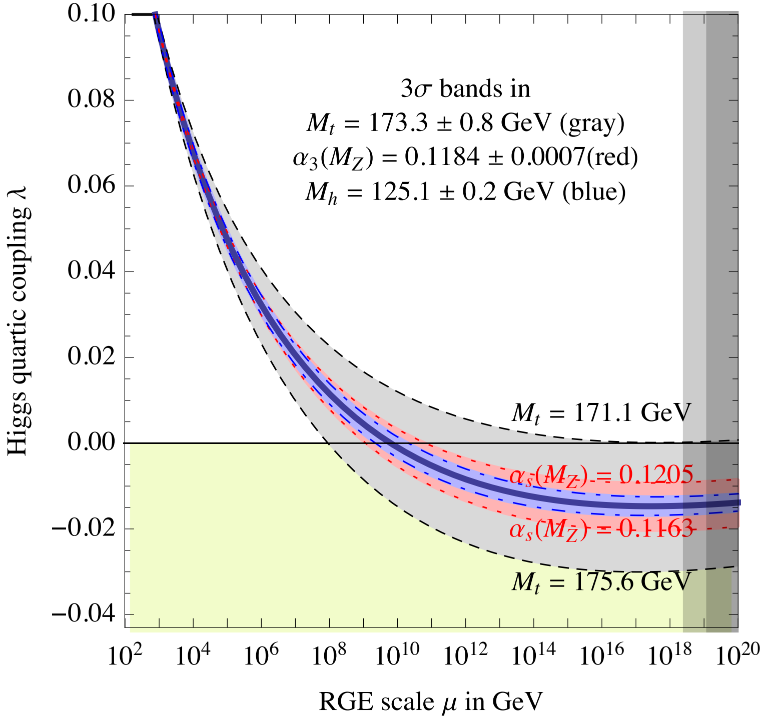
Higgs criticality: is there a story behind it?

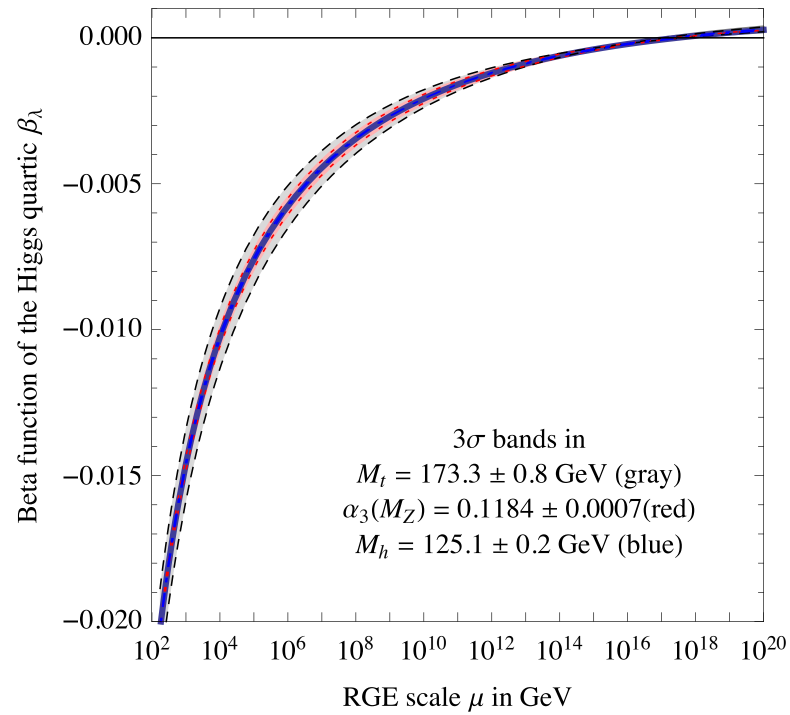
Any coincidence is worth noticing. You can throw it away later if it is only a coincidence.

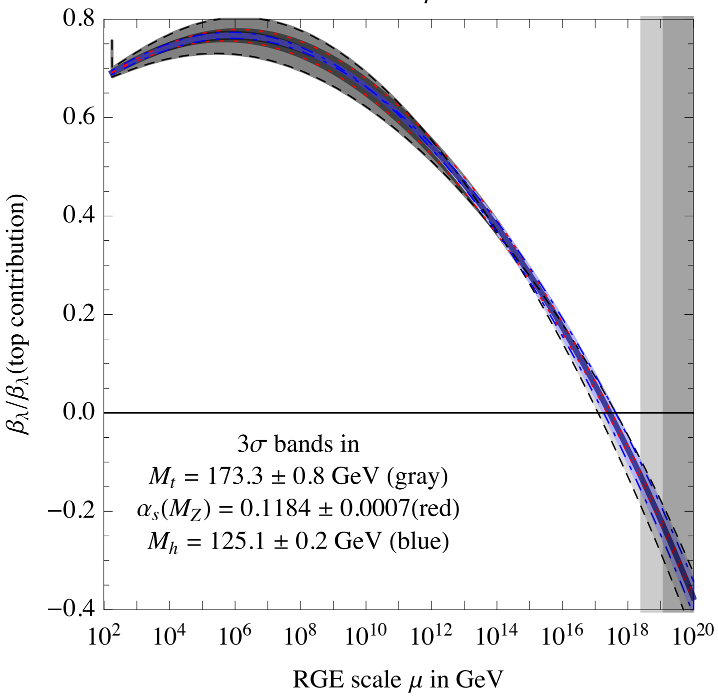


- Non-trivial in QFT to keep all couplings perturbative with no large instabilities for so many orders of magnitude

- Is λ special?



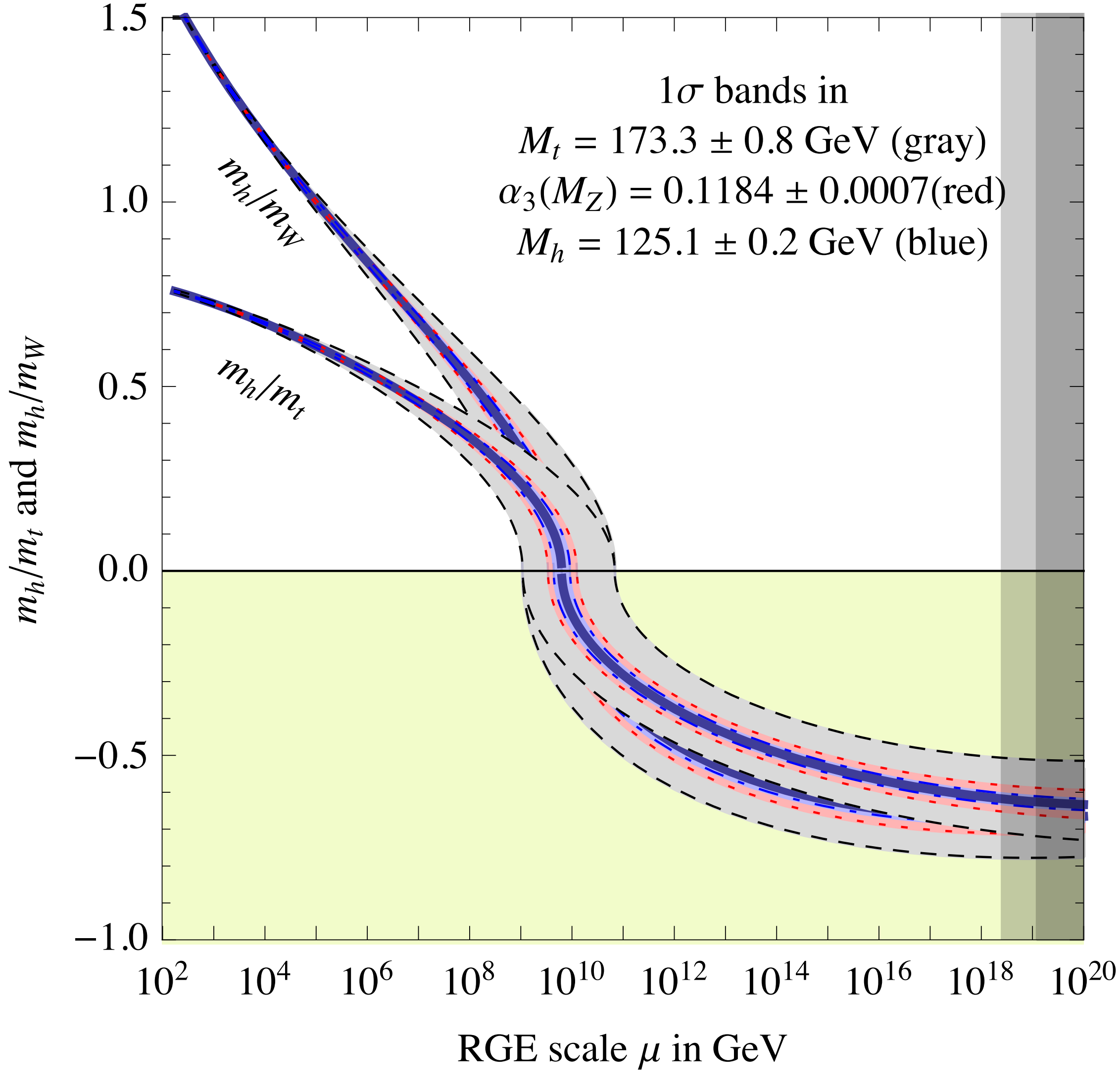




Evidence for $\lambda(M_P) \approx \beta(M_P) \approx 0$?

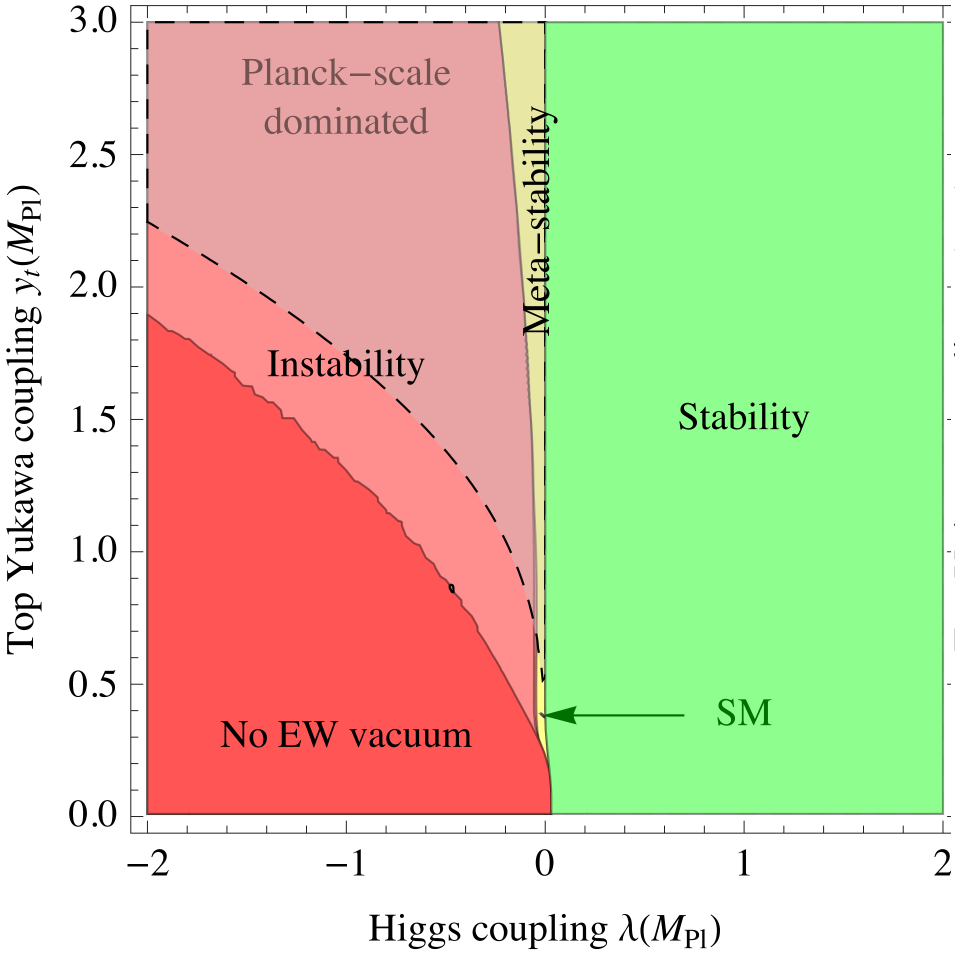
Is $\lambda(M_P)$ really small?

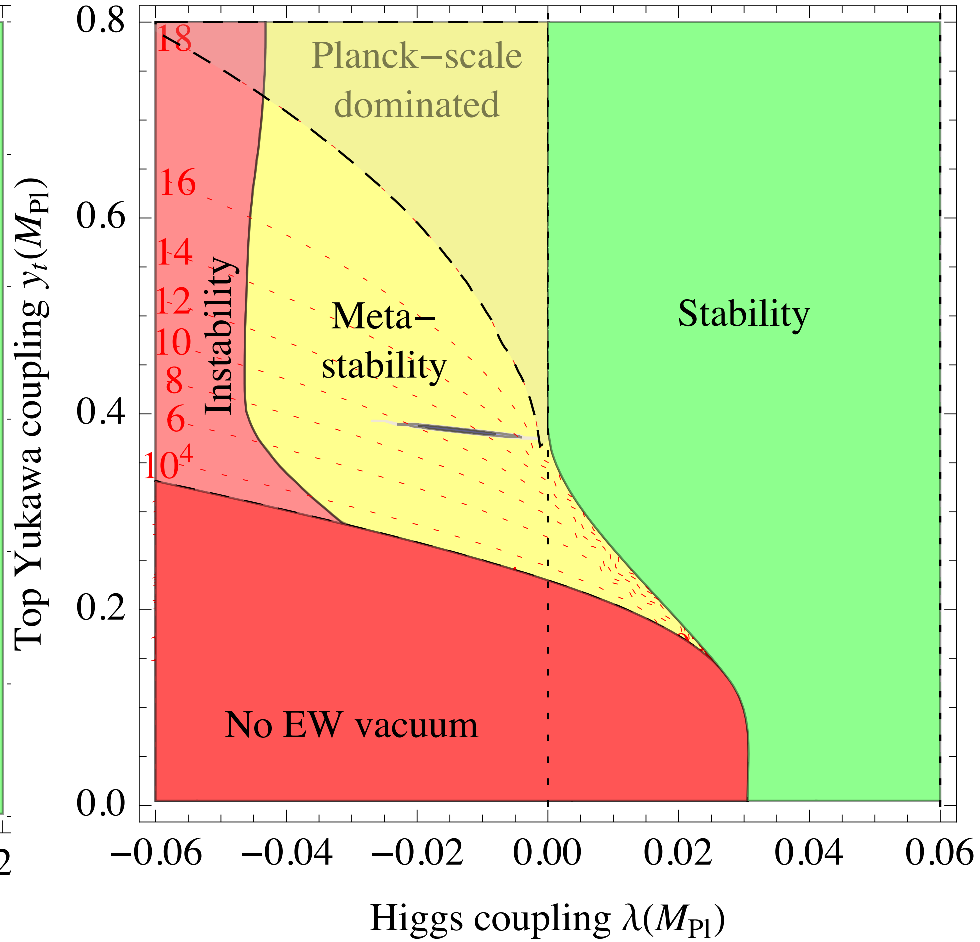
$[\lambda]=(c\hbar)^{-1}$



Is M_H really critical?

Use high-scale parameters:





Double criticality in top & Higgs couplings

Why is the universe near-critical?

Explanations

1) Matching conditions

- Goldstone or shift symmetry
- Supersymmetry with $\tan\beta \approx 1$
- Partial N=2 insuring *D*-flatness
- Power-law running of couplings

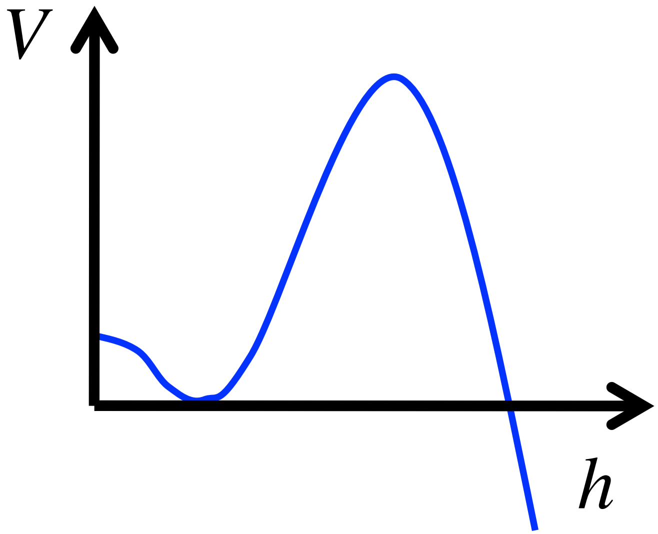
2) Criticality as an attractor

(multiverse but not anthropic arguments
or relaxation mechanism)

3) Living dangerously

(multiverse but not criticality)
Statistical pressure +(Meta)stability as an
anthropic boundary

Consequences



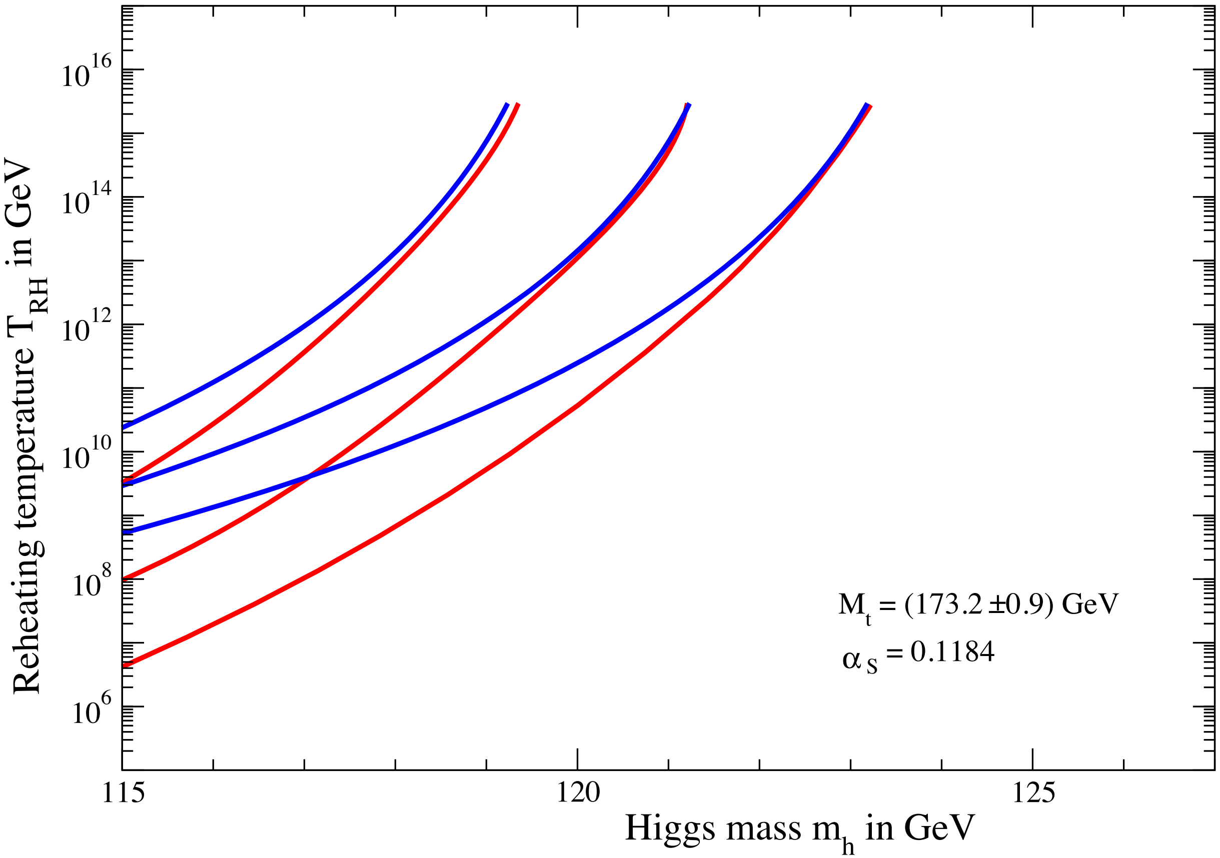
Why wasn't the vacuum destabilized during the cosmological evolution?

1) Quantum fluctuations

SM tunneling rate $\tau > 10^{200}$ yr

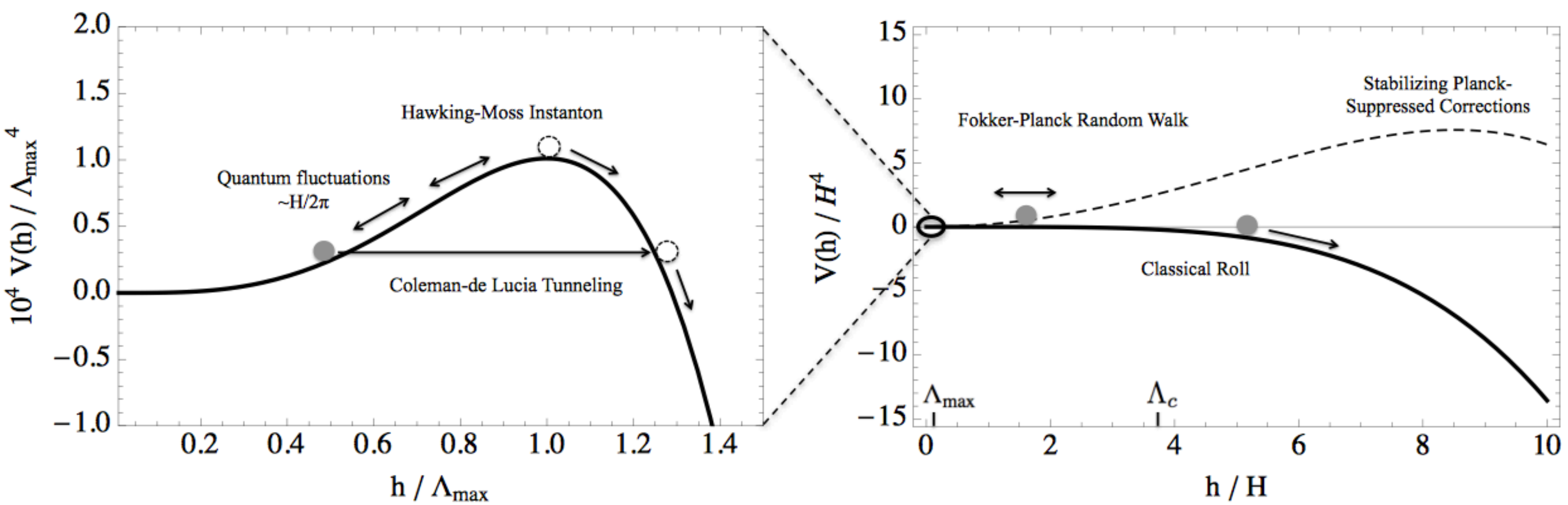
2) Thermal fluctuations

- Thermal mass $T^2\ h^2$
- Thermal field fluctuations



3) Inflationary fluctuations

$H << h_{\max}$ $H >> h_{\max}$



If Higgs is massless during inflation [$V''(h) << 9H^2/4$], it random walks due to $T_{dS} = H/2\pi$

Langevin

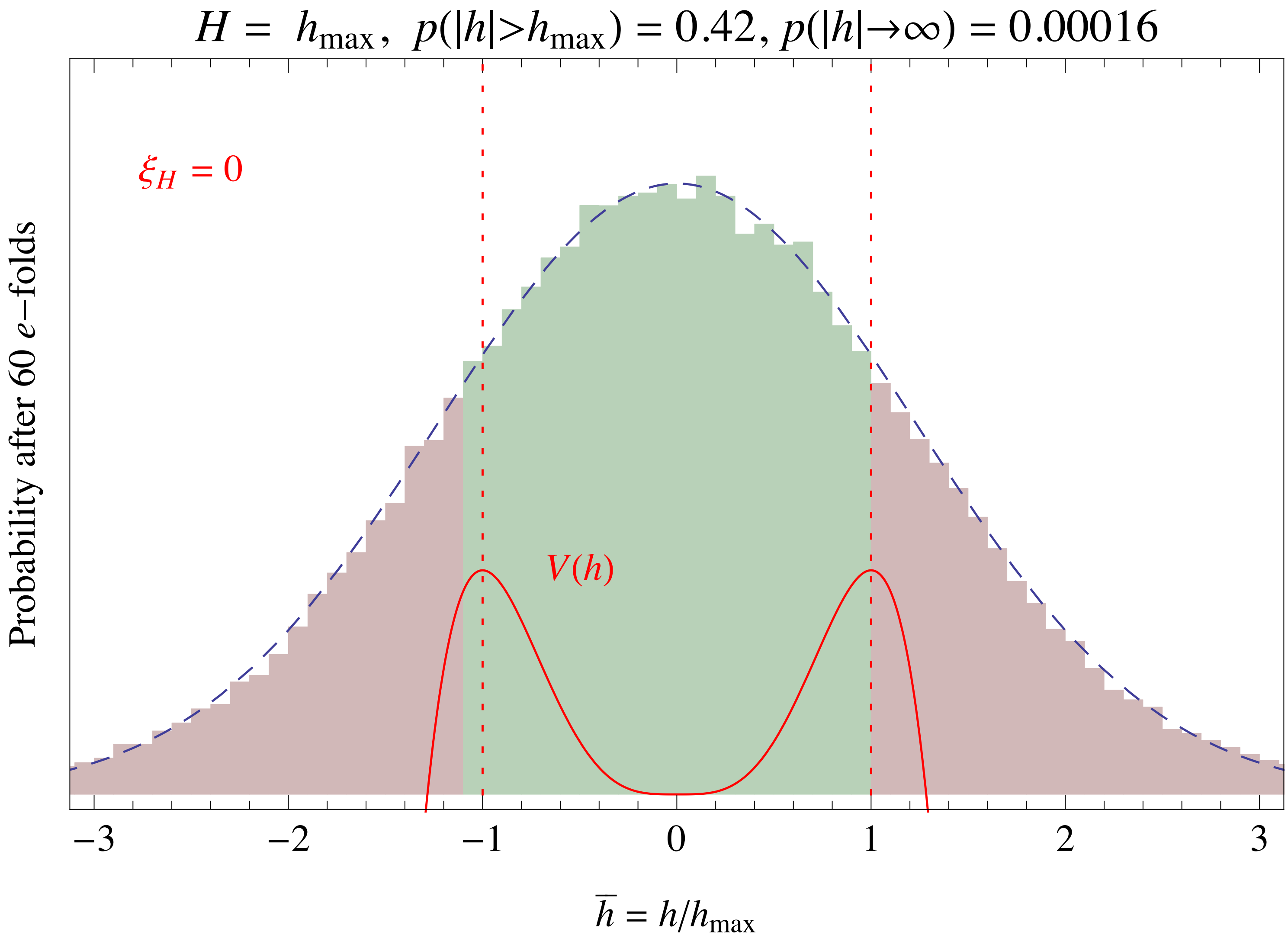
$$\frac{dh}{dt} + \frac{1}{3H}\frac{dV(h)}{dh} = \eta(t)$$

where η is a Gaussian random noise with

$$\langle \eta(t)\eta(t') \rangle = \frac{H^3}{4\pi^2}\delta(t-t')$$

Fokker-Planck

$$\frac{\partial P}{\partial N} = \frac{\partial^2}{\partial h^2}\left(\frac{H^2}{8\pi^2}P\right) + \frac{\partial}{\partial h}\left(\frac{V'}{3H^2}P\right)$$



cut at $|h| > 2H/\sqrt{|\lambda| N}$

$P(|h|>h_{max}) < e^{-3N}$: unlikely to find the Higgs away from its EW vacuum in any of the e^{3N} causally independent regions formed by inflation and constituting today's universe

$$\frac{H}{h_{\max}} < \sqrt{\frac{2}{3}\frac{\pi}{N}} \approx 0.04$$

$P(|h|\to\infty) < e^{-3N}$: unlikely to find the Higgs sliding away...

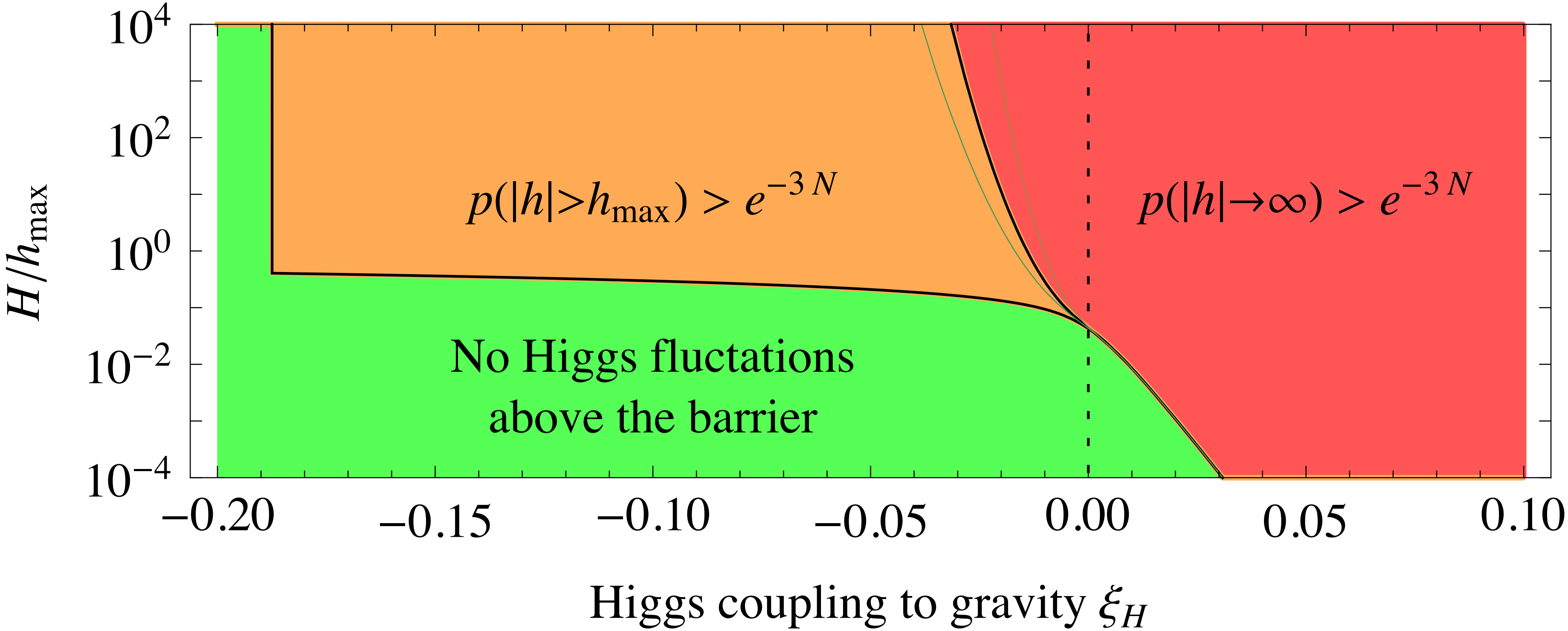
$$\frac{H}{h_{\max}} < \frac{\pi}{N}\sqrt{\frac{2}{3}} e^{\pi^2 k/2bN^3} \approx 0.045$$

Non-minimal gravitational coupling

$$S = \int d^4x \sqrt{g} \Big[-\frac{\bar{M}_{\rm Pl}^2}{2} R - \xi_H |\Phi_H|^2 R + |D_\mu \Phi_H|^2 - V + \cdots \Big]$$

$$m_H{}^2 = \xi_H R = -12 \xi_H H^2$$

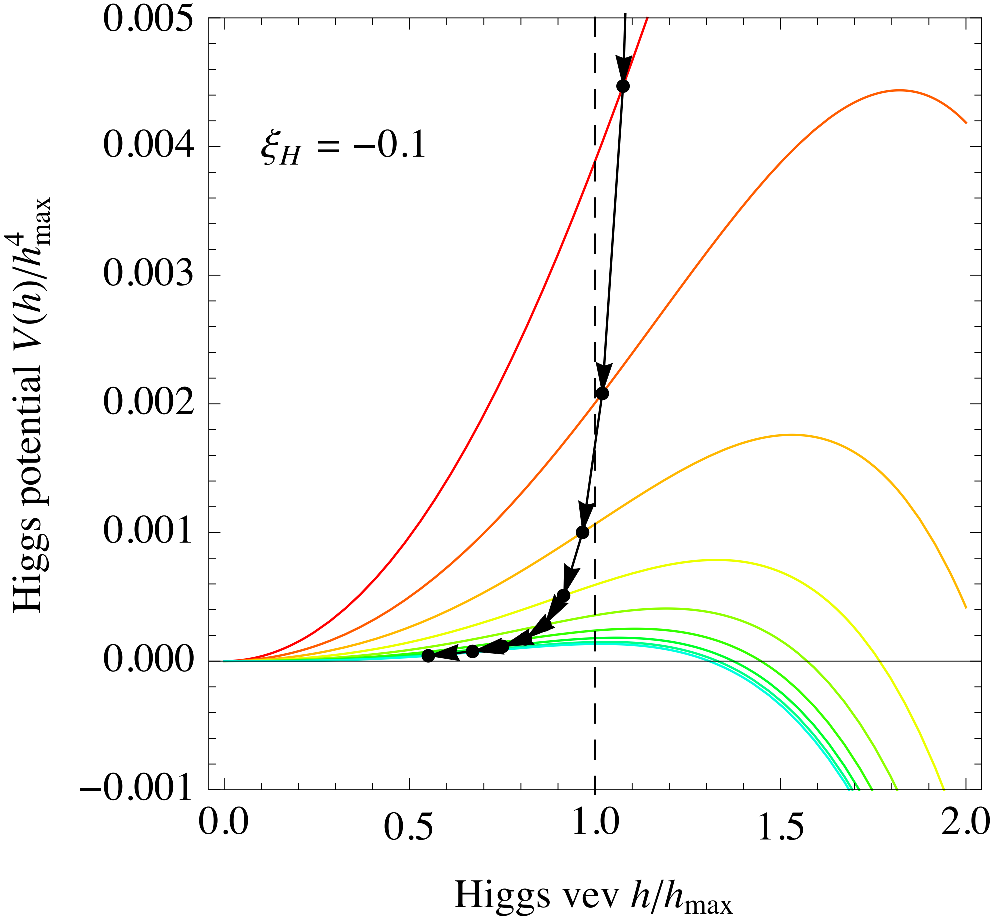
$$\frac{d\xi_H}{d\ln\bar{\mu}} = \frac{\xi_H + 1/6}{m^2} \frac{dm^2}{d\ln\bar{\mu}} = \frac{\xi_H + 1/6}{(4\pi)^2} \left(6y_t^2 - \frac{9}{2} g_2^2 - \frac{9}{10} g_1^2 + 12\lambda_H \right) + \cdots$$

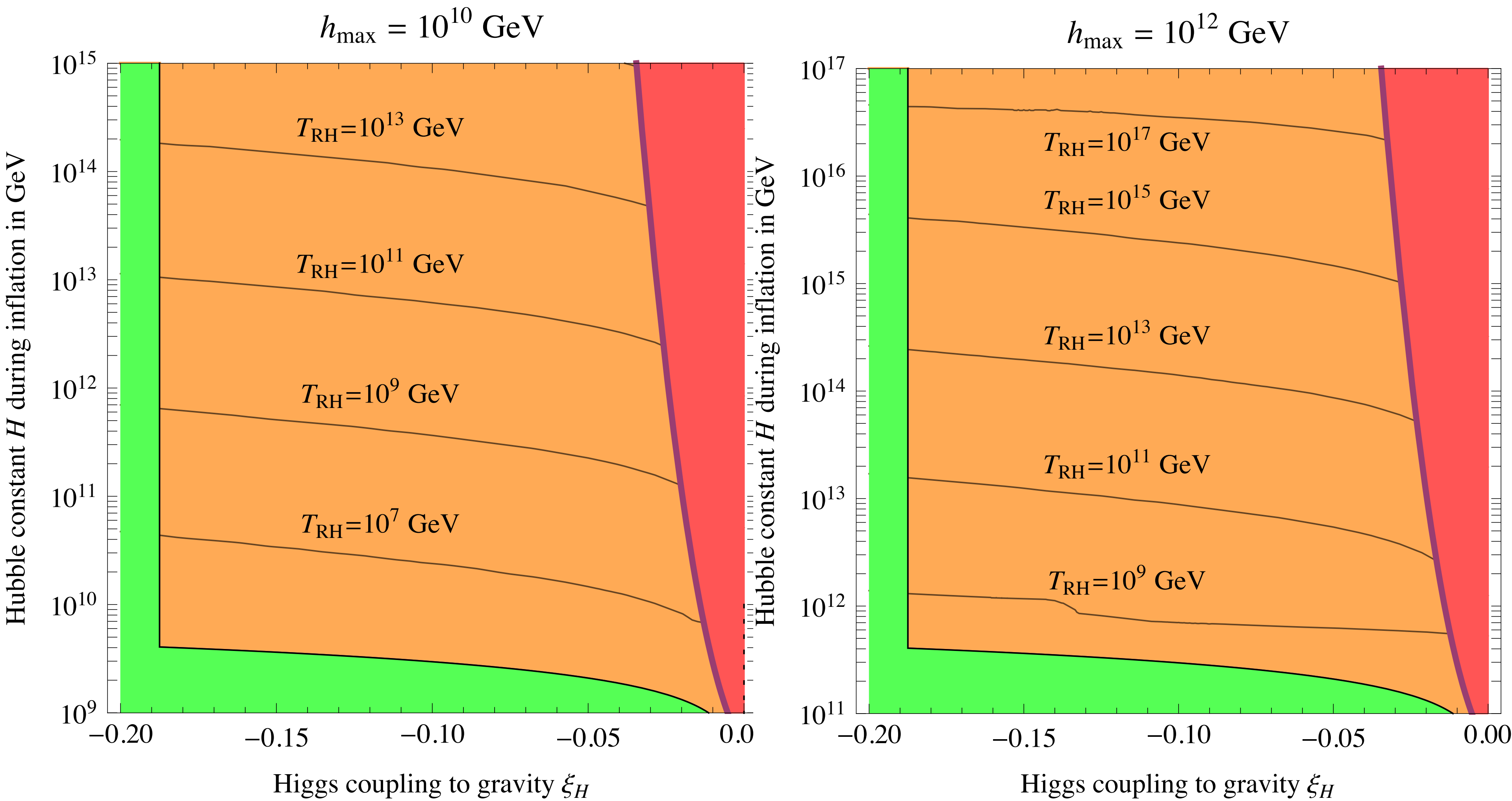


Orange region

Thermal epoch

- $m_H{}^2 \approx H^2$ gradually shuts off
- $m_H{}^2 \approx T^2$ gradually turns on
- Higgs follows classical evolution



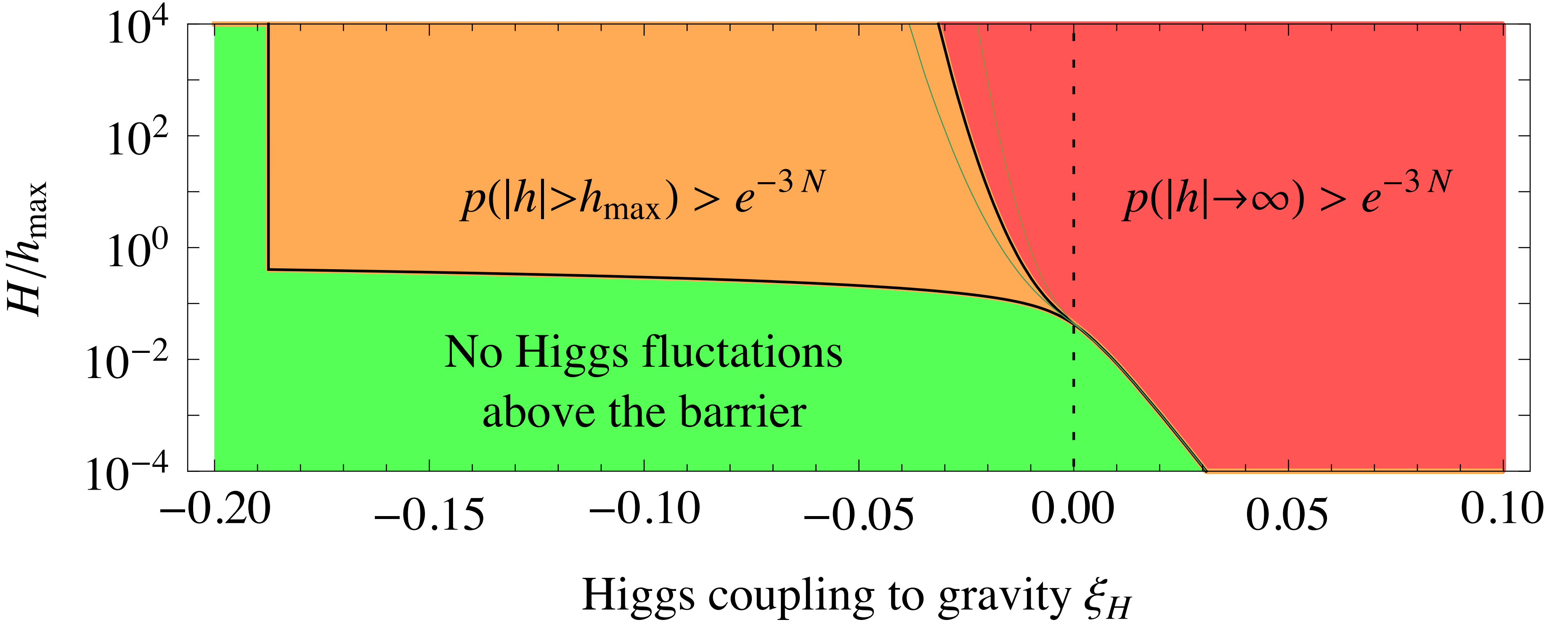


$h_{\max} = 10^{10}$ GeV
$T_{\rm RH}=10^{13}$ GeV
$T_{\rm RH}=10^{11}$ GeV
$T_{\rm RH}=10^{9}$ GeV
$T_{\rm RH}=10^{7}$ GeV
Hubble constant H during inflation in GeV
Higgs coupling to gravity ξ_H
$h_{\max} = 10^{12}$ GeV
$T_{\rm RH}=10^{17}$ GeV
$T_{\rm RH}=10^{15}$ GeV
$T_{\rm RH}=10^{13}$ GeV
$T_{\rm RH}=10^{11}$ GeV
$T_{\rm RH}=10^{9}$ GeV
Hubble constant H during inflation in GeV
Higgs coupling to gravity ξ_H

Red region

Evolution of AdS regions in dS and Minkowski

- Bubble evolution depends on size, internal energy, surface tension, initial wall velocity
- In dS, expanding bubbles are diluted away
- In Minkowski, expanding bubbles devour all space



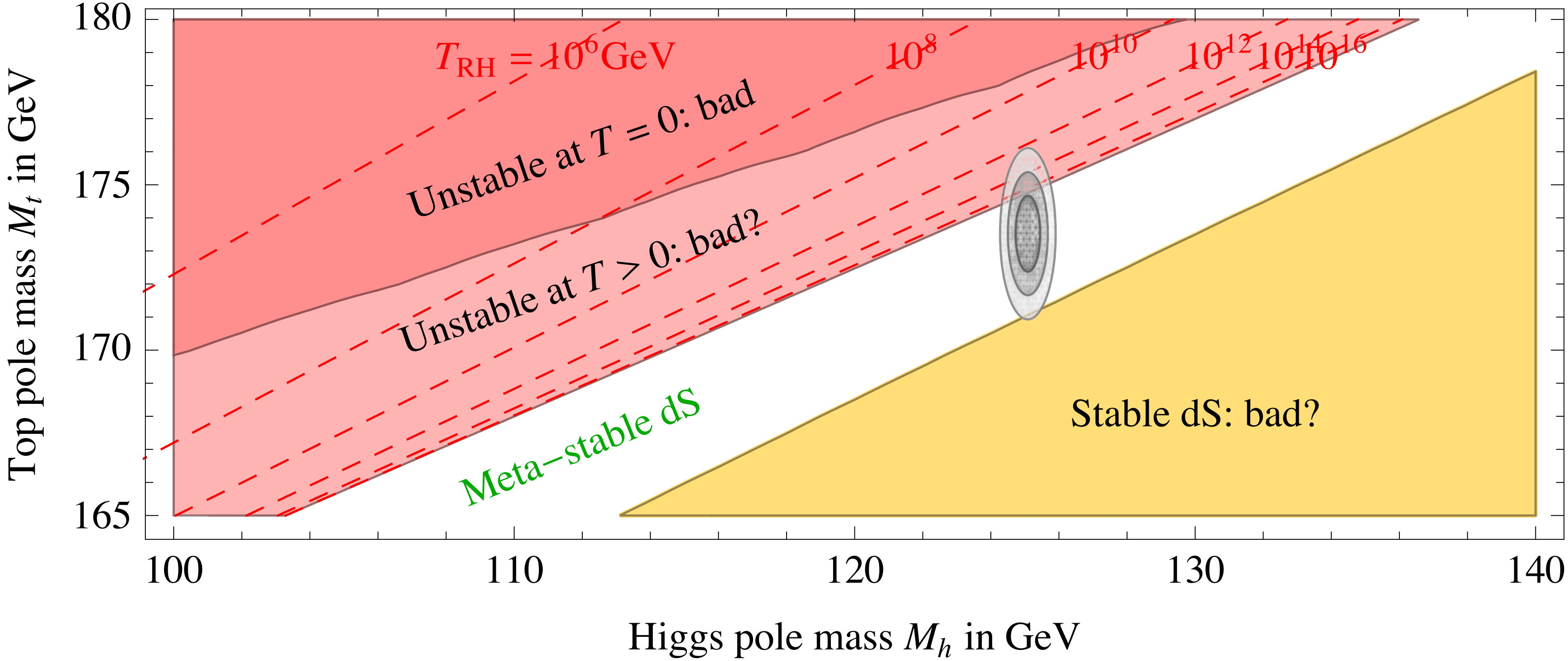
A speculation...

- Empirical fact: we live in an accelerating universe
- Theoretical conjecture: quantum gravity is ill-defined in dS space

Assuming this a problem, many possible solutions

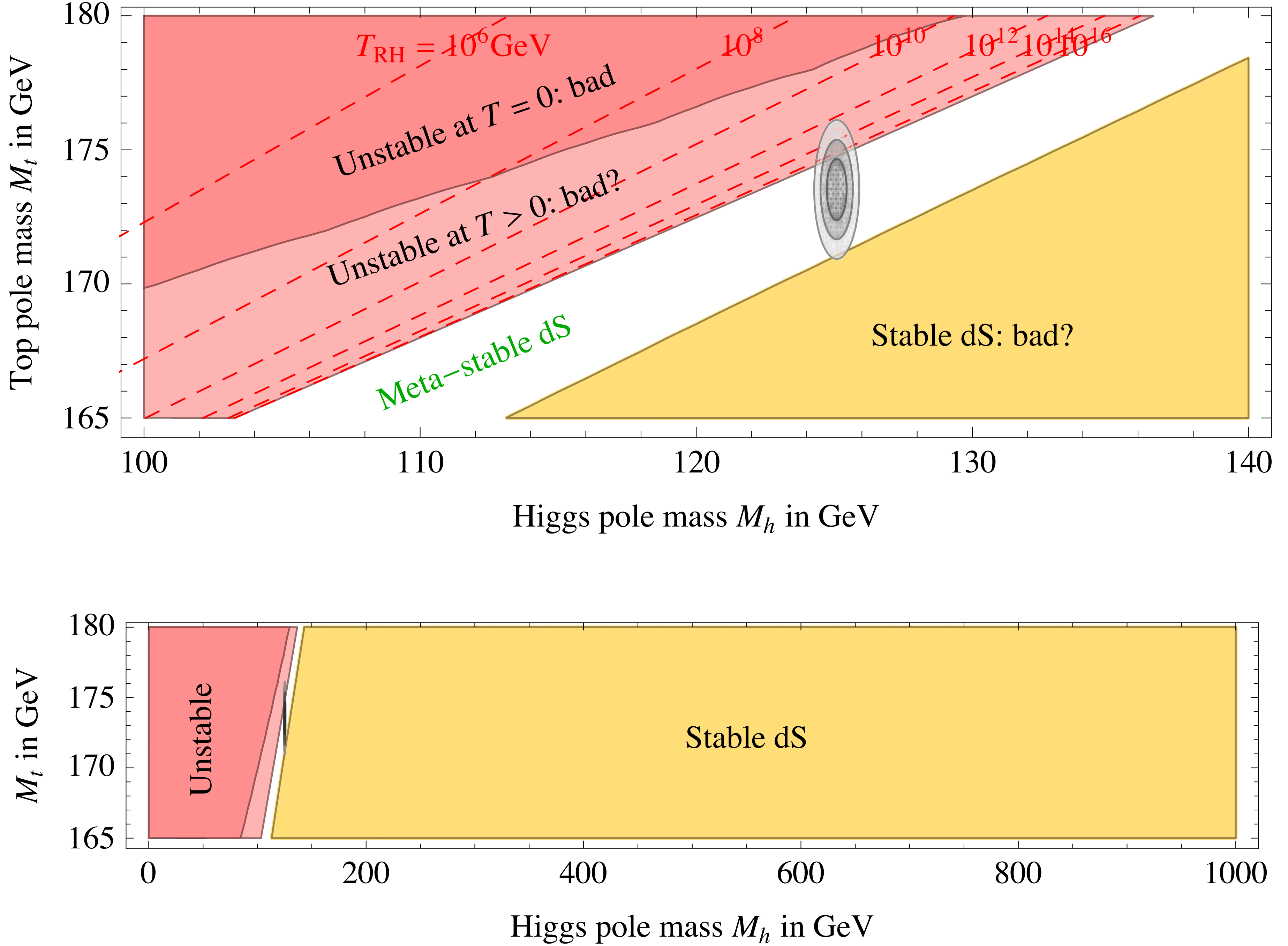
Higgs instability offers an easy way out

It seems that nature did not miss the opportunity



$$122\,\mathrm{GeV} < M_h < 129.4\,\mathrm{GeV} \qquad \text{for } M_t = 173.34\,\mathrm{GeV}$$

$$\boxed{171\,\mathrm{GeV} < M_t < 175\,\mathrm{GeV}\,.}$$



$T_{RH} = 10^6$ GeV
10^8
10^{10}
10^{12}
10^{14}
10^{16}
Unstable at $T = 0$: bad
Unstable at $T > 0$: bad?
Meta−stable dS
Stable dS: bad?
Top pole mass M_t in GeV
Higgs pole mass M_h in GeV
Unstable
Stable dS
M_t in GeV
Higgs pole mass M_h in GeV

Conclusions

- The Higgs discovery pressed upon us puzzles that appear to resist the symmetry-driven approach
- Higgs criticality is one of the most intriguing results of LHC Run1
- Multiverse, relaxation mechanism, matching conditions, self-organized criticality,... or coincidence?
- Higgs near-criticality can provide us with indirect information about inflationary dynamics; bounds on Hubble, linked to an observable:

$$H \approx 8\times10^{13}\ \text{GeV}\ (r/0.1)^{1/2}$$