Higgs mass implications on the scale (and the nature) of New Physics

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[*INFN, Frascati & CERN*]

- Introduction
- The metastability bound
- A closer look to the evolution of λ
- Conclusions

Introduction

The Higgs potential is at the origin of the main *theoretical problems* of the SM :

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L{}^i \psi_R{}^j \phi$$

Landau pole ($\lambda \to \infty$) / vacuum instability ($\lambda < 0$)

possible internal inconsistency
(depending on the value of m_H)

Quadratic divergences

$$\Delta\mu^2 \sim \Delta m_H{}^2 \sim \Lambda^2$$

(indication of *new physics* close to the electroweak scale ?)

SM flavour problem

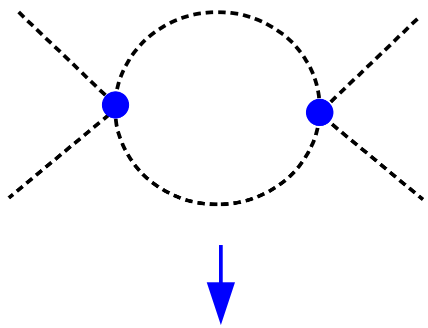
(unexplained span over 5 orders of magnitude and strongly hierarchical structure of the Yukawa coupl.)

Introduction

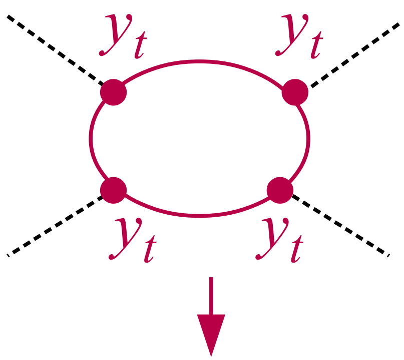
At large field values the shape of the Higgs potential is determined by the RGE evolution of the Higgs self coupling:

$$V_{eff}(|\phi| \gg v) \approx \lambda(|\phi|) \times |\phi|^4 + O(v^2|\phi|^2)$$

The evolution of λ is determined by two main effects:



growing λ at large energies



decreasing λ

$$\lambda(v) \propto \frac{m_h^2}{v^2}$$

$$y_t(v) \propto \frac{m_t}{v}$$

Given the large value of y_t, the destabilization due to top-quark loops is quite relevant

▶ *Introduction*

At large field values:

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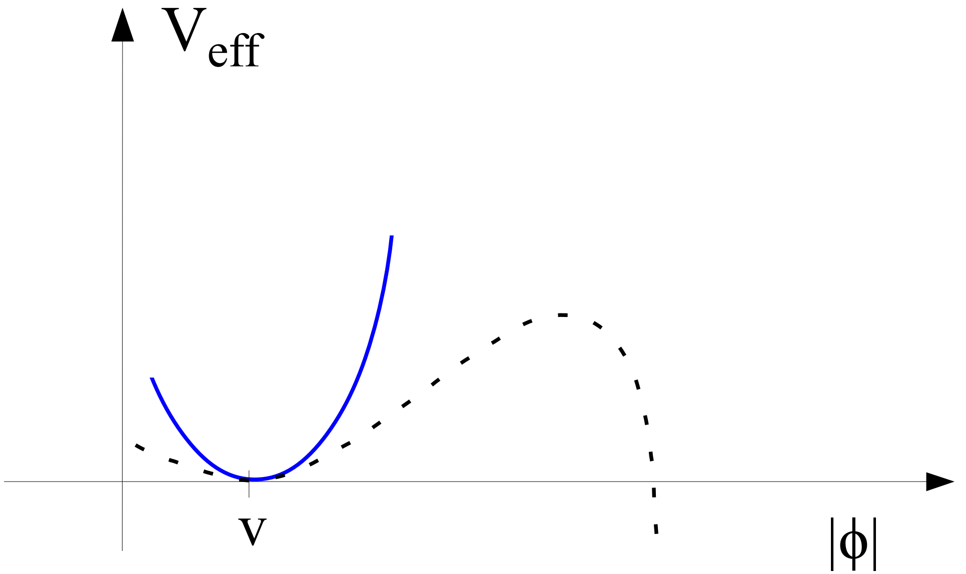
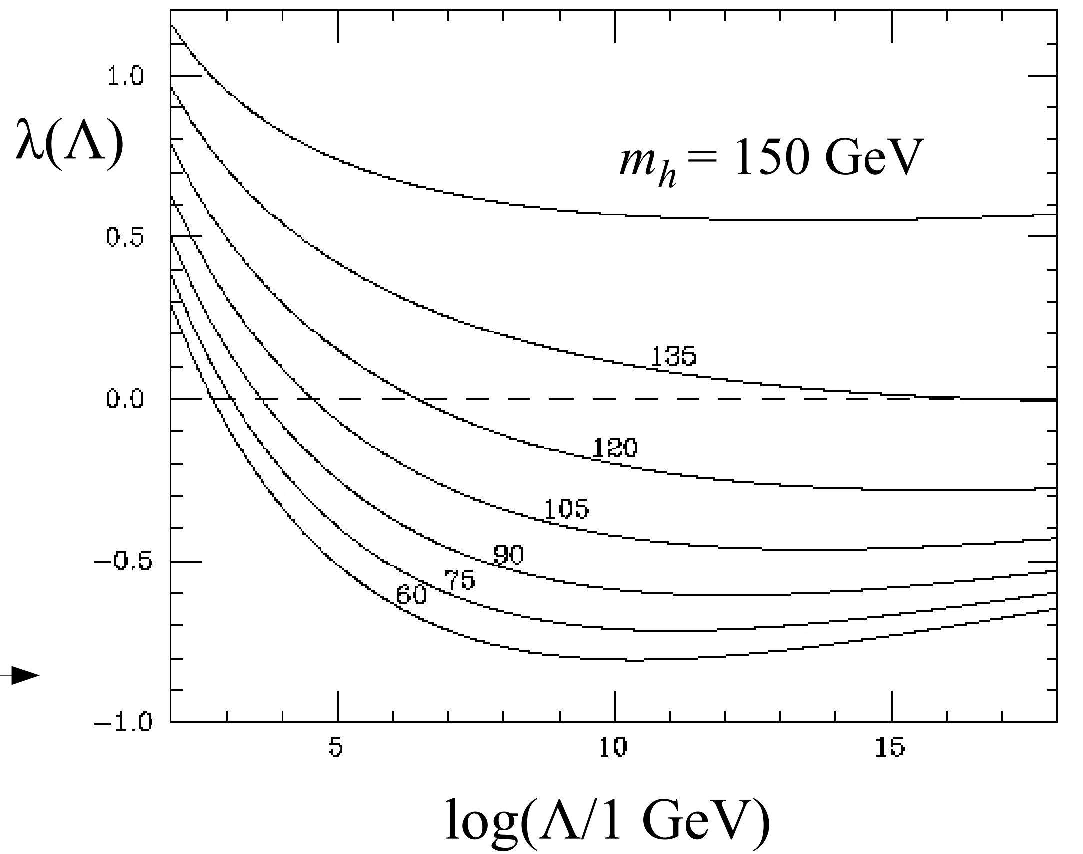
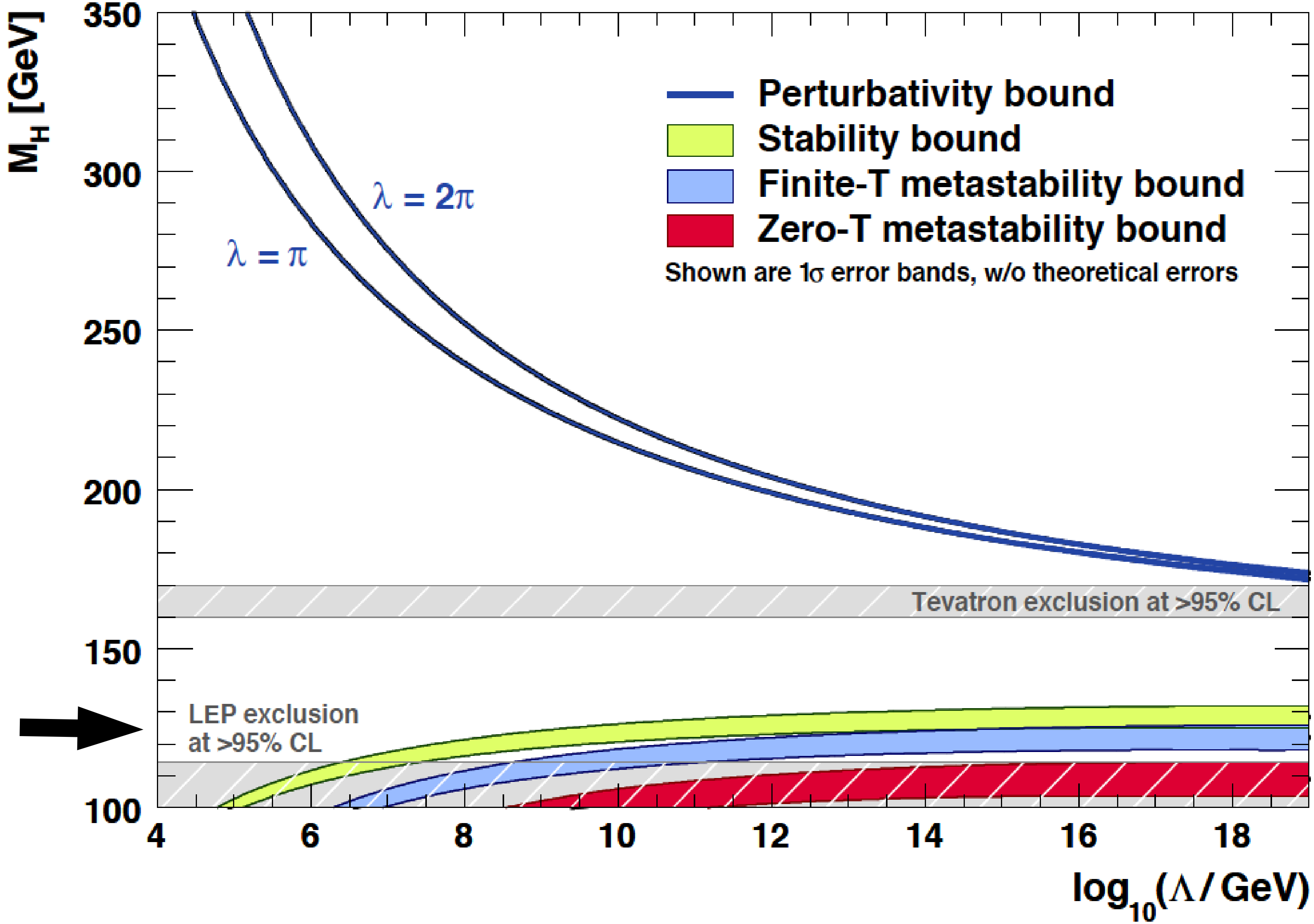




Ellis et al. '09



For $m_h \sim 125$ GeV we are (*most likely...*) in a region where the <u>Higgs potential is unstable</u>

The metastability bound

Can we rule out the model (and determine an upper bound on the new-physics scale Λ) if there is a second (deeper) minimum at large field values ?

Not really: The model could still be consistent if the lifetime of the (unstable) e.w. minimum is sufficiently long (i.e. longer than the age of the universe)

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We need to estimate the transition probability between false and true vacua.

Model-independent transition via quantum tunneling (occurring also a T=0).

Bubbles of true vacuum can from in the homogeneous background of the false vacuum. These bubbles are nothing but solutions of the e.o.m. (instantons) that interpolate between the two vacua (bounces).

Coleman '79

The bounces of the SM potential are characterised by a size R:

$$h(r) = \left(\frac{2}{|\lambda|}\right)^{1/2} \frac{2R}{r^2+R^2} \qquad (r = x_\mu x_\mu)$$

At the semiclassical level, this leads to: $p \sim e^{-\frac{8\pi^2}{3|\lambda|}}$

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A precise evaluation of the tunneling probability (integrated over the full volume of the universe) can only be obtained going beyond the semiclassical approximation.

Highly non-trivial problem, which has been solved in the SM case:

G.I., Ridolfi, Strumia '01

- The tunneling is dominated by bounces of size R, such that $\lambda(1/R)$ reaches its minimum value
- The critical R determine the reference scale of the volume pre-factor:

$$p \sim \max_R \frac{V_U}{R^4} e^{-\frac{8\pi^2}{3|\lambda(1/R)|}}$$

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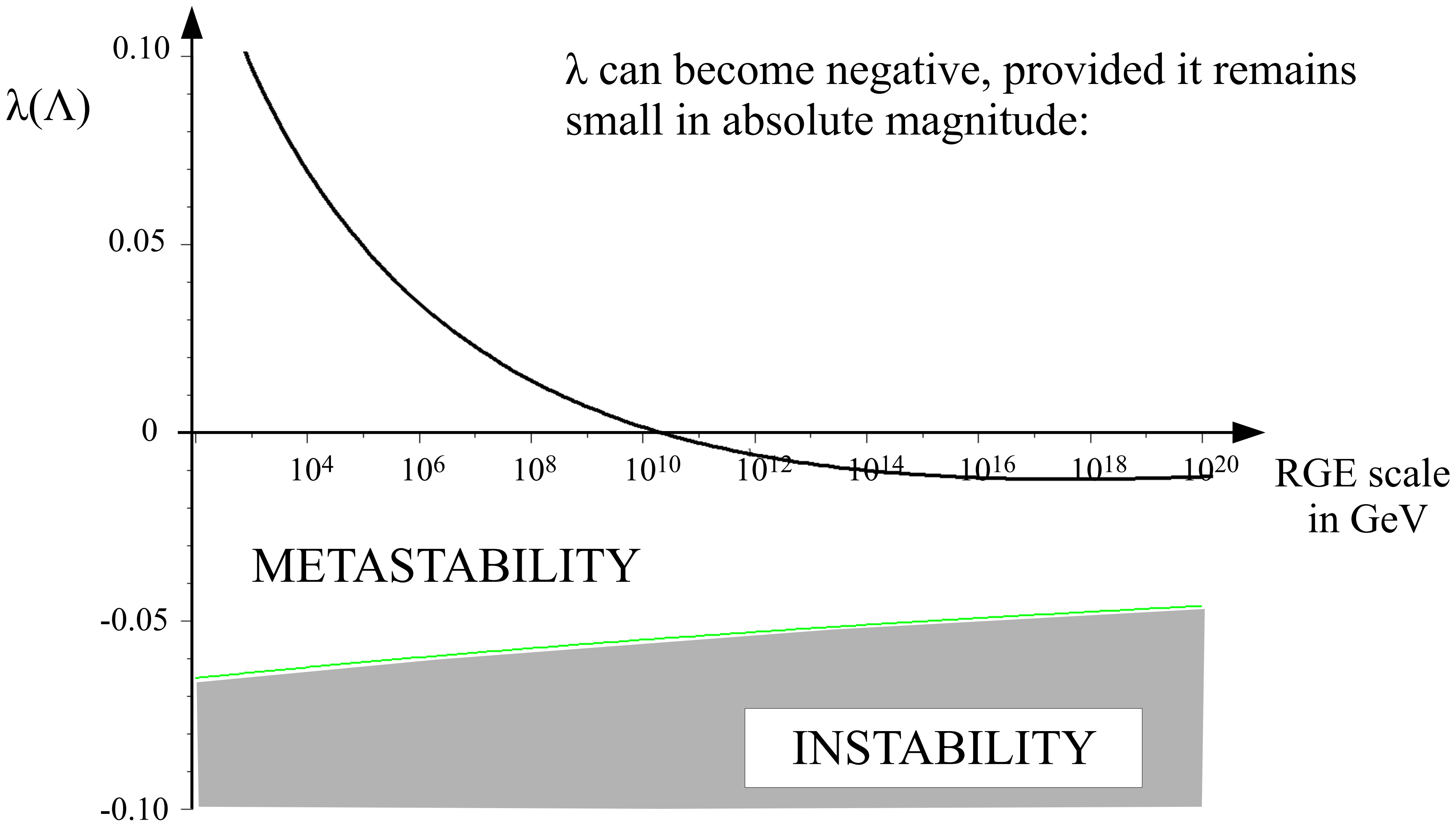
The leading gravitational effects are also calculable when 1/R is not far from M_{pl}

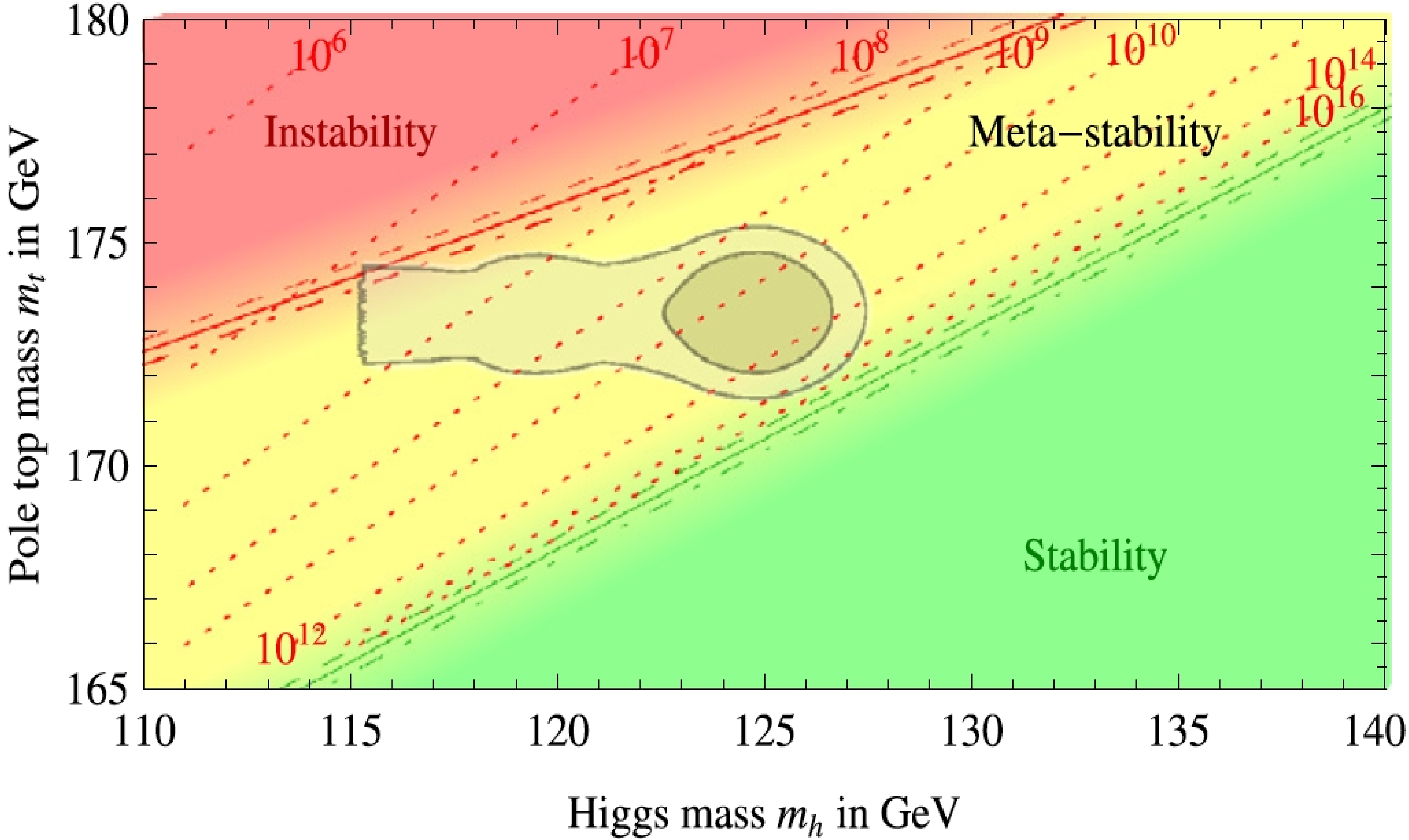
G.I., Rychkov, Strumia, Tetradis '08

$$p \sim \max \frac{V_U}{R^4} e^{-\frac{8\pi^2}{3|\lambda(1/R)|}}$$

λ can become negative, provided it remains small in absolute magnitude:

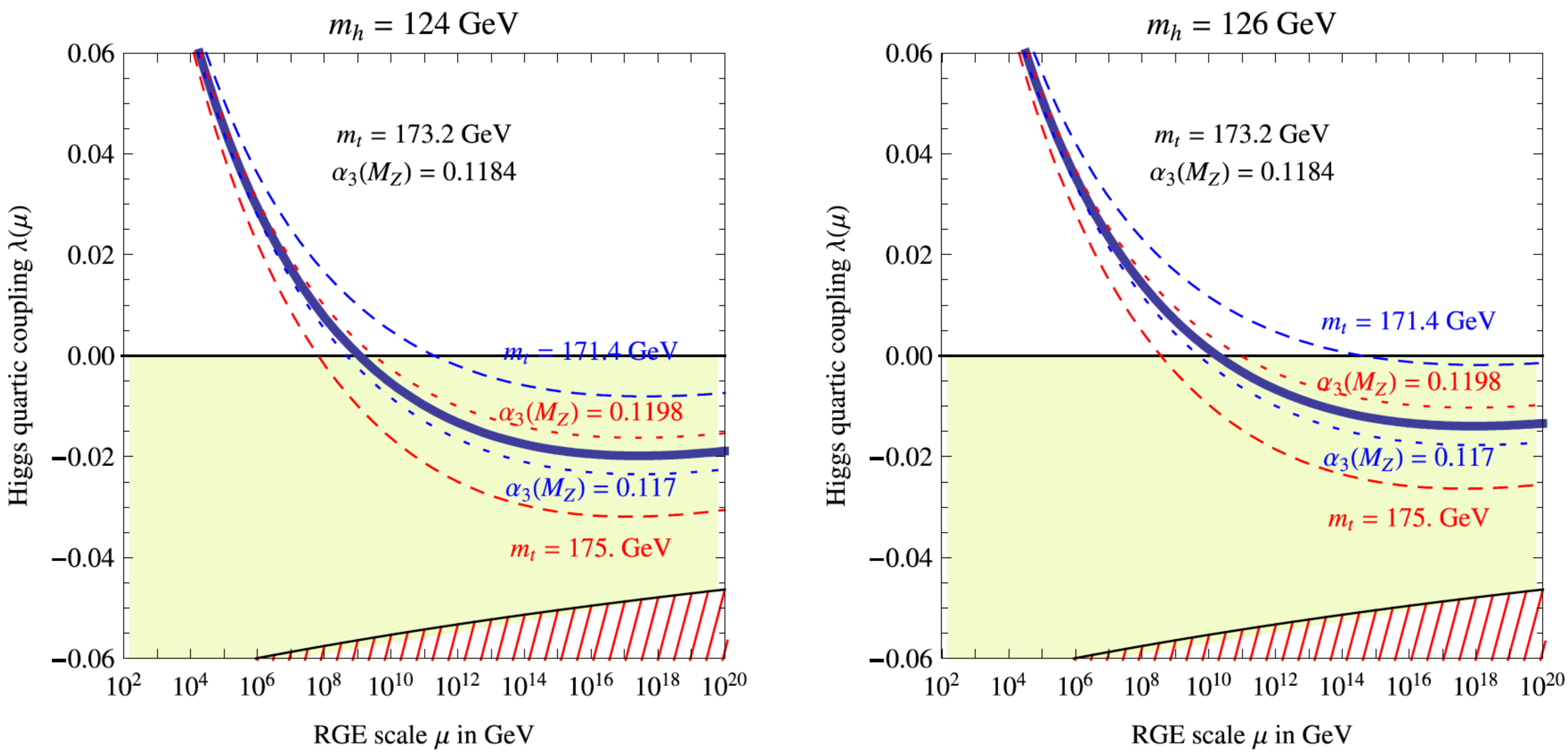


Elias-Miro, Espinosa, Giudice, G.I., Riotto, Strumia, '11



For $m_h \sim 125$ GeV we cannot derive model-independent bounds on the scale of NP from stability arguments: the Higgs potential is unstable, but “our vacuum” is sufficiently long lived.

A closer look to the evolution of λ



- The dominant "parametric uncertainty" is due to m_t [$\Delta m_h \sim 2\Delta m_t$]
- The dominant "theory error" is due to the initial value of λ at the e.w. scale (two-loop threshold corrections $\rightarrow \Delta m_h \sim 3$ GeV [conservative])

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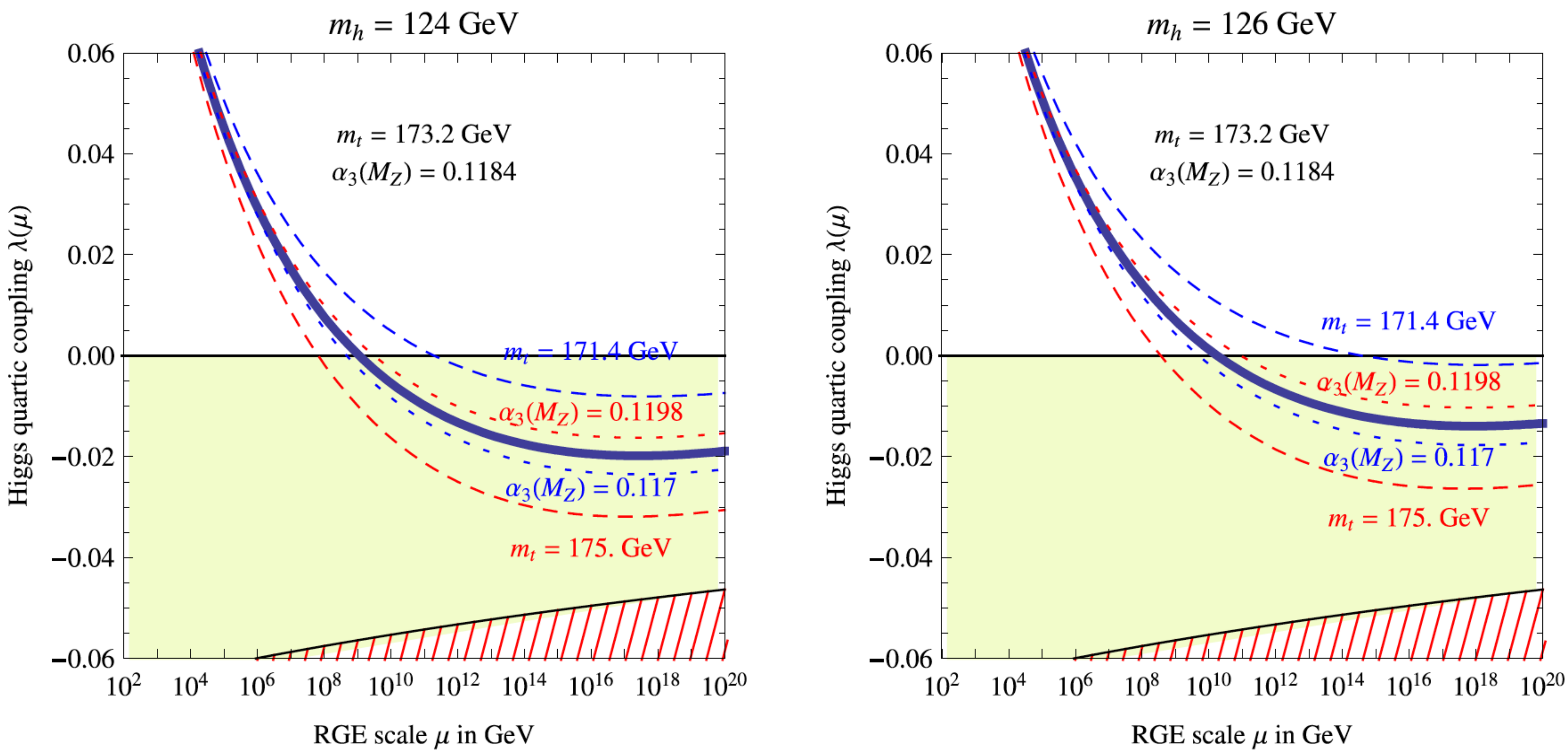
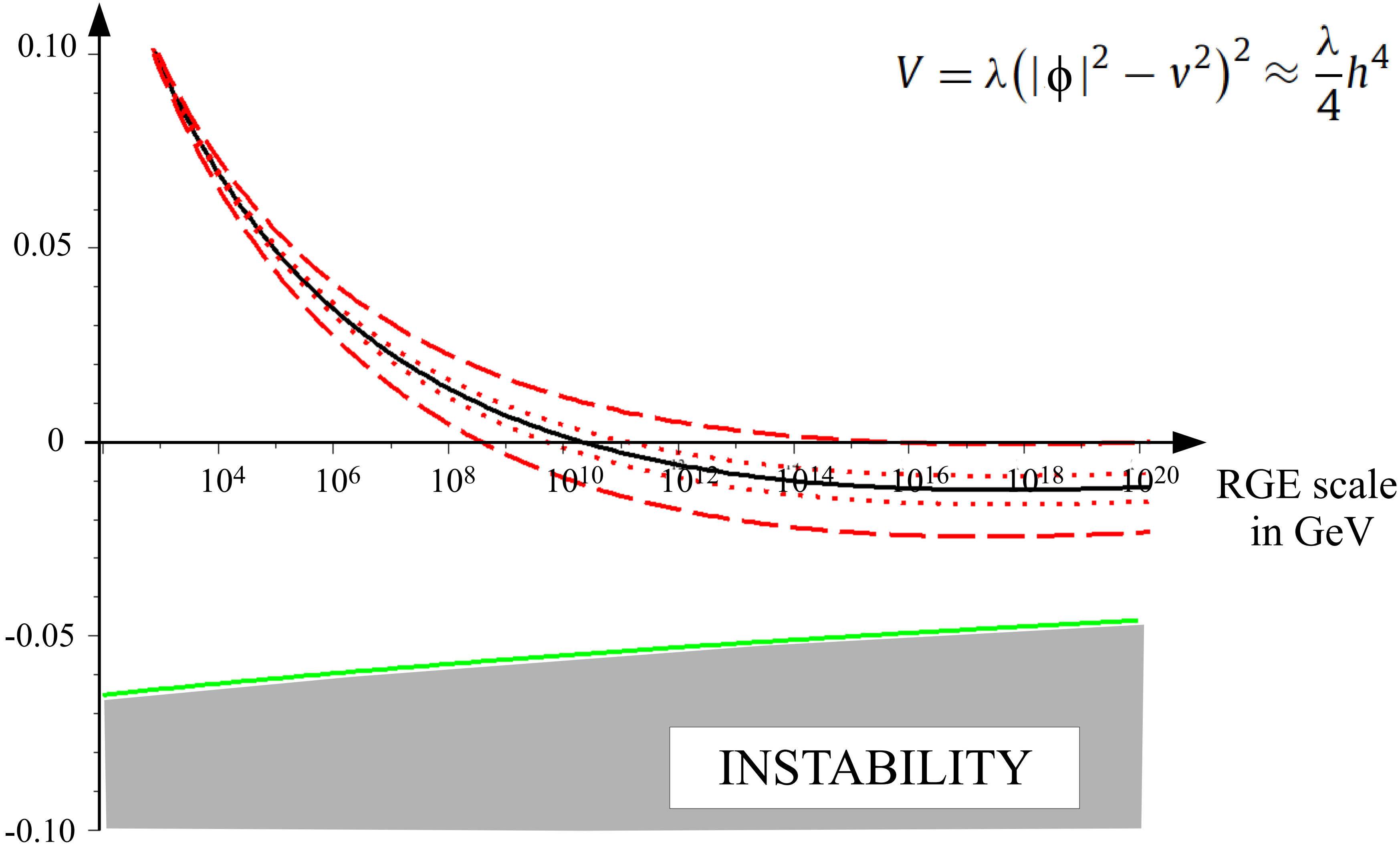


The interesting (?) possibility that λ=0 around the Planck scale (*assuming SM only*) is unlikely, but not impossible given present uncertainties.

Froggatt, Nielsen, Takanishi, '01
Arkani-Hamde *et al.*, '08
Shaposnikov, Wetterich, '10
Holthausen, Lim, Lindner, '11

A closer look to the evolution of λ

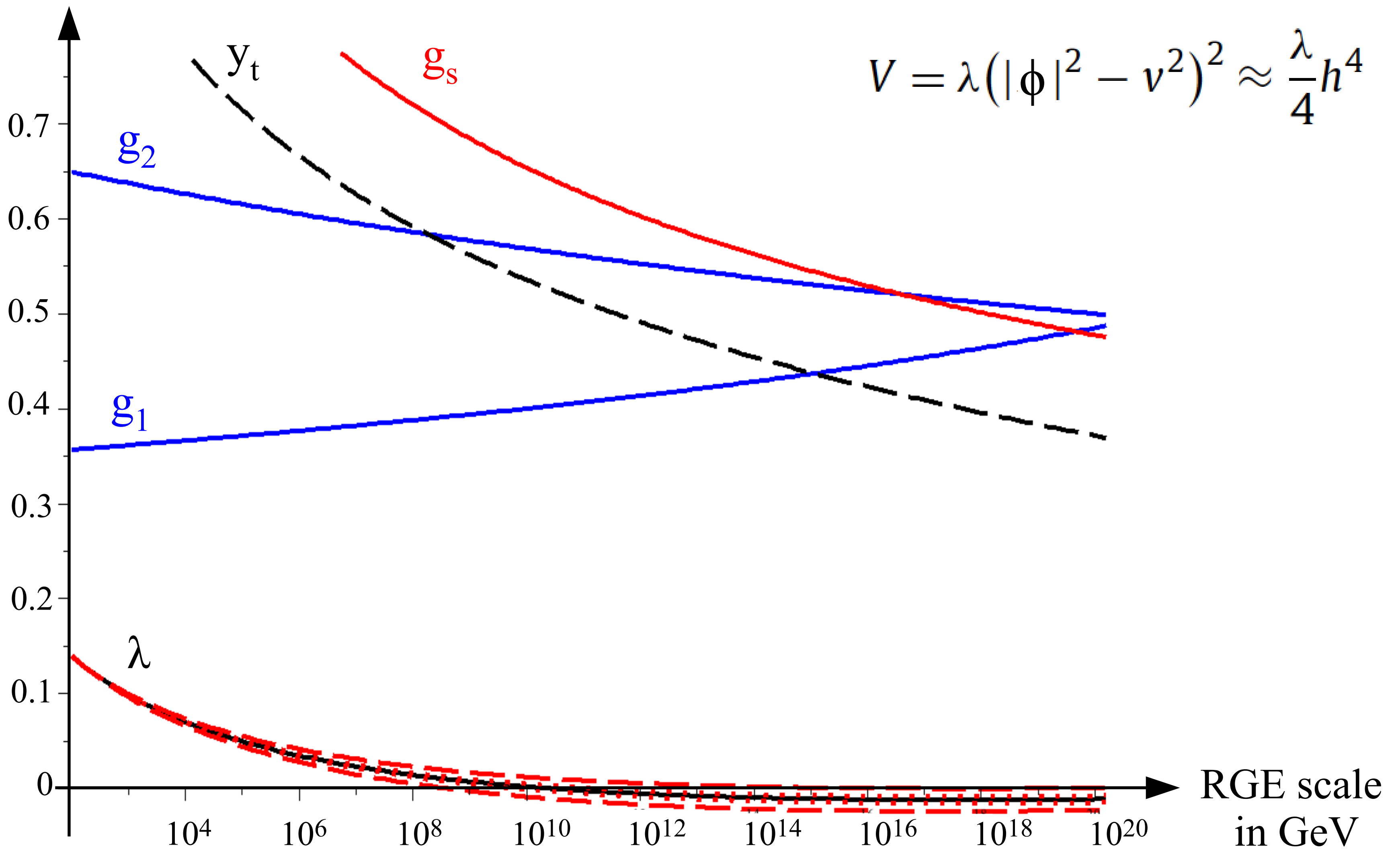
Personally I don't think there is anything special about $\lambda(M_{pl})=0$ (not a true fixed point); maybe more interesting the overall smallness of λ at high energies:



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

A closer look to the evolution of λ

At a scale $\Lambda \gtrsim 10^8$ GeV λ becomes of the same order of its typical e.w. quantum corrections



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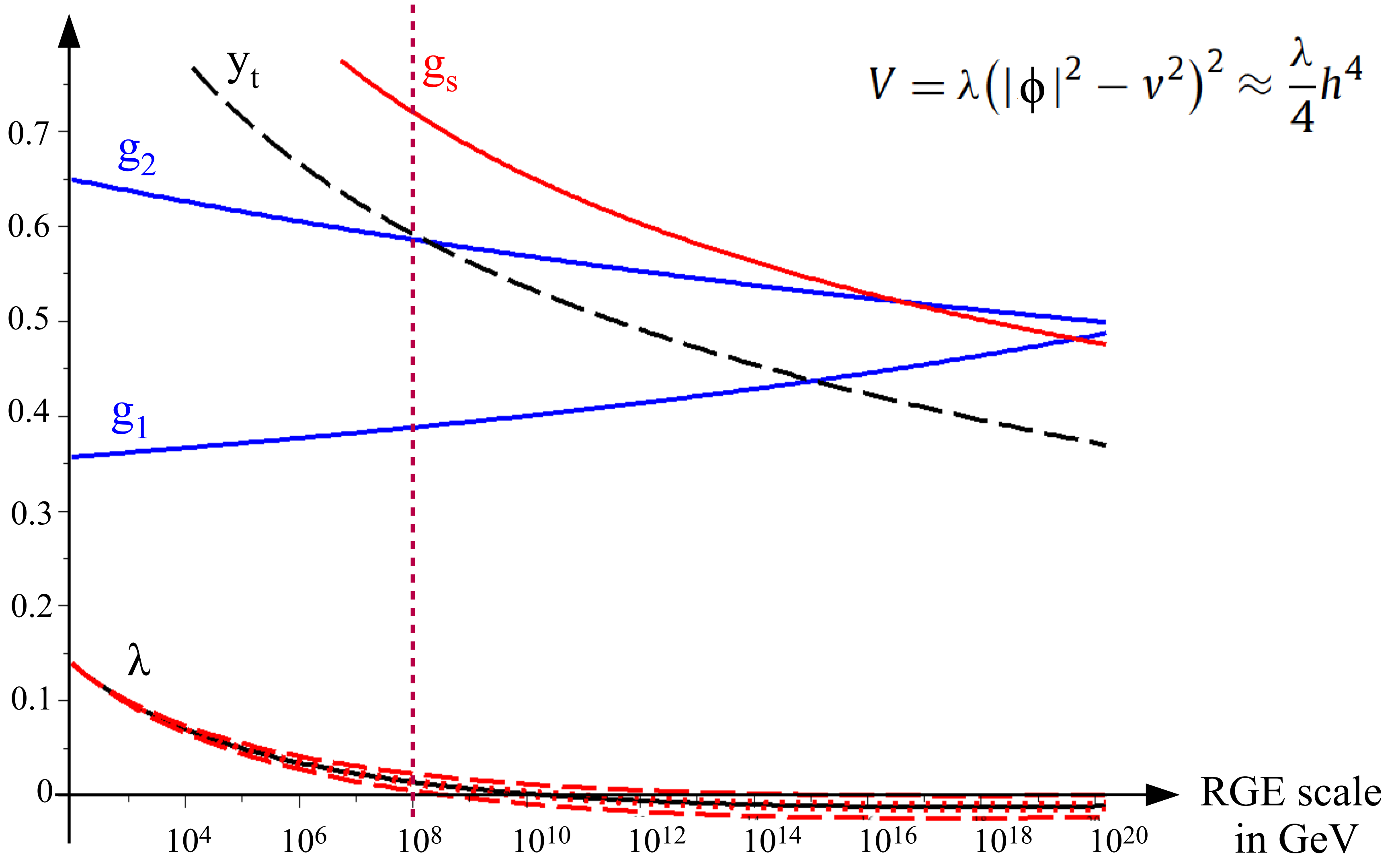

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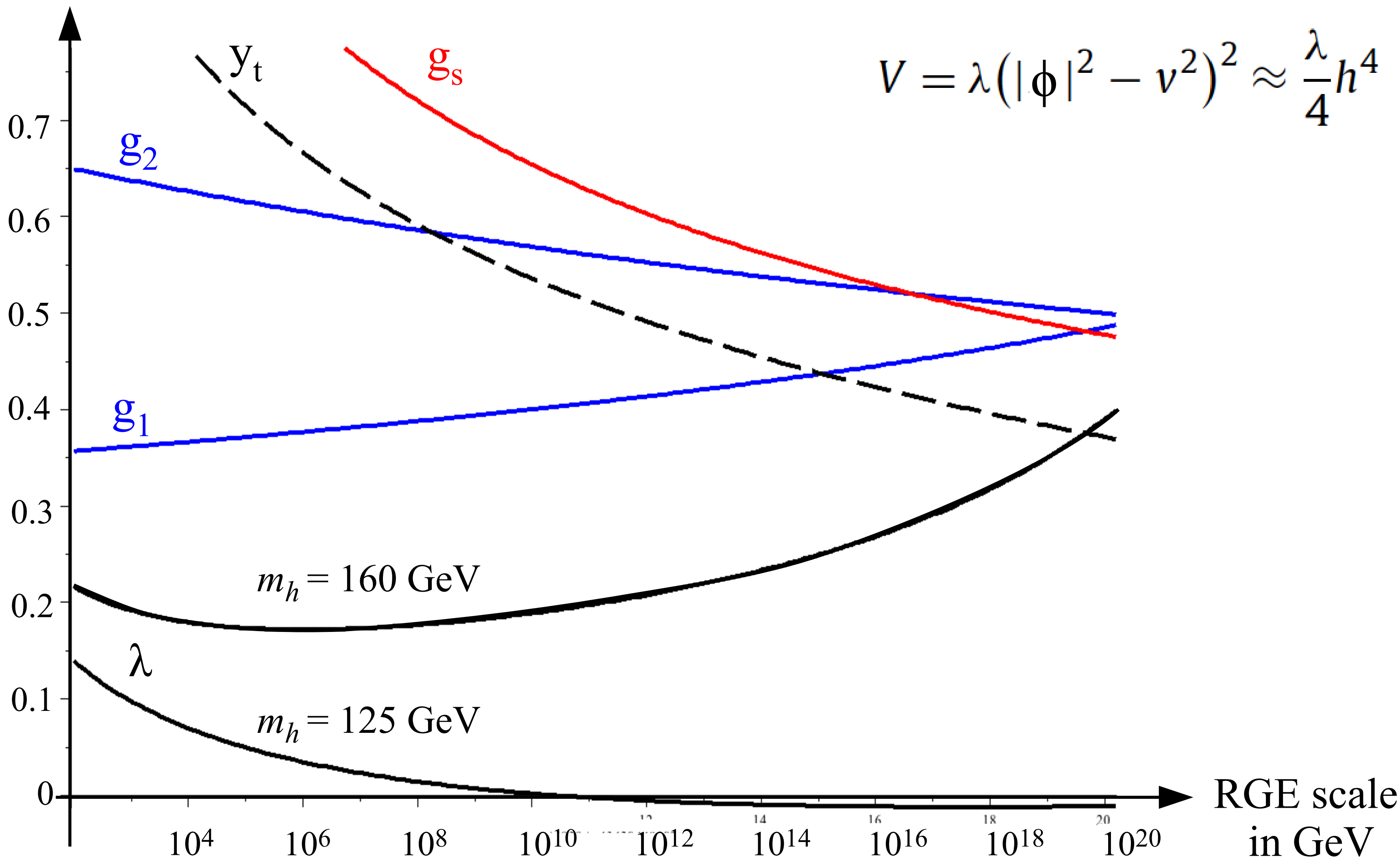

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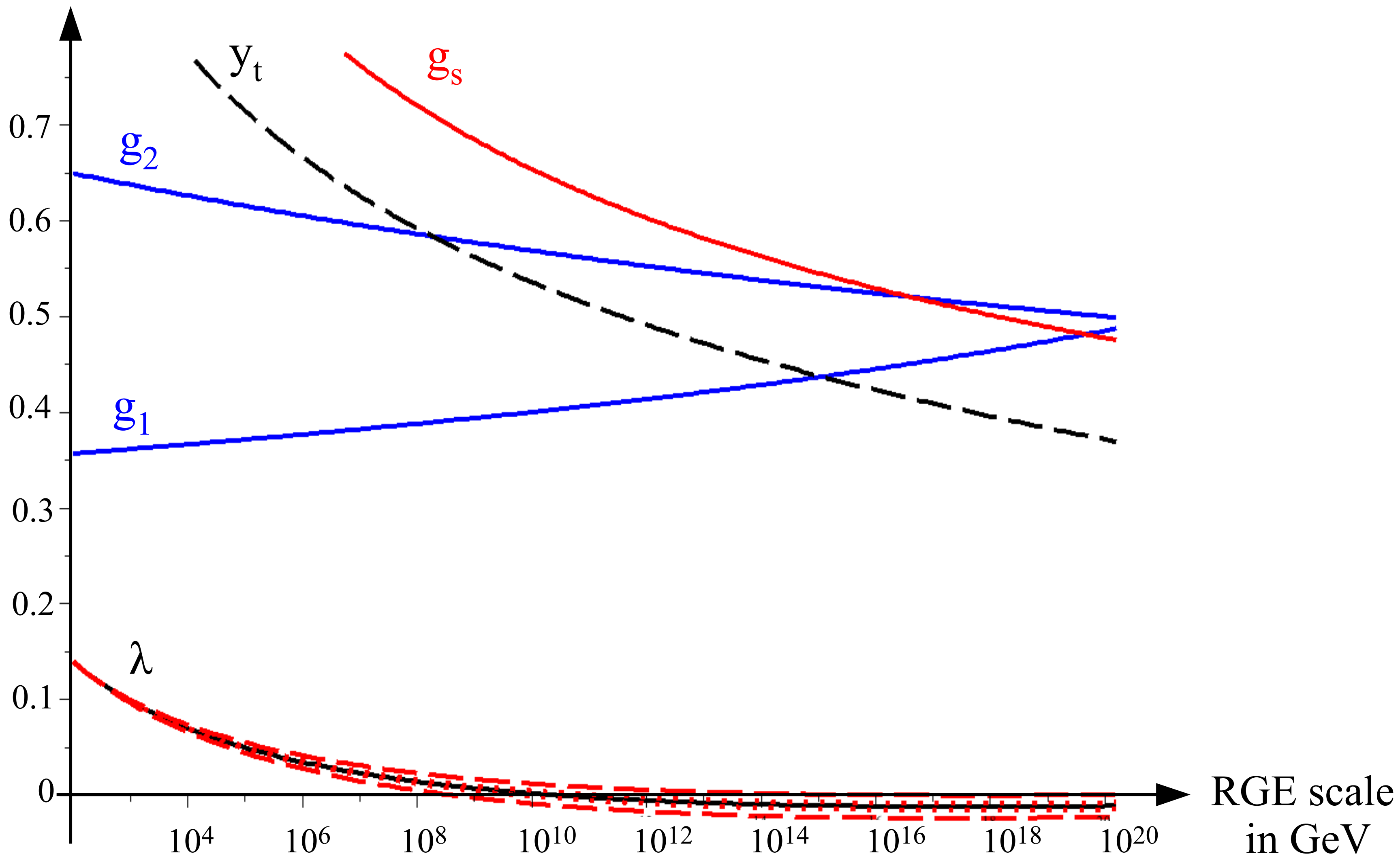
N.B.: The smallness of all the couplings at high energies is the reason why we can compute the SM evolution of λ so precisely [3-loop corrections in β_λ are irrelevant].



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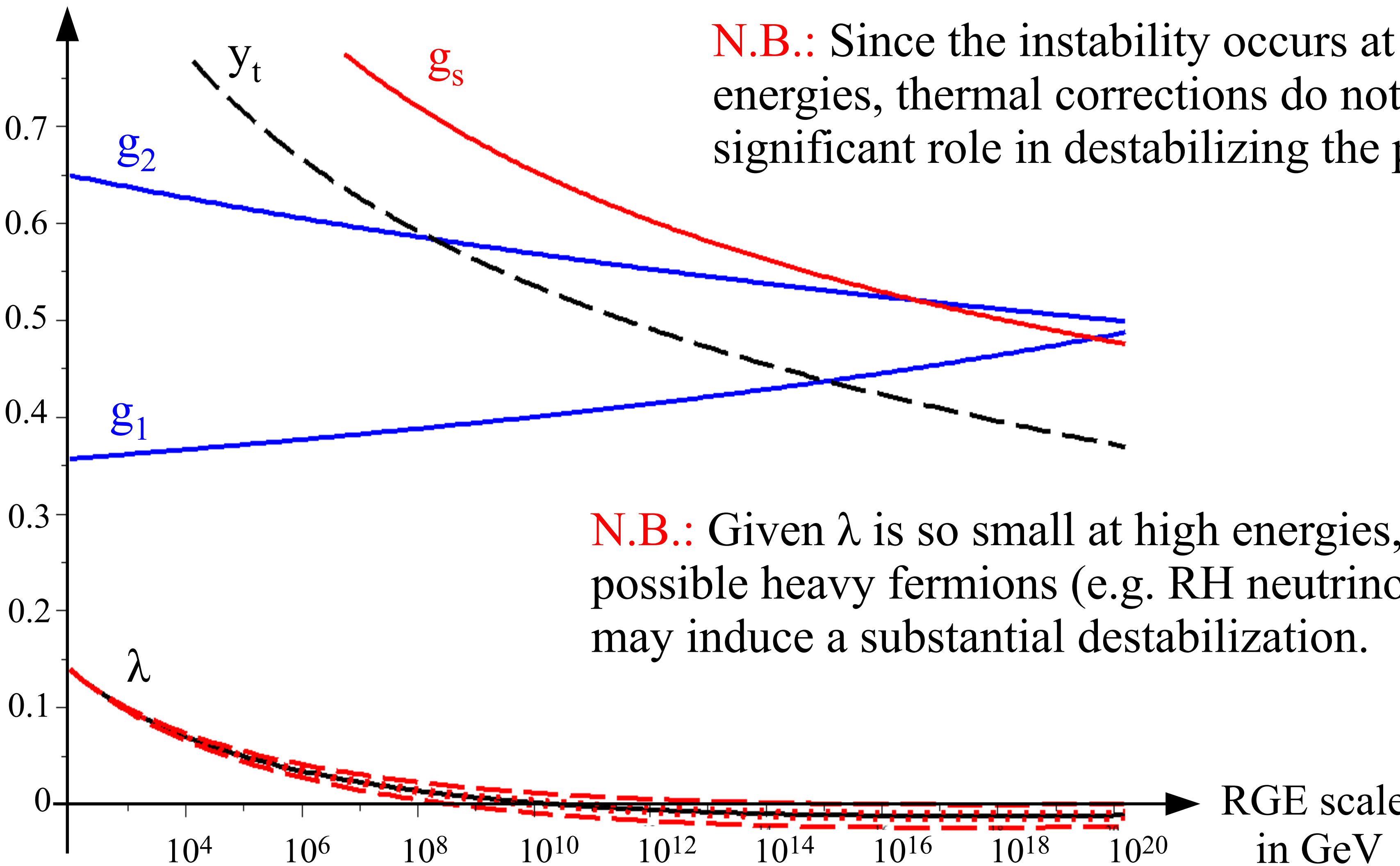

N.B.: Since the instability occurs at very high energies, thermal corrections do not play a significant role in destabilizing the potential.

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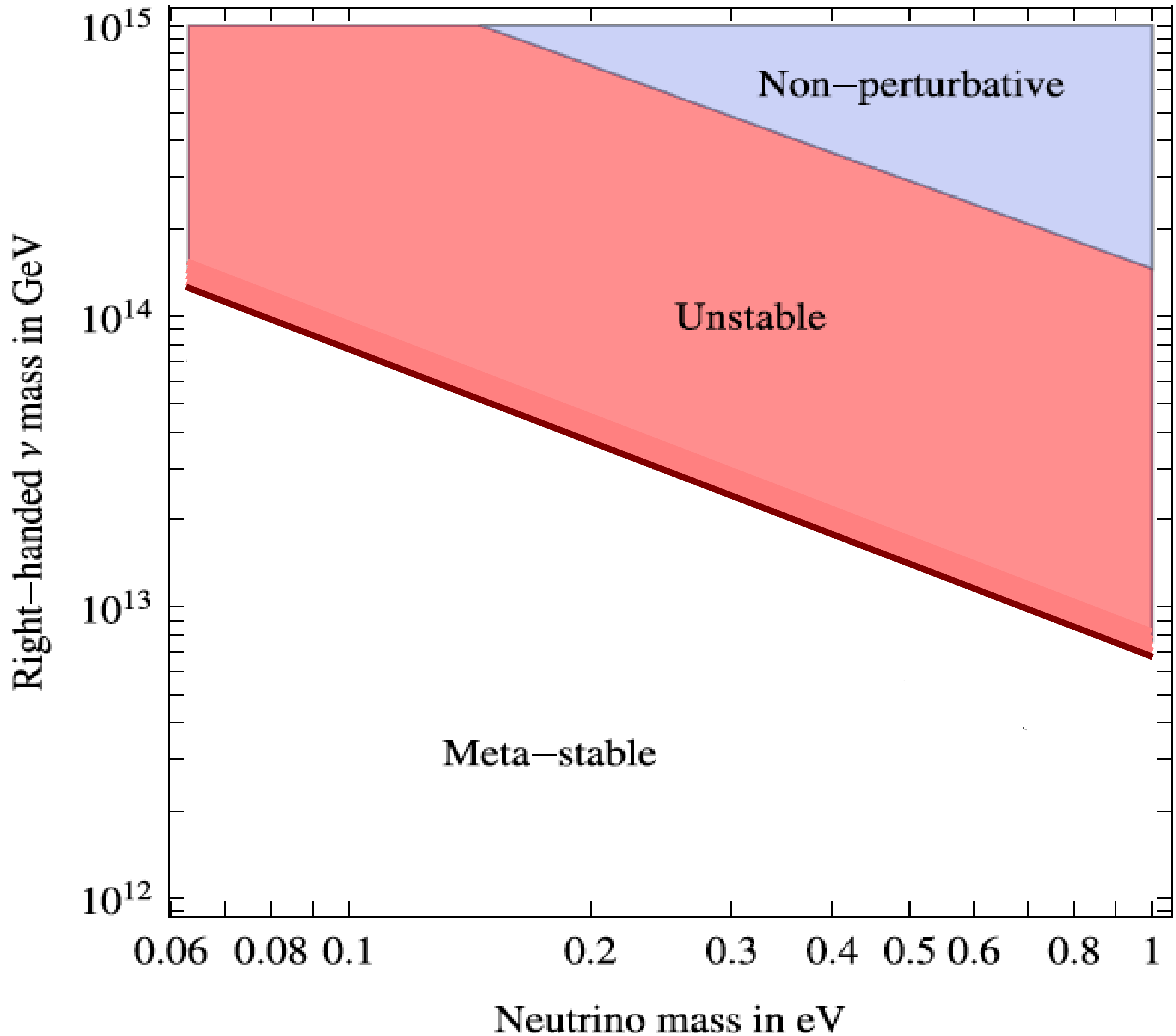
$$m_\nu \sim Y_n^T \frac{v^2}{M_R} Y_n$$



Significant bounds in the region of large Yukawa couplings,

but still enough room for leptogenesis to take place.

Conclusions

- A SM-like Higgs with $m_h \sim 125$ GeV does not allow us to derive model-independent conclusions about the scale of New Physics: the Higgs potential is most likely unstable, but the e.w. vacuum is sufficiently long-lived.

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- A SM-like Higgs with $m_h \sim 125$ GeV does not allow us to derive model-independent conclusions about the scale of New Physics: the Higgs potential is most likely unstable, but the e.w. vacuum is sufficiently long-lived.

- Clear indication about a small, or even vanishing, Higgs self-coupling at high energies: if the SM is only an effective theory, we have to match it into a model where the Higgs

  - is a weakly interacting particle, if the matching occurs close to the e.w. scale [*as indicated by naturalness*]

  - may have no intrinsic self-coupling (trivial $\lambda\phi^4$), if the matching occurs above $\sim 10^8$ GeV