Higgs potential, New Physics, and Stability of the EW Vacuum

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... Work in progress ...

Workshop HPNP 2019

18 - 22 February 2019, Osaka

Stability analysis of the EW vacuum (few references)

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After the discovery of the Higgs boson ... renewed interest ...

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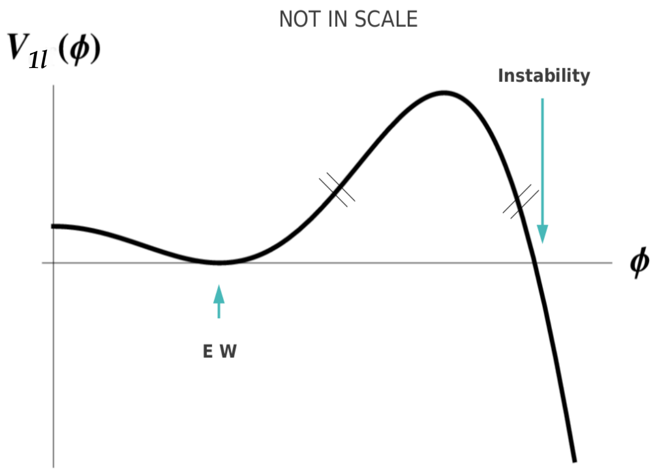
... many other references ...

Stability analysis of the EW vacuum

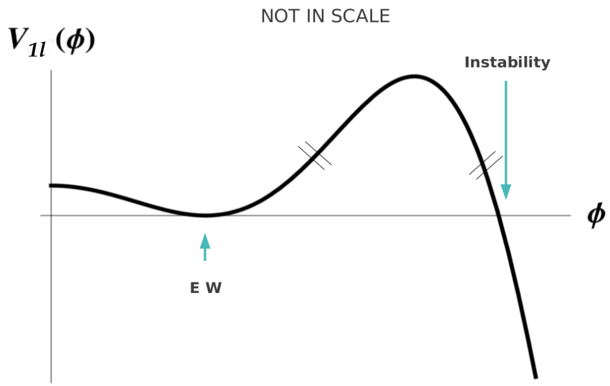
Key tool: Higgs Effective Potential

Top loop-corrections destabilize the EW Vacuum...



EW $= v \sim 246$ GeV ; For $M_H \sim 125$ GeV , $M_t \sim 173$ GeV : Instability $\sim 10^{11}$ GeV

One-Loop Higgs Effective Potential $V_{1l}(\phi)$

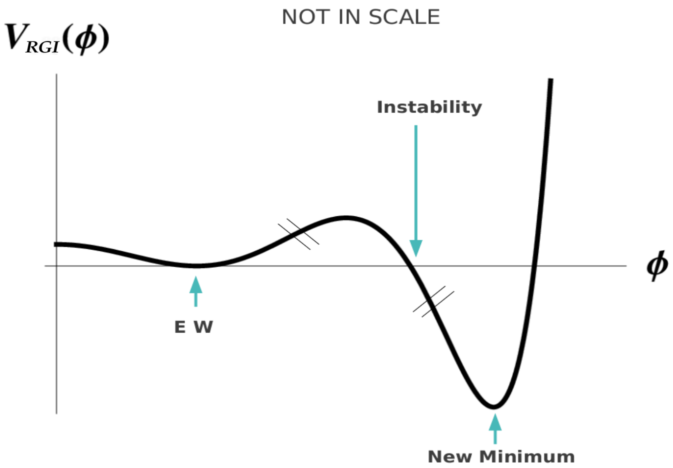


$$V_{1l}(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{24}\phi^4 + \frac{1}{64\pi^2}\left[\left(m^2 + \frac{\lambda}{2}\phi^2\right)^2\left(\ln\left(\frac{m^2 + \frac{\lambda}{2}\phi^2}{\mu^2}\right) - \frac{3}{2}\right)\right.$$

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

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

Running the RG eqs. for the SM couplings $\Rightarrow$ RGI Potential:



Depending on M_H and M_t, the second minimum can be :

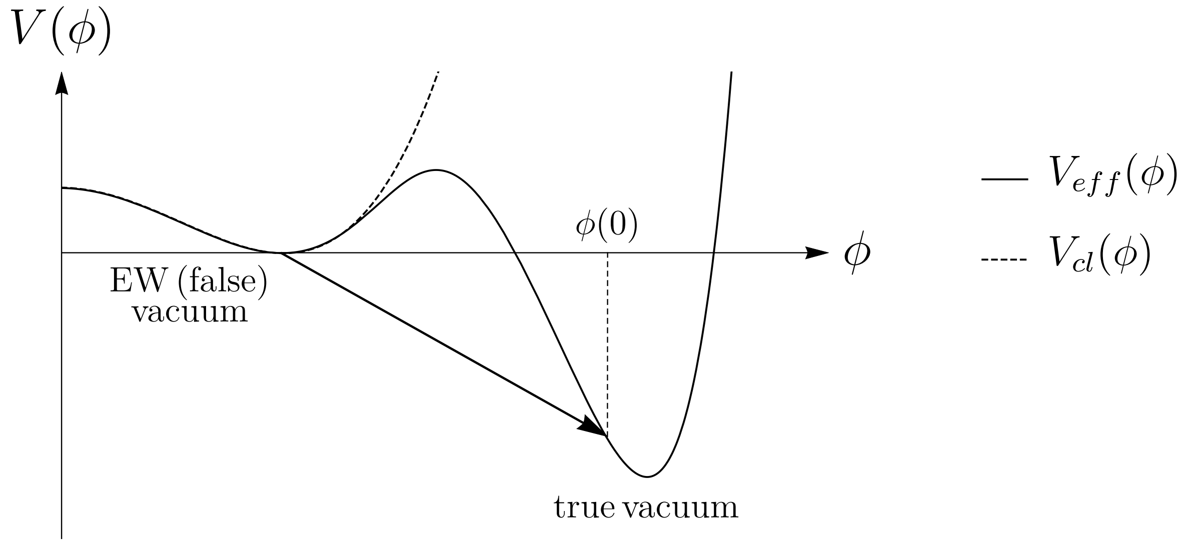
1. lower than the EW minimum (as in the figure) : This is the case for $M_H \sim 125$ GeV , $M_t \sim 173$ GeV (central values);

2. at the same height ... ;

3. higher ...

Case 1 (figure) : **EW vacuum Metastable**

Tunneling : EW vacuum (false) $\rightarrow$ True Vacuum



... If the EW vacuum lifetime larger than the age of the Universe ...

.... we may well live in such a Metastable Vacuum ....

Technically - Tunneling Rate (= inverse tunneling time) obtained as:

$$\Gamma = \frac{1}{\tau} = De^{-(S[\phi_b]-S[\phi_{\rm fv}])} \equiv D\, e^{-B}$$

$\phi_b(r)$ Bounce: Solution to the Euclidean EOM with appropriate b.c.

Euclidean equations of motion ($O(4)$ Symmetry)

$$-\partial_\mu\partial_\mu\phi + \frac{d\,V(\phi)}{d\,\phi} = -\frac{d^2\phi}{dr^2} - \frac{3}{r}\frac{d\phi}{dr} + \frac{d\,V(\phi)}{d\,\phi} = 0$$

Boundary conditions : $\phi'(0) = 0$, $\phi(\infty) = v \to 0$.

A well known example: $V(\phi) = \frac{\lambda}{4}\phi^4$ **with constant and negative** λ

Bounce (Fubini instanton) : $\phi_b(r) = \sqrt{\frac{2}{|\lambda|}}\frac{2R}{r^2+R^2}$ **(R = size)**

Degeneracy : $S[\phi_b] = \frac{8\pi^2}{3|\lambda|}$ **Bounce Action does not depend on R**

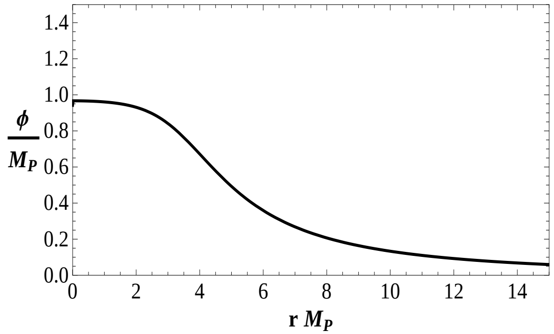
Classical Scale Invariance

Degeneracy removed at the Quantum Level

$$\Gamma = \frac{1}{\tau} = De^{-(S[\phi_b]-S[\phi_{\rm fv}])} \equiv D\, e^{-S[\phi_b]}$$

A good estimate for Γ is obtained by approximating the prefactor D in terms of the bounce size R, defined as the value of r such that: 1endbf

$$\phi_b(R) = \frac{1}{2}\phi_b(0)$$



and the age of the universe T_U.

For the EW vacuum lifetime $\tau = \Gamma^{-1}$ we get:

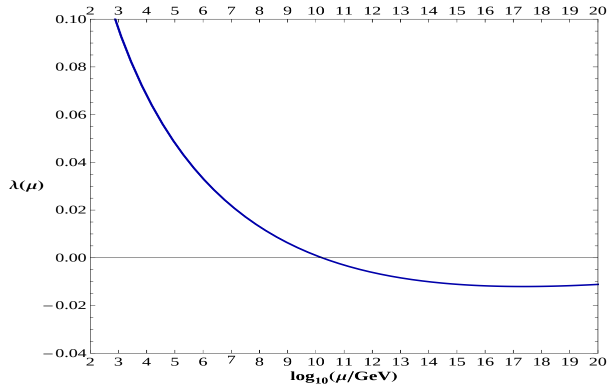
$$\tau \simeq \left(\frac{R^4}{T_U^3}\right) e^{S[\phi_b]}$$

For SM the instability occurs at large values of ϕ

$\Rightarrow$ $V_{eff}(\phi)$ **well approximated by keeping only the quartic term**

$$V_{SM}(\phi) \sim \frac{\lambda(\phi)}{24}\phi^4$$

$\lambda(\phi)$ depends on ϕ essentially as $\lambda(\mu)$ depends on μ

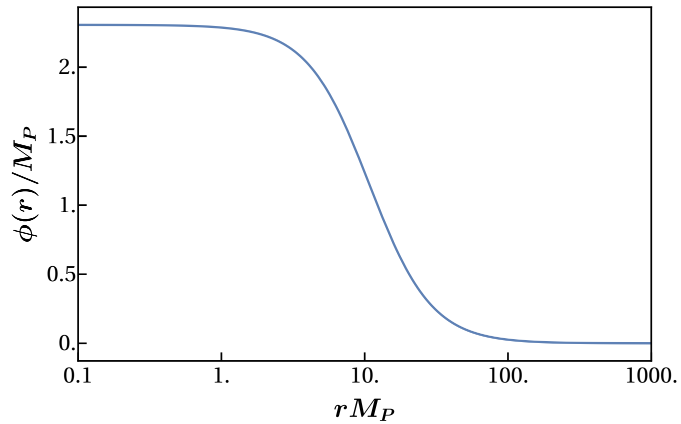


For large values of ϕ, the coupling λ becomes negative and almost constant in the region of interest ... close to the above example ... In fact people used analytical approximations, but we can do better ... we can calculate the bounce numerically ...

1. Stability Analysis in Flat Spacetime Background

Euclidean action $S[\phi] = \int d^4x \left[\frac{1}{2}(\partial_\mu \phi)^2 + V_{SM}(\phi)\right]$

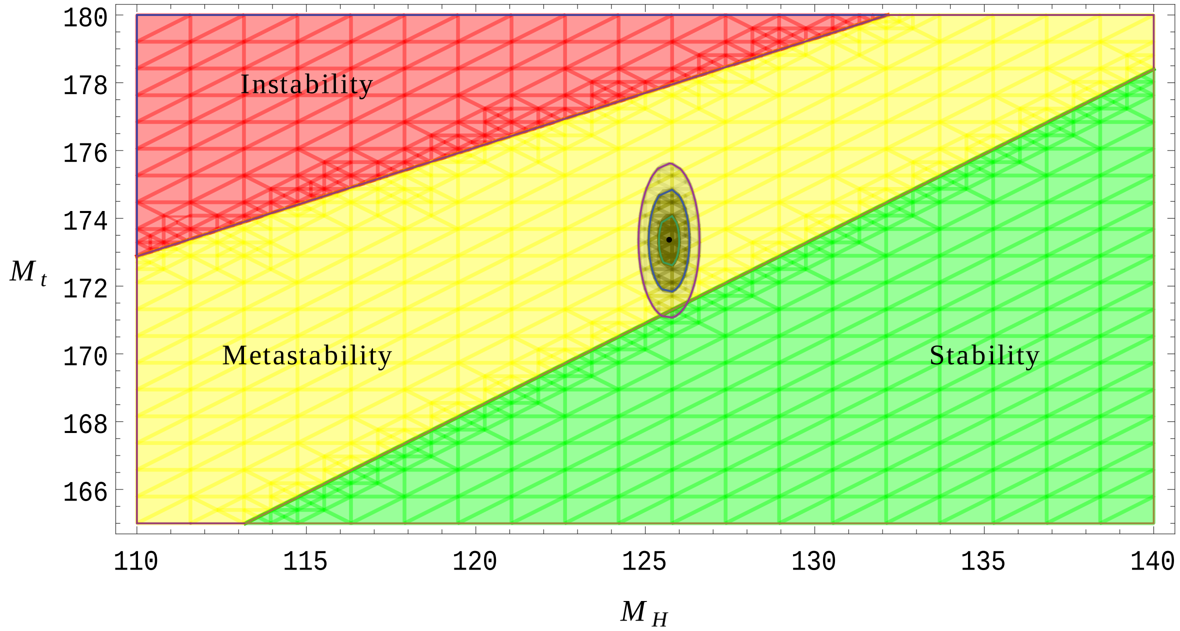
Bounce Solution



EW vacuum lifetime $$\tau_{flat} \simeq \left(\frac{R^4}{T_U^3}\right) e^B \simeq 10^{639} T_U$$

Obtained for $M_H \sim 125$ GeV and $M_t \sim 173$ GeV

More generally: Stability Diagram in the $M_H - M_t$ plane



Stability region : $V_{eff}(v) < V_{eff}(\phi^{(2)}_{min})$.

Meta-stability region : $V_{eff}(\phi^{(2)}_{min}) < V_{eff}(v)$ and $\tau > T_U$.

Instability region : $V_{eff}(\phi^{(2)}_{min}) < V_{eff}(v)$ and $\tau < T_U$.

Stability line : $V_{eff}(v) = V_{eff}(\phi^{(2)}_{min})$.

Instability line : M_H and M_t such that $\tau = T_U$.

2. Stability Analysis in Curved Spacetime Background

Including the Einstein-Hilbert term, the Euclidean action is:

$$S[\phi, g_{\mu\nu}] = \int d^4x \sqrt{g} \left[-\frac{R}{16\pi G} + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi + V_{SM}(\phi) \right]$$

R = Ricci scalar, G = Newton constant. Requiring again $O(4)$ symmetry, the (Euclidean) metric:

$$ds^2 = dr^2 + \rho^2(r) d\Omega_3^2$$

$d\Omega_3^2$ = unit 3-sphere line element, $\rho(r)$ = volume radius of the 3-sphere at fixed r. The **bounce** now : $(\phi_b(r), \rho_b(r))$, solutions of the coupled equations: $(\kappa \equiv 8\pi G)$:

$$\ddot{\phi} + 3\,\frac{\dot{\rho}}{\rho}\,\dot{\phi} = \frac{d\,V_{SM}(\phi)}{d\phi} \qquad \dot{\rho}^2 = 1 + \frac{\kappa \rho^2}{3} \left(\frac{1}{2}\dot{\phi}^2 - V_{SM}(\phi) \right)$$

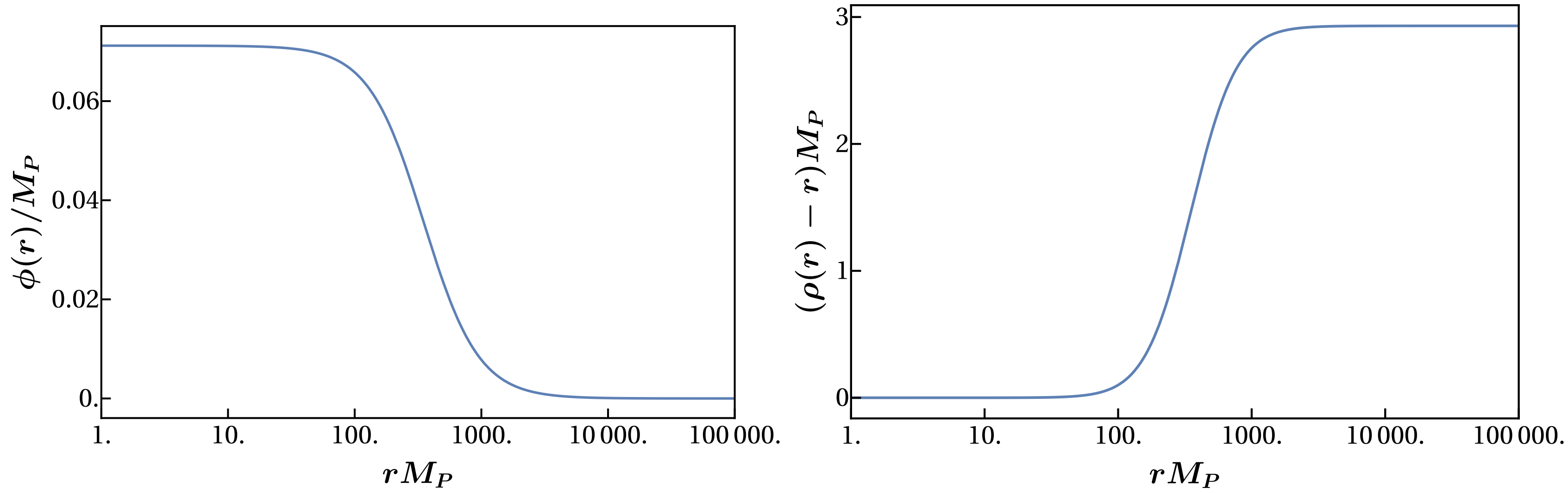
First equation: replaces the equivalent equation in flat spacetime;

Second equation: the only Einstein equation left by the symmetry.

For the decay of a Minkowski false vacuum to a true AdS vacuum (the case of interest to us) the boundary conditions are:

$$\phi_b(\infty) = 0 \qquad \dot{\phi}_b(0) = 0 \qquad \rho_b(0) = 0\,.$$

Bounce in Curved Spacetime Background



Profile of $\phi_b(r)$ and of the difference between $\rho(r)$ and its asymptotic value, $\rho(r) - r$ (asymptotically $\rho_b(r)$ reaches the Minkowskian $\rho_M(r) \sim r + Const$).

EW vacuum lifetime $\tau_{\text{grav}} \simeq 10^{661} T_U$

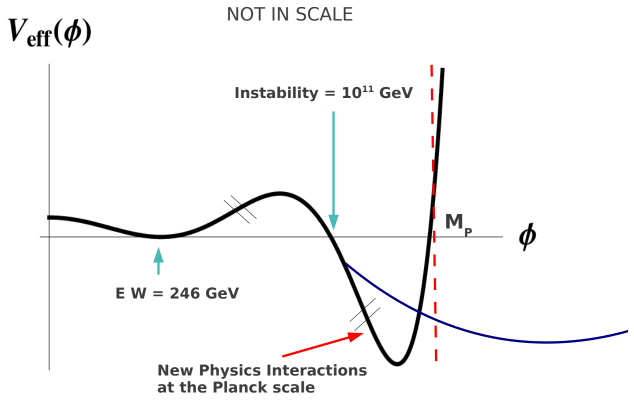
Obtained for $M_H \sim 125$ GeV and $M_t \sim 173$ GeV

Crucial point - Calculation of τ under the assumption that ...

... Even though New Physics Interactions are certainly present at the Planck scale, they has no impact on the EW vacuum lifetime, so they are neglected when computing τ.

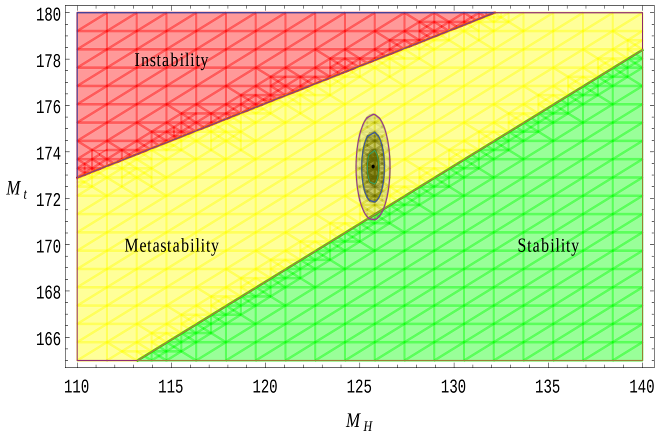
Argument: Instability scale, $\Lambda_{inst} \sim 10^{11}$ GeV, much lower than $M_P \Rightarrow$

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



... However, things are more subtle ...

The Stability Diagram is not universal



New Physics at Planck scale can strongly modify this Stability Diagram

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Soon after the appearance of the first of these papers, several other authors confirmed these results ... and were also inspired for applications and developments ...

Just to mention a few:

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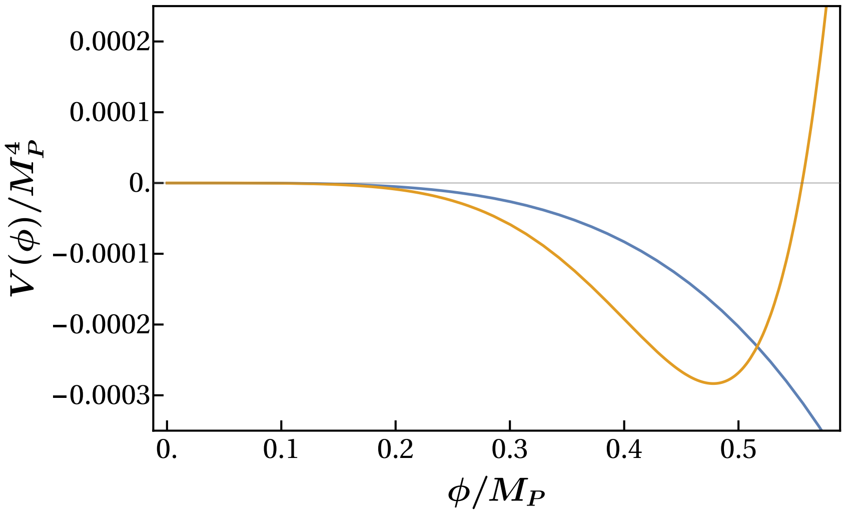
Burda, Gregory, Moss, JHEP 1508 (2015) 114

....

... Let's add New Physics around M_P ...

New Physics around M_P

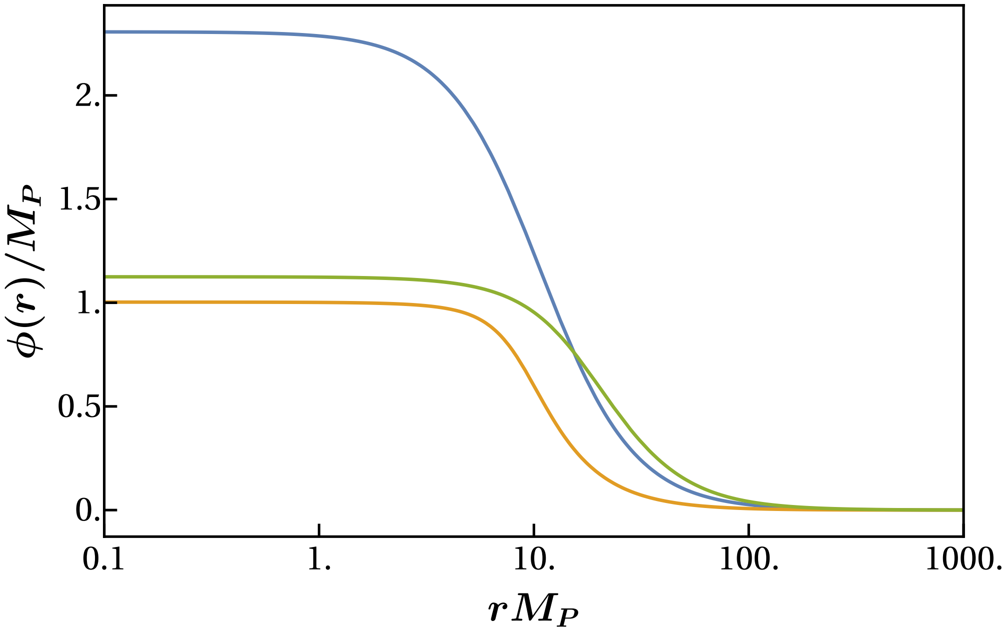
$$V(\phi) = \frac{\lambda(\phi)}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$



Yellow line: Potential with $\lambda_6 = -0.4$ and $\lambda_8 = 2$.

Blue line: SM alone.

Bounce profiles in Flat Spacetime Background



Blue curve: bounce obtained for the potential with $\lambda_6 = 0$ and $\lambda_8 = 0$ (**SM alone**).

Yellow curve: bounce for $\lambda_6 = -0.3$ and $\lambda_8 = 0.3$.

Green curve: bounce for $\lambda_6 = -0.01$ and $\lambda_8 = 0.01$.

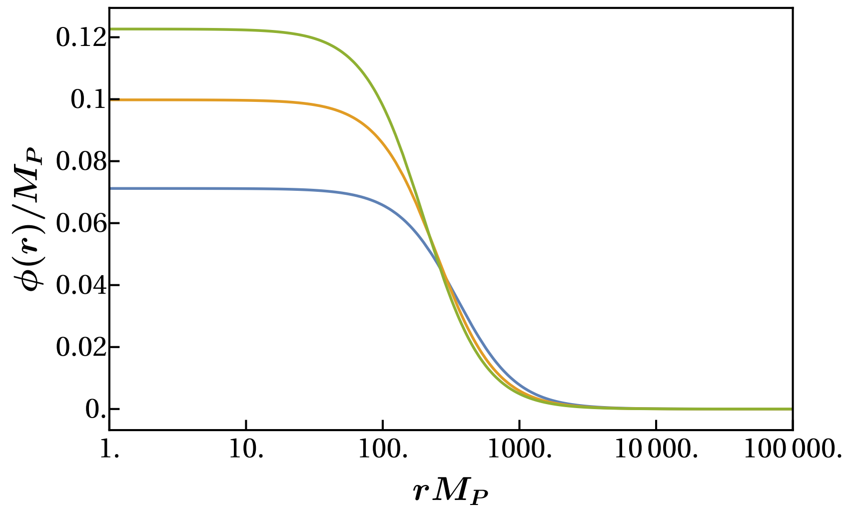
Tunneling times for different values of λ_6 and λ_8

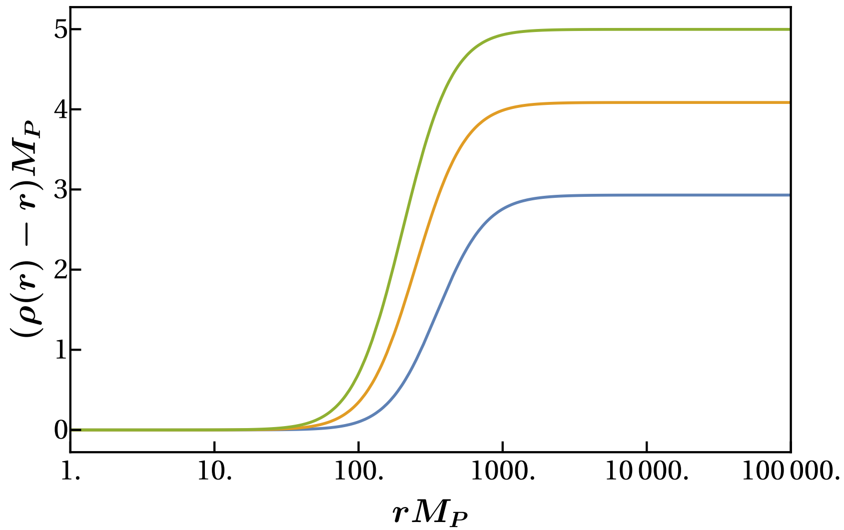
λ_6	λ_8	τ_{flat}/T_U
0	0	10^{639}
-0.05	0.1	10^{446}
-0.1	0.2	10^{317}
-0.3	0.3	10^{-52}
-0.45	0.5	10^{-93}
-0.7	0.6	10^{-162}
-1.2	1.0	10^{-195}
-2.0	2.1	10^{-206}

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

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

Bounce profiles in Curved Spacetime Background





Left Panel - Blue curve: profile of the bounce solution with $\lambda_6 = 0$ and $\lambda_8 = 0$, i.e. in the absence of new physics. Yellow curve: profile of the bounce solution for $\lambda_6 = -0.03$ and $\lambda_8 = 0.03$. Green curve: profile of the bounce solution for $\lambda_6 = -0.04$ and $\lambda_8 = 0.04$.

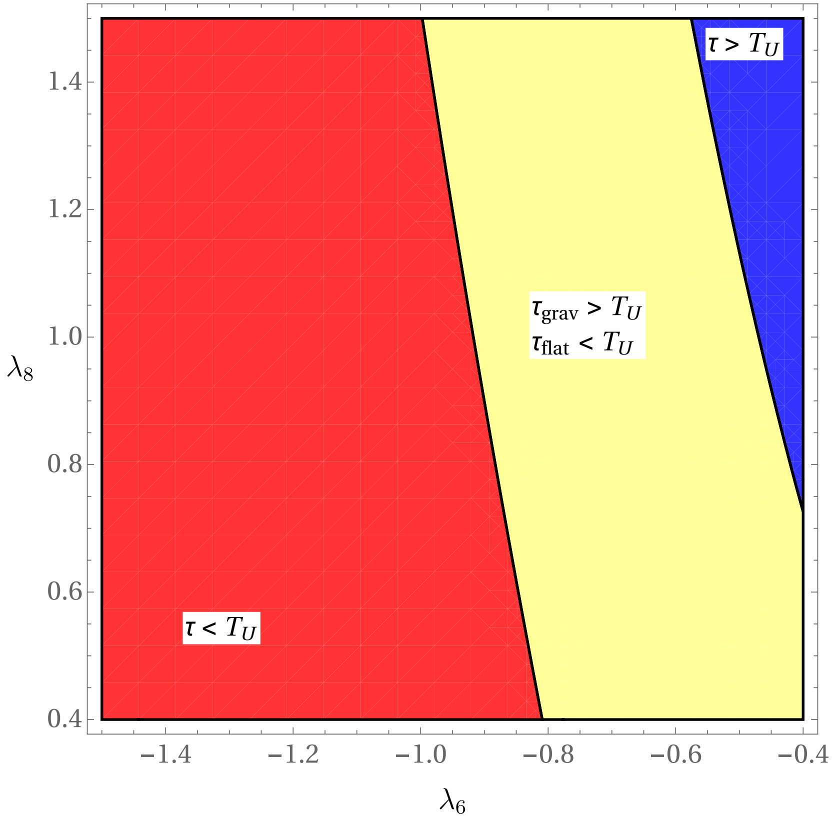
Right Panel - Profile of the difference between $\rho(r)$ and its asymptotic value: $\rho(r) - r$.

Tunneling times for different values of λ_6 and λ_8

λ_6	λ_8	τ_{flat}/T_U	τ_{grav}/T_U
0	0	10^{639}	10^{661}
-0.05	0.1	10^{446}	10^{653}
-0.1	0.2	10^{317}	10^{598}
-0.3	0.3	10^{-52}	10^{287}
-0.45	0.5	10^{-93}	10^{173}
-0.7	0.6	10^{-162}	10^{47}
-1.2	1.0	10^{-195}	10^{-58}
-2.0	2.1	10^{-206}	10^{-121}

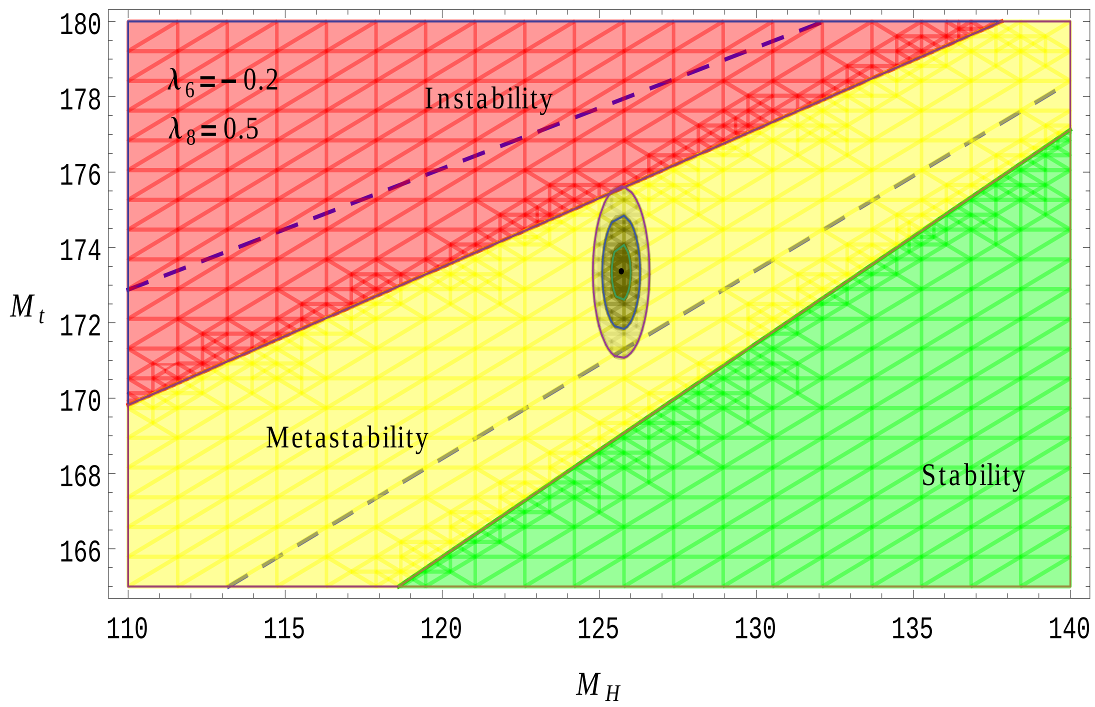
Gravity tends to stabilize the EW vacuum (τ_{grav} always higher than τ_{flat}). However, New Physics has always a strong (that can be even devastating) impact.

Stability Diagram in the (λ_6, λ_8) - plane



In the blue region $\tau > T_U$ both for the flat and curved spacetime analysis. In the yellow region $\tau < T_U$ for the flat spacetime background. In the red region $\tau < T_U$ in both cases.

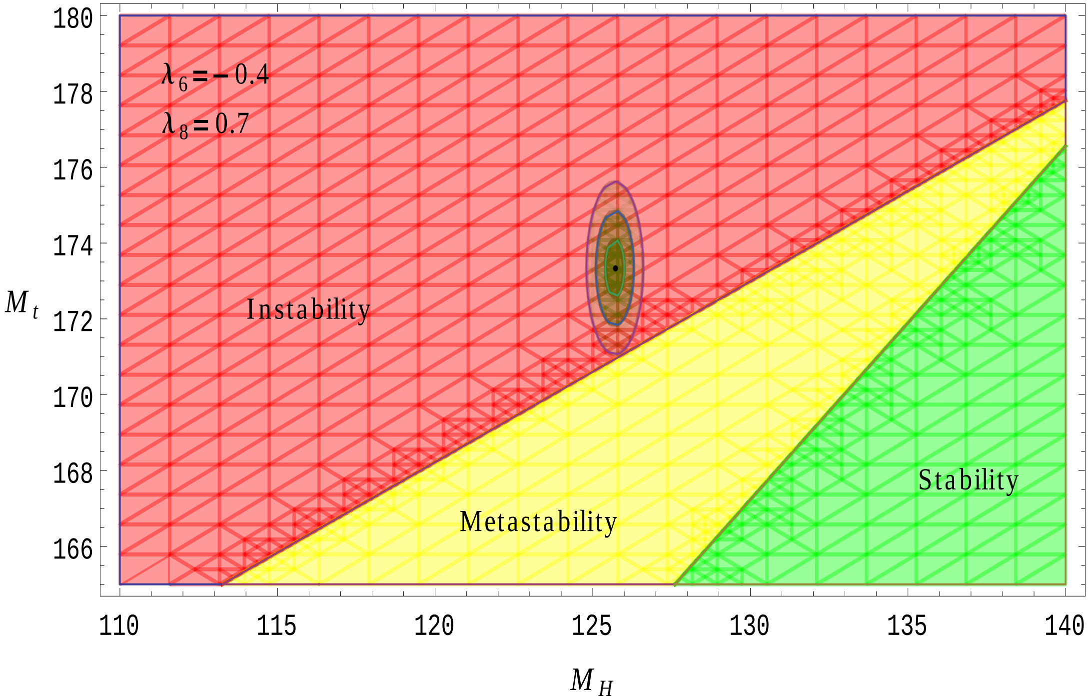
Stability Diagram in the (M_H, M_t) - plane for $\lambda_6 = -0.2$ and $\lambda_8 = 0.5$



The strips move downwards ... Central values no longer at $3\,\sigma$ from the stability line ...

... The Stability Diagram depends on new physics ...

Stability Diagram in the (M_H, M_t) - plane
for $\lambda_6 = -0.4$ and $\lambda_8 = 0.7$



... The Stability Diagram depends on new physics ...

As previously said ... These results came as a surprise ...

It was thought that New Physics at the Planck scale should have no impact on the EW vacuum lifetime ... on the Stability Diagram

How comes that New Physics at M_P has such an impact on τ ?

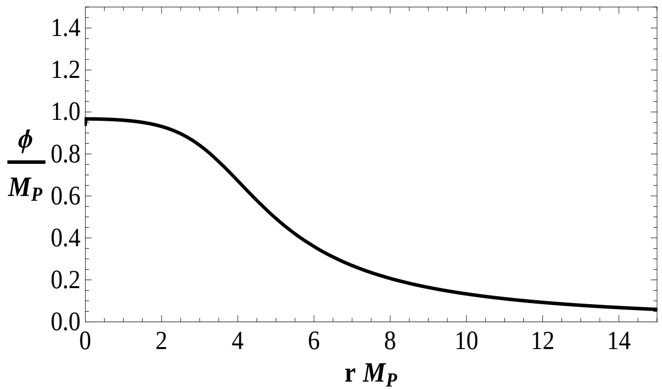
How comes that decoupling arguments do not apply ?

- As $\Lambda_{inst} \sim 10^{11}$ GeV, a decoupling effect was expected: the contribution of higher dimension operators $\frac{\phi^n}{M_P^n}$ was expected to be suppressed as $(\frac{\Lambda_{inst}}{M_P})^n$.
- However: Tunnelling is a non-perturbative phenomenon. We first select the saddle point, i.e. compute the bounce (tree level). Then, on the top of that, we compute the quantum fluctuations (loop corrections).
- 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 : $\tau \sim e^{S[\phi_b]} \quad \Rightarrow$

$$\text{New bounce } \phi_b^{(new)}(r) \quad \Rightarrow \quad \text{New bounce action } S[\phi_b^{(new)}] \quad \Rightarrow$$

New τ



... It seems that the problem is there ...

... Rescue ? ...

SM Potential ... Non-minimal coupling ...

$$S[\phi] = \int d^4x\sqrt{g}\left[-\frac{R}{2\kappa} + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi + V_{SM}(\phi) + \frac{1}{2}\xi\phi^2 R\right]$$

Again $O(4)$ symmetry:

$$\ddot{\phi} + 3\,\frac{\dot{\rho}}{\rho}\,\dot{\phi} = \frac{dV}{d\phi} + \xi\phi R \qquad \dot{\rho}^2 = 1 - \frac{\kappa}{3}\rho^2\,\frac{-\frac{1}{2}\dot{\phi}^2 + V(\phi) - 6\xi\frac{\dot{\rho}}{\rho}\phi\dot{\phi}}{1-\kappa\xi\phi^2}\,,$$

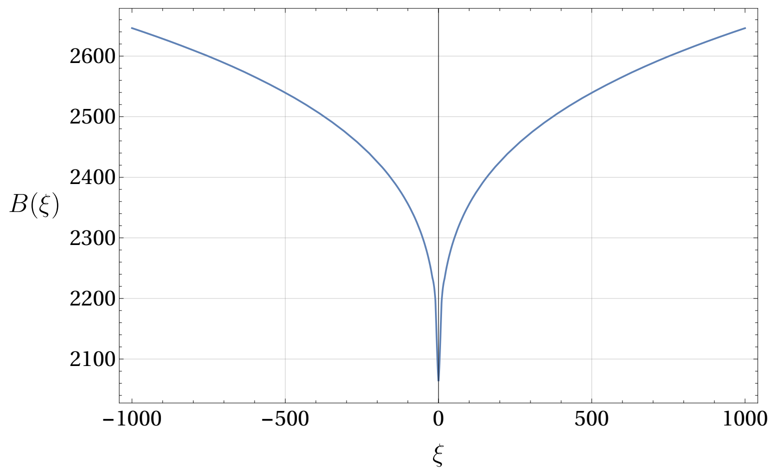
with R given by:

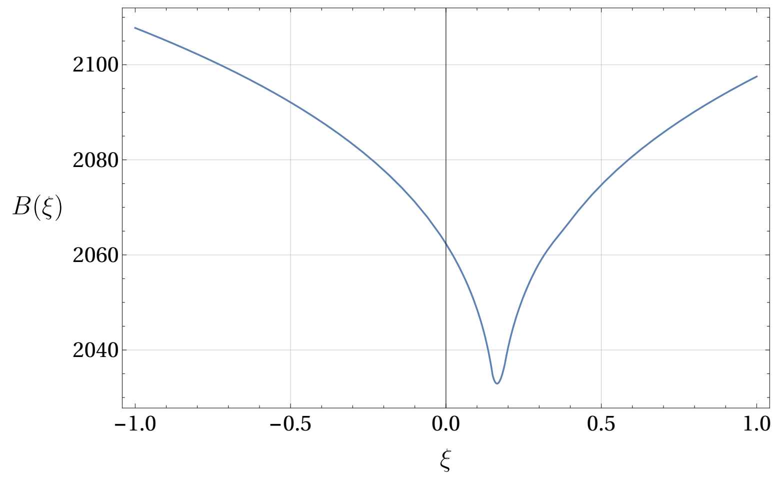
$$R = \kappa\,\frac{\dot{\phi}^2(1-6\xi) + 4V(\phi) - 6\xi\phi\,dV/d\phi}{1-\kappa\xi(1-6\xi)\phi^2}\,.$$

For $\xi = 0$ these Equations become the minimal coupling ones.

Asymptotics: For $r \to \infty$, $\dot{\rho}_b^2 = 1$, so $\rho(r)$ approaches the flat spacetime metric. In the same limit, $R \to 0$.

SM Potential. Non-minimal coupling. $S_{bounce} \equiv B(\xi)$





B very sensitive to ξ. Outside the range $[\xi = 0, \xi = 1/3]$, $B(\xi)$ is greater than $B(\xi = 0)$, and non-minimal coupled gravity stabilizes the EW vacuum more than minimally coupled gravity.

Minimum at $\xi_{min} \simeq 0.17$, close to the conformal value $\xi = 1/6$. Actually for the scale invariant potential $V(\phi) = \frac{\lambda}{4}\phi^4$ (constant λ) the minimum is reached at $\xi = 1/6$.

What happens if we Add New Physics at M_P ?

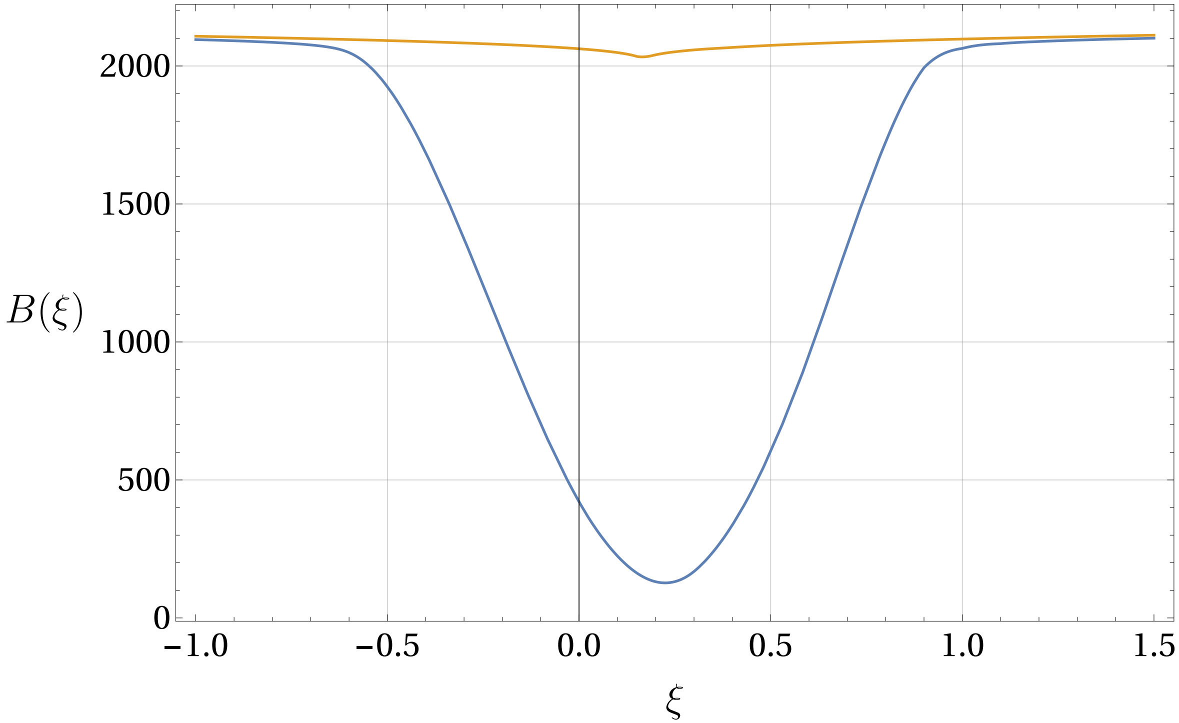
Add New Physics : $\lambda_6\,\phi^6$ and $\lambda_8\,\phi^8$

ξ	$(\tau/T_U)_{SM}$	$(\tau/T_U)_{NP}$
-15	10^{736}	10^{736}
-10	10^{726}	10^{726}
-5	10^{710}	10^{710}
-1	10^{684}	10^{680}
-0.5	10^{677}	10^{600}
-0.3	10^{672}	10^{358}
-0.1	10^{666}	10^{65}
0	10^{661}	10^{-58}

ξ	$(\tau/T_U)_{SM}$	$(\tau/T_U)_{NP}$
0.3	10^{660}	10^{-167}
0.5	10^{668}	10^{23}
0.7	10^{674}	10^{346}
0.8	10^{676}	10^{512}
1	10^{679}	10^{666}
5	10^{709}	10^{709}
10	10^{725}	10^{725}
15	10^{735}	10^{735}

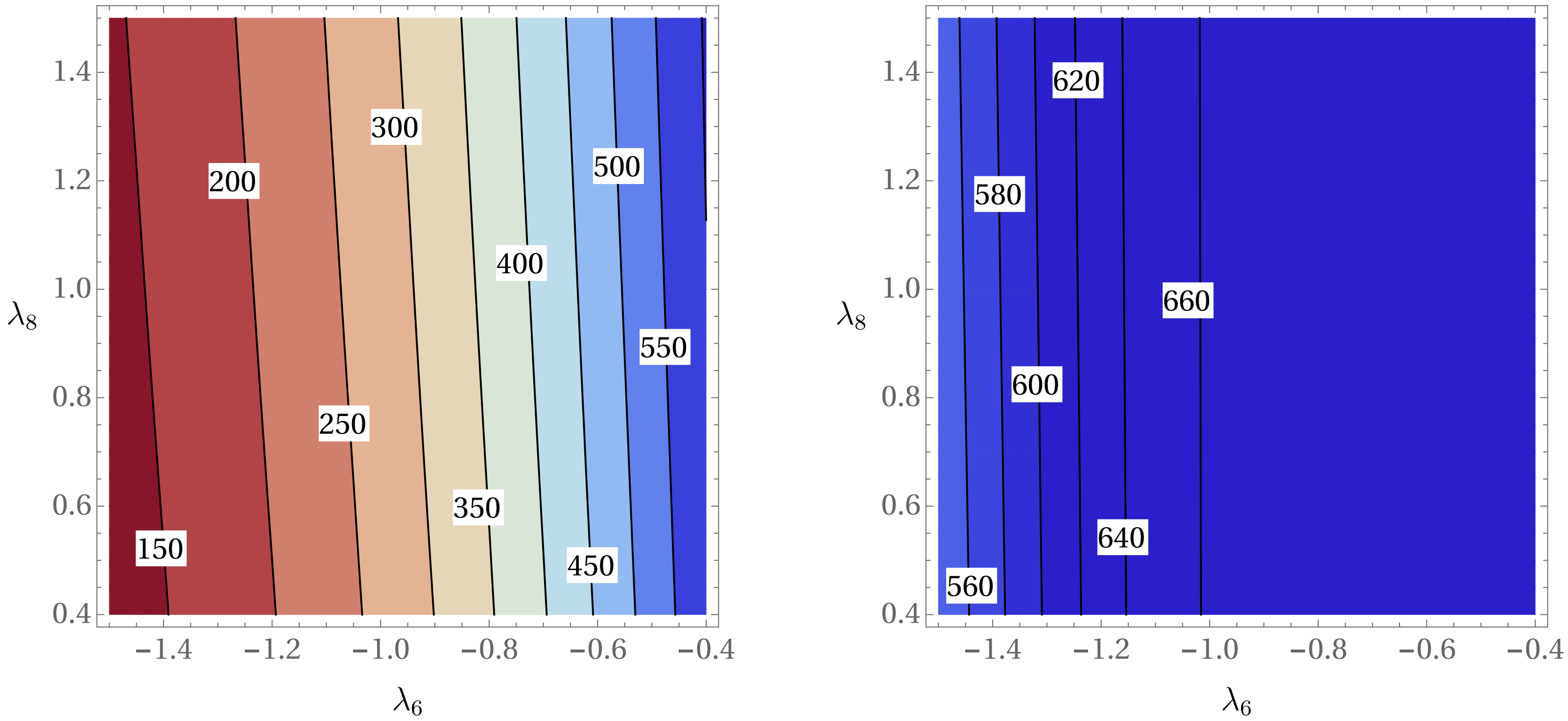
Values of τ with and without New Physics for different values of ξ, where $\lambda_6 = -1.2$ and $\lambda_8 = 1$.

Tunneling exponent $B(\xi)$ as a function of ξ



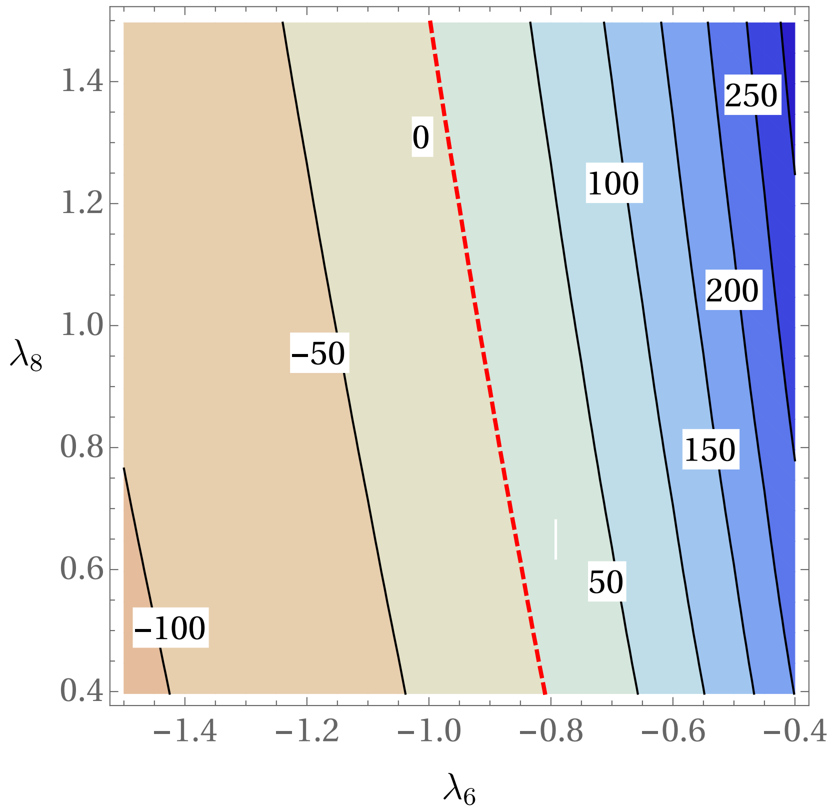
Yellow: $B(\xi)$ when the SM potential alone is considered. Blue: $B(\xi)$ when the New Physics potential with $\lambda_6 = -1.2$ and $\lambda_8 = 1$ is considered

Stability Diagrams for $\xi = -0.2$ and $\xi = 0.9$



Stability diagrams in the (λ_6, λ_8) plane with non-minimal coupling: $\xi = -0.2$ (left), $\xi = 0.9$ (right). In both cases, for the range of λ_6 and λ_8 considered, the EW vacuum is always stable ($\tau > T_U$), unlike the minimal coupling case ... see next page ...

The $\xi = 0$ case for comparison



The same range of values of λ_6 and λ_8 as in the previous slide.

... Protection from Non-Minimal Coupling ...

The dimension four operator $\xi\phi^2 R$ naturally arises when quantization is carried out in a curved space-time background ... in the SM the term $\xi\, R\, H\, H^*$ is required in order to make the theory multiplicatively renormalizable in curved spacetime.

In view of the above remarks, and of the enormous stabilizing effect induced by the $\xi\,\phi^2\,R$ term for values of ξ outside the tiny range of values $-1 \lesssim \xi \lesssim 1$, under the assumption that the physical (yet unknown) value of ξ lies outside this range, we could be lead to formulate the following ...

"Direct Coupling Stability Conjecture"

The quantum nature of physical laws and the very existence of gravity provide a model-independent stabilization mechanism that protects the EW vacuum against the destabilization that could come from unknown Planckian New Physics

Conclusions

- New Physics at Planckian scales, generically parametrized with the help of higher order operators in the Higgs potential (ϕ^6 and ϕ^8) can destabilize the EW vacuum.

- This result was first established in a flat spacetime background, and later confirmed by performing the analysis in a curved spacetime background (minimal coupling).

- Gravity shows a tendency toward stabilization. However, for large portions of the New Physics parameter space, the destabilizing impact of the latter wins against the competing stabilization tendency of gravity.

- Irrespectively of the specific model that might be responsible for generating the instability of the EW vacuum, if the Higgs field is non-minimally coupled to gravity (with the exception a tiny range of values of ξ) the destabilizing effect of unknown Planckian New Physics is washed out.

- "Direct Coupling Stabilization Conjecture".

BACK UP SLIDES

Non-Renormalizable New Phyisics $\rightarrow$ Renormalizable New Physics

... It was also argued that the fact that New Physics was parametrized in terms of Non-Renormalizable operators actually could invalidate these results ...

New Physics around M_P in terms of renormalizable operators

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

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

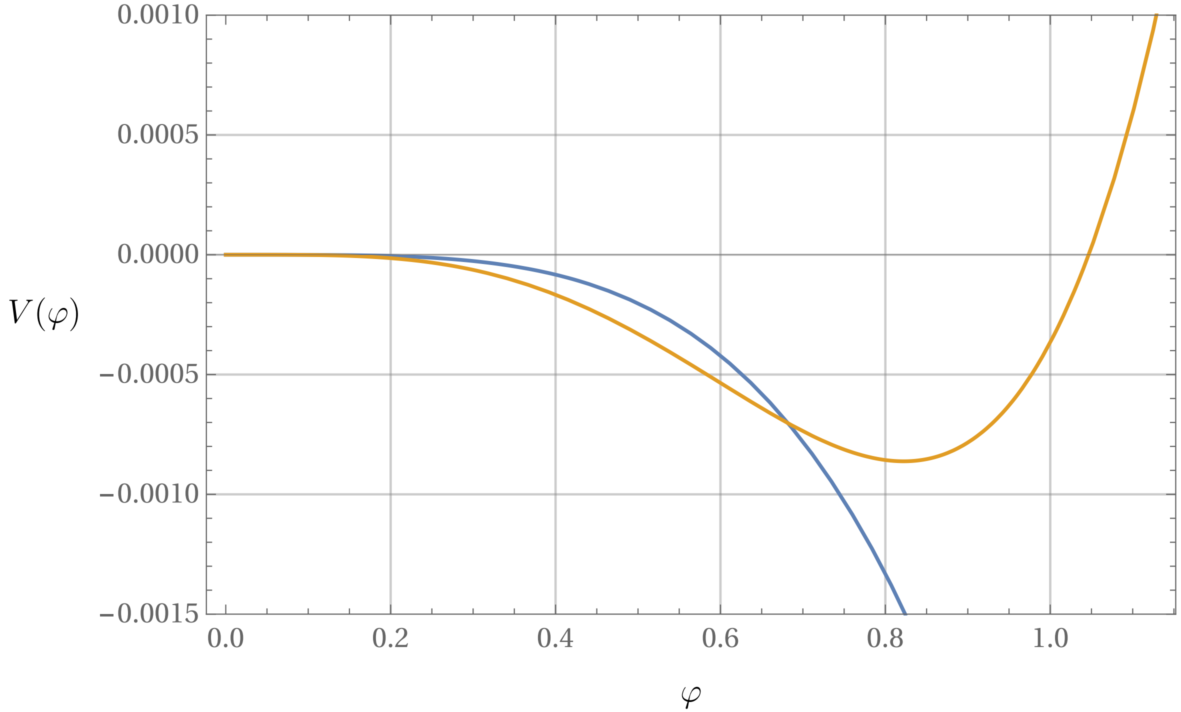
with $M_f \sim 10^{17}$ GeV and $M_S \sim 10^{18}$ GeV.

Integrating out this new scalar and fermion fields we get the

Modified Higgs Potential

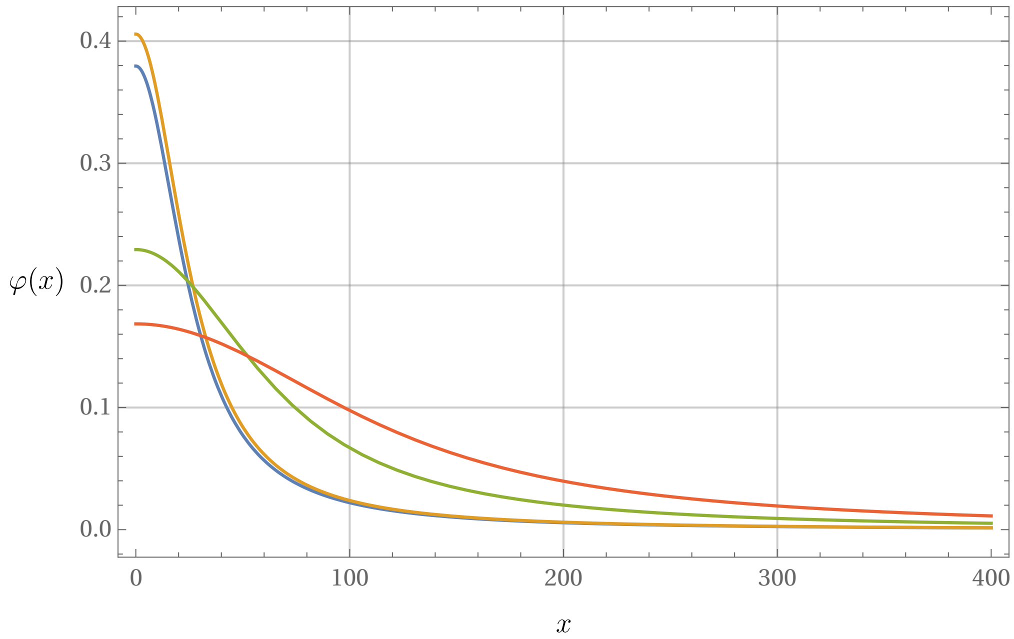
$$\begin{aligned} V(\phi) &= \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4} \phi^4 + \frac{1}{64\pi^2} \left(M_S^2 + \frac{g_S}{2} \phi^2 \right)^2 \left[\ln \left(\frac{M_S^2 + \frac{g_S}{2} \phi^2}{\mu^2} \right) - \frac{3}{2} \right] \\ &- \frac{1}{16\pi^2} \left(M_f^2 + \frac{g_f^2}{2} \phi^2 \right)^2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

Modifided potential (yellow) against SM potential (blue)



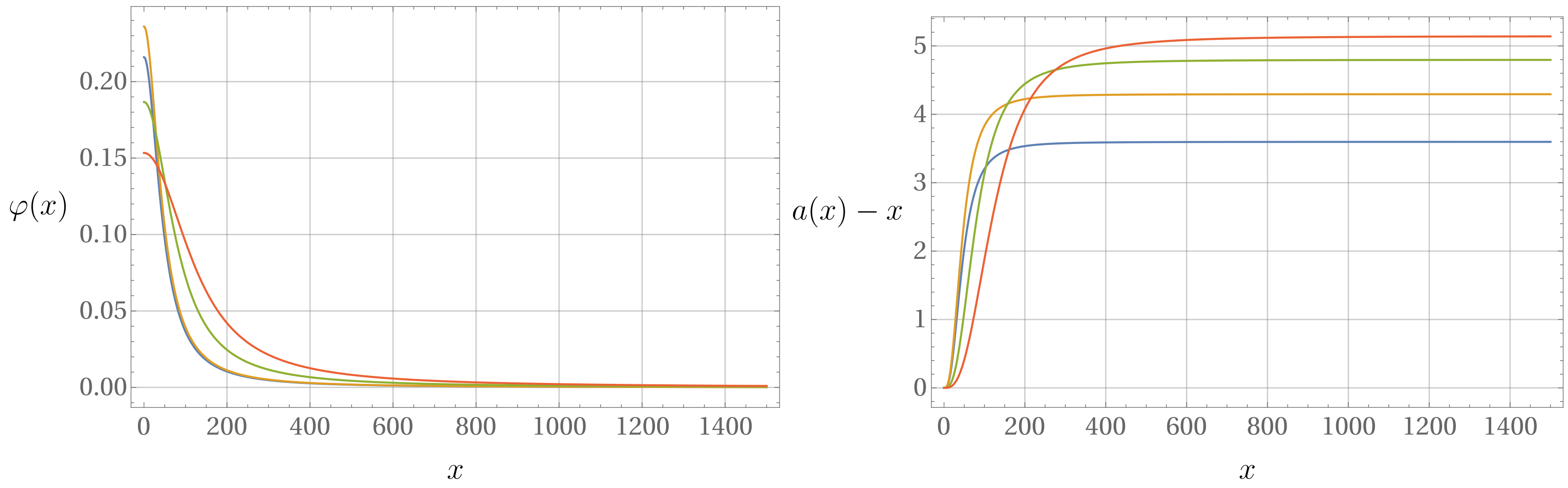
The values of the parameter are: $M_S = 2.0 \times 10^{-1} M_P$, $M_f = 10^{-3} M_P$, $g_S = 0.95$, $g_f^2 = 0.4$.

Bounce profiles for the Flat Spacetime Case



Profile of the bounce solutions $\varphi(x)$ relative to the four cases: $M_S = 2.5 \times 10^{-1}$, $M_f = 3 \times 10^{-4}$, $g_S = 0.96$, $g_f^2 = 0.5$ (yellow) ; $M_S = 2.0 \times 10^{-1}$, $M_f = 10^{-4}$, $g_S = 0.9$, $g_f^2 = 0.5$ (blue); $M_S = 2.0 \times 10^{-1}$, $M_f = 10^{-3}$, $g_S = 0.95$, $g_f^2 = 0.4$ (green); $M_S = 1.5 \times 10^{-1}$, $M_f = 5 \times 10^{-3}$, $g_S = 0.92$, $g_f^2 = 0.4$ (red).

Bounce profiles for the Curved Spacetime Case



Left panel: Profile of the bounce solutions $\varphi(x)$ relative to the four cases: $M_S = 2.5 \times 10^{-1}$, $M_f = 3 \times 10^{-4}$, $g_S = 0.96$, $g_f^2 = 0.5$ (yellow) ; $M_S = 2.0 \times 10^{-1}$, $M_f = 10^{-4}$, $g_S = 0.9$, $g_f^2 = 0.5$ (blue); $M_S = 2.0 \times 10^{-1}$, $M_f = 10^{-3}$, $g_S = 0.95$, $g_f^2 = 0.4$ (green); $M_S = 1.5 \times 10^{-1}$, $M_f = 5 \times 10^{-3}$, $g_S = 0.92$, $g_f^2 = 0.4$ (red).

Right panel: difference between the curvature radius and its asymptotic value, $a(x) - x$, for the same parameters as in the left panel.

Tunneling times for different values of the parameters

M_S	M_f	g_S	g_f^2	τ_{flat}/T_U	τ_{grav}/T_U
0	0	0	0	10^{639}	10^{661}
$1.5 \times 10^{-1} M_P$	$5 \times 10^{-3} M_P$	0.92	0.4	10^{293}	10^{307}
$2.0 \times 10^{-1} M_P$	$10^{-3} M_P$	0.95	0.4	10^{80}	10^{94}
$2.5 \times 10^{-1} M_P$	$3 \times 10^{-4} M_P$	0.96	0.5	10^{-80}	10^{-65}
$2.0 \times 10^{-1} M_P$	$10^{-4} M_P$	0.9	0.5	10^{-103}	10^{-93}

As for the case of the parametrization of New Phyiscs with

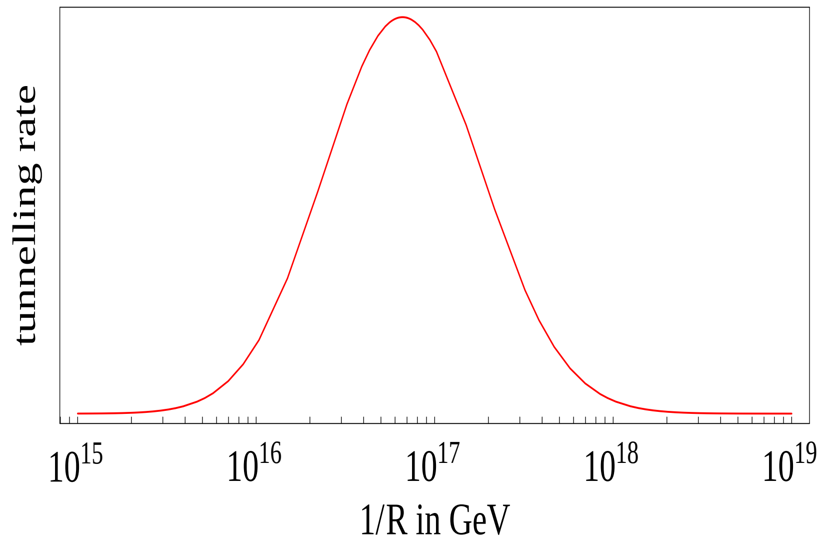
$$V_{NP}(\phi) = \frac{\lambda_6}{6} \frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8} \frac{\phi^8}{M_P^4}$$

we again observe that Gravity tends to stabilize the EW vacuum (τ_{grav} always higher than τ_{flat}). However, New Physics has always a strong (that can be even devastating) impact.

Degeneracy removed at the Quantum Level

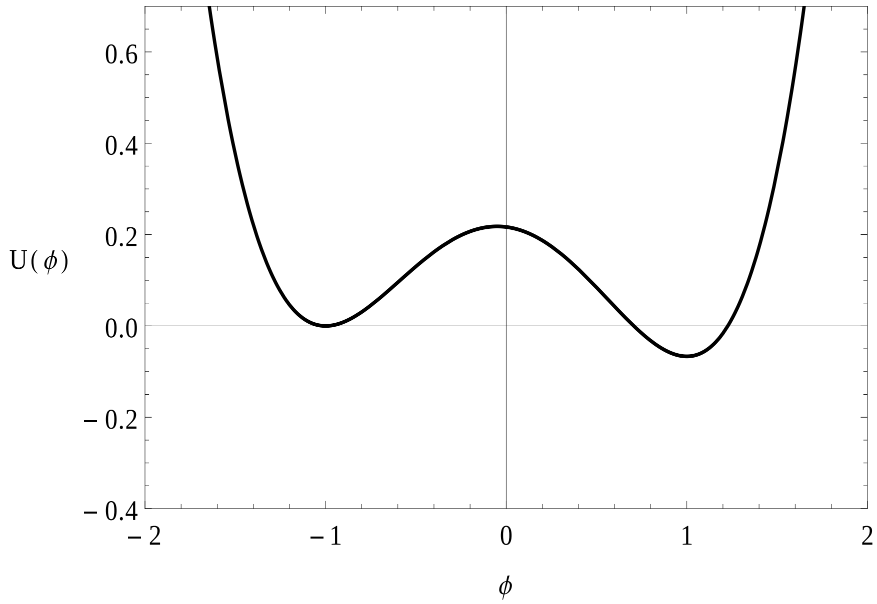
Transition rate as a function of R : ($\mu \sim \frac{1}{R}$)

$$p = \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3\,|\lambda(\mu)|} - \Delta S\right]$$



from : G. Isidori, G. Ridolfi, A. Strumia, Nucl.Phys.B 609 (2001) 387

False Vacuum Decay



Coleman analysis in flat space-time (1977)

Later (1980) Coleman - De Luccia considered the impact of gravity

In both cases... "Thin Wall" ...

In a gravitational background - Thin Wall Approximation

Comparing the action B in the gravitational background with the action B_0 in flat space-time

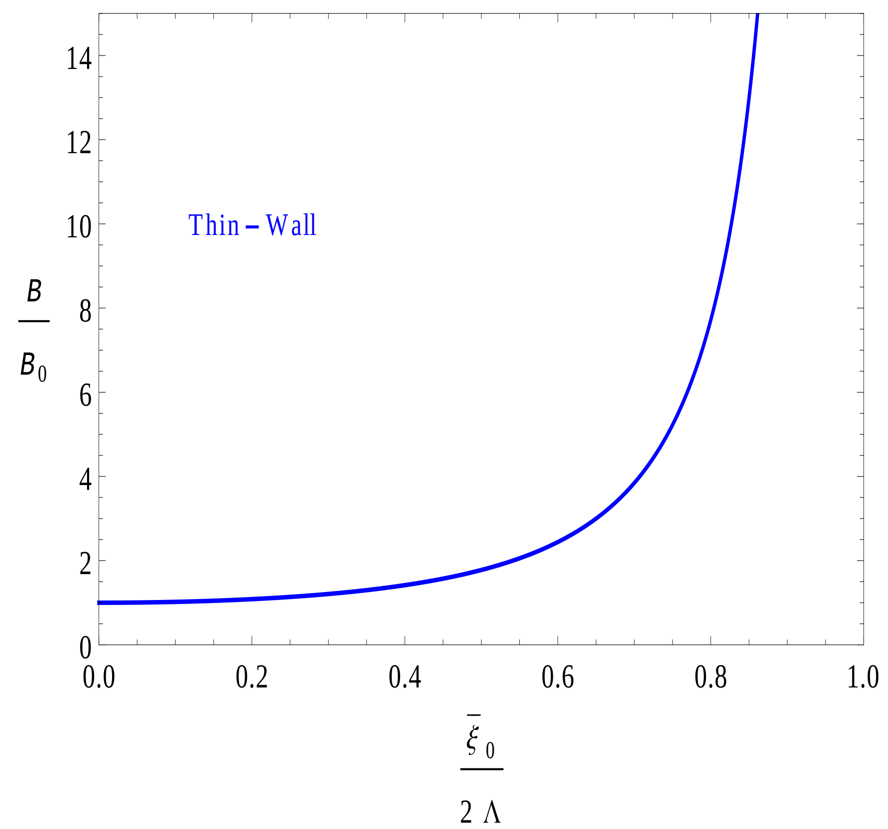
$$B = \frac{B_0}{\left[1 - \left(\bar{\xi}_0/(2\Lambda)\right)^2\right]^2}$$

with

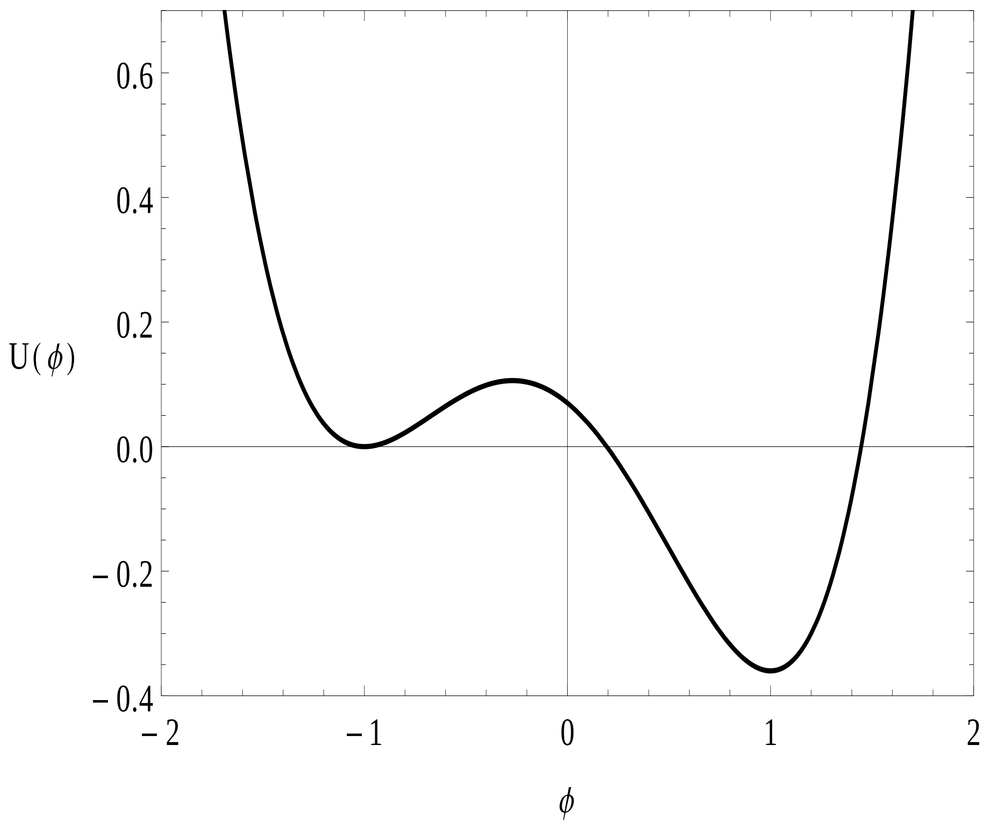
$$\Lambda = (8\pi\, G \cdot \Delta U/3)^{-1/2}$$

and

$$\Delta U = U(\phi_{fv}) - U(\phi_{tv})$$

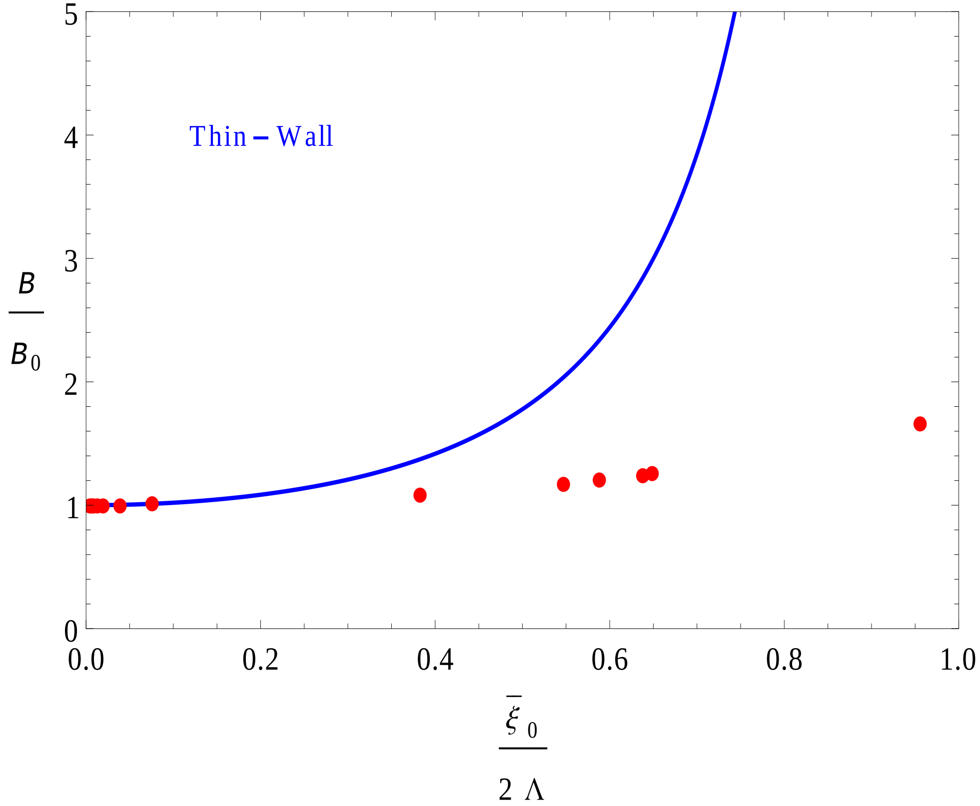

Thin – Wall
B
B0
14
12
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
ξ̄0
2 Λ

Out of Thin Wall



Comparing the action B in the gravitational background with the action B_0 in flat space-time

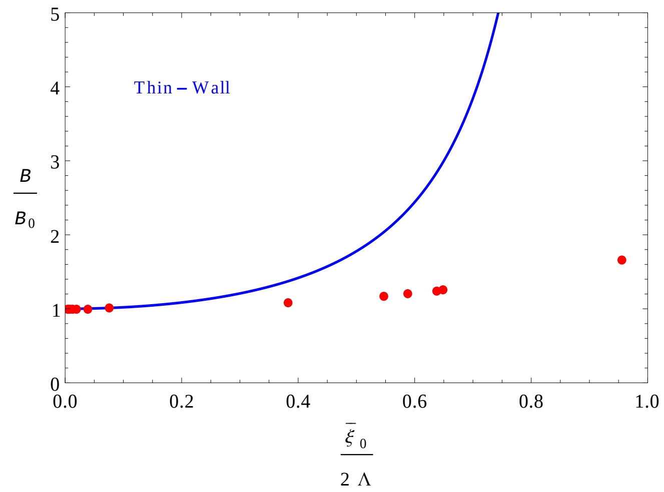
In the Thin Wall Approximation and Out of “Thin Wall”



LESSON

When $U(\phi_{fv}) - U(\phi_{tv})$ is not small, the intuition that we have developed from the Coleman-DeLuccia analysis on the Impact of Gravity does not apply !

It is no longer true that when the Bounce becomes larger and larger, the probability of materialization of the bounce becomes smaller and smaller ... eventually vanishing ...



... "Old Ideas" ...

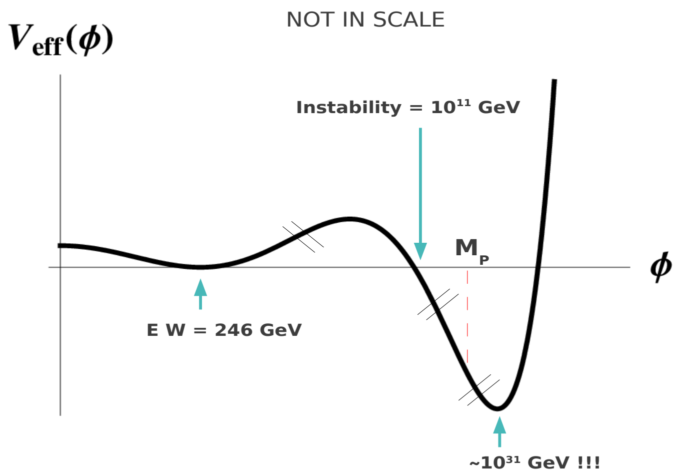
From: **J.R. Espinosa, G.F. Giudice, A. Riotto, JCAP 0805 (2008) 002**

"For most of the relevant values of the top and Higgs masses, the instability scale Λ_{inst} is sufficiently smaller than the Planck mass, **justifying the hypothesis of neglecting effects from unknown Planckian physics**."

From: **Isidori, Ridolfi, Strumia, Nucl.Phys. B609 (2001) 387**

"The SM potential is eventually stabilized by unknown new physics around M_P : because of this uncertainty, we cannot really predict what will happen after tunnelling has taken place. **Nevertheless, a computation of the tunnelling rate can still be performed, this result does not depend on the unknown new physics at the Planck scale.**"

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.