Stability of the EW vacuum (Universe) and Cosmic Rays

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References :

V B, E. Messina, Phys.Rev.Lett.111, 241801 (2013) (arXiv:1307.5193)

V B, arXiv:1405.7864, Moriond 2014

V B, E. Messina, A. Platania JHEP 1409 (2014) 182 (arXiv:1407.4112)

V B, E. Messina, M. Sher, Phys.Rev.D91 (2015) 1, 013003 (arXiv:1408.5302)

V B, E. Messina, arXiv:1507.08812

CRIS 2015, Gallipoli, September 14 - 16, 2015

Stability Condition of the Electroweak Vacuum

Stability Condition of the Universe as a whole

... a time honored subject ...

Stability condition of the EW vacuum ... Time honored subject

List of some References ... far from being exhaustive ...

I. V. Krive, A. D. Linde, Nucl.Phys. B432 (1976) 265.

N. Cabibbo, L. Maiani, G. Parisi, R. Petronzio, Nucl.Phys. **B158** (1979) 295.

M. S. Turner, F. Wilczek, Nature 298 (1982) 633.

R.A. Flores, M. Sher, Phys. Rev. **D27** (1983) 1679.

M. Lindner, Z. Phys. **31** (1986) 295.

D.L. Bennett, H.B. Nielsen and I. Picek, Phys. Lett. B 208 (1988) 275.

M. Sher, Phys. Rep. **179** (1989) 273.

M. Lindner, M. Sher, H. W. Zaglauer, Phys. Lett. **B228** (1989) 139.

C. Ford, D.R.T. Jones, P.W. Stephenson, M.B. Einhorn, Nucl.Phys. **B395** (1993) 17.

M. Sher, Phys. Lett. **B317** (1993) 159.

G. Altarelli, G. Isidori, Phys. Lett. **B337** (1994) 141.

J.A. Casas, J.R. Espinosa, M. Quirós, Phys. Lett. **B342** (1995) 171.

J.A. Casas, J.R. Espinosa, M. Quirós, Phys. Lett. **B382** (1996) 374.

List of some References ... far from being exhaustive ...

G. Anderson, Phys. Lett. **B243** (1990) 265

P. Arnold and S. Vokos, Phys. Rev. **D44** (1991) 3620

J.R. Espinosa, M. Quiros, Phys.Lett. **B353** (1995) 257-266

C. D. Froggatt and H. B. Nielsen, Phys. Lett. **B 368** (1996) 96.

C.D. Froggatt, H. B. Nielsen, Y. Takanishi (Bohr Inst.), Phys.Rev. **D64** (2001) 113014

G. Isidori, G. Ridolfi, A. Strumia, Nucl. Phys. **B609** (2001) 387.

J. R. Espinosa, G. F. Giudice, A. Riotto, JCAP 0805, 002 (2008).

J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto, A. Strumia, Phys.Lett. **B709** (2012) 222-228

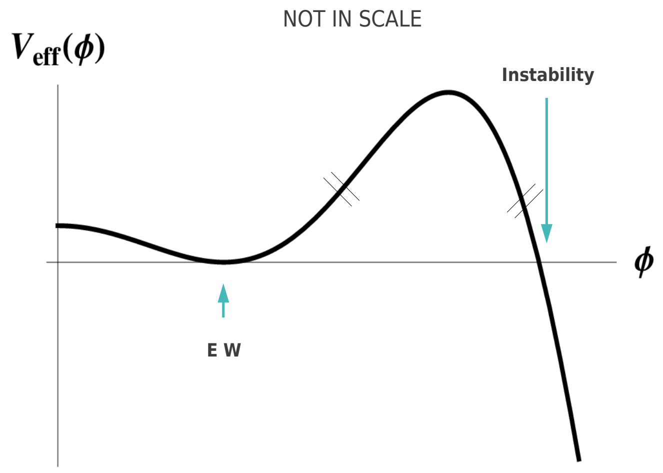
G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G.Isidori, A. Strumia, JHEP **1208** (2012) 098.

S. Alekhin, A. Djouadi, S. Moch, Phys.Lett. B716 (2012) 214.

F. Bezrukov, M. Yu. Kalmykov, B. A. Kniehl, M. Shaposhnikov, JHEP 1210 (2012) 140.

D. Buttazzo, G. Degrassi, P.P. Giardino, G.F. Giudice, F. Sala, A. Salvio, A. Strumia, JHEP 1312 (2013) 089.

Top loop-corrections to the Higgs Effective Potential destabilize the electroweak vacuum...



EW Scale $= v \sim 246$ GeV

Instability Scale $\sim 10^{11}$ GeV (for $M_H \sim 125$ GeV , $M_t \sim 173$ GeV)

MOREOVER

Higgs boson $M_H \sim 125$ GeV

Experimental data consistent with Standard Model predictions

No sign of New Physics

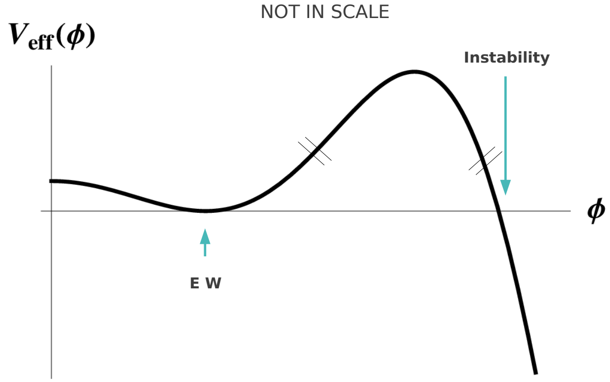
Boosted new interest and work on an old idea

... the possibility that

New Phyiscs shows up only at very high energies

... Planck scale ...

Back to the Higgs One-Loop Effective Potential $V^{1l}(\phi)$

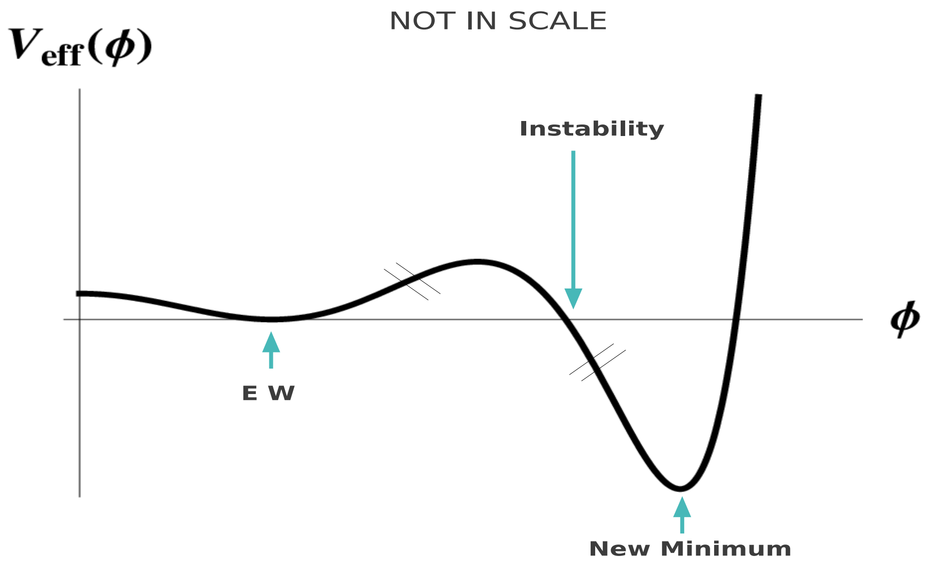


$$V^{1l}(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{24}\phi^4 + \frac{1}{64\pi^2}\left[\left(m^2+\frac{\lambda}{2}\phi^2\right)^2\left(\ln\left(\frac{m^2+\frac{\lambda}{2}\phi^2}{\mu^2}\right)-\frac{3}{2}\right)\right.$$

$$+3\left(m^2+\frac{\lambda}{6}\phi^2\right)^2\left(\ln\left(\frac{m^2+\frac{\lambda}{6}\phi^2}{\mu^2}\right)-\frac{3}{2}\right)+6\,\frac{{g_1}^4}{16}\phi^4\left(\ln\left(\frac{\frac{1}{4}{g_1}^2\phi^2}{\mu^2}\right)-\frac{5}{6}\right)$$

$$\left.+3\,\frac{\left({g_1}^2+{g_2}^2\right)^2}{16}\phi^4\left(\ln\left(\frac{\frac{1}{4}\left({g_1}^2+{g_2}^2\right)\phi^2}{\mu^2}\right)-\frac{5}{6}\right)-12\,h_t^4\phi^4\left(\ln\frac{g^2\phi^2}{\mu^2}-\frac{3}{2}\right)\right]$$

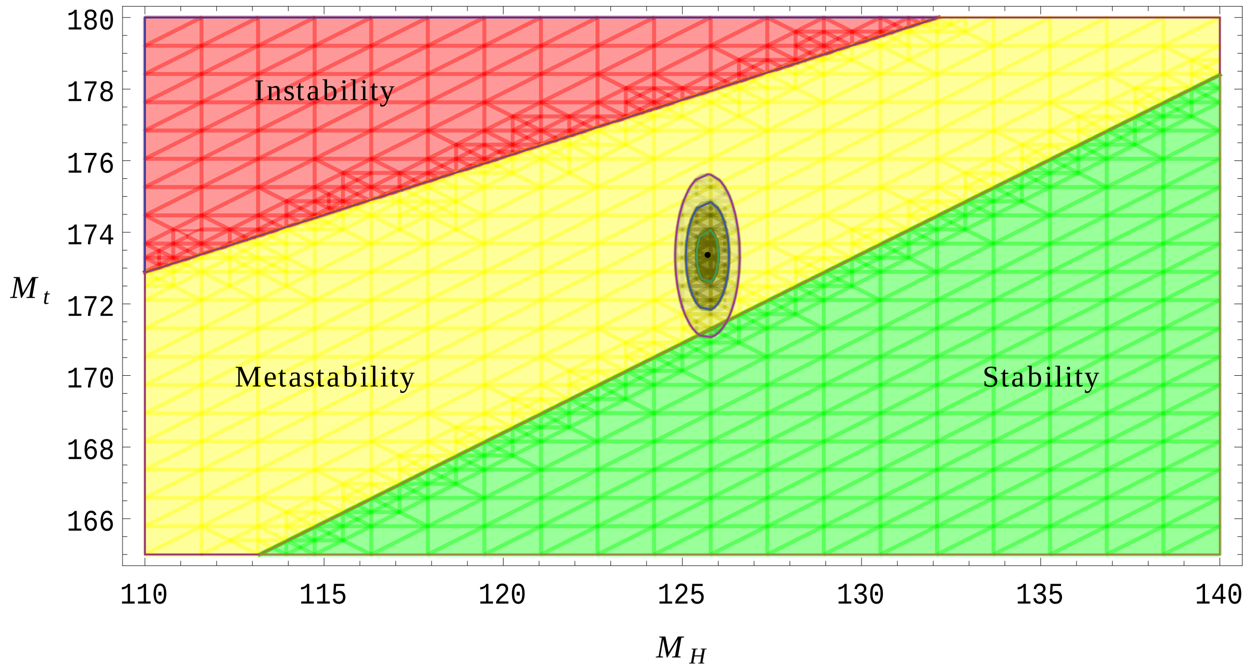
RG Improved Effective Potential $V_{RGI}(\phi)$



Depending on M_H and M_t , **the second minimum can be : (1) lower than the EW minimum (as in the figure) ; (2) at the same level of the EW minimum ; (3) higher than the EW minimum.**

When the potential at the New Minimum is lower than the potential at the EW Minimum, compute the Tunnelling Time ...

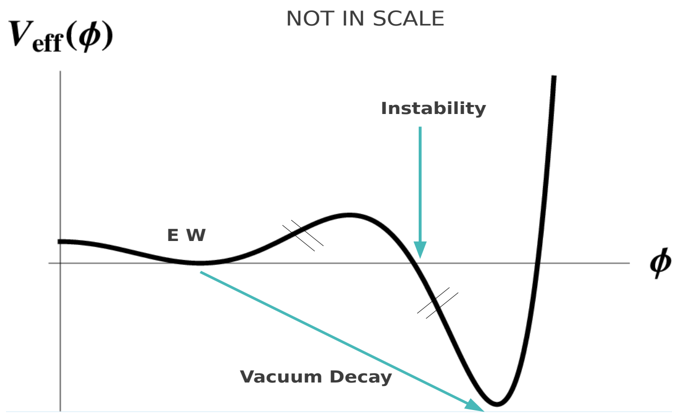
...and we draw the Stability Diagram in the $M_H - M_t$ plane



Stability region : $V_{eff}(v) < V_{eff}(\phi^{(2)}_{min})$. **Meta-stability** region : $\tau > T_U$. **Instability** region : $\tau < T_U$. Stability line : $V_{eff}(v) = V_{eff}(\phi^{(2)}_{min})$. Instability line : M_H and M_t such that $\tau = T_U$.

What is the so called "**Metastability Scenario**"?

When the second minimum is lower than EW $\Rightarrow$



Tunnelling between the Metastable EW Vacuum and the True Vacuum

As long as EW vacuum lifetime larger than the age of the Universe ...

.... we may well live in the Meta-Stable (EW) Vacuum ....

How do we compute the tunneling time ?

How do we compute the tunneling time ?

Semiclassical calculation - WKB - instantons

EW vacuum lifetime (= Tunneling Time τ)

$$\Gamma = \frac{1}{\tau} = T_U^3 \, \frac{S[\phi_b]^2}{4\pi^2} \left| \frac{\det' \left[-\partial^2 + V''(\phi_b)\right]}{\det \left[-\partial^2 + V''(v)\right]} \right|^{-1/2} e^{-S[\phi_b]}$$

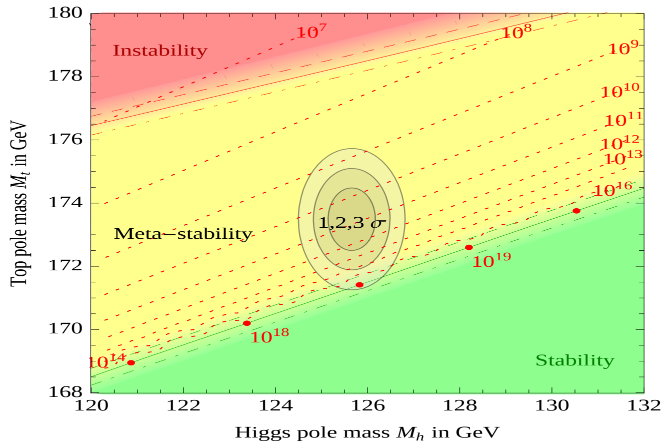
$\phi_b(r)$ **:** **Bounce Solution**

Solution to the Euclidean Equation of Motion with appropriate boundary conditions

S. Coleman, Phys. Rev. D 15 (1977) 2929

C.G.Callan, S.Coleman, Phys. Rev. D 16 (1977) 1762

With this Heavy Artilery ... Stability Diagram ...



Important : this Stability Diagram is obtained under the assumption that even if we have New Physics at the Planck scale (or at some other very high energy scale), this has **no influence** on the Diagram itself.

Tunnelling time for the experimental point ($M_H \sim 125$ GeV, $M_t \sim 173$ GeV) :

$$\tau \sim 10^{600}\, T_U$$

... However ...

I am going to show that

1. This is not the generic case : the Stability Diagram obtained above is not universal. In other words, even if New Physics shows up only at some very high energy scale, the Stability Diagram depends on New Physics ...

2. Even more important, we can argue that the Stability Diagram shown above is not what we should generically expect ...

... MOREOVER ...

... LET'S ASK THE FOLLOWING QUESTION ...

... Can Cosmic Rays have something to say on False Vacuum Decay? ...

Yes, they can !

How? .... Why?

- The False Vacuum Decay described up to now is nothing but a process of Spontaneous Decay: there is a non-vanishing probability that a bubble of true vacuum forms in a background of False Vacuum (the EW false vacuum state where we live). This is a Nucleation process... Similar to what happens in supercooled or superheated systems...

- The collision in the false vacuum (EW vacuum) of primary cosmic rays with a nucleon can catalise the creation of a bubble ot true vacuum ...

... And ... Can Cosmic Rays Catalised Decay dominate over the Spontaneous Decay (= Tunnelling) ? ...

... Not easy to answer ...

Some studies suggest that the cosmic rays catalised dacay should be more important than the spontaneous dacay ... to the point that our universe should have already decayed into the true vacuum !!! ...But we are here... in the false vacuum... In fact, on the basis of this argument, it is concluded that the observation itself of Cosmic Ray showers put stringent limits on the existence of other vacuum states lower than the one that we presently inhabit ...

P. Hut, M.J. Rees, Letters to Nature, 1983

... And ... Can Cosmic Rays Catalised Decay dominate over the Spontaneous Decay (= Tunnelling) ? ...

... Not easy to answer ...

Other studies question these results, as based upon somewhat uncertain physical reasoning and assumptions ... and it is argued that ... Cosmic Rays catalised decay is the dominant process only if the bubbles have sufficiently small walls (“thin walls”) ... However, for cosmologically significant false vacuum decays, that almost certainly decay via “thick-walled” bubbles ... the spontaneous false vacuum decay via tunnelling will always be the dominant decay mode ...

K. Enqvist, J. McDonald, Nucl.Phys. B513 (1998) 661-678

... More ...

In other works, the transition probability to the true vacuum due to Cosmic Rays collisions is studied as a function of the Standard Model parameters, mainly the top mass M_t and the Higgs mass M_H ... so bounds on the values of these parameters are found ...

J. Ellis, A. Linde, M. Sher, Physics Letters B, 1990

... But ... Does Cosmic Rays catalised decay dominate over the Spontaneous Decay (= Tunnelling) ? ...

... Not easy to answer ...

Another very recent work seems to suggest that ... no cosmic ray induced can ever occur ...

S. Demidov and D. Levkov

High - energy limit of collision - induced false vacuum decay

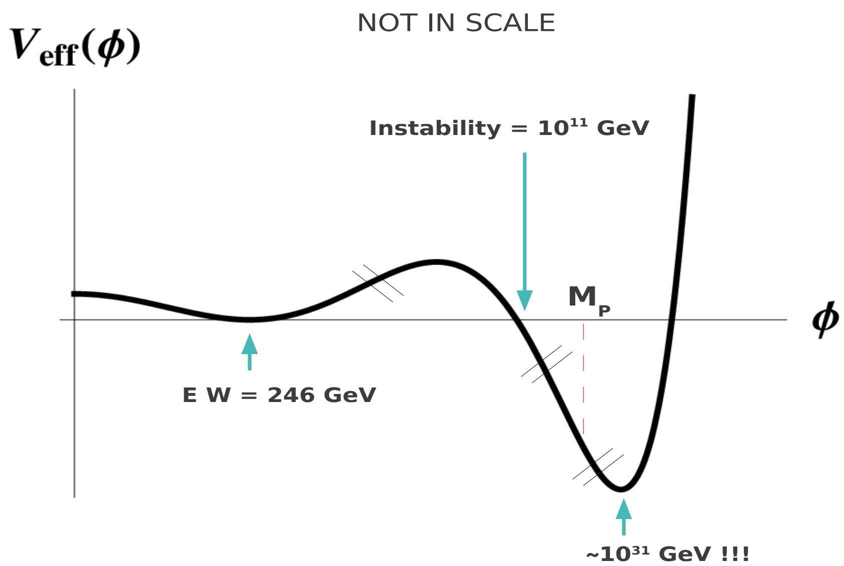
arXiv: 1503.06339

Am I going to provide the final answer to these questions ? ...

No !

... However I know that I am going to add an important element to the analysis ...

Probably worth to know that for $M_H \sim 125$ **GeV** and $M_t \sim 173$ **GeV**



New minimum at $\phi^{(2)}_{min} \sim 10^{30}$ **GeV !!!**

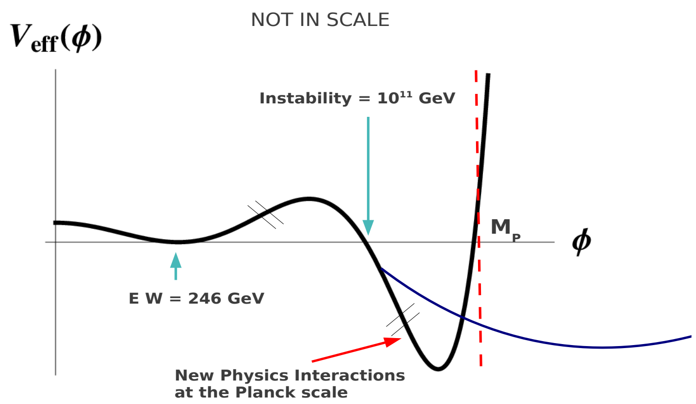
SM Effective Potential extrapolated well above M_P **!!!**

Remember : you normally hear... "assume SM valid up to M_P**"**

Does this make any sense ??? Is this a problem or not ???

To make sense out of this potential, people have/had some arguments ...

1. New Physics Interactions that appear at the Planck scale M_P eventually stabilize the potential around M_P ...



... meaning that if you take into account the presence of these new physics interactions at M_P

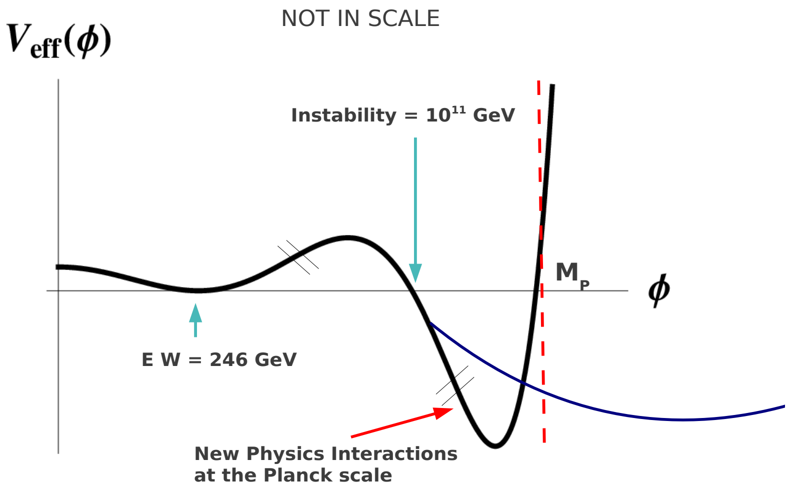
...these terms stabilize the Higgs potential around M_P...

2. These New Physics Interactions present at the Planck scale do not affect the **EW vacuum lifetime** τ (can be neglected when computing τ)

(a) - Instability scale much lower than Planck scale $\Rightarrow$

$$\Rightarrow \quad \text{suppression } \left(\frac{\Lambda_{inst}}{M_P}\right)^n$$

(b) - For tunnelling, only height of the barrier and turning points matter



... These arguments turn out to be incorrect ... we'll see why ...

... Toy UV completion of the SM

Add to the SM potential a "New Boson" and a "New Fermion" :

$$\Delta V(\phi, S, \psi) = \frac{M_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{g_S}{4}\phi^2 S^2 + M_f \bar{\psi}\psi + \frac{g_f}{\sqrt{2}}\phi\bar{\psi}\psi$$

with $M_f \sim 10^{17}$ **GeV and** $M_S \sim 10^{18}$ **GeV.**

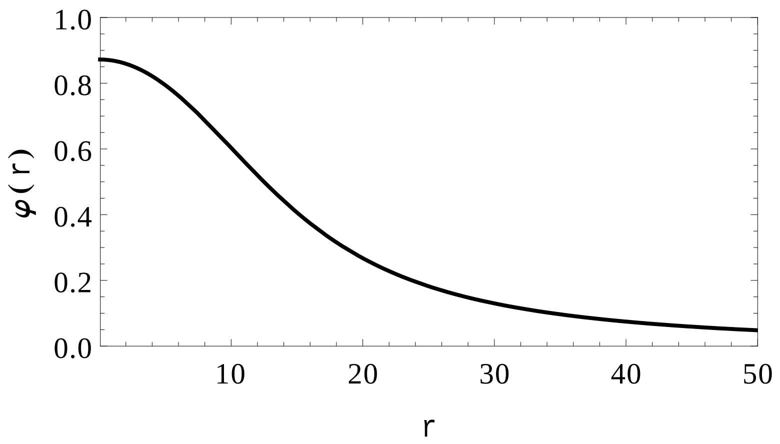
Integrating out this new scalar and fermion fields we get the

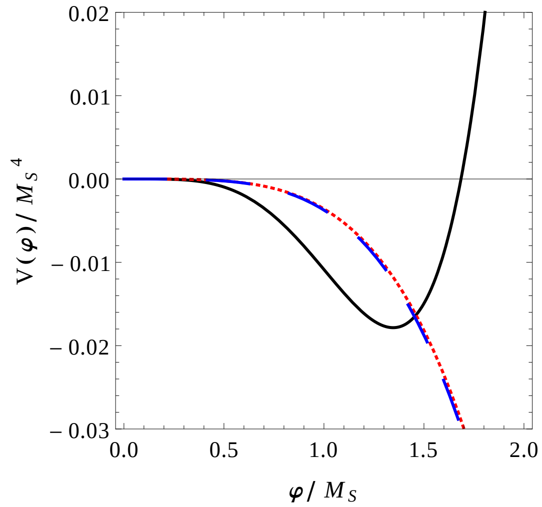
Modified Higgs Potential

$$\begin{aligned} V(\phi) &= \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{1}{64\pi^2}\left(M_S^2 + \frac{g_S}{2}\phi^2\right)^2\left[\ln\left(\frac{M_S^2 + \frac{g_S}{2}\phi^2}{\mu^2}\right) - \frac{3}{2}\right] \\ &- \frac{1}{16\pi^2}\left(M_f^2 + \frac{g_f^2}{2}\phi^2\right)^2\left[\ln\left(\frac{M_f^2 + \frac{g_f^2}{2}\phi^2}{\mu^2}\right) - \frac{3}{2}\right] \end{aligned}$$

... and ...

EXAMPLE 1 : τ modified and $\tau < T_U$





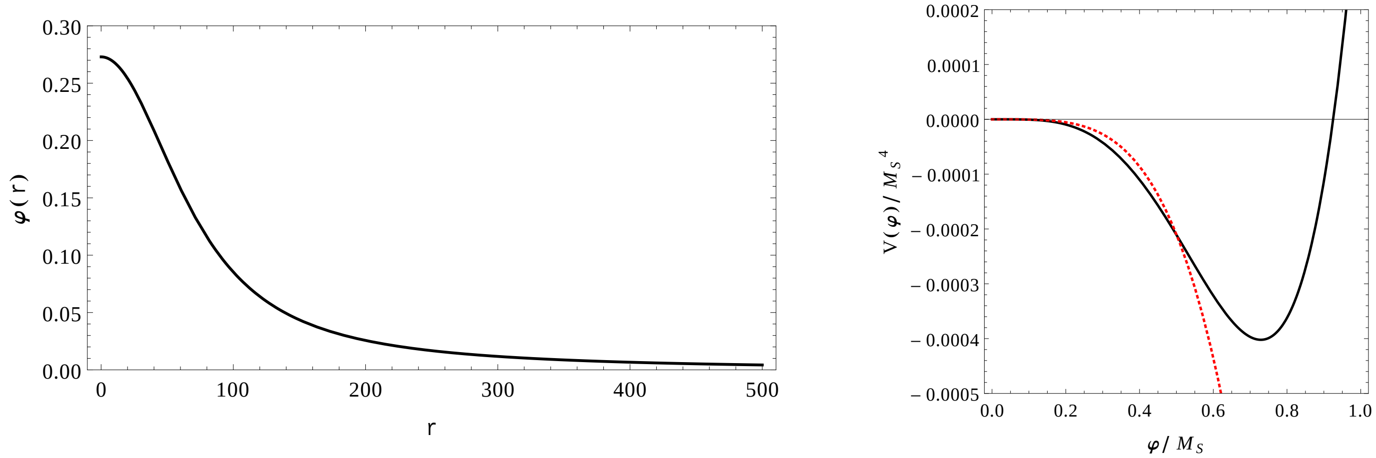
$M_H \sim 125$ **GeV and** $M_t \sim 173$ **GeV**

Left panel : New Bounce Solution. Right panel : SM-alone Effective Potential (blue dashed line); potential modified by the presence of M_f **and** M_S **(black solid line), for certain given values of** M_S, M_f, g_f **and** g_S

Here, with New Physics : $\tau \sim 10^{-30} T_U$

To be compared with : $\tau \sim 10^{600} T_U$ **(without New Physics)**

EXAMPLE 2 : τ modified and $\tau > T_U$



$$M_H \sim 125 \ \textbf{GeV and} \ M_t \sim 173 \ \ \textbf{GeV}$$

Right panel, black solid line : potential modified by the presence of M_f and M_S for other values of of M_S, M_f, g_f and g_S

This page with New Physics: $\tau \sim 10^{260} T_U$

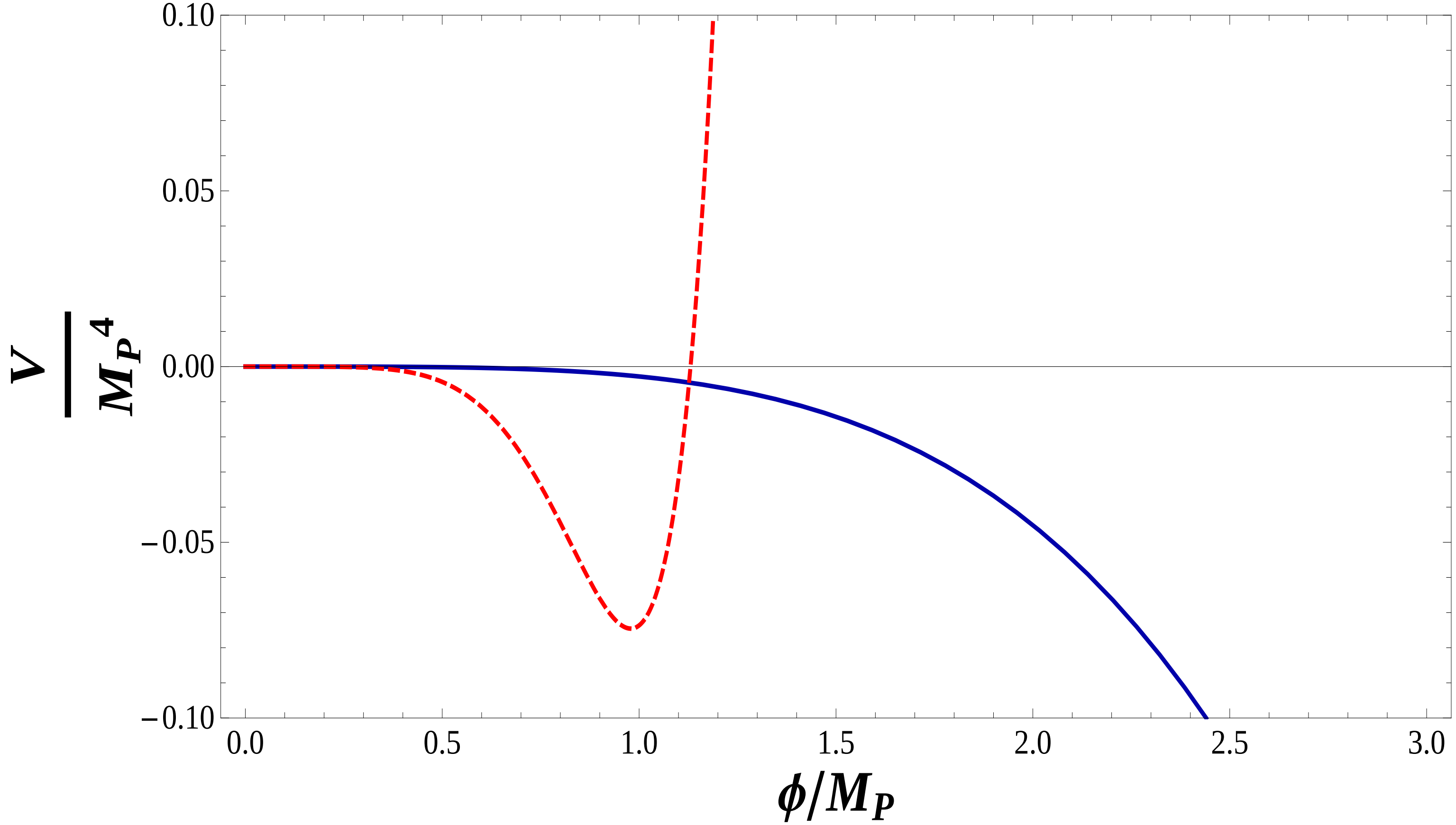
To be compared with : $\tau \sim 10^{600} T_U$ **(without New Physics)**

A very convenient and effective way to parametrize situations as those described above, i.e. New Physics at very high energy scales, close to M_P :

Add ϕ^6 and ϕ^8 to the SM Higgs potential at M_P :

$$V(\phi) \;=\; \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$

Zoom around M_P



Blue line : $V_{eff}(\phi)$ **no new physics terms (SM alone)**

Red line : $V_{eff}^{new}(\phi)$ **with** $\lambda_6(M_P) = -2$ $\lambda_8(M_P) = 2.1$

$$\Gamma = \frac{1}{\tau} = \frac{1}{T_U}\left[\frac{S[\phi_b]^2}{4\pi^2}\,\frac{T_U^4}{R_M^4}\,e^{-S[\phi_b]}\right] \times \left[e^{-\Delta S}\right]$$

In this example $(\lambda_6(M_P) = -2 \quad , \quad \lambda_8(M_P) = 2.1)$**:**

$$\tau \sim 10^{-200}\;T_U$$

This is a case as : EXAMPLE 1 (τ **modified, and** $\tau < T_U$)

We shall also see cases as : EXAMPLE 2 (τ **modified but still** $\tau > T_U$)

The tunnelling time depends on New Physics, even if the latter shows up only at very High Energies !

These result came as a surprise to the community ...

How comes that new physics can have such an impact on τ ?

Why the usual arguments on the suppression of new physics do not apply ?

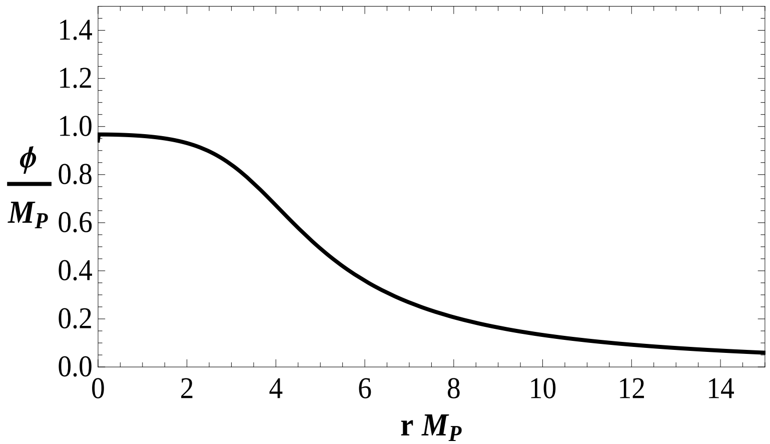
1. New physics appears in terms of higher dimension operators, and people expected their contribution to be suppressed as $(\frac{\Lambda_{inst}}{M_P})^n$

But: Tunnelling is a non-perturbative phenomenon. We first select the saddle point, i.e. compute the bounce (tree level), and then compute the quantum fluctuations (loop corrections) on the top of it.

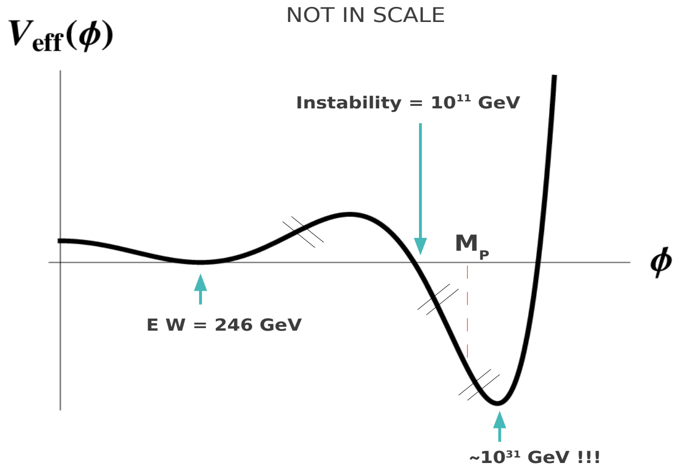
Suppression in terms of inverse powers of M_P (power counting theorem) concerns the loop corrections, not the selection of the saddle point (tree level).

Remember : $$\tau \sim e^{S[\phi_b]}$$

New bounce $\phi_b^{(2)}(r)$, New action $S[\phi_b^{(2)}]$, New τ



2. Height of the barrier and turning points...



This is QFT with "very many" dof, not 1 dof QM $\Rightarrow$ the potential is not $V(\phi)$ in figure with 1 dof, but...

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}(\vec{\nabla}\phi)^2 - V(\phi) = \frac{1}{2}\dot{\phi}(\vec{x},t)^2 - U(\phi(\vec{x},t))$$

where $U(\phi(\vec{x},t))$ **is :** $\quad U(\phi(\vec{x},t)) = V(\phi(\vec{x},t)) + \frac{1}{2}(\vec{\nabla}\phi(\vec{x},t))^2$

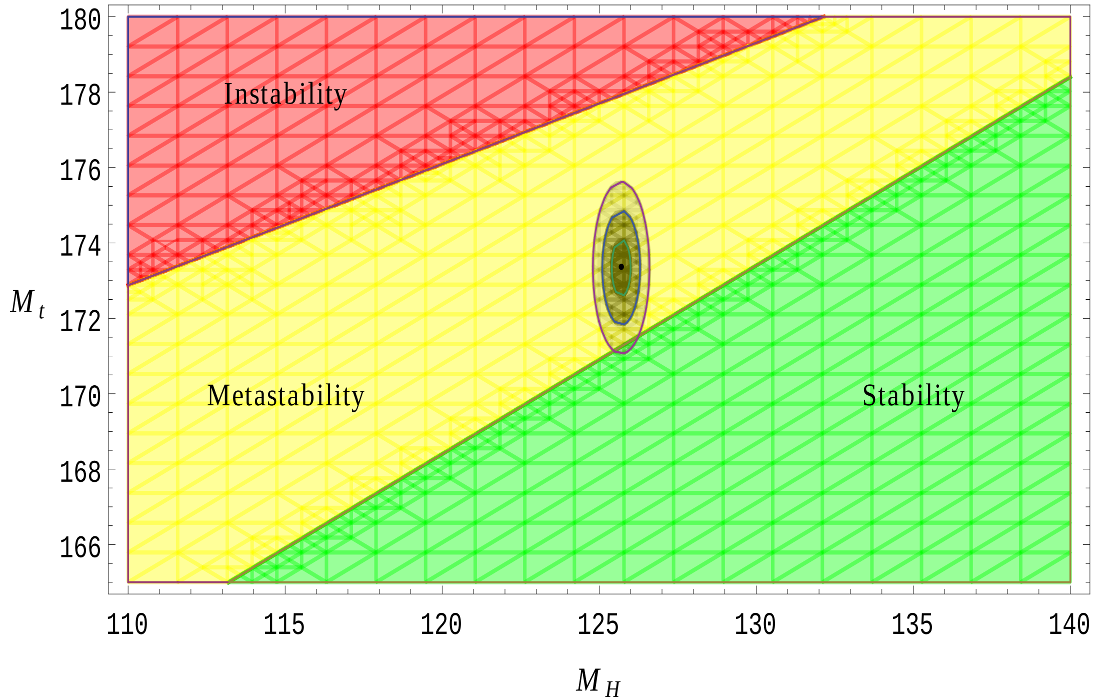
Very many dof, not 1 dof... The Potential is : $\sum_{\vec{x}} U(\phi(\vec{x},t))$

The bounce is not a constant configuration ... Gradients do matter a lot!

... We are now ready to go back to the

Stability Diagrams ...

Phase diagram with $\lambda_6 = 0$ and $\lambda_8 = 0$ - Literature case



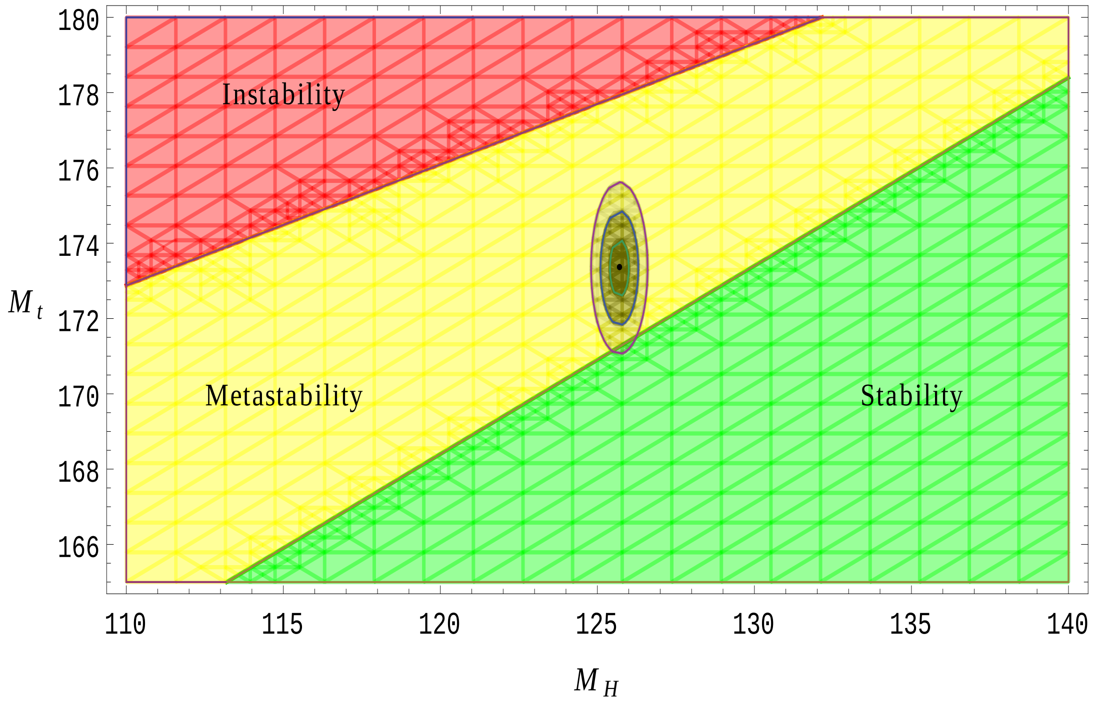
This is the well known Stability Diagram ... According to it :

(1) For $M_H \sim 125$ GeV and $M_t \sim 173$ GeV we live in a metastable state ;

(2) $\sim 3\,\sigma$ close to the stability line (Criticality) ;

(3) Precision measurements of the top mass should allow to discriminate between stable, metastable, or critical EW vacuum ...

Phase diagram with $\lambda_6 = 0$ and $\lambda_8 = 0$



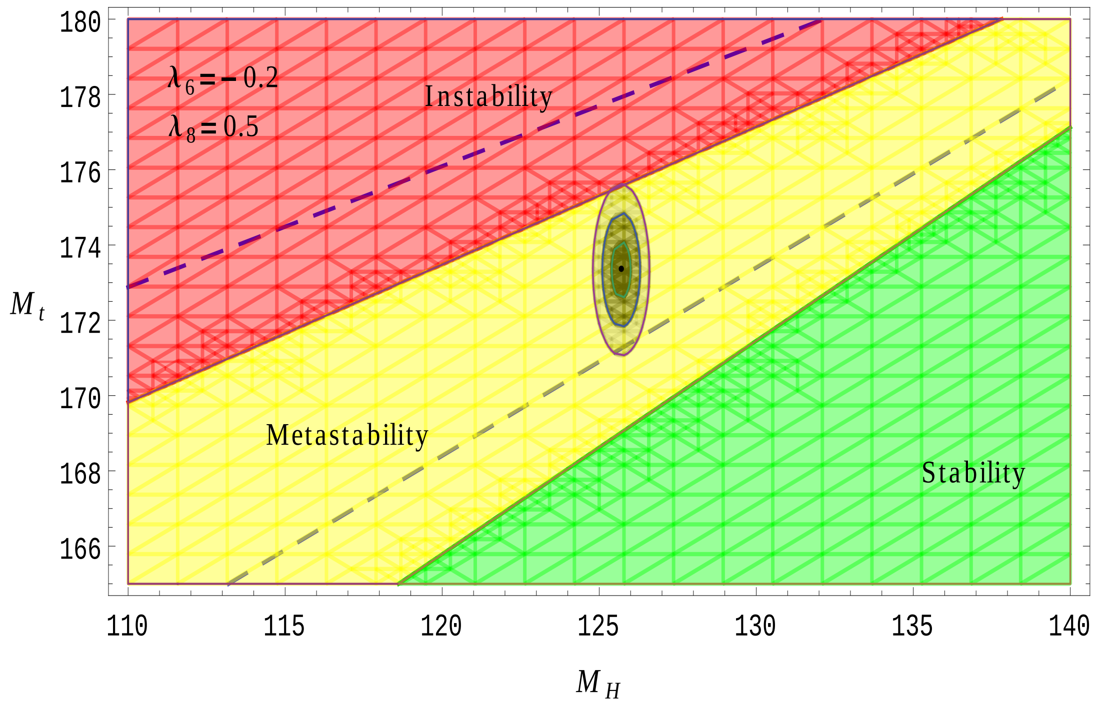
Add New Physics ... from what we have learned we expect ...

... Modification of the Instability Line (red)

... Modification of the Stability Line (green) = Critical Line

Phase diagram with $\lambda_6 = -0.2$ and $\lambda_8 = 0.5$

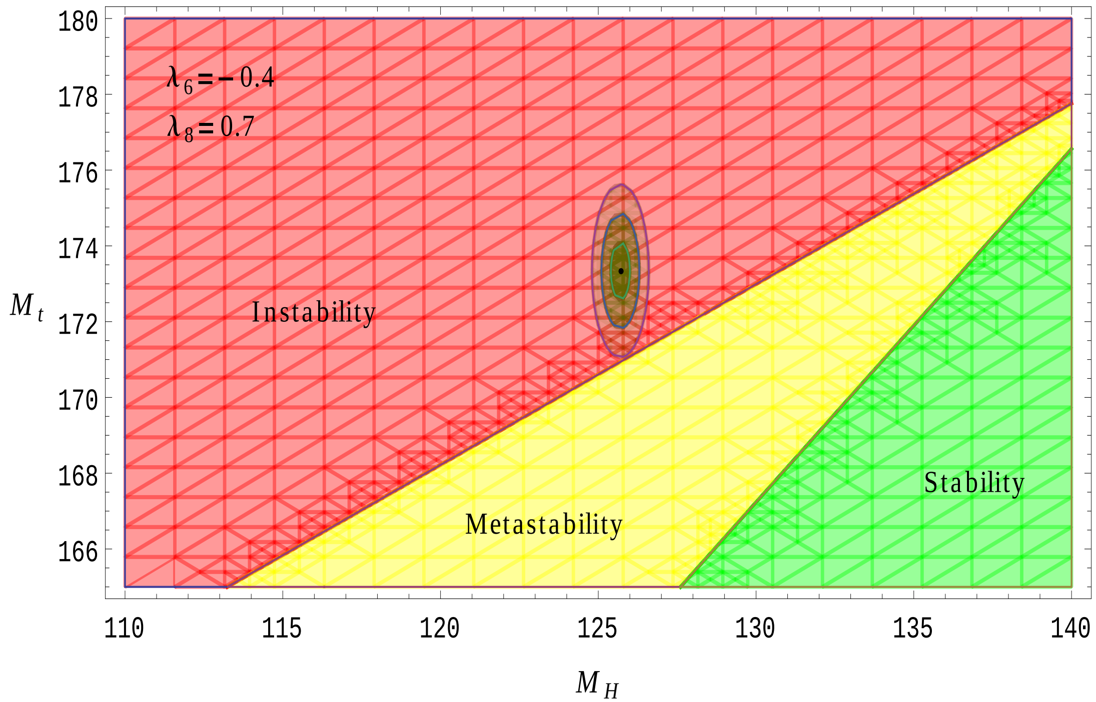
(This is like "Example 2" : $\tau << \tau_{SM}$, but still $\tau > T_U$)



The strips move downwards ... The Experimental Point no longer at $3\,\sigma$ from the stability line !!! ... Stability Diagram depends on new physics !

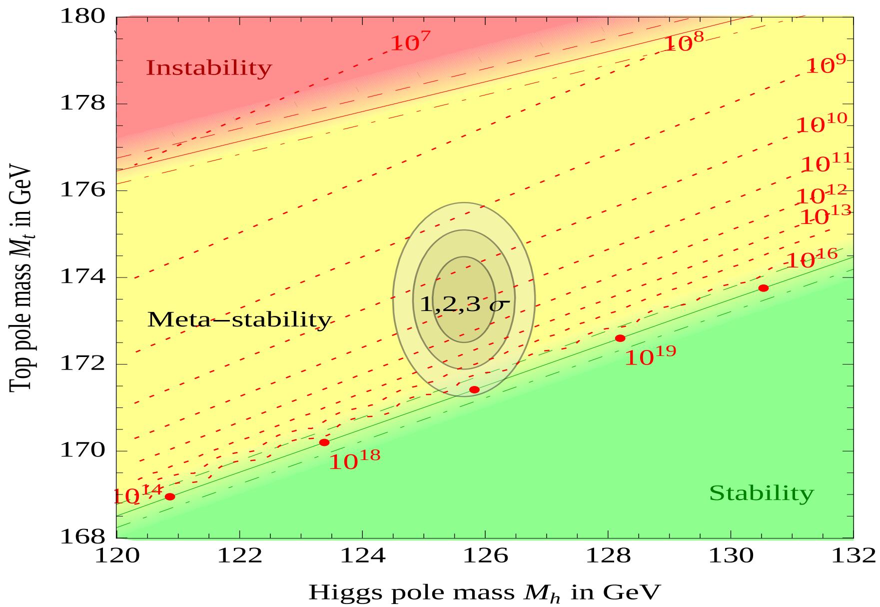
Phase diagram with $\lambda_6 = -0.4$ and $\lambda_8 = 0.7$

(This is like “Example 1” : $\tau << \tau_{SM}$, and $\tau < T_U$)



Lessons

The Phase Diagram

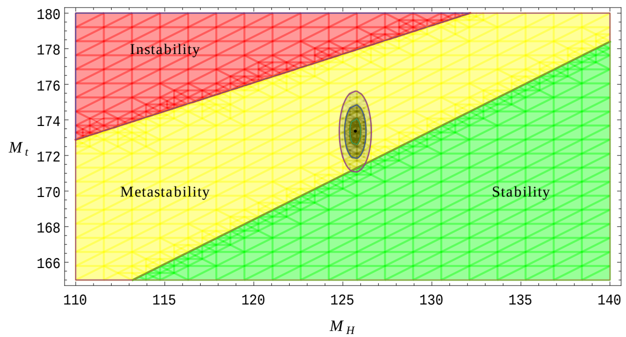


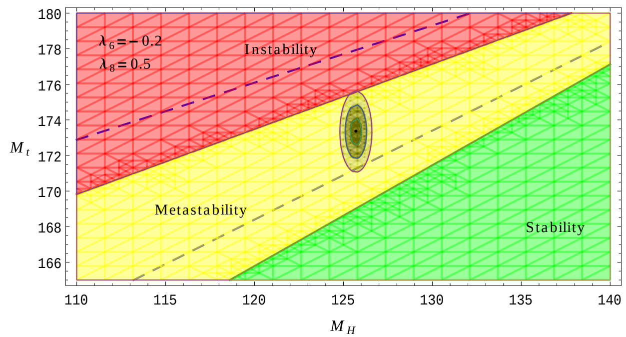
in not Universal !

... one out of different possibilities ...

... Moreover : arguably not the most probable ....

"Precision Measurements of M_H and M_t"

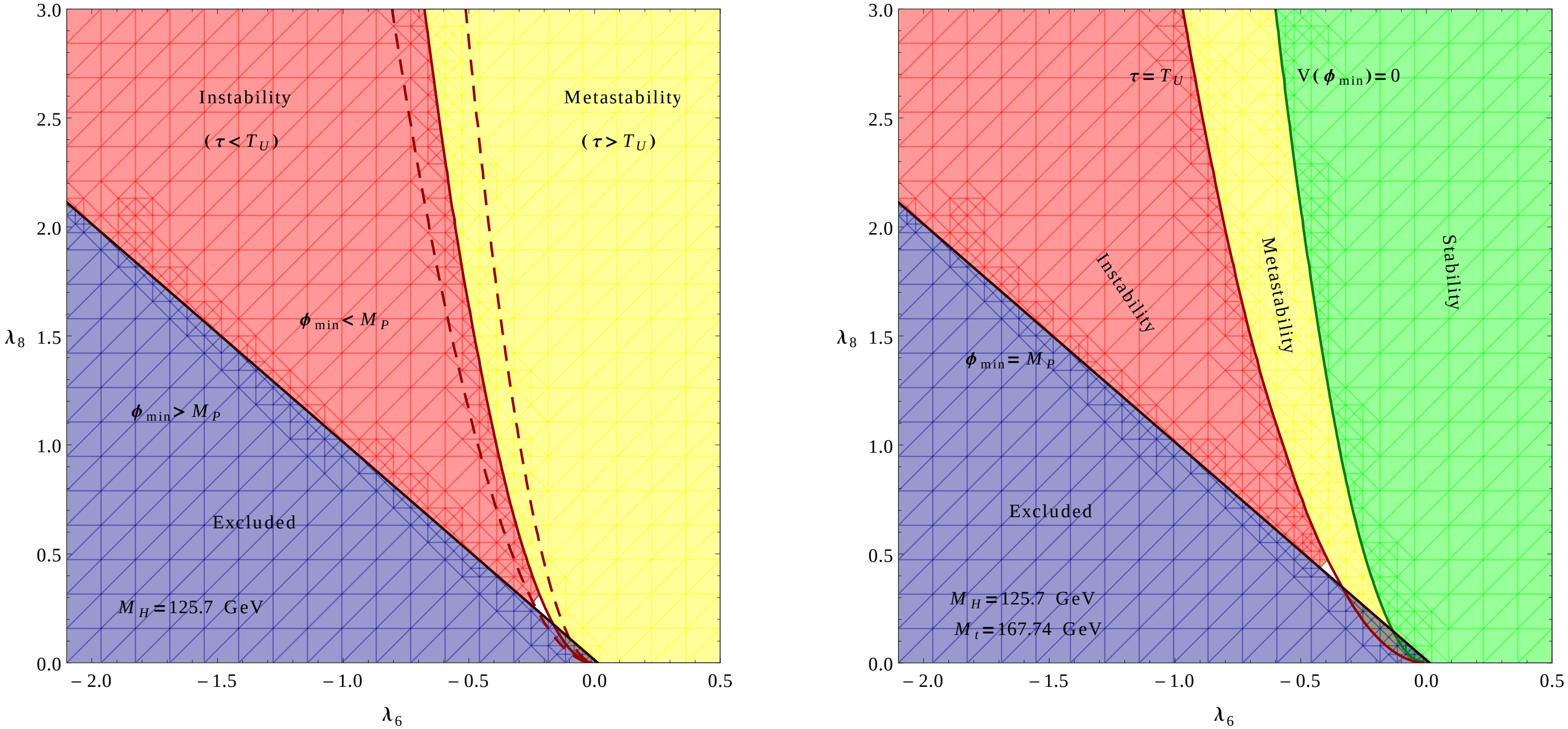




Precision measurements of M_t (and M_H) cannot discriminate between stability, metastability or criticality ... The knowledge of M_t and M_H alone is not sufficient to decide of the EW vacuum stability condition. We need informations on NEW PHYSICS in order to asses this question ...

... And also ... we need to understand the role of cosmic rays ... or other seeds that can CATALISE the Vacuum Decay ... In the presence of New Physics at High Energies all these analyses need to be reconsidered These findings have certainly an impact on the Cosmic Ray catalised Vacuum Decay ... Holy Grail Function ... $\tau \sim e^{S[\phi_b]}$

“Precision Measurements of M_H and M_t”



Constraints in the parameter space of New Physics Theories

BSM “Stability Test”

Summary - Conclusions - Outlook

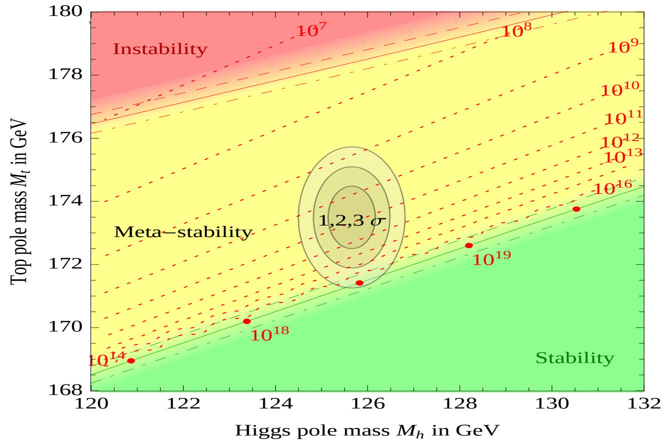
- **The Stability Phase Diagram of the EW vacuum strongly depends on New Physics even if it shows up at very high energies ($\sim M_P$)**
- **Precision Measurements of the Top and Higgs Masses will not allow to discriminate between stability, metastability or criticality of the EW vacuum. Phase Diagram too sensitive to New Physics ...**
- **The results that I presented provide a "BSM stability test". A BSM is acceptable if it provides either a stable EW vacuum or a metastable one, with lifetime larger than the age of the universe (No $\tau << T_U$!!).**
- **These findings have certainly an impact on the Cosmic Ray catalised Vacuum Decay ... Holy Grail Function ... Remember ...**

$$\tau \sim e^{S[\phi_b]}$$

... Limits ... Constraints ...

Last point ... My bottom line on the status of this Diagram ...

It seems to me that with with our results the "Stability Diagram"



has lost its interest ... despite the attempt to keep it alive with the new interpretation : 1. assume that there is no new Physics up to the Planck Scale ; 2. and also assume that New Physics at the Planck scale has no impact on the Stability condition of the EW vacuum.

This Diagram had an interest as long as it was thought (and this lasted for long time) that it had a Universal Meaning : Irrespectively of the form of New Physics at the Planck Scale, this was considered to be the Stability Diagram. Finally, this is unlikely to be the Stability Diagram...